ATLAS Jets measurements summary

Arantxa Ruiz Martínez (Iowa State University)

on behalf of the ATLAS Collaboration

Working Group on Electroweak precision measurements at the LHC, and PDF4LHC

- Jet and photon production -

October 8, 2012

Outline

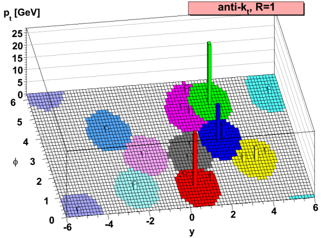
- Jet reconstruction
- Jet calibration
- Jet energy scale uncertainties
- Jet measurements
- Conclusions

Jet reconstruction

- Define distances between entities d_{ij} and an entity and the beam d_{iB}:

$$d_{ij} = min(k_{ti}^{2p}, k_{tj}^{2p}) \frac{\Delta y^2 + \Delta \phi^2}{R^2}; \quad d_{iB} = k_{ti}^{2p}; \quad p = \begin{cases} 1 & k_t \\ 0 & \text{Cambridge/Aachen} \\ -1 & \text{anti-}k_t \end{cases}$$

- Compute all $\{d_{ij}, d_{iB}\}$ using proto-jets and clusters and $d = min(d_{ij}, d_{iB})$
  - if $d = d_{ij}$, combine jet i and jet j
  - if $d = d_{iB}$, define jet as a final jet
- Continue until all jets are final



M. Cacciari, G. P. Salam and G. Soyez, JHEP 04 (2008) 063

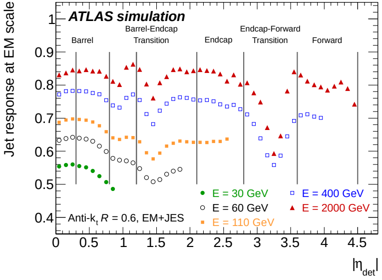
Anti-k_t jet algorithm used as the default one in ATLAS:

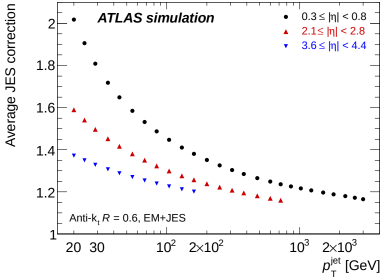
- Collinear and infrared safe
- Stable, cone-like jets
- Default distance parameters: 0.4, 0.6

Jet calibration

arXiv:1112.6426

- Baseline calorimeter energy scale: electromagnetic scale (extracted from $Z \to ee$, test beams, MIP μ)
- Jet calibration needs to correct for detector effects such as:
  calorimeter non-compensation, dead material, leakage, out of calorimeter jet cone, noise thresholds and particle reconstruction efficiency
- Default EM+JES calibration: (η, E)-dependent calibration constants from MC
- Other calibration schemes being developed: Global Sequential Calibration (GS), Global Calorimeter Cell Weighting (GCW) and Local Cluster Weighting (LCW)



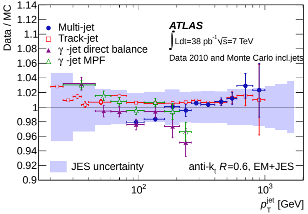


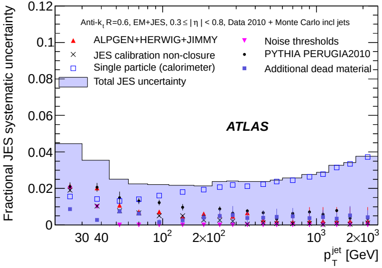
Jet energy scale uncertainties

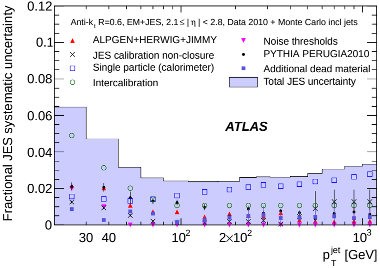
arXiv:1112.6426

JES uncertainty is determined from:

- Calorimeter response to single particles (in-situ/test beam)
- MC samples with systematic variations
- p_T balance in dijet events
- In-situ measurements







