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Jet Substructure and Boosted Objects

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August 23, 2011

Roadmap

Motivation

- High pT (fat) jets as search tool at LHC

Jet substructure techniques

- Jet grooming – filtering, trimming, pruning

Experimental limitations

- Detector effects on jet signals

First results from CMS & ATLAS

- First hints on reconstruction quality for internal jet variables useful for substructure analysis

Disclaimer

- This is not an in-depth review talk – focus on experimental aspects and concerns/challenges to be addressed in the very near future
  - First indications look promising but there is still a lot to learn concerning systematic uncertainties and resolution effects

More from Jets: Mass and Substructure

Jet Substructure

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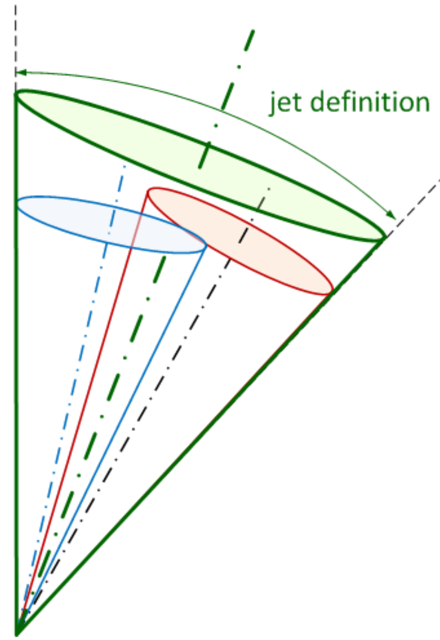
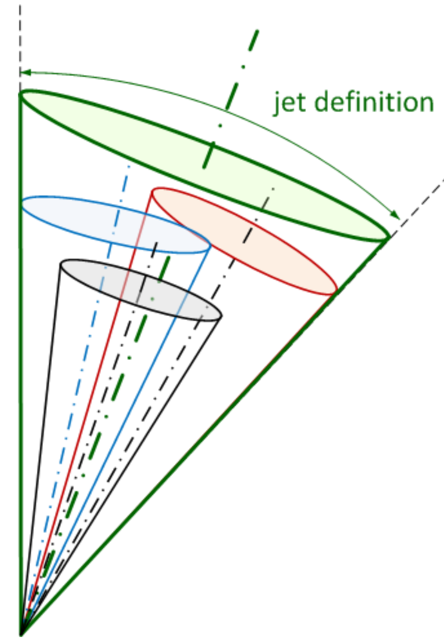
Particle flow inside a jet hints to source

- 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

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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

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

mass of gluon/light quark jets:

LO $\quad 1-$parton jets have vanishing mass

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

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

with:

$\bar{C}\left(p_{\text{jet}}/\sqrt{s}\right)$ 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} :

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

rule of thumb at $\sqrt{s} = 7$ TeV:

$$\sqrt{\left\langle m_{\text{jet}}^2 \right\rangle_{\text{NLO}}} \approx (0.1-0.2)\cdot p_{\text{jet}} R_{\text{cone}}$$

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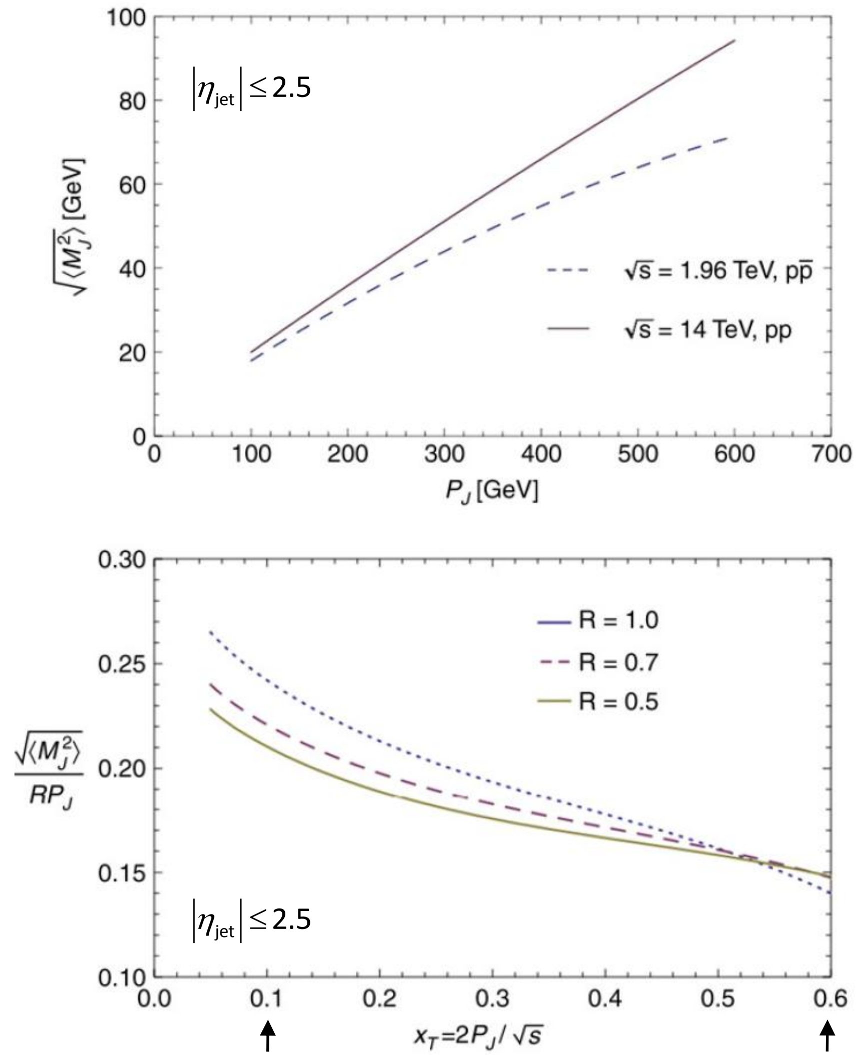
NLO Jet Mass Calculations



$p_{T,jet}^{min} \approx 115$ 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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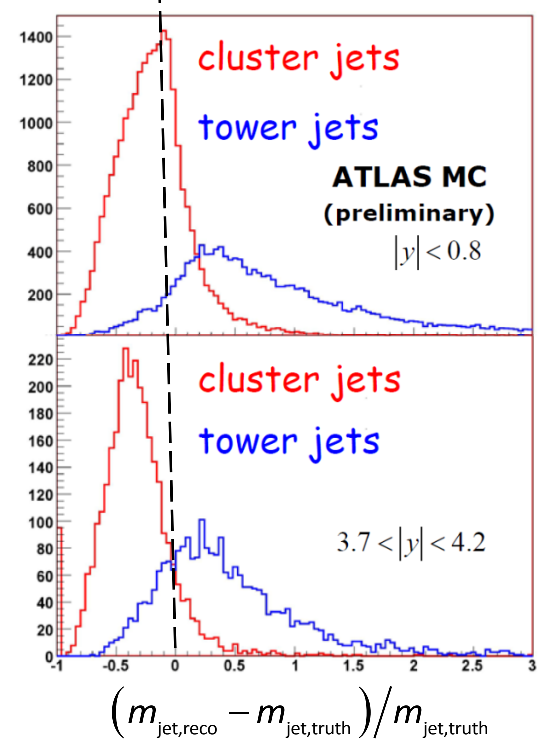
- requires good reconstruction of particle flow in jet by detector signal $\rightarrow$ depends on chosen calorimeter signal definition, e.g. test $\frac{m_{\text{jet,reco}} - m_{\text{jet,truth}}}{m_{\text{jet,truth}}}$ for matching truth and calorimeter jets
- plot on the right shows the spectrum of this relative mass difference for simulated QCD di-jets (kT, $R = 0.6$) in ATLAS

(old plot, educational purpose only!)

(plots from Chiara Paleari)



Detector Effects On Jets

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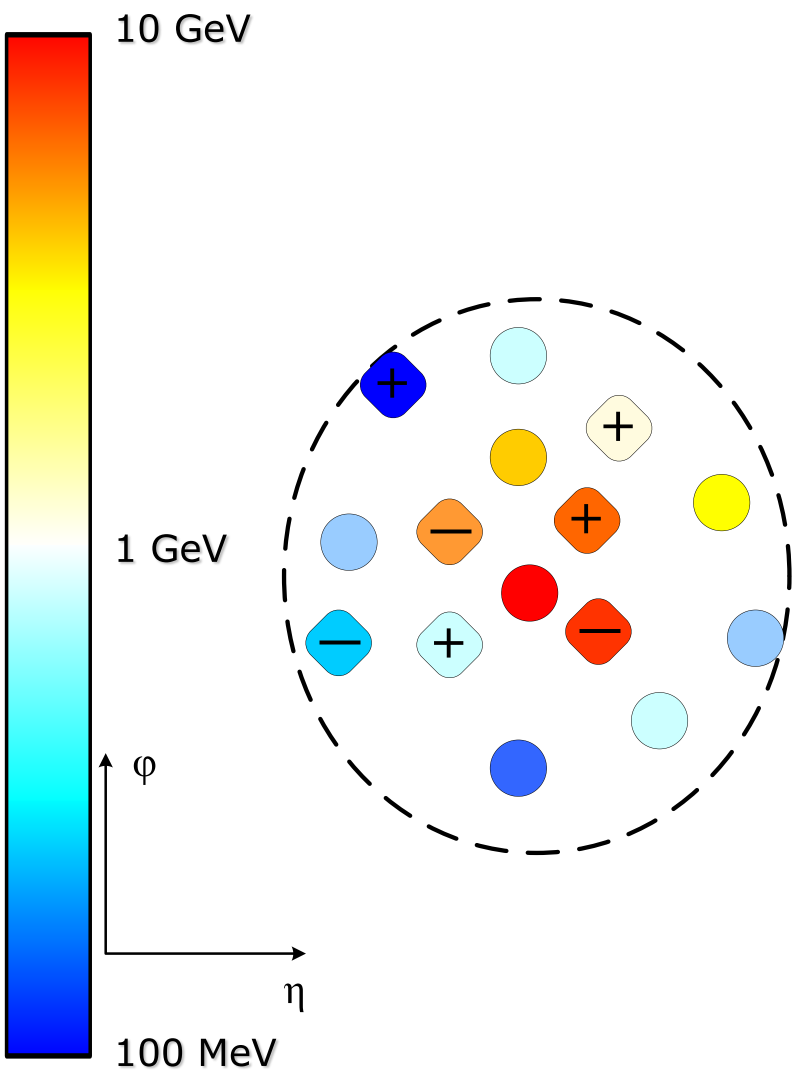

Change of composition

- 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 and partial 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

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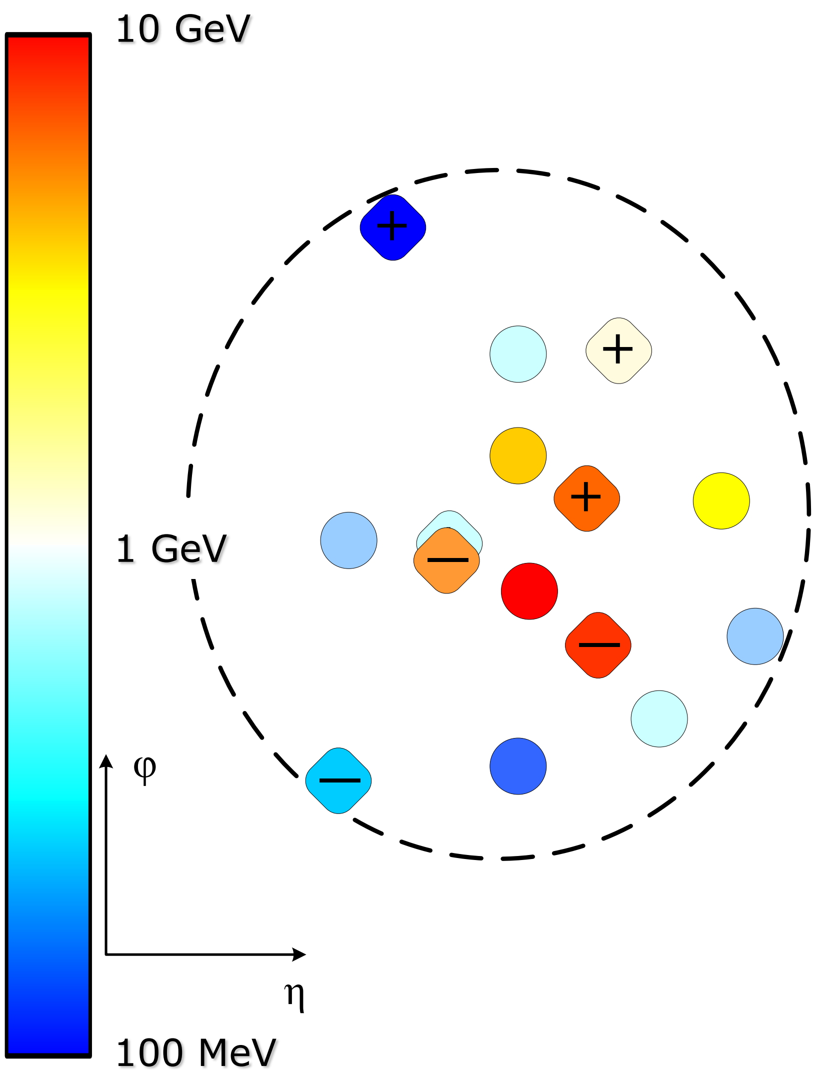

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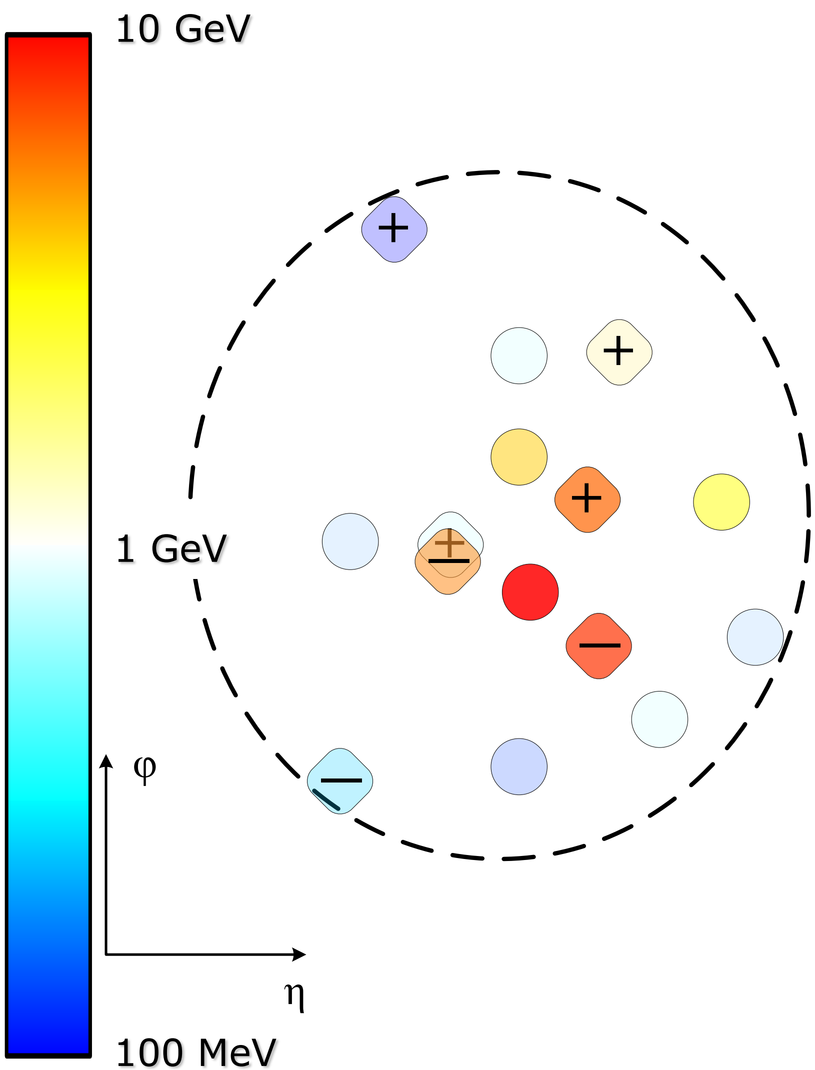

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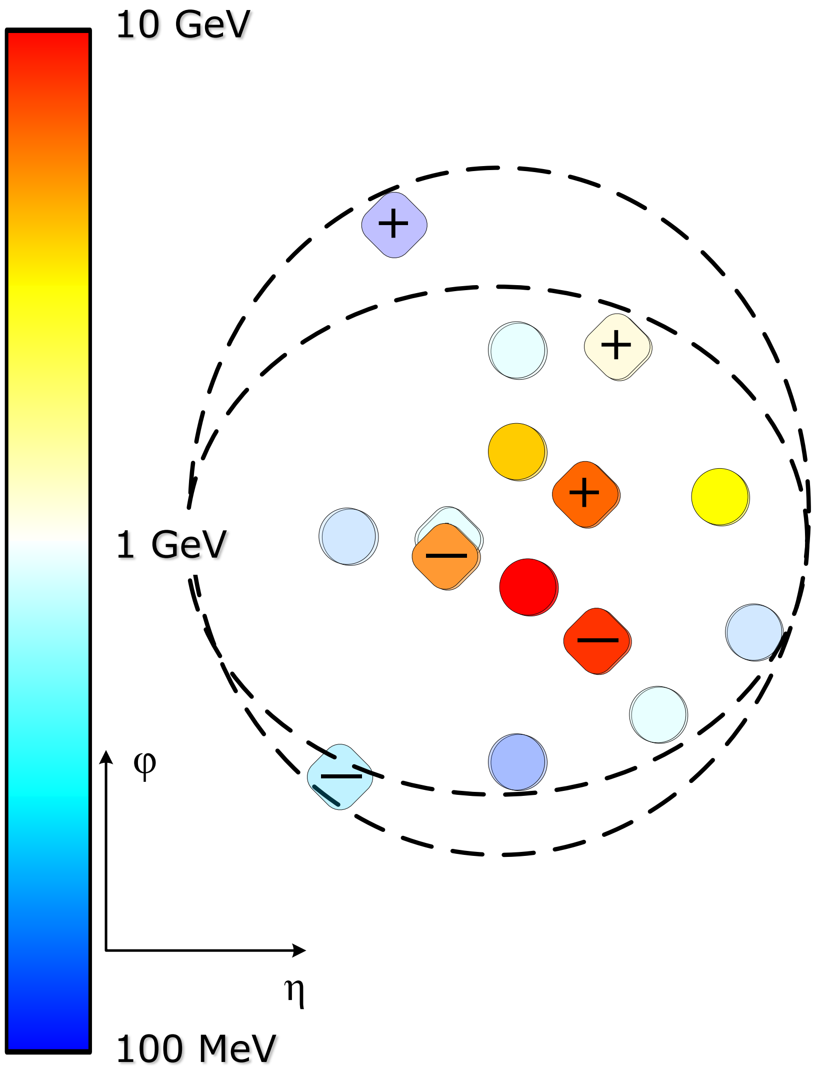

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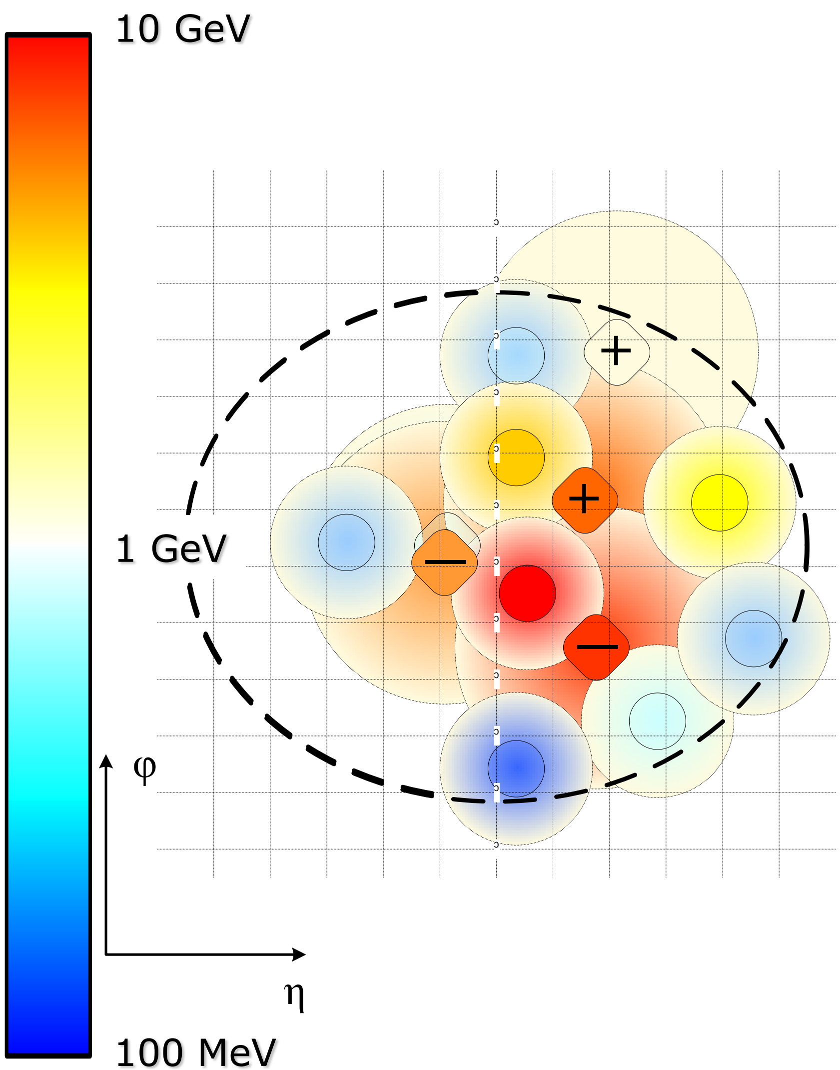

