# Internal structure of high $p_T$ jets at ATLAS

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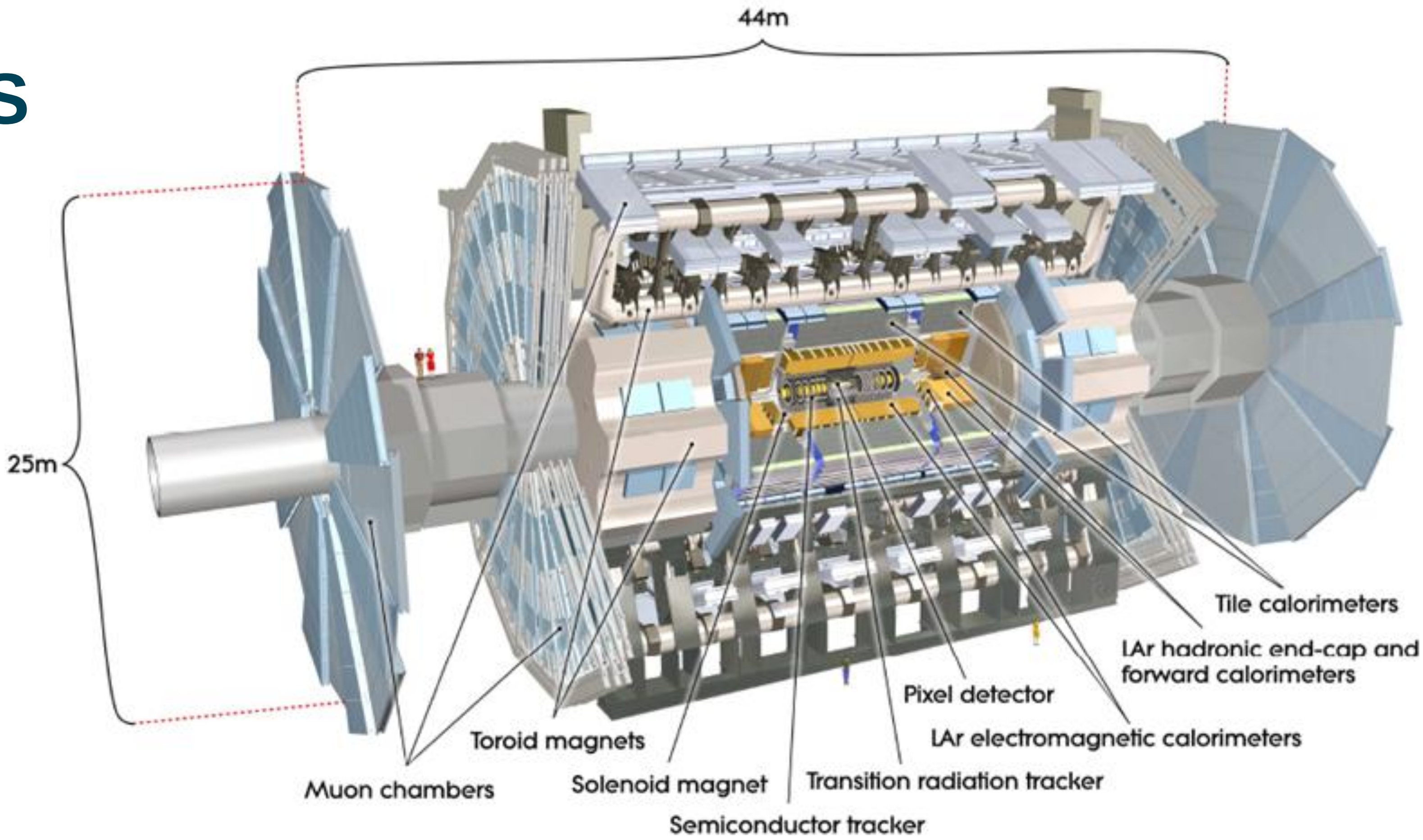
# ATLAS




- Recorded ~5 $fb^{-1}$ of 7 TeV *pp* collisions from the LHC
- Highly granular calorimetry (down to 0.025x0.025 in $\eta$-$\varphi$)

# Motivation

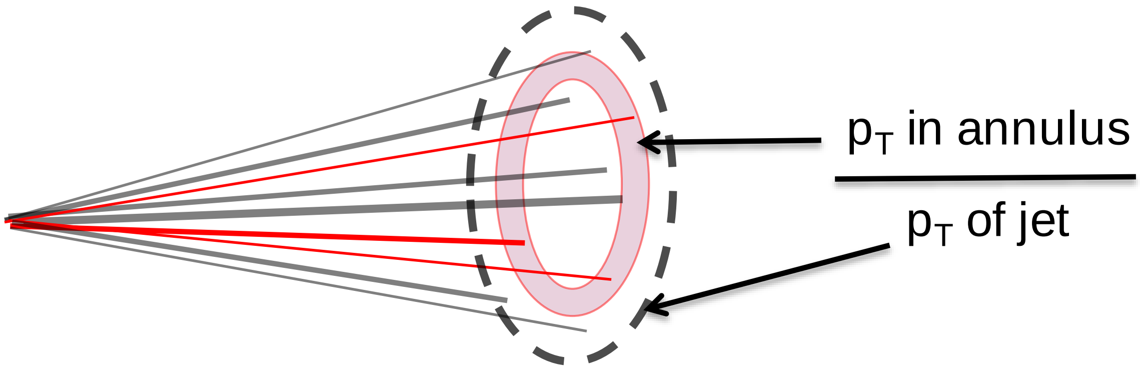
- At the LHC, high $p_T$ top quarks abundant
- High $p_T$ top quarks are exciting, probe high scale physics
- Boost means they are reconstructed as less than 3 jets
- Techniques involving looking inside jets can help
- However now looking at very different QCD backgrounds
- Modelling this is crucial for any search
- Also need to understand if substructure really works…

# Inside a Jet

- Jets can contain a lot of complex physics
  - Non-perturbative effects like fragmentation and hadronisation
  - Hard process, colour connections, UE, pile-up
  - Massive particle production (b, c, W, Z, top etc…)
- Need to get all of this right for boosted top searches
- Do measurements of jet properties in inclusive QCD

# Jet Shapes

- Jet shapes are the classic test of the internals of jets
- Measure the fraction of a jet's $p_T$ within an annulus



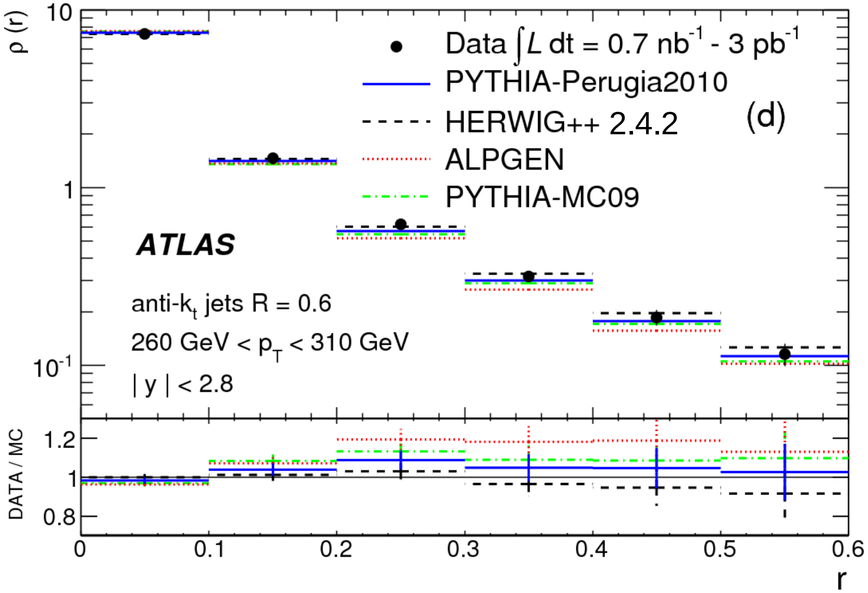

- Formally, measure the quantity:

