Jet and $E_{\mathrm{T}}^{\mathrm{miss}}$ Reconstruction and Calibration

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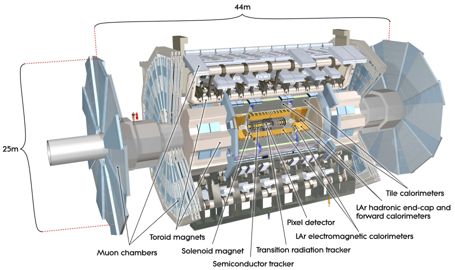
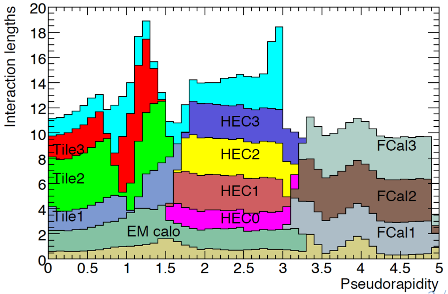
Introduction

- Jets are very important to almost all analyses at the LHC.
- While this workshop clearly focusses on boosted object reconstruction here I will cover the reconstruction and calibration of the $R = 0.4$ Anti-k_t jets that are used as standard by ATLAS analyses as well as the reconstruction of *missing transverse momentum*.
- Jets are used from 20 GeV to 3.8 TeV and up to $|\eta| < 4.5$ by analyses with their uses varying from jet vetoes, signal enhancement through their presence to unfolding their kinematic distributions.
- *Missing transverse momentum*, $E_{\mathrm{T}}^{\mathrm{miss}}$, is used to infer the existence of weakly interacting neutral particles that pass through the detector undetected, for example, neutrinos or other *more exotic* particles.
- The reconstruction of this requires the accurate measurement of all objects in the event to check if they balance in the transverse plane.

The ATLAS Detector

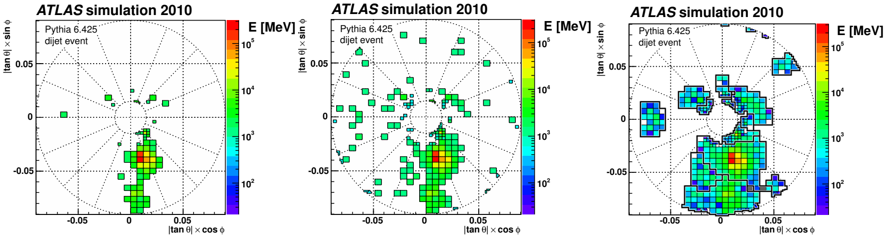
- The ATLAS detector - multi-purpose detector: inner tracker, EM + HAD calorimeters, muon spectrometer.
- Magnetic fields provided by thin solonoid (inside calorimeters) and outer toroid for muon measurements.
- The calorimeters are particularly important for jet measurements.
  - $>\sim 9$ interaction lengths gives good jet containment.
  - High granularity: 2nd EM layer 0.025×0.025, HAD barrel 0.1×0.1.





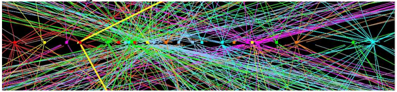
Topocluster Reconstruction arXiv:1603.02934

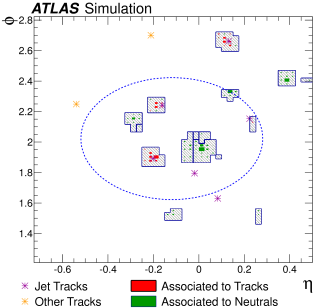
- Calorimeter object reconstruction starts with *topological clustering* of calorimeter cells.
- Cells 4σ above the noise (inc. pile-up) seed clusters.
- Neighboring cells 2σ above the noise are added iteratively.
- Finally a surrounding layer of cells is added.
- A splitting algorithm is then run to split local minima.
- For large-R jets these are then calibrated to account for EM and HAD differences, dead material and out-of-cluster deposits.

