34th Rencontres de Blois on "Particle Physics and Cosmology"

Redefining Performance: New Techniques for ATLAS Jet & MET Calibration

Peter Berta

Charles University

(on behalf of the ATLAS Collaboration)

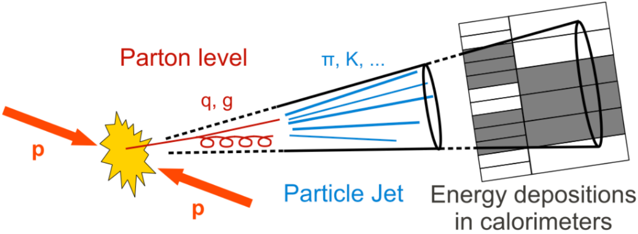
17^{th} May 2023

PRIMUS

This project has received funding from the Primus research programme of Charles University (project No 21/SCI/017)

Hadronic Jets and $E_{\mathrm{T}}^{\mathrm{miss}}$ at the Large Hadron Collider

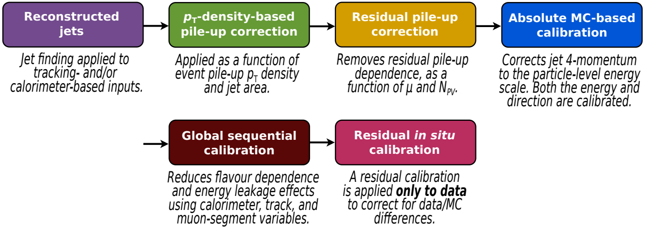
- Jets
  - collimated spray of particles originating from quarks and gluons
  - key ingredient of many Standard Model measurements and New Physics searches,
  - jet energy scale (JES) and resolution (JER) uncertainties
    - main contribution to the systematic uncertainty of many physics results
- Missing transverse energy ($E_{\mathrm{T}}^{\mathrm{miss}}$)
  - important signature for many physics processes (involving neutrinos or hypothetical particles not interacting in the detector)



https://cms.cern/news/jets-cms-and-determination-their-energy-scale

Jet reconstruction and calibration in ATLAS

- Baseline jet inputs: Particle Flow Objects (PFOs)
  - Combined track and calorimeter information
- Two main jet definitions:
  - Small-R jets - clustered using anti-k_t algorithm with distance parameter 0.4
  - Large-R jets - clustered using anti-k_t algorithm with distance parameter 1.0
- Calibration process for small-R jets:



Reconstructed jets

Jet finding applied to tracking- and/or calorimeter-based inputs.

p_T-density-based pile-up correction

Applied as a function of event pile-up p_T density and jet area.

Residual pile-up correction

Removes residual pile-up dependence, as a function of μ and N_{PV}.

Absolute MC-based calibration

Corrects jet 4-momentum to the particle-level energy scale. Both the energy and direction are calibrated.

Global sequential calibration

Reduces flavour dependence and energy leakage effects using calorimeter, track, and muon-segment variables.

Residual *in situ* calibration

*A residual calibration is applied **only to data** to correct for data/MC differences.*

- Eur. Phys. J. C 81 (2021) 689

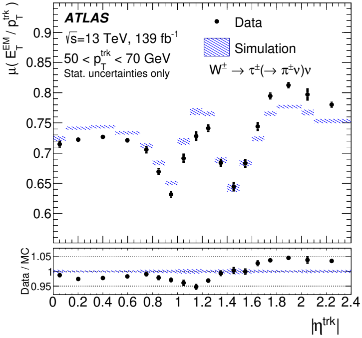
New techniques presented in this talk

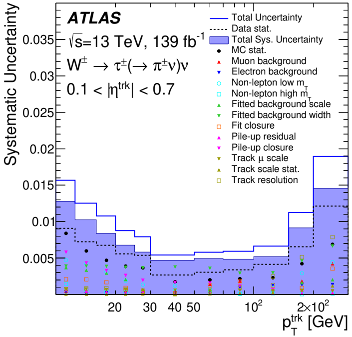
- Calorimeter response to charged pions - Eur. Phys. J. C 82 (2022) 223
- Dependence of the jet response on modelling of particle types and spectra - ATL-PHYS-PUB-2022-021
- Jet Energy Scale uncertainties with updated flavour treatment - JETM-2022-005
- New techniques for jet calibration - arXiv:2303.17312
  - Improved pileup mitigation
  - b-jet JES
- Unified Flow Objects, new jet inputs - ATL-PHYS-PUB-2022-038, Eur. Phys. J. C 81 (2021) 334
- $E_{\mathrm{T}}^{\mathrm{miss}}$ using neural networks - ATL-PHYS-PUB-2021-025

