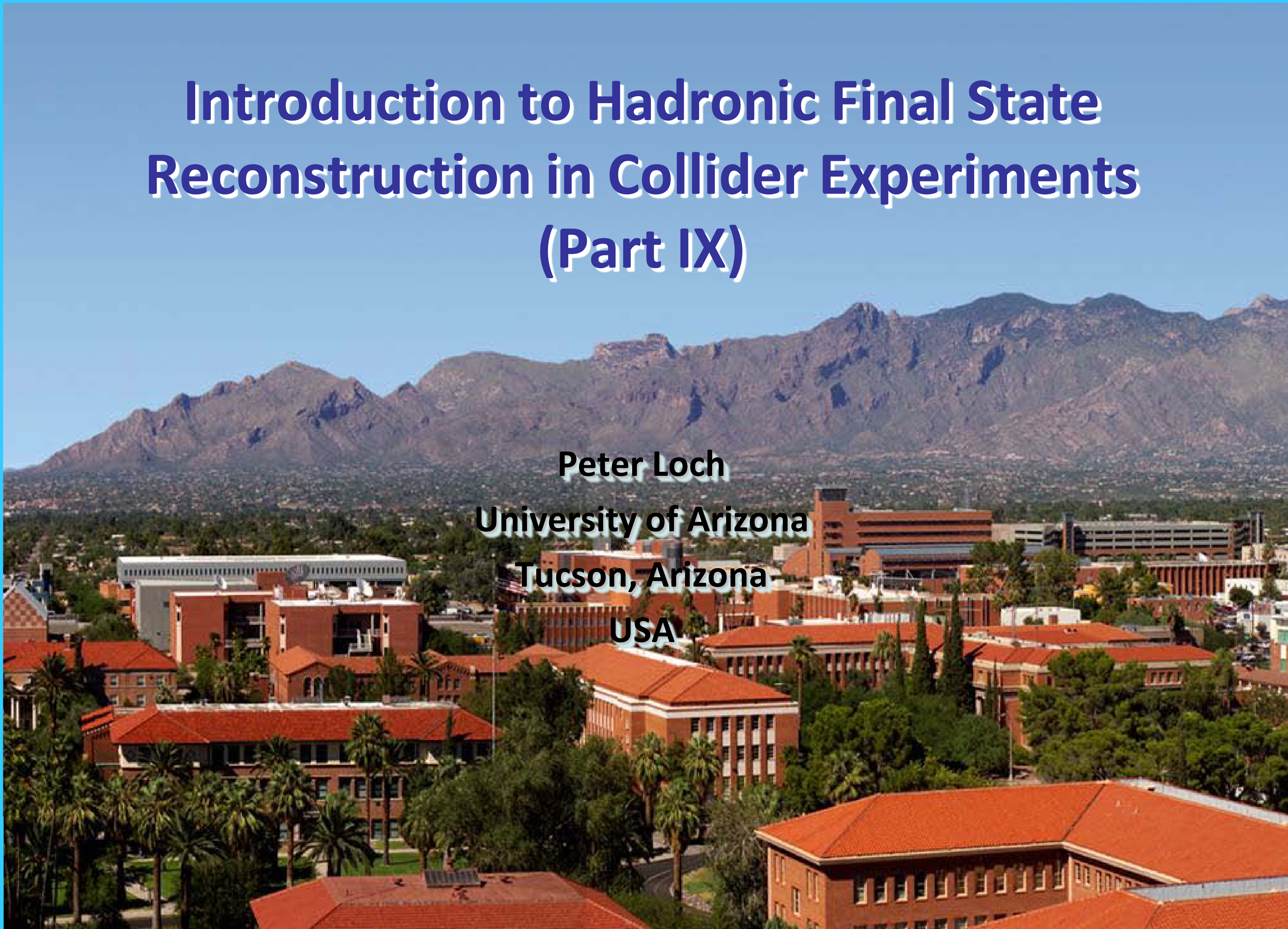


Introduction to Hadronic Final State Reconstruction in Collider Experiments

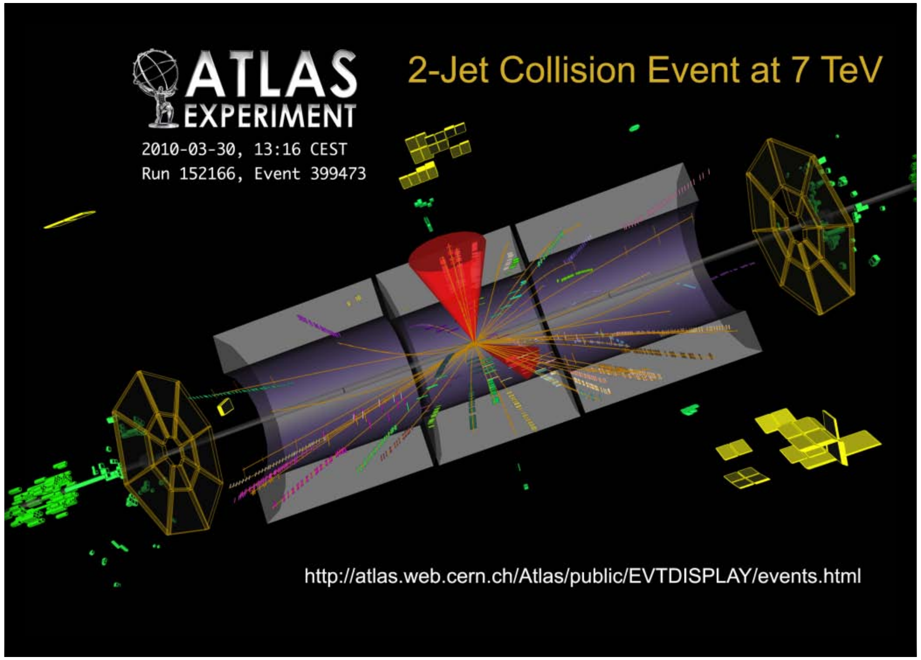
(Part IX)

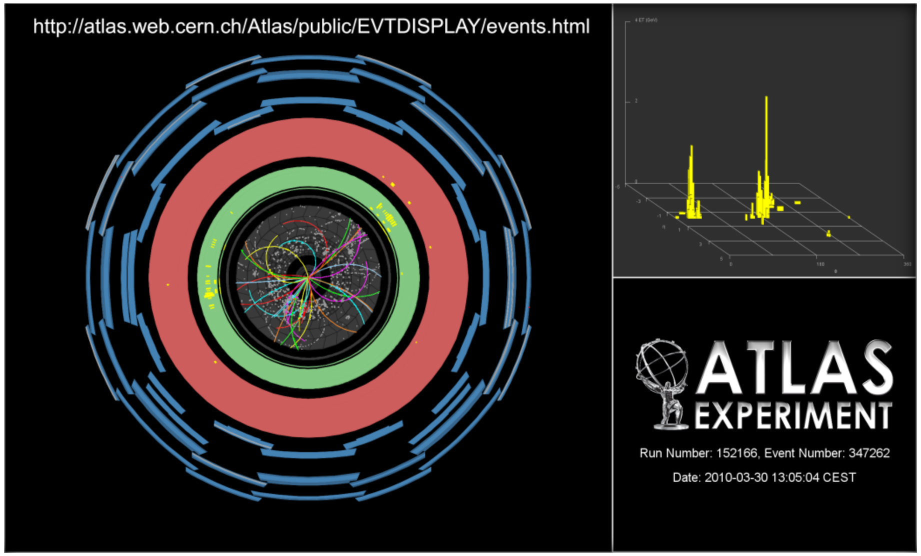
Peter Loch
University of Arizona
Tucson, Arizona
USA

pp Collisions at 7 TeV in LHC!

