In Situ Measurements of Jet Energy Scale in ATLAS

Doug Schouten[a], for the ATLAS Collaboration

[a]Simon Fraser University

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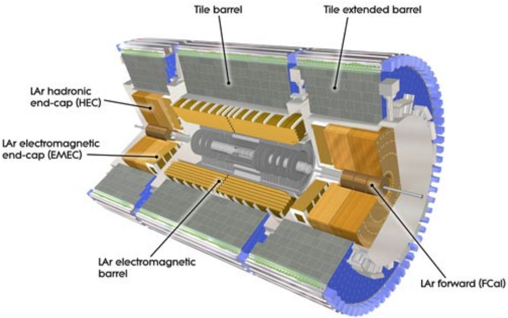
Introduction

- jet energy scale is strongly dependent on details of ATLAS calorimetry
  - see presentation from P. Loch's talk this morning for details



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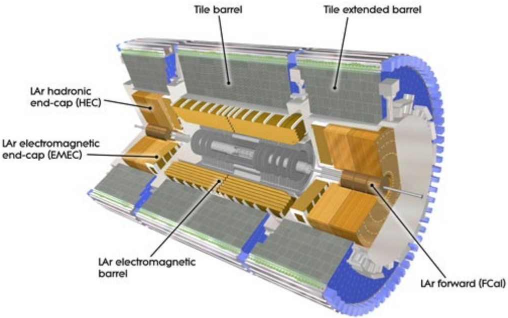

- this talk: **jet energy scale derived from 7 TeV collision data**[a]
- **focus for the scale in 2010 was on robustness**
  - resolution improvements with offline compensation techniques are forthcoming in ATLAS
  - overall uncertainty will also shrink as *in situ* techniques mature, and data accumulates

[a] also using input from 2004 combined testbeam (CTB) and 900 GeV data

Ingredients & Definitions

The goal of the JES calibration is to correct E and $\vec{p}$ of jets measured in the calorimeter to the corresponding particle jets.

Ingredients

- response non-compensation ($e/h > 1.3$ in ATLAS)
- inactive regions, leakage, and punch through
- calorimeter signal definition (noise thresholds, jet width parameter)

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Definitions

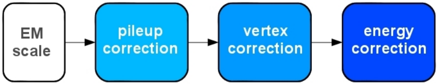
- the JES is defined for a particular class of "nominal" jets[a]:
  - in QCD dijet events (mostly jets from gluons)
  - isolated jets: $\Delta R(jet_i, jet_{j \neq i}) > 2.0$
- and with respect to a particular reference:
  - jets from final state, stable particles[b] excepting μ's and ν's
  - matched to measured jets in $\Delta R < 0.3$

[a] unless otherwise specified, all results shown are for jets defined with the anti-k_T algorithm[1], with a width parameter $R = 0.6$, built from 4/2/0 topological clusters

[b] stable is defined as $\tau > 10$ ps

EM+JES Scheme

$$p_T^{calibrated} = C(E - \mathcal{O}, \eta) \cdot V(p_T - \mathcal{O})\, p_T \quad (1)$$



The EM scale is validated in $Z \to e^+ e^-$ events for the EM LAr, and using MIP μ's for the Tile.

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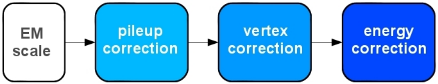

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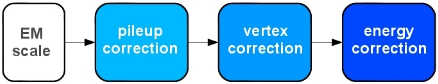

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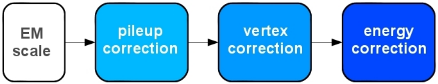

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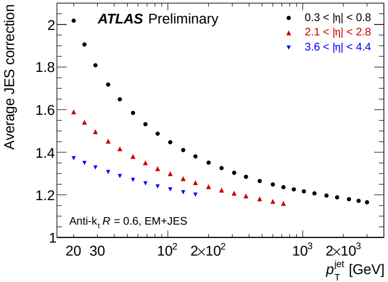
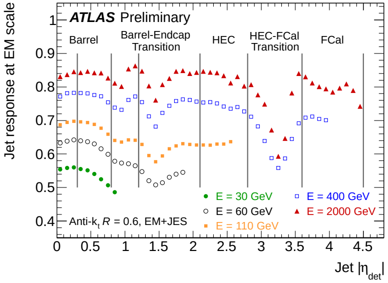
The **vertex correction**, $V(p_T)$, corrects the momentum of the constituent clusters to point from the primary vertex with highest $\sum(p_T^2)$.