Also see the talk from Xiang Chen about Improving ATLAS hadronic object performance with ML/AI Algorithms (Wednesday at 18:40)

Calorimeter response to charged pions

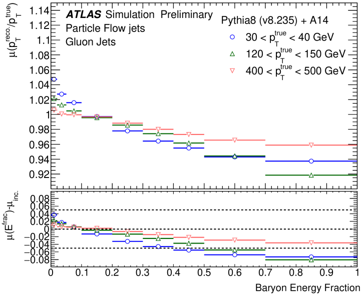
- A new in-situ method to measure hadronic energy response - Eur. Phys. J. C 82 (2022) 223
  - Using isolated charged pions from decay chain $W^\pm \to \tau^\pm \nu \to \pi^\pm \nu\nu$
- Measuring calorimeter response $\mu(E_T^{\mathrm{EM}}/p_T^{\mathrm{trk}})$
  - overestimated by ∼2% in the central region and underestimated by ∼4% in the endcaps
- Improved precision over the test-beam data previously used
- Useful for tuning of simulations to improve the hadron-shower modelling

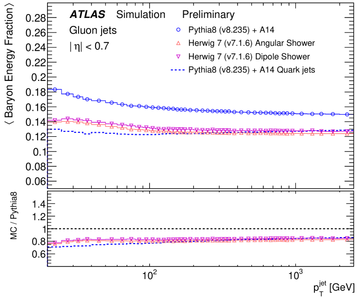




Simulated jet response dependence on the particle content

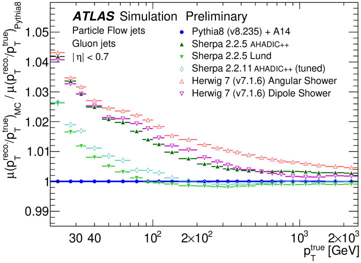
- Compared multiple hadronization models - ATL-PHYS-PUB-2022-021
- ATLAS calorimeters are non-compensating
    - ⇒ jet response depends on baryon and kaon energy fractions
        - these fractions vary significantly between generator configurations

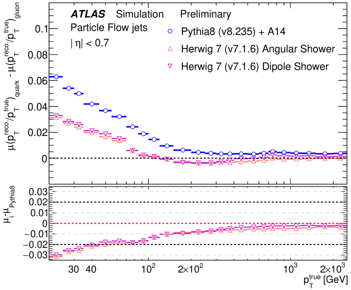




Simulated jet response dependence on the particle content

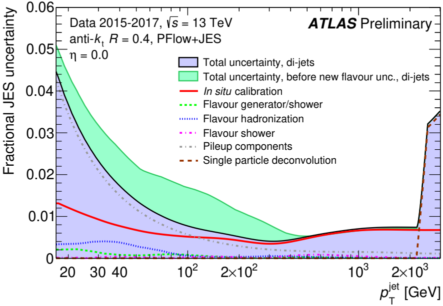
- Up to ∼3% differences for jet response between various generator configurations
    - leads to large JES uncertainties
- Quark vs gluon jets have different response
- This gives a large motivation to tune baryon and kaon production in the generator configurations
    - possibility to use the measurements from LEP
    - requires precise measurements of the baryon and kaon energy fractions of jets at the LHC (potentially possible by the ALICE detector)
    - can lead to a significant improvement of LHC precision measurements





New treatment of JES flavour uncertainties

- Achieved improvement in JES flavour uncertainty - JETM-2022-005
- Previous treatment: differences in gluon-jet response between Herwig7 and Pythia8 + flavour composition
- New treatment: Based on the studies from the 2 previous slides + comparison with LEP and ATLAS Data. Three components:
  - Hadronization - Sherpa tuned cluster vs Sherpa Lund string
  - Parton shower - angular ordered vs CS dipole shower in Herwig7
  - Generator/Parton shower - Pythia8 (p_{T} orderded shower) vs Sherpa (CS dipole shower) Lund string



Improved pileup mitigation for jets

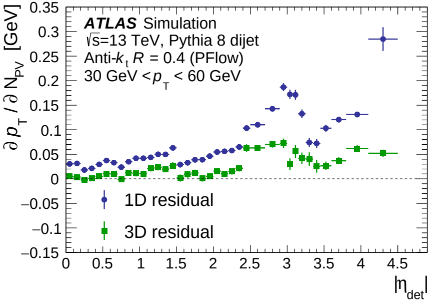
- Residual pileup correction in ATLAS
  - removes residual pileup dependence after the jet-area pileup correction
- Baseline method: 1D residual correction - Eur. Phys. J. C 81 (2021) 689

$$p_{\mathrm{T}}^{1D} = p_{\mathrm{T}}^{area} - \alpha(N_{\mathrm{PV}} - 1) - \beta\mu \qquad (1)$$

