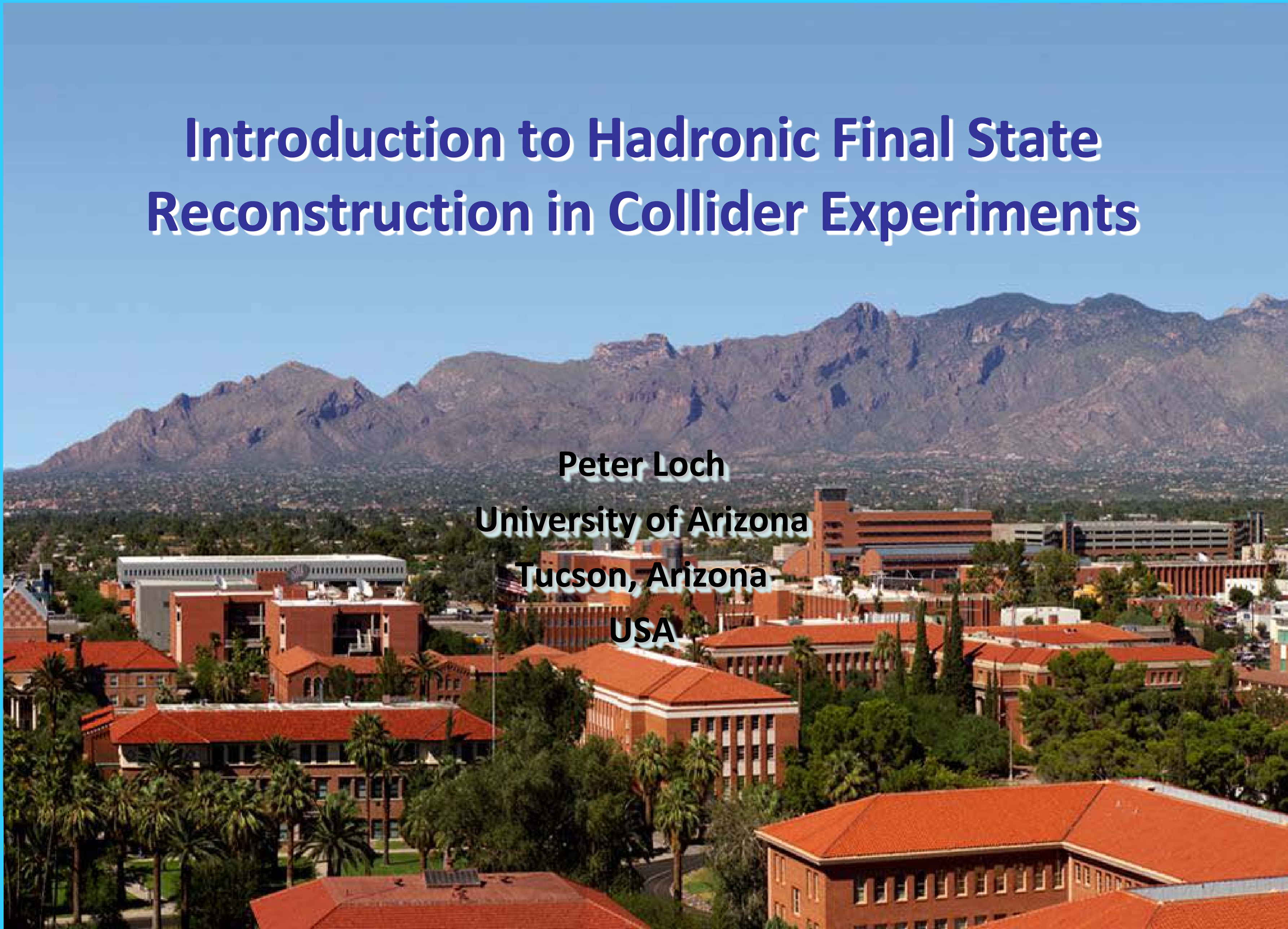

Introduction to Hadronic Final State Reconstruction in Collider Experiments

Peter Loch
University of Arizona
Tucson, Arizona
USA

Preamble

The material presented in this lecture series, which has been designed for ATLAS graduate students at the University of Arizona, is mostly used to explain complex signal features of calorimeters and other detectors we are using to analyze the final states in hadron collider experiments. Its intent is to be educational only, and it most certainly does not represent present evaluations of the actual performance of any of the experiments mentioned. Matter of fact, in some cases older low performance features, long since understood and corrected, are enhanced in the discussion for educational purposes, just to highlight the motivations and tools for the solutions applied. Also, there is a clear bias towards the methodology used by the ATLAS experiment, because I have been involved in this experiment for now 15 years. A serious attempt was made to show only common knowledge or otherwise approved specific material, of course – and to provide citations when available and appropriate.

The more than 200 slides comprising this lecture series would not have been possible to collect without the direct or indirect input from the HERA, Tevatron, and LHC experiment communities, and from colleagues from theory and phenomenology. It is a bit unfortunate that not all the knowledge available today, reflecting the result of hard work of so many people, could be included here. Nevertheless, I like to acknowledge everybody who helped getting us where we are today with the understanding of the detectors and the physics of hadron collisions, in particular with respect to jet reconstruction. I like to recognize and thank the colleagues who, in the last few years, spent nearly endless hours with me discussing topics related to these lectures, and without whom I am sure my own understanding of these subjects would not be as far advanced as it is today. Please find the names on the next slide.

For those of you who are reading these slides, and would like to use them for the purposes they have been put together for, please feel free to do so. Please let me know of any even smallest error or inconsistency, or any improvement concerning the wording and displayed material – thank you for that! I also appreciate suggestions for extension or change of focus, of course. The best way to contact me is by e-mail <loch_AT_physics.arizona.edu>.

Tucson, April 29, 2010

Peter Loch
Department of Physics, University of Arizona
Tucson, Arizona 85721
USA

Acknowledgements

The following people significantly contributed with their work and ideas to the material of this lecture series – in some case probably without their personal knowledge (yes, I was listening). Also, these are the people who pushed my understanding of the jets in the hadron collider environment in sometimes more or less controversial discussions, which I deeply enjoyed, by issuing relevant comments, or by raising interesting questions. Last but not least I am grateful to the colleagues who invited me to report on jet physics related topics at workshops, conferences, and seminars, either in form of lectures, or as introductory or status talks. Thank you all for this – it helped me a lot to understand the often complex signal features we see in hadron collisions.

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Brookhaven National Laboratory (USA)

Ketevi Assamagan, Hong Ma, Frank Paige, Srini Rajagopalan

Carleton University (Canada)

Gerald Oakham, Manuella Vincter

CERN (Switzerland)

David Berge, Tancredi Carli, Daniel Froidevaux, Fabiola Gianotti, Peter Skands, Guillaume Unal

CalTech/Columbia (USA)

David Lopez, K.Perez, Zach Taylor

DESY Hamburg (Germany)

Kerstin Borras, Jörg Gayler, Hannes Jung

Fermi National Laboratory (USA)

W.Giele

Florida State University (USA)

Rick Field

IFAE Barcelona (Spain)

Martine Bosman

INFN Milan (Italy)

Leonardo Carminati, Donatella Cavalli, Silvia Resconi

INFN Pavia (Italy)

Giacomo Polesello

INFN Pisa (Italy)

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Christian Bauer, Beate Heinemann, Marjorie Shapiro, Jesse Thaler

LPSC Grenoble (France)

Pierre-Antoine Delsart

LPNHE /UPMC Universite de Paris 6 (France)

Bernard Andrieu

LPTHE/UPMC Universite de Paris 6 (France)

Matteo Cacciari, Gavin Salam

Michigan State University (USA)

Joey Huston

Max Planck Institut für Physik München (Germany)

Paola Giovaninni, Andreas Jantzsch, Sven Menke, Horst Oberlack, Guennadi Pospelov, Vladimir Shekelyan, Peter Schacht, Rolf Seuster

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Universität Heidelberg (Germany)

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University of Chicago (USA)

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University of Glasgow (UK)

Craig Buttar , Arthur Moraes

University of Oregon (USA)

D.Soper, E. Torrence

University of Oxford (UK)

C.Doglioni, Cigdem Issever

University of Sheffield (UK)

Dan Tovey

University of Toronto (Canada)

Peter Krieger, Richard Teuscher

University of Victoria (Canada)

Frank Berghaus, Michel Lefebvre, Jean-Rafael Lessard, Rob McPherson

University of Washington (USA)

Steve Ellis, Chris Vermillion, Jon Walsh

Not working in HEP anymore…

Levan Babukhadia, Ambreesh Gupta, Kai Voss

… and all the other colleagues whom I may have forgotten and, so I hope, will forgive me for that!

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Roadmap

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U of Arizona
May 05, 2010

ATLAS

Focus on the experimental aspects

- Unfolding hadron collider physics from detector signals
  - Triggering, acceptance, calibration, resolution
- Mostly discussed using the LHC collision experiments (“ATLAS bias”)
  - Accumulation of experiences from previous experiments
  - Occasional highlights from SPS, HERA, Tevatron,…

Lecture style

- Informal
  - Please ask questions – we should have sufficient time!
- Student talks
  - Possibility to present selected aspects (end of semester)

Material

- Some material is private to the ATLAS experiment
  - Mostly used to explain signal features
  - Use only material with publication reference for public talks
- Slides on the web
  - Look for link on http://atlas.physics.arizona.edu/~loch
    - Will try to upload as soon as possible after each session
- Literature
  - Embedded in slides
    - Will extract and put on the web soon!

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Large Hadron Collider

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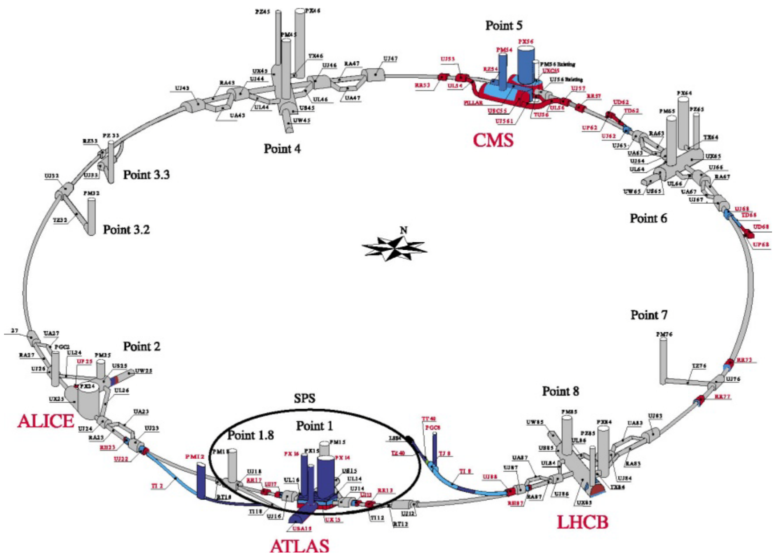

Machine

- Occupies old LEP tunnel at CERN, Geneva, Switzerland & France
- About 27 km long
- 50-100m underground
- 1232 bending magnets
- 392 focusing magnets
- All superconducting
  - ~96 tons of He for ~1600 magnets

Beams (design)

- pp collider
  - 7 TeV on 7 TeV (14 TeV collision energy)
  - Luminosity 10^{34} cm^{-2}s^{-1}
  - 2808 x 2808 bunches
  - Bunch crossing time 25 ns (40 MHz)
  - ~20 pp collisions/bunch crossing
- Heavy ion collider (Pb)
  - Collision energy 1150 TeV (2.76 TeV/nucleon)

Proton acceleration chain:
LINAC→Proton Synchrotron Booster (PSB)→Proton Synchrotron (PS)→Super Proton Synchrotron (SPS)→LHC

Pb ion acceleration chain:
LINAC→Low Energy Ion Injector Ring (LEIR)→Proton Synchrotron (PS)→Super Proton Synchrotron (SPS)→LHC

ATLAS

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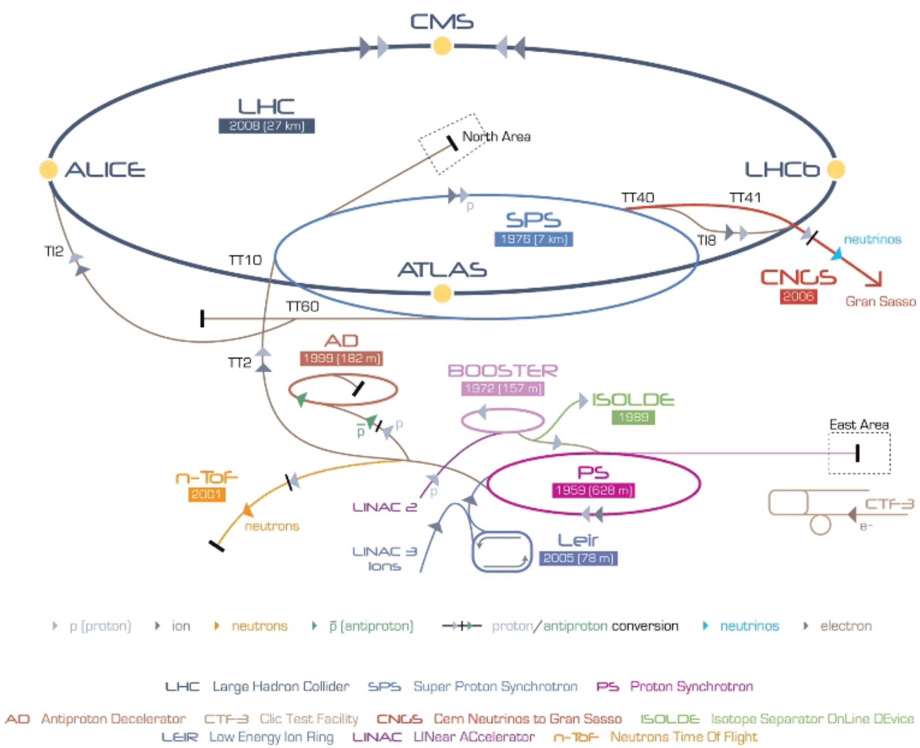
Large Hadron Collider



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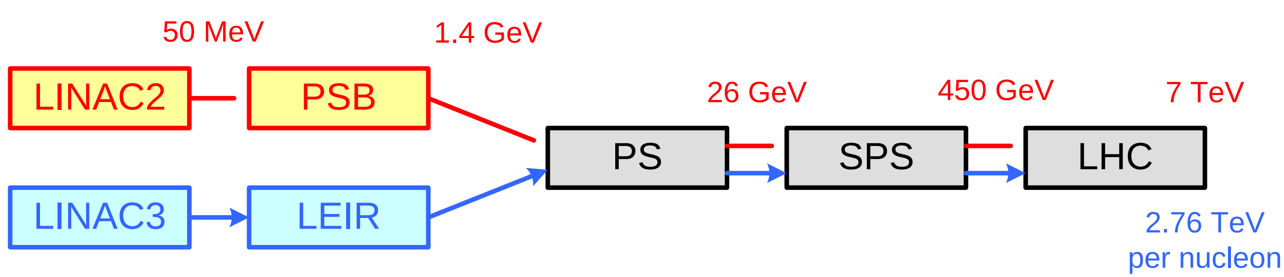

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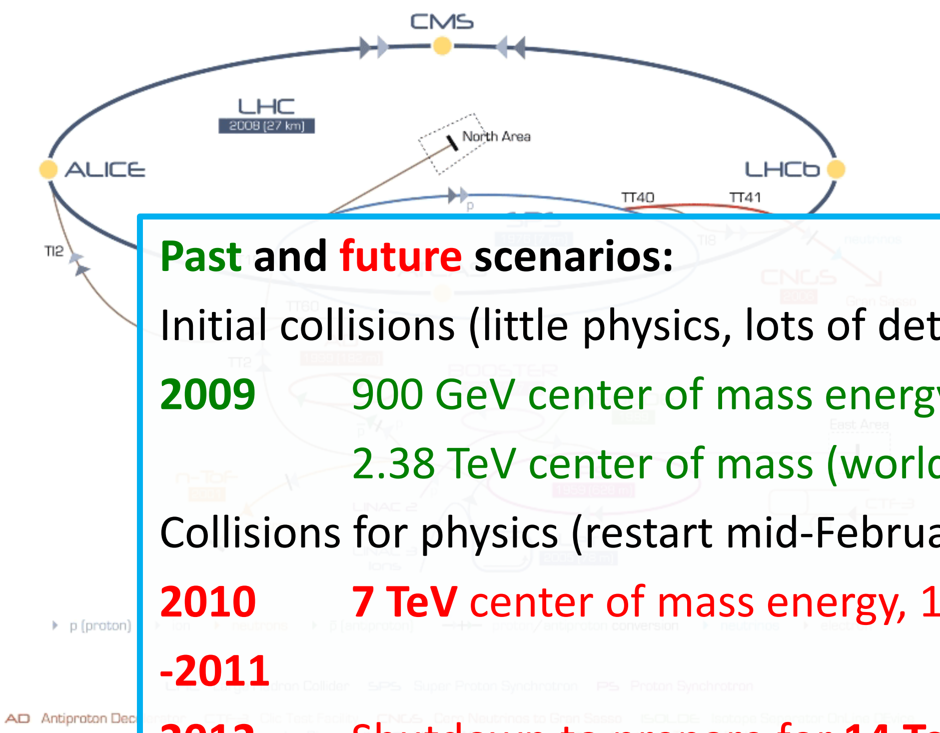

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Past and future scenarios:

Initial collisions (little physics, lots of detector commissioning)

2009 900 GeV center of mass energy

2.38 TeV center of mass (world record)

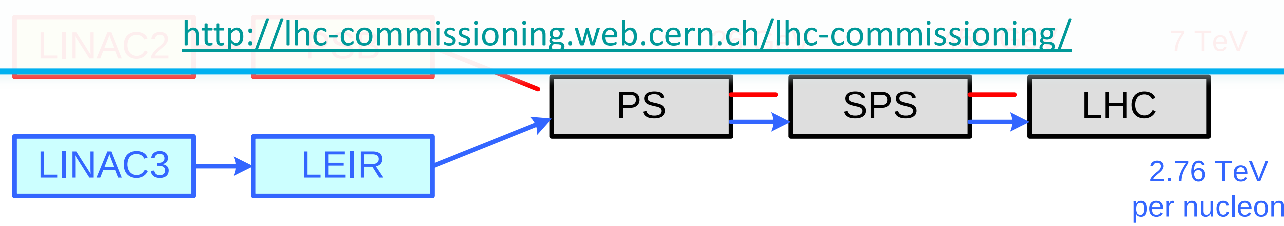
Collisions for physics (restart mid-February 2010)

2010 -2011 **7 TeV** center of mass energy, 10^{29}-10^{32} $cm^{-2}s^{-1}$, up to 1 fb^{-1}

2012 Shutdown to prepare for **14 TeV** center of mass energy

Latest status and plans at

http://lhc-commissioning.web.cern.ch/lhc-commissioning/



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Kinematic Domains @ LHC

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May 05, 2010

Enormous reach in (x,Q^2)

- Low x at relatively high Q^2
- Mostly unvcovered so far

No experimental data for parton densities

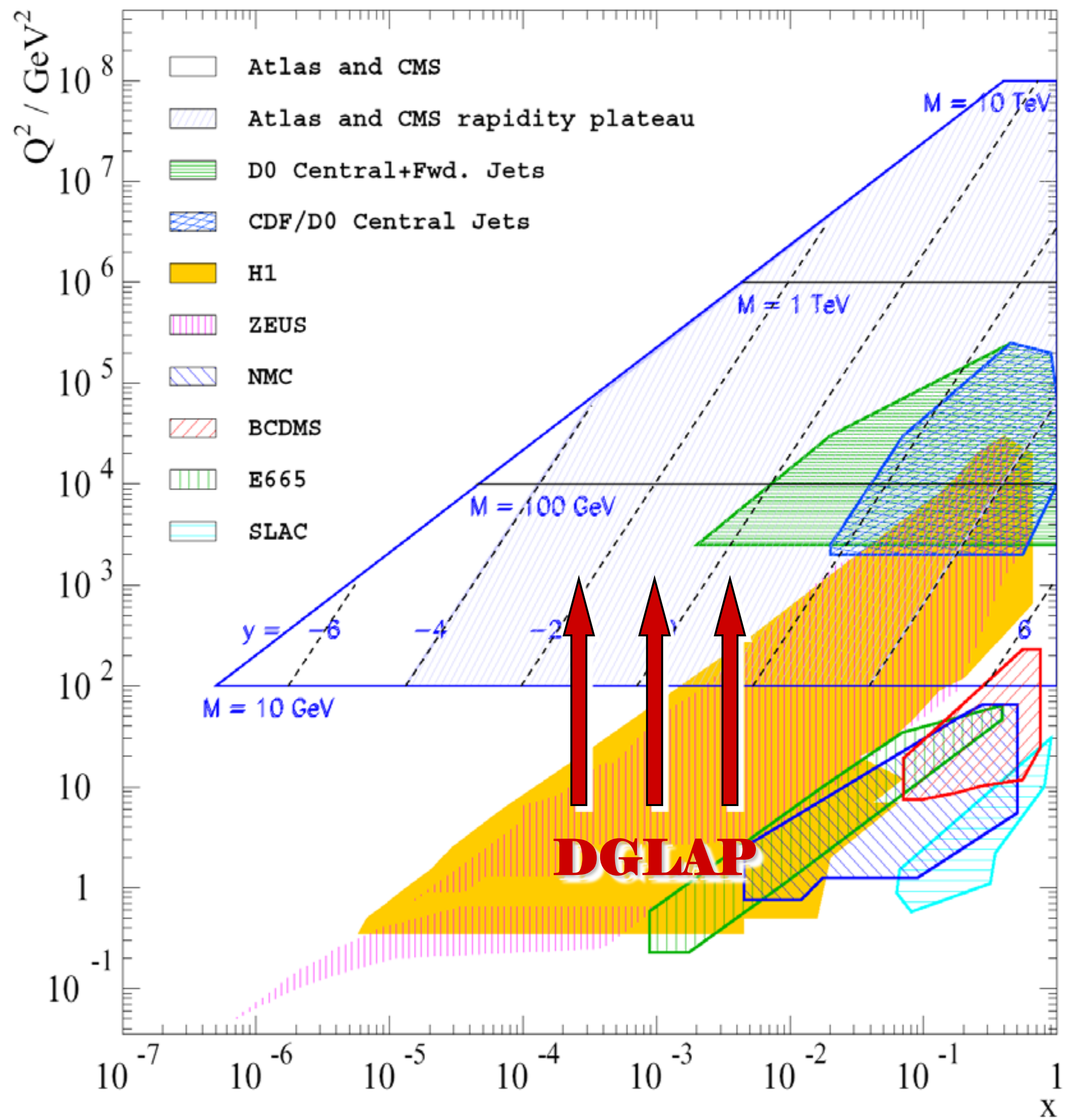
- Validation of proton structure part of LHC physics program
- Must rely on evolution of HERA structure functions

QCD probes whole region

- Di-jet production
- b/c-quark jets
- Prompt photons

$$x_{1,2} = \frac{E_T}{\sqrt{s}}\left(e^{\pm\eta_1} + e^{\mp\eta_2}\right)$$

$$Q^2 \approx 2E_T{}^2 \cosh^2\eta^*\left(1 - \tanh\eta^*\right)$$



Where do Jets come from at LHC?

Fragmentation of gluons and (light) quarks in QCD scattering

Most often observed interaction at LHC

Decay of heavy Standard Model (SM) particles

Prominent example:

$$t \rightarrow bW \rightarrow jjj$$

$$t \rightarrow bW \rightarrow l\nu jj$$

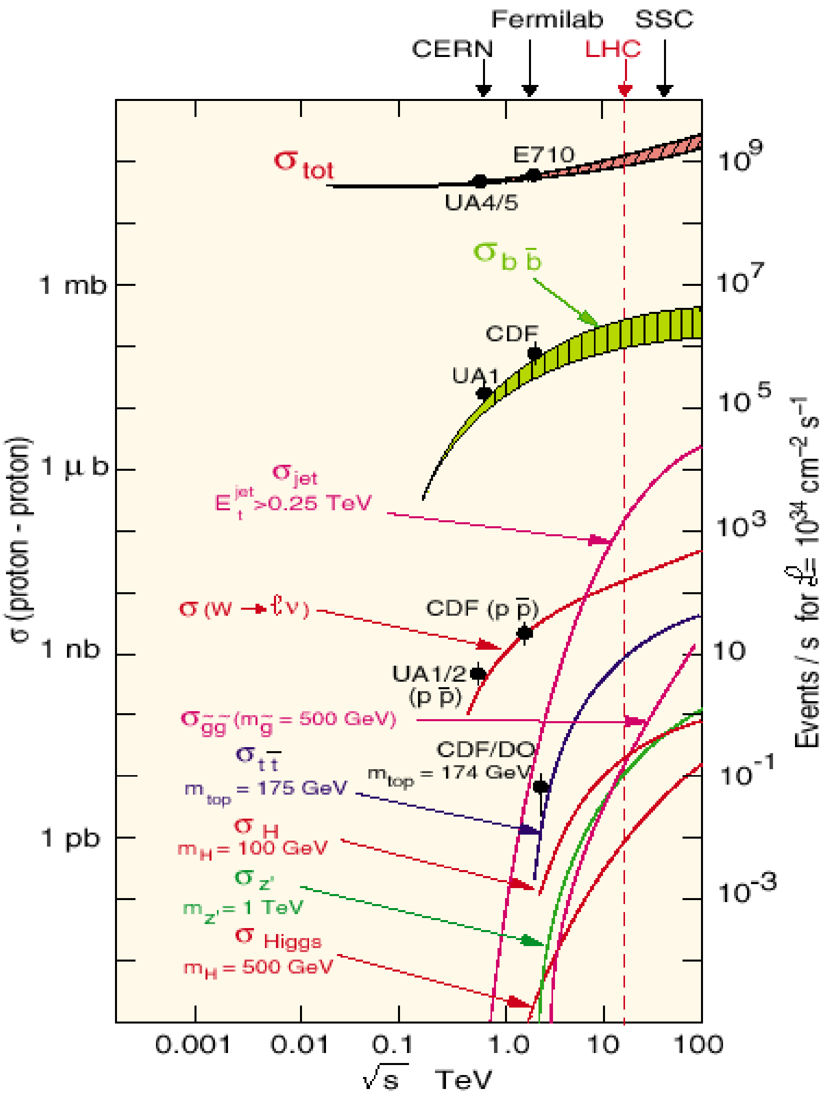
Associated with particle production in Vector Boson Fusion (VBF)

E.g., Higgs

$$qq \rightarrow q'q'WW \rightarrow Hjj$$

Decay of Beyond Standard Model (BSM) particles

E.g., SUSY



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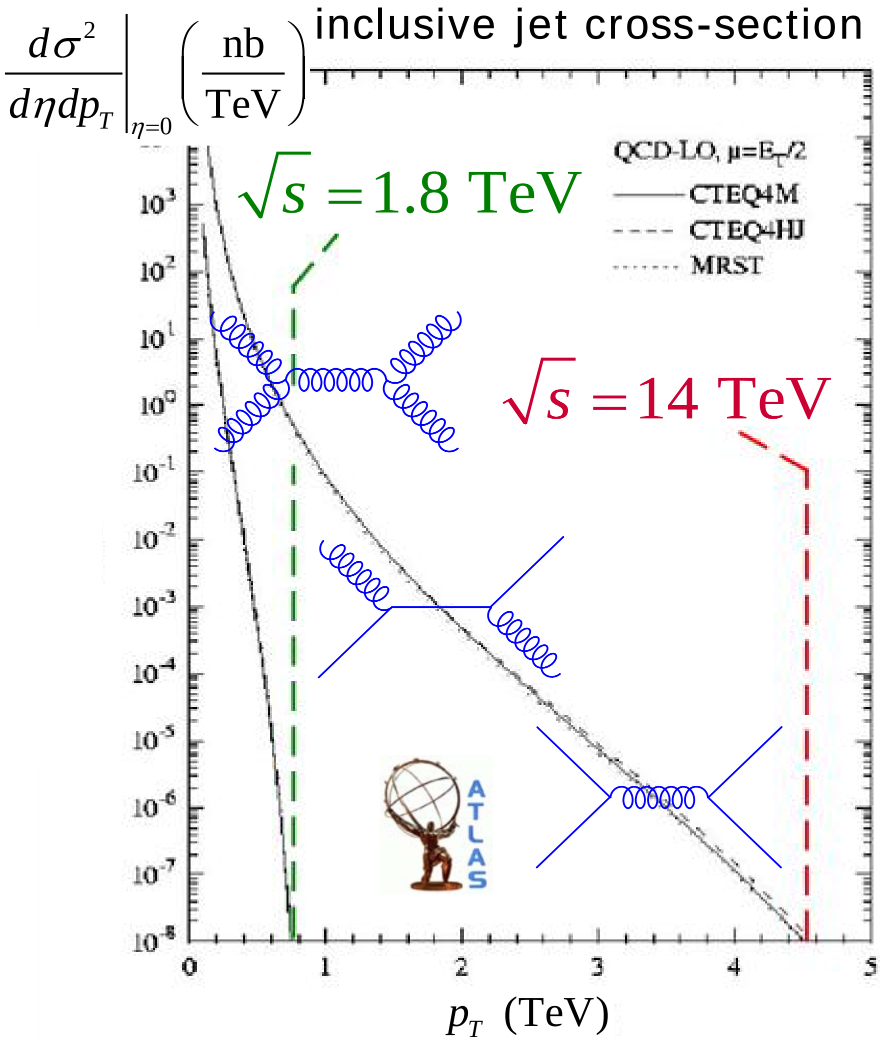

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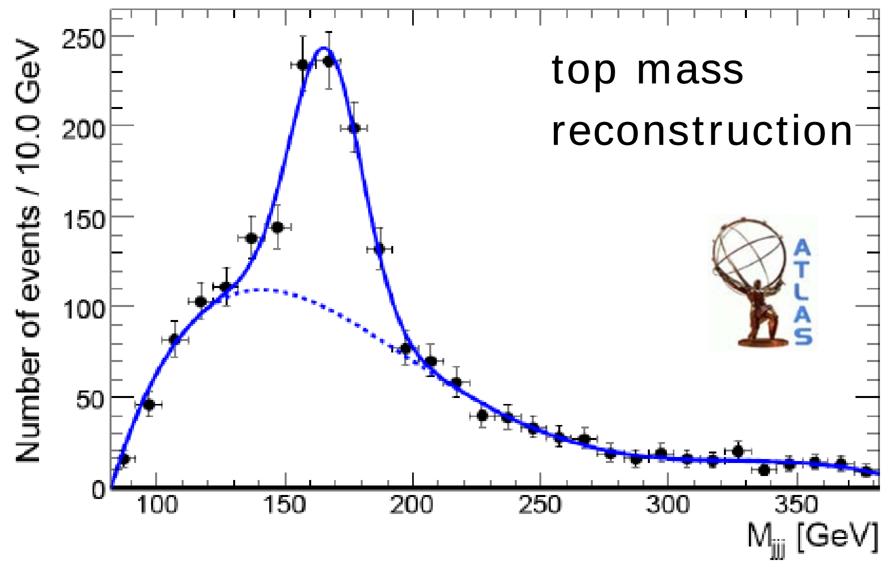

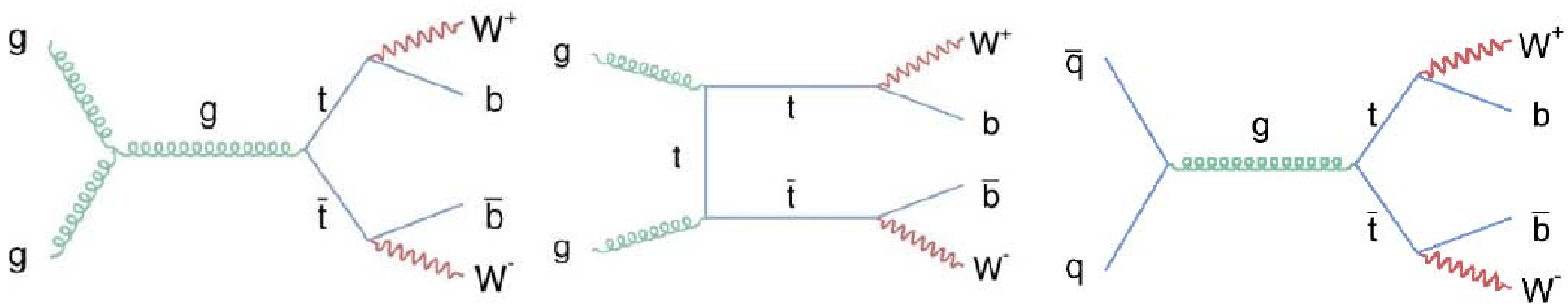

gg→tt 85%   qq→tt 15%

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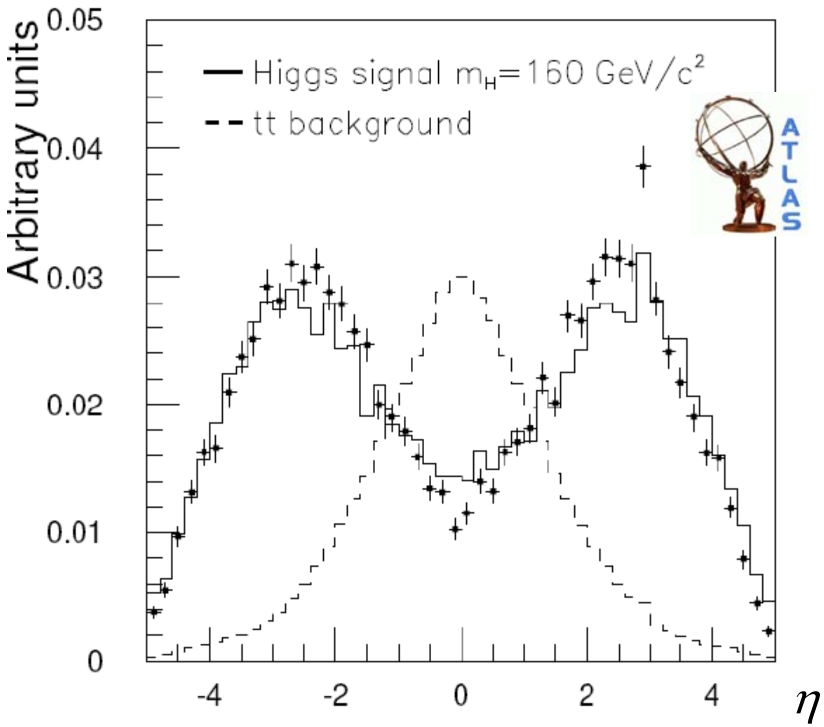

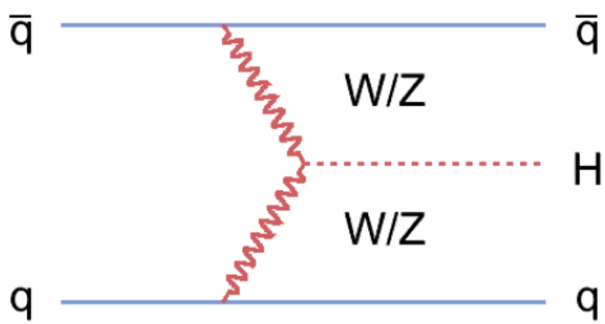

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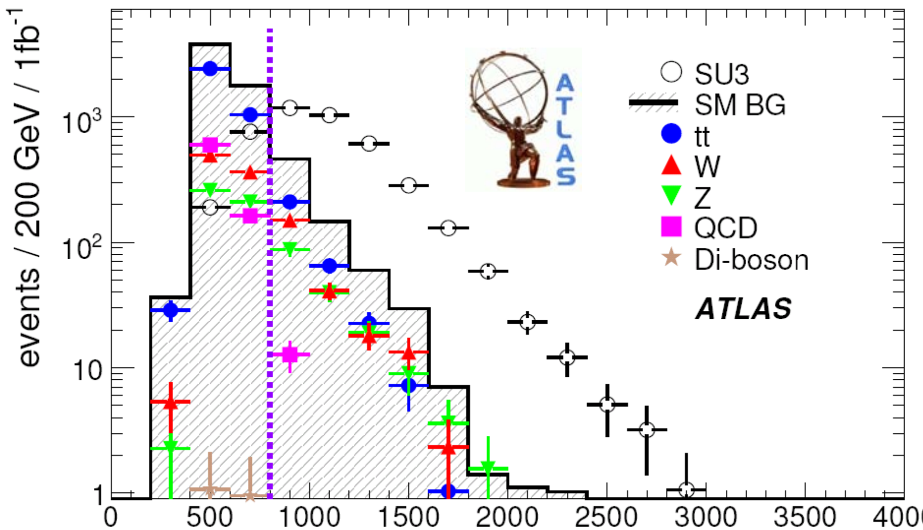
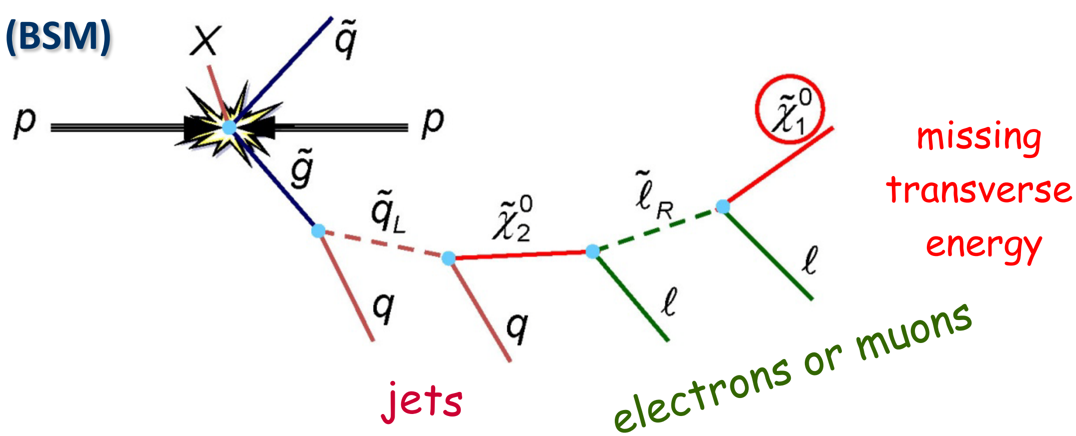


$$M_{eff} = \sum_{\text{jets}} \left| p_{T,j} \right| + \sum_{\text{leptons}} \left| p_{T,\ell} \right| + \not{p}_T$$



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Underlying Event

Collisions of other partons in the protons generating the signal interaction

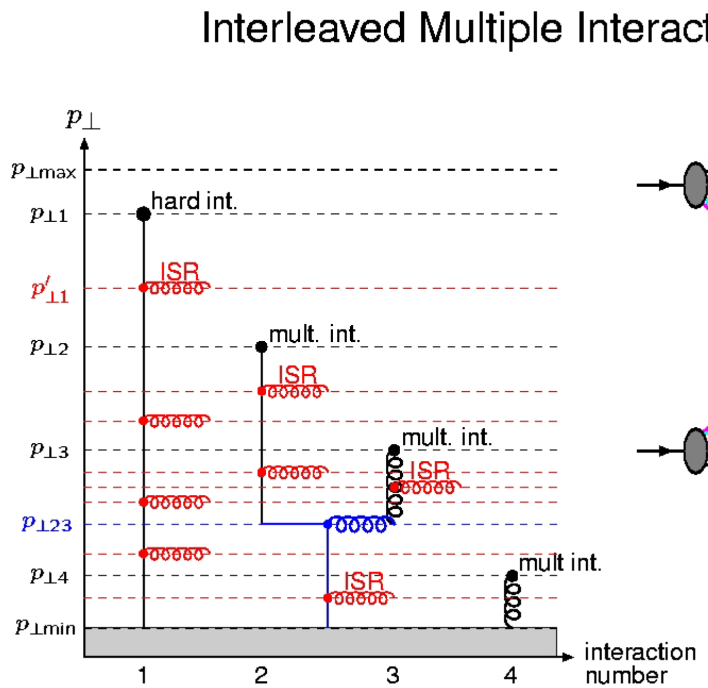
- Unavoidable in hadron-hadron collisions
- Independent soft to hard multi-parton interactions

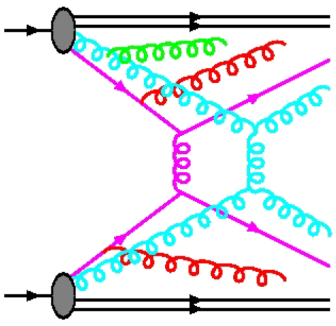
No real first principle calculations

- Contains low pT (non-pertubative) QCD
  - Tuning rather than calculations
- Activity shows some correlation with hard scattering (radiation)
  - pTmin, pTmax differences
- Typically tuned from data in physics generators

Carefully measured at Tevatron

- Phase space factor applied to LHC tune in absence of data
- One of the first things to be measured at LHC





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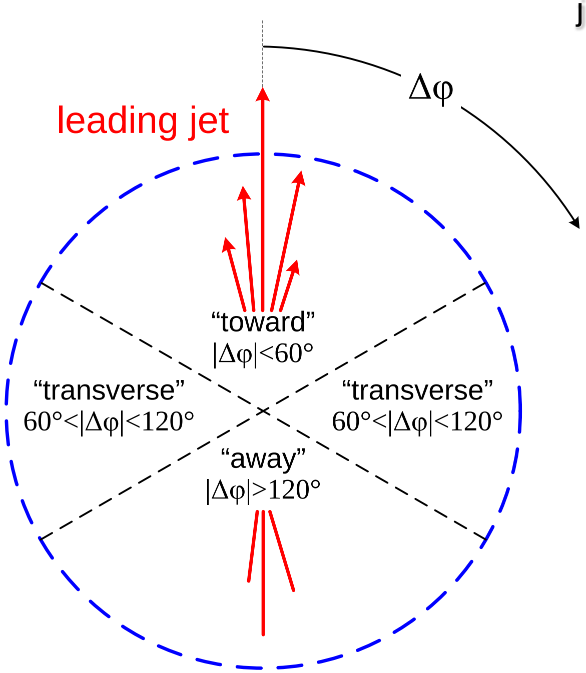
Rick Field's (CDF) view on di-jet events



Look at activity (pT, # charged tracks) as function of leading jet pT in transverse region

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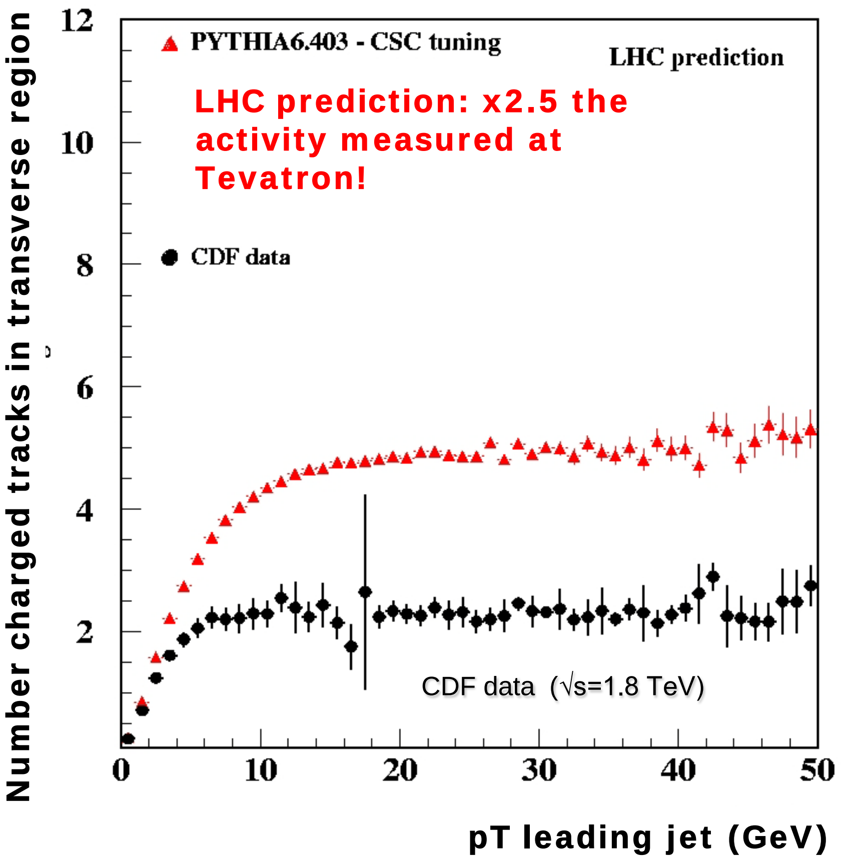
CDF data: Phys.Rev, D, **65** (2002)



Model depending extrapolation to LHC:

$\sim \ln^2 \sqrt{s}$ for PYTHIA

$\sim \ln \sqrt{s}$ for PHOJET

but both agree Tevatron/Sp$\bar{p}$S data!

Multiple interactions between partons in other protons in the same bunch crossing

- Consequence of high rate (luminosity) and high proton-proton total cross-section (~75 mb)

Statistically independent of hard scattering

- Similar models used for soft physics as in underlying event

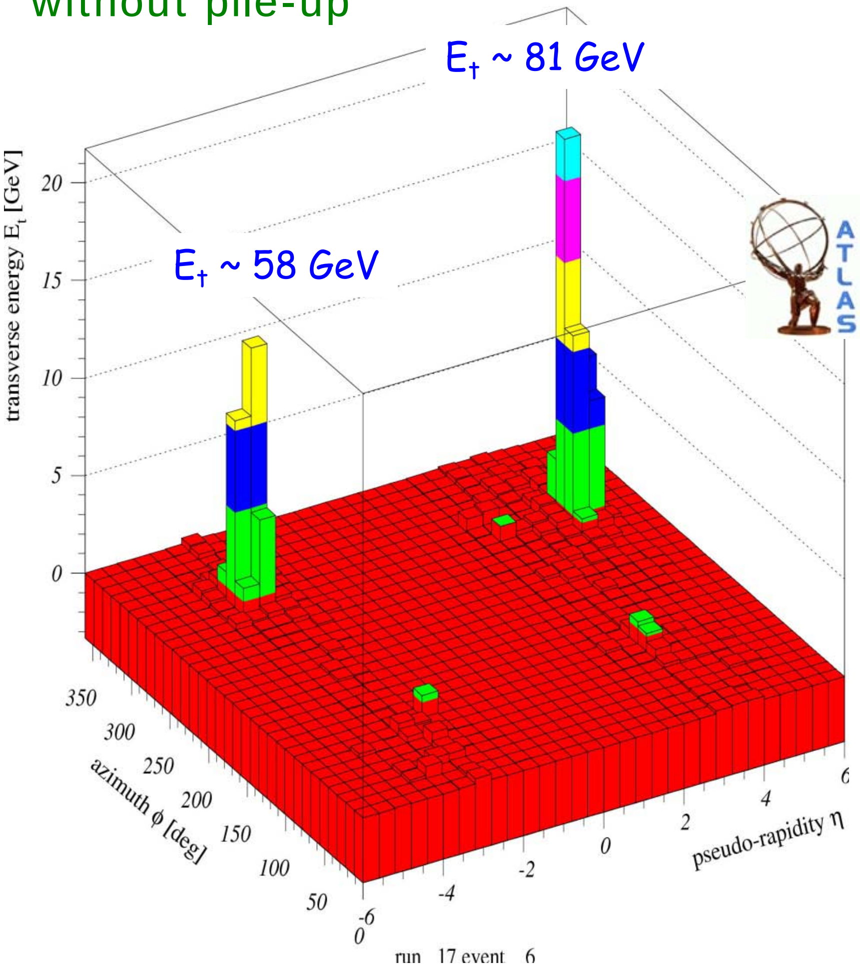
Signal history in calorimeter increases noise

- Signal 10-20 times slower (ATLAS) than bunch crossing rate (25 ns)

Noise has coherent character

- Cell signals linked through past shower developments

without pile-up



Prog.Part.Nucl.Phys. 60:484-551,2008

Pile-Up

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U of Arizona
May 05, 2010

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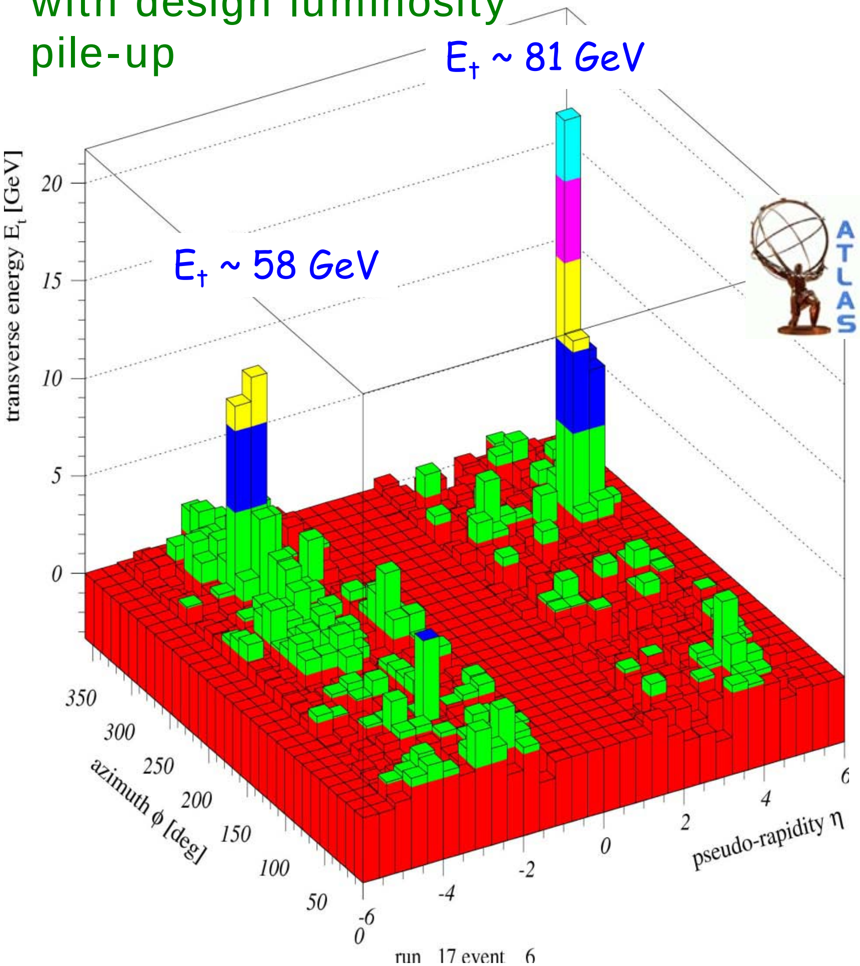

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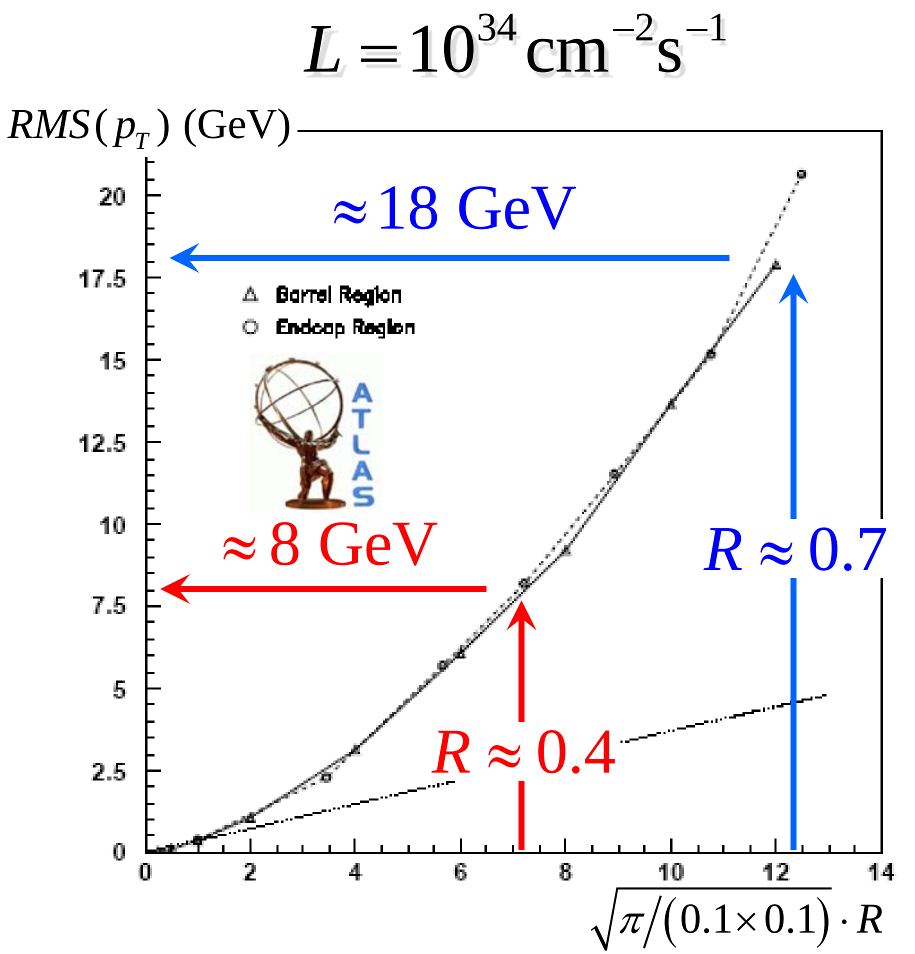

Prog.Part.Nucl.Phys. 60:484-551,2008

Jet calibration requirements very stringent

- Systematic jet energy scale uncertainties to be extremely well controlled
  - Top mass reconstruction
  - Jet cross-sections
- Relative jet energy resolution requirement
  - Inclusive jet cross-section
  - Di-quark mass spectra cut-off in SUSY

$$\Delta m_{top} < 1\ \mathrm{GeV} \Rightarrow \frac{\Delta E_{\mathrm{jet}}}{E_{\mathrm{jet}}} < 1\%$$

$$\frac{\sigma}{E} = \begin{cases} \frac{50\%}{\sqrt{E(\mathrm{GeV})}} \oplus 3\% & |\eta| < 3 \\ \frac{100\%}{\sqrt{E(\mathrm{GeV})}} \oplus 5\% & |\eta| > 3 \end{cases}$$

Event topology plays a role at 1% level of precision

- Extra particle production due to event color flow
  - Color singlet (e.g., *W*) vs color octet (e.g., gluon/quark) jet source
- Small and large angle gluon radiation
  - Quark/gluon jet differences

Detector needs for multi-purpose collider experiments

- Tracking for charged particle momentum measurement
- Calorimeters for charged and neutral particle energy measurement
- Muon spectrometers (tracking) for muon momentum measurements

Underlying physics for calorimetry: particle interaction with matter

- Electromagnetic cascades
- Hadronic cascades
- Muon energy loss

Calorimetric principles in particle detection

- Conversion of deposited energy into an extractable signal in homogeneous and sampling calorimeters
- Minimum ionizing particles and muons
- General signal features of electromagnetic and hadronic showers

Calorimeter characteristics in sampling calorimeters

- Sampling fraction
- Signal linearity and relative resolution
- Non-compensation

Signal extraction

- Charge collection
- Current measurement
- Pulse shapes

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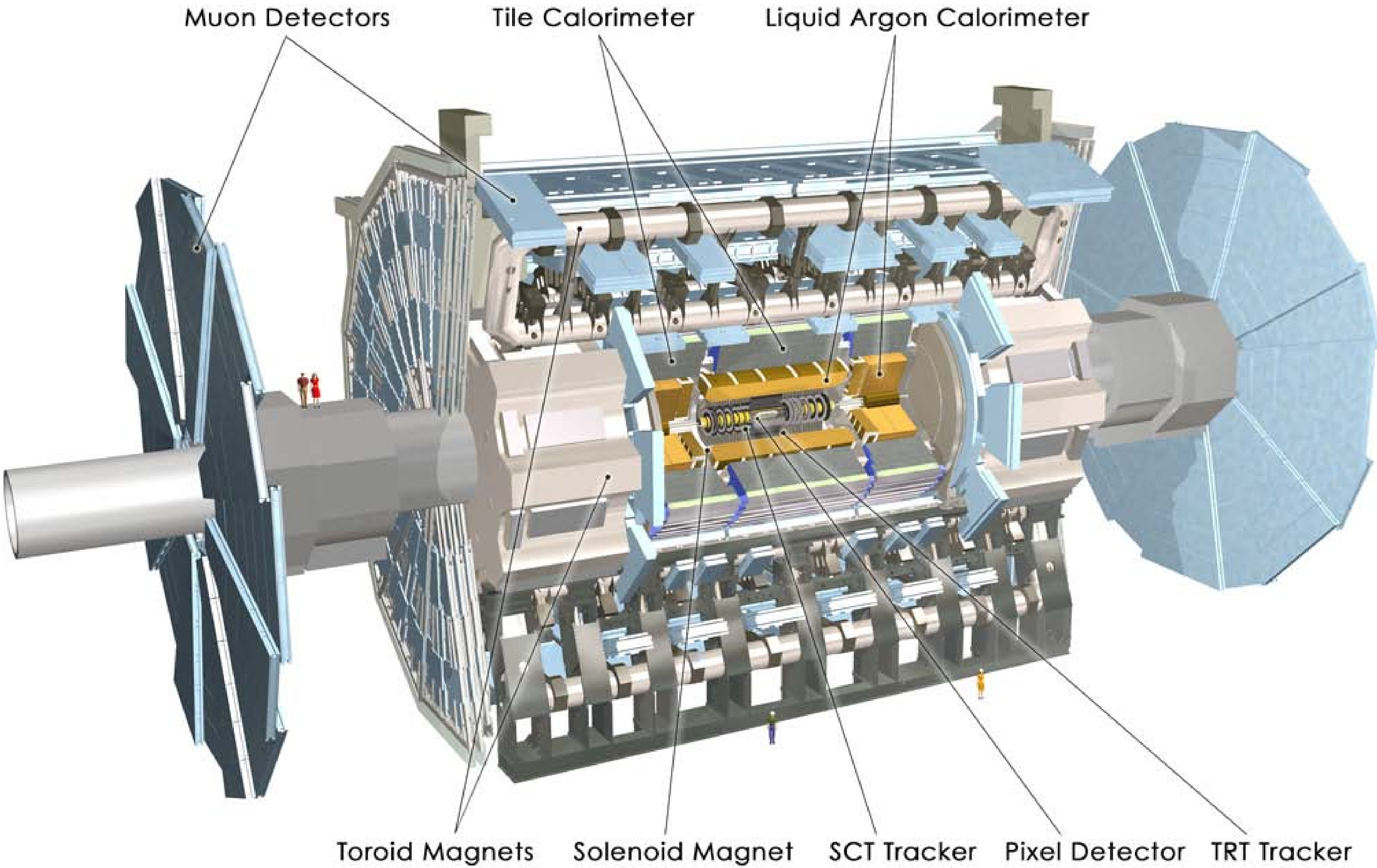
ATLAS – Multipurpose LHC Detector

P. Loch
U of Arizona
May 05, 2010



Total weight : 7000 t
Overall length: 46 m
Overall diameter: 23 m
Magnetic field: 2T solenoid
+ toroid

ATLAS

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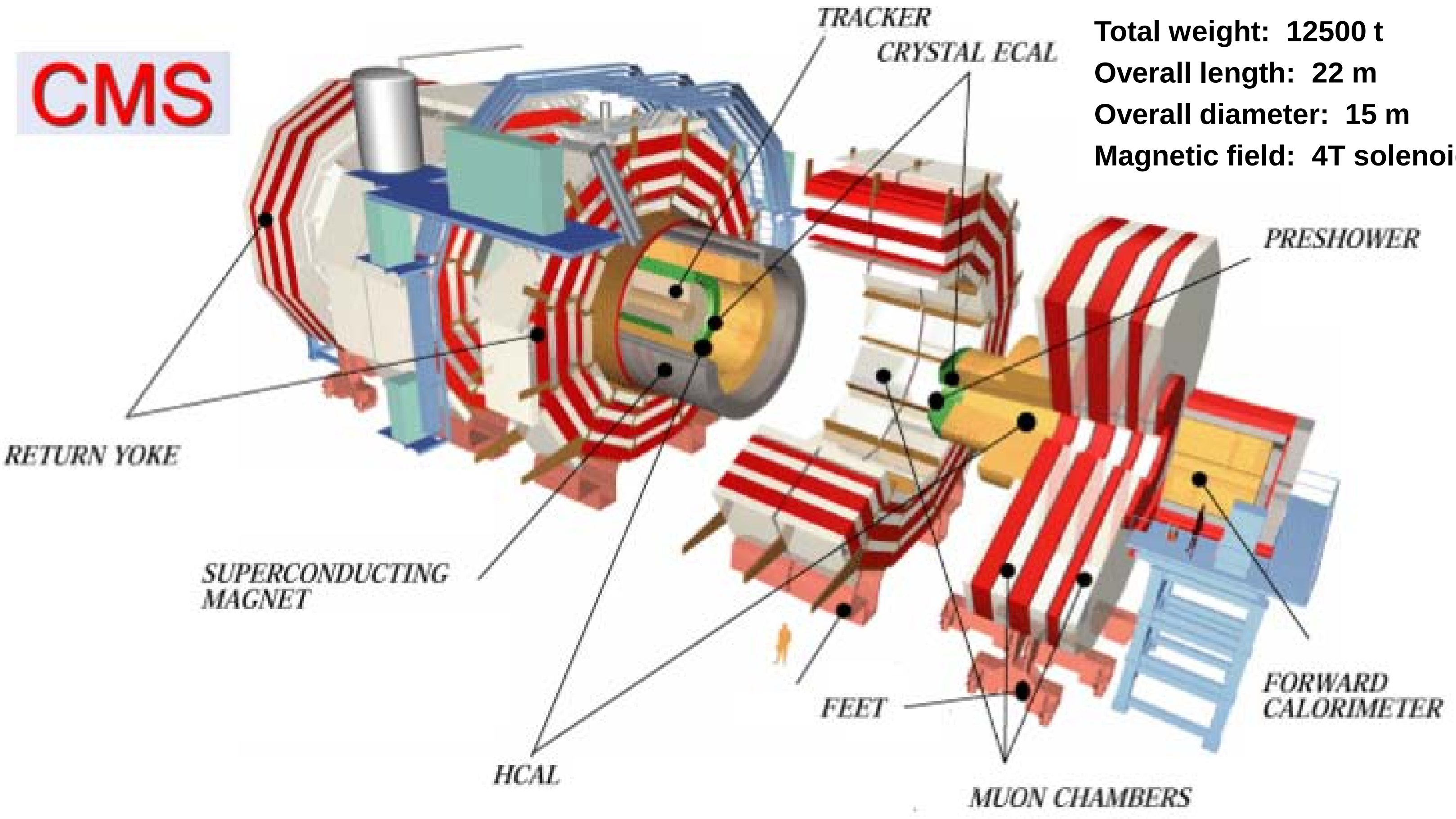
CMS – Multipurpose LHC Detector

P. Loch
U of Arizona
May 05, 2010

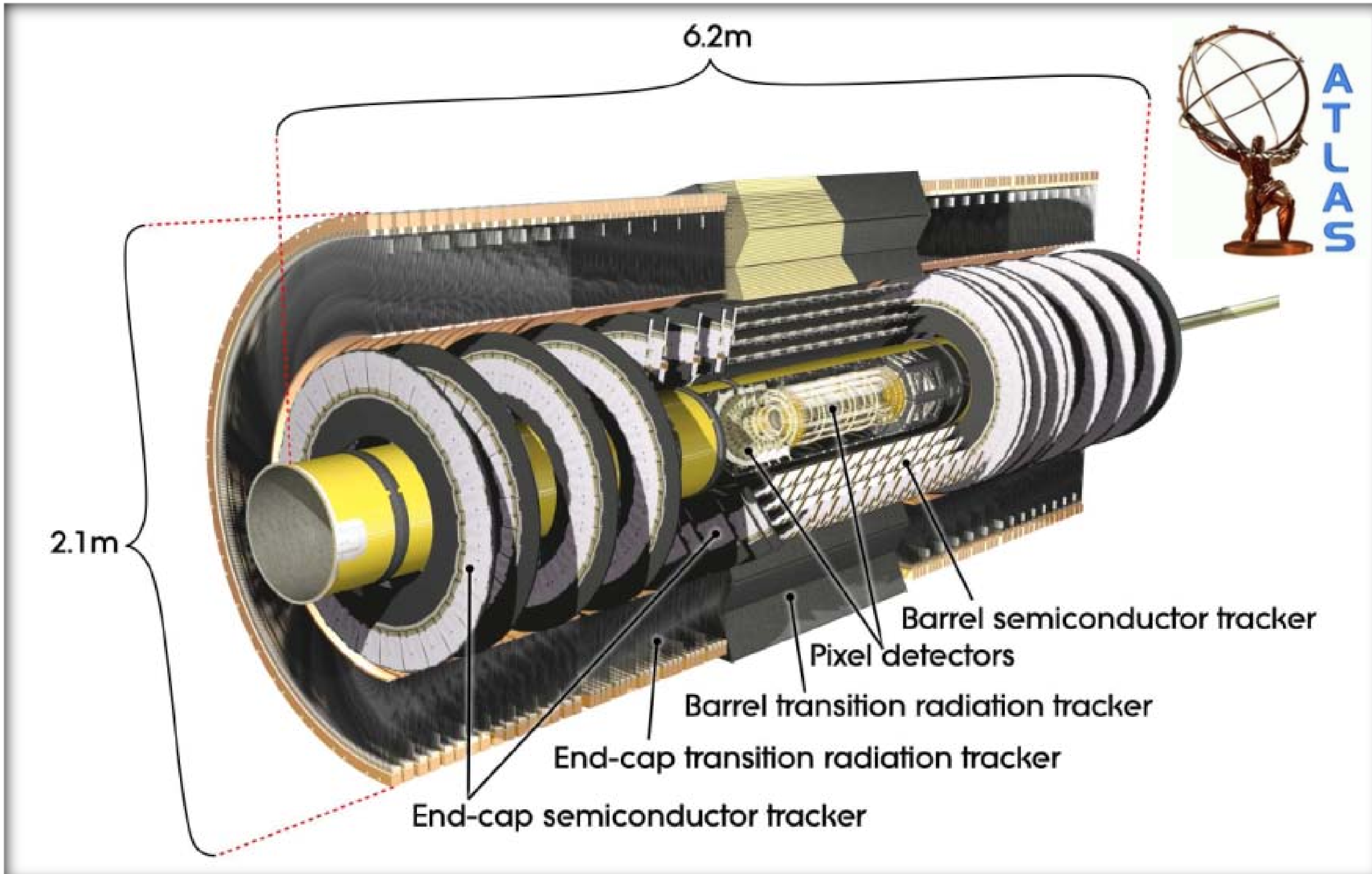


Total weight: 12500 t
Overall length: 22 m
Overall diameter: 15 m
Magnetic field: 4T solenoid

Tracking (inner detector)

- Closest to the interaction vertex
- Reconstructs charged particle tracks in magnetic field
  - Charged particles generate current Silicon pixel elements → fit tracks to (x,y,z) space points defined by hit sensor location
  - Collect secondary charges from gas ionizations by passing charged particles on wires in electric fields → fit tracks to space point in (x,y) plane and z from pulse timing
  - Solenoid field allows very precise pT reconstruction and less precise p reconstruction
- Reconstructs interaction vertices
  - Vertex reconstructed from track fits
  - More than one vertex possible
    - B-decays
    - Multiple proton interaction (pile-up)
  - Primary vertex defined by $\sum_{\text{tracks}} p_T = \max$ or $\sum_{\text{tracks}} p_T^2 = \max$
- Advantages and limitations
  - Very precise for low pT measurements $\frac{\Delta p_T}{p_T} \sim p_T$
  - Only sensitive to charged particles
  - Limited polar angle coverage
    - Forward region in experiment excluded

Tracking (inner detector)



x,y,z)

es on
pulse

Very precise for low pT measurements ~ p_T

p_T

Only sensitive to charged particles

Limited polar angle coverage

Forward region in experiment excluded

Calorimeters

- Usually wrapped around inner detector
- Measures the energy of charged and neutral particles
  - Uses the energy deposited by particles to generate signal
  - Collects light or electric charges/current from this energy deposit in relatively small volumes
  - Only works if particle energy can be fully absorbed
- Signals are space points with energy
  - Reconstructs direction and energy from known position of energy deposit
  - Needs assumption for "mass" to convert signal to full four momentum
    - ATLAS: m = 0
- Advantages and limitations
  - Gets more precise with increasing particle energy
  - Gives good energy measure for all particles except muons and neutrinos
    - Muons not fully absorbed!
  - Large coverage around interaction region
    - "4 π" detector – except for holes for beam pipes
  - Relation of incoming (deposited) energy and signal is particle type dependent
    - Also need to absorb all energy – large detector system
  - Does not work well for low energies
    - Particles have to reach calorimeter
    - Noise in readout
  - Slow signal formation in LHC environment

Detector Systems in Multi-purpose Collider Experiments (2)

P. Loch
U of Arizona
May 05, 2010

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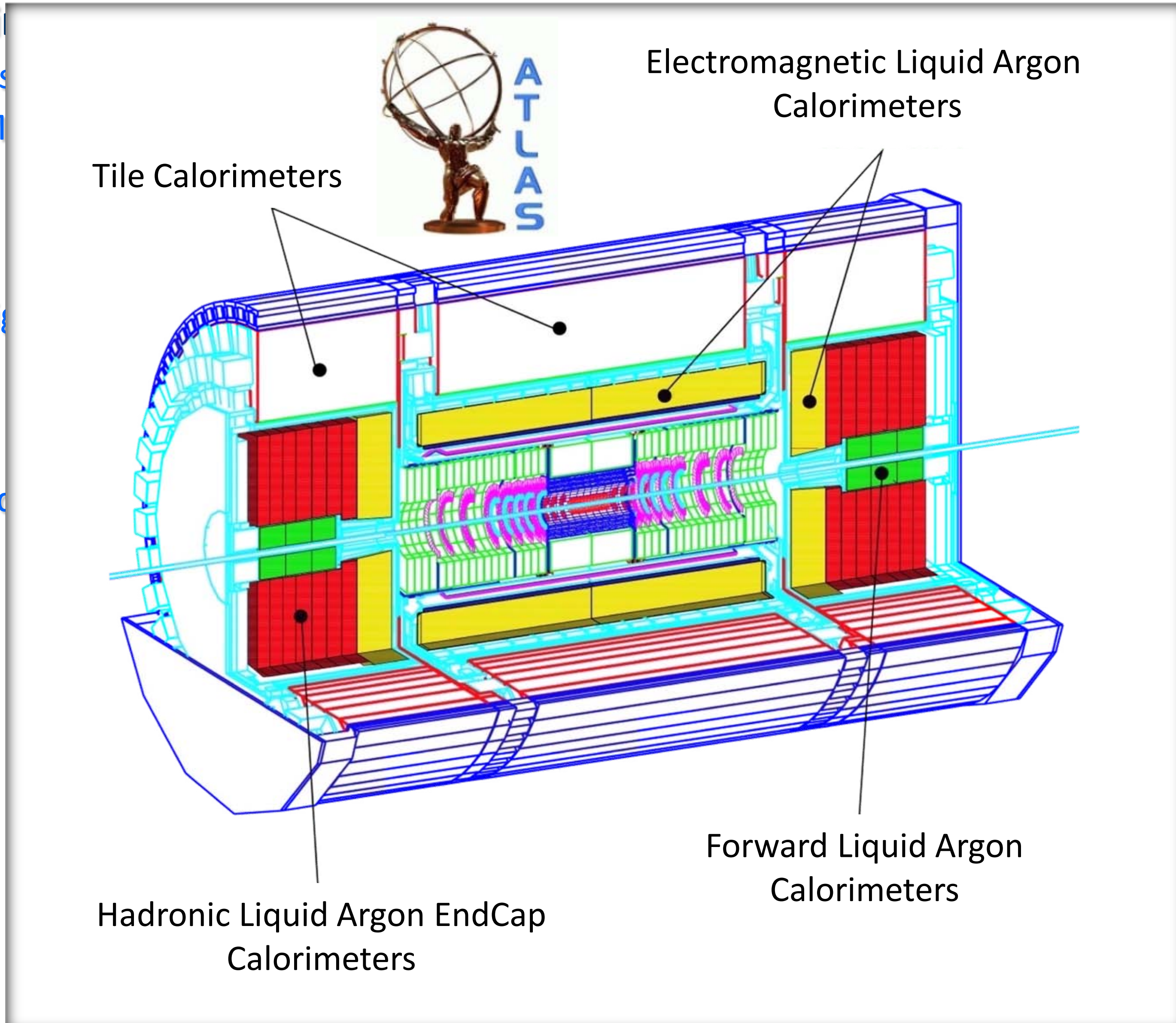

Cascades or showers

- Most particles entering matter start a shower of secondary particles
  - Exception: muons and neutrinos
- The character of these cascades depends on the nature of the particle
  - Electrons, photons: cascades are formed by QED processes
  - Hadrons: cascades are dominantly formed by QCD processes
- Extensions/size of these showers
  - Again depends on particle type
  - Electromagnetic showers typically small and compact
  - Hadronic showers much larger
  - Common feature: shower depths scales approximately as log(E)
    - Higher energies do not require much deeper detectors!

Shower development and age

- Shower maximum
  - Depth at which energy of shower particles is too small to continue production of secondaries
- Age of shower
  - Depth of shower
- Shower width
  - Extend of shower perpendicular to direction of flight of incoming particle

Electromagnetic Showers

QED drives cascade development

- High energetic electrons entering material emit photons in the electric field of the nuclei
  - Bremsstrahlung
- High energetic photons produce e+e- pairs in the electric field of the nuclei
  - Pair production

Rossi's shower model (1952!)

- Simple model of interplay of electron energy loss and photon pair production
  - Uses critical energy as cutoff for shower development

Electron energy loss through bremsstrahlung after 1 radiation length (X_0) in matter: $E_0/2$

Assume this energy is taken by 1 photon, meaning the energy of each shower particle after $t\ X_o$ is: $E(t) = E_0/2^{N(t)}$, with $N(t) = 2^t$

The shower develops until $E(t) = E_c$ (critical energy - ionization loss becomes large and suppresses further radiation) at the shower maximum $t_{\max} = \frac{\ln(E_0/E_c)}{\ln 2}$

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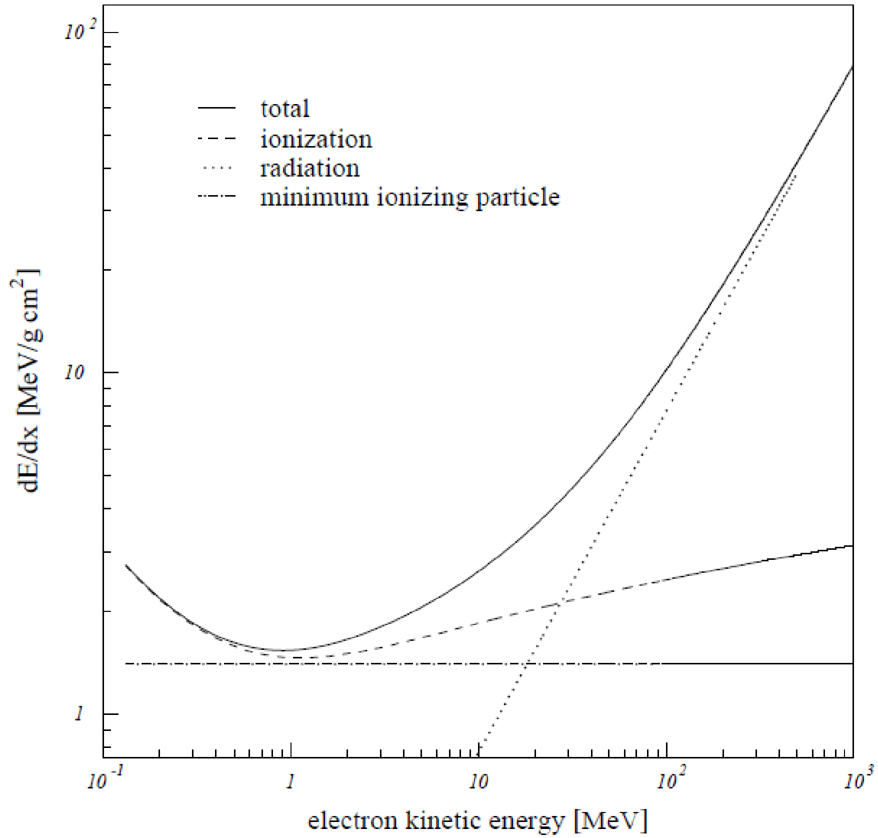

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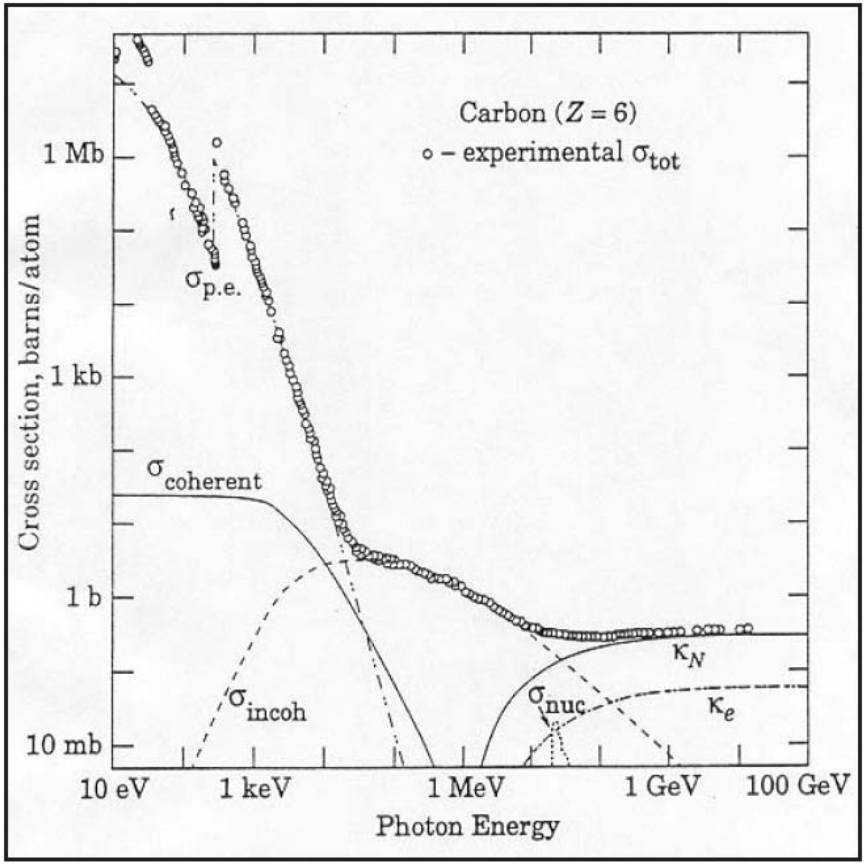

QCD drives fast shower development

- Hadron interactions with nucleon in nuclei
  - Like a fixed target collision
  - Develops intra-nuclear cascade (fast)
- Hadron production
  - Secondary hadrons escape nucleus
  - Neutral pions decay immediately into 2 photons → electromagnetic cascade
  - Other hadrons can hit other nucleons → internuclear cascade

Slow de-excitation of nuclei

- Remaining nucleus in excited state
  - Evaporates energy to reach stable (ground) state
  - Fission and spallation possible
- Binding energy and low energetic photons

Large process fluctuations

- ~200 different interactions
- Probability for any one of those < 1%!

QCD drives fast shower development

Hadron interacts with nucleon in nuclei

Had

etic cascade

Slow d

Rem

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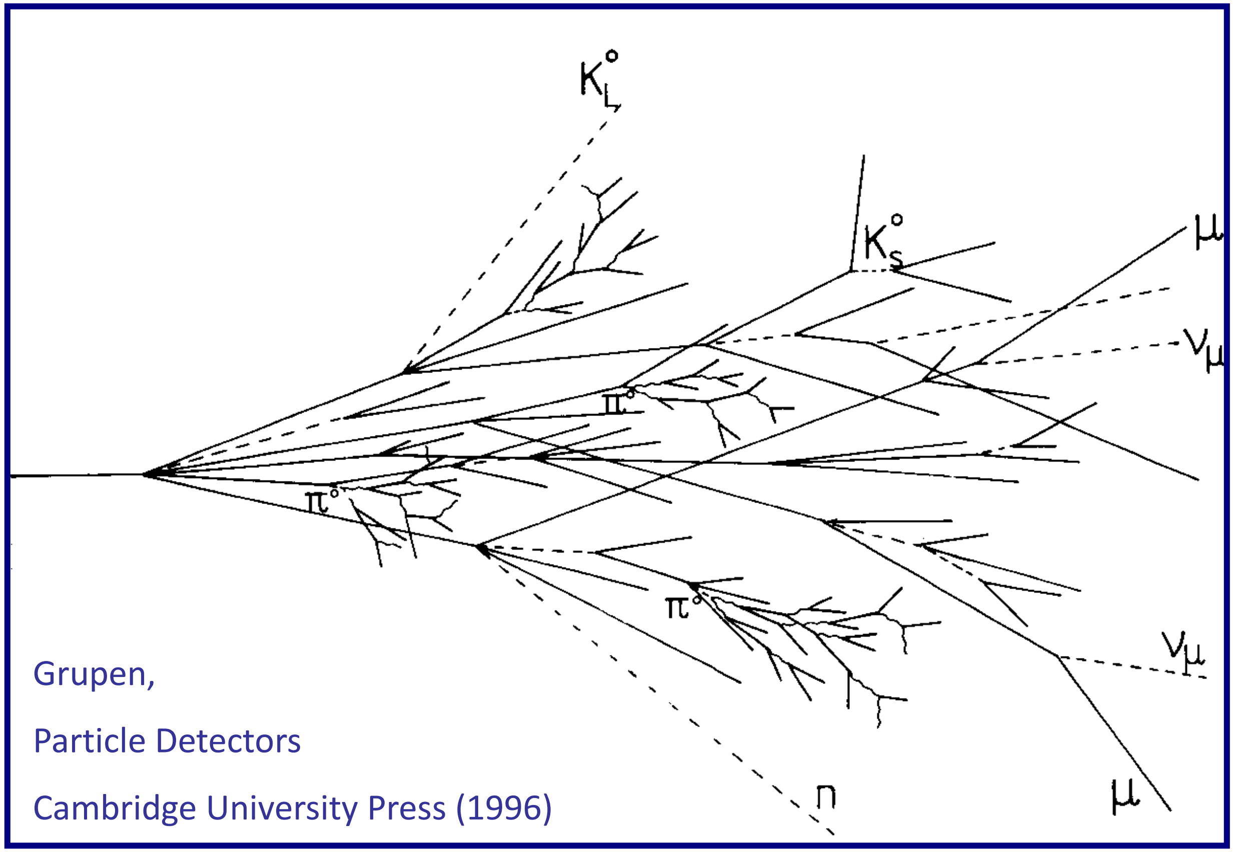
Large p



Grupen,

Particle Detectors

Cambridge University Press (1996)

~200 different interactions

Probability for any one of those < 1%!

Full absorption detector

- Idea is to convert incoming particle energy into detectable signals
  - Light or electric current
  - Should work for charged and neutral particles
- Exploits the fact that particles entering matter deposit their energy in particle cascades
  - Electrons/photons in electromagnetic showers
  - Charged pions, protons, neutrons in hadronic showers
  - Muons do not shower at all in general

Principal design challenges

- Need dense matter to absorb particles within a small detector volume
  - Lead for electrons and photons, copper or iron for hadrons
- Need "light" material to collect signals with least losses
  - Scintillator plastic, nobel gases and liquids
- Solution I: combination of both features
  - Crystal calorimetry, BGO
- Solution II: sampling calorimetry

Sampling calorimeters

- Use dense material for absorption power…
  - No direct signal
- …in combination with highly efficient active material
  - Generates signal
- Consequence: only a certain fraction of the incoming energy is directly converted into a signal
  - Typically 1-10%
- Signal is therefore subjected to sampling statistics
  - The same energy loss by a given particle type may generate different signals
  - Limit of precision in measurements

Need to understand particle response

- Electromagnetic and hadronic showers

Electromagnetic showers

- Particle cascade generated by electrons/positrons and photons in matter
- Developed by bremsstrahlung & pair-production

Compact signal expected

- Regular shower shapes
    - Small shower-to-shower fluctuations
- Strong correlation between longitudinal and lateral shower spread

RD3 note 41, 28 Jan 1993

Shower depth scales in radiation length X_0 :

$$X_0 \approx \frac{716.4 \cdot A}{Z(Z+1)\ln\frac{278}{\sqrt{Z}}}\ \mathrm{g \cdot cm^{-2}}$$

Approximation good within $\pm 2\%$ for all materials except Helium (5% low)

Shower width scales in Moliere Radii R_M :

$$R_M \approx \frac{E_s}{E_c} X_0 \approx \frac{21\ \mathrm{MeV} \cdot (Z+1.2)}{800\ \mathrm{MeV}} X_0$$

$$= 0.0265 \cdot X_0 (Z+1.2)$$

(90% energy containment radius)

with $\begin{cases} E_s \approx 21\ \mathrm{MeV} \\ E_c \approx \dfrac{800\ \mathrm{MeV}}{Z+1.2} \end{cases}$

C. Amsler *et al.* (Particle Data Group), Physics Letters **B667**, 1 (2008) and 2009 partial update for the 2010 edition

Electromagnetic Cascades in Calorimeters

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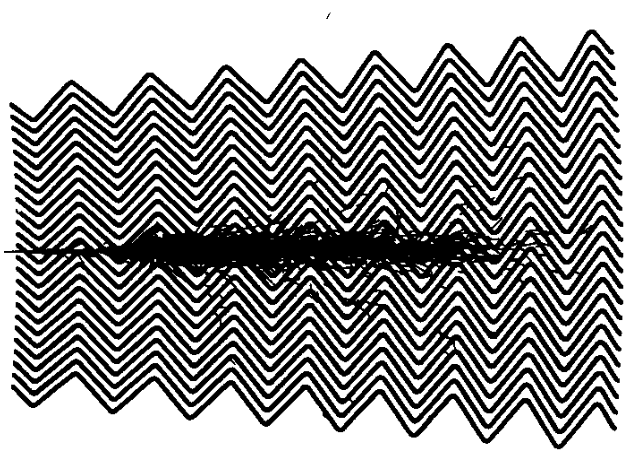
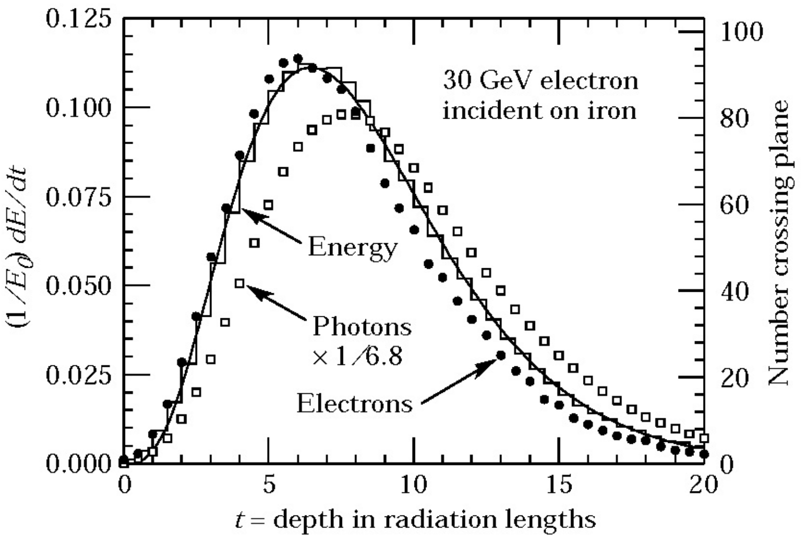


RD3 note 41, 28 Jan 1993



$$\frac{dE}{dt} = E_0 b \frac{(bt)^{a-1} e^{-bt}}{\Gamma(a)}, \text{ with } t = x/X_0$$

$$t_{\max} = (a-1)/b = 1.0 \times (\ln y + C_j),$$

with $y = E/E_c$ and

$$C_j = \begin{cases} -0.5 & \text{for } e^{\pm} \\ +0.5 & \text{for } \gamma \end{cases}$$

C. Amsler *et al.* (Particle Data Group), Physics Letters **B667**, 1 (2008) and 2009 partial update for the 2010 edition

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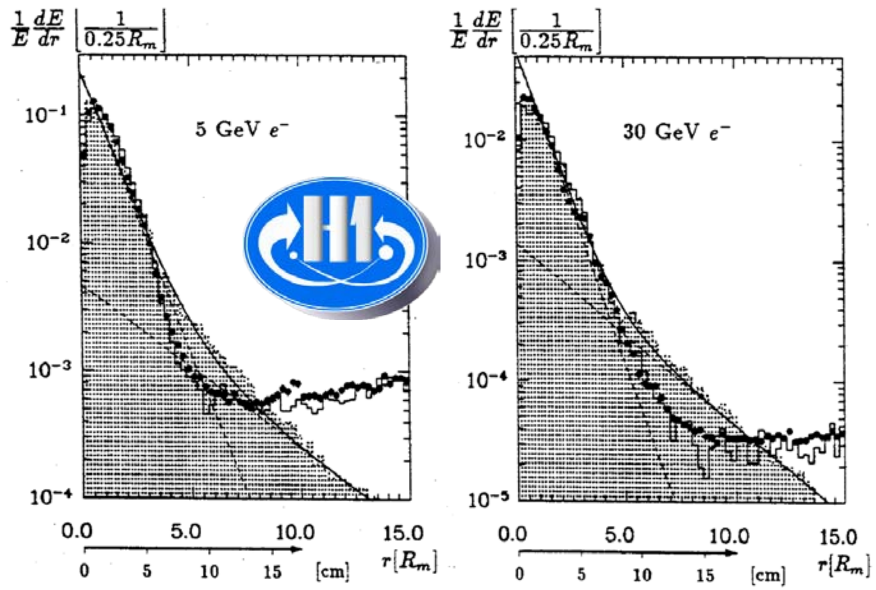
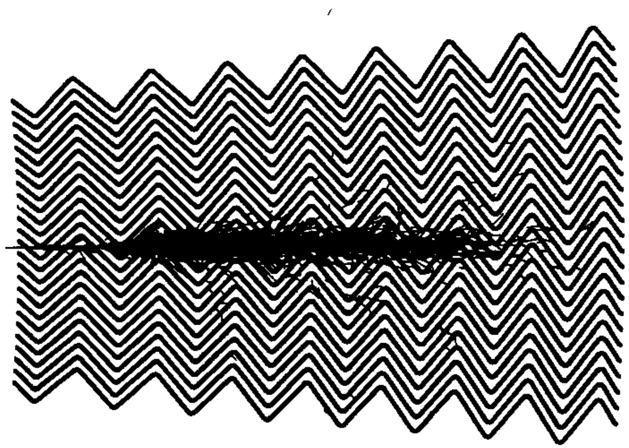


P. Loch (Diss.), University of Hamburg 1992

$$\frac{1}{E}\frac{dE}{dr} = a(E)\cdot e^{-\alpha(E)r} + b(E)\cdot e^{-\beta(E)r}$$

G.A. Akopdzhanov *et al.* (Particle Data Group), Physics Letters **B667**, 1 (2008) and 2009 partial update for the 2010 edition



RD3 note 41, 28 Jan 1993

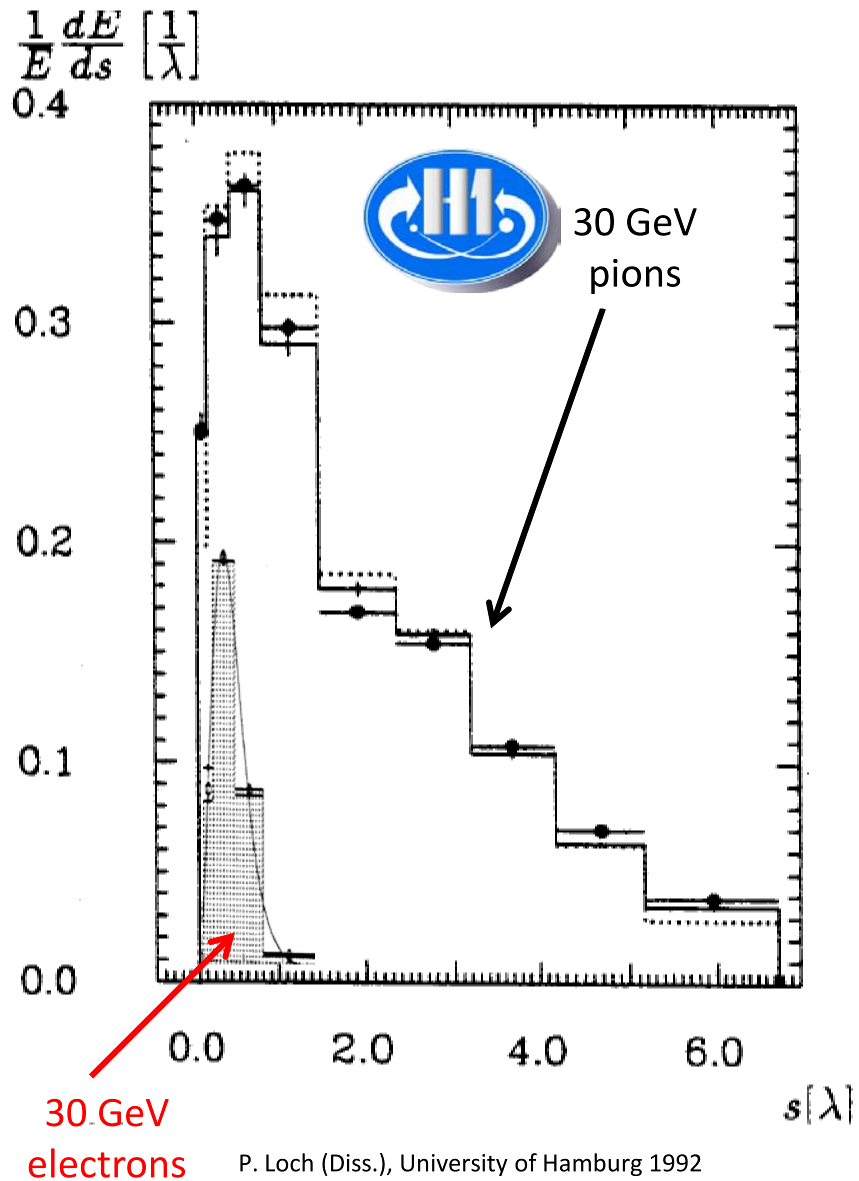
Hadronic Cascades in Calorimeters

Hadronic signals

- Much larger showers
  - Need deeper development
  - Wider shower spread
- Large energy losses without signal generation in hadronic shower component
  - Binding energy losses
  - Escaping energy/slow particles (neutrinos/neutrons)
- Signal depends on size of electromagnetic component
  - Energy invested in neutral pions lost for further hadronic shower development
  - Fluctuating significantly shower-by-shower
  - Weakly depending on incoming hadron energy

Consequence: non-compensation

- Hadrons generate less signal than electrons depositing the same energy



P. Loch (Diss.), University of Hamburg 1992

THE UNIVERSITY OF ARIZONA
P. Loch
U of Arizona
May 05, 2010

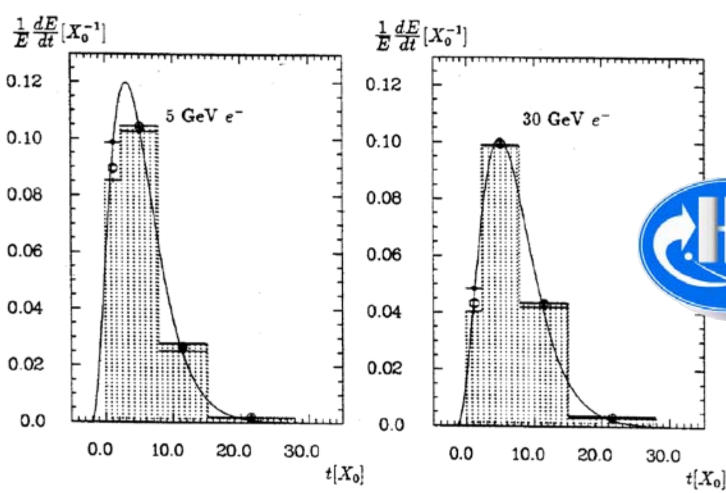
Shower Features Summary

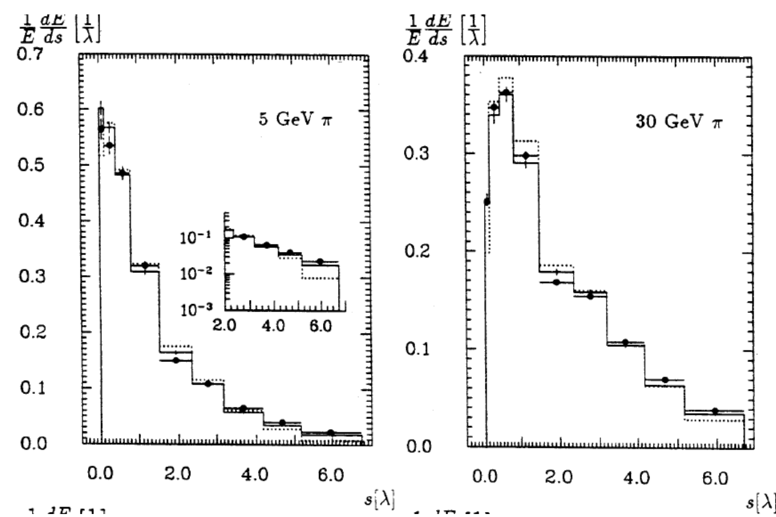
Electromagnetic

- Compact
  - Growths in depth ~log(E)
- Longitudinal extension scale is radiation length X_0
  - Distance in matter in which ~50% of electron energy is radiated off
  - Photons 9/7 X_0
- Strong correlation between lateral and longitudinal shower development
- Small shower-to-shower fluctuations
  - Very regular development
- Can be simulated with high precision
  - 1% or better, depending on features

Hadronic

- Scattered, significantly bigger
  - Growths in depth ~log(E)
- Longitudinal extension scale is interaction length $\lambda >> X_0$
  - Average distance between two inelastic interactions in matter
  - Varies significantly for pions, protons, neutrons
- Weak correlation between longitudinal and lateral shower development
- Large shower-to-shower fluctuations
  - Very irregular development
- Can be simulated with reasonable precision
  - ~2-5% depending on feature



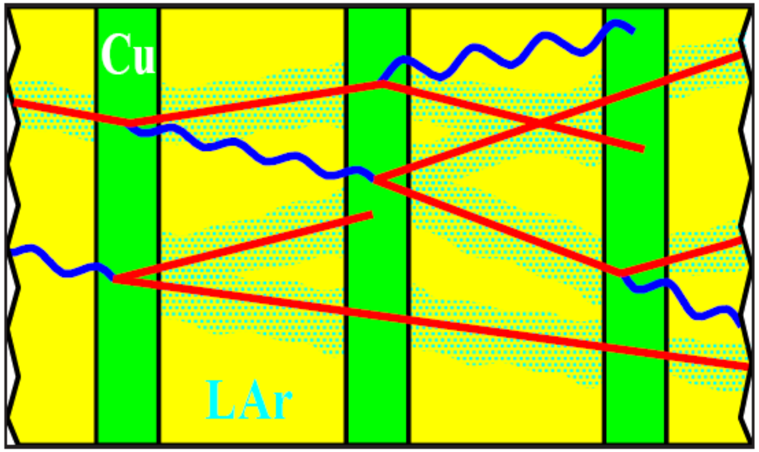


Electromagnetic Signals

P. Loch
U of Arizona
May 05, 2010

Signal features in sampling calorimeters

- Collected from ionizations in active material
  - Not all energy deposit converted to signal
- Proportional to incoming electron/photon
  - C.f. Rossi's shower model, Approximation B
    - Only charged tracks contribute to signal
    - Only pair-production for photons
    - Energy loss is constant
  - Signal proportional to integrated shower particle path
- Stochastical fluctuations
  - Sampling character
- Sampling fraction
  - Describes average fraction of deposited energy generating the signal



Integrated shower particle track length:

$$T = \int_0^{t_{\max}} N(t)dt \Rightarrow T_c = \frac{2}{3}T = \frac{2}{3\ln 2}\frac{E_0}{E_c}$$

(only charged tracks ionize!)

Number of crossings of active material:

$$N_\times = \frac{T_c}{d_{\mathrm{active}}} \propto E_0$$

Deposited energy contributing to the signal:

$$E_{\mathrm{vis}} = N_\times \int_0^{d_{\mathrm{active}}} \frac{dE}{dx}dx = N_\times \Delta E \propto E_0$$

Stochastic nature of sampling:

$$\sigma(N_\times) = \sqrt{N_\times} \Rightarrow \sigma(E_{\mathrm{vis}}) \propto \sqrt{N_\times \Delta E} \propto \sqrt{E_0}$$

Signal Formation: Sampling Fraction

P. Loch
U of Arizona
May 05, 2010

Characterizes sampling calorimeters

- Ratio of energy deposited in active material and total energy deposit
- Assumes constant energy loss per unit depth in material
  - Ionization only
- Can be adjusted when designing the calorimeter
  - Material choices
  - Readout geometry

$$S = \frac{E_{\text{vis}}}{E_{\text{dep}}} = \frac{dE/dx|_{\text{active}} \cdot d_{\text{active}}}{dE/dx|_{\text{active}} \cdot d_{\text{active}} + dE/dx|_{\text{absorber}} \cdot d_{\text{absorber}}}$$

$$= \frac{dE/dx|_{\text{active}}}{dE/dx|_{\text{active}} + dE/dx|_{\text{absorber}} \cdot d_{\text{absorber}}/d_{\text{active}}}$$

(with Rossi's assumption $dE/dx|_{\text{active}} = const$ and $dE/dx|_{\text{absorber}} = const$)

Multiple scattering

- Changes sampling fraction
  - Effective extension of particle path in matter
  - Different for absorber and active material

Showering

- Cannot be included in sampling fraction analytically
  - Need measurements and/or simulations

THE UNIVERSITY OF ARIZONA.

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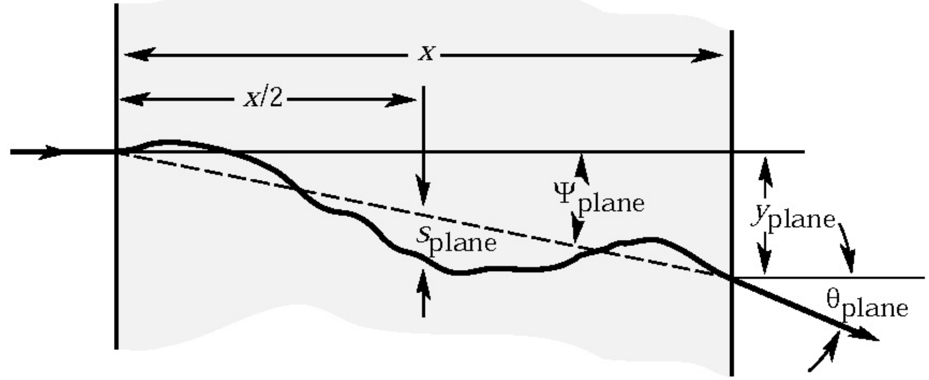

$$S = \frac{E_{\text{vis}}}{E_{\text{dep}}}$$

$$= \frac{dE/dx|_{\text{active}}}{dE/dx|_{\text{active}} + dE/dx|_{\text{absorber}} \cdot d_{\text{absorber}}/d_{\text{active}} \cdot \cos\theta_{\text{active}}/\cos\theta_{\text{absorber}}}$$

Approximation:

$$\theta = \frac{13.6\ \text{MeV}}{\beta c p} z \sqrt{x/X_0}\left[1 + 0.038 \cdot \ln\frac{x}{X_0}\right]$$

with
- βc particle velocity
- p particle momentum
- z particle charge number
- x/X_0 material thickness in radiation length

(good to 11% for singly charged particles with $\beta = 1$ for all matter and within $10^{-1} < x/X_0 < 100$)

Signal Formation: Sampling Fraction

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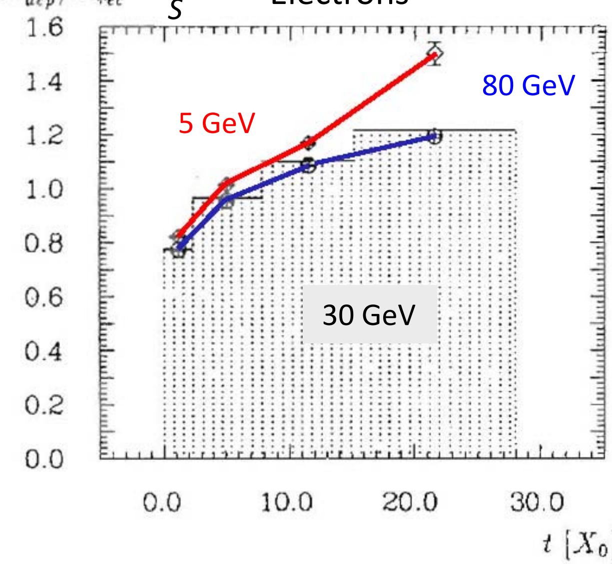
$$S = \frac{E_{\mathrm{vis}}}{E_{\mathrm{dep}}} \propto \frac{A(E_0)}{E_0}$$

$A(E_0)$ is the calorimeter signal from test beams or simulation, converted to energy units.

Showering changes the electron sampling fraction mostly due to the strong dependence of photon capture (photo-effect) on the material (cross-section $\sim Z^5$) leading to a non-proportional absorption of energy carried by soft photons deeper in the shower!

$E_{dep}^{Seg} / E_{rec}^{Seg} \propto \frac{1}{S}$ Electrons



P. Loch (Diss.), University of Hamburg 1992

Signal Extraction

Example: charge collection in noble liquids

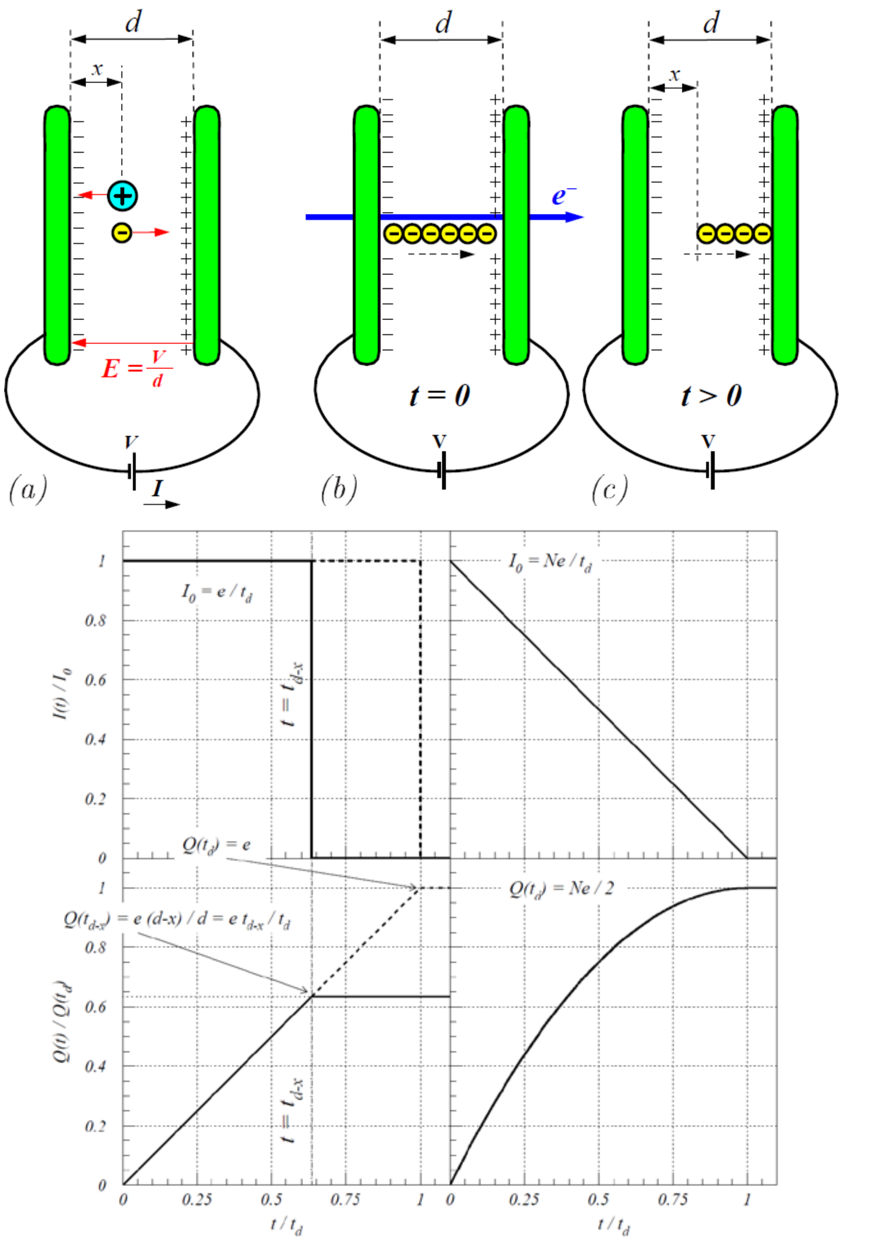
- Charged particles ionizing active medium when traversing it
  - Fast passage compared to electron drift velocity in medium
- Electrons from these ionizations are collected in external electric field
  - Similar to collection of 1-dim "line of charges" with constant charge density
- Resulting (electron) current is base of signal
  - Positive ions much slower
  - Can collect charges or measure current

Characteristic features

- Collected charge and current are proportional to energy deposited in active medium

$$Q(t=t_d)=\frac{N_e e}{2};\ I(t=t_0)=\frac{N_e e}{t_d};\ N_e=\frac{E_{vis}}{E_{ion}}$$

- Drift time for electrons in active medium
  - Determines charge collection time
  - Can be adjusted to optimize calorimeter performance



Calorimeter Response

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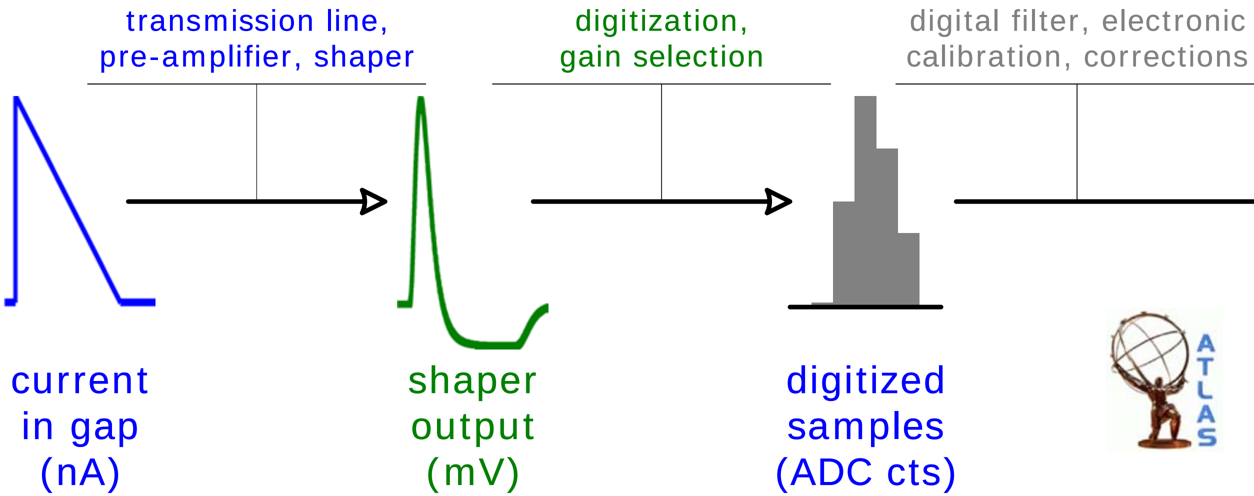
U of Arizona
May 05, 2010



Raw Channel Data

energy E_{raw} (MeV)
time t (ns)
quality Q
selected gain g
online id id_{online}

What is response?

- Reconstructed calorimeter signal
  - Based on the direct measurement – the raw signal
  - May include noise suppression
- Has the concept of **signal** (or **energy**) **scale**
  - Mostly understood as the basic signal before final calibrations
- Does not explicitly include particle or jet hypothesis
  - Uses only calorimeter signal amplitudes, spatial distributions, etc.

$$E_{raw} = A_{peak} \times \underbrace{[\mathrm{ADC} \to \mathrm{nA}]}_{\text{current calibration}}$$

$$\times \underbrace{([\mathrm{HV}] \times [\text{cross-talk}] \times [\text{purity}])}_{\text{electronic and efficiency corrections}}$$

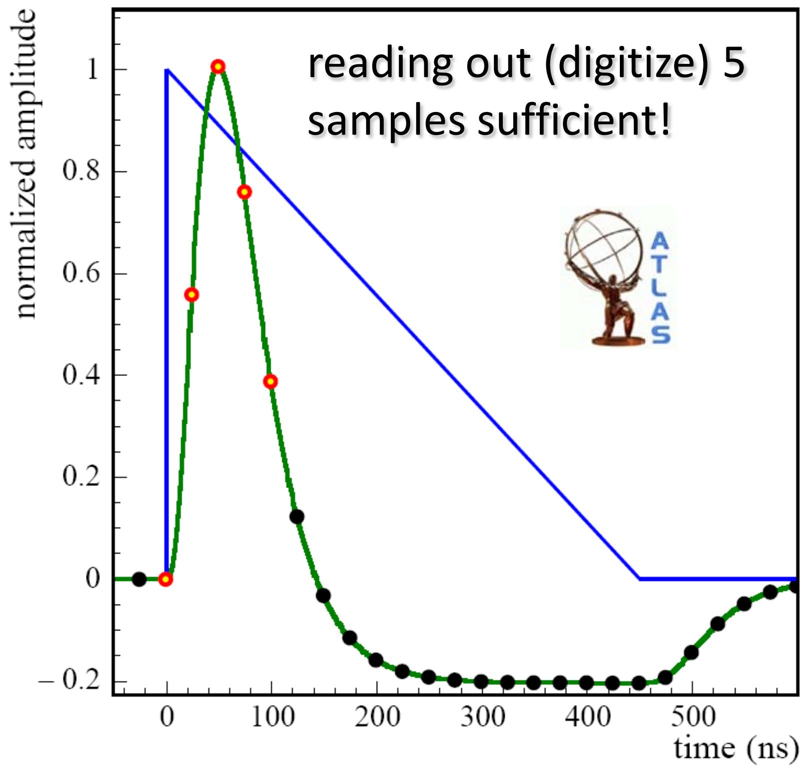
$$\times \underbrace{[\mathrm{nA} \to \mathrm{MeV}]}_{\text{energy calibration}}$$

Calorimeter Signal in ATLAS

P. Loch
U of Arizona
May 05, 2010

Slow signal collection in liquid argon calorimeters

- ~450 ns @ 1 kV/mm drift time versus 40 MHz/25 ns bunch crossing time
  - Measure only $I_0 = I(t_0)$ (integrate <25 ns)
- Applying a fast bi-polar signal shaping
  - Shaping time ~15 ns
    - With well known shape
  - Shaped pulse integral = 0
    - Net average signal contribution from pile-up = 0
    - Need to **measure the pulse shape** (time sampled readout)
  - Total integration ~25 bunch crossings
    - 23 before signal, 1 signal, 1 after signal



ATLAS Digital Filtering

What is digital filtering

- Unfolds the expected (theoretical) pulse shape from a measured pulse shape

Determines signal amplitude and timing

- Minimizes noise contributions
  - Noise reduced by ~1.4 compared to single reading
  - Note: noise depends on the luminosity
- Requires explicit knowledge of pulse shape
  - Folds triangular pulse with transmission line characteristics and active electronic signal shaping
  - Characterized by signal transfer functions depending on *R*, *L*, *C* of readout electronics, transmission lines

Filter coefficients from calibration system

- Pulse "ramps" for response
  - Inject known currents into electronic chain
  - Use output signal to constrain coefficients
- Noise for auto-correlation
  - Signal history couples fluctuations in time sampled readings

Signal amplitude A_{peak} (energy):

$$A_{\text{peak}} = \sum_{i=1}^{N_s} a_i \left(s_i - p \right), \text{ with } \begin{cases} a_i & \text{digital filter coefficient} \\ s_i & \text{reading in time sample} \\ p & \text{pedestal reading} \end{cases}$$

Signal peak time t_{peak}:

$$A_{\text{peak}} t_{\text{peak}} = \sum_{i=1}^{N_s} b_i \left(s_i - p \right)$$

W.E. Cleland and E.G. Stern, Nucl. Inst. Meth. **A338 (1994) 467.**

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$$A_{\text{peak}} = \sum_{i=1}^{N_s} a_i \left(s_i - p \right), \text{ with } \begin{cases} a_i & \text{digital filter coefficient} \\ s_i & \text{reading in time sample} \\ p & \text{pedestal reading} \end{cases}$$

Signal peak time t_{peak}:

$$A_{\text{peak}} t_{\text{peak}} = \sum_{i=1}^{N_s} b_i \left(s_i - p \right)$$

W.E. Cleland and E.G. Stern, Nucl. Inst. Meth. **A338 (1994) 467.**

Constraints for digital filter coefficients a_i:

$\sum_{i=1}^{N_s} a_i g_i = 1$, with g_i being the normalized physics pulse shape

$$\sum_{i=1}^{N_s} a_i \frac{\partial g_i}{\partial t} = 0$$

ATLAS Digital Filter Coefficients

S_i .... signal amplitude in sample i

P .... analog-to-digital converter pedestal

N_s .... number of digital samples (def. 5)

a_i .... digital filter coefficient

R_{ij} .... noise auto-correlation

g_i .... normalized physics pulse shape:

Filter Coefficients

Determined by:

- Known pulse shape
- Minimizing noise

to 1st order independent of time jitter!

$$\sum_{i=1}^{N_s} a_i g_i = 1$$

$$\sum_{i=1}^{N_s} a_i \frac{\partial g_i}{\partial t} = \sum_{i=1}^{N_s} a_i g_i' = 0$$

$$\sum_{i=1}^{N_s} \sum_{j=1}^{N_s} a_i a_j \sigma_i \sigma_j R_{ij} \rightarrow \min$$

Lagrange Multipliers

$$a_i = \sum_{j=1}^{N_s} R_{ij}^{-1} \left(\lambda g_j - \mu g_j' \right) \begin{cases} \lambda = \dfrac{1}{\Delta} \sum_{i=1}^{N_s} \sum_{j=1}^{N_s} R_{ij}^{-1} g_i' g_j' \\ \mu = \dfrac{1}{\Delta} \sum_{i=1}^{N_s} \sum_{j=1}^{N_s} R_{ij}^{-1} g_i g_j' \\ \Delta = \left(\sum_{i=1}^{N_s} \sum_{j=1}^{N_s} R_{ij}^{-1} g_i' g_j' \right) \cdot \left(\sum_{i=1}^{N_s} \sum_{j=1}^{N_s} R_{ij}^{-1} g_i g_j \right) - \left(\sum_{i=1}^{N_s} \sum_{j=1}^{N_s} R_{ij}^{-1} g_i g_j' \right)^2 \end{cases}$$

Calorimeter Response

What does signal or energy scale mean?