Finally, a Monte Carlo based **energy correction**, $C(E, \eta)$, corrects to the particle level, within $\pm 2\%$[a]

[a] See extra slides for more details on the procedure for extracting these corrections from the Monte Carlo.





Evaluating the EM+JES

- **overall strategy**: evaluate the JES by factorizing the components of EM+JES, and verifying that the Monte Carlo description of each feature in the data is correct

[1] the pileup correction is totally data-driven, so the correction and uncertainty are both derived from collision data

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in situ measurement	JES uncertainty component
E/p **single particle response**	**central calorimeter response**
dijet relative calibration	extrapolation to endcap and forward region
$\langle E \rangle_{tower}$ & track-jets	multiple interactions[1]

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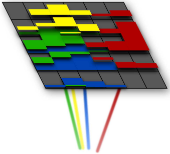
Single Particle Response - E/p (validate $C(E,\eta)$ in barrel)



- use pseudo experiments in Monte Carlo to extrapolate single particle response uncertainty to jet response uncertainty
- translation is non-trivial, but exhaustively cross-checked:
  1. threshold effects due to noise suppression,
  2. fragmentation model and soft physics

- E/p measurements for charged hadrons with $p < 20$ GeV
- for particles with $20 < p < 350$ GeV, use CTB measurements
- conservatively add 20% uncertainty for neutral hadron component

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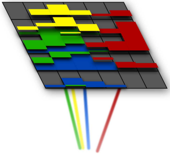

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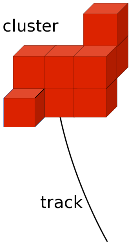
E/p analysis:

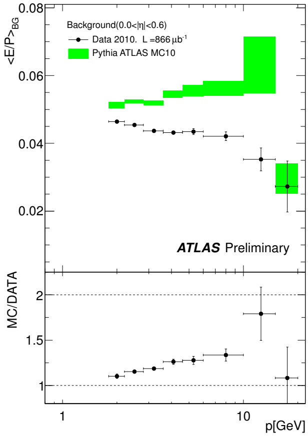
- select events using minimum bias trigger, using $\sim 0.9\text{pb}^{-1}$ of 7 TeV data
- 20M minimum bias events in Pythia
- collect isolated tracks ($\Delta R > 0.4$) with $p_T > 2$ GeV[a]
- considered systematics: E/p background, CTB $\rightarrow$ in situ, EM scale, detector simulation

[a] for particles with lower p_T, data collected at 900 GeV was used in analagous way

Single Particle Response - E/p (validate $C(E,\eta)$ in barrel)

- select calorimeter cells in topological clusters, within $\Delta R < 0.2^a$ of extrapolated track at each layer
- neutral background measured by looking in annulus $0.1 < R < 0.2$ around the axis for MIP's in the EM calorimeter ($E^{0.1}_{HAD}/p > 0.4$ & $E^{0.1}_{EM} < 1$ GeV)
  - discrepancy between MC & data at 7 TeV indicates mismodeling of soft QCD





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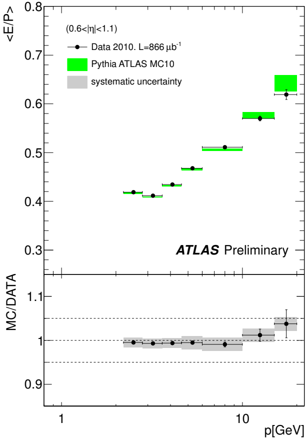
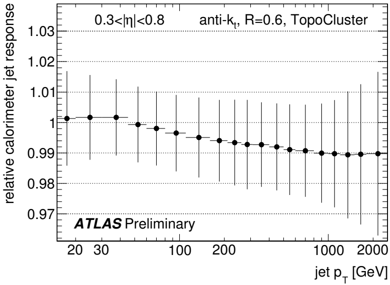
- difference between MC & data (right), and uncertainties on E/p measurement propagated to jet response (below)





Evaluating the EM+JES

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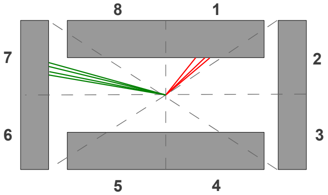
in situ measurement	**JES uncertainty component**
E/p single particle response	central calorimeter response
dijet relative calibration	**extrapolation to endcap and forward region**
$\langle E \rangle_{tower}$ & track-jets	multiple interactions[1]