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Calorimeter Towers

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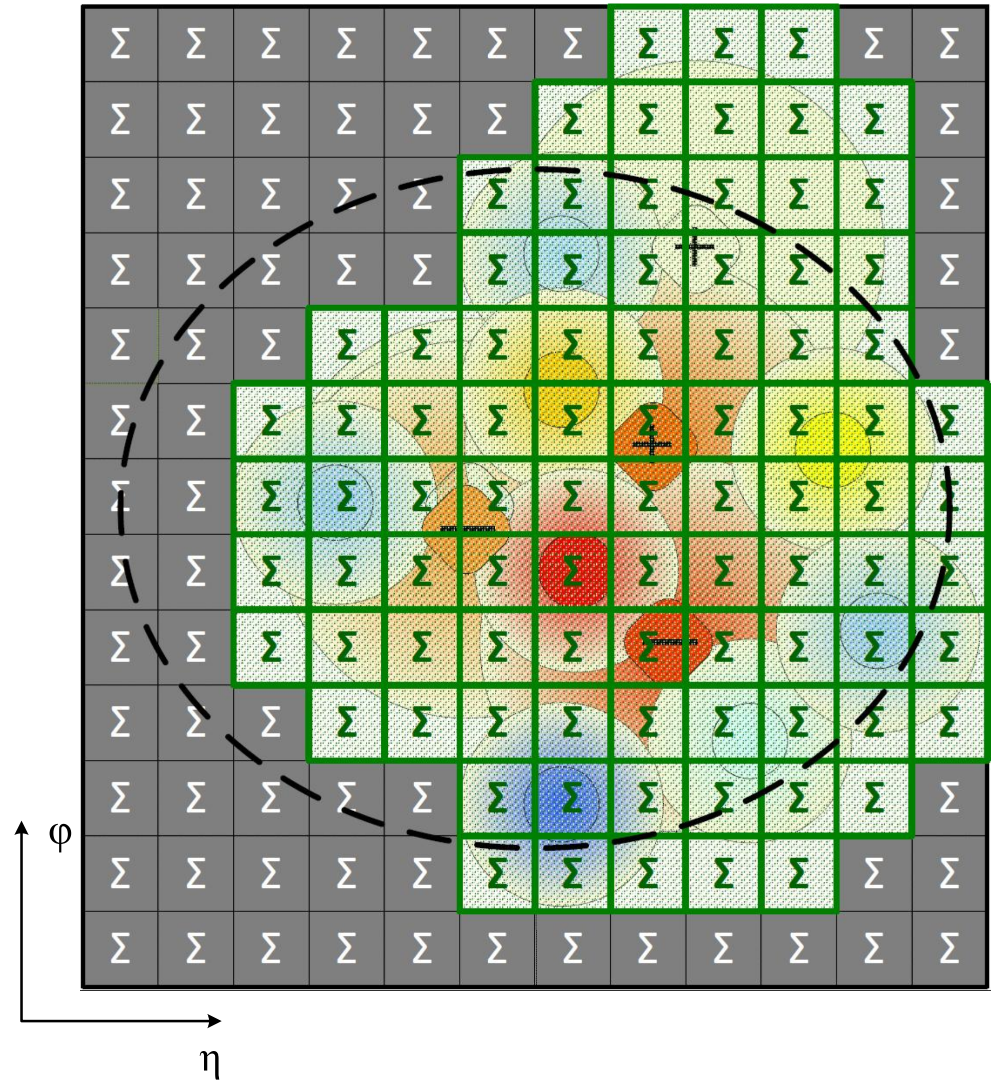

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Radial Energy Projection

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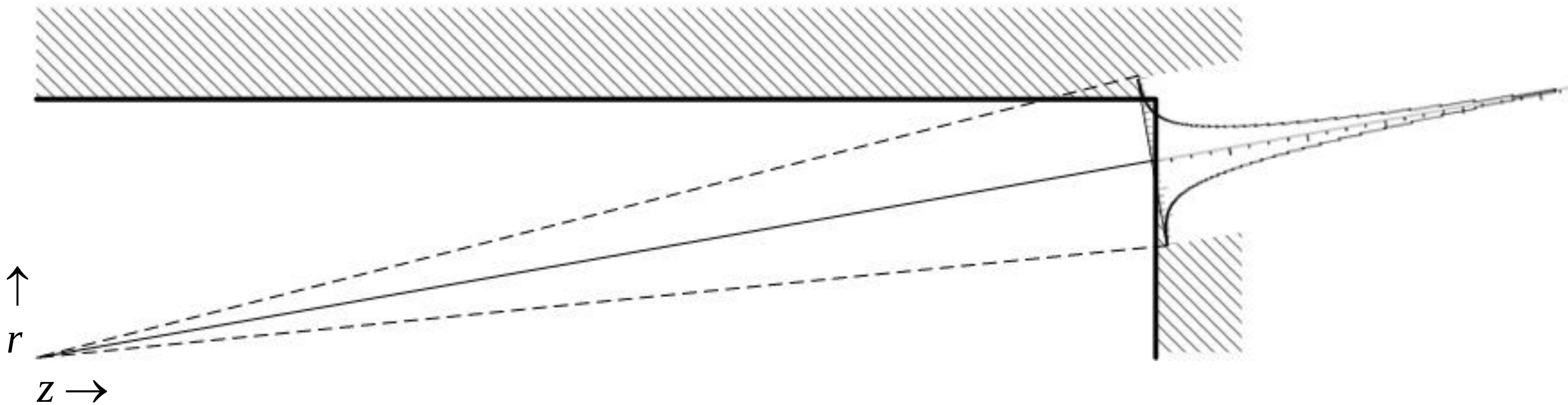

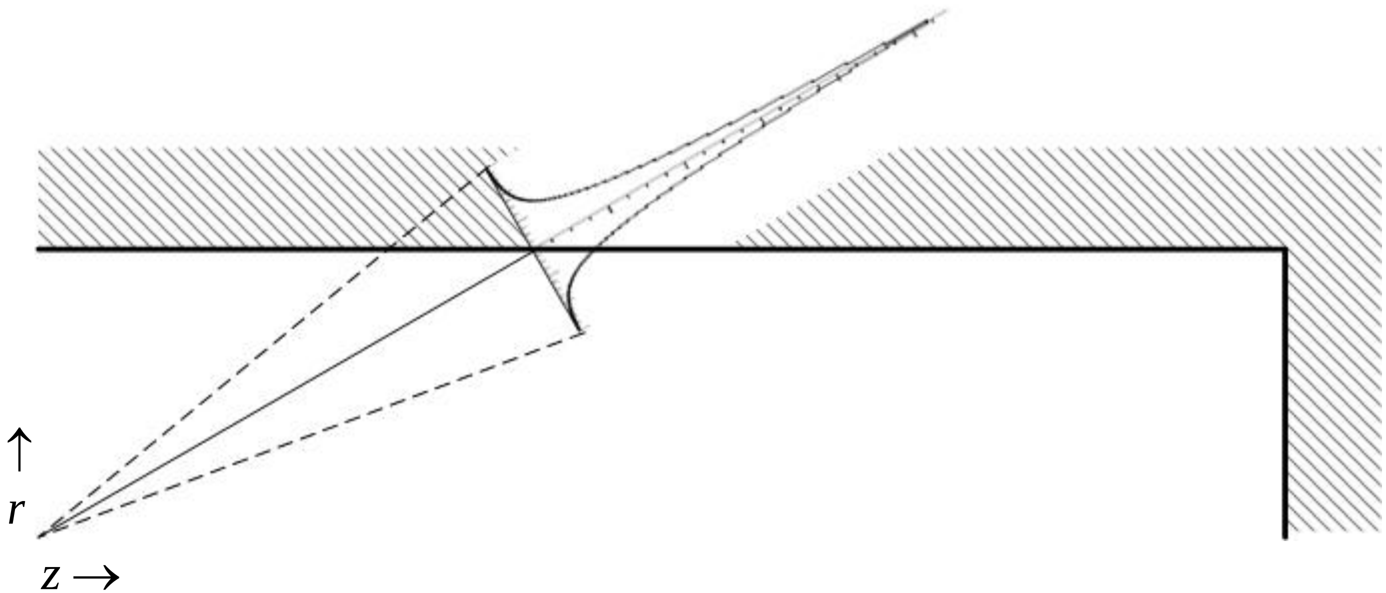

Electron Lateral Profile (H1)

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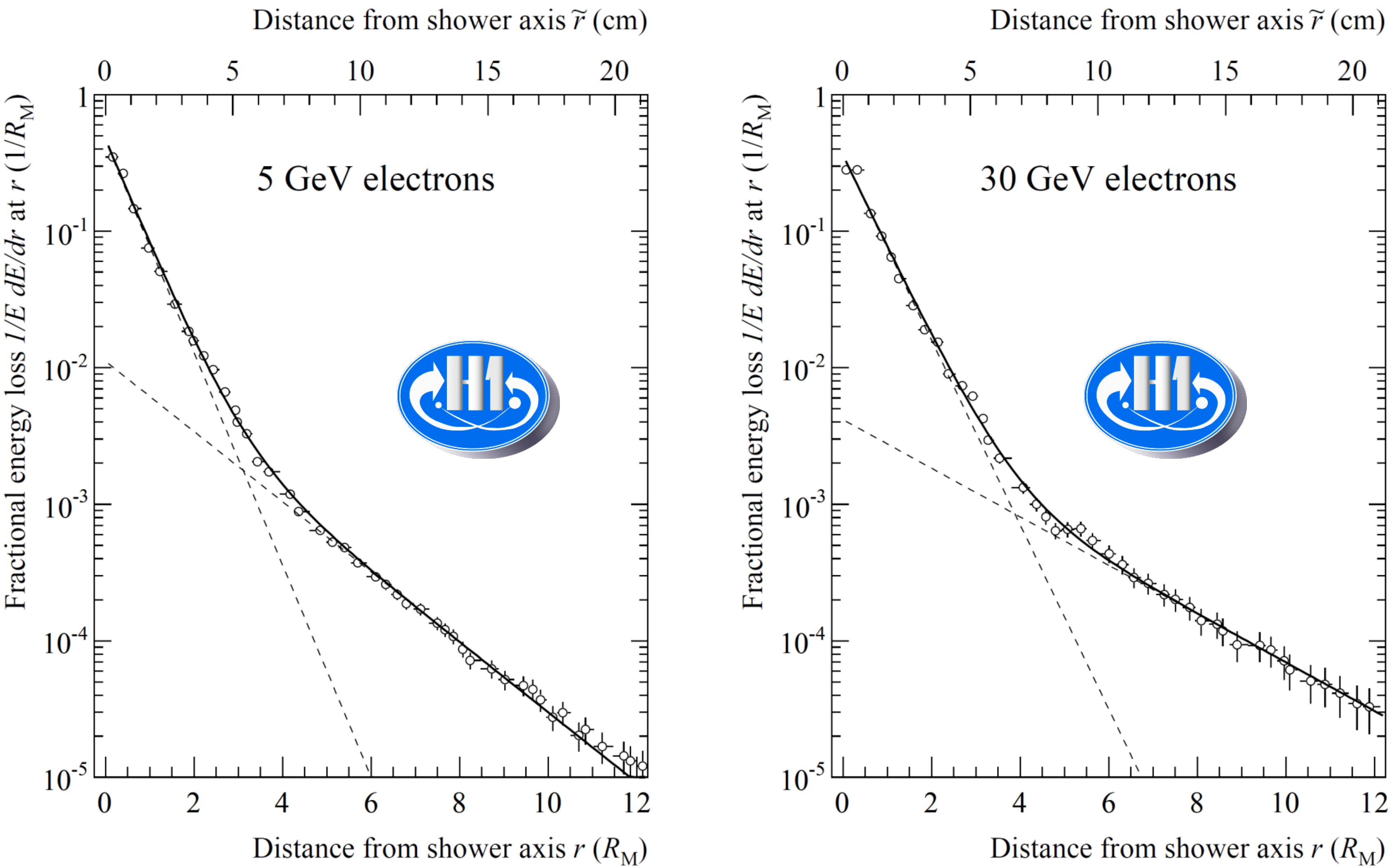
Radial (transverse) electron shower profile in H1 calorimeter (test beam data)



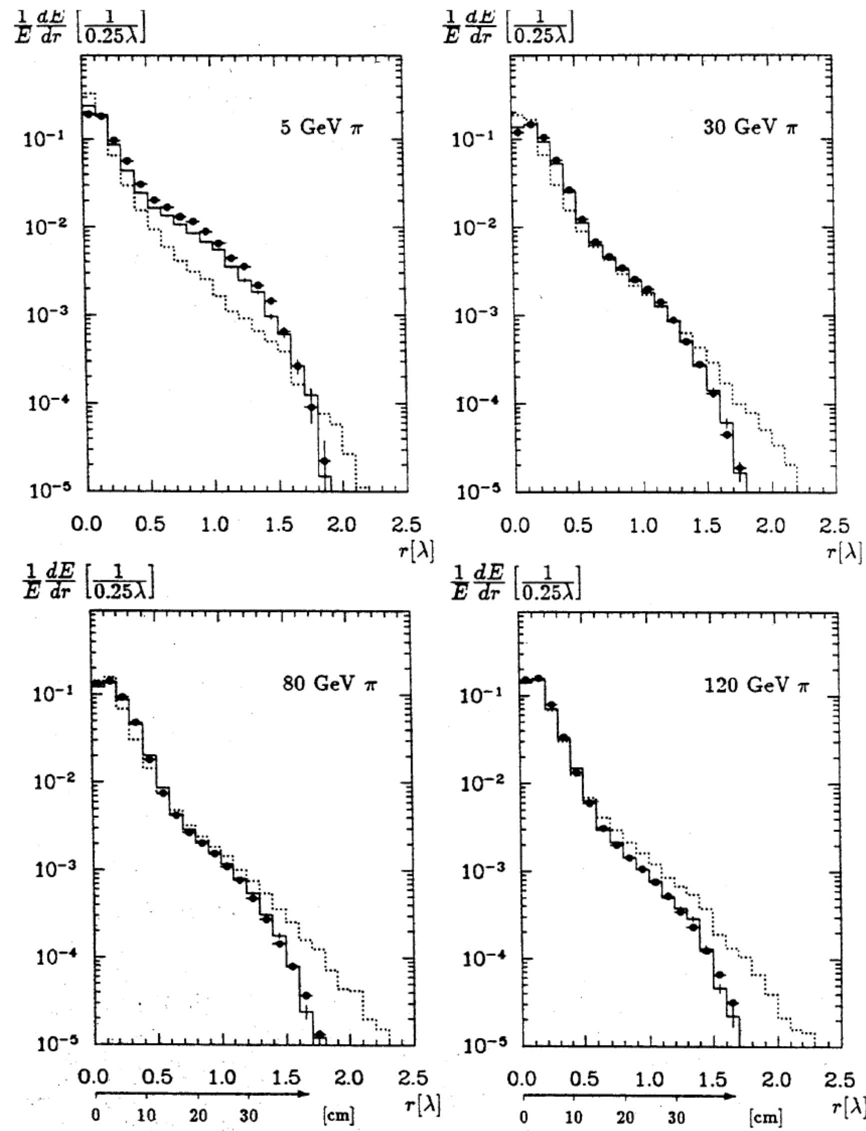
$$\frac{dE}{dr}(r) = E\left(a(E)e^{-\alpha(E)r} + b(E)e^{-\beta(E)r}\right)$$

PL Thesis, 1992

Hadronic Lateral Profile (H1)

Points/solid line histogram: data + simulated signal with noise cuts

Dashed line histogram: simulated shower development, no noise or cuts



PL Thesis, 1992

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:

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

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. $d_{12} < d_1, d_2$:

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

relates to mass in two-prong decays

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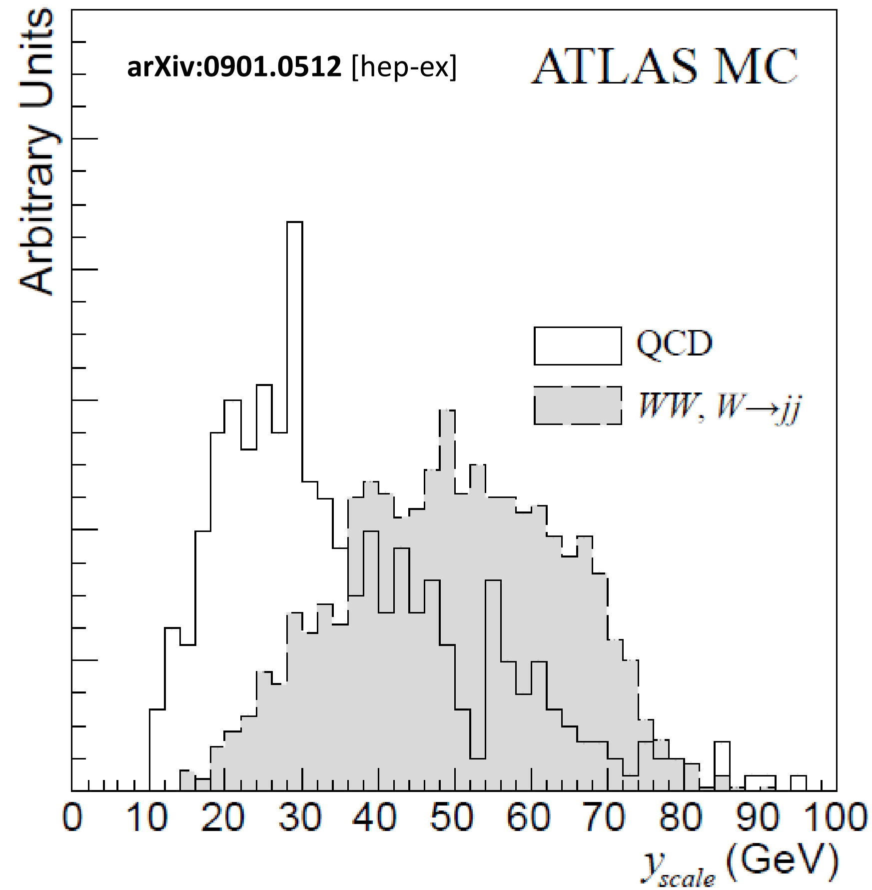

$y^{1\to2}_{\rm scale}$ for jets with $m_{\rm jet} > 40$ GeV, for QCD and hadronically decaying boosted W.