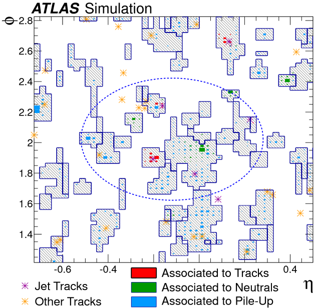


Pile-Up in the Calorimeter arXiv:1703.10485

- Pile-up is the resulting signals from other interactions - both from the same crossing and residual signals from close-by crossings.
- While the tracker can distinguish pile-up, the additional energy in the calorimeter pollutes jet measurements and also results in the reconstruction of additional jets.

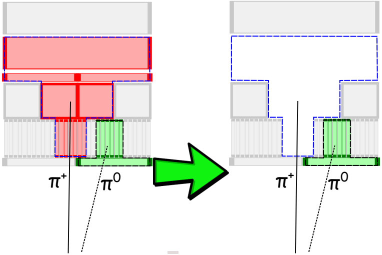






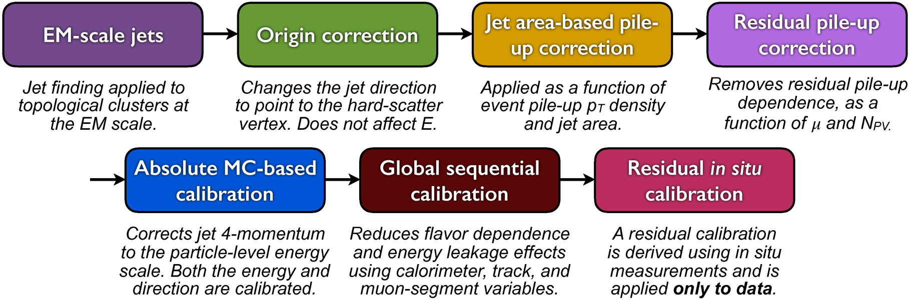
Particle Flow Reconstruction arXiv:1703.10485

- Particle Flow reconstruction starts from tracks and topological clusters.
- Tracks where the tracker is expected to be much better than calo are selected;
  - Low p_{T}- better tracker resolution
  - Not in very dense areas of calorimeter - easier to do the subtraction
- The energy deposited by tracks is subtracted cell-by-cell.
- Objects built from remaining clusters and hard-scatter tracks.



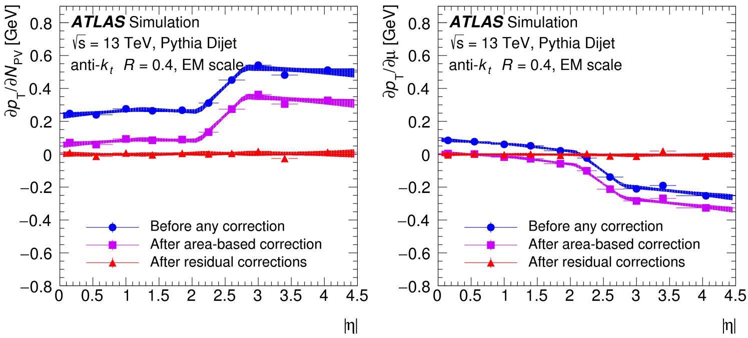
Jet Reconstruction and Calibration Sequence arXiv:1703.09665

- Jets are reconstructed using the Anti-k_t algorithm with radius parameter $R = 0.4$ - although we are also looking at other radii.
- The inputs are either *topological clusters* at the electromagnetic scale (we only use the calibrated clusters for sub-structure) or particle flow objects - tracks from the hard-scatter and remaining calorimeter clusters.
- Below is the full calibration sequence - I will go through each step in turn.



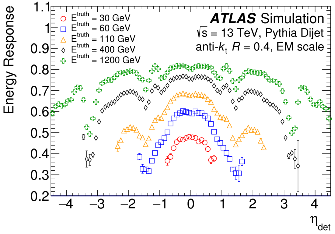
Pile-Up Correction arXiv:1703.09665

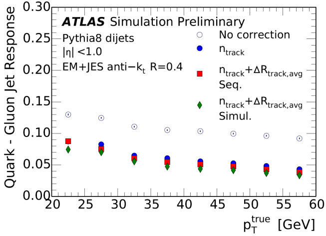
- To correct for pile-up falling within the jet cone first a $\rho \times A$ subtraction is performed.
- ρ is the average pile-up density per unit area determined in the region $|\eta| < 2.0$
- An additional correction is then applied based on the number of vertices and μ to account for residual pile-up dependence.



