ATLAS Jet Reconstruction, Calibration, and Tagging

Steven Schramm
On behalf of the ATLAS Collaboration

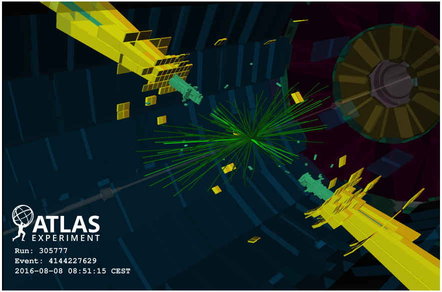
ICNFP 2017 – Crete, Greece

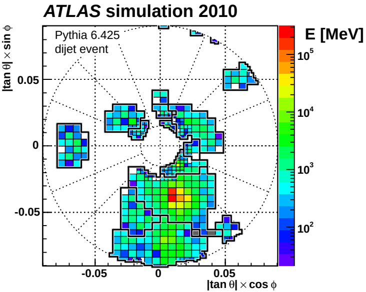
August 23, 2017

Introduction to jets

Left: EXOT-2016-21
Right: PERF-2014-07

- Jets are a tool to represent hadronic showers in a detector
- ATLAS primarily uses the anti-k_t algorithm, with topo-cluster inputs
  - Topo-clusters: topological groups of noise-suppressed calorimeter cells
  - Topo-clusters can be EM-scale or LCW-scale (hadronic scale)
- Depending on physics intent, different types of jets are useful
  - Primarily small-R ($R = 0.4$) EM jets and large-R ($R = 1.0$) LCW jets
- Jets can have different underlying sources → jet tagging
  - Small-R mostly for quarks/gluons, large-R for energetic W/Z/H/top/X

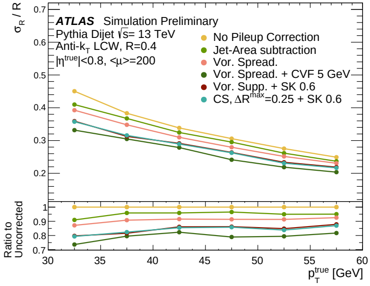


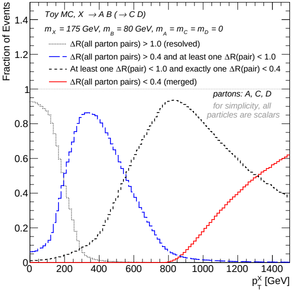


Jet inputs

Left: CONF-2017-065
Right: CONF-2017-062

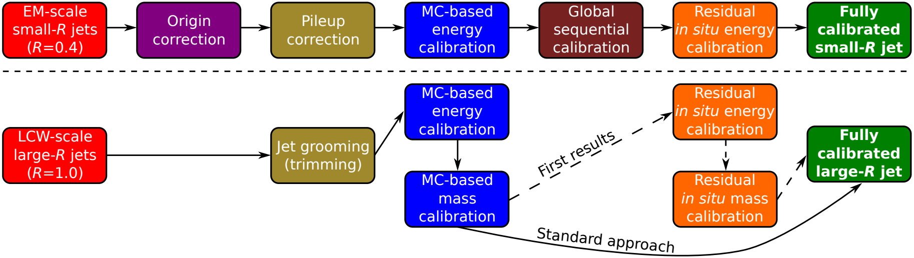
- Jets can be built from any set of 4-vectors
  - Topo-clusters, tracks, particle flow objects, truth particles, ...
- Topo-clusters can be pileup-suppressed (several techniques)
  - **S**oft**K**iller, Voronoi ($\times 2$), **C**onstituent **S**ub, **C**luster **V**ertex **F**raction, ...
  - Large improvements in low-p_{T} jet resolution in high lumi environments
- (Larger) jets can even be built from (smaller) jets: **reclustering**
  - Take advantage of well-known and well-measured small-R jets
- Unless mentioned, following slides use standard topo-clusters