With 2010 data, an uncertainty of $\sim$2% for jet $p_T = 100$ GeV is achieved

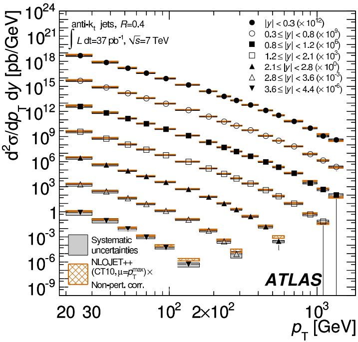
Jet measurements

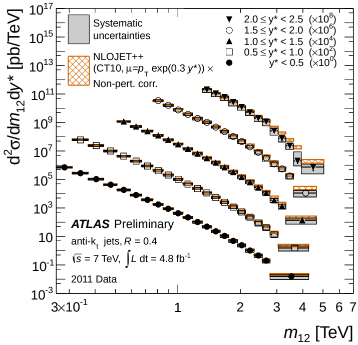
Glimpse of public jet measurements since the starting of the data taking:

- Inclusive jet and dijet cross sections with 17 nb^{-1} (Eur. Phys. J. C 71 (2011) 1512)
- Inclusive jet and dijet cross sections with 2010 data (Phys. Rev. D 86 (2012) 014022)
- **Dijet cross sections with 2011 data** (ATLAS-CONF-2012-021)
- **Jet cross section at 2.76 TeV and ratio** (ATLAS-CONF-2012-128)
- Multijet cross sections (Eur. Phys. J. C 71 (2011) 1763)
- Dijet azimuthal decorrelations (Phys. Rev. Lett. 106 (2011) 172002)
- Dijet production with a veto (JHEP 1109 (2011) 053)
- b-jet and $b\bar{b}$-dijet cross sections (Eur. Phys. J. C 71 (2011) 1846)
- $D^{*\pm}$ meson production in jets (Phys. Rev. D 85 (2012) 052005)
- **Flavor composition in dijet events** (arXiv:1210.0441)
- Jet shapes (Phys. Rev. D 83 (2011) 052003)
- Properties of jets measured from tracks (Phys. Rev. D 84 (2011) 054001)
- Jet fragmentation function and transverse profile (Eur. Phys. J. C 71 (2011) 1795)
- Jet mass and substructure (JHEP 1205 (2012) 128)
- **Properties of jets for boosted particle searches** (arXiv:1206.5369)
- **Event shapes at large momentum transfer** (arXiv:1206.2135)

Inclusive jet and dijet cross sections

- Early inclusive jet and dijet cross sections (Eur. Phys. J. C 71 (2011) 1512)
- Inclusive jet and dijet cross sections with full 2010 dataset (Phys. Rev. D 86 (2012) 014022)
- High mass dijet cross section with full 2011 dataset (ATLAS-CONF-2012-021)





Good agreement between data and theory over many orders of magnitude, although theory predictions tend to be larger at high jet p_T and dijet mass

Inclusive jet and dijet cross sections

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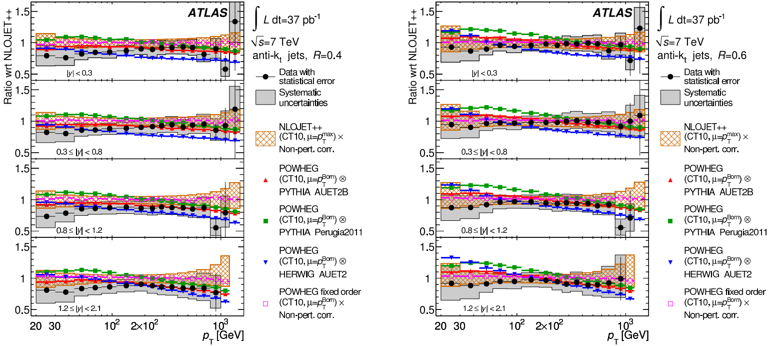
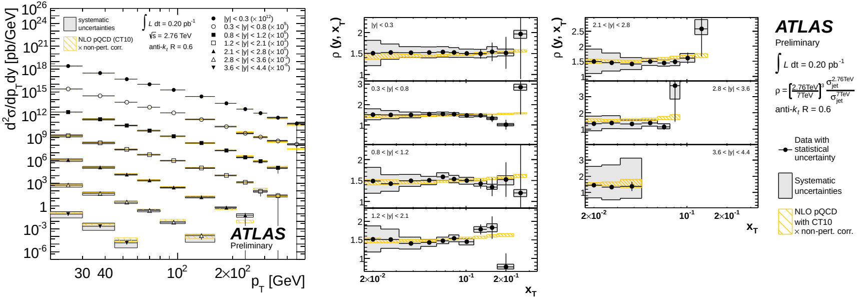