- Indicates a certain level of signal reconstruction
  - Standard reconstruction often stops with a **basic signal scale**
- **Electromagnetic energy scale** is a good reference
  - Uses direct signal proportionality to electron/photon energy
  - Accessible in test beam experiments
  - Can be validated with isolated particles in collision environment
  - Provides good platform for data and simulation comparisons
  - Does not necessarily convert the electron signal to the true photon/electron energy!
- Hadronic signals can also be calculated on this scale
  - Good platform for comparisons to simulations
  - But does not return a good estimate for the deposited energy in non-compensating calorimeters – see later discussion!
- Is not a fundamental concept of physics!
  - Is a calorimeter feature
  - Definition varies from experiment to experiment

Recall electrons/photons in sampling calorimeters:

$$E_{\rm vis} = N_\times \int_0^{d_{\rm active}} \frac{dE}{dx}\,dx = N_\times \Delta E \propto E_0$$

Electron sampling fraction $S_{\rm e}$ relates signal and deposited energy:

$$S_{\rm e} = \frac{E_{\rm vis}}{E_{\rm dep}} \approx \frac{E_{\rm vis}}{E_0} \rightarrow E_{\rm rec}^{\rm em} = \frac{1}{S_{\rm e}} E_{\rm vis} = c_{\rm e} A \overset{!}{\equiv} E_{\rm dep} \approx E_0$$

with $c_{\rm e}$ being the electron calibration constant.

($S_{\rm e}$ is a unitless fraction, $c_{\rm e}$ converts a signal unit into an energy unit, e.g. nA $\rightarrow$ MeV)

Response often denoted $e = e(E_{\rm dep}) = E_{\rm rec}^{\rm em}(c_{\rm e}, A)$

Hadronic Response (1)

Single hadron reponse:

$$\pi(E_0) = f_{em}(E_0)\cdot e + \left(1 - f_{em}(E_0)\right)\cdot h$$

$$\text{with } \begin{cases} f_{em}(E_0) & \text{intrinsic em fraction} \\ h & \text{response of pure hadronic shower branch} \end{cases}$$

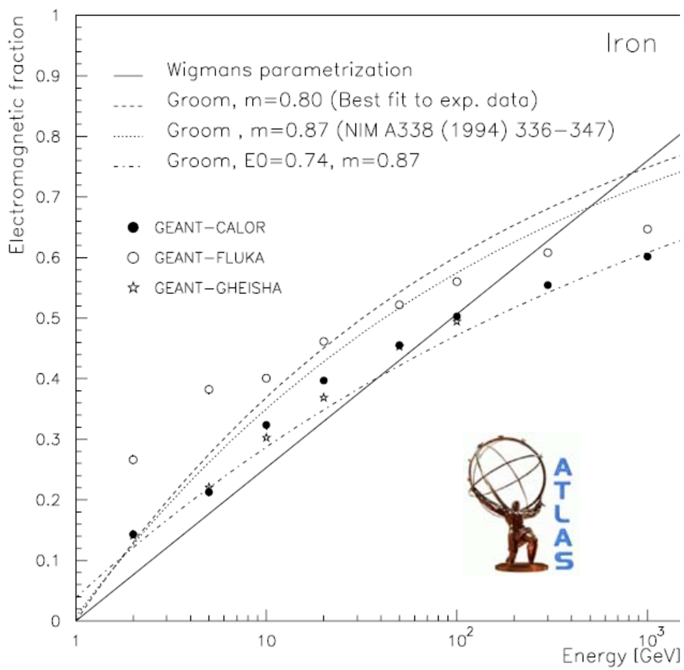
Non-compensation measure:

$$\frac{e}{\pi} = \frac{1}{f_{em}(E_0) + \left(1 - f_{em}(E_0)\right)\cdot h/e}$$

Popular parametrization by Groom et al.:

$$f_{em}(E_0) = 1 - \left(E_0/E_{base}\right)^{m-1}$$

$$m = 0.80 - 0.85,\ E_{base} = \begin{cases} 1.0\ \text{GeV} & \text{for } \pi^{\pm} \\ 2.6\ \text{GeV} & \text{for } p \end{cases}$$



D.Groom et al., NIM A338, 336-347 (1994)

Hadronic Response (2)

Observable

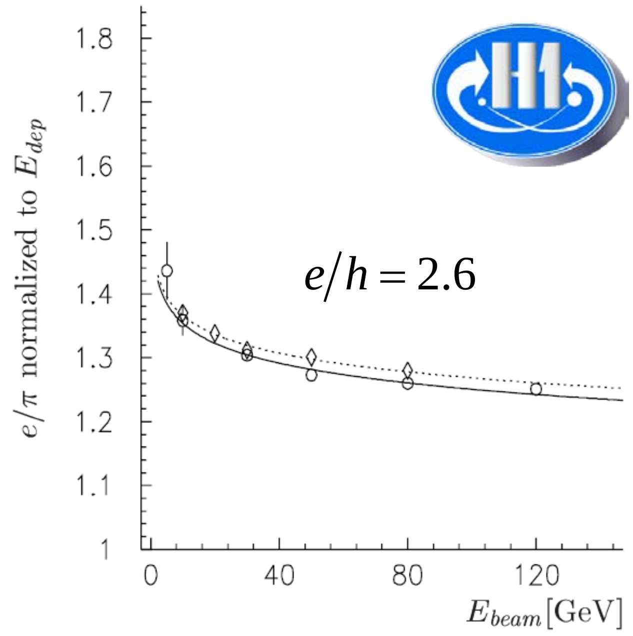
$$\frac{e}{\pi} = \frac{e}{\left(E_0/E_{\text{base}}\right)^{m-1} h + \left(1 - \left(E_0/E_{\text{base}}\right)^{m-1}\right) e}$$

$$= \frac{1}{1 - \left(1 - h/e\right)\left(E_0/E_{\text{base}}\right)^{m-1}}$$

provides experimental access to characteristic calorimeter variables in pion test beams by fitting *h/e*, E_{base} and *m* from the energy dependence of the pion signal on electromagnetic energy scale:

$$\frac{e}{\pi} = \frac{E_0}{E_{\text{rec}}^{\text{em}}(\pi)} \approx \frac{E_{\text{dep}}}{E_{\text{rec}}^{\text{em}}(\pi)}$$

Note that *e/h* is often constant, for example: in both H1 and ATLAS about 50% of the energy in the hadronic branch generates a signal independent of the energy itself



Jet Response

P. Loch
U of Arizona
May 05, 2010

Complex mixture of hadrons and photons

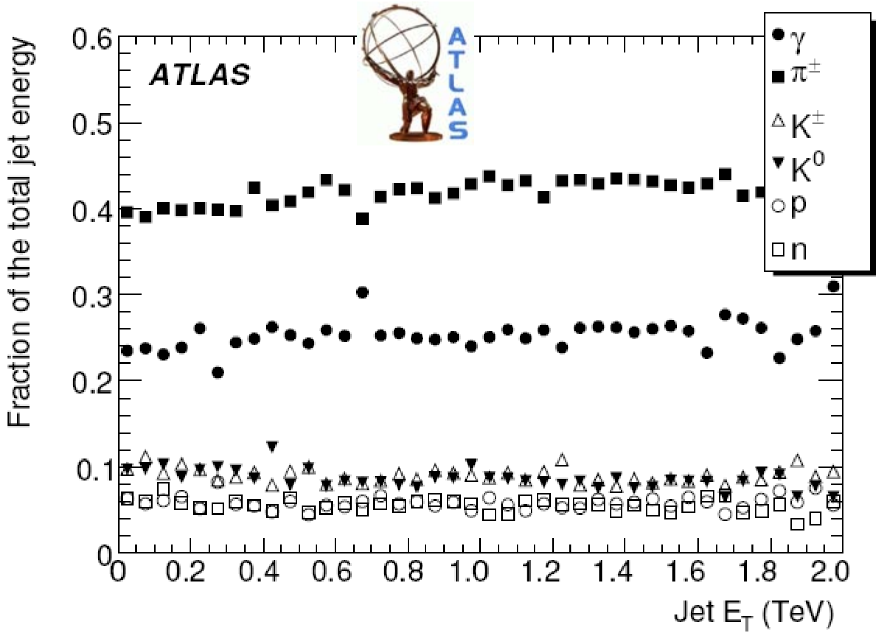
- Not a single particle response
- Carries initial electromagnetic energy
  - Mainly photons

Very simple response model

- Assume the hadronic jet content is represented by 1 particle only
  - Not realistic, but helpful to understand basic response features

More evolved model

- Use fragmentation function in jet response
  - This has some practical considerations
    - E.g. jet calibration in CDF
- Gets non-compensation effect
  - Does not address acceptance effect due to shower overlaps



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$$\frac{j(E_{\mathrm{jet}})}{e} = f_\gamma^{\mathrm{jet}} + \left(1 - f_\gamma^{\mathrm{jet}}\right) \cdot \left(f_{\mathrm{em}} + \left(1 - f_{\mathrm{em}}\right) \frac{h}{e} \right)$$

$$f_{\mathrm{em}} = f_{\mathrm{em}}(E_{\mathrm{jet}}^{\mathrm{had}}),\ E_{\mathrm{jet}}^{\mathrm{had}} = \left(1 - f_\gamma^{\mathrm{jet}}\right) E_{\mathrm{jet}}$$

[single particle approximation]

$$f_{\mathrm{em}} = 1 - \left(\frac{E_{\mathrm{jet}}^{\mathrm{had}}}{E_{\mathrm{base}}} \right)^{1-m}$$

[Groom's parameterization]

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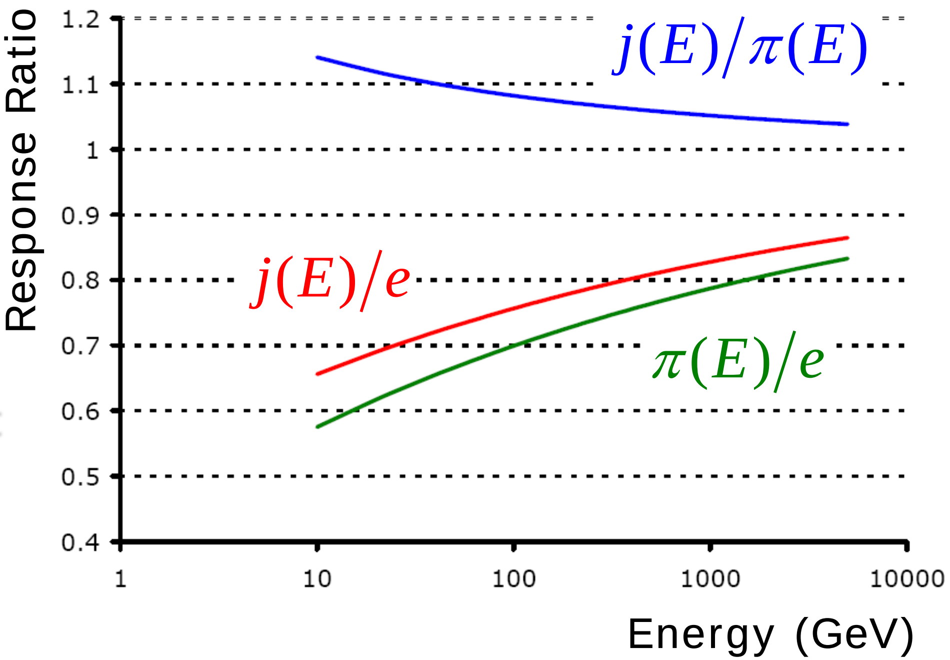

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$$\frac{j(E_{\mathrm{jet}})}{e}$$

$$= f_{\gamma}^{\mathrm{jet}} + \left(1 - f_{\gamma}^{\mathrm{jet}}\right) \int_{\mathrm{hadrons}} \left[f_{\mathrm{em}}(E_{\mathrm{had}}) + \left(1 - f_{\mathrm{em}}(E_{\mathrm{had}})\right)\frac{h}{e} \right] dE_{\mathrm{had}}$$

composition of hadronic component given by jet fragmentation function

$$= f_{\gamma}^{\mathrm{jet}} + \left(1 - f_{\gamma}^{\mathrm{jet}}\right) \sum_{\mathrm{hadrons}} \left[1 - \left(\frac{E_{\mathrm{had}}}{E_{\mathrm{base}}}\right)^{m-1} + \left(\frac{E_{\mathrm{had}}}{E_{\mathrm{base}}}\right)^{m-1} h/e \right]$$

$$= f_{\gamma}^{\mathrm{jet}} + \left(1 - f_{\gamma}^{\mathrm{jet}}\right) \sum_{\mathrm{hadrons}} \left(1 + \left(E_{\mathrm{had}}/E_{\mathrm{base}}\right)^{m-1}\left(h/e - 1\right)\right)$$

Acceptance and Noise in Jet Response

Noise

- Fluctuations of the “zero” or “empty” signal reading
  - Pedestal fluctuations
- Independent of the signal from particles
  - At least to first order
- Mostly incoherent
  - No noise correlations between readout channels
    - Noise in each channel is independent oscillator
- Gaussian in nature
  - Pedestal fluctuations ideally follow normal distribution around 0
  - Width of distribution (1 σ) is noise value

Signal significance

- Noise can fake particle signals
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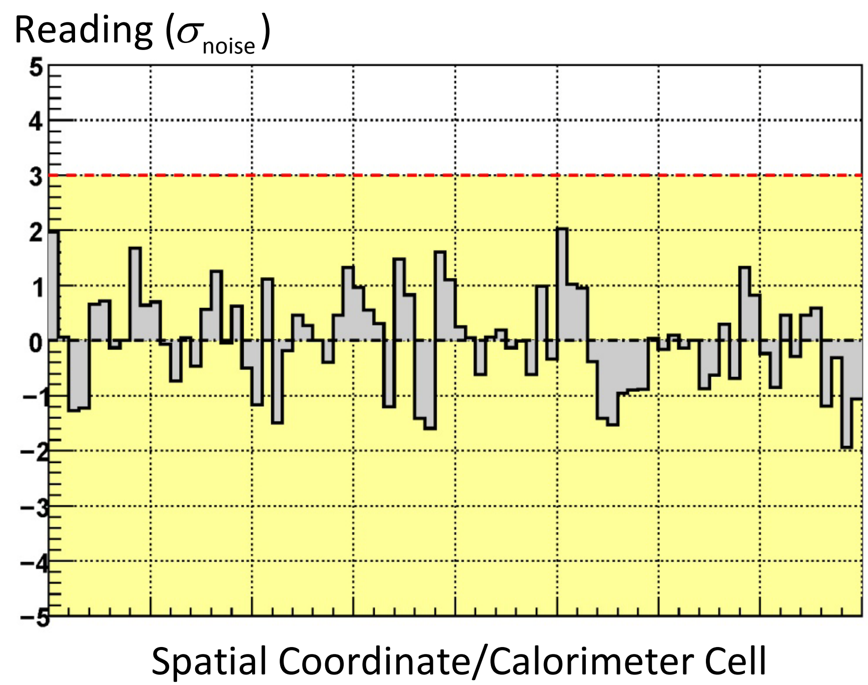

Small signal:

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Acceptance and Noise in Jet Response

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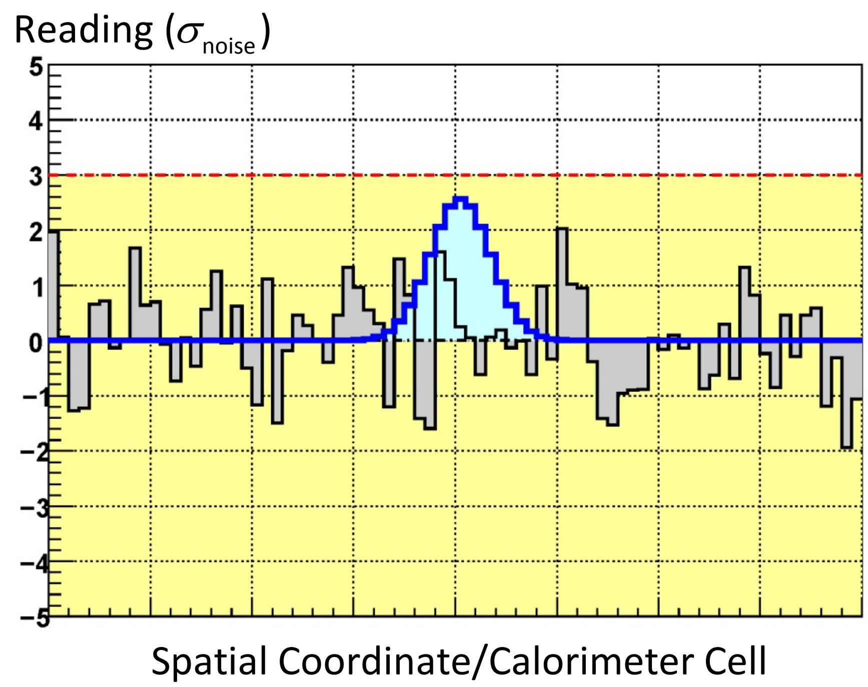

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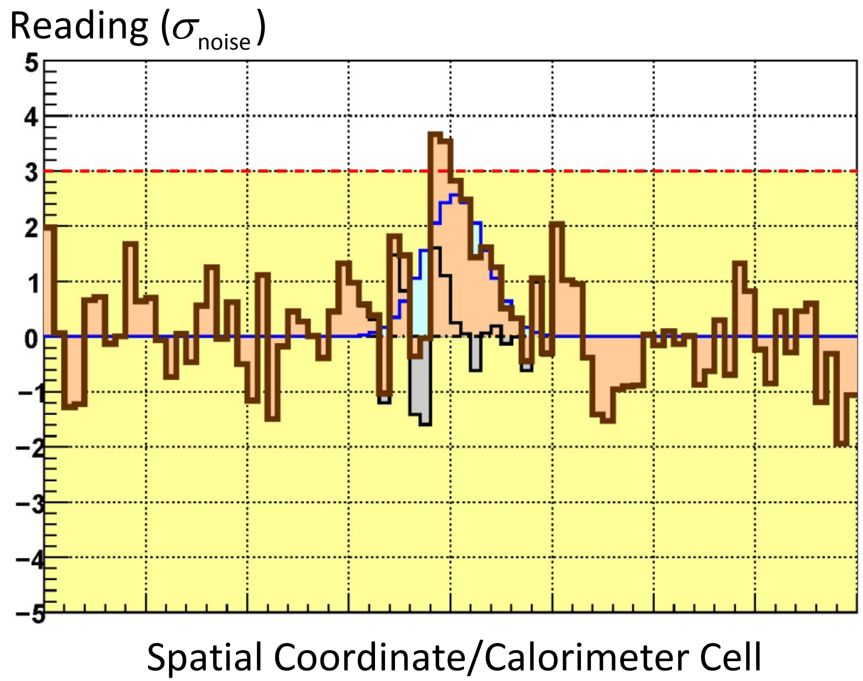

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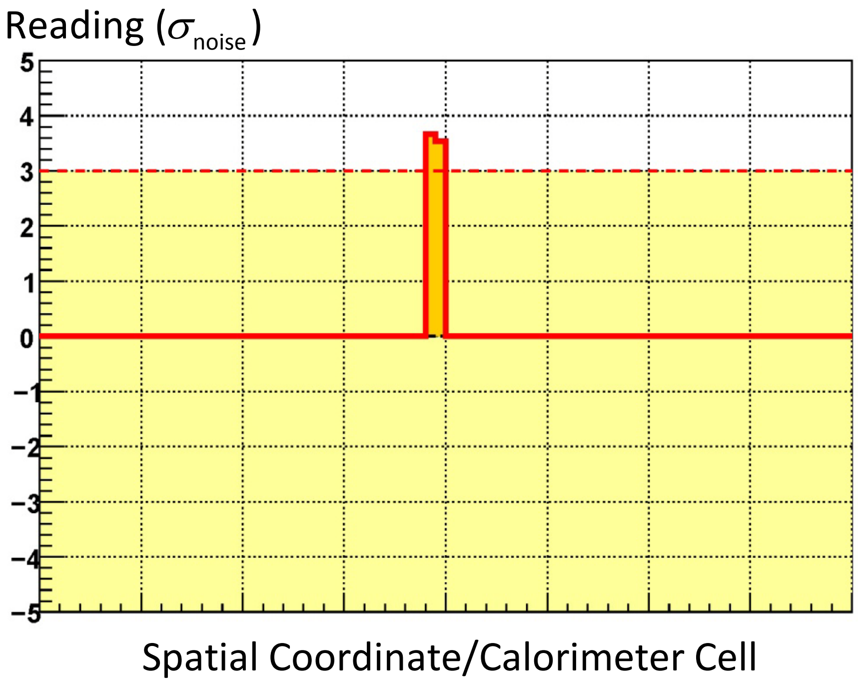

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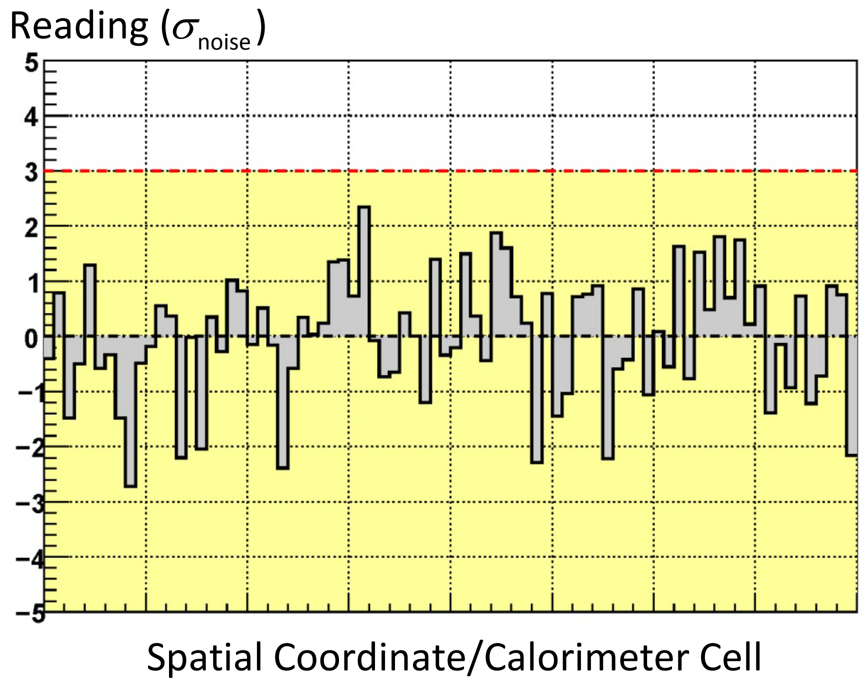

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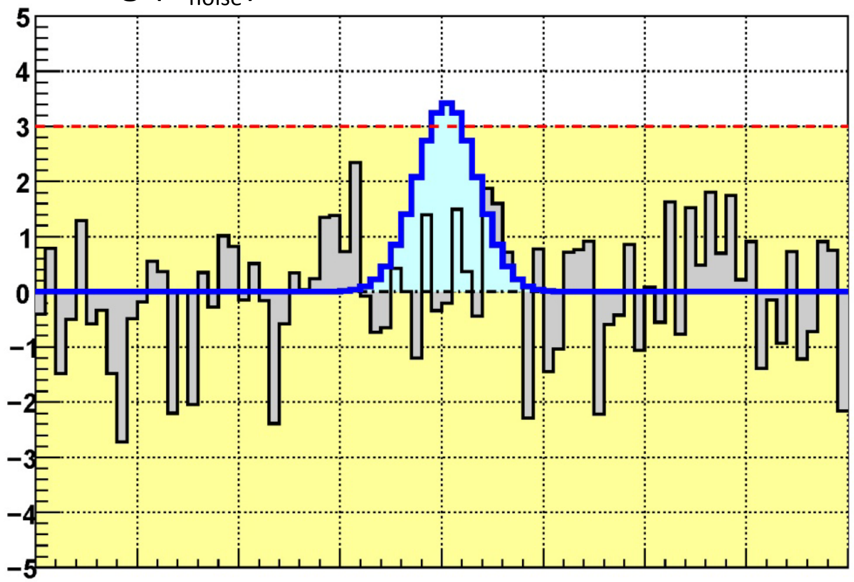

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ATLAS

Acceptance and Noise in Jet Response

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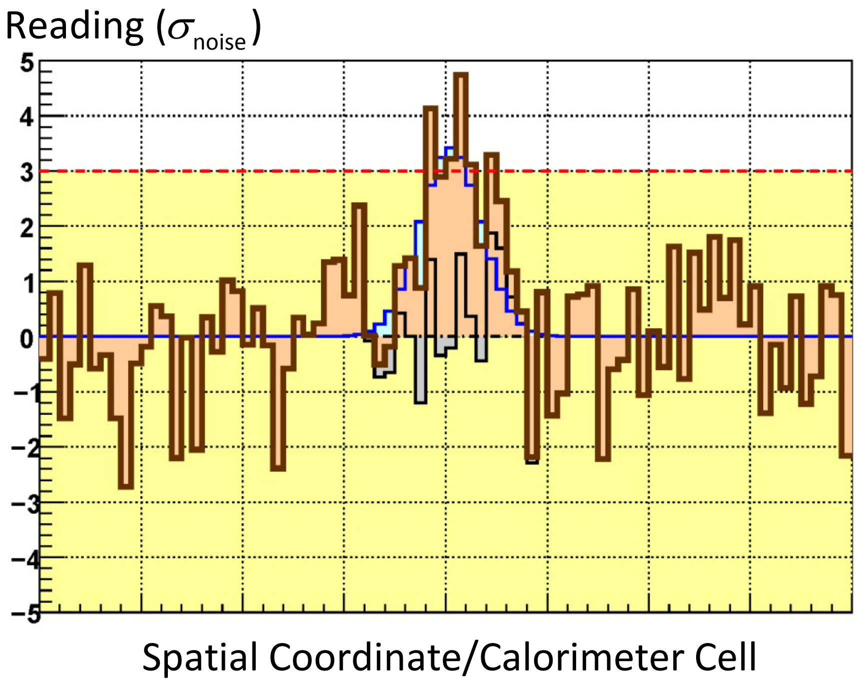

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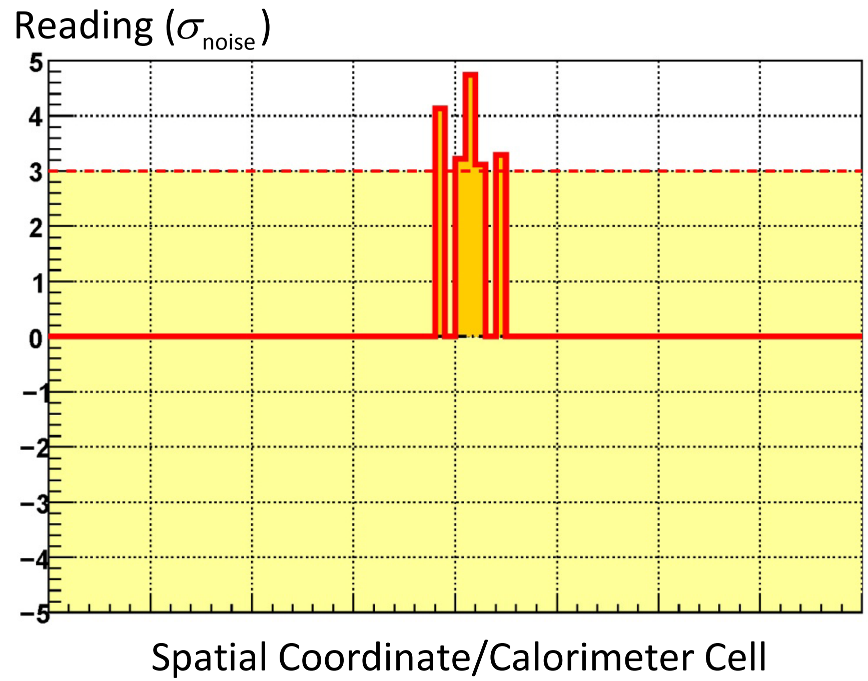

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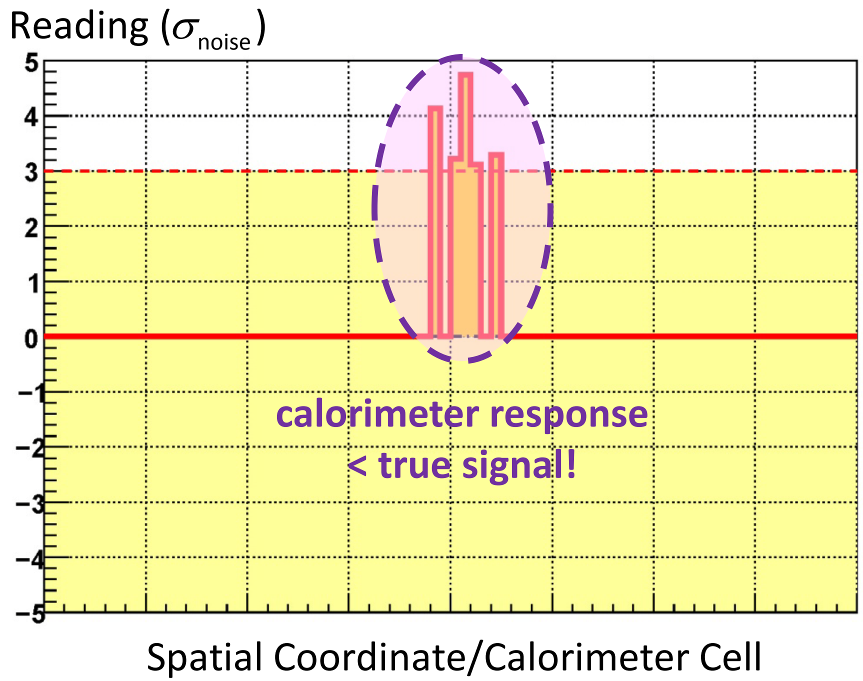

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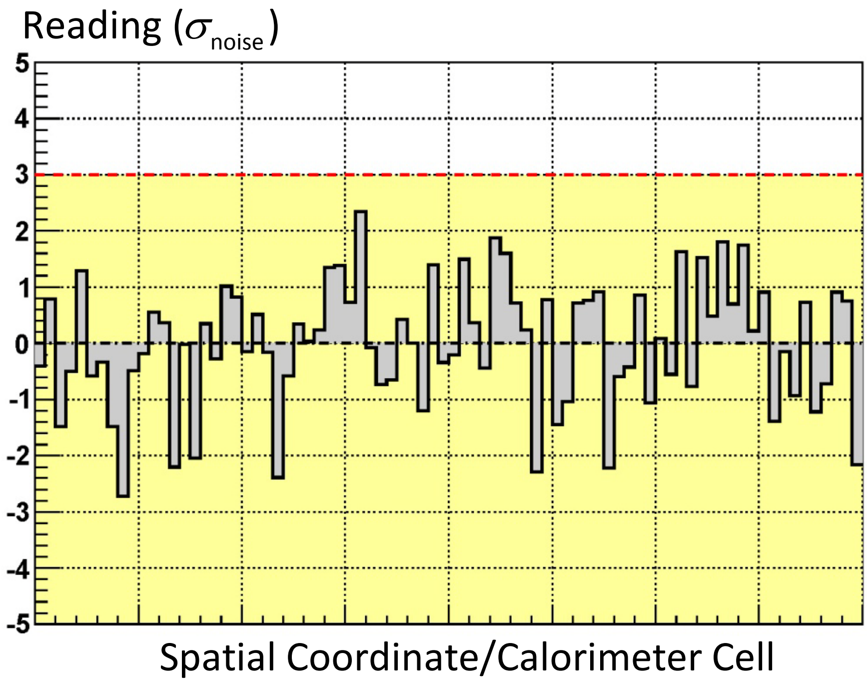

Small signal, two particles:

- Noise only
- Signal on top of noise
- Sum of noise and signal
- Signal after noise suppression

Acceptance and Noise in Jet Response

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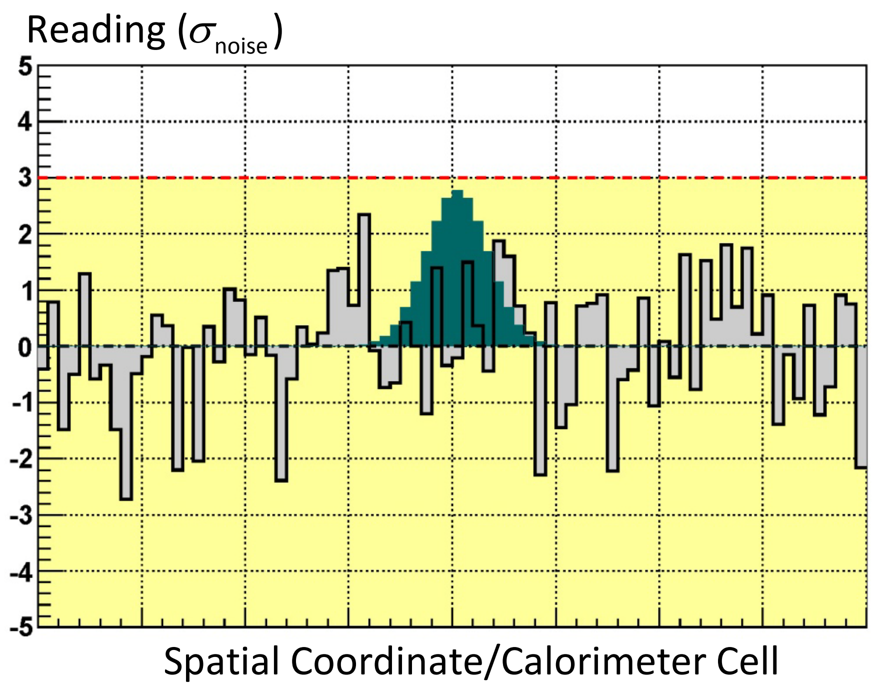

Small signal, first particle:

- Noise only
- Signal on top of noise
- Sum of noise and signal
- Signal after noise suppression

Acceptance and Noise in Jet Response

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Signal significance

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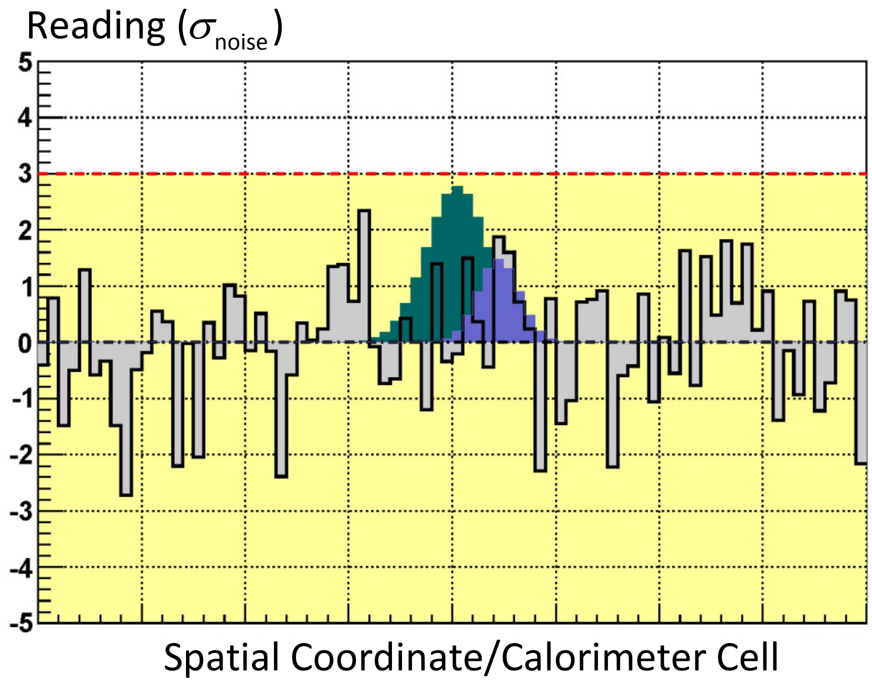

Small signal, first and second particle:

- Noise only
- Signal on top of noise
- Sum of noise and signal
- Signal after noise suppression

Acceptance and Noise in Jet Response

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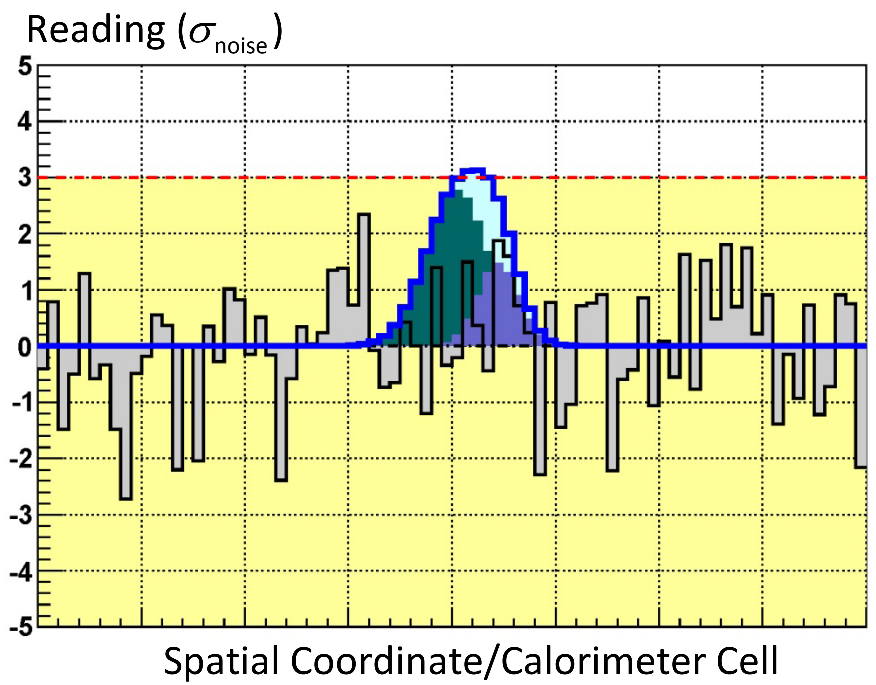

Small signal, two particle, sum:

- Noise only
- Signal on top of noise
- Sum of noise and signal
- Signal after noise suppression

Acceptance and Noise in Jet Response

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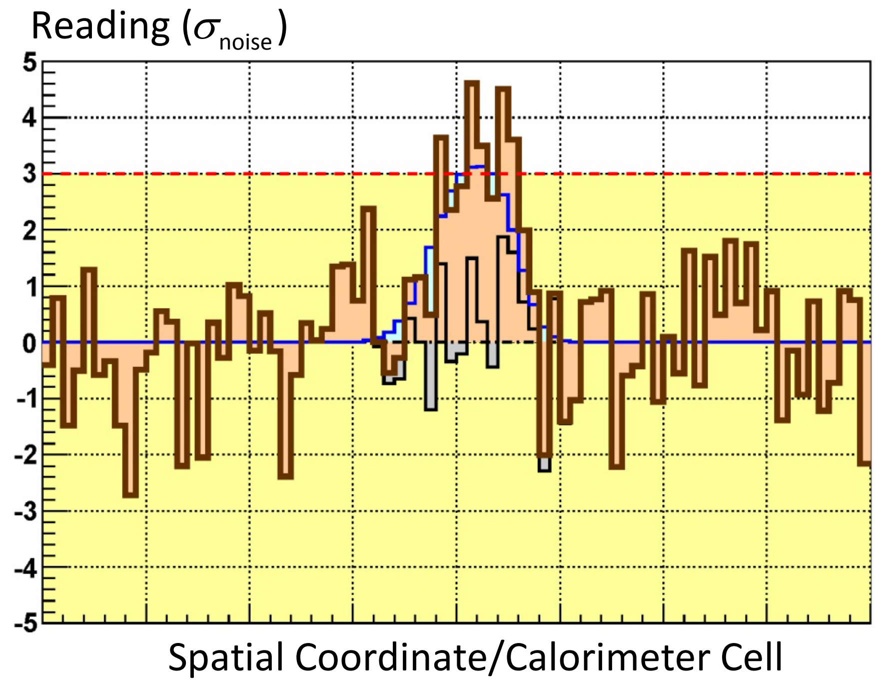

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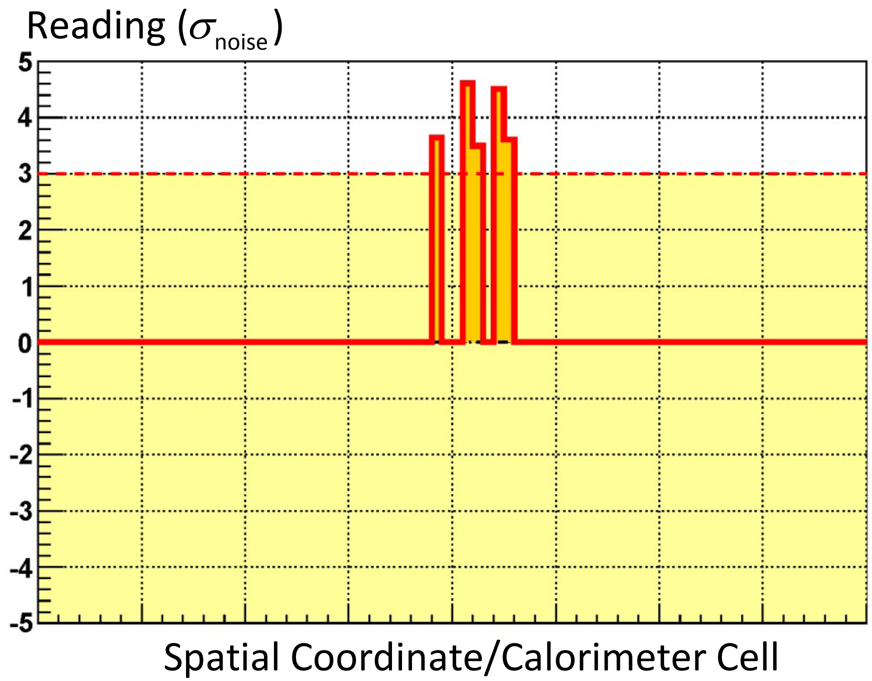
Signal significance

- Noise can fake particle signals
  - Only signals exceeding noise can be reliably measured
- Signals larger than 3 × noise are very likely from particles
  - Gaussian interpretation of pedestal fluctuations
- Calorimeter signal reconstruction aims to suppress noise
  - Average contribution = 0, but adds to fluctuations!



Small signal, two particles:

- Noise only
- Signal on top of noise
- Sum of noise and signal
- Signal after noise suppression

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Acceptance and Noise in Jet Response

P. Loch
U of Arizona

Noise

- Fluctuations of the "zero" or "empty" signal reading
  - Pedestal fluctuations
- Independent of the signal from particles
  - At least to first order
- Mostly incoherent
  - No noise correlations between readout channels
    - Noise in each channel is independent oscillator
- Gaussian in nature
  - Pedestal fluctuations ideally follow normal distribution around 0
  - Width of distribution (1 σ) is noise value

Signal significance

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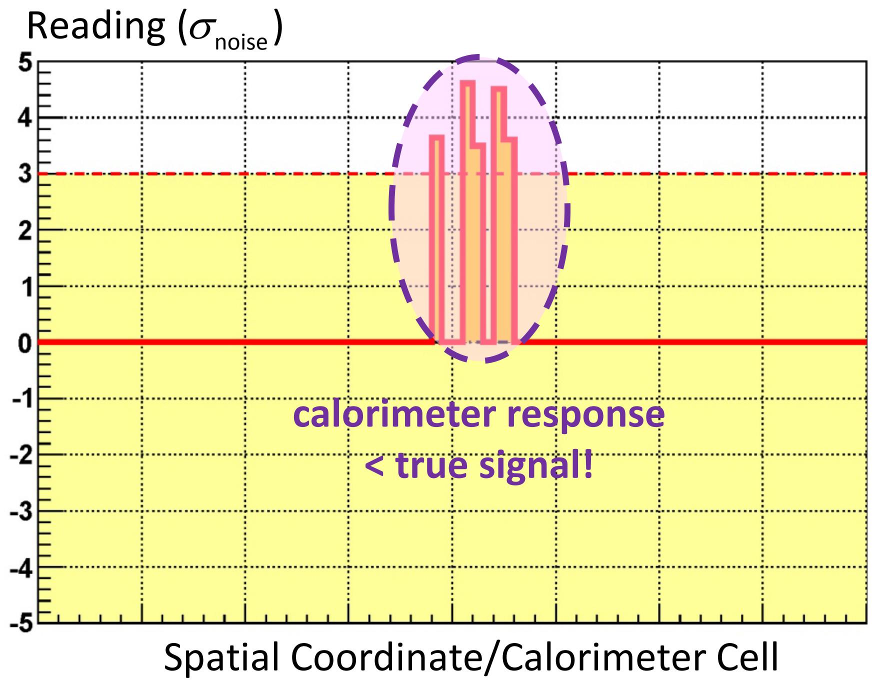

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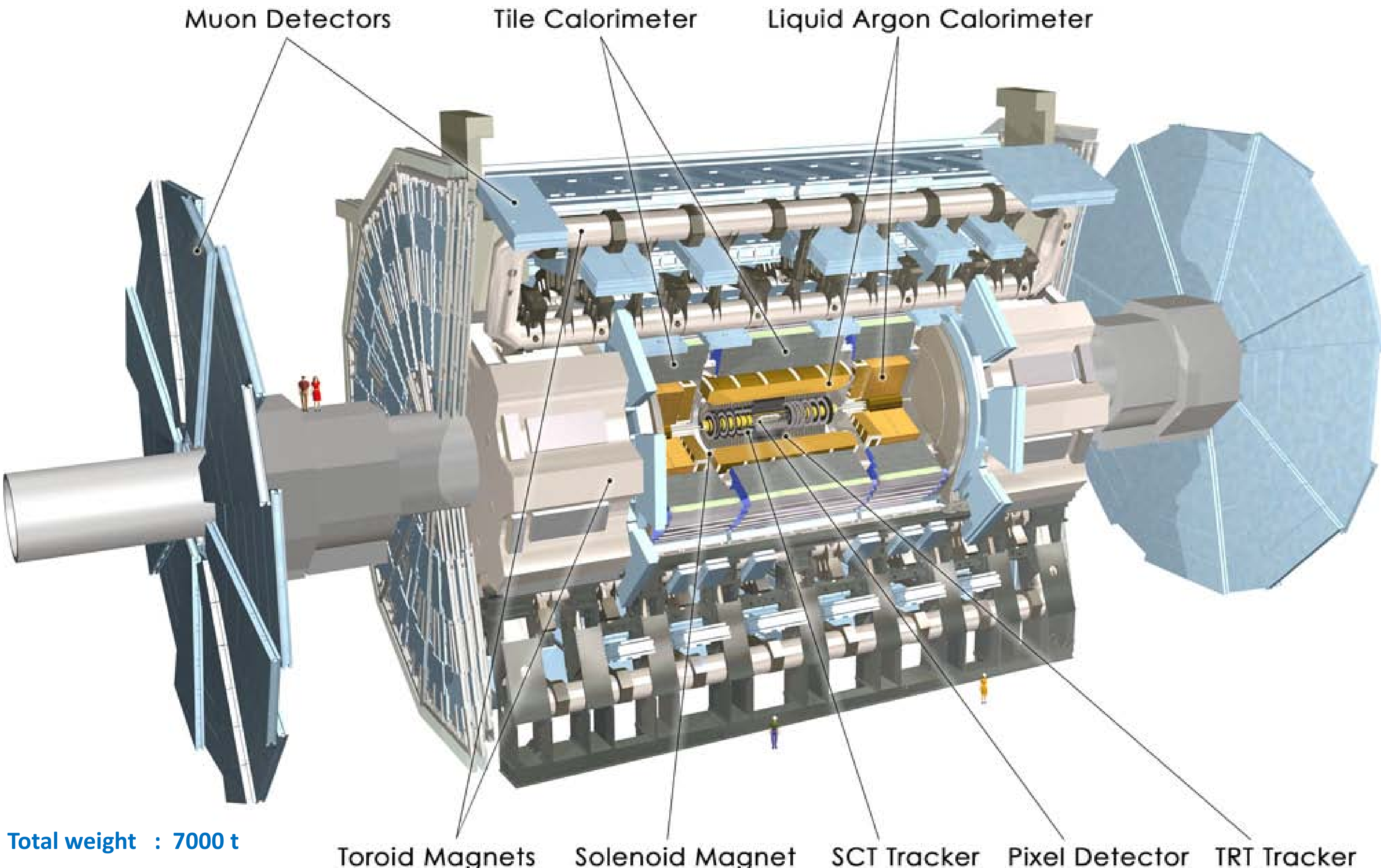
ATLAS: A General Purpose Detector For LHC

P. Loch
U of Arizona
May 05, 2010



Total weight : 7000 t
Overall length: 46 m
Overall diameter: 23 m
Magnetic field: 2T solenoid + (varying) toroid field

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ATLAS Calorimeters

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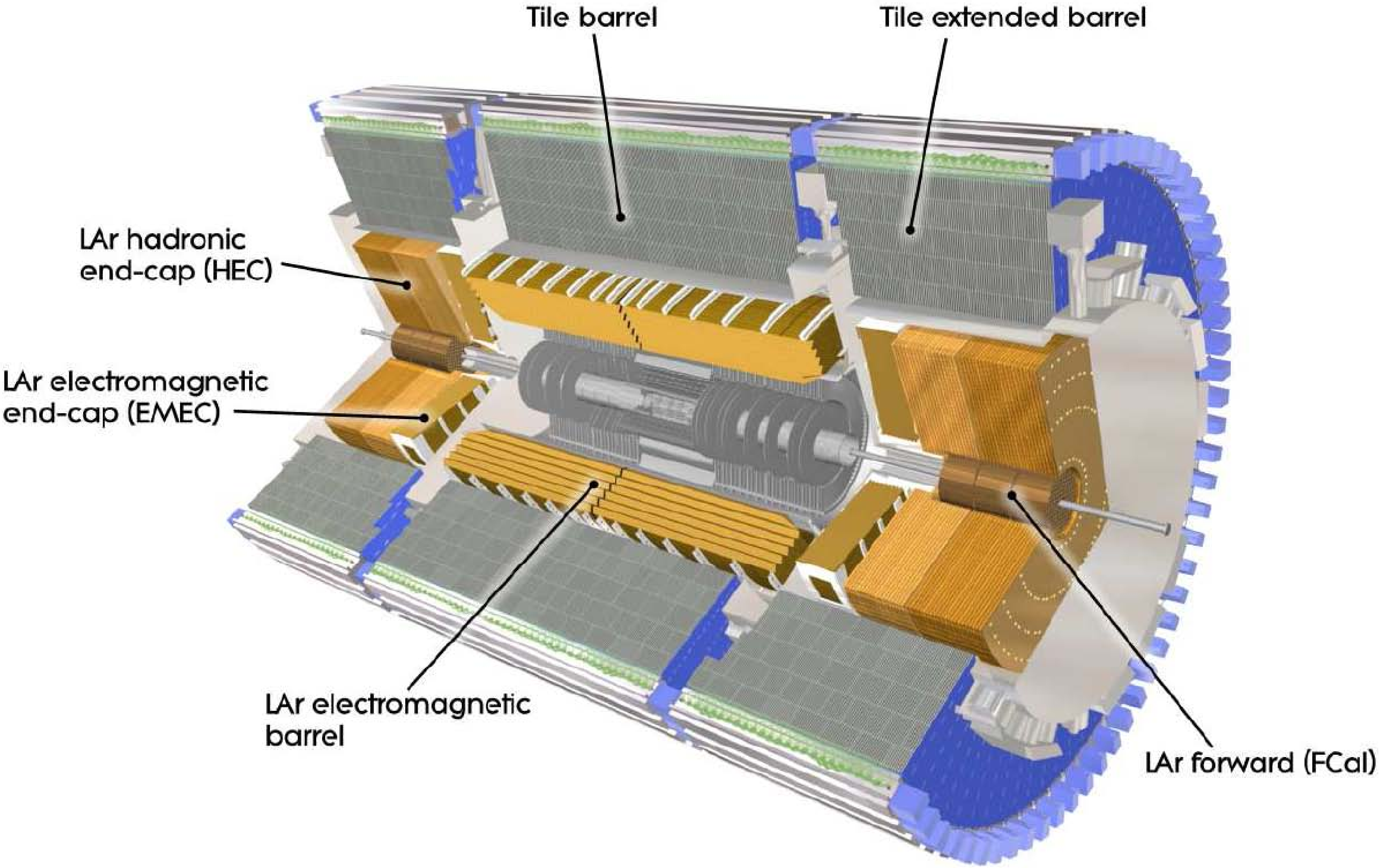
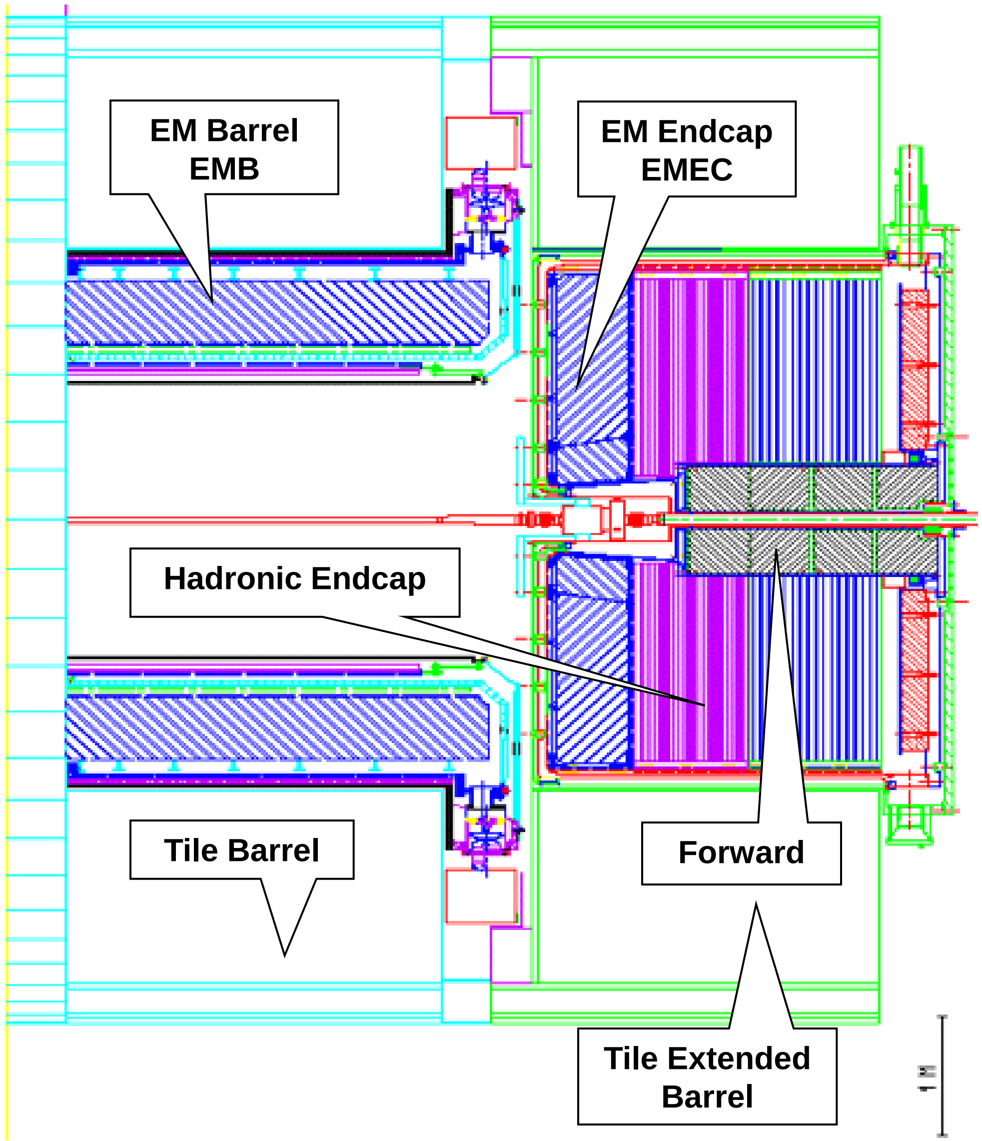
U of Arizona
May 05, 2010



The ATLAS Calorimeters

P. Loch
U of Arizona
May 05, 2010



Electromagnetic Barrel

- $|\eta| < 1.4$
- Liquid argon/lead

Electromagnetic EndCap

- $1.375 < |\eta| < 3.2$
- Liquid argon/lead

Hadronic Tile

- $|\eta| < 1.7$
- Scintillator/iron

Hadronic EndCap

- $1.5 < |\eta| < 3.2$
- Liquid argon/copper

Forward Calorimeter

- $3.2 < |\eta| < 4.9$
- Liquid argon/copper and liquid argon/tungsten

Varying (high) granularity

- Mostly projective or pseudo-projective readout geometries
- Nearly 200,000 readout channels in total

Overlaps and transitions

- Some complex detector geometries in crack regions

Electromagnetic Calorimetry

P. Loch
U of Arizona
May 05, 2010

Highly segmented lead/liquid argon accordion calorimeter

- Projective readout geometry in pseudo-rapdity and azimuth
  - More than 170,000 independent readout channels
- No azimuthal discontinuities (cracks)
  - Total depth > 24 X_0 (increases with pseudo-rapidity)
- Three depth segments
  - + pre-sampler (limited coverage, only η < 1.8)

Strip cells in 1st layer

- Thin layer for precision direction and e/π and e/γ separation
  - Total depth ≈ 6 X_0 (constant)
- Very high granularity in pseudo-rapidity
  - $\Delta\eta \times \Delta\varphi \approx 0.003 \times 0.1$

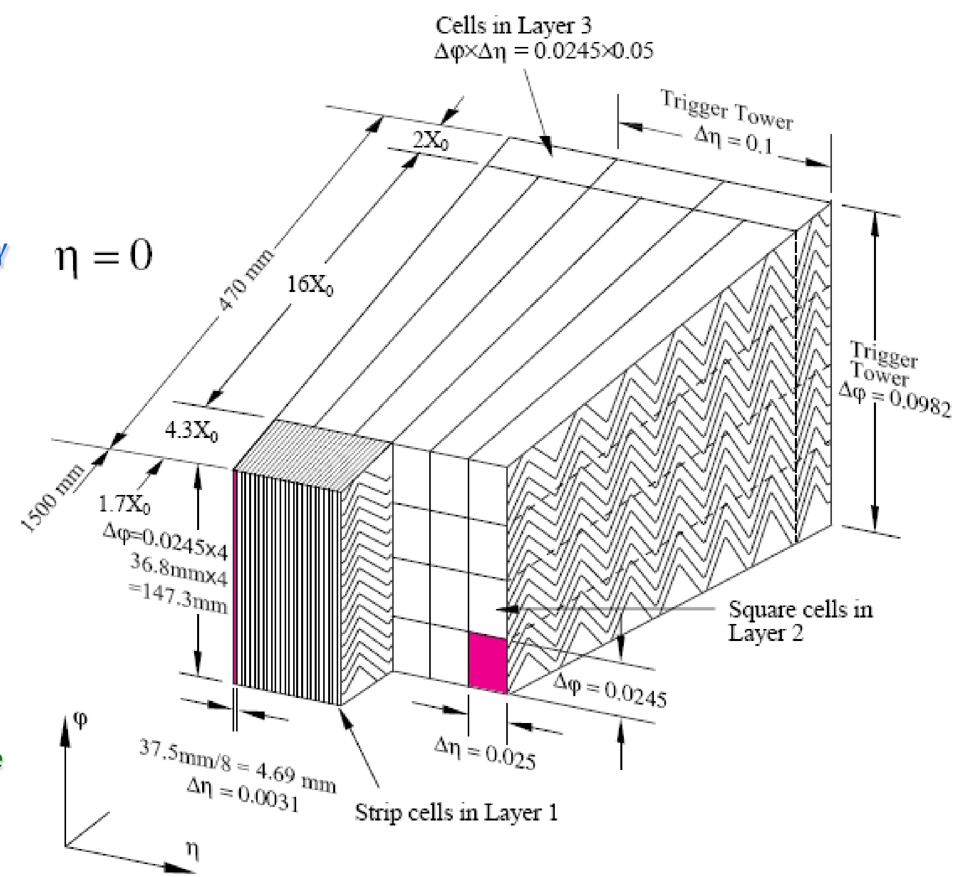
Deep 2nd layer

- Captures electromagnetic shower maximum
  - Total depth ≈ 16-18 X_0
- High granularity in both directions
  - $\Delta\eta \times \Delta\varphi \approx 0.025 \times 0.025$

Shallow cells in 3rd layer

- Catches electromagnetic shower tails
  - Electron and photon identification
  - Total depth ≈ 2-12 X_0 (from center to outer edge in pseudo-rapidity)
- Relaxed granularity
  - $\Delta\eta \times \Delta\varphi \approx 0.05 \times 0.025$

Electromagnetic Barrel



Hadronic Calorimetry

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May 05, 2010

Central and Extended Tile calorimeter

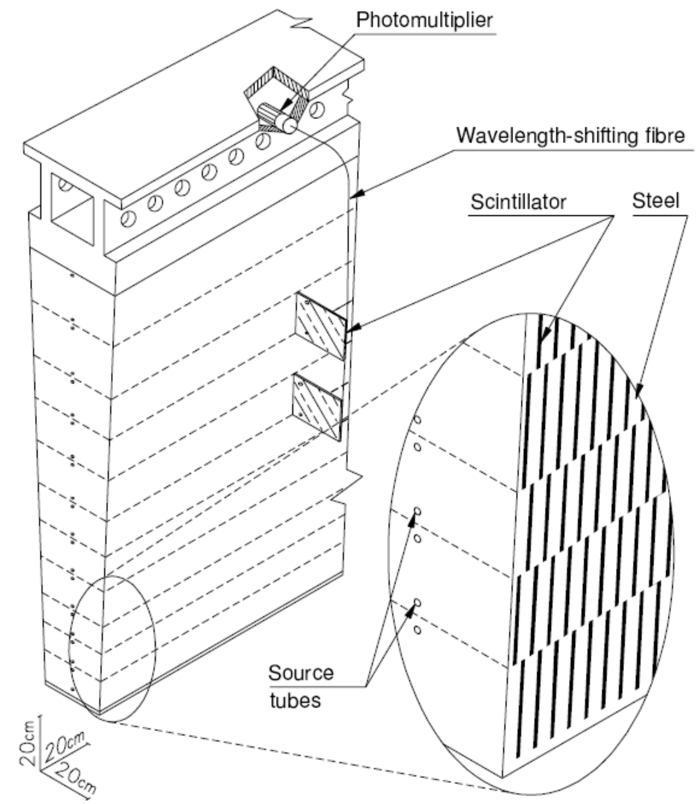
- Iron/scintillator with tiled readout structure
- Three depth segments

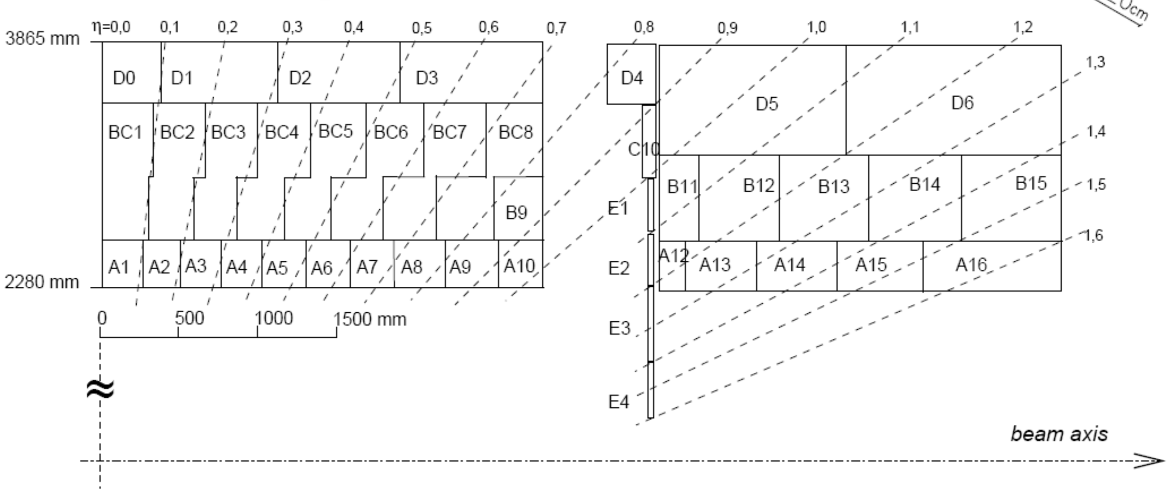
Quasi-projective readout cells

- Granularity first two layers
  - $\Delta\eta \times \Delta\varphi \approx 0.1 \times 0.1$
- Third layer
  - $\Delta\eta \times \Delta\varphi \approx 0.2 \times 0.1$

Very fast light collection

- ~50 ns reduces effect of pile-up to ~3 bunch crossings
- Dual fiber readout for each channel
  - Two signals from each cell





EndCap Calorimeters

Electromagnetic "Spanish Fan" accordion

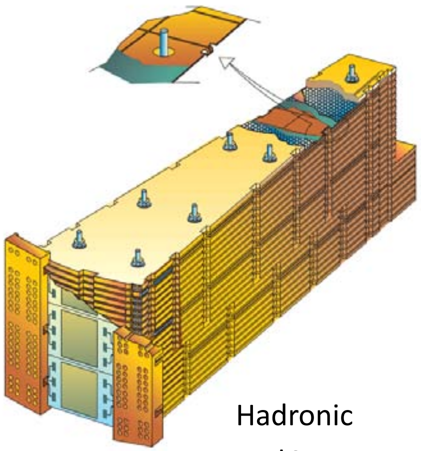
$$\Delta\eta\times\Delta\varphi\approx\begin{cases}0.025\times0.025 & |\eta|<2.5\text{, middle layer}\\ 0.1\times0.1 & 2.5<|\eta|<3.2\end{cases}$$

- Highly segmented with up to three longitudinal segments
- Complex accordion design of lead absorbers and electrodes
  - Looks like an unfolded spanish fan

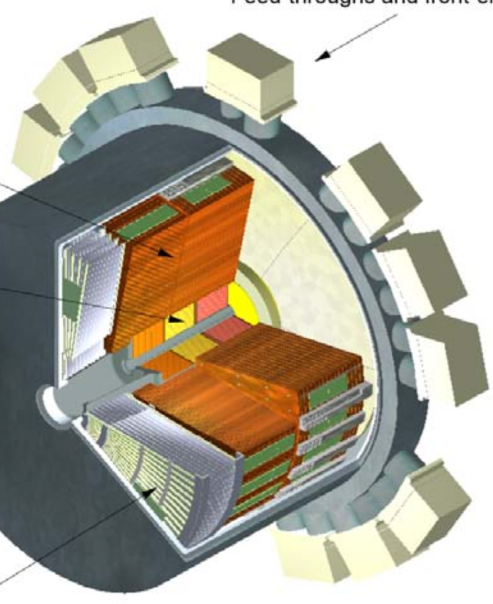
Hadronic liquid argon/copper calorimeter

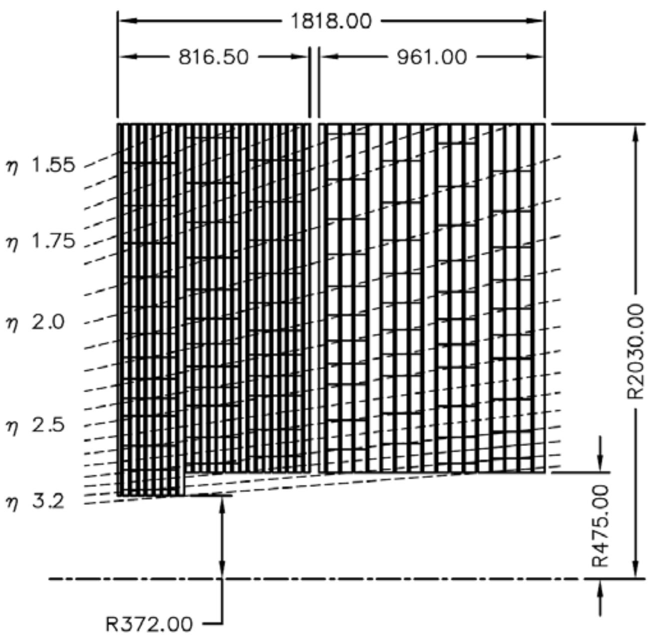
$$\Delta\eta\times\Delta\varphi\approx\begin{cases}0.1\times0.1 & |\eta|<2.5\\ 0.2\times0.2 & 2.5<|\eta|<3.2\end{cases}$$

- Parallel plate design
- Four longitudinal segments
- Quasi-projective cells



Hadronic EndCap wedge





Forward Calorimeters

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May 05, 2010

Design features

- Compact absorbers
  - Small showers
- Tubular thin gap electrodes
  - Suppress positive charge build-up (Ar+) in high ionization rate environment
  - Stable calibration
- Rectangular non-projective readout cells

Electromagnetic FCal1

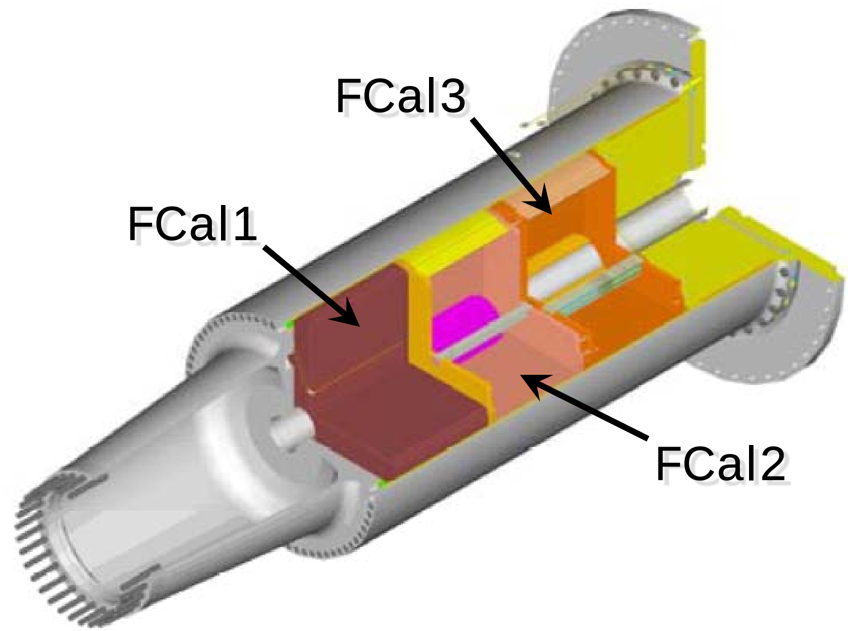
- Liquid argon/copper
  - Gap ~260 µm

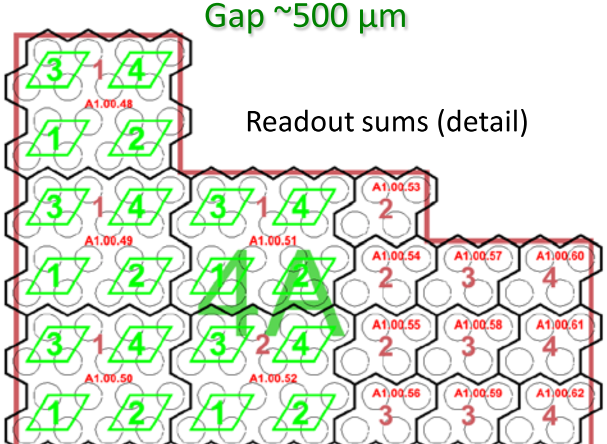
Hadronic FCal2

- Liquid argon/tungsten
  - Gap ~375 µm

Hadronic FCal3

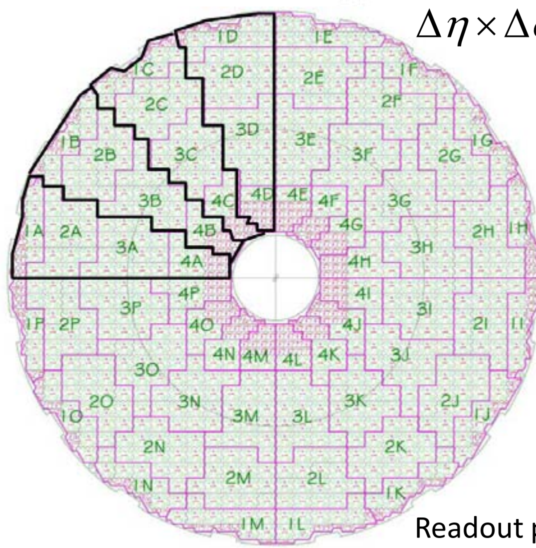
- Liquid argon/tungsten
  - Gap ~500 µm



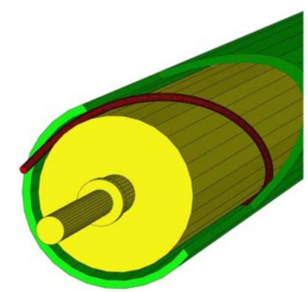


Readout sums (detail)

$\Delta\eta \times \Delta\varphi \approx 0.2 \times 0.2$



Readout pattern



Forward calorimeter electrode

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ATLAS Calorimeter Summary

P. Loch
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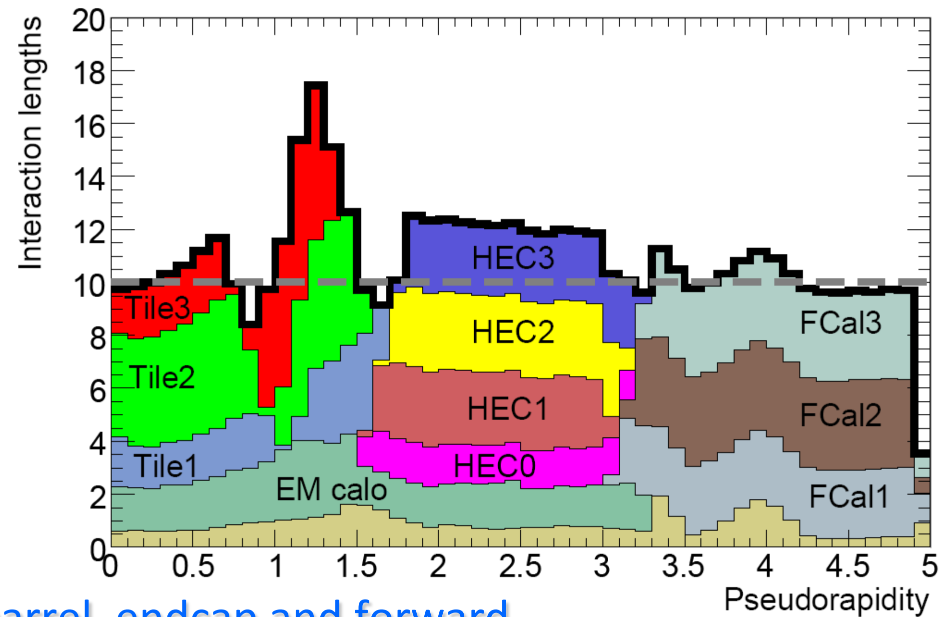
May 05, 2010

- **Non-compensating calorimeters**
  - Electrons generate larger signal than pions depositing the same energy
    - Typically $e/\pi \approx 1.3$
- **High particle stopping power over whole detector acceptance $|\eta|<4.9$**
  - $\sim$26-35 X_0 electromagnetic calorimetry
  - $\sim$ 10 λ total for hadrons



- **Hermetic coverage**
  - No significant cracks in azimuth
  - Non-pointing transition between barrel, endcap and forward
    - Small performance penalty for hadrons/jets
- **High granularity**
  - Nearly 200,000 readout channels
    - Highly efficient particle identification
    - Jet substructure resolution capabilities
    - Local hadronic calibration using signal shapes
    - …

ATLAS

What Are Jets?

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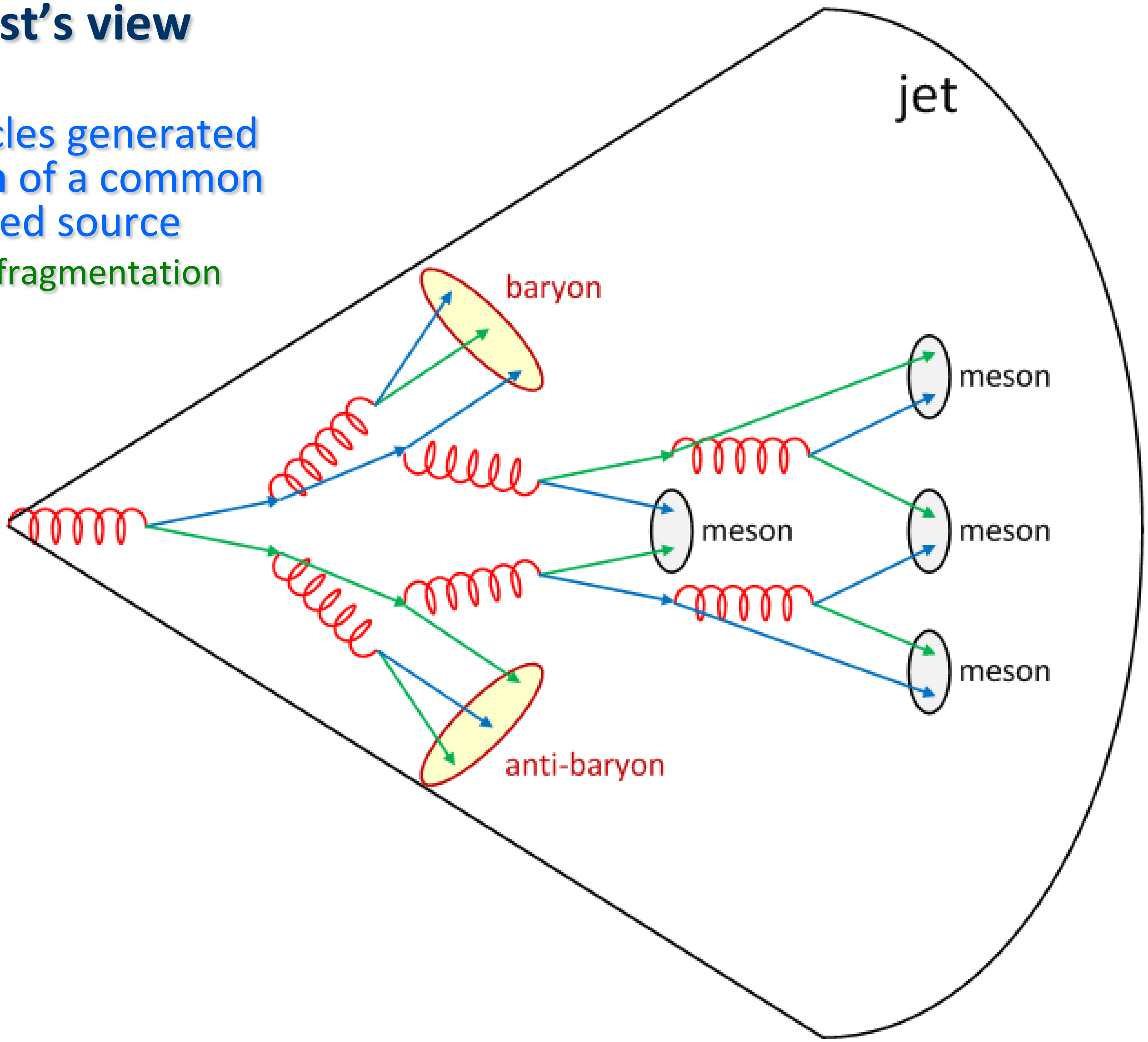
May 05, 2010

The experimentalist's view (…my view)

A bunch of particles generated by **hadronization** of a common otherwise confined source

Quark-, gluon fragmentation



What Are Jets?

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The experimentalist's view (…my view)

- A bunch of particles generated by **hadronization** of a common otherwise confined source
  - Quark-, gluon fragmentation
- Consequence of **common source**
  - Correlated kinematic properties
  - Jet reflects the source by sum rules and conservation
- Interacting particles in jet generate observable signal in detector
  - Protons, neutrons, pions, kaons, photons, electrons, muons, and others with laboratory lifetimes > 10 ps (incl. corresponding anti-particles
- Non-interacting particles in jet do not contribute to directly observable signal
  - Neutrinos, mostly

$$\left(E_{\text{jet}},\vec{p}_{\text{jet}}\right) = \sum_{\text{all particles}} \left(E_{\text{particle}},\vec{p}_{\text{particle}}\right) = \left(E_{\text{parton}},\vec{p}_{\text{parton}}\right)$$

$$q_{\text{jet}} = \sum_{\text{all particles}} q_{\text{particle}} = q_{\text{parton}}$$

$$m_{\text{jet}} = \sqrt{E_{\text{jet}}^2 - \left|\vec{p}_{\text{jet}}\right|^2} = \sqrt{\left[\sum_{\text{all particles}} E_{\text{particle}}\right]^2 - \left|\sum_{\text{all particles}} \vec{p}_{\text{particle}}\right|^2} = \sqrt{E_{\text{parton}}^2 - \left|\vec{p}_{\text{parton}}\right|^2} = m_{\text{parton}}$$

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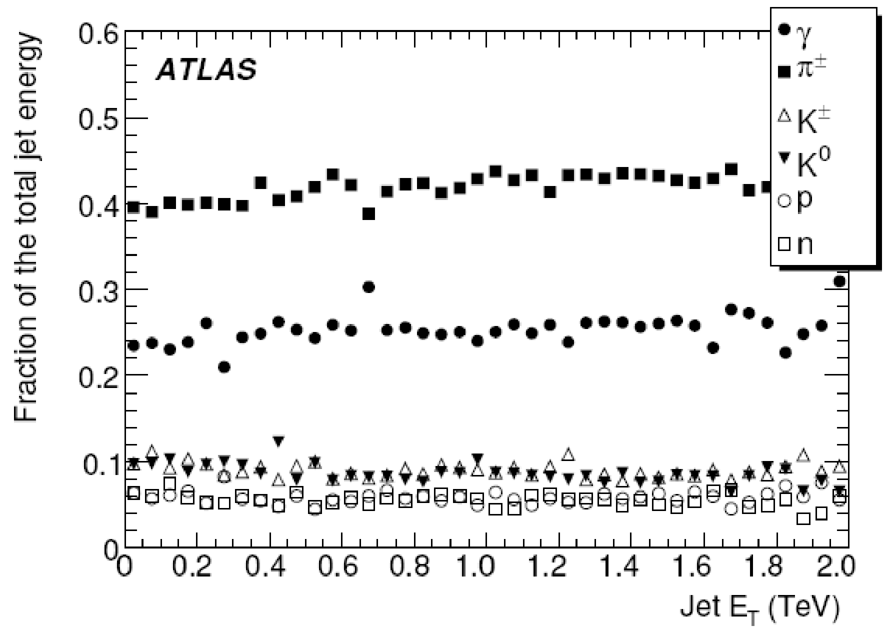
$$\left(E_{\text{jet}}, \vec{p}_{\text{jet}}\right)^{\text{obs}} = \sum_{\text{interacting particles}} \left(E_{\text{particle}}, \vec{p}_{\text{particle}}\right)$$

$$\neq \left(E_{\text{parton}}, \vec{p}_{\text{parton}}\right)$$

$$q_{\text{jet}}^{\text{obs}} \neq q_{\text{parton}}$$

$$m_{\text{jet}}^{\text{obs}} \neq m_{\text{parton}}$$



Particle jet composition generated by PYTHIA

What is fragmentation?

- Hadronization of partons into particles
  - Confinement in QCD: gluon pair production
  - Gluon radiation

How can fragmentation be measured in an experiment?

- Reconstruct charged tracks in a given jet
  - Momentum fraction carried by these tracks reflects charged (hadron) production in hadronization
- High track reconstruction efficiency and low momentum acceptance needed!
  - Final state in e^+e^- collisions at LEP ideal – very clean collision environment without underlying event, at center-of-mass energies from 90 to 209 GeV
- Fragmentation function are derived from LEP data (1989-2000)

Can we measure the fragmentation of a given jet in hadron colliders?

- Basically impossible, as collision environment is too “messy”
  - Accidental inclusion of charged tracks not from jet (underlying event, pile-up)
  - Loss of relevant tracks hard to detect
- Need to rely on models fully describing collision event
  - Compare composition of detector jets with particle jets from simulations (generators) like PYTHIA, which implement the LEP fragmentation functions!

Parton & Particle Jets

Parton jets – what is this?

- Basically a representation of an individual final state parton before hadronization
  - Still called a jet because a jet finding algorithm is applied to the simulated partonic final state
- Jet finders explicitly or implicitly apply spatial and kinematic resolution parameters and (kinematic) thresholds to the interactions
  - Two or more close-by partons can be combined to one jet
  - A parton may not make it into a jet because it is below threshold
- Parton jets are "biased" with respect to the jet finding algorithm and its configuration
  - Two different jet finders may generated two different views on the partonic event

Particle jets

- These are jets from final state particles with lifetime > 10 ps
  - E.g., after hadronization of partons
  - Sometimes non-observable particles like neutrinos or particles with very specific signal characteristics (muons) may not be included
    - E.g., the muon generated in semi-leptonic b-decays may not be considered part of the b-jet
- Here a jet finder is mandatory to produce these jets
  - Needs to recombine the bundle of particles coming from the same source (parton)
  - Subjects particles to the same resolution parameters and thresholds as used for parton jets
  - Attempt to match parton and particle jets may allow to understand effect of fragmentation on jet finding efficiencies, mis-clustering (wrong particles combined), and bias on kinematic reconstruction
- Particle jets are a good "truth" reference for detector jets
  - After all , particles generate the detector signal

Parton "jets"

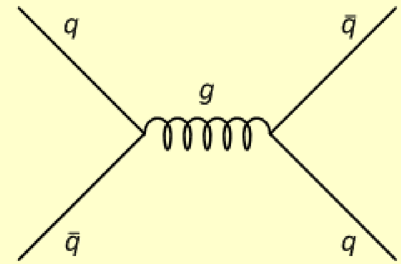
- Theoretical concept converting matrix element calculations in to jet picture
  - Depends on the order of the calculation
- Useful tool to link experimental results to calculations in di-quark resonance reconstruction
  - E.g., hadronic decays of the *W* boson and heavier new particles like *Z'*

Much less meaningful concept in QCD analysis like inclusive jet cross-section

- Jet counting as function of pT
- Number of parton jets not strictly linked to number of particle jets
  - Boundary between matrix element, radiation, parton showering, and underlying event washed out at particle level

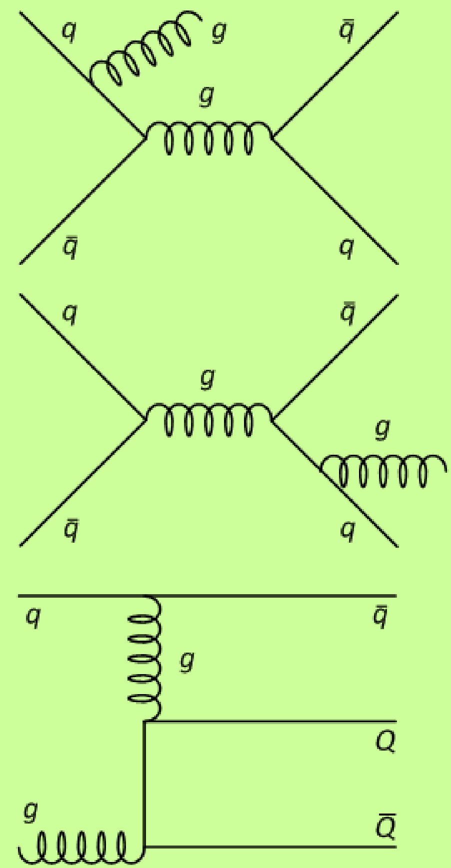
QCD LO:

$N_{\text{jets}} = 2$



QCD NLO:

$N_{\text{jets}} = 3$



Parton "Jets"

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May 05, 2010

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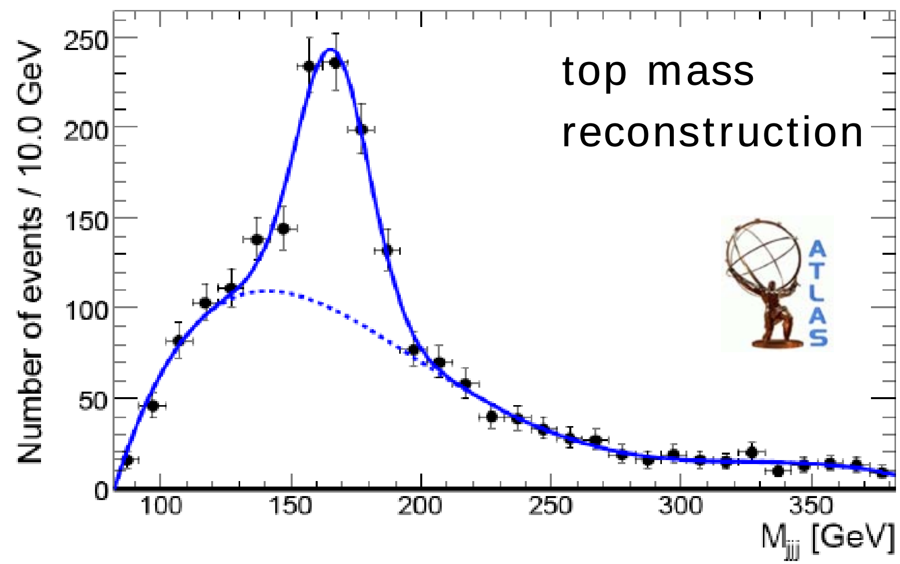
LO decays are easy to tag:

$W \to q\bar{q}'$ (2-prong decay)

$Z' \to q\bar{q}'$ (2-prong decay)

$t \to Wb \to q\bar{q}'b$ (3-prong decay)

$\to$ expectations for number of jets from decayed particle hypothesis at given order + mass of jet system pointing to certain source!



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Basic QCD $2 \to 2$ processes at LO:

$gg \to gg,\ gq \to gq,\ q\bar{q} \to q'\bar{q}'$

but often observe more than 2 jets in final state due to higher order contributions, initial and final state radiation, and additional interactions from the underlying event

$\to$ no obvious additional constraint on the appropriate parton level model from the observable final state, like in case of heavy particle decays!

$\to$ experimental final state "includes" all orders of calculations and collision environment!!

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Particle Jets

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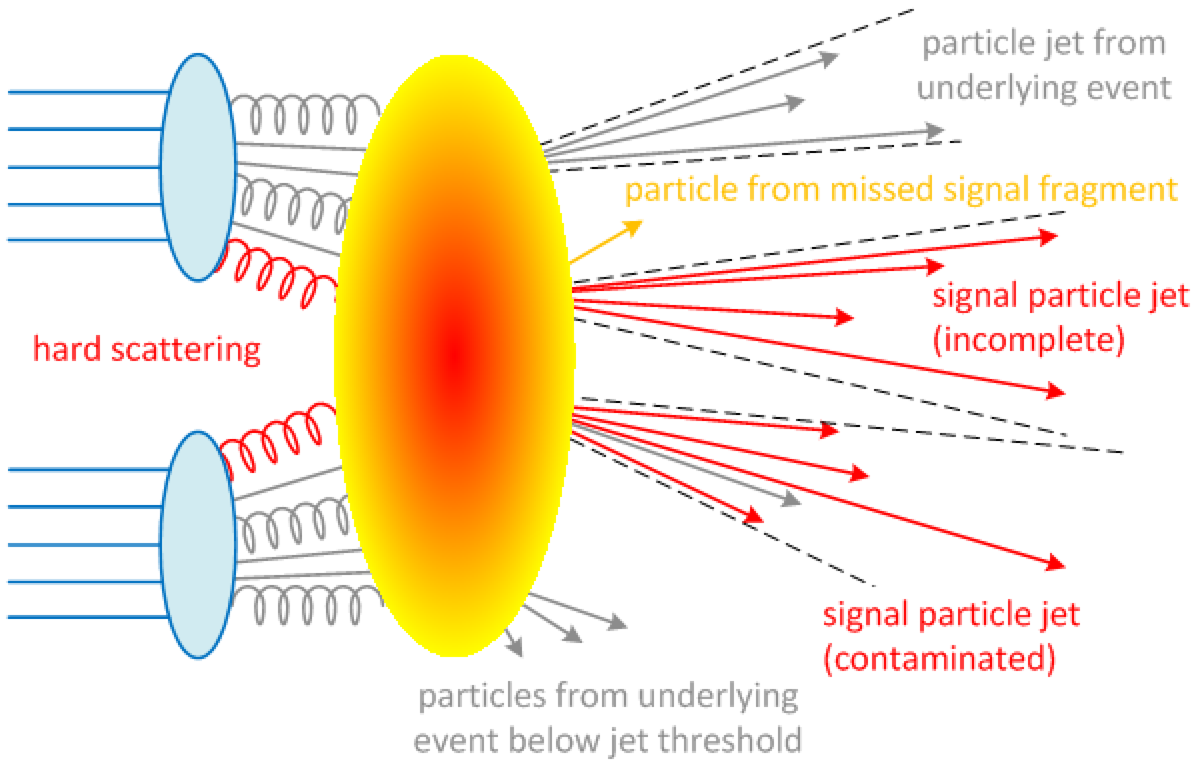
May 05, 2010

Collection of particles from common source

- Several sources in each collision
  - Hard scattering, multiple parton interactions in the underlying event, initial and final state radiation
- Describe the simulated collision viewed with a microscope (idealized)
  - Microscope **technology** – jet finding algorithm
  - **Resolution** – ability of a jet finder to (spatially) resolve jet structures of collision, typically a configuration parameter of the jet finder
  - **Sensitivity** – kinematic threshold for particle bundle to be called a jet, another configuration parameter of the jet finder



ATLAS

Usefulness of Particle Jets

Good reconstruction reference for detector jets

- Provide a truth reference for the reconstucted jet energy and momentum
  - E.g., can be used in simulations together with fully simulated detector jets to calibrate those (we will follow up on this point later!)
- Extract particle jets from measurement by calibration and unfolding signal characteristics from detector jets
  - Understand effect of experimental spatial resolution and signal thresholds at particle level
    - Remember: electromagnetic and hadronic showers have lateral extension → diffusion of spatial particle flow by distributing the particle energy laterally!
    - Remember: noise in calorimeter imply a "useful" signal threshold → may introduce acceptance limitations for particle jets!

Good reference for physics

- Goal of all selection and unfolding strategies in physics analysis
  - Reproduce particle level event from measurement as much as possible!
- Require correct simulations of all aspects of particle spectrum of collision right
  - Matrix element, parton showers, underlying event (non-pertubative soft QCD!), parton density functions,…
    - Parton shower matching to higher order matrix calculation in complex *pp* collision environment is a hot topic among theorists/phenomenologists today!
- Allow to compare results from different experiments
  - Specific detector limitations basically removed
  - Also provides platform for communication with theorists (LO and some NLO)
- Important limitations to be kept in mind
  - NLO particle level generators not available for all processes (more and more coming)
  - NNLO etc. not in sight

Basic idea

- Attempt to collect all particles coming from the same source in a given collision
  - Re-establishing the original correlations between these particles to reconstruct the kinematics and possibly even the nature of the source
- Is an algorithmic challenge
  - Many algorithms on the market, with different limitations
  - No universal algorithm or algorithm configuration for all final state analysis
    - More later, but good to know right away!
- Requires theoretical and experimental guidelines
  - Theory – physical features of particle jets addressed by sum (recombination) rules, stability of algorithm, validity for higher order calculations,…
  - Experiment – requirements for features of measured jets to allow most precise unfolding of particle jet, drives detector designs!
- Guidelines often not very appreciated by older analysis/experiments
  - Often focus on extracting signal structures from experiment without worrying too much about theoretical requirements
    - LO analysis: apply any jet algorithm to measured signals and corresponding simulations with expectations to get the same physics
  - LHC kinematic reach and phase space need considerations of higher order calculations – need jet finders valid to (arbitrary!) order!

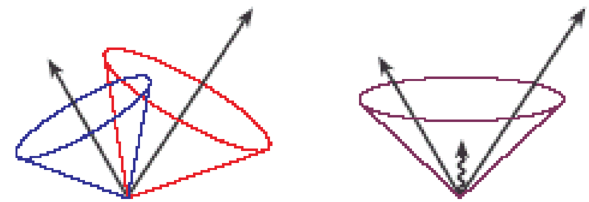
Theoretical Requirements For Jet Finders

Very important at LHC

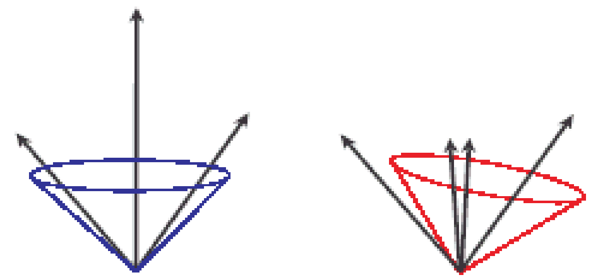
- Often LO (or even NLO) not sufficient to understand final states
  - Potentially significant K-factors can only be applied to jet driven spectra if jet finding follows theoretical rules
    - E.g., jet cross-section shapes
- Need to be able to compare experiments and theory
  - Comparison at the level of distributions
    - ATLAS and CMS will unfold experimental effects and limitations independently – different detector systems

Theoretical guidelines

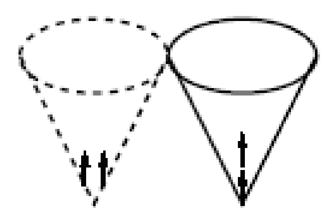
- Infrared safety
  - Adding or removing soft particles should not change the result of jet clustering
- Collinear safety
  - Splitting of large pT particle into two collinear particles should not affect the jet finding



infrared sensitivity
(soft gluon radiation merges jets)



collinear sensitivity (1)
(sensitive to E_t ordering of seeds)



collinear sensitivity (2)
(signal split into two towers below threshold)

Iterative Seeded Fixed Cone

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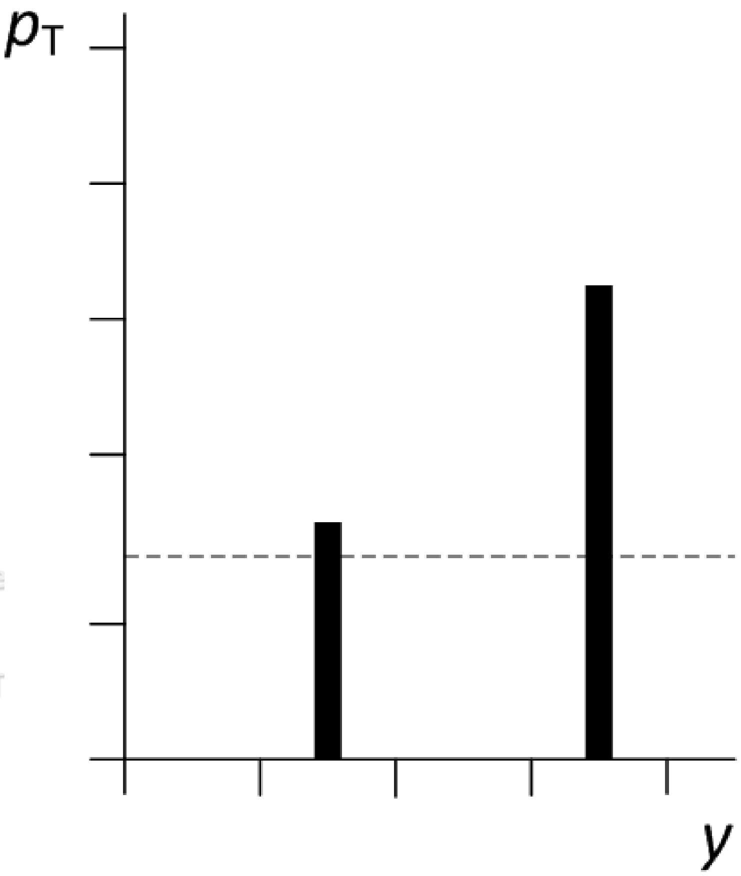
U of Arizona
May 05, 2010

Use following jet finder rules:

- Find particle with largest pT above a seed threshold
  - Create an ordered list of particles descending in pT and pick first particle
- Draw a cone of fixed size around this particle
  - Resolution parameter of algorithm
- Collect all other particles in cone and re-calculate cone directions from those
  - Use four-momentum re-summation
- Collect particles in new cone of same size and find new direction as above
  - Repeat until direction does not change → cone becomes stable
- Take next particle from list if above pT seed threshold
- Repeat procedure and find next proto-jet
  - Note that this is done with all particles, including the ones found in previous cones
- Continue until no more proto-jets above threshold can be constructed
  - The same particle can be used by 2 or more jets
- Check for overlap between proto-jets
  - Add lower pT jet to higher pT jet if sum of particle pT in overlap is above a certain fraction of the lower pT jet (merge)
  - Else remove overlapping particles from higher pT jet and add to lower pT jet (split)
- All surviving proto-jets are the final jets



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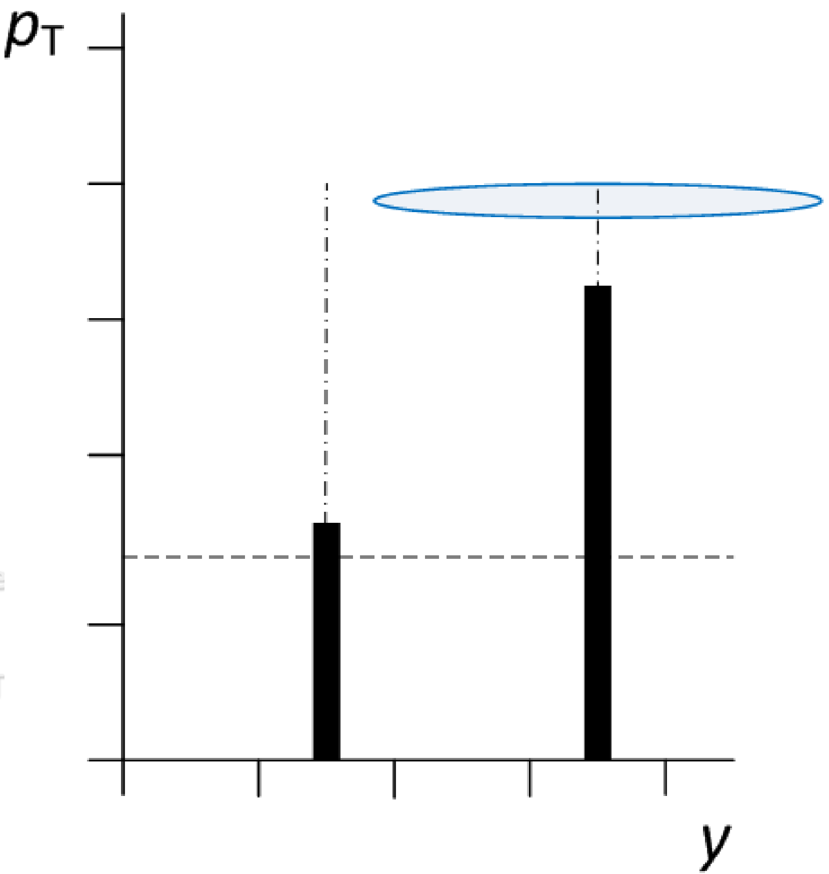
$$\Delta R = \sqrt{\Delta\eta^2 + \Delta\varphi^2} < R_{\mathrm{cone}}$$



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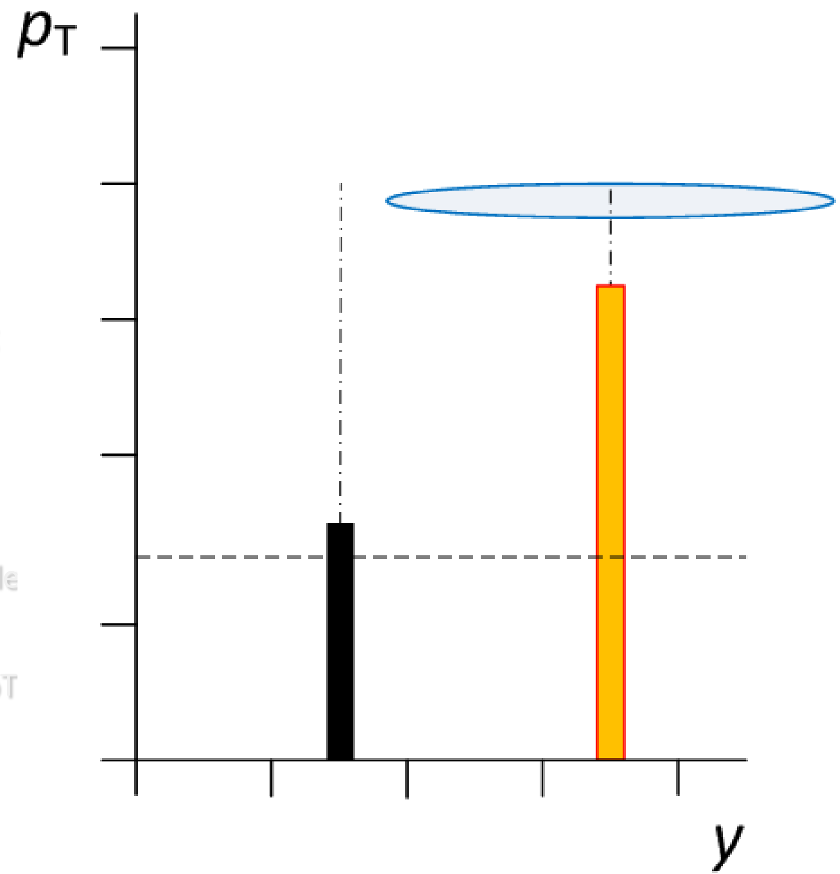
(first protojet)



Iterative Seeded Fixed Cone

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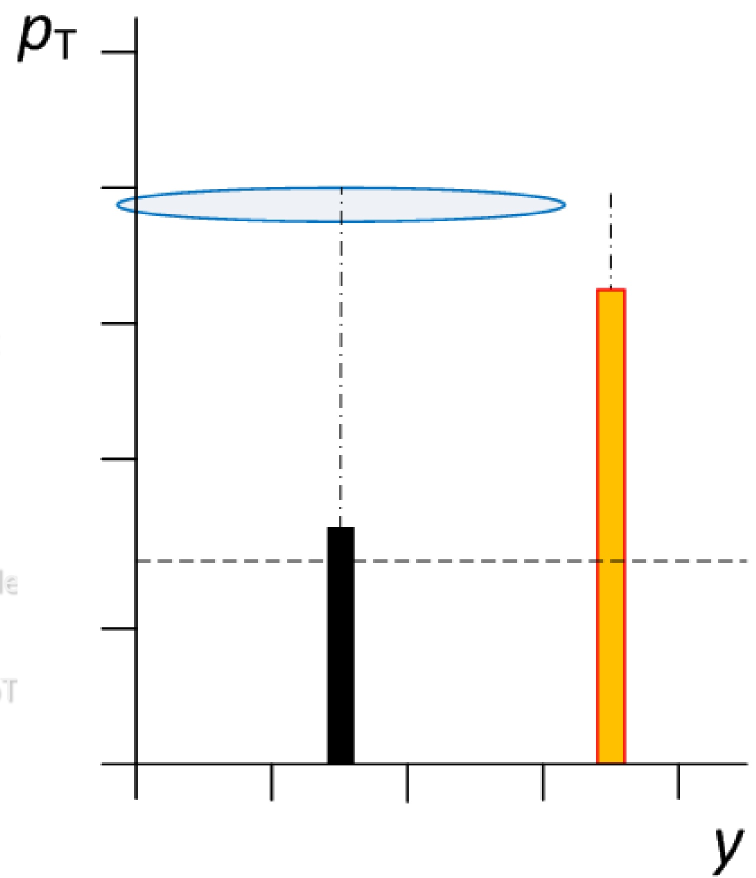

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U of Arizona
May 05, 2010

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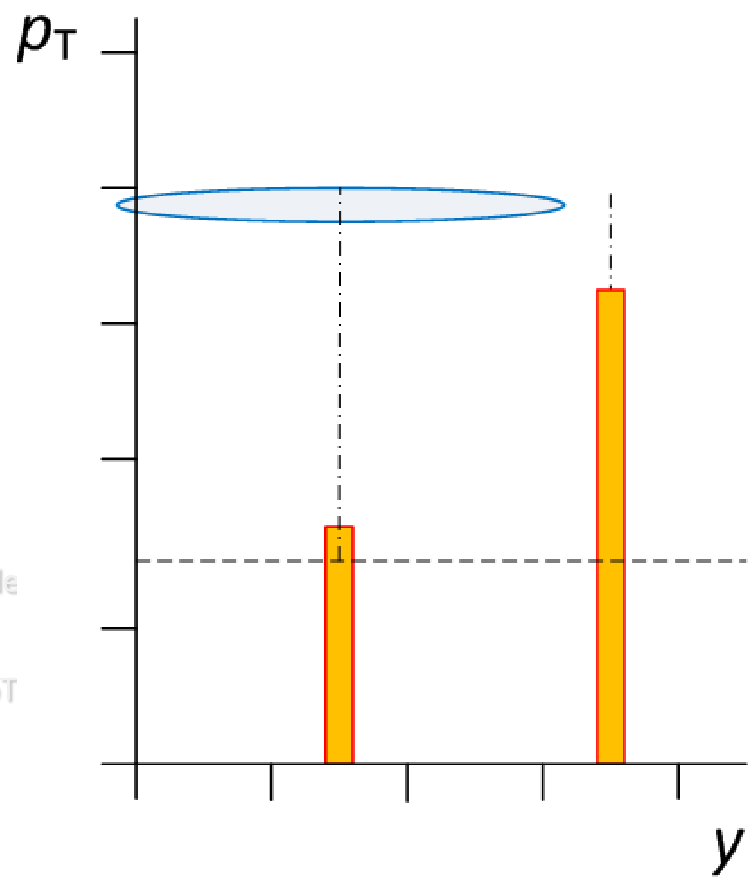

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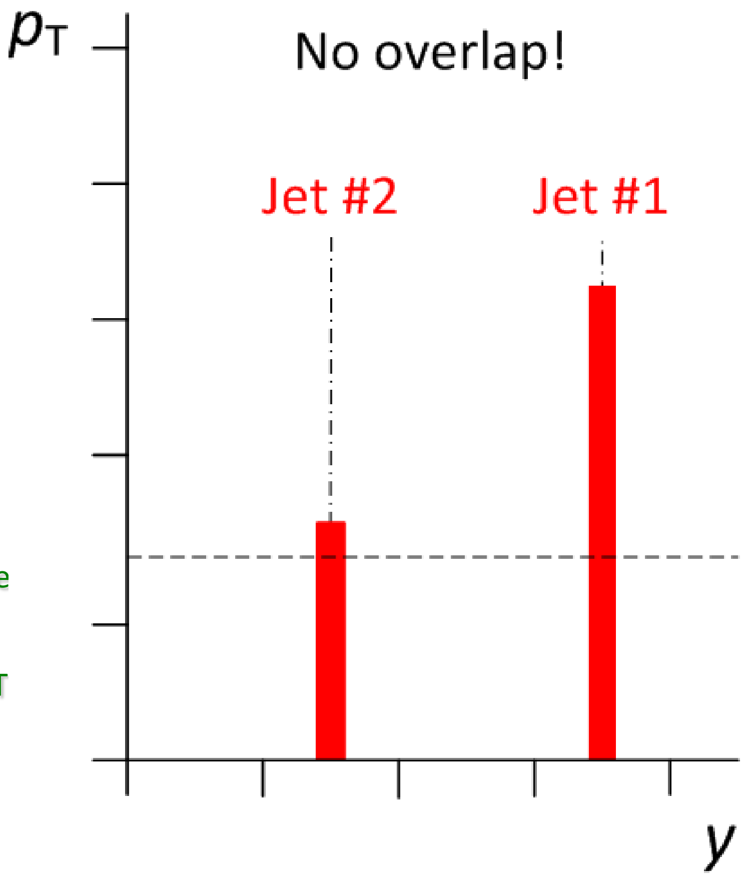

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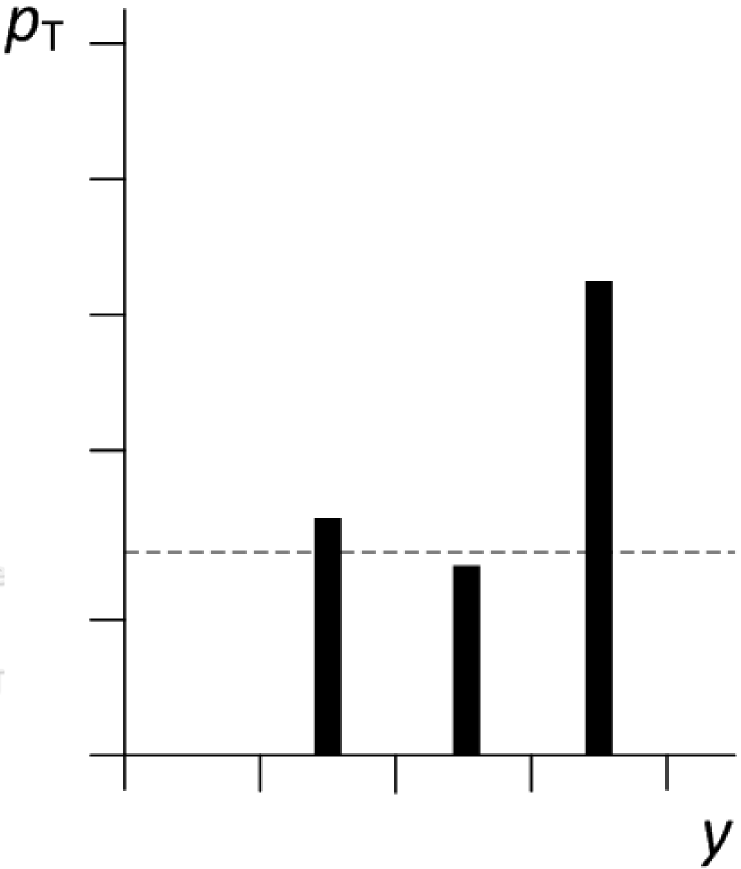