Note that for QCD $y^{1\to2}_{\rm scale}$ is logarithmically below $p_{\rm T,jet}$ due to the strong ordering (in $k_{\rm T}$) in QCD evolution, while $\langle y^{1\to2}_{\rm scale}\rangle \approx m_W$ reflects the 2-prong decay of the W boson

kT Jet Y_{scale} Relation to Jet Mass

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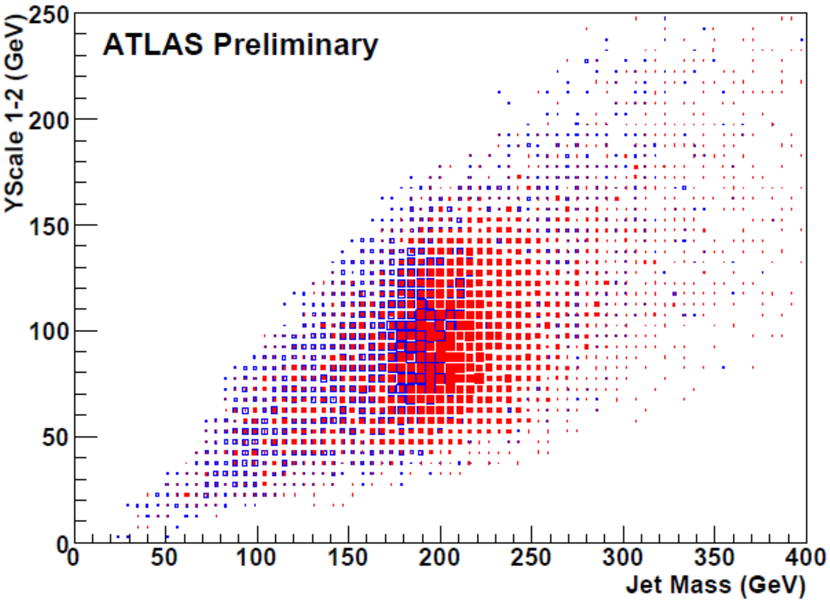
G. Brooijmnas, ATL-PHYS-CONF-2008-008



ATLAS simulation:

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

$p_T(t) > 300$ GeV

- $y_{scale}^{1\to 2}$ 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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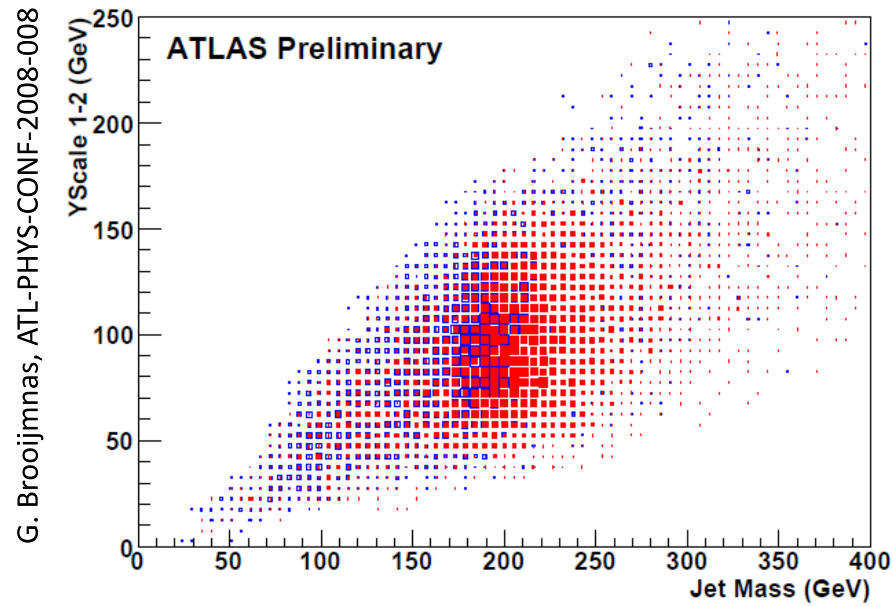

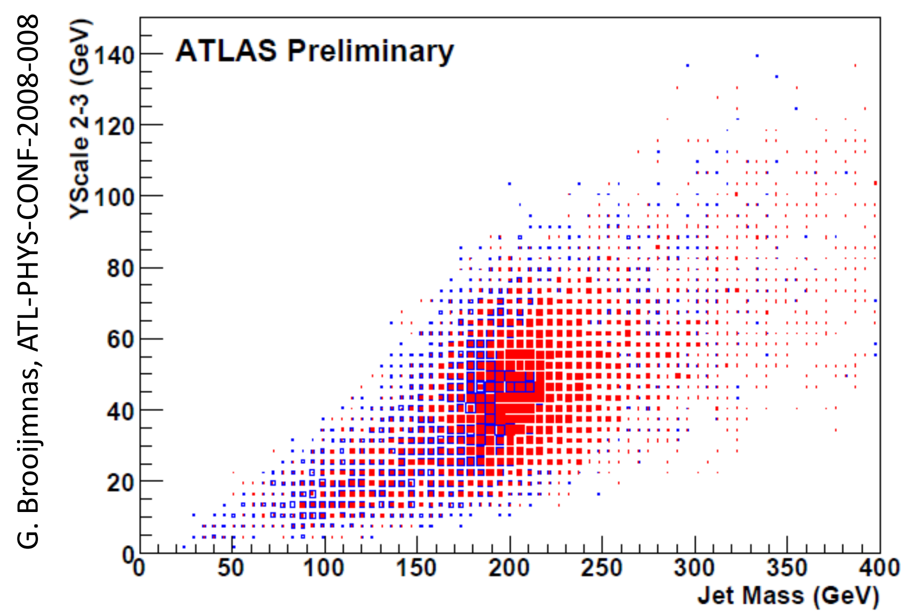

kT Jet Y_{scale} Performance Estimates

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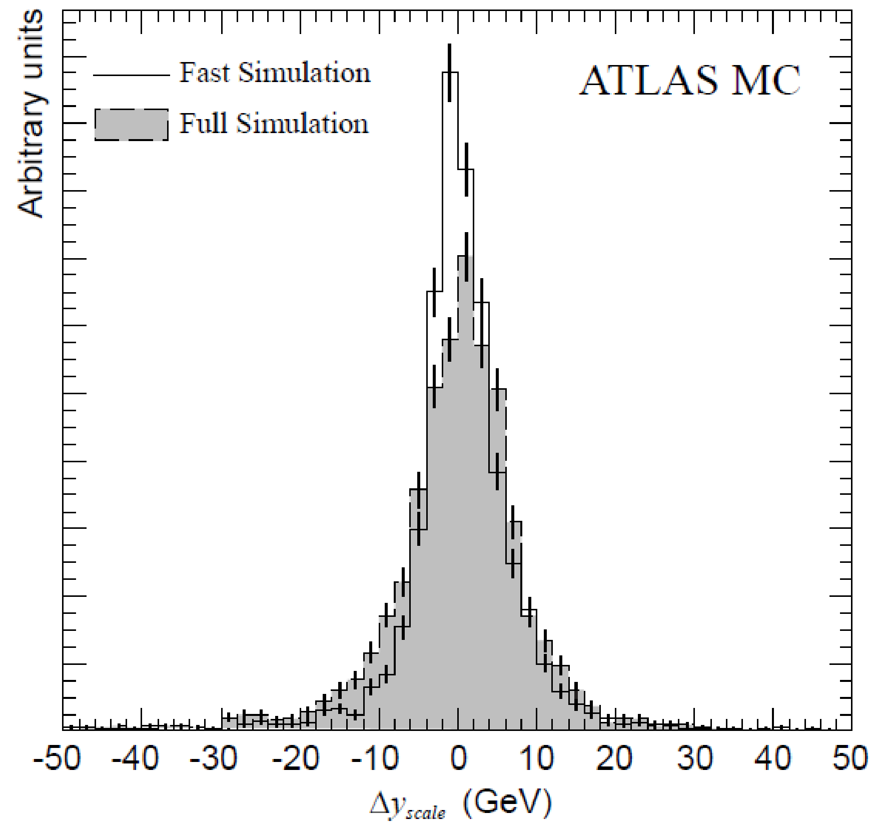
arXiv:0901.0512 [hep-ex]



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

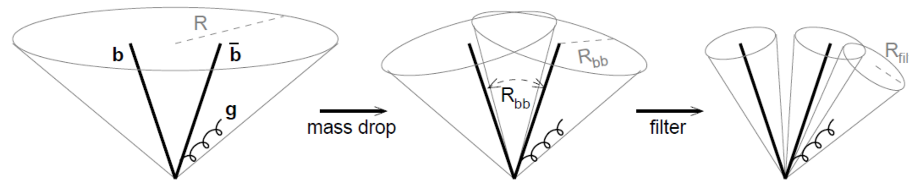
Sub-Jet Analysis: Filtering

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.

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

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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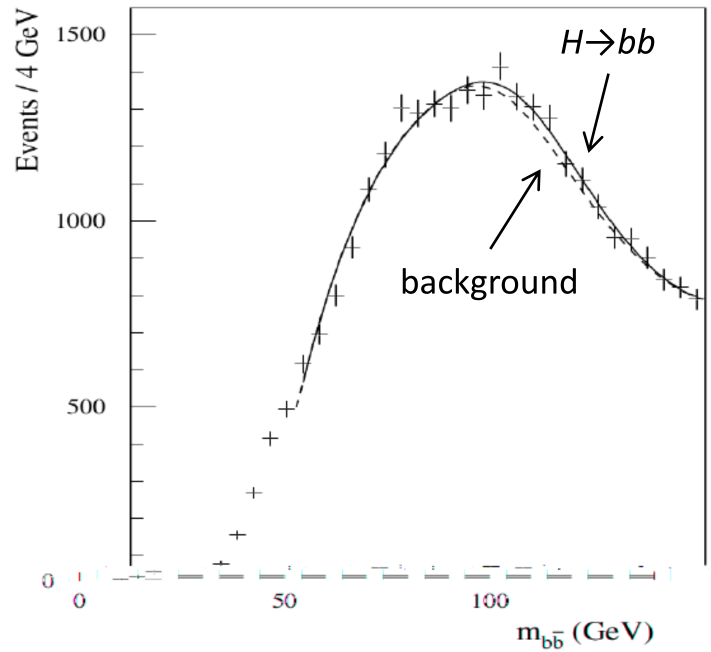

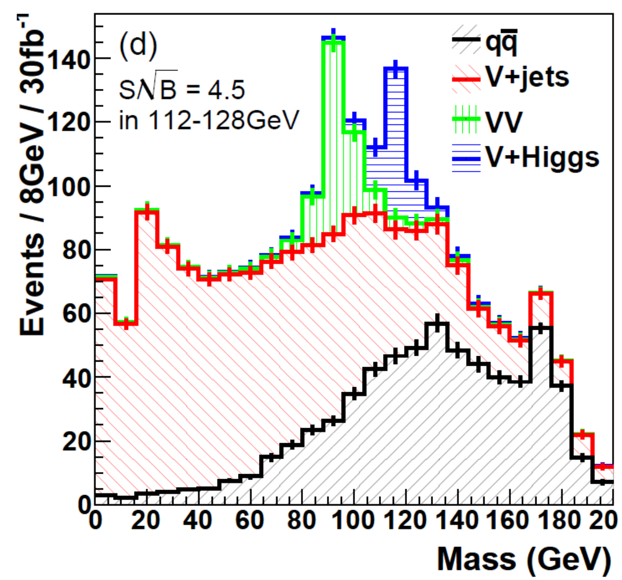

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Jet Pruning

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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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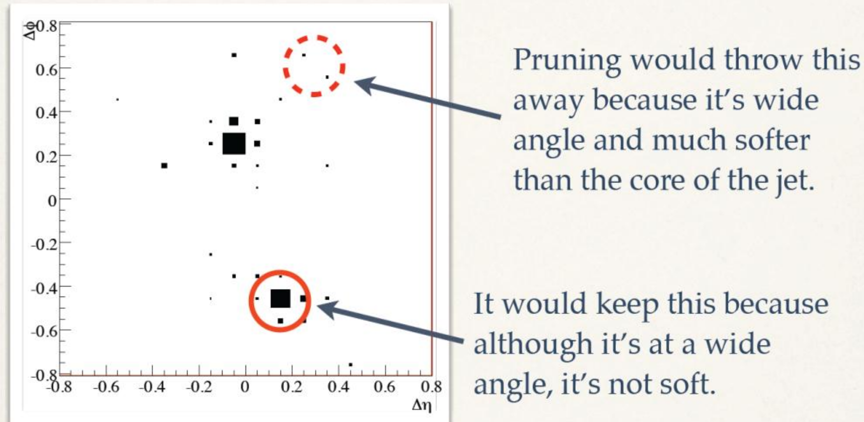

Boosted Higgs Jet

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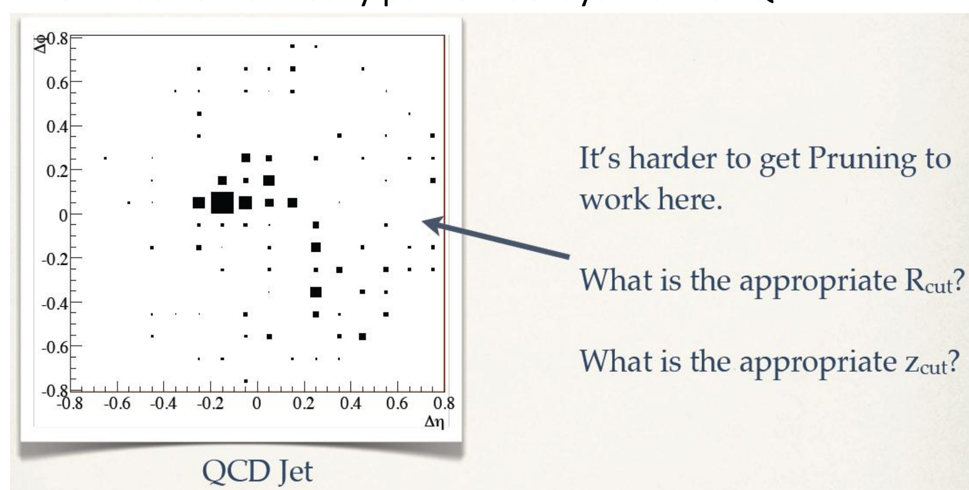

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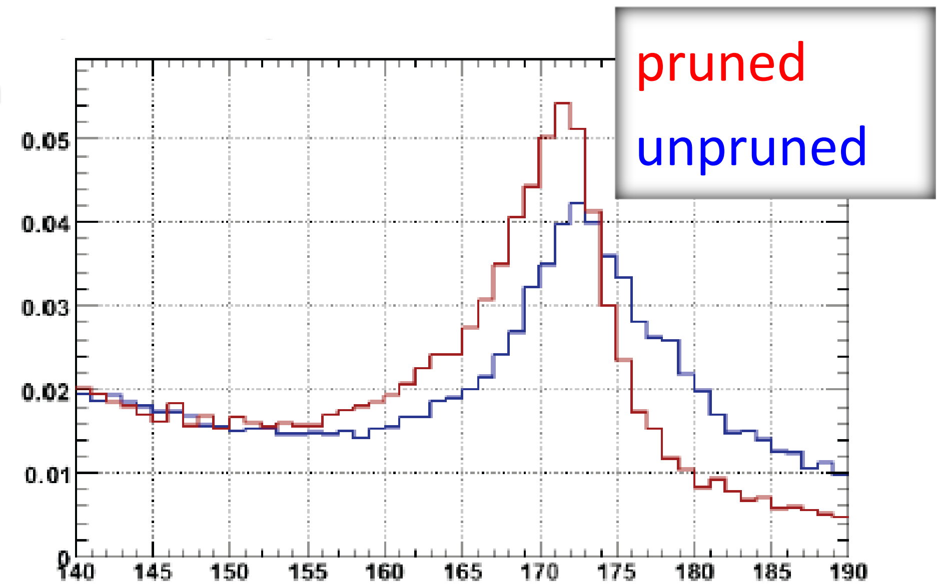
- Soft pT cut-off evaluated dynamically jet by jet

Jet Pruning

- improves jet mass measurement for boosted top etc.



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

Jet pruning

Enhancement of jet components to increase substructure resolution

Applied in kT-style jet clustering procedure

Jet trimming

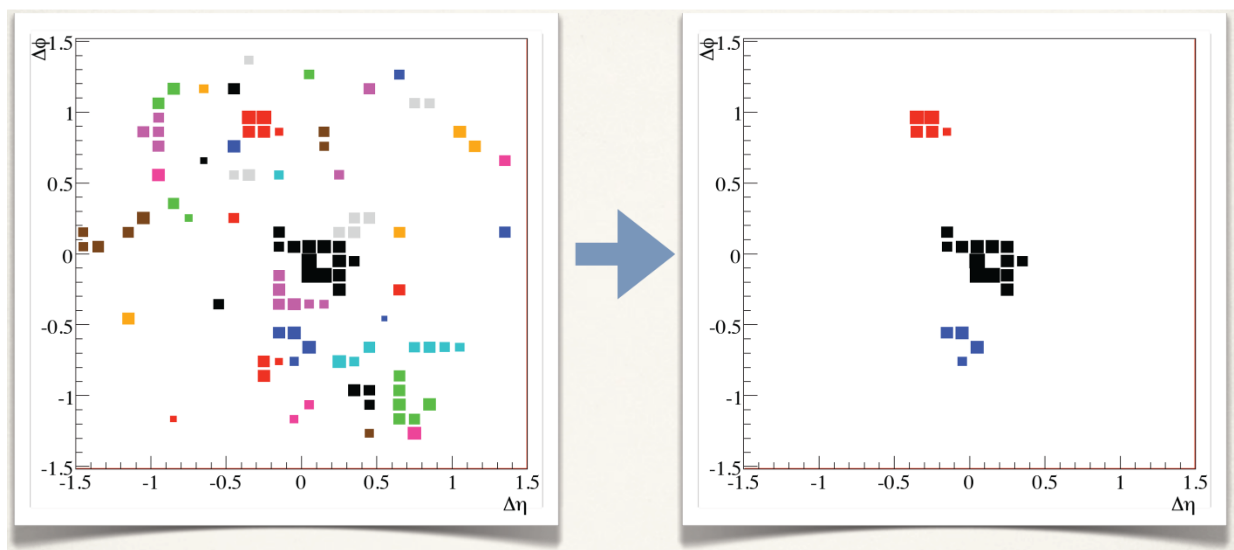
Applies a filter by removing soft sub-jets in a jet

Soft pT cut-off evaluated dynamically jet by jet

Jet 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 $\Lambda_{\mathrm{hard}} = p_{\mathrm{T,jet}}$

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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Jet Trimming

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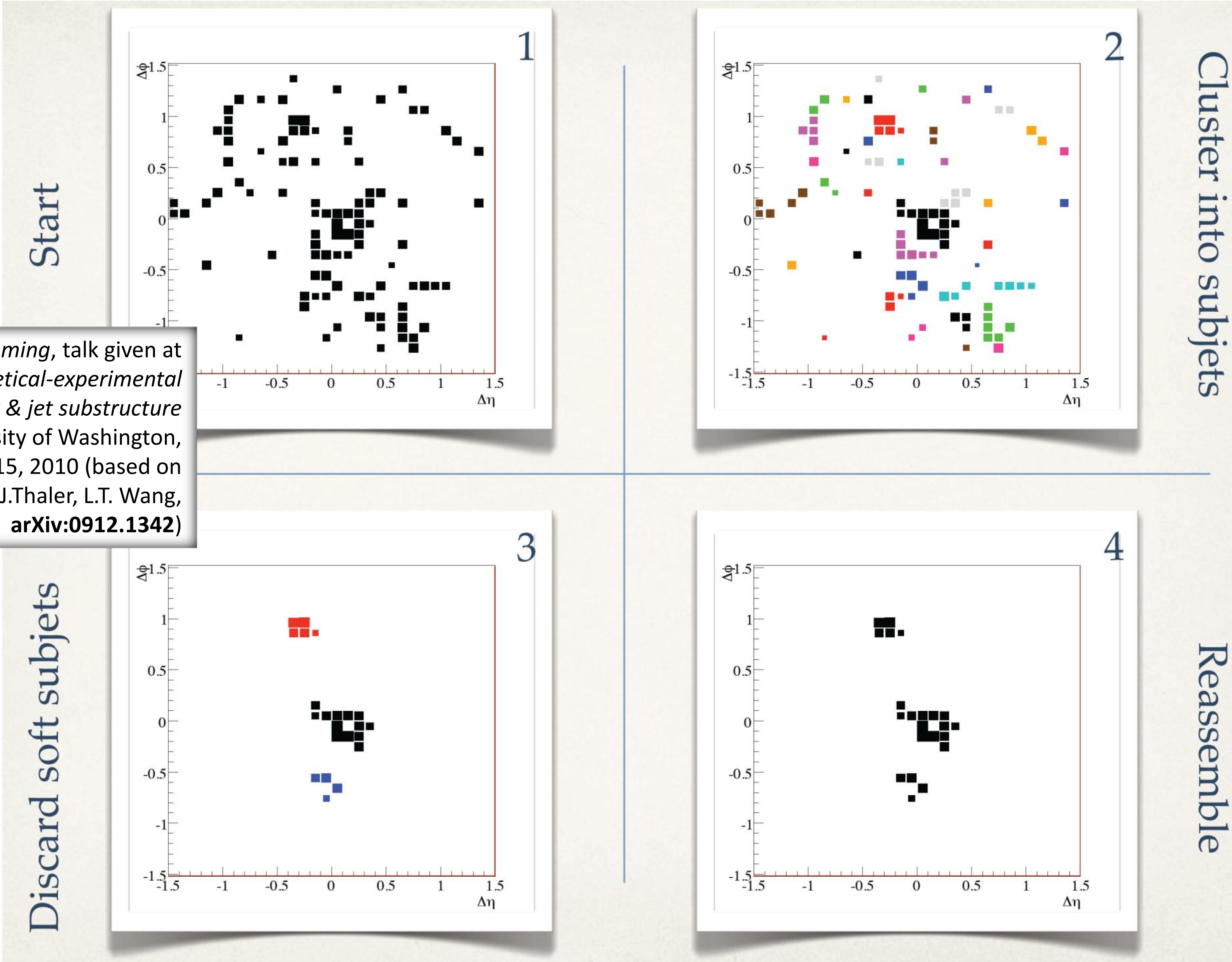
U of Arizona
August 23, 2011