CERN press release March 30, 2010

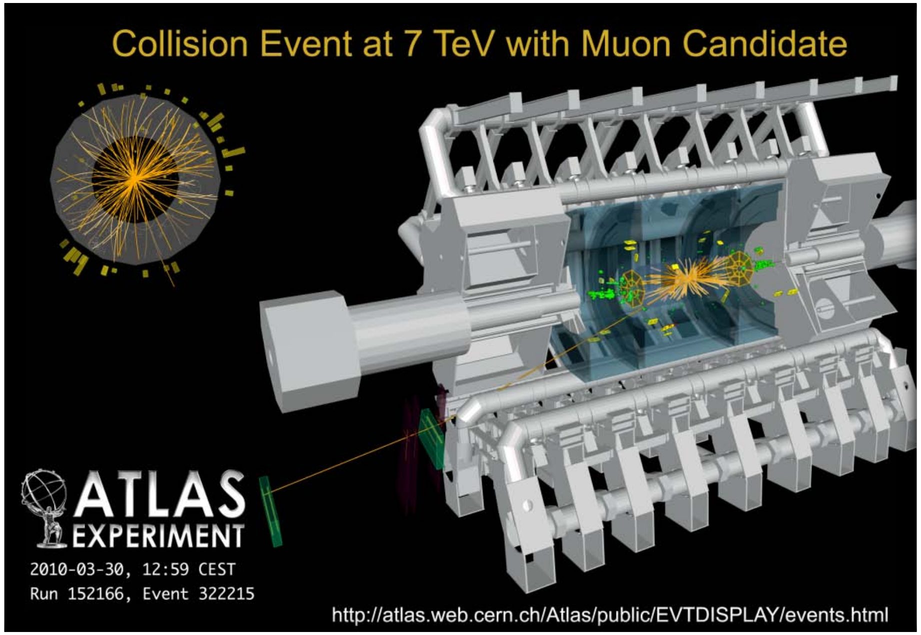
- Rolf Heuer (Director General, CERN):
  - "Beams collided at 7 TeV in the LHC at 13:06 CEST today, marking the start of the LHC research program. Particle physicists around the world are looking forward to a potentially rich harvest of new physics as the LHC begins its first long run at an energy three 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



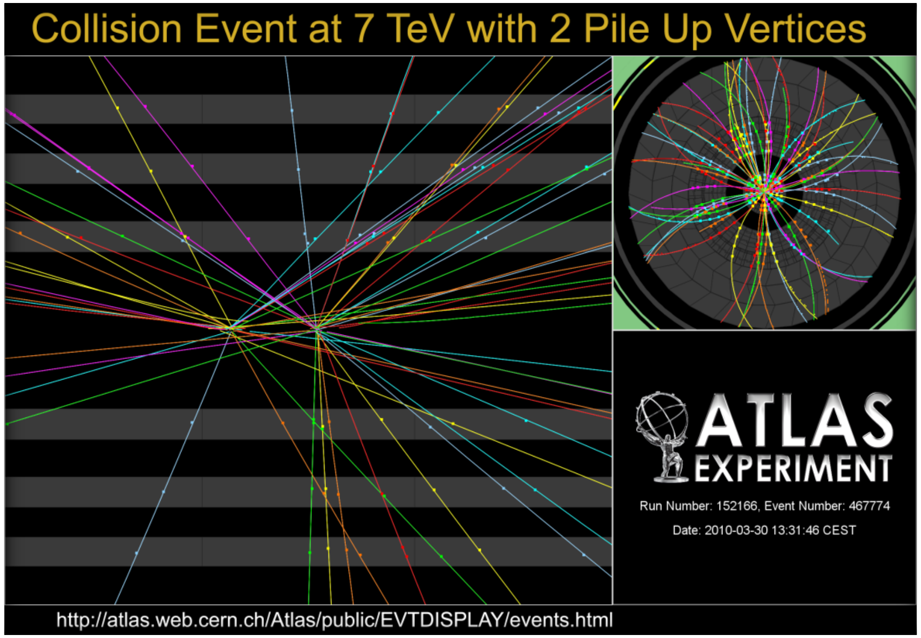
Collision Event at 7 TeV with Muon Candidate

2010-03-30, 12:59 CEST
Run 152166, Event 322215

http://atlas.web.cern.ch/Atlas/public/EVTDISPLAY/events.html

Two collisions at the same time

Pile-up!



Collision Event at 7 TeV with 2 Pile Up Vertices

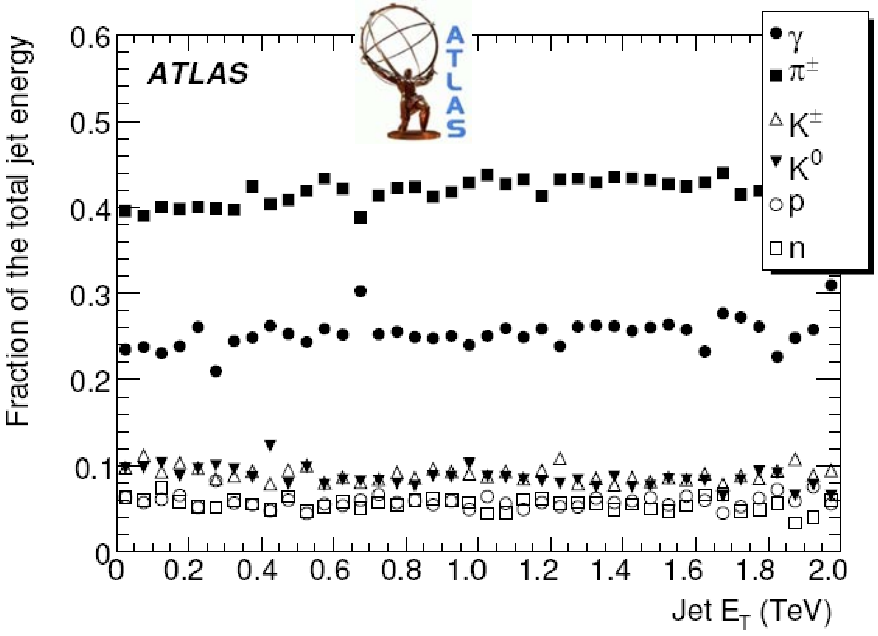
Run Number: 152166, Event Number: 467774
Date: 2010-03-30 13:31:46 CEST

http://atlas.web.cern.ch/Atlas/public/EVTDISPLAY/events.html

Recall!