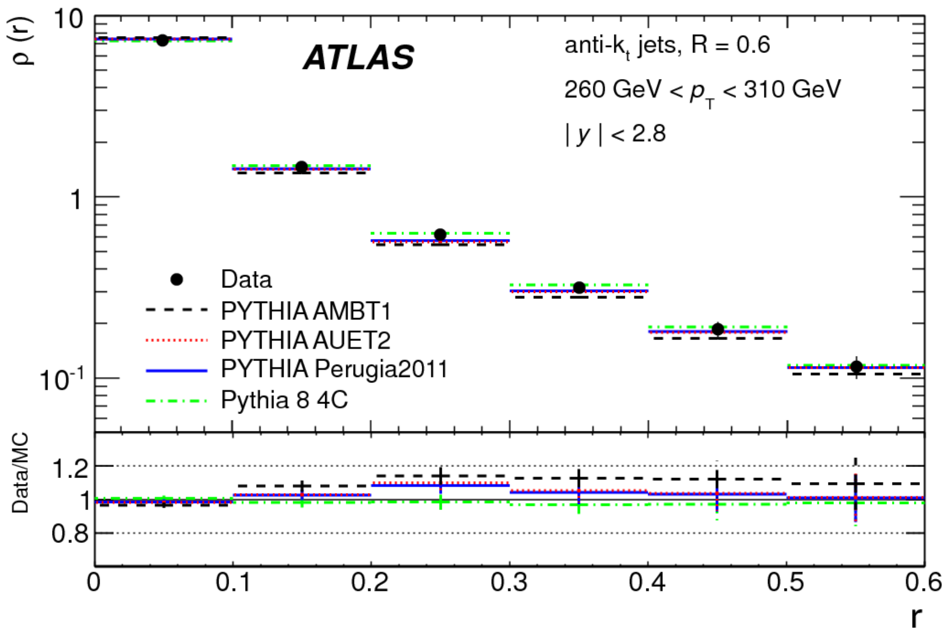
$$\rho(r) = \frac{1}{\Delta r} \frac{1}{N^{\mathrm{jet}}} \sum_{\mathrm{jets}} \frac{p_T(r - \Delta r/2, r + \Delta r/2)}{p_T(0, R)}$$

# Jet Shapes

- Results released 2010, now published:

  [Phys. Rev. D83 (2011) 052003]



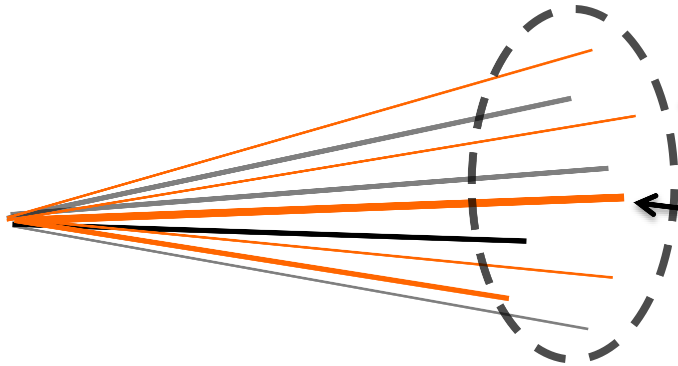




- More recently, newer tunes tested

  [ATL-PHYS-PUB-2011-010]

# Fragmentation

- Can also study the distribution of charged particles




- Distribution of energy parallel or transverse to jet axis:

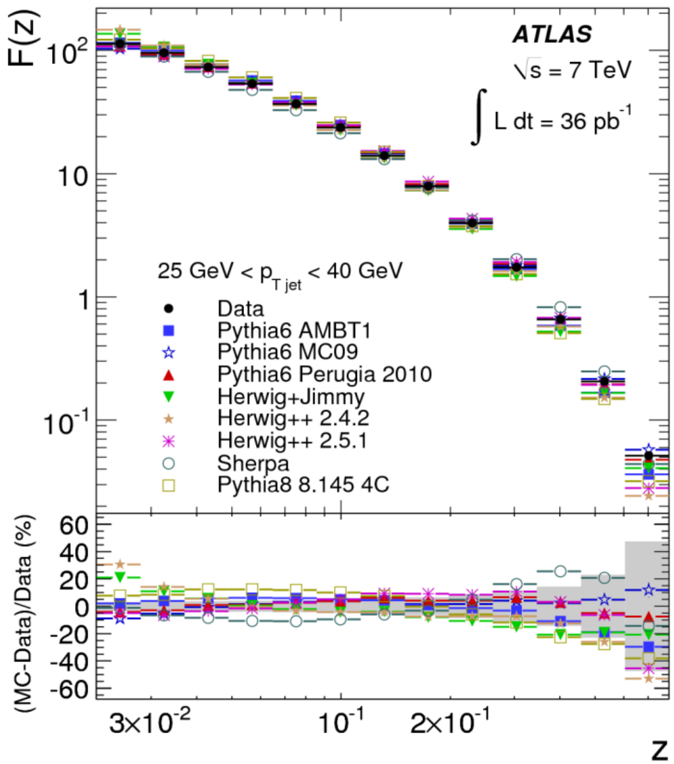
$$z = \frac{\boldsymbol{p}_{\text{jet}} \cdot \boldsymbol{p}_{\text{ch}}}{|\boldsymbol{p}_{\text{jet}}|^2} \qquad p_{\text{T}}^{\text{rel}} = \frac{|\boldsymbol{p}_{\text{ch}} \times \boldsymbol{p}_{\text{jet}}|}{|\boldsymbol{p}_{\text{jet}}|}$$

Eur. Phys. J. C 71 (2011) 1795

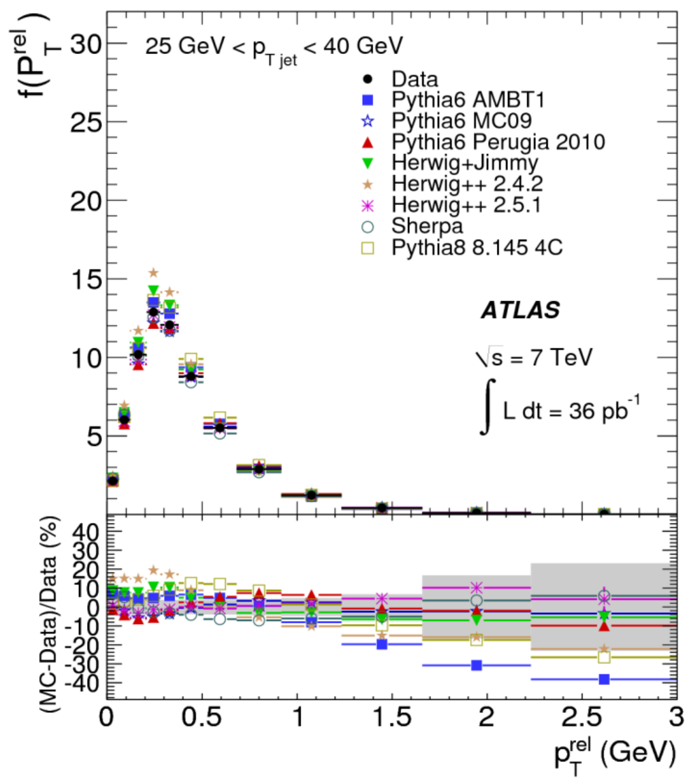
# Fragmentation

- Charged particles seem reasonably well modelled

$$F(z, p_{\mathrm{T\,jet}}) \equiv \frac{1}{N_{\mathrm{jet}}} \frac{dN_{\mathrm{ch}}}{dz},$$