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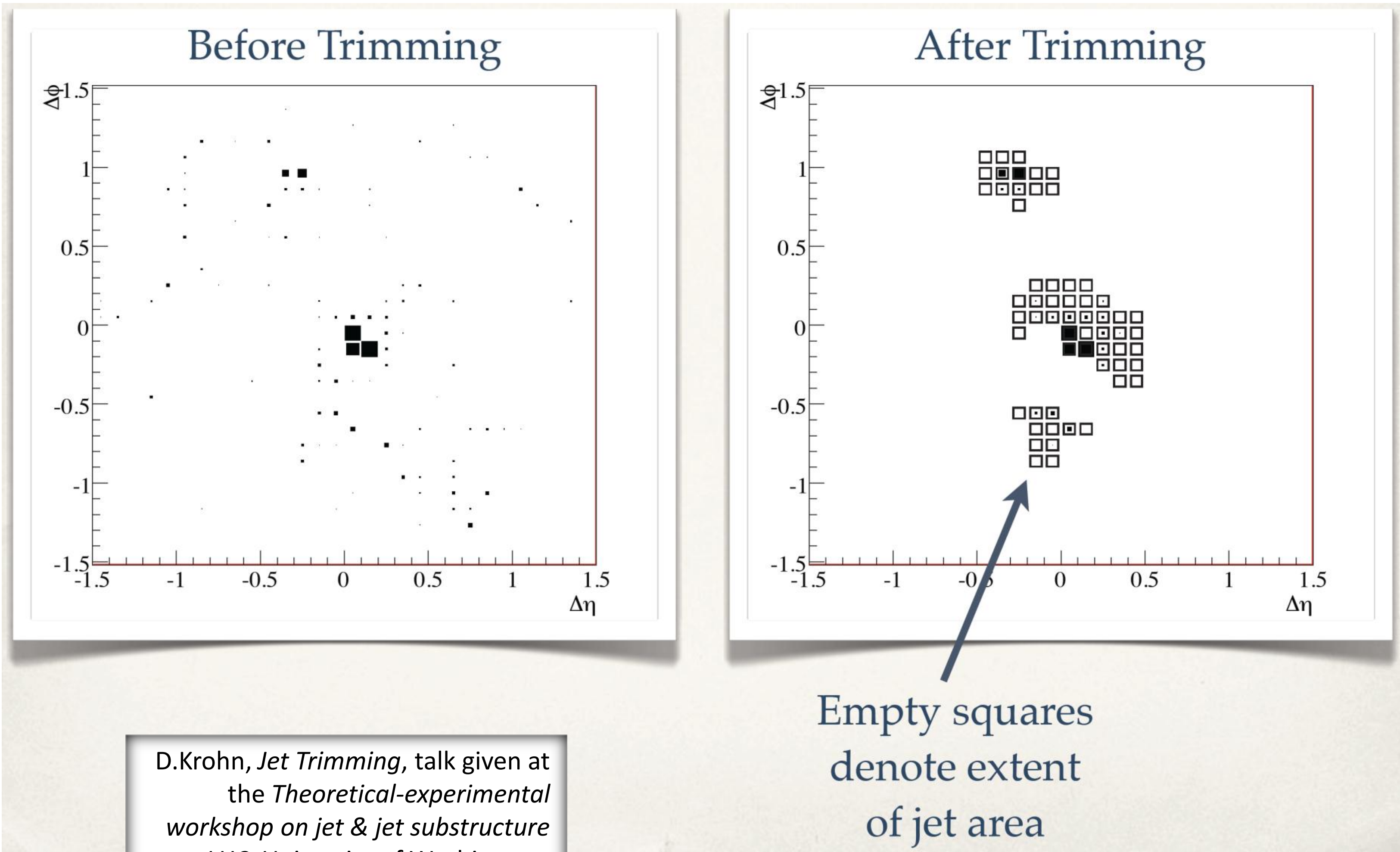

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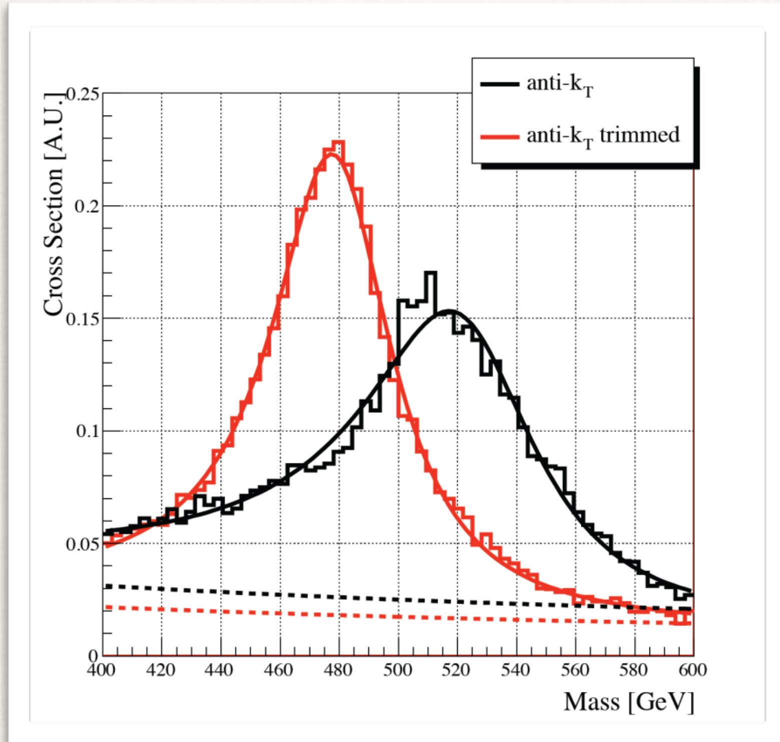

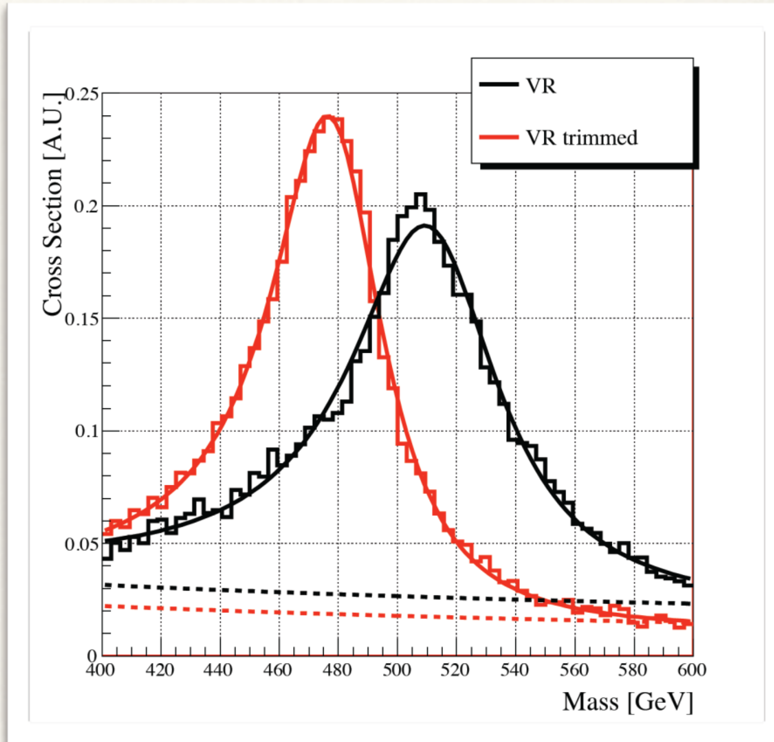

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Trimmed and variable radius (VR) jets from

$\phi \rightarrow qq, gg$

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

A. Larkoski, M. Jankowiak (BOOST2011) ***arXiv:1104.1646***

Angular Correlations

- For any IRC safe set of particles {*i*}:

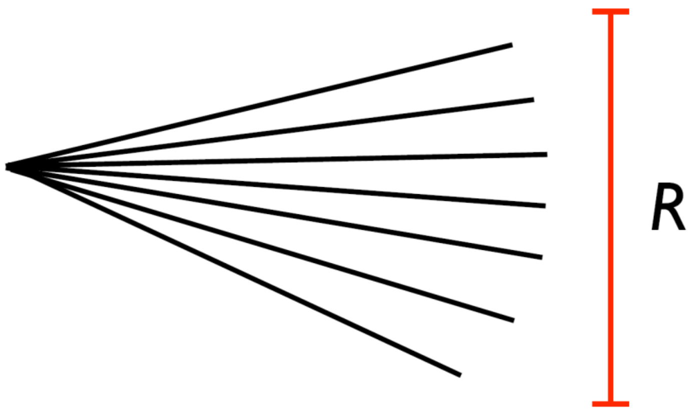
$$\mathcal{G}(R) \equiv \frac{\sum_{i\neq j} p_{Ti} p_{Tj} \Delta R_{ij}^2 \Theta(R - \Delta R_{ij})}{\sum_{i\neq j} p_{Ti} p_{Tj} \Delta R_{ij}^2} \approx \frac{\sum_{i\neq j} p_i \cdot p_j \Theta(R - \Delta R_{ij})}{\sum_{i\neq j} p_i \cdot p_j}$$

- *R* is **not** measured wrt jet center
  - Distinct from angular profile
- Quantifies jet scaling in an IRC safe way

A. Larkoski, M. Jankowiak (BOOST2011) *arXiv:1104.1646*

Angular Correlations

- What is the physical picture?
  - Jet with ~no substructure



  - Angular correlation function is smooth
  - In QCD, $\mathcal{G}(R) \sim R^2$

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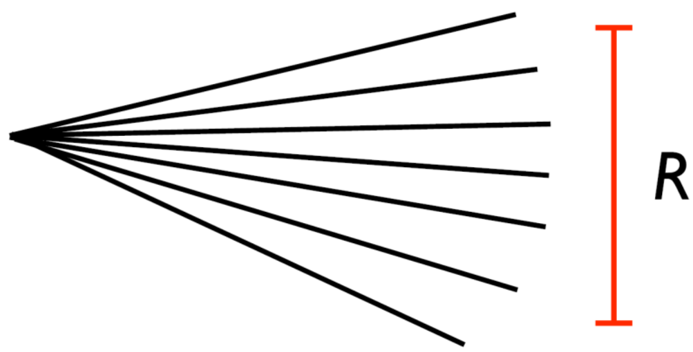

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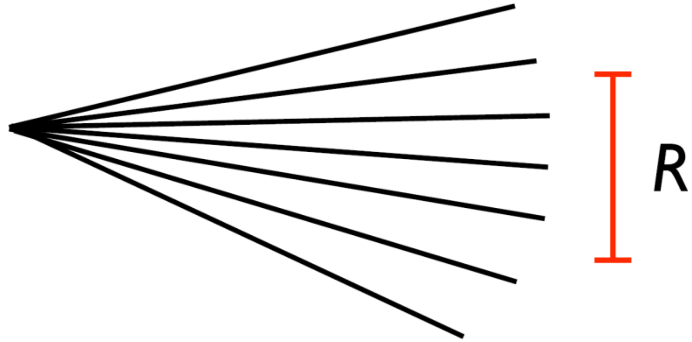

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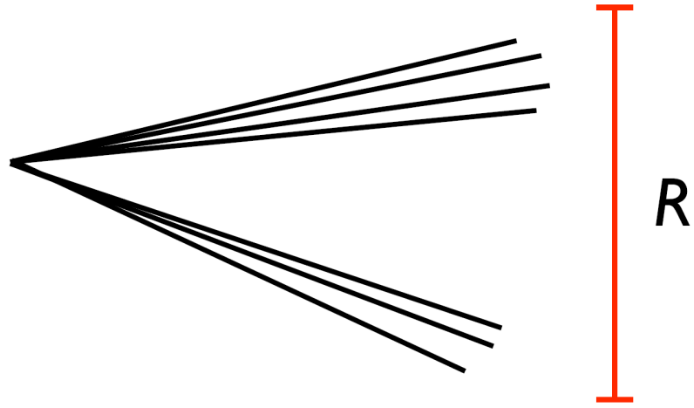

  - $\mathcal{G}(R) \sim 1$

A. Larkoski, M. Jankowiak (BOOST2011) ***arXiv:1104.1646***

Angular Correlations

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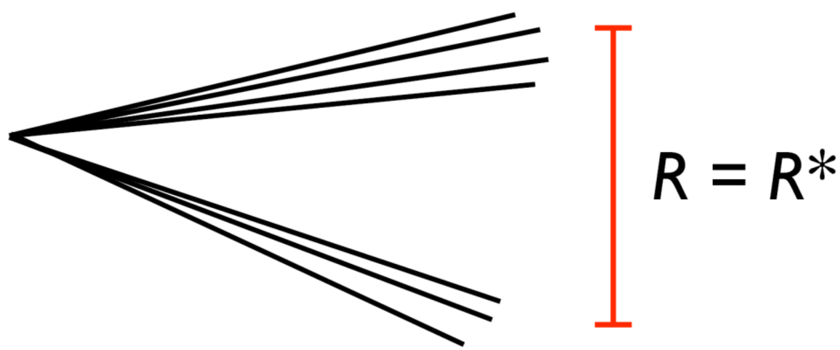
  - Jet with substructure



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A. Larkoski, M. Jankowiak (BOOST2011) ***arXiv:1104.1646***

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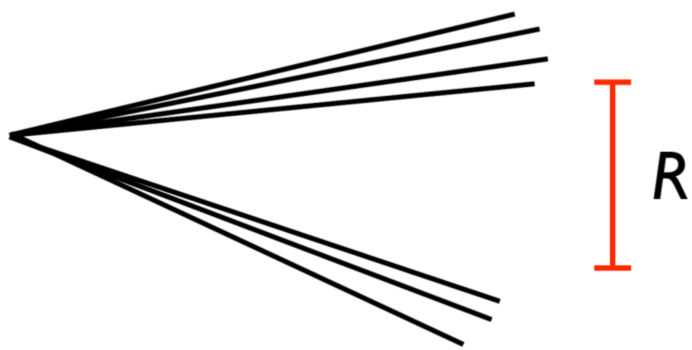

  - $\mathcal{G}(R) \sim 0$
  - Angular correlation is discontinuous at R^*

Jet Decomposition Without Trees

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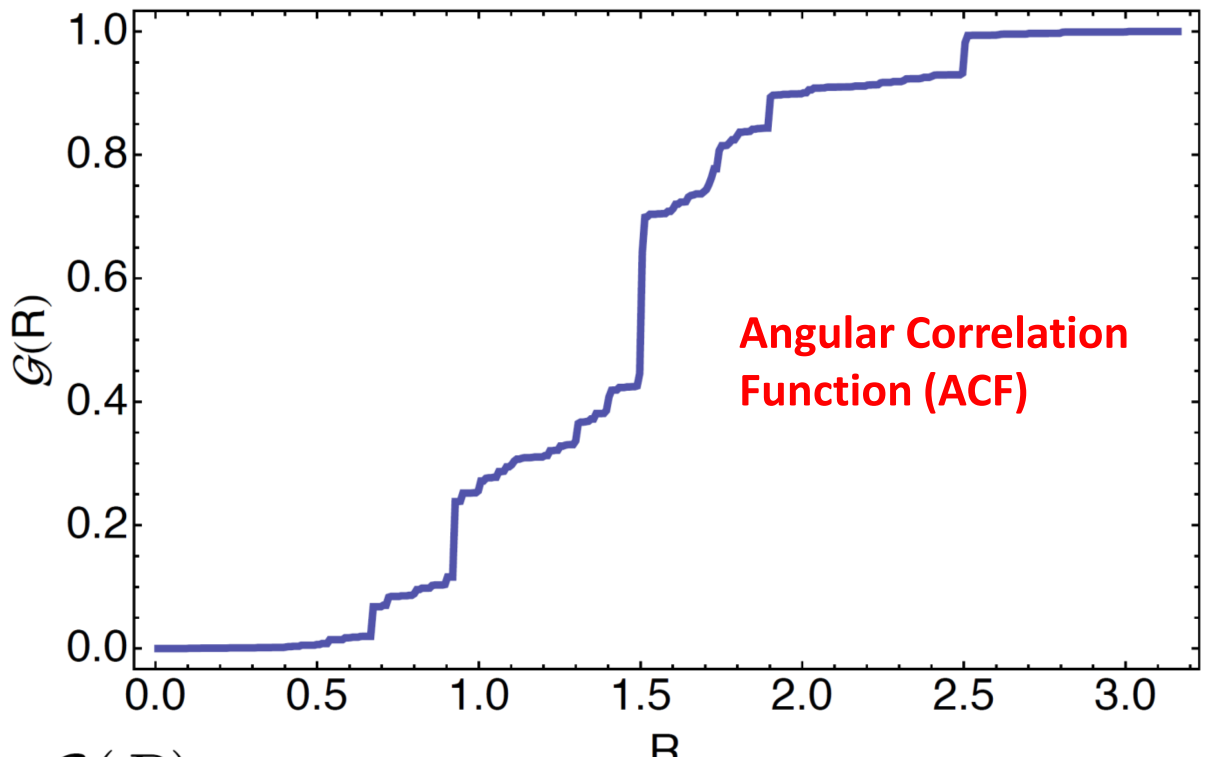
U of Arizona
August 23, 2011

A. Larkoski, M. Jankowiak (BOOST2011) ***arXiv:1104.1646***

Angular Correlations

- Ledges in $\mathcal{G}(R)$ = separation of hard subjets



- $\mathcal{G}(R)$ for a top quark jet

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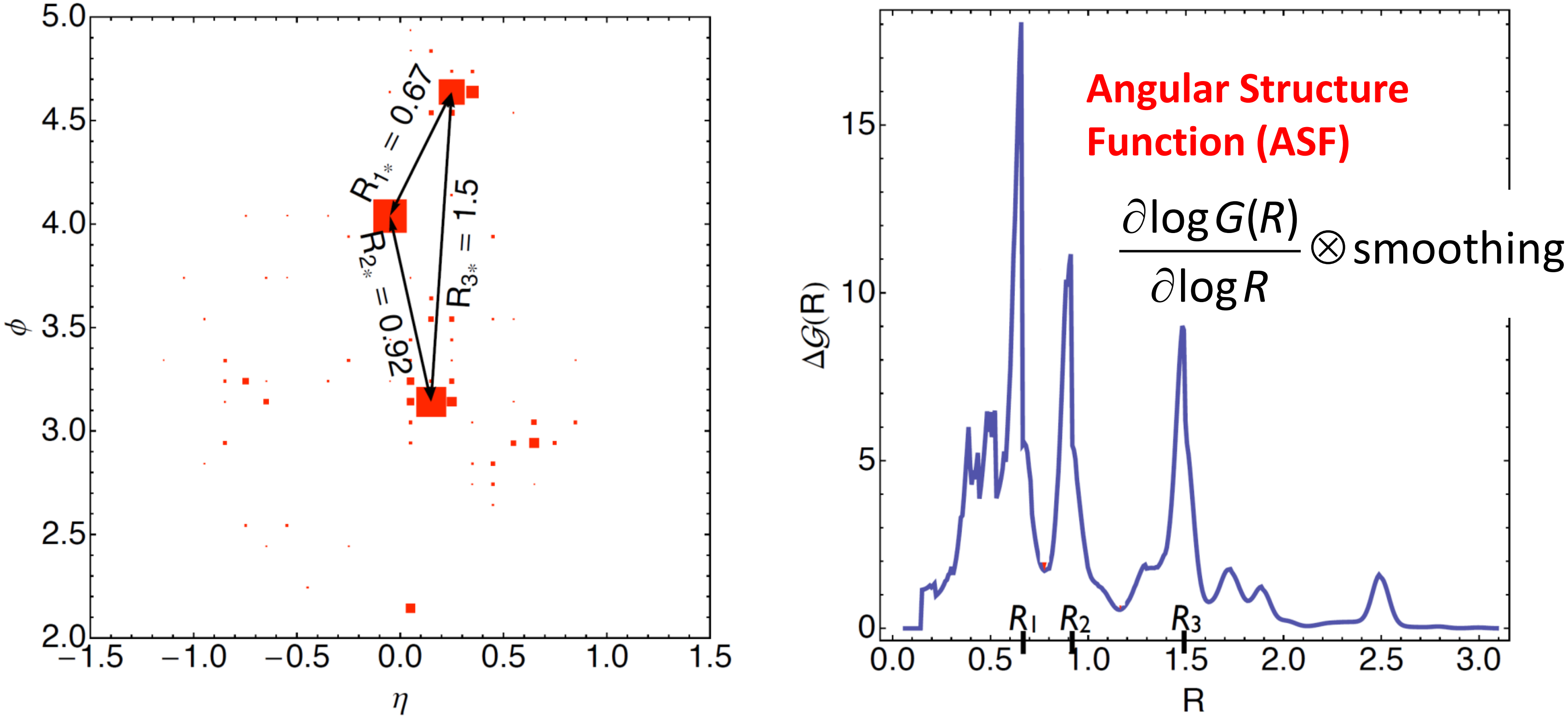
Angular Structure

Question: Does $\Delta\mathcal{G}(R)$ determine interesting ledges?



Answer: Yes!