Recall: the experimentalists' view on jets

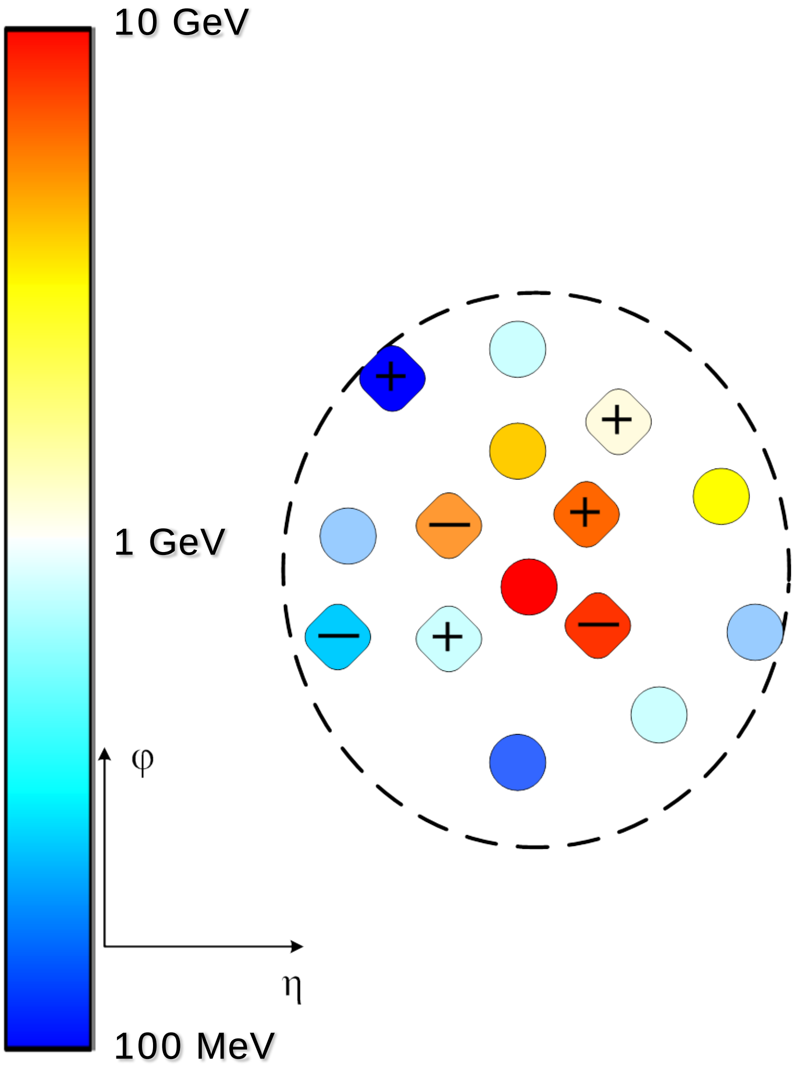
- A bunch of particles generated by hadronization of a common source
  - Quark, gluon fragmentation
- As a consequence, the particles in this bunch have correlated kinematic properties
  - Reflecting the source by sum rules and Conservation laws
- The **interacting** particles in this bunch generated 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?

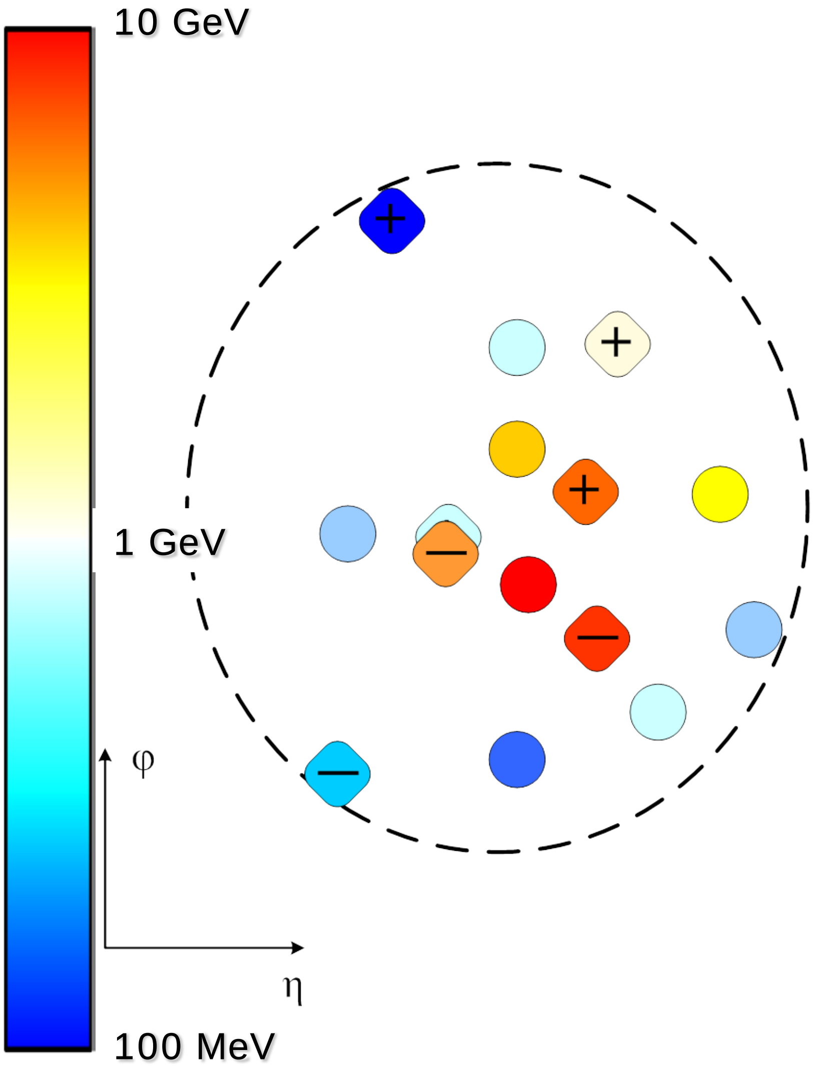
- Model/simulation: particle jet
  - Attempt to collect the final state particles described above into objects (jets) representing the original parton kinematic
  - Re-establishing the correlations
- Experiment: detector jet
  - Attempt to collect the detector signals from these particles to measure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

Detector Effects On Jets



- **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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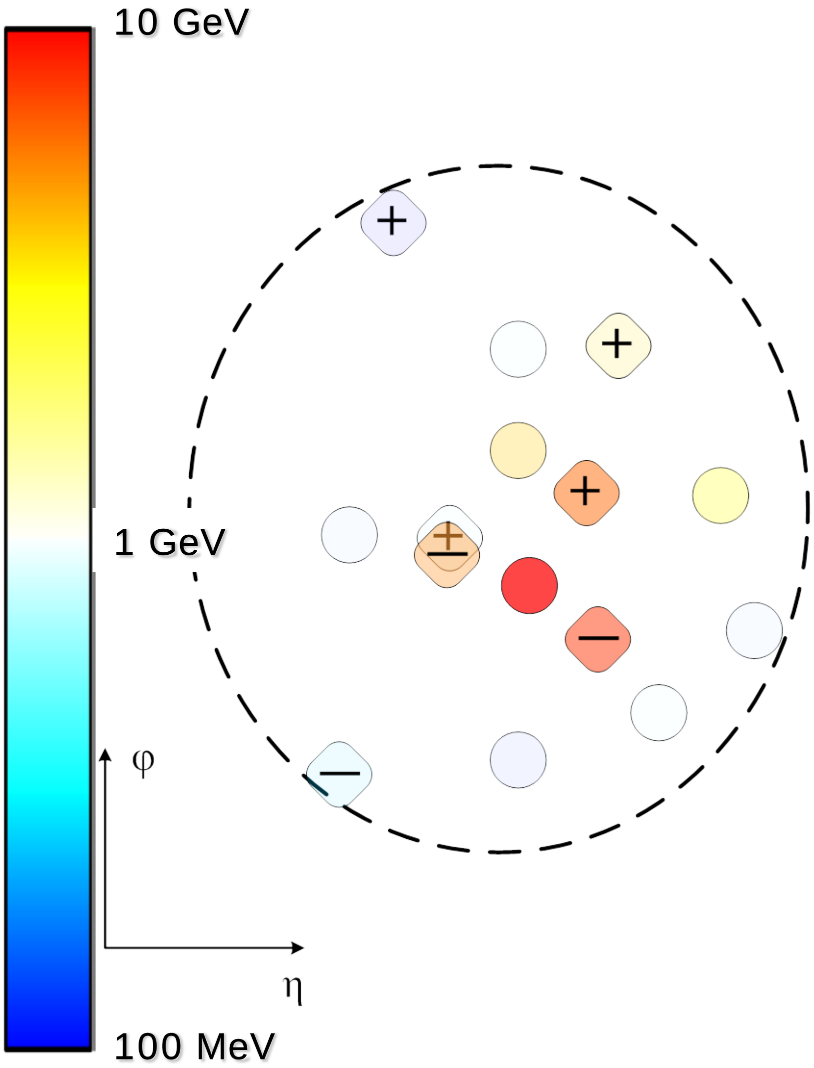