Jet calibration overview

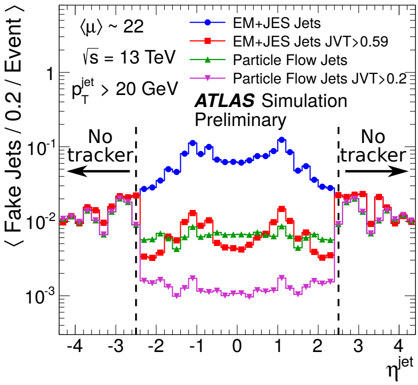
- Jets need to be calibrated to account for several effects
  - Pileup, non-compensating calorimeter response, data/MC diffs, etc
- The calibration chain is different for small-R and large-R jets
  - In particular, Large-R jets include mass calibrations, not just energy
- Calibrations are becoming more similar as large-R jet usage grows
  - First results of large-R jet *in situ* calibrations will be presented

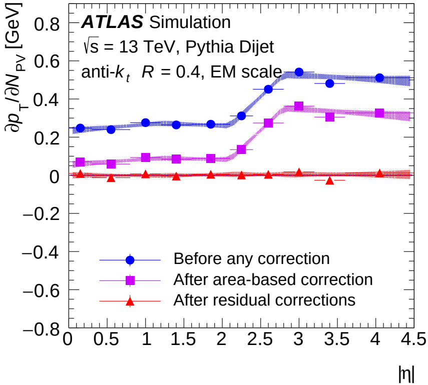


Small-*R* jet pileup suppression

Left: JETM-2017-006
Right: PERF-2016-04

- Suppress pileup jets by exploiting tracking information
  - Jet Vertex Tagger (JVT): veto if most tracks from additional vertices
  - Particle flow: build jets from a mix of track and cluster information
- Dynamically remove pileup energy from hard-scatter jets
  - $p_{\mathrm{T}}^{\mathrm{corr}} = p_{\mathrm{T}} - \rho \mathcal{A}_{\mathrm{jet}} - \alpha(N_{\mathrm{PV}} - 1) - \beta\mu$

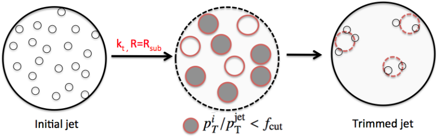


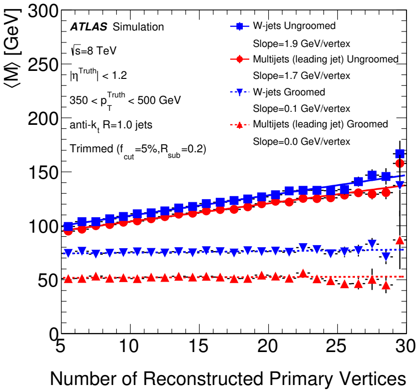


Large-R jet pileup suppression

Top: PERF-2012-02
Bottom: PERF-2015-03

- Larger radius means more susceptible to pileup
- Significant impact on key variables, even at high p_{T}
- ATLAS uses **trimming** to counteract pileup effects
    - Build $R = 0.2$ sub-jets
    - Check if $\frac{p_{\mathrm{T}}^{R=0.2}}{p_{\mathrm{T}}^{R=1.0}} < 5\%$
    - Remove such sub-jets
- Resulting jets are very stable with respect to pileup
    - Even stable for $\langle\mu\rangle = 200$