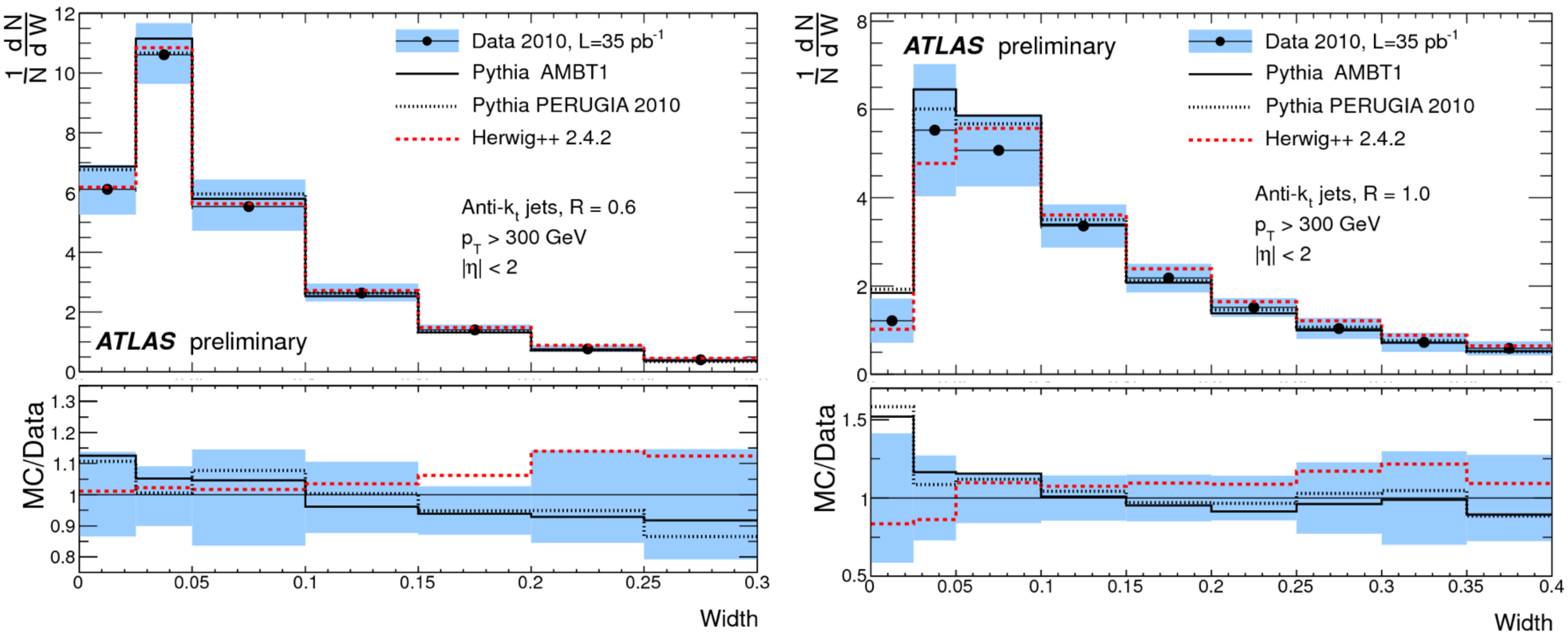



$$f(p_{\mathrm{T}}^{\mathrm{rel}}, p_{\mathrm{T\,jet}}) \equiv \frac{1}{N_{\mathrm{jet}}} \frac{dN_{\mathrm{ch}}}{dp_{\mathrm{T}}^{\mathrm{rel}}}$$



# Shape-like Variables

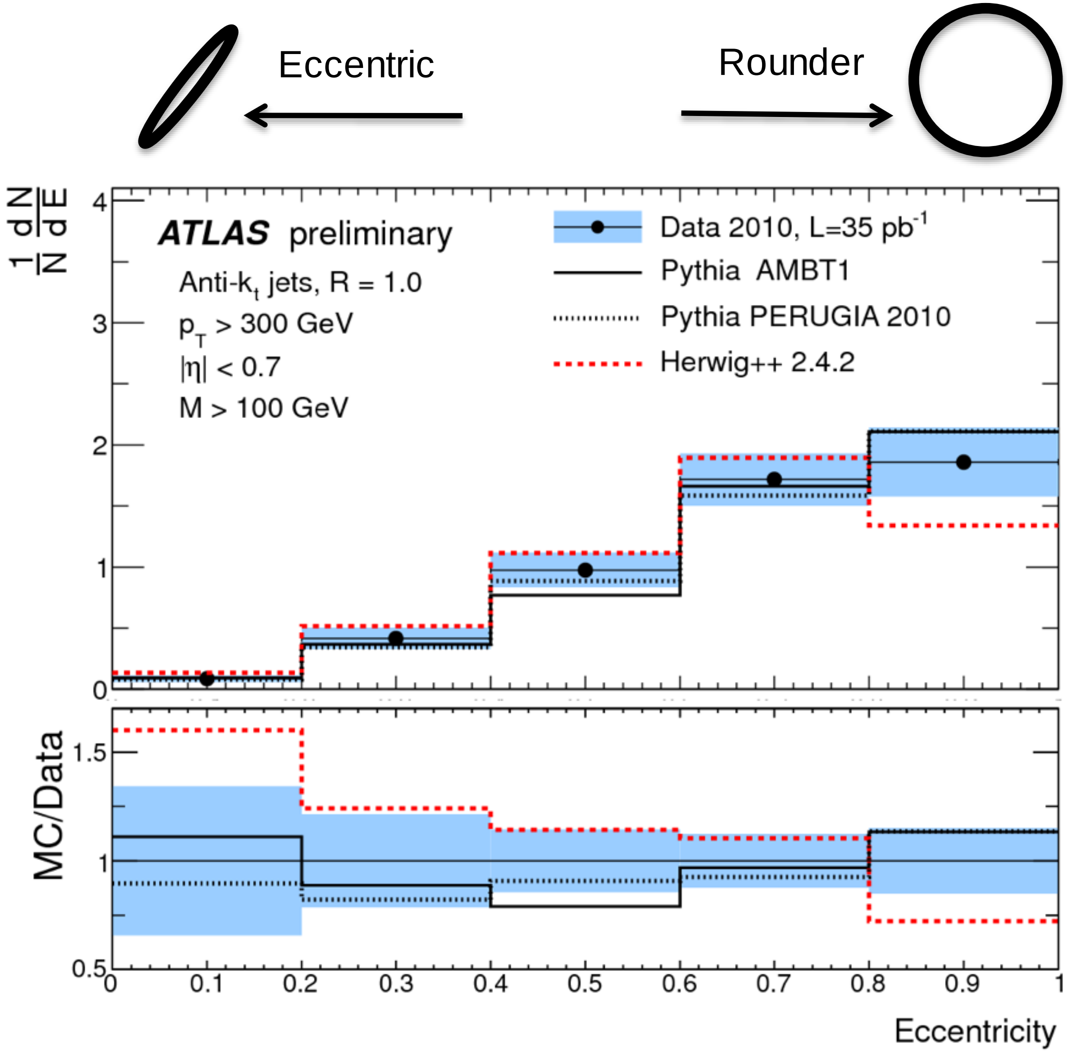
- Many other variables can be defined similarly
- Jet width: $p_T$ weighted average distance to jet axis