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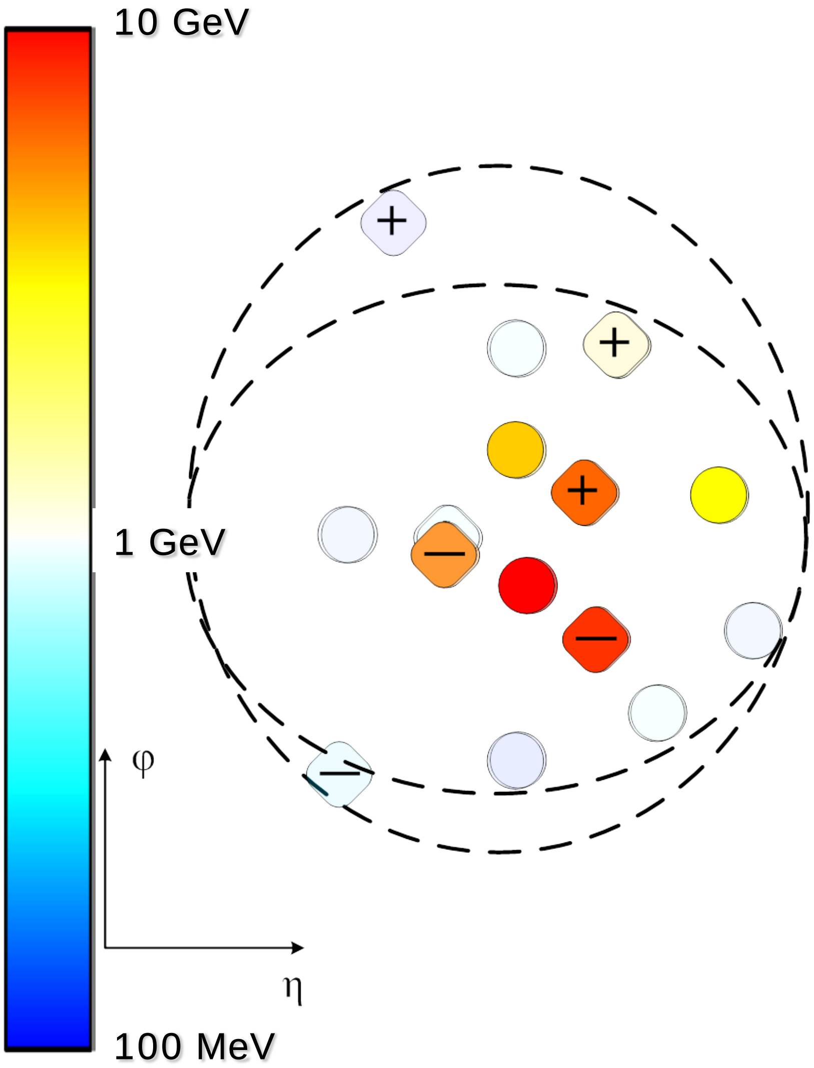

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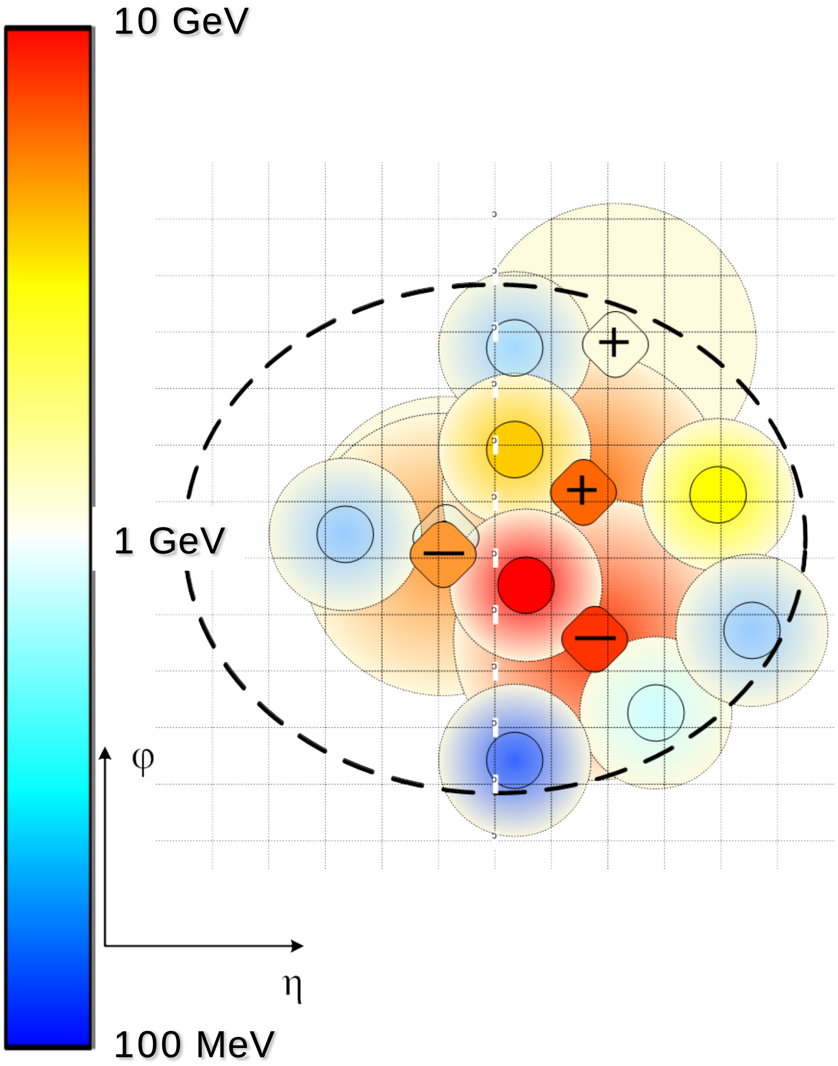

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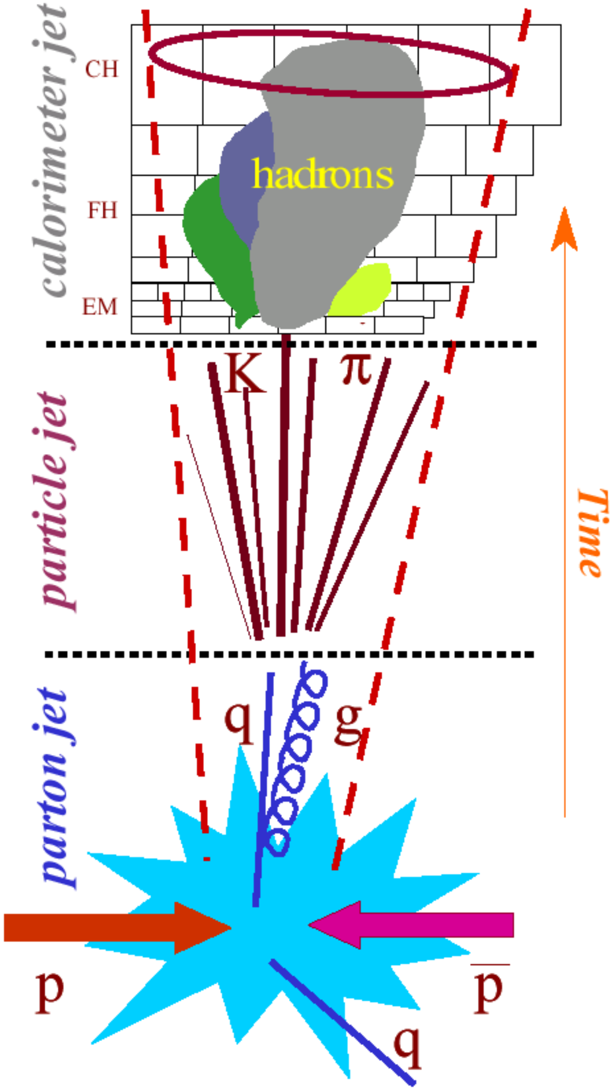
Jet Reconstruction Challenges

Experiment ("Nature")