MC-based Calibration and GSC arXiv:1703.09665, ATL-PHYS-PUB-2018-013

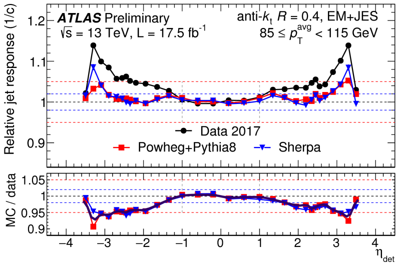
- A Monte Carlo based calibration corrects the jet energy to the truth jet scale - particle level jets formed from stable hadrons.
- Following this the η of jets is corrected to account for biases due to cracks in the calorimeter.
- The next stage of the calibration is to improve the resolution and reduce quark/gluon differences by removing the dependence on fraction of energy in different calorimeter layers, number of tracks, track width and muon spectrometer hits (which accounts for punch-through).
- Now looking at using Machine Learning for this - see A. Cukierman's poster!





η-Intercalibration JETM-2017-008

- Different detector technologies are utilized as a function of $|\eta|$.
- To ensure that the data-to-MC ratio is uniform as a function of η di-jet events are used as they are expected to balance in the transverse plane.
- Events are selected with no 3rd jets and large $\Delta\phi$ but still some truth imbalance remains.
- The modeling of this imbalance forms one of the major systematics for the forward JES.
- The size of the corrections required is $\sim 5\%$ in the most forward regions.



Jet and $E_{\mathrm{T}}^{\mathrm{miss}}$ Reconstruction and Calibration

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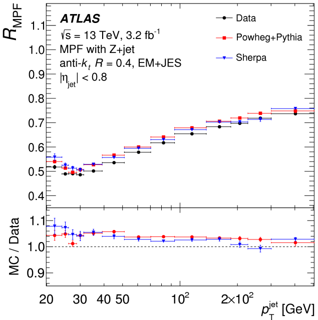
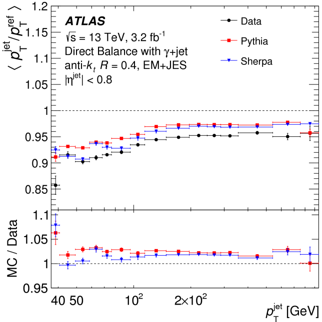
In situ V+jet Calibration arXiv:1703.09665

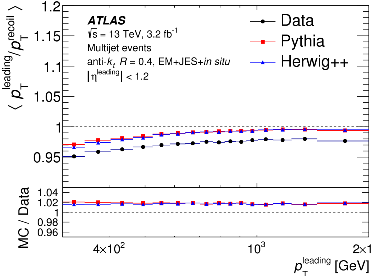
- The energy scale of electrons, muons and photons is very well known.
- A boson ($Z \rightarrow ll$ or γ) recoiling off a jet should balance in p_{T}.
- We look at both the direct balance between the jet and boson and also the *Missing E_T Projection Fraction* (MPF) method where we look at the full hadronic recoil against the boson.
- The methods are found to be compatible and one is chosen as they are not statistically independent.

