Introduction to Hadronic Final State Reconstruction in Collider Experiments (Part XIV)

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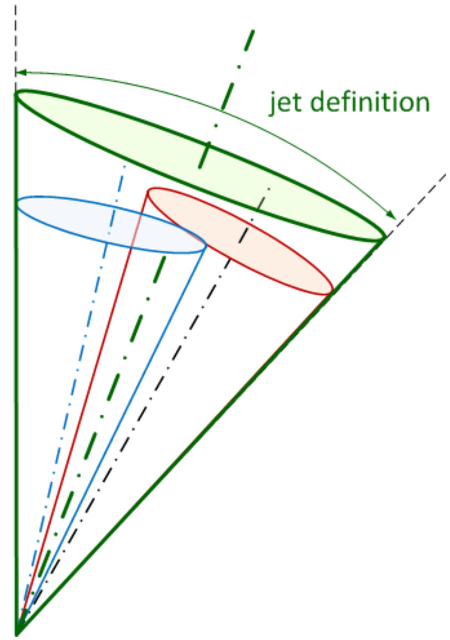
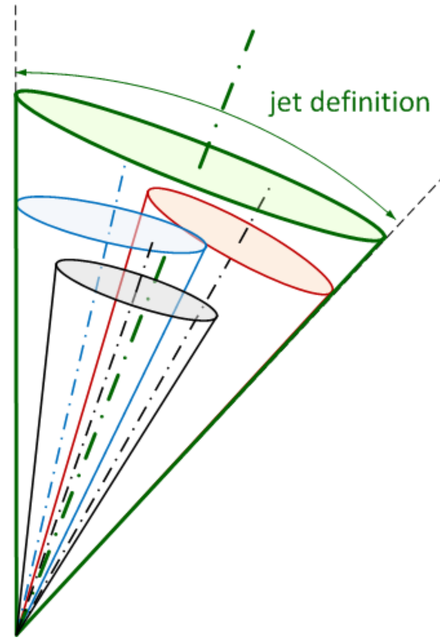
Particle flow inside a jet hints to source

- 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 $W \to q\bar{q}$ (SM) or heavy new object like $\phi \to gg$ or $Z' \to q\bar{q}$ (BSM)



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

Jet Mass

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

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

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:

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

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} :

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

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

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

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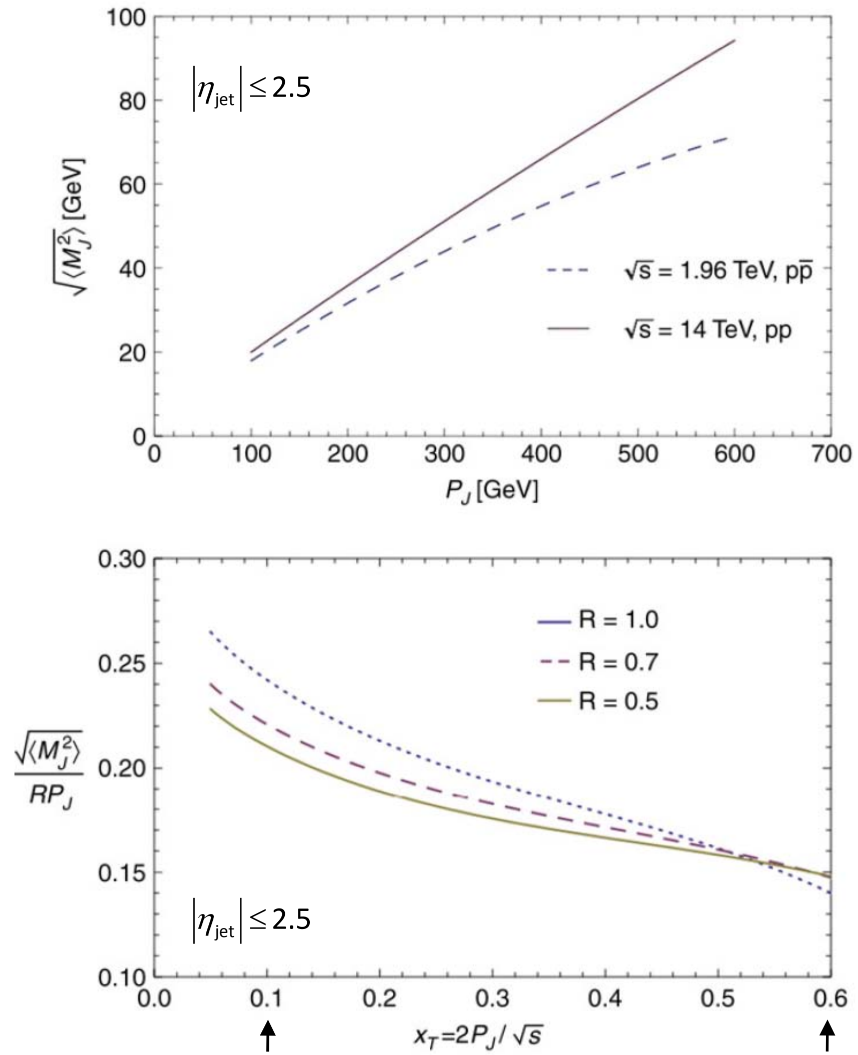
NLO Jet Mass Calculations



