Redefining Performance: New Techniques for ATLAS Jet & MET Calibration

SUSY23 Conference, Southampton

On behalf of the ATLAS Collaboration
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July 17, 2023

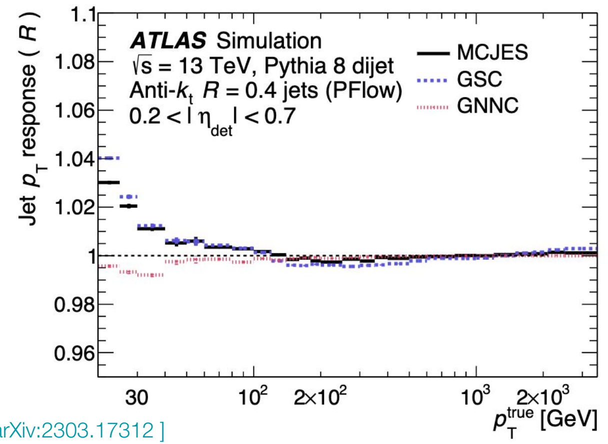
ATLAS EXPERIMENT

MAX-PLANCK-INSTITUT FÜR PHYSIK

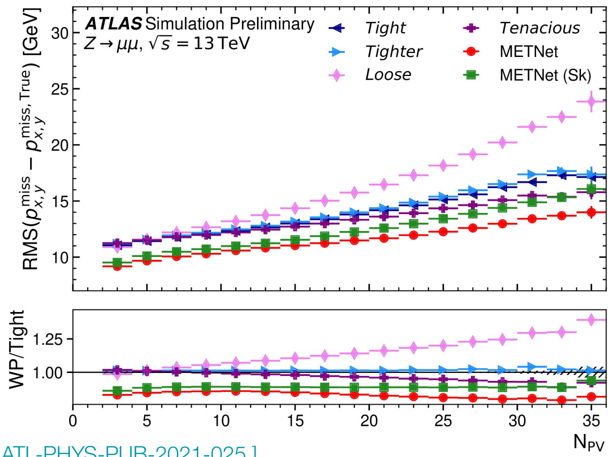
Outline

New Techniques for Jet Calibration

- Simulation-based calibration via ML



[arXiv:2303.17312]



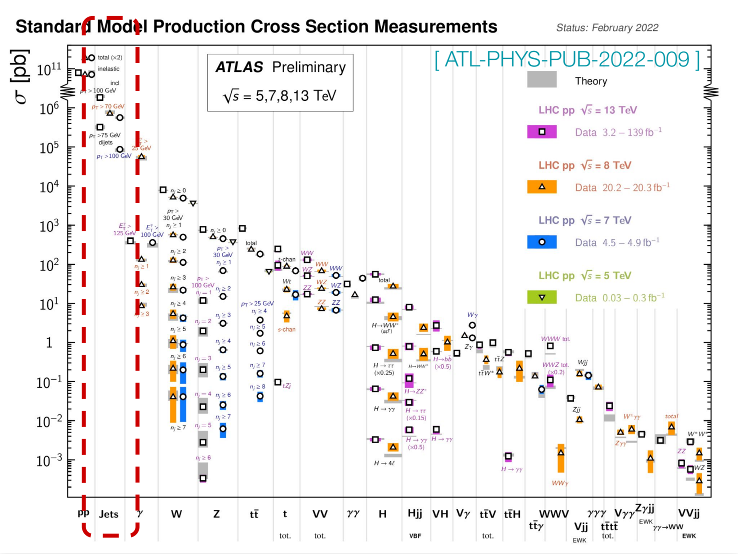
[ATL-PHYS-PUB-2021-025]

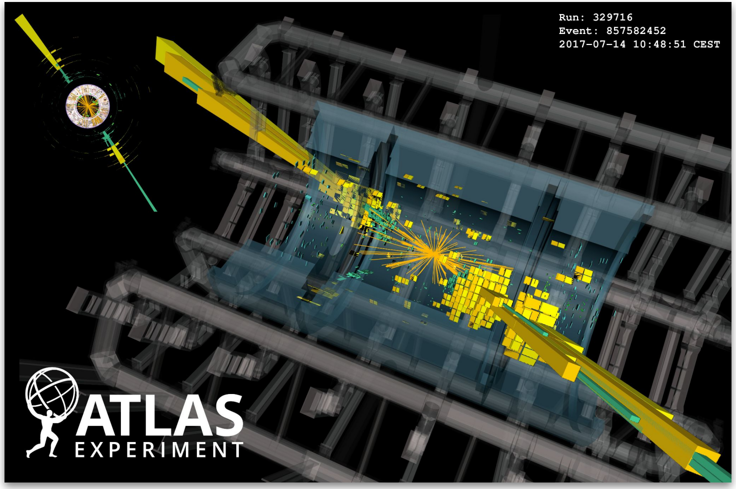
METNet: ML-based p_T^{miss} Reconstruction