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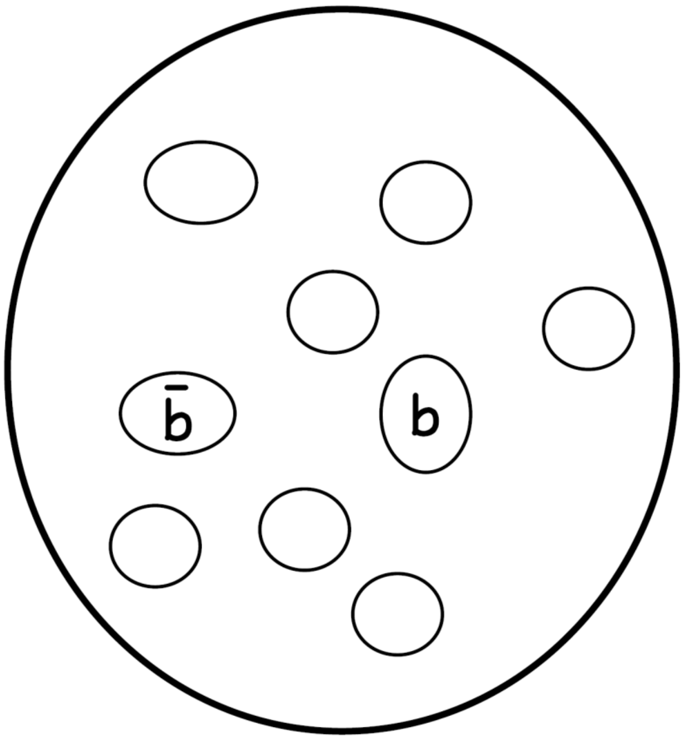
Shower Deconstruction

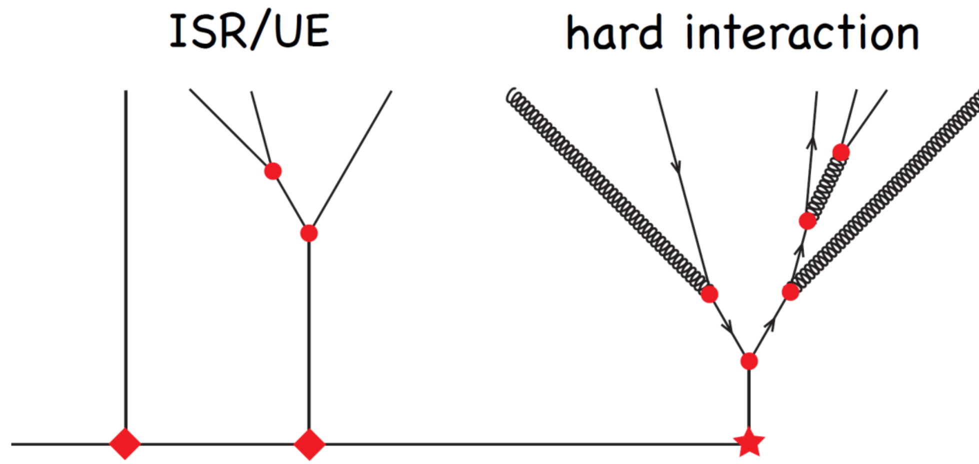
M. Spannowsky & D. Soper (BOOST2011) ***arXiv:1102.3480***

Analysis of radiation & decay patterns in a jet

Fat jet: R=1.2, anti-kT



microjets
R=0.15, kT



Build all possible shower histories

signal vs background hypothesis based on:

- Emission probabilities
- Color connection
- Kinematic requirements
- b-tag information

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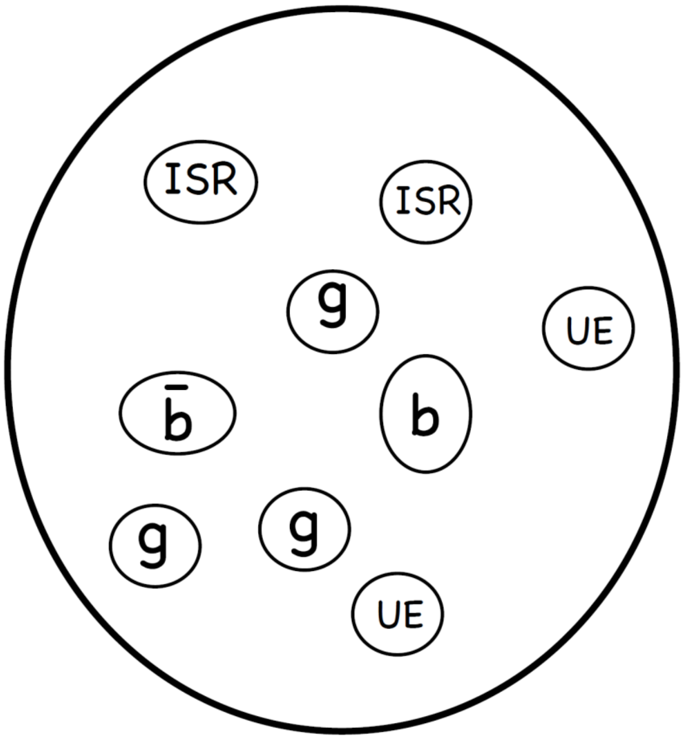

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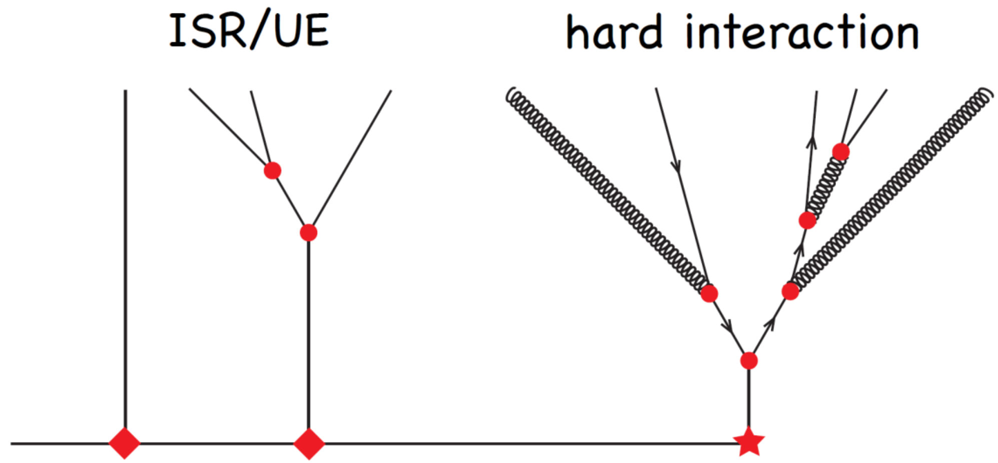

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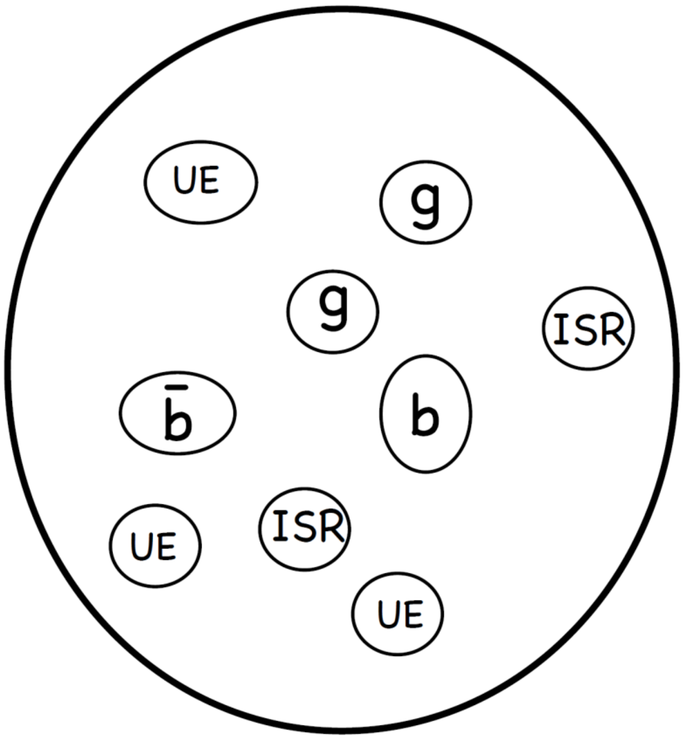

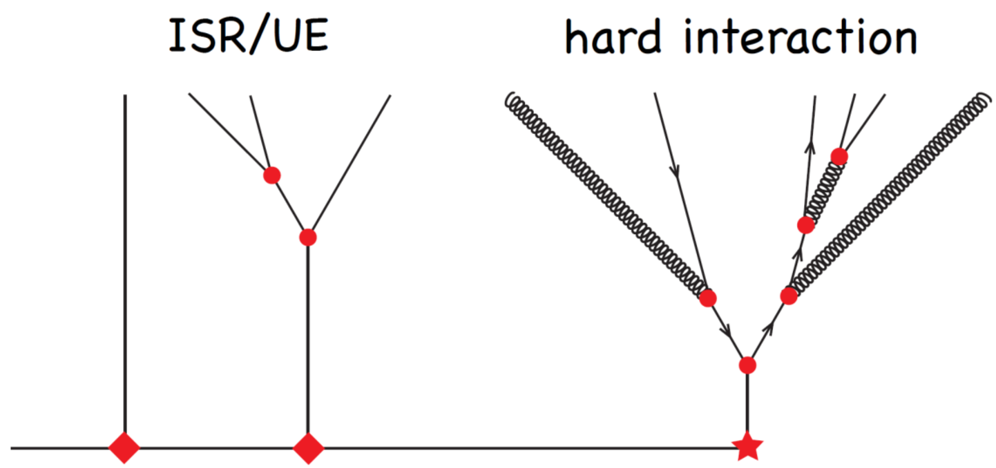

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Shower Deconstruction

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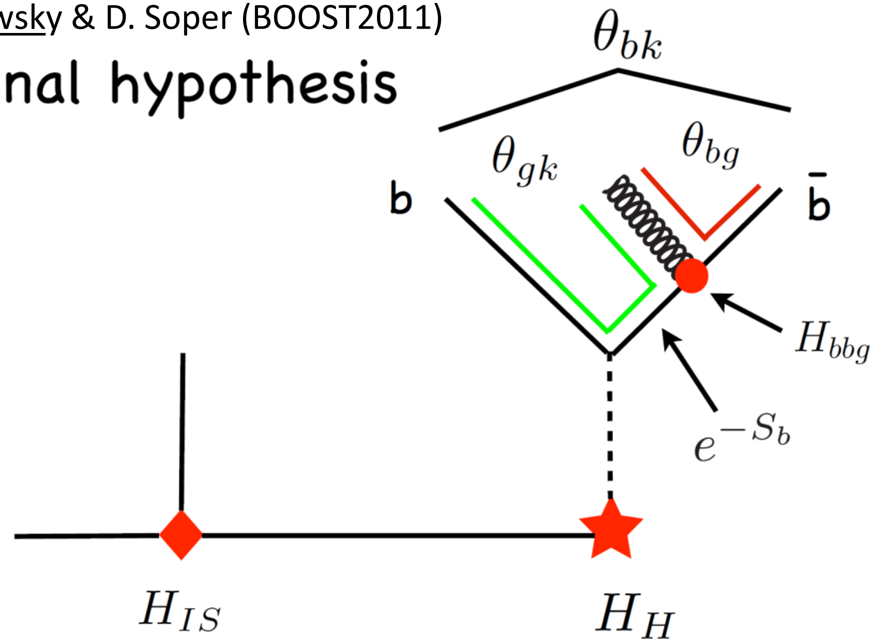
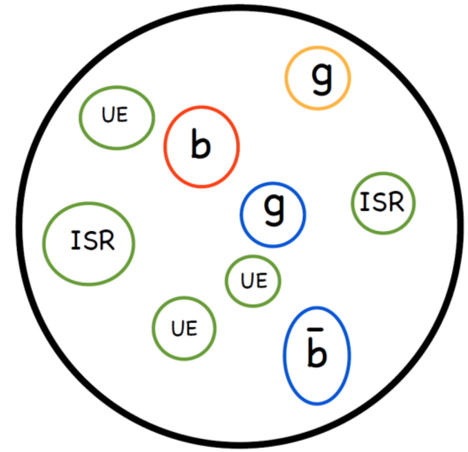
U of Arizona
August 23, 2011

M. Spannowsky & D. Soper (BOOST2011)

Signal hypothesis





b-quarks radiate gluons

See Dave's talk Link

$$\int d\mathcal{P} = \int d\mu_J^2 \int d\Delta\phi \int d\Delta y \sum_s J\, H e^{-S}$$

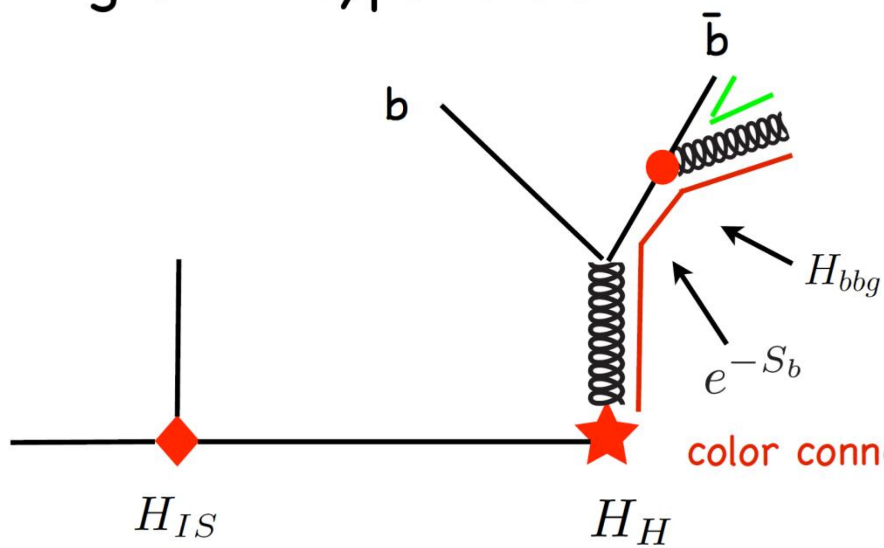
$$S \approx \int d\bar{\mu}_J^2\, \Theta(\mu_J^2 < \bar{\mu}_J^2) \int d\Delta\bar{y} \int d\Delta\bar{\phi} \sum_{\bar{s}} J(\bar{p}_A, \bar{p}_B)\, H(\bar{p}_A, \bar{p}_B)\, \Theta(\{\bar{p}_A, \bar{p}_B\} \in \text{fat jet})$$

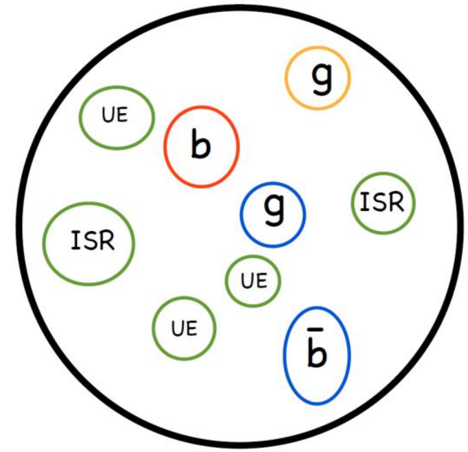
$$H_{bbg} = H_{\bar{b}g\bar{b}} = \frac{C_A \alpha_s(\mu_J^2)}{2} \frac{1}{\mu_J^2} \frac{k_J^2}{k_b k_g} \frac{\theta_{bk}^2}{\theta_{gb}^2 + \theta_{gk}^2} \Theta(k_g < k_b)\, \Theta\left(2\frac{\mu_J^2}{k_J} < \frac{\mu_K^2}{k_K}\right)$$

Shower Deconstruction

M. Spannowsky & D. Soper (BOOST2011) **arXiv:1102.3480**

Background hypothesis





color connected partner outside fat jet

See Dave's talk Link

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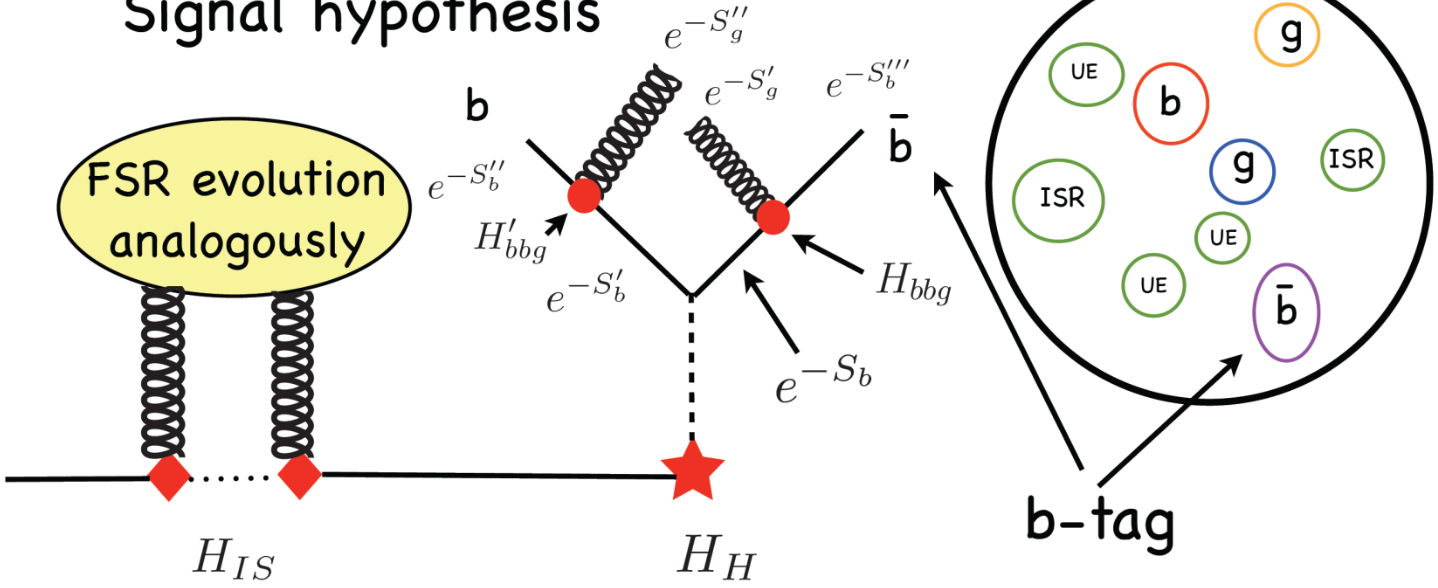
Shower Deconstruction

M. Spannowsky & D. Soper (BOOST2011) ***arXiv:1102.3480***

Signal hypothesis



Wrapping up all factors gives weight for shower history

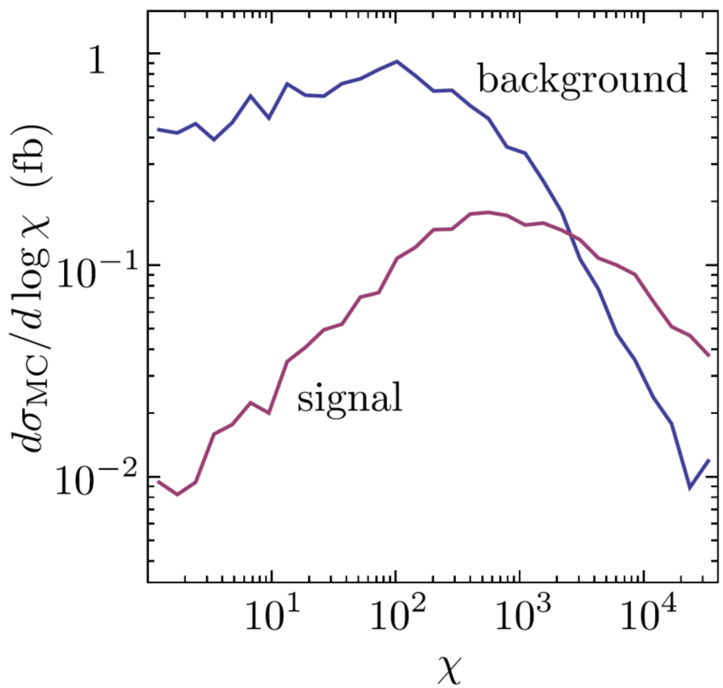
$$\chi = \frac{\sum_{ISR/Hard}\left(\sum_i \mathrm{ISR_i} \times \sum_j \mathrm{Signal_j}\right)}{\sum_{ISR/Hard}\left(\sum_i \mathrm{ISR_i} \times \sum_j \mathrm{Backg_j}\right)}$$

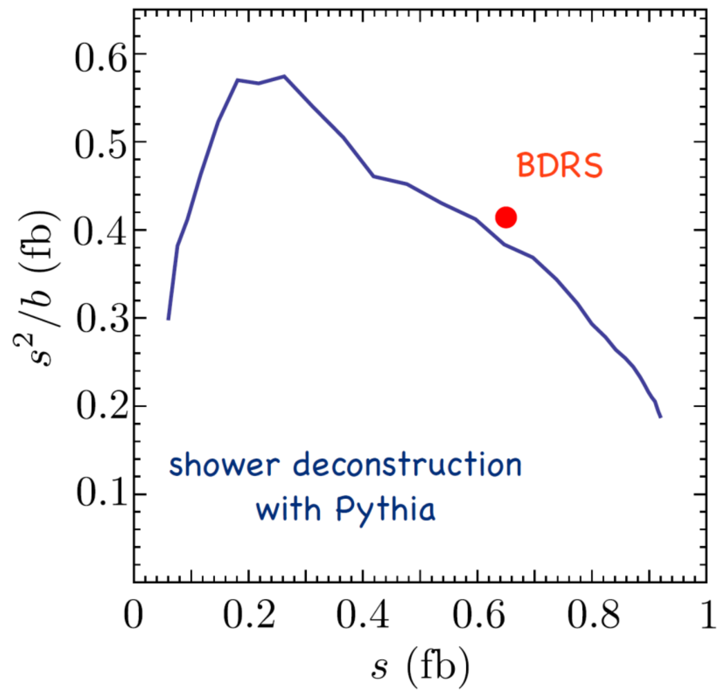
Here $\mathrm{Signal_1} = \mathrm{H_H H_{split} e^{-S_{split}} H_{bbg} e^{-S'_b} e^{-S'''_b} e^{-S'_g} H'_{bbg} e^{-S''_b} e^{-S_b} e^{-S''_g}}$

Shower Deconstruction

M. Spannowsky & D. Soper (BOOST2011) ***arXiv:1102.3480***

perfect b-tagging 2 b-tagged microjets





- Profits more from information than BDRS, e.g. b-tagging

Additional info and updated plots from Michael tomorrow!