$p_{T,jet}^{min} \approx 115$ 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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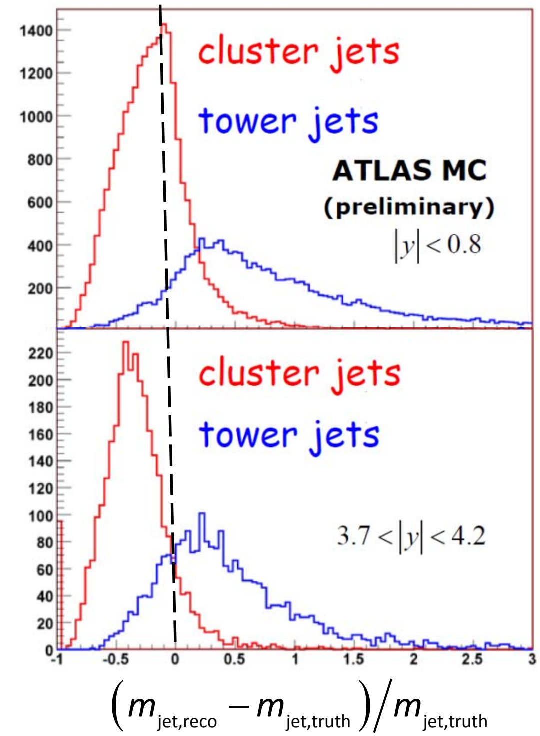
- requires good reconstruction of particle flow in jet by detector signal $\rightarrow$ depends on chosen calorimeter signal definition, e.g. test $\frac{m_{\text{jet,reco}} - m_{\text{jet,truth}}}{m_{\text{jet,truth}}}$ for matching truth and calorimeter jets
- plot on the right shows the spectrum of 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

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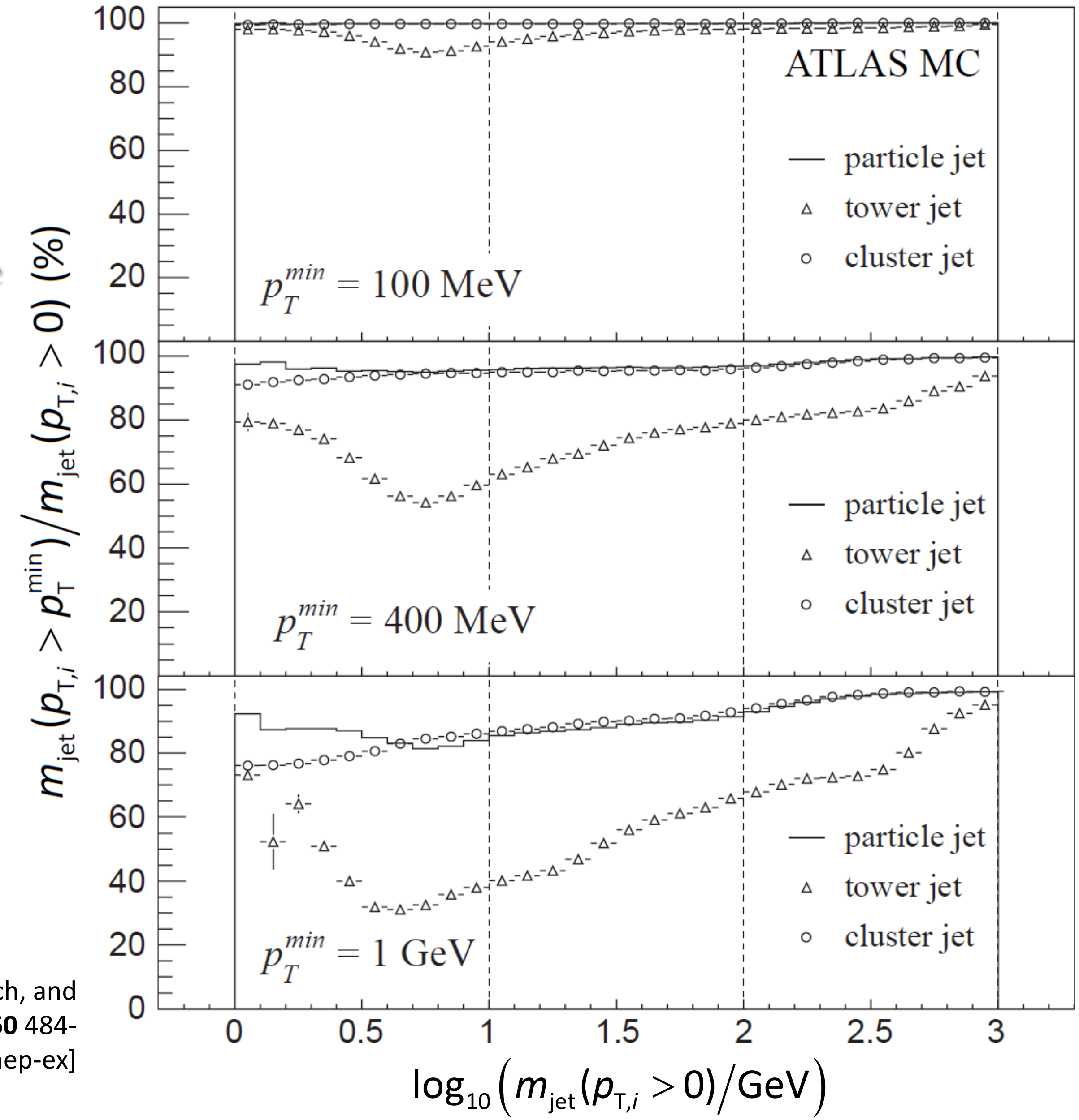
Relative mass change

- 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]

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kT Jets Y_{scale}

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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:

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

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

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

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

$$y^{1\to2}_{\text{scale}} = \sqrt{y_2} \times p_{\mathrm{T,jet}} = \sqrt{\min(d_1, d_2)}$$

relates to mass in two-prong decays

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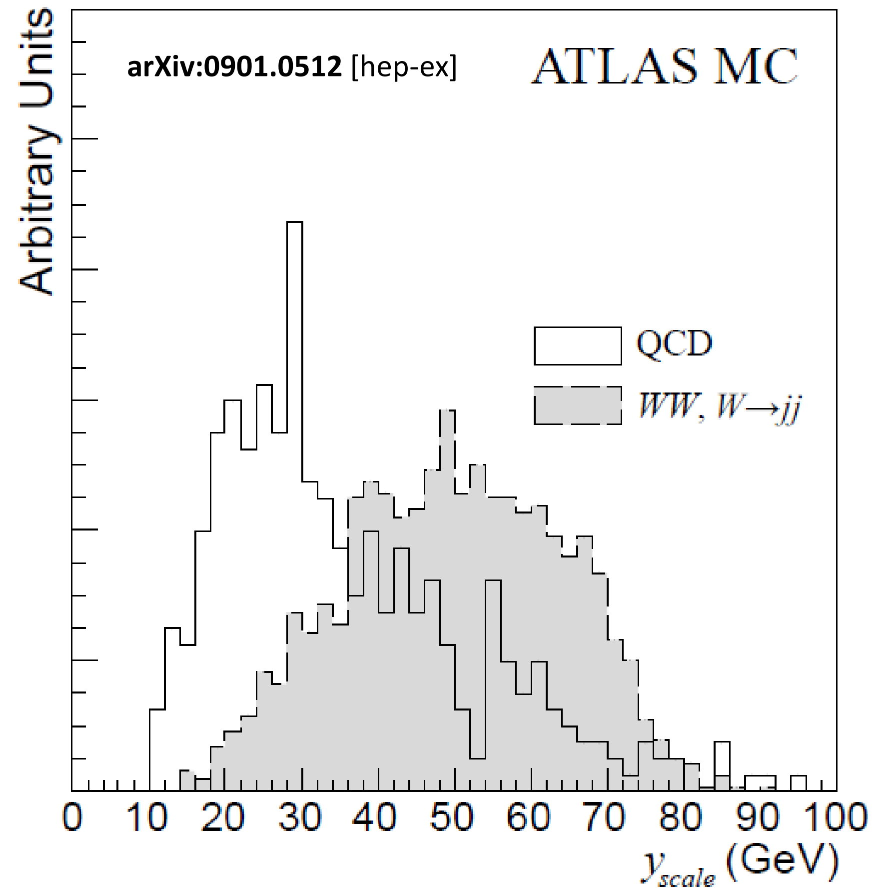

$y_{\text{scale}}^{1\to 2}$ for jets with $m_{\text{jet}} > 40$ GeV, for QCD and hadronically decaying boosted W.

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

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kT Jet Y_{scale} Relation to Jet Mass

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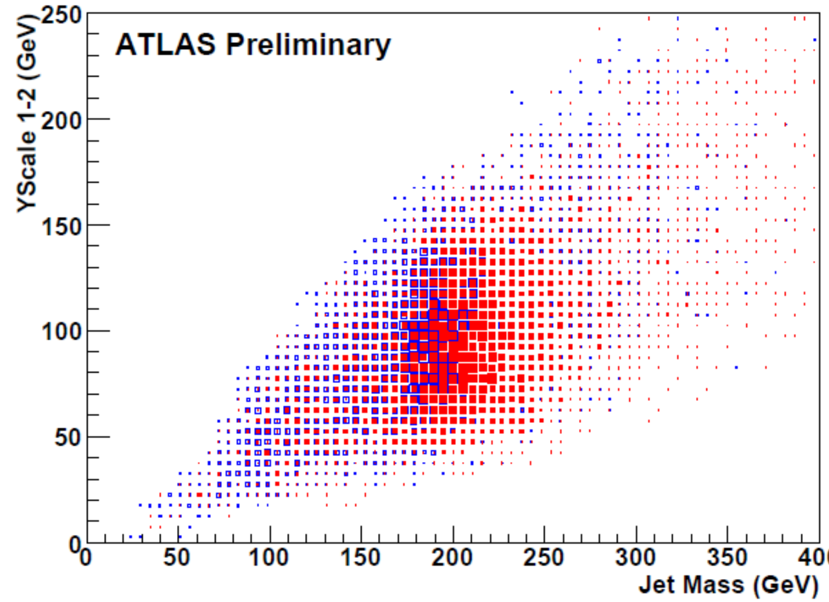
G. Brooijmnas, ATL-PHYS-CONF-2008-008



ATLAS simulation:

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

$p_T(t) > 300$ GeV

- $y_{\text{scale}}^{1\to 2}$ probes top decay, peaks at ≈ 100 GeV $\approx \dfrac{m_{\text{top}}}{2}$
- $y_{\text{scale}}^{2\to 3}$ probes W decay, peaks at ≈ 40 GeV $\approx \dfrac{m_W}{2}$