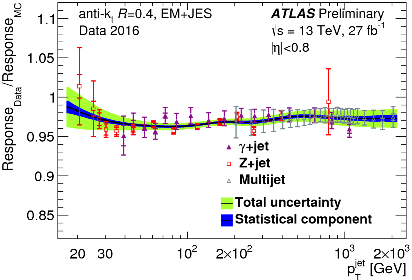




Multi-Jet Balance + Combination arXiv:1703.09665, JETM-2017-003

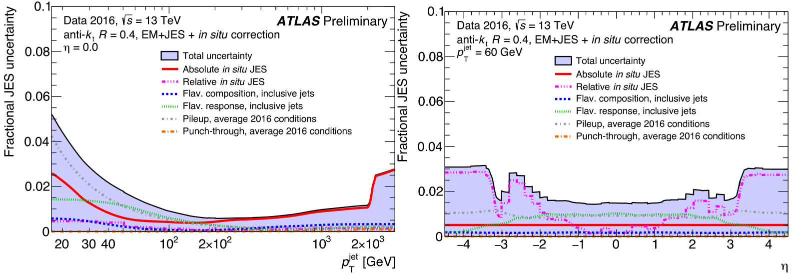
- The V+jet balance techniques run out of statistics around 1 TeV so a different technique is required beyond this.
- The balance of a single leading jet against a multi-jet system is used to extend the data driven techniques to higher p_T.
- The methods are then all combined to form the final JES *in situ* correction and its uncertainty.
- The methods are found to agree well in the regions of overlap and the independence of their uncertainties reduce the overall level of uncertainty.





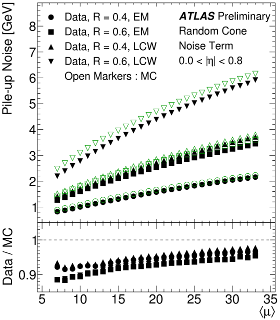
Jet Energy Scale Uncertainties JETM-2017-003

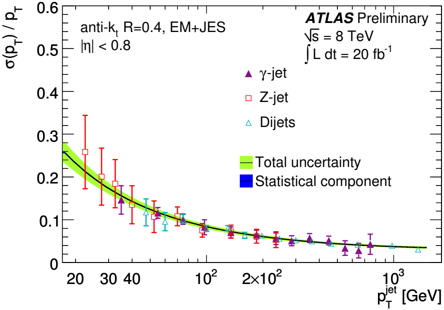
- The full JES uncertainties contain the previously described *in situ* uncertainties as well as additional uncertainties for the modeling of pile-up, the flavour composition and response differences between generators, and finally single particle response at the highest p_{T}.
- At low p_{T} the pile-up uncertainties dominate, then the flavour response of gluon jets which are not directly probed by the *in situ* measurements, then the photon energy scale and finally single particle uncertainties.
- At high $|\eta|$ we are dominated by modeling issues of the balance between forward and central jets.



Jet Energy Resolution Measurement (Run I) ATLAS-CONF-2015-037

- These same balance distributions (γ-jet, Z-jet and di-jet) can be used to extract the Jet Energy Resolution.
- The truth level imbalance of the systems is corrected for by subtracting it in quadrature.
- The results from the 3 systems are combined with a measurement of the noise from pile-up taken from the fluctuations seen in random cones in unbiased data.





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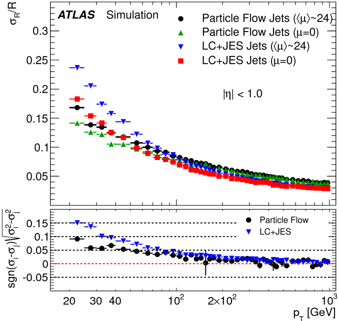
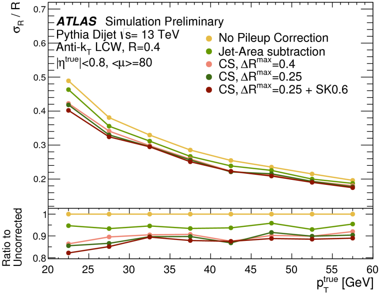
Pile-Up Effect on Jet Resolution arXiv:1703.10485,ATLAS-CONF-2017-065

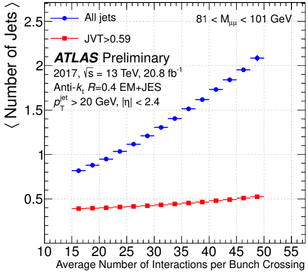
- Pile-up falling within a jet cone affects the scale and also the resolution.
- While the pile-up corrections correct for the former effect they cannot eliminate the latter such that the resolution grows with increasing μ - particularly at low p_T.
- Particle flow mitigates this by subtracting pile-up track-by-track.
- Additional constituent based subtraction techniques are being investigated as well.

