New techniques for reconstructing and calibrating hadronic objects with ATLAS

Arnau Morancho Tardà (Niels Bohr Institute)
on behalf of the ATLAS Collaboration

EPS-HEP2025

July 8th, 2025 - Marseille (France)

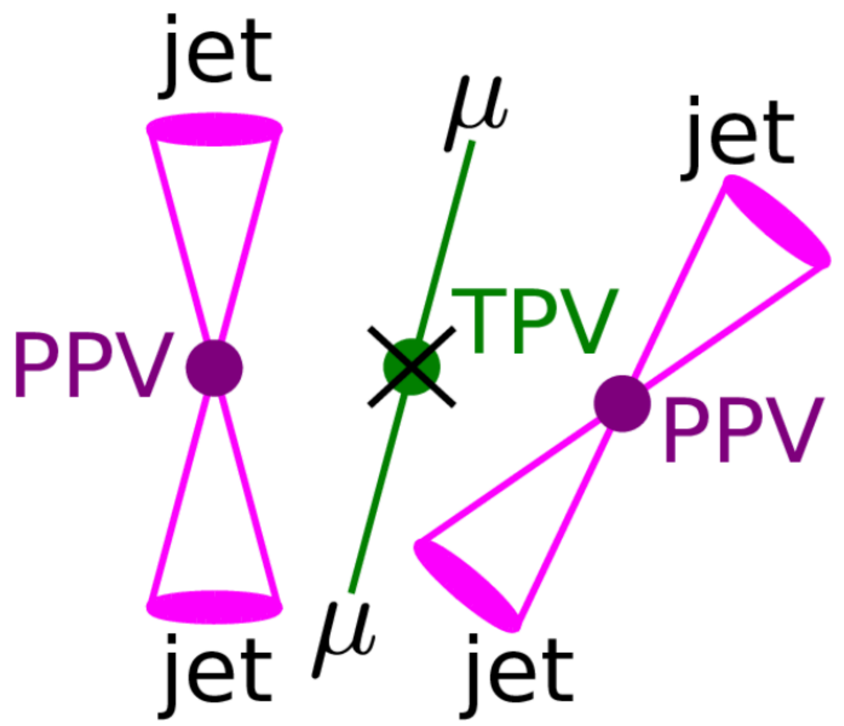
Event display: 2407.10819

UNIVERSITY OF COPENHAGEN

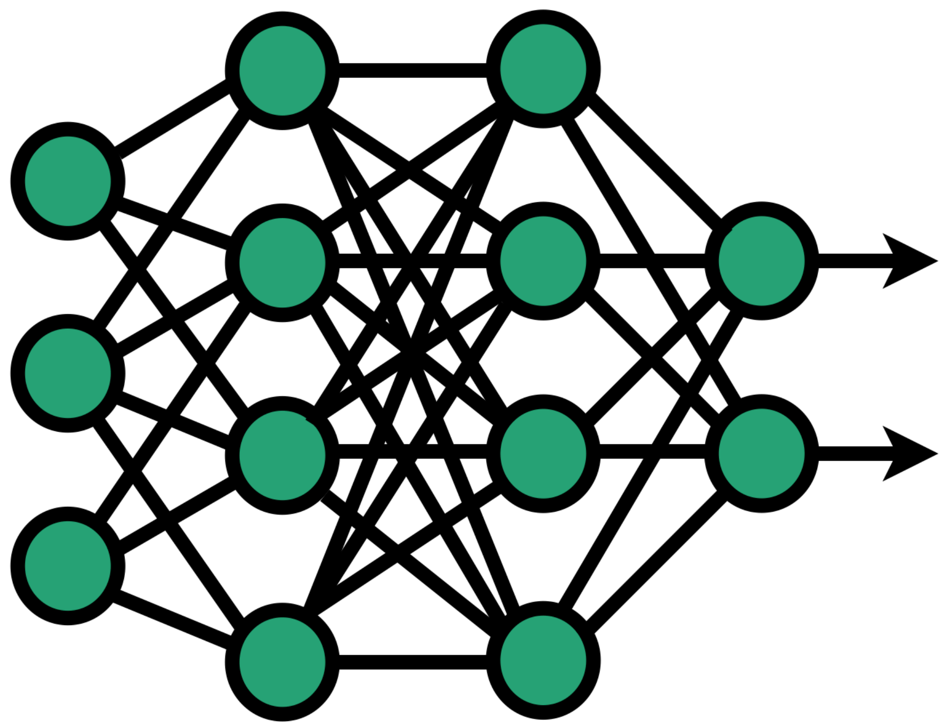
arnau.morancho.tarda@cern.ch

Outline

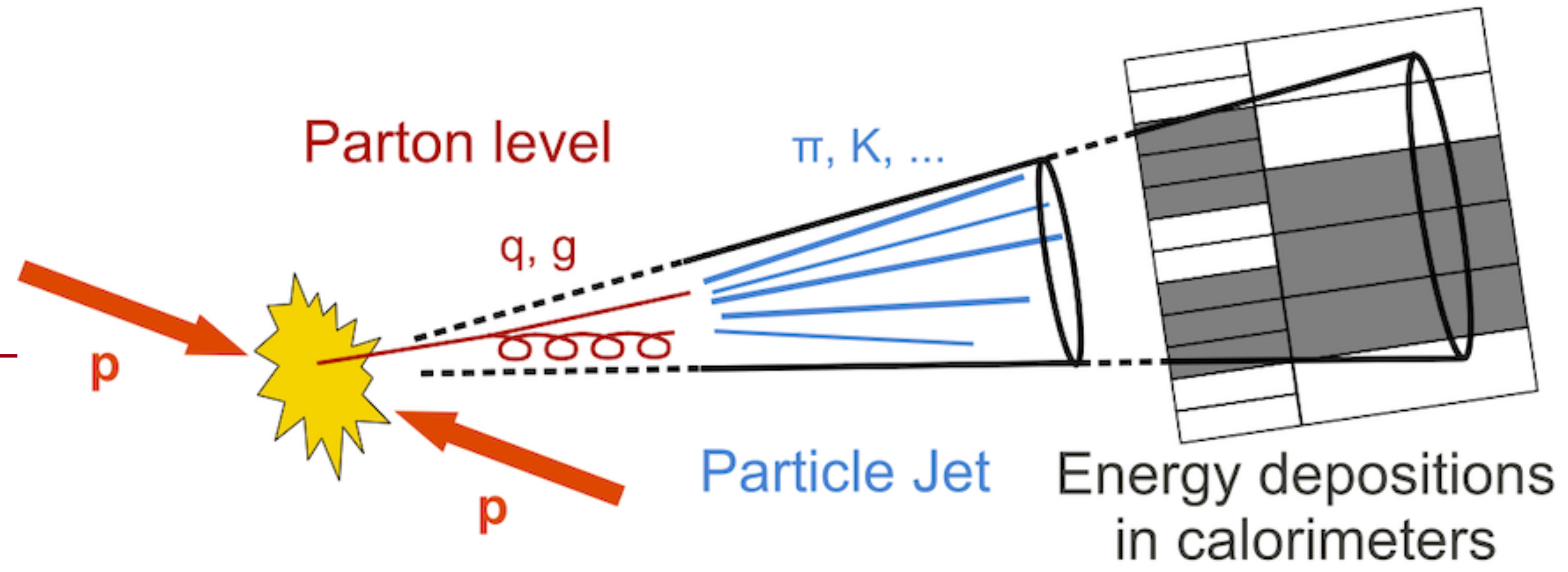
Performance gains on hadronic objects are achieved by different ideas shown in this presentation