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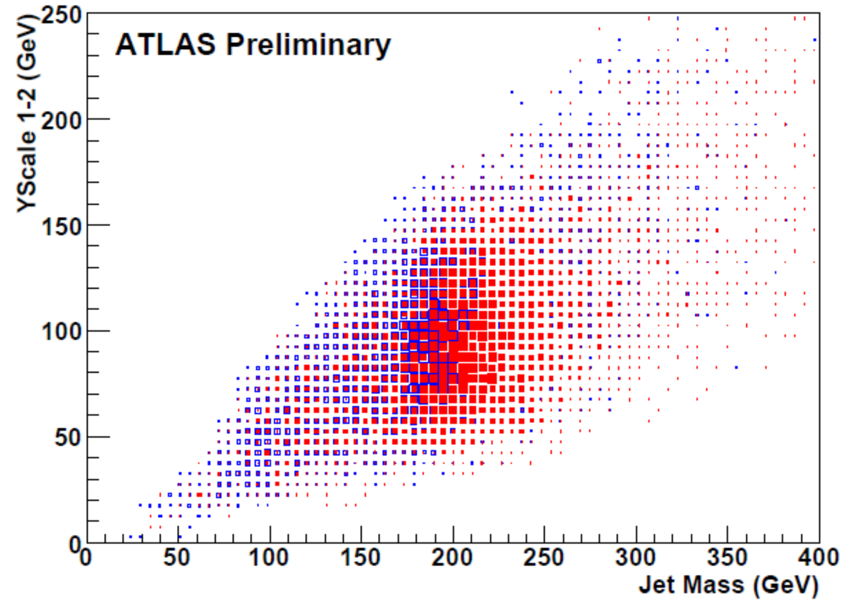

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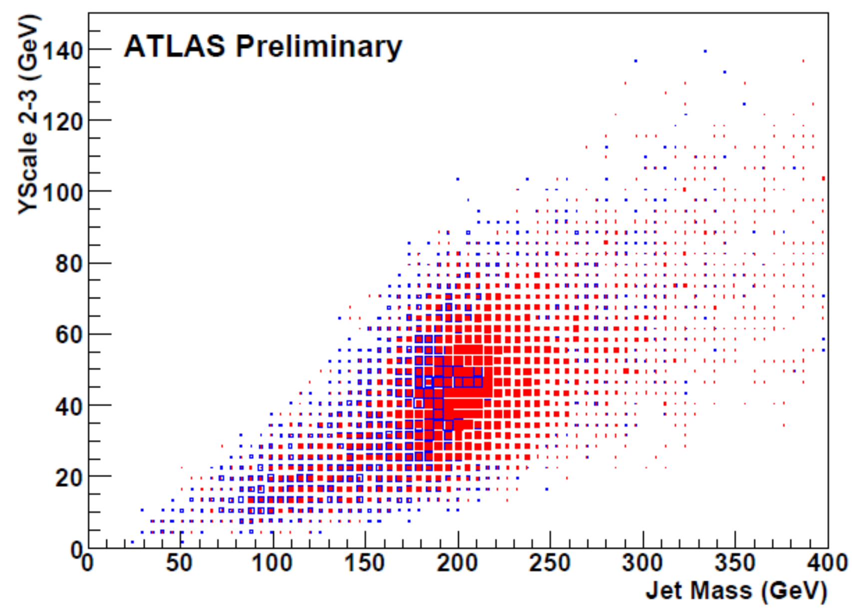

kT Jet Y_{scale} Performance Estimates

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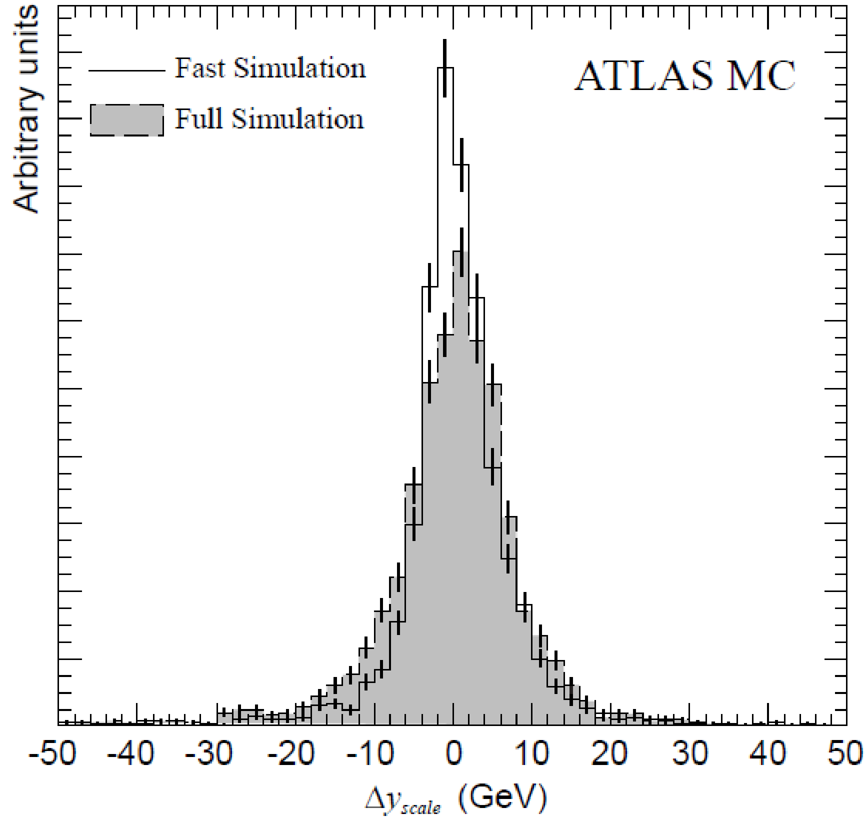
arXiv:0901.0512 [hep-ex]



$\Delta y_{scale} = y^{1\to2}_{scale}\big|_{\text{particle}} - y^{1\to2}_{scale}\big|_{\text{calo}}$ for jets with $m_{\text{jet}} > 40$ GeV from hadronically decaying boosted W. $y^{1\to2}_{scale}\big|_{\text{calo}}$ is calculated for parameterized, response smearing simulation (fast, no lateral shower spread) and from detailed full simulation $\rightarrow$ indications that $y^{1\to2}_{scale}$ is little sensitive to details of showering.