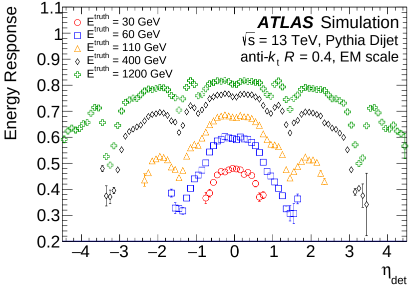


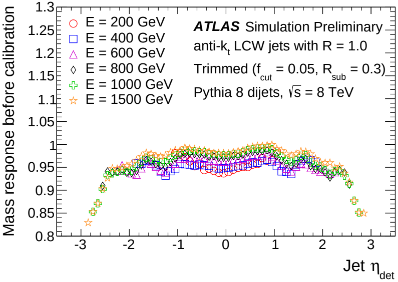


Monte Carlo (MC) calibration

Left: PERF-2016-04
Right: CONF-2015-037

- A substantial fraction of hadronic shower energy is not measured
  - Nuclear binding energy from strong interactions, inactive material, etc
- MC information is used to correct for such effects
  - Response: $X_{\mathrm{reco}}/X_{\mathrm{true}}$, numerical inversion gives calibration factor
  - After energy calibration, average jet is at the truth scale
- Small-R jets: further energy corrections to fix residual effects (GSC)
  - Shower development, flavour differences (q vs g), punch-through
- Large-R jets: subsequent mass calibration

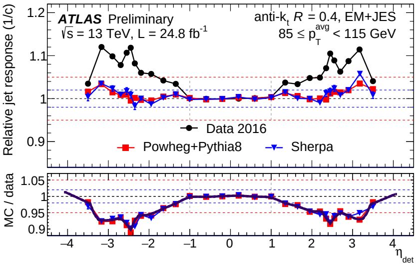


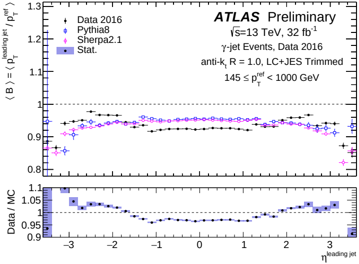


Relative *in situ* correction

Left: JETM-2017-003
Right: CONF-2017-063

- Previous calibration steps assume that MC perfectly represents data
- It is important to fix residual data/MC differences
- Small-R jets use η-intercalibration to do this
  - Correct scale of forward jets with respect to well-known central jets
  - Do in both data and MC to fix data/MC differences
- Large-R jets: first studies demonstrate η dependence
  - Balance of photon and jet varies, requires a correction for $|\eta| \gtrsim 1.2$

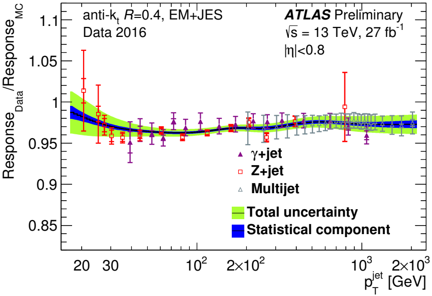


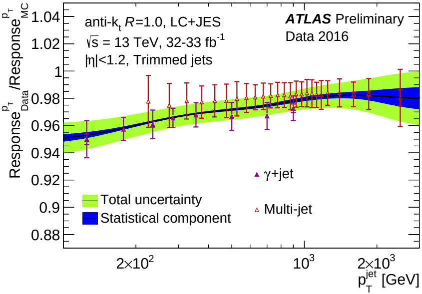


Absolute *in situ* correction

Left: JETM-2017-003
Right: CONF-2017-063

- Relative scale of jets across the detector is now fixed
  - The absolute scale may still differ between data and MC
- Investigate with three methods, using well-known reference objects
  - Balance of $Z \to \ell\ell$ and a jet, for low p_{T} jets
  - Balance of a photon γ and a jet, for medium p_{T} jets
  - Multi-jet balance, using a recoil system of Z/γ calibrated jets
- The results are then combined, providing a final calibration