ATLAS-CONF-2012-044

# Shape-like Variables

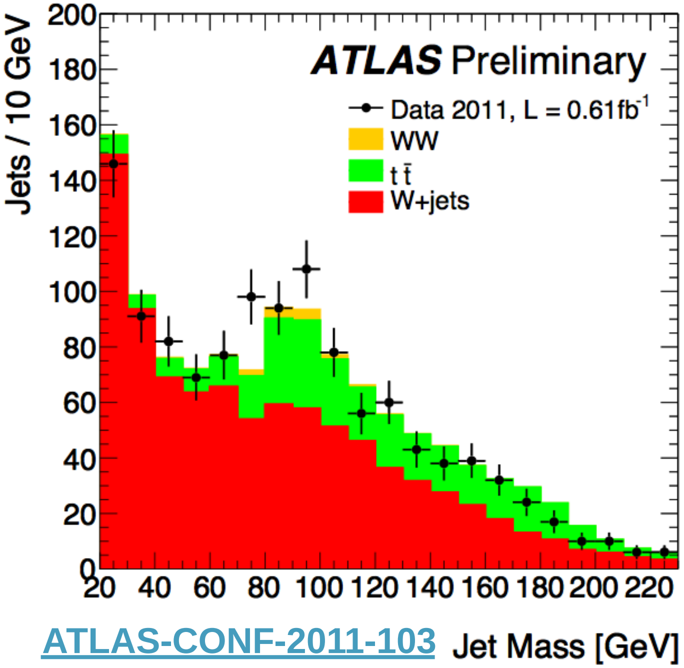
- Jet eccentricity, is a jet circular or oval?
- Again lots of variation between generators




ATLAS-CONF-2012-044

# Jet Mass

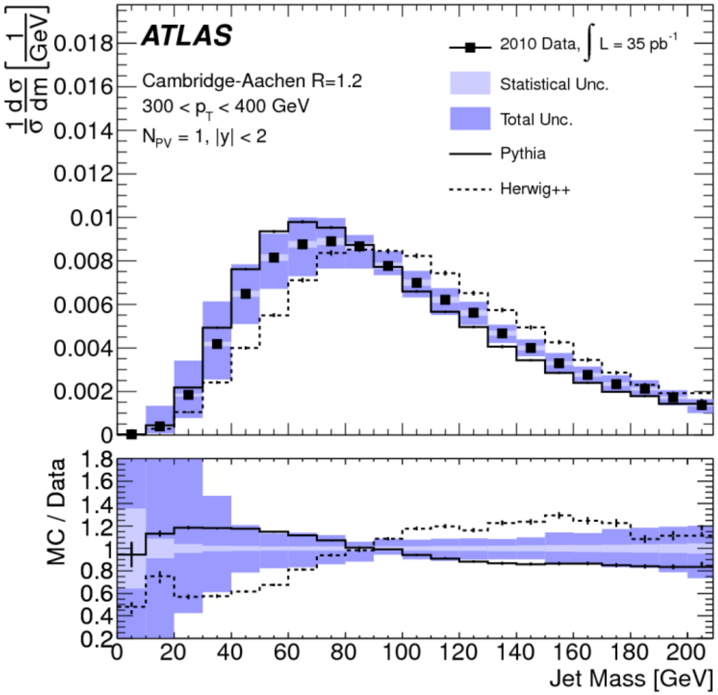
- Jets are 4-vectors, for example $(E/p_T, \eta, \varphi, m)$
- Of these, mass is probably the least studied
- At the LHC, lots of interest in jet mass
  - Especially large radius jets
  - Jets can contain boosted W, Z, H…
  - and of course top quarks
- Measurements targeted at this




ATLAS-CONF-2011-103

# Jet Mass

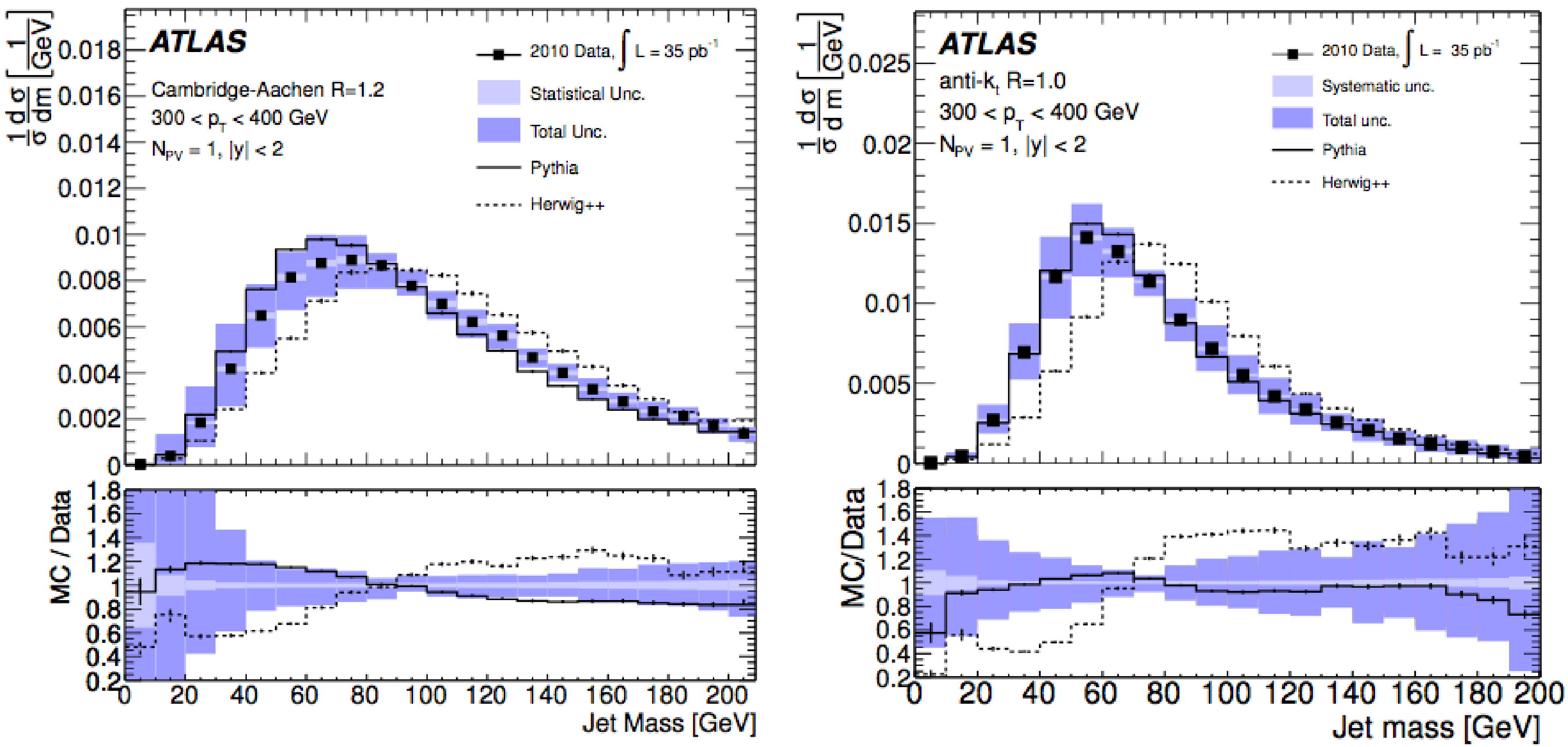
- Looking at Cambridge-Aachen R=1.2 and anti-$k_t$ R=1.0
- Jet mass measured for jet $p_T$ of 200 – 600 GeV
- Systematics determined in-situ using inner-detector track jets
- Herwig++ didn't describe this terribly well in version 2.4.2