- Regression of p_T^{miss} via DNN

The LHC: A “*Jetty*” Environment

- Our “*tools*”: Large-Hadron Collider (LHC) & ATLAS: *pp*-collisions at $\sqrt{s}$ = 13 TeV (13.6) in Run 2 (3) recorded with multi-purpose detector
- Strongly-interacting quarks & gluons hadronise
  → Reconstructed as ***jets***: collimated spray of particles





- Jets produced copiously at LHC!
  → Ingredient of nearly every SM measurement or BSM search
- Precise measurement of jet four-momenta crucial
  → Improvements directly “leverage” our physics results
- Percent-level precision already achieved, but still improving!

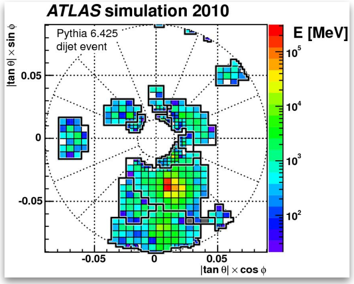
Jet Reconstruction at ATLAS in Run 2

Main objective: cluster tracks and calorimeter deposits together to obtain properties of initial quark/gluon

Step 1: Create low-level cluster objects (constituents)

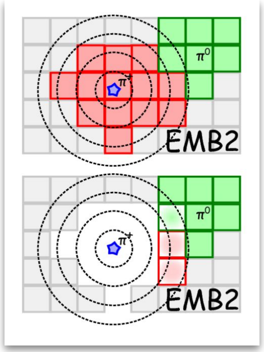
Topological Clusters
[arXiv:1603.02934v3]

Connected groups of calorimeter cells



Particle-Flow Objects (PFOs)
[arXiv:1703.10485v2]

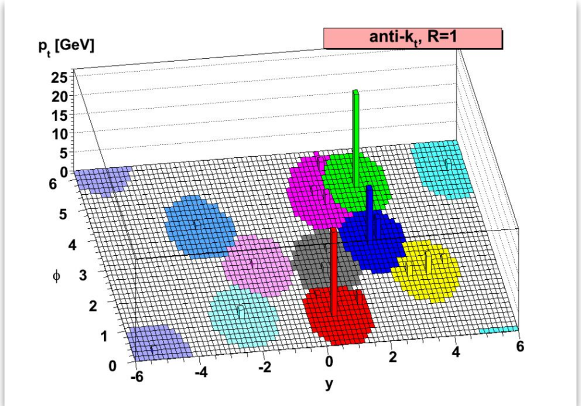
Combine tracks and topo-clusters



Step 2: Group clusters/PFOs into jets

Anti-k_T Algorithm
[arXiv:0802.1189v2]

Sequentially gather nearby constituents



Here: focus on small-radius jets with R=0.4

Please see Tobias' talk for *large-R jet reco, tagging & more*!

ATLAS Run 2 Jet Calibration Sequence

Calibrate Jets in Simulation & Data to Particle Level — *Correct for Data/MC Discrepancies*

Pileup Corrections → **Absolute MC-Based Calibration** → **Global Property Calibration** → **Residual *In Situ* Calibration**

Pileup Corrections

1) Correction based on pileup density & jet area
2) Removal of residual pileup dependence

Absolute MC-Based Calibration

Correction of energy & direction to particle-level scale

Response: $\mathcal{R} = \frac{E^{detector}}{E^{particle}}$

Global Property Calibration

Scale depends e.g. on quark/gluon nature of jet

Improve resolution by sequentially removing dependencies on visible features like n_{track}

Residual *In Situ* Calibration

Simulation not a perfect description of data

In situ corrections derived in data w.r.t. well-measured reference objects (Z, γ, ..)