Experimental Challenges

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August 23, 2011

Jet reconstruction

- Energy scale and direction well controlled
  - Detector response, pile-up, UE, …
- Jet shapes can be reconstructed
  - Not too dependent on signal definition (calorimeter towers/clusters, particle flow, tracks…)
- Jet mass more challenging
  - Spatial energy distribution by em and had showers, noise, pile-up,…
  - Stronger dependence on signal definition

Fat jet reconstruction (high pT)

- Global jet easy to find (= trigger & reconstruct) but maybe not so easy to calibrate
  - Occupies large regions of the detector with different response characteristics (local calibrated energy scale needed?)
  - Much larger global pile-up contributions

Internal jet structures, sub-jets

- Structure reconstruction
  - Spatial and energy resolution inside jet – larger local signal fluctuations, dependence on signal definition
  - Some small distance scales suggested – experimental limitations need to be considered
- Internal kinematic, thrusts and flows
  - Sub-jet calibration non-trivial – e.g., full jet calibration depends on neighbouring activity, how does this translate to sub-jets?
  - Signal definition crucial – e.g., can cell clusters merge internal energy flow too much?
  - How much is detector image disturbed by pile-up – adds internal jet structure but with different dynamics/scales…
- Systematic uncertainties
  - Internal (sub-)jet scales need to be validated
  - Not clear how to do this without fat jets from (boosted) massive decay, e.g. hadronic W, full hadronic top
  - Angular measurement error folds with response uncertainty

Quite some activity in the experiments

- Understanding effect of signal definition
- Finding limitations in distance scales
- Calibration of sub-jets
- …

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Experimental Challenges

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Quite some activity in the experiments

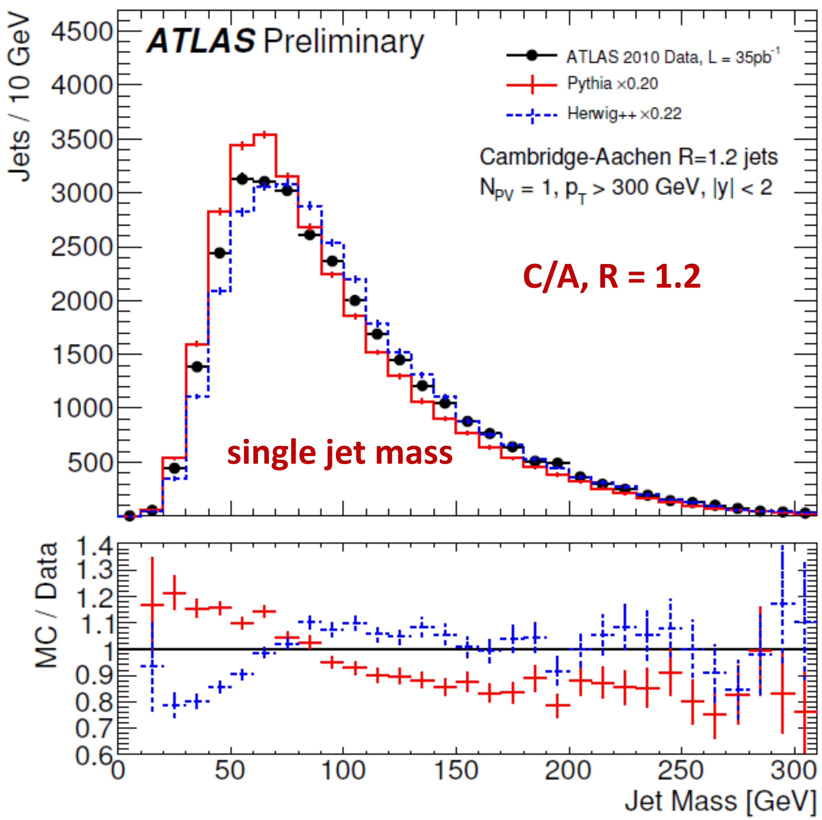
- Understanding effect of signal definition
- Finding limitations in distance scales
- Calibration of sub-jets
- …

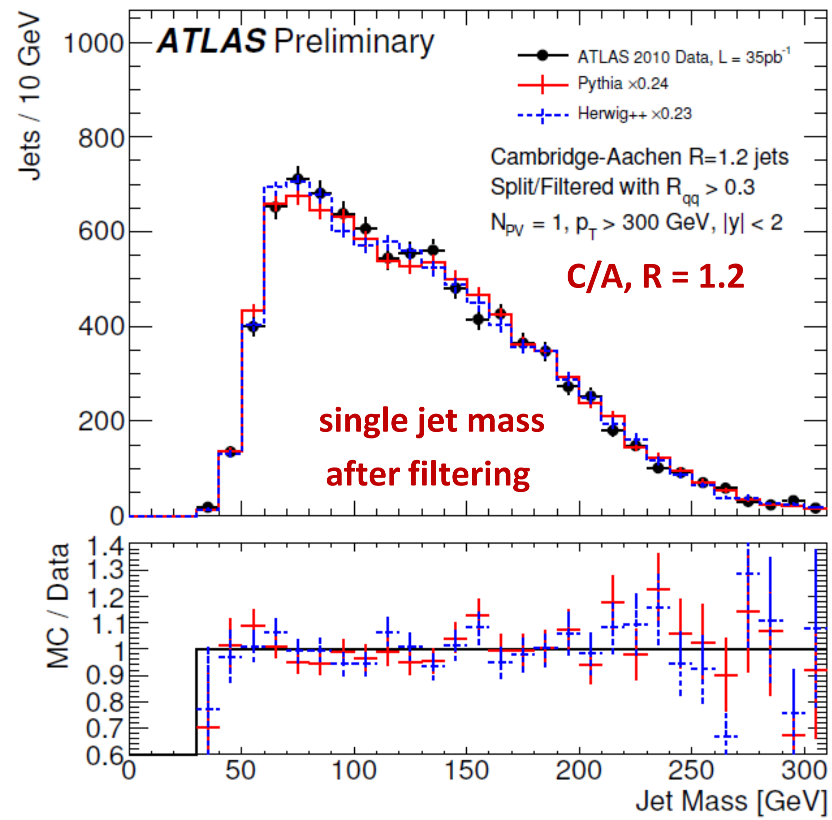
In general calibrated jet constituents help with several issues – new/improved signal definitions for hadron colliders at LHC (CMS – particle flow, ATLAS – local hadronic cluster calibration)!

High pT jet sample

- Motivated by boosted object search
  - Relevant scale for massive particle is (fat) jet distance parameter $R = m_{jet}/p_{T,jet}$
- Jet filtering used to measure mass
  - Compare mass from all constituents with mass from filtered subjet recombination

(all plots from **ATLAS CONF-2011-073***)*

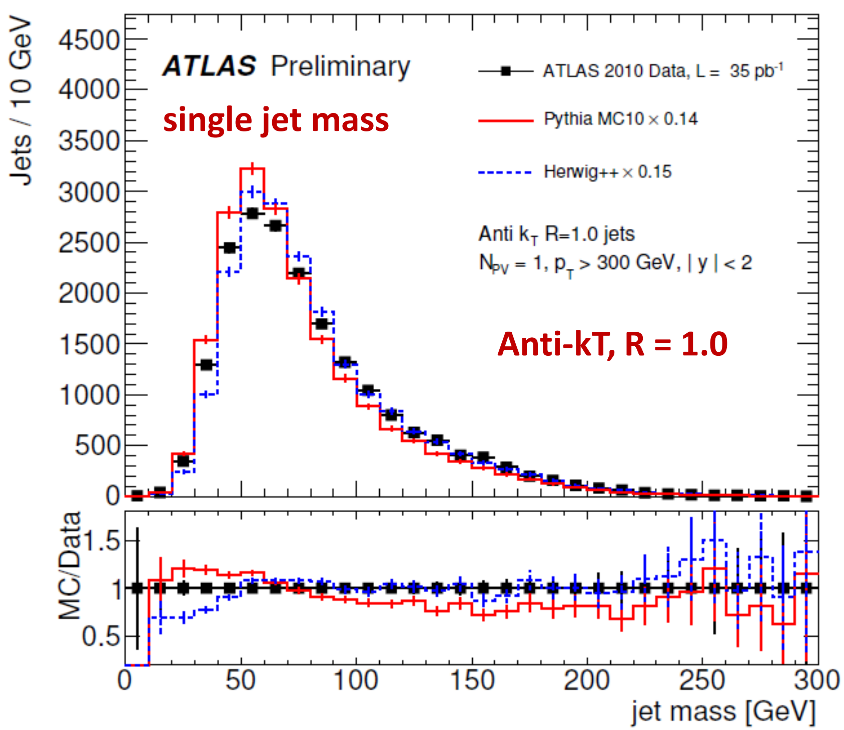


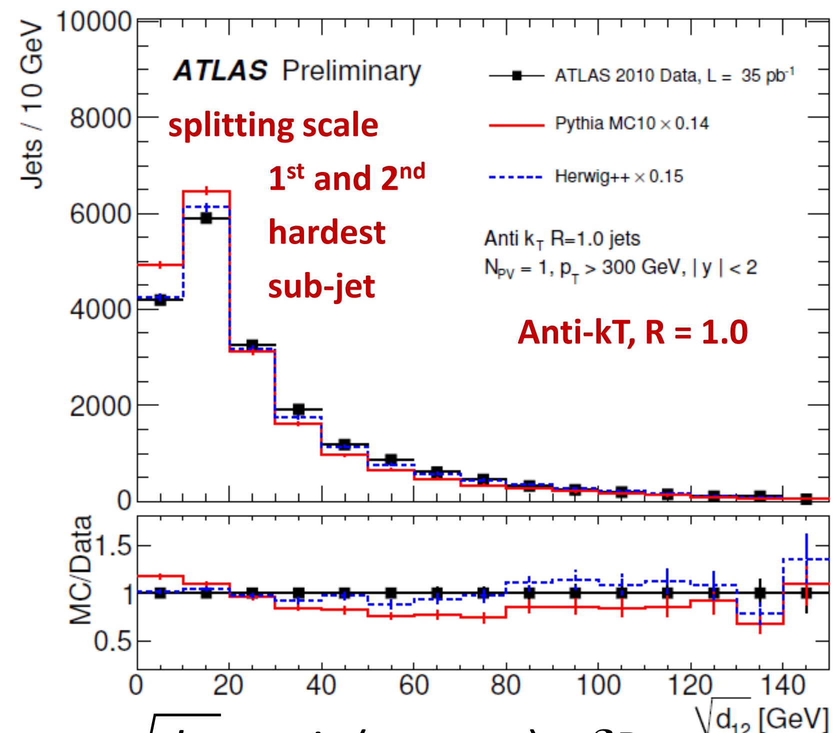


Mass and internal resolution scales for Anti-kT

- High pT jets reconstructed w/o meaningful clustering sequence
  - C/A, kT – meaningful cluster sequences based on distance scales
  - Anti-kT – regularly shaped jets with no specific meaning for the clustering sequence
- Internal distance scale experimentally challenging
  - Requires sufficient spatial resolution in clustering

(all plots from **ATLAS CONF-2011-073***)*





$$\sqrt{d_{12}} = \min(p_{T,1}, p_{T,2}) \times \delta R_{12}$$

First Look at Jet Substructure Systematics

P. Loch
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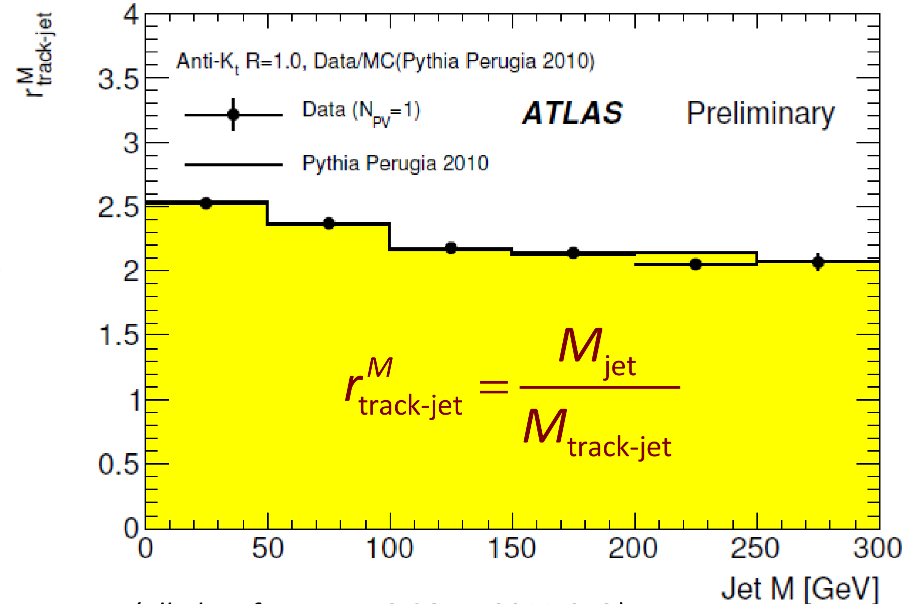
August 23, 2011

Not easy to determine

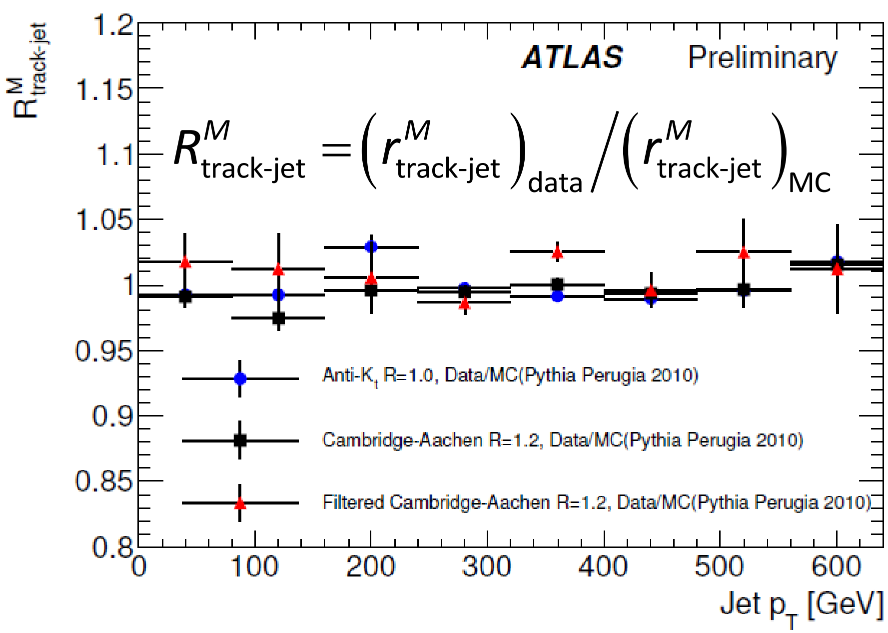
- Only full jet systematic uncertainties available
  - Local energy scales inside jet not well known
- Use track jet mass as unbiased reference for calorimeter mass measurement

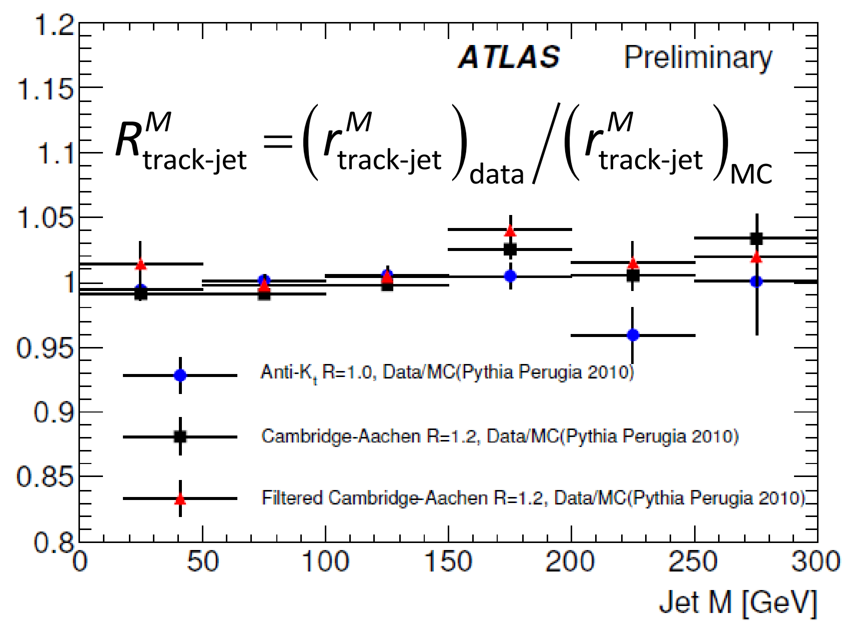
$$r^{M}_{\text{track-jet}} = \frac{M_{\text{jet}}}{M_{\text{track-jet}}}$$

- Double-ratio MC/data establishes systematics



(all plots from **ATLAS CONF-2011-073**)





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Fully Unfolded Jet Mass & Substructure

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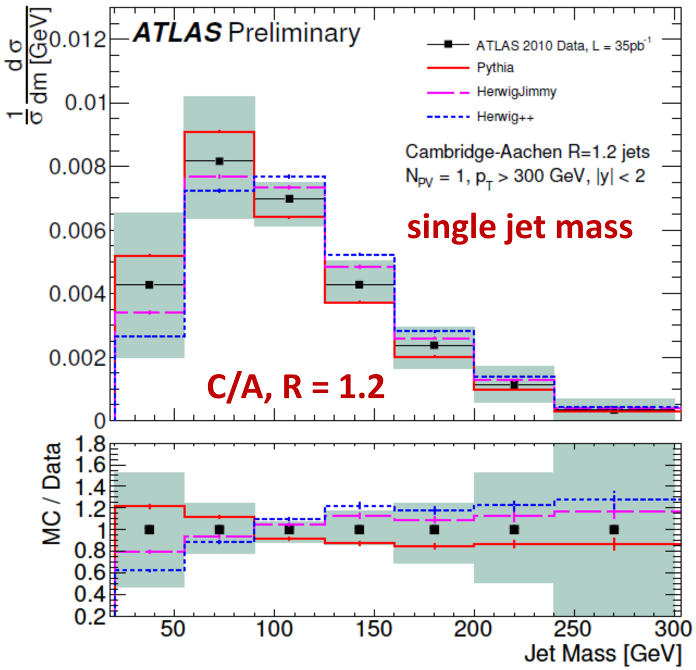
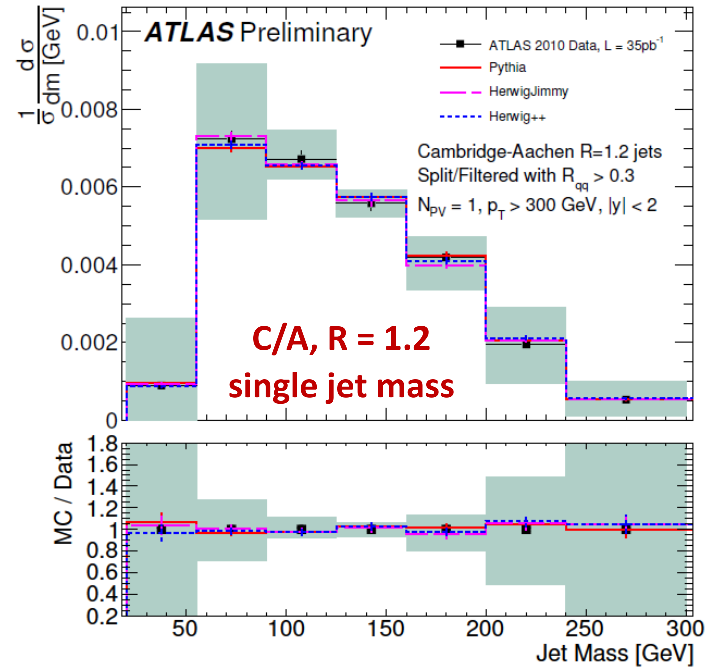
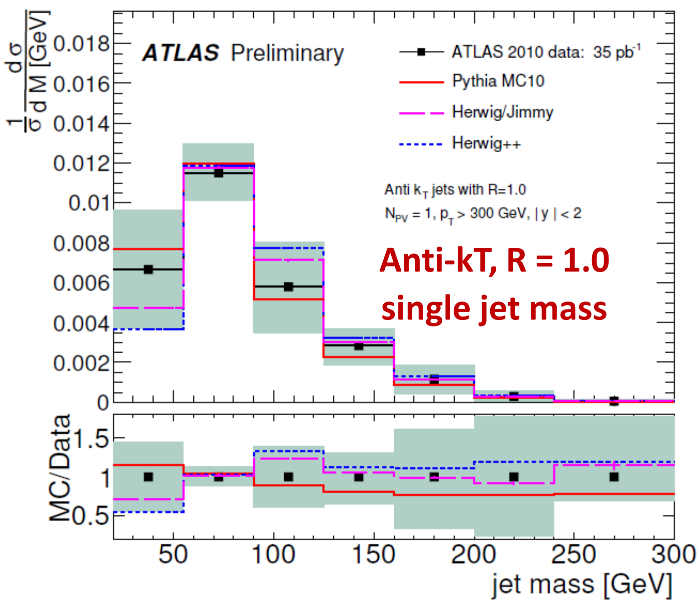
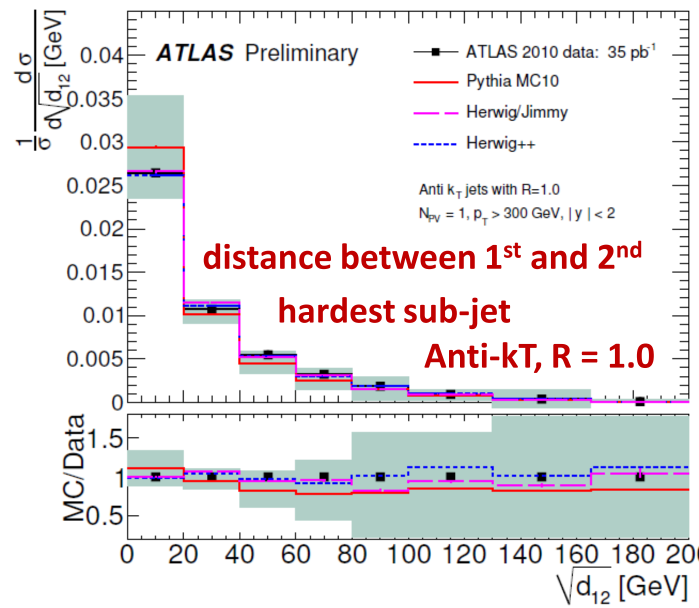
August 23, 2011