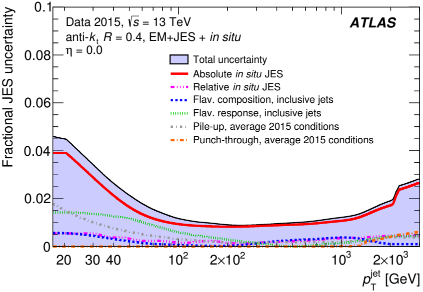


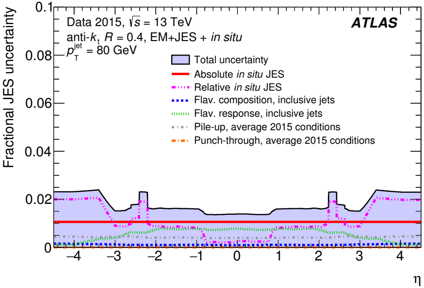


Small-R jet uncertainties

Both: PERF-2016-04

- The *in situ* corrections (relative and absolute) correct data to MC
  - This correction has uncertainties, which are evaluated
- There are additional uncertainties beyond the *in situ*
  - Flavour dependence, pileup, and punch-through are also considered
- 1-2% uncertainty on the energy scale from p_T of $50\,\mathrm{GeV}$ to $2\,\mathrm{TeV}$

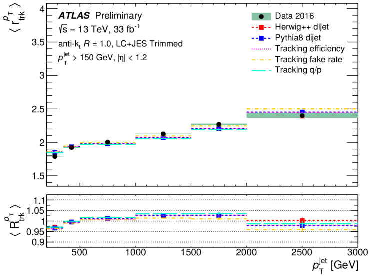


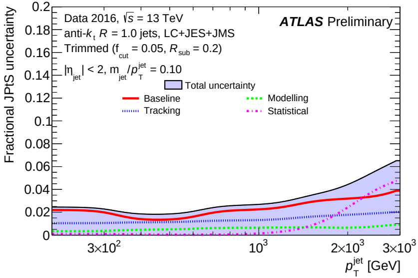


$\mathcal{R}_{\text{trk}}$ and large-R jet uncertainties

Both: CONF-2017-063

- First look at large-R jet *in situ* corrections was shown
  - However, do not yet cover full kinematic range (lack of η correction)
- Different procedure for uncertainty on X: $\mathcal{R}_{\text{trk}} = \frac{(X_{\text{calo}}/X_{\text{track}})_{\text{data}}}{(X_{\text{calo}}/X_{\text{track}})_{\text{MC}}}$
  - Does not correct data/MC differences, only an uncertainty on them
  - Baseline: raw $\mathcal{R}_{\text{trk}}$ difference from 1 between data and Pythia8
  - Modelling: Pythia8 vs Herwig++ difference in $\mathcal{R}_{\text{trk}}$
  - Tracking: tracking efficiency, momentum, and fake tracks
- Larger uncertainties, but quick and can be used for any variable

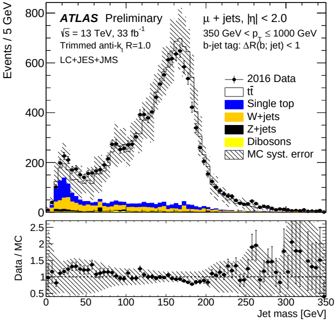


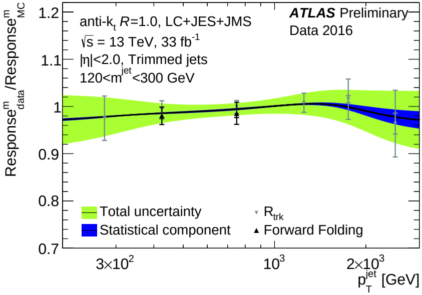


Jet mass and forward folding

Both: CONF-2017-063

- Forward folding allows for measuring the mass scale and resolution
- Idea: construct high-purity W or top selection, look at data and MC
    - Shift and smear the distribution until data and MC agree
    - This gives the mass scale and resolution data/MC difference
- Forward folding is very limited in where it can be derived (statistics)
    - $\mathcal{R}_{\mathrm{trk}}$ is used to extrapolate to other kinematic regimes