ATLAS Run 2 Jet Calibration Sequence - Revised

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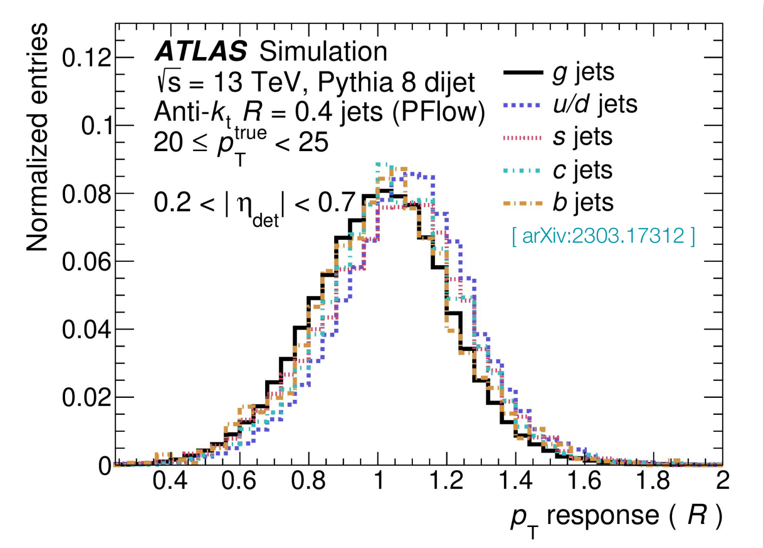
New Techniques [arXiv:2303.17312v1]

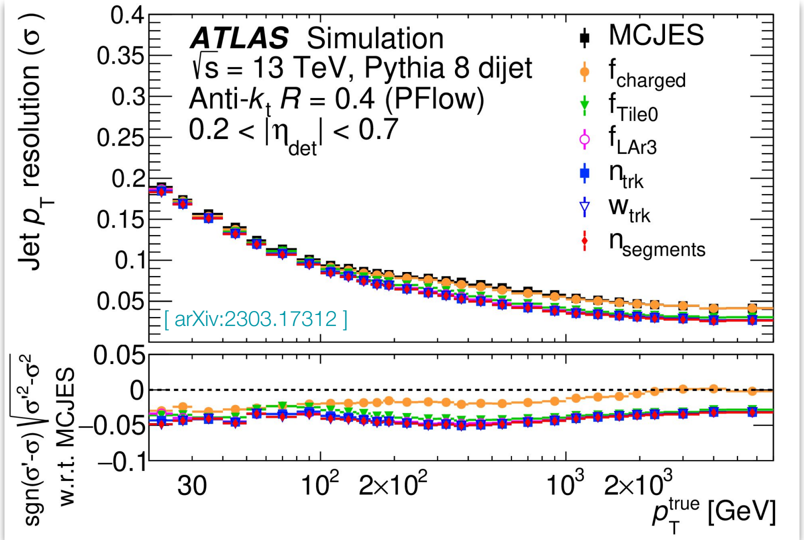
- Pileup Corrections: Sideband estimation of pileup density; 1D → 3D residual pileup correction
- Absolute MC-Based Calibration: Use penalised splines to fit jet response
- Global Property Calibration: DNN-based corrections
- Residual *In Situ* Calibration: Improved η-intercalibration; Measurement of *b*-jet JES in γ+jet events

Focus on this in the following!

Global Jet Property Calibration

- After absolute calibration, response still depends on characteristics of jet (width, charged fraction, …)
- Degrades jet energy resolution (JES)
- Mitigated by **Global Sequence Calibration (GSC)**
  → Series of 6 corrections applied one after another





- Subsequent improvement of resolution after each step!
- Reduces also differences in MC predictions
- Limitation of GSC: variables need to be uncorrelated

Simultaneous calibration in many "dimensions" desirable
→ **Perfect use case for Deep Neural Networks (DNNs)!**

Global Neural Network Calibration (GNNC)