The marginally smaller cross section in data is more pronounced for the measurements corresponding to the anti-k_t algorithm with parameter $R = 0.4$, compared to $R = 0.6$

Jet cross section at 2.76 TeV and ratio ATLAS-CONF-2012-128

New Measurement

- 2.76 TeV run with a total integrated luminosity of 0.20 pb^{-1} collected in 2011
- Ratio measured as a function of $x_T = 2p_T/\sqrt{s}$ $\rightarrow$ Important cancellation of theoretical uncertainties $\rightarrow$ Precise test of NLO pQCD calculations
- Good agreement with NLO pQCD calculations
- Evaluated the impact on PDF fits with HERAFitter together with the HERA-I data $\rightarrow$ See Mark Sutton's talk this morning

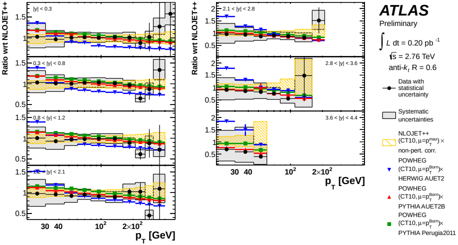


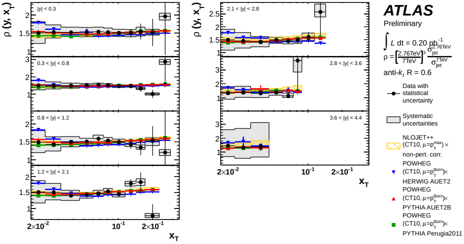
Waiting for final luminosity uncertainty, using preliminary uncertainty of 2.8%

Jet cross section at 2.76 TeV and ratio ATLAS-CONF-2012-128

New Measurement

- Only the statistical uncertainty on the POWHEG predictions are shown
- The uncertainty from the luminosity measurement is not shown



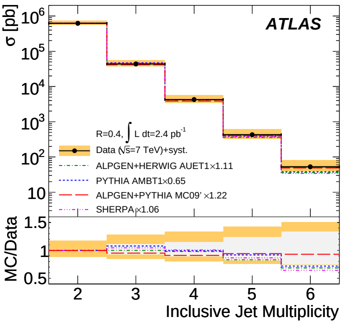


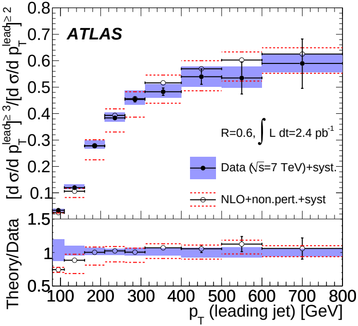
Waiting for final luminosity uncertainty, using preliminary uncertainty of 2.8%

Multijet cross sections

EPJC 71 (2011) 1763

- Measured as a function of the jet multiplicity, jet p_T, H_T (scalar sum of the p_T of the jets) and $H_T^{(2)}$ (scalar sum of the p_T of the two leading jets)
- Using 2.4 pb^{-1} of 2010 data





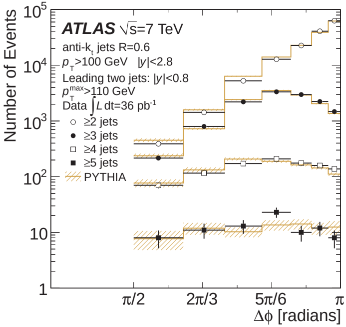
Comparison to several MC generators and NLO pQCD predictions obtained with NLOJET++:

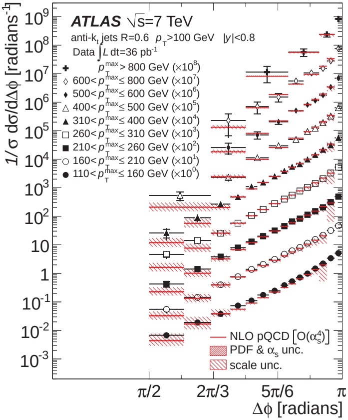
- The three-to-two-jet cross section shows some discrepancy at low jet p_T