1. Cell time cut
2. Single E/p measurements
3. Using pile-up events
4. Large-R regression with DNN
5. b-jet regression with transformer
6. Missing Transverse Energy



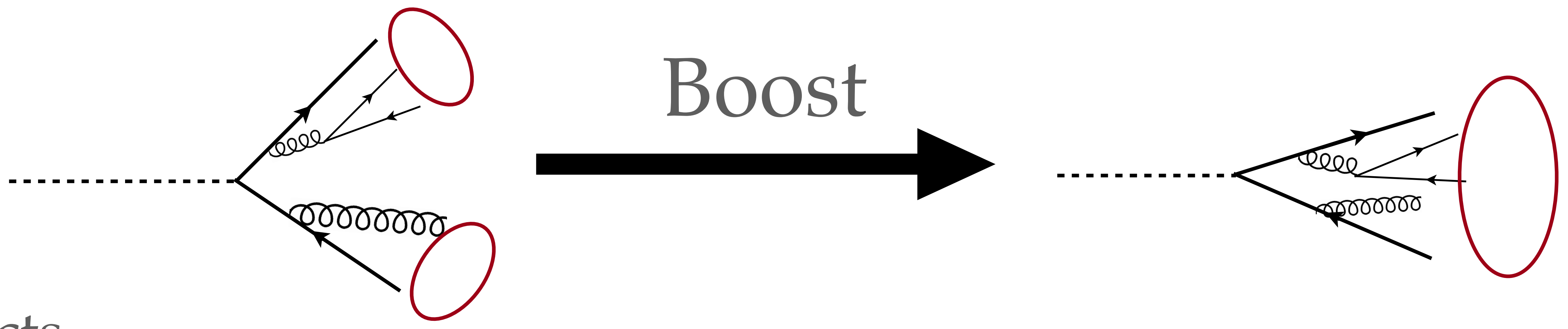
Introduction



What do we mean by hadronic objects?

- **Jets** are the outcome of the partons after showering and hadronisation giving the hadronic activity in pp collisions

  - In ATLAS, they are built with the anti-k_t algorithm of cone size R=0.4 or 1.0 (Small-R or Large-R)

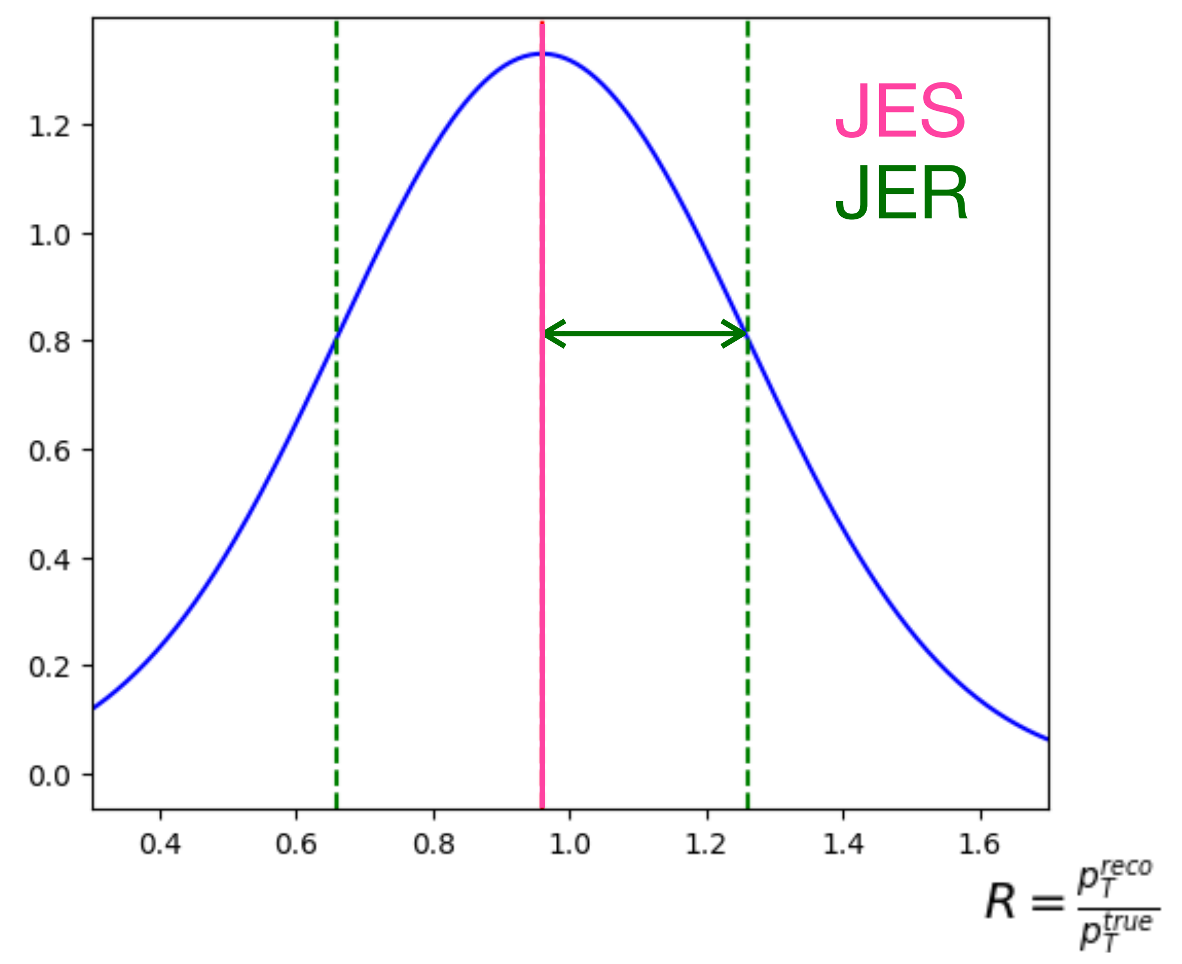


- Jets need to be calibrated to take into account detector effects

- We use the response $\langle \mathscr{R}_x \rangle = \left\langle \dfrac{x^{reco}}{x^{true}} \right\rangle$