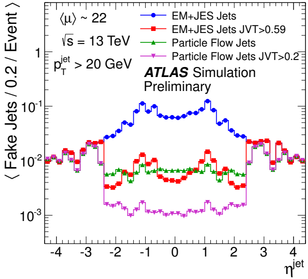




Pile-Up Jets and Rejection JETM-2017-009, JETM-2017-006

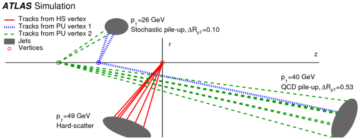
- Pile-up creates additional reconstructed jets - affects analyses and E_T^{miss}
- *Jet Vertex Tagger* is a likelihood based on the tracks pointing at the jet, designed to reject pile-up jets while keeping hard-scatter jets. ATLAS-CONF-2014-018
- It uses the fraction of track p_T from the HS as a fraction of the total, and the ratio of track p_T from the HS and the calorimeter p_T.
- Particle Flow also helps the rejection of pile-up jets (but maintains high efficiency).

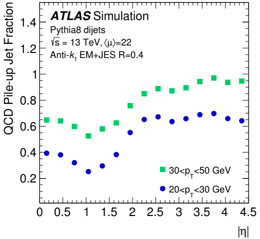


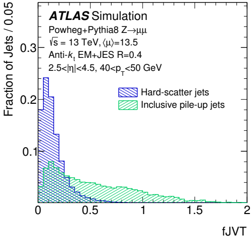


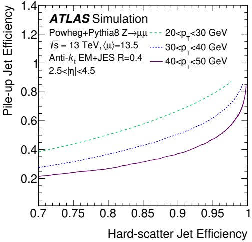
Forward Pile-Up Jets and Rejection arXiv:1705.02211

- Pile-up jets can either be from a combination of other vertices (stochastic) or a single vertex (QCD).
- For forward jets we try to identify central pile-up jets that balance forward jets as these are mainly QCD.
- Also looking at calo timing and jet shapes to reject stochastic pile-up.



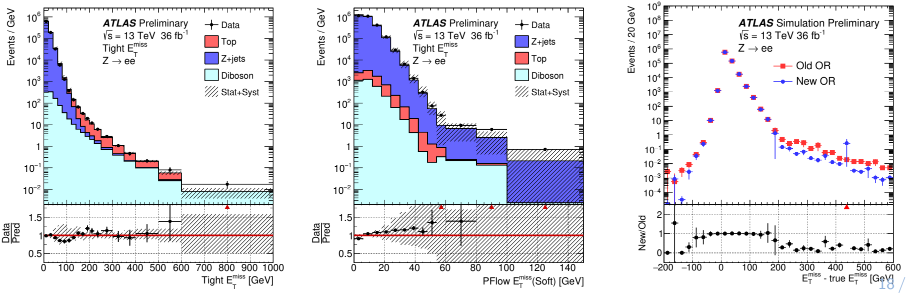






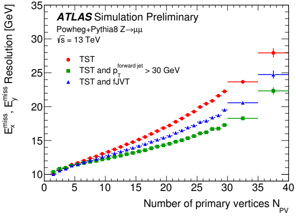
E_T^{miss} - NEW CONF ATLAS-CONF-2018-023

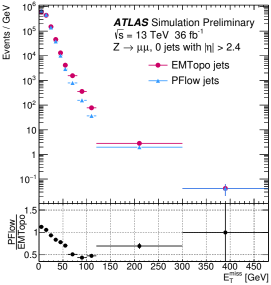
- ATLAS uses a object-based definition of the E_T^{miss}
- We take all the hard objects in the event; muons, electrons, photons, taus and jets, which are above threshold.
- We resolve the overlap between these at the cluster/track level - this has been further optimized in this CONF.
- For soft energy flow we take tracks from the primary vertex (soft neutral particles are not included as pile-up contaminates that calorimeter).