http://arxiv.org/abs/1203.4606

# Jet Mass

- Can compare the two algorithms

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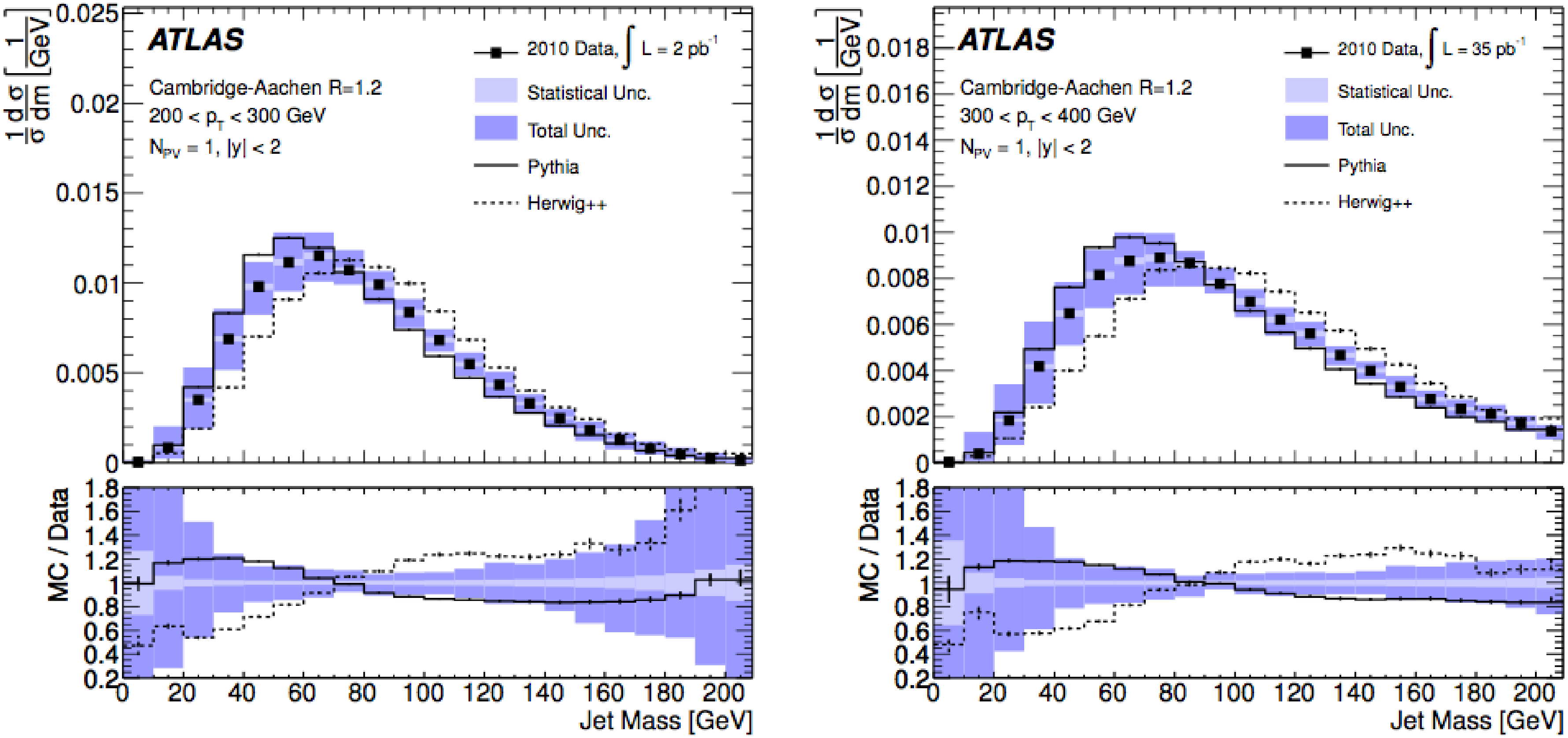
# Jet Mass

- Can also see $p_T$ scaling

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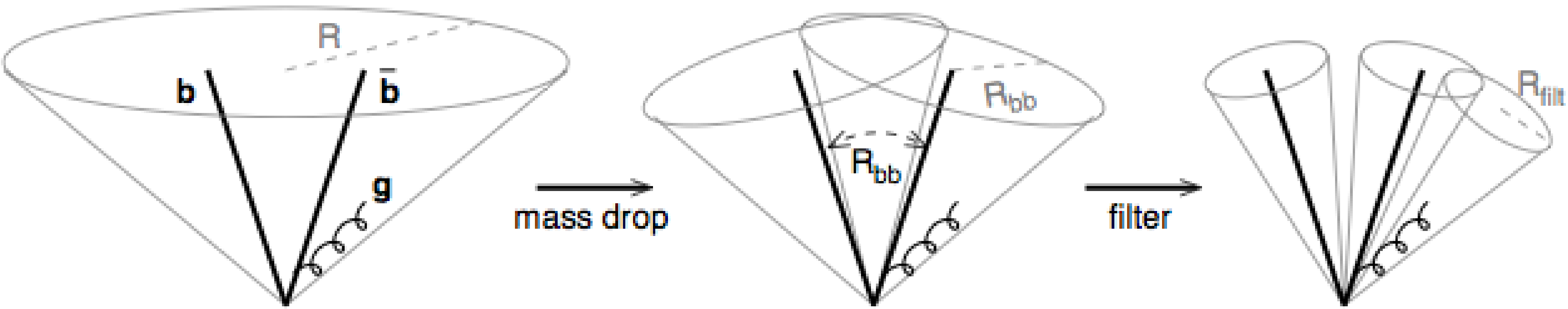
# Jet Mass and Substructure