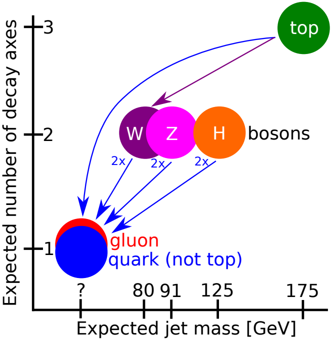


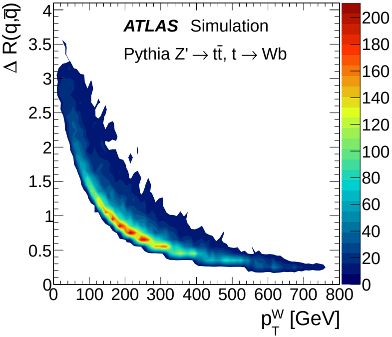


Hadronic object tagging

Right: PERF-2012-02

- Hadronic decays of massive particles can come from many sources
  - Main examples: W→ qq', Z→ $q\bar{q}$, H→ $b\bar{b}$, top→ bW→ bqq'
- Higher parent particle energy $\implies$ decay product collimation
  - Idea of "boosted decays", rule-of-thumb $\Delta R \gtrsim 2m^X/p_{\mathrm{T}}^X$
- Results in all decay products within a single jet
  - *Jet substructure* distinguishes different parent particles (or q vs g)

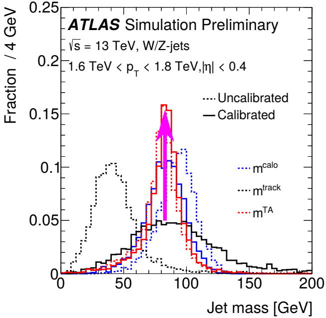


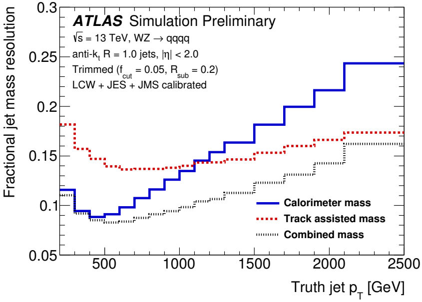


Combined jet mass

Left: CONF-2016-035
Right: JETM-2017-002

- Jet mass is the most intuitive substructure variable
  - Signal jets should have the mass of the parent particle
- Mass defined by energy and angular separation between constituents
- At very high p_T, calorimeter may not resolve the constituents
  - *Track-assisted* jet mass addresses this, $m_\mathrm{jet}^\mathrm{TA} = m_\mathrm{jet}^\mathrm{track} \frac{p_\mathrm{T}^\mathrm{calo}}{p_\mathrm{T}^\mathrm{track}}$
- Combination $m_\mathrm{jet}^\mathrm{comb} = A(p_\mathrm{T}) \times m_\mathrm{jet}^\mathrm{calo} + B(p_\mathrm{T}) \times m_\mathrm{jet}^\mathrm{TA}$ is best of both worlds

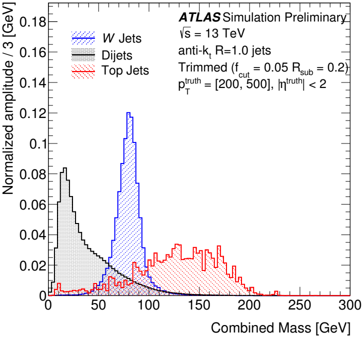


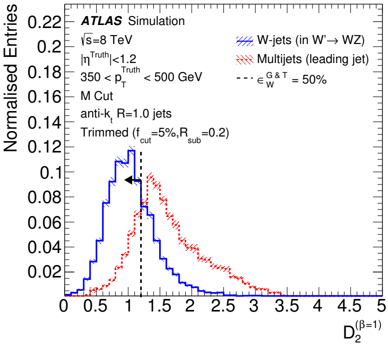


Jet substructure

Left: CONF-2017-064
Right: PERF-2015-03

- Combined mass provides good separation between QCD, W, and top
  - A good first step to tagging a hadronic decay
- Other substructure variables quantify further differences
  - $D_2^{\beta=1}$ is the most powerful variable (after mass) for W/Z tagging
  - τ_{32}^{wta} is the most powerful variable (after mass) for top tagging
  - Both quantify consistency of jet angular distribution with signal