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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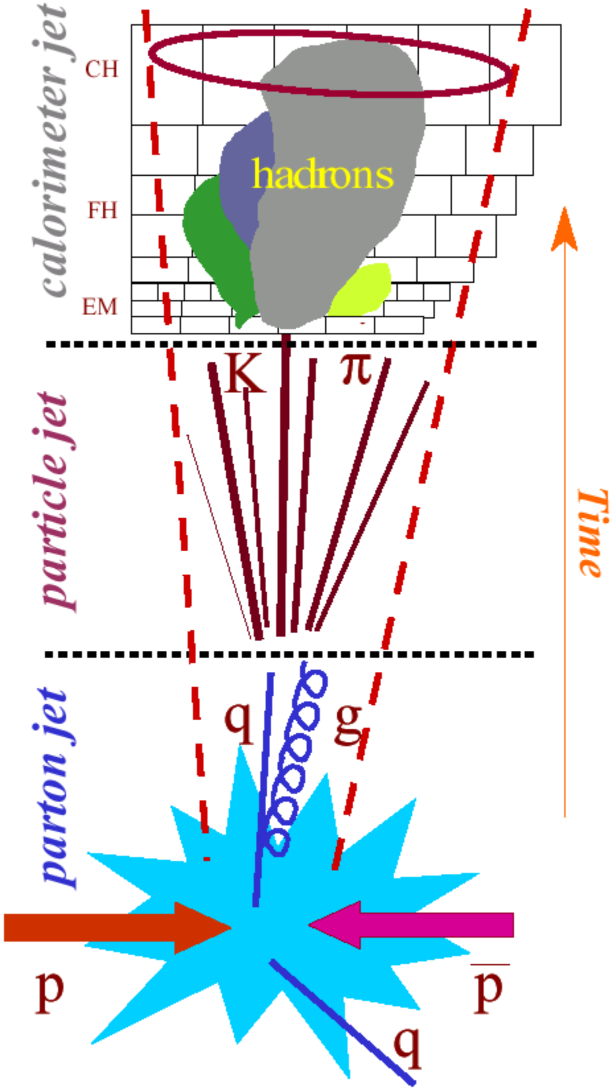

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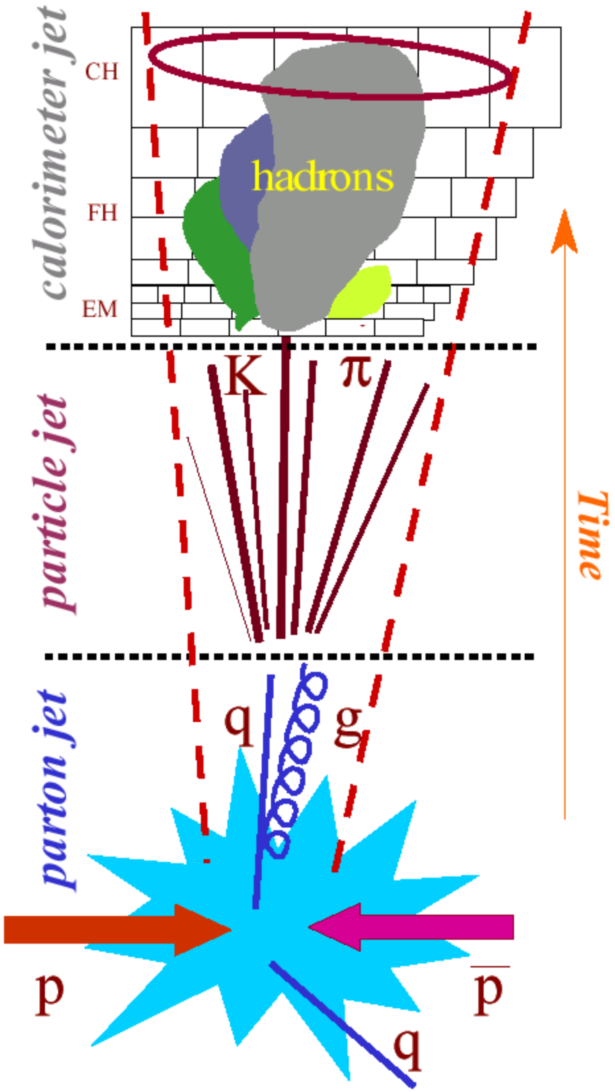

Jet Reconstruction Challenges

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…

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Jet Reconstruction Challenges

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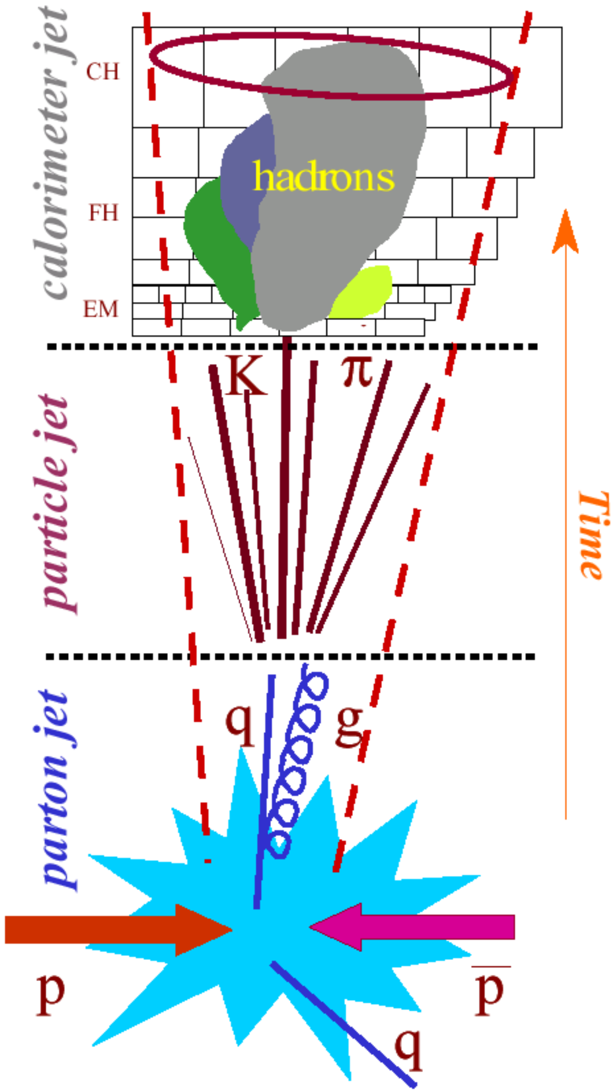

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added tracks from underlying event
added tracks from in-time (same trigger) pile-up event
jet reconstruction algorithm efficiency

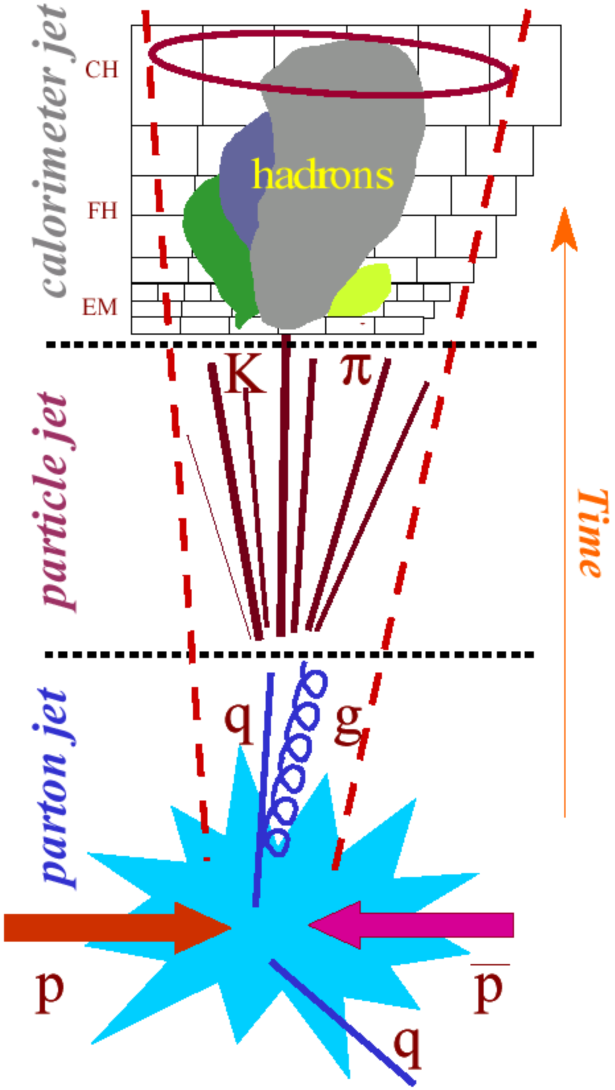
…modeling and calculations establish the link between particle and interaction level…

…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!