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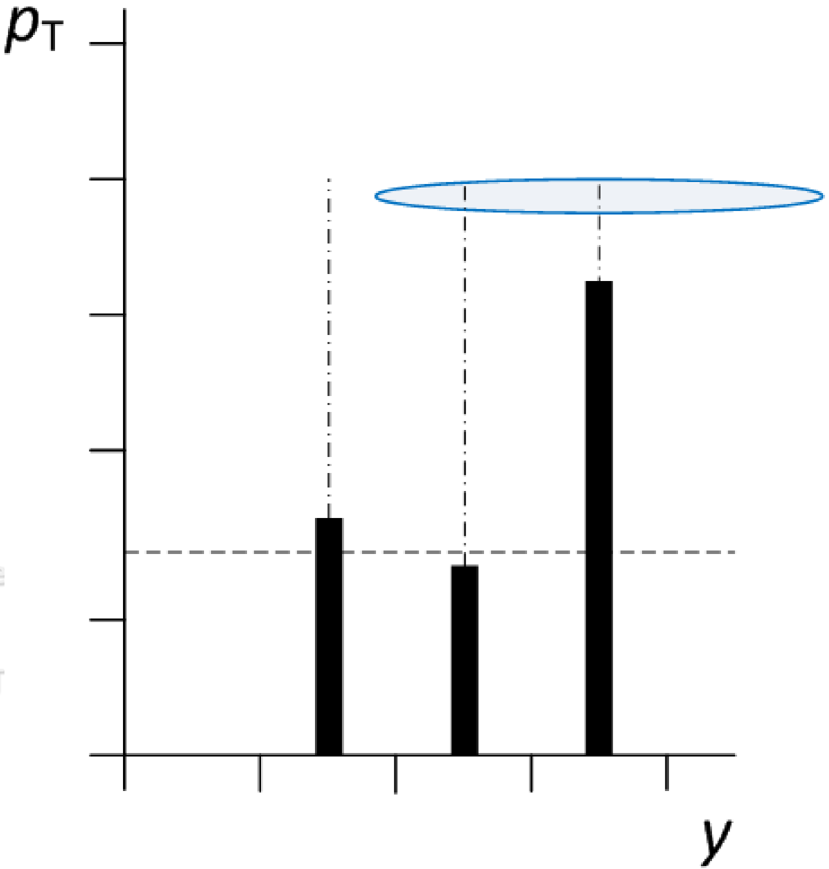

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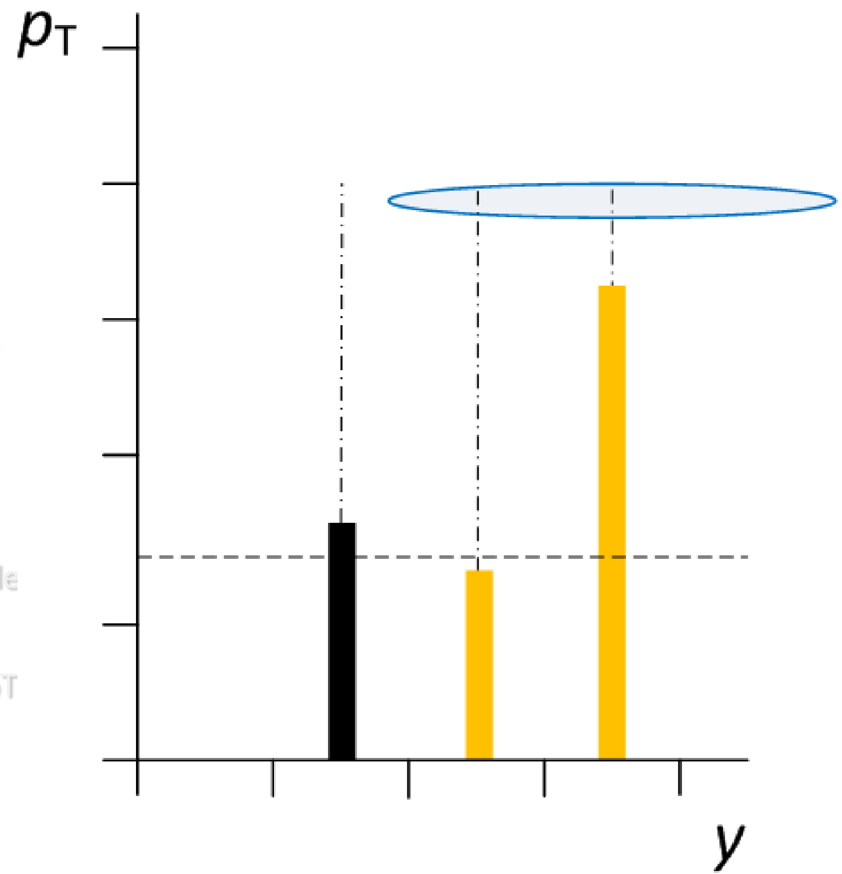

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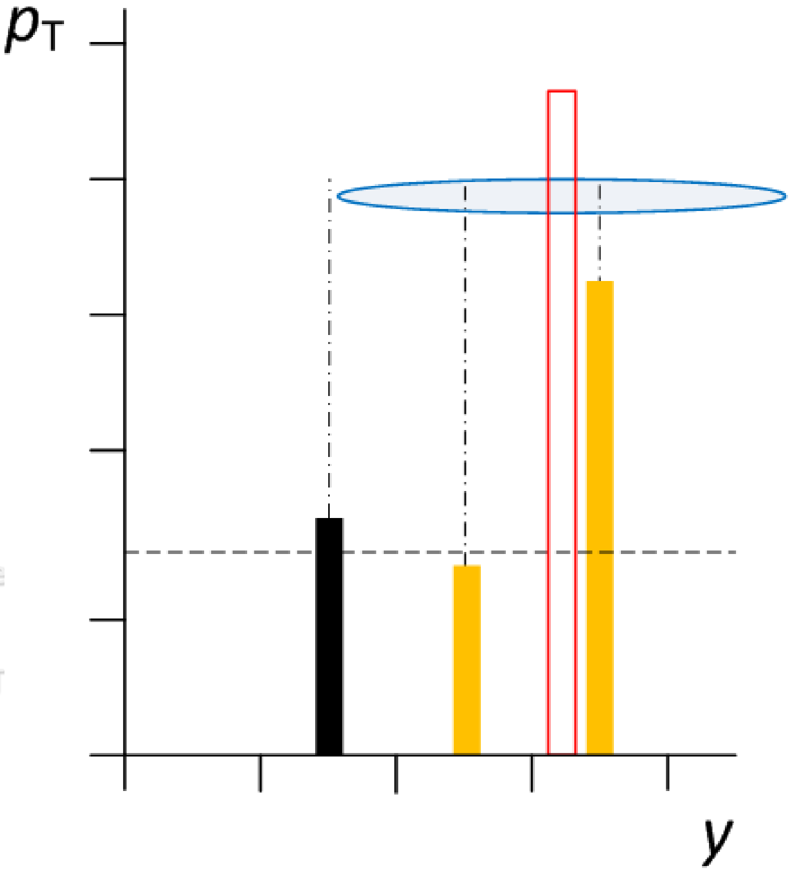

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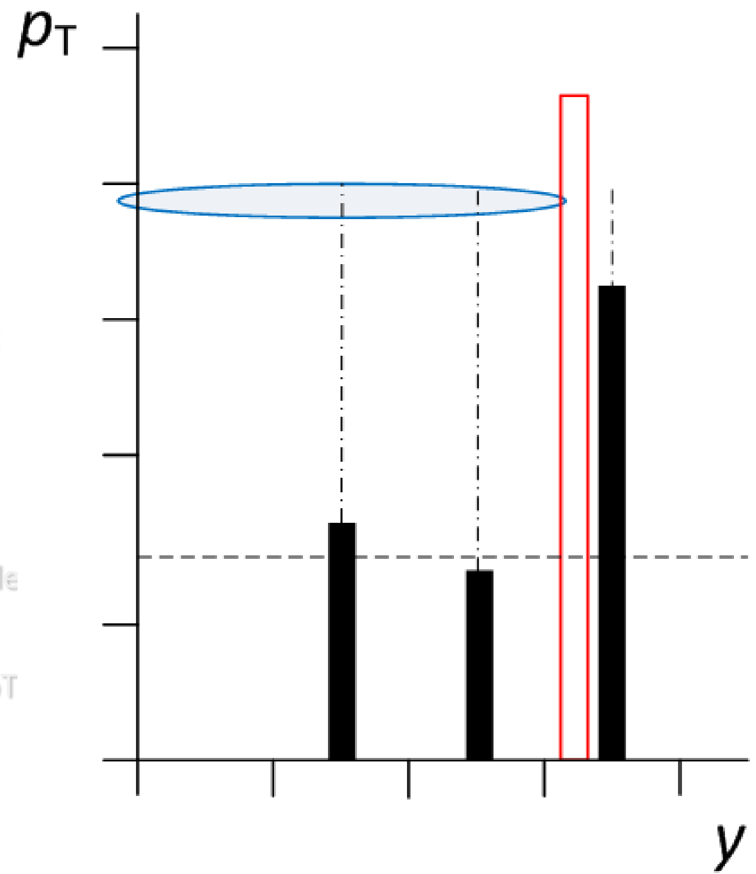

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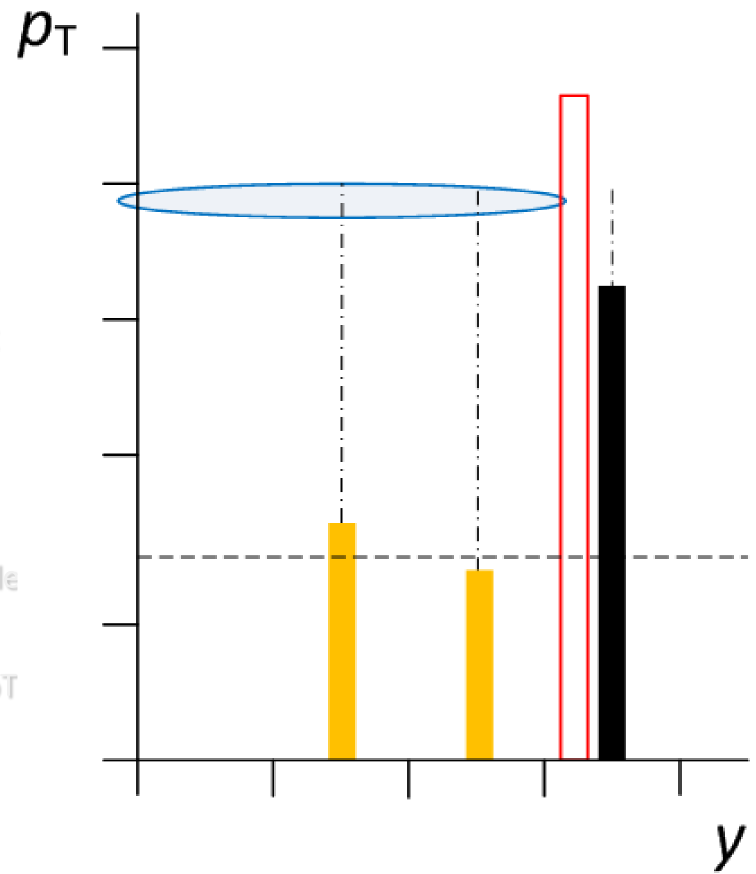

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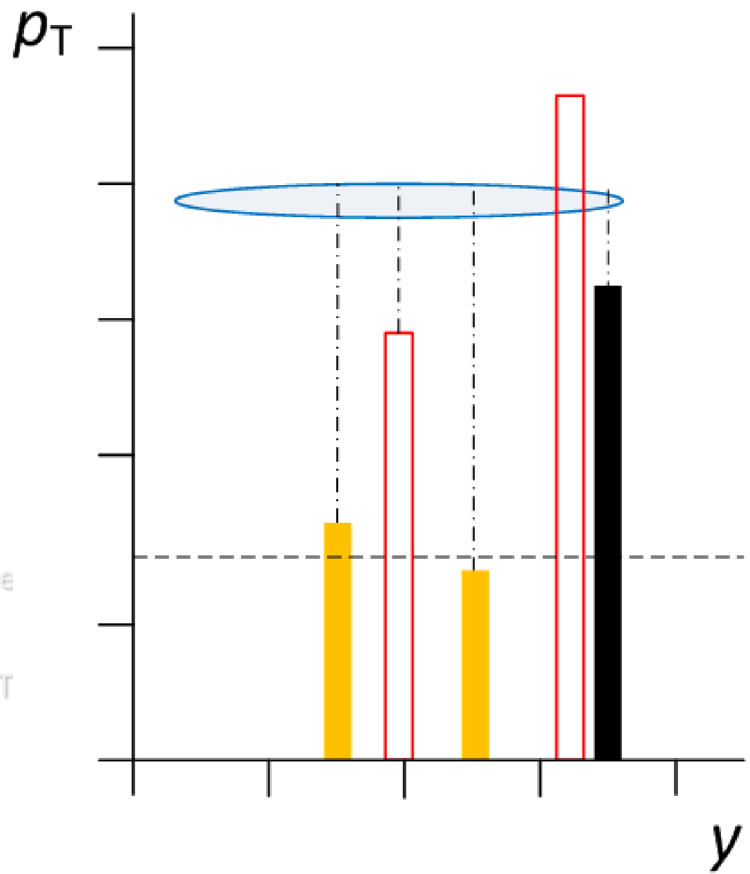

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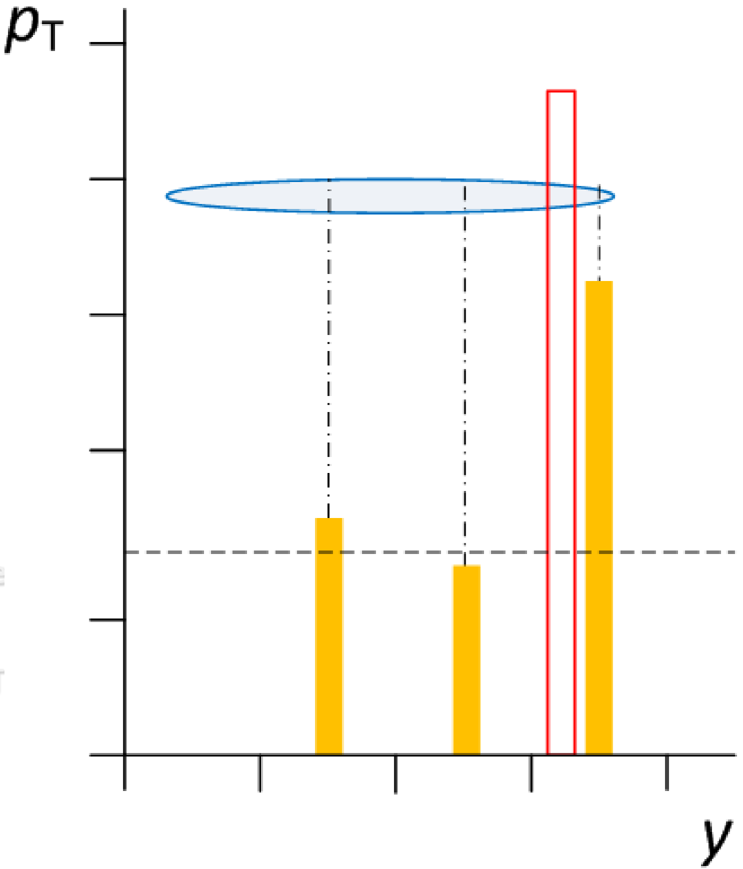

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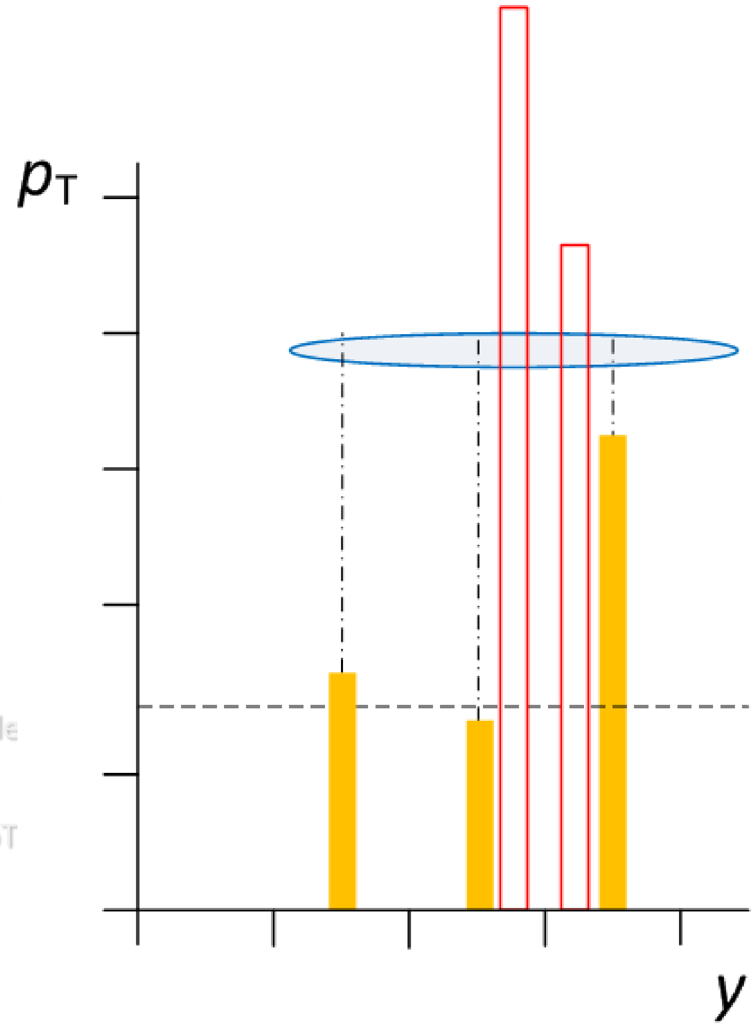
(second protojet)



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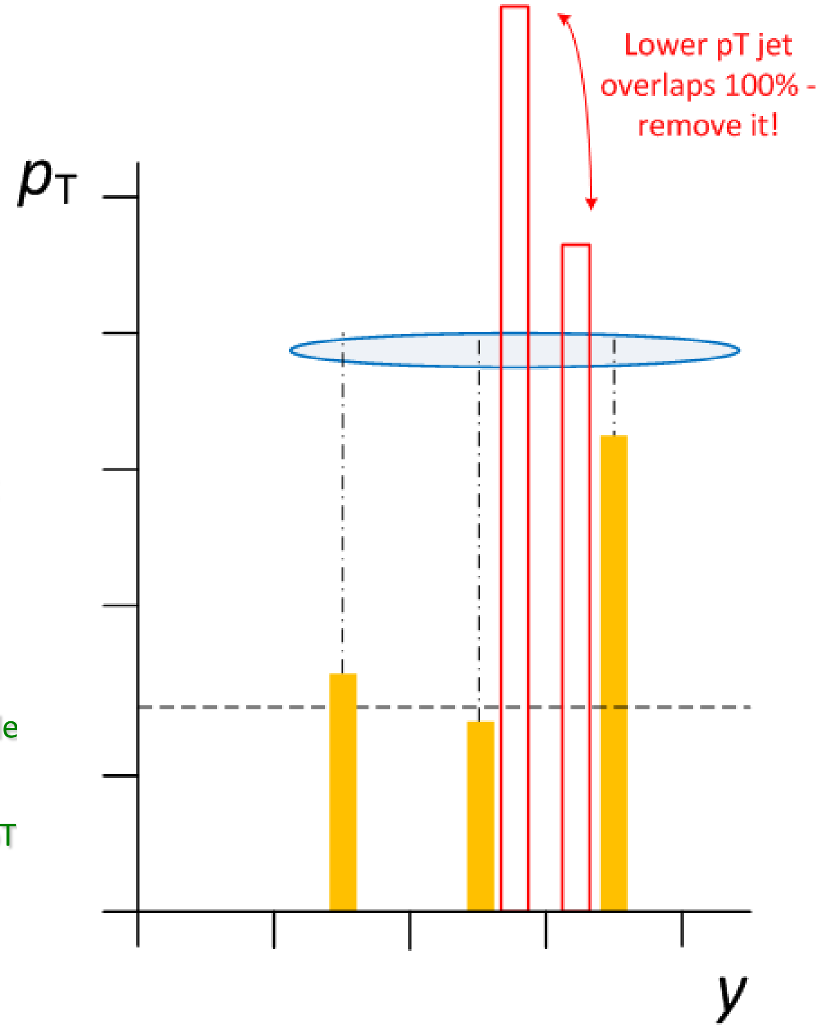

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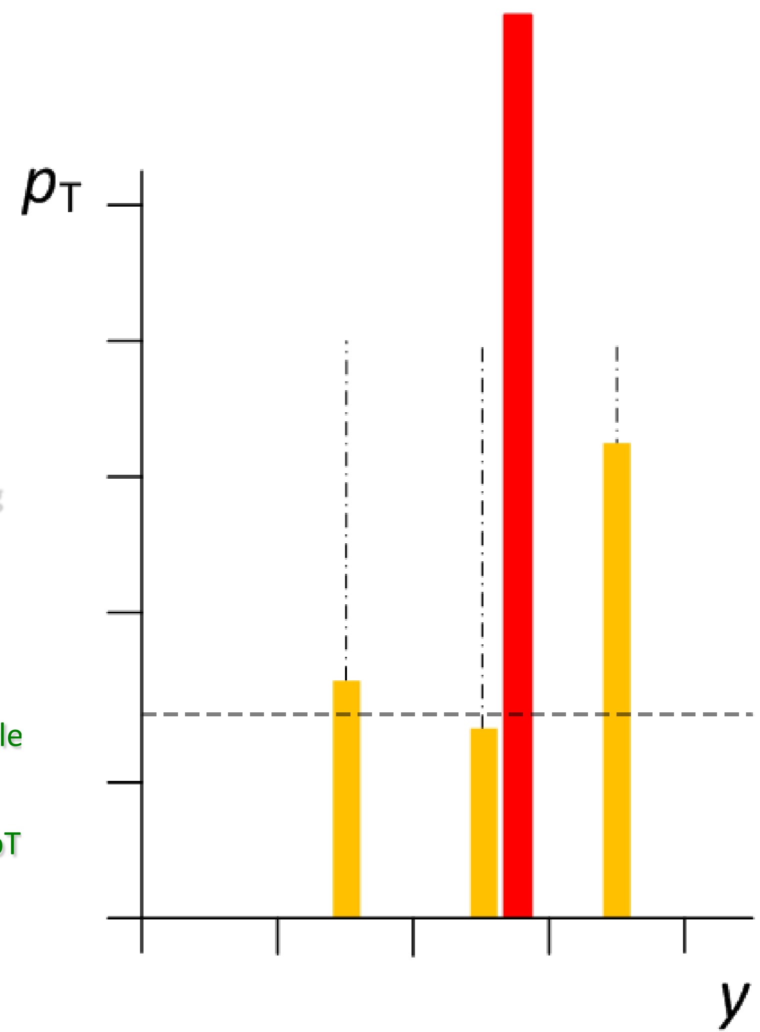

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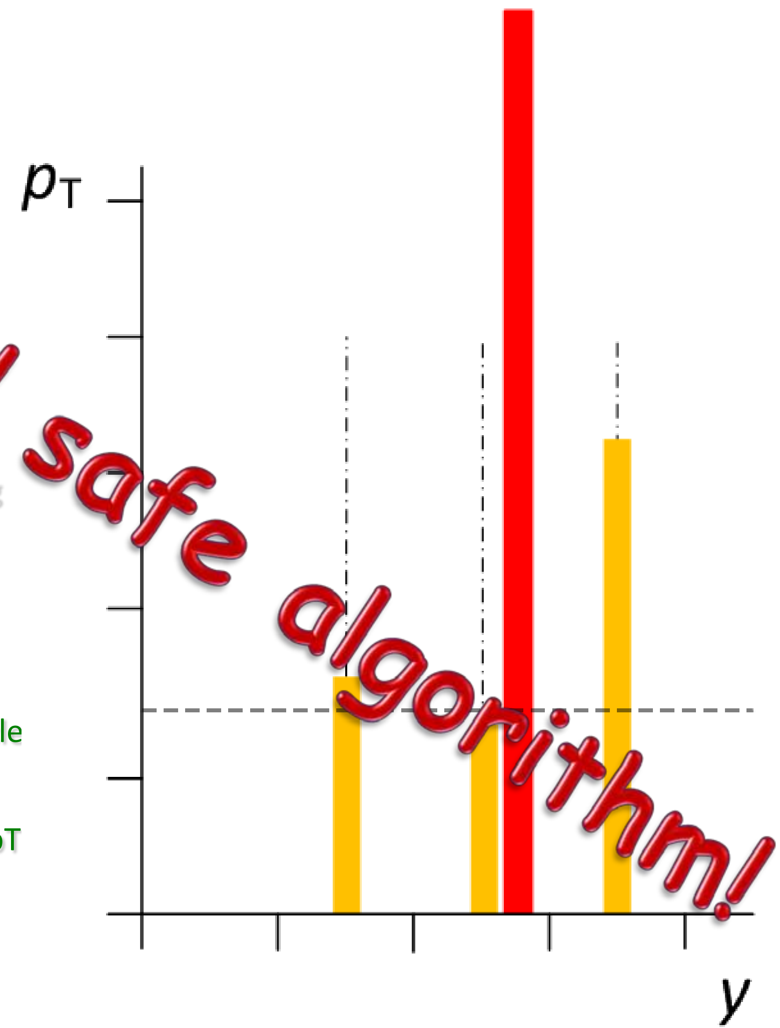

not an infrared safe algorithm!

Iterative Seeded Fixed Cone

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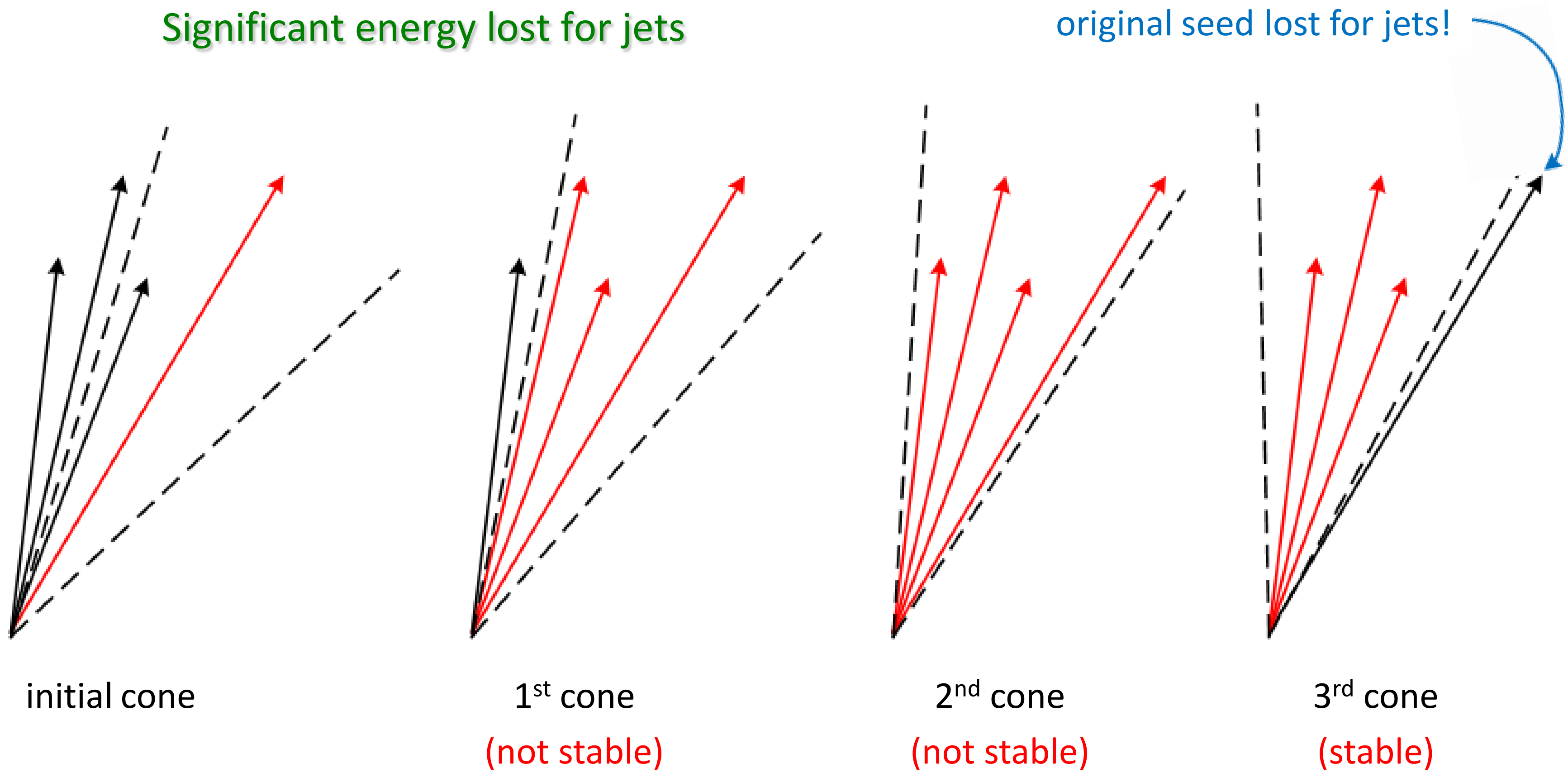
Other problems with iterative cone finders:

- "Dark" tower problem
  - Original seed moves out of cone
  - Significant energy lost for jets



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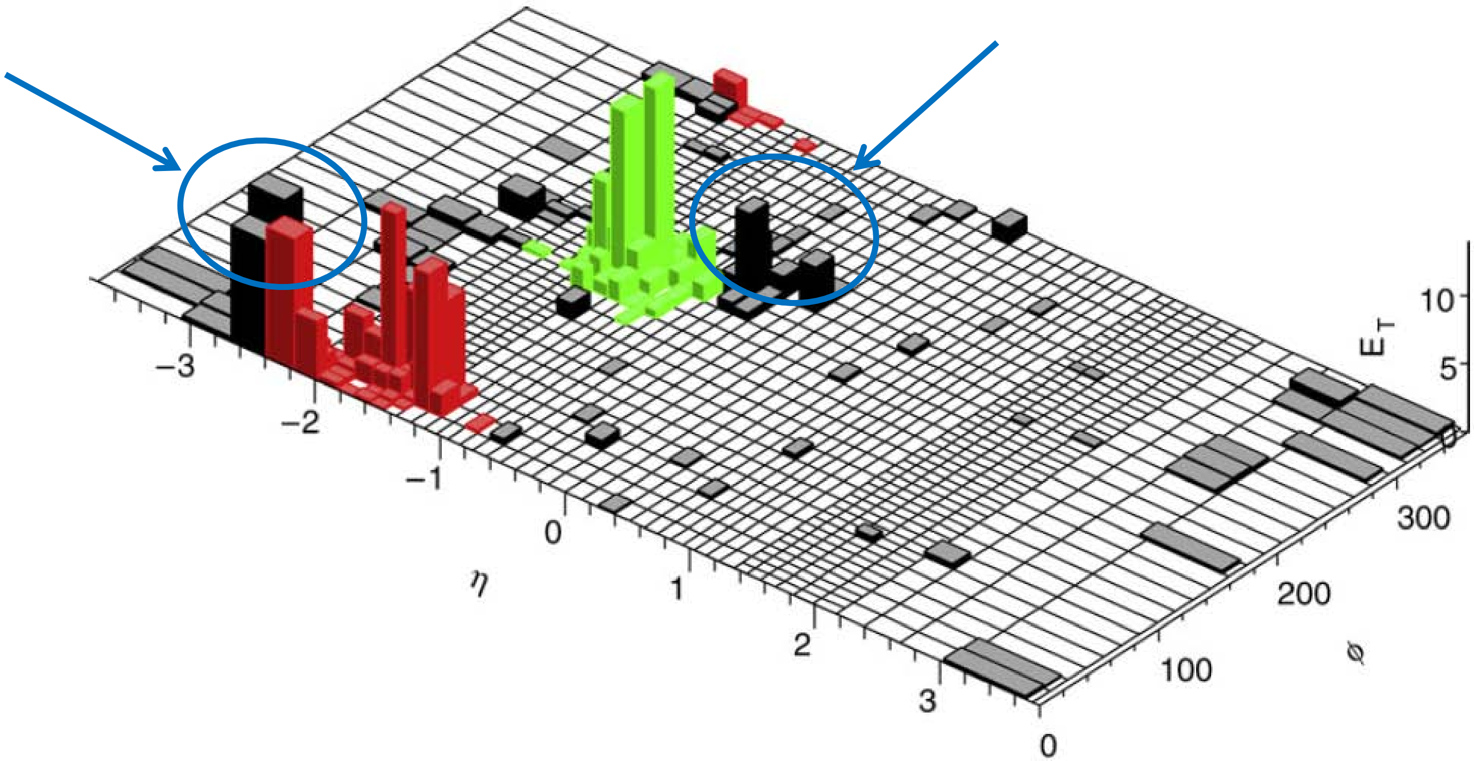

Advantages

- Simple geometry based algorithm
  - Easy to implement
- Fast algorithm
  - Ideal for online application in experiment

Disadvantages

- Not infrared safe
  - Can partially be recovered by splitting & merging
    - Introduces split/merge pT fraction *f* (typically 0.50 - 0.75)
  - Kills "trace" of pertubative infinities in experiment
    - Hard to confirm higher order calculations in "real life" without infinities!
- Not collinear safe
  - Used pT seeds (thresholds)
- Jets not cone shaped
  - Splitting and merging potentially makes jets bigger than original cone size and changes jet boundaries

Recursive Recombination

Motivated by gluon splitting function

- QCD branching happens all the time
  - Attempt to undo parton fragmentation
- Pair with strongest divergence likely belongs together
  - kT/Durham, first used in e^+e^-
  - Catani, Dokshitzer, Olsson, Turnock & Webber 1991

Longitudinal invariant version for hadron colliders

- Transverse momentum instead of energy
  - Catani, Dokshitzer, Seymour & Webber 1993
  - S.D. Ellis & D. Soper 1993
- Valid at all orders!

$$\left[dk_j\right]\left|M^2_{g\to g_i g_j}(k_j)\right| \simeq \frac{2\alpha_s C_A}{\pi}\frac{dE_j}{\min(E_i,E_j)}\frac{d\Theta_{ij}}{\Theta_{ij}}$$

$$(E_j \ll E_i, \Theta_{ij} \ll 1)$$

Distance between all particles *i* and *j*

$$y_{ij} = \frac{2\min(E_i^2,E_j^2)(1-\cos\Theta_{ij})}{Q^2}$$

$y_{ij} < y_{\rm cut} \rightarrow$ combine *i* and *j*, else stop

Drop normalization to Q^2 (not fixed in pp)

$$y_{ij} \rightarrow d_{ij} = \min(d_i,d_j)\Delta R_{ij}^2,\; d_{i,j} = p^2_{\mathrm{T}i,j}$$

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(exclusive kT)

Inclusive longitudinal invariant clustering

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Recursive Recombination

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Longitudinal invariant version for hadron colliders

- Transverse momentum instead of energy
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- Valid at all orders!

$$\left[dk_j\right]\left|M^2_{g\to g_i g_j}(k_j)\right| \simeq \frac{2\alpha_s C_A}{\pi}\frac{dE_j}{\min(E_i,E_j)}\frac{d\Theta_{ij}}{\Theta_{ij}}$$

$$(E_j \ll E_i, \Theta_{ij} \ll 1)$$

Distance between all particles *i* and *j*

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kT –like Algorithms

Classic procedure

- Calculate all distances d_{ji} for list of particles
  - Uses distance parameter
- Calculate d_i for all particles
  - Uses pT
- If minimum of both lists is a d_{ij}, combine *i* and *j* and add to list
  - Remove *i* and *j*, of course
- If minimum is a d_i, call *i* a jet and remove from list
- Recalculate all distances and continue all particles are removed or called a jet

Features

- Clustering sequence is ordered in kT
  - Follows jet structure

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  - No particular ordering, sequence not meaningful

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cluster smallest d_{ij} first until $d_{ij}>1$

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kT –like Algorithms

P. Loch
U of Arizona
May 05, 2010

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follow classic algorithm

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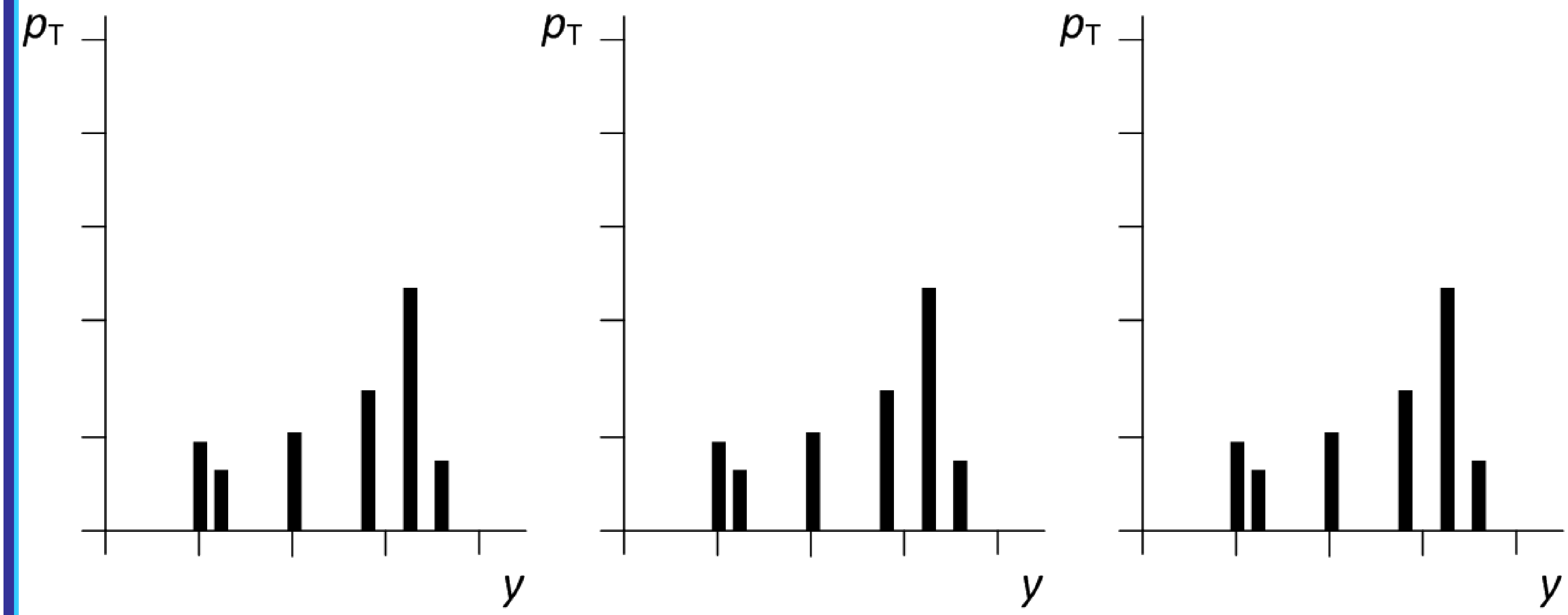
kT Examples

kT, *n*=1 | Anti-kT, *n*=-1 | Cambridge/Aachen, *n*=0



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kT Examples

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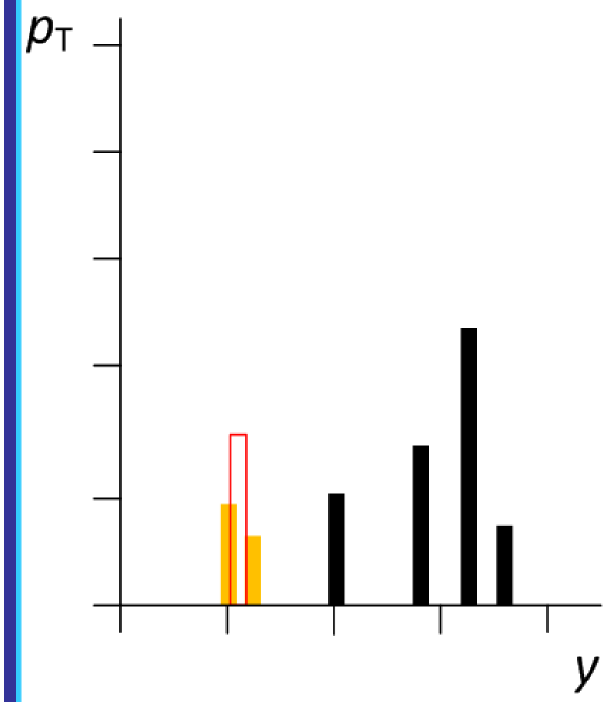
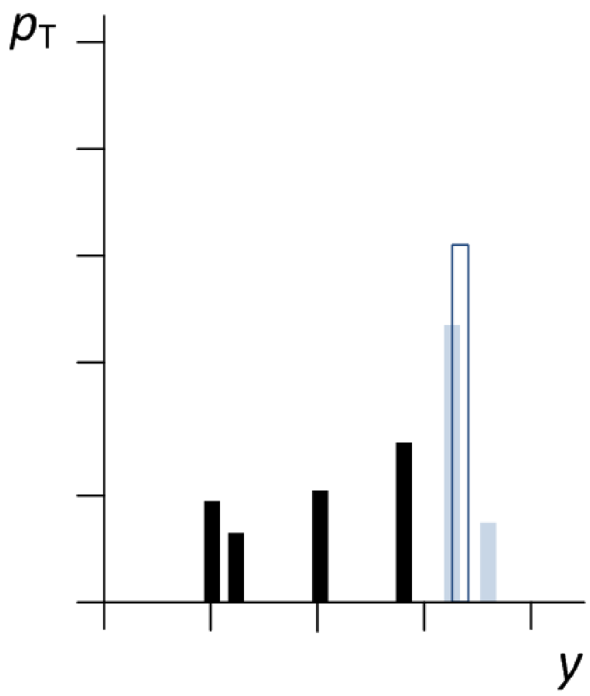
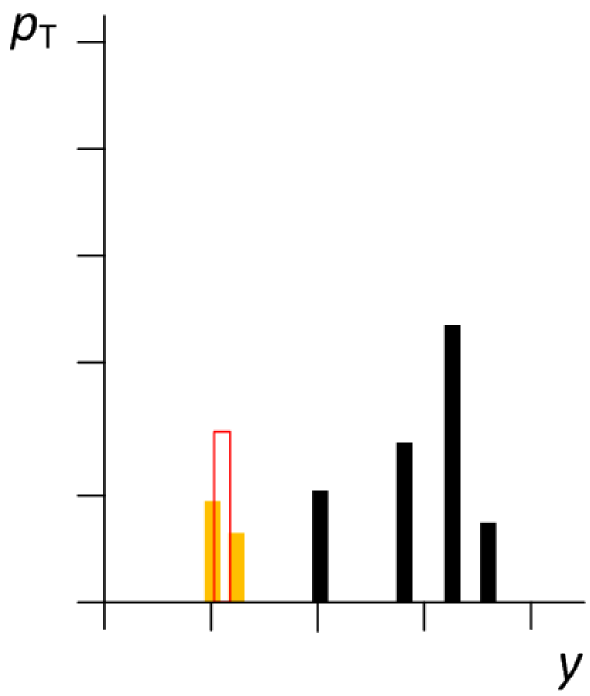


Anti-kT, *n*=-1



Cambridge/Aachen, *n*=0



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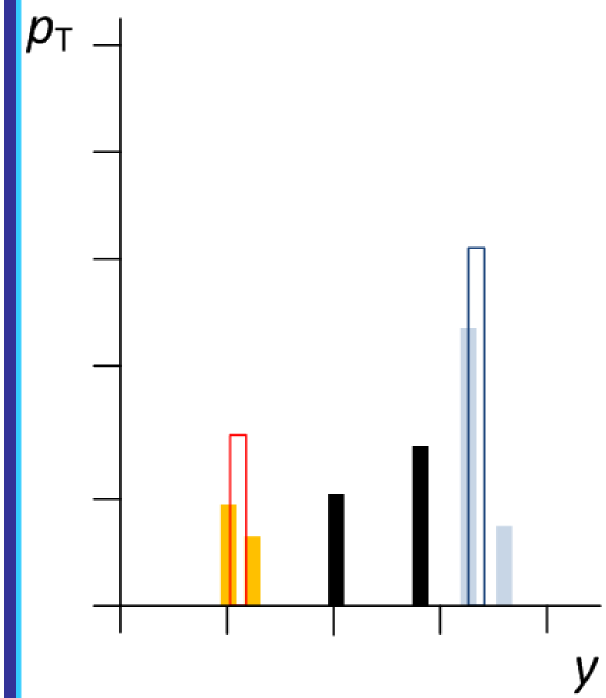

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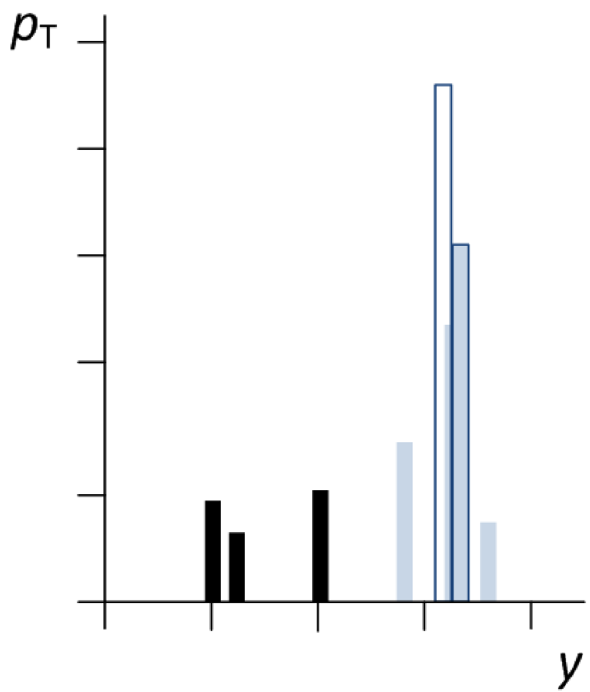

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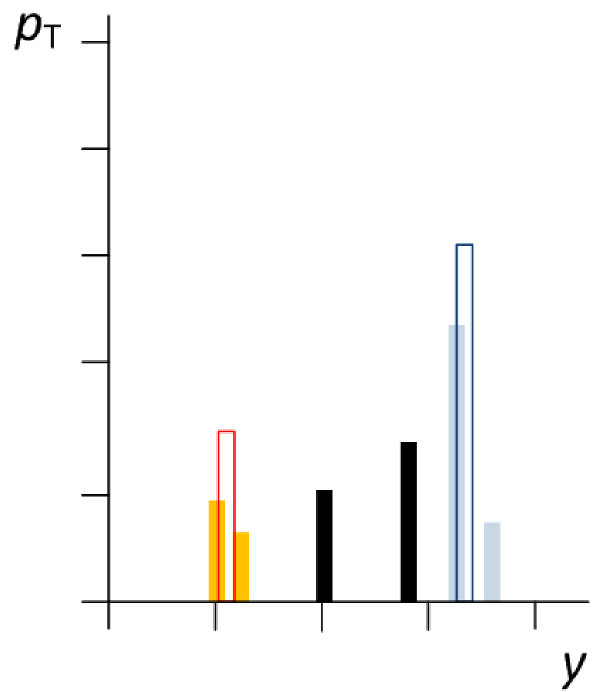

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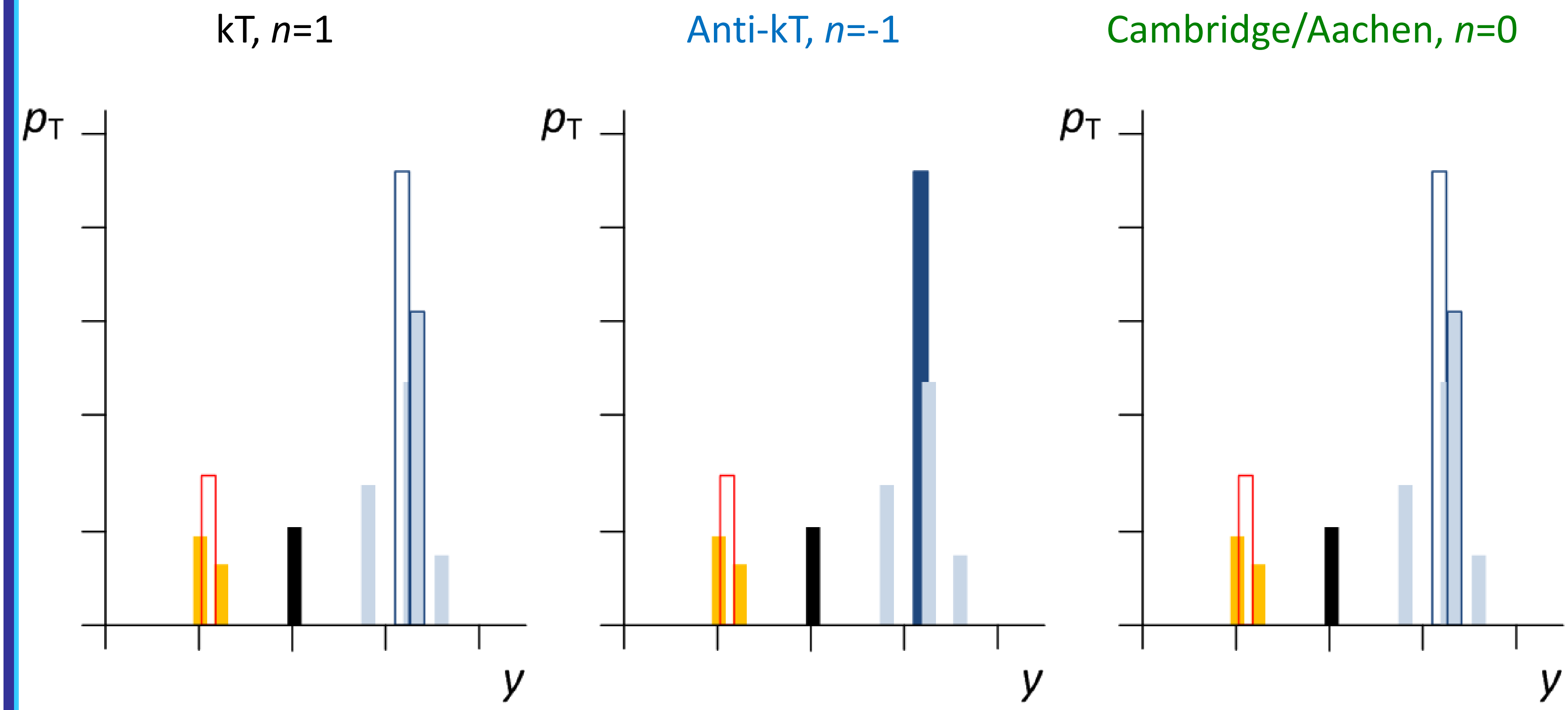

kT Examples

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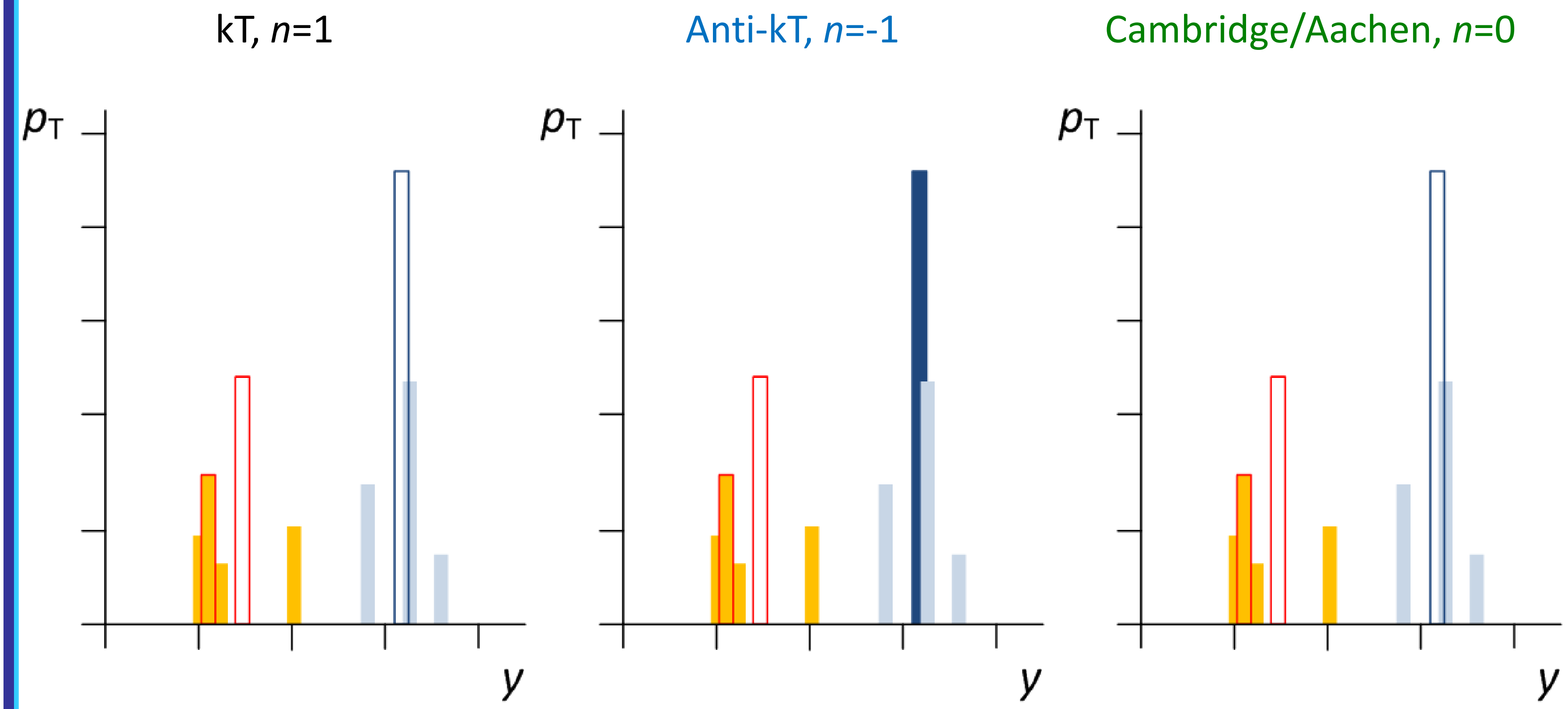

kT Examples

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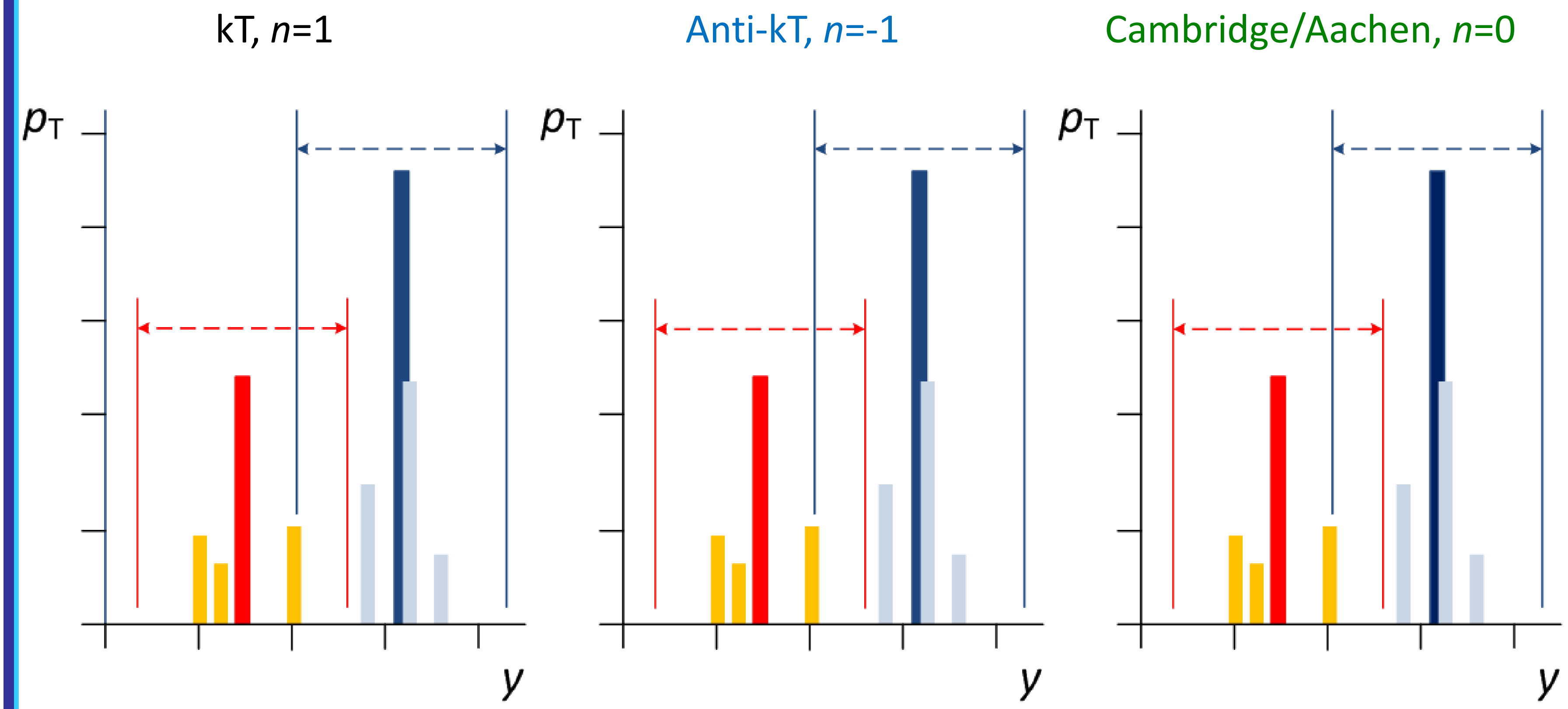

Recursive Recombination Algorithms

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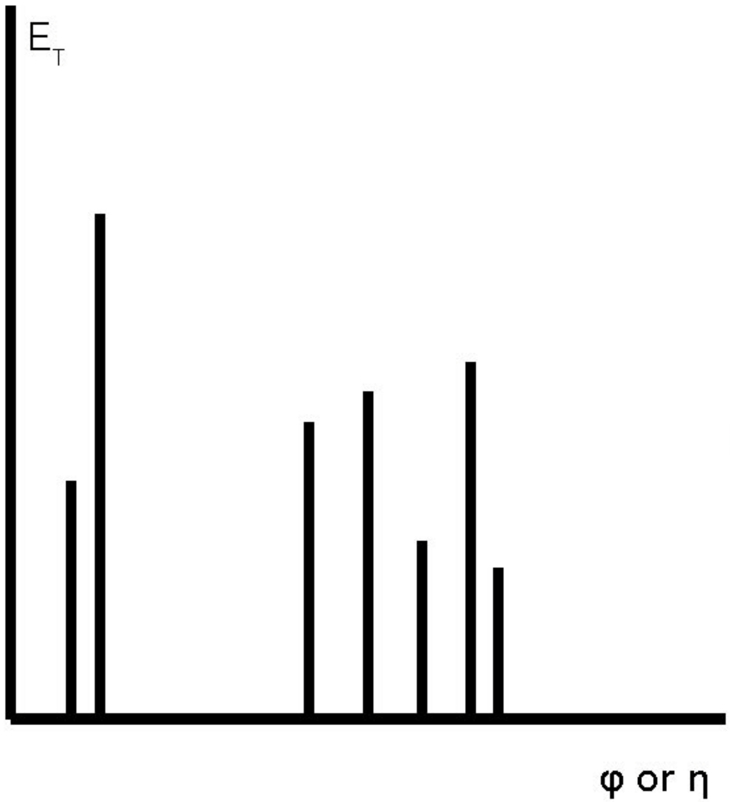
Clustering Algorithms

CTEQ-MCnet school 2008
Gavin Salam Lectures on Jets



Clustering Algorithms:

- Define a distance d_{ij} between two objects i, j :

$$\Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$

$$d_{ij} = \min(k_{ti}^2, k_{tj}^2)\Delta R_{ij}^2/R^2$$

and a distance d_{iB} between one object i and the beam direction B:

$$d_{iB} = k_{ti}^2$$

- Find the smallest of d_{ij}, d_{iB} .

  If d_{ij} recombine i, j ;

  If d_{iB} , i is a jet.

Clustering Algorithms

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Kt

(Catani/Dokshitzer/Seymour/Webber - S.Ellis/Soper)

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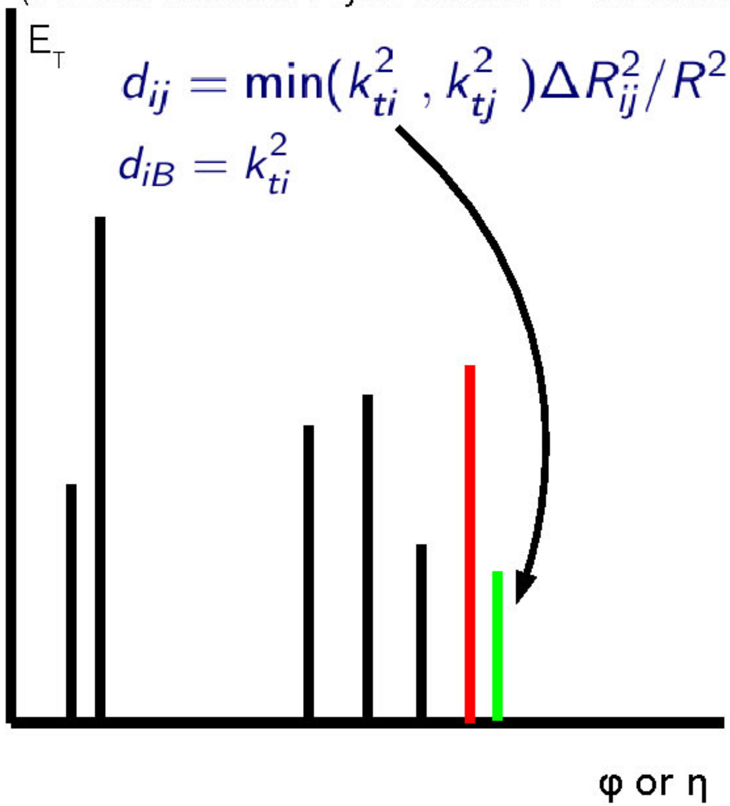

AntiKt

(Cacciari/Salam/Sovez)

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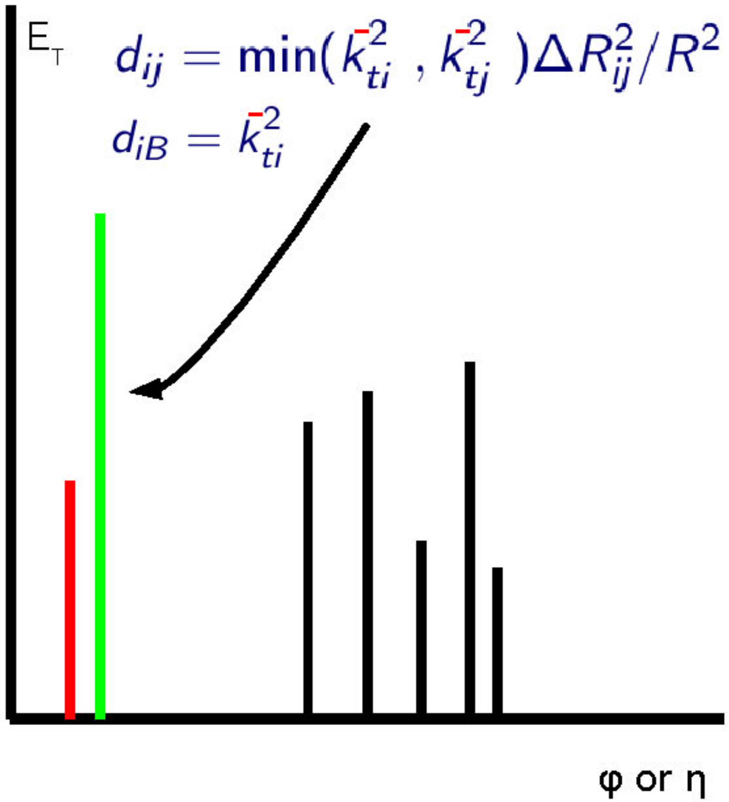

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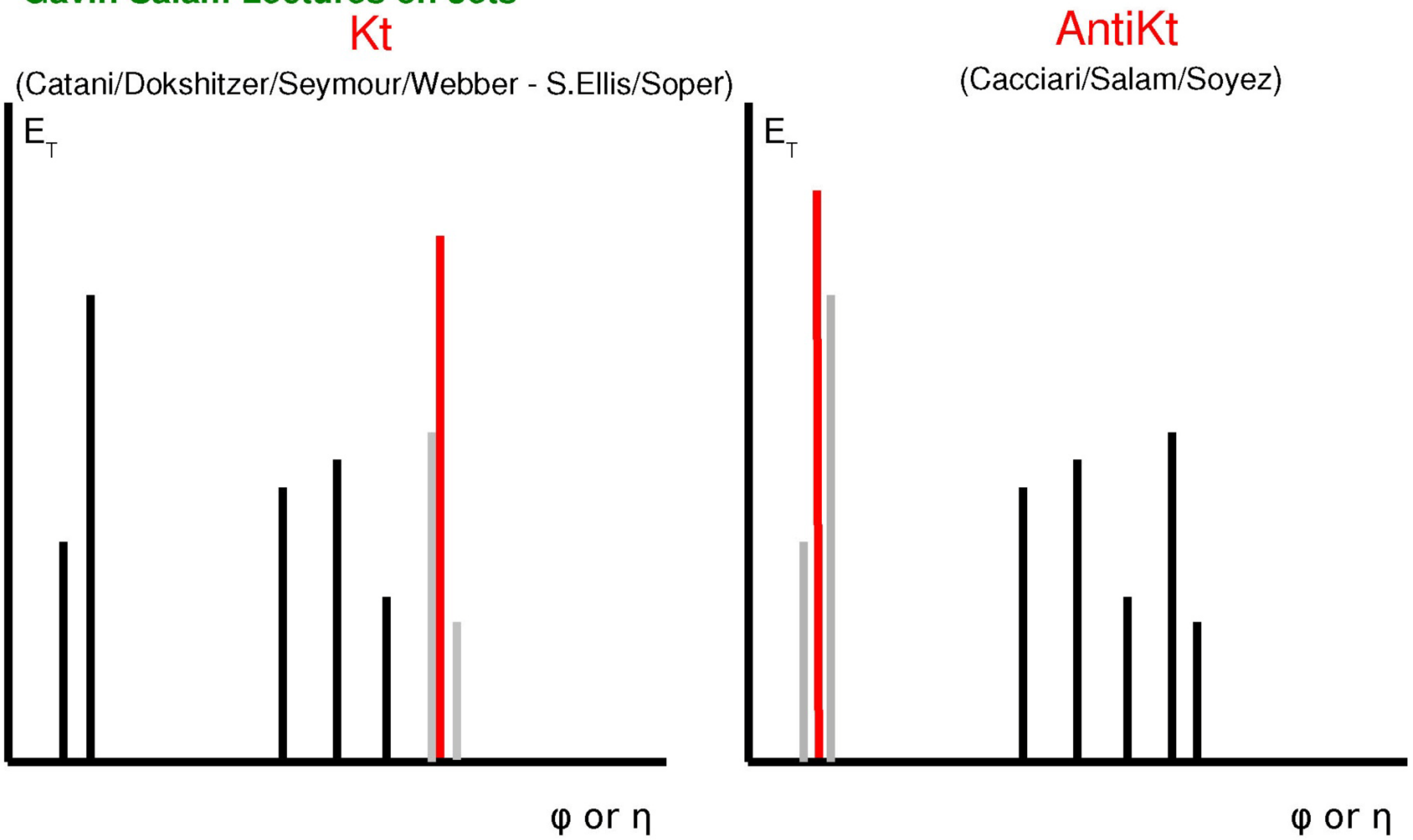

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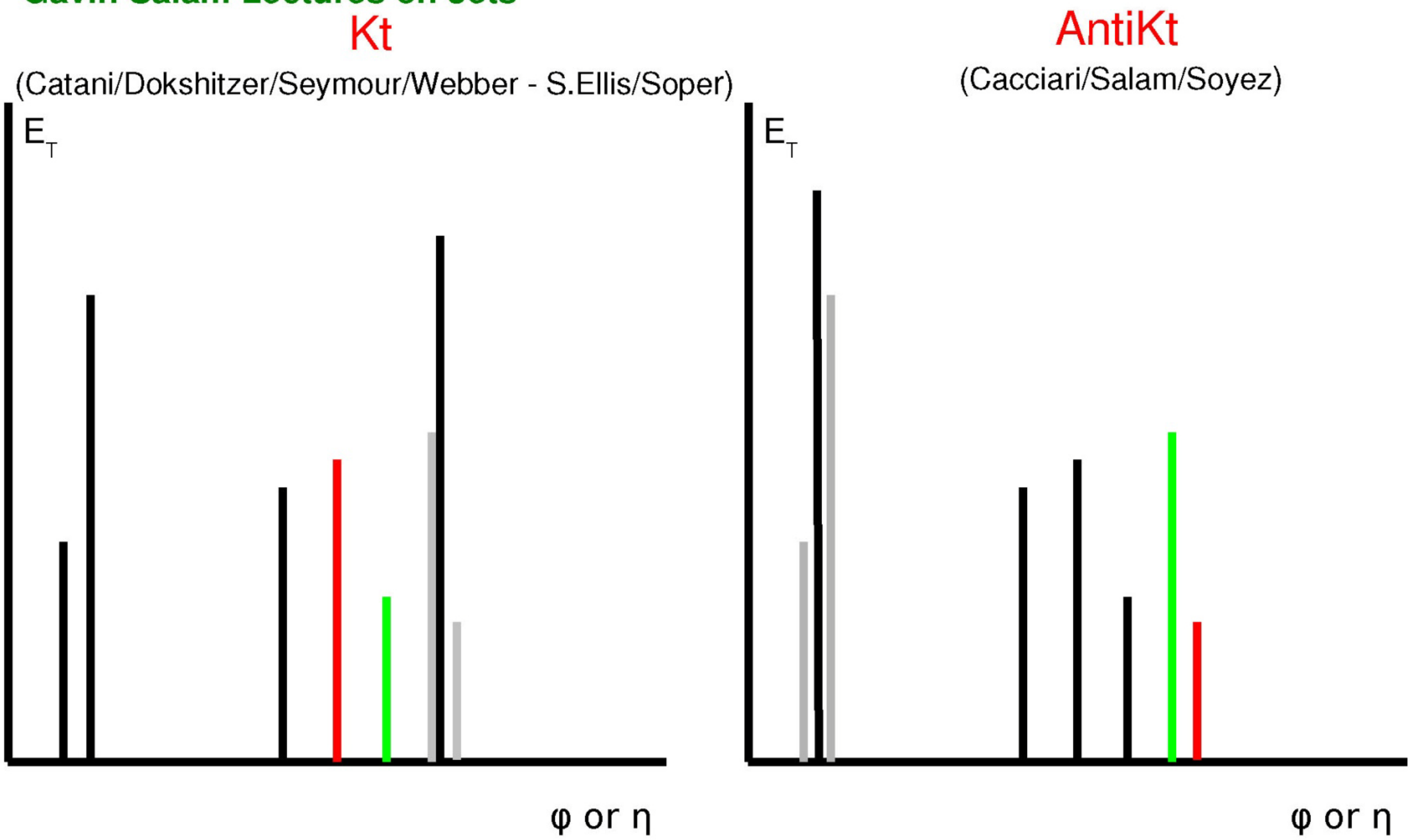

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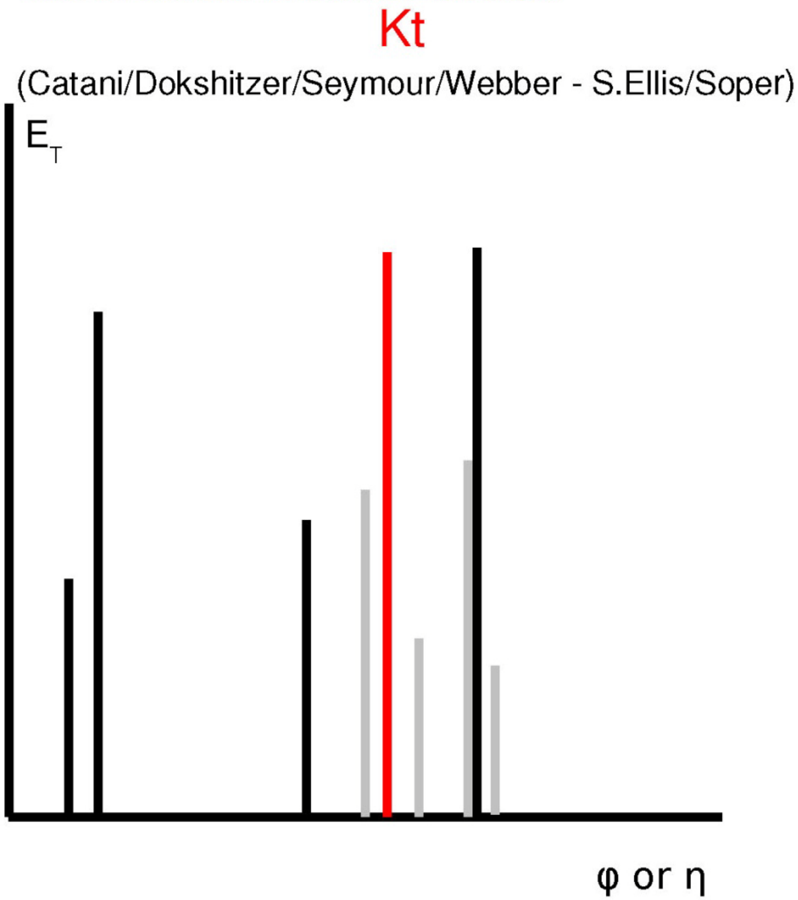

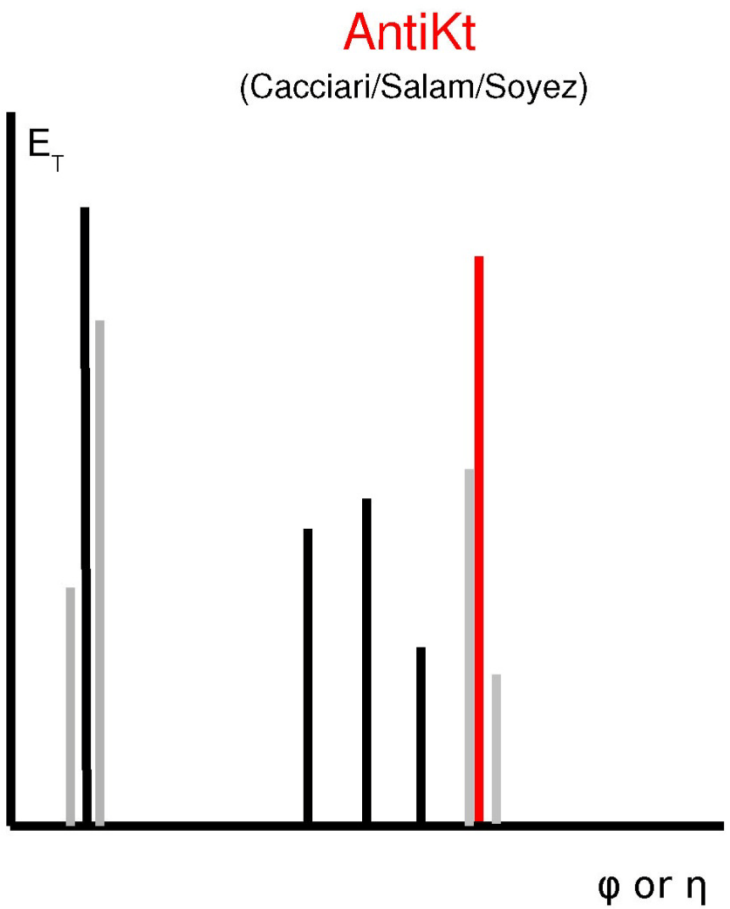

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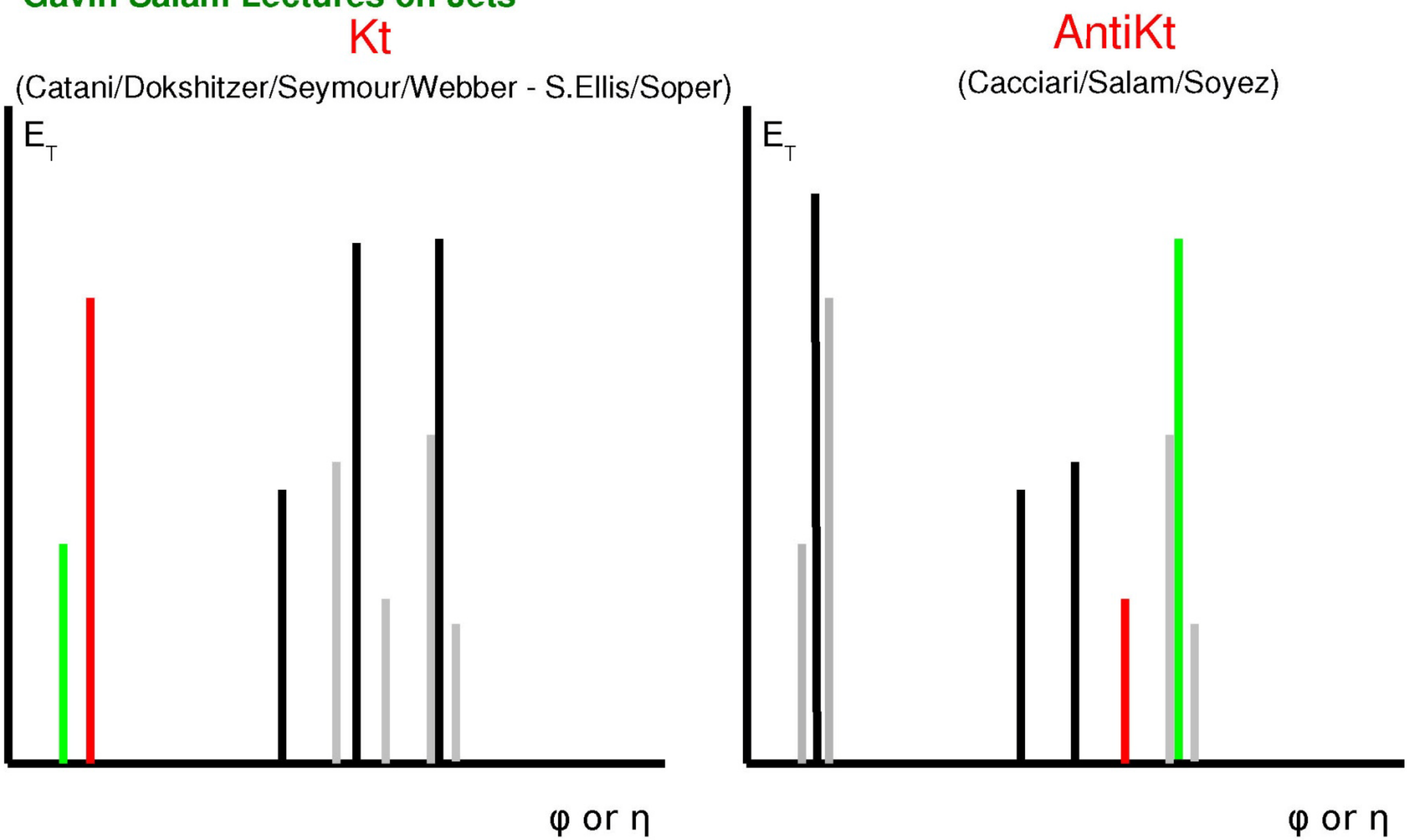

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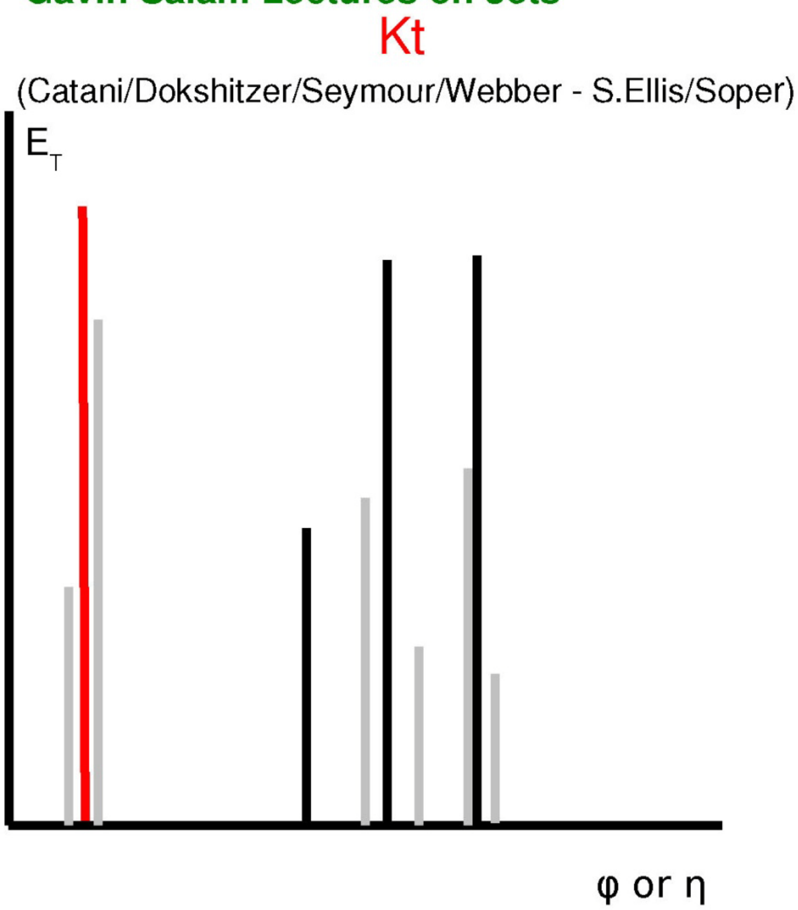

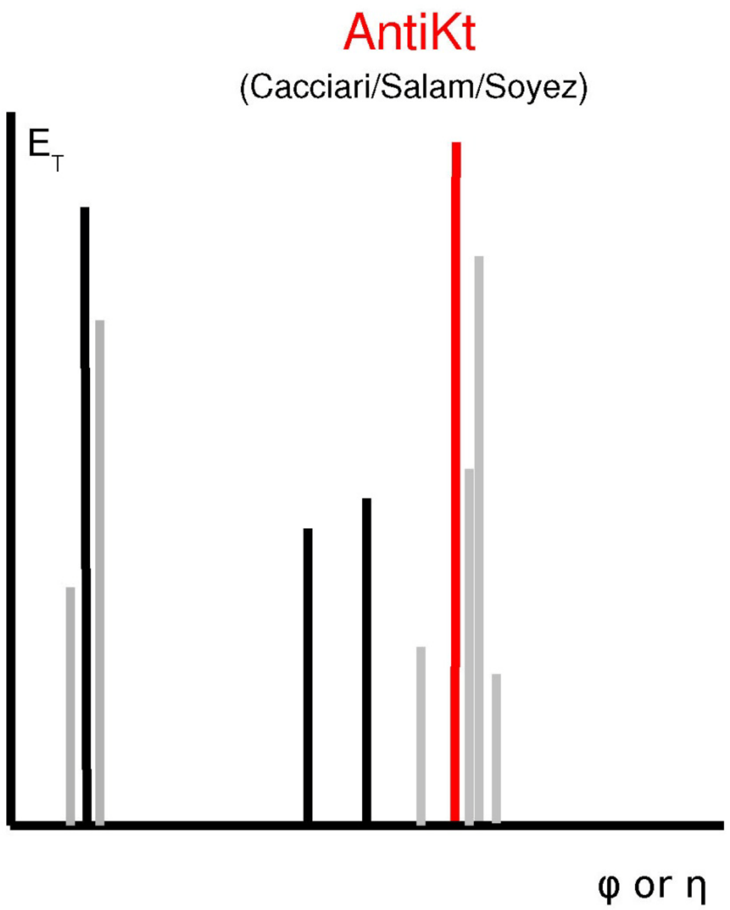

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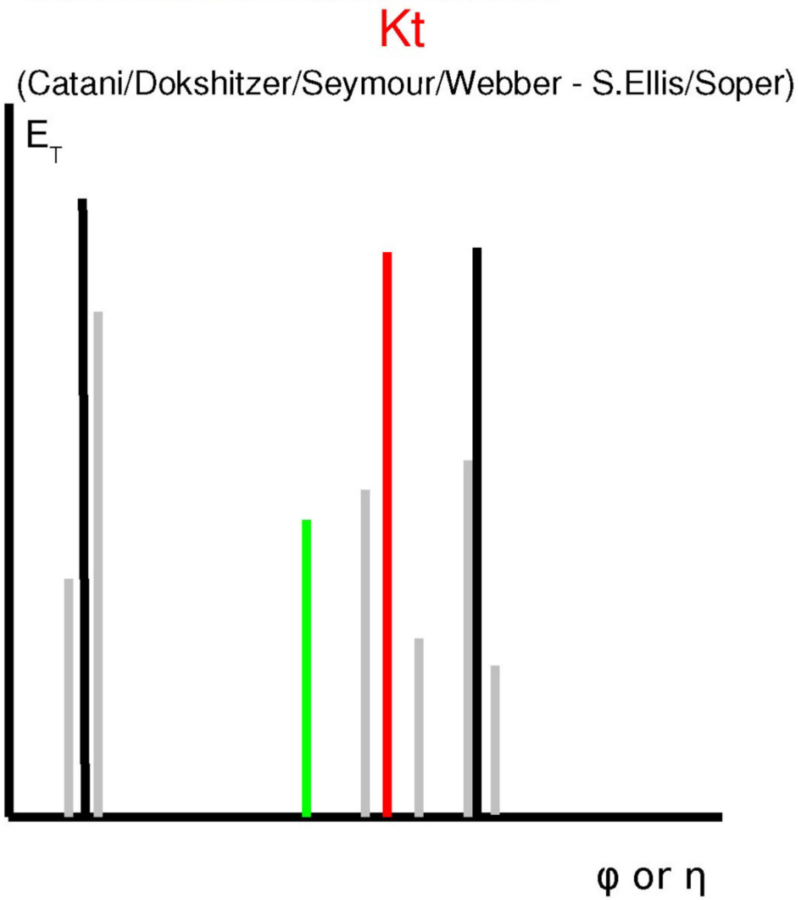

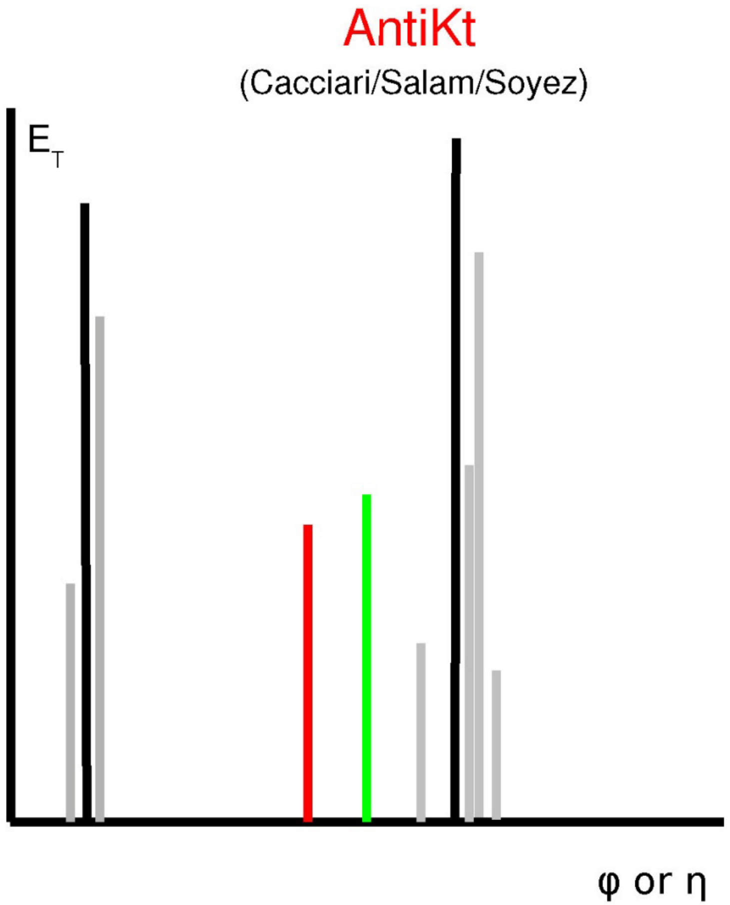

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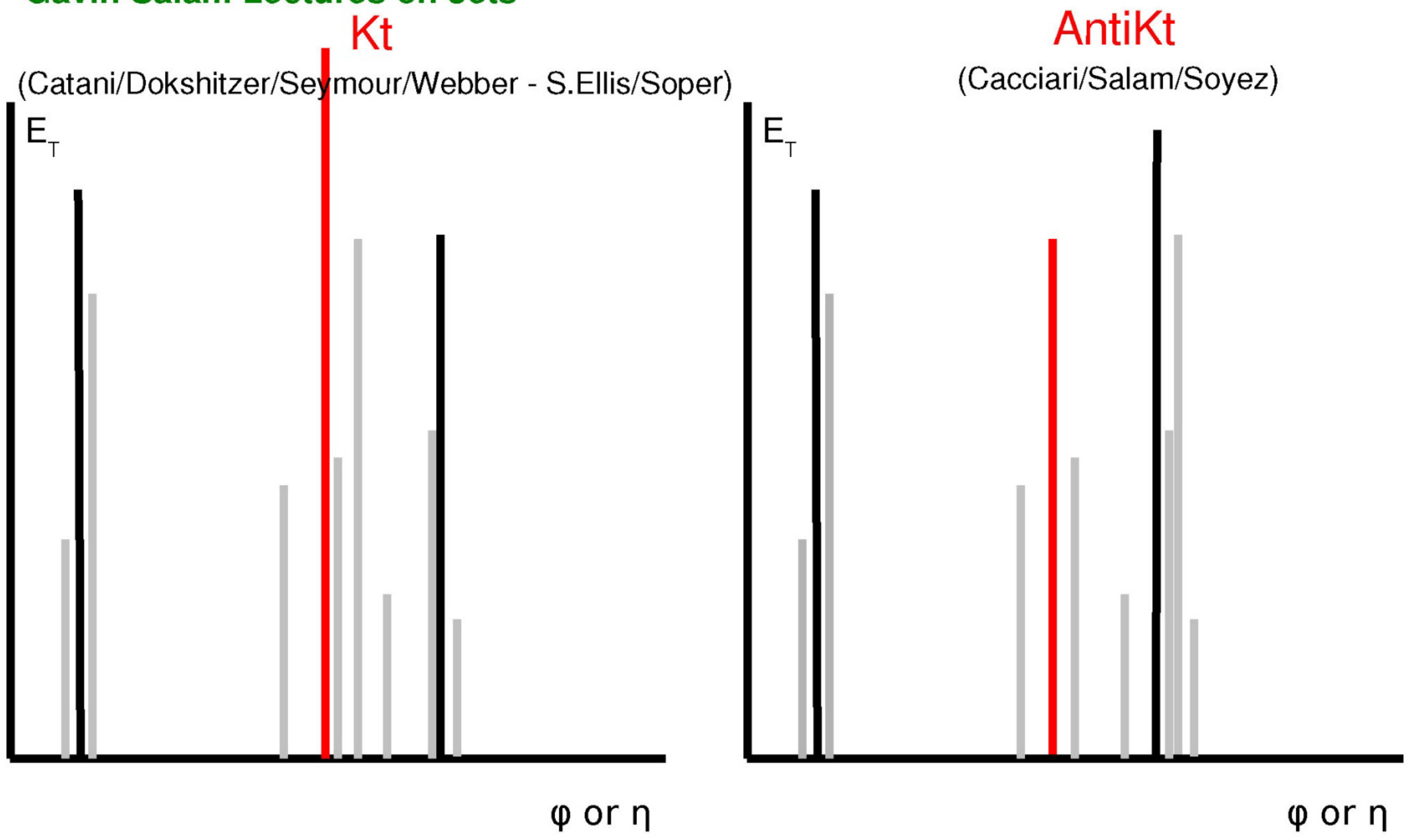

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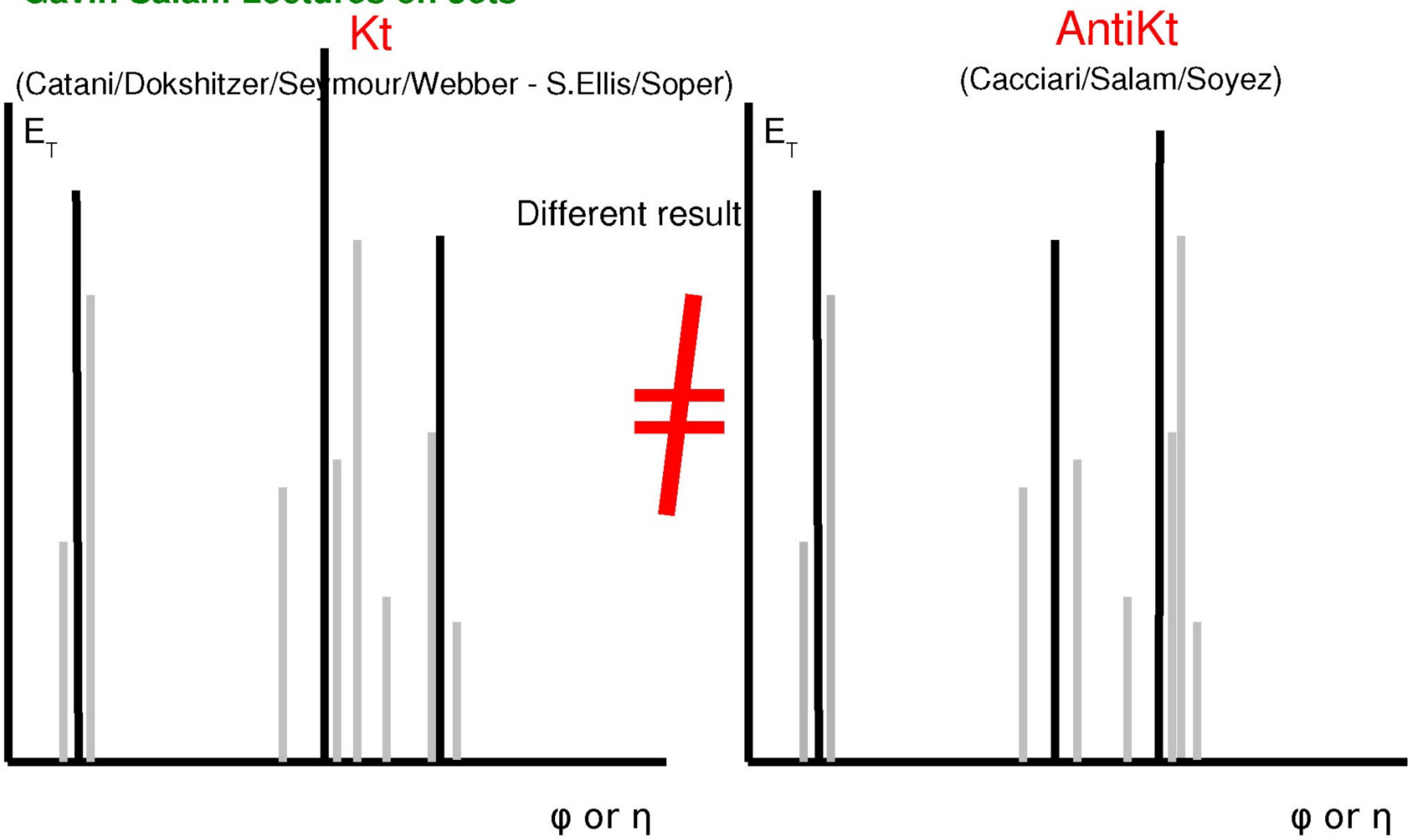

Validity of Jet Algorithms

P. Loch
U of Arizona
May 05, 2010

Need to be valid to any order of perturbative calculations

- Experiment needs to keep sensitivity to perturbative infinities
  - Jet algorithms must be infrared safe!
  - Stable for multi-jet final states

Clearly a problem for classic (seeded) cone algorithms

- Tevatron: modifications to algorithms and optimization of algorithm configurations
  - Mid-point seeded cone: put seed between two particles
  - Split & merge fraction: adjust between 0.5 – 0.75 for best "resolution"

LHC: need more stable approaches

- Multi-jet context important for QCD measurements
  - Extractions of inclusive and exclusive cross-sections, PDFs
- Signal-to-background enhancements in searches
  - Event selection/filtering based on topology
  - Other kinematic parameters relevant for discovery

Among consequences of IR unsafety:

	Last meaningful order			
	JetClu, ATLAS cone [IC-SM]	MidPoint [IC$_{mp}$-SM]	CMS it. cone [IC-PR]	Known at
Inclusive jets	LO	NLO	NLO	NLO ($\rightarrow$ NNLO)
W/Z + 1 jet	LO	NLO	NLO	NLO
3 jets	none	LO	LO	NLO [nlojet++]
W/Z + 2 jets	none	LO	LO	NLO [MCFM]
m_{jet} in $2j + X$	none	none	none	LO

NB: $30 – 50M investment in NLO

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Starts to miss cones at next order!

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Midpoint Seeded Cone

Attempt to increase infrared safety for seeded cone

- Midpoint algorithm starts with seeded cone
  - Seed threshold may be 0 to increase collinear safety
- Place new seeds between two close stable cones
  - Also center of three stable cones possible
- Re-iterate using midpoint seeds
  - Isolated stable cones are unchanged

Still not completely safe!

- Apply split & merge
  - Usually split/merge fraction 0.75

Find midpoints for stable cones within

$$\Delta R = \sqrt{\Delta y^2 + \Delta\varphi^2} \leq 2R_{\text{cone}}$$

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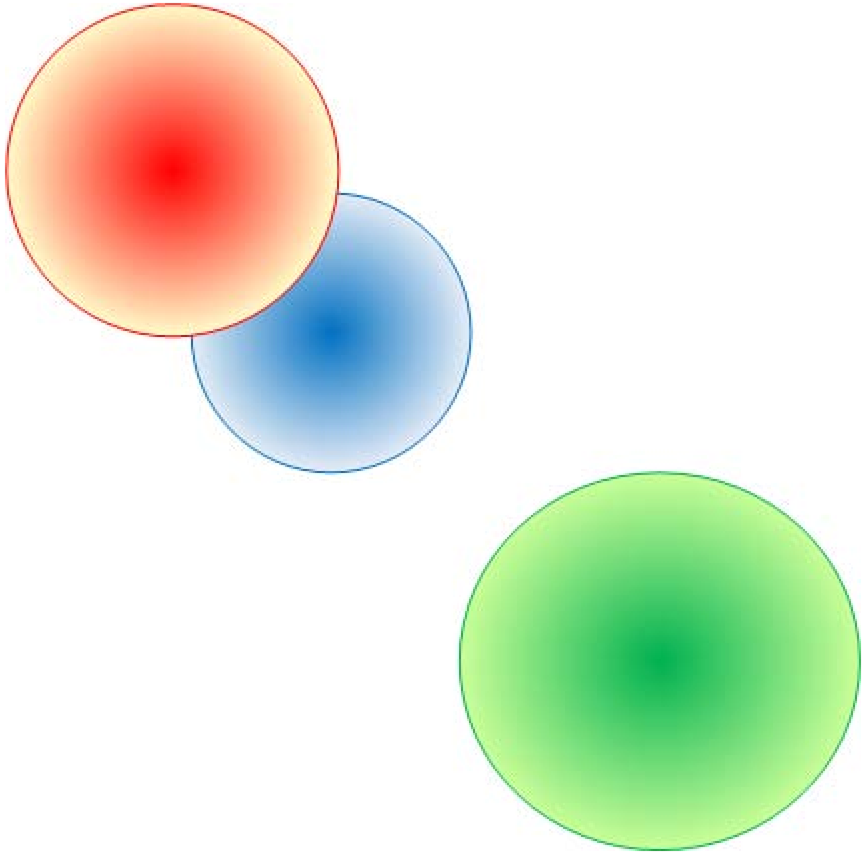

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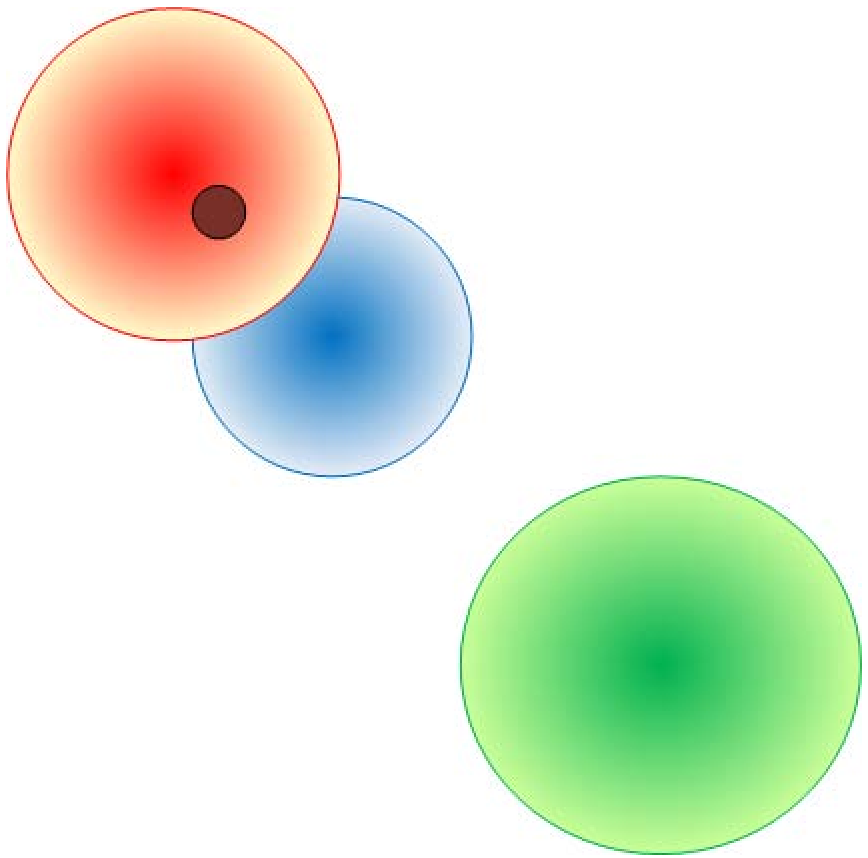

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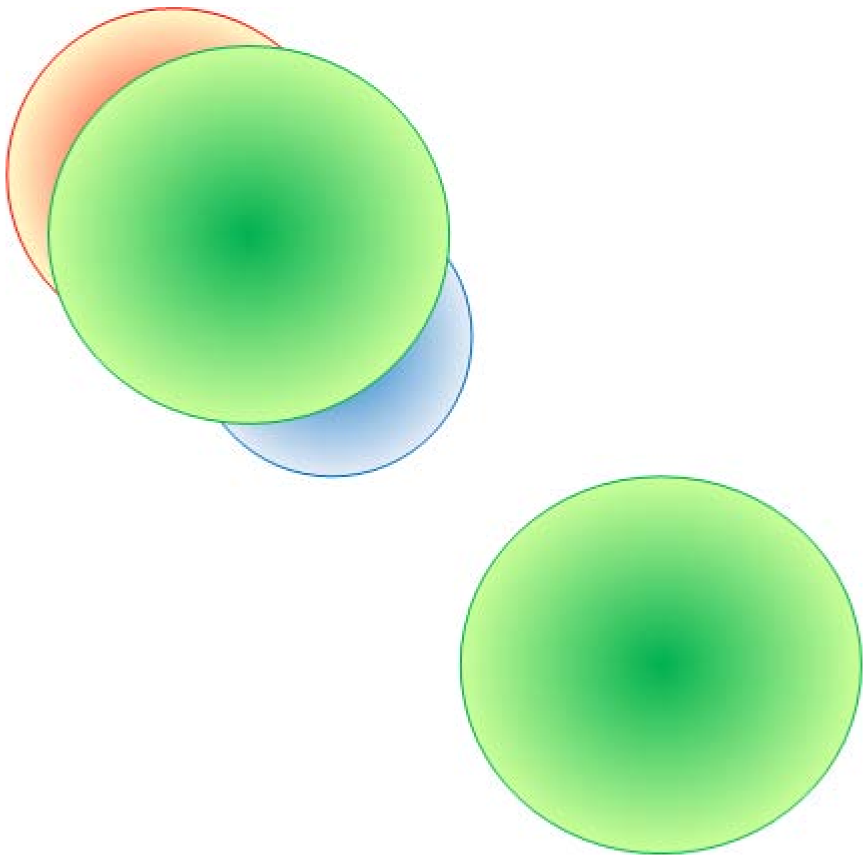

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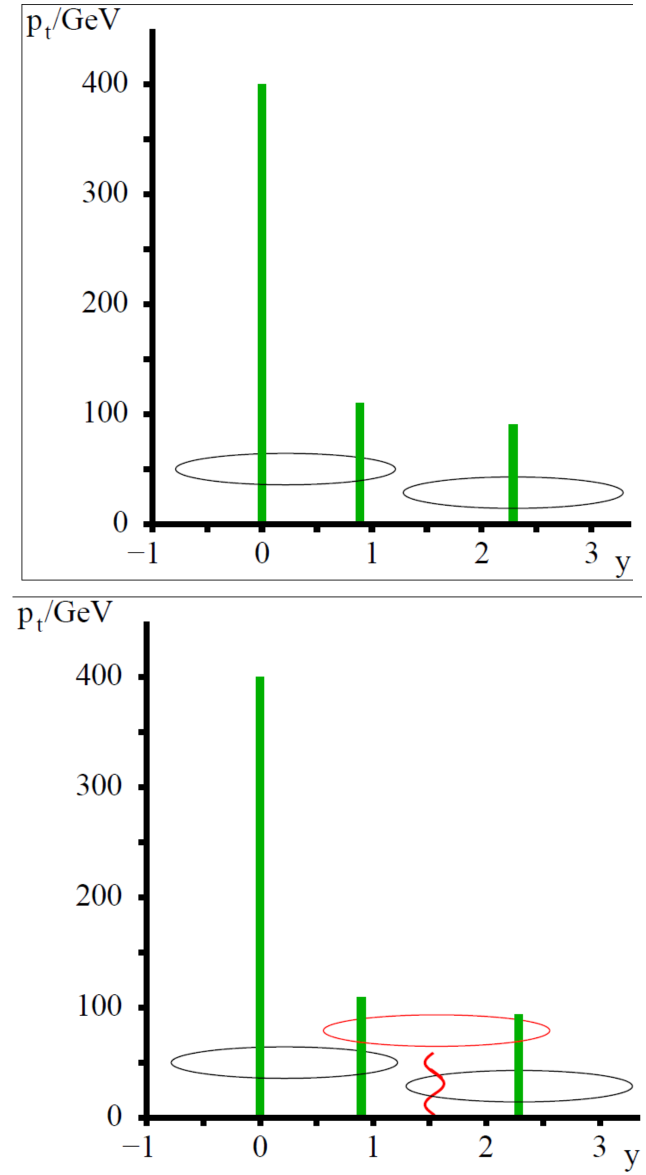

(from G. Salam & G. Soyez, **JHEP 0705:086,2007**)

Seedless Fixed Cone

P. Loch
U of Arizona
May 05, 2010

Improvements to cone algorithms: no seeds

- All stable cones are considered
  - Avoid collinear unsafety in seeded cone algorithm
- Avoid infrared safety issue
  - Adding infinitively soft particle does not lead to new (hard) cone
- Exact seedless cone finder
  - Problematic for larger number of particles
- Approximate implementation
  - Pre-clustering in coarse towers
  - Not necessarily appropriate for particles and even some calorimeter signals

Exact seedless cone for N particles:

$O(N \cdot 2^N)$ operations

N	# operations	remark
4	64	fixed order parton level
10	10240	very low multiplicity final state
100	$\sim 1.3 \cdot 10^{32}$	low multiplicity LHC final state
1,000	$\sim 1.6 \cdot 10^{153}$	typical LHC final state
10,000	∞	LHC high luminosity final state

Approximate seedless cone ($\Delta\eta \times \Delta\varphi = 0.2 \times 0.2$):

N	# operations	remark
40	$\sim 4.4 \cdot 10^{13}$	surviving bins with two narrow jets
70	$\sim 8.3 \cdot 10^{22}$	surving bins with two wide jets

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  - Adding infinitively soft particle does not lead to new (hard) cone
- Exact seedless cone finder
  - Problematic for larger number of particles
- Approximate implementation
  - Pre-clustering in coarse towers
  - Not necessarily appropriate for particles and even some calorimeter signals

Exact seedless cone for N particles:

$O(N \cdot 2^N)$ operations

N	# operations	remark
4	64	fixed order parton level
10	10240	very low multiplicity final state
100	$\sim 1.3 \cdot 10^{32}$	low multiplicity LHC final state
1,000	$\sim 1.6 \cdot 10^{153}$	typical LHC final state
10,000	∞	LHC high luminosity final state

Approximate seedless cone ($\Delta\eta \times \Delta\varphi = 0.2 \times 0.2$):

N	# operations	remark
40	$\sim 4.4 \cdot 10^{13}$	surviving bins with two narrow jets
70	$\sim 8.3 \cdot 10^{22}$	surving bins with two wide jets

ATLAS

Seedless Fixed Cone

P. Loch
U of Arizona
May 05, 2010

Improvements to cone algorithms: no seeds

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70	[illegible]	[illegible]

Note: 100 particles need ~10^{17} years to be clustered!

Seedless Fixed Cone

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SISCone (Salam, Soyez 2007)

- Exact seedless cone with geometrical (distance) ordering
  - Speeds up algorithm considerably!
- Find all distinctive ways on how a segment can enclose a subset of the particles
  - Instead of finding all stable segments!
- Re-calculate the centroid of each segment
  - E.g., pT weighted re-calculation of direction
  - “E-scheme” works as well
- Segments (cones) are stable if particle content does not change
  - Retain only one solution for each segment
- Still needs split & merge to remove overlap
  - Recommended split/merge fraction is 0.75
- Typical times
  - $N^2 \ln N$ for particles in 2-dim plane

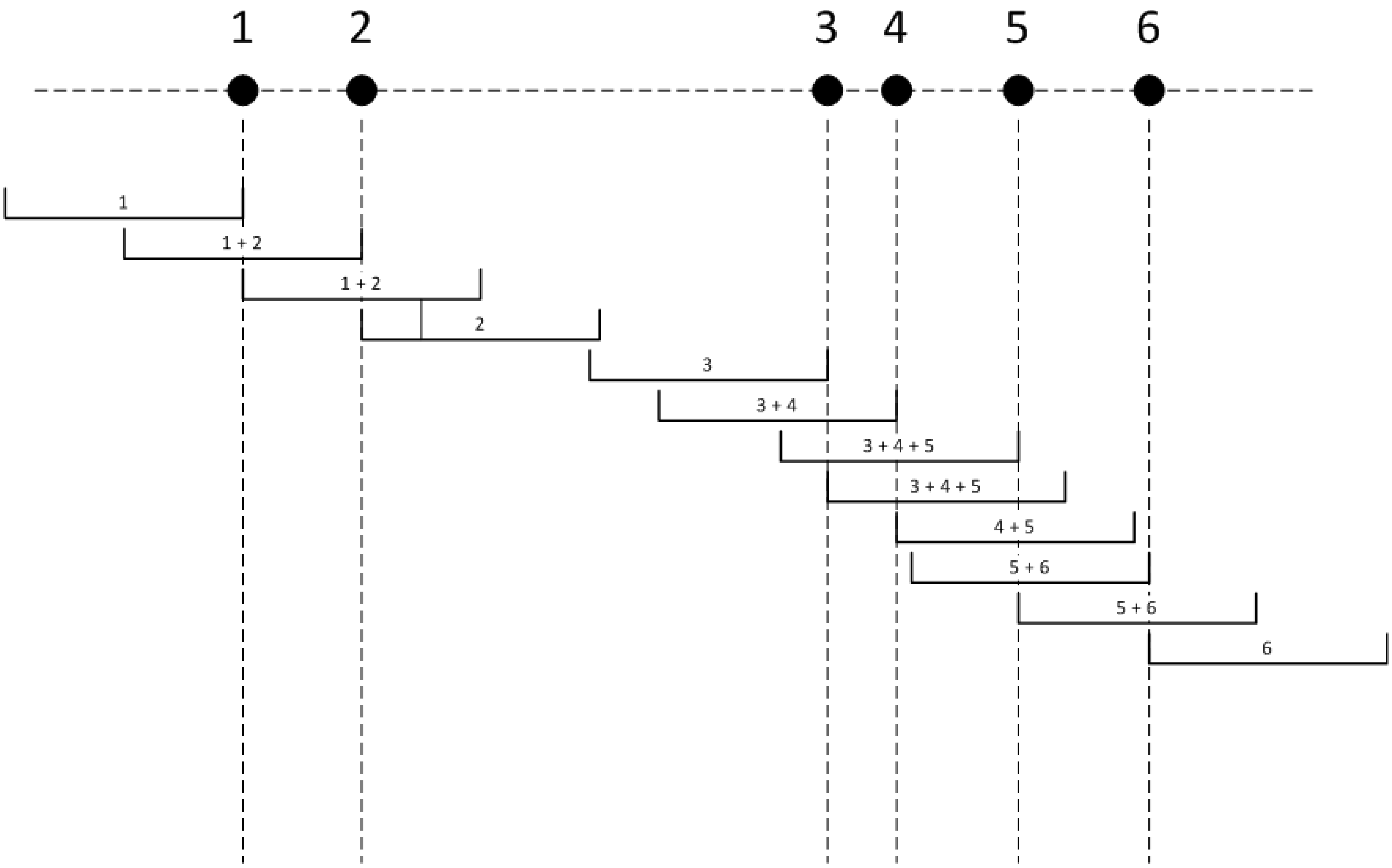
1-dim example:

- See following slides!

(inspired by G. Salam & G. Soyez, **JHEP 0705:086,2007**)

SISCone Principle (1-dim!)

Find all distinctive segments of size $2R_{cone}$ ($O(N)$ operations in 1-dim)



SISCone Principle (1-dim!)