Dijet azimuthal decorrelations

PRL 106 (2011) 172002

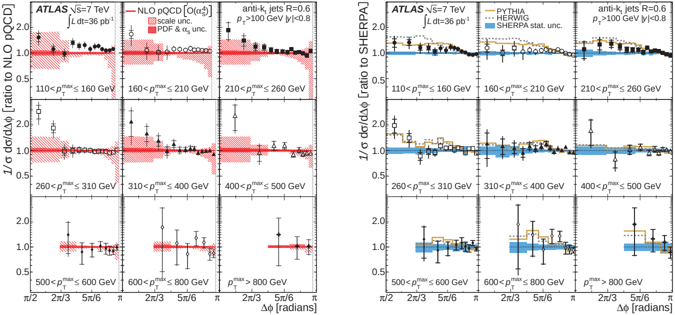
- QCD predicts the decorrelation in the azimuthal angle between the two most energetic jets, $\Delta\phi$, as a function of the number of partons produced
- QCD also describes the evolution of the shape of the $\Delta\phi$ distribution, which narrows with increasing leading jet p_T
- Using full 2010 dataset





Dijet azimuthal decorrelations

PRL 106 (2011) 172002

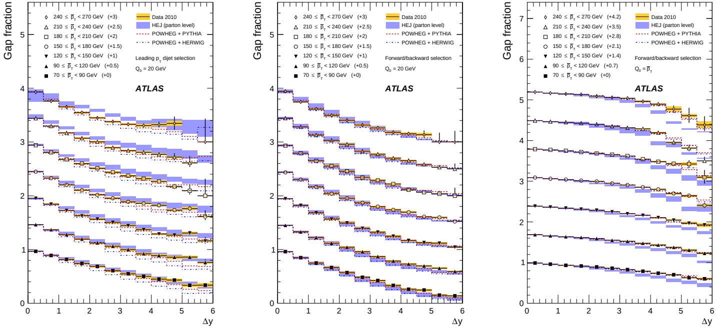


- Normalized differential cross section in good agreement with NLO pQCD expectations (relatively low $110 < p_T^{max} < 160$ GeV predictions)
- Data also compared to SHERPA, PYTHIA and HERWIG predictions:
  - In the region $\pi/2 < \Delta\phi < 5\pi/2$, SHERPA which includes higher order tree level diagrams performs well, while PYTHIA and HERWIG also describe the data after adjusting parameters to previous ATLAS measurements
  - In the region $\Delta\phi \to \pi$, parton-shower models give good description of the data

Dijet production with a veto

JHEP 1109 (2011) 053

- Gap fraction defined as the fraction of events that do not have an additional jet with $p_T > Q_0$ (veto scale) in the rapidity interval bounded by the dijet system
- Dijet system identified using two different selection criteria:
  - Two highest p_T jets in the event
  - Most forward and most backward jets in the event



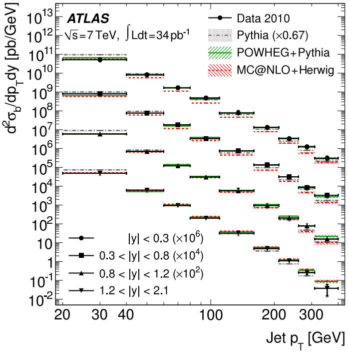
POWHEG+PYTHIA gave the best description of the data, POWHEG+HERWIG predicting too much jet activity in the Δy between the boundary jets, HEJ describes the data well using the leading p_T dijet selection and $\bar{p}_T$ close to the veto scale

b-jet cross section

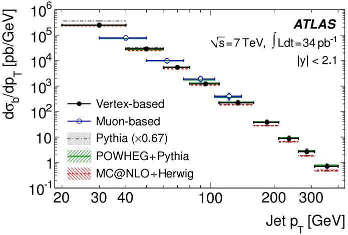
EPJC 71 (2011) 1846

Measured using two different methods:

- Vertex-based: lifetime-based method where secondary decay vertices of *b*-hadrons in jets are reconstructed using information from the tracking detectors
- Muon-based: using jets containing a muon of $p_T > 4$ GeV within a cone of $\Delta R = 0.4$ from the jet axis



