ATLAS Jets measurements summary

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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 $d_{iB}$:

$$d_{ij} = \min(k_{ti}^{2p}, k_{tj}^{2p}) \frac{\Delta y^2 + \Delta \phi^2}{R^2};$$

$$d_{iB} = k_{ti}^{2p};$$

$$p = \begin{cases} 1 & k_t \\ 0 & \text{Cambridge/Aachen} \\ -1 & \text{anti-}k_t \end{cases}$$

- 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

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

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

- Baseline calorimeter energy scale: electromagnetic scale (extracted from $Z \rightarrow ee$, test beams, MIP $\mu$)

- 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: ($\eta$, $E$)-dependent calibration constants from MC

- Other calibration schemes being developed: Global Sequential Calibration (GS), Global Calorimeter Cell Weighting (GCW) and Local Cluster Weighting (LCW)

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Jet response at EM scale

**ATLAS simulation**

- $|\eta_{\text{det}}|$ vs. Jet response at EM scale
- $E = 30$, $60$, $110$, $400$, $2000$ GeV
- $R = 0.6$, EM+JES

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Average JES correction

**ATLAS simulation**

- $0.3 \leq |\eta| < 0.8$
- $2.1 \leq |\eta| < 2.8$
- $3.6 \leq |\eta| < 4.4$
- $p_T^{\text{jet}}$ vs. Average JES correction
- $R = 0.6$, EM+JES
Jet energy scale uncertainties

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:

- Dijet cross sections with 2011 data (ATLAS-CONF-2012-021)
- Jet cross section at 2.76 TeV and ratio (ATLAS-CONF-2012-128)
- 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)
- Properties of jets measured from tracks (Phys. Rev. D 84 (2011) 054001)
- 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

- 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.
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

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 \(x_T = 2p_T/\sqrt{s}\) → Important cancellation of theoretical uncertainties → 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 → 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

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

- 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 $p_T$
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

- Normalized differential cross section in good agreement with NLO pQCD expectations (relatively low $110 < p_T^{\text{max}} < 160$ 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 $\Delta \phi \rightarrow \pi$, parton-shower models give good description of the data
Dijet production with a veto

- 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 $\Delta y$ 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**

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¯b-dijet cross section**

- 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.

**Graphs:**
- ATLAS:
  - Measured $d^2\sigma/dm_{jj}$ [pb/GeV] as a function of $m_{jj}$ [GeV] and $1/\sigma_b d^3\sigma_b/d\phi d\psi$ [rad$^{-3}$] for $\sqrt{s} = 7$ TeV, $L_d = 34$ pb$^{-1}$.
  - Good agreement with normalized PYTHIA ($\times 0.85$), POWHEG+PYTHIA and MC@NLO+HERWIG cross sections.

A. Ruiz (ISU)  
PDF4LHC and LHC EW WG meeting  
October 8, 2012
$D^{*\pm}$ meson production in jets

- $D^{*\pm}$ 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:

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

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

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

ATLAS

Data/Theory

ATLAS

Data/Theory

ATLAS
**New Measurement** → 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 $p_T$
Jet shapes

- 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 $30 < p_T < 60$ GeV and $|y| < 2.8$ for 3 pb$^{-1}$ of 2010 data:

\[
\rho(r) = \frac{1}{\Delta R} \frac{1}{N_{jet}} \sum_{jets} \frac{p_T(r - \Delta r/2, r + \Delta r/2)}{p_T(0, R)} \quad \text{with} \quad \Delta r/2 \leq r \leq R - \Delta r/2
\]

\[
\Psi(r) = \frac{1}{N_{jet}} \sum_{jets} \frac{p_T(0, r)}{p_T(0, R)} \quad \text{with} \quad 0 \leq r \leq R
\]

- 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.
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:**
\[ z = \frac{\vec{p}_{\text{ch}} \cdot \vec{p}_{\text{jet}}}{|\vec{p}_{\text{jet}}|^2} \]

**Transverse momenta of charged particles:**
\[ p_{\text{T}}^{\text{rel}} = \frac{|\vec{p}_{\text{ch}} \times \vec{p}_{\text{jet}}|}{|\vec{p}_{\text{jet}}|} \]

Comparisons are sensitive to Monte Carlo parton showering, hadronization, and soft physics models.
The jet transverse profile is described by:

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

Measured using jets with $25 < p_T < 500$ GeV and $|\eta| < 1.2$ and the full 2010 dataset.

Good agreement with PYTHIA6 AMBT1
Jet mass and substructure

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

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.
Heavily boosted particles can be observed as a single merged jet in the final state. Jet substructure is 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 ($\eta$, $\phi$) 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.
Heavily boosted particles can be observed as a single merged jet in the final state
Jet substructure 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:

- **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

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

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

**Aplanarity:**
Defined as \( A = \frac{3}{2} \lambda_3 \) where \( \lambda_3 \) is an eigenvalue of the diagonalized sphericity tensor
Range: \( 0 \leq A < 1/2 \)

**Transverse thrust:**
Defined as \( \tau_\perp = 1 - T_\perp \) with
\[
T_\perp = \max_{\hat{n}_\perp} \frac{\sum_i |\vec{p}_{Ti} \cdot \hat{n}_\perp|}{\sum_i |\vec{p}_{Ti}|}
\]
where \( \hat{n}_\perp \) defines the thrust axis of the event
Range: \( 0 \leq \tau_\perp < 1/3 \)

**Transverse thrust minor:**
Defined as \( T_{m,\perp} = \frac{\sum_i |\vec{p}_{Ti} \times \hat{n}_\perp|}{\sum_i |\vec{p}_{Ti}|} \)
Range: \( 0 \leq T_{m,\perp} < 2/3 \)

**Sphericity:**
Defined as \( S = \frac{3}{2} (\lambda_2 + \lambda_3) \) where \( \lambda_2 \) and \( \lambda_3 \) are eigenvalues of the diagonalized sphericity tensor
Range: \( 0 \leq S < 1 \)

**Transverse sphericity:**
Defined as \( S_{\perp} = \frac{2\lambda_2}{(\lambda_1 + \lambda_2)} \) where \( \lambda_1 \) and \( \lambda_2 \) 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

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