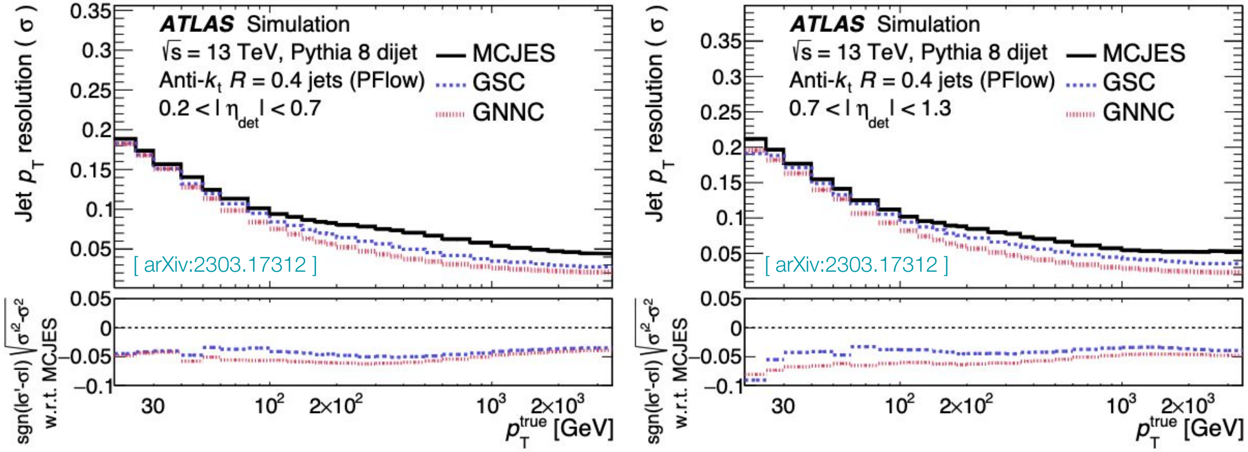
- Dedicated DNN trained in each η-bin to accommodate detector geometry
- DNNs designed to correct the p_T response by minimizing a leaky Gaussian Kernel loss:

$$\mathrm{Loss}(x^{\mathrm{target}}, x^{\mathrm{pred}}) = -\frac{1}{\sqrt{2\pi}} \exp\left(-\frac{(x^{\mathrm{target}} - x^{\mathrm{pred}})^2}{2\alpha^2}\right) + \beta|x^{\mathrm{target}} - x^{\mathrm{pred}}|,$$

p_T Response

Tunable Parameters

- Use more variables than in GSC to fully exploit potential of DNNs:
  More granular calorimeter information, jet kinematics & pile-up measures

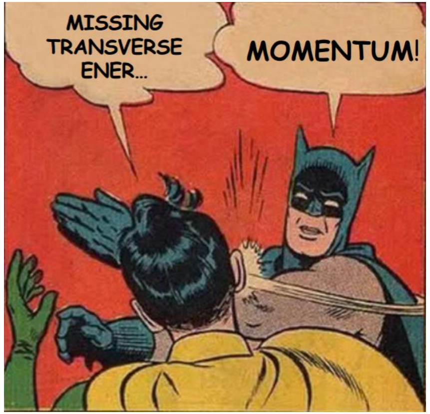


Up to 30% improvement on JES!

Smaller differences in response between gluon and quark jets → reduced reduced flavour uncertainty as well (backup)

Reminder: p_T^{miss} Reconstruction

- Infer presence of *"invisible"* particles via momentum imbalance in transverse plane
- Basic reconstruction algorithm is taking negative vector sum:



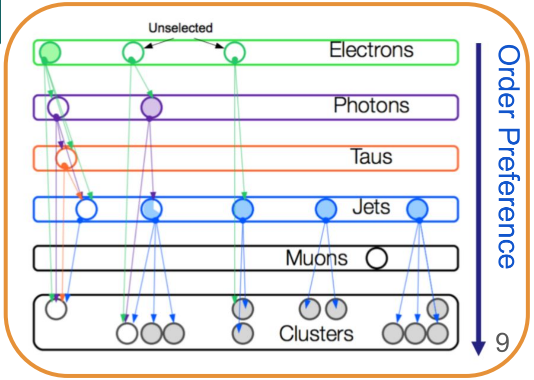
Object selection specified by Analysis

Specified by p_T^{miss} WP

$$\mathbf{p}_T^{miss} \; / \; \cancel{E}_T^{miss} = \underbrace{\underbrace{-\sum_{\substack{\text{selected}\\\text{electrons}}} \mathbf{p}_T^{e}}_{E_T^{miss,e}} \underbrace{-\sum_{\substack{\text{accepted}\\\text{photons}}} \mathbf{p}_T^{\gamma}}_{E_T^{miss,\gamma}} \underbrace{-\sum_{\substack{\text{accepted}\\\tau\text{-leptons}}} \mathbf{p}_T^{\tau_{had}}}_{E_T^{miss,\tau_{had}}} \underbrace{-\sum_{\substack{\text{selected}\\\text{muons}}} \mathbf{p}_T^{\mu}}_{E_T^{miss,\mu}} \underbrace{-\sum_{\substack{\text{accepted}\\\text{jets}}} \mathbf{p}_T^{jet}}_{E_T^{miss,jet}}}_{\text{hard term}} \boxed{\underbrace{\underbrace{-\sum_{\substack{\text{unused}\\\text{tracks}}} \mathbf{p}_T^{track}}_{E_T^{miss,soft}}}_{\text{soft term}}}$$

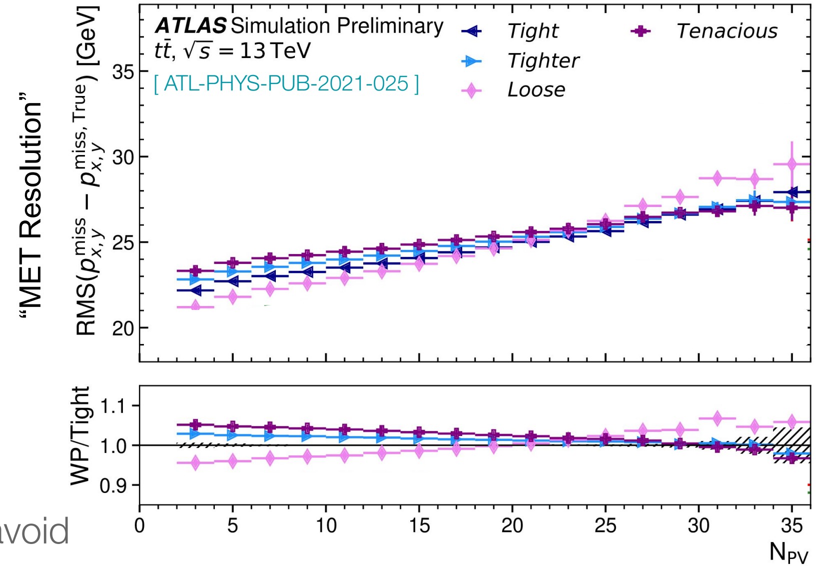
(+ internal overlap removal)

- Several p_T^{miss} WPs available (Tight, Loose, …) balancing resolution and pile-up resilience
- Track soft term (TST) contains tracks associated with hard-scatter vertex but not with any hard object
- Estimate for "p_T^{miss} significance" via likelihood-based technique



METNet: ML-based p_T^{miss} Reconstruction

- General idea: performance of p_T^{miss} WPs depend on event topology and level of pile-up
  → Let a DNN choose optimal WP for each event!
- Regression-based "METNet" trained on 60 inputs
  - Predictions of jet/soft terms of each p_T^{miss} WP
  - Lepton p_T^{miss} terms
  - Event-level pile-up quantities
- Training target: (p_x^{miss}, p_y^{miss}) at particle level
- Considered two different loss functions:
  - Huber loss & Huber + Sinkhorn loss
- Network trained on top-antitop events, evaluated on other topologies to validate generalization
- Training sample "flattened" up to p_T^{miss} = 300 GeV to avoid bias towards 0 in predictions