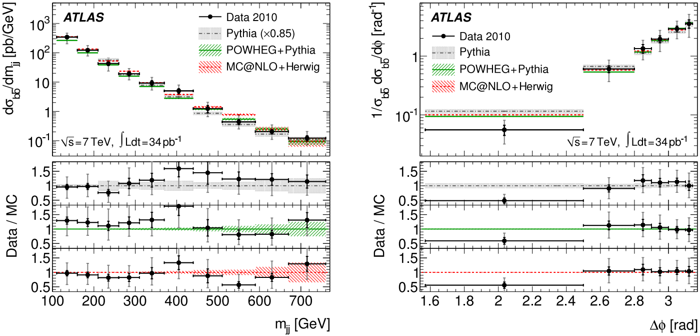
- Normalized PYTHIA prediction ($\times 0.67$) shows broad agreement
- POWHEG+PYTHIA predictions in good agreement with data
- MC@NLO+HERWIG predicts a significantly different behaviour of the double-differential cross section



$b\bar{b}$-dijet cross section

EPJC 71 (2011) 1846

- Measured as a function of the dijet invariant mass, $\Delta\phi$ and $\chi = \exp|y_1 - y_2|$ for anti-k_t $R = 0.4$ jets with $p_T > 40$ GeV and $|y| < 2.1$
- Vertex-based: lifetime-based method where secondary decay vertices of b-hadrons in jets are reconstructed using information from the tracking detectors

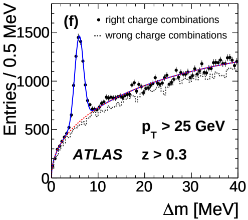


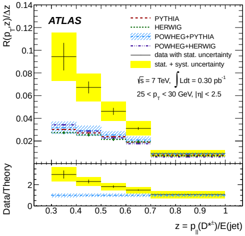
Good agreement with normalized PYTHIA (×0.85), POWHEG+PYTHIA and MC@NLO+HERWIG cross sections

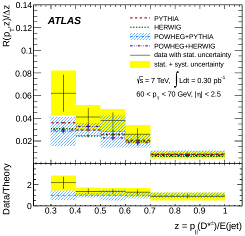
- $D^{*\pm}$ can be produced either by a prompt charm or from a secondary charm from a b-hadron decay
- $D^{*\pm}$ meson production in jets measured for $z = p_{||}(D^{*\pm})/E(\text{jet}) > 0.3$ and jets with $25 < p_T < 70$ GeV and $|\eta| < 2.5$ using 0.30 pb^{-1} of 2010 data:

$$\mathcal{R}(p_T, z) = \frac{N_{D^{*\pm}}(p_T, z)}{N_{\text{jet}}(p_T)}$$

Using $D^{*\pm} \to K^{\mp}\pi^{\pm}\pi^{\pm}$







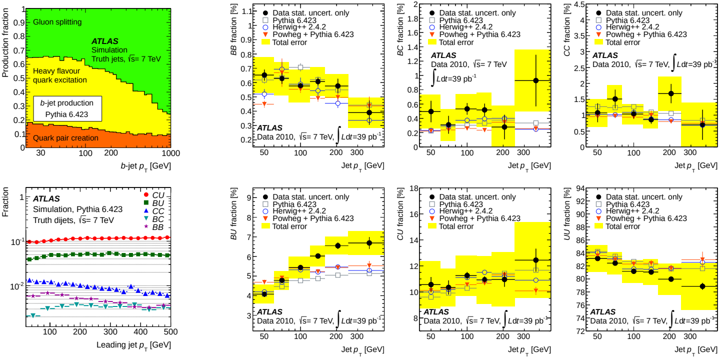
- $N(D^{*\pm})/N(\text{jet}) = 0.025 \pm 0.001(\text{stat.}) \pm 0.004(\text{syst.})$
- Results compared to PYTHIA, HERWIG, POWHEG+PYTHIA and POWHEG+HERWIG predictions
- Discrepancies in the $D^{*\pm}$ production in jets for low p_T and z

Flavor composition in dijet events

arXiv:1210.0441

New Measurement $\rightarrow$ submitted for publication last week

- Measured as function of the leading anti-k_t $R = 0.4$ jet p_T with $40 < p_T < 500$ GeV and $|y| < 2.1$ for the full 2010 dataset
- Kinematic variables, based on the properties of displaced decay vertices and optimized for jet flavour identification, used in a multidimensional template fit



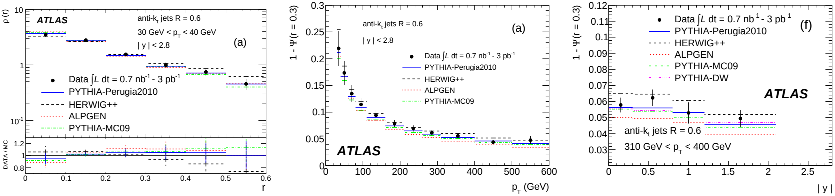
Mixed BU dijet fraction is systematically above MC predictions for high p_T