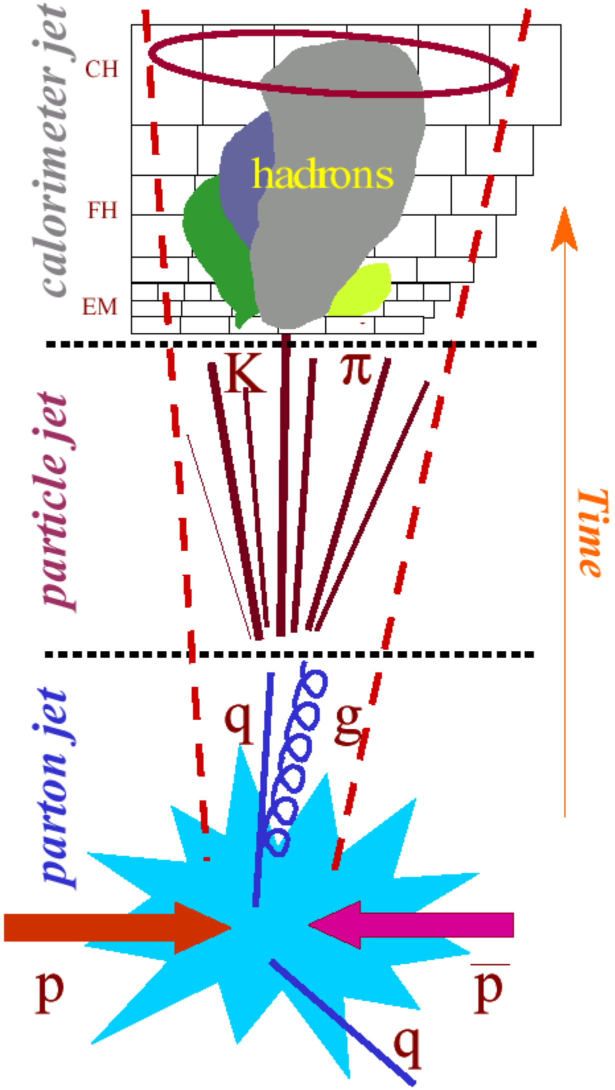
- Complex – need to include all experimental biases like event selection (trigger bias), topology and detector inefficiencies

This establishes particle jet references for the detector jets!

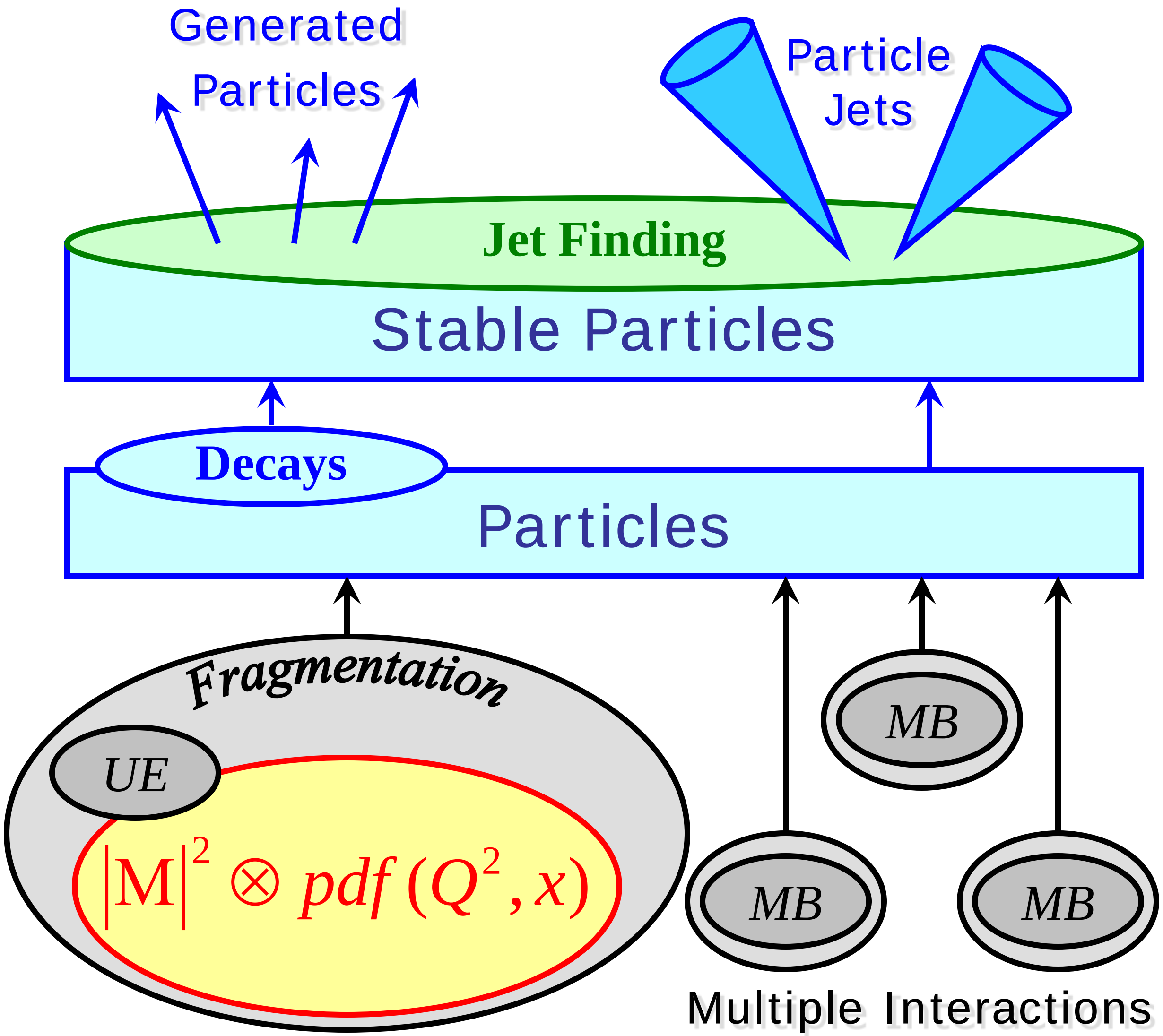
- Of course only in a statistical sense, i.e. at the level of distributions!