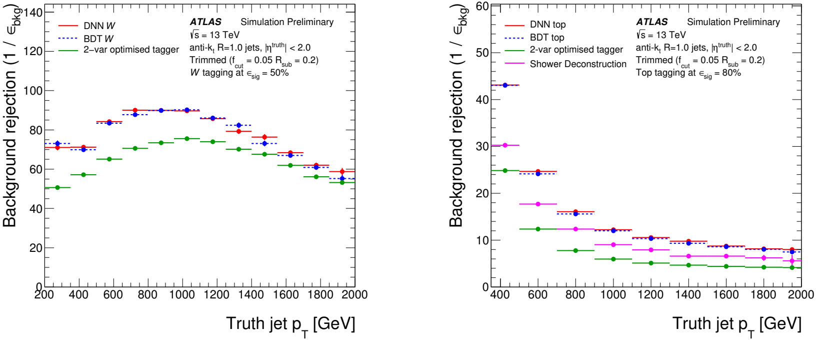




W-boson and top-quark tagging

Both: CONF-2017-064

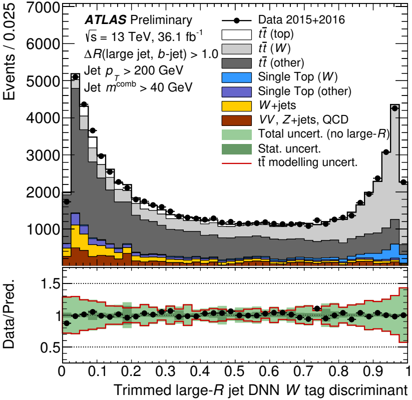
- W and top taggers are optimized with two-variable cuts
- Plots show QCD rejection as a function of p_{T}
  - W-tagging is for a 50% signal efficiency, top uses 80% signal efficiency
- Boosted Decision Trees and Deep Neural Networks also studied
  - Use roughly 10 substructure variables as inputs
  - Reasonable gains with respect to simpler methods

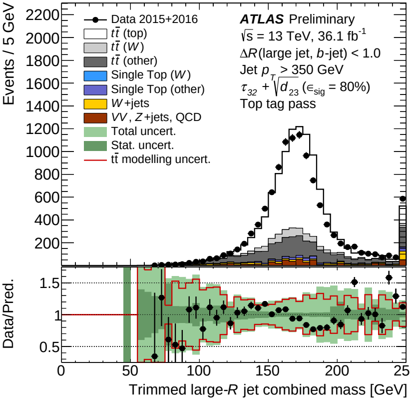


W-bosons and top-quarks in data

Both: CONF-2017-064

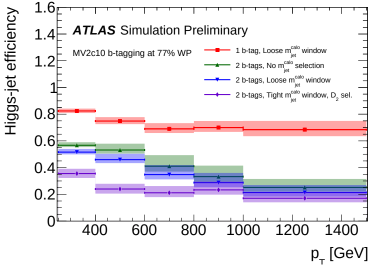
- BDT and DNN discriminants agree nicely between data and MC
  - Shown for W-tagging using a DNN
- Application of taggers can select high purity regions
  - Shown for top-tagging using a two-variable tagger

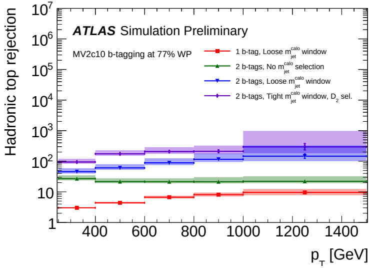




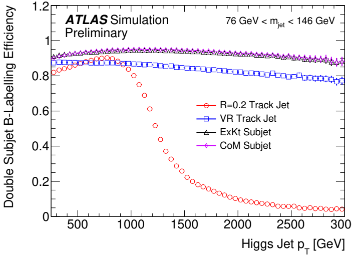
H→bb tagging

Left: PUB-2017-010
Right: CONF-2016-039





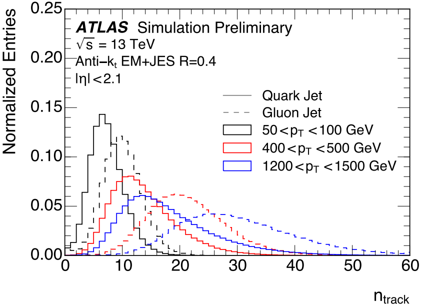
- H-tagging uses *b*-tagging and substructure information
  - *b*-tagging: QCD rejection
  - Substructure: top, $g \to bb$
- At high p_T, track-jets for *b*-tagging merge (truth-level)
  - New jet types recover eff.