- Constrain the current phenomenological models for soft gluon radiation, UE activity, and nonperturbative fragmentation processes in the final state
- Studied in terms of the differential and integrated jet shapes using anti-k_t $R = 0.6$ jets with $30 < p_\mathrm{T} < 60$ GeV and $|y| < 2.8$ for 3 pb^{-1} of 2010 data:

$$\rho(r) = \frac{1}{\Delta R}\frac{1}{N^{\mathrm{jet}}}\sum_{\mathrm{jets}}\frac{p_\mathrm{T}(r-\Delta r/2, r+\Delta r/2)}{p_\mathrm{T}(0,R)} \quad \text{with} \quad \Delta r/2 \le r \le R - \Delta r/2$$

$$\Psi(r) = \frac{1}{N^{\mathrm{jet}}}\sum_{\mathrm{jets}}\frac{p_\mathrm{T}(0,r)}{p_\mathrm{T}(0,R)} \quad \text{with} \quad 0 \le r \le R$$

- Jets become narrower as the jet p_T and rapidity increase



- PYTHIA-Perugia2010 describes well the data
- HERWIG++ predicts jets slightly broader than the data
- ALPGEN, PYTHIA-DW and PYTHIA-MC09 predict jets narrower than the data

Properties of jets measured from tracks

- The transverse momenta and longitudinal momentum fractions of charged particles within jets are measured using anti-k_t $R = 0.4$ and 0.6 jets

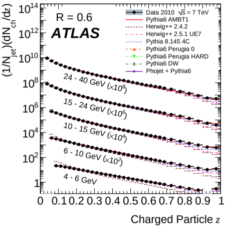
Longitudinal momentum fraction:

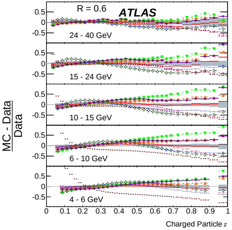
$$z = \frac{\vec{p}_{\mathrm{ch}} \cdot \vec{p}_{\mathrm{jet}}}{|\vec{p}_{\mathrm{jet}}|^2}$$

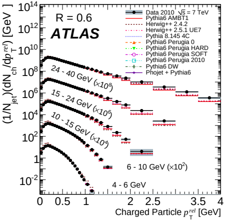
Transverse momenta of charged particles:

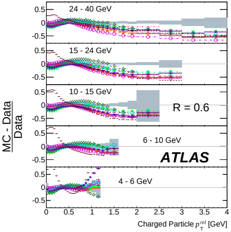
$$p_{\mathrm{T}}^{\mathrm{rel}} = \frac{|\vec{p}_{\mathrm{ch}} \times \vec{p}_{\mathrm{jet}}|}{|\vec{p}_{\mathrm{jet}}|}$$

Comparisons are sensitive to Monte Carlo parton showering, hadronization, and soft physics models







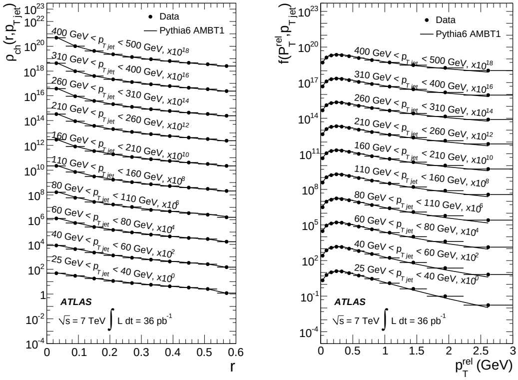


Jet fragmentation func & transverse profile EPJC 71 (2011) 1795

- The jet transverse profile is described by:

$$\rho_{\mathrm{ch}}(r, p_{\mathrm{T,\ jet}}) = \frac{1}{N_{\mathrm{jet}}}\frac{dN_{\mathrm{ch}}}{2\pi r dr} \quad \text{and} \quad f(p_{\mathrm{T}}^{\mathrm{rel}}, p_{\mathrm{T,\ jet}}) = \frac{1}{N_{\mathrm{jet}}}\frac{dN_{\mathrm{ch}}}{dp_{\mathrm{T}}^{\mathrm{rel}}}$$

- Measured using jets with $25 < p_{\mathrm{T}} < 500$ GeV and $|\eta| < 1.2$ and the full 2010 dataset