[1] the pileup correction is totally data-driven, so the correction and uncertainty are both derived from collision data

η Intercalibration (validate $C(E,\eta)$ in endcap)

- for jets in $|\eta| > 0.8$, the central results are extrapolated using dijet balance
  - CTB included only barrel Tile calorimeter
  - better knowledge of central geometry
- use matrix method to couple all regions
  - improves statistics since σ falls steeply with $\Delta\eta$



$$A = \frac{p_T^i - p_T^j}{\frac{1}{2}\left(p_T^i + p_T^j\right)}$$

$$R_{ij} = \frac{2 - \langle A_{ij} \rangle}{2 + \langle A_{ij} \rangle} = \frac{\alpha_i}{\alpha_j}$$

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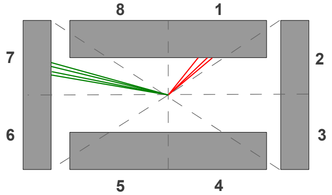

$$S = \sum_{i<j} \left(\frac{1}{\Delta R_{ij}} (\alpha_j \langle R_{ij} \rangle - \alpha_i) \right)^2 + \chi(\alpha)$$

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- yields coefficients $\alpha(p_T)|_\eta \pm \Delta$

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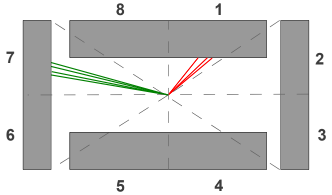

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η analysis

- use combination of minimum bias and jet triggers for different p_T regions
- require $\Delta\phi(j_1, j_2) > 2.6$, $p_T^{j_3} < \max(0.15\, p_T, 7\ \mathrm{GeV})$

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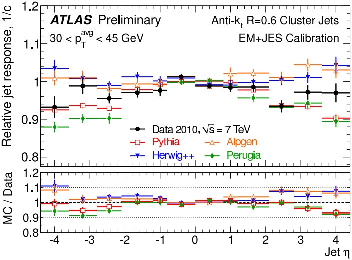

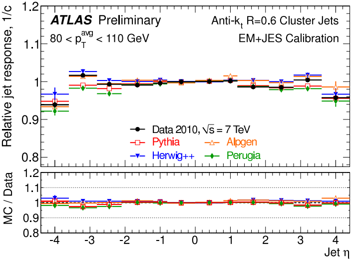

- puzzling inconsistency between Monte Carlo generators
  - compare Herwig++, Alpgen (cluster model, $2 \to N$) to Pythia and Perugia tune ($2 \to 2$, Lund string model)
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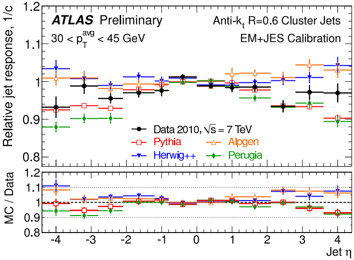

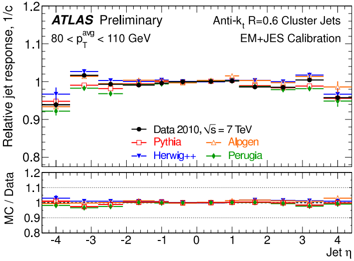

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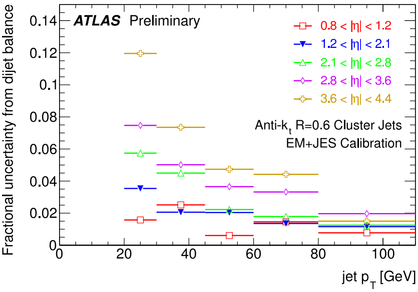
- use RMS deviation between MC and data as systematic uncertainty $\oplus$ uncertainty in central region



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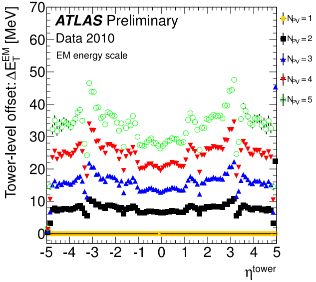
Pileup Correction (derive $\mathcal{O}$)