ATLAS

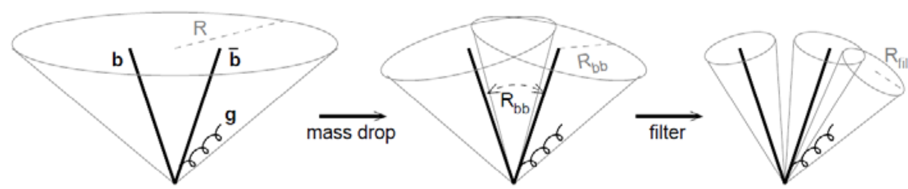
Sub-Jet Analysis

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 $p_{\mathrm{T},H}$>200 GeV in WH / ZH production - about 5% of total cross-section:



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

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.

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

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 $R_\mathrm{filter} < R_{bb}$, e.g., $R_\mathrm{filter} = \min(0.3, R_{bb}/2)$ 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.

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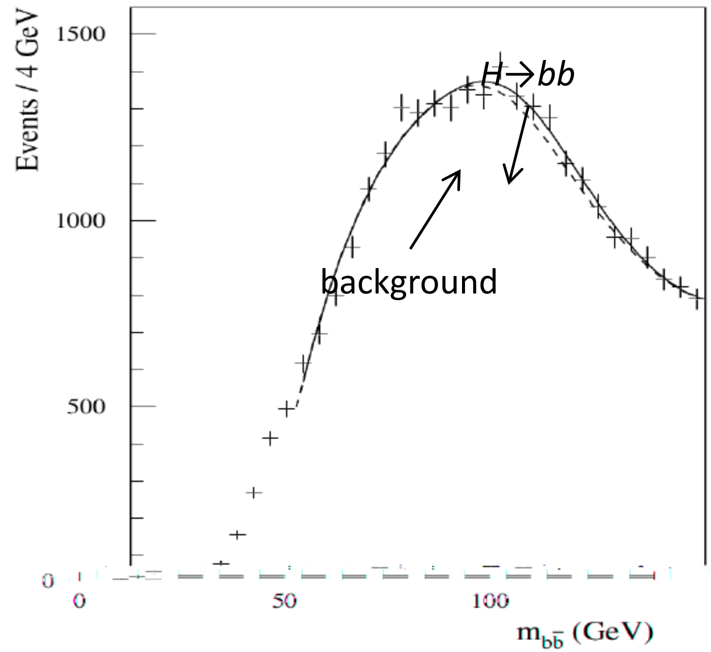

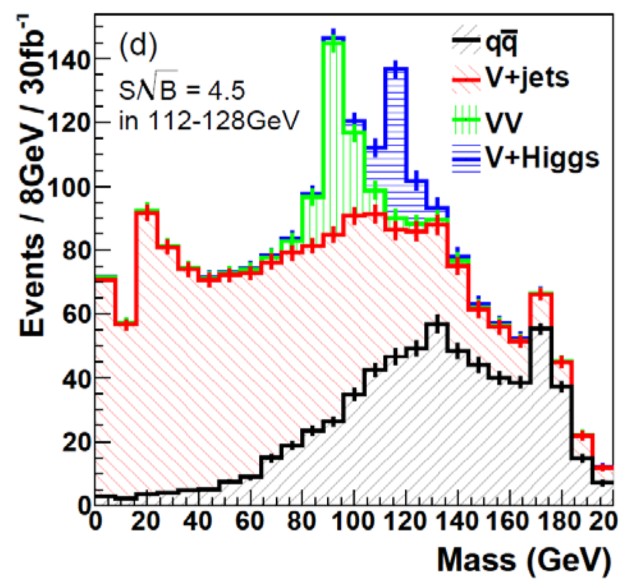

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Observables and tools

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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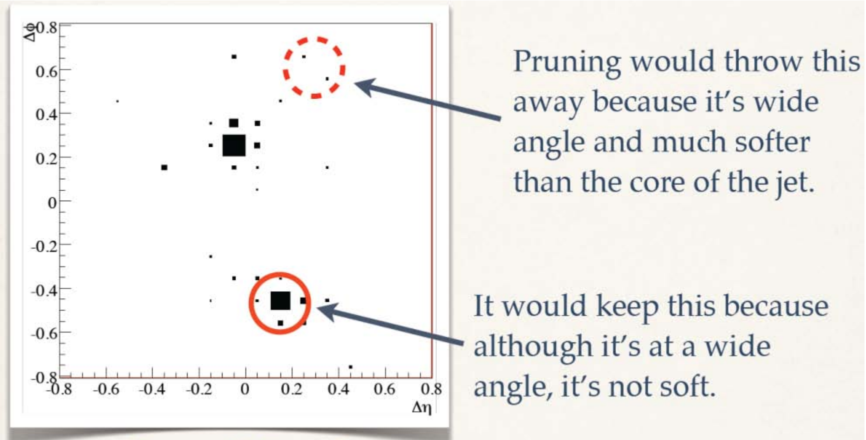