  - Jet Energy Scale (JES): response mean

  - Jet Energy Resolution (JER): response width



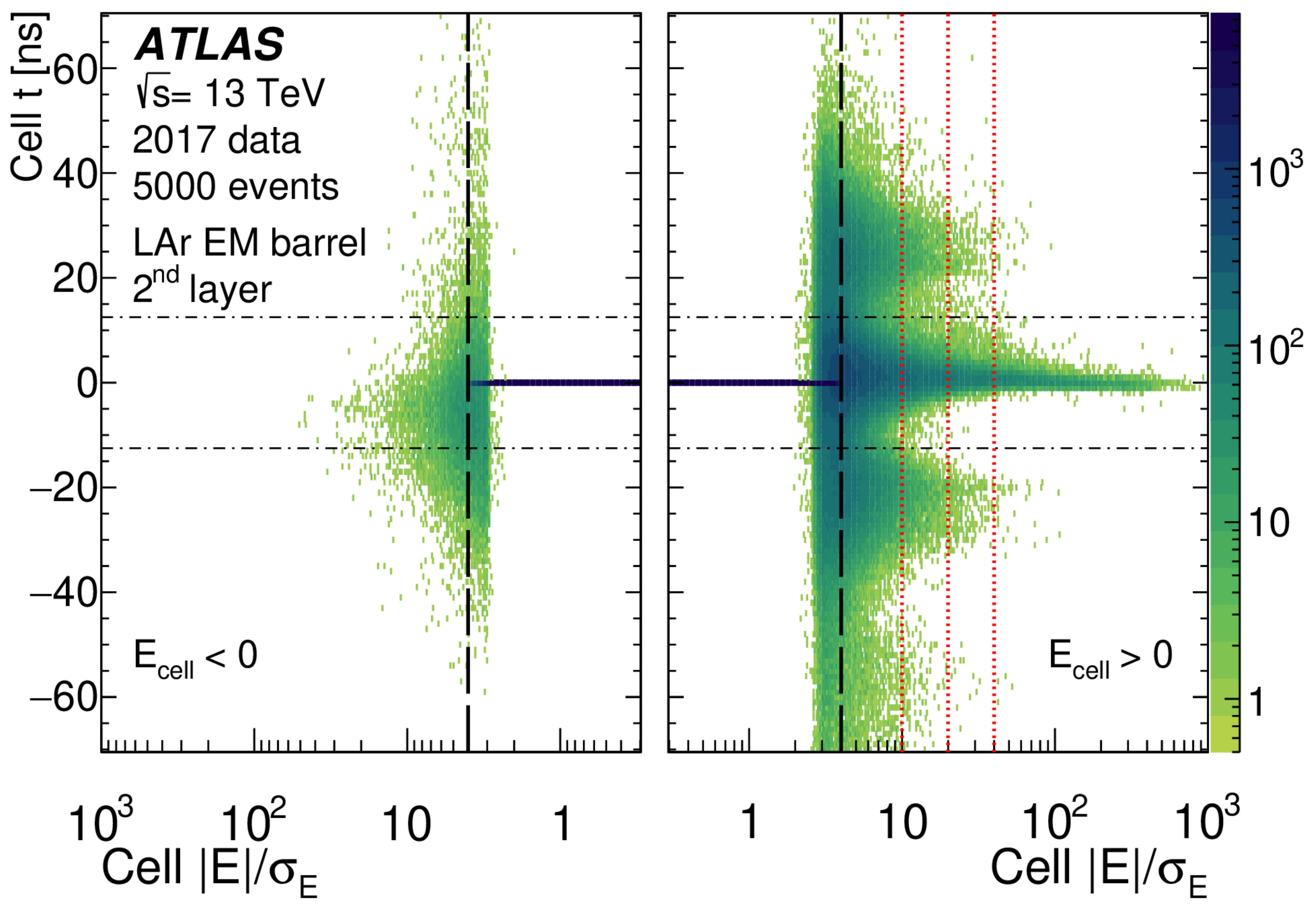
- The **Missing Transverse Energy** uses energy conservation to compute the p_T^{miss} of undetected objects

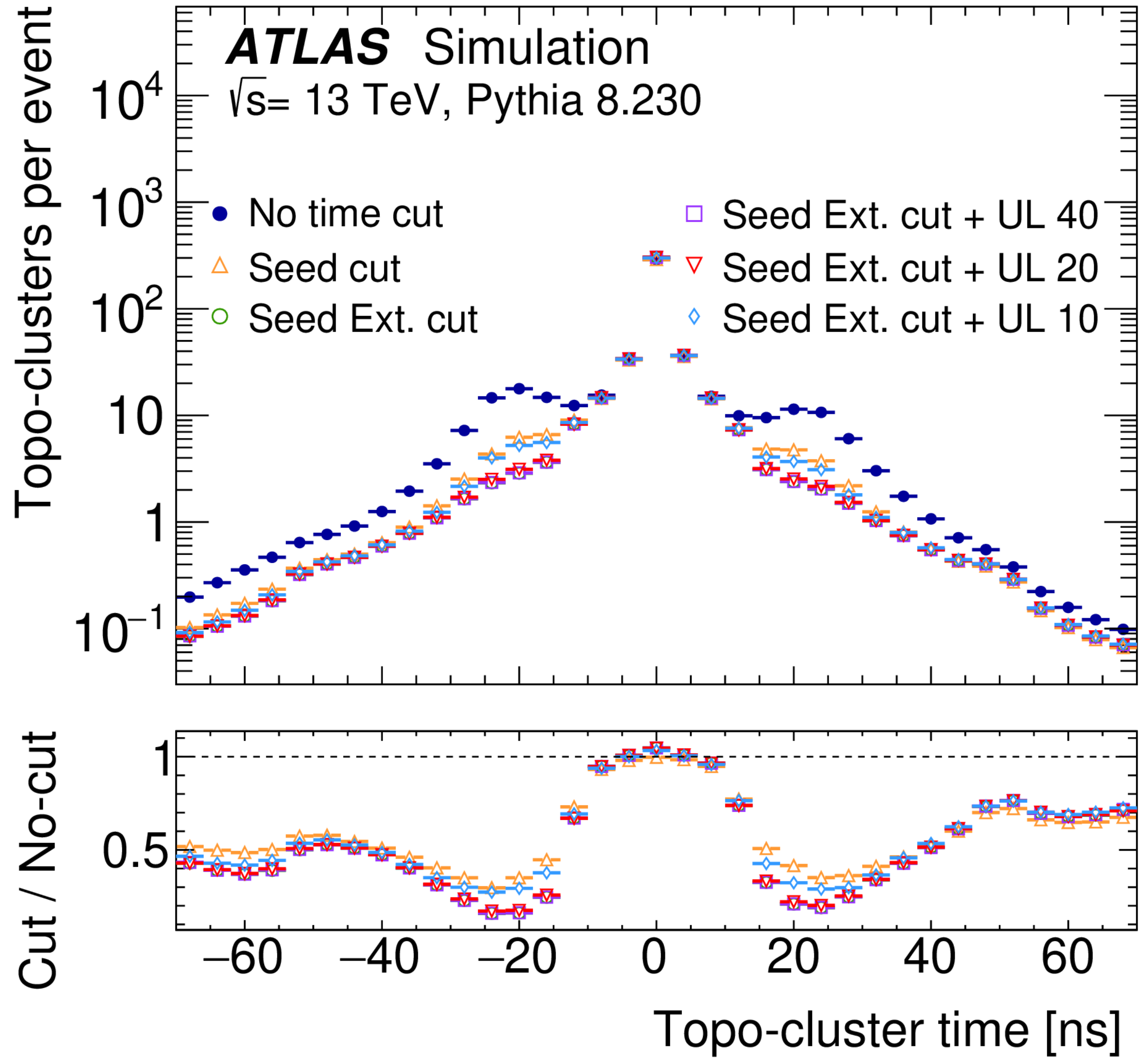
Improving topo-clusters using calorimeter cell timing

[2310.16497]

- **Method**: use cell timing information on the cell level before forming the clusters to **reduce out-of-time** (OOT) **pile-up**
- Topo-clustering is based on cell signal significance $\zeta^{EM}_{cell} = \frac{E^{EM}_{cell}}{\sigma^{EM}_{noise,cell}}$; different cuts are studied:

- Seed cut: if $\zeta^{EM}_{cell} > 4$ and $|t_{cell}|$>12.5 ns rejected
- Seed Extended: reject cells failing the time cut during seed neighbour clustering
- **Seed Ext+UpperLimit X**: if $\zeta^{EM}_{cell} > X$, we skip the time cut to retain long-lived-particle signals





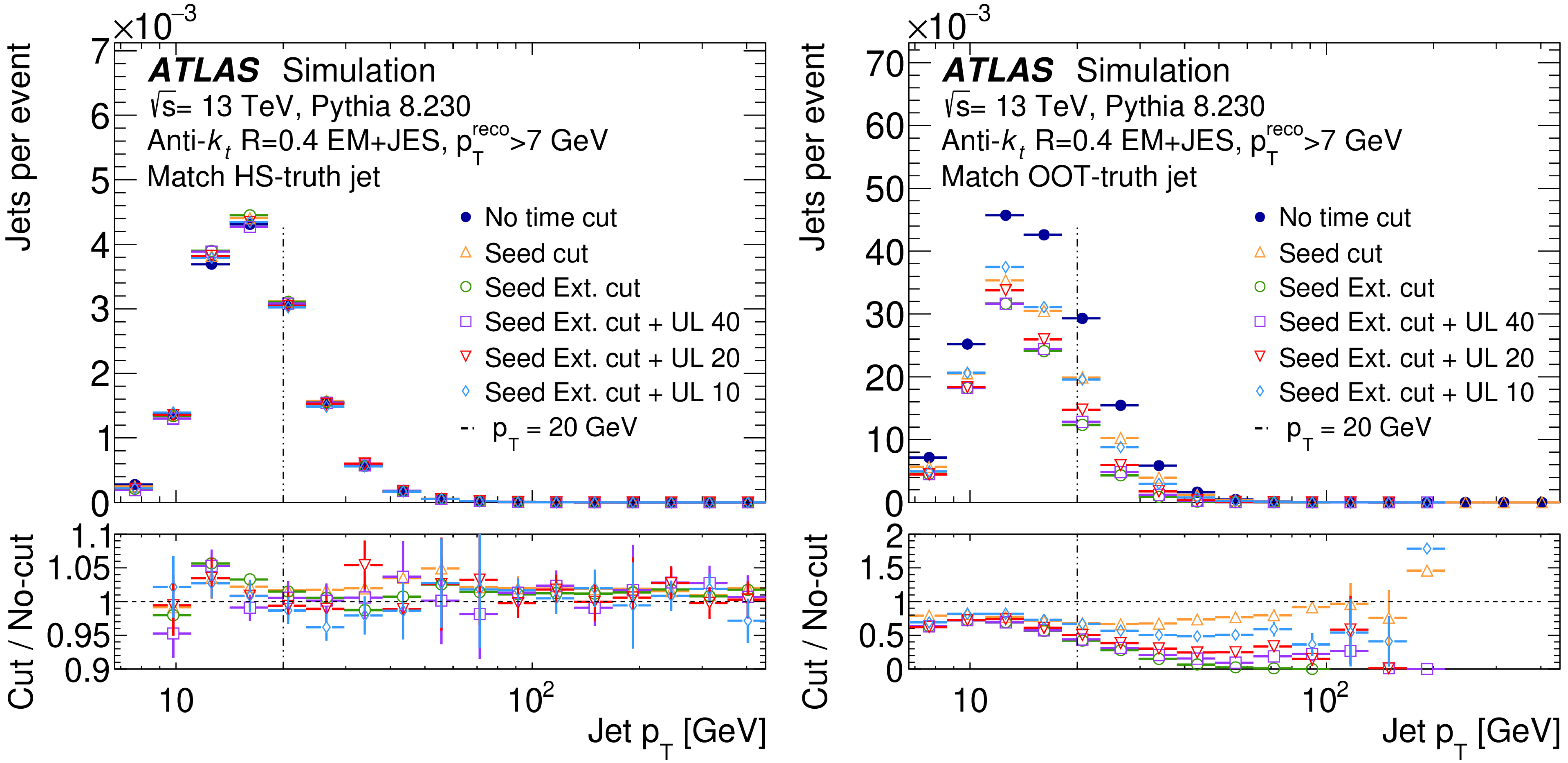
Improving topo-clusters using calorimeter cell timing

[2310.16497]

- **Method**: use cell timing information on the cell level before forming the clusters to **reduce out-of-time** (OOT) **pile-up**
- Topo-clustering is based on cell signal significance $\zeta_{cell}^{EM} = \frac{E_{cell}^{EM}}{\sigma_{noise,cell}^{EM}}$; different cuts are studied:

- Seed cut: if $\zeta_{cell}^{EM} > 4$ and $|t_{cell}|$>12.5 ns rejected
- Seed Extended: reject cells failing the time cut during seed neighbour clustering

➡ **Seed Ext+UpperLimit 20**: if $\zeta_{cell}^{EM} > 20$, we skip the time cut to retain long-lived-particle signals

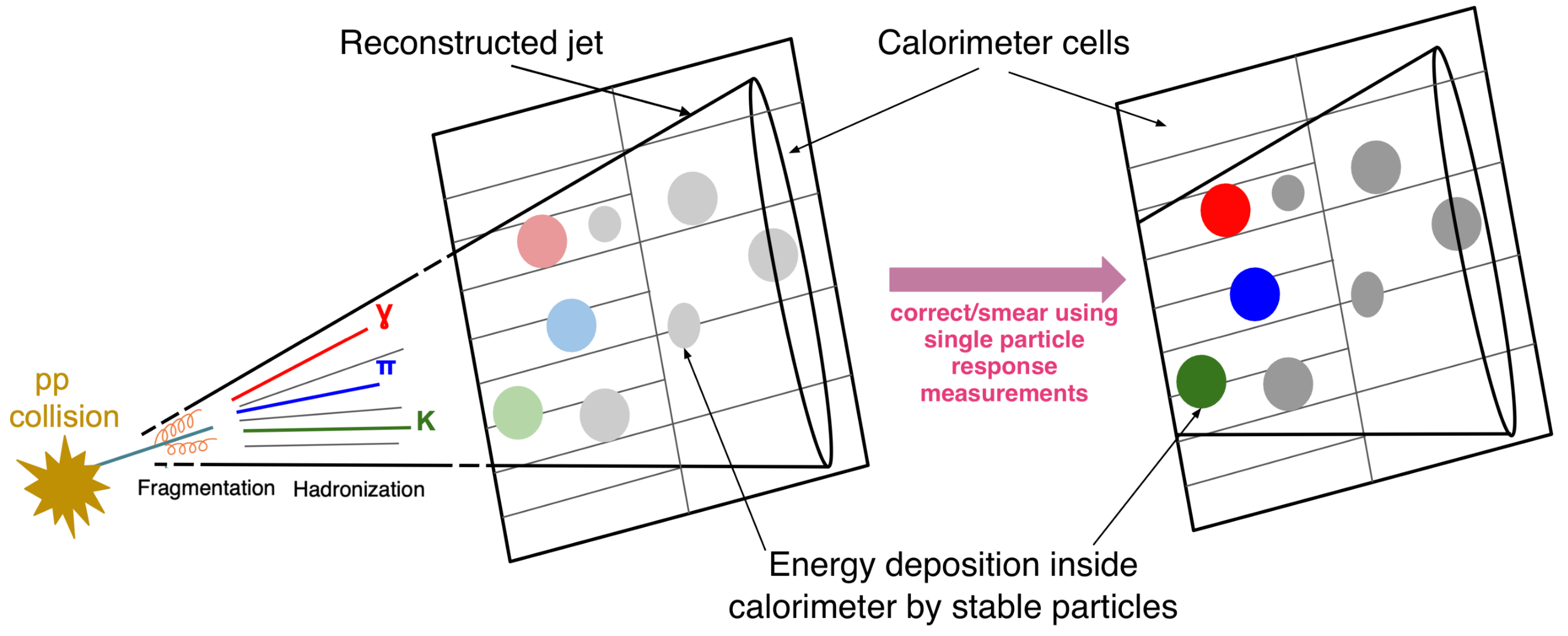


✓ **Reduce OOT** ~50% for $p_T = 20$ GeV and ~80% for $p_T \gtrsim 50$ GeV, while HardScatter not changed