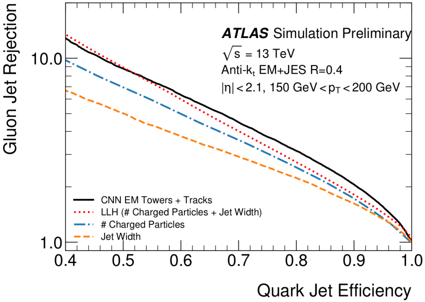


Quark vs gluon tagging

Left: PUB-2017-009
Right: PUB-2017-017

- Differentiating quarks from gluons is different in several ways
  - Jet mass is not useful (not a hadronically decaying massive particle)
  - Uses small-R jets rather than large-R jets
- Best single variable is track multiplicity (gluons radiate more)
- Also tried a convolutional neural network (CNN)
  - Some gains over a two-variable tagger for high quark efficiencies

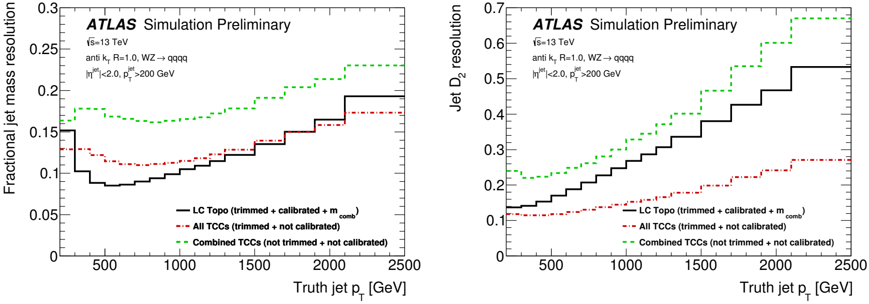




Tagging into the future

Both: PUB-2017-015

- Calorimeter's ability to resolve highly boosted decays is degraded
    - Ideal: angular resolution of the tracker and scale of the calorimeter
- ATLAS is developing a substructure-oriented particle flow "TCC"
    - Combined mass currently superior at low p_T, TCC better at high p_T
    - TCC vastly superior for non-mass substructure variables
- TCC algorithm promises large gains to future hadronic object tagging



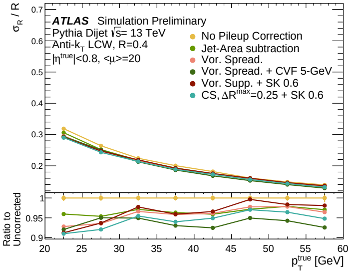
Summary

- ATLAS jets are typically built of calorimeter topo-clusters
  - Jets built using particle flow objects are also starting to be used
- ATLAS makes use of small-R (0.4) and large-R (1.0) jets
  - Both jet types are calibrated in several steps
  - Account for pileup, calorimeter response, and data/MC differences
- Jets are also used to tag hadronic showers
  - W, Z, H, and top tagging using large-R jets
  - quark vs gluon discrimination using small-R jets
  - Machine learning methods (BDTs, DNNs, CNNs) studied for tagging
  - Work ongoing to improve highly boosted jet substructure and tagging
- This talk focused on current techniques, used in 2015 and 2016
  - Lots of work is ongoing to prepare for the future!