Good agreemet with PYTHIA6 AMBT1

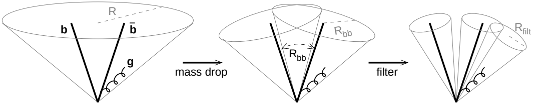
Jet mass and substructure

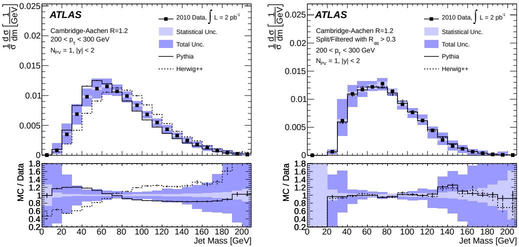
JHEP 1205 (2012) 128

- Jet invariant mass, k_t splitting scales and n-subjettiness variables are presented for anti-k_t $R = 1.0$ jets and Cambridge-Aachen $R = 1.2$ jets

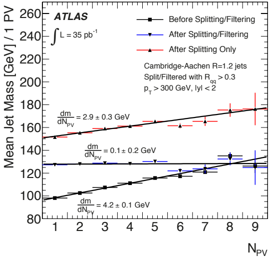
Jet invariant mass spectra for Cambridge-Aachen $R = 1.2$ jets before and after splitting and filtering

arXiv:0802.2470





The dependence of mean jet mass on additional pp interactions is also explored

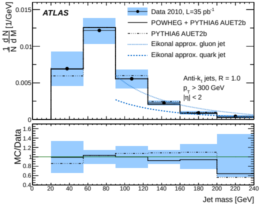


In general, LO parton-shower Monte Carlo predictions for the measured variables are found to be broadly in agreement with data

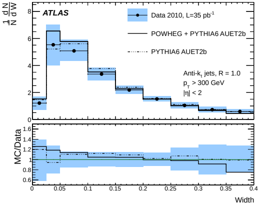
Properties of jets for boosted particle searches arXiv:1206.5369

- Heavily boosted particles can be observed as a single merged jet in the final state
- Jet substruct. studied to provide discriminating power in heavy particle searches
- Jet mass, width, eccentricity, planar flow and angularity are measured for anti-k_t $R = 0.6$ and 1.0 jets with $p_T > 300$ GeV and $|\eta| < 2$ for the full 2010 dataset:

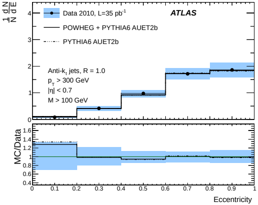
Jet mass: calculated from the jet constituents



Width: p_T-weighted distance of jet constituents from axis



Eccentricity: deviation of jet profile from circle in (η, ϕ) plane



- Good agreement between data and PYTHIA for all observables
- POWHEG+PYTHIA describes the jet mass distribution well for $M > 20$ GeV
- HERWIG++ 2.4.2 predicts jets with a slightly more isotropic energy flow and higher mass than data, while HERWIG++ 2.5.1 is in good agreement with data

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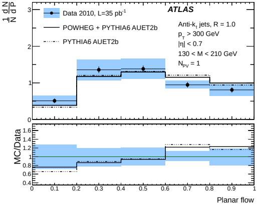
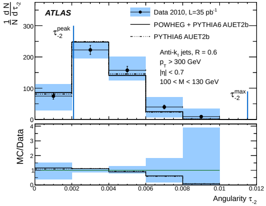
Planar flow: distinguish between planar or linear energy configuration inside the jet



Angularity: sensitive to the degree of symmetry in the energy deposition inside a jet



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Event shapes at large momentum transfer arXiv:1206.2135

- Six event shape variables calculated using hadronic jets are studied in inclusive multi-jet events $\rightarrow$ Measure event isotropicity

Third-jet resolution parameter:
Defined as $y_{23} = p_{\mathrm{T},3}^2/(p_{\mathrm{T},1} + p_{\mathrm{T},2})^2$ where p_{T} is the transverse momentum of the jet
Range: $0 \leq y_{23} < 1/4$

Transverse thrust minor:
Defined as $T_{m,\perp} = \frac{\sum_i |\vec{p}_{\mathrm{T}i} \times \widehat{n}_\perp|}{\sum_i |\vec{p}_{\mathrm{T}i}|}$
Range: $0 \leq T_{m,\perp} < 2/3$