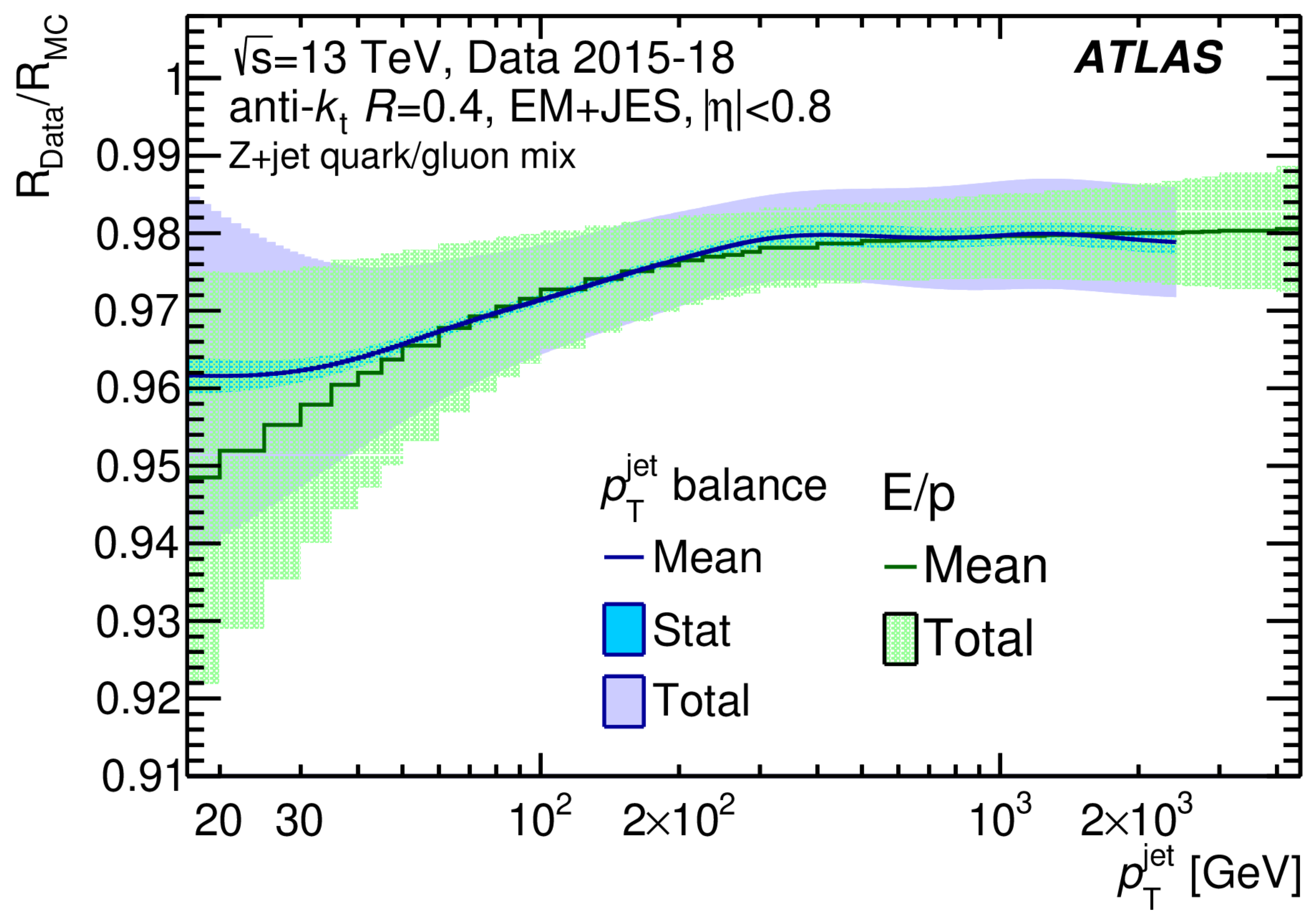
✓ Also beneficial for size on disk, with an 8% reduction

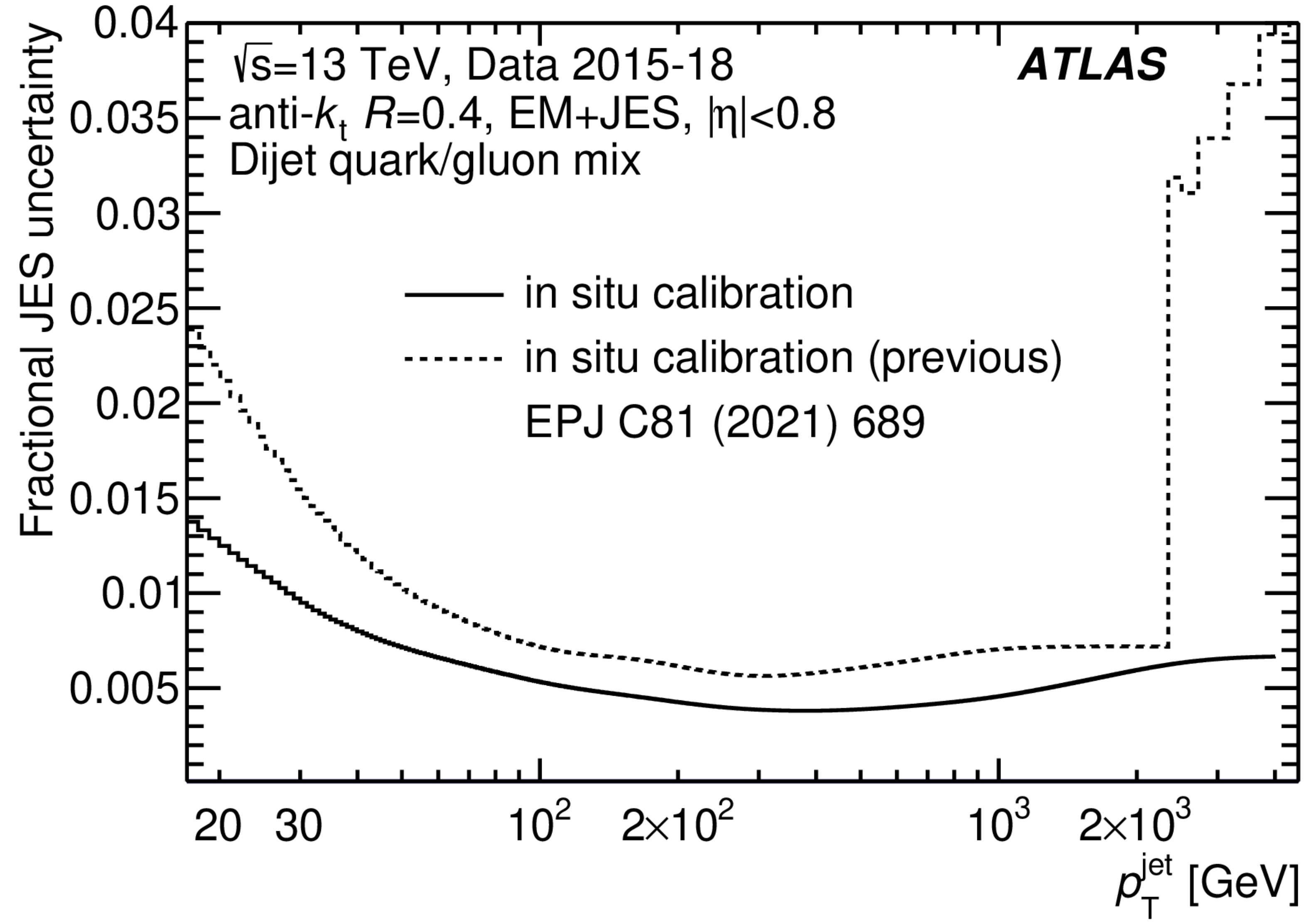
Precise measurement of JES using E/p single particles