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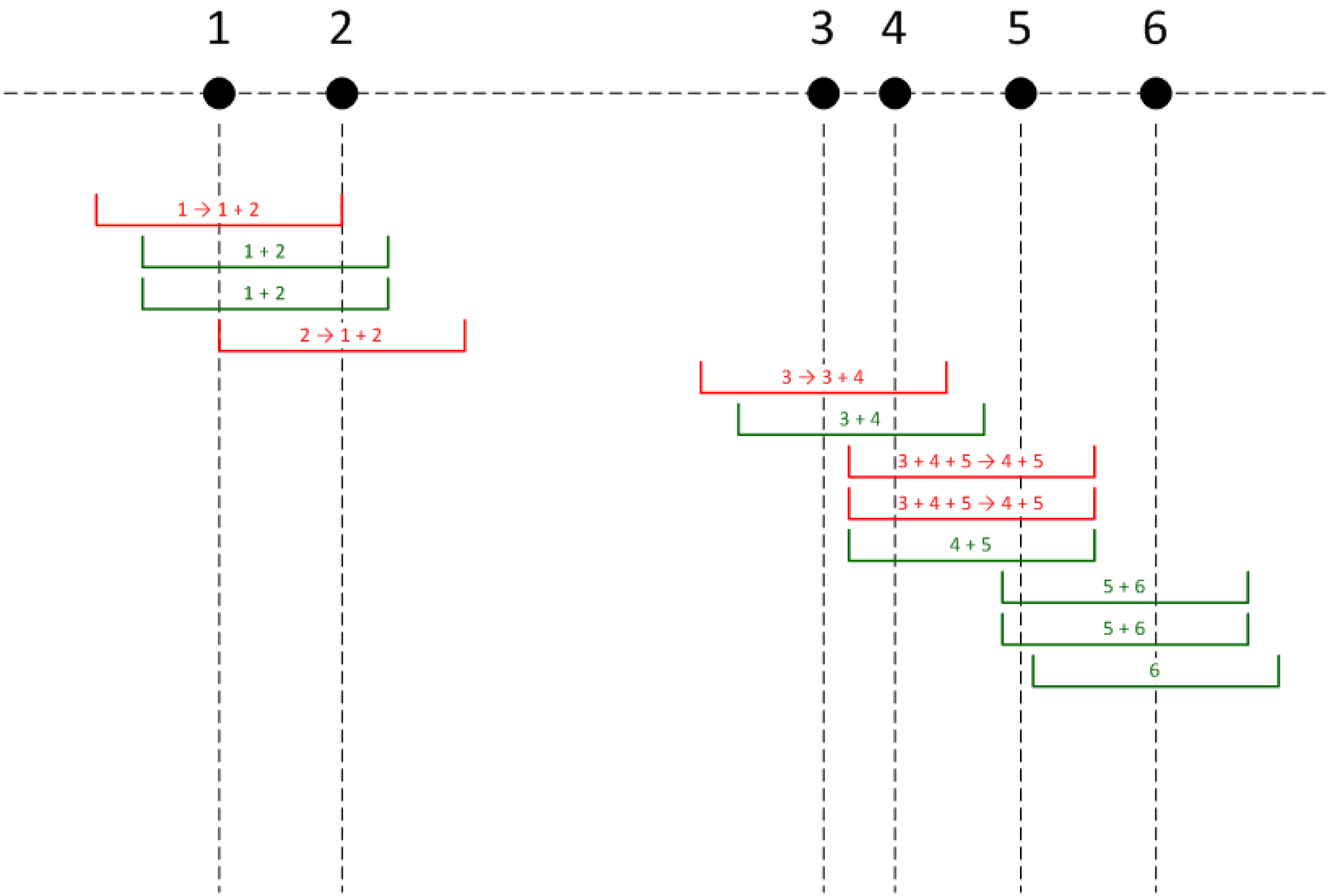
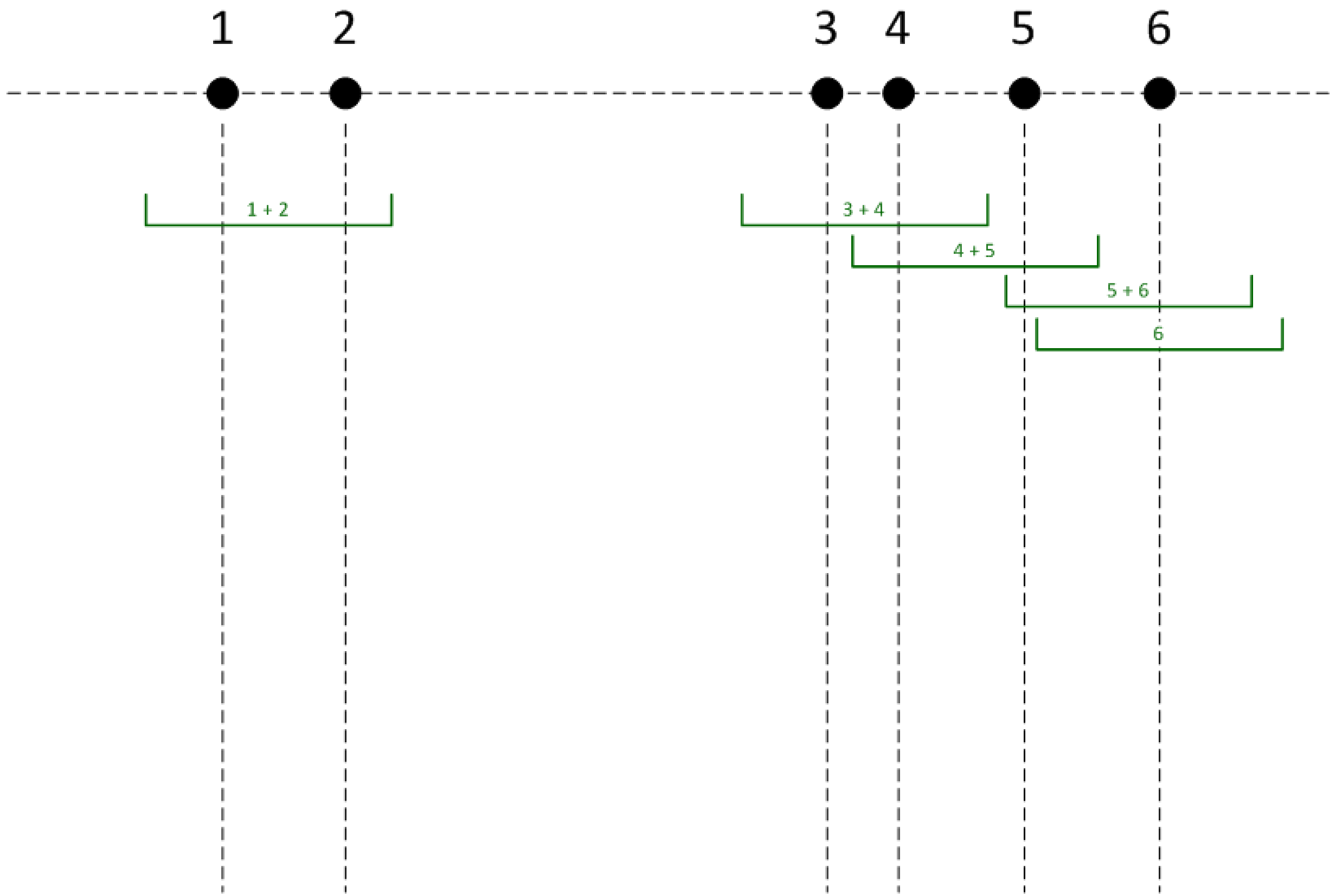
Reposition segments to centroids (green - unchanged, red - changed)



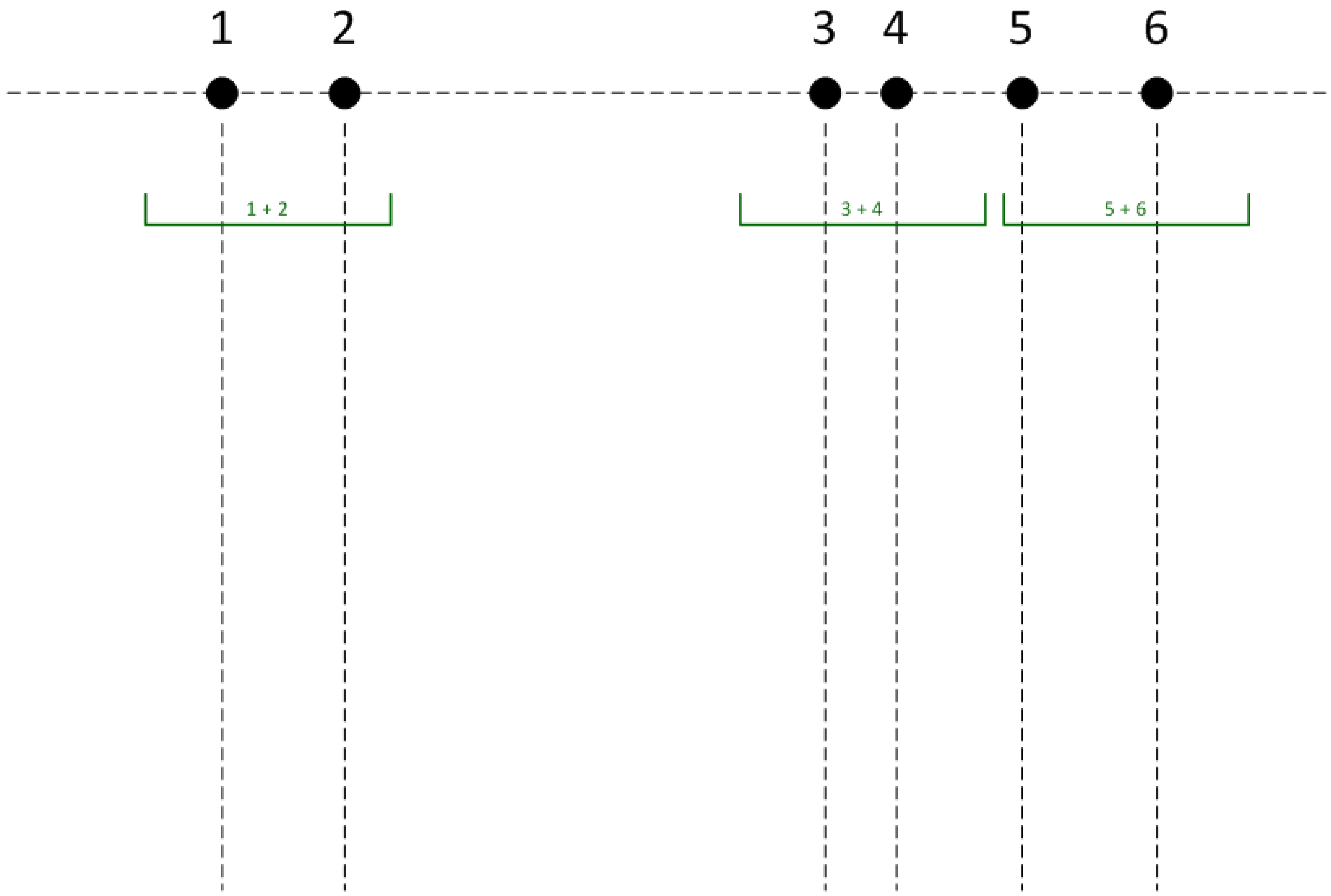
SISCone Principle (1-dim!)

Retain only one stable solution for each segment



SISCone Principle (1-dim!)

Apply split & merge



Similar ordering and combinations in 2-dim

Use circles instead of linear segments

(from G. Salam & G. Soyez, **JHEP 0705:086,2007**)

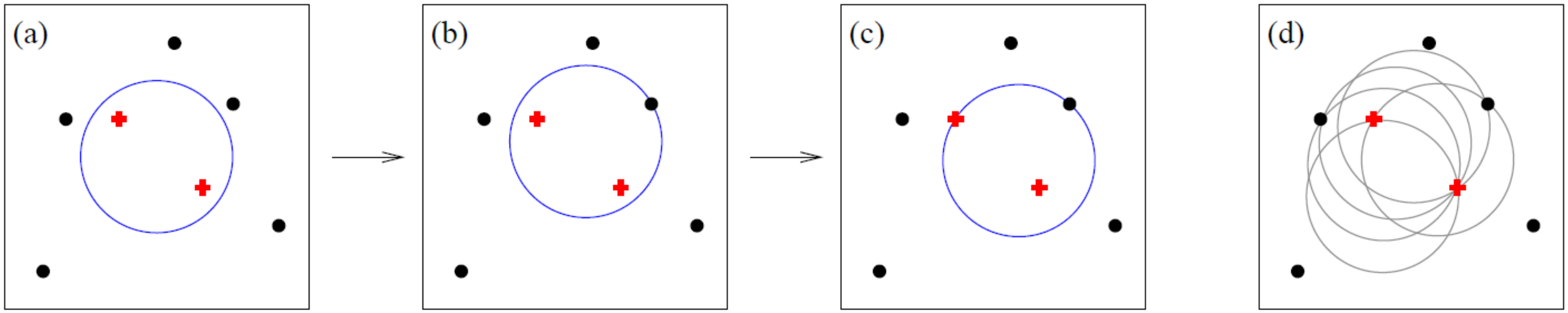


Figure 3: (a) Some initial circular enclosure; (b) moving the circle in a random direction until some enclosed or external point touches the edge of the circle; (c) pivoting the circle around the edge point until a second point touches the edge; (d) all circles defined by pairs of edge points leading to the same circular enclosure.

Still need split & merge

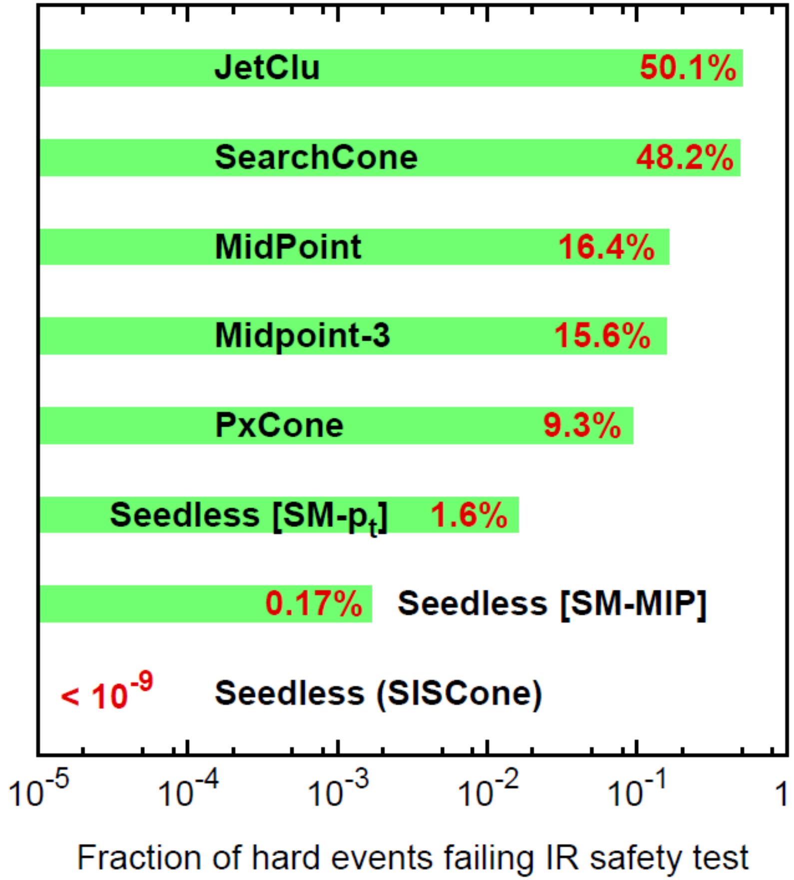
- One additional parameter outside of jet/cone size
  - Not very satisfactory!
- But at least a practical seedless cone algorithm
  - Very comparable performance to e.g. Midpoint!

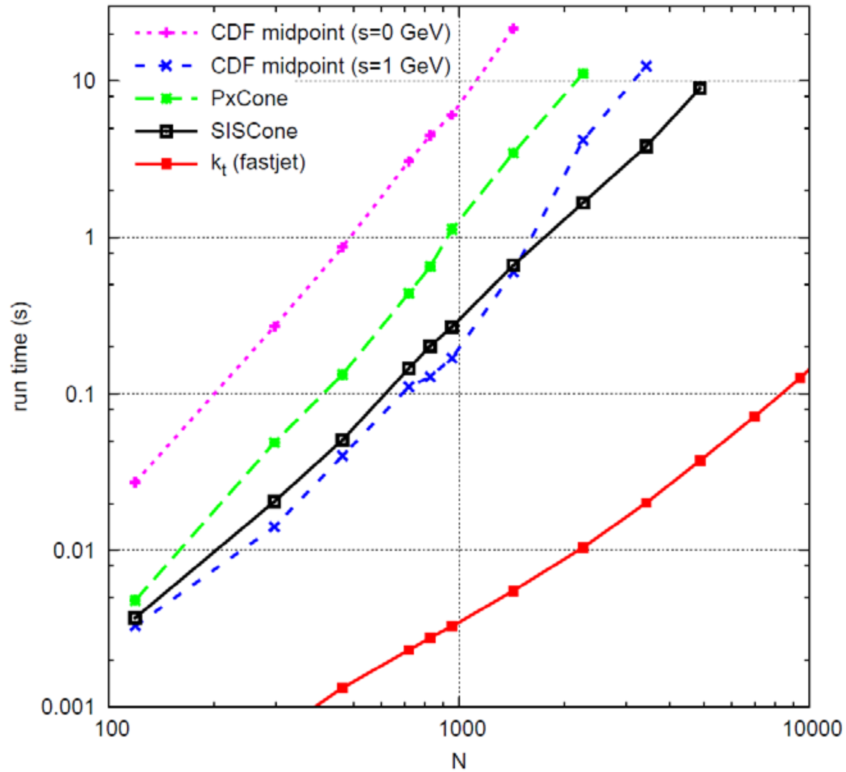
SISCone Performance

Infrared safety failure rates

Computing performance

(from G. Salam & G. Soyez, **JHEP 0705:086,2007**)





Recursive Recombination (kT)

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May 05, 2010

Computing performance an issue

- Time for traditional kT is ~N^3
  - Very slow for LHC
- FastJet implementations
  - Use geometrical ordering to find out which pairs of particles have to be manipulated instead of recalculating them all!
- Very acceptable performance in this case!

LHC events (*pp* collisions):

N	# operations	time [s]*
10	10^3	0.05
100	10^6	0.50
1,000	10^9	5.00

LHC events (heavy ion collisions):

N	# operations	time [s]*
10,000	10^{12}	$5 \cdot 10^3$
50,000	$1.25 \cdot 10^{14}$	$6.25 \cdot 10^5$

*on a modern computer (3 GHz clock)

ATLAS

Recursive Recombination (kT)

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Computing performance an issue

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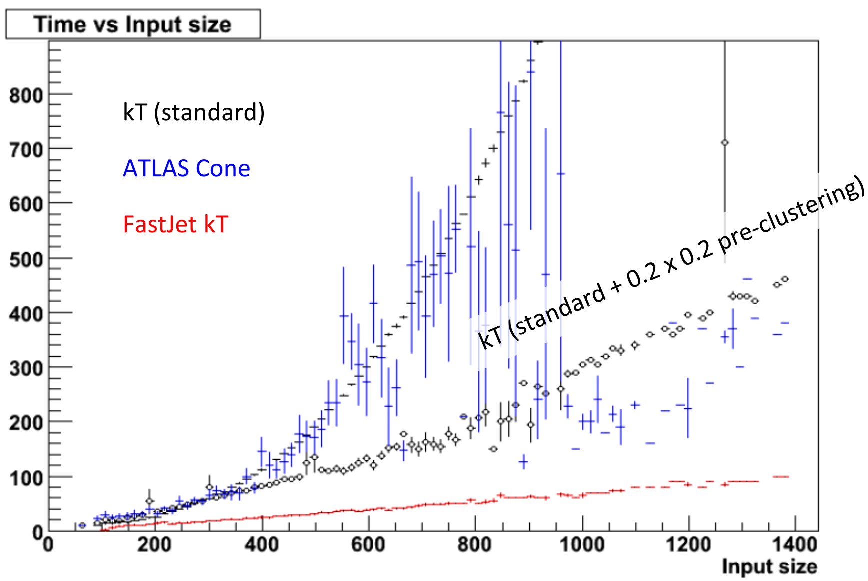


FastJet implementations:

kT & Cambridge/Aachen $\sim N \ln N$

N	# operations	time [s]*
10	24	$0.1 \cdot 10^{-6}$
100	460	$2 \cdot 10^{-6}$
1,000	6,900	$35 \cdot 10^{-6}$
10,000	92,000	$0.5 \cdot 10^{-3}$
50,000	541,000	$3 \cdot 10^{-3}$

Anti-kT $\sim \sqrt{N^3}$

N	# operations	time [s]*
10	32	$0.2 \cdot 10^{-6}$
100	1,000	$5 \cdot 10^{-6}$
1,000	32,000	$0.2 \cdot 10^{-3}$
10,000	1,000,000	$5 \cdot 10^{-3}$
50,000	11,200,000	$56 \cdot 10^{-3}$

FastJet kT

Address the search approach

- Need to find minimum in standard kT
  - Order N^3 operations
- Consider geometrically nearest neighbours in FastJet kT
  - Replace full search by search over (jet, jet neighbours)
- Need to find nearest neighbours for each proto-jet fast
  - Several different approaches: ATLAS (Delsart 2006) uses simple geometrical model, Salam & Cacciari (2006) suggest Voronoi cells
- Both based on same fact relating d_{ij} and geometrical distance in ΔR
  - Both use geometrically ordered lists of proto-jets

Find minimum for N particles in standard kT:

$$\left\{ d_{ij} = \min(d_i, d_j)\Delta R_{ij}/R, d_i = p_{T,i}^2 \right\}, \; i,j = 1,\ldots,N$$

$O(N^2)$ searches, repeated N times $\rightarrow O(N^3)$

FastJet kT uses nearest neighbours search:

$$d_{ij} = \min \;\wedge\; p_{T,i} < p_{T,j}$$

$$\Rightarrow R_{ij} < R_{ik} \;\forall\; k \neq j, \text{ i.e. } (i,j) \text{ geometrical nearest neighbours in } (y,\varphi) \text{ plane}$$

Proof:

Assume an additional particle k exists with geometrical distance R_{ik} to particle i:

$$d_{ik} = \min(d_i, d_k) R_{ik}/R \leq d_i R_{ik}/R$$

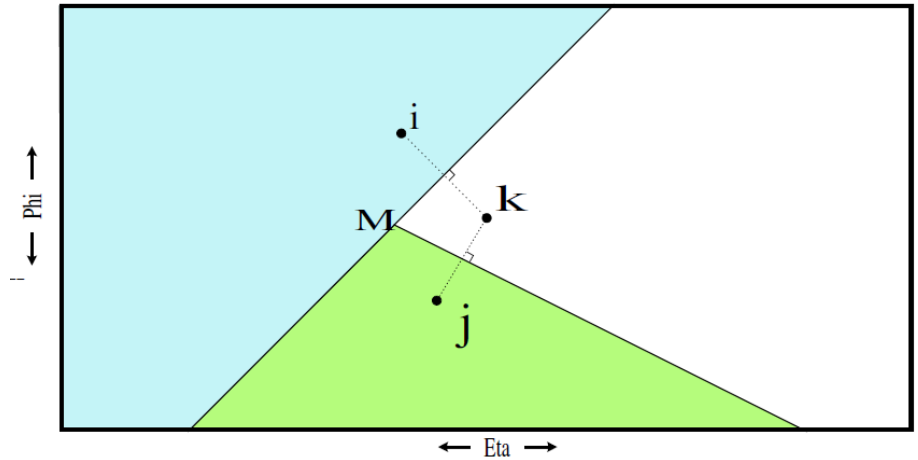
$$> \min = d_{ij} = d_i R_{ij}/R$$

works only for $R_{ik} > R_{ij}$

Fast kT (ATLAS – Delsart)

Possible implementation (P.A. Delsart, 2006)

- Nearest neighbour search
  - Idea is to only limit recalculation of distances to nearest neighbours
- Try to find all proto-jets having proto-jet *k* as nearest neighbour
  - Center pseudo-rapdity (or rapdity)/azimuth plane on *k*
  - Take first proto-jet *j* closest to *k* in pseudo-rapidity
  - Compute middle line L_{jk} between *k* and *j*
  - All proto-jets below L_{jk} are closer to *j* than *k* → *k* is not nearest neighbour of those
- Take next closest proto-jet *i* in pseudo-rapidity
  - Proceed as above with exclusion of all proto-jets above L_{ik}
  - Search stops when point below intersection of L_{jk} and L_{ik} is reached, no more points have *k* as nearest neighbour



Complexity estimate:

Assume *N* proto-jets are uniformly distributed in (η,φ) plane (rectangular with fintie size, area *A*)

Average number of proto-jets in circle with radius R:

$$\bar{N} = N\frac{\pi R^2}{A}$$

If R is mean distance between two proto-jets:

$$\bar{N} \approx 1 \Rightarrow R \approx \sqrt{\frac{A}{\pi N}}$$

Computation of proto-jet *k*'s nearest neighbours is restricted to

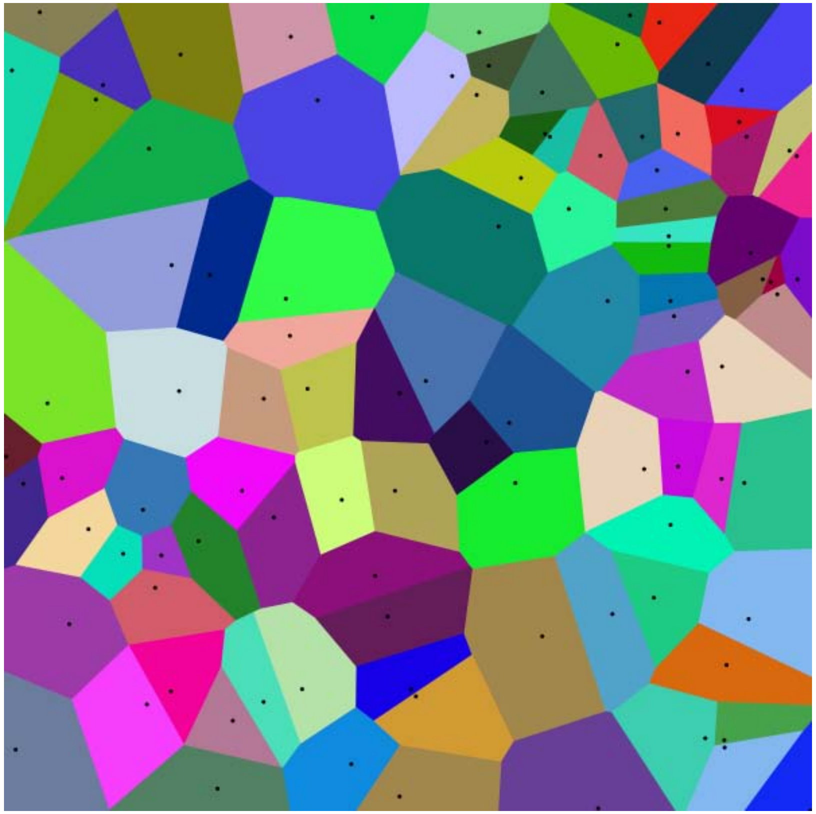
$$\eta \approx [\eta_k - R, \eta_k + R] \mapsto \approx N \cdot 2R \propto \frac{N}{\sqrt{N}} = \sqrt{N} \text{ operations for } k$$

$\Rightarrow N\sqrt{N}$ total complexity (estimate)

FastJet kT (Salam & Cacciari)

Apply geometrical methods to nearest neighbour searches

- Voronoi cell around proto-jet *k* defines area of nearest neighbours
  - No point inside area is closer to any other protojet
  - Apply to protojets in pseudo-rapdity/azimuth plane
- Useful tool to limit nearest neighbour search
  - Determines region of re-calculation of distances in kT
  - Allows quick updates without manipulating too many long lists
- Complex algorithm!
  - Read G. Salam & M. Cacciari, Phys.Lett.B641:57-61 (2006)



(source **http://en.wikipedia.org/wiki/Voronoi_diagram**)

Complexity estimate (Monte Carlo experiment):

*N*ln*N* total complexity

Jet Algorithm Performance

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May 05, 2010

Various jet algorithms produce different jets from the same collision event

- Clearly driven by the different sensitivities of the individual algorithms
  - Cannot expect completely identical picture of event from jets
  - Different topology/number of jets
  - Differences in kinematics and shape for jets found at the same direction
- Choice of algorithm motivated by physics analysis goal
  - E.g., IR safe algorithms for jet counting in $W + n$ jets and others
  - Narrow jets for W mass spectroscopy
  - Small area jets to suppress pile-up contribution

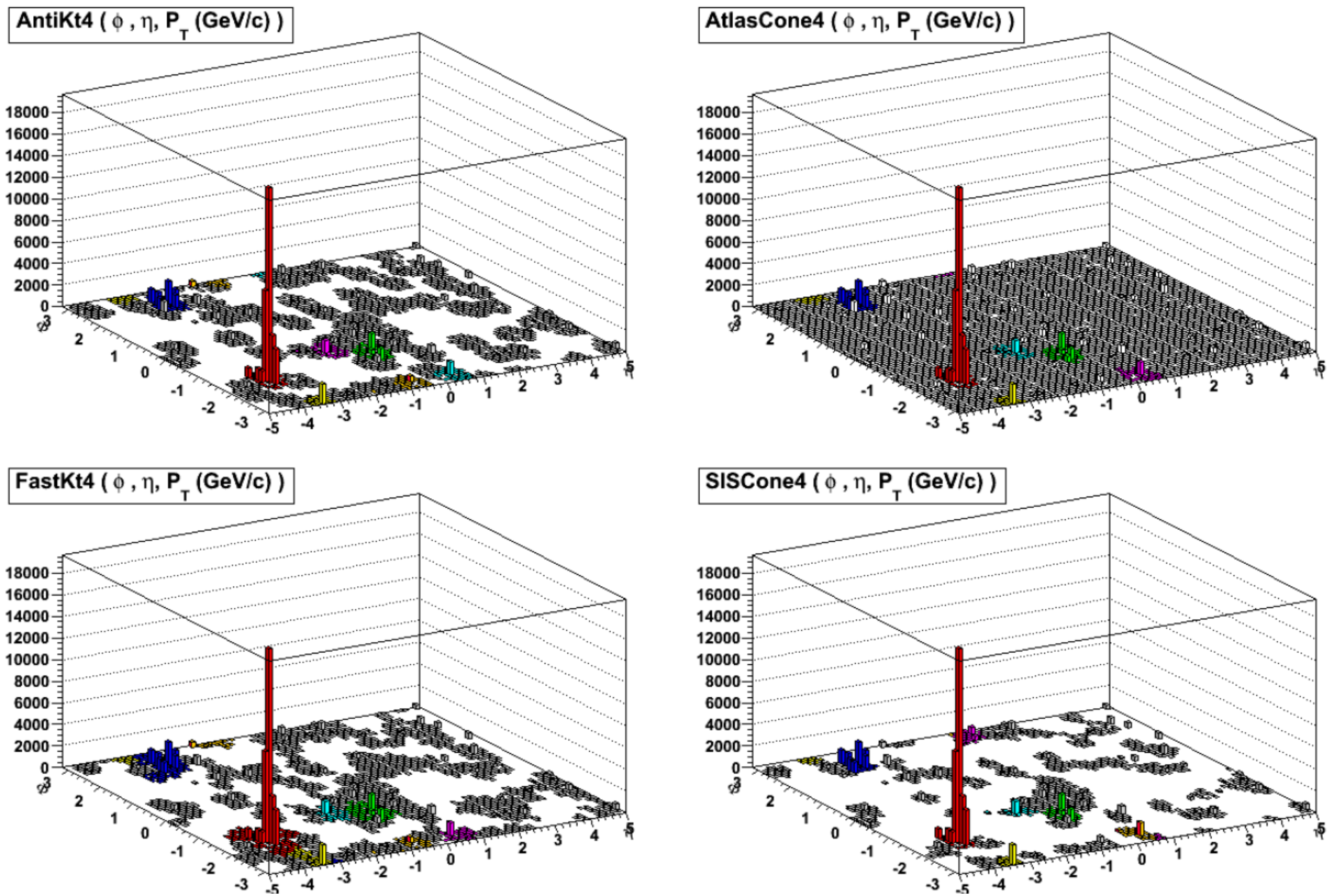
Measure of jet algorithm performance depends on final state

- Cone preferred for resonances
  - E.g., 2 – 3…*n* prong heavy particle decays like top, *Z'*, etc.
  - Boosted resonances may require jet substructure analysis – need kT algorithm!
- Recursive recombination algorithms preferred for QCD cross-sections
  - High level of IR safety makes jet counting more stable
- Pile-up suppression easiest for regularly shaped jets
  - E.g., Anti-kT most cone-like, can calculate jet area analytically even after split and merge

Measures of jet performance

- Particle level measures prefer observables from final state
  - Di-jet mass spectra etc.
- Quality of spectrum important
  - Deviation from Gaussian etc.

Jet Shapes (1)



(from P.A. Delsart)

Jet Shapes (2)

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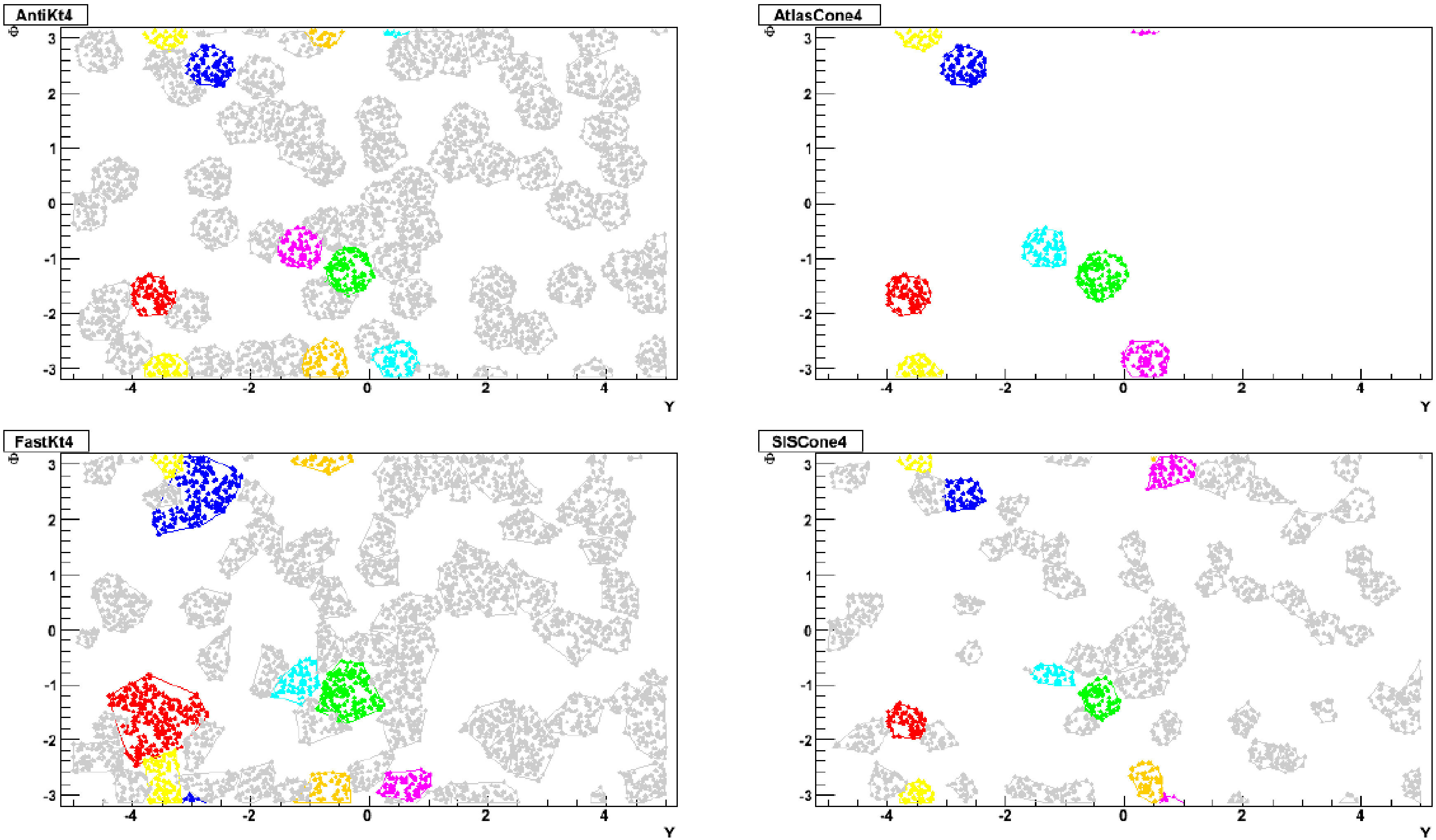

(from P.A. Delsart)

Jet Shapes (3)

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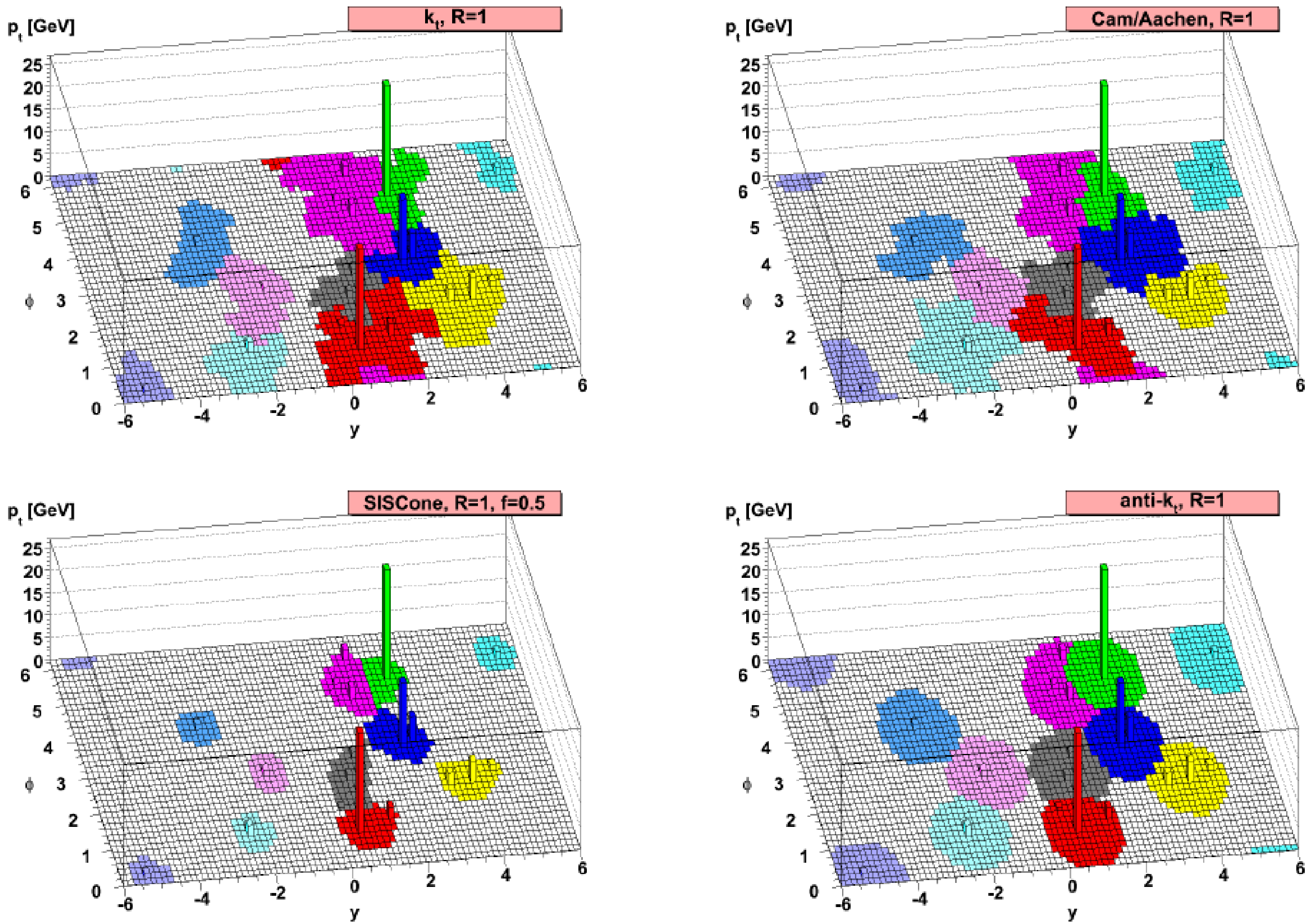

(from G. Salam's talk at the ATLAS Hadronic Calibration Workshop Tucson 2008)

Jet Reconstruction Performance (1)

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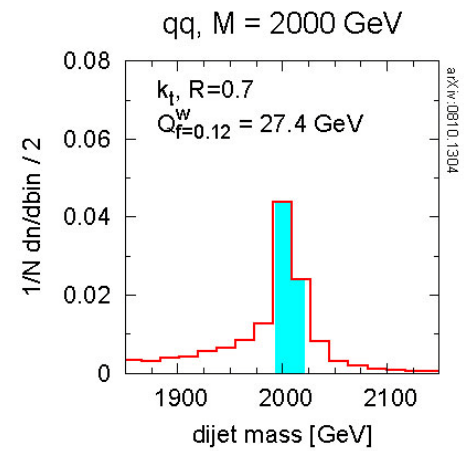
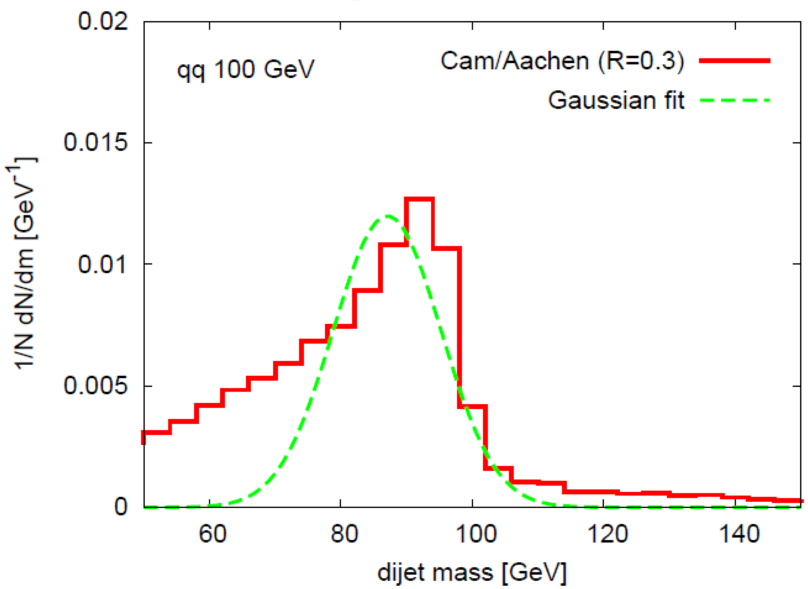
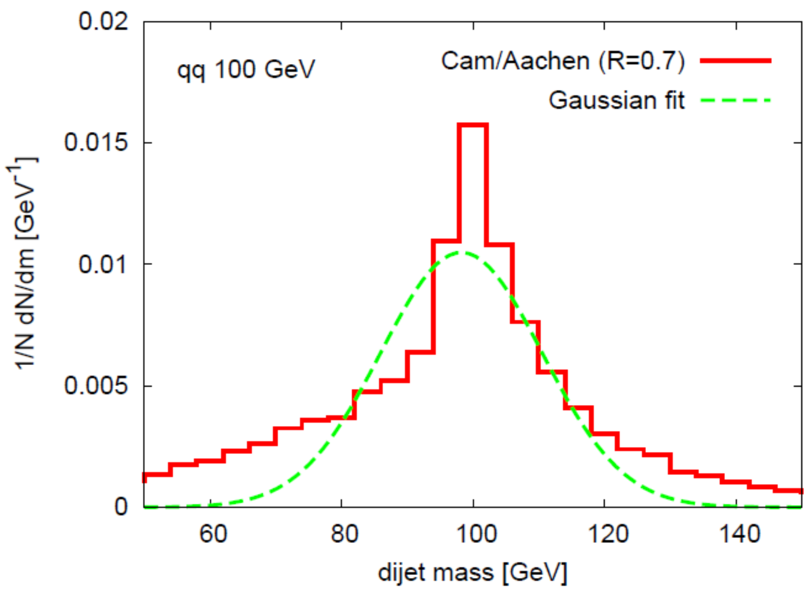
Quality estimator for distributions

- Best reconstruction: narrow Gaussian
  - We understand the error on the mean!
- Observed distributions often deviate from Gaussian
  - Need estimators on size of deviations!
  - Should be least biased measures
- Best performance gives closest to Gaussian distributions
  - List of variables describing shape of distribution on next slide
- Focus on unbiased estimators
  - E.g., distribution quantile describes the narrowest range of values containing a requested fraction of all events
  - Kurtosis and skewness harder to understand, but clear message in case of Gaussian distribution!



(from Salam ,Cacciari, Soyez, http://quality.fastjet.fr)





Jet Reconstruction Performance Estimators

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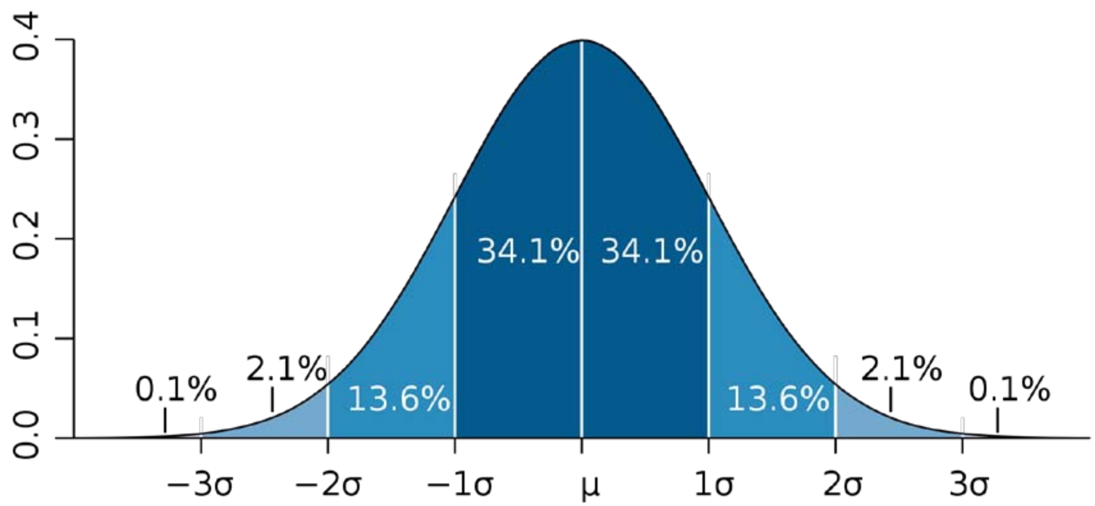
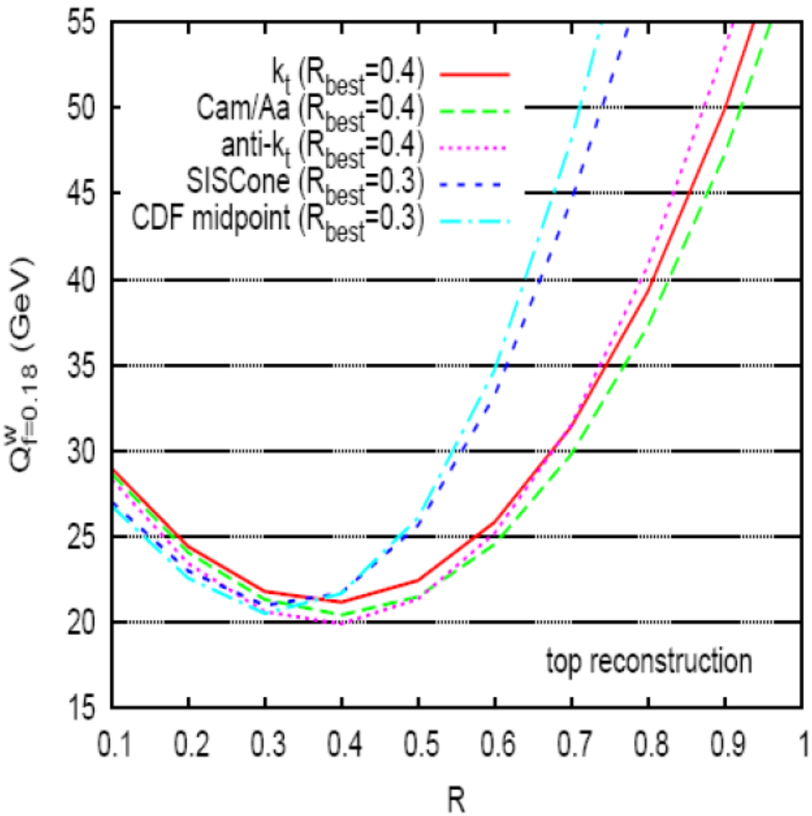
May 05, 2010

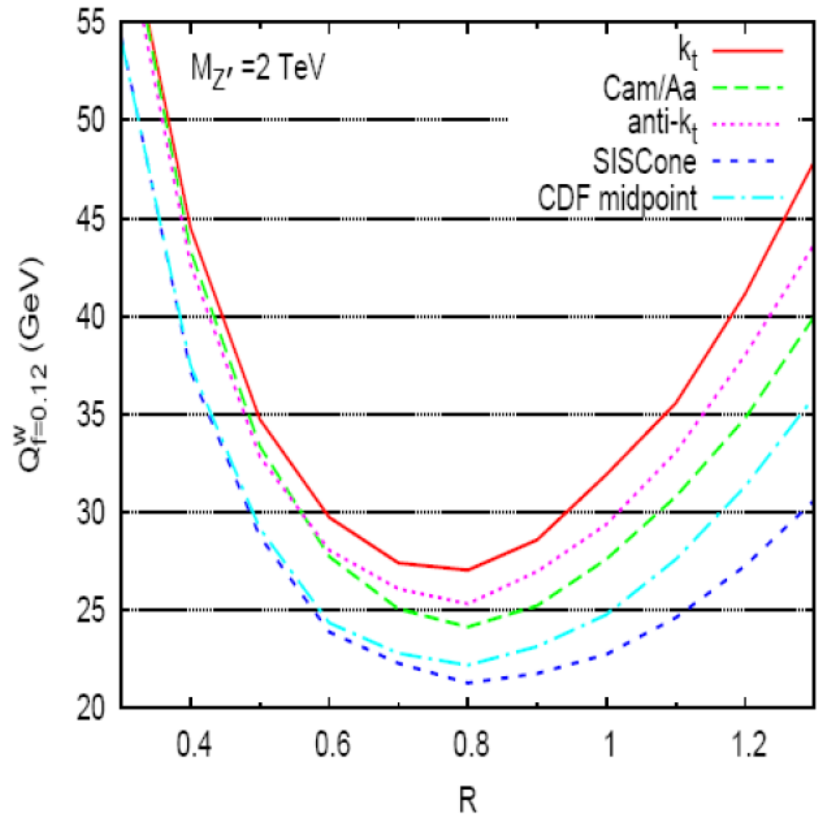
Estimator	Quantity	Expectation for Gaussian
$\langle R \rangle$	statistical mean	$\mu = \langle R \rangle = R_{\text{mop}} = R_{\text{median}}$
R_{median}	median	
R_{mop}	most probable value	
$RMS = \sqrt{\langle R^2 \rangle - \langle R \rangle^2}$	standard deviation	$\sigma = RMS$
$\gamma_3 = \frac{\sum_{i=1}^{N} \left(R_i - \langle R \rangle\right)^3}{N\sigma^3}$	skewness/left-right asymmetry	0
$\gamma_4 = \frac{\sum_{i=1}^{N} \left(R_i - \langle R \rangle\right)^4}{N\sigma^4} - 3$	kurtosis/"peakedness"	0
Q_f^w	quantile	$Q_{f \approx 68\%}^w = 2\sigma$



Quality of mass reconstruction for various jet finders and configurations

- Standard model – top quark hadronic decay
  - Left plot – various jet finders and distance parameters
- BSM – *Z'* (2 TeV) hadronic decay
  - Right plot – various jet finders with best configuration





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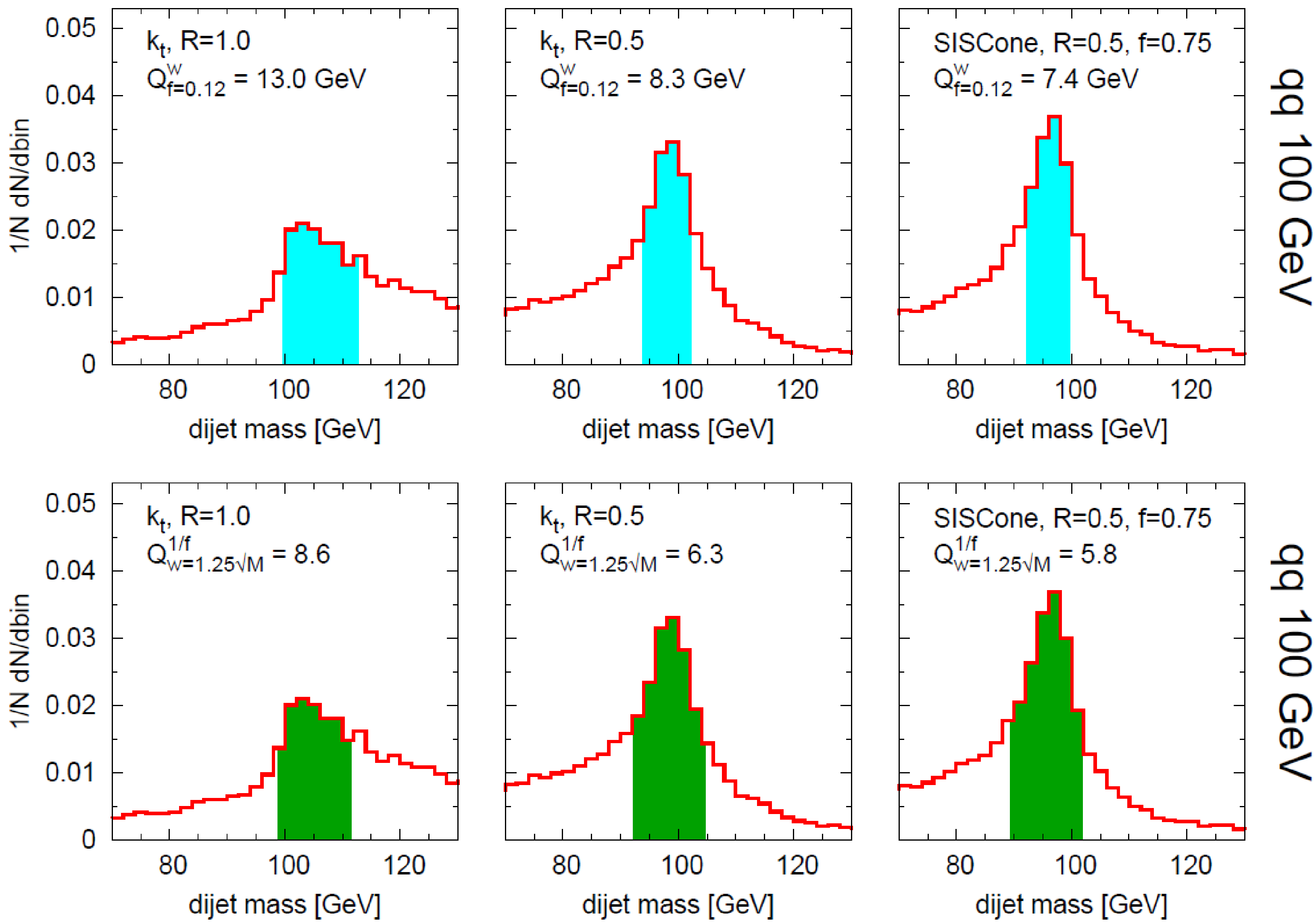
Jet Performance Examples (1)

$$Q^{1/f}_{w=x\sqrt{M}} \equiv \left(\frac{\text{Max \# reco. massive objects in window of width } w = x\sqrt{M}}{\text{Total \# generated massive objects}}\right)^{-1}$$



(from Cacciari, Rojo, Salam, Soyez, **JHEP 0812:032,2008**)

Jet Performance Examples (2)

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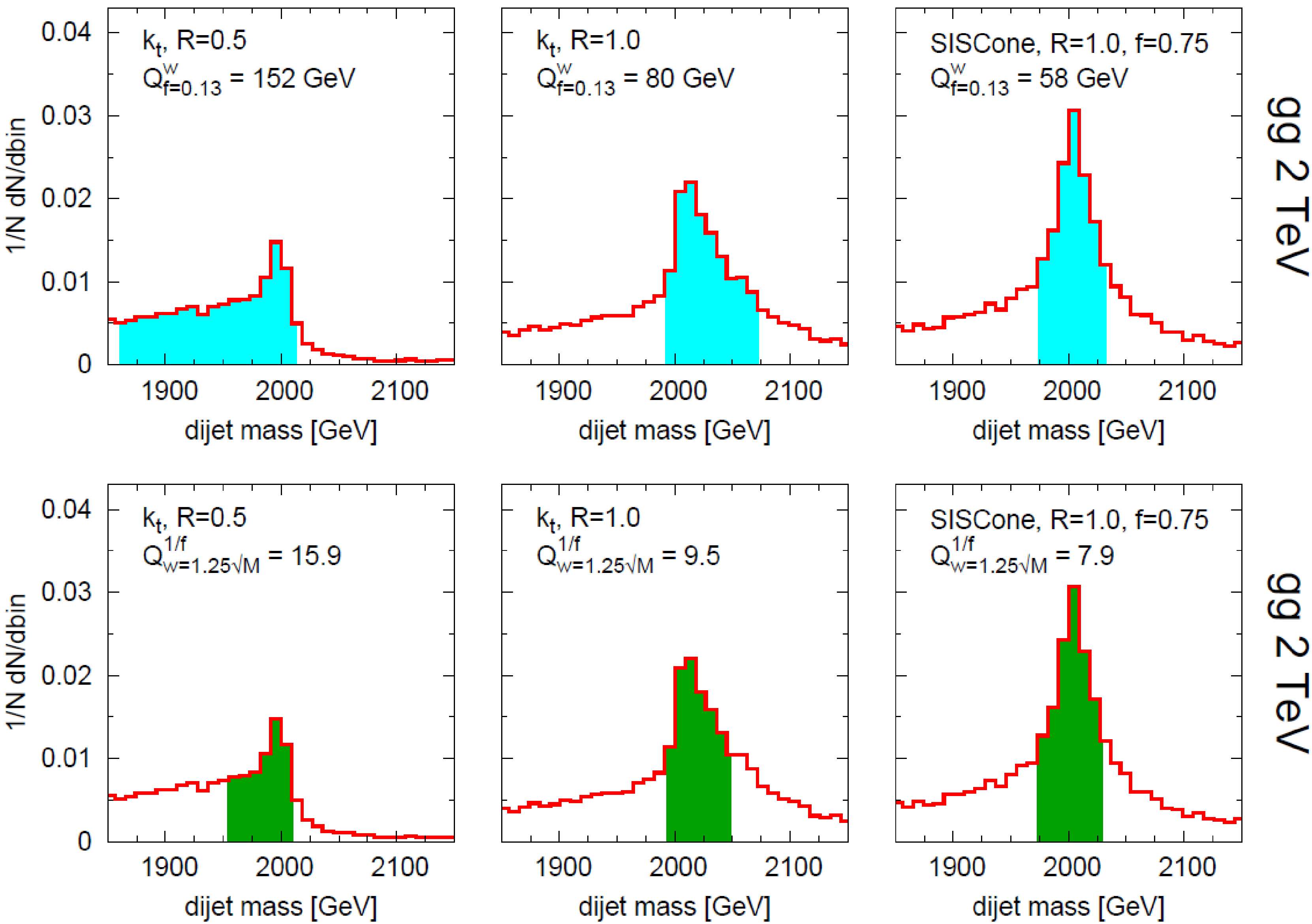
$$Q^{1/f}_{w=x\sqrt{M}} \equiv \left(\frac{\text{Max \# reco. massive objects in window of width } w = x\sqrt{M}}{\text{Total \# generated massive objects}} \right)^{-1}$$



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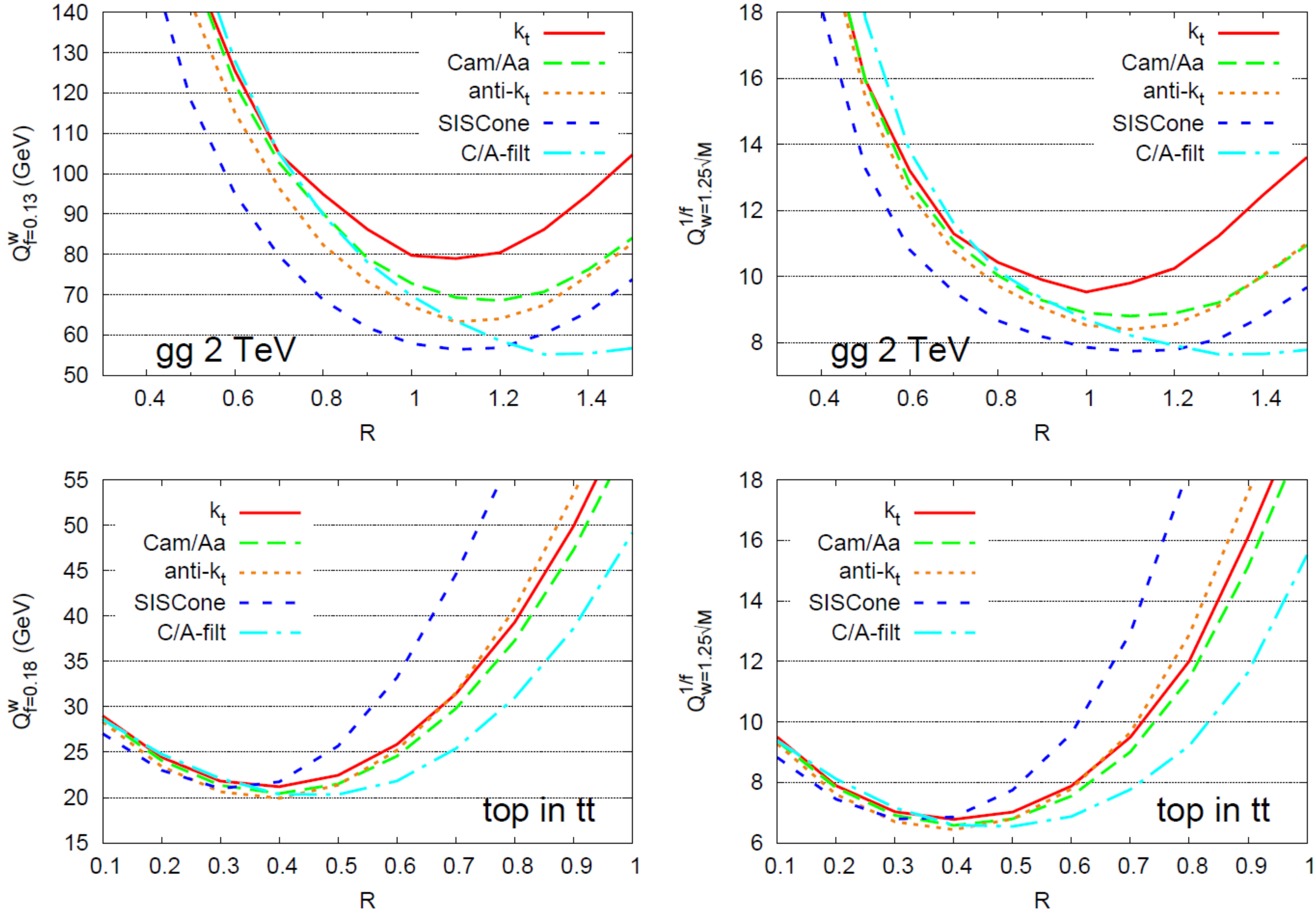
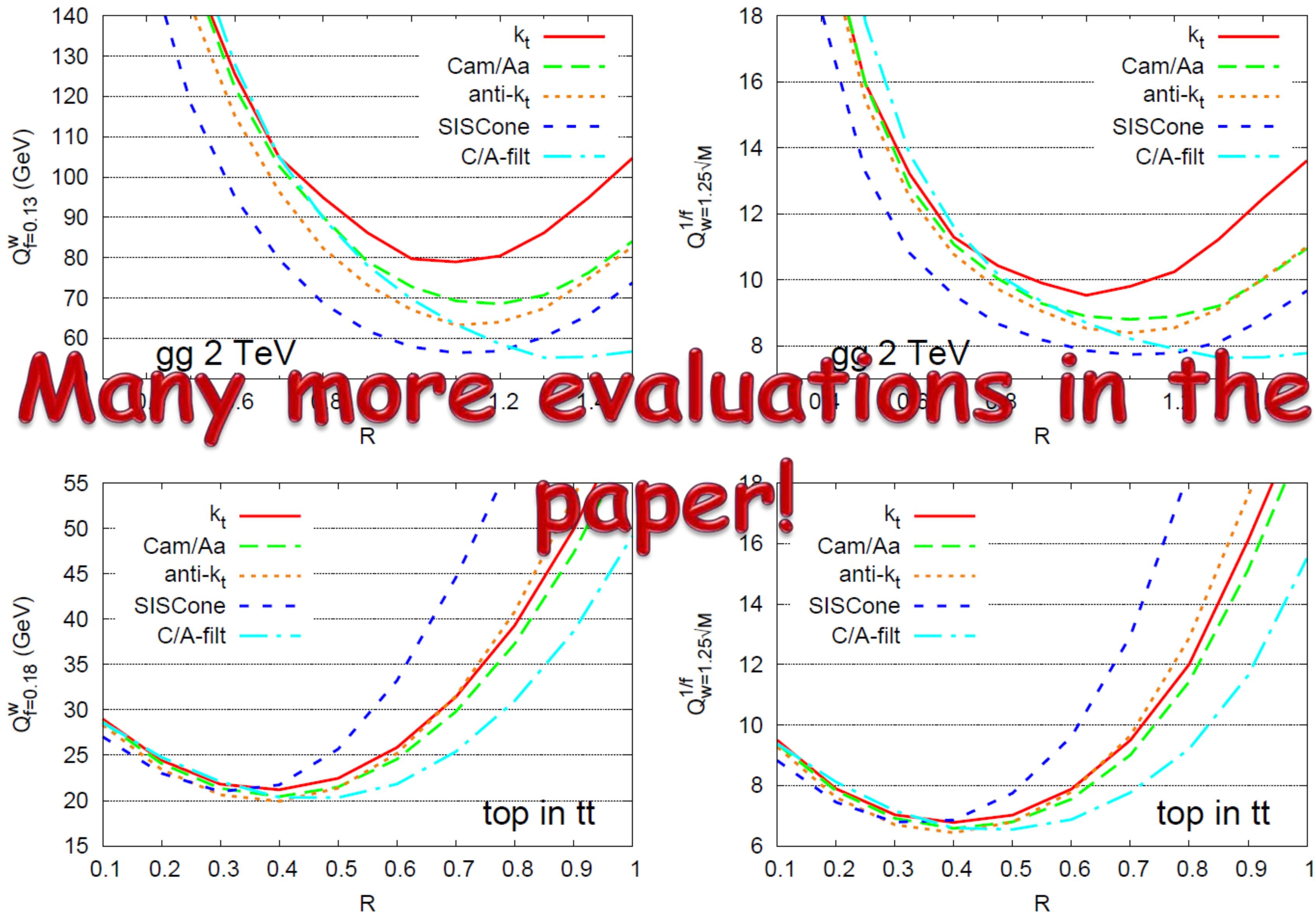
Jet Performance Examples (3)



(from Cacciari, Rojo, Salam, Soyez, **JHEP 0812:032,2008**)

Jet Performance Examples (3)

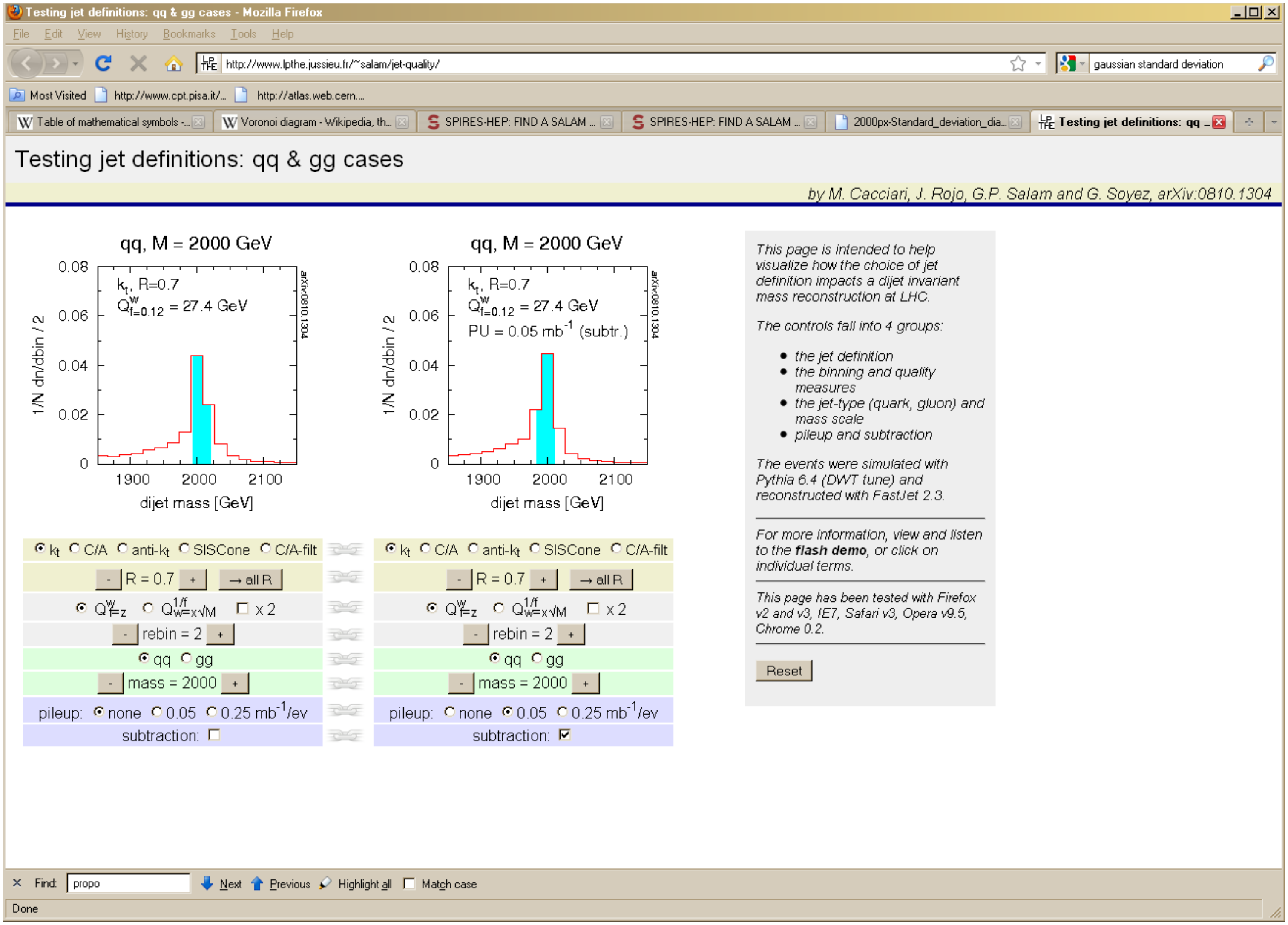


Many more evaluations in the paper!

(from Cacciari, Rojo, Salam, Soyez, **JHEP 0812:032,2008**)

Web-based jet performance evaluation available

http://www.lpthe.jussieu.fr/~salam/jet-quality

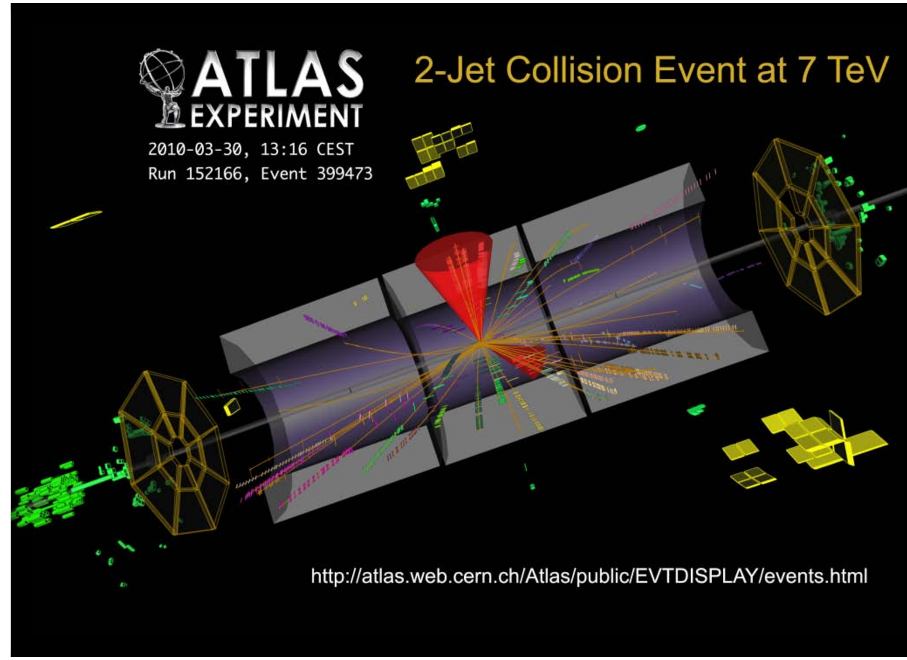


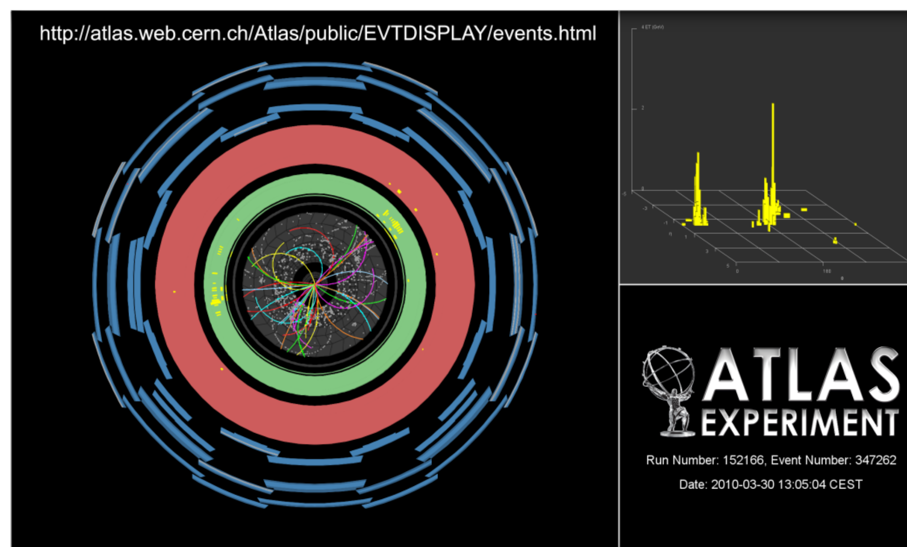
pp Collisions at 7 TeV in LHC!

CERN press release March 30, 2010

- Rolf Heuer (Director General, CERN):
  - "Beams collided at 7 TeV in the LHC at 13:06 CEST today, marking the start of the LHC research program. Particle physicists around the world are looking forward to a potentially rich harvest of new physics as the LHC begins its first long run at an energy three and a half times higher than previously achieved at a particle accelerator. …"
- That was at 4:06am (Arizona) this morning…
  - We were probably not awake but are as excited!
- … and we already see two-jet events!
  - See event displays on the right!

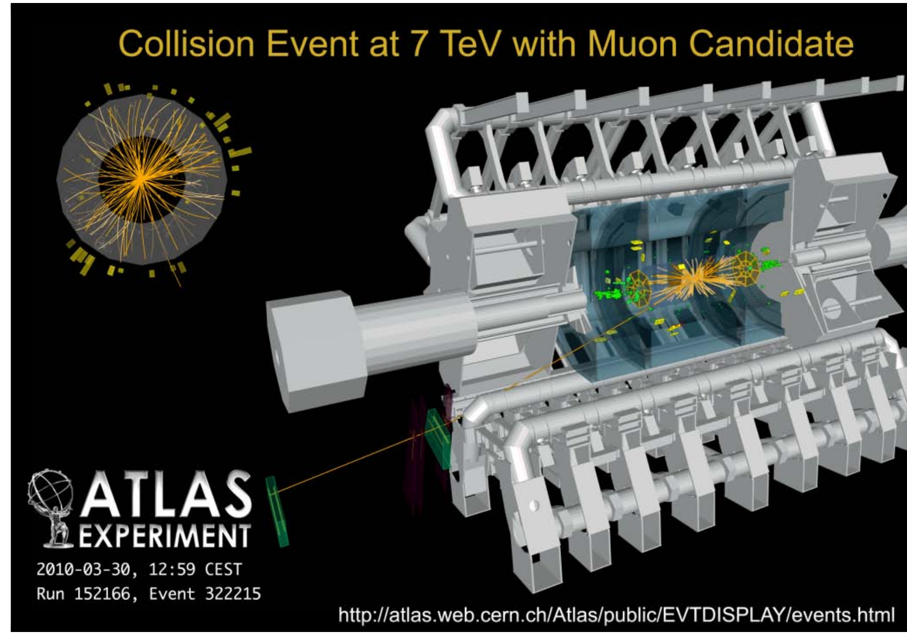
Two different events!





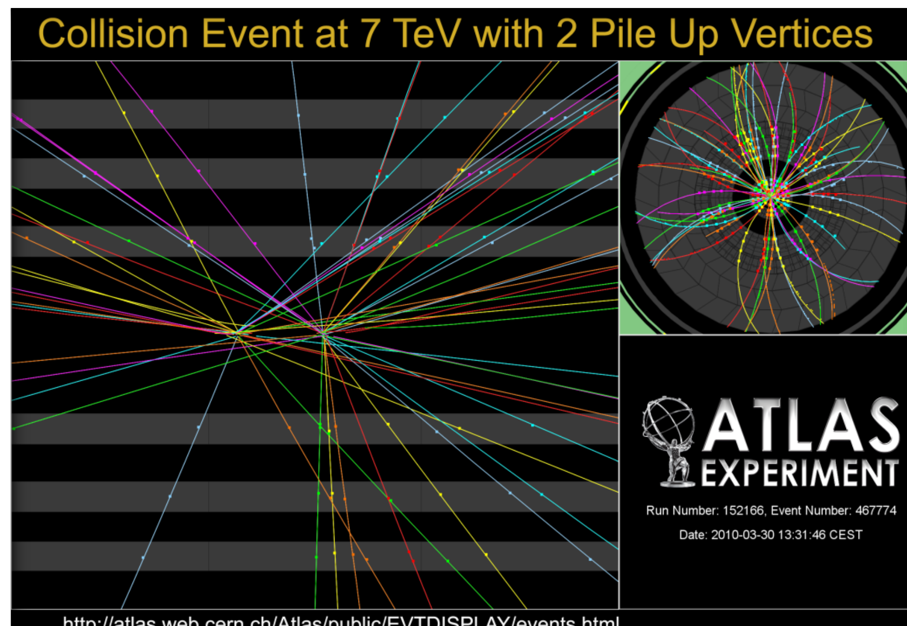
pp Collisions at 7 TeV in LHC!

Top: Muon candidate



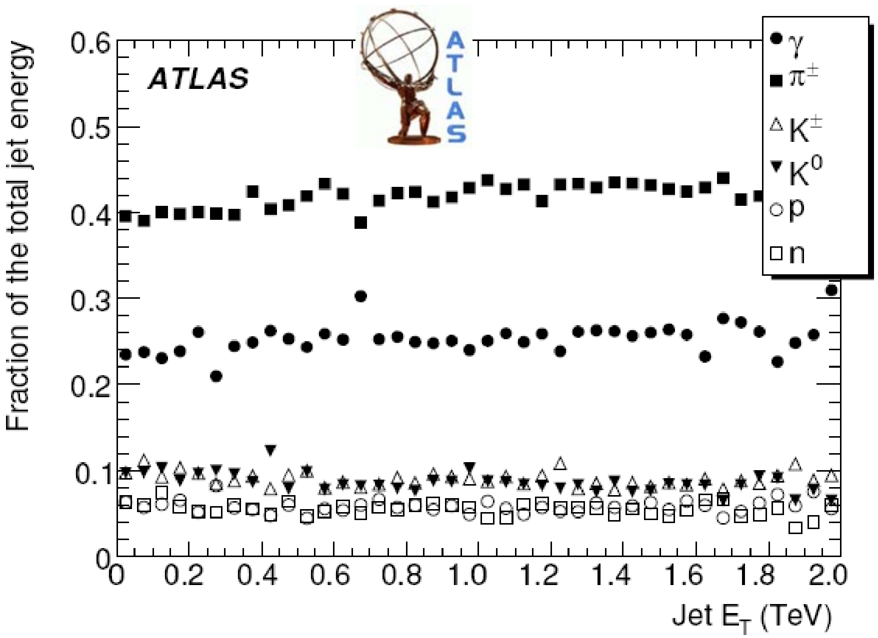
Two collisions at the same time

Pile-up!



Recall: the experimentalists' view on jets

- A bunch of particles generated by hadronization of a common source
  - Quark, gluon fragmentation
- As a consequence, the particles in this bunch have correlated kinematic properties
  - Reflecting the source by sum rules and Conservation laws
- The **interacting** particles in this bunch generated an observable signal in a detector
  - Protons, neutrons, pions, photons, electrons, muons, other particles with laboratory lifetimes >~10ps, and the corresponding anti-particles
- The **non-interacting** particles do not generate a directly observable signal
  - Neutrinos, mostly



What is jet reconstruction, then?

- Model/simulation: particle jet
  - Attempt to collect the final state particles described above into objects (jets) representing the original parton kinematic
  - Re-establishing the correlations
- Experiment: detector jet
  - Attempt to collect the detector signals from these particles to measure their original kinematics
  - Usually not the parton!

Detector Effects On Jets

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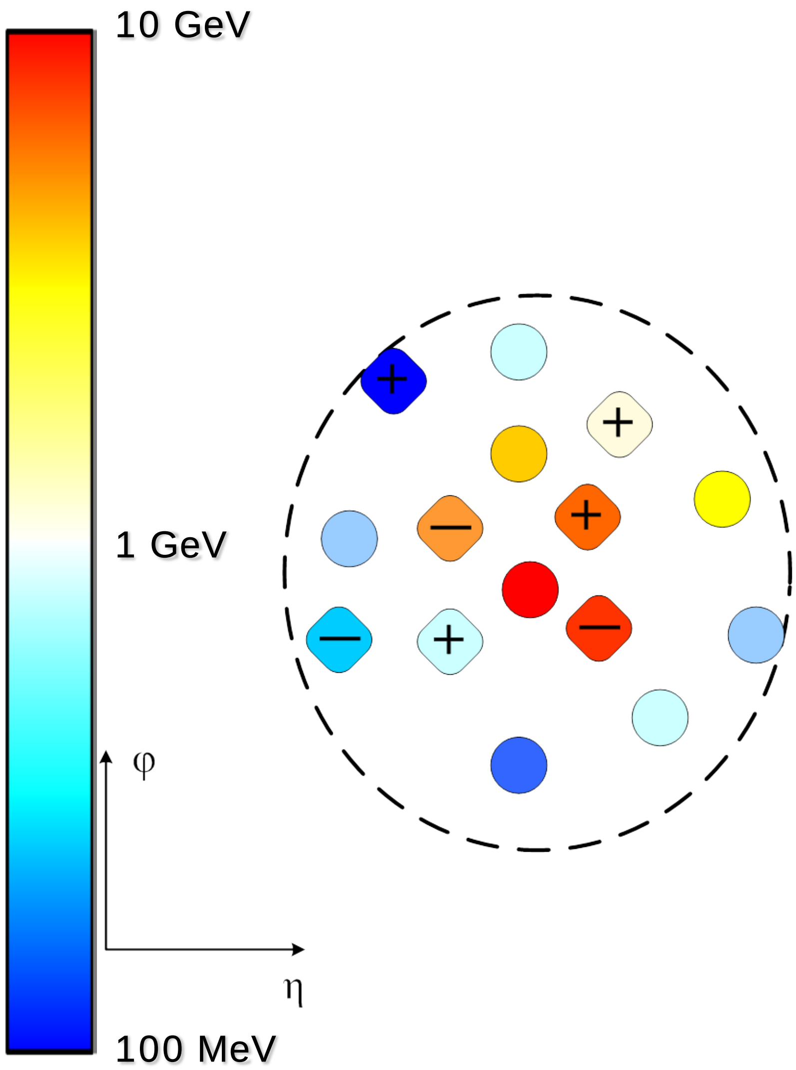
May 05, 2010



Change of composition

- Radiation and decay inside detector volume
- "Randomization" of original particle content

Defocusing changes shape in lab frame

- Charged particles bend in solenoid field

Attenuation changes energy

- Total loss of soft charged particles in magnetic field
- Partial and total energy loss of charged and neutral particles in inactive upstream material

Hadronic and electromagnetic cacades in calorimeters

- Distribute energy spatially
- Lateral particle shower overlap

Detector Effects On Jets

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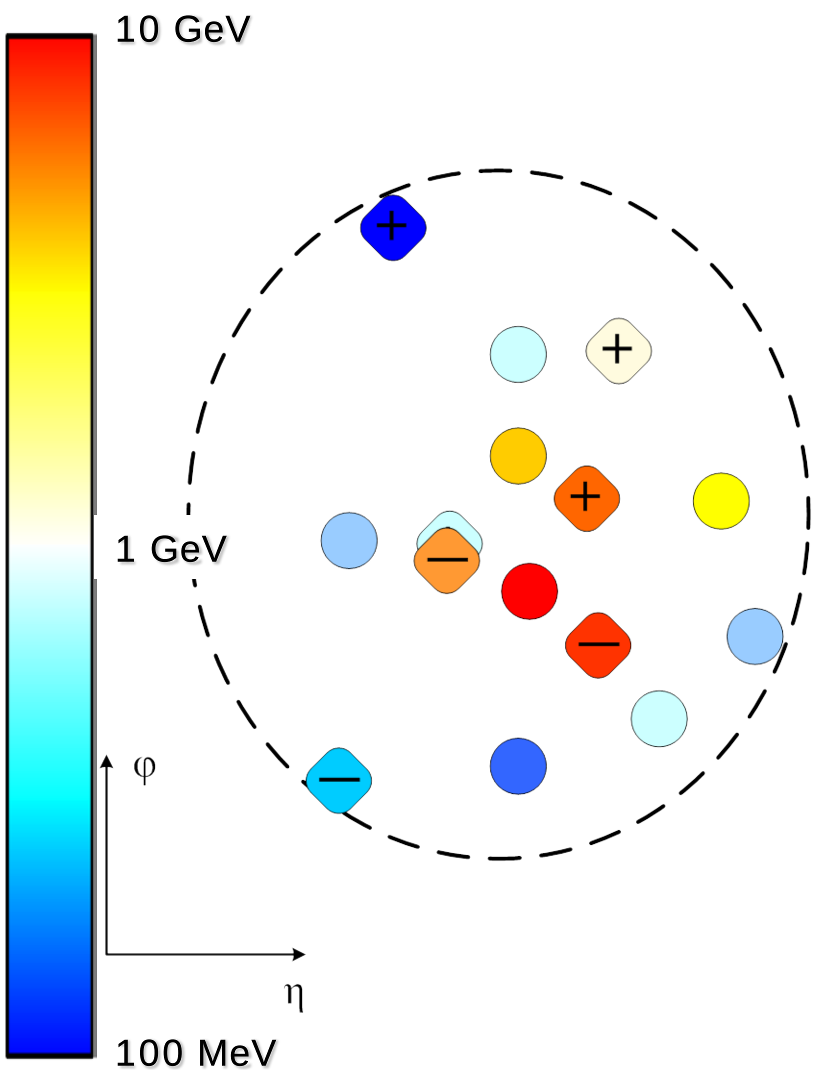
May 05, 2010



Change of composition

- Radiation and decay inside detector volume
- "Randomization" of original particle content

Defocusing changes shape in lab frame

- Charged particles bend in solenoid field

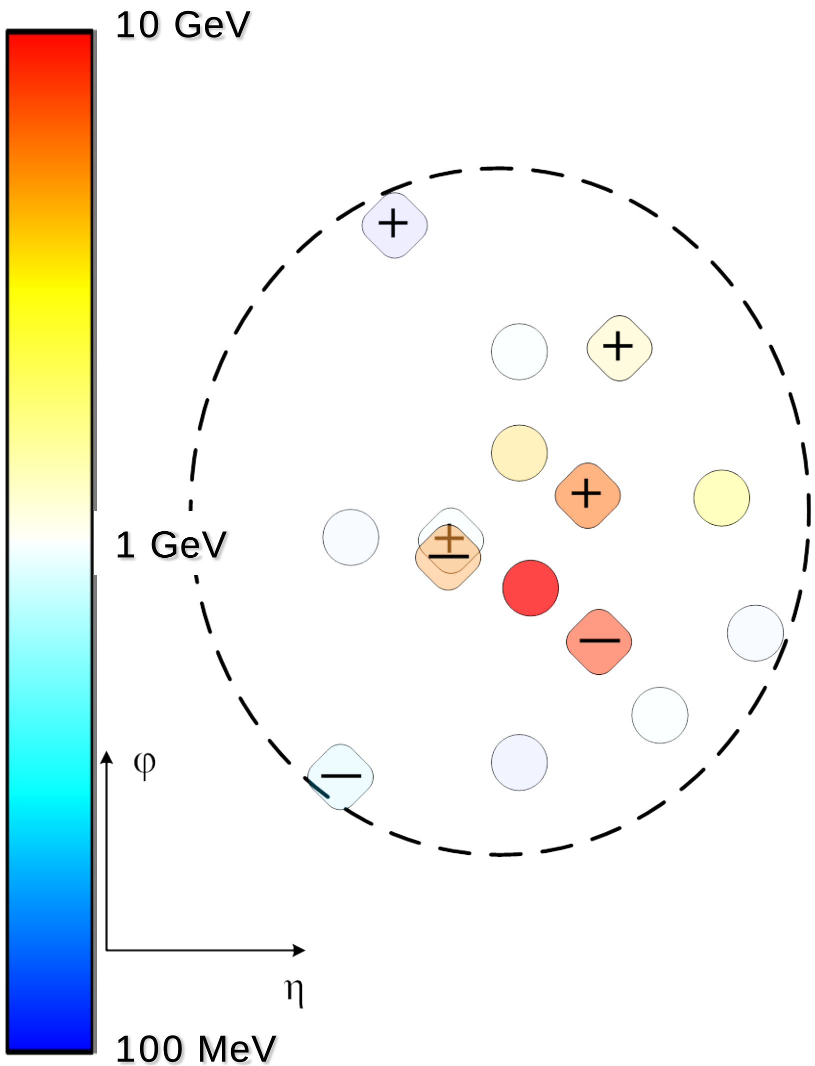
Attenuation changes energy

- Total loss of soft charged particles in magnetic field
- Partial and total energy loss of charged and neutral particles in inactive upstream material

Hadronic and electromagnetic cacades in calorimeters

- Distribute energy spatially
- Lateral particle shower overlap

Detector Effects On Jets



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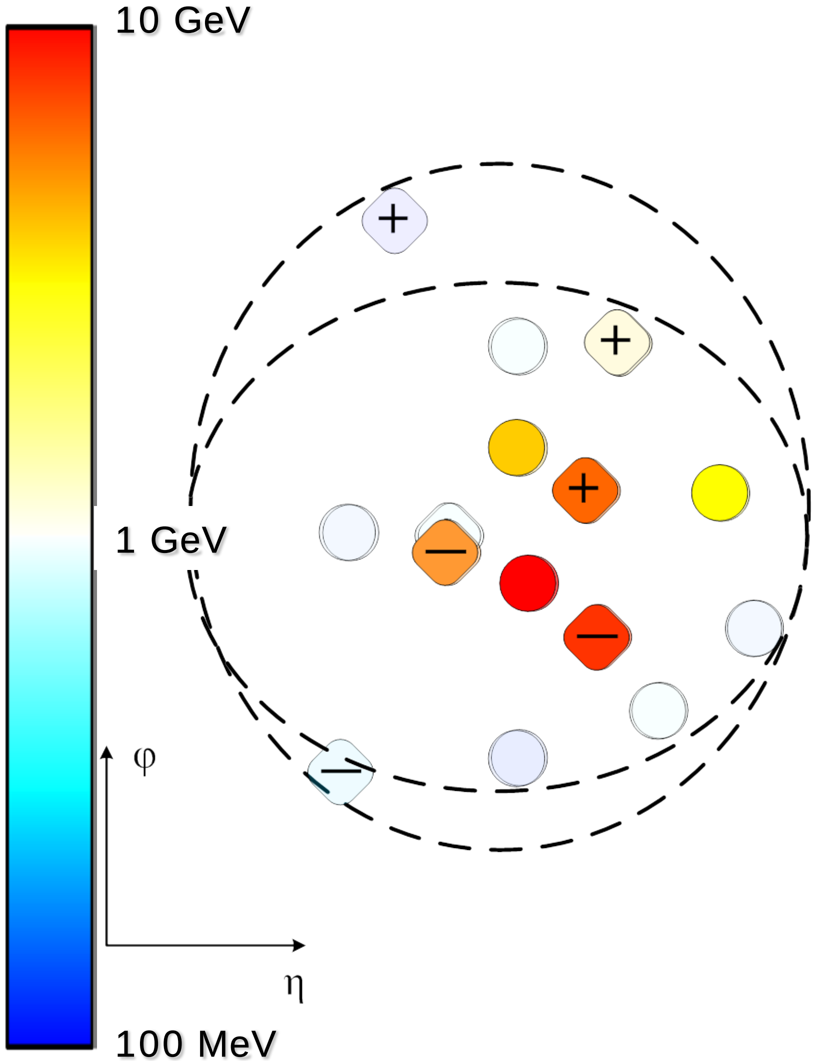

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Detector Effects On Jets

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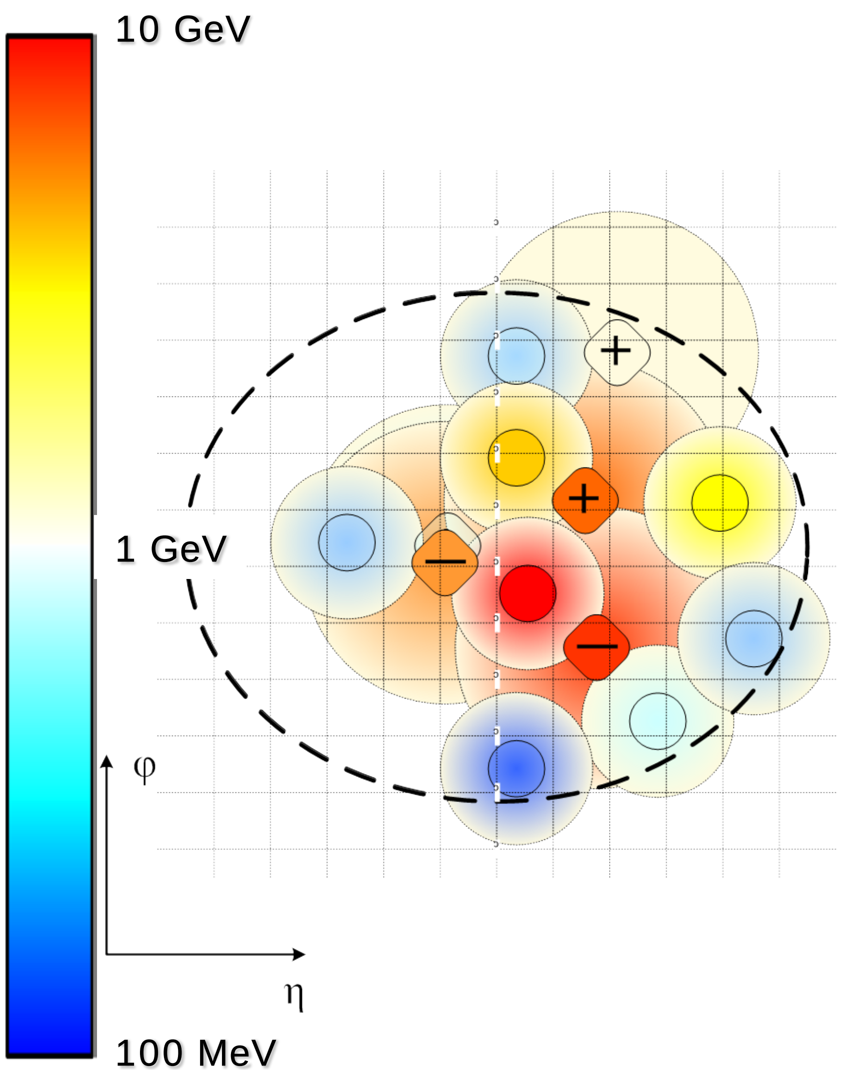

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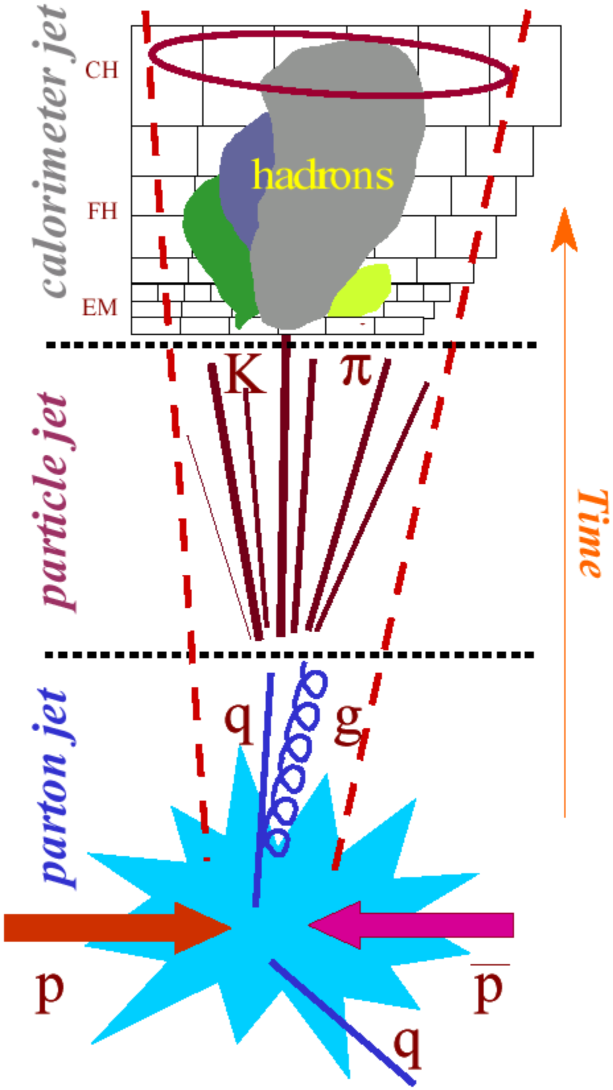

Jet Reconstruction Challenges

longitudinal energy leakage
detector signal inefficiencies (dead channels, HV…)
pile-up noise from (off- and in-time) bunch crossings
electronic noise
calo signal definition (clustering, noise suppression…)
dead material losses (front, cracks, transitions…)
detector response characteristics (e/h ≠ 1)
jet reconstruction algorithm efficiency
lost soft tracks due to magnetic field

added tracks from underlying event
added tracks from in-time (same trigger) pile-up event
jet reconstruction algorithm efficiency

physics reaction of interest (interaction or parton level)

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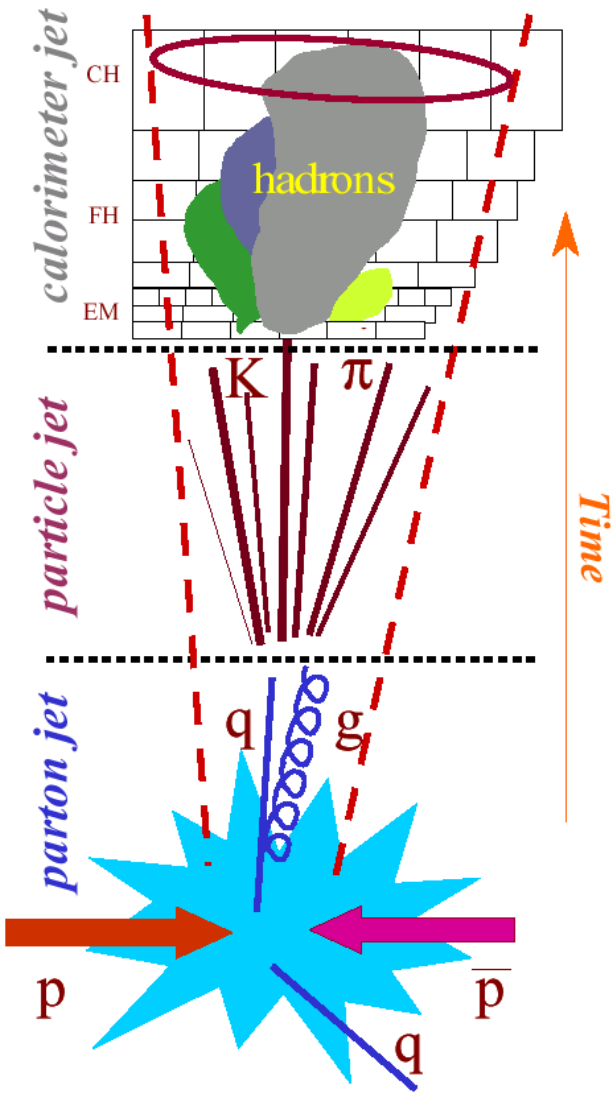

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jet calibration task is to unfold all this to reconstruct the particle level jet driving the signals…

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Jet Reconstruction Challenges

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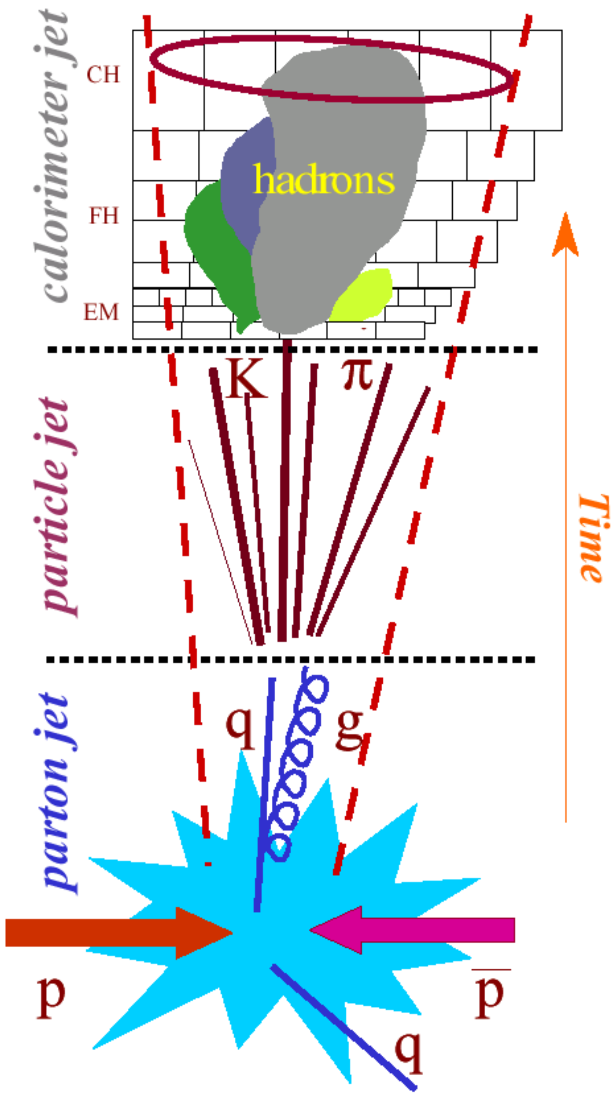

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…modeling and calculations establish the link between particle and interaction level…

physics reaction of interest (interaction or parton level)

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Jet Reconstruction Challenges

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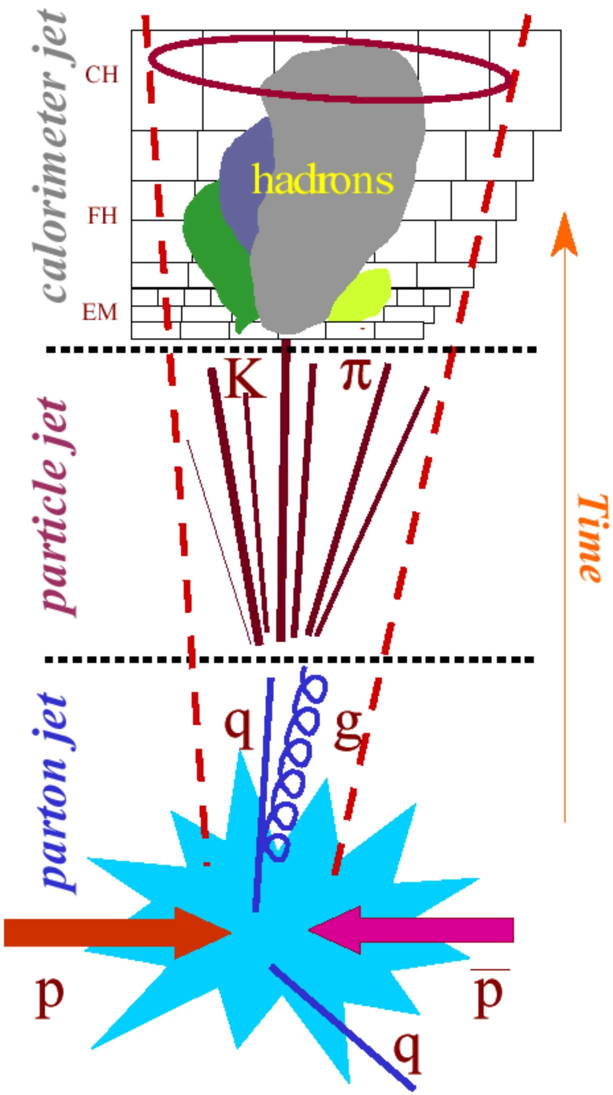


Jet Reconstruction Challenges

jet calibration task is to unfold all this to reconstruct the particle level jet driving the signals…

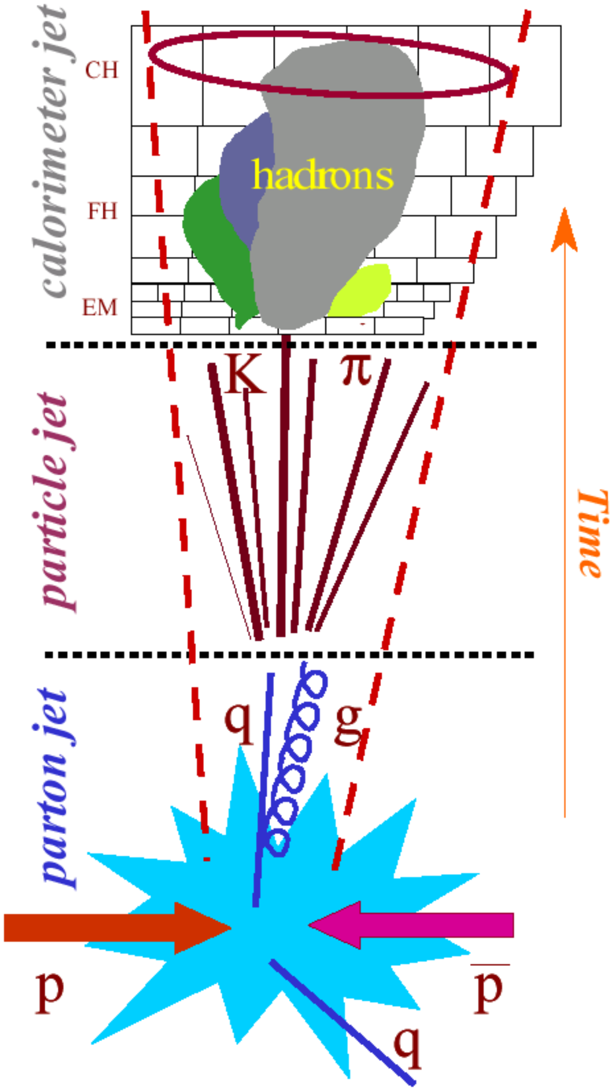
…modeling and calculations establish the link between particle and interaction level…

…but how is this really done?

physics reaction of interest (interaction or parton level)

Jet Reconstruction Task

Experiment ("Nature")



The experiment starts with the actual collision or the generator…

- Triggered collision with signal parton collision, fragmentation & underlying event (**experiment**), or:
- Interaction level calculation with fragmentation and underlying event modeling (**simulations**)

… go to the particles in the simulation …

- Here particle level event represent the underlying interaction and the full complexity of the physics of the collision in the experiment

… collect the detector signals …

- From the readout (**experiment**), or:
- Take the stable (observable) particles and simulate the signals in the detector (e.g., the calorimeter and tracking detector)(**simulations**)

… and compare them!

- Complex – need to include all experimental biases like event selection (trigger bias), topology and detector inefficiencies

This establishes particle jet references for the detector jets!

- Of course only in a statistical sense, i.e. at the level of distributions!

Jet Reconstruction Task

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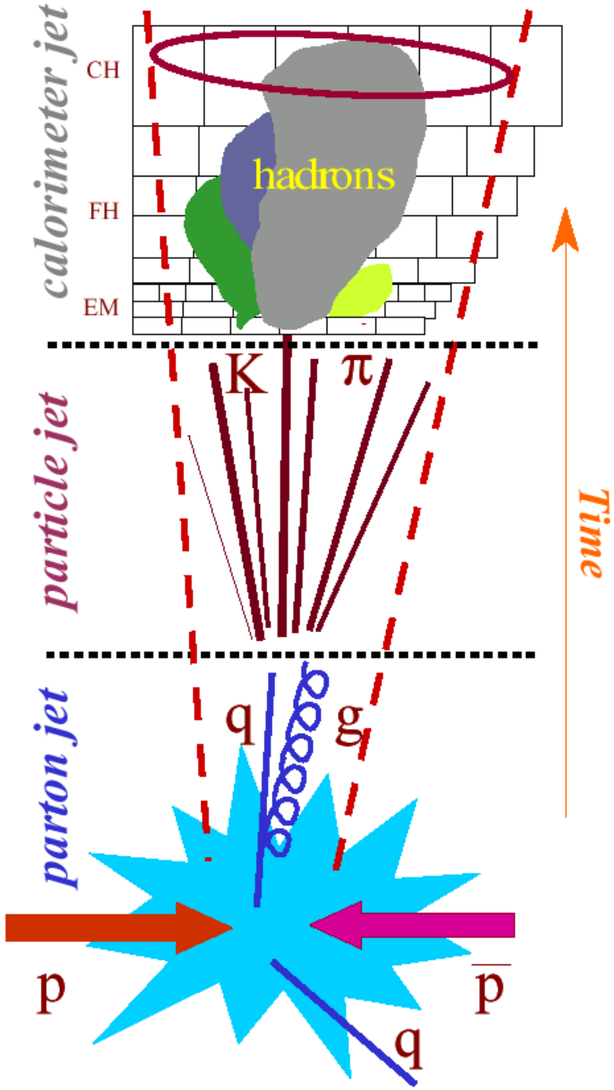
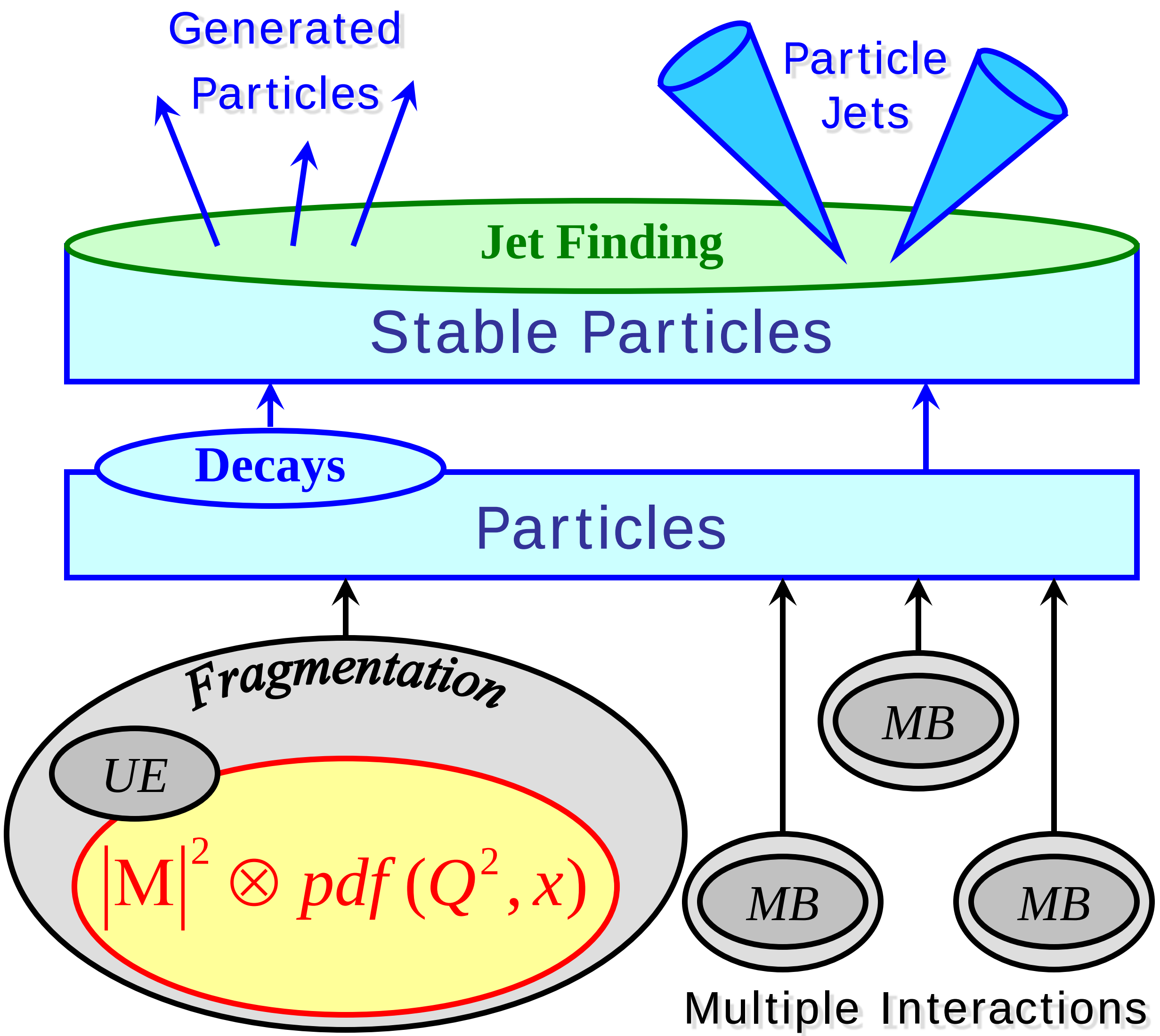
Experiment ("Nature")



Modeling Particle Jets



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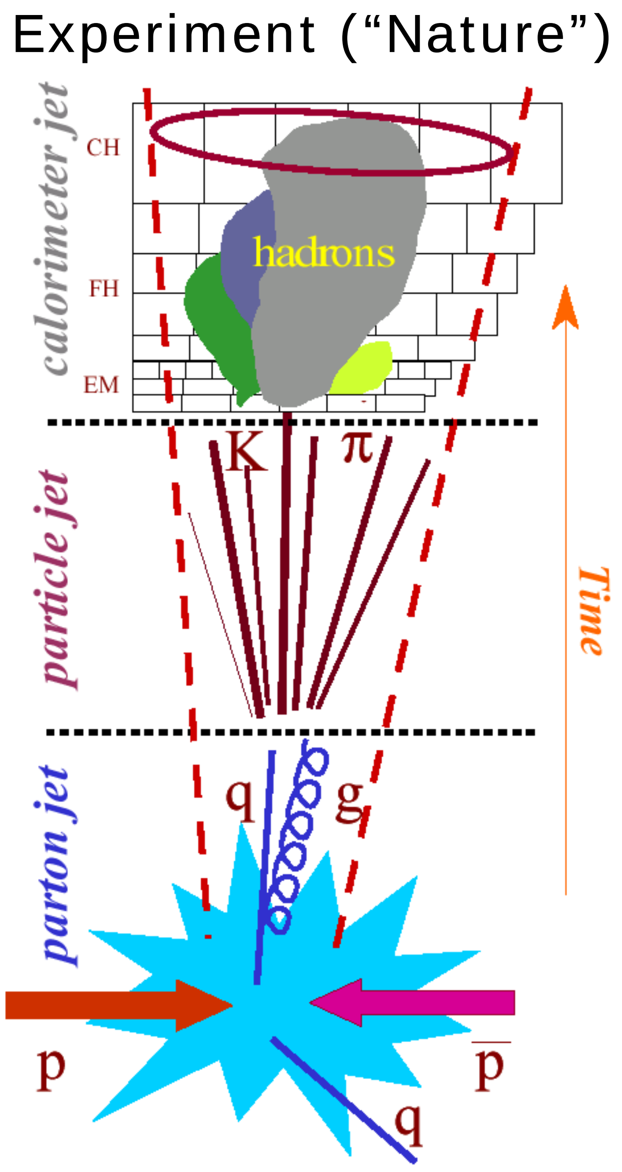

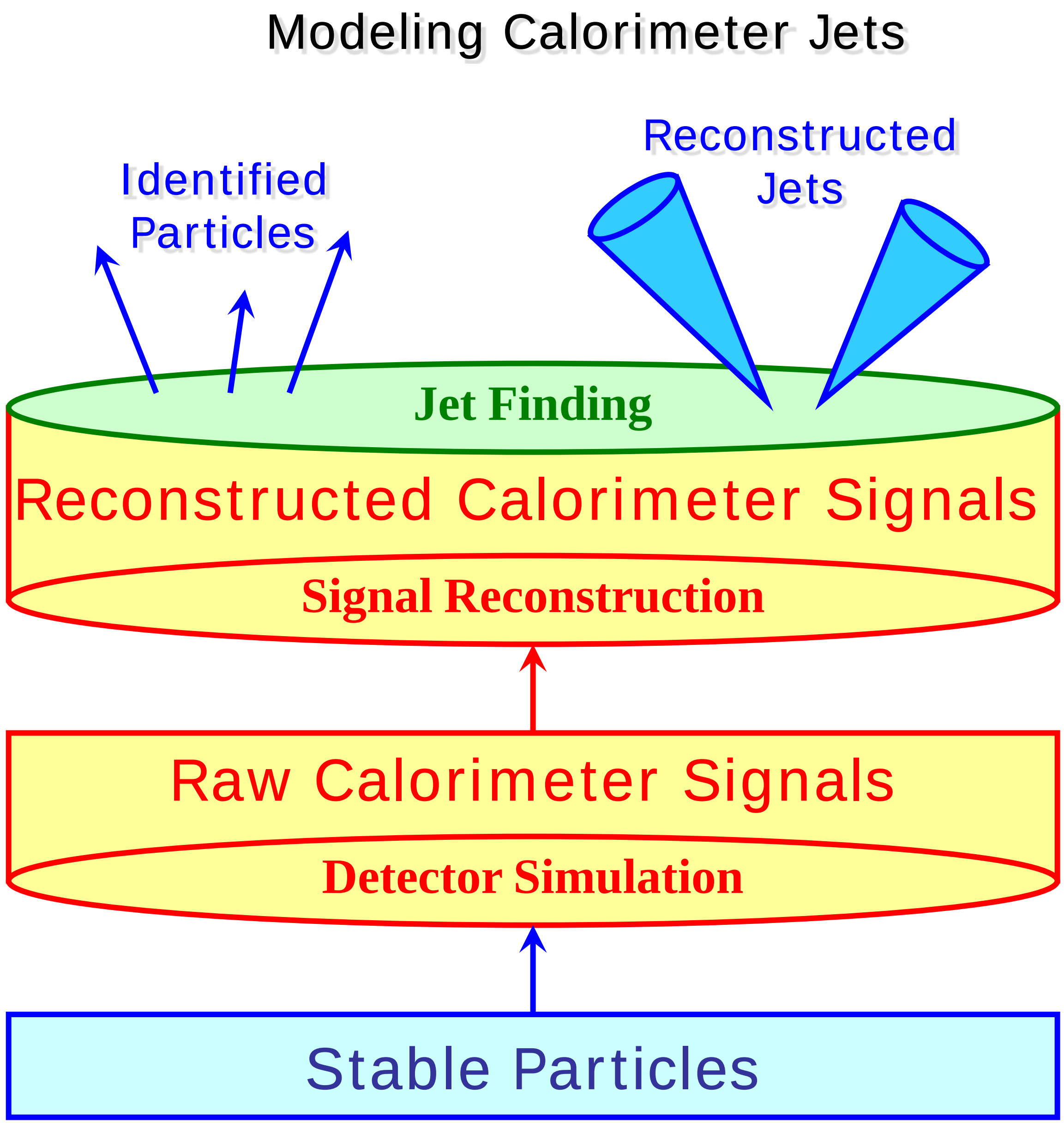

Jet Reconstruction Task

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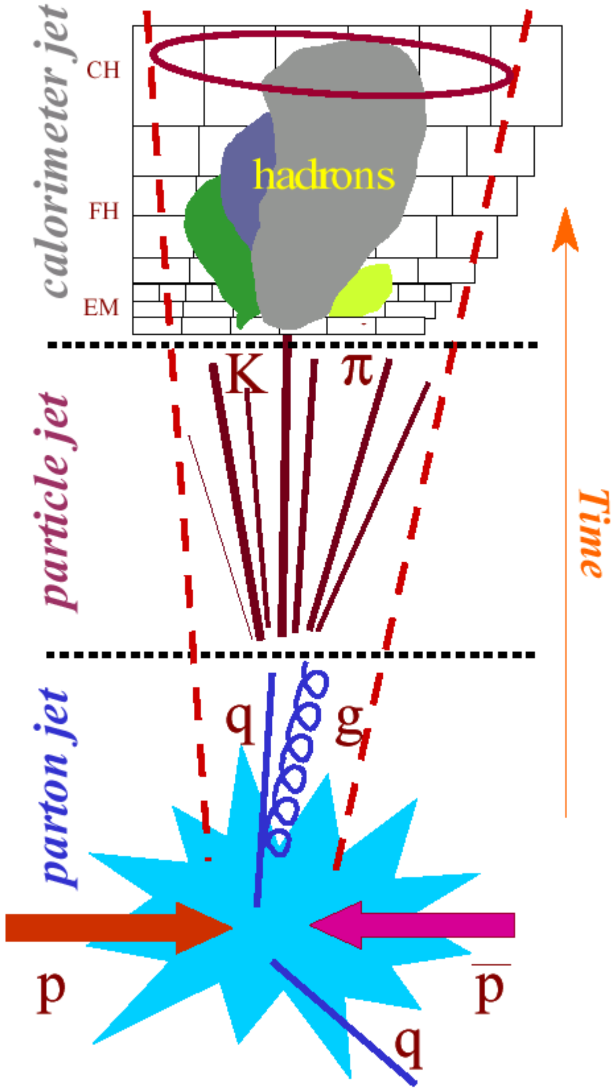
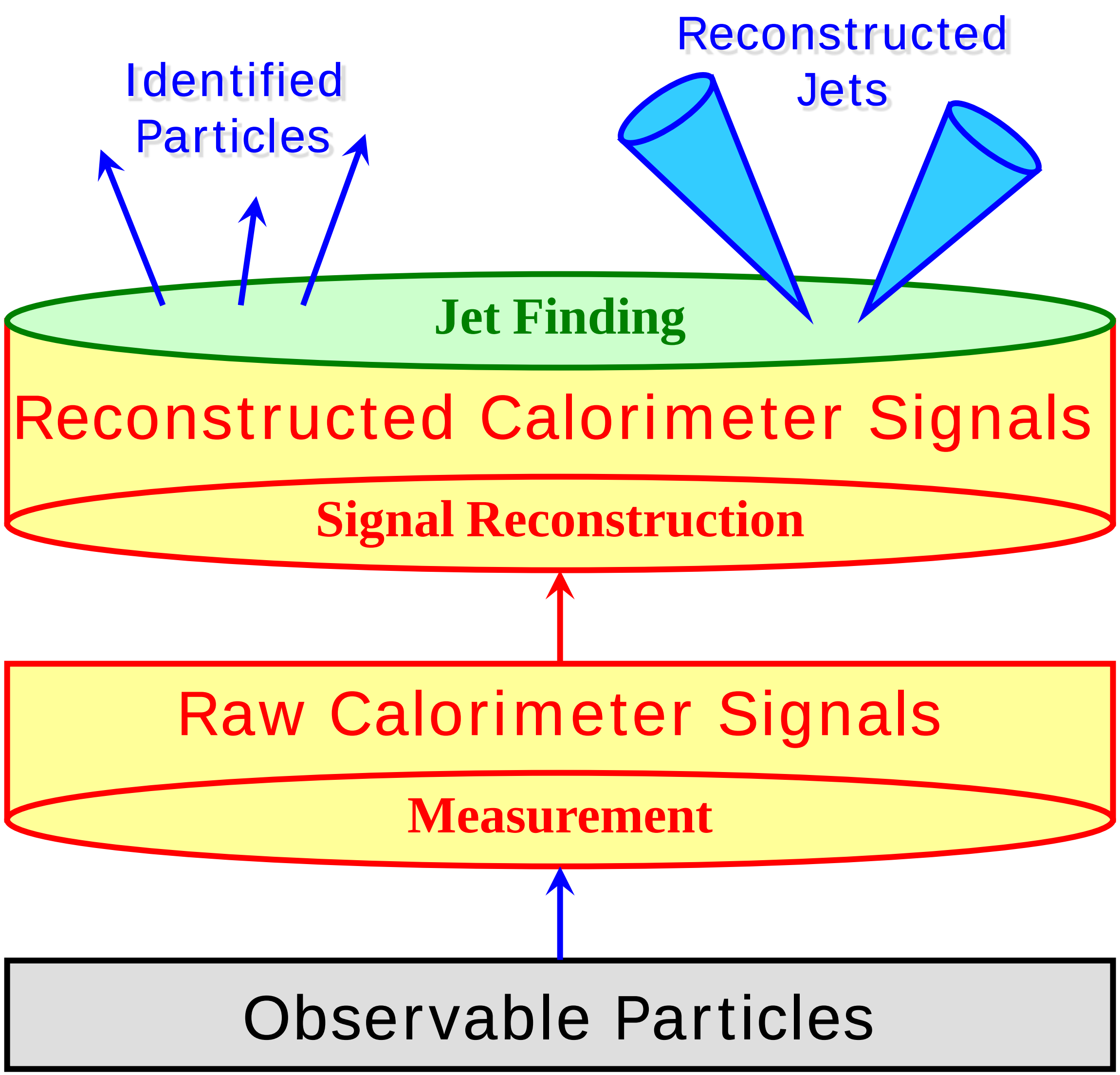


Measuring Calorimeter Jets



Jet Calibration

What is jet calibration?