- Also look at application of a substructure procedure

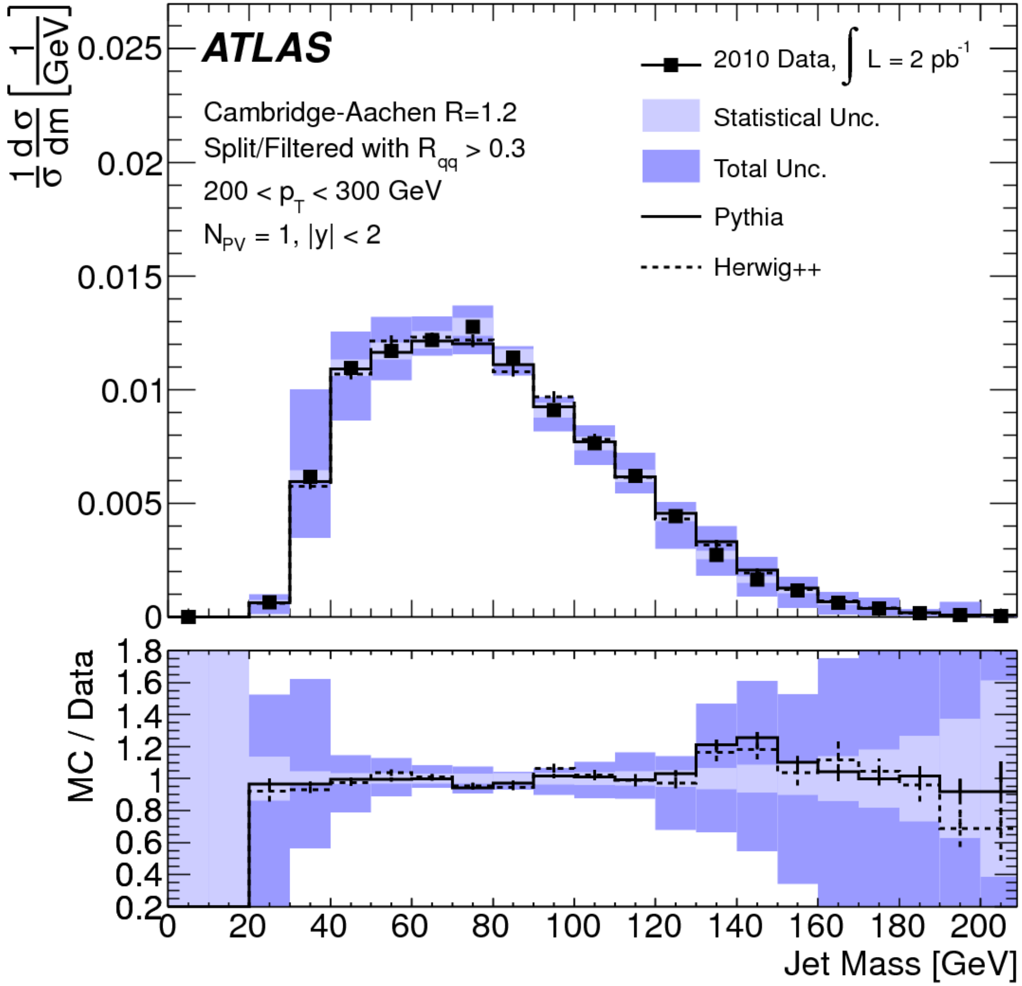



- Search clustering history for mass drop, recluster
- Targeted at two-body decays (Higgs specifically)
- Similar to Johns Hopkins top tagger and HEPTopTagger

Phys. Rev. Lett. 100, 242001 (2008) J. Butterworth, AD, G. Salam, M. Rubin

# Jet Mass and Substructure

- Similarly measure jet mass after this procedure
- Less sensitive to soft physics
- Observe better agreement than in plain jet mass

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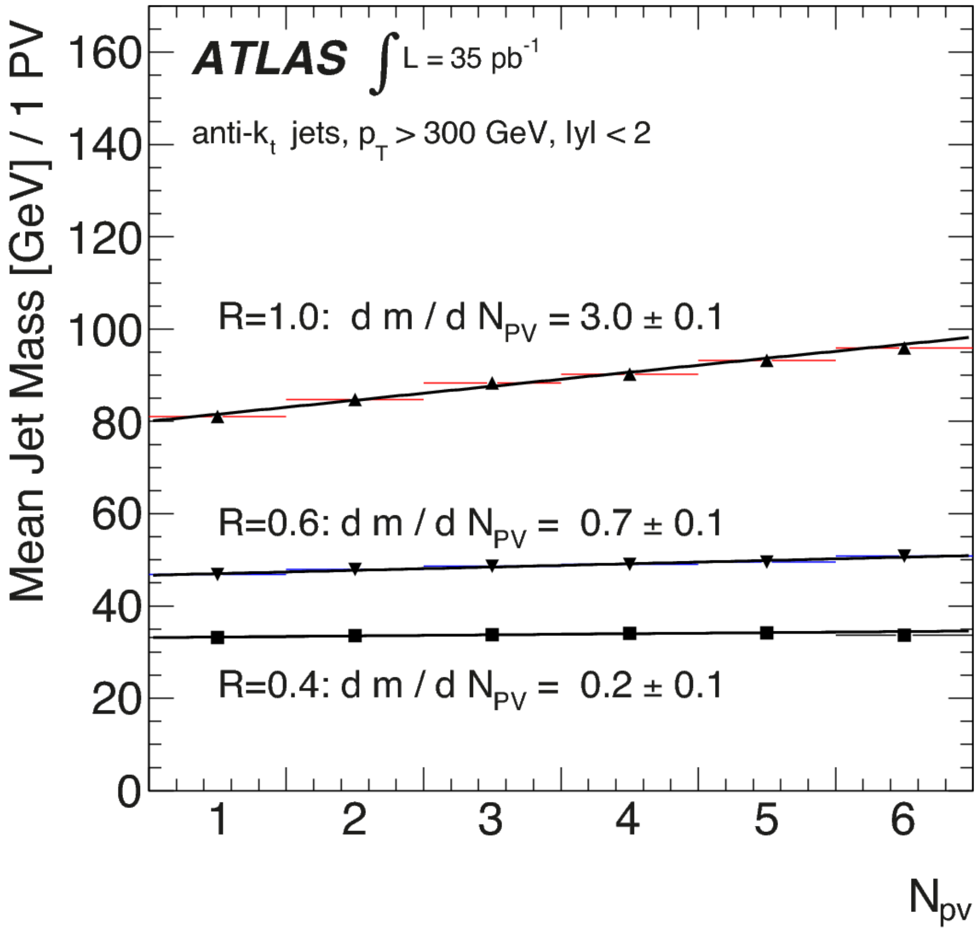
# Jet Mass and Pile-up

- Looking at mean mass vs. pile-up
- Scaling with R parameter is as expected

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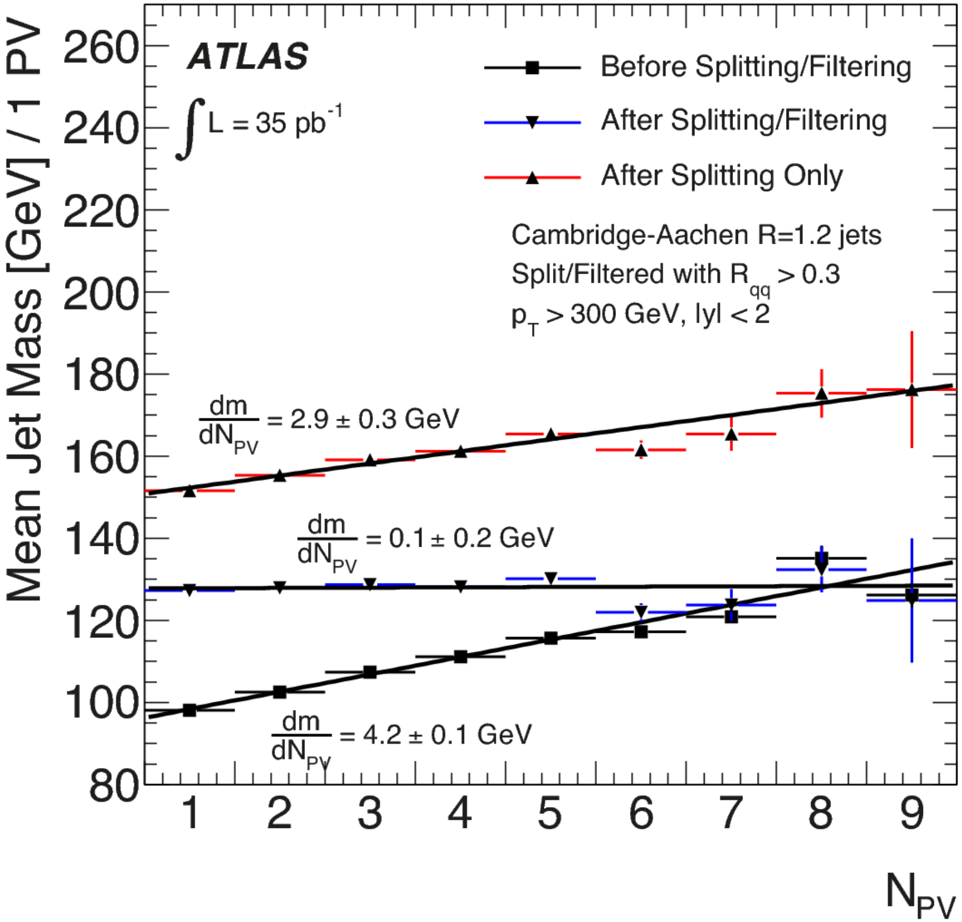
# Jet Mass and Pile-up