[2407.15627]



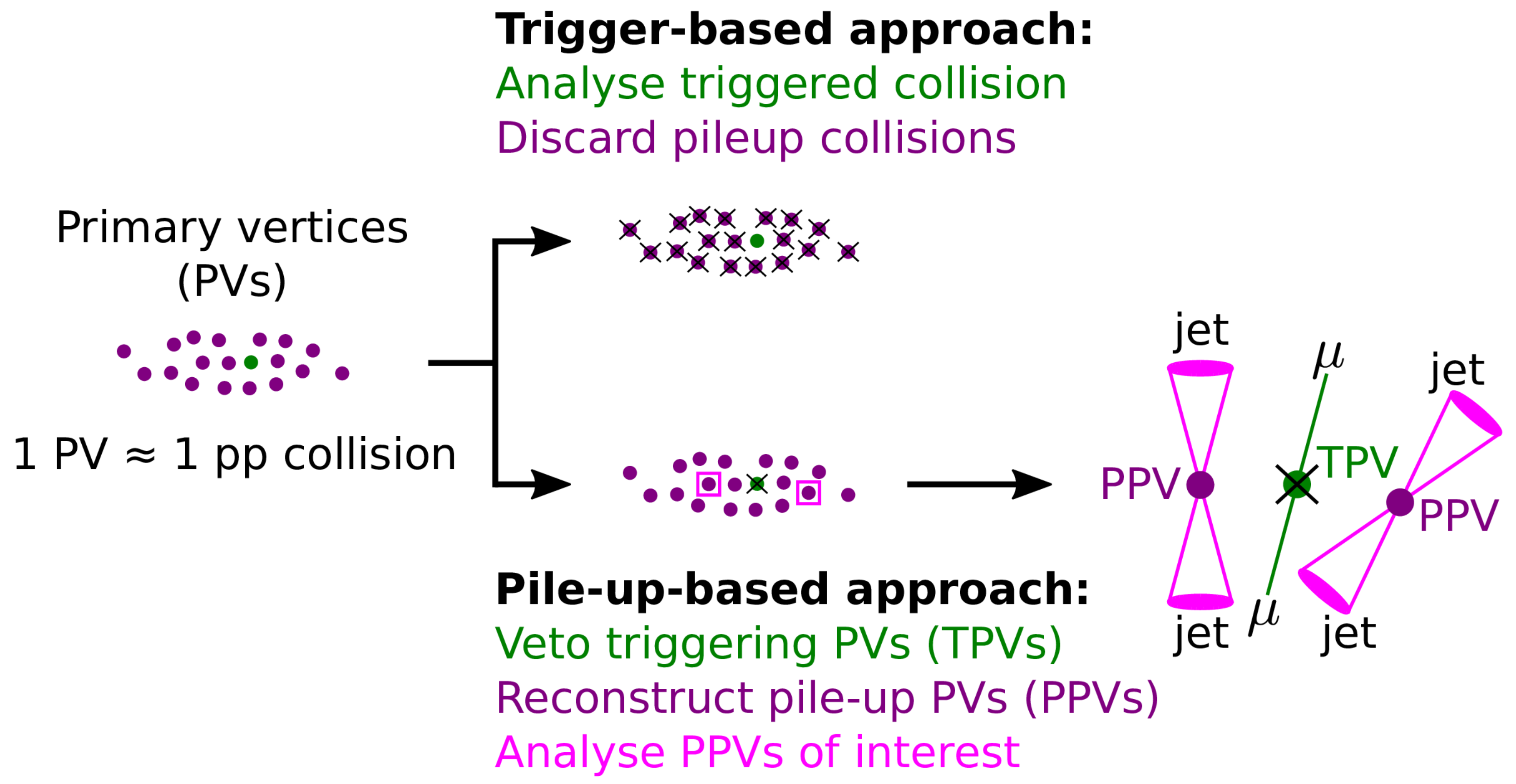
- E/p single measurement corrections using:
  - $p_T < 10$ GeV: single charged hadrons using minimum bias sample (low μ)
  - $10 < p_T < 300$ GeV: **single isolated pions from $W \to \tau\nu$**
- Deconvolution method: propagates E/p corrections to the constituents of the jet
- E/p combination with p_T^{jet} balance in Small-R:
  - Both methods are in good agreement and they are uncorrelated
  - ✓ **Improved JES uncertainty**: 0.3% at $p_T = 300$ GeV and **0.6% at $p_T = 4$ TeV** (last studies were 4.0%)