Boosted Higgs Jet

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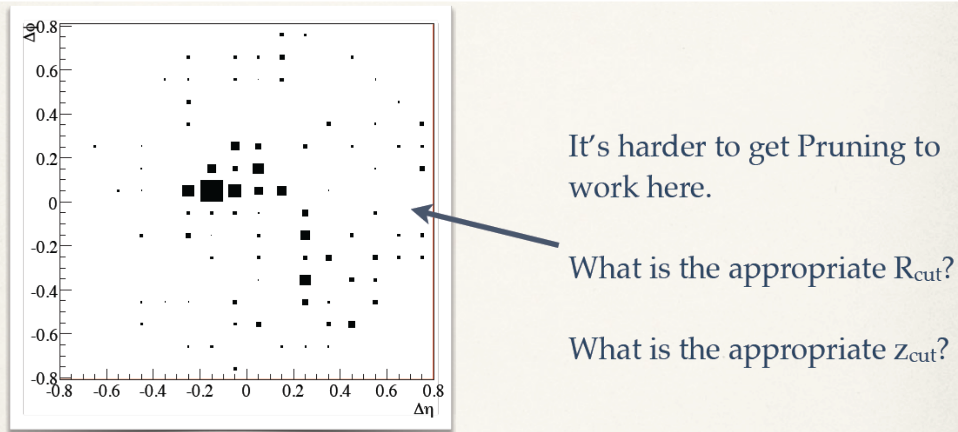

QCD Jet

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Jet Pruning

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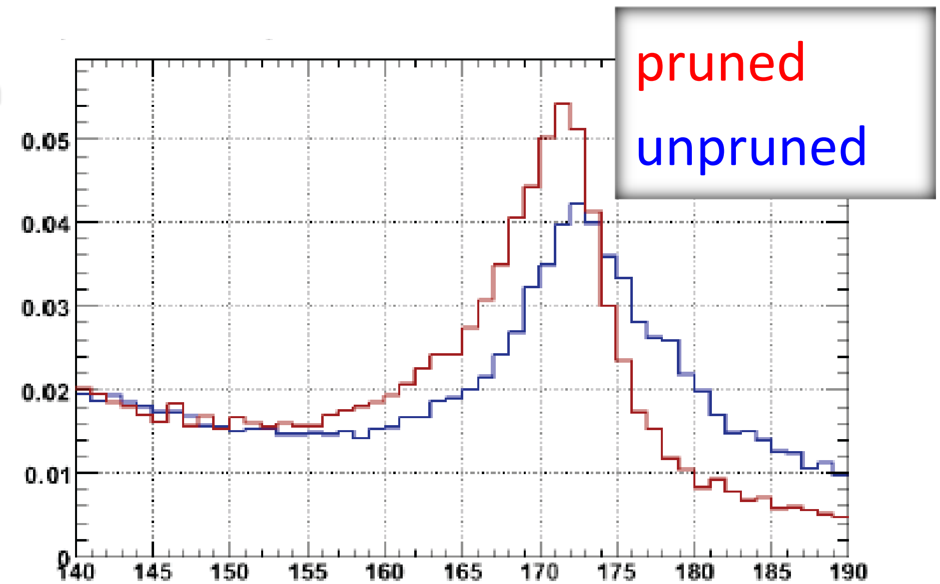
Jet Pruning

- improves jet mass measurement for boosted top etc.



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

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

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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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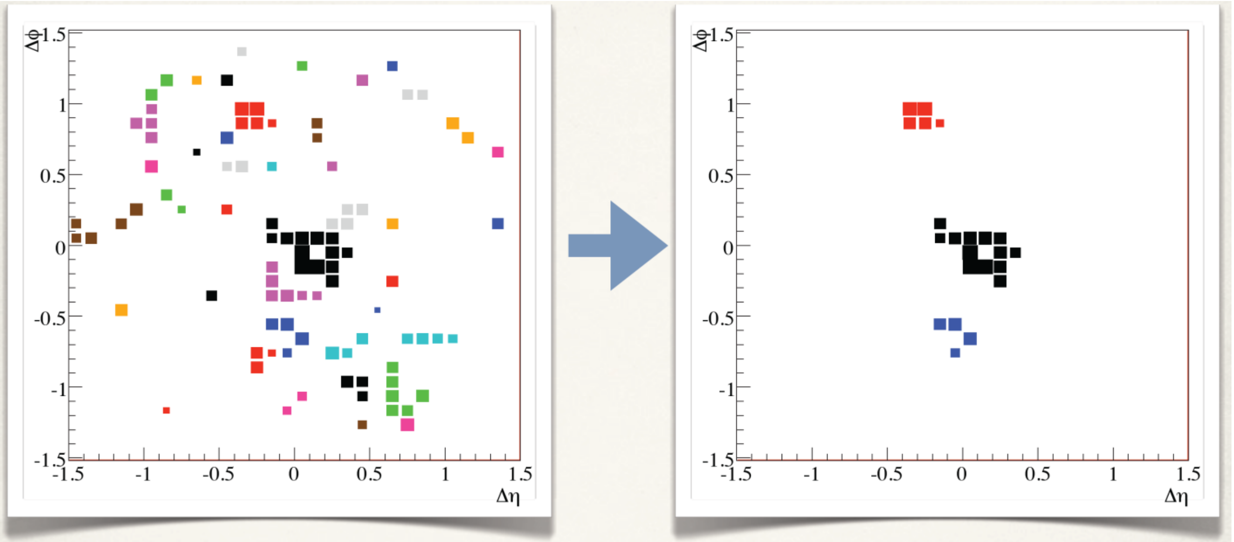