- Alternative method: 3D residual correction - arXiv:2303.17312

$$p_{\mathrm{T}}^{3D} = p_{\mathrm{T}}^{area} - \Delta p_{\mathrm{T}}^{area-truth}\left(N_{\mathrm{PV}}, \mu, p_{\mathrm{T}}^{area}\right) \qquad (2)$$

- Significant reduction of pileup dependence with the alternative method

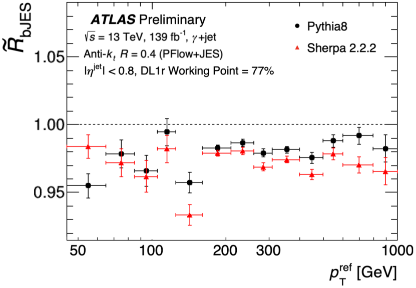


JES for b-jets

- Investigated how JES differs between b-jets and other-flavour jets - arXiv:2303.17312
- Using $\gamma + \mathrm{jet}$ balance method
  - exploits the p_T balance between a jet and a reference photon
  - obtained double ratio of responses:

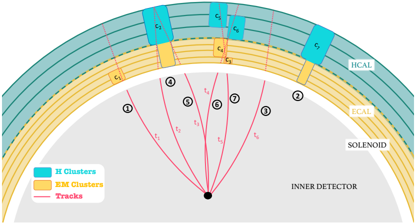
$$\tilde{R}_{bJES} = \frac{R^{MC}_{b-tagged} / R^{Data}_{b-tagged}}{R^{MC}_{inclusive} / R^{Data}_{inclusive}} \tag{3}$$

- Data/MC ratio is underestimated for b-tagged jets by $1 - 3.5\%$
- This will help to measure the top-quark mass or b-quark Yukawa coupling



Unified Flow Objects - new jet inputs

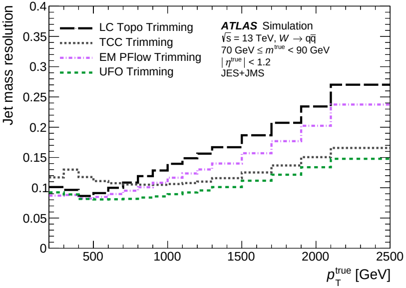
- Unified Flow Objects (UFOs) - Eur. Phys. J. C 81 (2021) 334
  - improved particle flow objects by applying the "Track-CaloClusters" technique
    - ATL-PHYS-PUB-2017-015
    - use tracks to split up large clusters based on the energy flow and their direction
    - improvement of the jet mass resolution at high jet p_T
- Event-wide pileup correction applied on UFOs before jet clustering:
  - Charged Hadron Subtraction (CHS) - to mitigate charged pileup
  - Constituent Subtraction followed by SoftKiller (CS+SK) - to mitigate neutral pileup

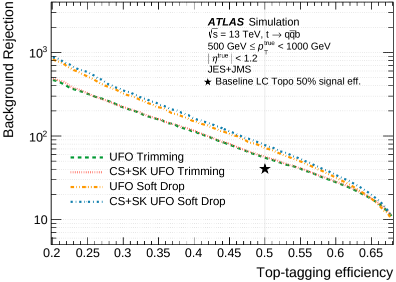


A schematic demonstrating the creation of TCC objects

Unified Flow Objects - large-R jet performance

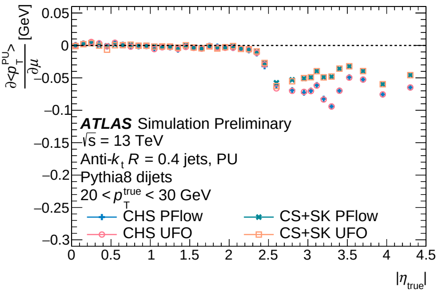
- Performed a reoptimisation of the large-R jet reconstruction algorithms in ATLAS - Eur. Phys. J. C 81 (2021) 334
  - performance comparison for different jet input objects (including UFOs), pileup mitigation algorithms and jet grooming algorithms
- Improved jet mass resolution for jets from UFOs
- Jets from UFOs significantly improve the identification of boosted objects
- Jets from UFOs using CS+SK pileup mitigation and additional soft-drop grooming provide the best performance