(all plots from **ATLAS CONF-2011-073***)*

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Jet Mass Reconstruction in Pile-up

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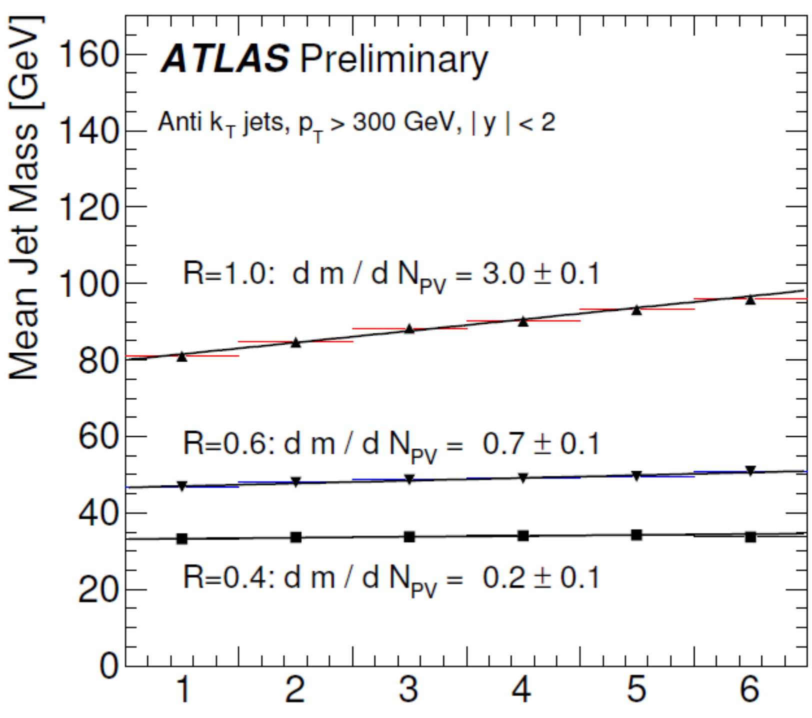
August 23, 2011

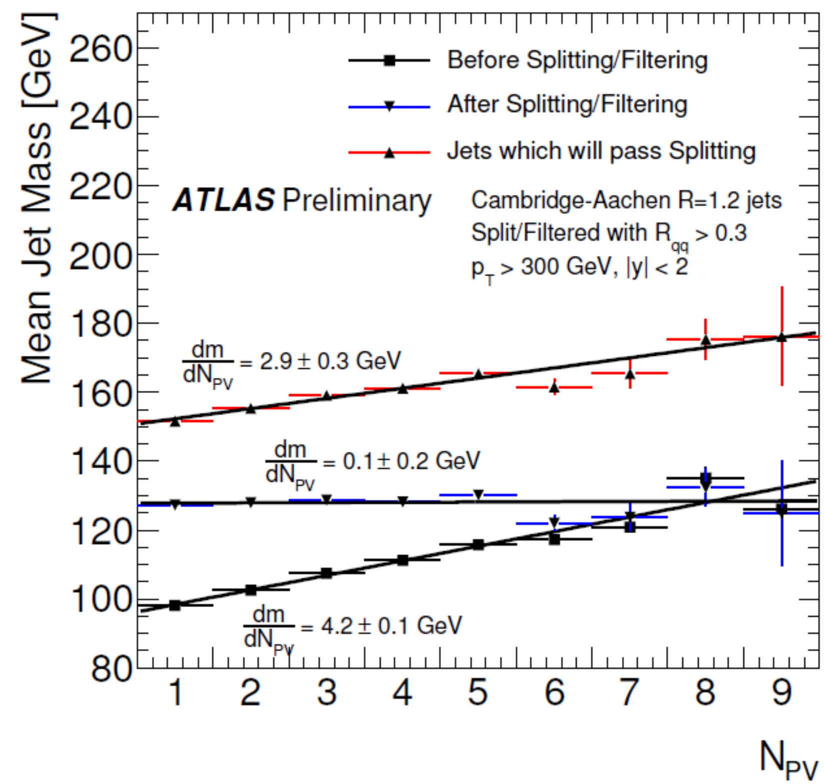
Pile-up "disturbs" particle flow inside jet

- Gain of mass with increasing pile-up expected
  - More energy added at larger distance from jet axis
- Pure in-time pile-up considered here
  - ATLAS 2010 data, no pile-up history
- Effect strongly reduced for narrow jets
  - That's why like Anti-kT with small distance parameter!

Boosted object search

- Prefers substructure in "fat jets"
  - Better extraction of decay structure
- Jet grooming suppresses pile-up
  - Focuses on hard sub-jet structure
  - Suppresses soft (pile-up and UE) contributions in jet
- First hints that cluster jets are useful for sub-structure analysis in more hostile environment





(all plots from **ATLAS CONF-2011-073***)*

Hints of Boosted Objects in ATLAS

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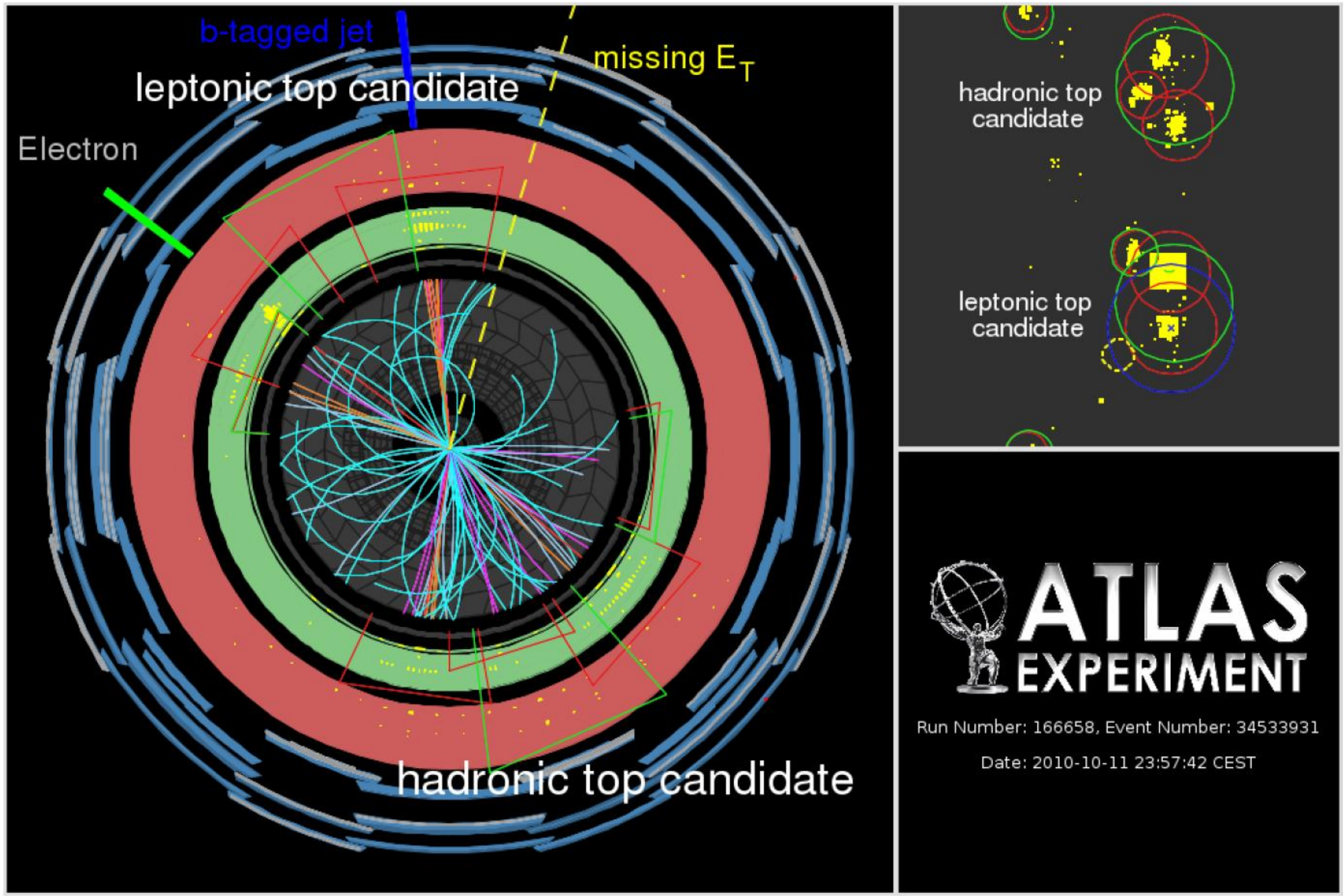

Leptonic top	E_T^{miss}: E_T = 36 GeV, ϕ = -1.5 electron: p_T = 145 GeV, η = 1.1, ϕ = 2.5 jet: index = 1, E_T = 194 GeV, η = 1.2, ϕ = 1.7, m_j = 17 GeV
Hadronic top (R =0.4 clustering)	jet 2, E_T = 155 GeV, η = 1.1, ϕ = -0.7 rad, m_j = 22.7 GeV + jet 3, E_T = 113 GeV, η = 1.3, ϕ = -1.7 rad, m_j = 14 GeV + jet 4, E_T = 54 GeV, η = 0.6, ϕ = -1.7 rad, m_j = 8 GeV
Hadronic top (R =1.0 clustering)	jet 1, E_T = 356 GeV, η = 1.3, ϕ = -1.1 rad, m_j = 197 GeV $\sqrt{d_{12}}$ = 110, $\sqrt{d_{23}}$ = 40

Hints of Boosted Objects in ATLAS

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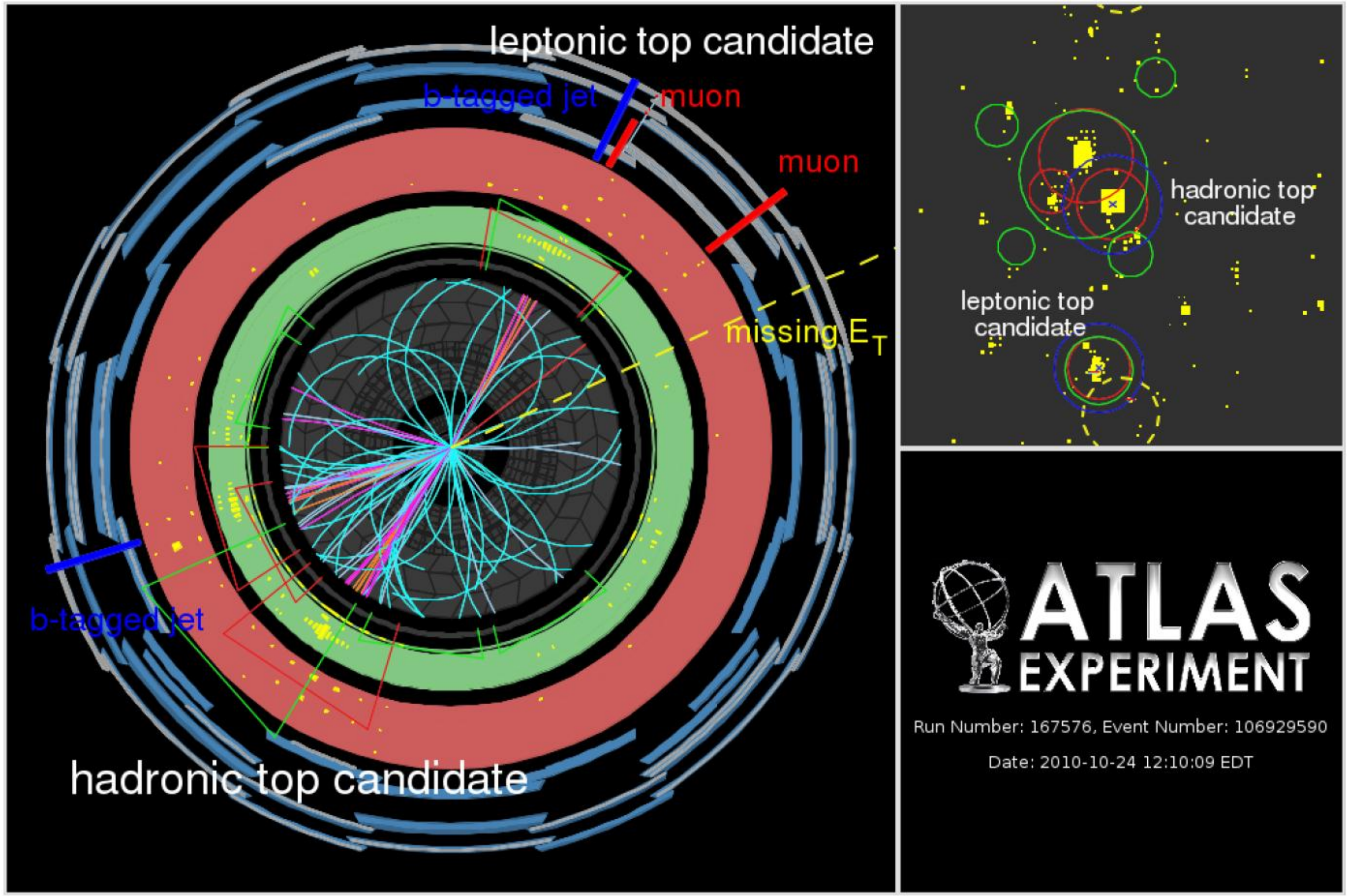
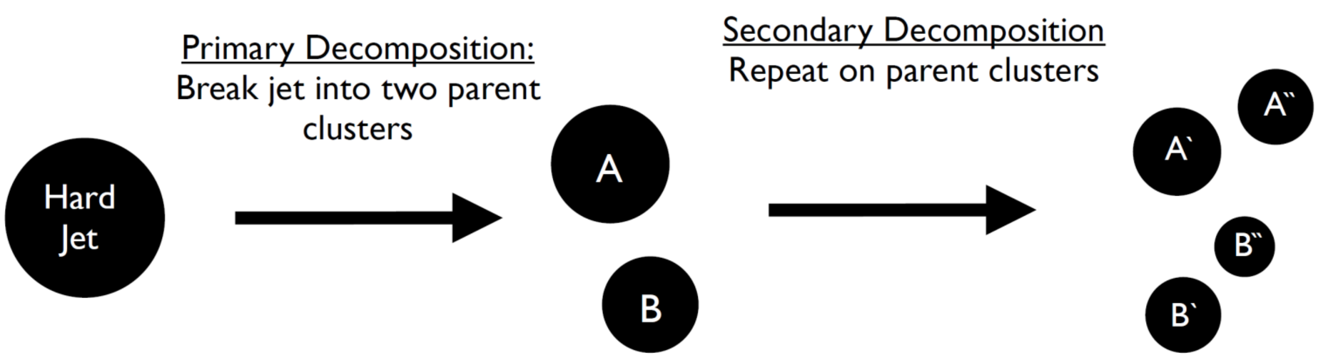


Leptonic top	E_T^{miss}: E_T = 159 GeV, ϕ = 0.4 muon: p_T = 114 GeV, η = 0.21, ϕ = 0.66 jet: index = 3, E_T = 90 GeV, η = -0.5, ϕ = 1.1, m_j = 11 GeV
Hadronic top (R =0.4 clustering)	jet 1, E_T = 205 GeV, η = -0.8, ϕ = -2.2 rad, m_j = 18.3 GeV + jet 2, E_T = 115 GeV, η = -0.2, ϕ = -2.8 rad, m_j = 10 GeV + jet 4, E_T = 49 GeV, η = -1.3, ϕ = -2.7 rad, m_j = 11 GeV
Hadronic top (R =1.0 clustering)	jet 1, E_T = 418 GeV, η = -0.8, ϕ = -2.4 rad, m_j = 225 GeV $\sqrt{d_{12}}$ = 105, $\sqrt{d_{23}}$ = 44

Top Tagging Details

- Based on Kaplan et al. (arXiv:0806.0848)
- Cluster particle flow candidates using Cambridge Aachen
- Reverse the clustering sequence in order to find substructure
- Subjets must satisfy two requirements
  - Momentum fraction criterion: pTsubjet > 0.05×pThard jet ← Removes soft clusters
  - Adjacency criterion: ΔR(A, B) > 0.4 - 0.0004×pT ← Removes wide angle clusters
- Iterative process - throw out objects that fail momentum fraction cut and try to decluster again



Require >= 3 subjets

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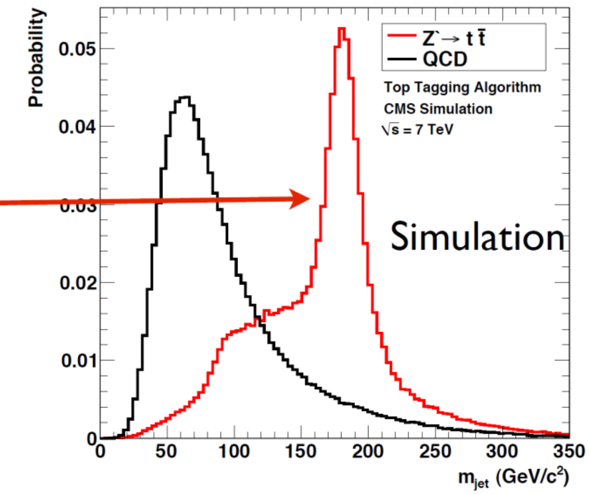
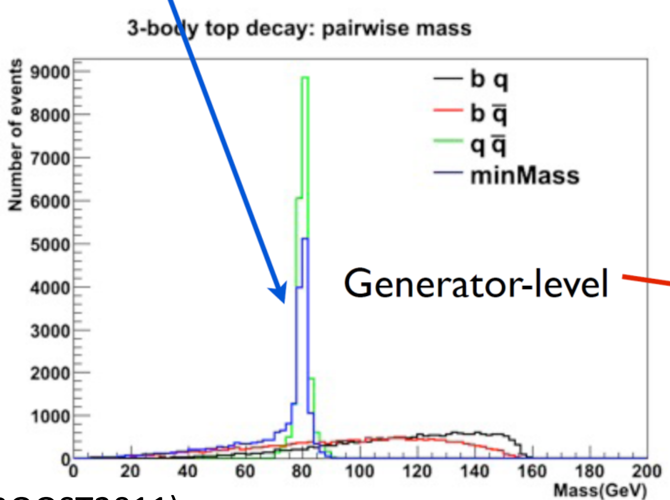
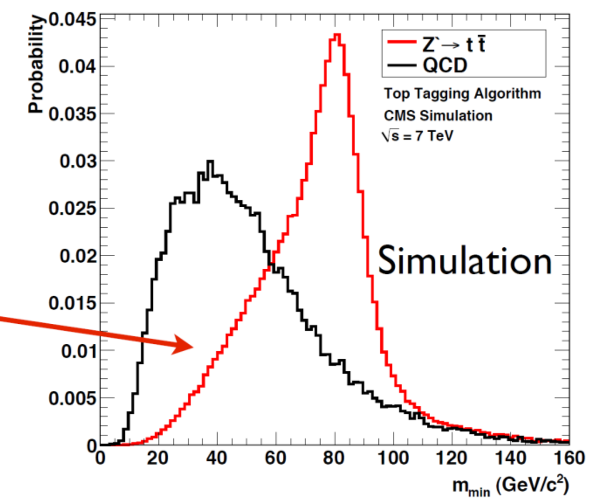
Top Tagging Details