Jet Reconstruction Task

Experiment ("Nature")



Modeling Particle Jets



Generated Particles

Particle Jets

Jet Finding

Stable Particles

Decays

Particles

Fragmentation

UE

$|M|^2 \otimes pdf(Q^2, x)$

MB

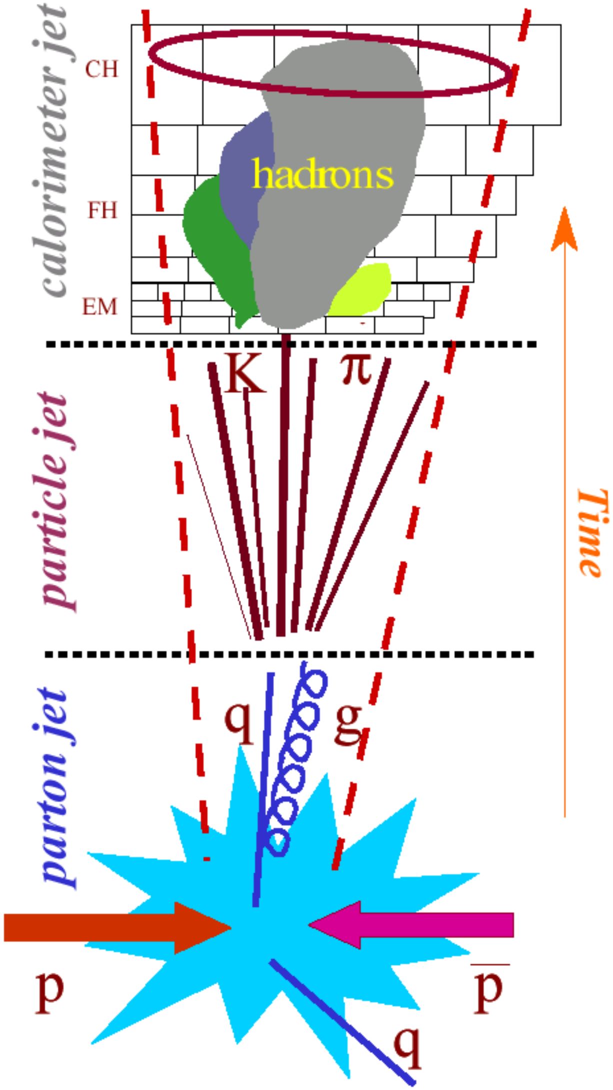
MB

MB

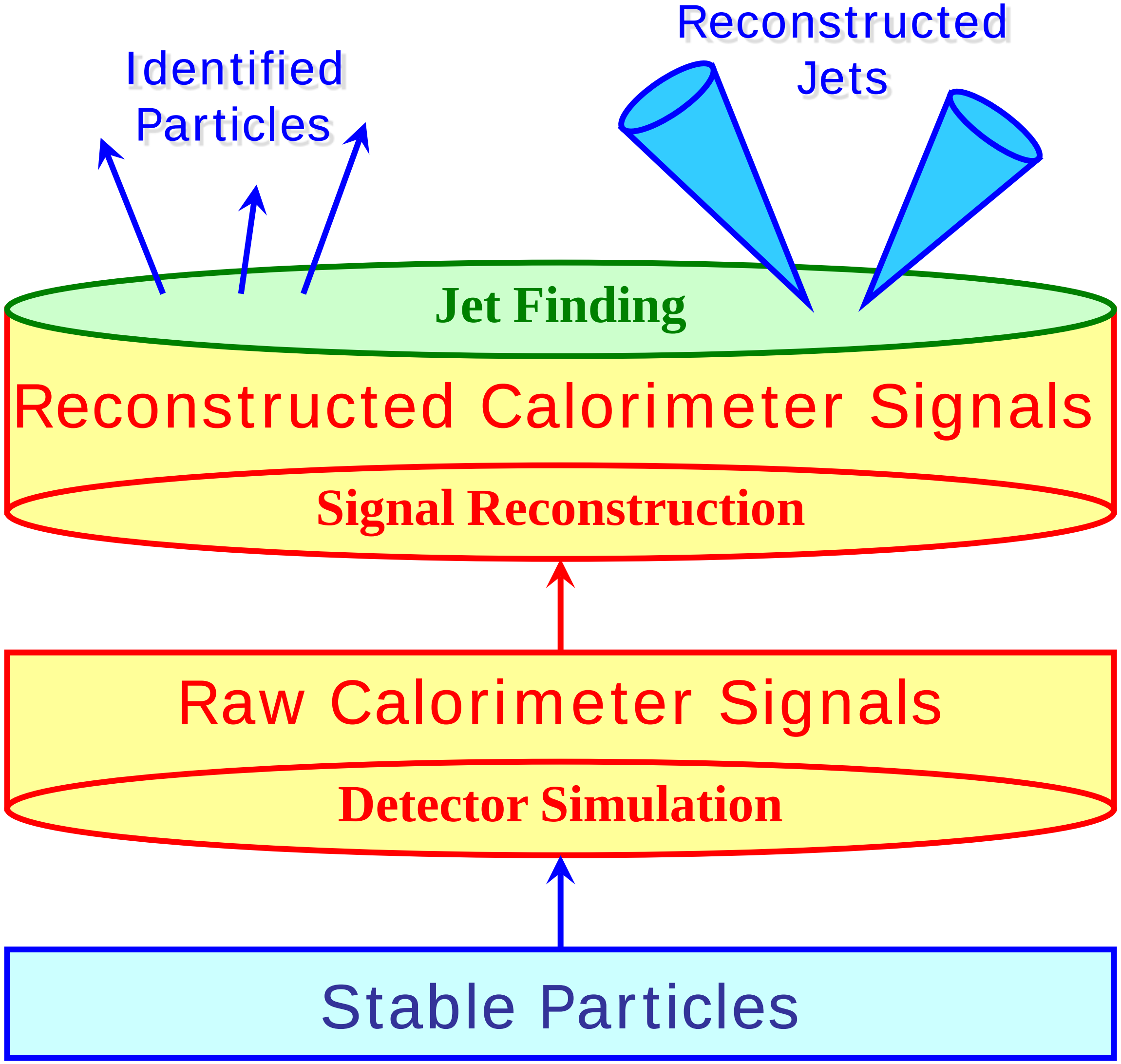
Multiple Interactions

Jet Reconstruction Task

Experiment (“Nature”)