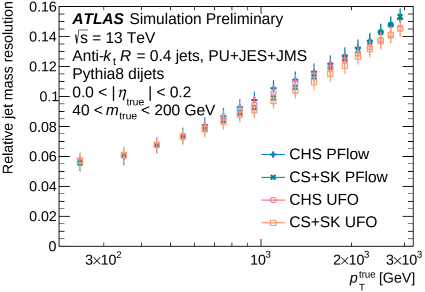




Unified Flow Objects - small-R jet performance

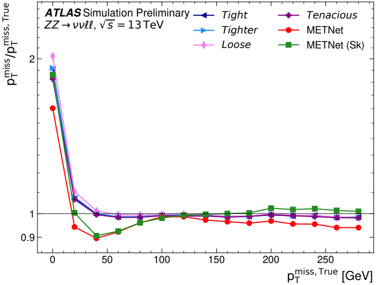
- Investigated the performance of small-R jets clustered from UFOs - ATL-PHYS-PUB-2022-038
- Jets reconstructed from UFOs are found to have similar or better performance than the baseline jet definition
- CS+SK pileup mitigation reduces pileup dependence

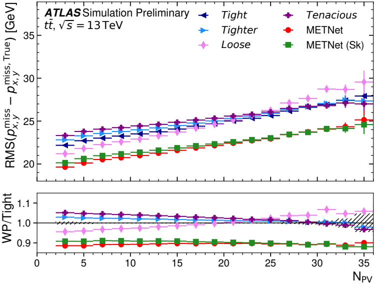




Improved $E_{\mathrm{T}}^{\mathrm{miss}}$ reconstruction using machine learning

- ATLAS employs a suite of working points for $E_{\mathrm{T}}^{\mathrm{miss}}$ reconstruction
  - each is optimal for different event topologies and beam conditions
- *METNet* - regressed $E_{\mathrm{T}}^{\mathrm{miss}}$ from a neural network ATL-PHYS-PUB-2021-025
  - trained on $E_{\mathrm{T}}^{\mathrm{miss}}$ terms for four established working points + variables that characterise event topology
- METNet has a significantly improved resolution
- Large potential to significantly improve $E_{\mathrm{T}}^{\mathrm{miss}}$ reconstruction using machine learning techniques.





Summary

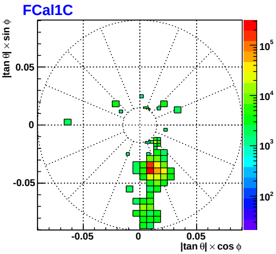
- Hadronic jets and $E_{\mathrm{T}}^{\mathrm{miss}}$ are key objects for most of the measurements in ATLAS
    - important to improve their resolution and calibration
- Many new techniques are explored in ATLAS
    - Lots of improvements at every step of the reconstruction and calibration of jets
- Run 3 just started - can exploit these developments and continue improving our strategies

- More ATLAS Jet and MET results: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/JetEtmissPublicResults

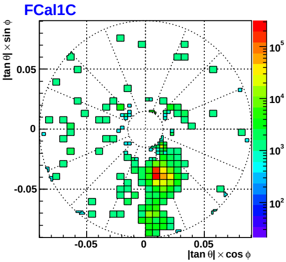
BACKUP

Topo-clusters

- group of calorimeter cells topologically connected,
- topo-cluster finding:
  - optimized to noise and pileup suppression
  - procedure:
    1. seeds - cells with $E > 4\sigma_{\text{noise}}$,
    2. neighbors - all cells with $E > 2\sigma_{\text{noise}}$ neighboring seed or other neighbors,
    3. perimeter cells - all cells with $E > 0$ on the perimeter of the group of seed and neighbors,

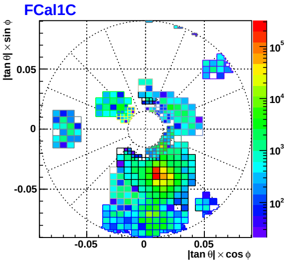


$E > 4\sigma_{\text{noise}}$



$E > 2\sigma_{\text{noise}}$

$\Longrightarrow$



topo-clusters (one layer)

ATL-LARG-PUB-2008-002

Topo-cluster calibration

Two options:

- electromagnetic scale (**EM topo-clusters**)
    - all topo-clusters calibrated to the response for electrons,
    - zero topo-cluster mass,
- local calibration weighting (**LCW topo-clusters**):
    - each topo-cluster classified as electromagnetic or hadronic deposit (depending on its energy density and depth),
    - a weighting scheme corrects for the different e/π response in the calorimeters,
    - out-of-cluster correction,
    - dead material correction,
    - zero topo-cluster mass.