- Splitting/filtering reduces dependence significantly
- Consistent with previous results, reduced impact of soft physics

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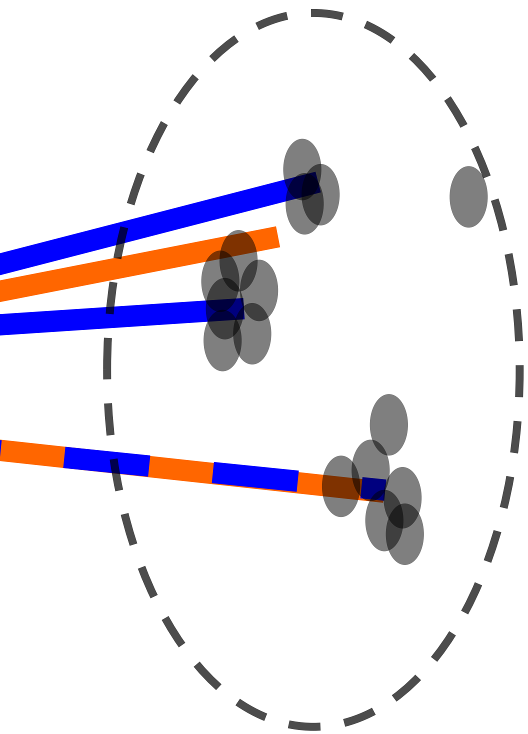
# N-Subjettiness

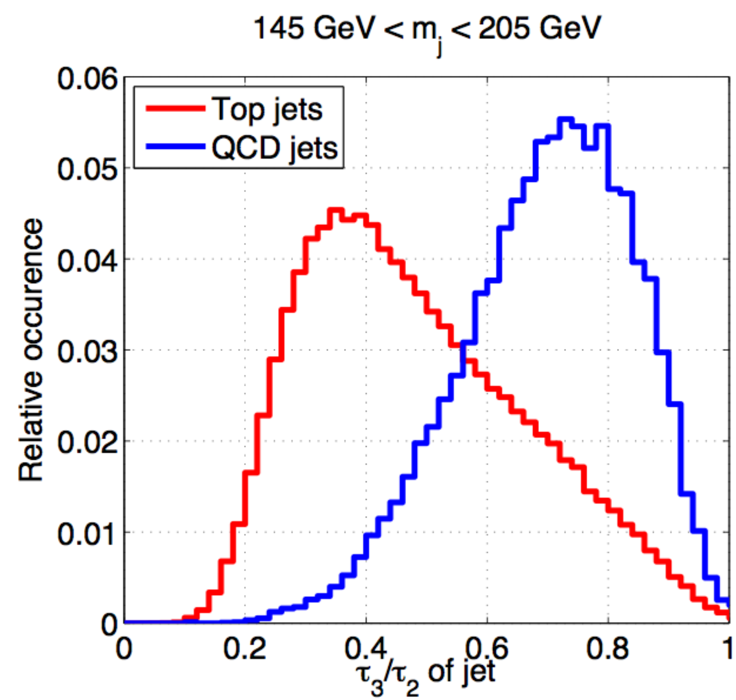
- New variables (arXiv:1011.2268 (2011) Thaler, Tilburg)



Sum distances from constituents to 2 or 3 $k_t$ subjet axes

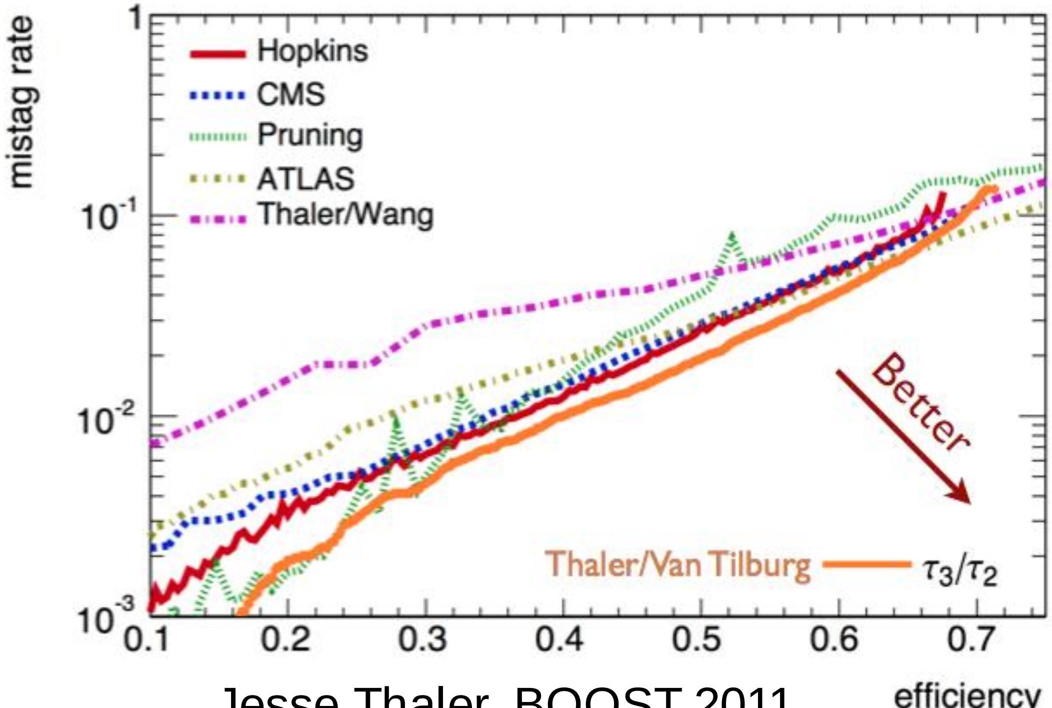
Take ratio of sums

More like 3 subjets than 2



# N-Subjettiness

- Seems to perform very well in hadron-level studies
- Also, all ratios, potential to be experimentally robust