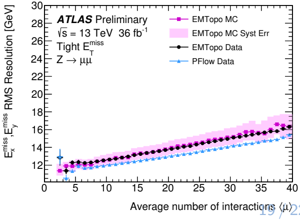


E_T^{miss} Working Points ATLAS-CONF-2018-023

- Several different working points are provided for analyses.
- In particular as pile-up increases the forward pile-up jets contribute to the E_T^{miss} resolution a lot.
- Therefore better performance is achieved either using the forward pile-up rejection, or increasing the threshold for forward jets to be included in the E_T^{miss}.
- Using particle flow jets improves the resolution, particularly in events without forward jets.

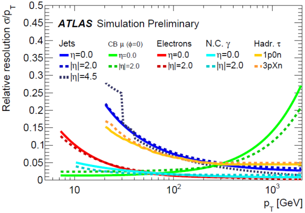


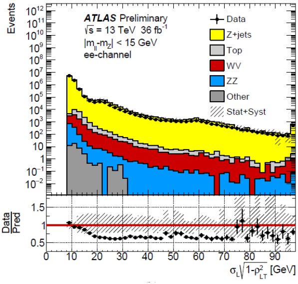


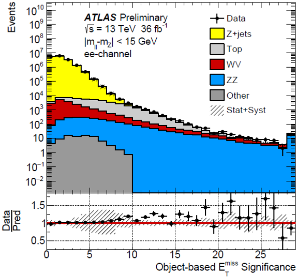


$E_{\mathrm{T}}^{\mathrm{miss}}$ Significance - NEW CONF ATLAS-CONF-2018-038

- As the $E_{\mathrm{T}}^{\mathrm{miss}}$ consists of a series of well defined hard objects and a soft term we can determine an object-based significance of the $E_{\mathrm{T}}^{\mathrm{miss}}$.
- The resolutions of all the hard objects are propagated as well as a gaussian to account for the missing neutral particles in the soft term.
- This exploits both the scale of the $E_{\mathrm{T}}^{\mathrm{miss}}$ as well as its direction.
- Good data-to-MC agreement is seen both for the $E_{\mathrm{T}}^{\mathrm{miss}}$ significance.

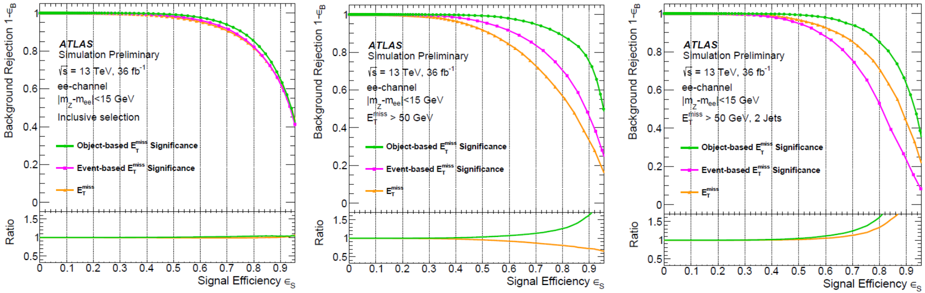






E_T^{miss} Significance Performance ATLAS-CONF-2018-038

- To test the performance of this significance we create ROC curves for a signal of $ZZ \to ll\nu\nu$ against a background of $Z \to ll$.
- For an inclusive selection little gain is found but when combined with a soft E_T^{miss} cut or a more realistic analysis selection significant improvements in the performance are observed.
- Also see D. Portillo's poster at the conference on this topic!



Conclusions

- Jet reconstruction is an important part of the ATLAS physics program.
- The Jet Energy Scale is derived from data and the uncertainty is $< 1\%$ for a $0.1 < p_{\mathrm{T}} < 1$ TeV in the central region.
- Despite this the JES uncertainty remains one of the leading experimental uncertainties in many analyses.
- Therefore work continues to measure this more precisely using the larger full Run II dataset.
- $E_{\mathrm{T}}^{\mathrm{miss}}$ reconstruction also important for many searches and measurements.
- Careful reconstruction of this to avoid fake $E_{\mathrm{T}}^{\mathrm{miss}}$ tails continues.
- The newly developed $E_{\mathrm{T}}^{\mathrm{miss}}$ significance shows promise for extracting signals more effectively from background.
- We still find that the $E_{\mathrm{T}}^{\mathrm{miss}}$ is dependent on pile-up and work continues to reduce this dependence.