Pileup correction

- offset correction for 2011 data
  - corrected jet p_{T}:

$$p_{\mathrm{T}}^{\mathrm{corr}} = p_{\mathrm{T}} - \alpha \cdot (N_{PV} - 1) - \beta \cdot \mu \quad (4)$$

    - N_{PV} - number of primary vertices,
    - μ - mean number of interactions,
    - α and β - parameters obtained from MC
  - reliance on the correct identification of tracks and vertices
- jet-area-based correction + residual offset correction for 2012 data
  - corrected jet p_{T}:

$$p_{\mathrm{T}}^{\mathrm{corr}} = p_{\mathrm{T}} - A \cdot \rho \quad (5)$$

  A - jet area, ρ - pileup p_{T} density
  - after it, residual offset correction similarly as for 2011 data

Residual in situ calibration

- Applied to Data only,
- Jet p_{T} correction: multiplication by the response ratio of the MC to the Data:

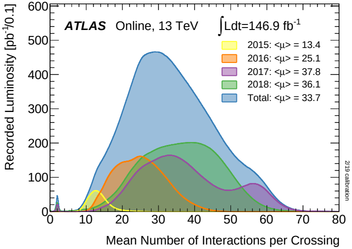
$$\frac{\mathrm{Response}_{\mathrm{MC}}}{\mathrm{Response}_{\mathrm{Data}}} = \frac{\left\langle p_{\mathrm{T}}^{\mathrm{jet}} / p_{\mathrm{T}}^{\mathrm{ref}} \right\rangle_{\mathrm{MC}}}{\left\langle p_{\mathrm{T}}^{\mathrm{jet}} / p_{\mathrm{T}}^{\mathrm{ref}} \right\rangle_{\mathrm{Data}}} \tag{6}$$

  Response $\left\langle p_{\mathrm{T}}^{\mathrm{jet}} / p_{\mathrm{T}}^{\mathrm{ref}} \right\rangle$ obtained from transverse momentum balance between jet and a reference object.

- several methods to cover large kinematic phase space:
  - dijet η-intercalibration,
  - γ+jet balance,
  - Z+jet balance,
  - multijet balance.

Pileup

- Additional proton-proton (pp) interactions in bunch crossings:
  - in-time pileup - pp interactions in the same bunch crossing, characterized by number of primary vertices, N_{PV},
  - out-of-time pileup - pp interactions in preceding bunch crossings, characterized by mean number of interactions, μ,
- One of the main challenges for jets due to additional energy deposits in calorimeters causing:
  - jet energy offset and worse resolution,
  - additional (fake) jets.



https://twiki.cern.ch/twiki/bin/view/AtlasPublic/LuminosityPublicResultsRun2

Missing transverse energy $E_{\mathrm{T}}^{\mathrm{miss}}$

- event quantity based on momentum conservation in the transverse plane:

$$E_{\mathrm{T}}^{\mathrm{miss}} = \sqrt{(E_x^{\mathrm{miss}})^2 + (E_y^{\mathrm{miss}})^2} \tag{7}$$

$$E_{x(y)}^{\mathrm{miss}} = -\left(E_{x(y)}^{\mathrm{jets}} + E_{x(y)}^{e} + E_{x(y)}^{\gamma} + E_{x(y)}^{\tau} + E_{x(y)}^{\mu} + E_{x(y)}^{\mathrm{Soft\ \ Term}}\right) \tag{8}$$

- $E_{x(y)}^{\mathrm{jets}}$, $E_{x(y)}^{e}$, $E_{x(y)}^{\gamma}$, $E_{x(y)}^{\tau}$ and $E_{x(y)}^{\mu}$ - sum of $x(y)$-component of the momentum of all jets, electrons, photons, taus and muons, respectively,
  - using anti-k_t $R = 0.4$ jets calibrated with LCW+JES scheme with $p_{\mathrm{T}} > 20\ \mathrm{GeV}$,
  - all objects are corrected for pileup and calibrated,
  - suppression of pileup jets: rejecting jets with $\mathrm{JVF} = 0$, $p_{\mathrm{T}} < 50\ \mathrm{GeV}$ and $|\eta| < 2.4$,
- Soft Term $E_{x(y)}^{\mathrm{Soft\ \ Term}}$ - sum of $x(y)$-component of the momentum of all topo-clusters and tracks not associated to above physics objects - avoiding double counting.