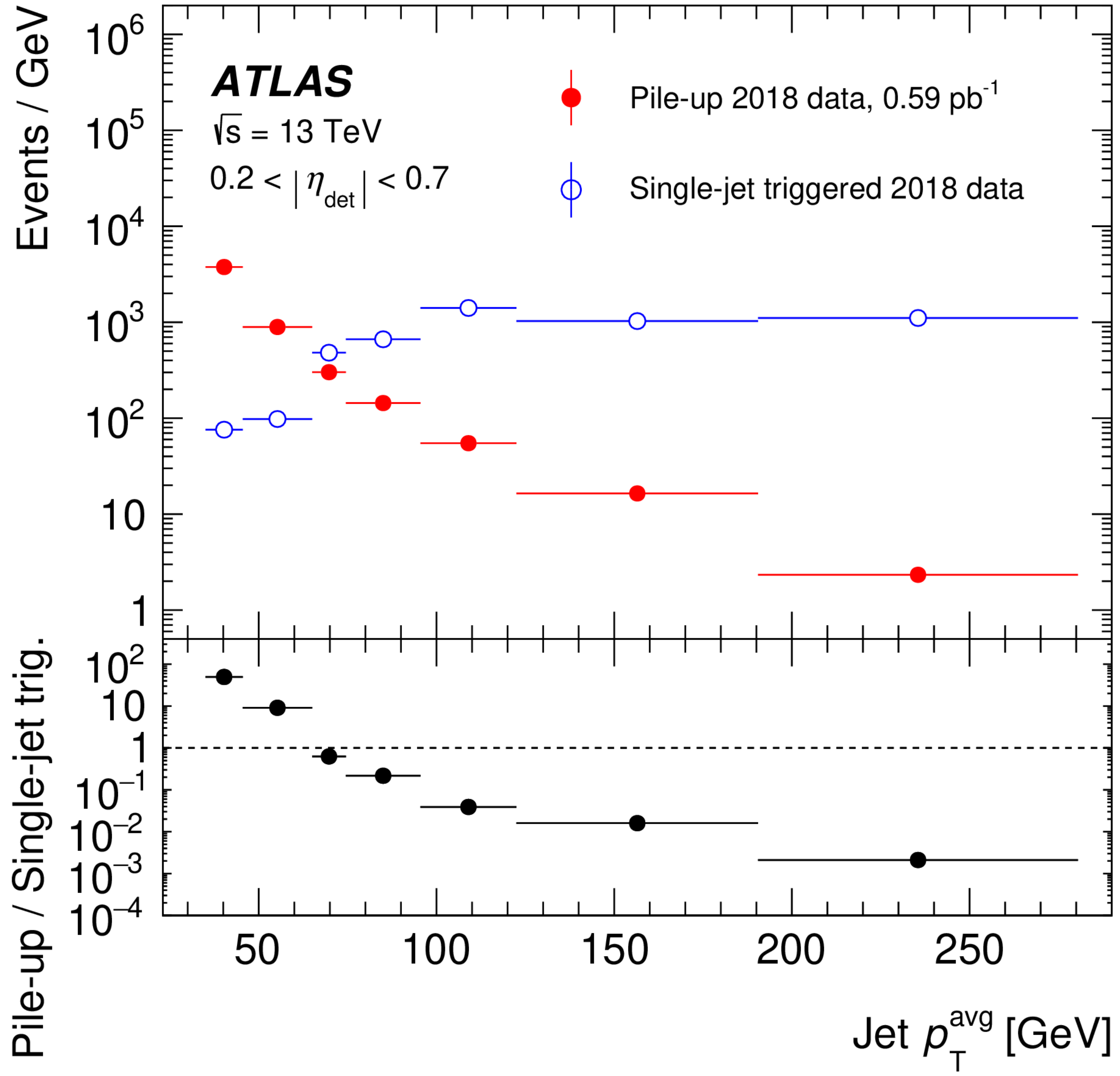


Using pile-up collisions as source of low-energy hadronic physics for JER

[2407.10819]

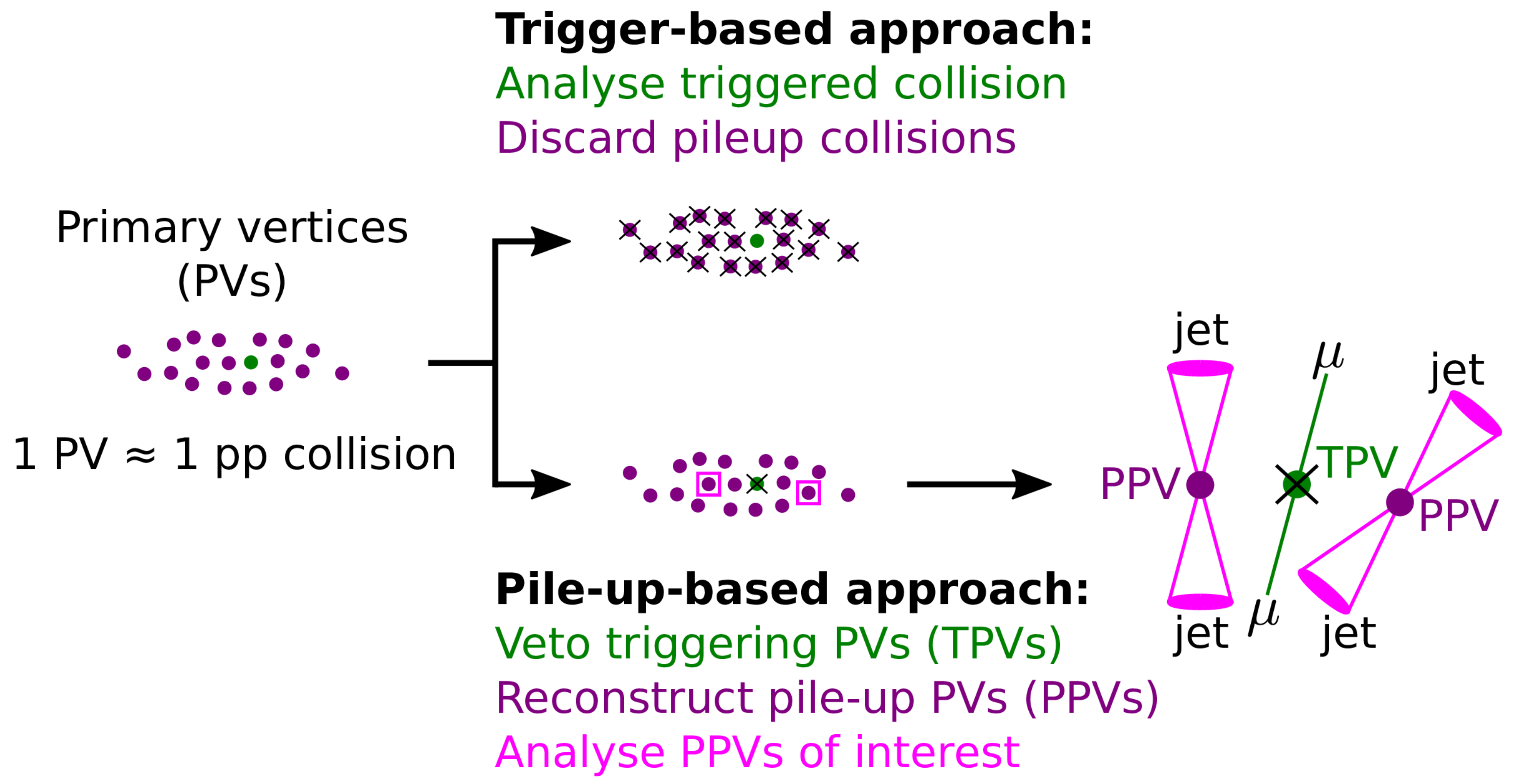


- **Pile-up as abundant source of dijet** events at low-p_T, using single lepton trigger
- Complex problem of selecting pile-up Primary Vertices
  - Prioritise good quality of jets → no overlap between different vertices jets