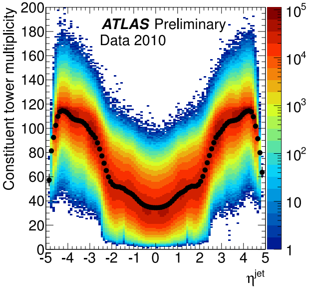
Offset analysis

- L1 jet trigger, only subleading jets are used to avoid trigger bias
- count N_{PV} using vertices near beam line with $N_{trk}^{p_T > 150\,\mathrm{MeV}} \geq 5$

- two methods for estimating pileup contribution
  1. tower-based offset:

$$\mathcal{O}_{jet|tower}(\eta, N_{PV}) = \mathcal{O}_{tower}(\eta, N_{PV}) \cdot \left\langle N_{tower}^{jet} \right\rangle_{\eta}$$





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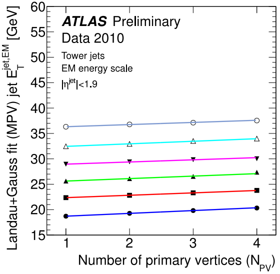
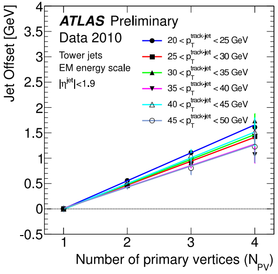
  2. track $\leftrightarrow$ calorimeter jet comparison

$$\mathcal{O}_{jet|track}(\eta, N_{PV}) = \left\langle E_T^{jet}(\eta, N_{PV} | p_T^{track-jet}) \right\rangle - \left\langle E_T^{jet}(\eta, N_{PV} = 1 | p_T^{track-jet}) \right\rangle$$

technique	systematic uncertainty
tower	26% ($\sim$)
track jet	34% ($\sim$)





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- further, we validate the uncertainty using various other measurements: γ + jet, QCD multijet balancing, and relative track $\leftrightarrow$ calorimeter jet comparisons

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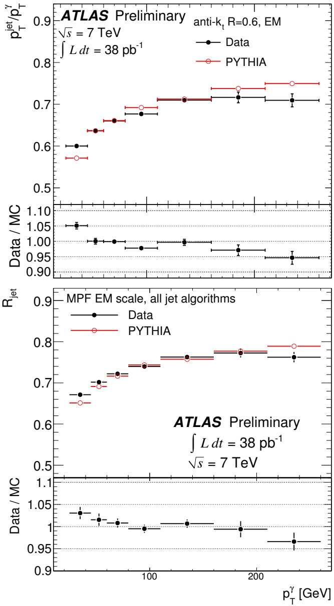
γ + Jet

- jet response probed with two complementary methods[1]:
  1. direct p_T balance: p_T^{jet}/p_T^{γ}
  2. $\not{E}_T$ projection fraction (MPF): $1 + \not{E}_T \cdot \hat{n}_{\gamma}/p_T^{\gamma}$

γ + jet analysis

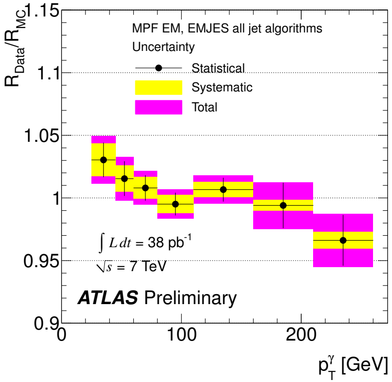
- using $\int \mathcal{L} = 38\text{pb}^{-1}$
- γ selected based on shower shape, isolation[2]
- back-to-back topology ($\Delta\phi > \pi - 0.2$, $p_T^{j_2}/p_T^{\gamma} < 0.1$)
- considered systematics from: QCD jet background, ISR/FSR mismodelling, γ energy scale, pileup