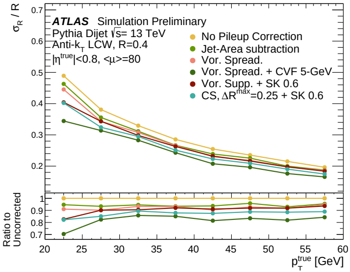
Backup Material

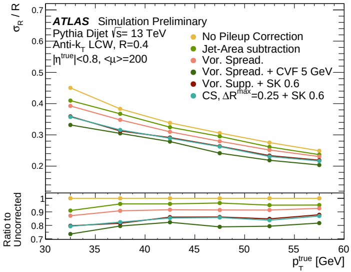
Constituent-level pileup suppression

All: CONF-2017-065



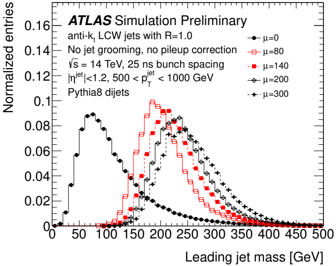
- Small gains compared to nominal (jet areas) in low pileup environment
- Large gains by $\langle \mu \rangle = 200$

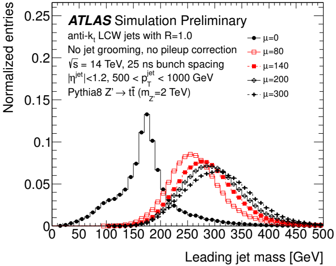


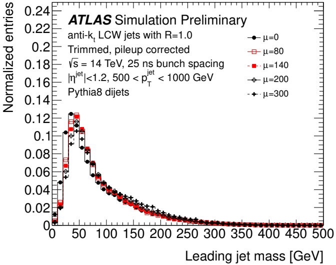


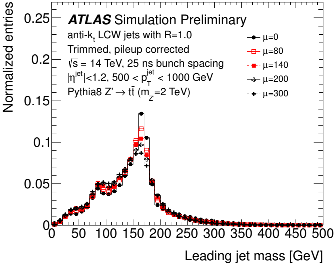
Trimming at high luminosity

All: JetSubstructureECFA2014





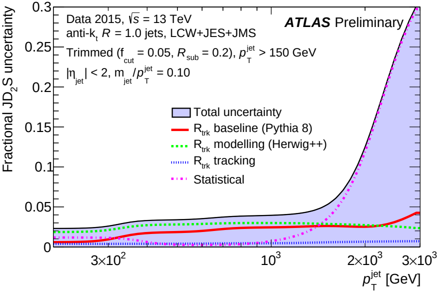


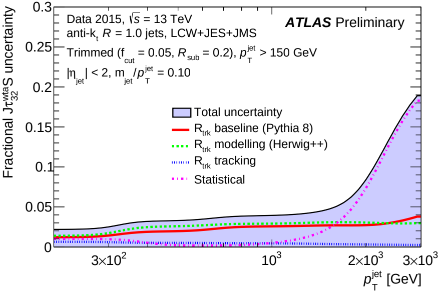


Jet substructure uncertainties

Both: JETM-2016-009

- The $\mathcal{R}_{\mathrm{trk}}$ method is used to derive substructure uncertainties
- Shown for $\mathrm{D}_2^{\beta=1}$ (W/Z tagging) and τ_{32}^{wta} (top tagging)
- Plots are older (2015 data only), and thus are statistically limited
    - Update with 2016 data reduces the statistical component significantly
- Uncertainties are under control, so they can be used for object tagging





Jet reclustering

Both: CONF-2017-062

- Idea: small-R jets are already carefully calibrated and understood
  - Build large-R jets from them, take advantage of small-R knowledge
  - Allows for choosing the jet radius you want, not only $R = 1.0$
- Typically smaller uncertainties in the range of interest ($p_\mathrm{T} \lesssim 1\,\mathrm{TeV}$)
- Also improved mass resolution, compared to $m_\mathrm{jet}^\mathrm{calo}$ (not $m_\mathrm{jet}^\mathrm{comb}$)
- Performance degrades at higher p_T (increased boost)
  - Effective reclustered jet size becomes one small-R jet