- Straight forward: attempt to reconstruct a measured jet such that its final four-momentum is close to the true jet kinematics generating the signal

Why is it needed?

- Could compare simulated and measured calorimeter signals at any scale and deduct the true kinematics from the corresponding particle jet in simulation
  - Remember energy scales in calorimeters?
- But need to reconstruct **any** jet in the experiment
  - Even (or especially) the ones in events we have not simulated – which probably means new physics?
  - To understand these events the best measurement of the true jet independent of the availability of simulations for this specific event – no simulation bias allowed in general!
- Can we calibrated without simulations at all?
  - Complex physics and detector environment – hard to avoid simulations for precision reconstruction!
  - But there are **in-situ** jet calibrations (more at another time from a special guest speaker!)

So jet reconstruction needs to include a calibration

- Use a simulated calibration sample representing simple final state
  - Chose a somewhat understood Standard Model topology like QCD di-jets
- Calibrate using measurable jet features
  - Establish functions using jet observables as parameters to calibrate calorimeter jets from a basic scale to the final jet energy scale
  - If done right, simulation biases can be reduced, especially concerning the correct simulation of the event topology
- Understand the limitations (systematic error) in the context of the analysis

All this is the global subject of the remaining lectures!

Jet Calibration Validation

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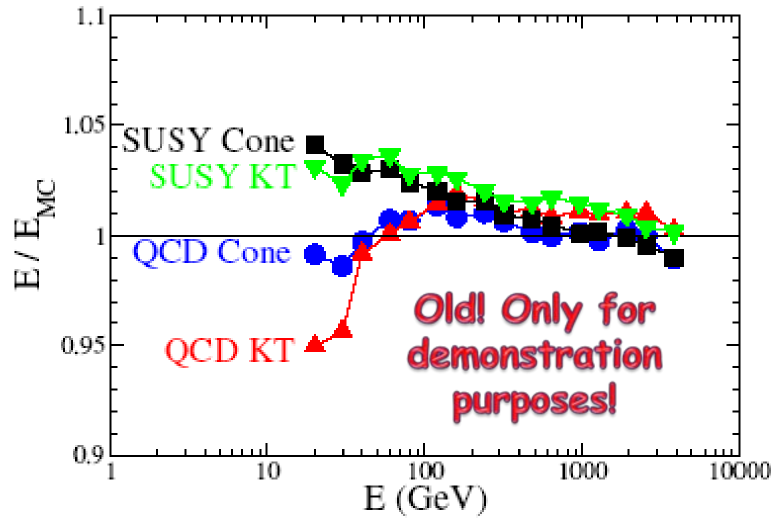
Any jet calibration needs to be validated

- First step is the initial **closure test** – apply the calibration to the same samples which were used to extract it
  - Residual (average) deviations from the expected or true jet energy should be small – can be considered a first input to the systematic error!
- Then apply calibration to jets in other topologies/physics channels and measure deviation from expected kinematics – this is the **validation**
  - Often done with simulated physics as they have an intrinsic truth reference (particle jets)
  - Samples with widely different topology than calibration sample preferred, possibly even several topologies

Understanding biases introduced in any given procedure is part of the validation

- Need to develop calibrations with least biases
  - Biases can be introduced by the use of simulations – physics model limitations, inappropriate calorimeter shower simulations and signal extraction modeling, …
  - Also experimental biases due to trigger and event selections changing shapes of distributions etc. – more later!
- Need to understand if small or hidden biases in calibration sample and chosen calibration model do not increase for other topologies
  - Calorimeter signal definition can introduce biases due to different sensitivities to noise, jet shape reconstruction,…



Some obvious procedural requirements

- Need the same signal treatment in data and simulation
  - Including the same jet finder and jet finder configuration
- Need to understand the detector data very well
  - Need to unfold all signal extraction inefficiencies and any detector problem
  - Can be done by including those into the simulated signal reconstruction (e.g. noise) or by developing corrections for the experimental data
- Need to understand the detector simulation very well
  - Signal defining electromagnetic and hadronic shower features need to be reproduced to highest possible precision

Jet reconstruction validation

- Compare basic performance measures for data and simulation
  - Signal linearity, relative energy resolution, jet shapes…
- Level of comparison is good estimate for systematic error of a given reconstruction and calibration
  - Assumes that simulation reflects state-of-art understanding of physics and detector
  - Lack of understanding (data is the "truth") then reflects measurement error

Ok, but…

- Still have not told you **how** simulation based jet calibration is really done!
  - Like to lay down the ground rules first!

Step Back: Calorimeter Signals

Need to have another look at the calorimeter

- Basically all calorimeters at collider experiments show some level of non-compensation
  - For sure the ones in ATLAS and CMS are!
- Needs to be corrected for jet calibration
  - And all other hadronic final state contributions like isolated hadrons, tau-leptons, and low pT hadronic signals
- Can this be done for highest spatial calorimeter granularity (cells)?
  - Not easy to see – individual cell signal without any other context hard to calibrate in non-compensating calorimeters
- Better to establish a larger context first to find out which calibration the calorimeter cell signal needs
  - Reconstructed jet itself – in ATLAS this is called **Global Calibration**
  - Topological cell clusters without jet context – in ATLAS this is called **Local Calibration**
- Cannot recommend to use cells directly to find jets:
  - High multiplicity on input for jet finders
  - Negative signal treatment required for four-momentum recombination
    - Noise can create E<0 in cells
  - Jets should consistent of significant (relevant) signal objects
    - Cell signal not a good image of the particle flow in jets
- Larger calorimeter signal objects clearly preferred
  - **Towers** of cells – add cell signal up in projective calorimeter towers
  - Topological **clusters** of cells – add cell signals following signal correlations in showers

Calorimeter Towers

Impose a regular grid view on event

- $\Delta\eta \times \Delta\varphi = 0.1 \times 0.1$ grid
- Motivated by particle Et flow in hadron-hadron collisions
- Well suited for trigger purposes

Collect cells into tower grid

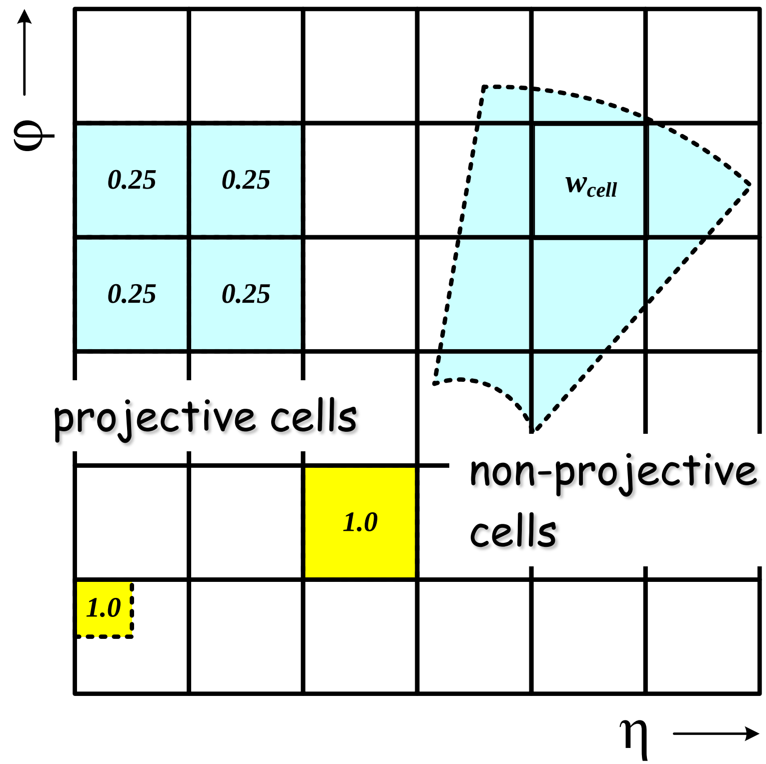
- Cells signals can be summed with geometrical weights
  - Depend on cell area containment ratio
  - Weight = 1 for projective cells of equal or smaller than tower size
- Summing can be selective
  - Noise filter can be applied!

Towers have massless four-momentum representation

- Fixed direction given by geometrical grid center

$$\left(E_{\eta\varphi},\eta,\varphi\right) \mapsto \left(E = p, p_x, p_y, p_z\right)$$

$$p = \sqrt{p_x^2 + p_y^2 + p_z^2}$$



$$E_{\eta\varphi} = \sum_{\left(A_{\text{cell}}^{\eta\varphi} \cap A_{\eta\varphi}\right) \neq 0} w_{\text{cell}} E_{\text{cell}}$$

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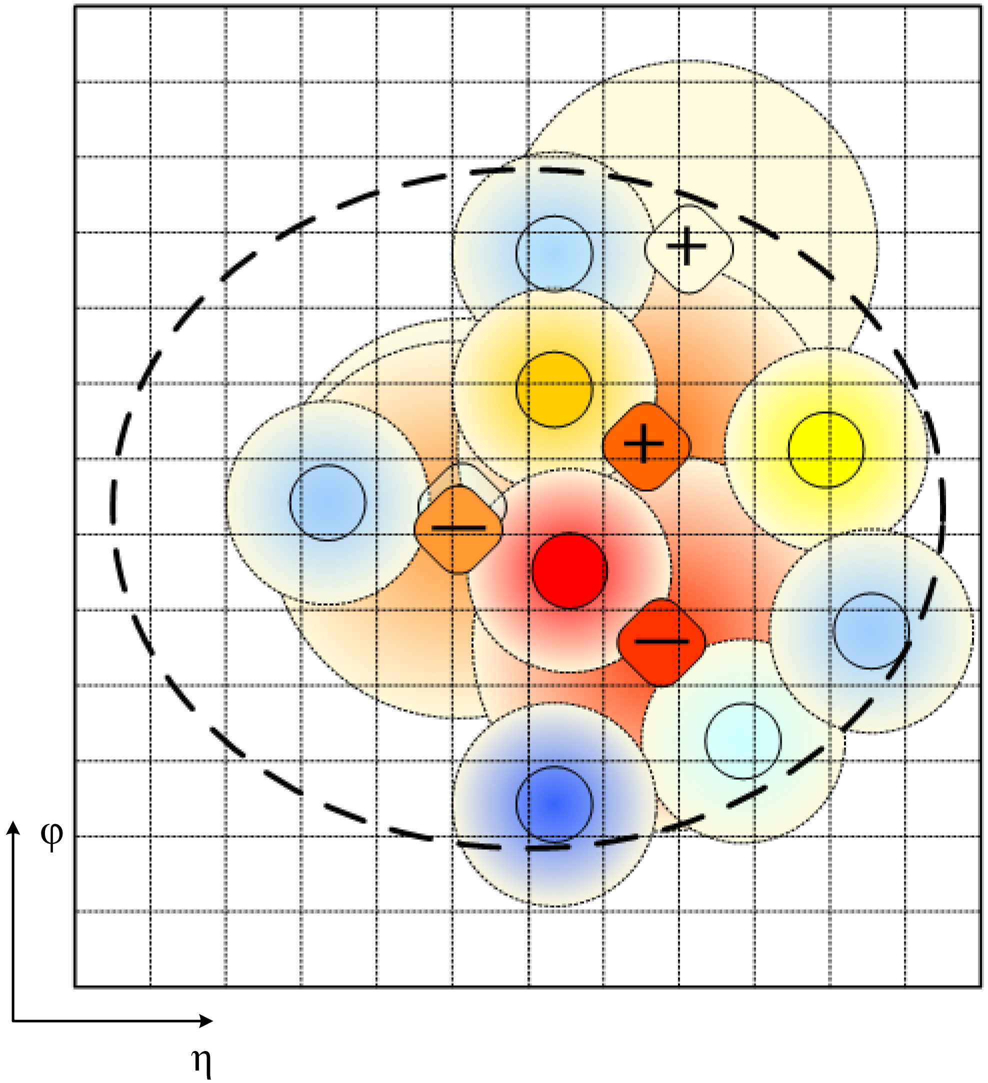

Calorimeter Towers

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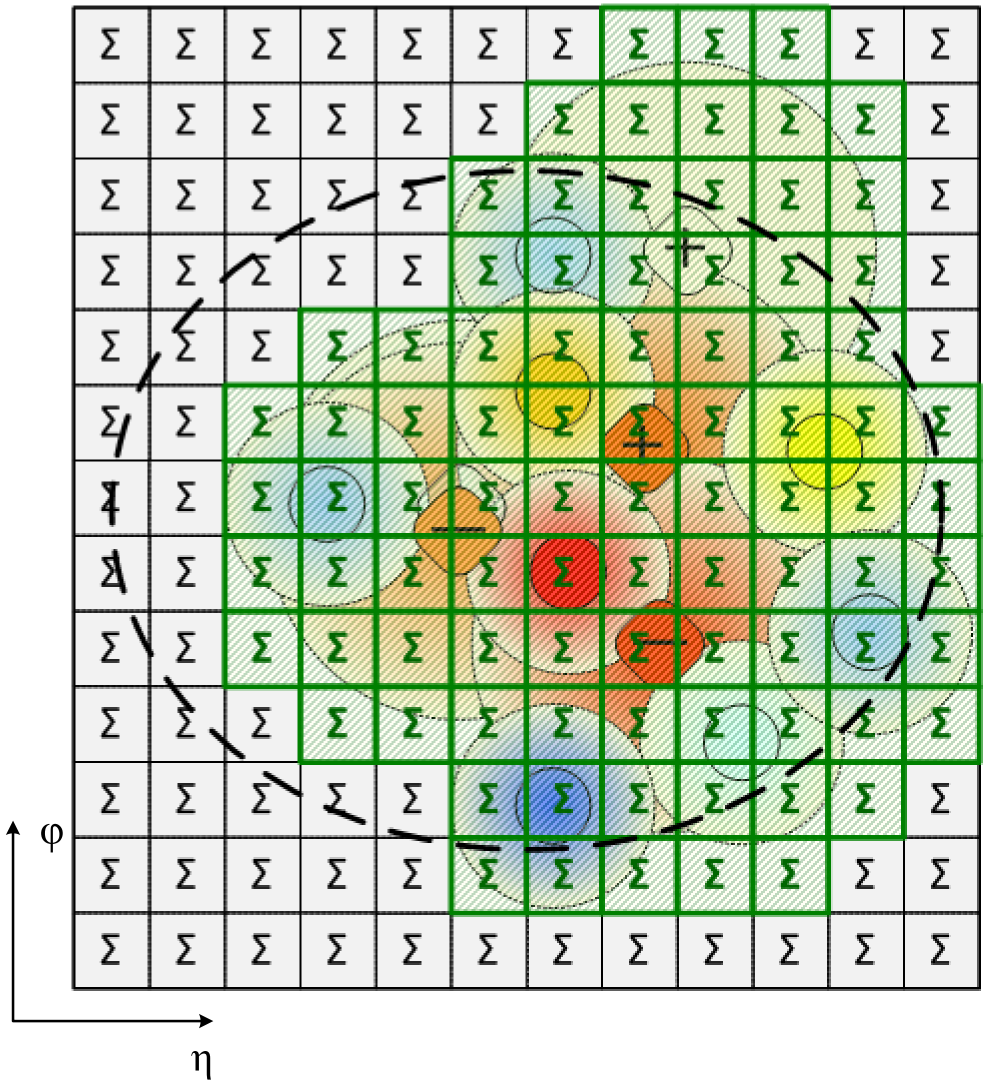

Calorimeter Towers: Sum Rules

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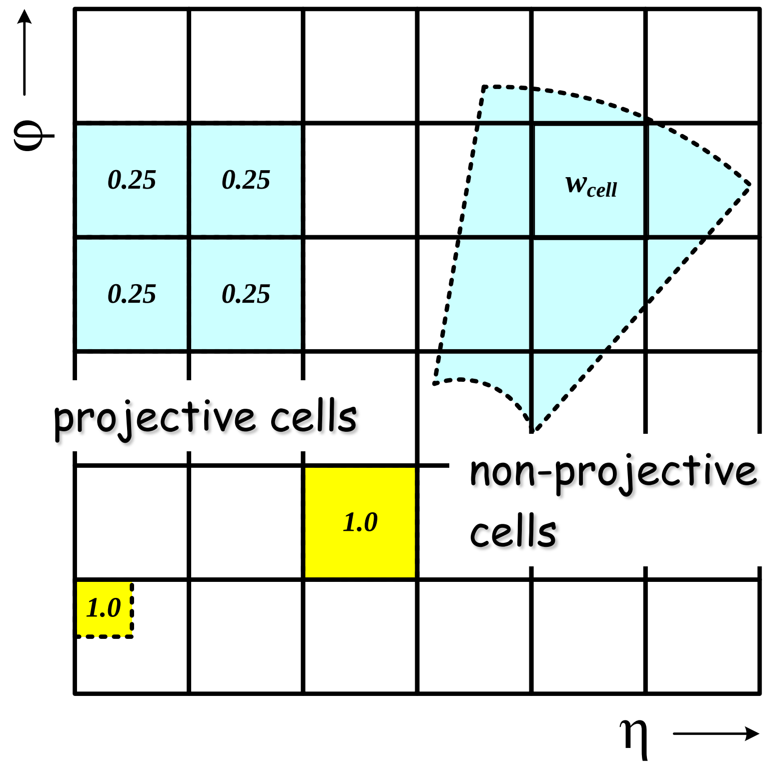

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More On Calorimeter Towers

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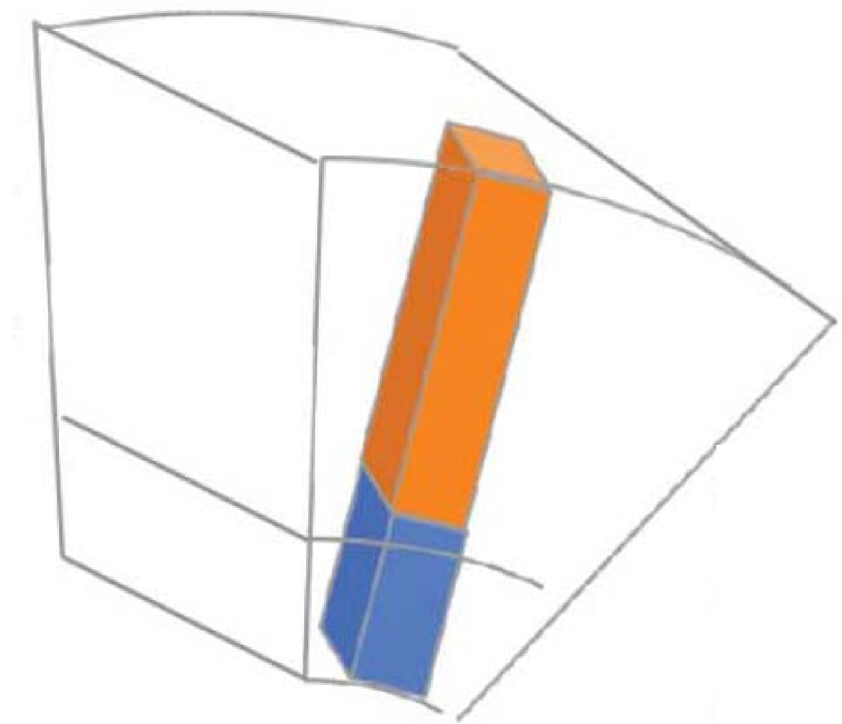
Signal integration

- Towers represent longitudinally summed cell signals
  - 2-dimensional signal objects
  - Can include partial and complete signals from several particles
- Towers can preserve more detailed signal features
  - Associated information to be collected at tower formation
  - E.g., energy sharing in electromagnetic and hadronic calorimeters
  - Longitudinal signal center of gravity

Signal splitting

- Towers can split signal from single particles
  - Hadronic shower width can be larger then tower bin, especially at higher pseudo-rapidity
  - Can cause problems with infrared safety
- Can cause problems for seeded jet finders
  - Collateral instability
- Can lead to lost signals cone-like jets
  - Energy in tower bins outside of jet can belong to particle signal in jet

(drawing by K. Perez, Columbia University)



Unbiased calorimeter tower is a "slab" of energy in a regular pseudorapidity-azimuth grid (each tower covers the same area in these coordinates)

Topological Cell Clusters

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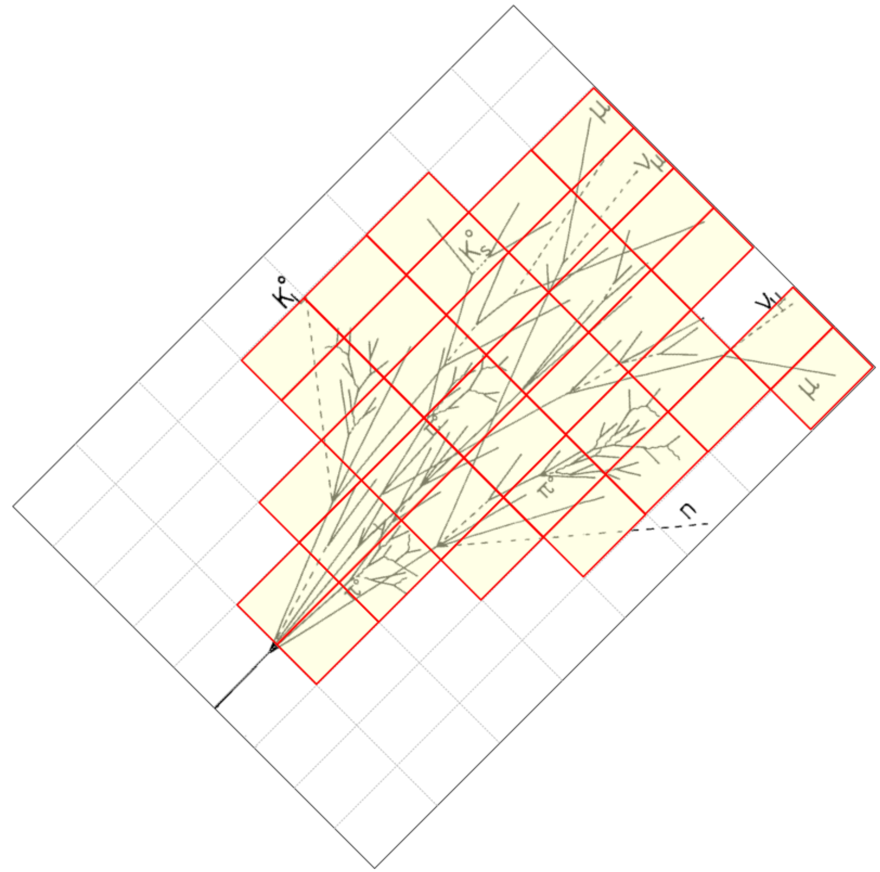
Collect cell into energy "blobs"

- Idea is to collect all cell signals belonging to a given particle into one cluster of cells
  - Basically reconstruct the shower for each particle entering the calorimeter
- Needs algorithm to form energy blobs at the location of the shower signal in the calorimeter
  - Follow the shower-induced cell signal correlations



Extract most significant signal from all calorimeter cells

- Cluster formation uses signal significance as guidance
  - Not the total signal – noise changes from calorimeter region to calorimeter region
- Implicit noise suppression in cluster formation
  - Cluster signals should include least amount of noise

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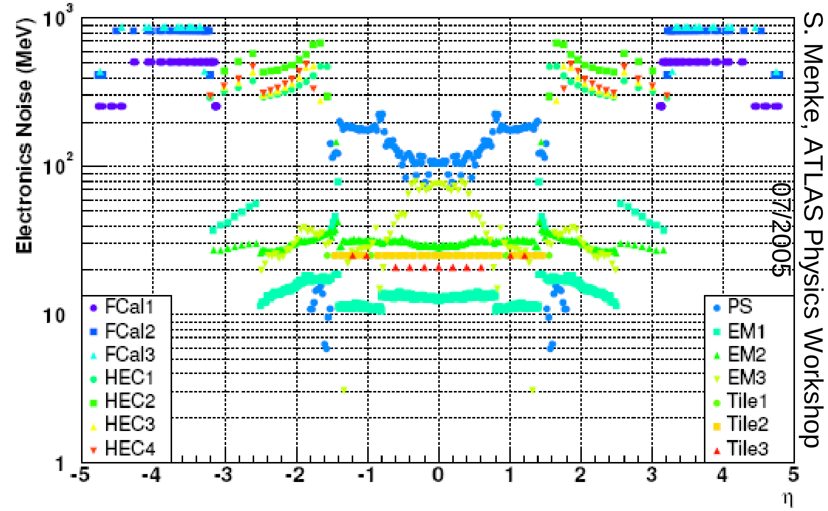
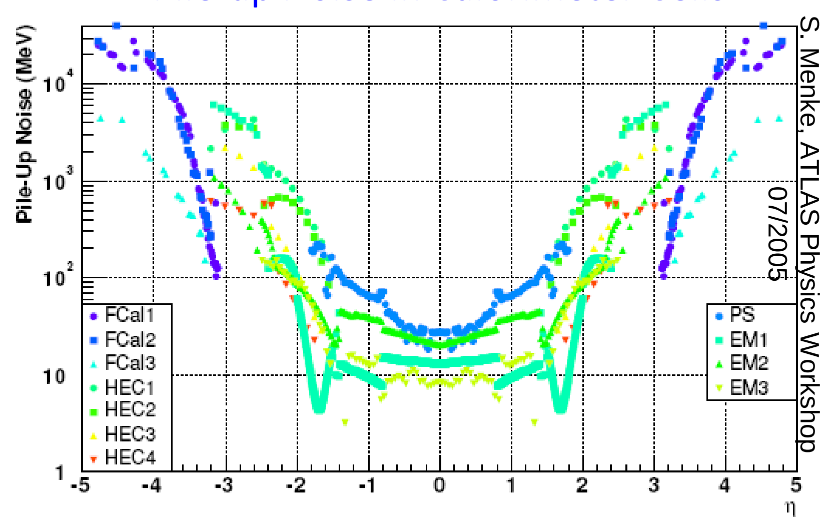
Electronic Noise in Calorimeter Cells



Pile-up Noise in Calorimeter Cells



Cluster seeding

- Defined by signal significance above primary threshold
  - Cells above this threshold can seed cluster

Cluster growth

- Defined by signal significance above secondary threshold
  - Cells neighbouring seeds with significance above this threshold drive cluster growths

Cluster signal

- Defined by cells with significance above basic threshold
  - Cells to be considered in cluster energy sums

Use of negative signal cells

- Thresholds are considered for the absolute (unsigned) signal magnitude
  - Large negative signals can seed and grow clusters

Parameters for each stage optimized with testbeam data

- Experimental single pion shower shapes guide cluster algorithm development
  - Clean tuning reference!

Primary threshold

$$\left|\frac{E_{\text{cell}}}{\sigma_{\text{cell}}}\right| > S, \text{ default } S = 4$$

Secondary threshold

$$\left|\frac{E_{\text{cell}}}{\sigma_{\text{cell}}}\right| > N, \text{ default } N = 2$$

Collecting

$$\left|\frac{E_{\text{cell}}}{\sigma_{\text{cell}}}\right| > P, \text{ default}$$

$$P = 2$$

(note $S \geq N \geq P$)

Famous "4/2/0" clustering in ATLAS

ATLAS Topological Cell Clustering

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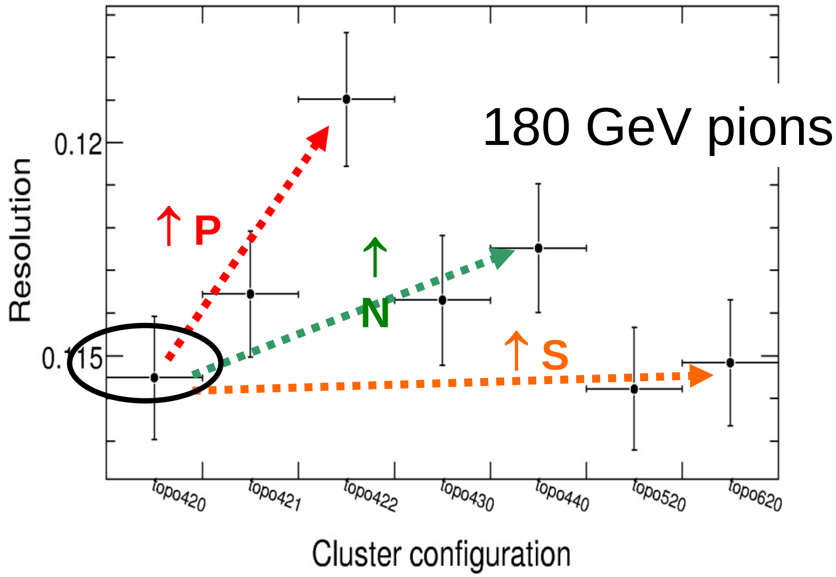
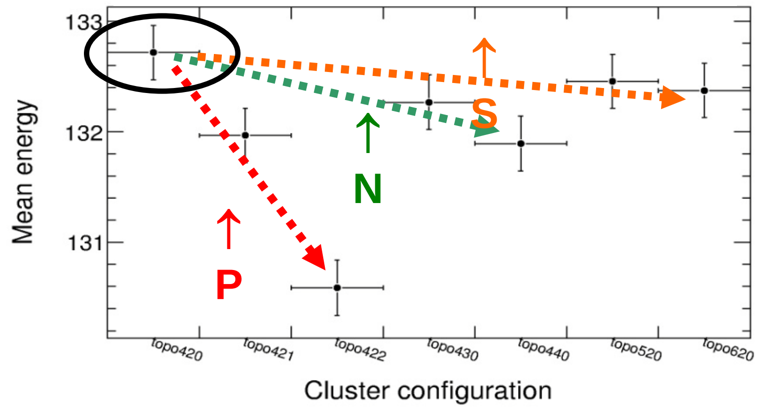


Mean of Sum E_{clus}



Clustering Algorithms

1. **Find cell with most significant seed over primary threshold *S***
2. **Collect all cells with significance above basic threshold *P***
   - Consider neighbours in three dimensions
     - Defined by (partly) shared area, (partly) shared edge, or shared corner point
     - E.g., 26 neighbours for perfectly cubed volumes of equal size
   - Neighbours can be in other calorimeter regions or even other calorimeter sub-systems
     - Granularity change to be considered in neighbouring definition
3. **For all cells neighbouring seeds with signal significance above secondary threshold *N*, collect neighbours of neighbours if their signal significance is above *P***
   - Same rules as for collection around primary seed
4. **Continue until cluster does not grow anymore**
   - Automatically generate “guard ring” of small signal cells at cluster margin
     - In three dimensions, of course
5. **Take next not yet used seed cell and collect next cluster**

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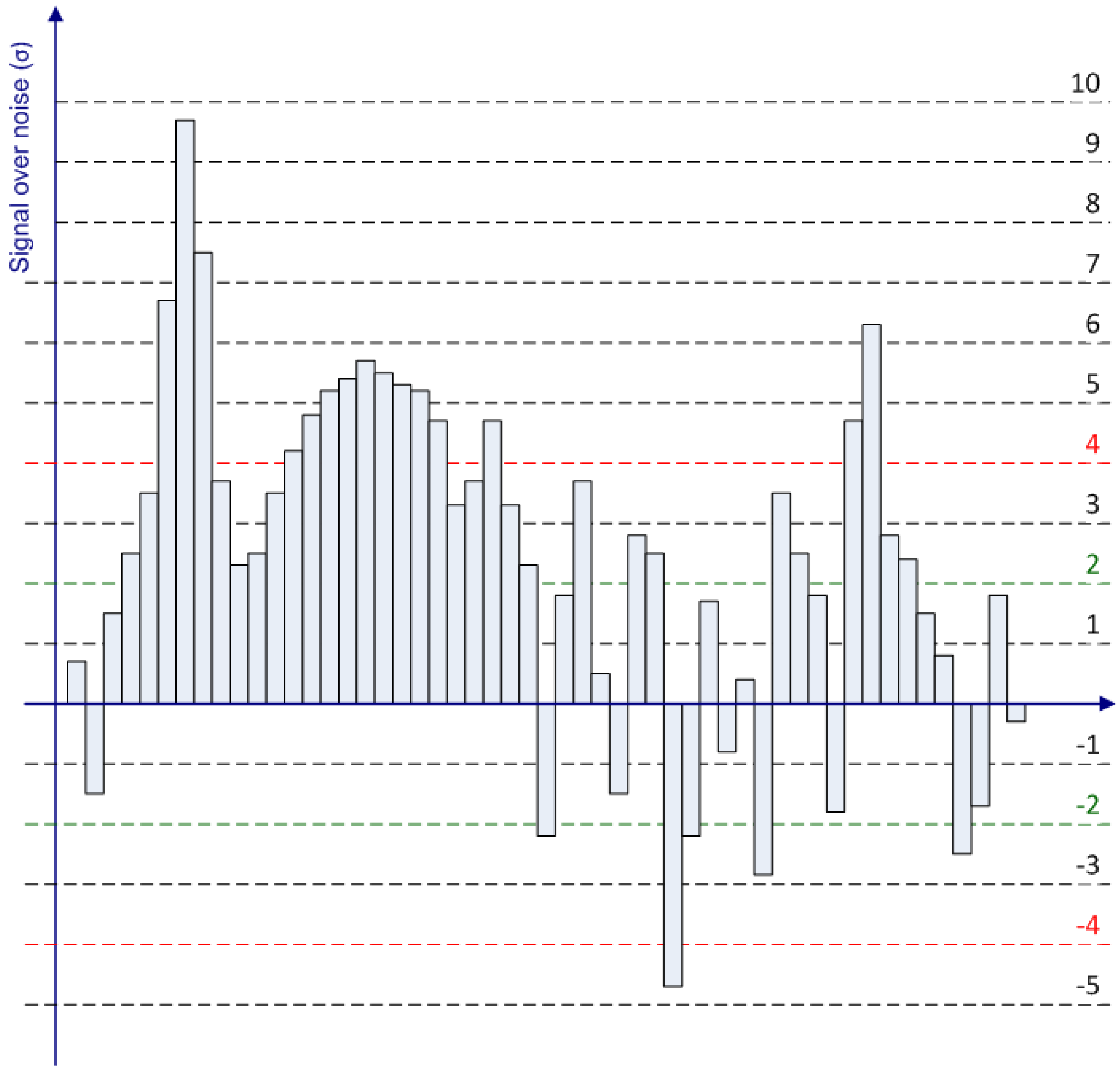
Clustering Example



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Clustering Example

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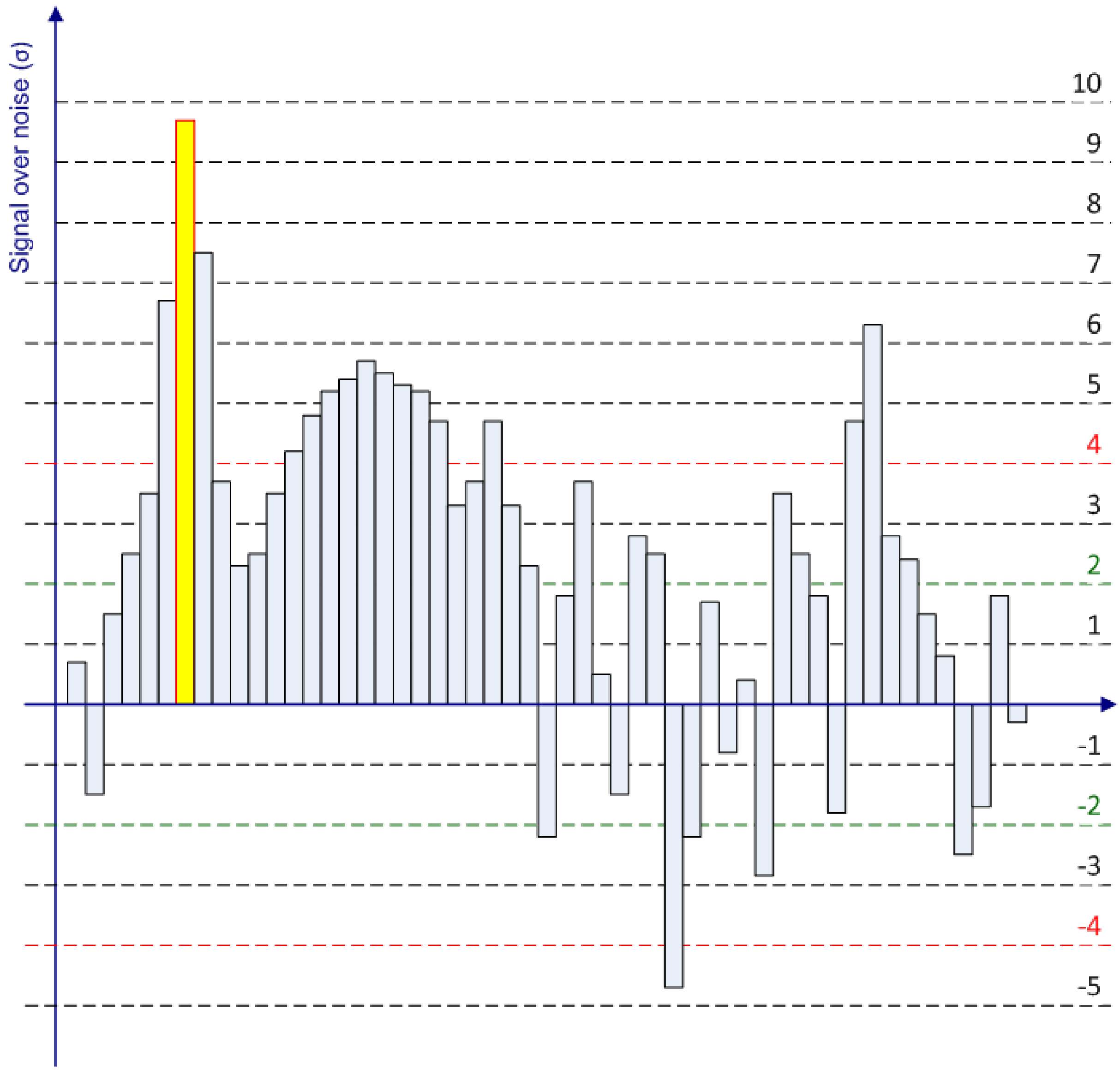

ATLAS

Clustering Example

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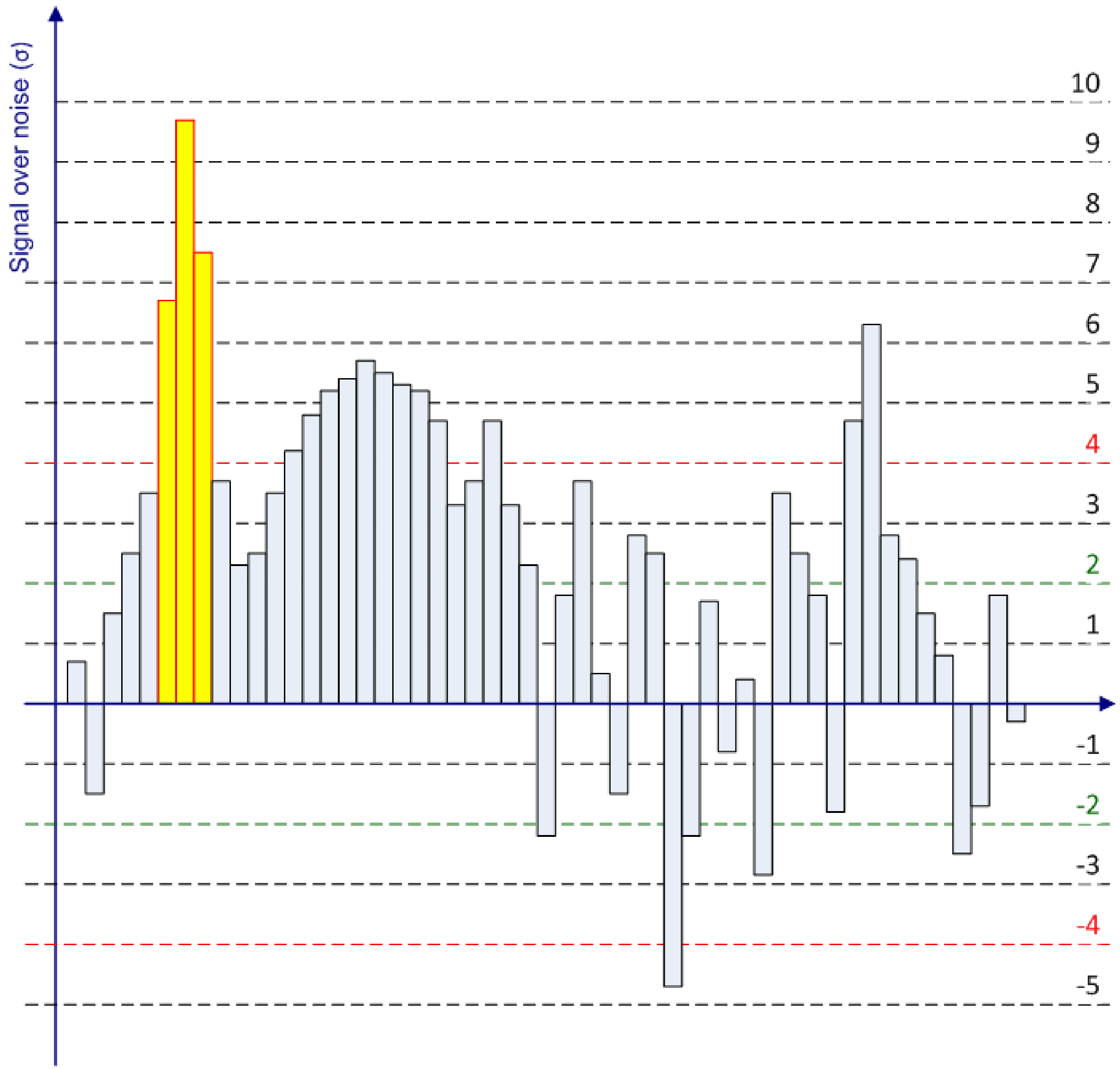

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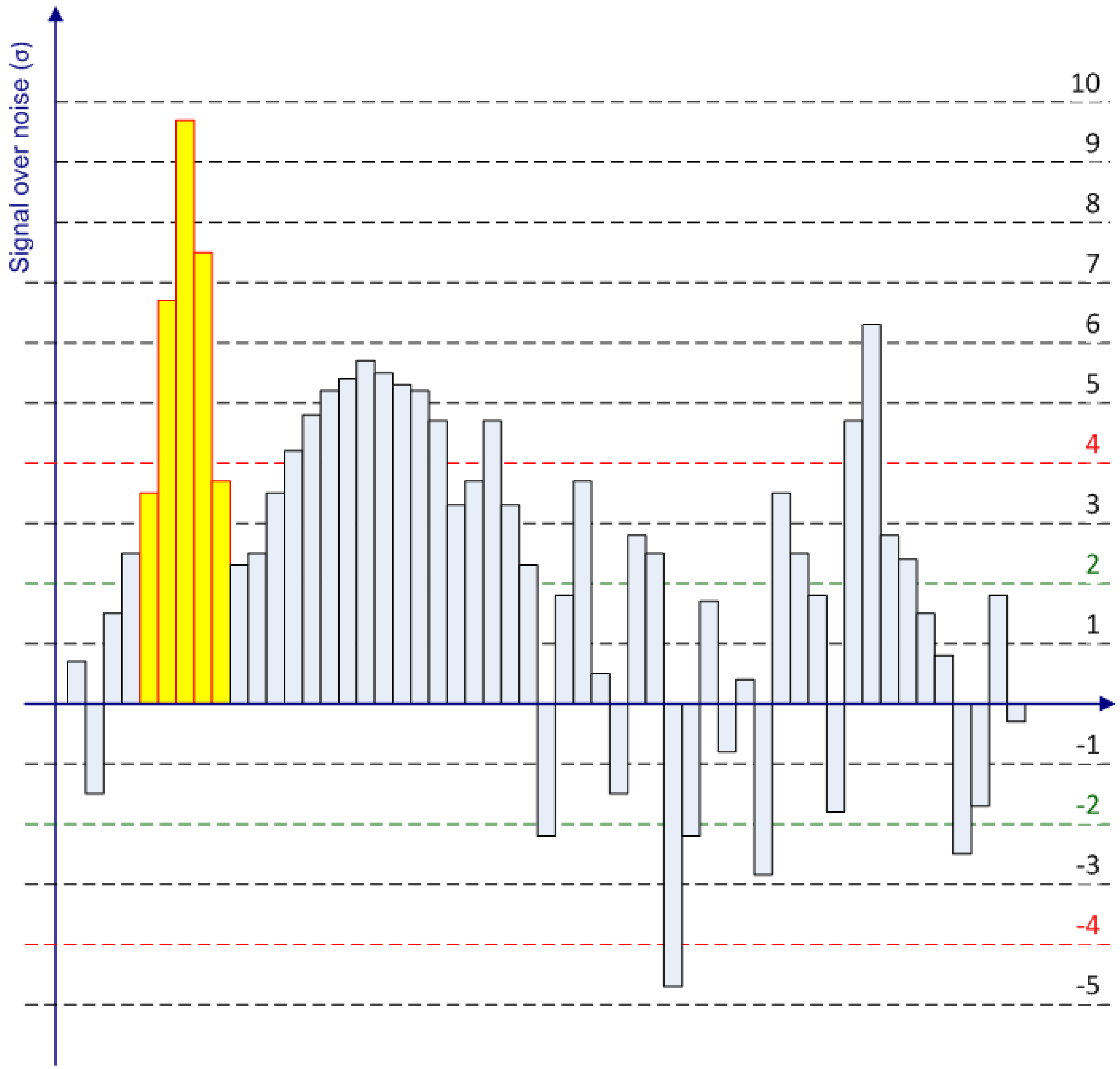

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Clustering Example

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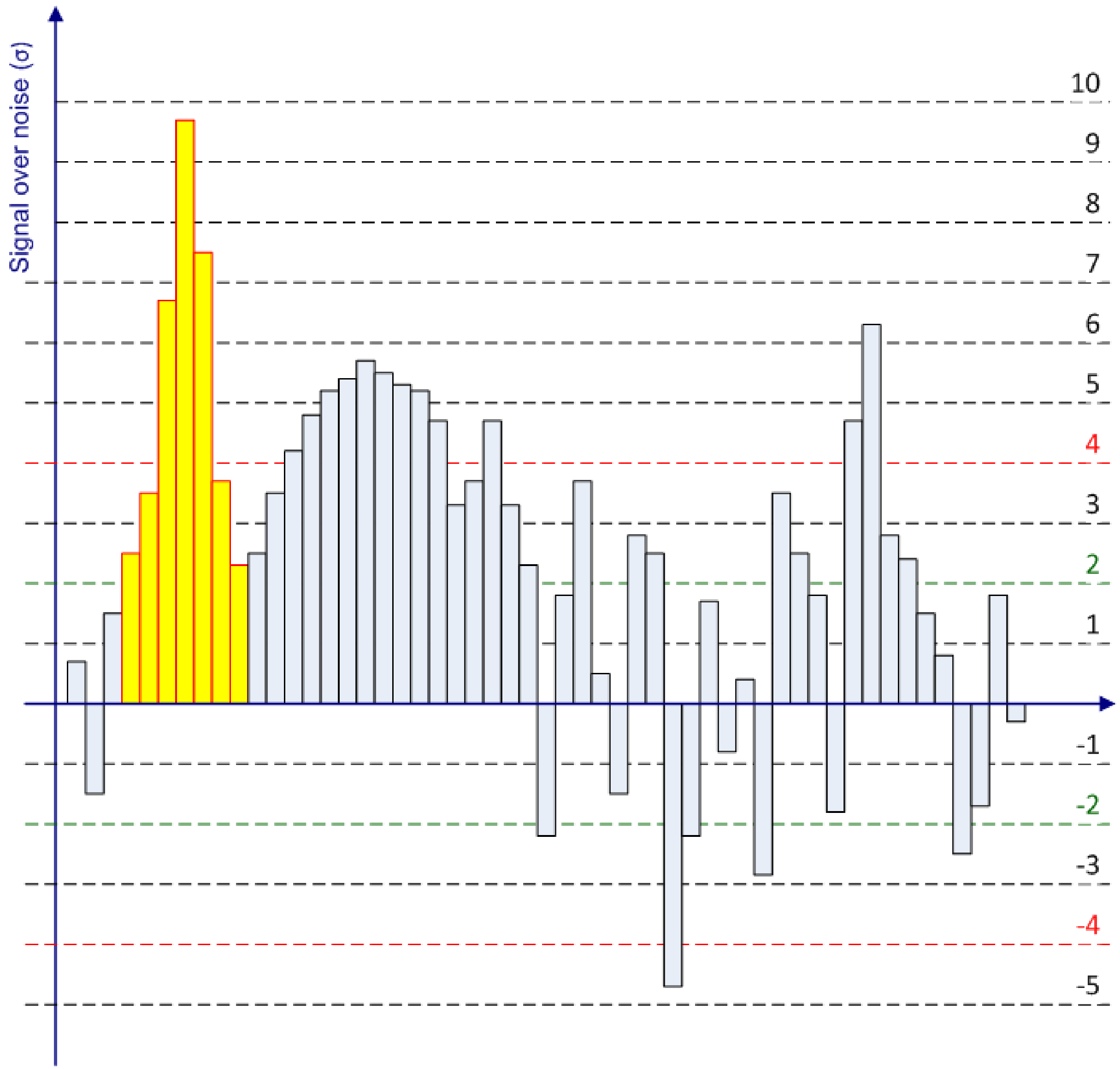

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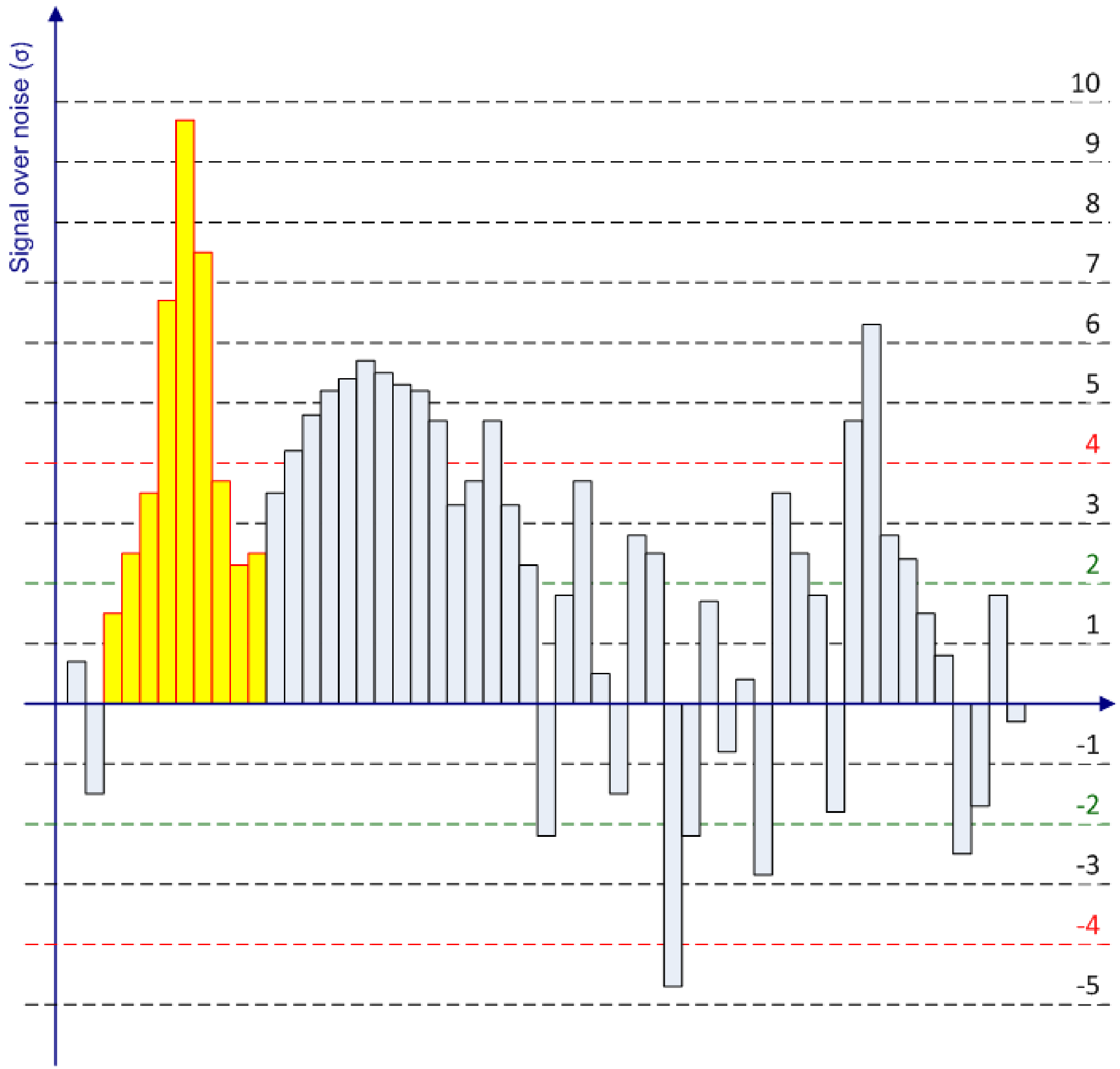

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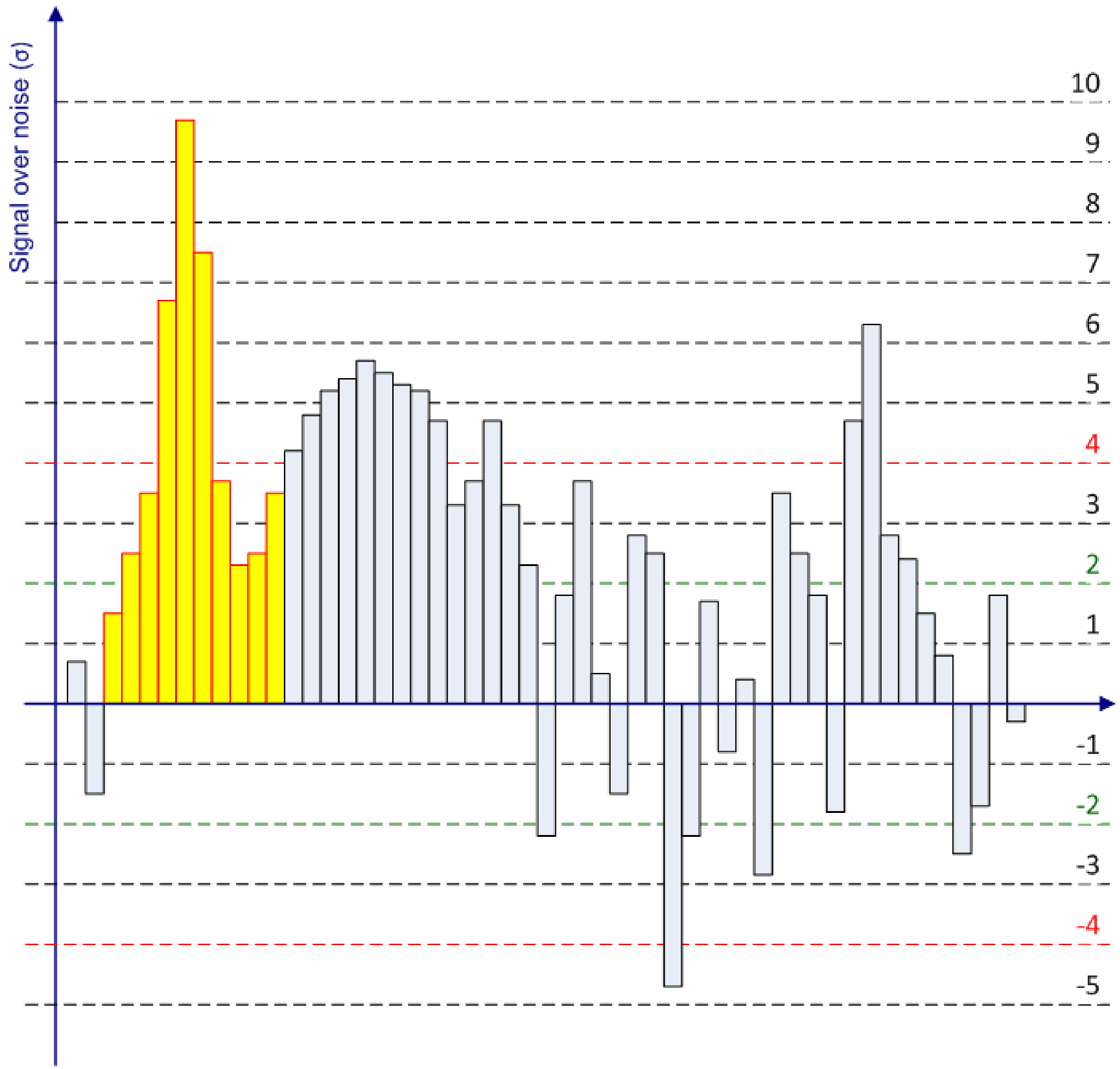

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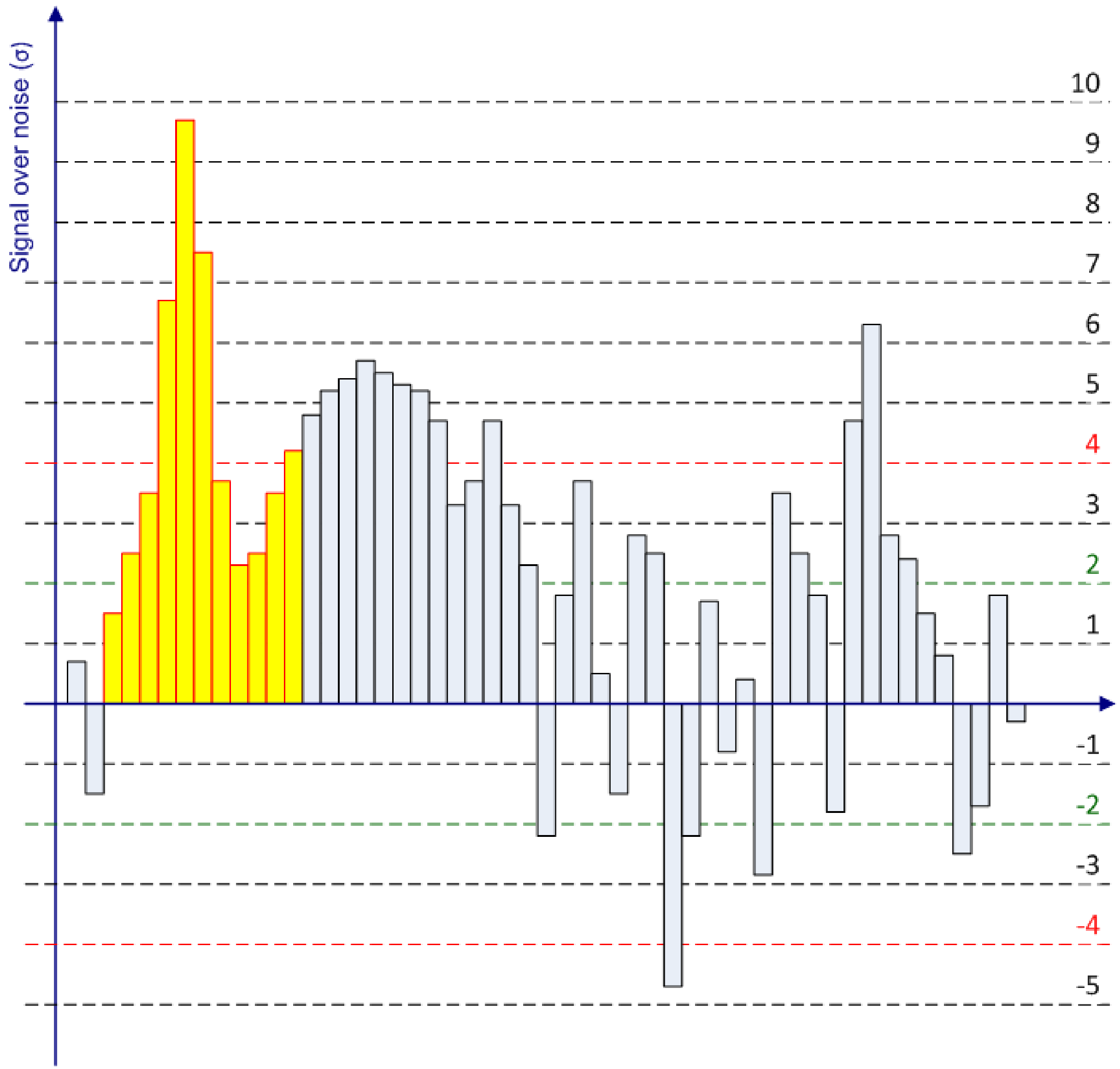

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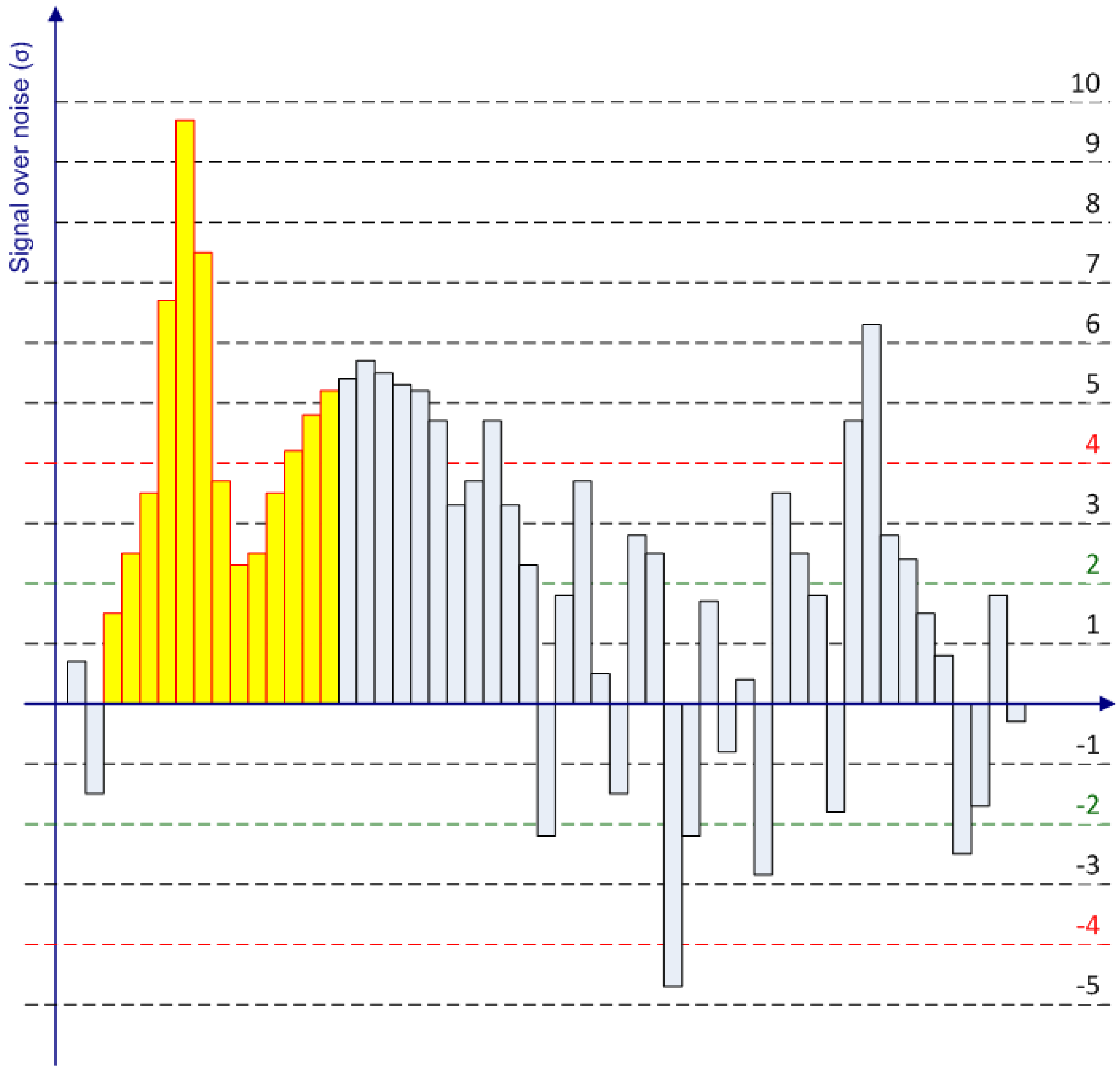

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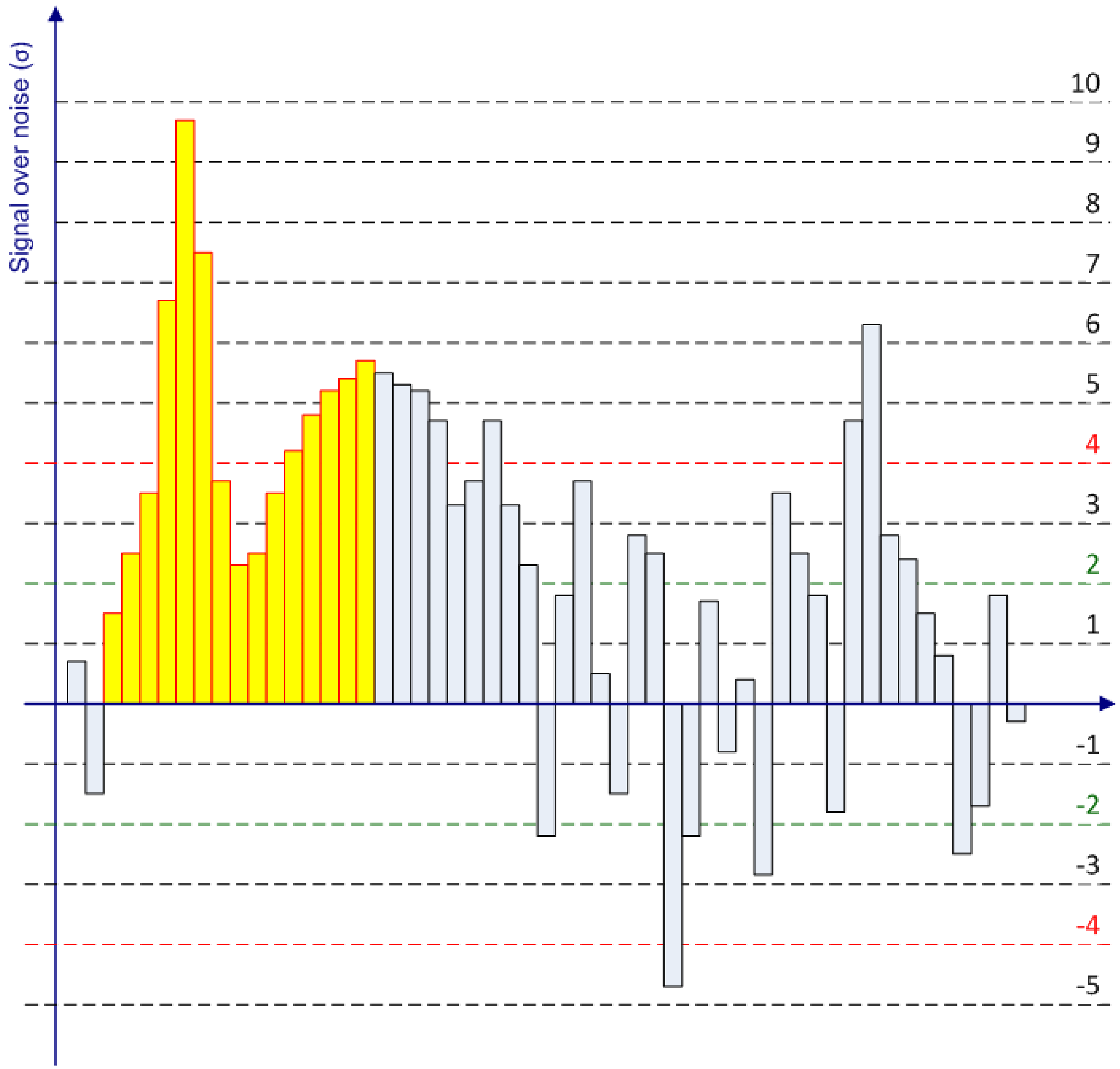

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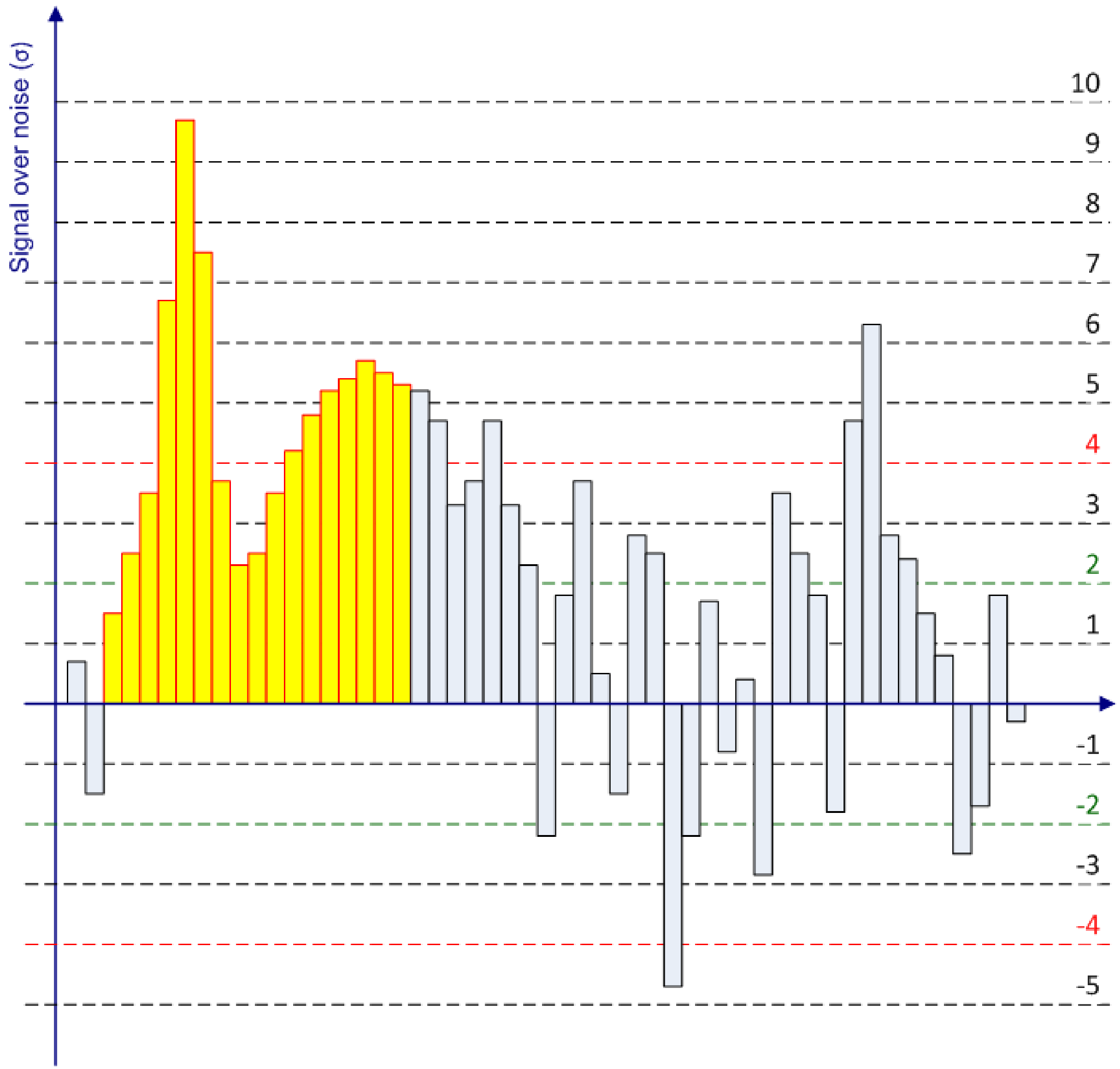

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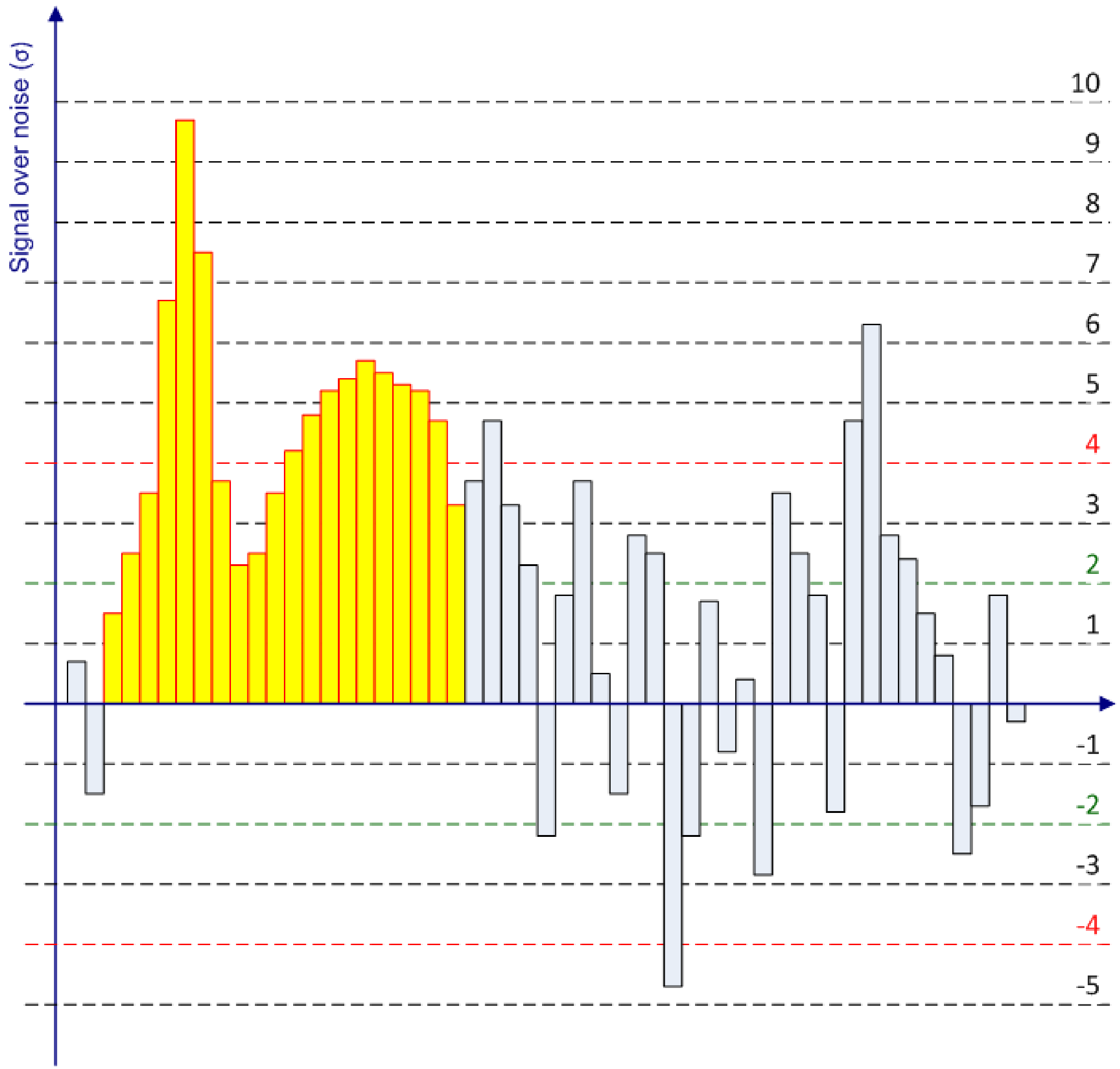

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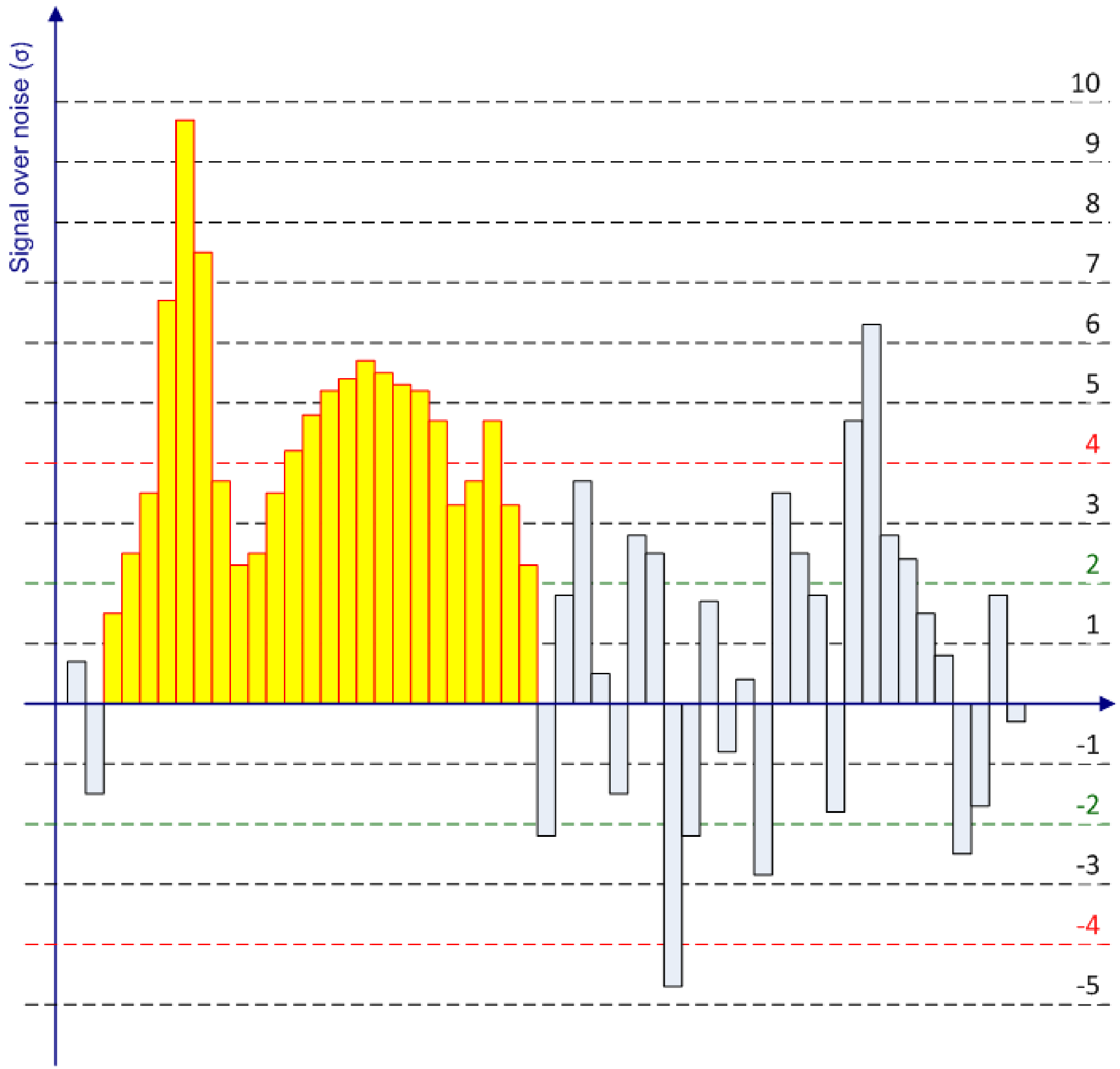

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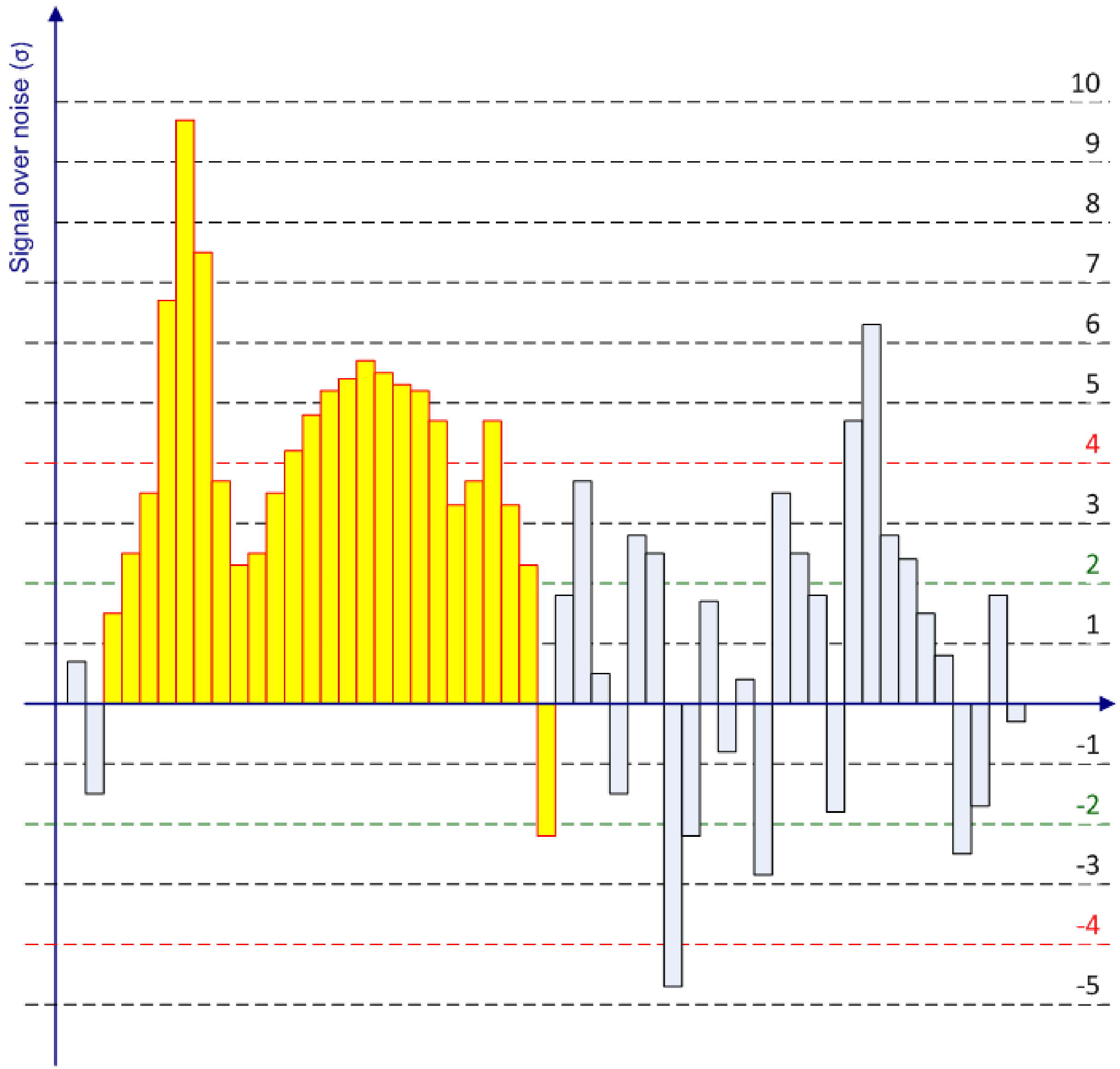

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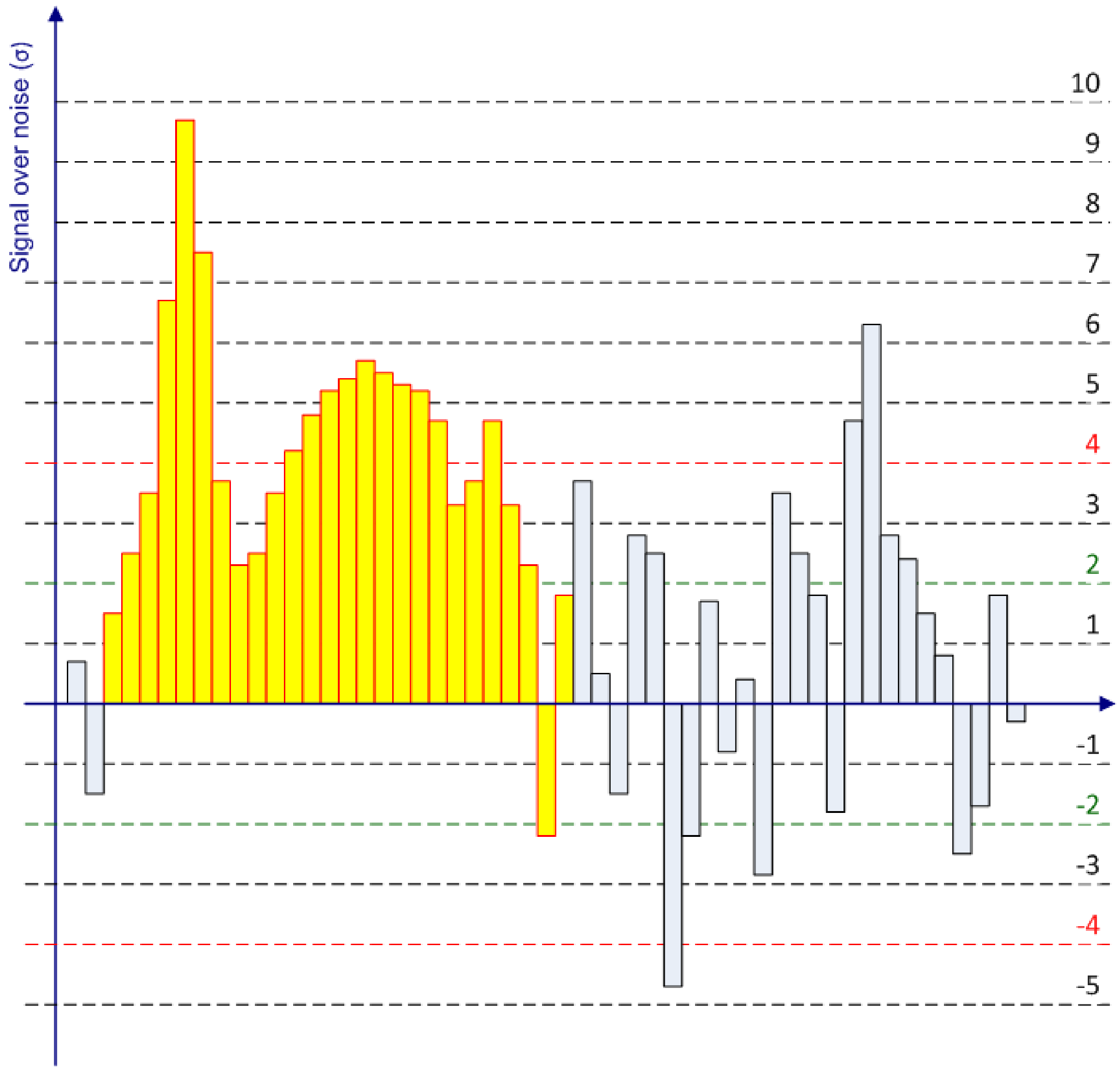

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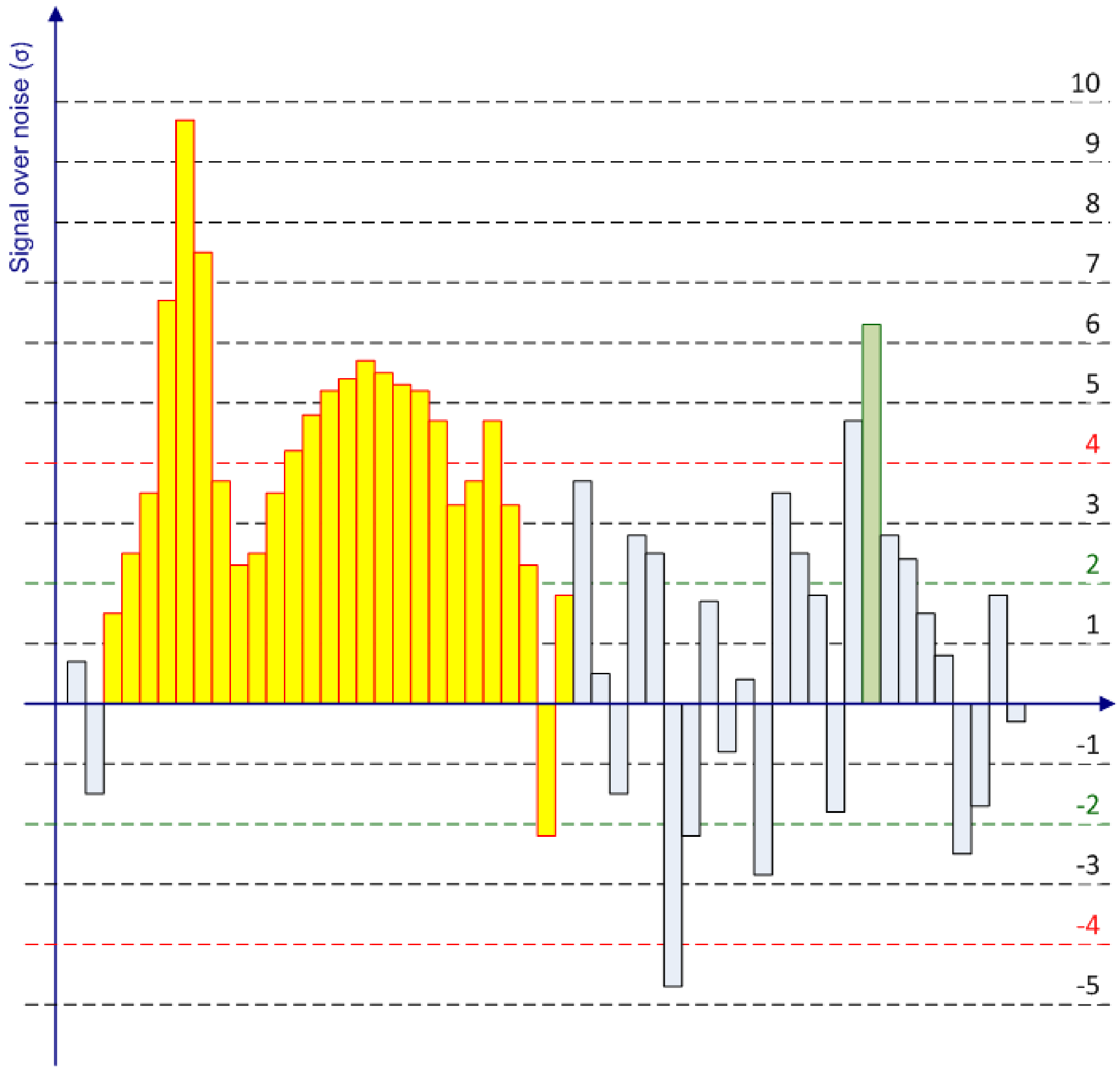

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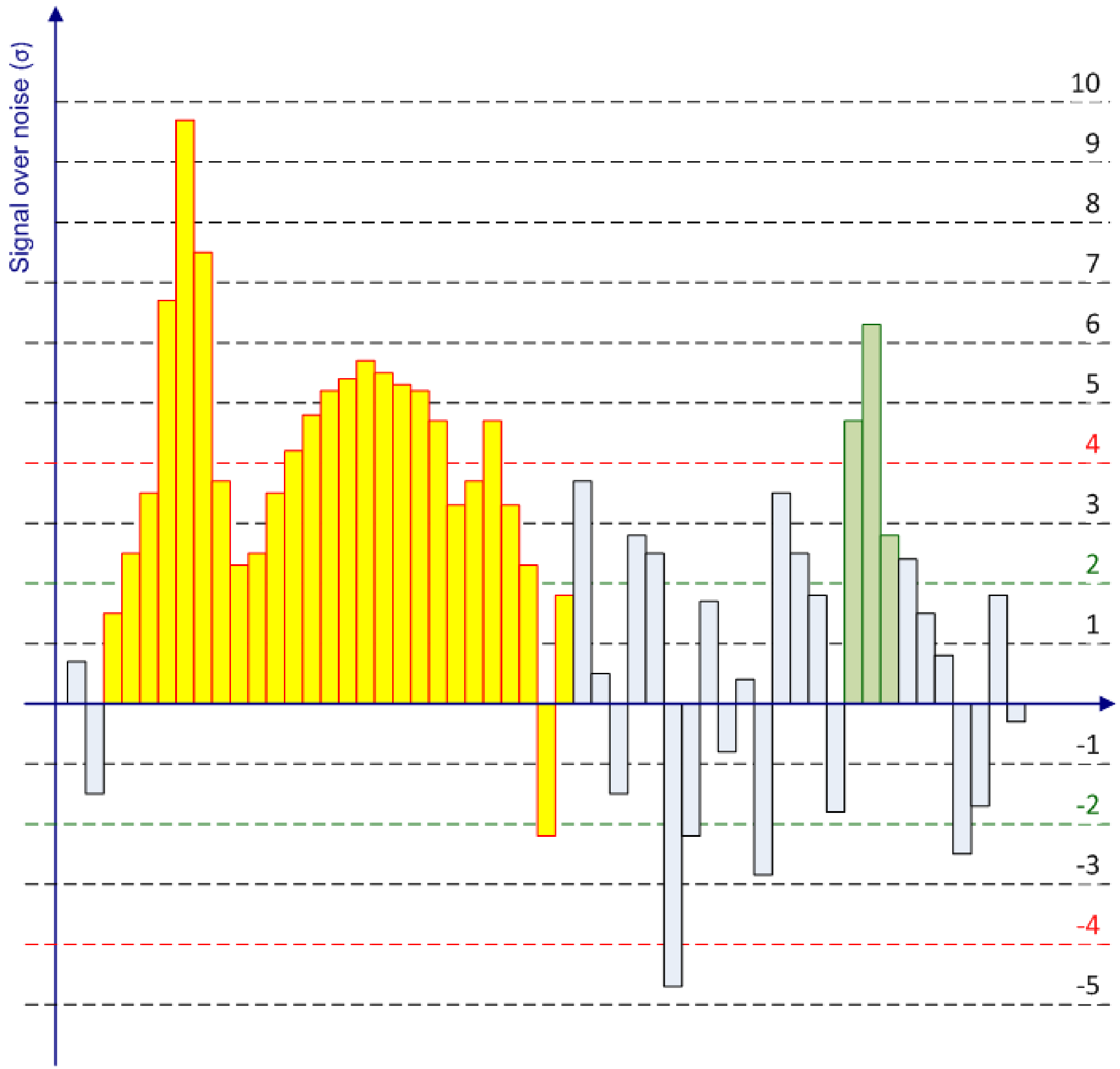

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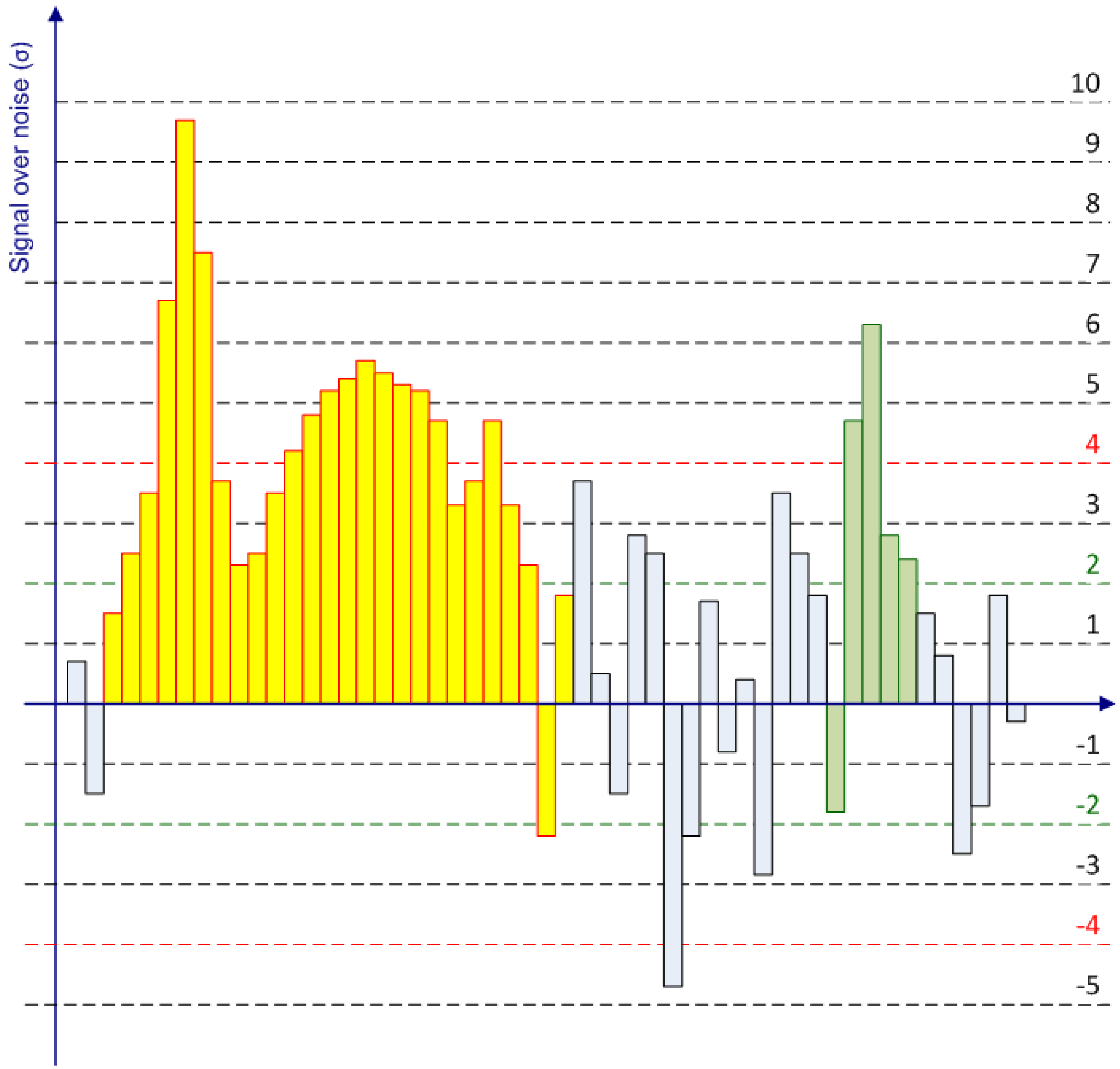

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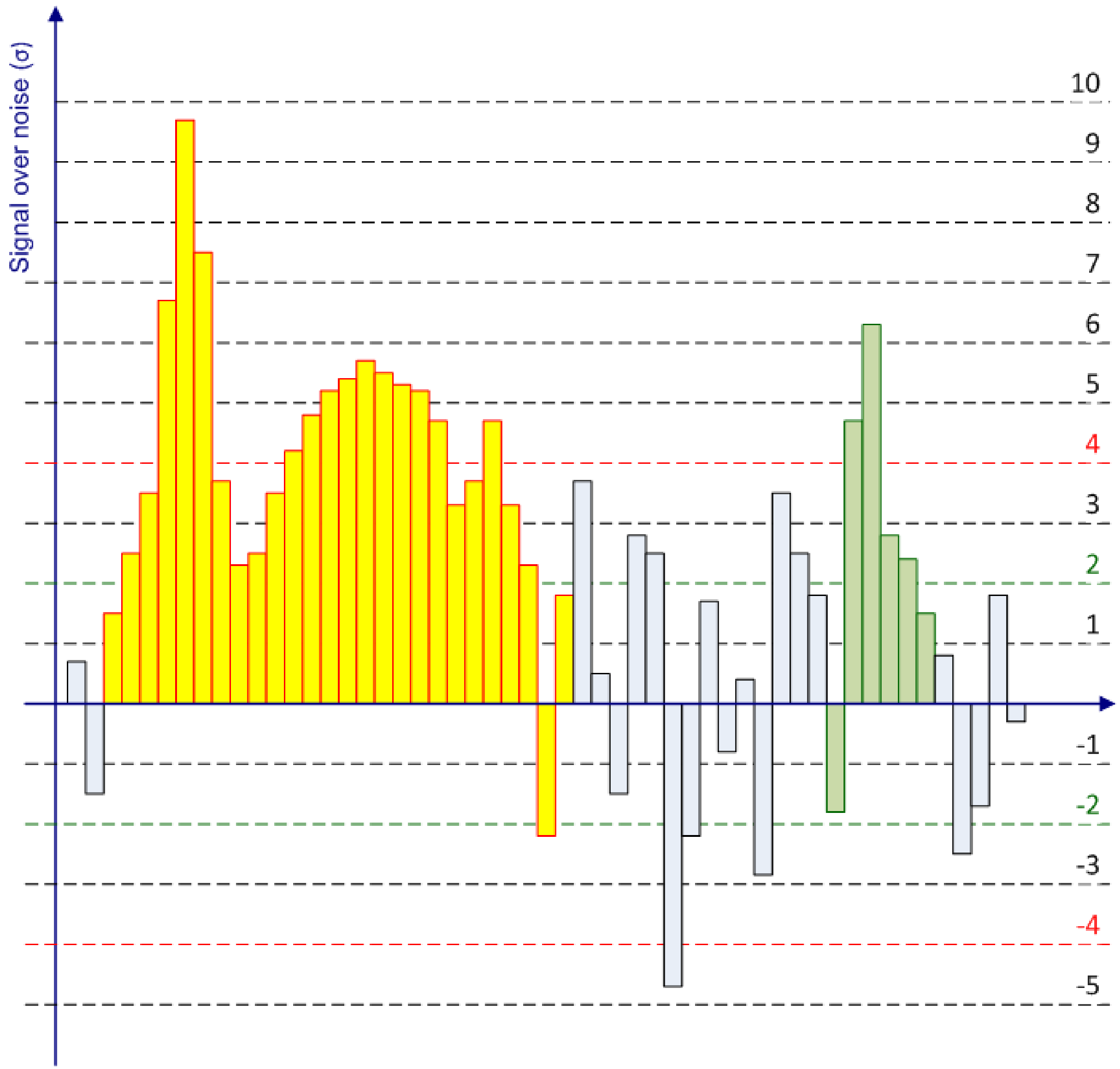

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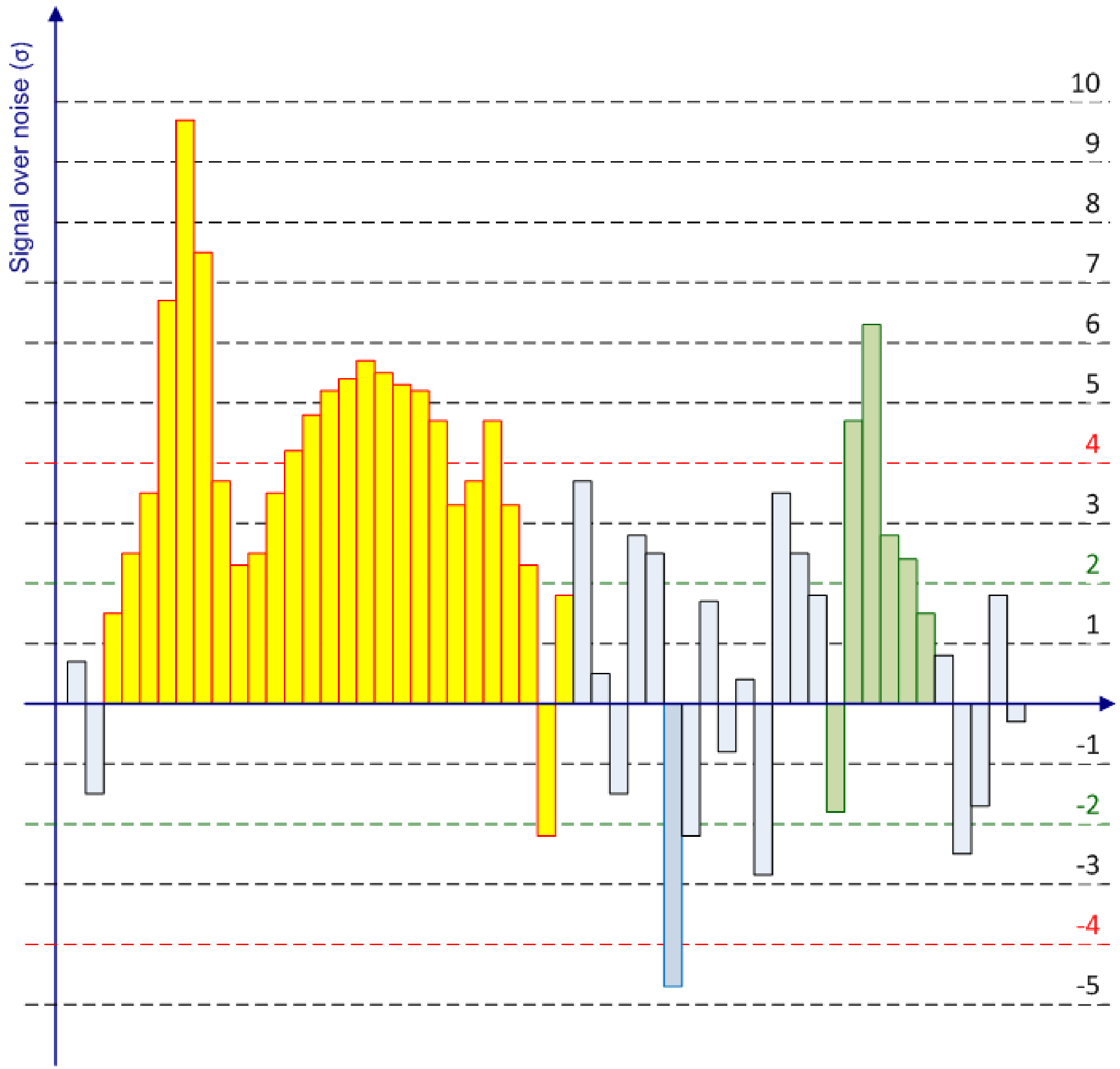

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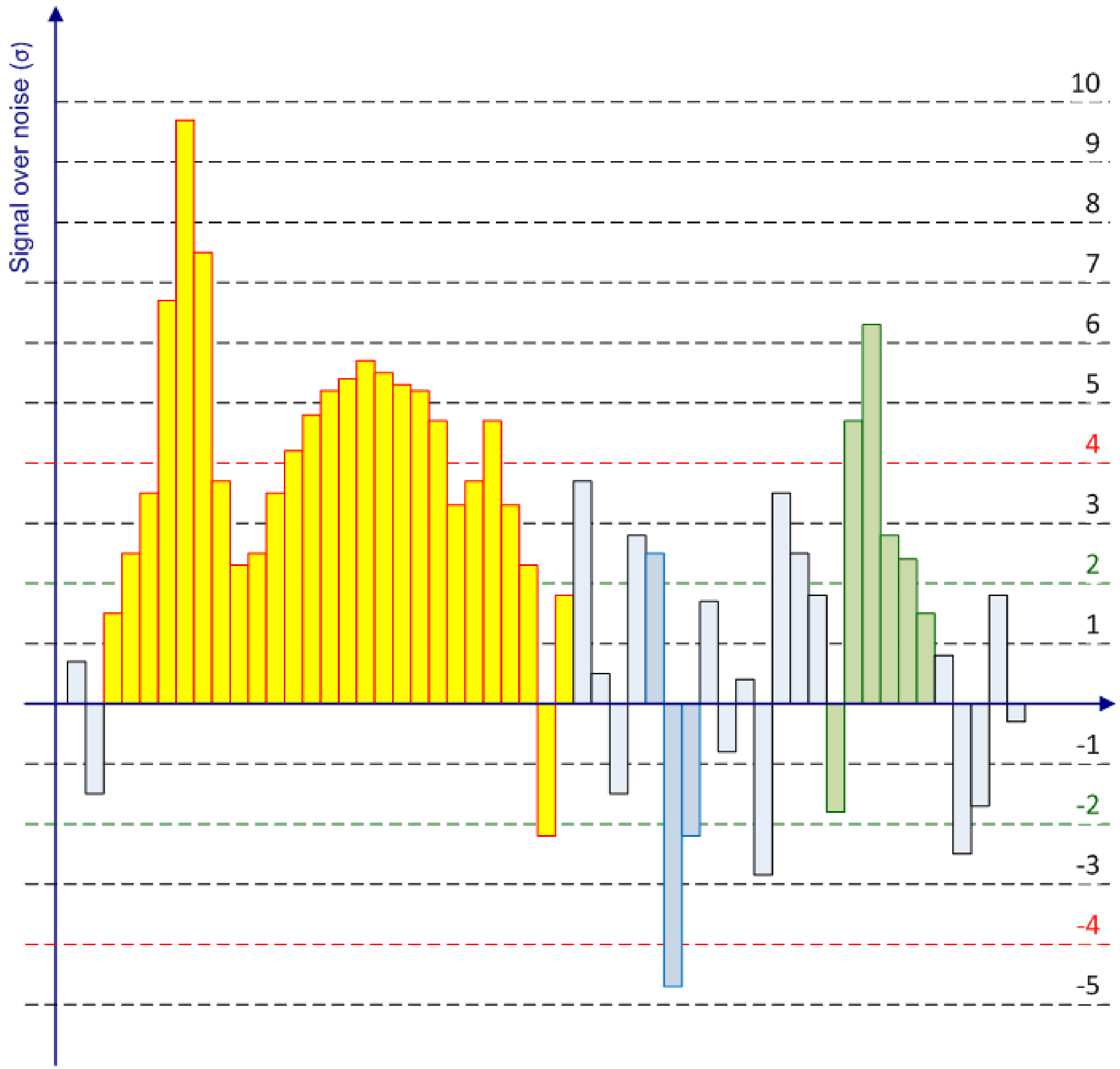

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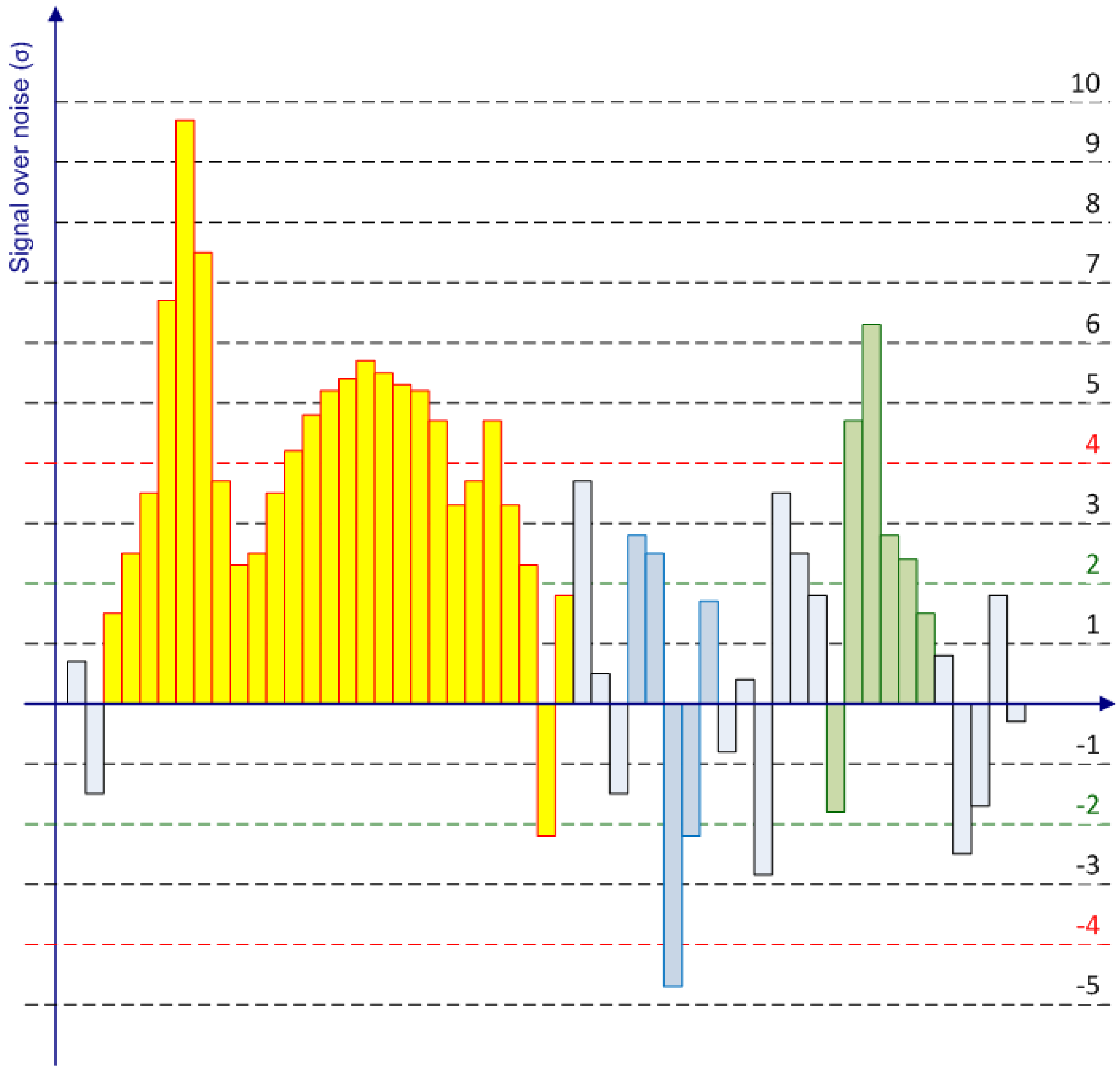

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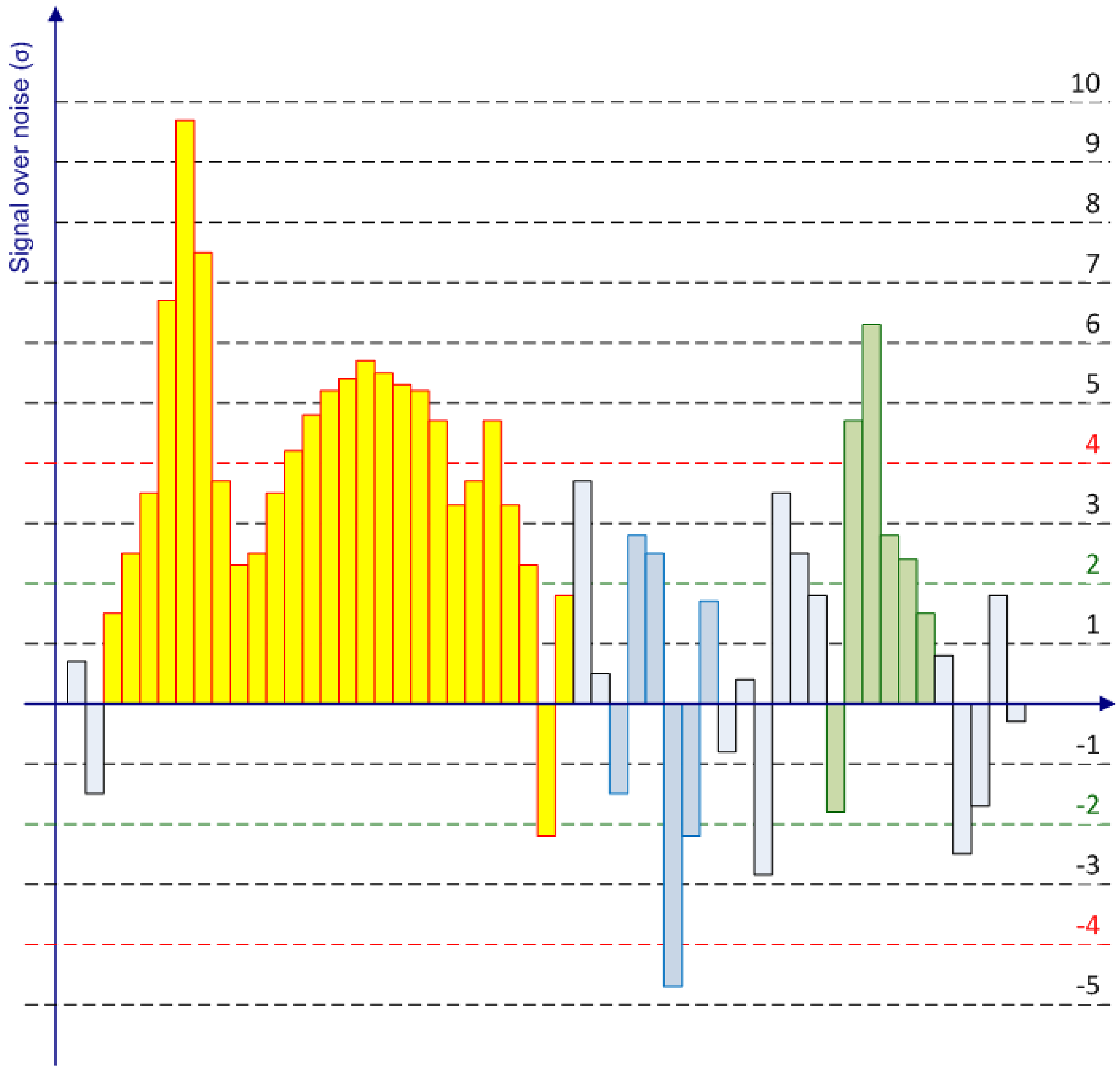

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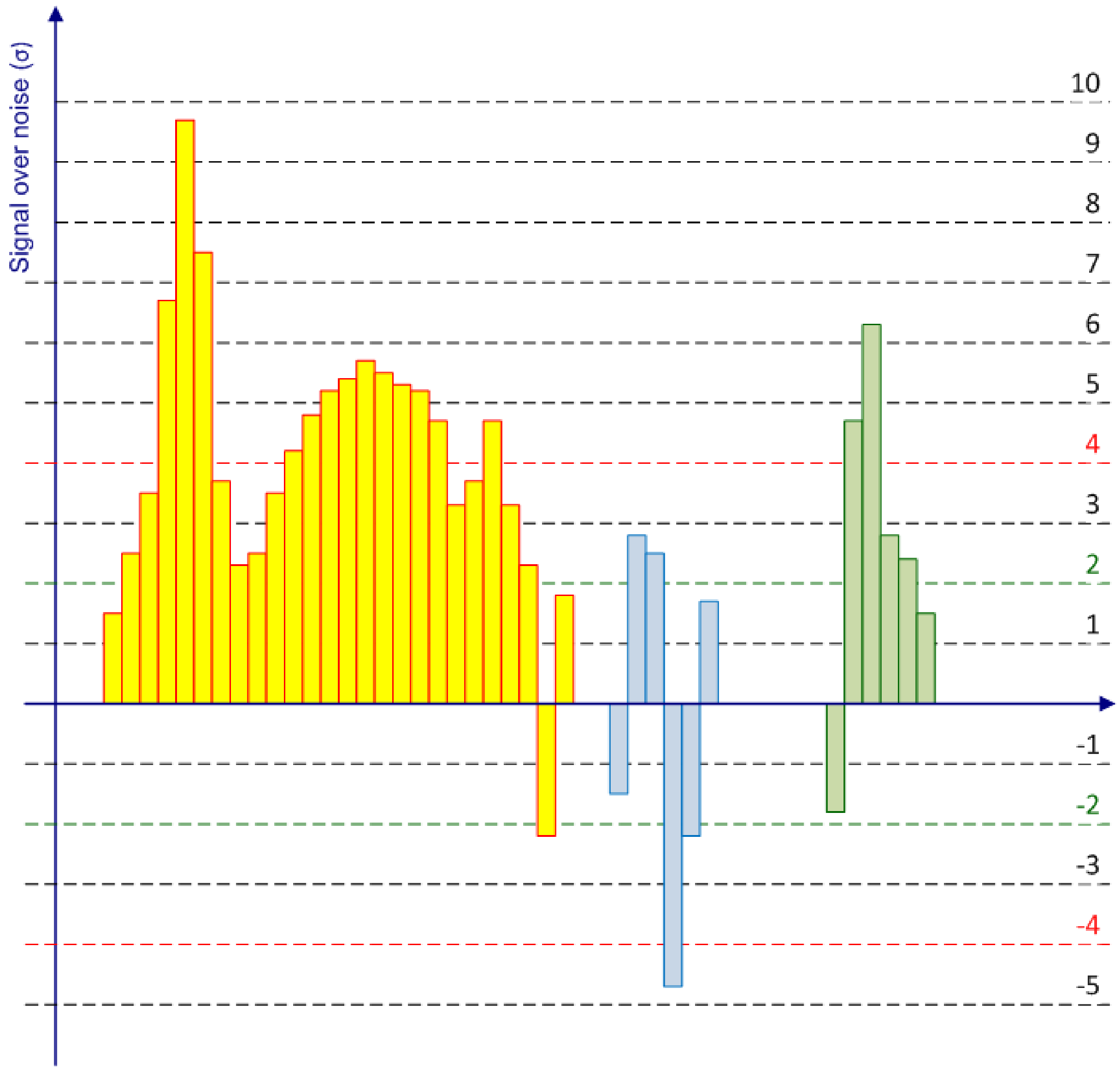

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Effect Of Strict Nearest Neighbour Approach

- **Large topologically connected regions in calorimeter can lead to large cell clusters**
  - Lost particle flow structure can introduce problems for jets
    - Infrared safety, in particular
  - Need to refine the clustering algorithm
    - Try to match single particle shower shapes better
- **Splitting the clusters**
  - Examine spatial cluster signal structure – find local signal maxima
    - "hill and valley" structural analysis in three dimensions
  - Split cluster between two maxima
    - In three dimensions, of course!
  - Share energy of cells in signal valleys
    - Needs sharing rules – introduces "geometrically" weighted cell energy contribution to cluster signal
  - Introduces new tunable parameter
    - Local signal maximum threshold is defined in units of energy, not significance!