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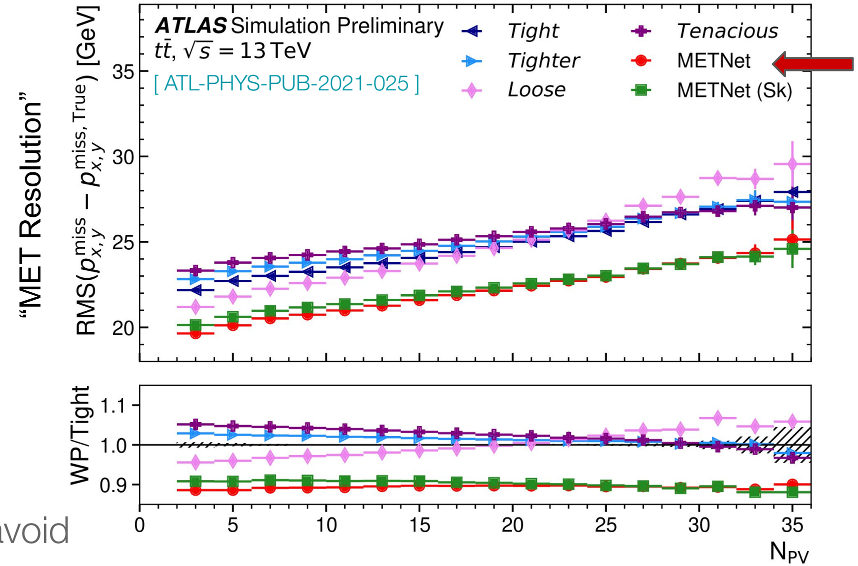
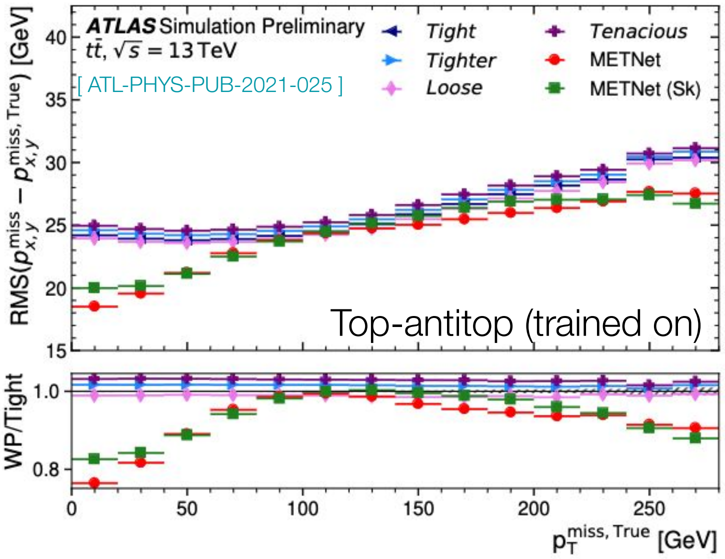
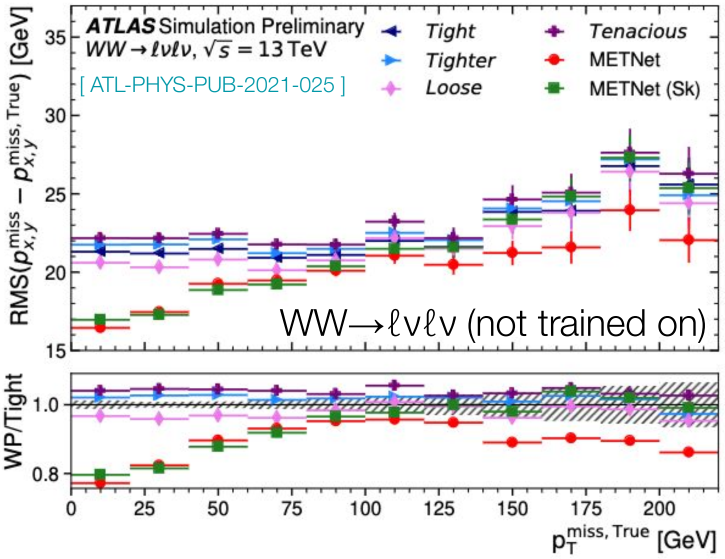


Substantial improvements in resolution by METNet!