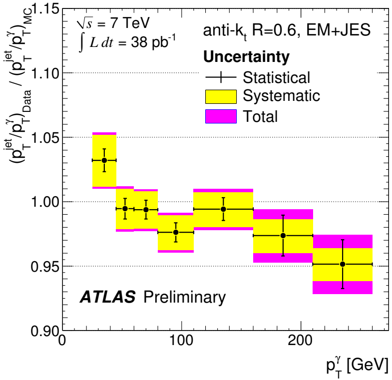


[1] both depend on p_T conservation but are differently sensitive to systematics

[2] corrected for UE and γ cluster leakage

γ + Jet

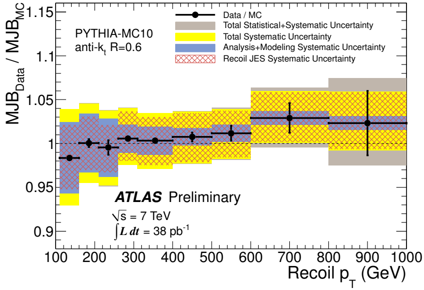


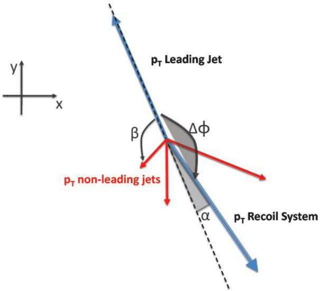


Monte Carlo : Data comparison for MPF and direct balance, versus p_T^γ

QCD Multijet Balancing

- extrapolate $\gamma + \text{jet}$ to high p_T using events where a high p_T jet recoils against an $N > 1$ jet system





multijet analysis

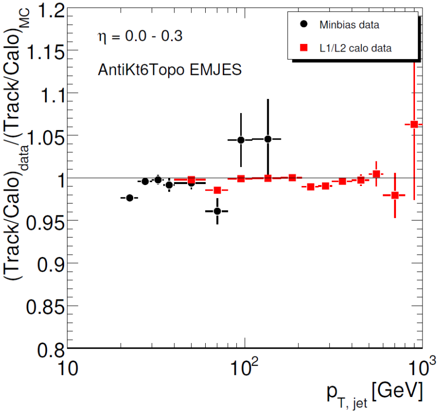
- $\Delta\phi(lead, recoil) > \pi - 0.3$, $\Delta\phi(lead, closest\ recoil) \equiv \beta > 1$
- require $A = p_T^{j_2} / p_T^{recoil} < 0.6$
- exhaustive list of systematics: recoil JES, ISR & FSR, nearby jets, flavor

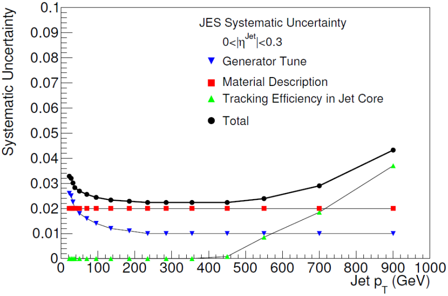
Track ↔ Calorimeter Jet

Despite uncertainties in jet fragmentation, ratio of charged to total energy is highly constrained.

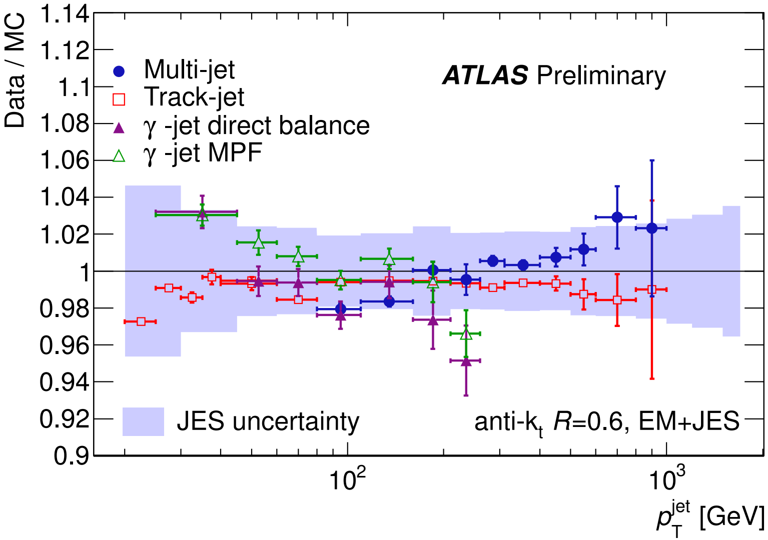
Trackjet analysis

- construct jets from selected tracks and match to jets from calorimeter clusters
- compare distribution of p_T^{track}/p_T^{calo} with Pythia dijet simulation





JES Summary



JES uncertainty for jets in barrel region, with $N_{PV} = 1$

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2. multiple, independent cross-checks confirm JES
   - $\gamma +$ jet
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   - multi-jet balancing