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Cluster Splitting

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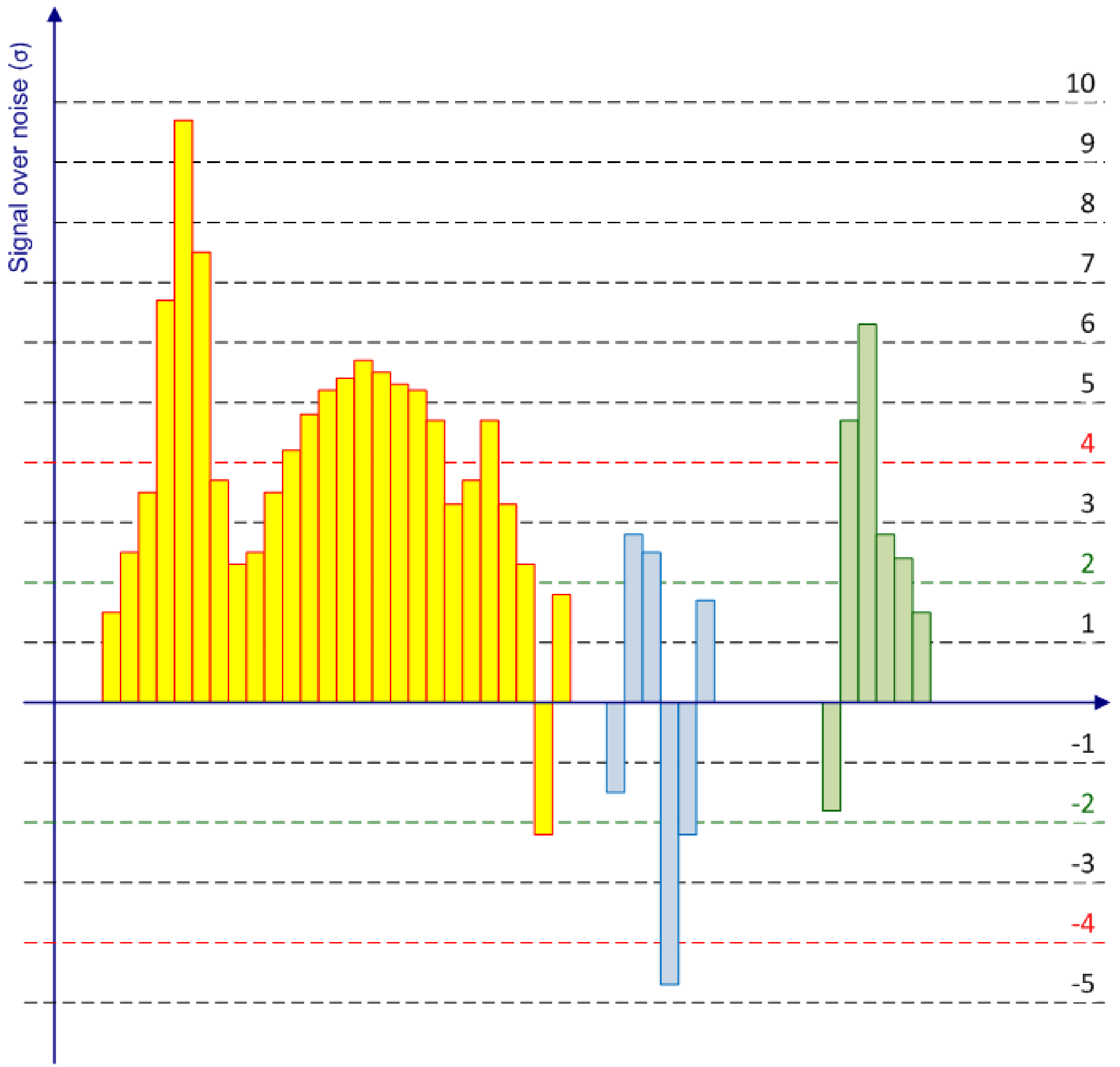

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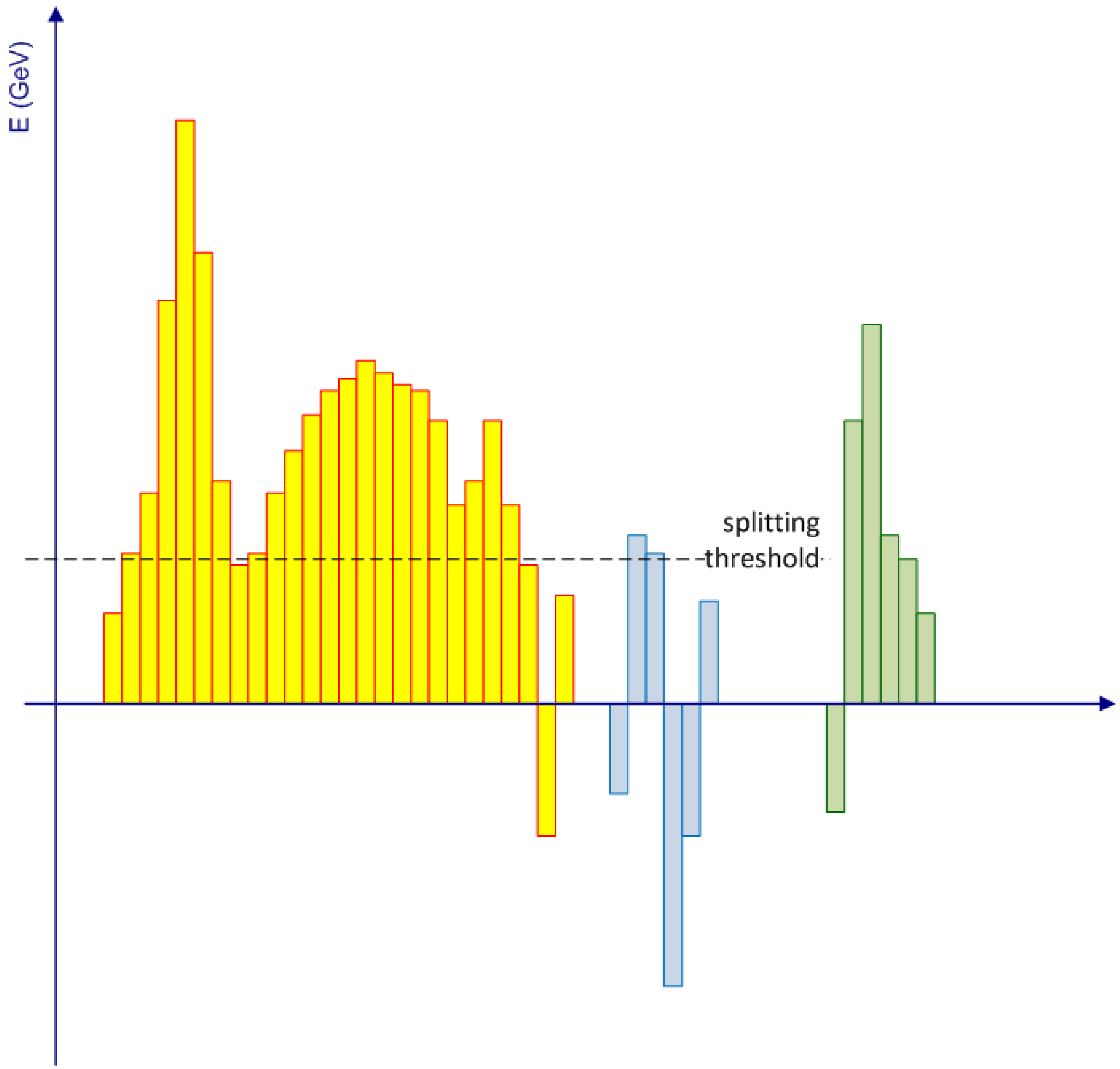

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Cluster Splitting

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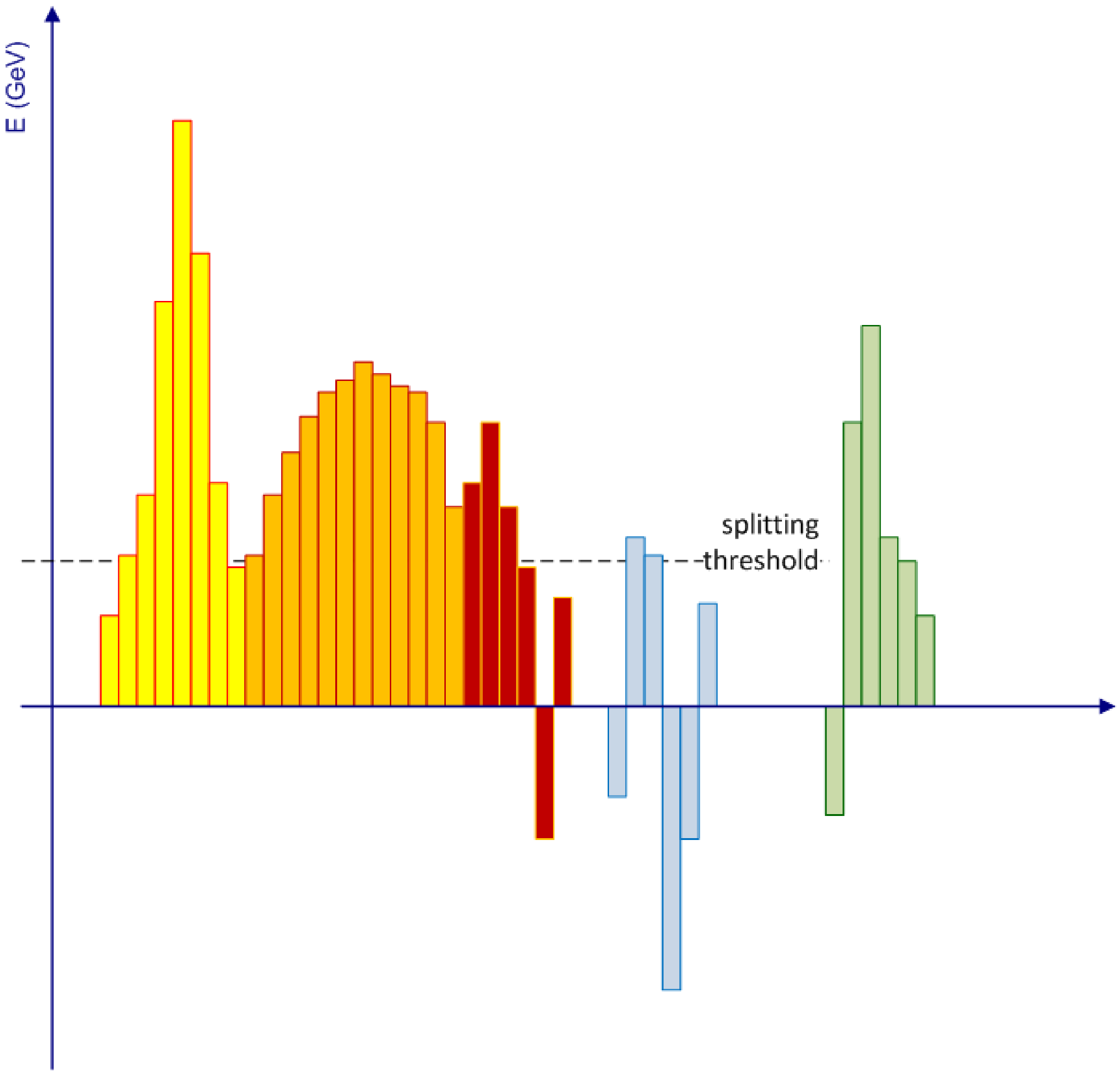

Splitting & Cell Energy Sharing

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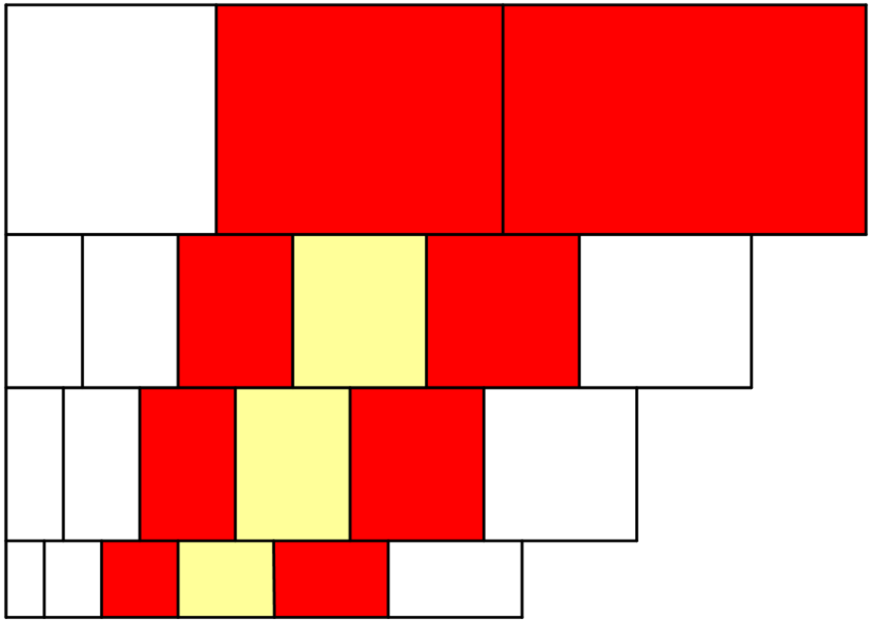
Splitting technique

- Guided by finest calorimeter granularity
  - Typically in electromagnetic calorimeter
- Allows to split larger cell signals without signal valley
  - Typically in hadronic calorimeters



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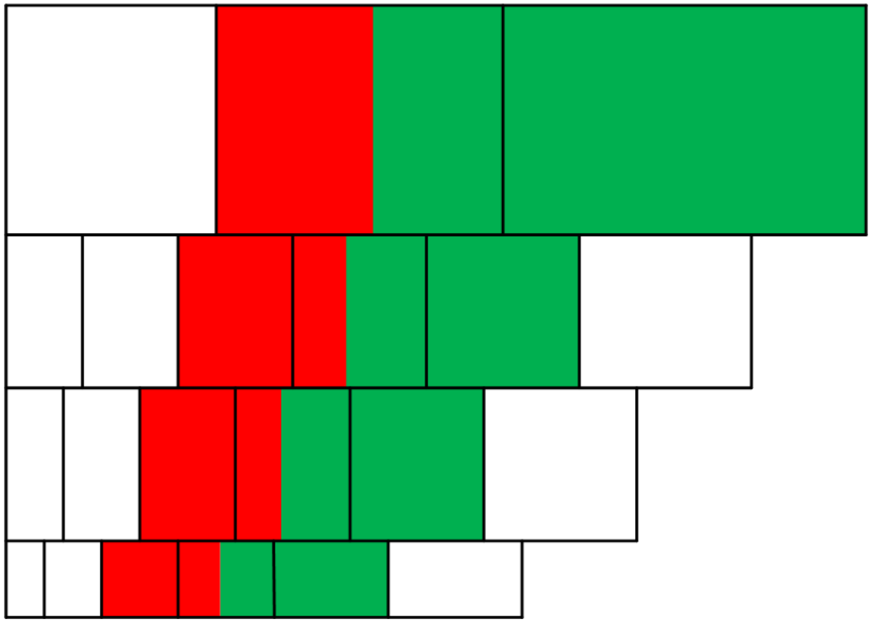


Rule for energy sharing (ATLAS example):

$$w_1 = \frac{E_1}{E_1 + rE_2}$$

$$w_2 = 1 - w_1$$

$$r = e^{d_1 - d_2}$$

(d_i is the distance of the cell from the centroid of cluster i)

Each cell can only appear in up to two clusters

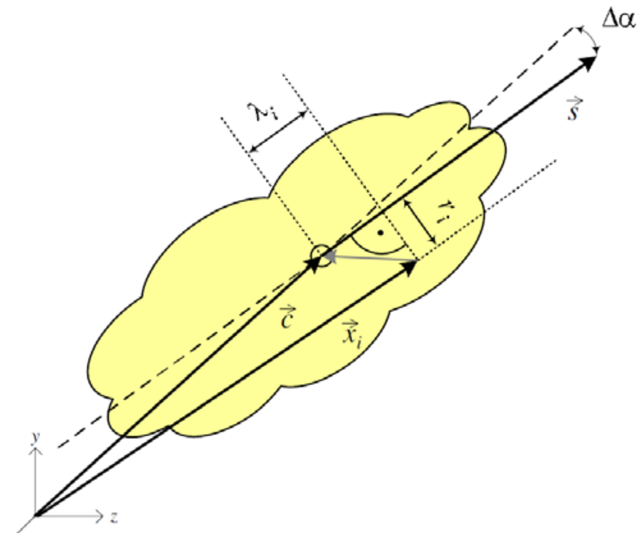
Cluster Shapes

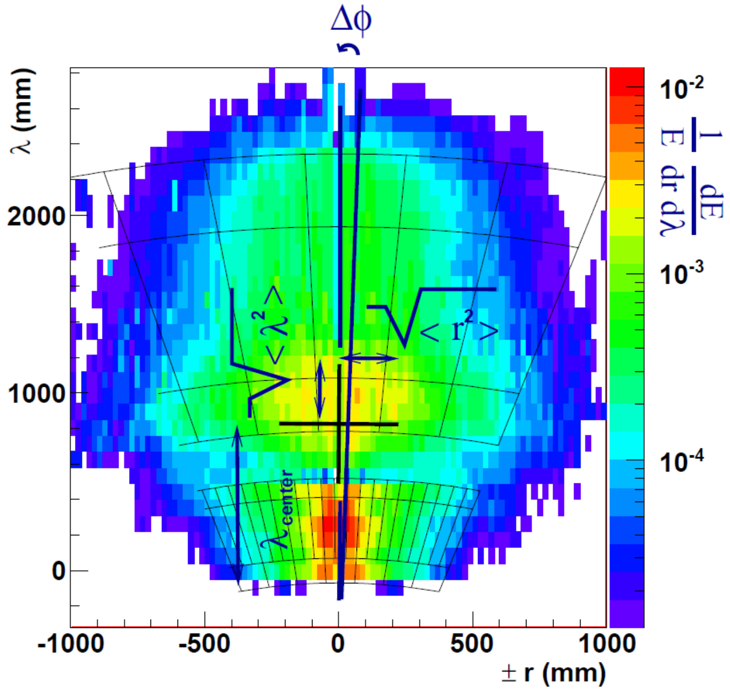
Clusters have shapes

- Geometrical moments and sizes
  - Lateral and longitudinal
- Tilt of principal axis
  - With respect to direction extrapolation from primary vertex (magnetic field!)
- Density and compactness measures
  - Cluster energy distribution in cells
- Energy sharing between calorimeter segments and modules
  - Shower structures

Useful for cluster calibration

- Exploit shape sensitivity to shower character
  - Hadronic versus electromagnetic





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Cell Signal Significance Spectrum

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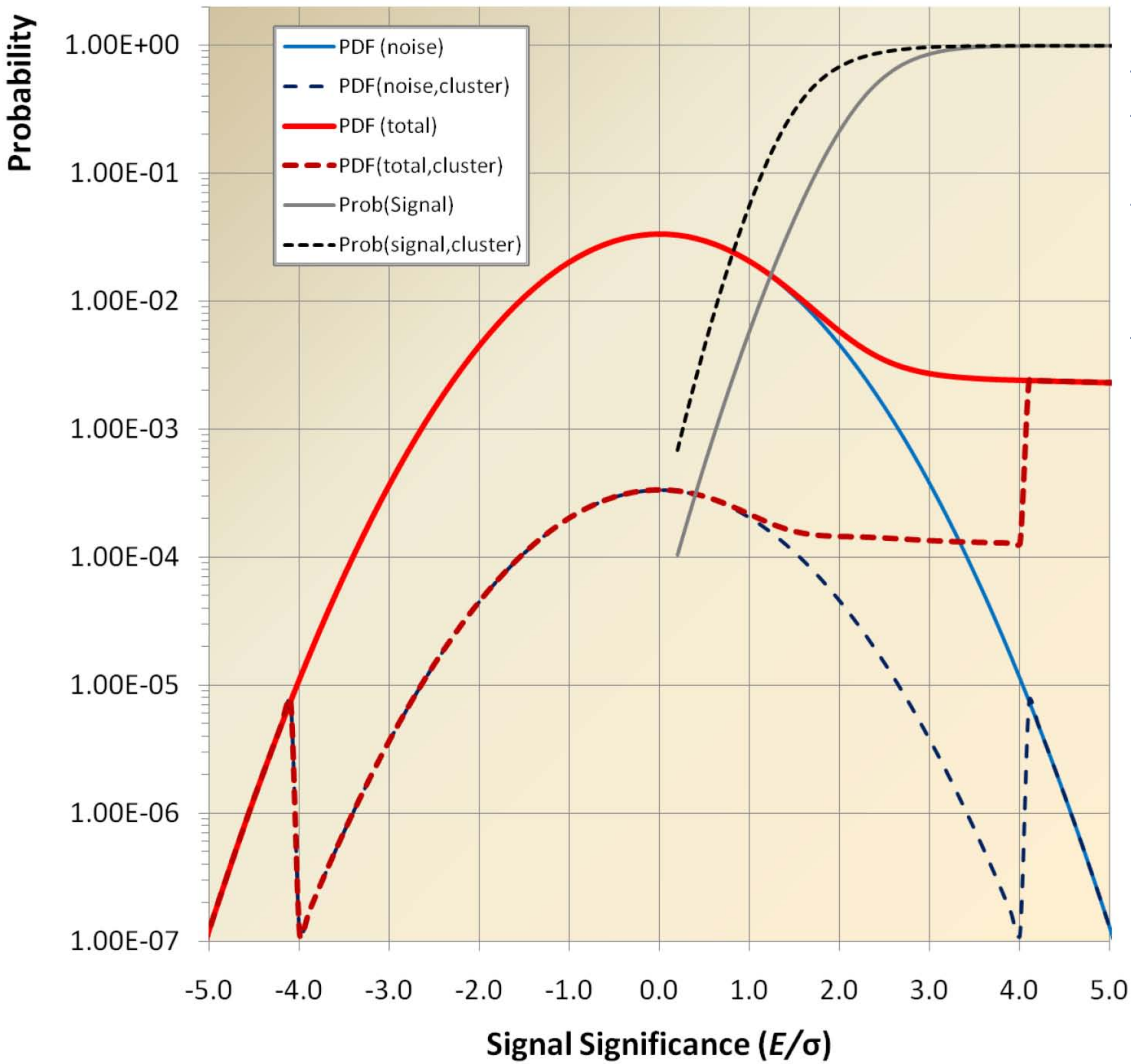

Modeled effect of topological clustering on the cell signal significance spectrum, for purposes of illustration here with only the primary (seed) threshold, no secondary (growth) threshold.

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Cell Signal Significance Spectrum

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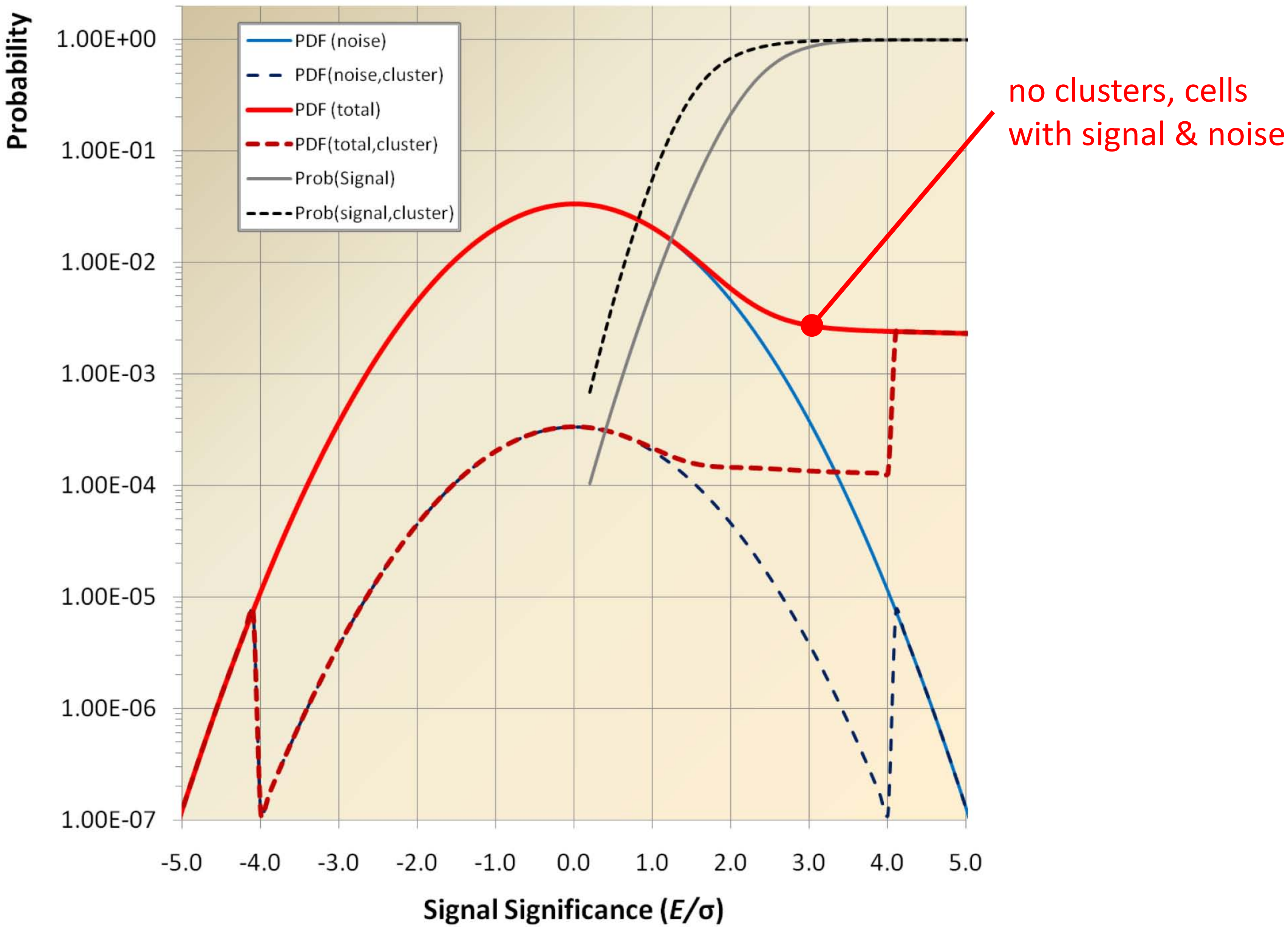

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Cell Signal Significance Spectrum

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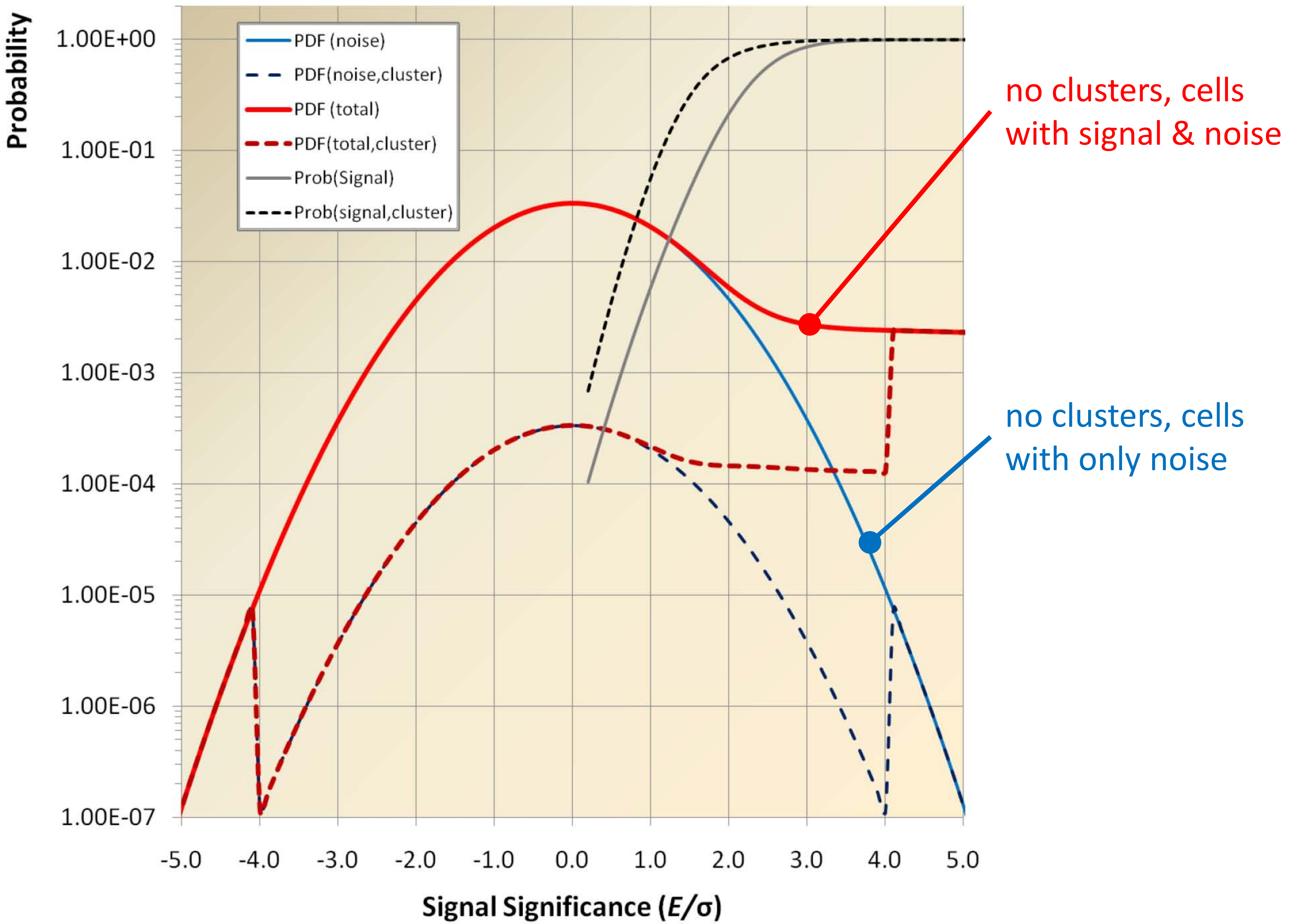

Cell Signal Significance Spectrum

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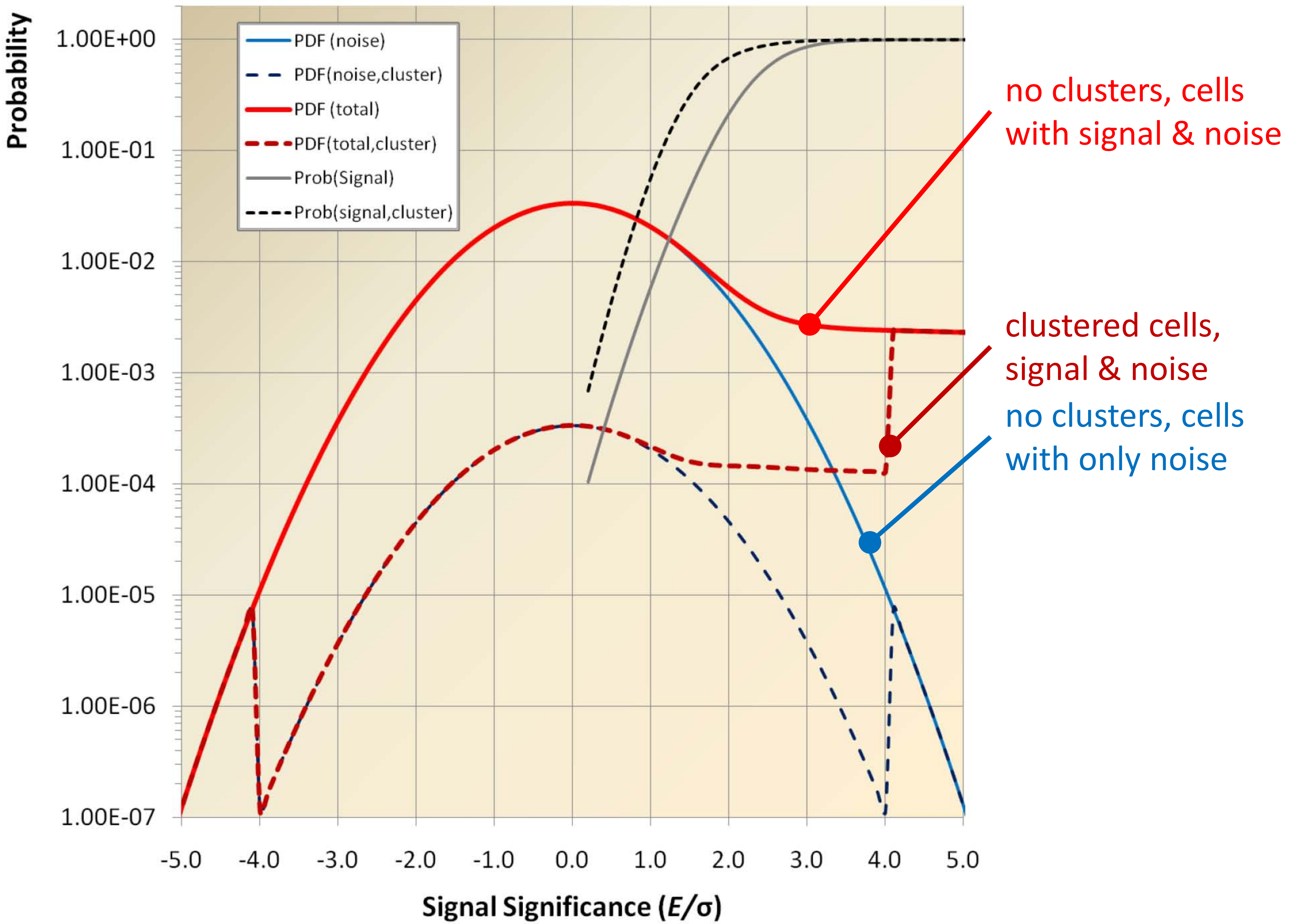

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Cell Signal Significance Spectrum

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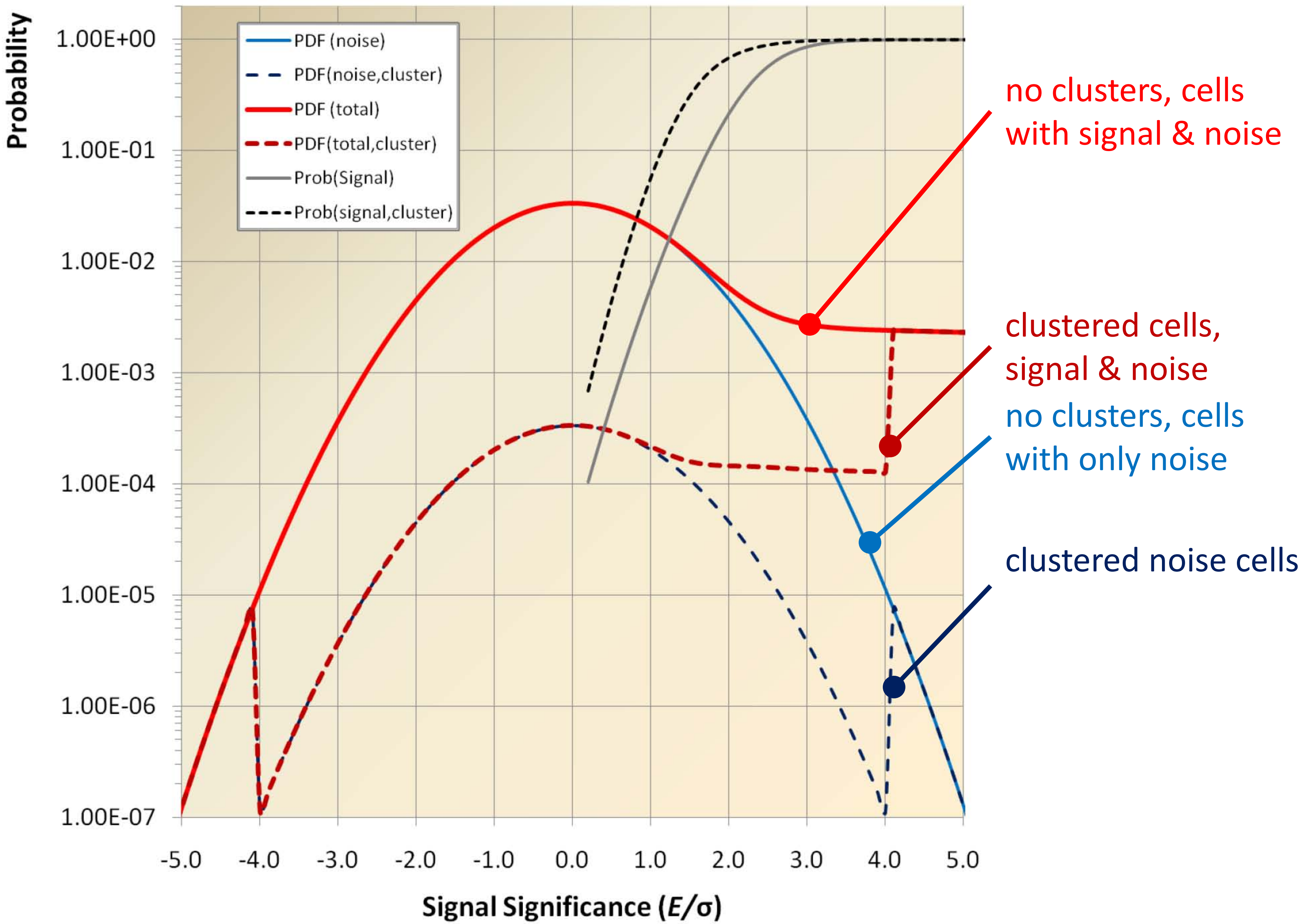

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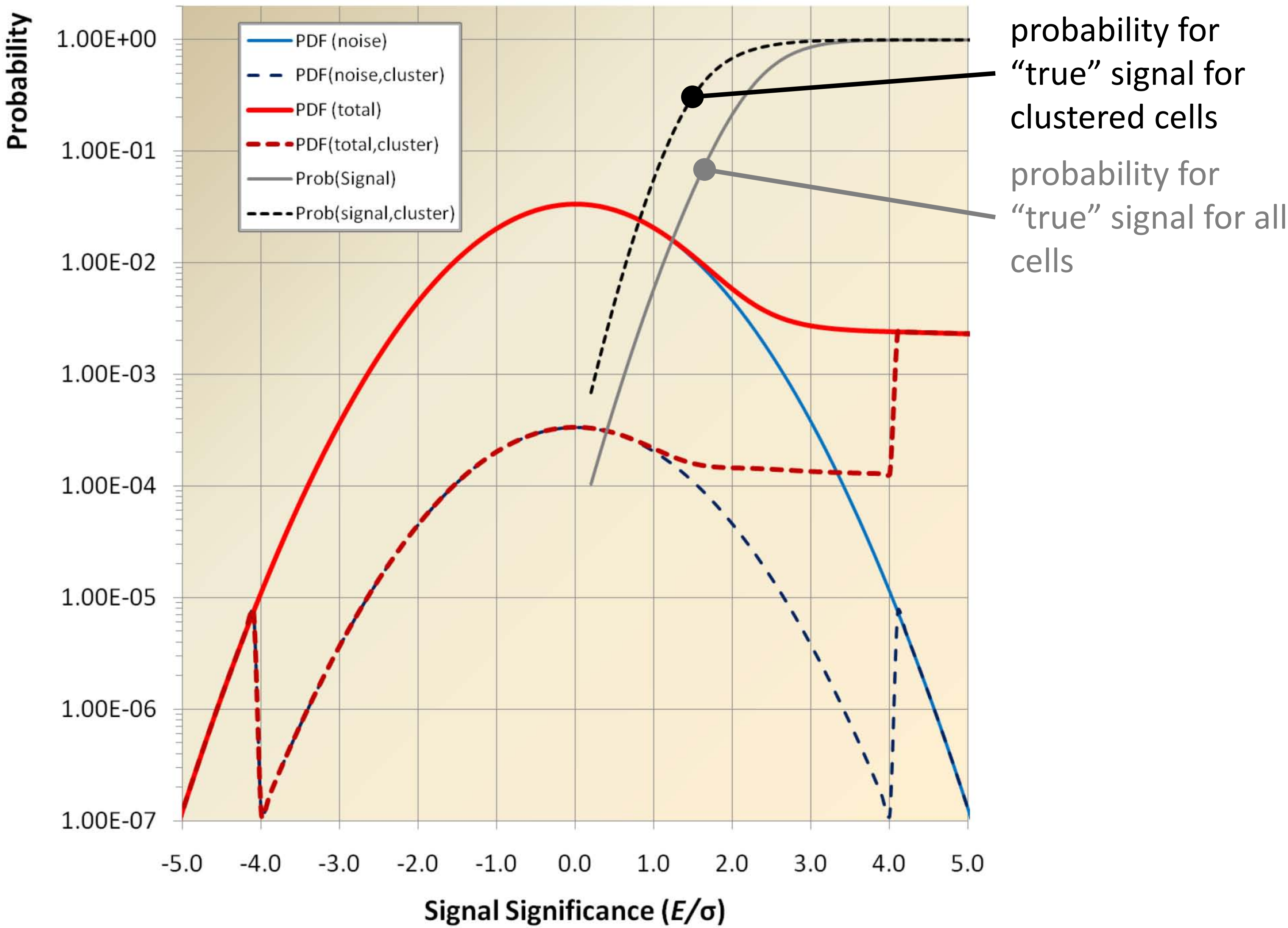

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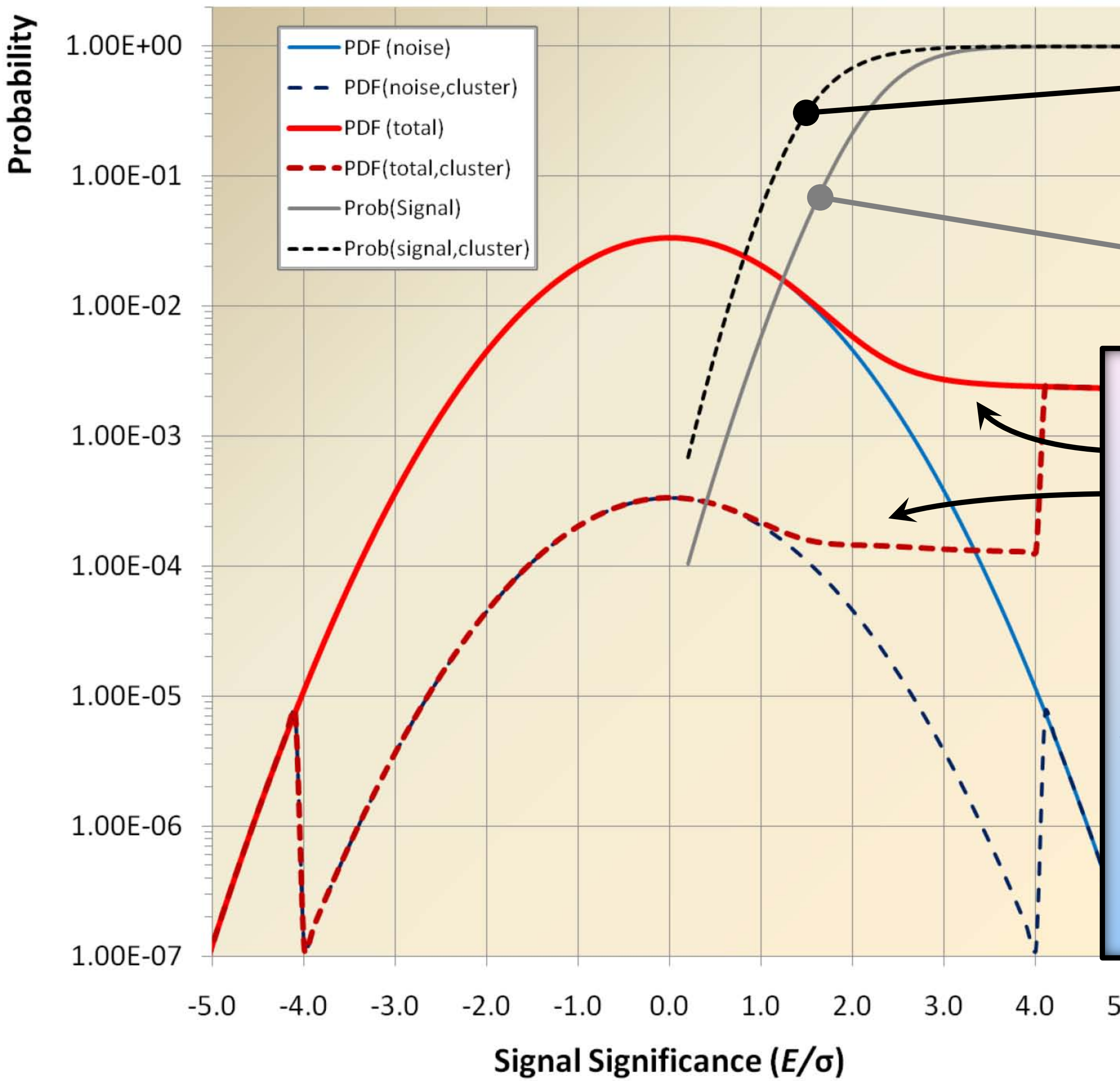

probability for “true” signal for clustered cells

probability for “true” signal for all cells

Note change of shape of probability density function due to correlations introduced by showering – clustered small signal cells have more likely some true signal because they are in the neighbor-hood of a cell with significant signal, while cells with the same signal from noise only are more often suppressed!

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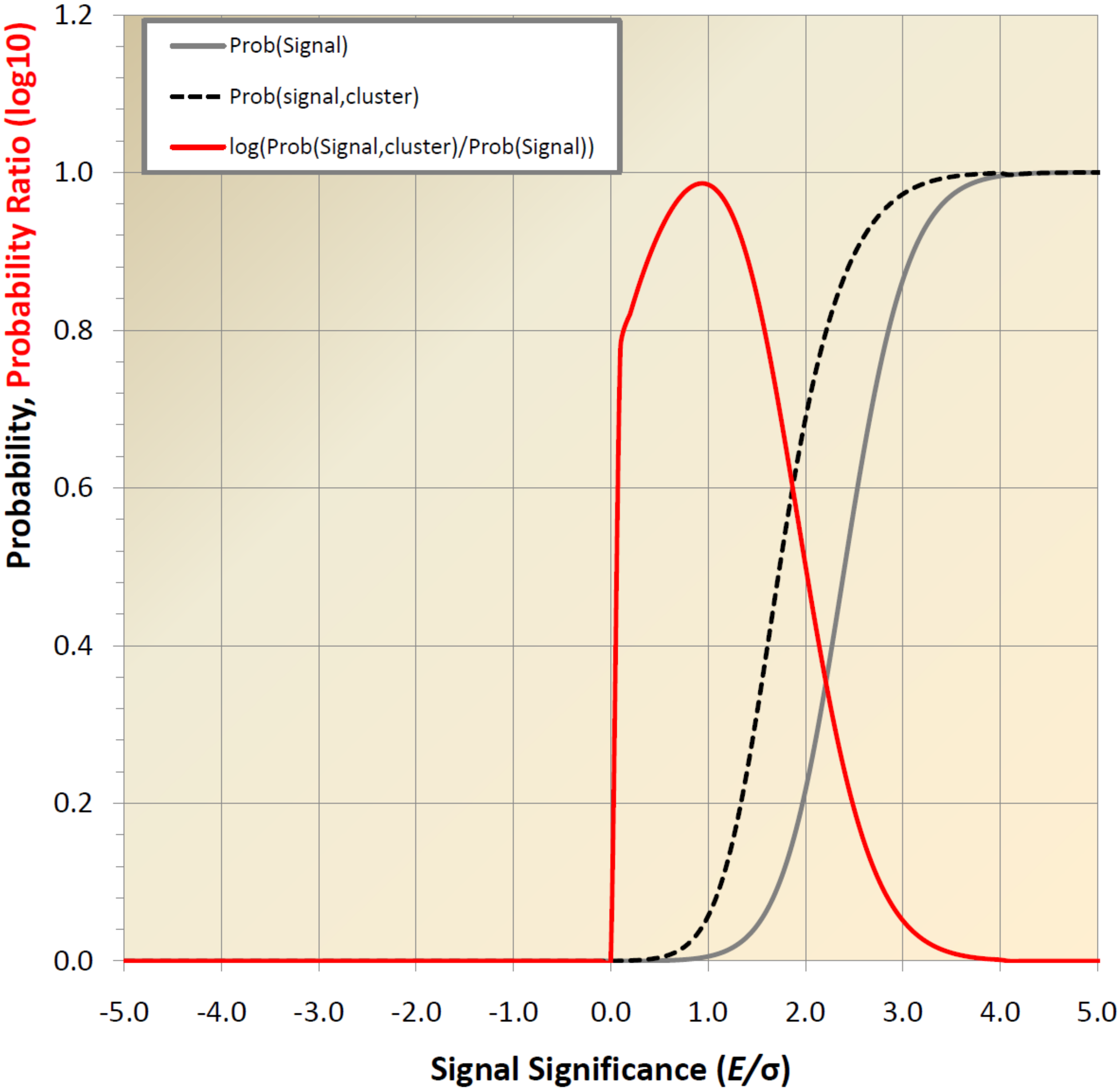
Probably For Cell To Have True Signal



Significant boost of likelihood that small signals are generated by particles (rather than noise) in clustered cells!

Cluster Kinematics

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Cluster signal

- Sum of clustered cell energies
  - Possibly with geometrical weight introduced by cluster splitting

Cluster direction & location

- Barycenter in (η,φ) from energy weighted cell directions
  - Negative signal cells contribute with absolute of their signal
  - Small effect on direction of final cluster from particles – negative signals are noise, i.e. small!
- Consistent approach for direction calculation
  - Leaves true signal and noise clusters at the right direction
- Same approach for geometrical signal center
  - "center of gravity"

Cluster four-momentum

- Massless pseudo-particle approach similar to tower
  - Consistent with cluster idea of reconstructing showers rather than particles

Total cluster signal:

(electromagnetic energy scale)

$$E_{0,\mathrm{cluster}} = \sum_{\text{clustered cells}} w_{\text{cell, cluster}} E_{0,\mathrm{cell}}$$

(with $w_{\text{cell, cluster}} \neq 1$ only for cells shared between clusters)

Direction and location:

$$\eta_{\mathrm{cluster}} = \frac{\sum_{\text{clustered cells}} w_{\text{cell, cluster}} \left|E_{0,\mathrm{cell}}\right| \eta_{\mathrm{cell}}}{\sum_{\text{clustered cells}} w_{\text{cell, cluster}} \left|E_{0,\mathrm{cell}}\right|}$$

$$\varphi_{\mathrm{cluster}} = \frac{\sum_{\text{clustered cells}} w_{\text{cell, cluster}} \left|E_{0,\mathrm{cell}}\right| \varphi_{\mathrm{cell}}}{\sum_{\text{clustered cells}} w_{\text{cell, cluster}} \left|E_{0,\mathrm{cell}}\right|}$$

$$\left(x_{\mathrm{cluster}}, y_{\mathrm{cluster}}, z_{\mathrm{cluster}}\right) = \frac{\sum_{\text{clustered cells}} w_{\text{cell, cluster}} \left|E_{0,\mathrm{cell}}\right| \left(x_{\mathrm{cell}}, y_{\mathrm{cell}}, z_{\mathrm{cell}}\right)}{\sum_{\text{clustered cells}} w_{\text{cell, cluster}} \left|E_{0,\mathrm{cell}}\right|}$$

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  - Consistent with cluster idea of reconstructing showers rather than particles

Cluster four-momentum

(electromagnetic energy scale)

$$\left(E_{\text{cluster}},\vec{p}_{\text{cluster}}\right)=E_{0,\text{cluster}}\begin{pmatrix}1\\ \cos\varphi_{\text{cluster}}/\sinh\eta_{\text{cluster}}\\ \sin\varphi_{\text{cluster}}/\sinh\eta_{\text{cluster}}\\ \tanh\eta_{\text{cluster}}\end{pmatrix}$$

with:

$$E_{\text{cluster}}=\left|\vec{p}_{\text{cluster}}\right|=p_{\text{cluster}}$$

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Cluster Features

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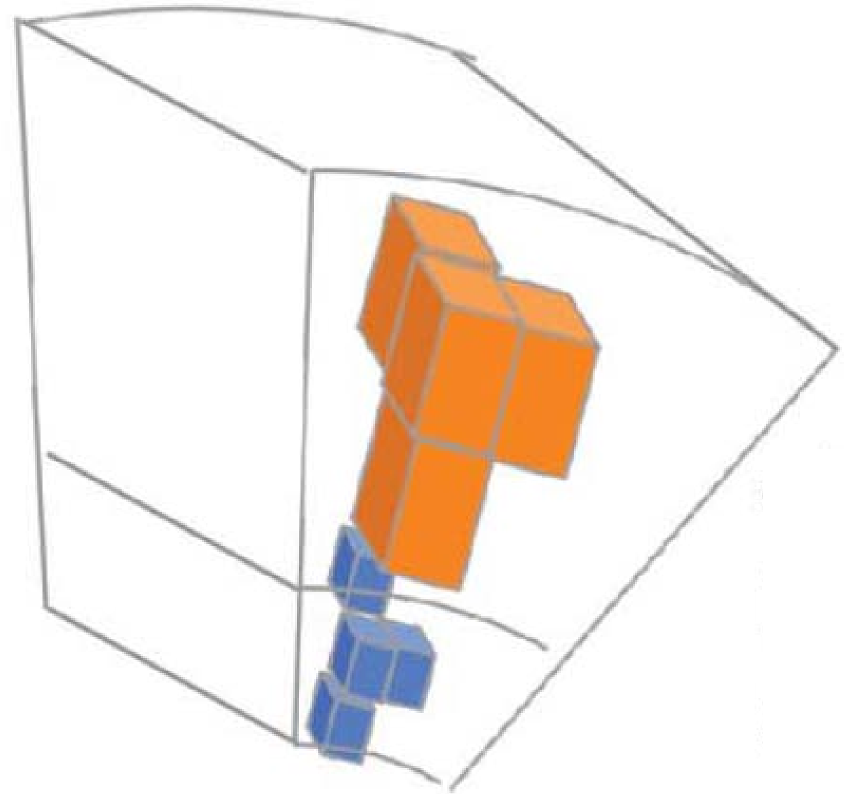
Signal integration

- Clusters sum cell signals without grid
  - 3-dimensional signal objects
  - Can include partial and complete signals from several particles
- Clusters preserve some detailed signal features
  - Associated information to be collected at cluster formation
  - E.g., energy sharing in electromagnetic and hadronic calorimeters
  - Longitudinal signal center of gravity
  - Shapes

Signal splitting

- Topological clusters need splitting algorithm
  - Cannot follow individual showers perfectly in jet environments
  - Can cause problems with infrared safety
- Few problems with seed and energy leakage
  - Can include energy from cells even outside of jet cone

(drawing by K. Perez, Columbia University)



Topological cell cluster is a "blob" of energy dynamically located inside the calorimeter (even crossing sub-detector boundaries)

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Noise Suppressed Tower Signals

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Signal formation

- Fill towers with cells from topological clusters
  - These survived noise suppression
- Same energy collection as unbiased towers

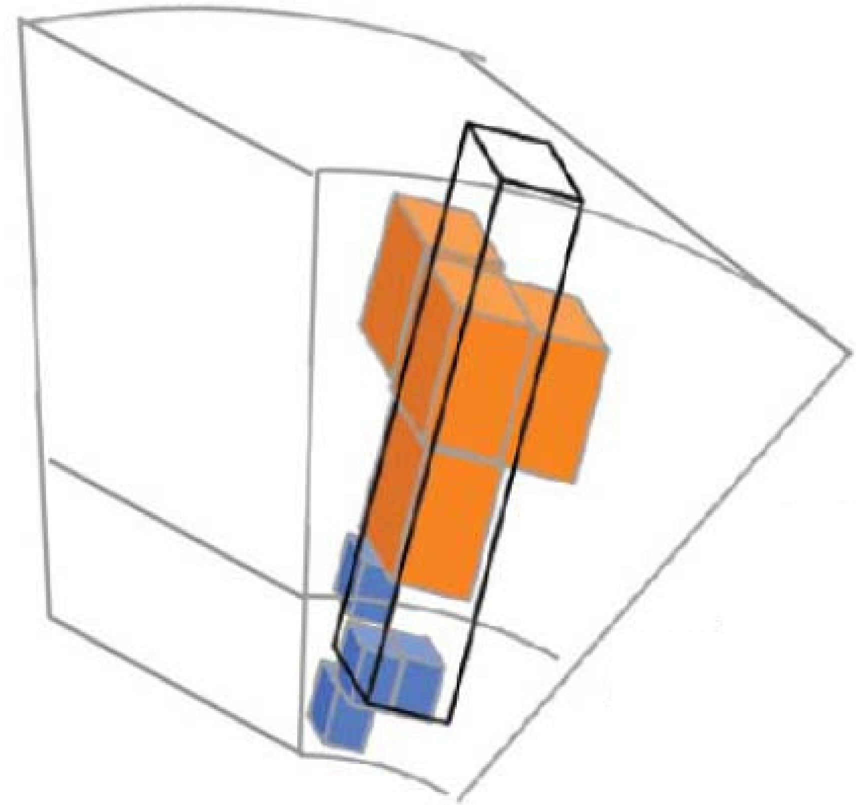
Signal integration

- Sum cell signals on tower grid
  - 2-dimensional signal objects
  - Can include partial and complete signals from several particles
- Same additional signal features as unbiased towers
  - Associated information to be collected at tower formation
  - E.g., energy sharing in electromagnetic and hadronic calorimeters
  - Longitudinal signal center of gravity

Signal splitting

- Can split showers, have problems with seeds, and cell energy "leakage"
  - Same problems as unbiased tower
- Applies regular geometrical splitting
  - Transverse energy flow motivated energy distribution
  - Avoid splitting threshold parameter

(drawing by K. Perez, Columbia University)



Noise suppressed towers are sparsely populated slabs of energy in a regular pseudorapidity-azimuth grid (each tower covers the same area in these coordinates)

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Cluster Calibration

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General cluster features

- Motivated by shower reconstruction
  - No bias in signal definition towards reconstruction of a certain, possibly very specific, physics signal object like a jet
- Clusters have shapes and location information
  - Spatial cell energy distributions and their correlations drive longitudinal and lateral extensions
  - Density and energy sharing measures
  - Signal center of gravity and (directional) barycenter
- Shapes are sensitive to shower nature
  - At least for a reasonable clustering algorithm

Local (cluster) calibration strategy

- First reconstruct truly deposited energy at cluster location…
  - e/h, mostly
- …then correct for other energy losses in the vicinity of signal cluster
  - Dead material energy losses and signal losses due to noise suppression

Calibration input

- Reconstructed cluster shapes represent shower shapes
  - E.g., dense and compact clusters indicate electromagnetic shower activity anywhere in the calorimeter
    - Can be intrinsic to a hadronic shower!
  - Calibration functions can exploit the cluster shapes to apply the corrections for $e/h \neq 1$ dynamically
- Location of cluster together with shape
  - E.g., dense and compact clusters located in electromagnetic calorimeter indicate electron or photon as particle originating the signal
    - Cluster not (part of) hadronic shower signal!
  - Clusters can classified before calibration
    - Electron/photon clusters need different calibration than dense clusters from hadronic showers!

Cluster calibration extensions

- Shapes, location and size also indicate possible energy losses around the cluster
  - Some correlations between energy losses in inactive material in front or inside of clusters
- Cluster size and signal neighbourhood sensitive to lost true signal in noise suppression algorithm
  - Out-of-cluster corrections

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Cluster Calibration Sequence

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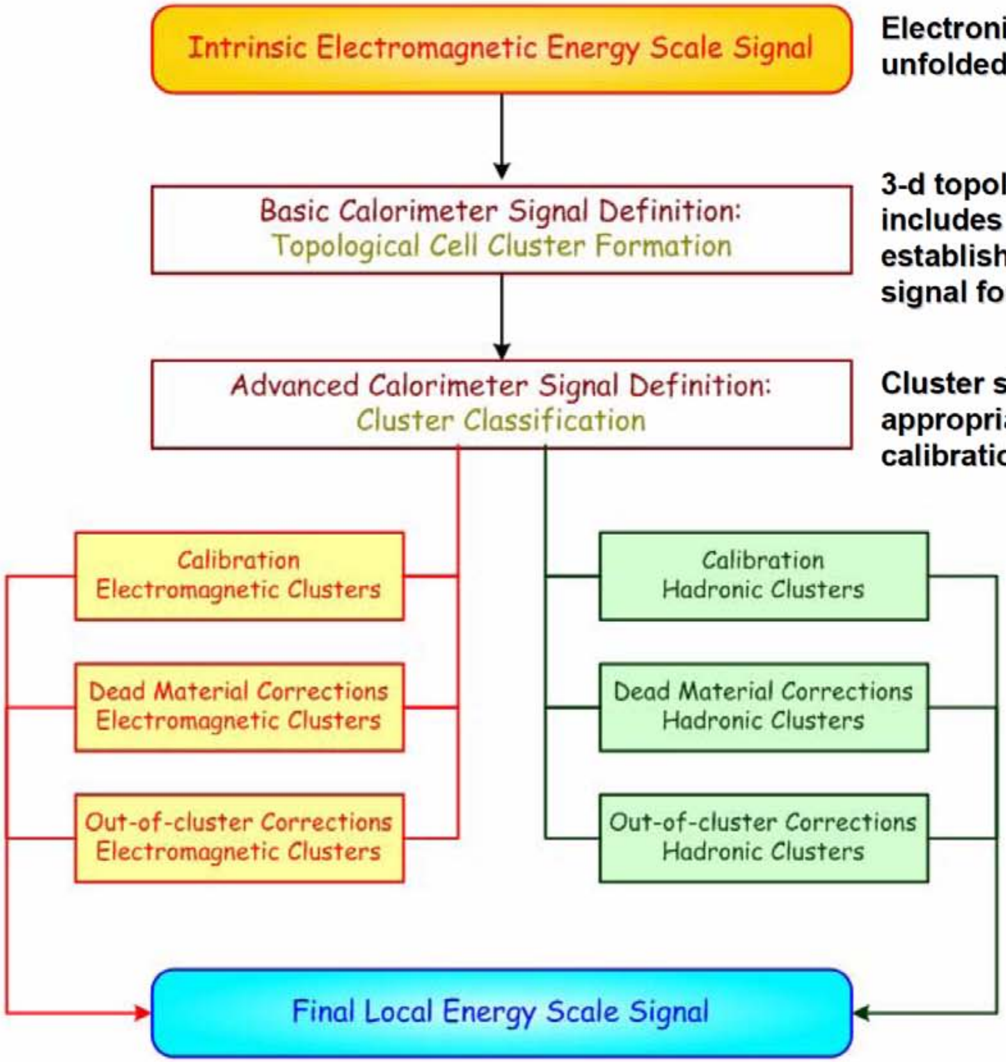


Electronic and readout effects unfolded (nA->GeV calibration)

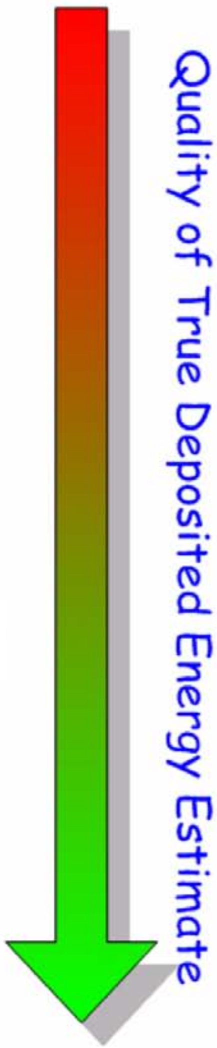
3-d topological cell clustering includes noise suppression and establishes basic calorimeter signal for further processing

Cluster shape analysis provides appropriate classification for calibration and corrections

Cluster character depending calibration

Apply dead material corrections specific for hadronic and electromagnetic clusters, resp.

Apply specific out-of-cluster corrections for hadronic and electromagnetic clusters, resp.



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Phase-space pion counting method

Classify clusters using the correlation of

Shower shape variables in single $\pi^{\pm}$ MC events

$$\lambda_{\text{cluster}} = \text{cluster center of gravity depth in calorimeter}$$

$$\bar{\rho}_{\text{cluster}} = \frac{1}{E_{0,\text{cluster}}} \sum_{\text{cells in cluster}} E_{0,\text{cell}} \cdot \rho_{\text{cell}}$$

Electromagnetic fraction estimator in bin of shower shape variables:

$$F \equiv \frac{\varepsilon(\pi^0)}{\varepsilon(\pi^0) + 2\varepsilon(\pi^-)}$$

$$\varepsilon(X) = \frac{N(X) \text{ producing a cluster in a given } (\eta, E_{0,\text{cluster}}, \lambda_{\text{cluster}}, \bar{\rho}_{\text{cluster}})}{N(X) \text{ total}}$$

Implementation

keep *F* in bins of η, *E*, λ, ρ of clusters for a given cluster

If $E < 0$, then classify as unknown

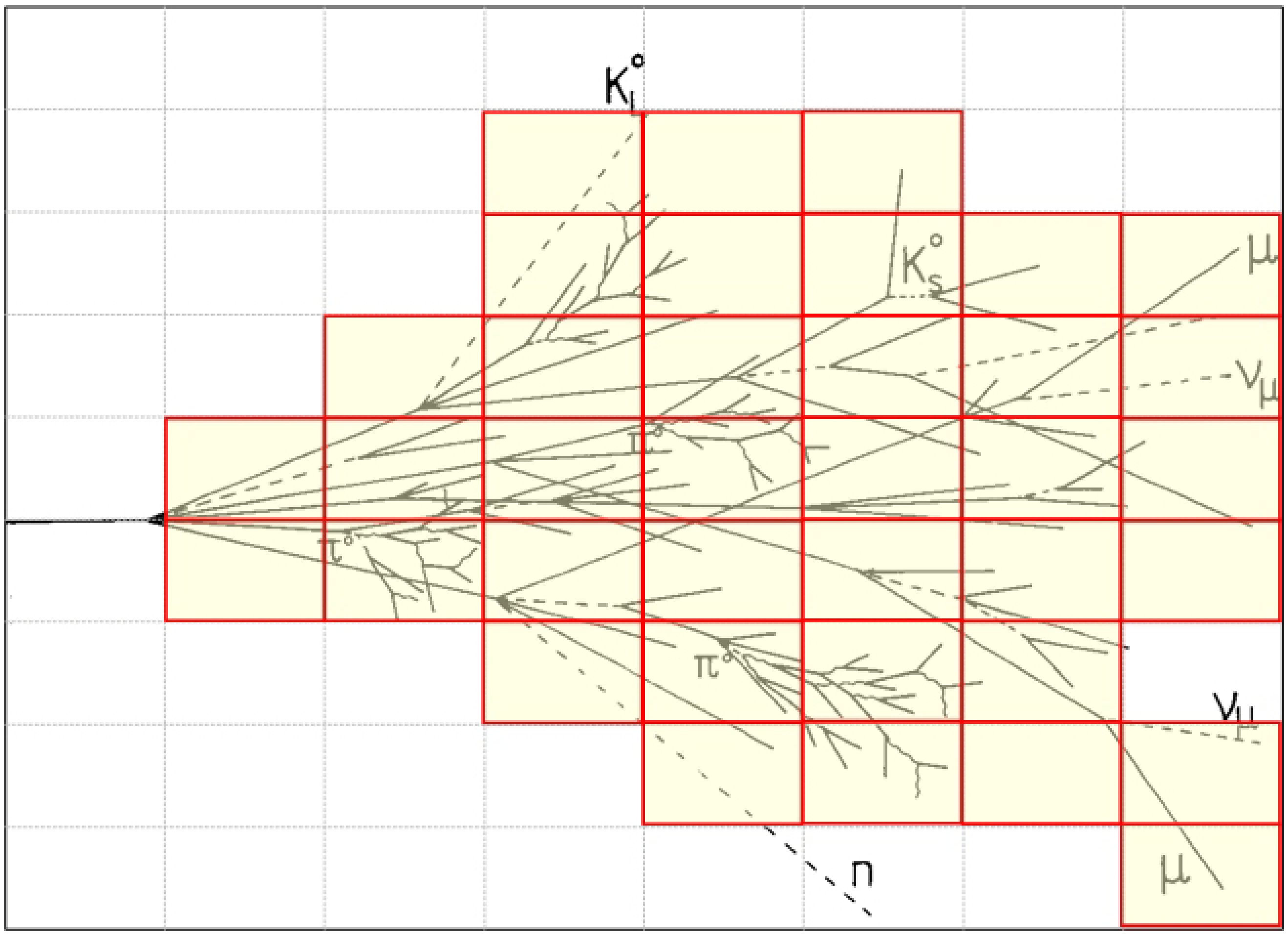
Lookup *F* from the observables $|\eta|$, *E*, λ, ρ

Cluster is EM if $F > 50\%$, hadronic otherwise

Calibration with cell signal weights

Idea is to compensate for lack of pion response in each cell

Pioneered in CDHS and applied in H1



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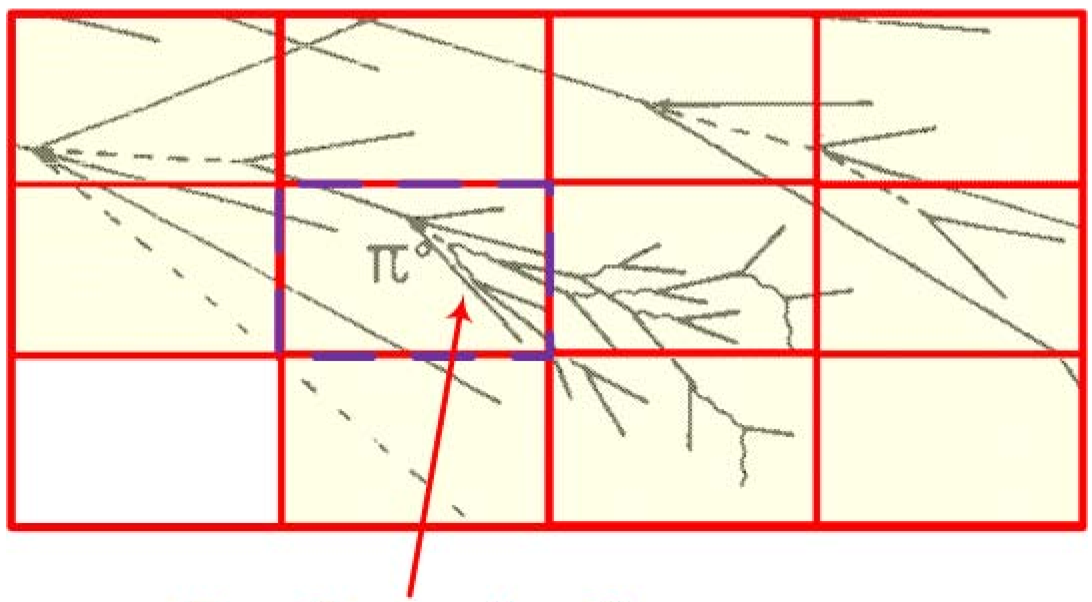

$$E_{\text{cell}}^{\text{em}} = \left[E_{\text{cell}}^{\text{em}}\right]_{\text{active}} + \left[E_{\text{cell}}^{\text{em}}\right]_{\text{passive}}$$

Calibration with cell signal weights

Idea is to compensate for lack of pion response in each cell

Pioneered in CDHS and applied in H1

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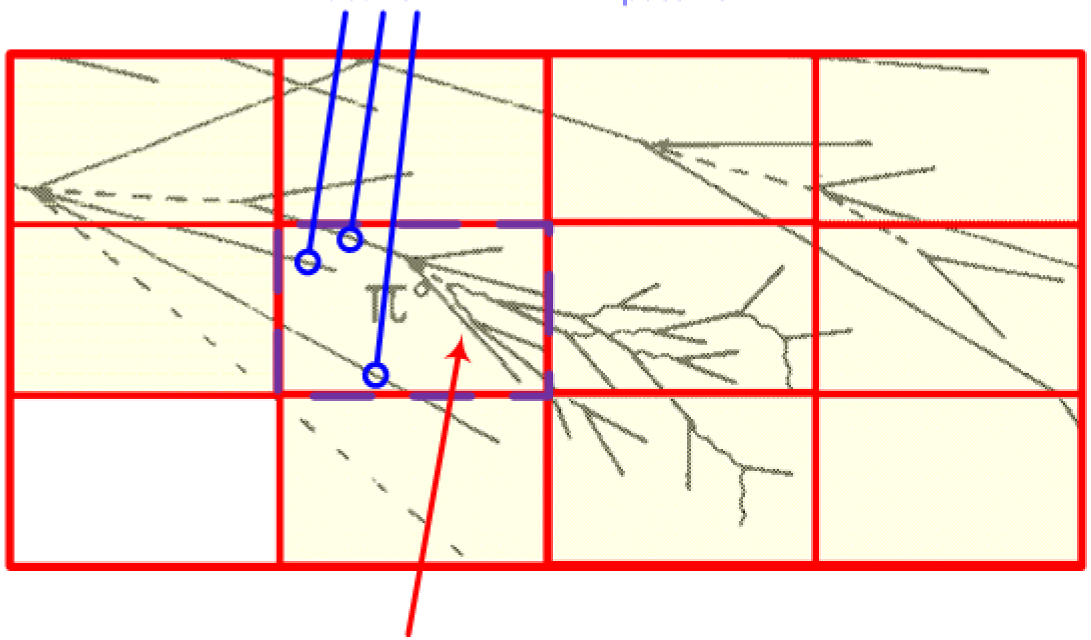

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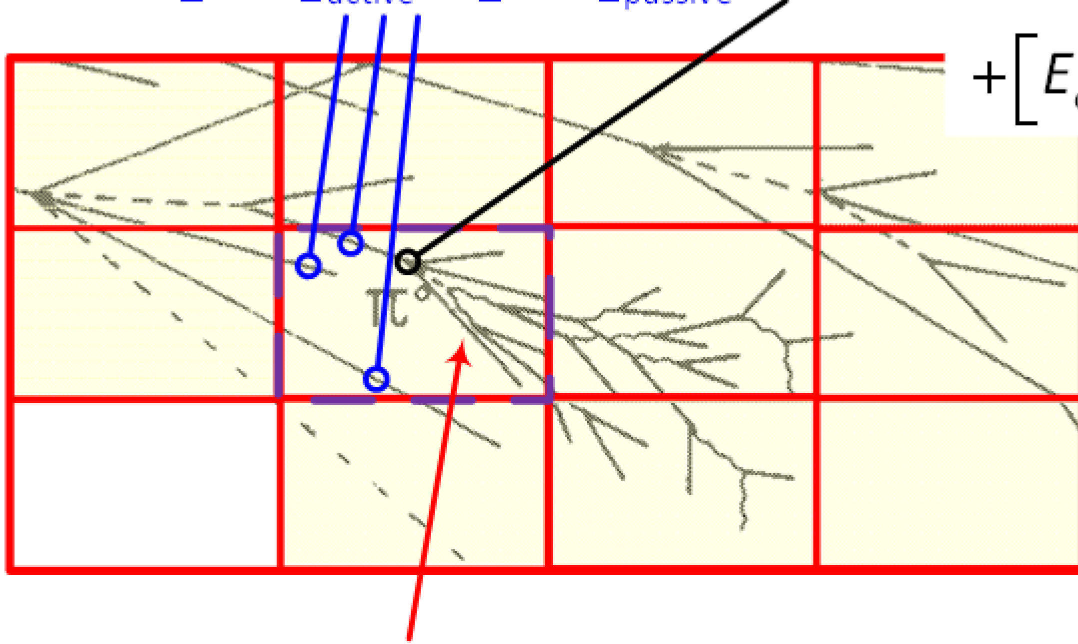
$$E_{\mathrm{cell}}^{\mathrm{ion}} = \left[E_{\mathrm{cell}}^{\mathrm{ion}}\right]_{\mathrm{active}} + \left[E_{\mathrm{cell}}^{\mathrm{ion}}\right]_{\mathrm{passive}}$$

$$E_{\mathrm{cell}}^{\mathrm{invisible}} = \left[E_{\mathrm{cell}}^{\mathrm{invisible}}\right]_{\mathrm{active}} + \left[E_{\mathrm{cell}}^{\mathrm{invisible}}\right]_{\mathrm{passive}}$$



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Calibration with cell signal weights

- Idea is to compensate for lack of pion response in each cell
  - Pioneered in CDHS and applied in H1
- Uses deposited energies in cells
  - Deposit can be in active or passive medium of calorimeter!

$$w_{\text{cell,cluster}}^{\text{calib}} = \left\langle \frac{\underbrace{E_{\text{deposited,cell}} = E_{\text{cell}}^{\text{em}} + E_{\text{cell}}^{\text{ion}} + E_{\text{cell}}^{\text{invisible}} + E_{\text{cell}}^{\text{escaped}}}_{\text{"deposited" energy anywhere within cell boundaries}}}{\underbrace{E_{0,\text{cell}} = c_{\text{em}} \cdot A\left(\left[E_{\text{cell}}^{\text{em}} \oplus E_{\text{cell}}^{\text{ion}}\right]_{\text{active}}, t, \vec{x}, \ldots\right)}_{\text{reconstructed em scale signal}}} \right\rangle$$

($E_{\text{cell}}^{\text{escaped}}$ is the energy escaping the calorimeter, i.e. carried by neutrinos - it is often assigned to the cell in which the neutrino vertex is located)

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Only signal contribution from energy deposited by electromagnetic sub-showers and through ionization by charged particles!

Calibration with cell signal weights

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Energy deposited in cell not available in experiment

- Use of detector simulations
  - Deposited energy and signal available
  - Use "unit cell" volume concept to collect invisible energies
  - Shower model dependent!
- Use single pion testbeam data
  - Develop model for weights in cells
  - Fit parameters of model using cells testbeam
    - Minimize resolution with beam energy constraint
  - Statistical – does not necessarily produce the correct weights!

Cell Signal Weights

Basic idea

- Use a dynamically self-adjusting calibration weight
  - High cell signal density → electromagnetic deposit
  - Low cell signal density → hadronic deposit
- Principal weighting function characteristics
  - Depends on cell energy density
  - Depends on cell location
  - Accidental application to electron signals should yield correct energy as well

Extraction of weighting functions

- Minimize resolution in (pion) testbeam data
  - Fitting function model
  - May not produce the correct weights – may even be unphysical!
- Use simulation
  - Deterministic approach relates signal to deposited energy within cell volume – no fitting!
  - May depend on details of (hadronic) shower modeling

$$E_{\text{rec,cell}} = w_{\text{cell}}(\ldots) \cdot E_{0,\text{cell}} = E_{\text{deposited,cell}}$$

Cell Signal Weights

P. Loch
U of Arizona
May 05, 2010

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ATLAS

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$$w_{\text{cell}}(\ldots) = w(\rho_{\text{cell}} = E_{0,\text{cell}} / V_{\text{cell}}, \vec{x}, \ldots)$$

e.g. in H1:

$$E_{\text{rec,cell}} = \underbrace{\left(1 + \alpha(\vec{x}, \ldots) \cdot e^{-\beta(\vec{x}, \ldots) \cdot \rho_{\text{cell}}}\right)}_{= w(\rho_{\text{cell}}, \vec{x}, \ldots)} \cdot E_{0,\text{cell}},$$

with $\lim\limits_{\rho_{\text{cell}} \to \infty} E_{\text{rec,cell}} = E_{0,\text{cell}}$

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Fit $\alpha(\vec{x},\ldots)$, $\beta(\vec{x},\ldots)$ with

$$\chi^2 = \sum_{\text{events}} \frac{\left(E_{\text{rec,cell}} - E_{\text{beam}}\right)^2}{\sigma^2} = \min$$

i.e.:

$$\frac{\partial\chi^2}{\partial\alpha} = 0 \text{ and } \frac{\partial\chi^2}{\partial\beta} = 0$$

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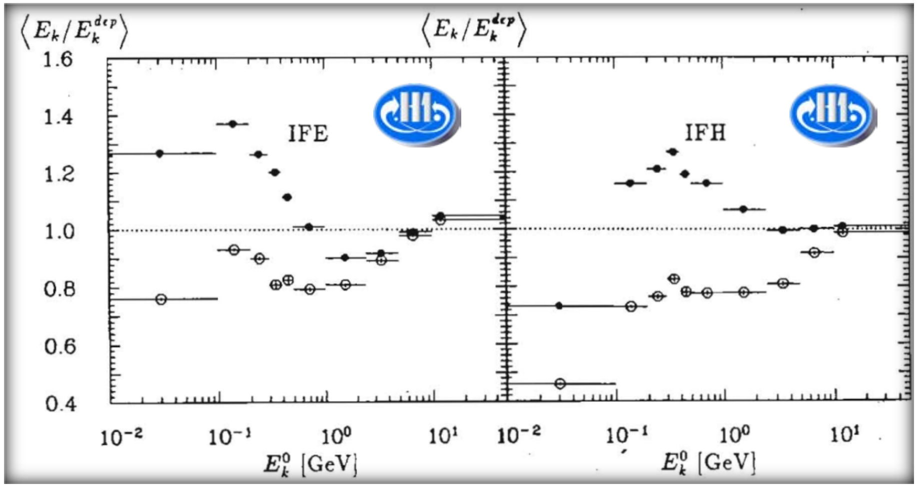

$\circ \; \frac{E_{\text{rec,cell}}}{E_{0,\text{cell}}}$ $\qquad \bullet \; \frac{E_{\text{deposited,cell}}}{E_{0,\text{cell}}}$

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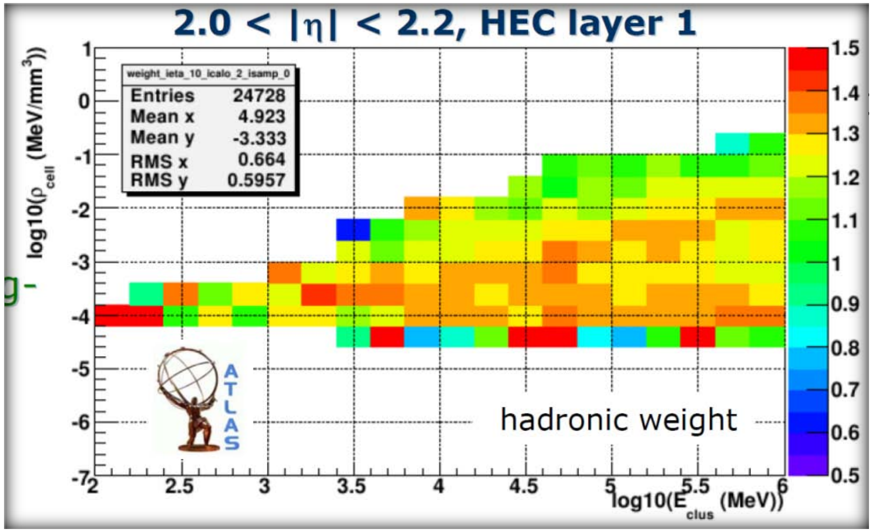
ATLAS cluster-based approach:

1. Use only cells in hadronic clusters
2. Cluster sets global energy scale as a reference for densities
3. Calculate $E_{\mathrm{deposited,cell}}/E_{0,\mathrm{cell}}$ from single pion simulations in bins of cluster energy, cell energy density, cluster direction, and calorimeter sampling layer
4. Store $[E_{\mathrm{deposited,cell}}/E_{0,\mathrm{cell}}]^{-1}$ in look-up tables



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4. Store $[E_{\text{deposited,cell}}/E_{0,\text{cell}}]^{-1}$ in look-up tables
5. Retrieve weights for any cell in any cluster from look-up table to reconstruct cell and cluster energies

$$E_{\text{rec,cluster}}^{\text{calib}} = \sum_{\text{cells in cluster}} E_{\text{rec,cell}} = \sum_{\text{cells in cluster}} w_{\text{cell,cluster}}^{\text{calib}}(E_{0,\text{cluster}}, \eta_{\text{cluster}}, S_{\text{cell}}, \rho_{\text{cell}}) \cdot E_{0,\text{cell}}$$

THE UNIVERSITY OF ARIZONA

Cluster Dead Material Corrections

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Dead material

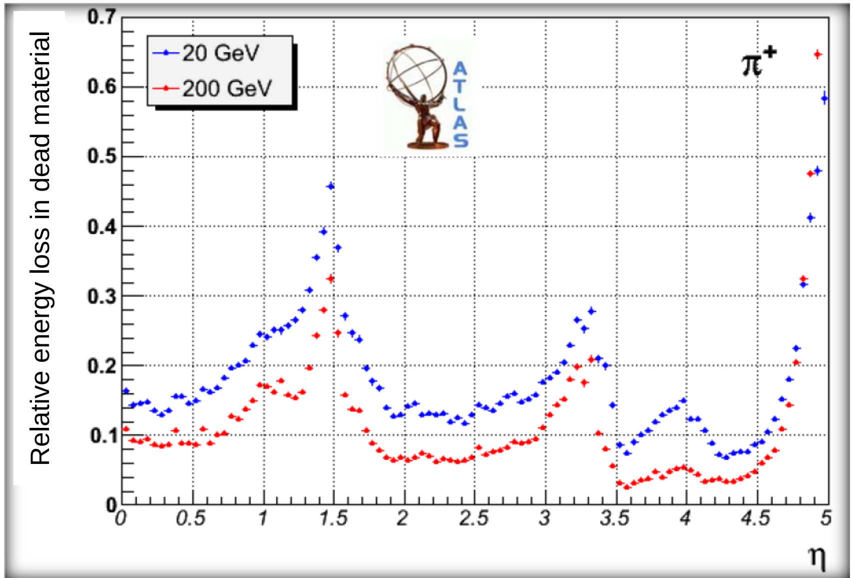
- Energy losses not directly measurable
  - Signal distribution in vicinity can help
- Introduces need for signal corrections up to O(10%)
  - Exclusive use of signal features
  - Corrections depend on electromagnetic or hadronic energy deposit
- Major contributions
  - Upstream materials
  - Material between LArG and Tile (central)

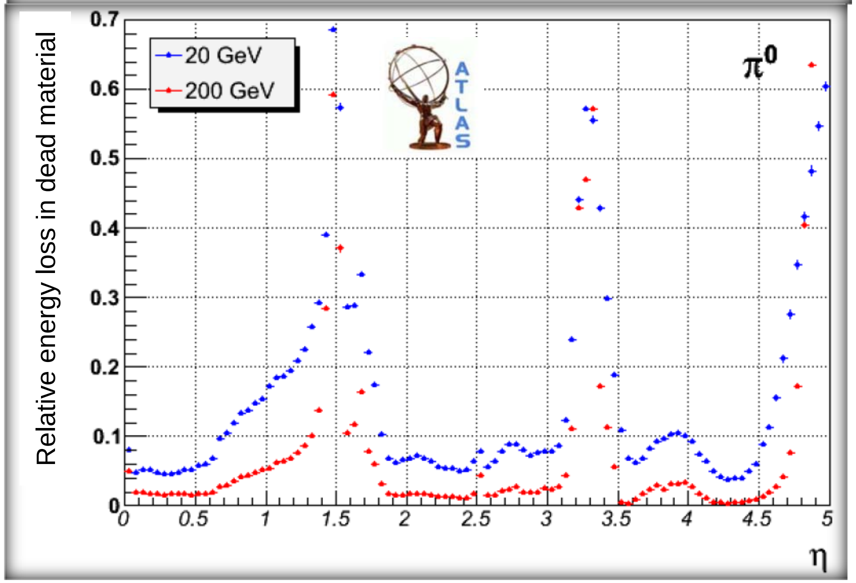
Cracks

- dominant sources for signal losses
  - $|\eta|\approx 1.4\text{-}1.5$
  - $|\eta|\approx 3.2$
- Clearly affects detection efficiency for particles and jets
  - Already in trigger!
  - Hard to recover jet reconstruction inefficiencies
- Generate fake missing Et contribution
  - Topology dependence of missing Et reconstruction quality

Additive correction:

$$E_{\text{rec,cluster}}^{\text{calib+DM}} = E_{\text{rec,cluster}}^{\text{calib}} + E_{\text{rec,cluster}}^{\text{DM}}(\vec{x}_{\text{cluster}},\ldots)$$

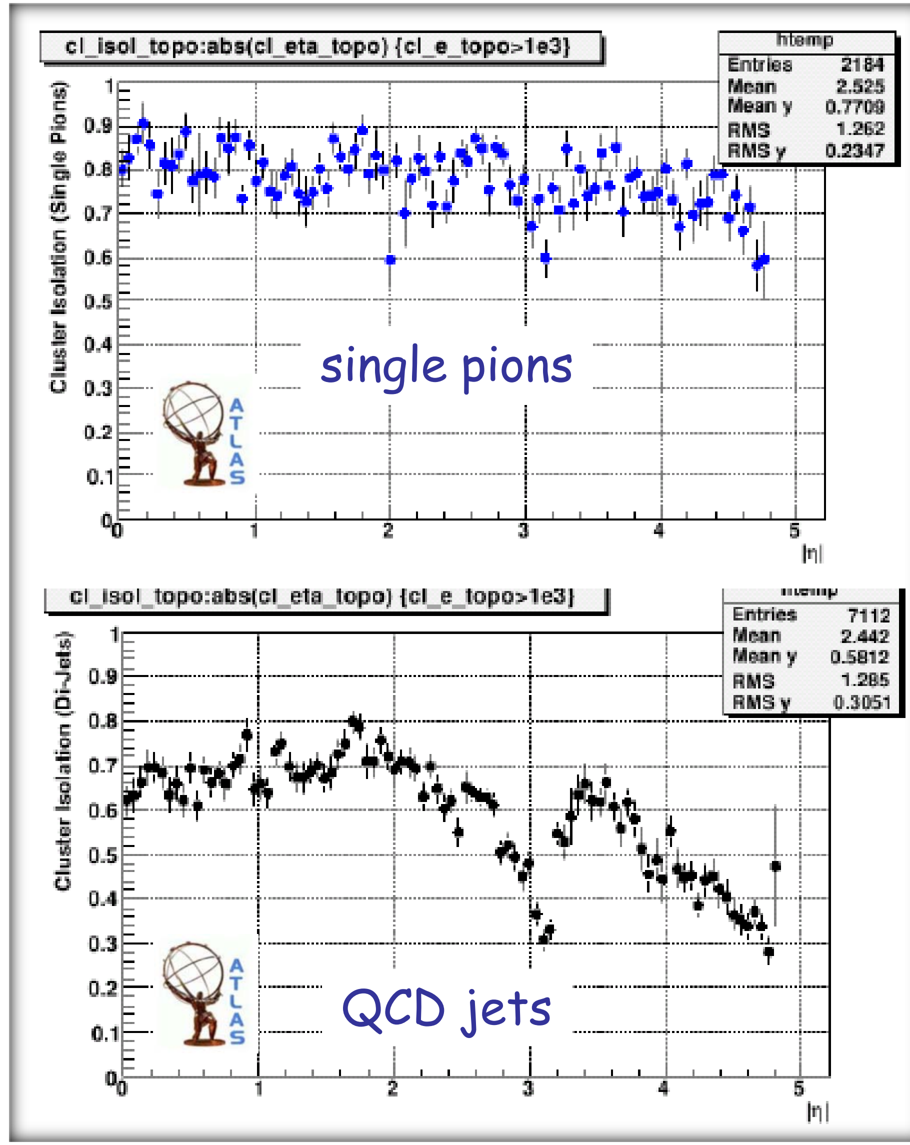




Out-of-cluster Corrections

Compensate loss of true signal

- Limited efficiency of noise suppression scheme
  - Discard cells with small true energy not close to a primary or secondary seed
  - Accidental acceptance of a pure noise cell
- Can be significant for isolated pions
  - 10% at low energy
- Correction derived from single pions
  - Compensates the isolated particle loss
  - But in jets neighboring clusters can pick up lost energy
- Use isolation moment to measure effective "free surface" of each cluster
  - Scale single pion correction with this moment (0…1)



Additive correction:

$$E_{\mathrm{rec,cluster}}^{\mathrm{calib+DM+OOC}} = E_{\mathrm{rec,cluster}}$$
$$= E_{\mathrm{rec,cluster}}^{\mathrm{calib+DM}} + E_{\mathrm{rec,cluster}}^{\mathrm{OOC}}(\vec{x}_{\mathrm{cluster}}, m_{\mathrm{isol}}, E_{0,\mathrm{cluster}}, \ldots)$$

Local Calibration Features

Attempt to calibrate hadronic calorimeter signals in smallest possible signal context

- Topological clustering implements noise suppression with least bias signal feature extraction
  - Residual concerns about infrared safety!
- No bias towards a certain physics analysis
  - Calibration driven by calorimeter signal features without further assumption
- Good common signal base for all hadronic final state objects
  - Jets, missing Et, taus

Factorization of cluster calibration

- Cluster classification largely avoids application of hadronic calibration to Electromagnetic signal objects
  - Low energy regime challenging
- Signal weights for hadronic calibration are functions of cluster and cell parameters and variables
  - Cluster energy and direction
  - Cell signal density and location (sampling layer)
- Dead material and out of cluster corrections are independently applicable
  - Factorized calibration scheme

Local calibration does not reproduce jet energy

- Energy losses not correlated with cluster signals can not be corrected
  - Magnetic field losses
  - Dead material losses
- Needs additional jet energy scale corrections
  - Use specific jet context to derive those

Only applicable to cluster jets!

$$E_{true}^{jet} = E_{dep}^{calo} + E_{mag}^{loss} + E_{low}^{loss} + E_{leak}^{loss} + E_{out}^{loss} - E_{UE\otimes PU}^{gain} - E_{env}^{gain}$$

E_{dep}^{calo}	energy deposited in the calorimeter within signal definition
E_{mag}^{loss}	charged particle energy lost in solenoid field
E_{low}^{loss}	particle energy lost in dead material
E_{leak}^{loss}	energy lost due to longitudinal leakage
E_{out}^{loss}	energy lost due to jet algorithm/calorimeter signal definition
$E_{UE\otimes PU}^{gain}$	energy added by underlying event and/or pile-up
E_{env}^{gain}	energy added by response from other nearby particles/jets

only source of signal!

Global Calibration Techniques

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Use jet context for cell calibration

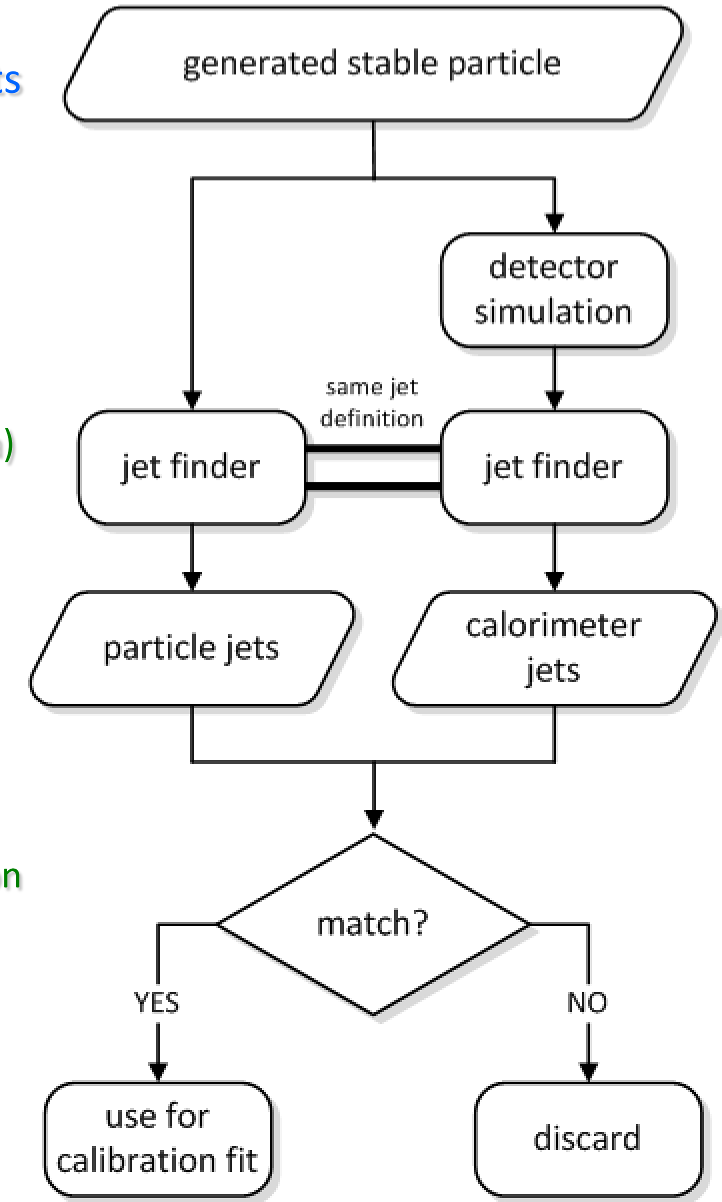
- Determine cell weights using jet energy constraints
  - Same principle idea as for local cell weighting, but different global energy scale
  - Needs jet truth reference
- Jet context relevant
  - Supports assumption of hadronic signal activity
  - Has enhanced electromagnetic component contributing to the weighting function parameterizations of all cells – larger (volume/area) context than topological clustering
  - May be biased with respect to calorimeter signal definition and jet algorithms

Jet energy references for calorimeter jets

- Simulation
  - Matching particle level jet (same jet definition) energy
- Experiment
  - pT balance with electromagnetic system like photon or Z-boson
  - W mass spectroscopy

Sampling energy based jet calibration

- Coarser than cell signals but less numerical complexity
  - Fewer function parameters



Truth Jet Matching

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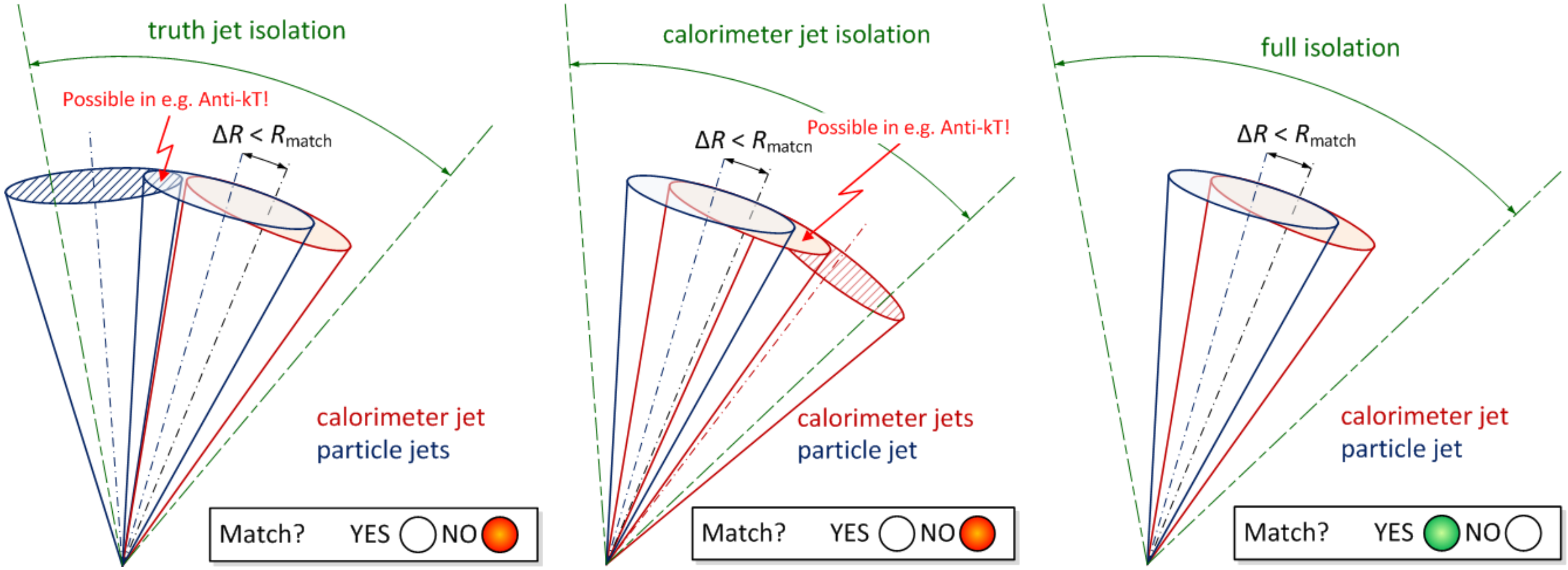
Simulated particle jets

- Establish "true" energy reference to constrain calibration function fits for calorimeter jets
  - Attempt to reconstruct true jet energy
- Need matching definition
  - Geometrical distance
  - Isolation and unique 1-to-1 jet matching

$$\Delta R = \sqrt{(\eta_{\text{particle,jet}} - \eta_{\text{rec,jet}})^2 + (\varphi_{\text{particle,jet}} - \varphi_{\text{rec,jet}})^2}$$

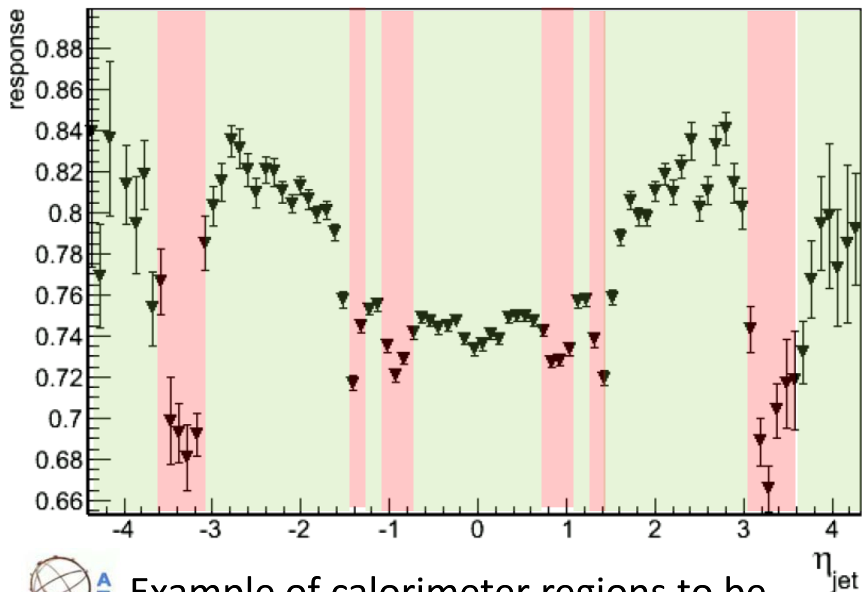


Select matched jet pair

- Typically small matching radius
  - $R_{match} = 0.2 - 0.3$
- Restrict jet directions to regions with good calorimeter response
  - No excessive dead material
  - Away from cracks and complex transition geometries

Calibration functions

- Cell signal weighting
  - Large weights for low density signals
  - Small weights for high density signals
- Sampling layer signal weighting
  - Weights determined by longitudinal energy sharing in calorimeter jet
- Functions can be complex
  - Often highly non-linear systems



Example of calorimeter regions to be considered for jet calibration fits in ATLAS (tinted green). The red tinted regions indicate calorimeter cracks and transitions. The points show the simulated jet response on electro-magnetic energy scale, as function of the jet pseudorapidity.

(figure for illustration purposes only!)

Global Calibration Fits Using Simulations

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$$E_{\text{rec,cell}} = w_{\text{cell}}(\rho_{\text{cell}},\ldots)\cdot E_{0,\text{cell}}$$

$$w_{\text{cell}}(\rho_{\text{cell}},\ldots) \begin{cases} \searrow & \text{for } \rho_{\text{cell}} \uparrow \\ \nearrow & \text{for } \rho_{\text{cell}} \downarrow \end{cases}$$

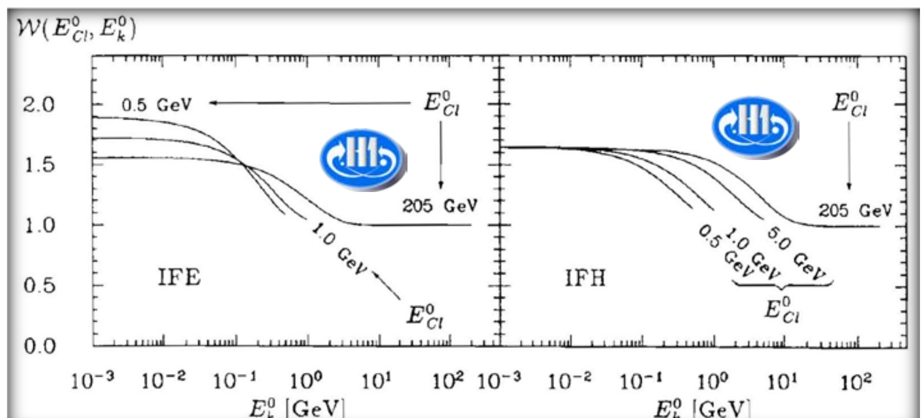
Typical boundary conditions:

$\max(w_{\text{cell}}(\rho_{\text{cell}},\ldots)) \approx 1.5 - 3.0$

(avoid boosting noise!)