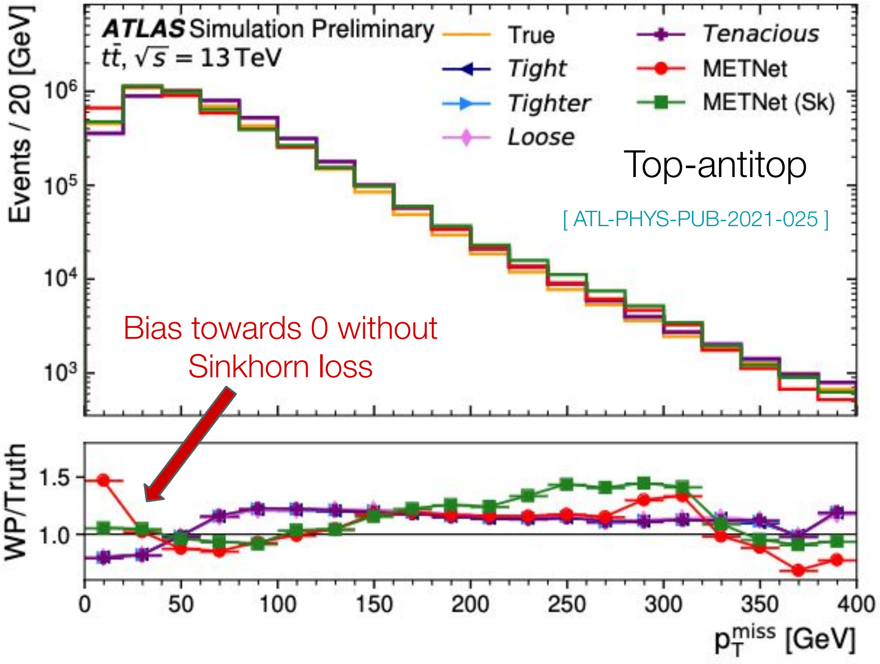
METNet: Generalization





- METNet has superior resolution across the p_T^{miss} range trained on
- Generalizes well to topologies not seen during training, such as Z→μμ and WW→ℓνℓν

METNet: Training Bias & Limitations



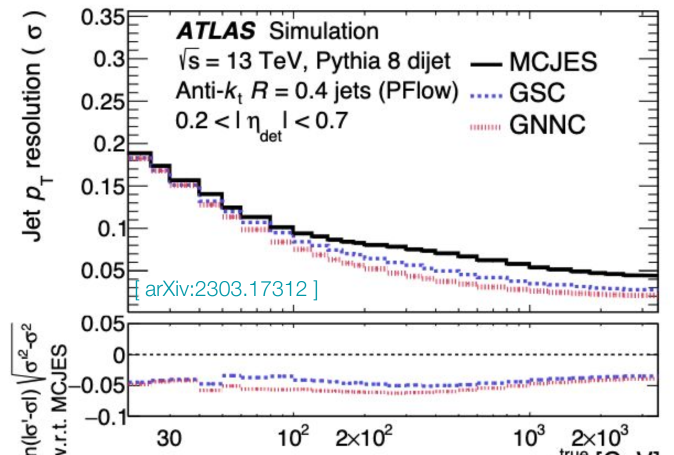
"Training bias": more events with low than with high p_T^{miss} → Challenging to tackle!

Limited performance of METNet outside training range ("*extrapolation*")

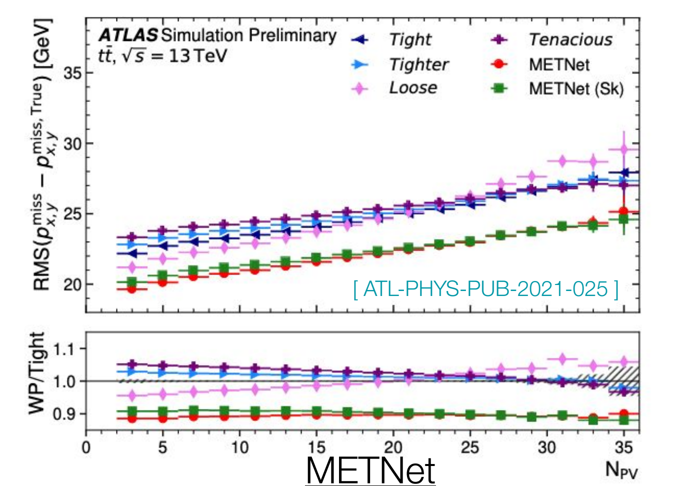
Classification-based METNet approach under study
→ Build weighted average of "classical" p_T^{miss} WPs

Summary & Outlook

- Jets and missing transverse momentum essential part of nearly all ATLAS measurements & searches
- Improvements in these areas directly translate into better physics results
- Established reconstruction and calibration techniques already provide percentage-level precision
- Many ongoing efforts for further improvements to be applied in Run 3!
  → Promising applications of ML-based techniques in jet calibration and p_T^{miss} reconstruction