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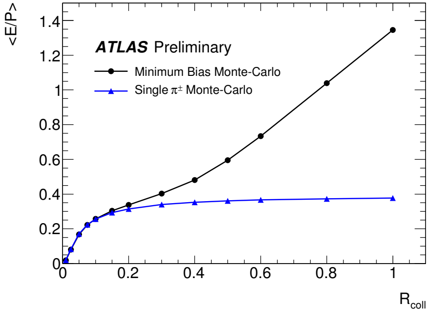
2. multiple, independent cross-checks confirm JES
   - γ + jet
   - track $\leftrightarrow$ calorimeter jet comparison
   - multi-jet balancing
3. local calibration schemes are being commissioned
   - results for local and sequential schemes already tested at jet level, and show good resolution improvement
4. in situ techniques will improve scale with increased statistics

EXTRA SLIDES

Topological Clustering Algorithm

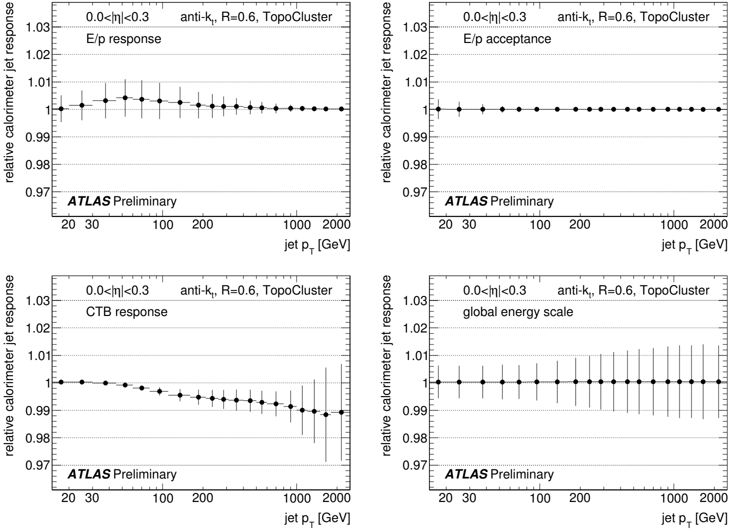
1. select cells with $|E|/\sigma > 4$ as seed cells
2. collect all cells with $|E|/\sigma > 2$ that are connected to seed cells
3. add in all neighbouring cells $(0 - \sigma)$

Selection of Cone Radius for E/p

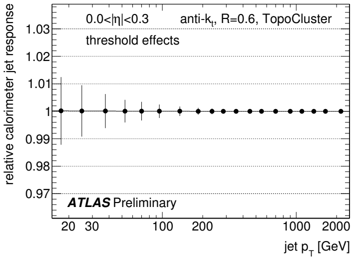


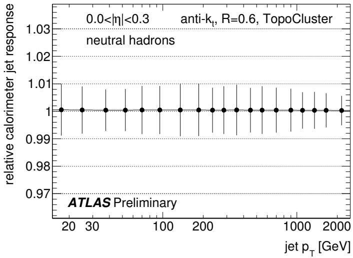
$\Delta R < 0.2$ collects $\simeq 90\%$ of deposited energy but
is simultaneously unaffected by nearby particle showers