$\min(w_{\text{cell}}(\rho_{\text{cell}},\ldots)) = 1.0$

(avoid suppressing em response!)



Example: cell signal weights $\mathcal{W}$, parameterized as function of the cell energy E_k^0 and the cluster energy E_{cl}^0

Global Calibration Fits Using Simulations

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(avoid suppressing em response!)

Example for non-algebraic functional form:

(similar in ATLAS)

$$w_{\mathrm{cell}}(\rho_{\mathrm{cell}},\Re_{\mathrm{cell}}) = \omega_{ij} \text{ for } \begin{cases} \log(\rho)_i \le \log(\rho_{\mathrm{cell}}) < \log(\rho)_{i+1} \\ \Re_{\mathrm{cell}} \in \Re_j \end{cases}$$

$\Re_{\mathrm{cell}}$ is a region descriptor for a given cell,

like $\Re_{\mathrm{cell}} = \underbrace{\{M_{\mathrm{cell}}, S_{\mathrm{cell}}\}}_{\text{calorimeter module id, sampling id}}$

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$$E_{\mathrm{rec},S} = w_S E_{0,S} = w_S \cdot \sum_{\substack{\text{cells in}\\ \text{sampling } S}} E_{0,\mathrm{cell}}$$

Possible parameterizations:

$$w_S = w_S(f_{\mathrm{EMC}}), \text{ with } f_{\mathrm{EMC}} = \frac{\sum_{\substack{\text{jet cells in}\\ EMC}} E_{0,\mathrm{cell}}}{\sum_{\text{all jet cells}} E_{0,\mathrm{cell}}}$$

Example for non-algebraic functional form:

$$w_S(f_{\mathrm{EMC}}) = \omega_{S,i} \text{ for } F_{EMC,i} \leq f_{EMC} < F_{EMC,i+1}$$

Fitting

- Possible constraints
  - Resolution optimization
  - Signal linearity
  - Combination of both
- Regularization of calibration functions
  - Try to linearize function ansatz
  - Use polynomials
  - Can reduce fits to solving system of linear equations
- Non-linear function fitting
  - Use numerical approaches to find (local) minimum for multi-dimensional test functions (e.g., software like MINUIT etc.)

Reconstructed jet energy with cell calibration:

$$E_{\text{rec,jet}} = \sum_{\text{cells in jet}} w_{\text{cell}}(\rho_{\text{cell}}, \Re_{\text{cell}}) \cdot E_{0,\text{cell}}$$

Fit $\{\omega_{ij}\}$ such that...

$$\chi^2 = \sum_{\substack{\text{matching}\\ \text{jet pairs}}} \frac{\left(E_{\text{rec,jet}} - E_{\text{particle,jet}}\right)^2}{\sigma^2_{\text{rec,jet}} + \sigma^2_{\text{particle,jet}}} = \min$$

Reconstructed jet energy with sampling calibration:

$$E_{\text{rec,jet}} = \sum_{S \text{ in jet}} w_S(f_{\text{EMC}}) \cdot E_{0,S}$$

Fit $\{\omega_{i,S}\}$ using the same χ^2 test function!

Note that $\sigma^2_{\text{rec,jet}} \sim E^{-1}_{\text{rec,jet}}$!

Global Calibration Fits Using Simulations

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Attempted de-convolution of signal contributions

- Normalization choice convolutes various jet response features
  - E.g., cell weights correct for dead material and magnetic field induced energy losses, etc.
- Limited de-convolution
  - Fit corrections for energy losses in material between calorimeter modules with different functional form
  - Separation in terms, but still a correlated parameter fit

Reconstructed jet energy with cell calibration:

$$E_{\text{rec,jet}} = \sum_{\text{cells in jet}} w_{\text{cell}}(\rho_{\text{cell}}, \Re_{\text{cell}}) \cdot E_{0,\text{cell}} + E_{\text{DM,jet}}$$

Use χ^2 test function such that...

$$\chi^2 = \sum_{\substack{\text{matching}\\ \text{jet pairs}}} \frac{\left(E_{\text{rec,jet}} - E_{\text{particle,jet}}\right)^2}{\sigma^2_{\text{rec,jet}} + \sigma^2_{\text{particle,jet}}}$$

$$= \sum_{\substack{\text{matching}\\ \text{jet pairs}}} \frac{\left(\left[\sum_{cells\ in\ jet} w_{cell}(\rho_{cell}, \Re_{cell}) \cdot E_{0,cell} + \alpha \cdot \sqrt{E_{0,S=before} \cdot E_{0,S=behind}}\right] - E_{\text{particle,jet}}\right)^2}{\sigma^2_{\text{rec,jet}} + \sigma^2_{\text{particle,jet}}}$$

$$= \min$$

with empirically motivated ansatz for $E_{\text{DM,jet}}$ for dead material between sampling layers $S = \text{before}$ and $S = \text{behind}$, in a combined fit of $\left(\{W_{\text{cell}}\}, \alpha\right)$

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Attempted de-convolution of signal contributions

- Normalization choice convolutes various jet response features
  - E.g., cell weights correct for dead material and magnetic field induced energy losses, etc.
- Limited de-convolution
  - Fit corrections for energy losses in material between calorimeter modules with different functional form
  - Separation in terms, but still a correlated parameter fit

Reconstructed jet energy with cell calibration:

$$E_{\text{rec,jet}} = \sum_{\text{cells in jet}} w_{\text{cell}}(\rho_{\text{cell}}, \Re_{\text{cell}}) \cdot E_{0,\text{cell}} + E_{\text{DM,jet}}$$

Use χ^2 test function such that...

$$\chi^2 = \sum_{\substack{\text{matching}\\ \text{jet pairs}}} \frac{\left(E_{\text{rec,jet}} - E_{\text{particle,jet}}\right)^2}{\sigma^2_{\text{rec,jet}} + \sigma^2_{\text{particle,jet}}}$$

$$= \sum_{\substack{\text{matching}\\ \text{jet pairs}}} \frac{\left(\left[\sum_{cells\ in\ jet} w_{cell}(\rho_{cell}, \Re_{cell}) \cdot E_{0,cell} + \alpha \cdot \sqrt{E_{0,S=before} \cdot E_{0,S=behind}}\right] - E_{\text{particle,jet}}\right)^2}{\sigma^2_{\text{rec,jet}} + \sigma^2_{\text{particle,jet}}}$$

$$= \min$$

Relatively low level of factorization in this particular approach with correlated (by combined fit) parameters!

with empirically motivated ansatz for $E_{\text{DM,jet}}$ for dead material between sampling layers $S = \text{before}$ and $S = \text{behind}$, in a combined fit of $\left(\{W_{\text{cell}}\}, \alpha\right)$

Plots for this session

- Most if not all plots shown in this session are meant as examples and for illustration purposes
  - Educational showcases to highlight certain features of energy scales and calorimeter response
- They do not represent the up-to-date estimates for ATLAS jet reconstruction performance
  - In general much better than the (old) results shown here!
  - Not many new plots can be shown in public yet!
- The performance plots shown are published
  - Reflection of state-of-art at a given moment in time
  - No experimental collision data available at that time!

Summary Of Jet Inputs

Experiment and simulation

Calorimeter towers

2-dim signal objects from all cells or only cells surviving noise suppression (topological towers in ATLAS)

Calorimeter clusters

3-dim signal objects with implied noise suppression (topological clusters in ATLAS)

Tracks

Reconstructed inner detector tracks – only charged particles with $pT > pT_{threshold}$ = 500 MeV – 1 GeV (typically)

Simulation only

Generated stable particles

Typically τ_{lab} > 10 ps to be a signal source

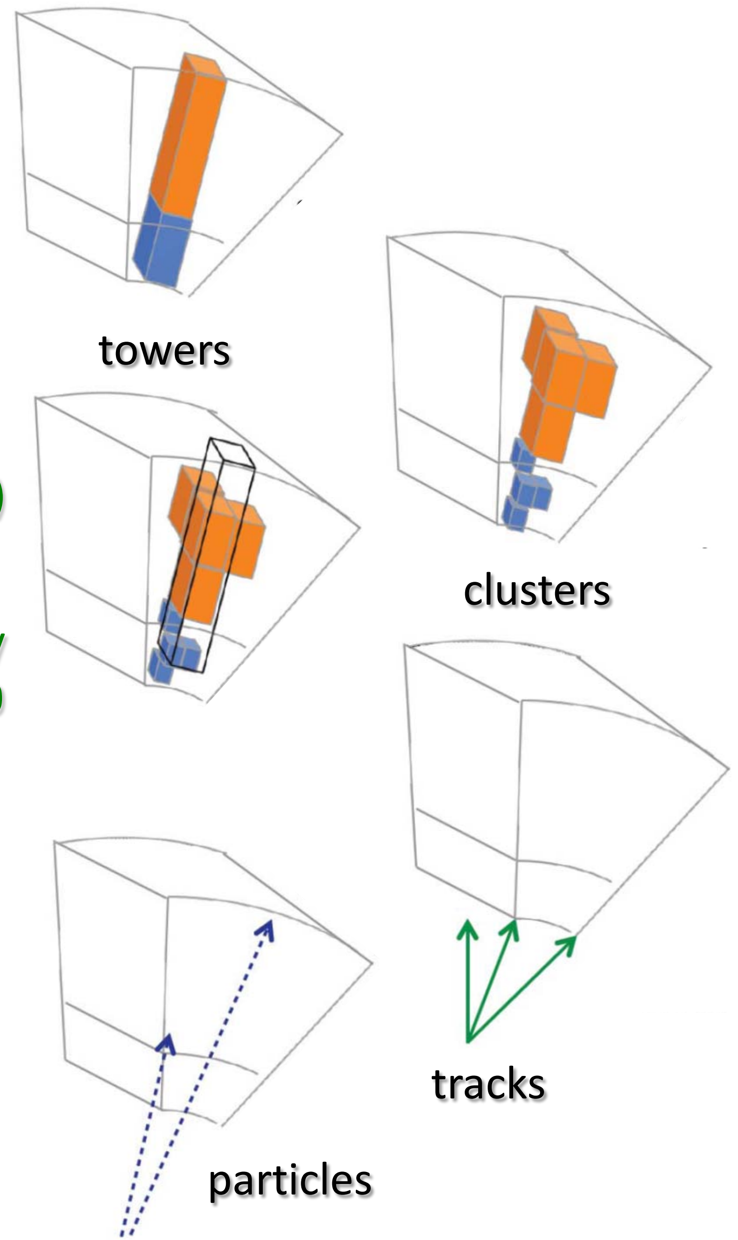

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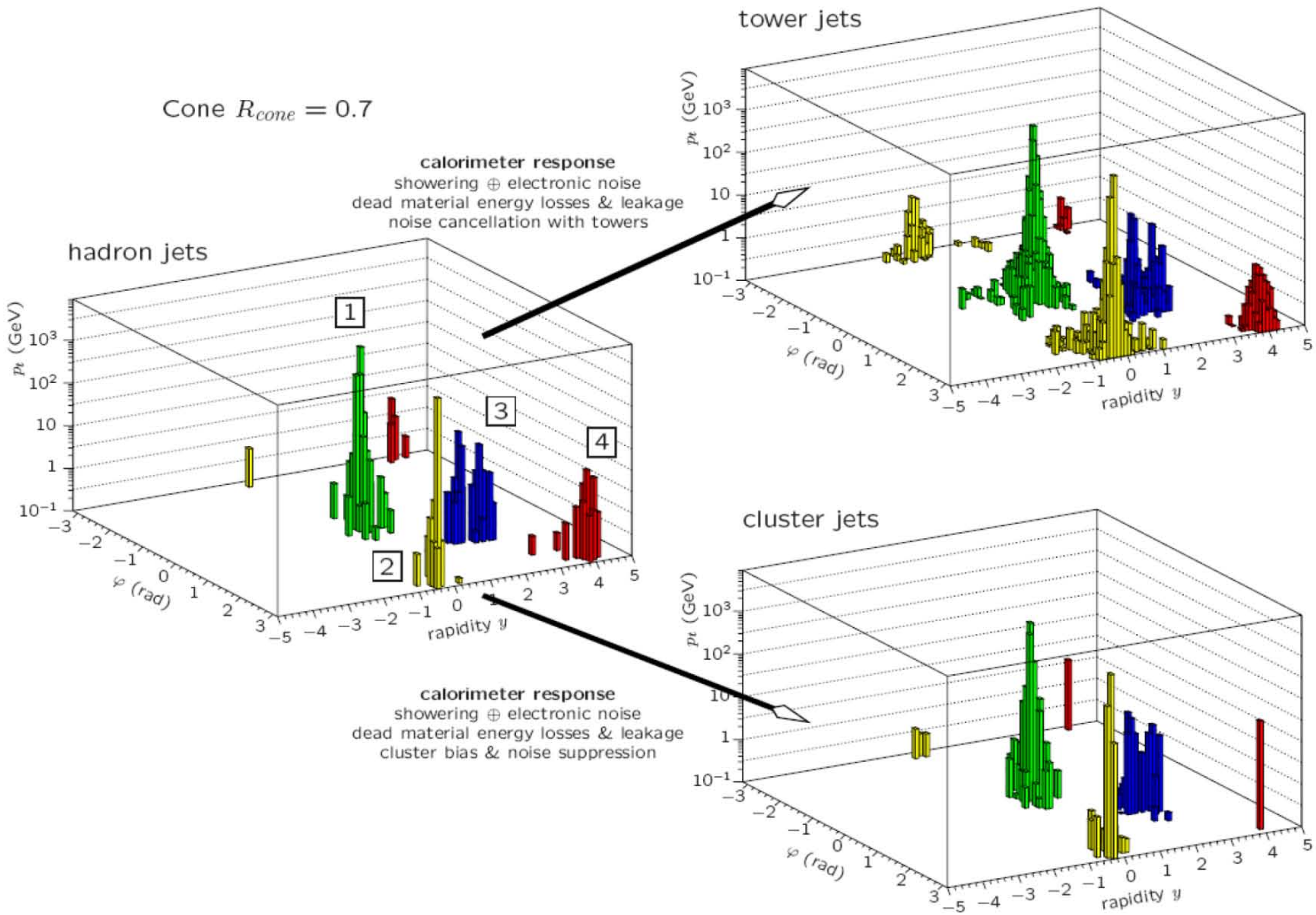
Image Of Jets In Calorimeter

P. Loch
U of Arizona
May 05, 2010



S.D. Ellis, J. Huston, K. Hatakeyama, P. Loch, M. Toennesmann, **Prog.Part.Nucl.Phys.60:484-551,2008**

Calorimeter jet response

- Electromagnetic energy scale
  - Available for all signal definitions
  - No attempt to compensate or correct signal for limited calorimeter acceptance
- Global hadronic energy scale
  - All signal definitions, but specific calibrations for each definition
  - Calibrations normalized to reconstruct full true jet energy in "golden regions" of calorimeter
- Local hadronic energy scale
  - Topological clusters only
  - No jet context – calibration insufficient to recover calorimeter acceptance limitations – no corrections for total loss in dead material and magnetic field charged particles losses)

Unbiased and noise-suppressed towers:

$$\underbrace{\begin{pmatrix} E_{0,\mathrm{jet}} \\ \vec{p}_{0,\mathrm{jet}} \end{pmatrix} = \begin{pmatrix} \sum\limits_{\text{towers in jet}} E_{0,\mathrm{tower}} \\ \sum\limits_{\text{towers in jet}} \vec{p}_{0,\mathrm{tower}} \end{pmatrix}}_{\text{reconstructed calorimeter jet}} < \underbrace{\begin{pmatrix} \sum\limits_{\text{particles in jet}} E_{\mathrm{particle}} \\ \sum\limits_{\text{particles in jet}} \vec{p}_{\mathrm{particle}} \end{pmatrix}}_{\text{matched particle jet (truth reference)}}$$

Topological cell clusters:

$$\underbrace{\begin{pmatrix} E_{0,\mathrm{jet}} \\ \vec{p}_{0,\mathrm{jet}} \end{pmatrix} = \begin{pmatrix} \sum\limits_{\text{clusters in jet}} E_{0,\mathrm{cluster}} \\ \sum\limits_{\text{clusters in jet}} \vec{p}_{0,\mathrm{cluster}} \end{pmatrix}}_{\text{reconstructed calorimeter jet}} < \underbrace{\begin{pmatrix} \sum\limits_{\text{particles in jet}} E_{\mathrm{particle}} \\ \sum\limits_{\text{particles in jet}} \vec{p}_{\mathrm{particle}} \end{pmatrix}}_{\text{matched particle jet (truth reference)}}$$

Note at any scale:

$$m_{\mathrm{jet}} = \sqrt{E_{\mathrm{jet}}^2 - \vec{p}_{\mathrm{jet}}^{\,2}} > 0 \text{ for } N_{\mathrm{towers}}, N_{\mathrm{clusters}} > 1$$

Calorimeter jet response

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  - Topological clusters only
  - No jet context – calibration insufficient to recover calorimeter acceptance limitations – no corrections for total loss in dead material and magnetic field charged particles losses)

Cell based calibration for all calorimeter signals and jets in "golden spot":

$$\begin{pmatrix} E_{\text{rec,jet}} \\ \vec{p}_{\text{rec,jet}} \end{pmatrix} = \overbrace{\begin{pmatrix} \sum\limits_{\text{cells in jet}} w(\rho_{\text{cell}}, \Re_{\text{cell}}) \cdot E_{0,\text{cell}} + E_{\text{DM}} \\ \sum\limits_{\text{cells in jet}} w(\rho_{\text{cell}}, \Re_{\text{cell}}) \cdot \vec{p}_{0,\text{cell}} + E_{\text{DM}} \dfrac{\vec{p}_{0,\text{jet}}}{\left|\vec{p}_{0,\text{jet}}\right|} \end{pmatrix}}^{\text{reconstructed calorimeter jet}} = \underbrace{\begin{pmatrix} \sum\limits_{\text{particles in jet}} E_{\text{particle}} \\ \sum\limits_{\text{particles in jet}} \vec{p}_{\text{particle}} \end{pmatrix}}_{\text{matched particle jet (truth reference)}}$$

(cells are extracted from unbiased or noise suppressed towers or topological clusters forming the jet)

Calorimeter Jet Response

Calorimeter jet response

Electromagnetic energy scale

- Available for all signal definitions
- No attempt to compensate or correct signal for limited calorimeter acceptance

Global hadronic energy scale

- All signal definitions, but specific calibrations for each definition
- Calibrations normalized to reconstruct full true jet energy in "golden regions" of calorimeter

Local hadronic energy scale

- Topological clusters only
- No jet context – calibration insufficient to recover calorimeter acceptance limitations – no corrections for total loss in dead material and magnetic field charged particles losses)

Locally calibrated clusters only:

$$\underbrace{\begin{pmatrix} E_{\text{rec,jet}} \\ \vec{p}_{\text{rec,jet}} \end{pmatrix} = \begin{pmatrix} \sum\limits_{\text{clusters in jet}} E_{\text{rec,cluster}} \\ \sum\limits_{\text{towers in jet}} \vec{p}_{\text{rec,cluster}} \end{pmatrix}}_{\text{reconstructed calorimeter jet}} \leq \underbrace{\begin{pmatrix} \sum\limits_{\text{particles in jet}} E_{\text{particle}} \\ \sum\limits_{\text{particles in jet}} \vec{p}_{\text{particle}} \end{pmatrix}}_{\text{matched particle jet (truth reference)}}$$

Final Jet Energy Scale (JES)

- Final jet calibration
  - All corrections applied
- Best estimate of true (particle) jet energy
  - Flat response as function of pT
  - Uniform response across whole calorimeter
- Relative energy resolution
  - Depends on the calorimeter jet response – calibration applies compensation corrections
- Resolution improvements by including jet signal features
  - Requires corrections sensitive to measurable jet variables
  - Can use signals from other detectors

Determination with simulations

- Measure residual deviations of the calorimeter jet response from truth jet energy
  - Derive corrections from the calorimeter response at a given scale as function of pT (linearity) and pseudorapidity (uniformity) for all particle jets
- Use numerical inversion to parameterize corrections
  - Conversion from truth variable dependence of response to reconstructed variable response

Signal Linearity

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U of Arizona
May 05, 2010

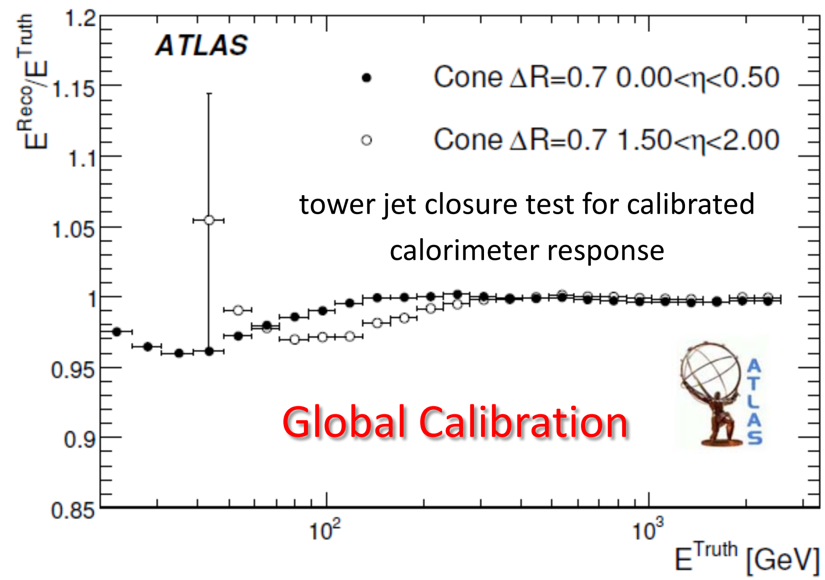
ATLAS plots from **arXiv:0901.0512** [hep-ex]

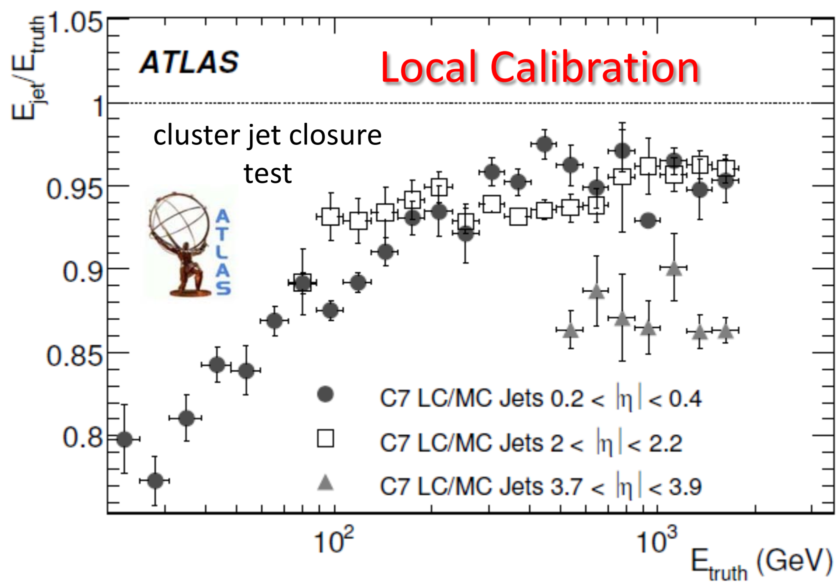
From simulations

- Compare calorimeter response with particle jet energy as function of the particle jet energy
  - All jets, all regions, full kinematic coverage
- Residual deviation from linearity
  - Depend on calorimeter energy scale – large for electromagnetic energy scale and local calibration due to missing jet level corrections
  - Small for global calibration due to jet energy normalization
- Corrections can be extracted from residuals
  - A bit tricky – need to use numerical inversion (see later)

From experiment

- Validate and extract calibrations from collision data
  - W boson mass in hadronic decay is jet energy scale reference
  - pT balance of electromagnetic signal (Z boson, photon) and jet
- Note change of reference scale
  - In-situ channels provide interaction (parton) level truth reference!





ATLAS plots from **arXiv:0901.0512** [hep-ex]

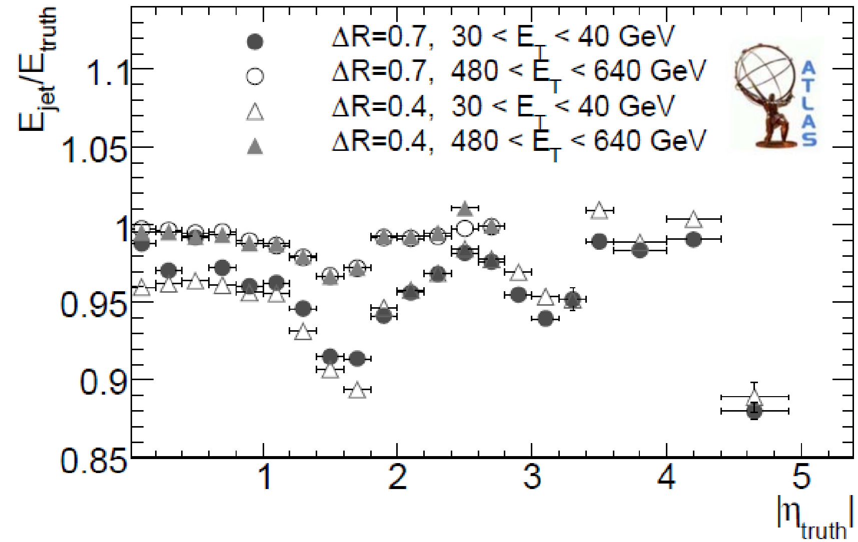
Simulations

- Compare calorimeter response with particle jet energy as function of the jet direction
  - All jets in full kinematic range
- Residual non-uniformities expected in cracks
  - Only jets in "golden regions" used for calibration

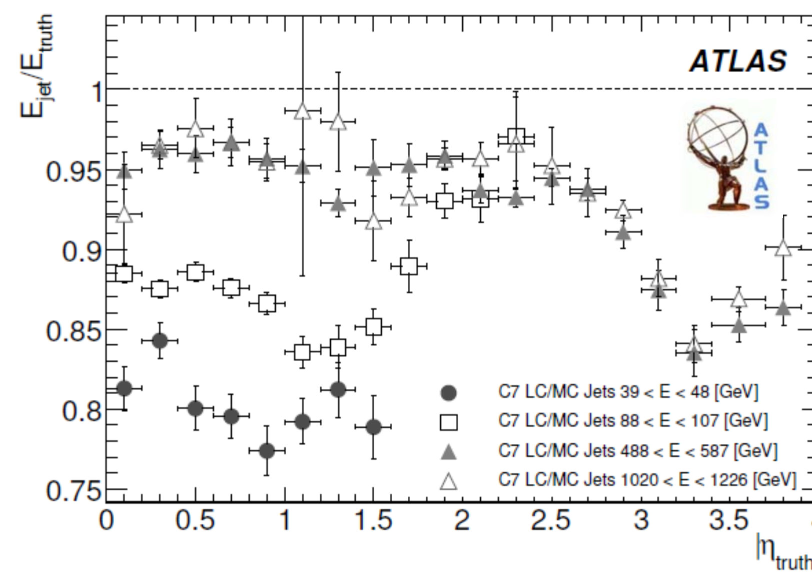
From experiment

- Di-jet pT balance
  - Balance pT of well calibrated jet in "golden region" with jet in other calorimeter regions
  - Can also use photon pT balance with jets outside of "golden region"

Global Calibration



Local Calibration



Relative Jet Energy Resolution

ATLAS plots from **arXiv:0901.0512** [hep-ex]

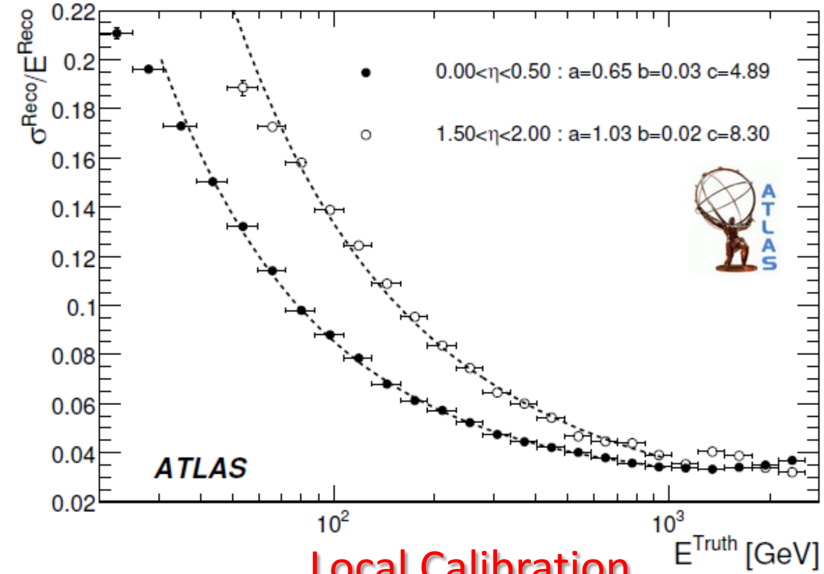
Simulations

- Measure fluctuations of calorimeter jet energy as function of truth jet energy
  - All jets in full kinematic range and in various regions of pseudo-rapidity

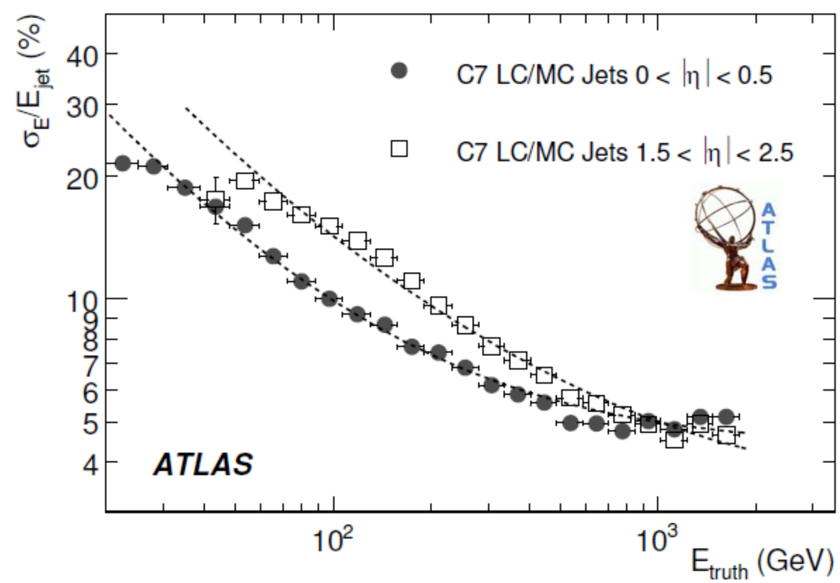
From experiment

- Di-jet final states
  - Measure relative fluctuations of jet energies in back-to-back (pT) balanced di-jets

Global Calibration



Local Calibration



JES Calibration Parameterizations

Golden rule of calorimetric energy measurement

- The fully calibrated calorimeter signal is most probably the true jet (or particle) energy
  - Interpretation holds only for symmetrically distributed fluctuations – mean value is identical to average value
- The resolution of the measurement is given by the characteristics of the signal fluctuations
  - Can only be strictly and correctly understood in case of Gaussian response distributions
- We need a normally distributed response!

Problem for all calibration techniques

- Residual deviations from expected jet reconstruction performance must be measure as function of true quantities
  - Only then is the fluctuation of the response $R = E_{reco}/E_{true}$ really Gaussian after calibration
- But need to apply corrections to measured jets
  - Need parameterization as function of reconstructed quantities
  - Simple re-binning does not maintain the Gaussian characteristics of the fluctuations – hard to control error!
- Use numerical inversion to transfer the calibrations from true to measured parameters
  - Maintains Gaussian character

Understanding Response Fluctuations

Toy model

- Generate flat jet energy spectrum
  - Uniform energy distribution for E_{jet} in $[E_{min}, E_{max}]$
- Smear true jet energy with Gaussian
  - Assume perfect average calibration
  - Width of distribution follows calorimetric energy resolution function
- Calculate the response
  - In bins of E_{true} and in bins of $E_{smear} = E_{reco}$
- Repeat exercise with steeply falling energy spectrum

Calibrated response:

$$\langle E_{smear} \rangle = \langle E_{reco} \rangle = \langle E_{true} \rangle$$

Calorimeter resolution function (no noise):

$$\frac{\sigma_E}{E} = \sqrt{\frac{a^2}{E_{true}} + c^2}$$

Smeared energy:

$$E_{smear} = E_{true} + r \cdot \sigma_E$$

r is a random number following the Gaussian PDF:

$$g(r) = \frac{1}{\sqrt{2\pi}} \exp\left[-\frac{1}{2} r^2\right]$$

i.e. distributed around 0 with a width of 1

Response fluctuations:

$$R = \frac{E_{smear} - E_{true}}{E_{true}} \text{ with } \langle R \rangle = 0$$

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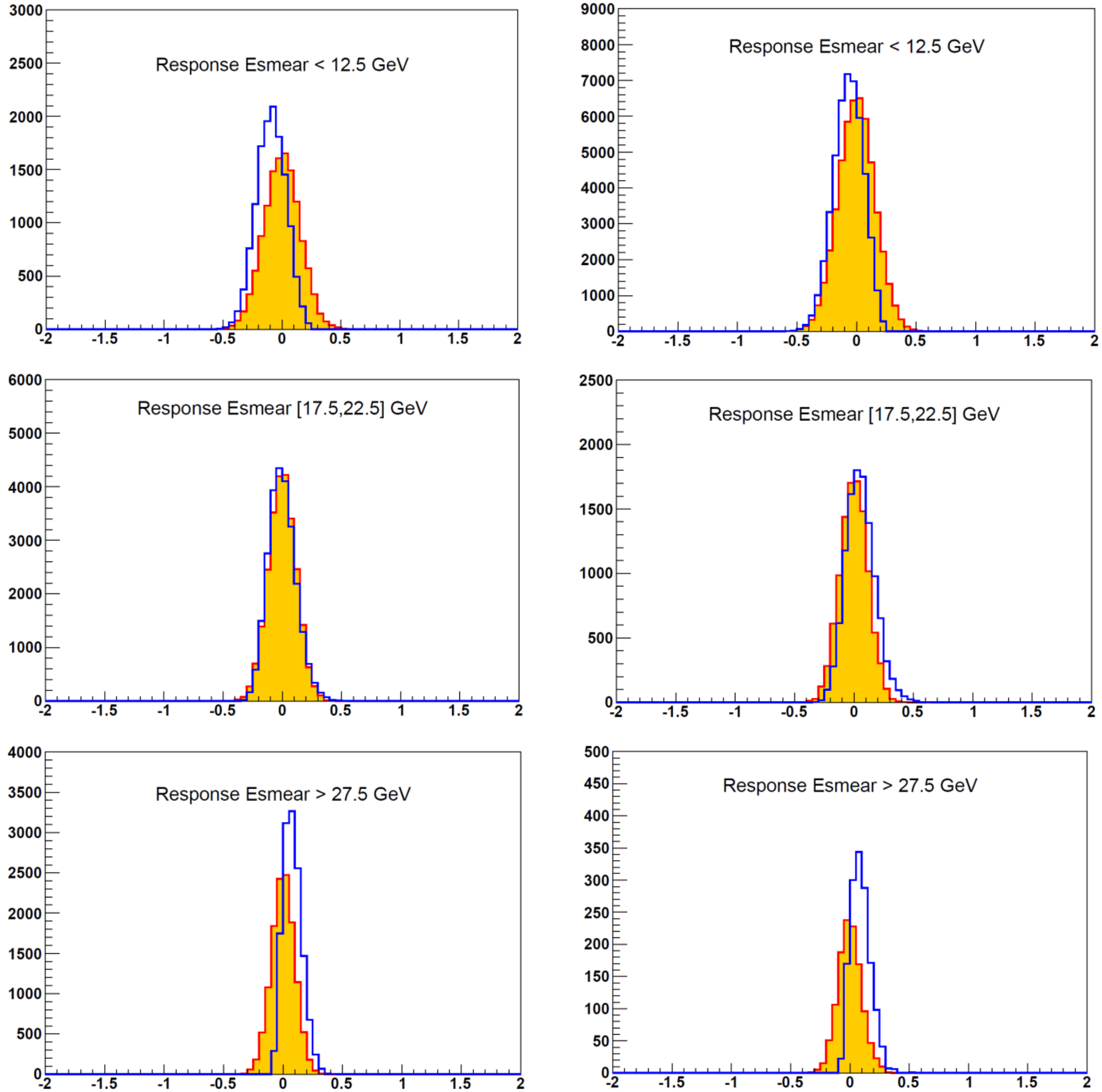
Response Distributions

P. Loch
U of Arizona
May 05, 2010

$p(E_{true}) = const$ $\qquad$ $p(E_{true}) \propto E_{true}^{-4}$



binned in E_{true}

binned in E_{smear}

Lower edge of E spectrum

Center of E spectrum

High end of E spectrum

ATLAS

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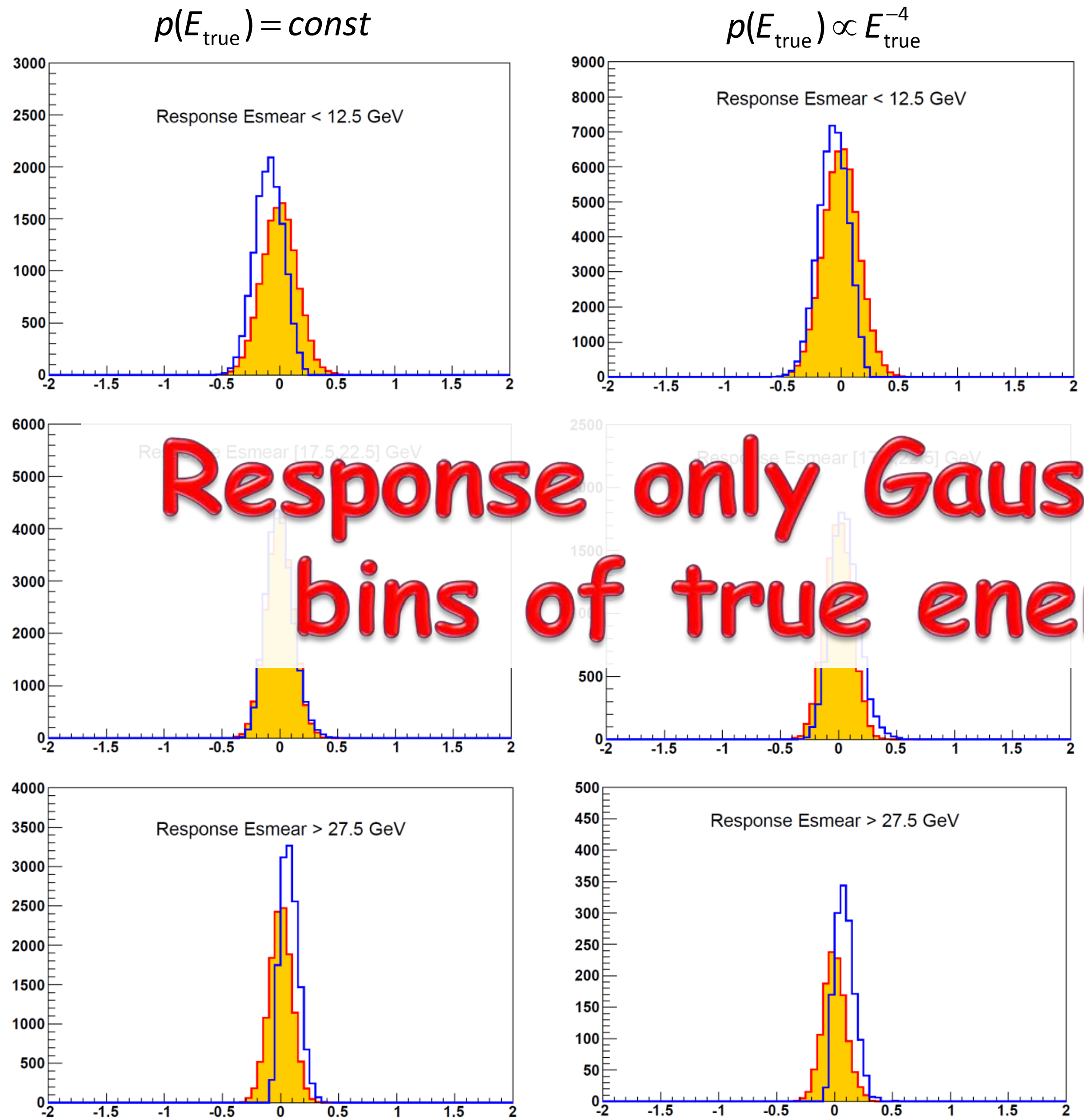
Response Distributions



binned in E_{true}

binned in E_{smear}

Lower edge of *E* spectrum

Center of *E* spectrum

High end of *E* spectrum

Response only Gaussian in bins of true energy!

Numerical Inversion

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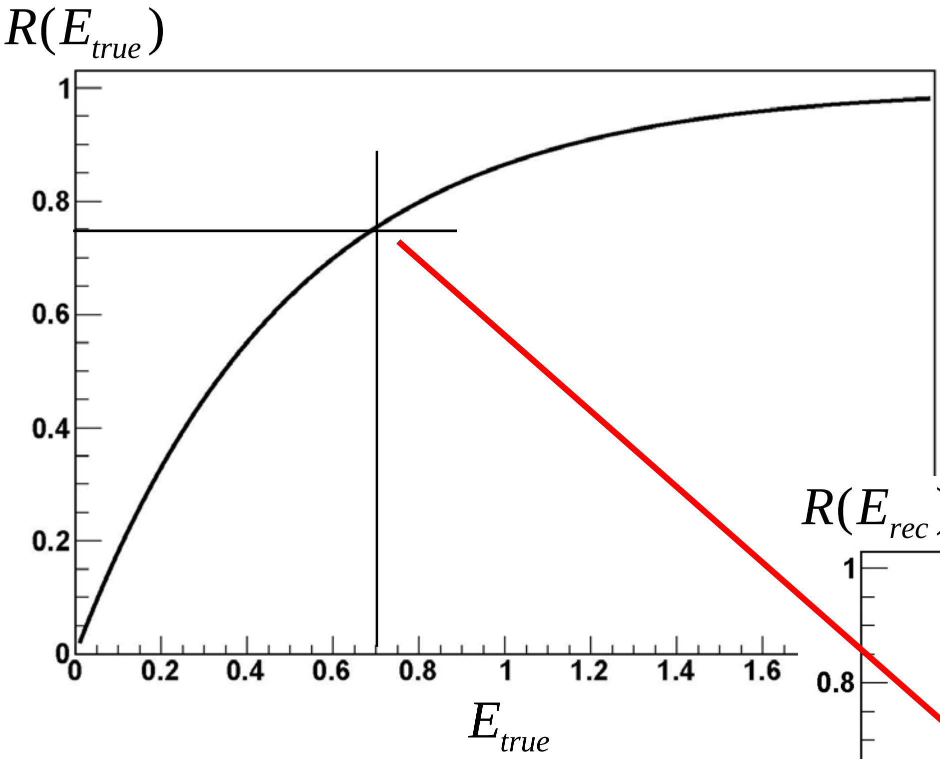
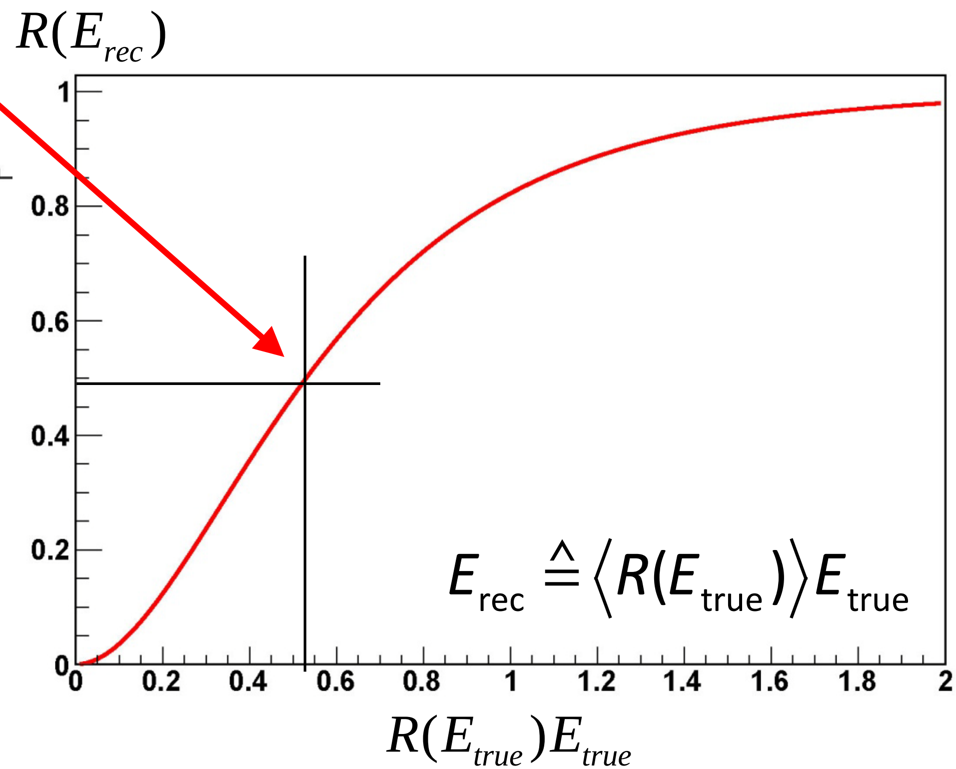
Transfer of response function from dependence on true variable to dependence on measured variable



$$R(E_{\mathrm{rec}}) = R\left(\left\langle R(E_{\mathrm{true}})\right\rangle \cdot E_{\mathrm{true}}\right)$$



$$E_{\mathrm{rec}} \triangleq \left\langle R(E_{\mathrm{true}})\right\rangle E_{\mathrm{true}}$$

Numerical Inversion Functions

P. Loch
U of Arizona
May 05, 2010

Often simple functions

- Address residual energy (pT) and direction dependence of calorimeter jet response
  - Determine response functions *R* in bins of true jet pT and reconstructed pseudo-rapidity $\eta_{\mathrm{rec,jet}}$
  - Apply numerical inversion to determine calibration functions in reconstructed variable space ($p_{\mathrm{T,rec,jet}}$, $\eta_{\mathrm{rec,jet}}$)
- Use calibration functions to get jet energy scale
  - Technique can be applied to locally or globally calibrated jet response, with likely different calibration functions

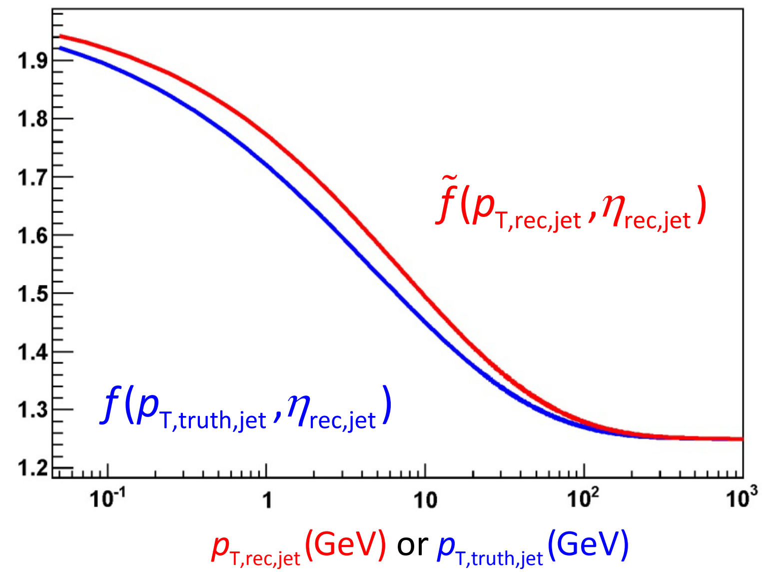
$$f(p_{\mathrm{T,truth,jet}},\eta_{\mathrm{reco,jet}}) = R^{-1}(p_{\mathrm{T,truth,jet}},\eta_{\mathrm{reco,jet}})$$

with $\eta_{\mathrm{reco,jet}} \simeq \eta_{\mathrm{truth,jet}}$ and

$$R^{-1}(p_{\mathrm{T,truth,jet}},\eta_{\mathrm{reco,jet}}) = \left\langle \frac{E_{\mathrm{truth,jet}}}{E_{\mathrm{rec,jet}}} \right\rangle (p_{\mathrm{T,truth,jet}},\eta_{\mathrm{reco,jet}})$$

then apply numerical inversion

$$f(p_{\mathrm{T,truth,jet}},\eta_{\mathrm{reco,jet}}) \overset{\text{numerical inversion}}{\longmapsto} \tilde{f}(p_{\mathrm{T,reco,jet}},\eta_{\mathrm{reco,jet}})$$



Numerical Inversion Functions

Often simple functions

- Address residual energy (pT) and direction dependence of calorimeter jet response
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- Use calibration functions to get jet energy scale
  - Technique can be applied to locally or globally calibrated jet response, with likely different calibration functions

global calibration:

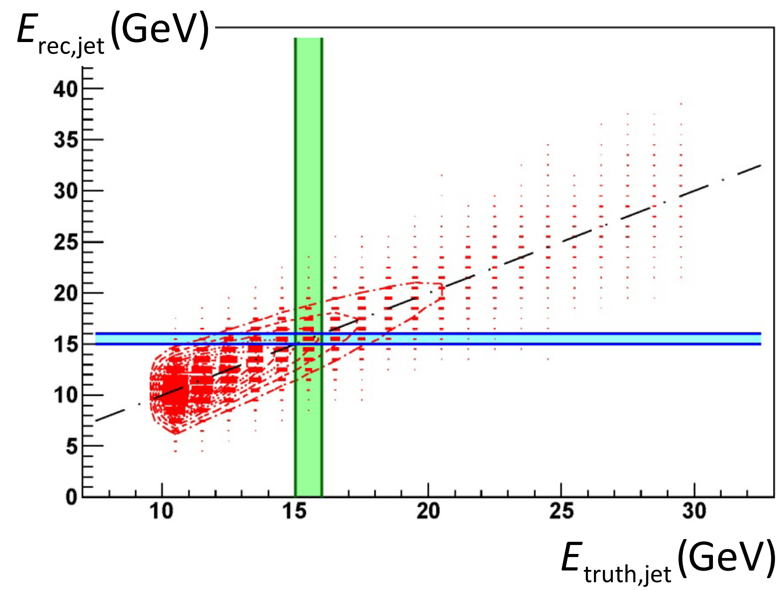
$$\begin{pmatrix} E_{\mathrm{calib,jet}} \\ \vec{p}_{\mathrm{calib,jet}} \end{pmatrix} = \tilde{f}(p_{\mathrm{T,reco,jet}}, \eta_{\mathrm{reco,jet}}) \cdot \begin{pmatrix} \overbrace{\sum_{\substack{\text{cells in}\\ \text{jet}}} w(\rho_{\mathrm{cell}}, \Re_{\mathrm{cell}}) \cdot E_{0,\mathrm{cell}} + E_{\mathrm{DM}}}^{E_{\mathrm{reco,jet}}} \\ \underbrace{\sum_{\substack{\text{cells in}\\ \text{jet}}} w(\rho_{\mathrm{cell}}, \Re_{\mathrm{cell}}) \cdot \vec{p}_{0,\mathrm{cell}} + E_{\mathrm{DM}} \frac{\vec{p}_{0,\mathrm{jet}}}{|\vec{p}_{0,\mathrm{jet}}|}}_{\vec{p}_{\mathrm{reco,jet}},\ \text{with } p_{\mathrm{T,reco,jet}} = |\vec{p}_{\mathrm{reco,jet}}| \sqrt{1-\tanh^2 \eta_{\mathrm{reco,jet}}}} \end{pmatrix}$$

local calibration:

$$\begin{pmatrix} E_{\mathrm{calib,jet}} \\ \vec{p}_{\mathrm{calib,jet}} \end{pmatrix} = \tilde{f}'(p_{\mathrm{T,reco,jet}}, \eta_{\mathrm{reco,jet}}) \cdot \begin{pmatrix} \sum_{\substack{\text{clusters in}\\ \text{jet}}} E_{\mathrm{rec,cluster}} \\ \sum_{\substack{\text{towers in}\\ \text{jet}}} \vec{p}_{\mathrm{rec,cluster}} \end{pmatrix}$$

Why not use direct relation between reconstructed and true energy?

- Same simulation data input
  - Has been used in some experiments
- Dependence on truth energy spectrum
  - Need to make sure calibration sample is uniform in truth energy
  - Alternatively, unfold driving truth energy spectrum
- Residual non-gaussian behaviour of truth energy distribution
  - Error on reconstructed energy hard to understand
  - Could still use response distribution → same issues as discussed on previous slide!



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$E_{\mathrm{rec,jet}}$ Versus $E_{\mathrm{truth,jet}}$

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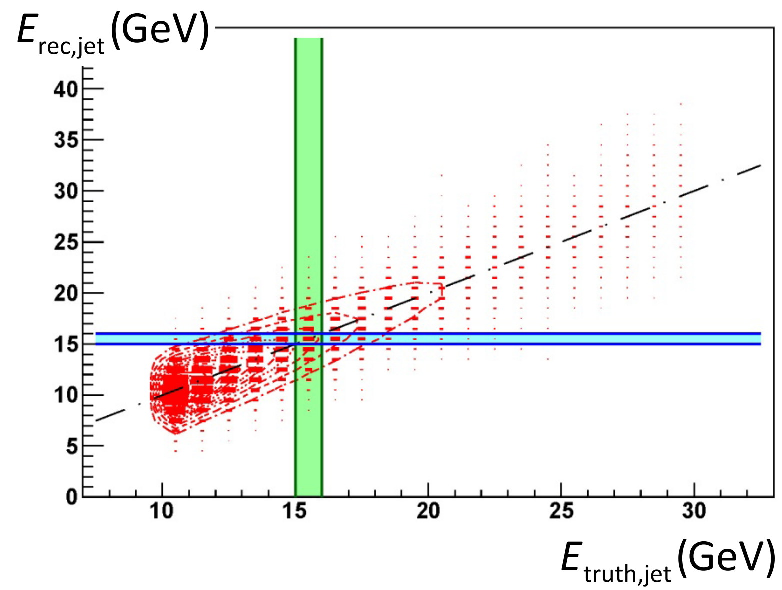

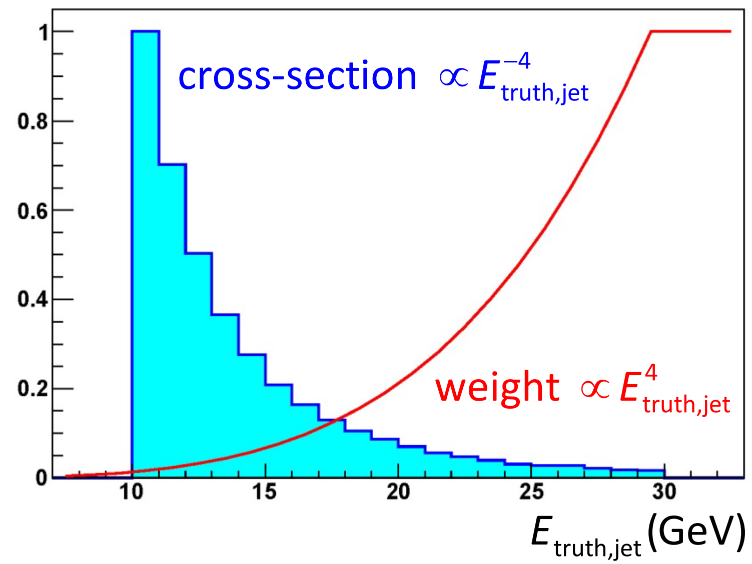

ATLAS

$E_{rec,jet}$ Versus $E_{truth,jet}$

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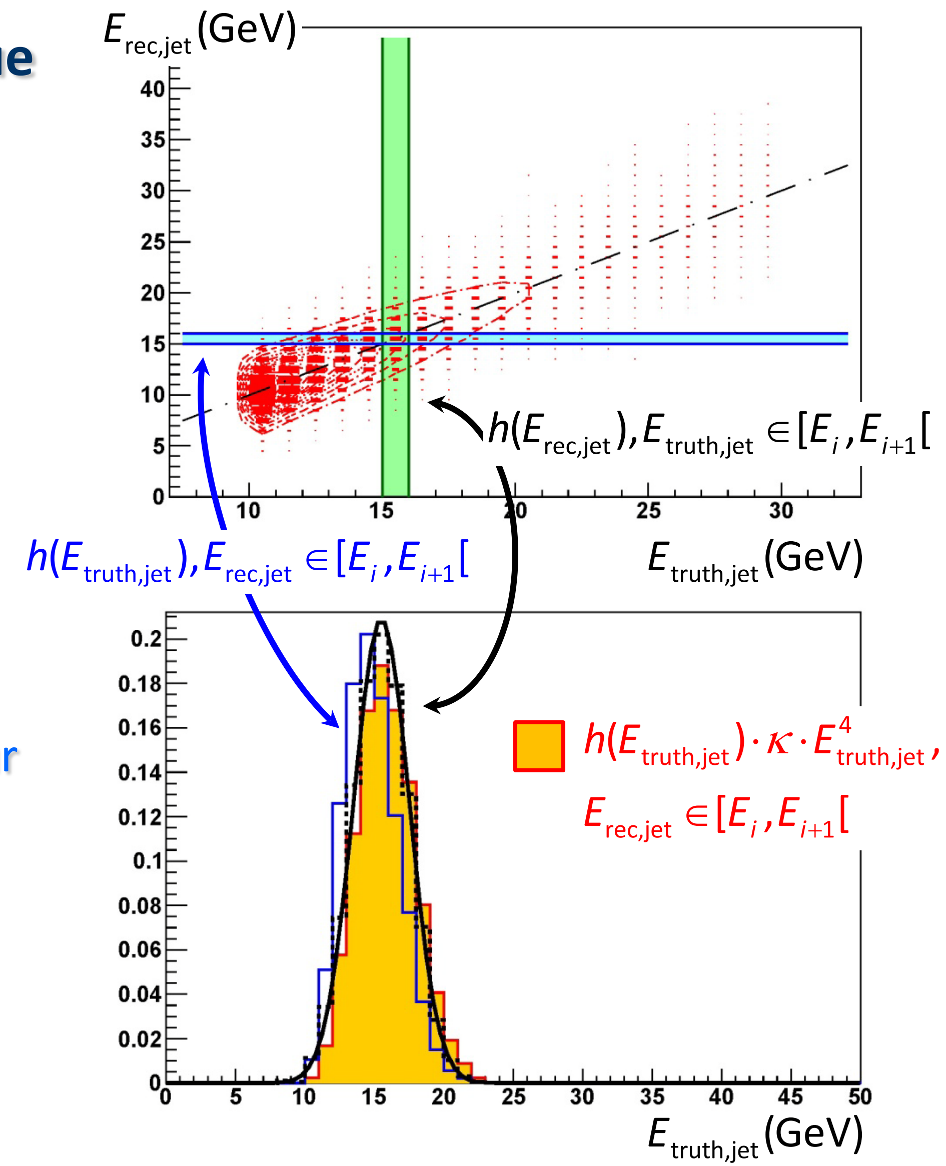

Systematic Error

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Strategy from simulations

- Determine all calibrations with fixed conditions
  - Ideal detector model – everything is aligned
  - Fixed (best) GEANT4 shower model – from testbeam evaluations
  - Fixed calorimeter signal definition – e.g., towers
  - Fixed jet definition – like seeded cone with size 0.7
  - Fixed final state – QCD di-jets preferred
- Study change in performance for changing conditions with ideal calibration applied
  - Detector misalignment and changes in material budgets
  - Different shower GEANT4 model
  - Different calorimeter signal definitions – e.g., clusters
  - Different jet definitions – e.g., kT, AntikT, different cone or cone sizes…
  - Different physics final state – preferably more busy ones like SUSY, ttbar,…
- Use observed differences as systematic error estimates

Use of collision data

- Compare triggered final states with simulations
  - Level of comparison represents understanding of measurement – systematic error (at least for standard final states)
- Use in-situ final states to validate calibration
  - Careful about biases and reference levels (see session 9)

Performance Evaluation

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- **Calibration functions determined with "perfect" detector description and one reference jet definition**
  - Validate performance in perfect detector
    - Signal linearity & resolution
- **Quality of calibration for a real detector**
  - A priori unknown real detector
    - Absolute and relative alignments, inactive material distributions
  - Estimate effect of distorted (real) detector
    - Implement realistic assumptions for misalignment in simulations
    - Small variations of inactive material thicknesses and locations
    - But use "perfect" calibration for reconstruction
- **Change jet signals**
  - Tower or clusters
    - E.g, change from reference calorimeter signal
  - Different jet finder
    - E.g., use kT instead of cone
  - Different configuration
    - E.g., use narrow jets (cone size 0.4) instead of wide jets (0.7)

Signal Linearity & Resolution

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May 05, 2010

ATLAS plots from **arXiv:0901.0512** [hep-ex]

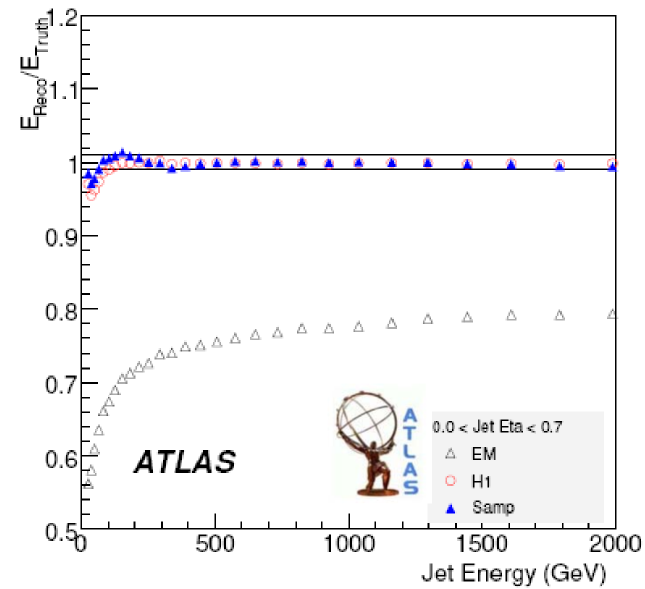
Response

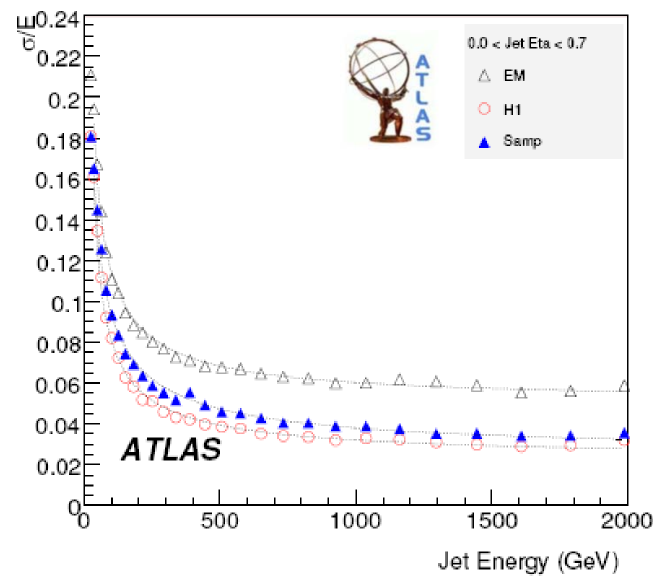
- Linear within +/-1% after calibration applied for pT>100 GeV
  - Clear improvement compared to basic signal scale
- Problems with low pT regime
  - ATLAS limit pT>20-40 GeV, depending on luminosity
  - May be resolution bias – under study

Resolution

- Jet energy resolution clearly improved by calibration as well
  - Slight dependence on calibration strategy
- Close to required performance

$$\frac{\sigma}{E} \approx \frac{65\%}{\sqrt{E}} \oplus 3\%$$





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Signal Uniformity

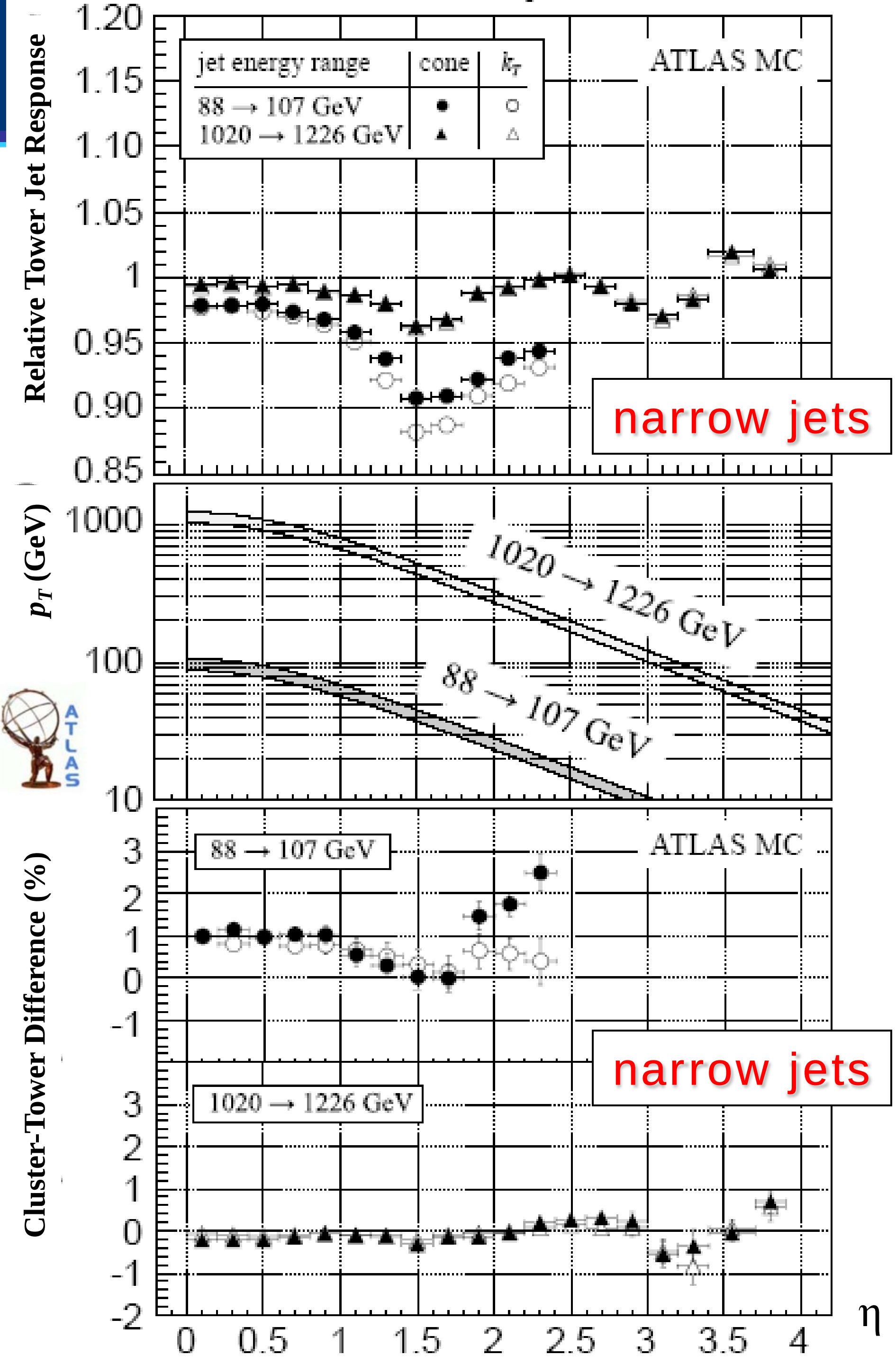
ATLAS plots from **arXiv:0901.0512** [hep-ex]

Characterizes "real" detector jet response

- Variation of response with direction
- Changing inactive material distribution
- Cracks between calorimeter modules

Variations

- No strong dependence on calorimeter signal definition
  - Towers/clusters
- ATLAS cone jet performs better in crack region at low pT



Deviation From Signal Linearity

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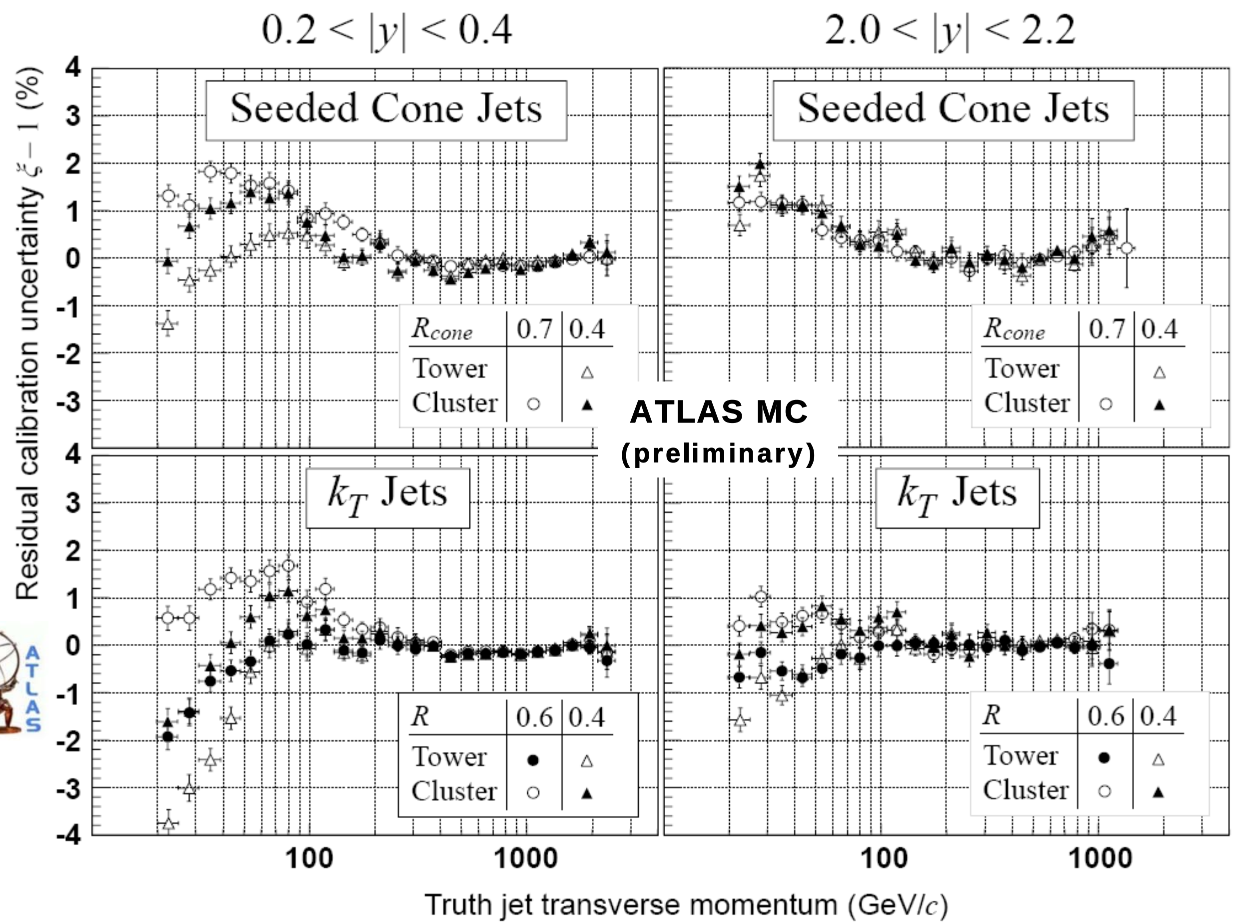
Estimated effect of a distorted detector

ATLAS plots from **arXiv:0901.0512** [hep-ex]

Effect of detector distortion depends on jet size, calo signal choice, and kinematic domain



$$\xi = \frac{\left(E_{\text{rec,jet}} / E_{\text{truth,jet}}\right)_{\text{distorted}}}{\left(E_{\text{rec,jet}} / E_{\text{truth,jet}}\right)_{\text{ideal}}}$$

Resolution Direction Dependence

ATLAS plots from **arXiv:0901.0512** [hep-ex]

Larger fluctuations for kT jets at low pT

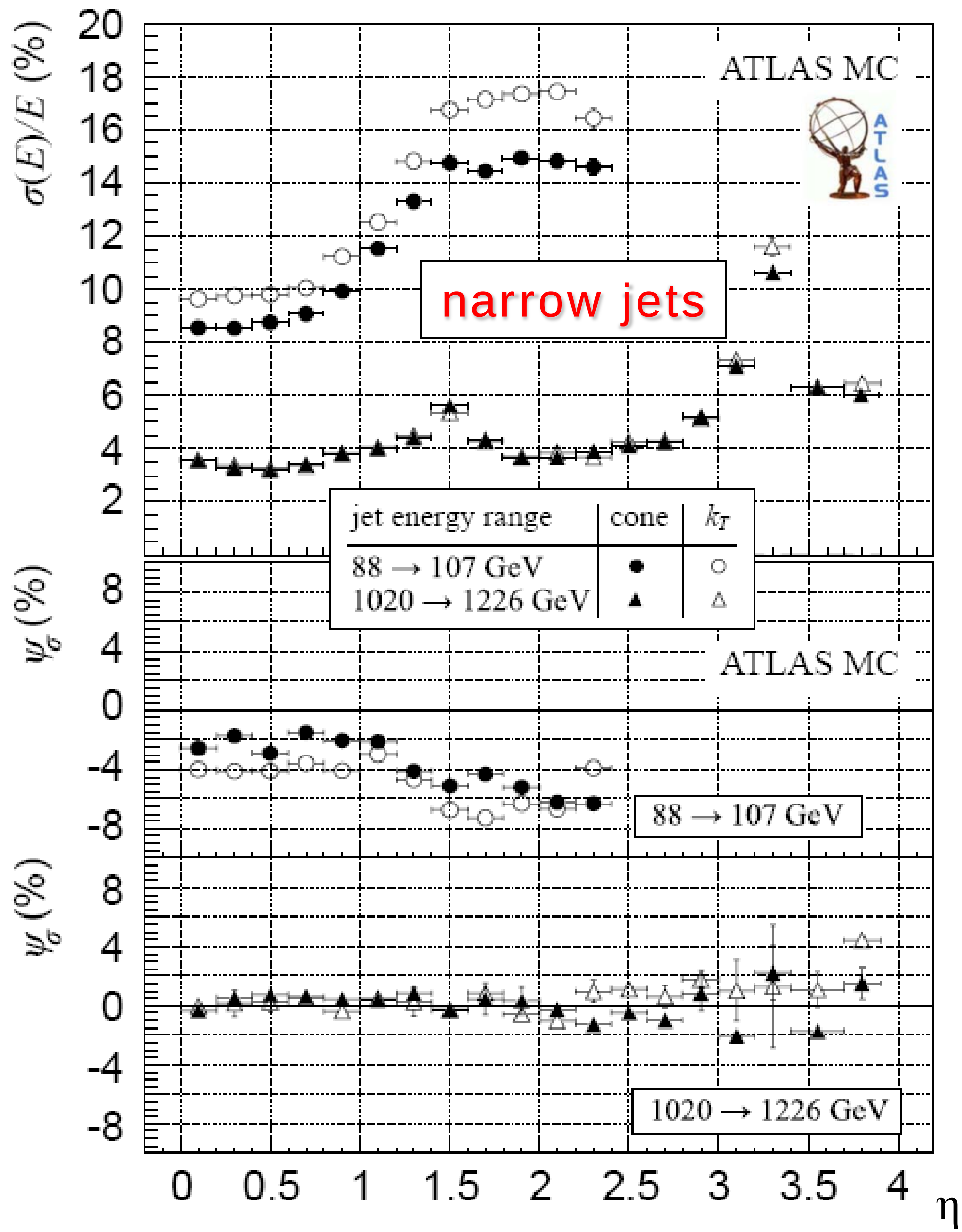
- Vacuum effect for tower jets?
- Less pronounced for cluster jets
  - Noise suppression important in this domain

Very similar resolutions at high pT

- No strong dependence on jet definition
- No strong dependence on calorimeter signal definition
  - No significant noise contribution anymore

$$\Delta_\sigma = \left(\frac{\sigma}{E}\right)^2_{\text{cluster}} - \left(\frac{\sigma}{E}\right)^2_{\text{tower}}$$

$$\psi_\sigma = \begin{cases} \sqrt{\Delta_\sigma} & \text{for } \Delta_\sigma > 0 \\ -\sqrt{-\Delta_\sigma} & \text{for } \Delta_\sigma < 0 \end{cases}$$



Different Final States: Quark Jets

P. Loch
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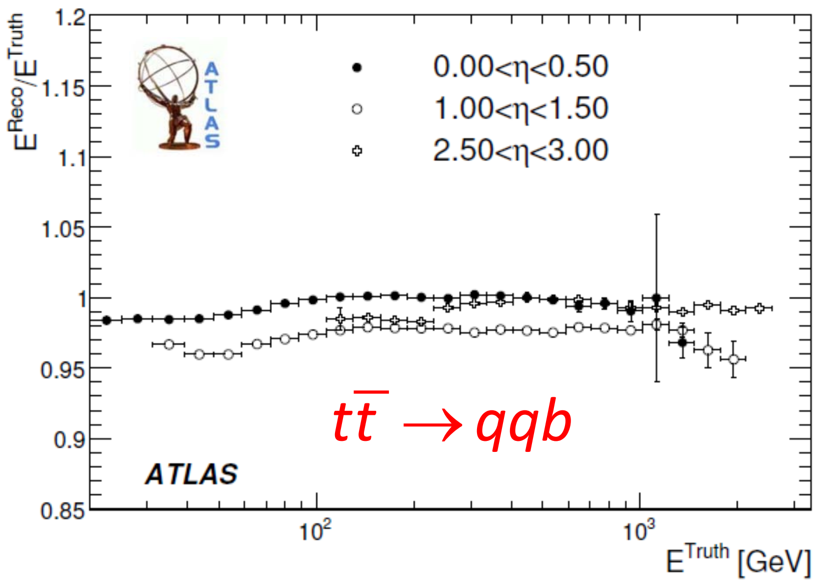
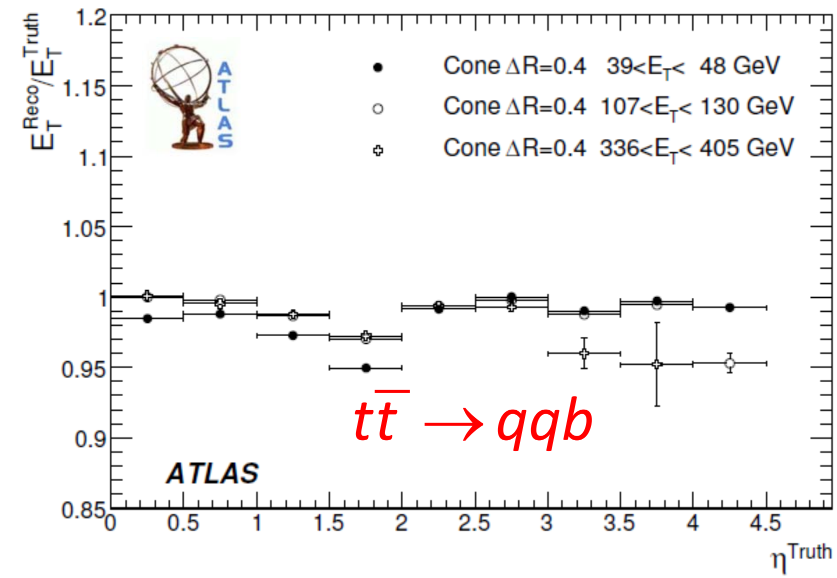
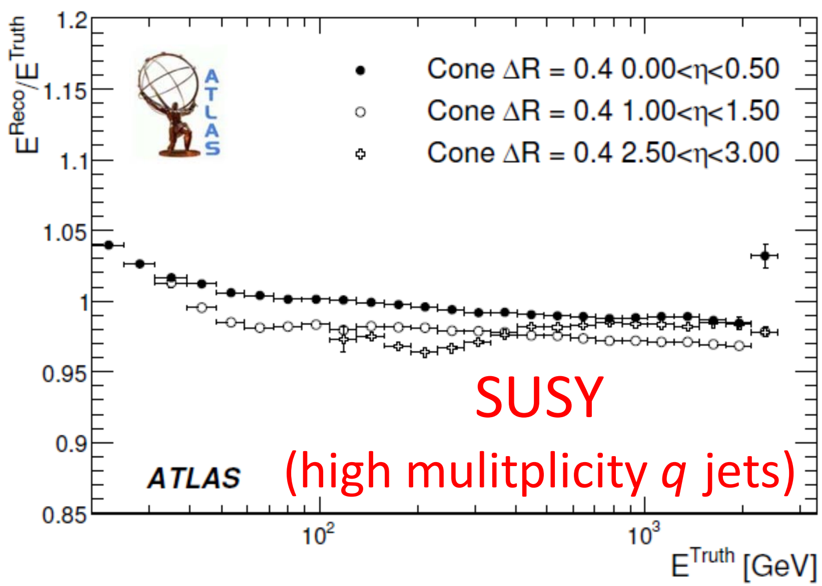
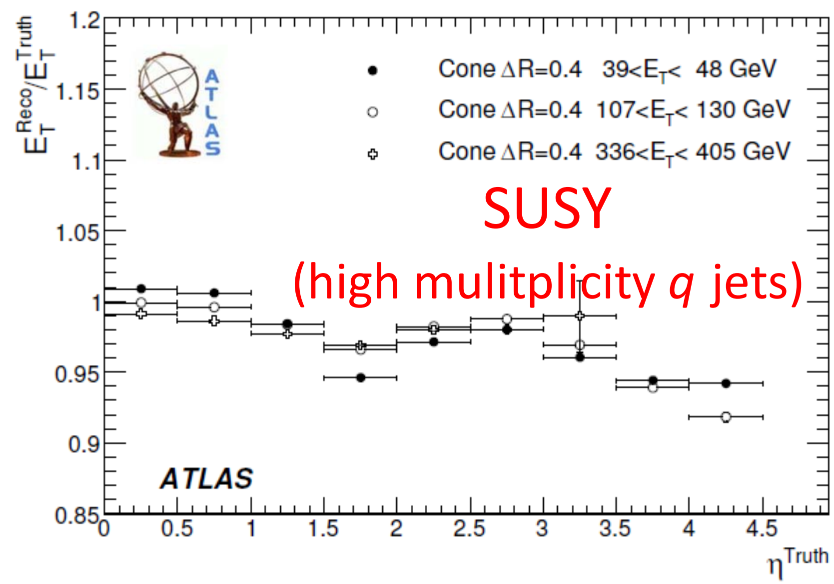
May 05, 2010

ATLAS plots from **arXiv:0901.0512** [hep-ex]









CMS Factorized Jet Calibration

P. Loch
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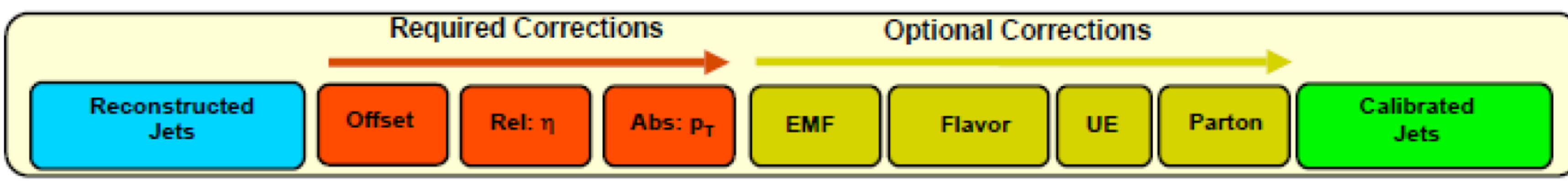
May 05, 2010

Factorized calibration allows use of collision data

- CMS sequence applies factorized scheme with required and optional corrections
- Required corrections can initially be extracted from collision data
  - Average signal offset from pile-up and UE can be extracted from minimum bias triggers
  - Relative direction dependence of response can be corrected from di-jet pT balance
  - The absolute pT scale correction can be derived from prompt photon production
- Optional corrections refine jet calibration
  - Use jet by jet calorimeter or track observables to reduce fluctuations
  - Includes energy fractions in EMC, track pT fractions, underlying event corrections using jet areas, flavor dependencies and others…
  - May need very good simulations!



Correct CaloJets to have same pT as GenJet on average

correcctions back to parton level quantities

ATLAS JES Correction Model for First Data

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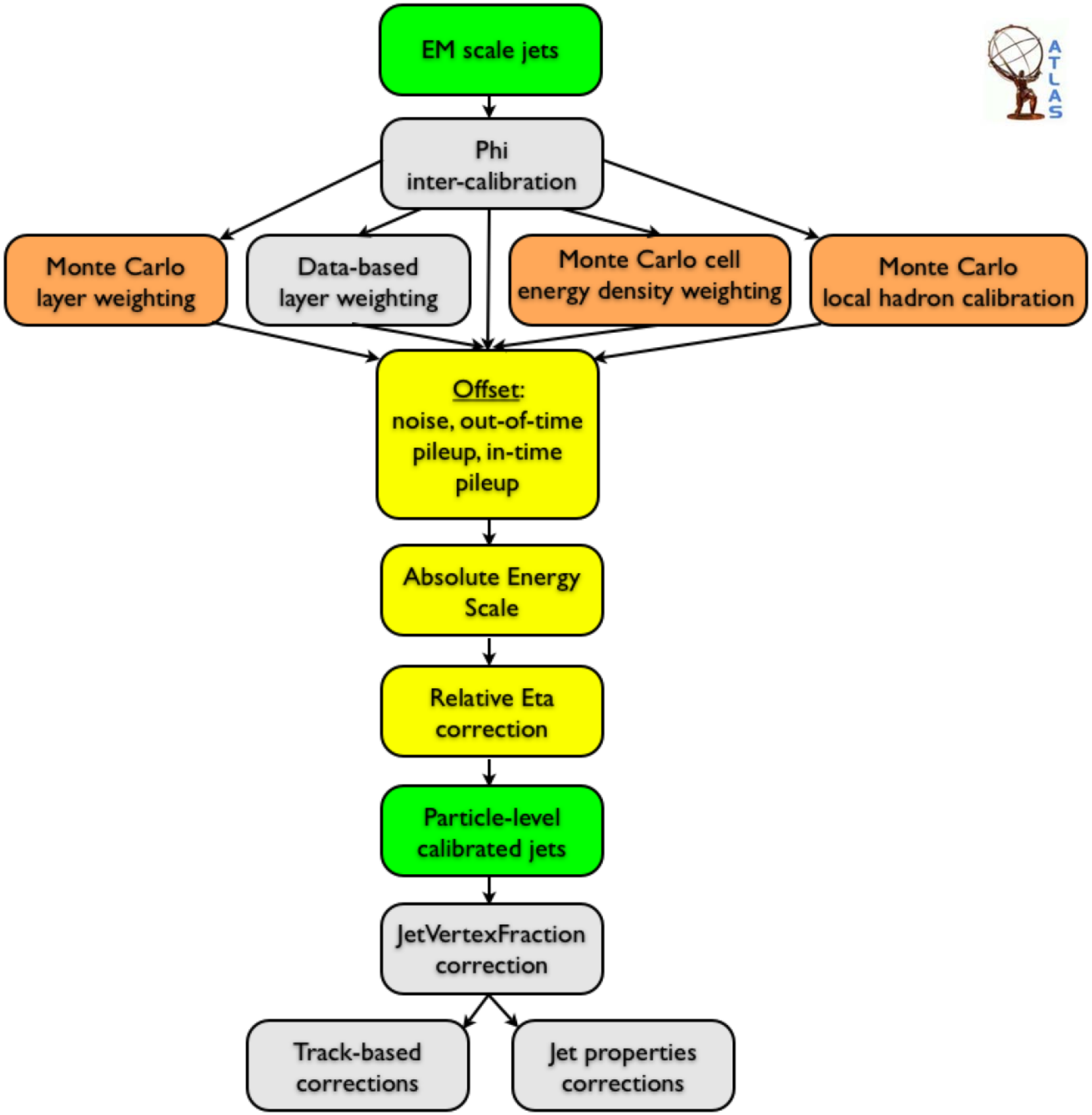
optional

data driven

MC



Data Driven JES Corrections: PileUp

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May 05, 2010

PileUp subtraction

Goal:

Correct in-time and residual out-of-time pile-up contribution to a jet on average

Tools:

Zero bias (random) events, minimum bias events

Measurement:

Et density in Δη × Δφ bins as function of

vertices

TopoCluster feature (size, average energy as function of depth) changes as function of # vertices

Remarks:

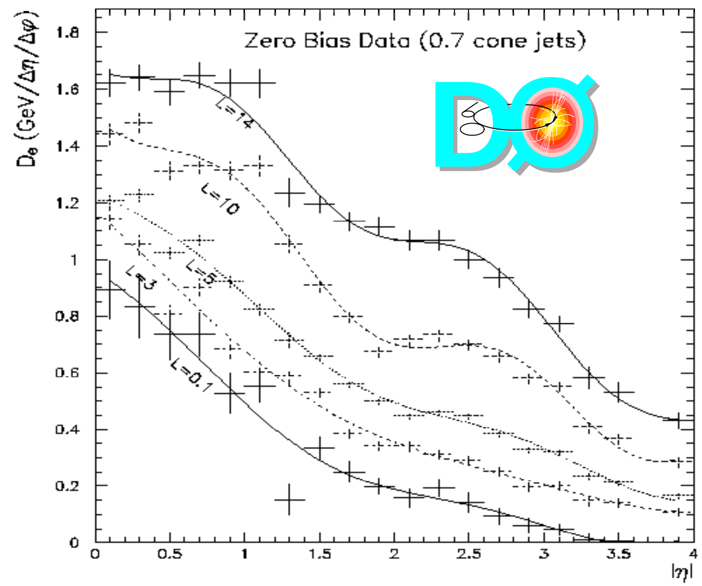
Uses expectations from the average Et flow for a given instantaneous luminosity

Instantaneous luminosity is measured by the # vertices in the event

Requires measure of jet size (AntiKt advantage)

Concerns:

Stable and safe determination of average



Determination of the Absolute Jet Energy Scale in the D0 Calorimeters. NIM A424, 352 (1999)

$$\rho_{\text{PU}}(\eta,\mathcal{L}) = \rho_{\text{PU}}(\eta,N_{\text{vtx}}) = \frac{\left\langle E_{\text{T}}^{\text{PU}}\right\rangle(\eta,N_{\text{vtx}})}{\Delta\eta\times\Delta\varphi}$$

$$E_{\text{offset,jet}}^{\text{PU}} = \underbrace{\rho_{\text{PU}}(\eta,N_{\text{vtx}})\cdot\overbrace{A_{\text{jet}}}^{\text{jet area}}}_{E_{\text{T,jet}}^{\text{PU}}}$$

Note that magnitude of correction depends on calorimeter signal processing & definition – application easier to see for tower based jets!

In-Situ Calibration Validation

Balancing jet pT with electromagnetic system

- Truth from collision
  - Based on idea that electromagnetic particles are well measured
  - Limits accuracy to precision of photon or electron signal reconstruction
- Provides interaction (parton) level reference
  - Note that simulation based approaches use particle level reference
- Can use direct photon production
  - Kinematic reach for jet pT ~200-400 GeV for 1% precision – depends on center of mass energy
  - Relatively large cross-section
  - Background from QCD di-jets – one jet fluctuates into π^0 faking photon
- Can also use Z+jet(s)
  - Cross-section suppressed, but less background – two electron final state cleaner
  - Can also use two muon final state

Note specific physics environment

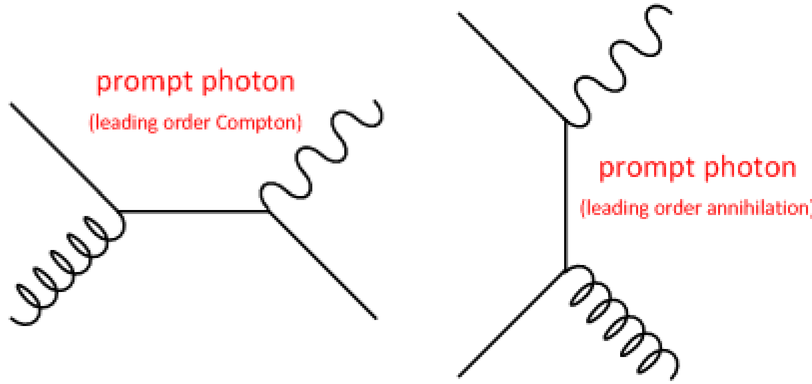
- Underlying event different from other final states
  - Less radiation in photon/Z hemisphere
- Often only good reference for quark jets
  - Narrow jets in lower radiation environment

prompt (direct) photon production:

$gq \rightarrow \gamma q$ QCD Compton scattering

$(\sim 95\%$ of $\sigma_\gamma^{\text{tot}})$

$q\bar{q} \rightarrow \gamma g$ annihilation



balance photon with (mostly) quark jet pT to validate or constrain $p_{\text{T,reco,jet}}$

In-Situ Calibration Validation

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May 05, 2010

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  - Less radiation in photon/*Z* hemisphere
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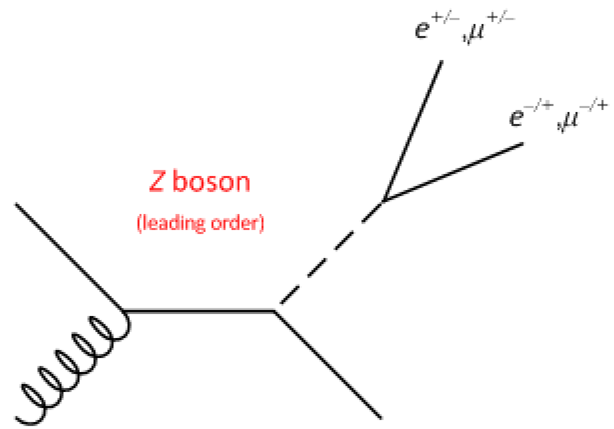
Z-boson + jet production:



balance Z pT reconstructed from decay leptons with quark jet pT to validate or constrain $p_{T,\mathrm{reco,jet}}$

Data Driven JES Corrections: Scale

Absolute response

Goal:

Correct for energy (pT) dependent jet response

Tools:

Direct photons, *Z*+jet(s),…

Measurement:

pT balance of well calibrated system (photon, *Z*) against jet in central region

Remarks:

Usually uses central reference and central jets (region of flat reponse)

Concerns:

Limit in precision and estimates for systematics w/o well understood simulations not clear

Needs corrections to undo out-of-cone etc. to compare to particle level calibrations

ratio test variable ($\kappa = \gamma, Z$):

$$f_{\text{absolute}}(\zeta_{\text{probe}}) = \underbrace{\left[1 + \frac{p_{\text{T,reco,jet}} - p_{\text{T},\kappa}}{p_{\text{T},\kappa}}\right]^{-1}}_{\text{variation of jet response with photon/}Z\ p_{\text{T}}}$$

with

$$\zeta_{\text{T,probe}} = \begin{cases} p_{\text{T},\kappa} & \text{reference pT} \\ \dfrac{p_{\text{T},\kappa} + p_{\text{T,reco,jet}}}{2} & \text{average pT} \\ E' = p_{\text{T},\kappa} \cosh \eta_{\text{reco,jet}} & \text{expected jet energy} \end{cases}$$

(relate to reconstructed jet variables with numerical inversion)

relative projection along reference pT:

$$\frac{\mathcal{P}_{\parallel}}{p_{\text{T},\kappa}} = \frac{p_{\text{T,reco,jet}} \cos \sphericalangle(\vec{p}_{\text{T,reco,jet}}, \vec{p}_{\text{T},\kappa})}{p_{\text{T},\kappa}} = \frac{\vec{p}_{\text{T,reco,jet}} \cdot \vec{p}_{\text{T},\kappa}}{p^2_{\text{T},\kappa}}$$

correction from $\dfrac{\mathcal{P}_{\parallel}}{p_{\text{T},\kappa}} + 1 \equiv 0$ for well calibrated jets:

$$f_{\text{absolute}}(\zeta_{\text{probe}}) = \left| \frac{p_{\text{T},\kappa}}{\mathcal{P}_{\parallel}} \right|$$

ATLAS

Missing Transverse Energy Projections

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May 05, 2010

Missing Transverse Energy Projection Fraction method (MPF)

- Uses pT balance in photon+jet events to determine jet response
  - Technically on any jet response scale, but most useful if jet signal is corrected for e/h and other (local) detector effects
- Based on projection of event missing transverse energy (MET) on photon pT direction
  - MET mostly generated by jet response
  - Least sensitive to underlying event and pile-up due to randomization in azimuth
- Allows to validate the jet energy response
  - Reference can be energy instead of pT
- Basis of absolute jet energy scale in DZero
  - Also under study for LHC

Considerations

- Perfect balance at parton level perturbed at particle level
  - Parton showering and hadronization, including initial and final state radiation (ISR & FSR)
  - Can be suppressed by selecting back-to-back photon-jet topologies
- Imperfect calorimeter response generates missing transverse energy
  - Handle for calibration

p_{T} balance in prompt photon production:

$$\underbrace{\vec{p}_{\mathrm{T},\gamma} + \vec{p}_{\mathrm{T,jet}}}_{\text{parton level}} = \underbrace{\vec{E}_{\mathrm{T},\gamma} + \vec{p}_{\mathrm{T,jet}}}_{\text{parton level}} = 0 \Rightarrow \underbrace{\vec{E}_{\mathrm{T},\gamma} + \vec{E}_{\mathrm{T,jet}}}_{\text{particle level}} \approx 0$$

with calorimeter response and projection on $\vec{E}_{\mathrm{T},\gamma}$:

$$e\vec{E}_{\mathrm{T},\gamma} + j(E_{\mathrm{jet}})\vec{E}_{\mathrm{T,jet}} = -\vec{E}_{\mathrm{T}}^{\mathrm{miss}}$$

$$\Rightarrow E_{\mathrm{T},\gamma} + j(E_{\mathrm{jet}})\vec{E}_{\mathrm{T,jet}} \cdot \hat{n}_{\gamma} = -\hat{n}_{\gamma} \cdot \vec{E}_{\mathrm{T}}^{\mathrm{miss}}$$

calculate $\vec{E}_{\mathrm{T}}^{\mathrm{miss}}$ from all calorimeter signals excluding the photon signal:

$$\vec{E}_{\mathrm{T}}^{\mathrm{miss}} = -\vec{E}_{\mathrm{T},\gamma} - \sum_{\substack{\text{all calo signals}\\ \text{not from } \gamma}} \vec{E}_{\mathrm{T,calo}}$$

$$\Rightarrow j(E_{\mathrm{jet}}) = \frac{\sum_{\substack{\text{all calo signals}\\ \text{not from } \gamma}} \vec{E}_{\mathrm{T,calo}} \cdot \hat{n}_{\gamma}}{\vec{E}_{\mathrm{T,jet}} \cdot \hat{n}_{\gamma}} \overset{!}{=} \frac{\sum_{\substack{\text{all calo signals}\\ \text{not from } \gamma}} \vec{E}_{\mathrm{T,calo}} \cdot \hat{n}_{\gamma}}{E_{\mathrm{T},\gamma}}$$

suppress biases by measuring response as function of $E' = E_{\mathrm{T},\gamma} \cosh \eta_{\mathrm{jet}}$ yielding empirically:

$$j(E') = b_0 + b_1 \ln \frac{E'}{E_{\mathrm{scale}}} + b_2 \ln^2 \frac{E'}{E_{\mathrm{scale}}}$$

use numerical inversion for $E_{\mathrm{rec,jet}} \mapsto E'$!

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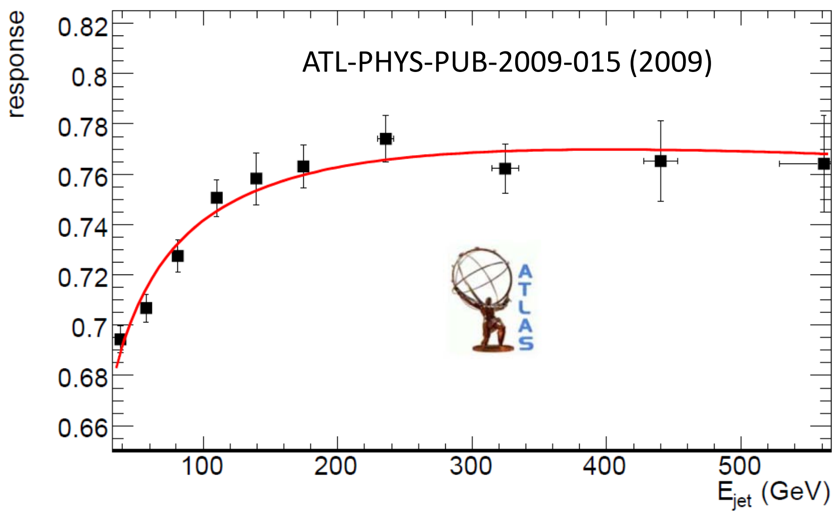
ATLAS Simulations



$$j(E') = b_0 + b_1 \ln \frac{E'}{E_{scale}} + b_2 \ln^2 \frac{E'}{E_{scale}}$$

Data Driven JES Evaluation

P. Loch
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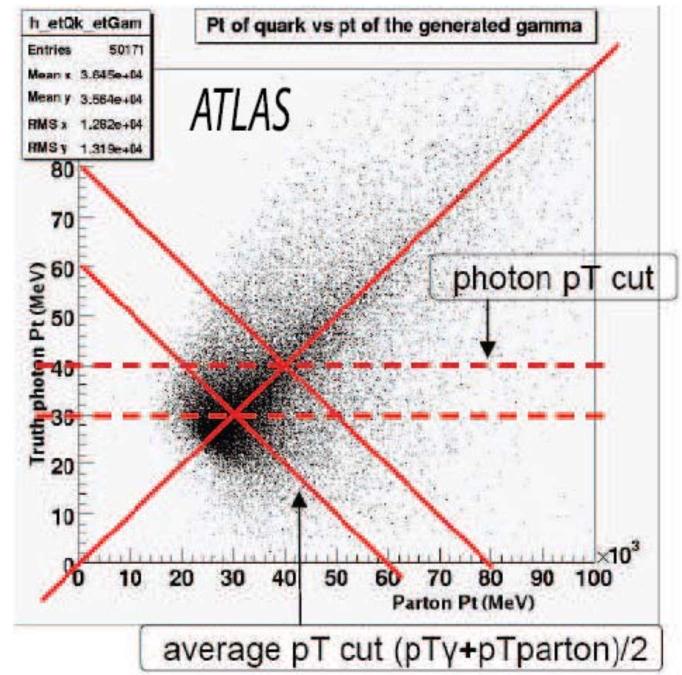
May 05, 2010

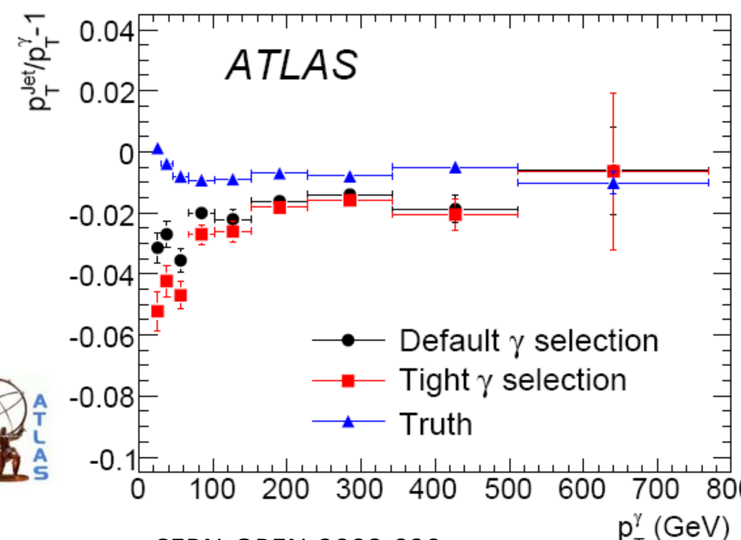
Photon+jet(s)

- Well measured electromagnetic system balances jet response
  - Central value theoretical uncertainty ~2% limits precision
    - Due to photon isolation requirements
  - But very good final state for evaluating calibrations
- Can test different correction levels in factorized calibrations
  - E.g., local hadronic calibration in ATLAS
- Limited pT reach for 1-2% precision
  - 25->300 GeV within 100 pb^{-1}

Z+jet(s)

- Similar idea, but less initial statistics
  - Smaller reach but less background





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Data Driven JES Evaluation

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May 05, 2010

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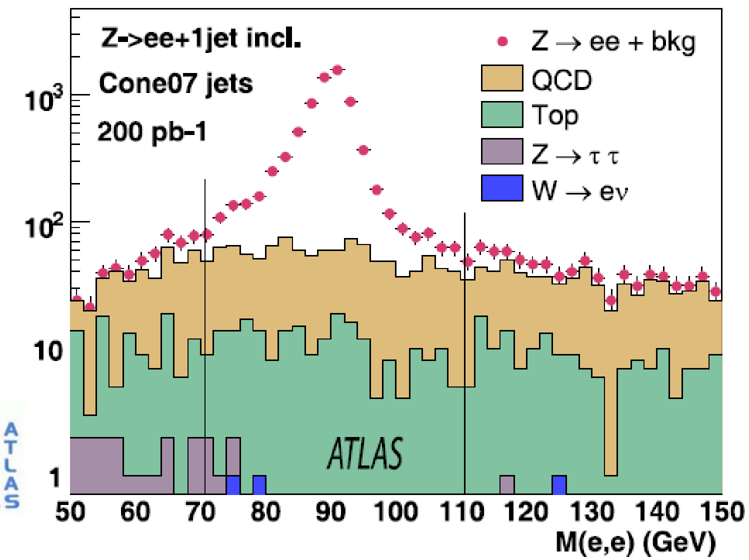

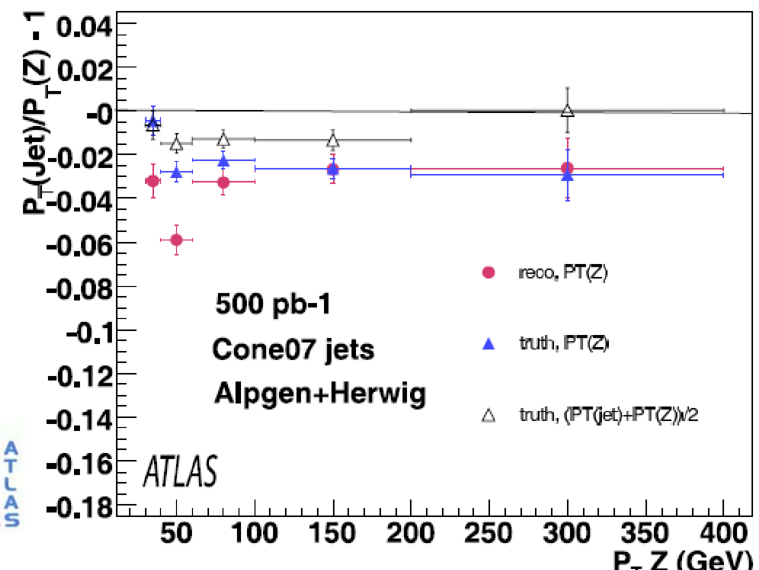

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W Mass Spectroscopy

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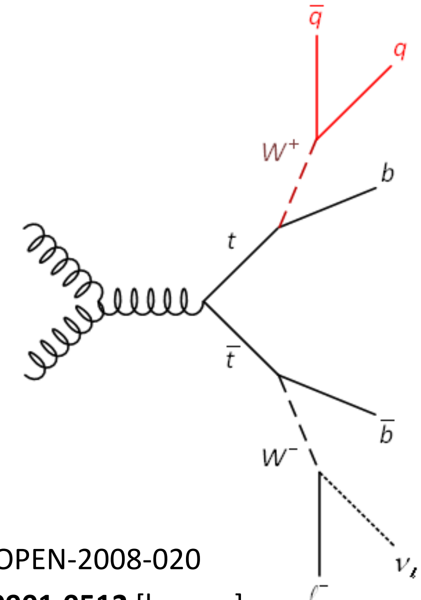
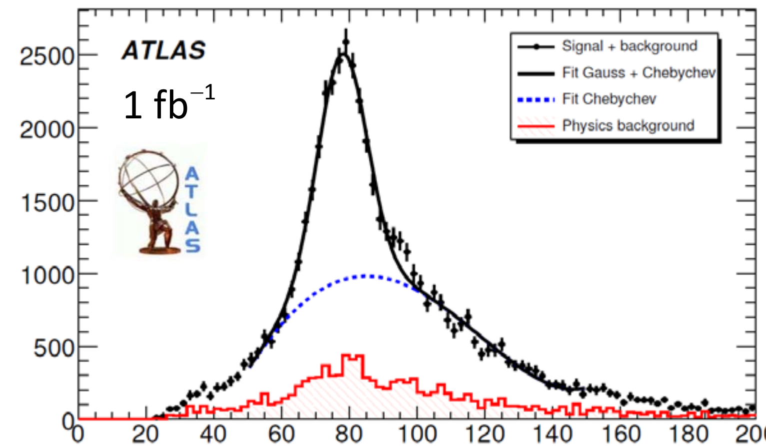
May 05, 2010

In-situ calibration validation handle

- Precise reference in ttbar events
  - Hadronically decaying W-bosons
- Jet calibrations should reproduce W-mass
  - Note color singlet source
  - No color connection to rest of collision – different underlying event as QCD
  - Also only light quark jet reference
- Expected to be sensitive to jet algorithms
  - Narrow jets perform better – as expected



CERN-OPEN-2008-020
arXiv:0901.0512 [hep-ex]



Simulated di-jet invariant mass ($M_{W,\mathrm{reco}}$) spectrum for kT jets with $R = 0.4$ (narrow jets) in $t\bar{t}$ final states at $\sqrt{s} = 14$ TeV

JES From *W* Mass Reconstruction

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May 05, 2010

W boson mass from two jets

- Clean event sample can be accumulated quickly
  - Original studies for center of mass energy of 14 TeV and luminosity of 10^{33} cm^{-2}s^{-1}
  - ~130 clean events/day in ttbar
- Angular and energy scale component in reconstruction
  - Energy scale dominant

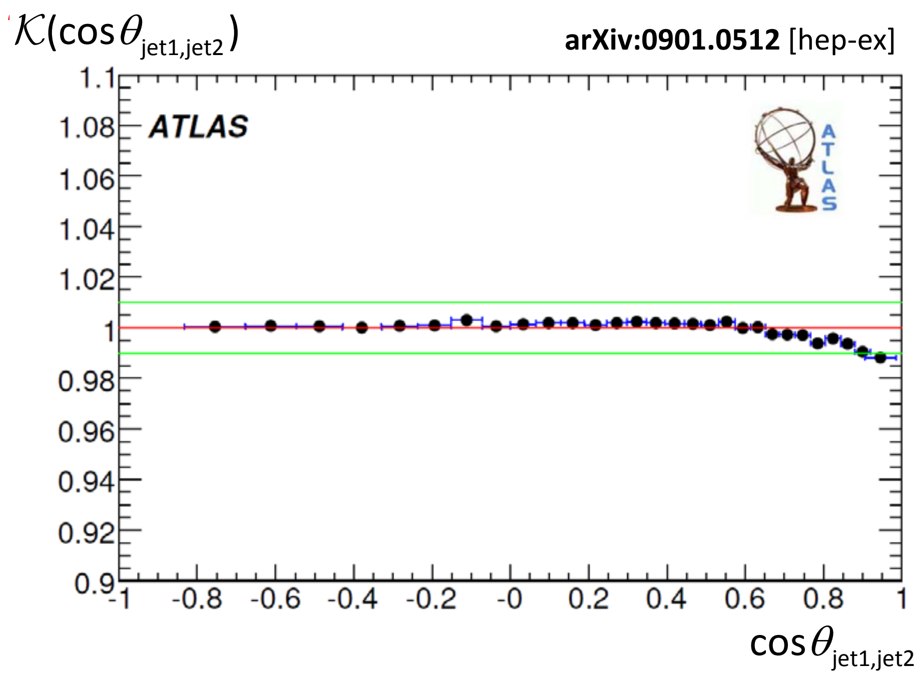
invariant mass from decay jets:

$$M_{W,\mathrm{reco}} = \sqrt{2E_{\mathrm{jet},1}E_{\mathrm{jet},2}\left(1-\cos\theta_{\mathrm{jet1,jet2}}\right)}$$

bias from angular mismeasurement:

$$\mathcal{K}(\cos\theta_{\mathrm{jet1,jet2}}) = \frac{1-\cos\theta_{\mathrm{parton1,parton2}}}{1-\cos\theta_{\mathrm{jet1,jet2}}} \approx 1$$

is small



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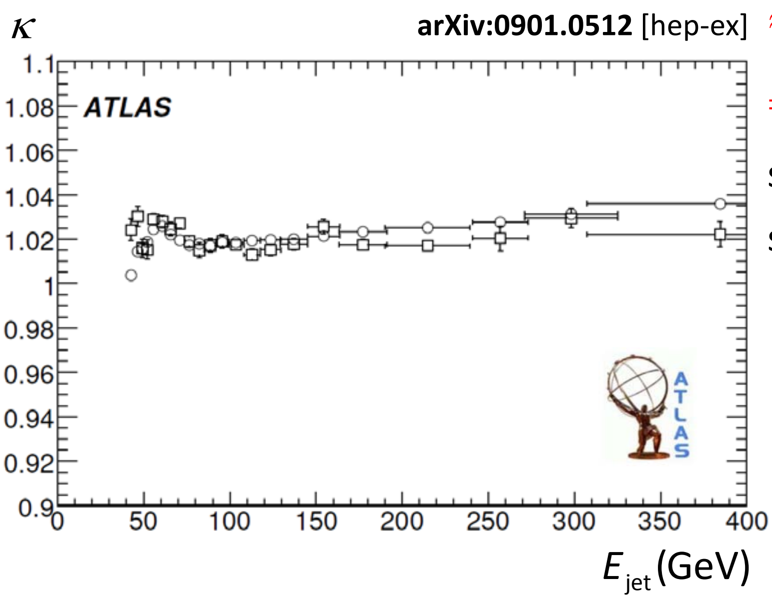
arXiv:0901.0512 [hep-ex]



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bias from angular mismeasurement:

$$\mathcal{K}(\cos\theta_{\mathrm{jet1,jet2}}) = \frac{1-\cos\theta_{\mathrm{parton1,parton2}}}{1-\cos\theta_{\mathrm{jet1,jet2}}} \approx 1$$

is small $\rightarrow$ major contribution from energy scale:

$$M_{W,\mathrm{PDG}}$$

$$= \sqrt{2\kappa(E_{\mathrm{jet},1})E_{\mathrm{jet},1}\kappa(E_{\mathrm{jet},2})E_{\mathrm{jet},2}\mathcal{K}(\cos\theta_{\mathrm{jet1,jet2}})\left(1-\cos\theta_{\mathrm{jet1,jet2}}\right)}$$

$$\approx \sqrt{2\kappa(E_{\mathrm{jet},1})E_{\mathrm{jet},1}\kappa(E_{\mathrm{jet},2})E_{\mathrm{jet},2}\left(1-\cos\theta_{\mathrm{jet1,jet2}}\right)}$$

$$= \sqrt{\kappa(E_{\mathrm{jet},1})\kappa(E_{\mathrm{jet},2})} \cdot M_{W,\mathrm{reco}}$$

simple rescaling method assuming energy independent scale shift $\rightarrow \kappa(E_{\mathrm{jet},1}) = \kappa(E_{\mathrm{jet},2}) = \kappa$ works reasonably well

JES From *W* Mass Reconstruction

W mass from templates

- Produce W mass distribution templates
  - Use parton or particle level simulations
  - Smear with JES and resolution variations
  - Store W mass distributions as function of smearing parameters
- Find response and resolution smearing parameters
  - Find best fit template

JES scale α relative to perfect jet response;

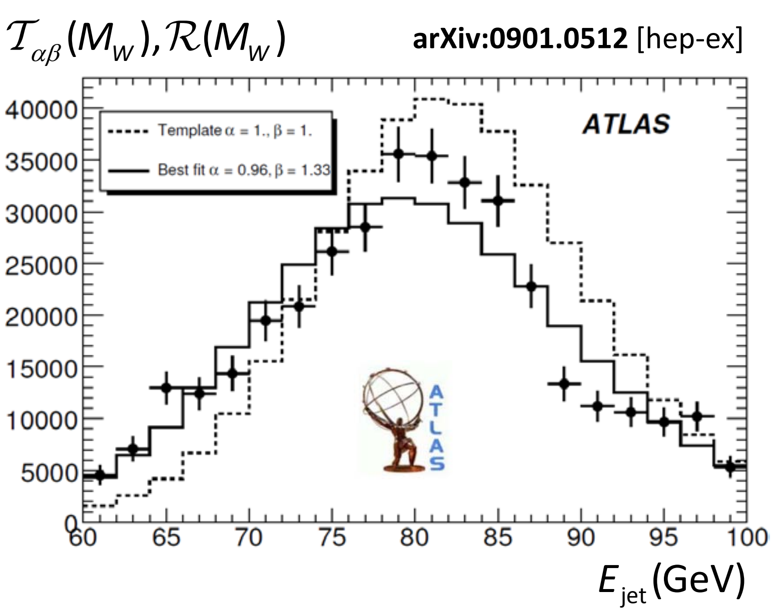
resolution parameter β relative to nominal jet energy resolution;

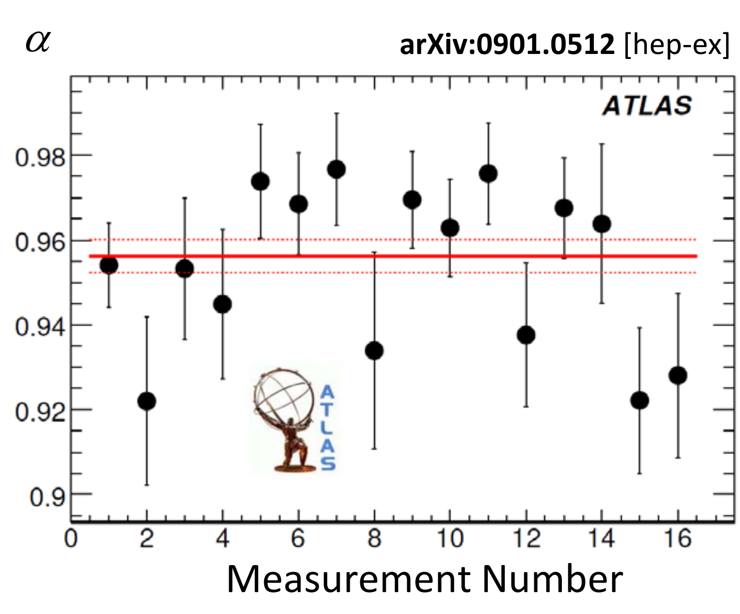
find best matching template distribution $\mathcal{T}_{\alpha\beta}(M_W)$

for reconstructed distribution $\mathcal{R}(M_W)$:

$$\chi^2 = \int \left(\mathcal{T}_{\alpha\beta}(M_W) - \mathcal{R}(M_W)\right)^2 \Big/ \left(\sigma^2_{\mathcal{T}_{\alpha\beta}(M_W)} + \sigma^2_{\mathcal{R}(M_W)}\right) dM_W = \min$$

stability of fit tested by subdividing total sample into 16 "measurements" (770 pb^{-1} $\rightarrow 16 \times 48$ pb^{-1}):



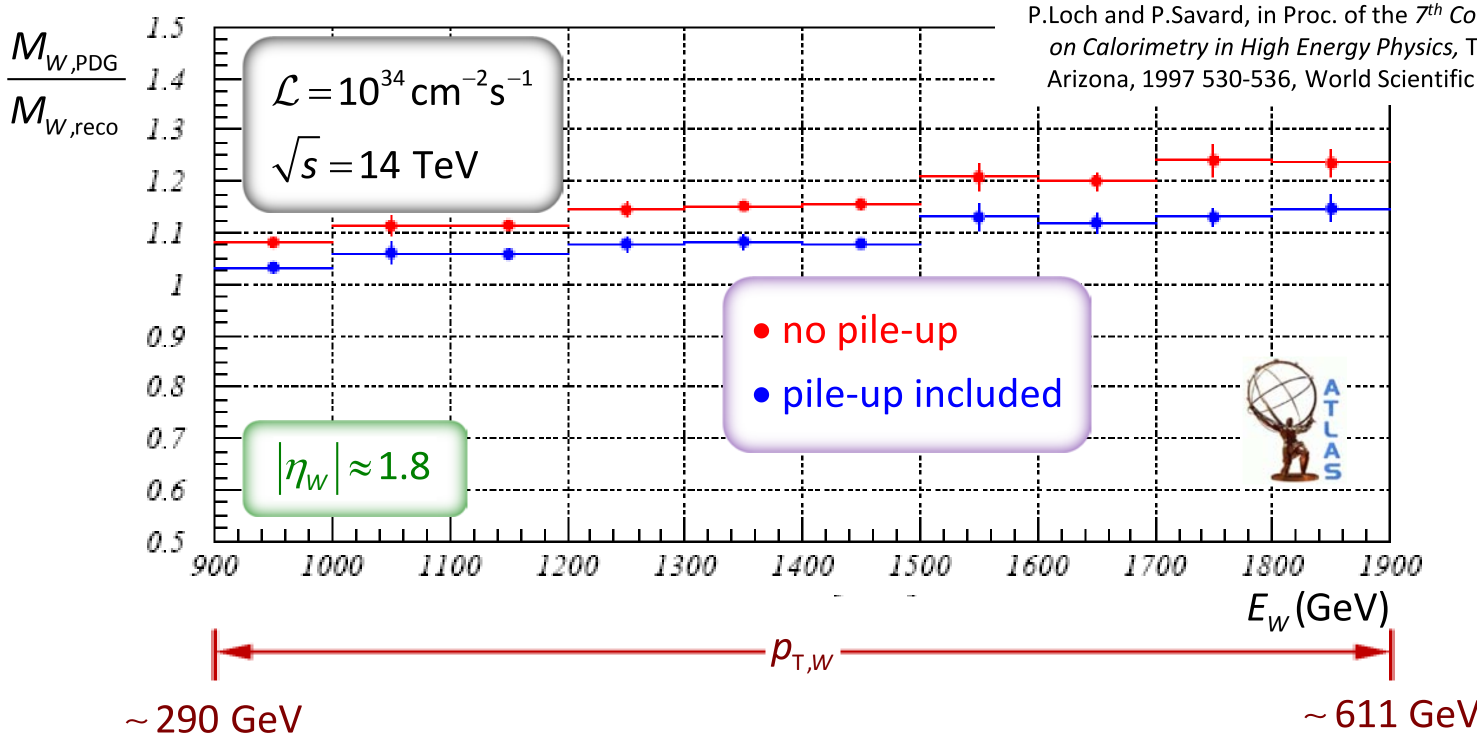


Biases In *W* Mass Reconstruction

Boosted *W*

- pT boost reduces angle between decay jets
  - Reconstructed mass underestimates true *W* mass
  - See example below for *W* boosted into the ATLAS end-cap calorimeter region
- Pile-up can add energy to the system
  - Not an improvement of the measurement – accidental and thus uncorrelated jet energy shifts lead to shift in reconstructed mass

P.Loch and P.Savard, in Proc. of the 7th *Conference on Calorimetry in High Energy Physics,* Tucson, Arizona, 1997 530-536, World Scientific (1998)



Data Driven JES Corrections: Direction

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May 05, 2010

Di-jet balance

- Calibrate jet in "golden" reference region
  - Use e.g. photon pT balance
  - Use this jet as "truth" reference
- Balance pT with jet in more complex calorimeter region
  - Note: relative energy resolution of reference jet can be worse than probe jet – more forward jet has more energy at same pT
  - Resolution bias needs to be controlled
- Apply corrections to all jets at given direction
  - Need to understand topology – additional soft jet contribution
- Can also be used to measure jet energy resolution
  - Need to consider phase space sharing with possible additional soft jets

Multi-jet balance

- Validation of very high pT jets
  - In-situ calibrations with photons etc. only reaches 200-300 GeV (pT)
  - But need to validate very high pT jet scale as well
- Bootstrap approach
  - Find multi-jet events with one hard jet in non-validated phase-space
  - Balance hard jet with several well calibrated lower pT jets (e.g., from photons)
  - Look for more harder jets and use scale corrections from lower pT jets (bootstrap corrections)
- Note that errors evolve from low to high pT
  - Hard to achieve O(1%) precision
  - Likely need simulation based approach

Di-jet balance

Correct direction-dependent jet response

- Establish absolute scale in “golden region” of the detector
  - Balancing pT of a central (lower energy) jet with a more forward (higher energy jet)
  - Avoid biases by compensating reference jet response first
- Determine direction dependent correction factors
  - Use pT asymmetry measure for back-to-back jet
  - Careful – resolution bias due to different jet energy ranges can still be present!