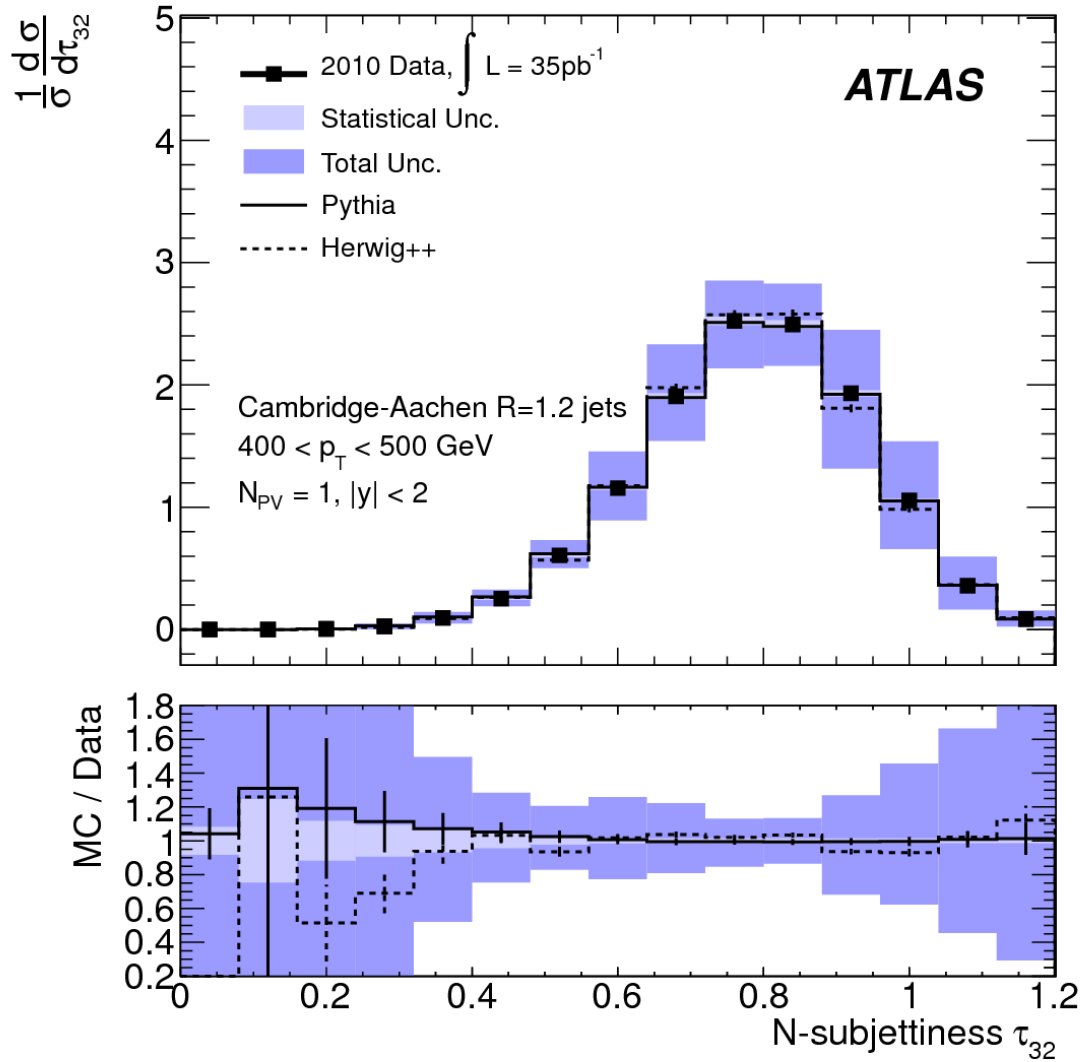



Jesse Thaler, BOOST 2011

# N-Subjettiness

- Measured, again in inclusive QCD
- Appears to be quite well modelled

More like 3 subjets than 2 ←

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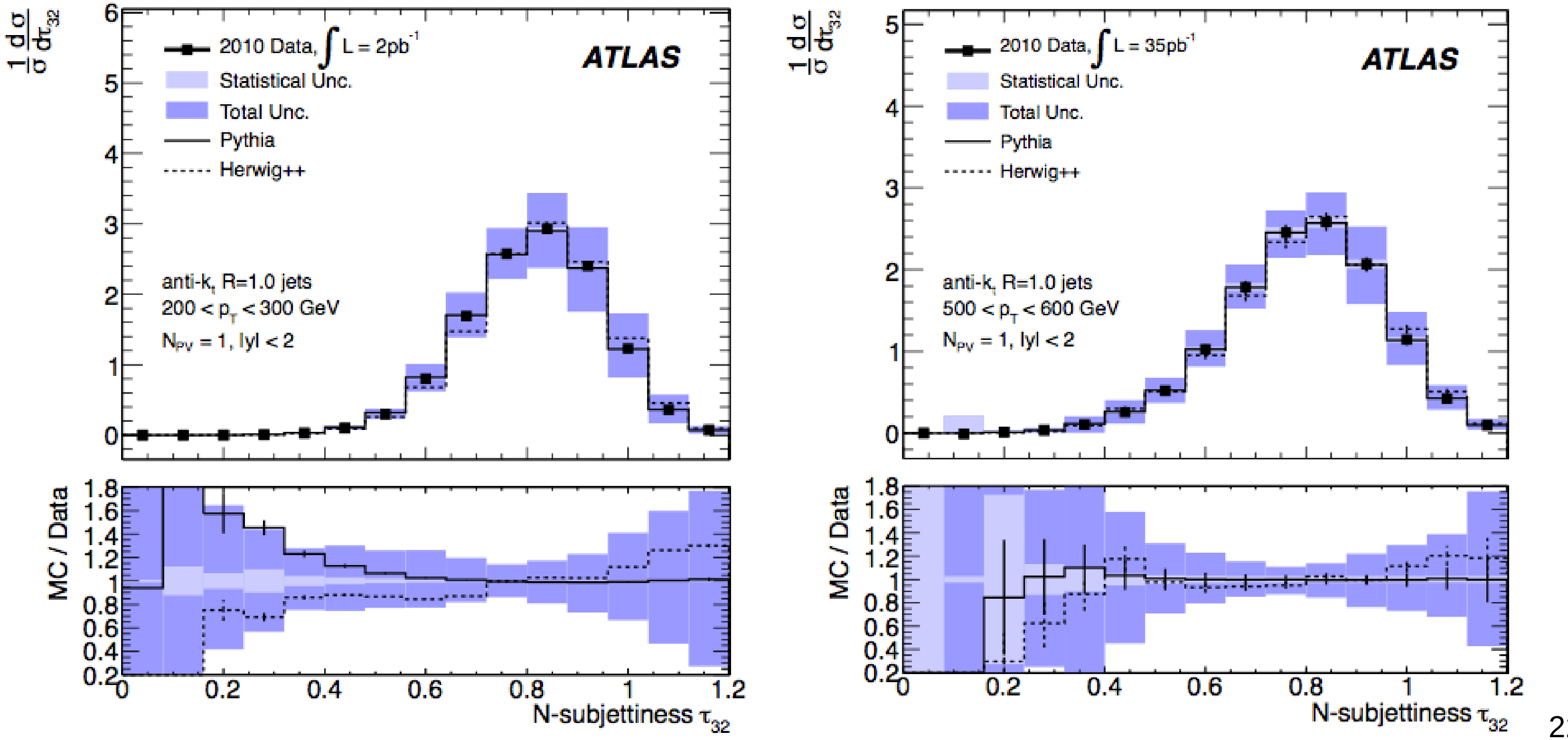
# N-Subjettiness

- Measured for anti-$k_t$ and C-A jets, in $p_T$ bins
- Can again see evolution



# Conclusions

- ATLAS has made many measurements of internals of jets
  - Jet shapes (Phys. Rev. D83 (2011) 052003)
  - Jet fragmentation (Eur. Phys. J. C 71 (2011) 1795)
  - Jet mass and substructure variables (arxiv:1203.4606)
  - Shape-like variables (Preliminary: ATLAS-CONF-2012-044)
- All good tests of QCD in the regime of boosted tops
- But lots of variation between MC models and tunes
- Need to turn this into robust QCD background estimates