Components of JES Uncertainty from Single Particle Response

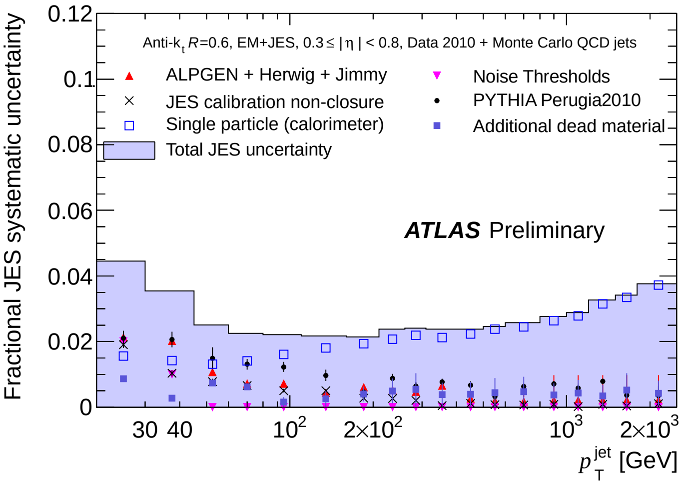


Components of JES Uncertainty from Single Particle Response

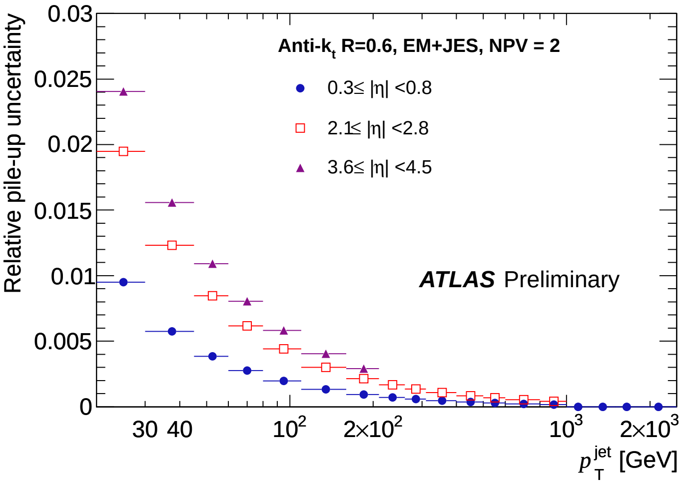




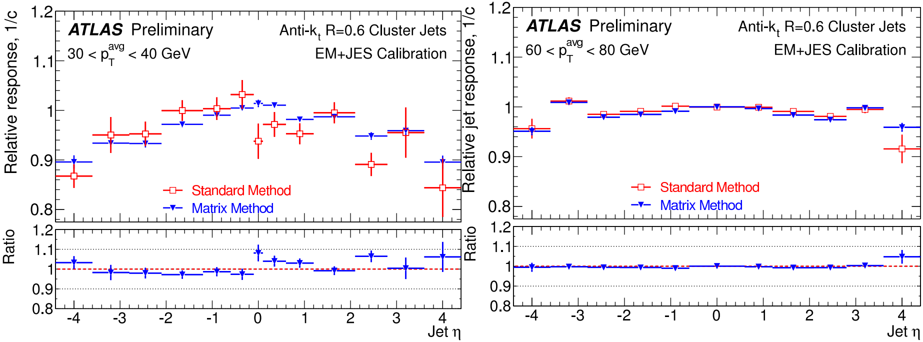
Components of JES Uncertainty in $0.3 < \eta < 0.8$



Relative Uncertainty for Jets in Events with Pileup

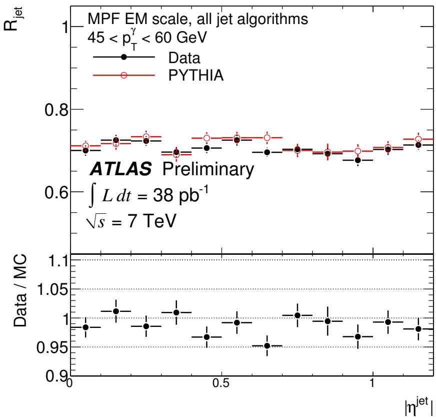


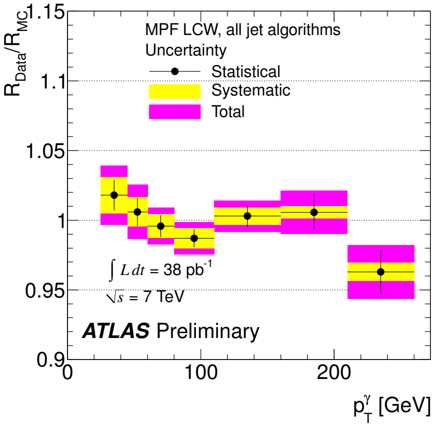
Comparison of Matrix Solution to Reference Method



Compare relative calibration coefficients for the case where only events are used in which a jet is in the central $\eta < 0.8$ and a jet is in a probe region in $\eta > 0.8$, compared to the method where all events are used.

Extra Plots





Validating JES in η with MPF (left) and other calibration scheme, based on local hadronic response correction (right).

1. M. Cacciari, G. P. Salam, and G. Soyez, The anti-kt jet clustering algorithm, JHEP 04 (2008) 063, arXiv:0802.1189 [hep-ph].
2. ATLAS Jet/ETMiss Conference Notes