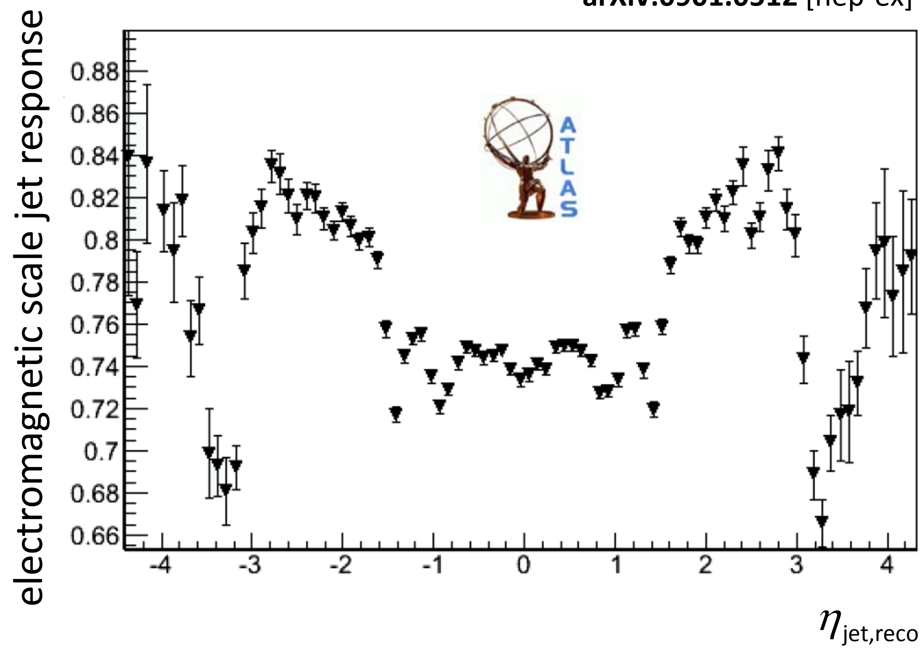
Jet energy resolution from di-jet pT balance

- Select event topology
  - Di-jets back-to-back in azimuth
  - Same rapidity region
  - Similar pT
- Use asymmetry measure to calculate jet energy resolution
  - Width of the distribution of *A*

Understand soft radiation contribution

- pT balance approach (DØ)
  - Use di-jet energy resolution dependence on third jet pT as scale to unfold radiation contribution
- kT balance approach (UA2, CDF)
  - Determination of radiation contribution using bisector decomposition

arXiv:0901.0512 [hep-ex]



asymmetry measure:

$$A = \frac{p_{\mathrm{T,reco}}^{\mathrm{probe}} - p_{\mathrm{T,reco}}^{\mathrm{reference}}}{\left(p_{\mathrm{T,reco}}^{\mathrm{probe}} + p_{\mathrm{T,reco}}^{\mathrm{reference}}\right)/2} = \frac{p_{\mathrm{T,reco}}^{\mathrm{probe}} - p_{\mathrm{T,reco}}^{\mathrm{reference}}}{p_{\mathrm{T,reco}}^{\mathrm{average}}}$$

correction factors (use numerical inversion):

$$c(p_{\mathrm{T,reco}}^{\mathrm{average}}, \eta_{\mathrm{probe}}) = \frac{2 - A(p_{\mathrm{T,reco}}^{\mathrm{average}}, \eta_{\mathrm{probe}})}{2 + A(p_{\mathrm{T,reco}}^{\mathrm{average}}, \eta_{\mathrm{probe}})} \mapsto c(p_{\mathrm{T,reco}}^{\mathrm{probe}}, \eta_{\mathrm{probe}})$$

Di-jet balance

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May 05, 2010

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Jet energy resolution from di-jet pT balance

- Select event topology
  - Di-jets back-to-back in azimuth
  - Same rapidity region
  - Similar pT
- Use asymmetry measure to calculate jet energy resolution
  - Width of the distribution of *A*

Understand soft radiation contribution

- pT balance approach (DØ)
  - Use di-jet energy resolution dependence on third jet pT as scale to unfold radiation contribution
- kT balance approach (UA2, CDF)
  - Determination of radiation contribution using bisector decomposition

asymmetry measure (slightly modified):

$$A = \frac{p_{\mathrm{T,reco}}^{\mathrm{jet1}} - p_{\mathrm{T,reco}}^{\mathrm{jet2}}}{p_{\mathrm{T,reco}}^{\mathrm{jet1}} + p_{\mathrm{T,reco}}^{\mathrm{jet2}}} = \frac{p_{\mathrm{T,reco}}^{\mathrm{jet1}} - p_{\mathrm{T,reco}}^{\mathrm{jet2}}}{2p_{\mathrm{T,reco}}^{\mathrm{average}}}$$

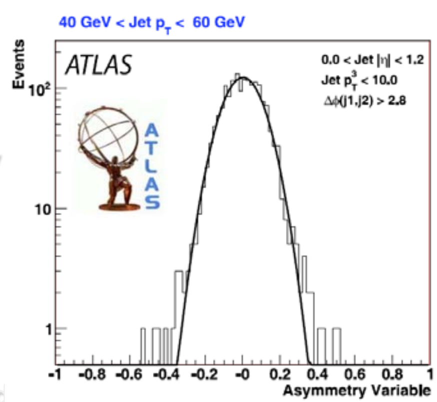
p_{T} resolution for jets in same η region with similar p_{T}:

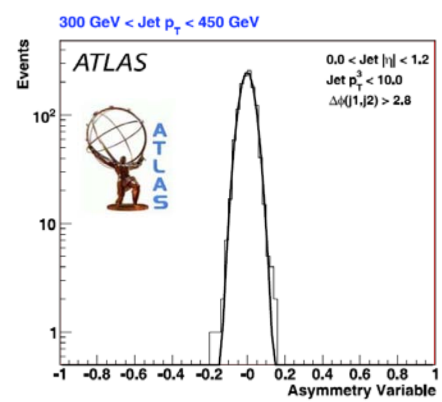
$$\frac{\sigma_{p_{\mathrm{T}}}}{p_{\mathrm{T,reco}}^{\mathrm{average}}} = \sqrt{2}\sigma_A \approx \frac{\sigma_E}{E}$$

resolution is symmetrized by randomly computing

$p_{\mathrm{T,reco}}^{\mathrm{jet1}} - p_{\mathrm{T,reco}}^{\mathrm{jet2}}$ or $p_{\mathrm{T,reco}}^{\mathrm{jet2}} - p_{\mathrm{T,reco}}^{\mathrm{jet1}}$

for each event





arXiv:0901.0512 [hep-ex]

Di-jet balance

P. Loch
U of Arizona
May 05, 2010

Correct direction-dependent jet response

- Establish absolute scale in "golden region" of the detector
  - Balancing pT of a central (lower energy) jet with a more forward (higher energy jet)
  - Avoid biases by compensating reference jet response first
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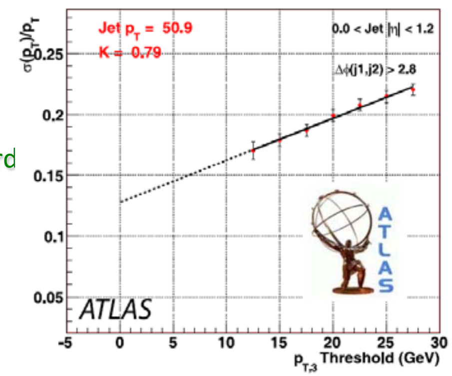
determine clean di-jet resolution by linear extrapolation of

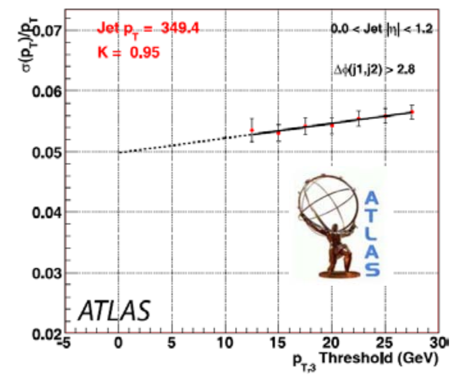
$$\frac{\sigma_{p_T}}{p_T}\left(p_{T,\mathrm{reco,jet3}} < p_{T,\mathrm{threshold}}, p_{T,\mathrm{reco}}^{\mathrm{average}}\right),$$

typically with $p_{T,\mathrm{theshold}} \geq p_{T,\min} = (7-10)\ \mathrm{GeV}$, implied by calorimeter jet reconstruction, to $p_{T,\mathrm{reco,jet3}} = 0$:

$$\lim_{p_{T,\mathrm{reco,jet3}} \to 0} \frac{\sigma_{p_T}}{p_T}\left(p_{T,\mathrm{reco}}^{\mathrm{average}}\right)$$

fit has some bias problems due to phase space limitations at low $p_{T,\mathrm{reco}}^{\mathrm{average}}$ together in the presence of $p_{T,\min}$





arXiv:0901.0512 [hep-ex]

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resolution correction factor from

$$\mathcal{K}(p_{\mathrm{T,reco}}^{\mathrm{average}}) = \mathcal{K}(p_{\mathrm{T,reco}}) = \frac{\lim\limits_{p_{\mathrm{T,reco,jet3}}\to\infty}\left(\sigma_{p_{\mathrm{T}}}/p_{\mathrm{T,reco}}\right)(p_{\mathrm{T,reco}})}{\sigma_{p_{\mathrm{T}}}/p_{\mathrm{T,reco}}\left(p_{\mathrm{T,reco,jet3}} < 10\ \mathrm{GeV}, p_{\mathrm{T,reco}}\right)}$$

such that

$$\left(\frac{\sigma_{p_{\mathrm{T}}}}{p_{\mathrm{T,reco}}}\right)_{\mathrm{corrected}} = \mathcal{K}(p_{\mathrm{T,reco}})\frac{\sigma_{p_{\mathrm{T}}}}{p_{\mathrm{T,reco}}}\left(p_{\mathrm{T,reco,jet3}} < 10\ \mathrm{GeV}, p_{\mathrm{T,reco}}\right)$$

with a parameterization of the p_{T} dependence of the correction by

$$\mathcal{K}(p_{\mathrm{T,reco}}) = a + b\cdot\log p_{\mathrm{T,reco}}$$

The detailed documentation of this approach, including a full systematic evaluation and discussion of the low pT bias using ATLAS simulations, is available to ATLAS members only in:

E.Hughes, *D.Lopez*, *A.Schwartzman*,

ATL-COM-PHYS-2009-408 (2009)

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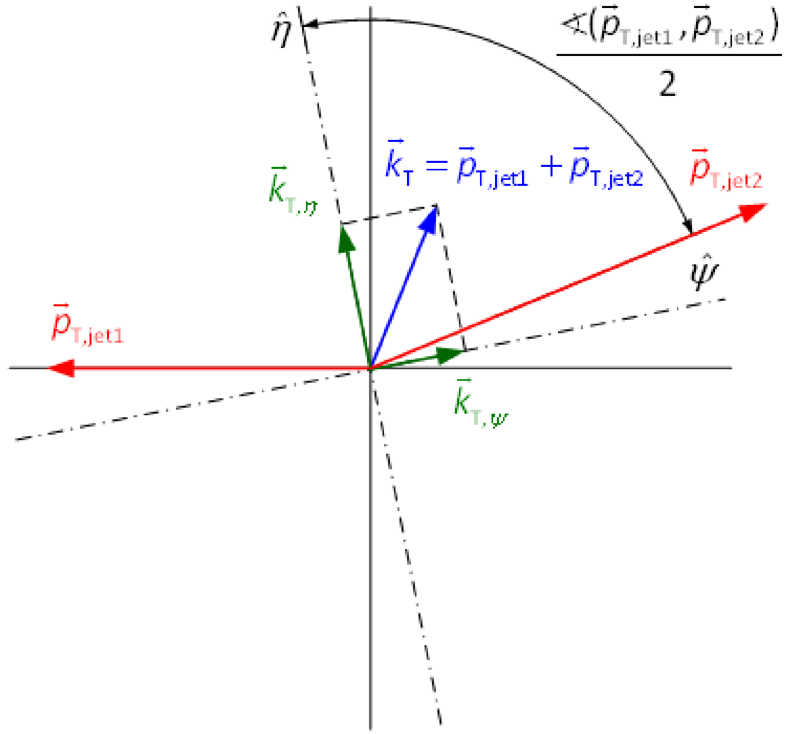

$\vec{k}_{T,\psi}$ most sensitive to calorimeter resolution effects:

$\sigma_\psi^2 = \sigma_{E,calo}^2 + \sigma_{radiation,||}^2$, with $\sigma_{E,calo} \gg \sigma_{radiation,||}$

$\vec{k}_{T,\eta}$ most sensitive to (gluon) radiation effects:

$\sigma_\eta^2 = \sigma_{radiation,\perp}^2$

(ignoring effects from angular resolution, underlying event, out of cone losses)

assume radiation is random wrt jet directions:

$$\sigma_{radiation,\perp}^2 = \sigma_{radiation,||} \Rightarrow \sigma_{E,calo}^2 = \sqrt{\sigma_\psi^2 - \sigma_\eta^2}$$

Di-jet balance

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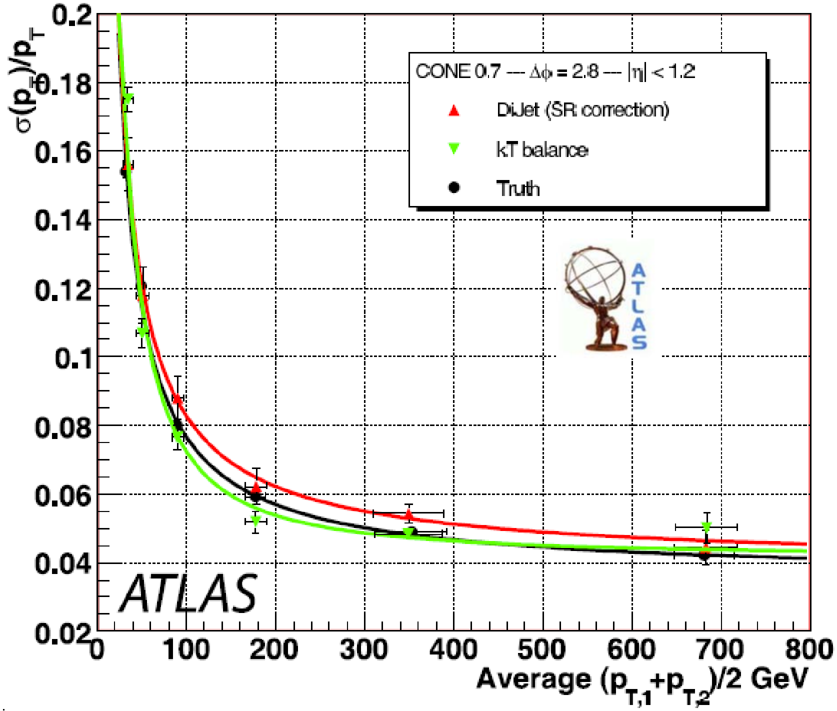
note $\sigma_{\psi}(p_{\mathrm{T,reco}}^{\mathrm{average}}) \propto \sqrt{p_{\mathrm{T,reco}}^{\mathrm{average}}}$, and

$\sigma_{\eta} \approx const < \sigma_{\psi}(p_{\mathrm{T,reco}}^{\mathrm{average}} > p_{\mathrm{T,min}})$

as expected!



arXiv:0901.0512 [hep-ex]

Jets Not From Hard Scatter

P. Loch
U of Arizona
May 05, 2010

Dangerous background for W+n jets cross-sections etc.

- Lowest pT jet of final state can be faked or misinterpreted as coming from underlying event or multiple interactions

Extra jets from UE are hard to handle

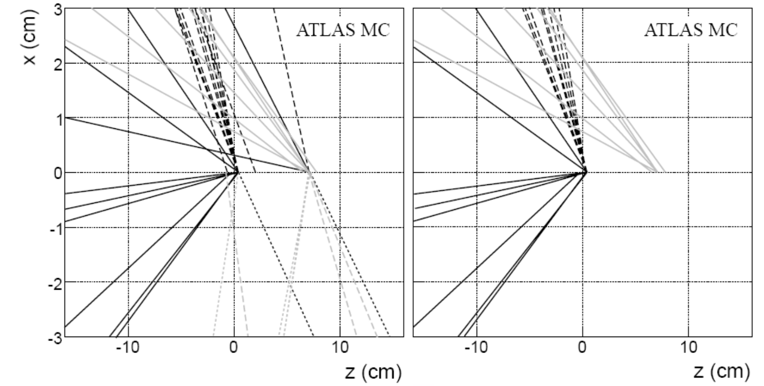
- No real experimental indication of jet source
- Some correlation with hard scattering?
- Jet area?
- No separate vertex

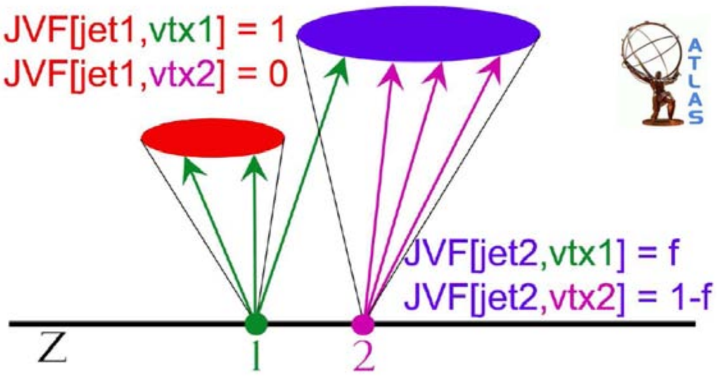
Jet-by-jet handle for multiple proton interactions

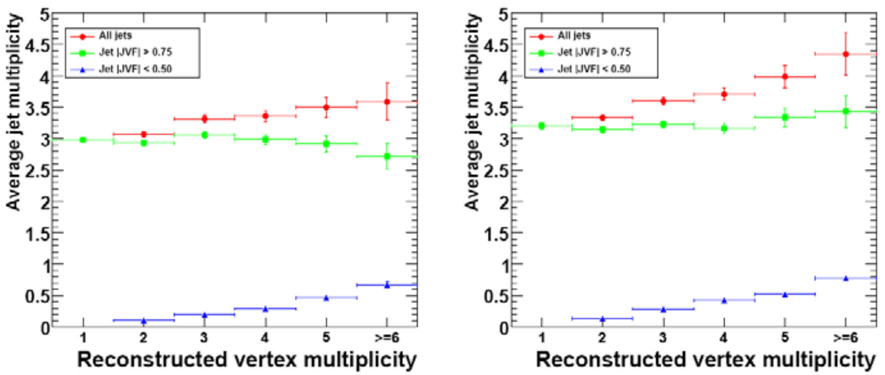
- Match tracks with vertices to calorimeter jet
  - Calculate track pT fraction from given vertex
- Classic indicator for multiple interactions is number of reconstructed vertices in event
  - Tevatron with RMS(z_vertex) ~ 30 cm
  - LHC RMS(z_vertex) ~ 8 cm
- If we can attach vertices to reconstructed jets, we can in principle identify jets not from hard scattering

Limited to pseudorapidities within 2.5!

CERN-OPEN-2008-020







(c) Di-jet (J6)

(d) $t\bar{t}$, $W \rightarrow$jets

Jets Not From Hard Scatter

Track jets

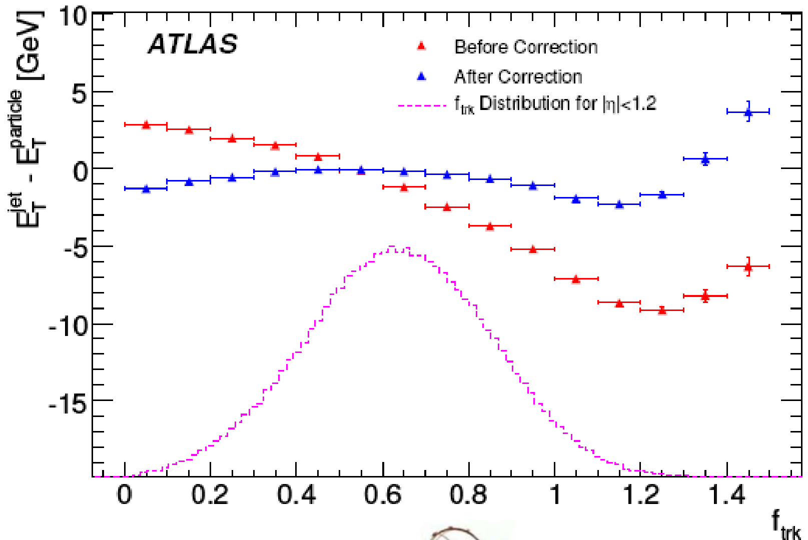
- Find jets in reconstructed tracks
- ~60% of jet pT, with RMS ~0.3 – not a good kinematic estimator

Dedicated 3-dim jet algorithm

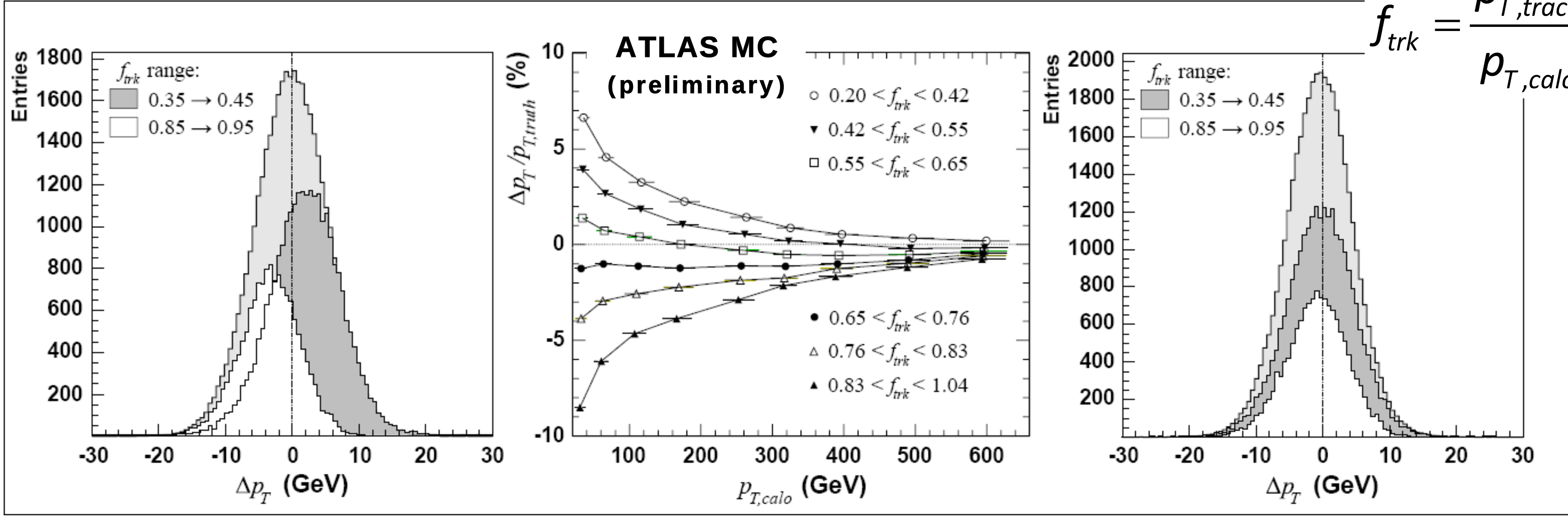
- Cluster track jets in pseudo-rapidity, azimuth, and delta(ZVertex)

Match track and calorimeter jet

- Helps response!



$$f_{trk} = \frac{p_{T,track}}{p_{T,calo}}$$



CERN-OPEN-2008-020

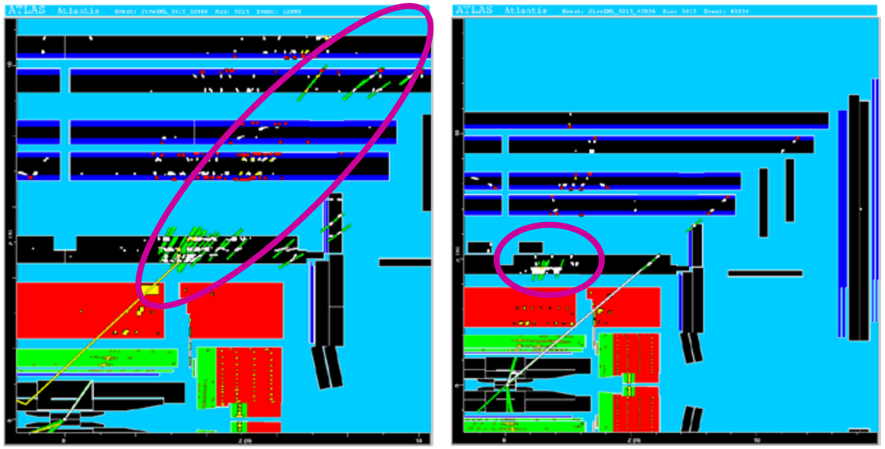
Longidtudinal jet energy leakage

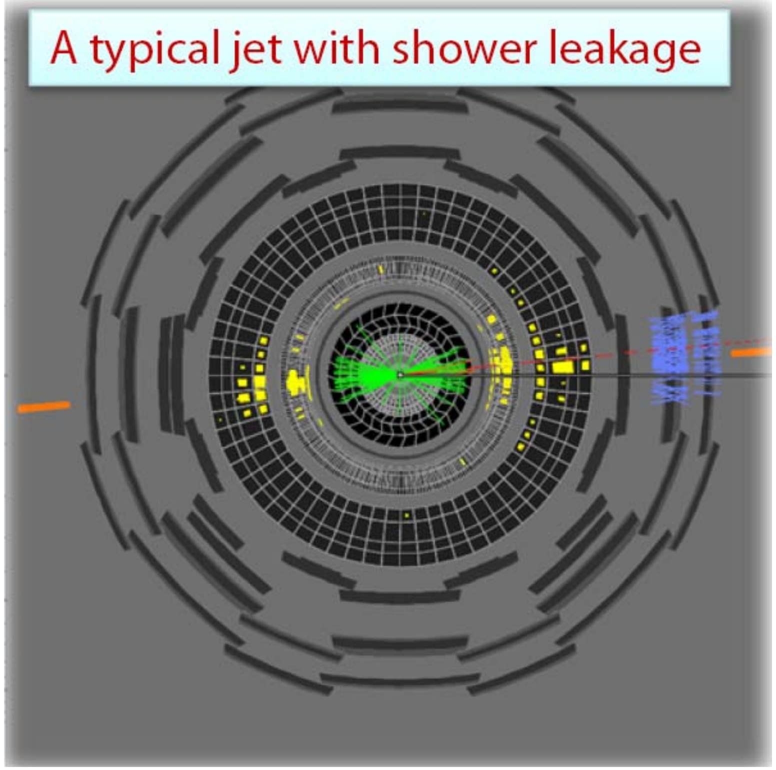
- Dangerous – can changes jet pT cross-section shape at high pT
  - Fake compositeness signal

Correlated with muon spectrometer hits

- Not strong correlation expected
  - Insufficient for precise JES
  - Will likely not produce reconstructed tracks, only
- Helps to tag suspicious jets
  - Suppress suspicious events/jets
- Careful – real muon may be inside jet
  - b decay
  - Should produce track – cleaner signal inside jet

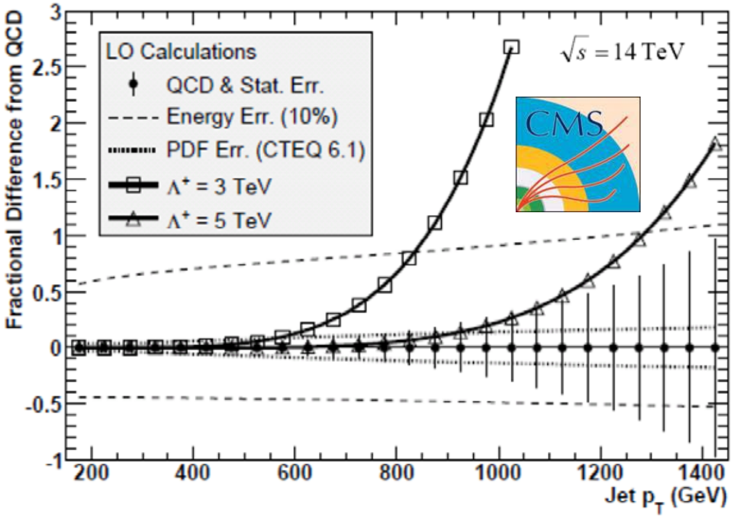
Also background for missing transverse energy!

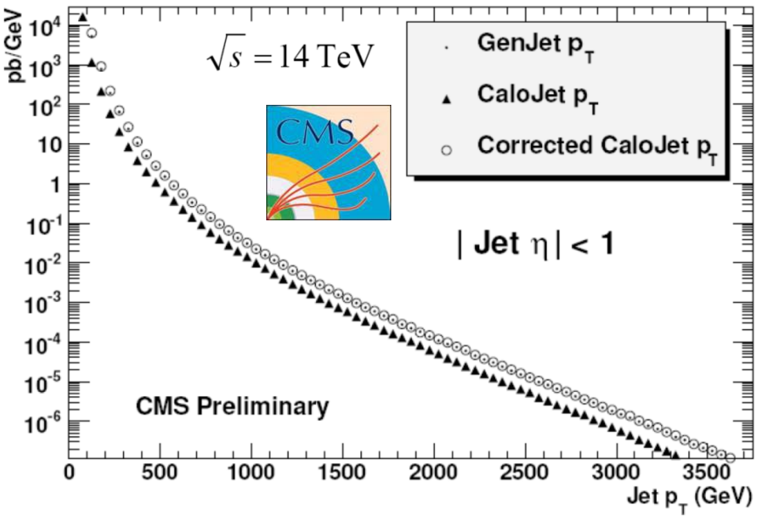




Effect of calibration on inclusive jet cross-section

One the first physics results expected from ATLAS & CMS





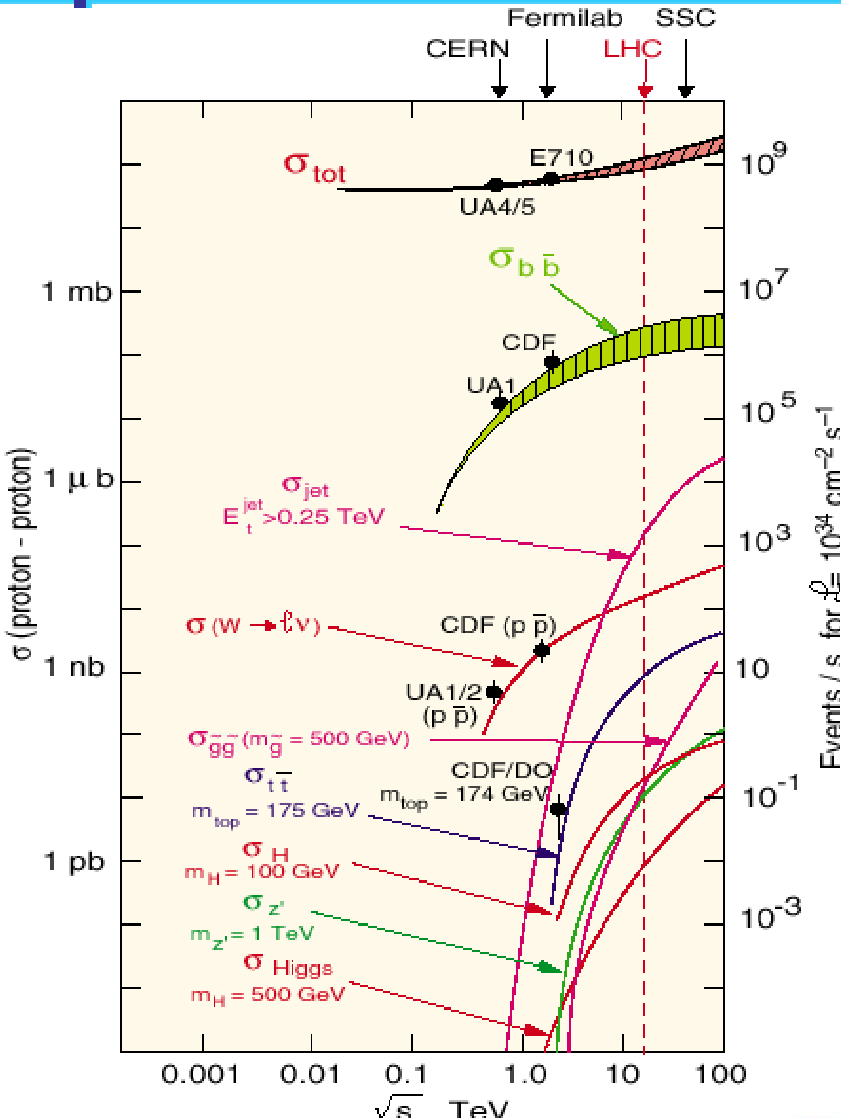
CMS PAS SBM-07-001

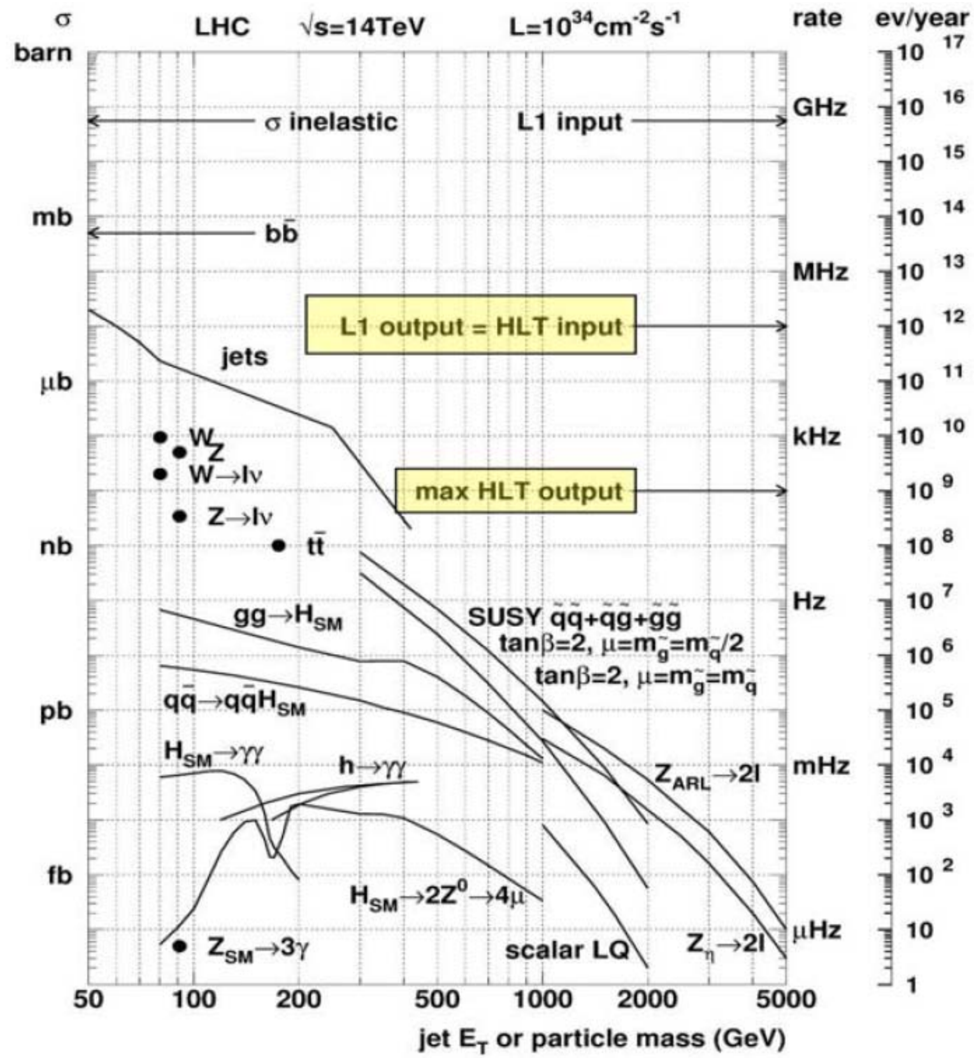
Extras

THE UNIVERSITY OF ARIZONA.

QCD Dominates Cross-sections

P. Loch
U of Arizona
May 05, 2010





QCD Jet Production @ LHC

P. Loch
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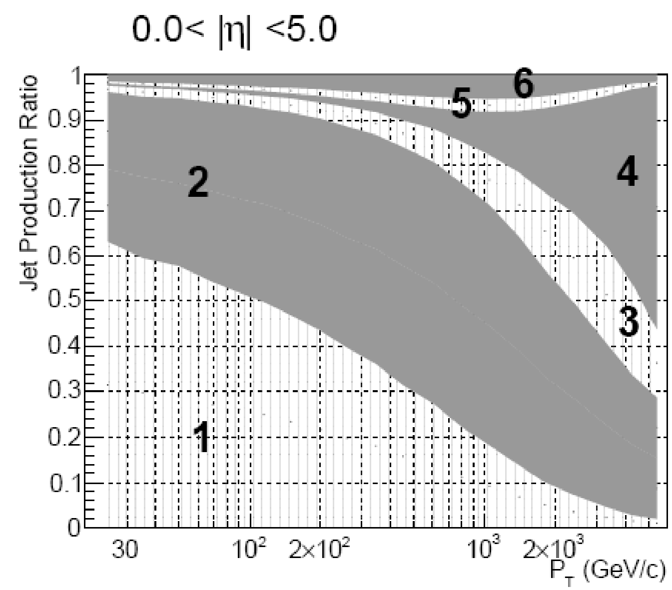
May 05, 2010

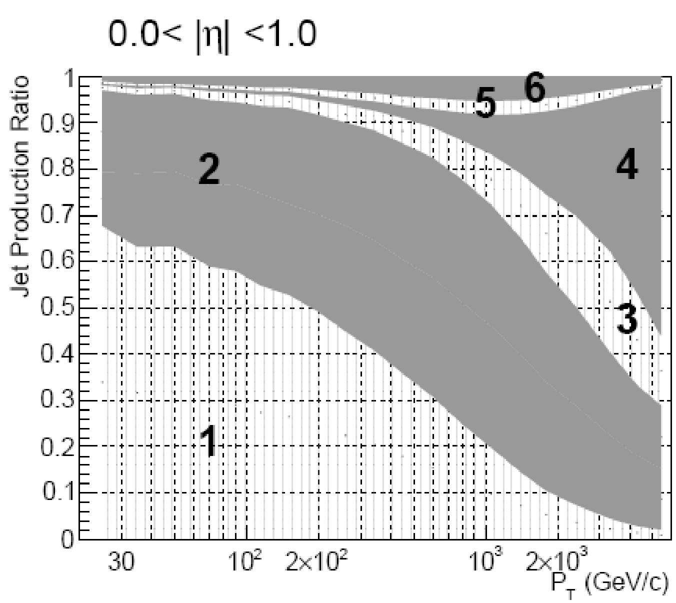
Jet physics

- High transverse momentum jets quickly accessible!
- 100,000 jets with pT > 1 TeV at 1 fb-1

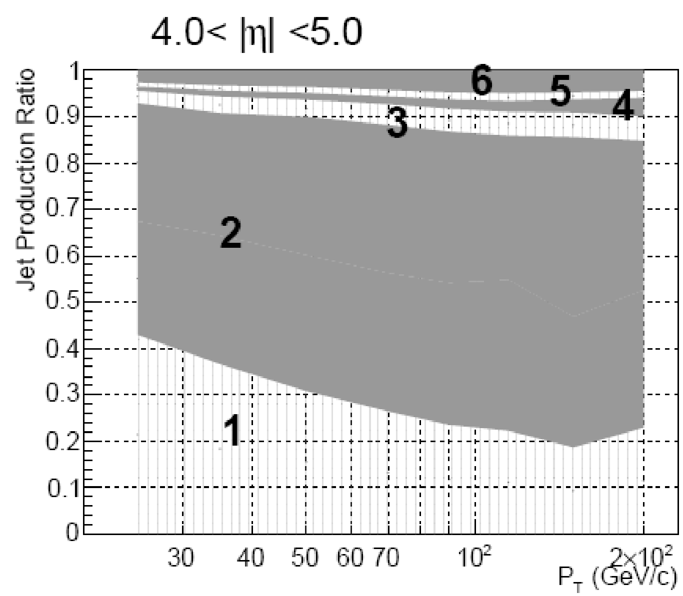
Early attempt at inclusive cross-section

- Most likely jet origin changes with pT and direction





1	gg
2	gq
3	qq
4	qq'
5	$q\bar{q}$
6	$q\bar{q}'$



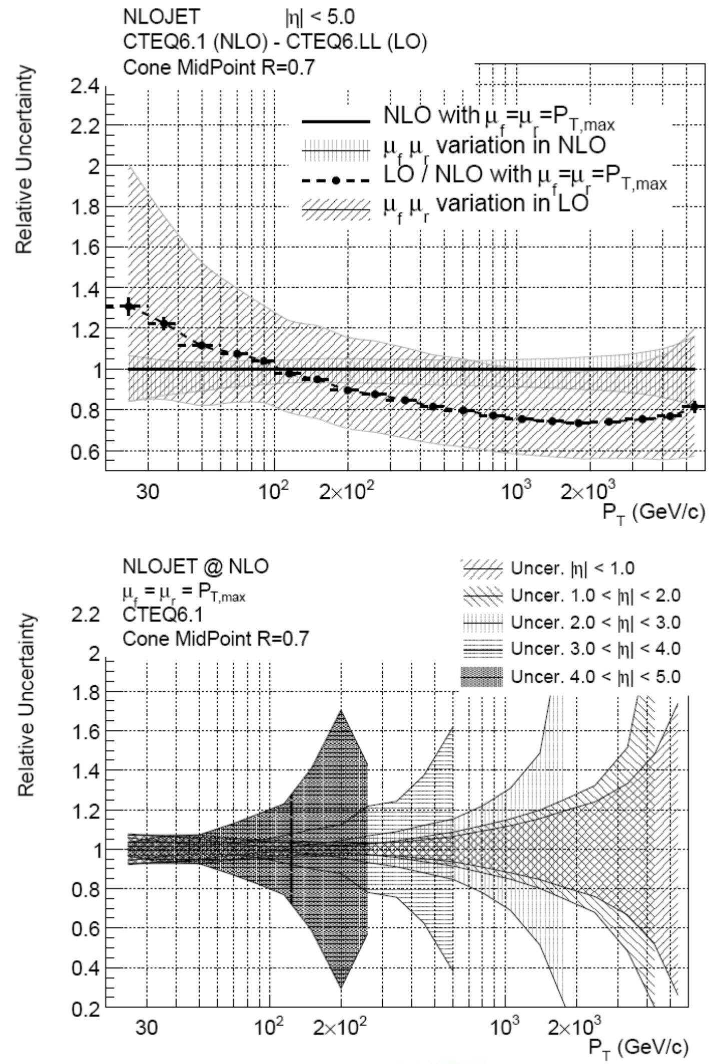
Francavilla/Roda, ATL-PHYS-2008-062

Neglecting orders in ME calculations

- K-factor NLO-LO can be significant
- Much smaller effect of scale variations in NLO

PDF uncertainties

- Diven by gluon structure function uncertainties
  - Especially at higher pT
- Plot shows error PDFs in various regions
  - CTEQ 6.1 family



Francavilla/Roda, ATL-PHYS-2008-062

Inclusive Jet Cross-section Measurement

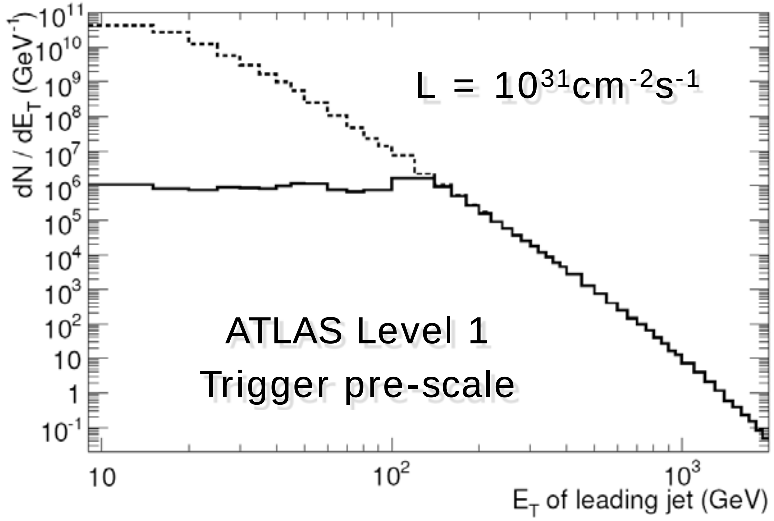
P. Loch
U of Arizona
May 05, 2010

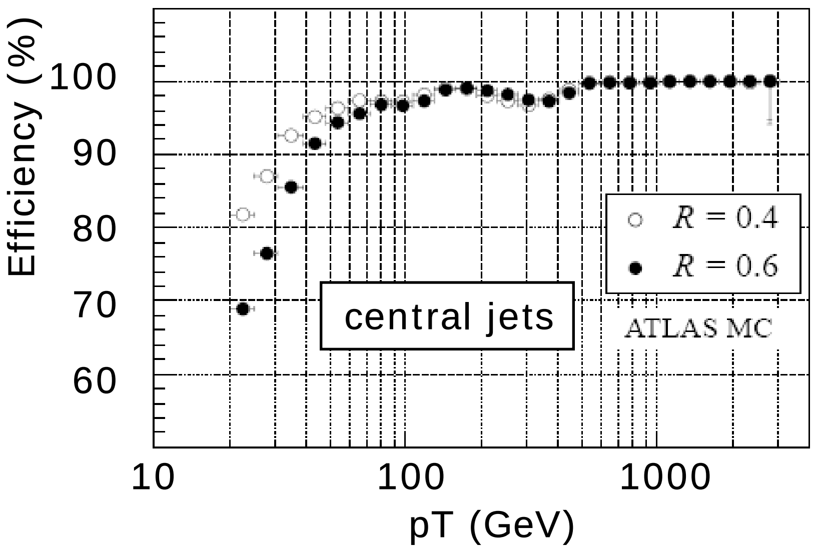
QCD swamps trigger and acquisition band width

- Highly prescaled low pT triggers
- Trigger rates follow cross-section for pT>~300 GeV
  - Depending on luminosity

Need to understand trigger bias effect on cross-section measurement

- Low pT problematic due to efficiency and purity issues anyway!
- Safe pT>~60-80 GeV

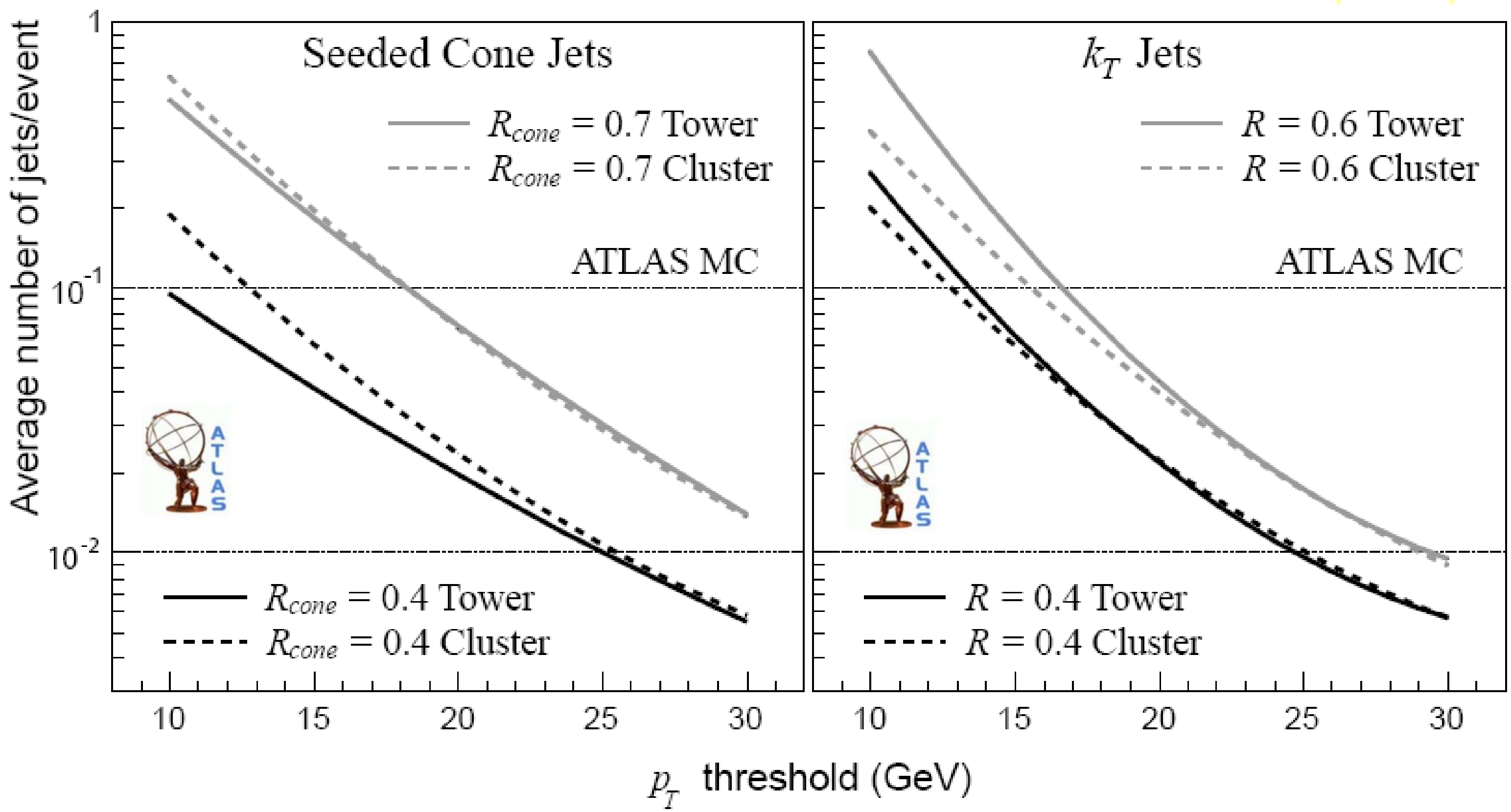




Fake Jets

Average number of jets in minimum bias events estimates fake jet reconstruction rate as function of pT threshold

no pileup!



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May 05, 2010

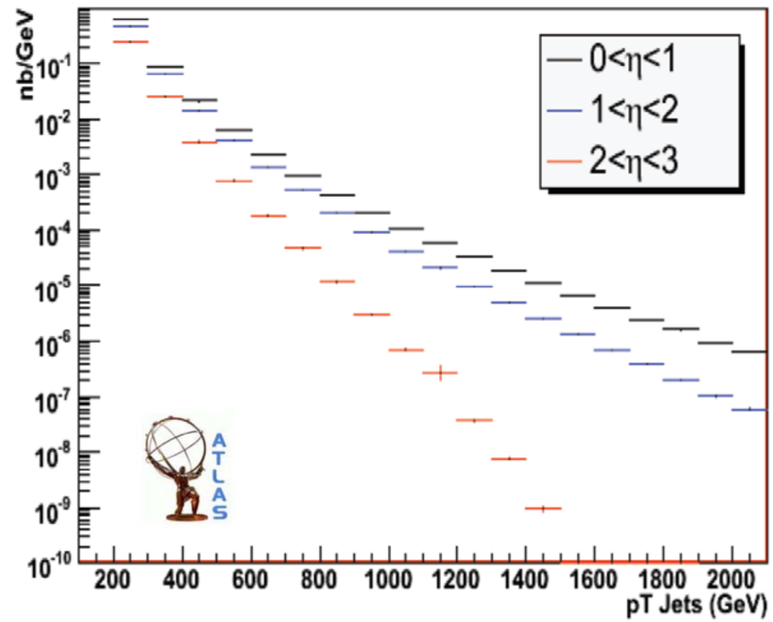
Extracting PDFs

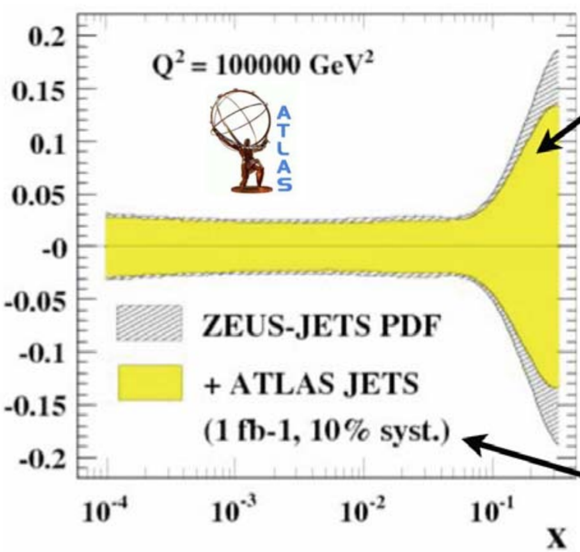
From inclusive jet cross-sections

- Measure cross-section in regions of pseudo-rapidity

Statistical error quickly reduced

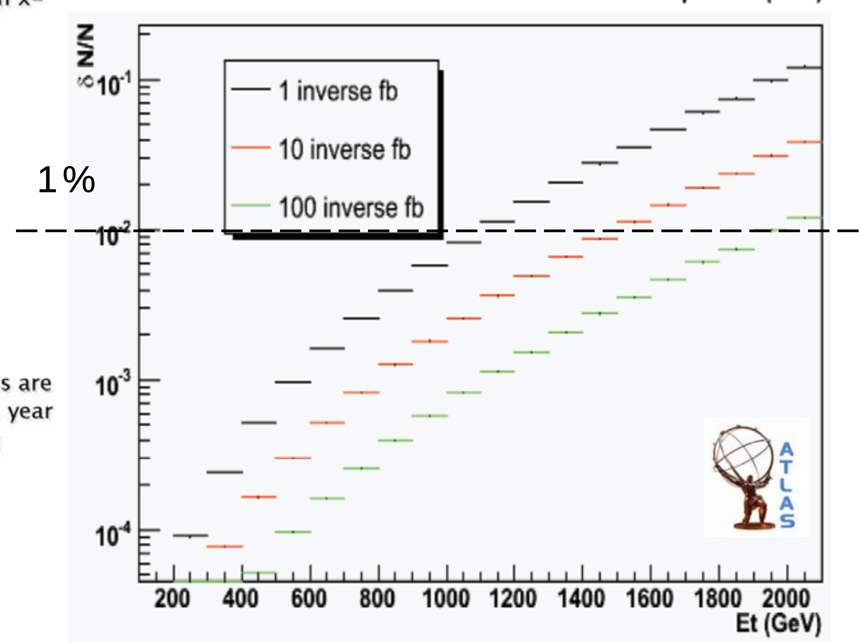
- Trigger, JES more important





Preliminary indications suggest that ATLAS data can constrain the high x-gluon.

Systematic uncertainties are uncorrelated, 10fb-1=1 year of nominal data-taking



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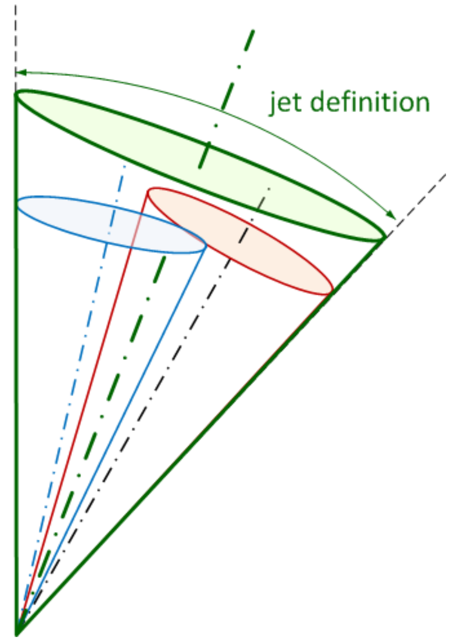
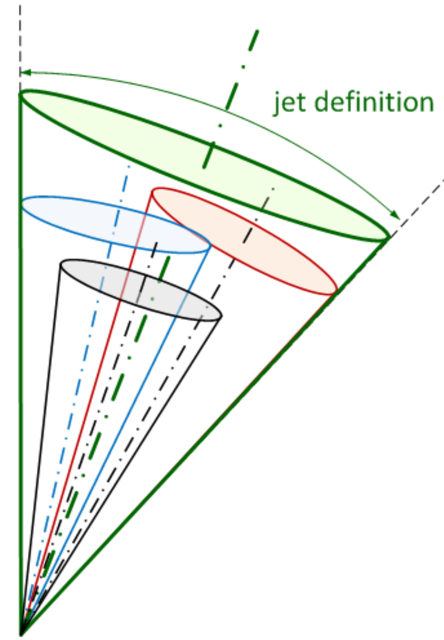
U of Arizona
May 05, 2010

Particle flow inside a jet hints to source

- Jet can be a discovery tool by itself
  - In particular most interesting for boosted (new) heavy particle like Kaluza-Klein excitations
  - But also interesting for Standard Model particles like boosted top quarks
- Usefulness depends on the ability to resolve decay structure
  - E.g., 2-prong (like W) or 3-prong (top) decays
  - Resolution scale given by mass of particle (or by particle hypothesis) – to be reflected with detector capabilities



$2-$prong decay inside reconstructed jet, e.g. from $W \rightarrow q\bar{q}$ (SM) or heavy new object like $\phi \rightarrow gg$ or $Z' \rightarrow q\bar{q}$ (BSM)



$3-$prong decay inside reconstructed jet, e.g. from $t \rightarrow q\bar{q}b$ (SM) or heavy new object like $\phi_{KK} \rightarrow Q\bar{Q}b + X$ or $t' \rightarrow q\bar{q}b$ (BSM)

Observables and tools

Single jet mass

- Mass generated by four-momentum recombination should reflect heavy source
- Scales proportional to pT for light quark or gluon jet

Subject to severe detector effects

- Lateral energy spread by individual particle cascades reduces single jet mass resolution
- Calorimeter signal definition choices on top of shower spread can enhance or reduce sensitivity to in-jet particle flow and thus improve or worsen single jet mass resolution

$$\begin{pmatrix} E_{\text{jet}} \\ \vec{p}_{\text{jet}} \end{pmatrix} = \begin{pmatrix} \sum_{\text{constituents}} E_{\text{constituent}} \\ \sum_{\text{constituents}} \vec{p}_{\text{constituent}} \end{pmatrix} \Rightarrow m_{\text{jet}} = \sqrt{E_{\text{jet}}^2 - |\vec{p}_{\text{jet}}|^2}$$

mass of gluon/light quark jets:

LO $1-$parton jets have vanishing mass

NLO $2-$parton configurations at given p_{jet} generate average invariant jet mass:

$$\langle m_{\text{jet}}^2 \rangle_{\text{NLO}} \simeq \bar{\mathcal{C}}\left(p_{\text{jet}}/\sqrt{s}\right)\alpha_s\left(p_{\text{jet}}/2\right)p_{\text{jet}}^2 R_{\text{cone}}^2$$

with:

$\bar{\mathcal{C}}\left(p_{\text{jet}}/\sqrt{s}\right)$ pre-function of magnitude $\mathcal{O}(1)$ (absorbes color charges and pdf, slowly decreases with rising p_{jet})

$\alpha_s\left(p_{\text{jet}}/2\right)$ strong coupling at scale $\mu = p_{\text{jet}}/2$

$\Rightarrow$ expect linear mass in NLO to scale with p_{jet} :

$$\sqrt{\langle m_{\text{jet}}^2 \rangle_{\text{NLO}}} \simeq \sqrt{\bar{\mathcal{C}}\alpha_s}\, p_{\text{jet}} R_{\text{cone}}$$

rule of thumb at $\sqrt{s} = 14$ TeV:

$$\sqrt{\langle m_{\text{jet}}^2 \rangle_{\text{NLO}}} \approx 0.2 \cdot p_{\text{jet}} R_{\text{cone}}$$

Jet Mass

Observables and tools

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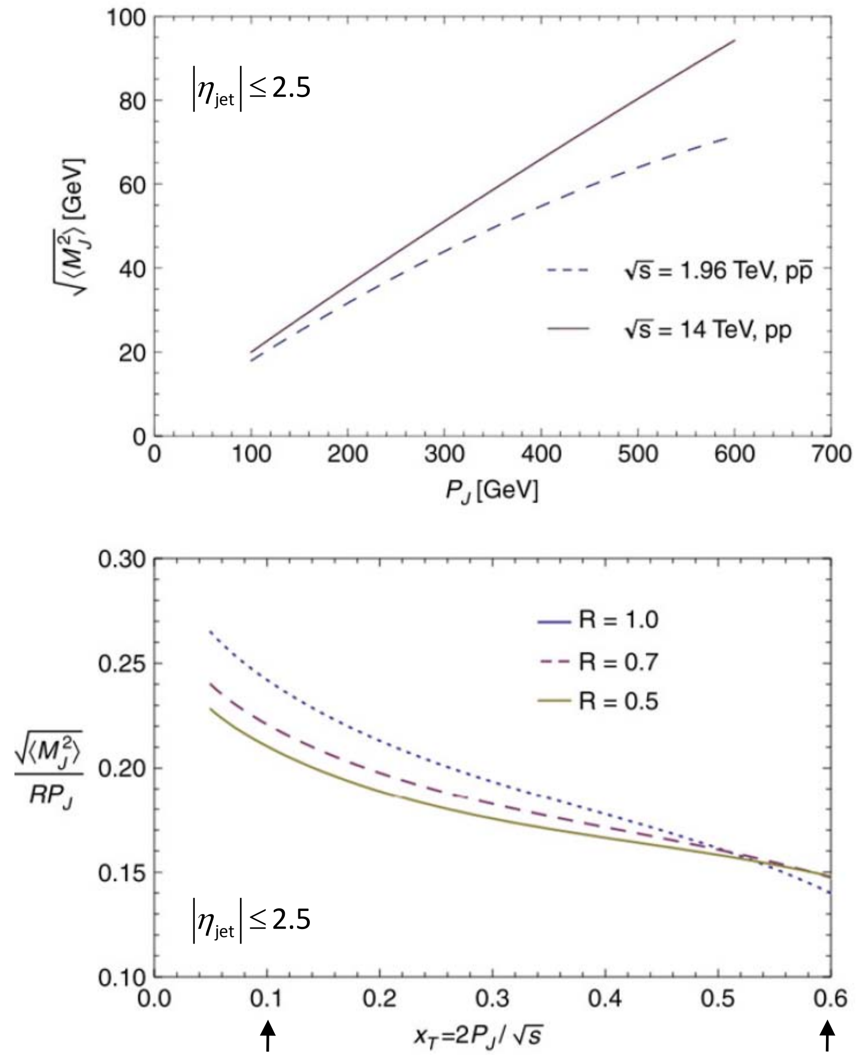
NLO Jet Mass Calculations



$p_{T,jet}^{min} \approx 115$ GeV → $p_{T,jet}^{min} \approx 685$ GeV

$p_{jet} = 700$ GeV → $p_{jet} = 4.2$ TeV

S.D.Ellis, J.Huston, K.Hatakeyama, P.Loch, and M.Tönnesmann, **Prog.Part.Nucl.Phys.60** 484-551 (2008)

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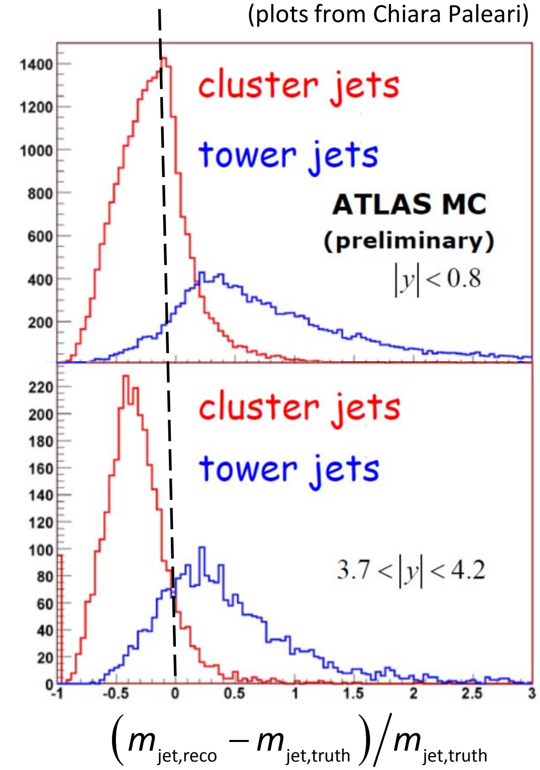
- requires good reconstruction of particle flow in jet by detector signal $\rightarrow$ depends on chosen calorimeter signal definition, e.g. test $\frac{m_{\mathrm{jet,reco}} - m_{\mathrm{jet,truth}}}{m_{\mathrm{jet,truth}}}$ for matching truth and calorimeter jets
- plot on the right shows the spectrum of this relative mass difference for simulated QCD di-jets (kT, $R = 0.6$) in ATLAS

(old plot, educational purpose only!)

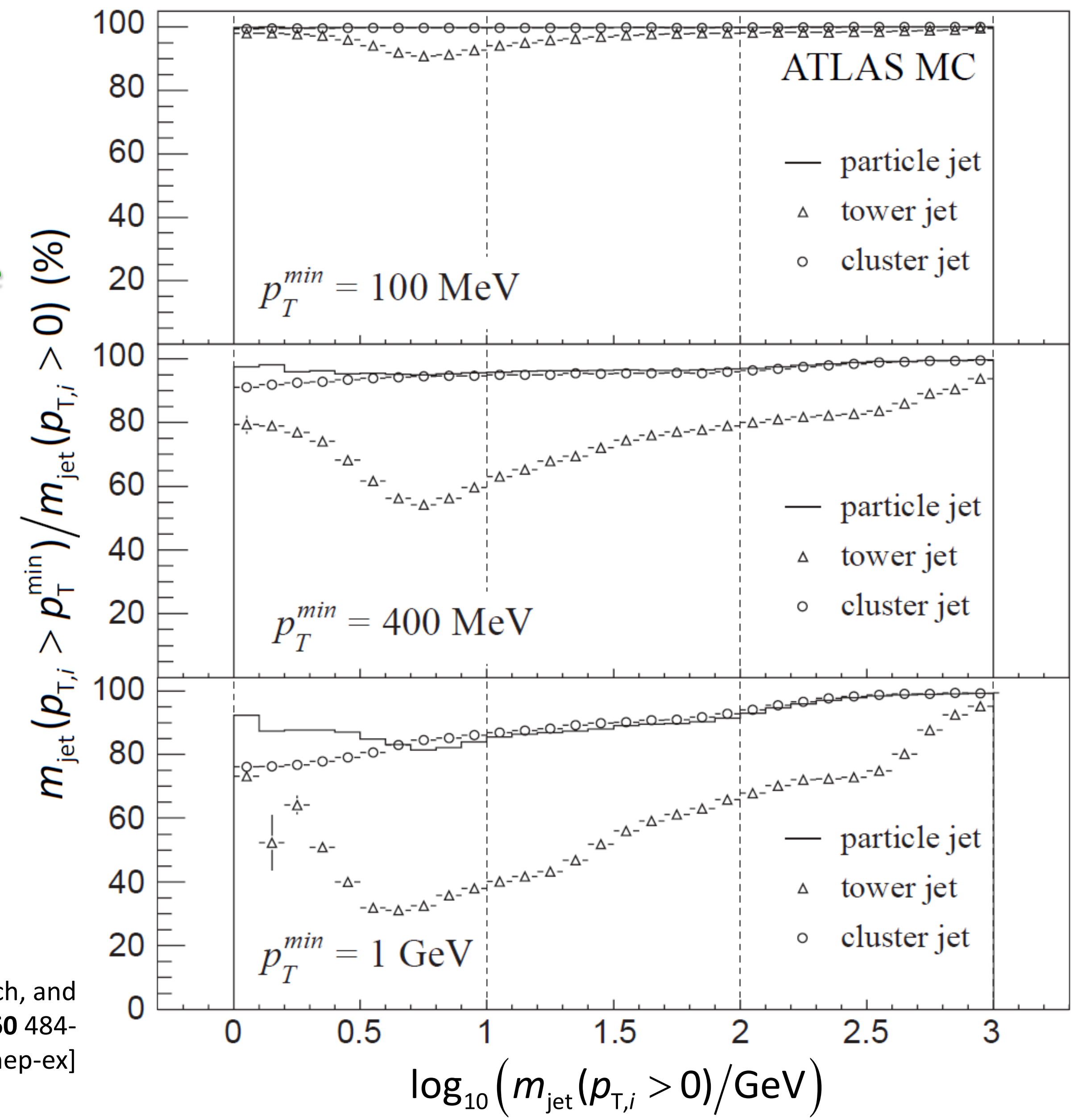
(plots from Chiara Paleari)



Jet Mass

Relative mass change

- Truncate jet mass
  - Calculate mass using only constituents above pT thresholds
- Compare ratio to unbiased mass
  - Particle (hadron), cluster, tower jets



S.D.Ellis, J.Huston, K.Hatakeyama, P.Loch, and M.Tönnesmann, **Prog.Part.Nucl.Phys.60** 484-551 (2008); also in **arXiv:0901.0512** [hep-ex]

kT Jets Y_{scale}

Observables and tools

- Recombination scales and order in kT like algorithms
  - Jet decomposition tracing back the (recursive) recombination
- Can be considered resolving fragmentation to a given scale
  - Scale of last clustering step relates to mass of source in two-prong decay
  - Scale of next-to-last clustering step relates to mass of source in three-prong decay
- Can be expected to correlate with jet mass in heavy particle decays
  - But different resolution – likely less sensitive to detector effects!

$y-$scale in kT algorithms provides a p_{T} scale at which a given recombination can be undone

recall variables:

$$d_i = p_{\mathrm{T},i}^2 \text{ and } d_{ij} = \min(d_i, d_j)\frac{\Delta R_{ij}}{R}$$

principal kT clustering rules:

(1) build list of d_i and d_{ij} from all protojets

(2) if common minimum is a d_i, call i from list and call it a jet

(3) else combine i and j to a jet and add to list, and remove the previous protojets i and j

(4) repeat from (1) until no protojets are left

define $y-$scale

$y_{\text{scale}}^2 = y_n \times p_{\mathrm{T,jet}}^2$, with n being a resolution parameter

example: $n=2$ refers to the last recombination in the clustering sequence, i.e. $d_{12} < d_1, d_2$:

$$y_{\text{scale}}^{1\rightarrow 2} = \sqrt{y_2} \times p_{\mathrm{T,jet}} = \sqrt{\min(d_1, d_2)}$$

relates to mass in two-prong decays

kT Jets Y_{scale}

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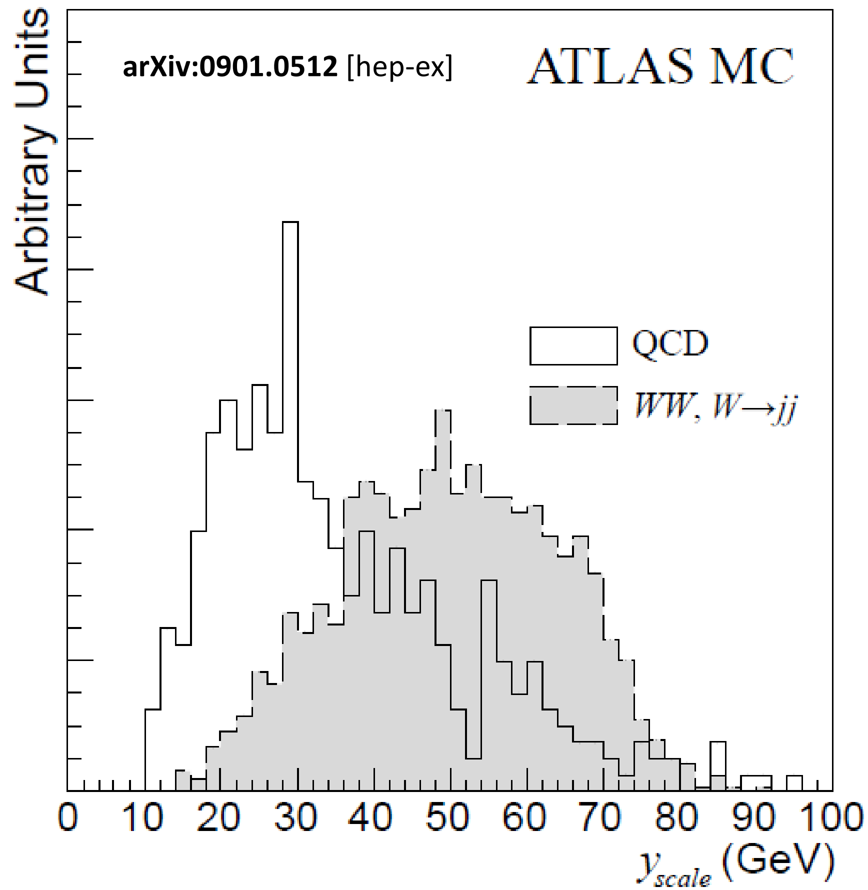

$y^{1\to 2}_{\text{scale}}$ for jets with $m_{\text{jet}} > 40$ GeV, for QCD and hadronically decaying boosted W.

Note that for QCD $y^{1\to 2}_{\text{scale}}$ is logarithmically below $p_{\text{T,jet}}$ due to the strong ordering (in k_{T}) in QCD evolution, while $\langle y^{1\to 2}_{\text{scale}} \rangle \approx m_W$ reflects the 2-prong decay of the W boson

kT Jet Y_{scale} Relation to Jet Mass

P. Loch
U of Arizona
May 05, 2010

Observables and tools

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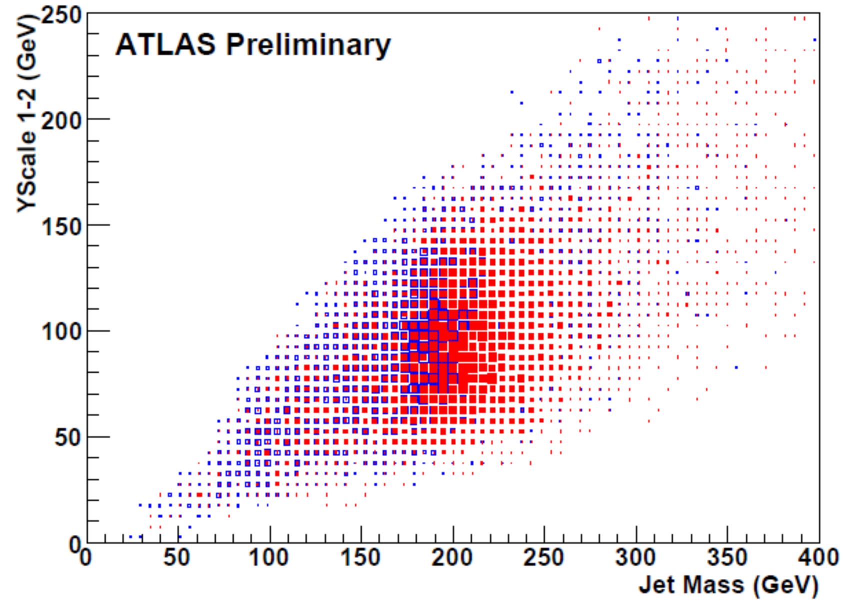
G. Brooijmnas, ATL-PHYS-CONF-2008-008



ATLAS simulation:

$Z' \to t\bar{t}$, $m_{Z'} = 2(3)$ TeV

$p_T(t) > 300$ GeV

- $y_{scale}^{1\to 2}$ probes top decay,

  peaks at ≈ 100 GeV $\approx \frac{m_{top}}{2}$

- $y_{scale}^{2\to 3}$ probes W decay,

  peaks at ≈ 40 GeV $\approx \frac{m_W}{2}$

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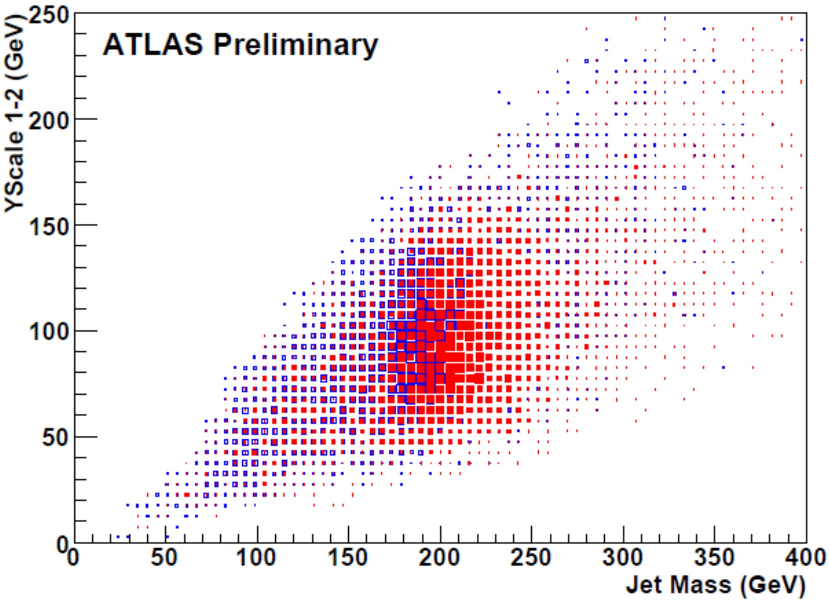
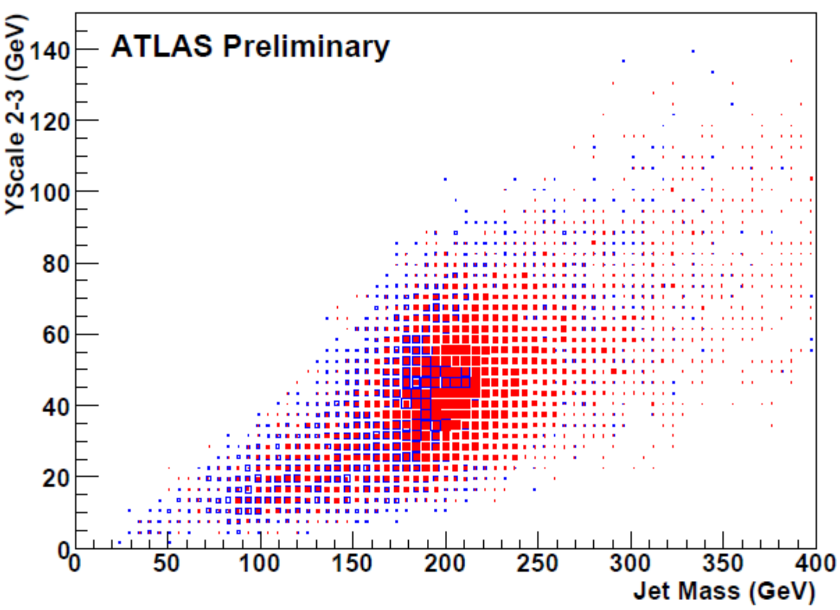


G. Brooijmnas, ATL-PHYS-CONF-2008-008



kT Jet Y_{scale} Performance Estimates

P. Loch
U of Arizona
May 05, 2010

Observables and tools

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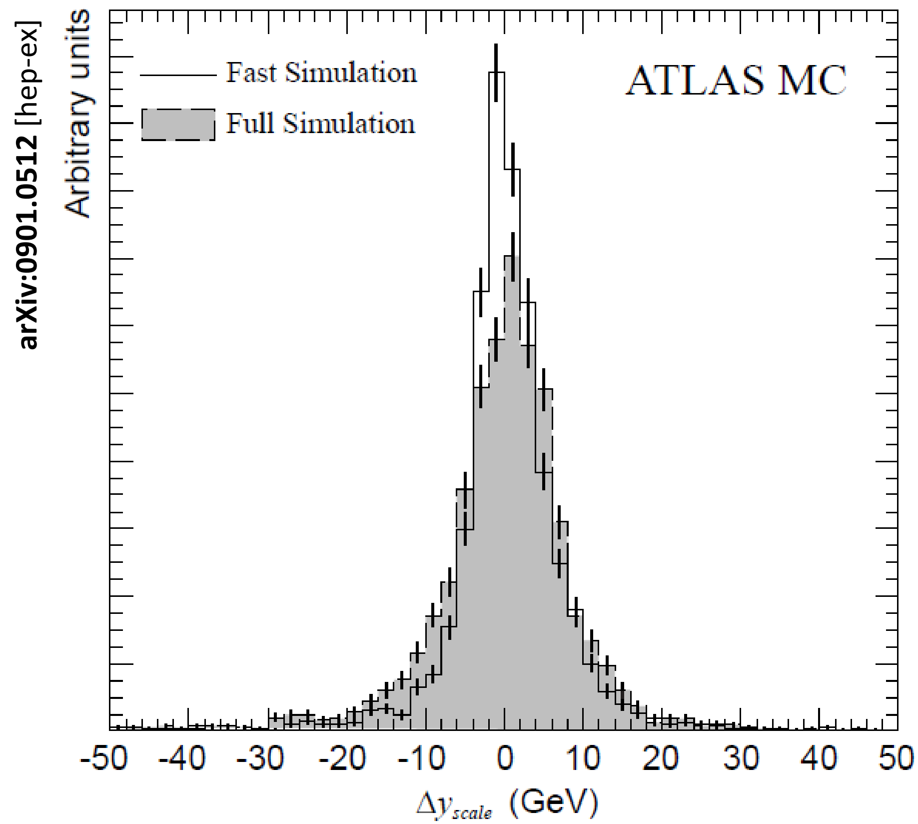


$\Delta y_{scale} = y_{scale}^{1\to 2}\big|_{\text{particle}} - y_{scale}^{1\to 2}\big|_{\text{calo}}$ for jets with $m_{\text{jet}} > 40$ GeV from hadronically decaying boosted W. $y_{scale}^{1\to 2}\big|_{\text{calo}}$ is calculated for parameterized, response smearing simulation (fast, no lateral shower spread) and from detailed full simulation $\rightarrow$ indications that $y_{scale}^{1\to 2}$ is little sensitive to details of showering.

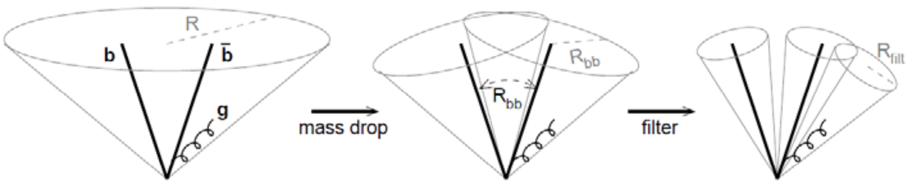
Sub-Jet Analysis

Observables and tools

- Direct attempt to reconstruct sub-jets within jet
  - Narrow jet reconstruction in bigger jet motivated by mass drop
- Includes signal enhancement strategy
  - Requires additional (3rd) jet from gluon radiation in the decay system

J.M. Butterworth, A.R. Davison, M.Rubin, G.P.Salam, Phys.Rev.Lett.100:242001,2008

Look for $H \to b\bar{b}g$ with $p_{T,H}$>200 GeV in WH / ZH production - about 5% of total cross-section:



$$R_{bb} \simeq \frac{1}{\sqrt{z(1-z)}} \frac{m_H}{p_T}, \; p_T \gg m_H$$

use Cambridge/Aachen kT flavour jet finder to find large jet ($R = 1.2$), p_T>200 GeV for sub-jet analysis

(1) break jet j into two subjects j_1, j_2, with $m_{j_1} > m_{j_2}$, by undoing last recombination

(2) if there is a significant mass drop such that $m_{j_1} < \mu m_j$, and the splitting $j \to (j_1, j_2)$ is not too asymmetric, i.e.

$$\min(p_{j_1}^2, p_{j2}^2) / m_j^2 \Delta R_{j_1,j_2}^2 > y_{\text{cut}},$$

then the jet j is assumed to be the heavy particle neighbourhood and the analysis stops

(3) else, set $j = j_1$ and go back to step (1)

apply filter to all heavy particle neighbourhoods, with a finer angular scale $R_{\text{filter}} < R_{bb}$, e.g., $R_{\text{filter}} = \min(0.3, R_{bb}/2)$ seems to be good for LHC, and take the 3 hardest objects that appear $\to H \to b\bar{b}g$, including the hardest ($\mathcal{O}(\alpha_s)$) radiation. Tag the b jets and calculate the invariant mass.

Observables and tools

- Direct attempt to reconstruct sub-jets within jet
    - Narrow jet reconstruction in bigger jet motivated by mass drop
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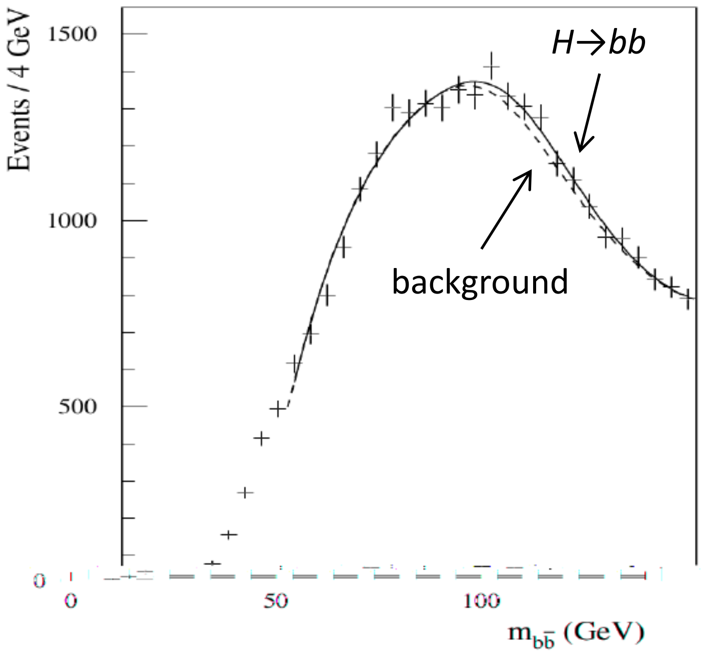

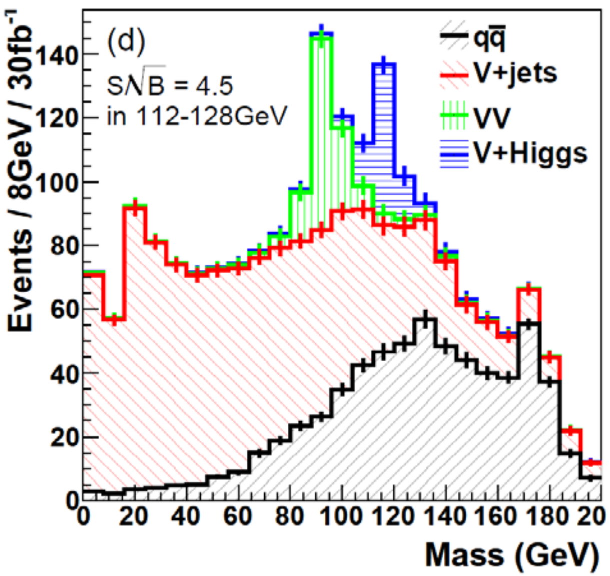

J.M. Butterworth, A.R. Davison, M.Rubin, G.P.Salam, Phys.Rev.Lett.100:242001,2008

Observables and tools

Jet pruning

Enhancement of jet components to increase substructure resolution

Applied in kT-style jet clustering procedure

Jet trimming

Applies a filter by removing soft sub-jets in a jet

Soft pT cut-off evaluated dynamically jet by jet

Jet Pruning

- attempt to suppress underlying event and pile-up contributions to jets
- cleans jets by vetoing spurious recombinations during clustering $\rightarrow$ kT and C/A jets only!
- sensitive variables are angular distance $\phi = \Delta R_{12}$ and relative p_{T} hierarchy $z \equiv \min(p_{\mathrm{T},1}, p_{\mathrm{T},2})/p_{\mathrm{T},p}$, in recombination $1,2 \rightarrow p$
- suppress large distances and large hierarchies at each clustering iteration

  $\phi > R_{\mathrm{cut}}$

  $z < z_{\mathrm{cut}}$

works better for heavy particle decays than for QCD:

- not clear what R_{cut} is for QCD – $R_{\mathrm{cut}} \approx m/p_{\mathrm{T}}$ for heavy particle decays
- also not clear what z_{cut} should be – contamination looks hard early in clustering, especially for kT; for heavy particles, $z_{\mathrm{cut}} = 0.1(0.15)$ works well for kT(C/A) jets from boosted top

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D.Krohn, *Jet Trimming*, talk given at the *Theoretical-experimental workshop on jet & jet substructure at LHC*, University of Washington, January 10-15, 2010 (based on D.Krohn, J.Thaler, L.T. Wang, **arXiv:0912.1342**)

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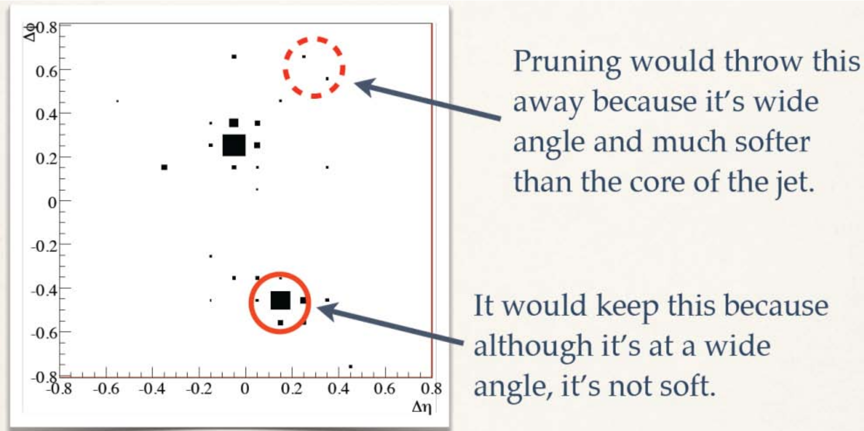

Boosted Higgs Jet

Observables and tools

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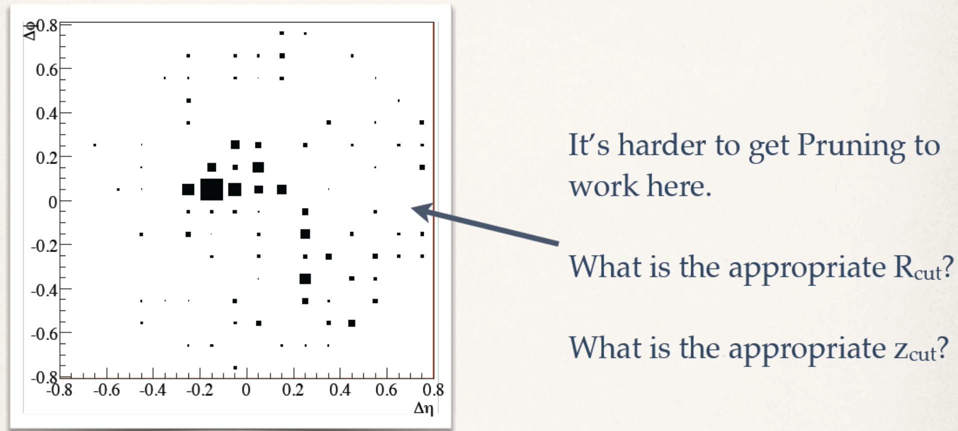

QCD Jet

Jet Pruning

Observables and tools

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Jet trimming

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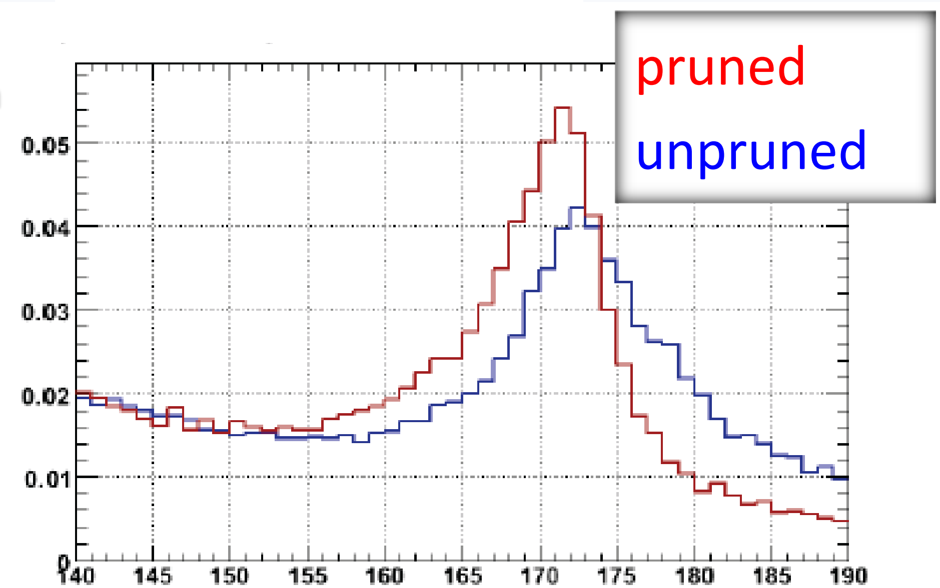
Soft pT cut-off evaluated dynamically jet by jet

Jet Pruning

- improves jet mass measurement for boosted top etc.



m_{jet} (GeV) for boosted top decays ($p_{T,jet} > 200$ GeV)

J. Walsh, *Understanding Jet Substructure*, talk given at the *Theoretical-experimental TeraScale workshop on event shapes*, University of Oregon, February 23-27, 2009

Observables and tools

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Enhancement of jet components to increase substructure resolution

Applied in kT-style jet clustering procedure

Jet trimming

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Soft pT cut-off evaluated dynamically jet by jet

Jet Trimming

- main motivation is removing contaminations from e.g. pile-up and underlying event, from a fully reconstructed jet
- measures softness/hardness of contamination relative to whole jet – no judgements at the clustering stage
- approach:
  (1) fully reconstruct jet from calorimeter signals
  (2) cluster narrow sub-jets, typically with $R_{\mathrm{sub}} = 0.2$
  (3) discard sub-jets i with $p_{\mathrm{T},i} < f_{\mathrm{cut}} \Lambda_{\mathrm{hard}}$
  (4) rebuild jet from surviving sub-jets
- typical choice for Λ_{hard} is $\Lambda_{\mathrm{hard}} = p_{\mathrm{T,jet}}$

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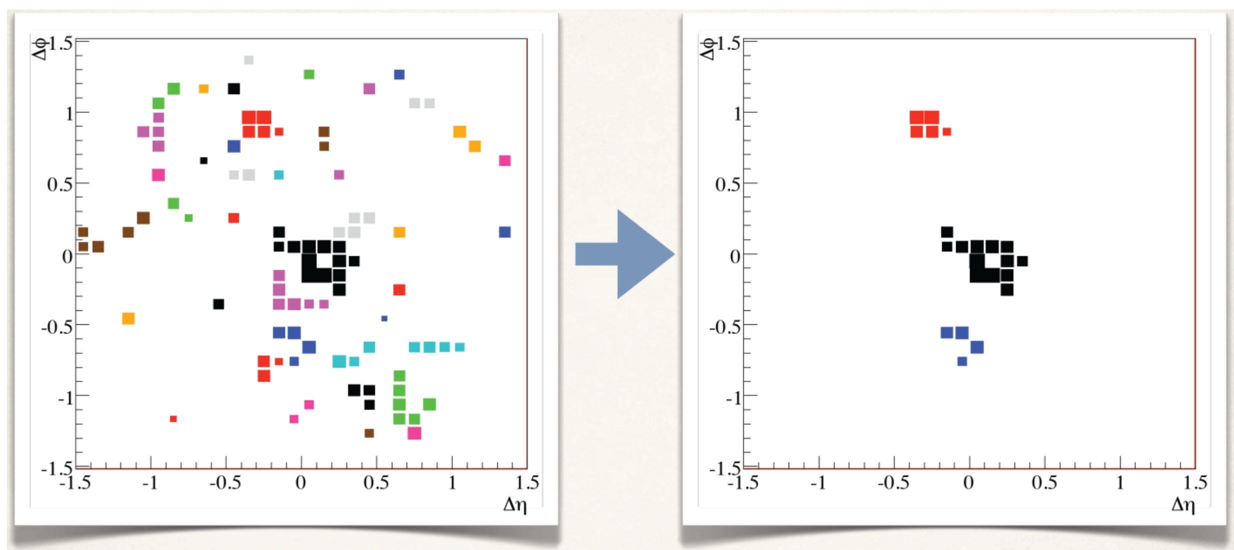
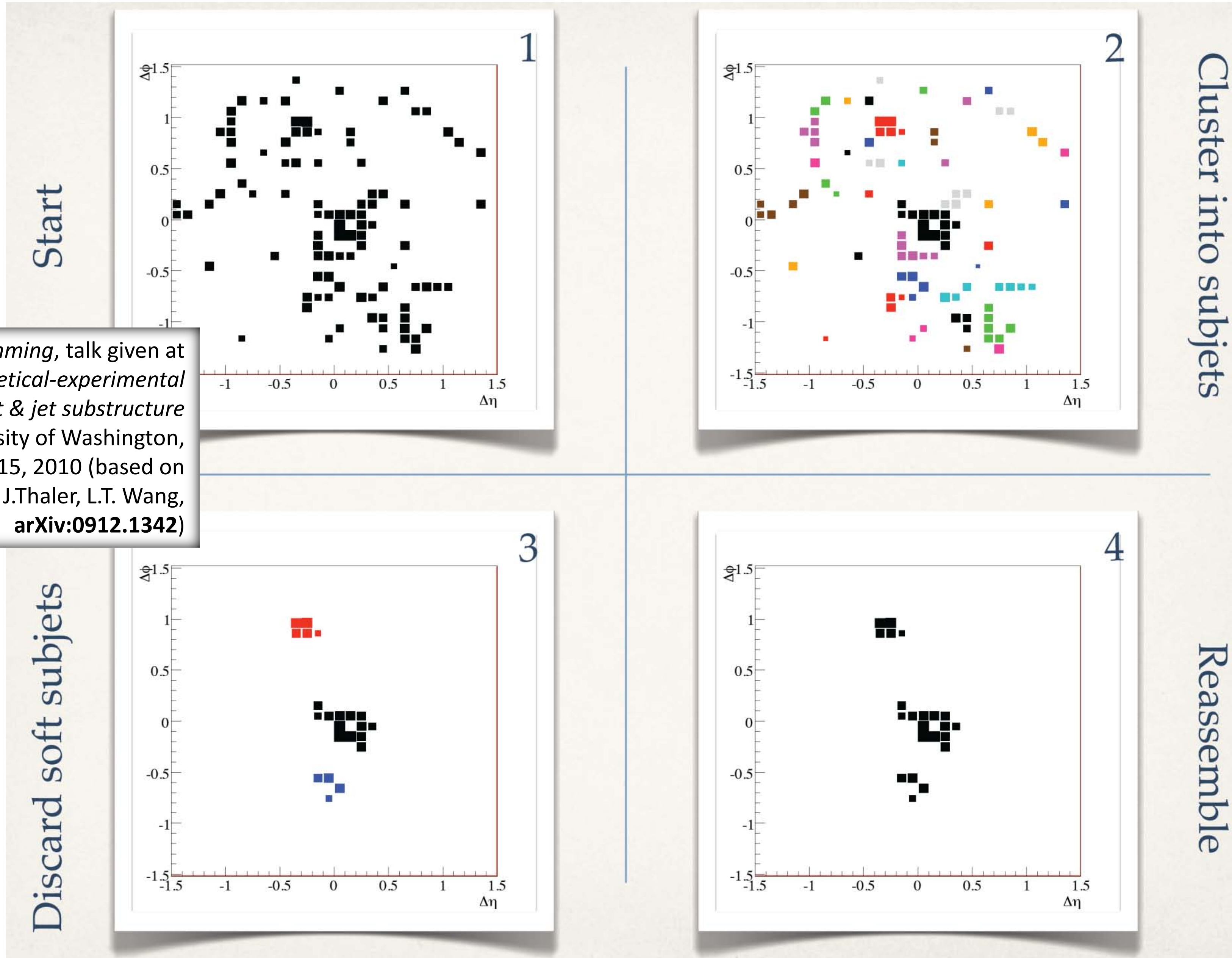


THE UNIVERSITY OF ARIZONA

Jet Trimming

P. Loch
U of Arizona
May 05, 2010



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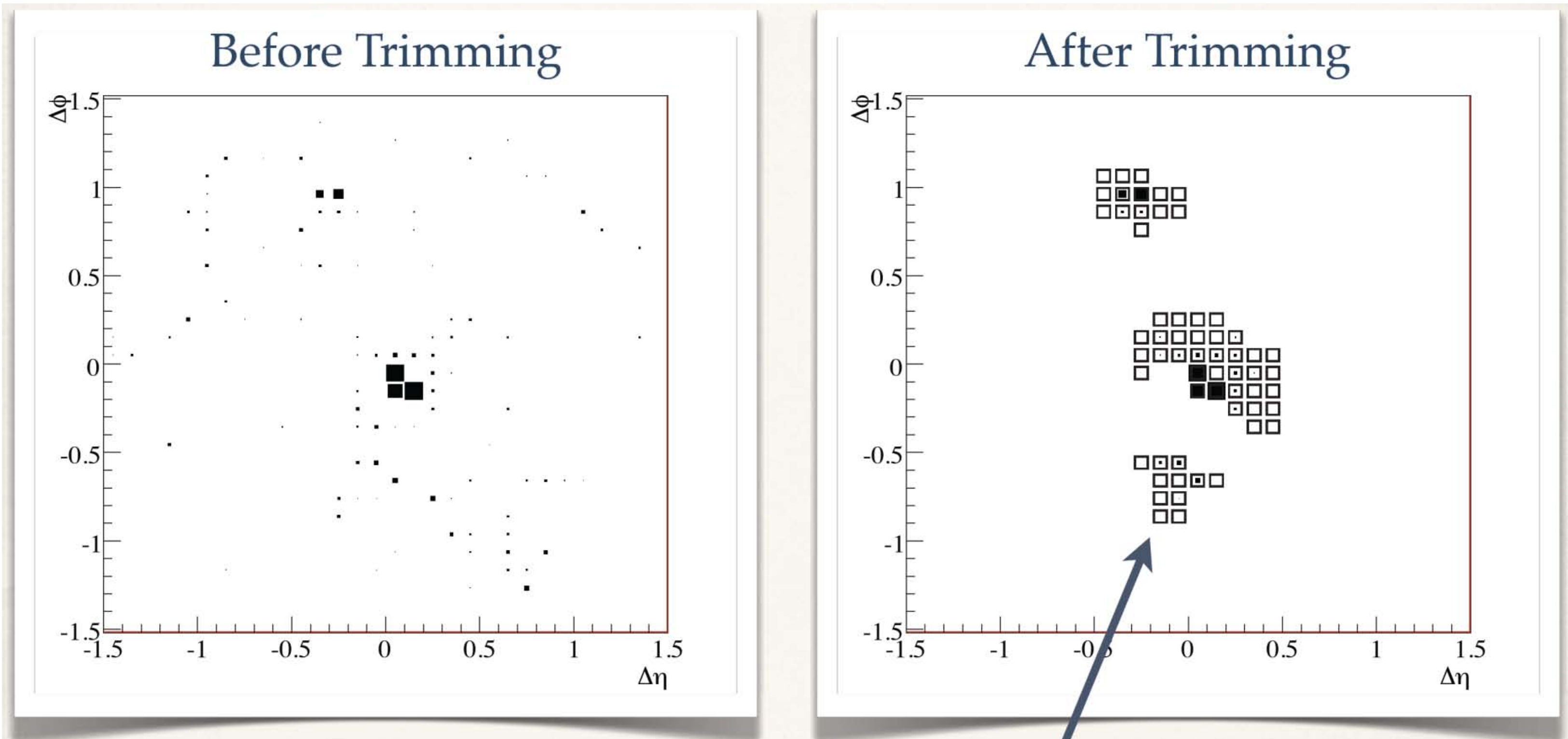
Jet Trimming



Empty squares denote extent of jet area

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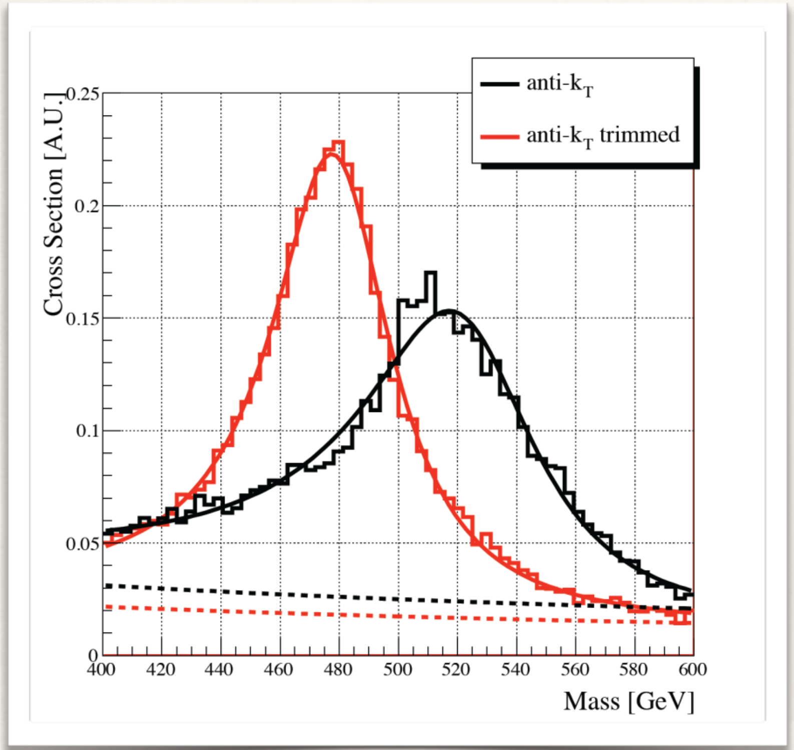

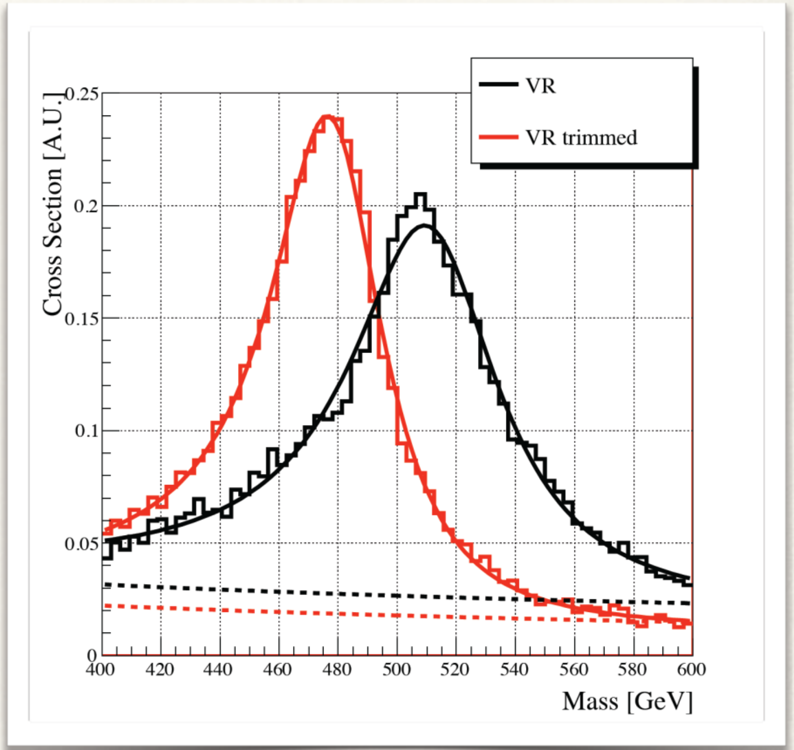

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Trimmed and variable radius (VR) jets from

$\phi \rightarrow qq, gg$

(for VR, see D. Krohn, J. Thaler, and L.-T. Wang, Jets with Variable *R*, JHEP 06 (2009) 059)