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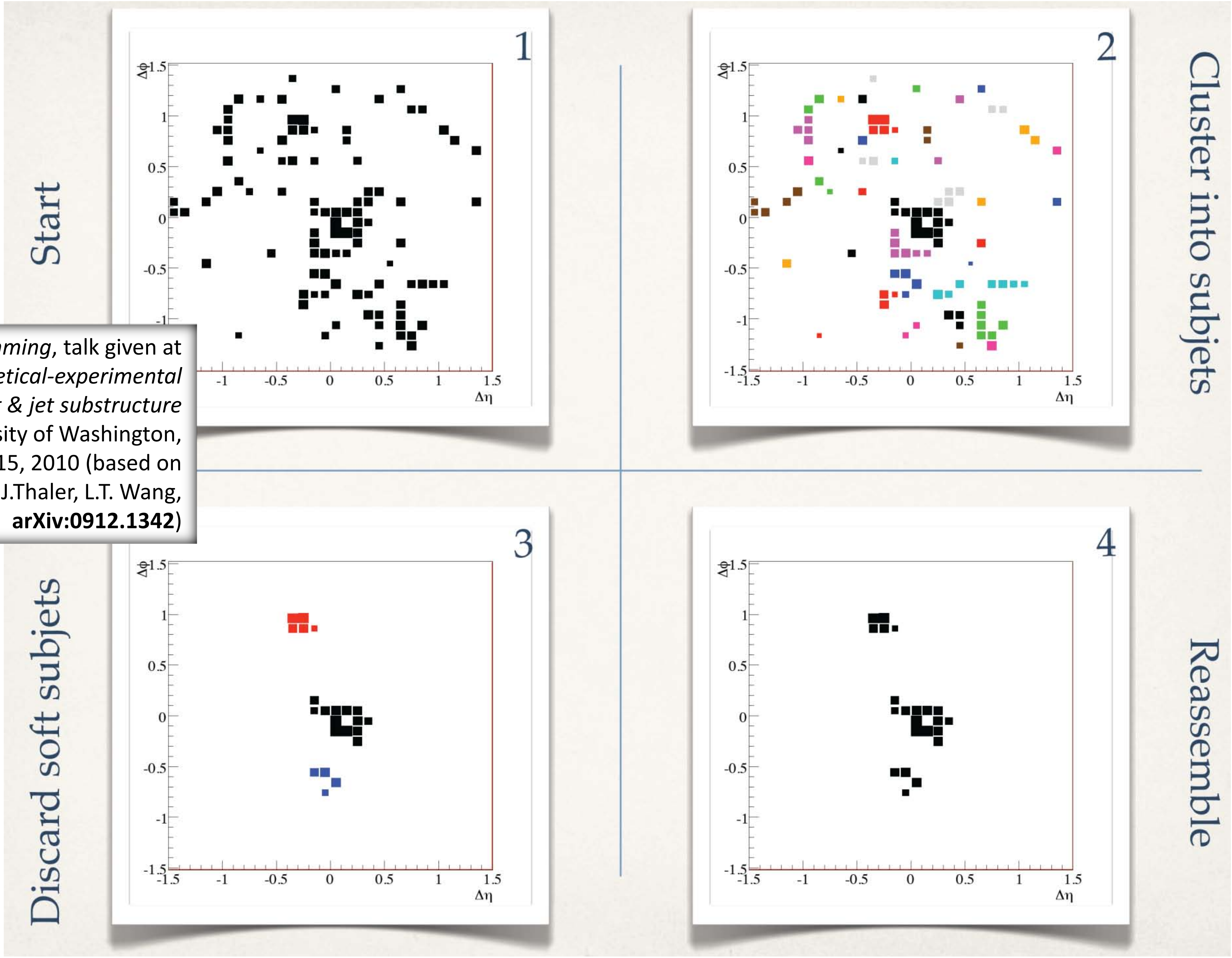

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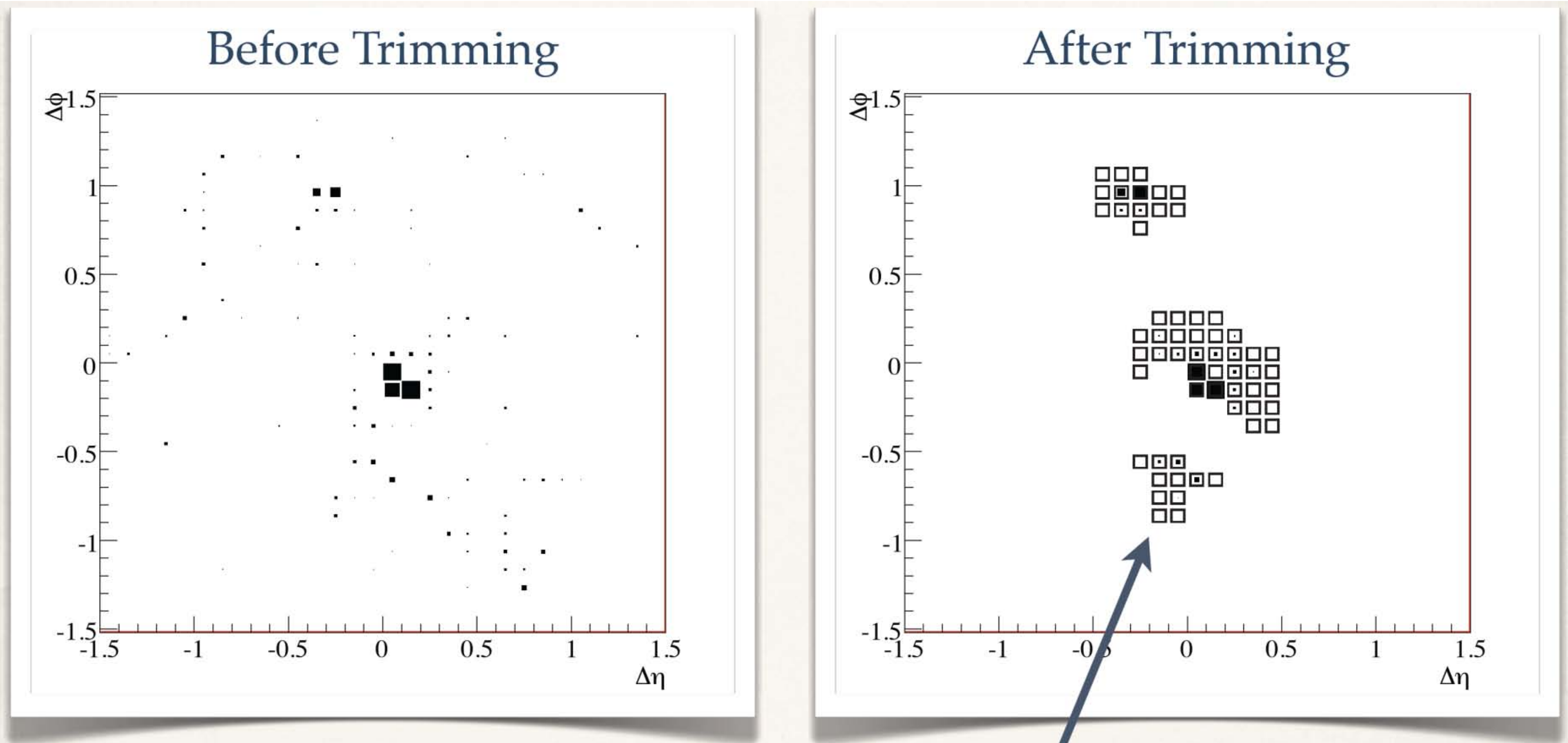