Modeling Calorimeter Jets



Identified Particles

Reconstructed Jets

Jet Finding

Reconstructed Calorimeter Signals

Signal Reconstruction

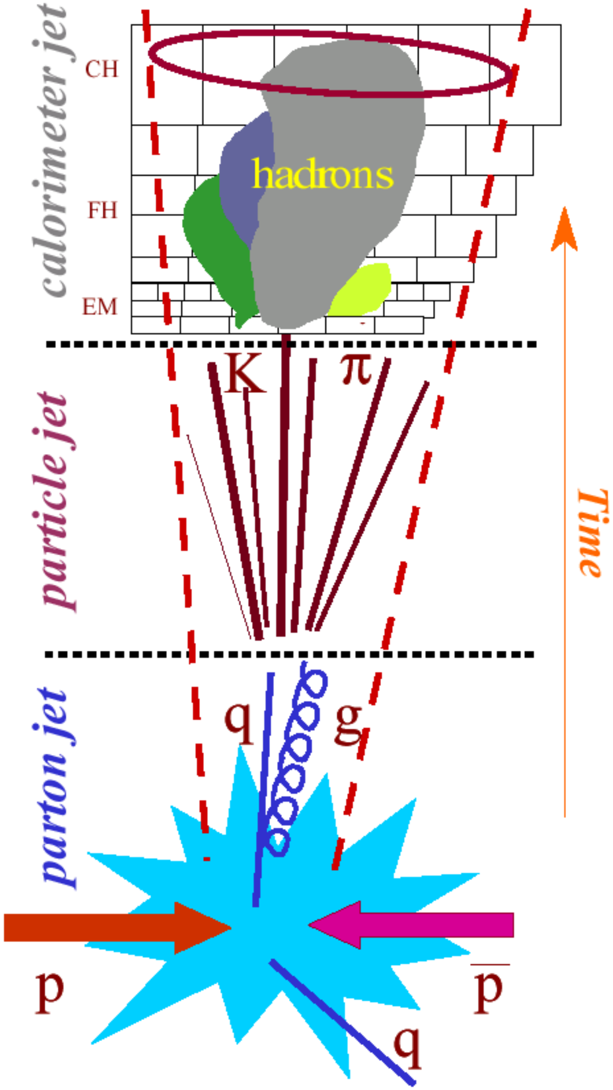
Raw Calorimeter Signals

Detector Simulation

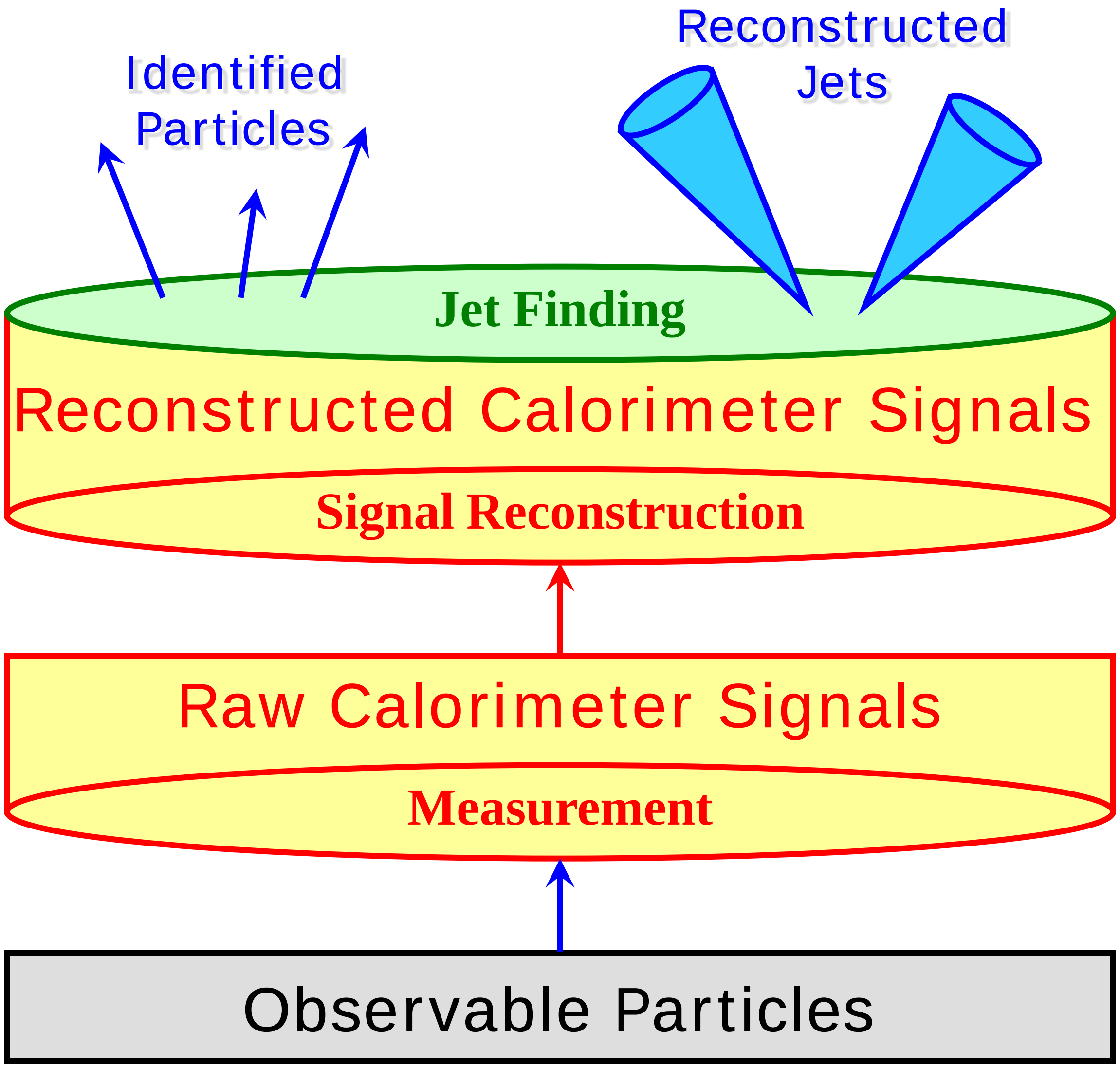
Stable Particles

Jet Reconstruction Task

Experiment ("Nature")



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!

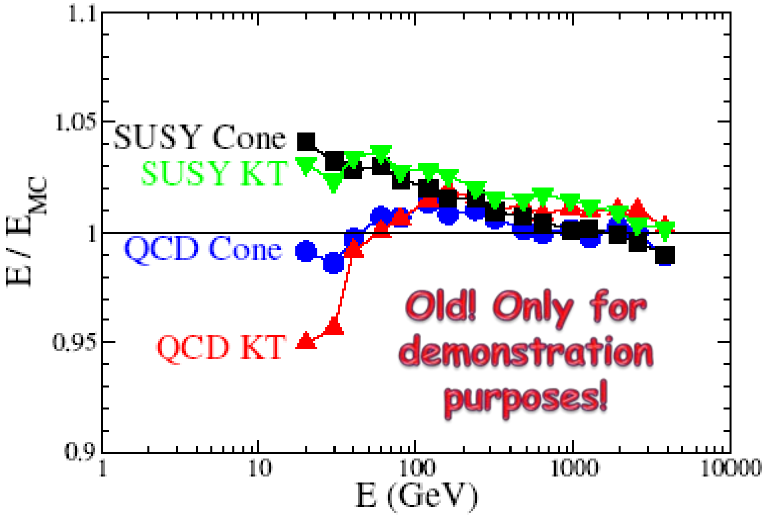
Jet Calibration Validation

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,…



Old! Only for demonstration purposes!

Requirements For Jet Reconstruction Validation

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!

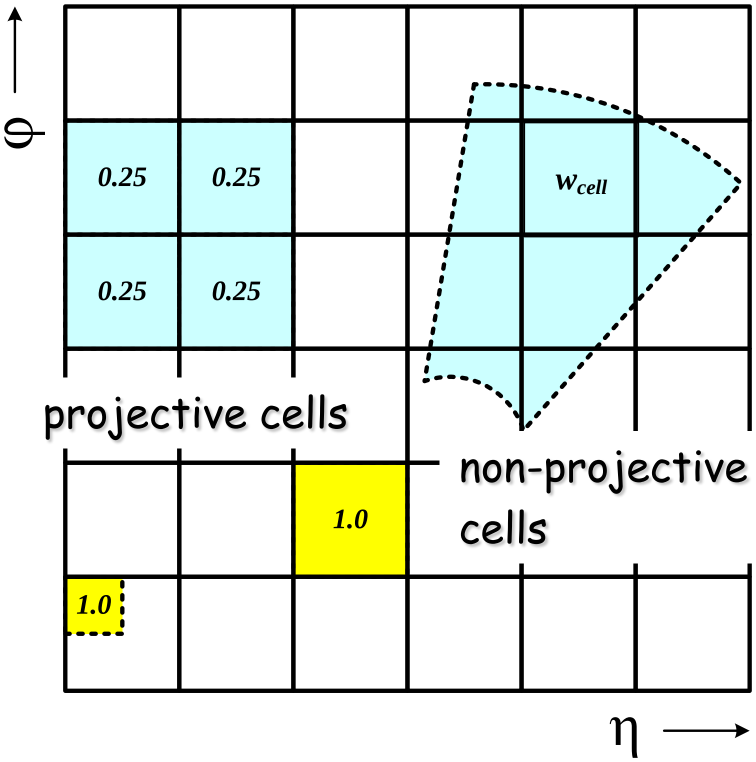
Step Back: Calorimeter Signals

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



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

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

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

$$w_{\text{cell}}=\begin{cases}1 & \text{if } A_{\text{cell}}^{\eta\varphi}\leq\Delta\eta\times\Delta\varphi\\ <1 & \text{if } A_{\text{cell}}^{\eta\varphi}>\Delta\eta\times\Delta\varphi\end{cases}$$