GNNC



METNet

Extras

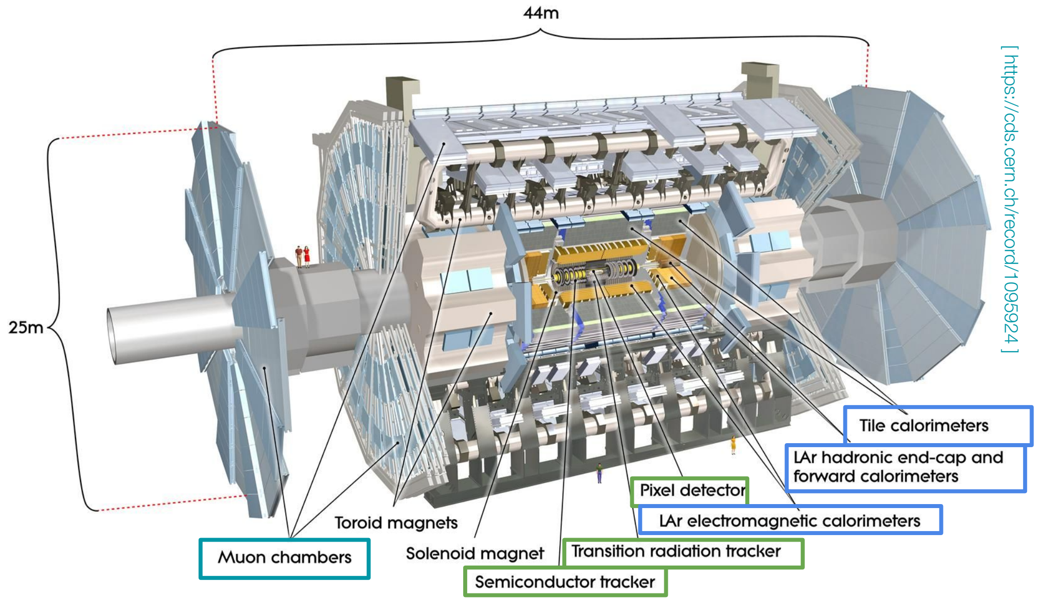
ATLAS Detector

Goal: Reconstruct products from *pp*-collisions: electrons, muons, jets, ..

Inner Detector
- Semiconductor & gas detectors
- Tracks and vertex reconstruction

Calorimeters
- LAr as active material
- Contain electromagnetic and hadronic showers
- Rebuild electrons, photons & jets

Muon Spectrometer
- Cover large area with gas detectors
- Reconstruction of muons



[https://cds.cern.ch/record/1095924]

- Collisions occur at ~30 Mhz
- Up to ~65 simultaneous *pp*-interactions in Run 2

Global Neural Network Calibration Inputs

Calorimeter	$f_{\mathrm{LAr}0-3*}$ $f_{\mathrm{Tile}0*-2}$ $f_{\mathrm{HEC},0-3}$ $f_{\mathrm{FCAL},0-2}$ $N_{90\%}$	The E_{frac} measured in the 0th-3rd layer of the EM LAr calorimeter The E_{frac} measured in the 0th-2nd layer of the hadronic tile calorimeter The E_{frac} measured in the 0th-3rd layer of the hadronic end cap calorimeter The E_{frac} measured in the 0th-2nd layer of the forward calorimeter The minimum number of clusters containing 90% of the jet energy
Jet kinematics	$p_{\mathrm{T}}^{\mathrm{JES}}$ * η^{det}	The jet p_{T} after the MCJES calibration The detector η
Tracking	w_{track}* N_{track}* f_{charged}*	The average p_{T}-weighted transverse distance in the η-ϕ plane between the jet axis and all tracks of $p_{\mathrm{T}} > 1$ GeV ghost-associated with the jet The number of tracks with $p_{\mathrm{T}} > 1$ GeV ghost-associated with the jet The fraction of the jet p_{T} measured from ghost-associated tracks
Muon segments	N_{segments}*	The number of muon track segments ghost-associated with the jet
Pile-up	μ N_{PV}	The average number of interactions per bunch crossing The number of reconstructed primary vertices

[arXiv:2303.17312]

GNNC - Flavor Uncertainties

$$\sigma_{\text{response}} = f_g(\mathcal{R}_{g,\text{Pythia8}} - \mathcal{R}_{g,\text{Herwig}})$$

$$\sigma_{\text{composition}} = \sigma_g^f \frac{\mathcal{R}_q - \mathcal{R}_g}{f_g\mathcal{R}_g + (1 - f_g)\mathcal{R}_q}$$