Empty squares denote extent of jet area

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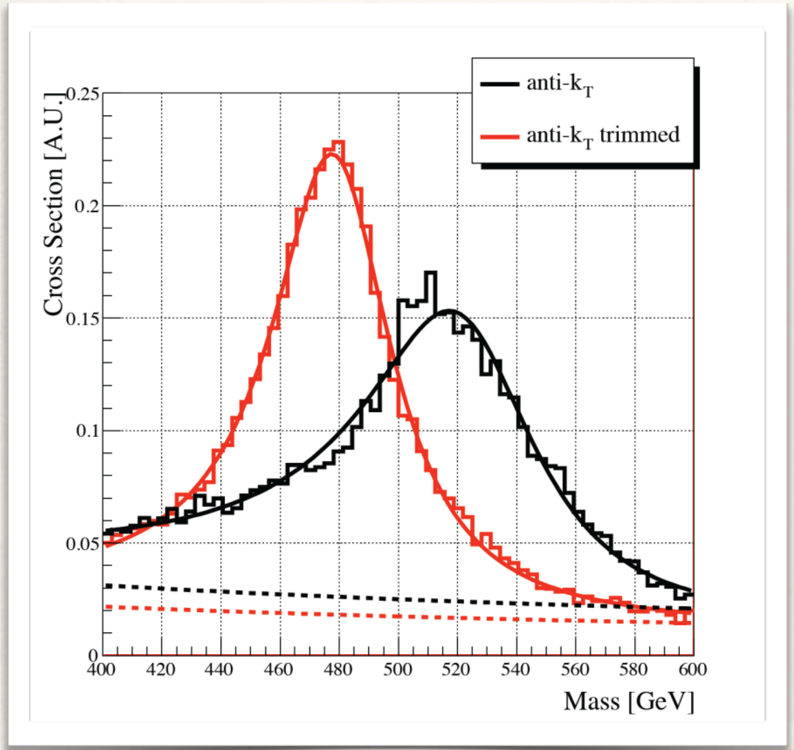

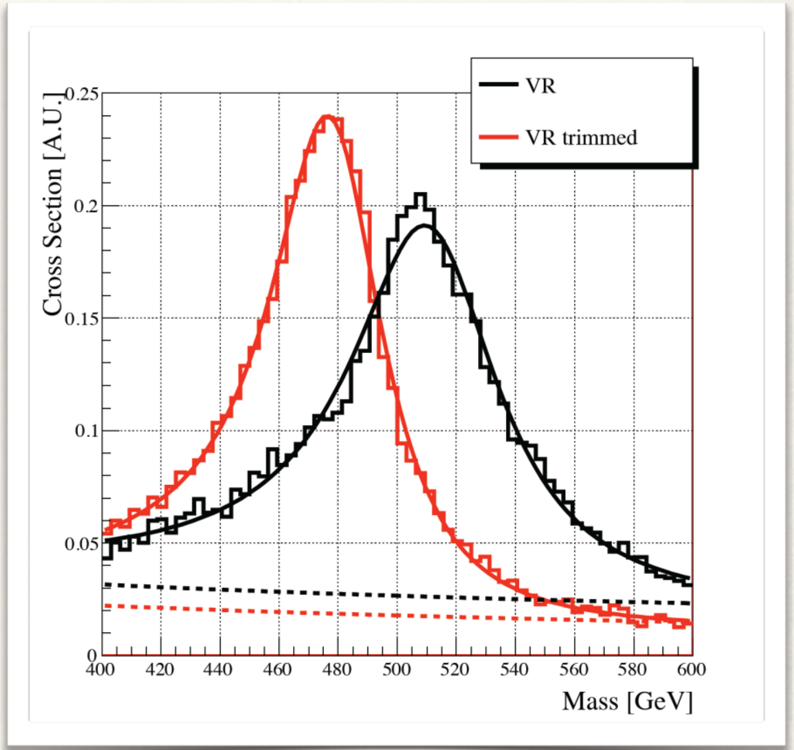

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Trimmed and variable radius (VR) jets from $\phi \rightarrow qq, gg$

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

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