- Discriminating variables:
  - Number of subjets: 3 or 4
  - Top Mass: Approximated by jet mass
    - Mass in 100-250 GeV/c^2
  - W Mass: Approximated by min pairwise mass
    - Min mass > 50 GeV/c^2

$$m_{\min} = \min[m_{12}, m_{13}, m_{23}]$$







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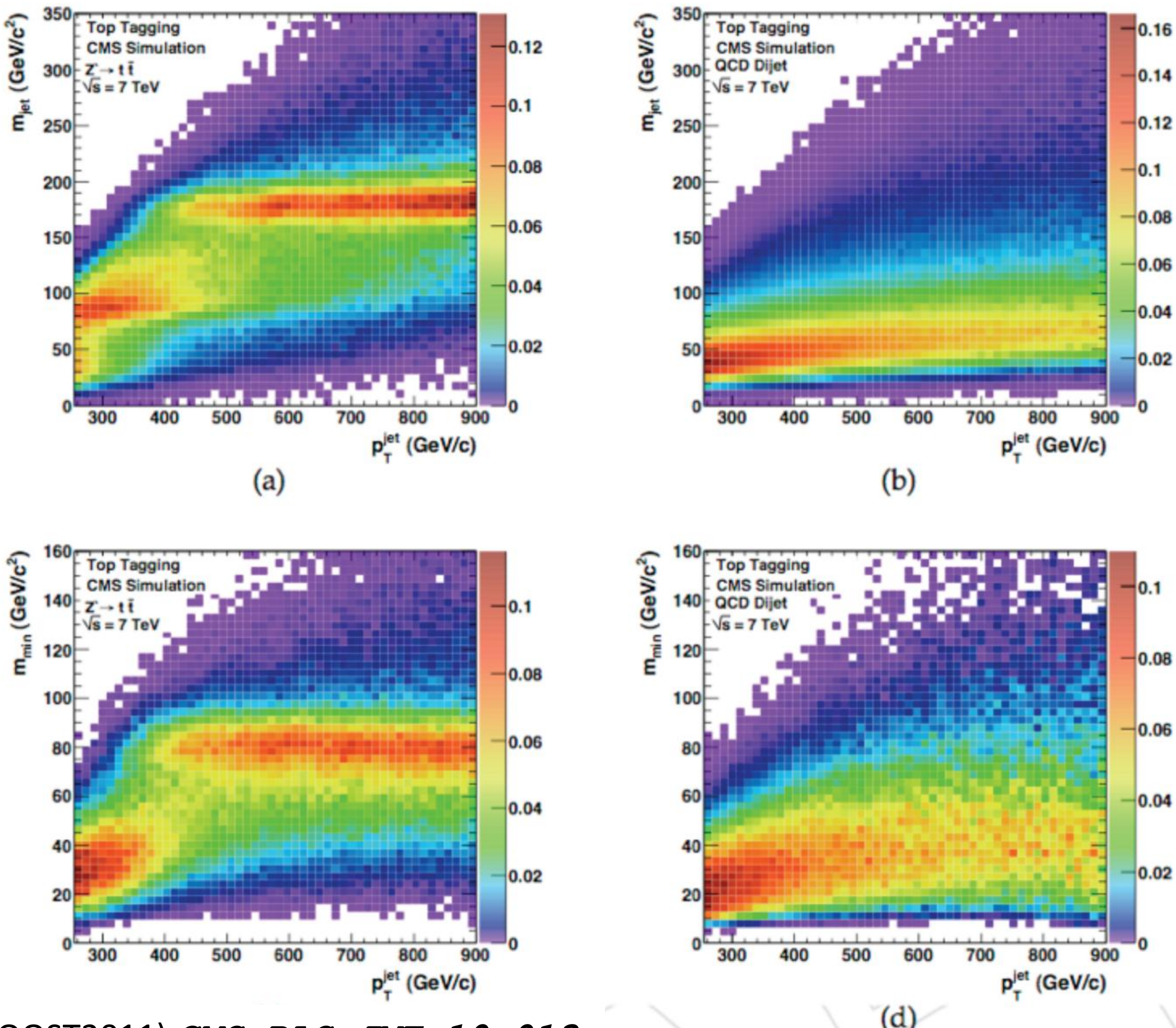
Top Tagging Details



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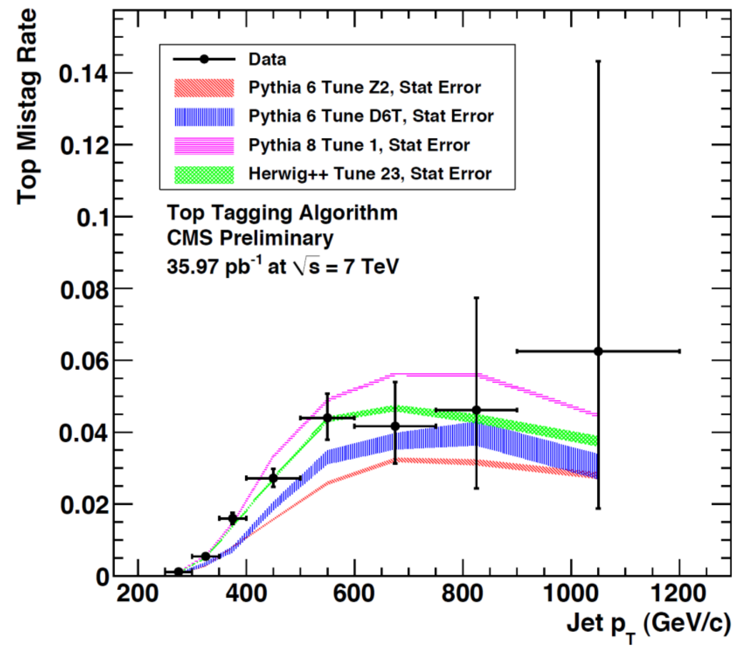
Top Tagging Mistag Rate

- Anti-tag and probe method
  - Randomly select one jet, check if its tagged
  - If the random jet is vetoed, the opposite jet is the probe jet

Anti-tagged jet
(mass<140 or mass >250 or minmass<50 or nsubjets <3)

Probe jet



$$\text{Mistag Rate} = \frac{\text{Number of probe jets that are tagged}}{\text{Number of probe jets}}$$

Dependence on shower model and tune, overall good agreement

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Conclusion/Discussion

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First look at jet substructure in LHC collision data

- Very promising indications of sufficient experimental performance to be useful
  - Limitations not yet quite understood – need massive and well known jet sources for performance evaluations
- It's all kind of new for experimentalists…
  - All standard substructure tools (filtering, trimming, pruning) are evaluated
  - Newer approaches are under study (decomposition w/o trees, N sub-jettiness…)

Future experimental focus

- Next on the list: boosted top
  - First events available – allows to understand resolution, scales, pile-up,…
- Sub-structure tools for in-jet pile-up suppression
  - Non-search paradigm – which tool(s) are useful to suppress jet structure introduced by pile-up? Trimming and simple filtering may be candidates…
  - Must be applicable to gluon/quark jets
  - Improve general jet mass reconstruction
- More tagging
  - Gluon/(light) quark jet tagging with sub-structure tools (e.g., N sub-jettiness)
- Combining detectors (outside of particle flow reconstruction a la CMS)
  - Use of track sub-jets to guide calorimeter sub-jet finding, reconstruction and calibration

Generic testbeds

- Quick evaluation of new strategies wrt typical experimental signal features and limitations
  - Particle level may not be sufficient for evaluation – lateral (and longitudinal) energy distributions important for suib-jets,…
- Hard to provide realistic fast simulation of generic ("typical") LHC detector
  - We are looking into it in the context of the BOOST workshops…

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Additional Slides

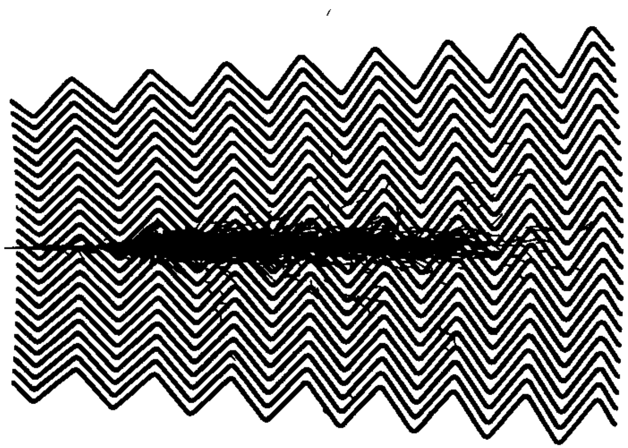
Electromagnetic Cascades in Calorimeters

Electromagnetic showers

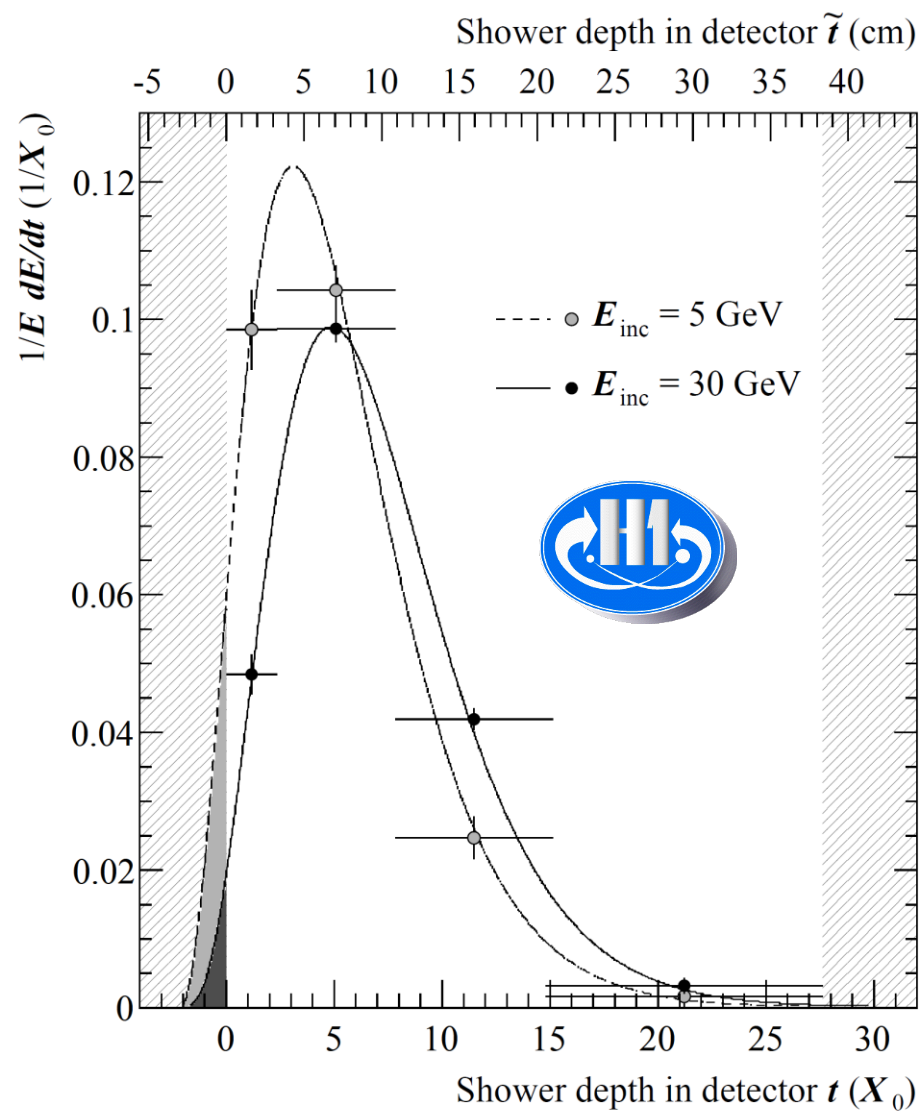
- Particle cascade generated by electrons/positrons and photons in matter
- Developed by bremsstrahlung & pair-production

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



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

Electromagnetic Cascades in Calorimeters

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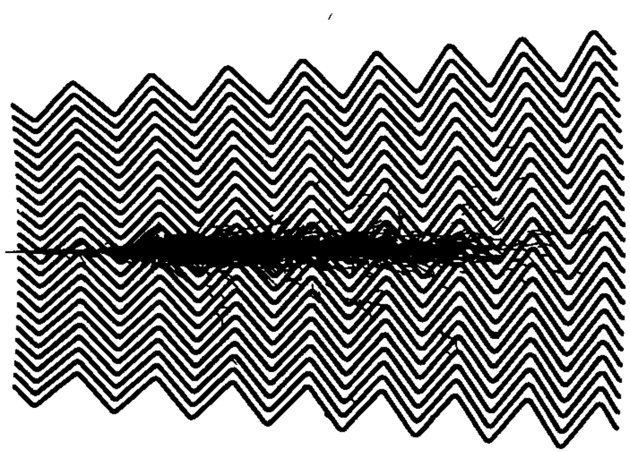

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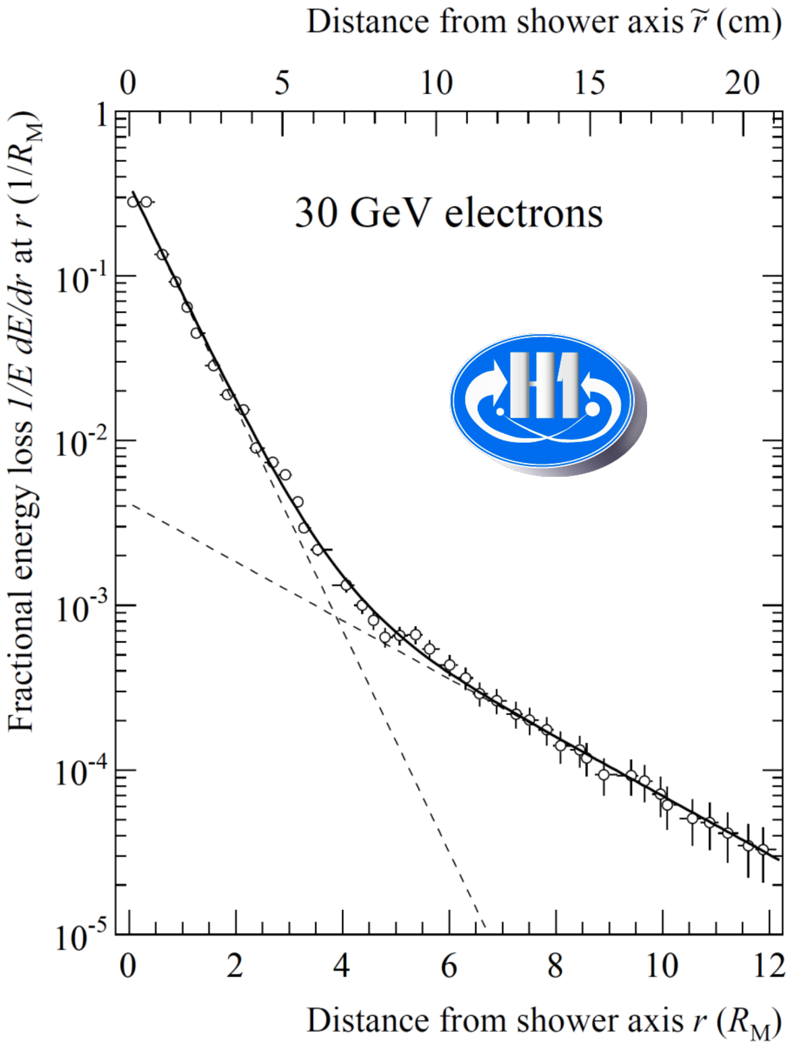

$$\frac{1}{E}\frac{dE}{dr} = a(E)\cdot e^{-\alpha(E)r} + b(E)\cdot e^{-\beta(E)r}$$

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

Hadronic Cascades in Calorimeters

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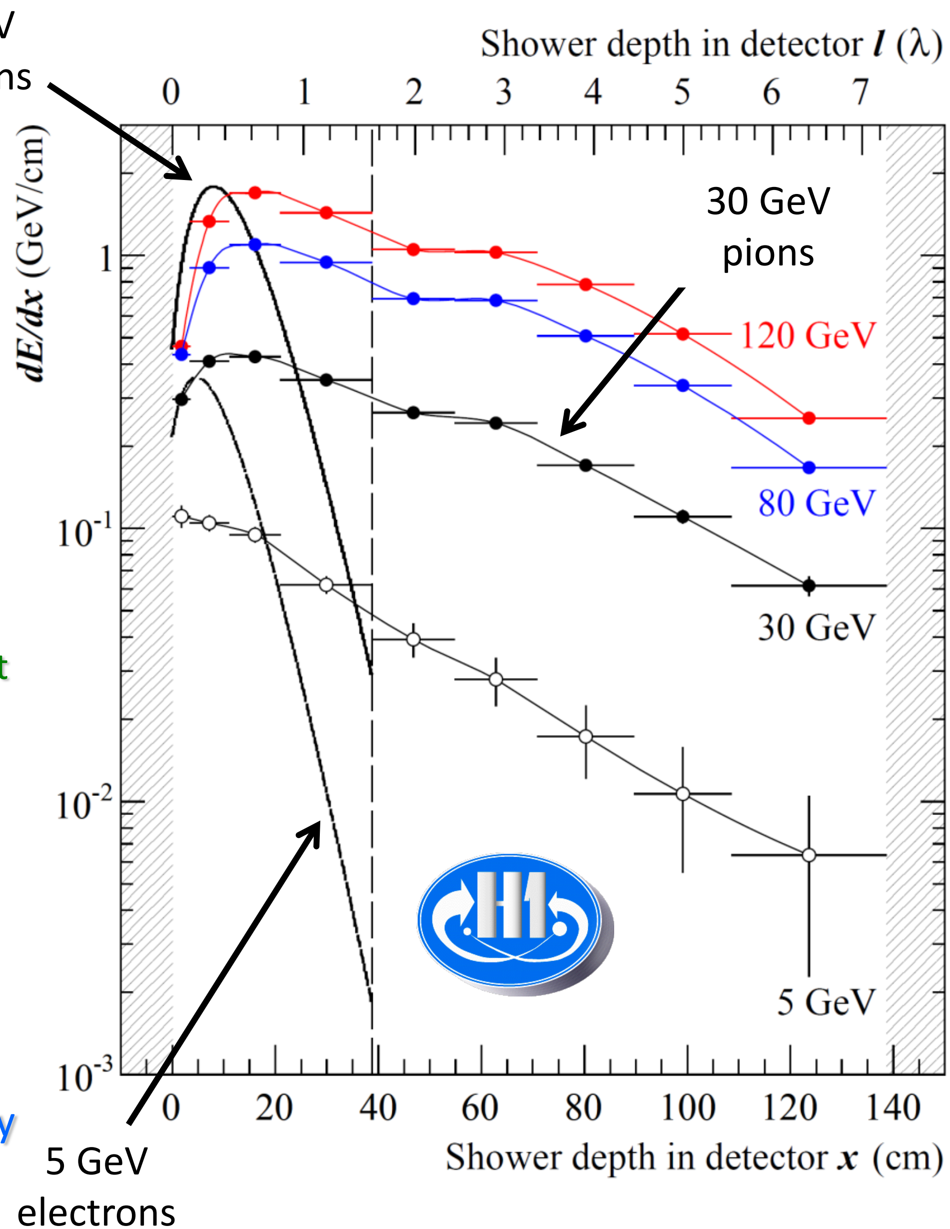
Hadronic signals

- 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



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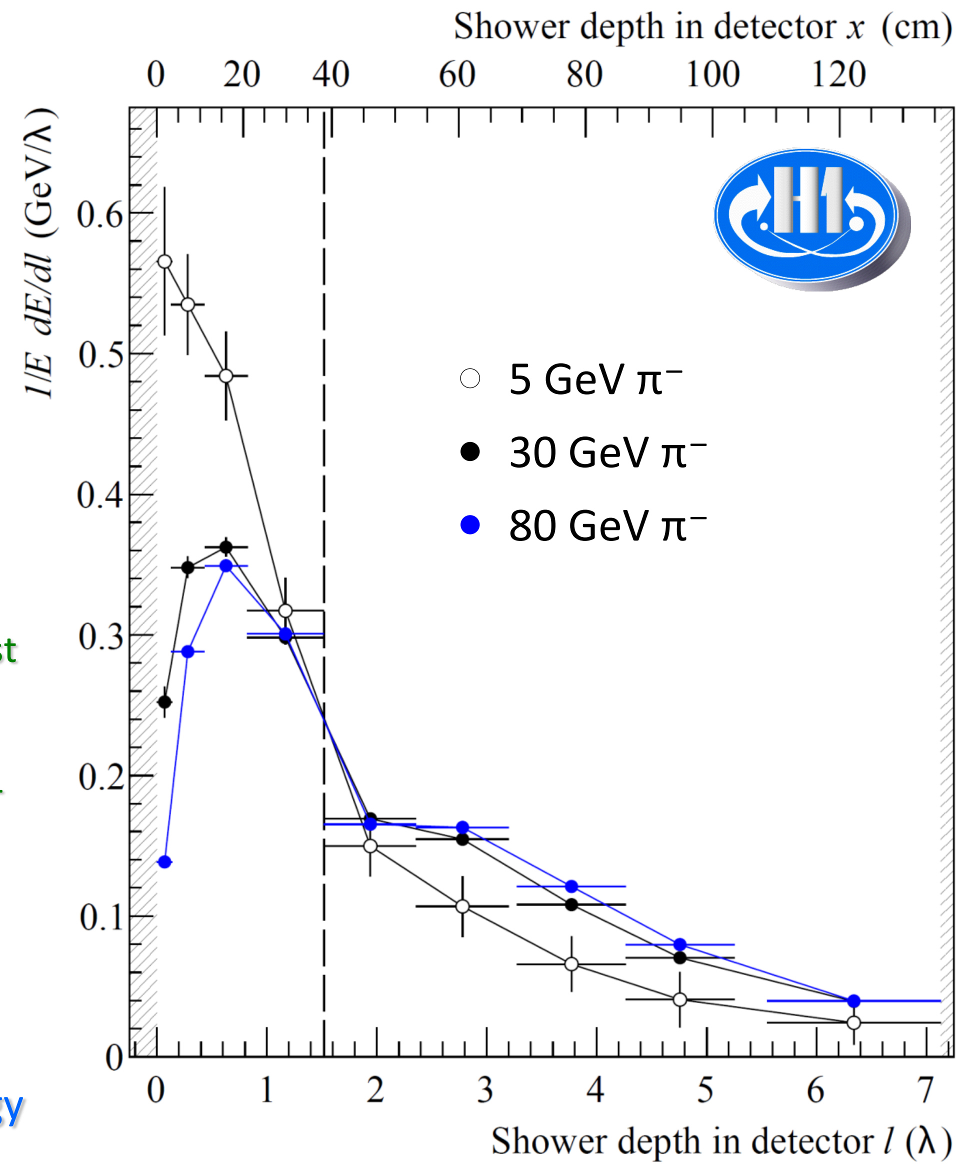

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