Aplanarity:
Defined as $A = 3/2\ \lambda_3$ where λ_3 is an eigenvalue of the diagonalized sphericity tensor
Range: $0 \leq A < 1/2$

Sphericity:
Defined as $S = 3/2\ (\lambda_2 + \lambda_3)$ where λ_2 and λ_3 are eigenvalues of the diagonalized sphericity tensor
Range: $0 \leq S < 1$

Transverse thrust:
Defined as $\tau_\perp = 1 - T_\perp$ with

$$T_\perp = \max_{\widehat{n}_\perp} \frac{\sum_i |\vec{p}_{\mathrm{T}i} \cdot \widehat{n}_\perp|}{\sum_i |\vec{p}_{\mathrm{T}i}|}$$

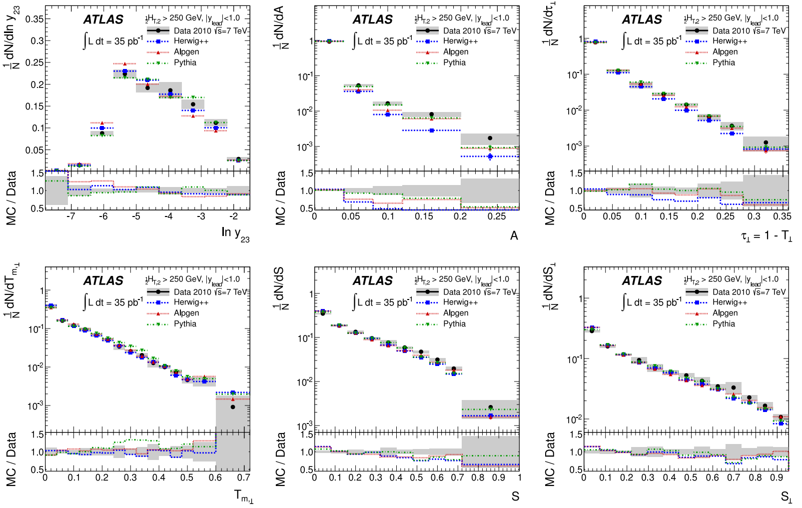
where $\widehat{n}_\perp$ defines the thrust axis of the event
Range: $0 \leq \tau_\perp < 1/3$

Transverse sphericity:
Defined as $S_\perp = 2\lambda_2/(\lambda_1 + \lambda_2)$ where λ_1 and λ_2 are eigenvalues of the diagonalized sphericity tensor
Range: $0 \leq S_\perp < 1$

- The mean value of each event shape variable is also evaluated as a function of the average momentum of the two leading jets

Event shapes at large momentum transfer

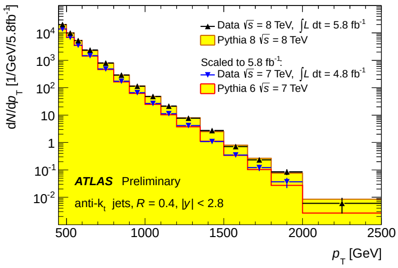
arXiv:1206.2135

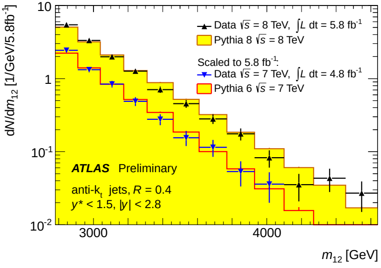


Measured event shape variables are generally well described

First 8 TeV results for jets

- Many papers in the pipeline using 2011 and 2012 data
- Last minute plots for jets at detector level prepared for ICHEP with 8 TeV data:
  - Compared to 7 TeV data (scaled to 2012 luminosity)
  - Expect to extend the kinematical range
  - Continuing the effort towards a paper





Conclusions

- ATLAS is performing very well, triggering on and measuring jets over a huge kinematical range
- Wide program of SM jet physics measurements in ATLAS, covering different aspects:
  - Basic cross section measurements: inclusive jets, dijets, multijets, ...
  - Heavy flavor jet measurements: b-jet and $b\bar{b}$-dijet cross sections, $D^{*\pm}$ production in jets, flavor composition in dijet events, etc.
  - Also exploring jet shapes and global event shapes
  - Studies about jet substructure and properties aiming at boosted particle searches
- Results compared to NLO pQCD predictions and different MC generators
- Numerical results available in HepData, Rivet analysis routines also made public