Using pile-up collisions as source of low-energy hadronic physics for JER

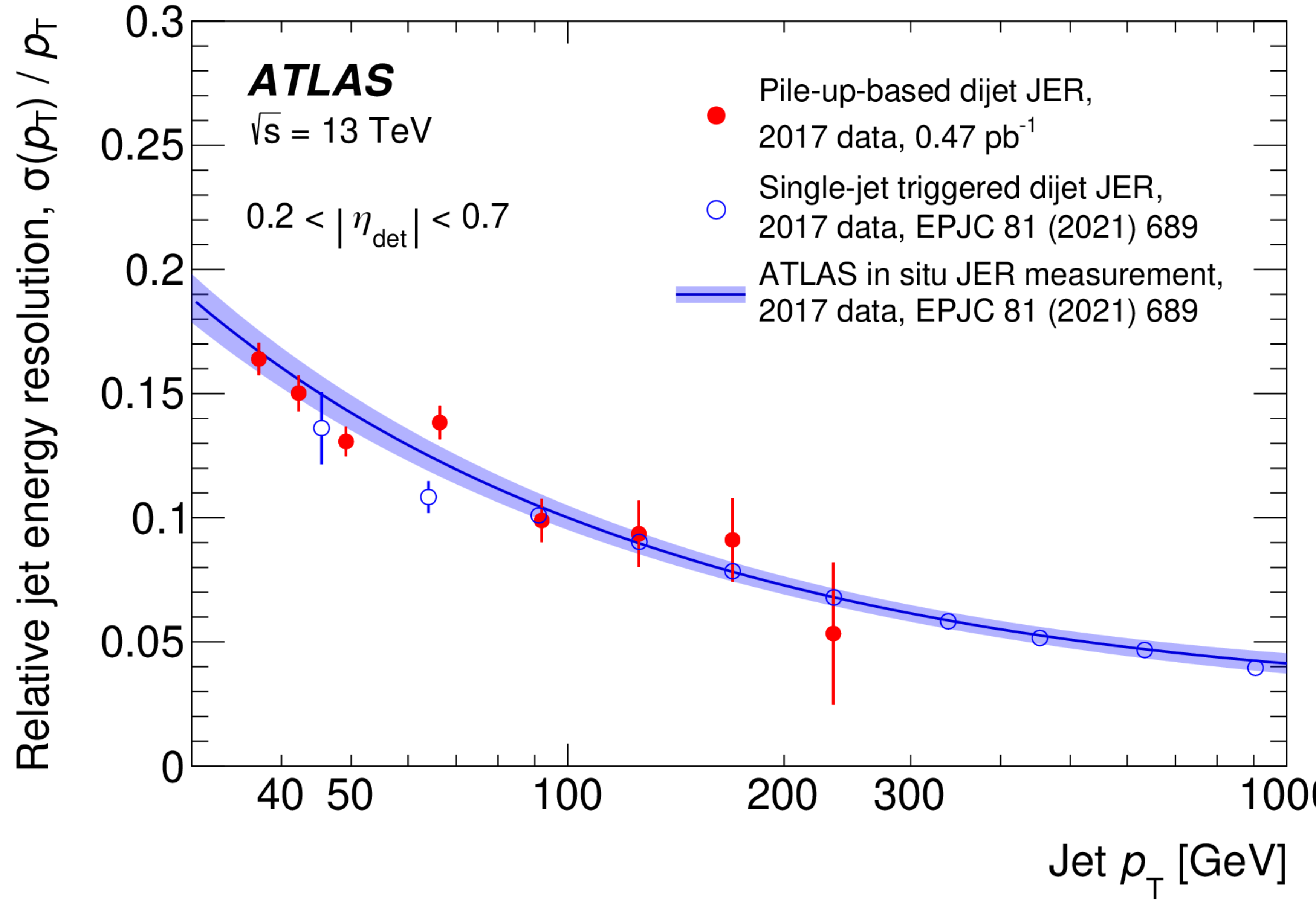
[2407.10819]

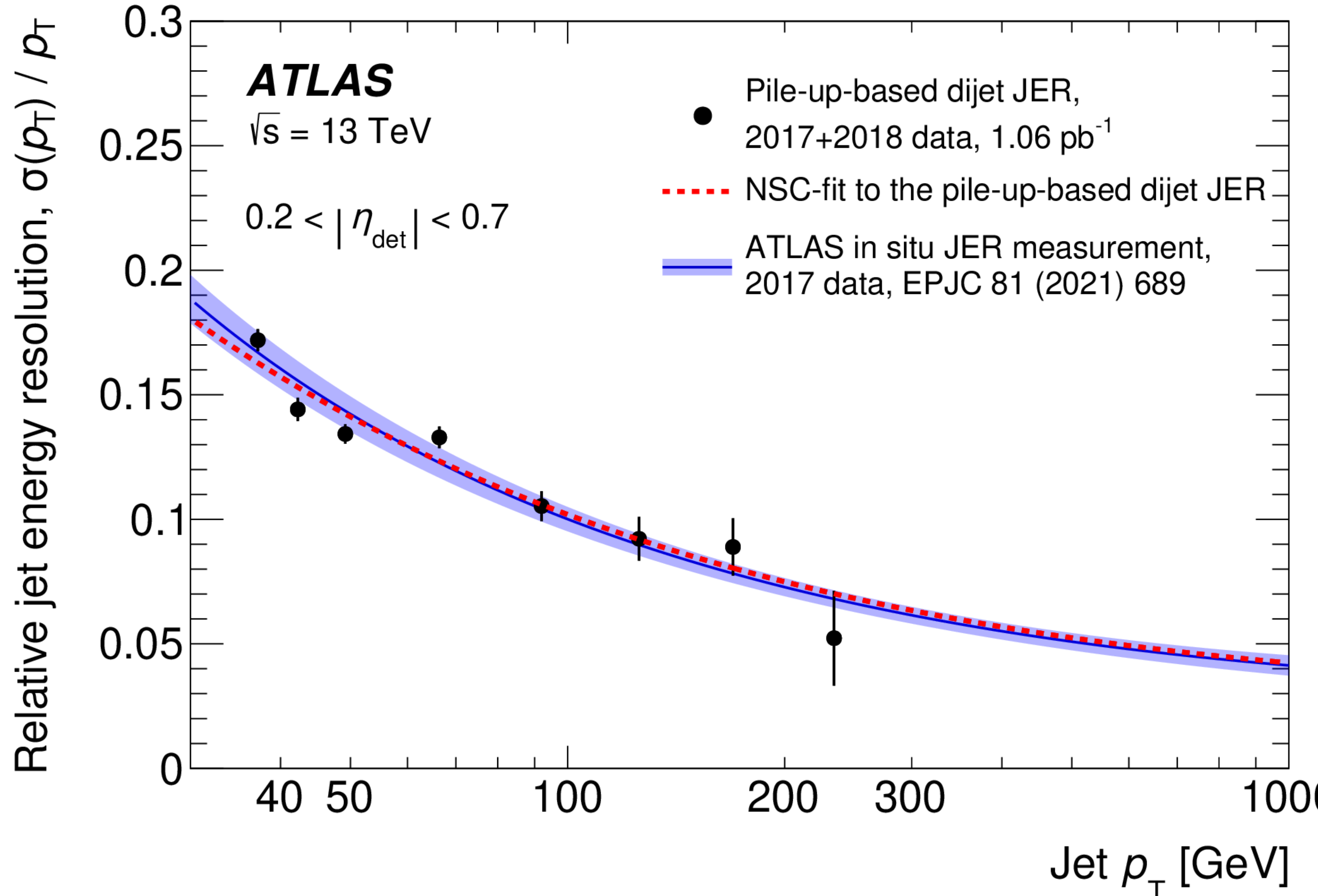


- **Pile-up as abundant source of dijet** events at low-p_T, using single lepton trigger
- Complex problem of selecting pile-up Primary Vertices
  - Prioritise good quality of jets → no overlap between different vertices jets
- Dijet analysis: $\frac{\sigma(p_T)}{p_T} = \frac{N}{p_T} + \frac{S}{\sqrt{p_T}} + C$

✓ Method provides superior **statistical precision for p_T^{lead}< 60 GeV**

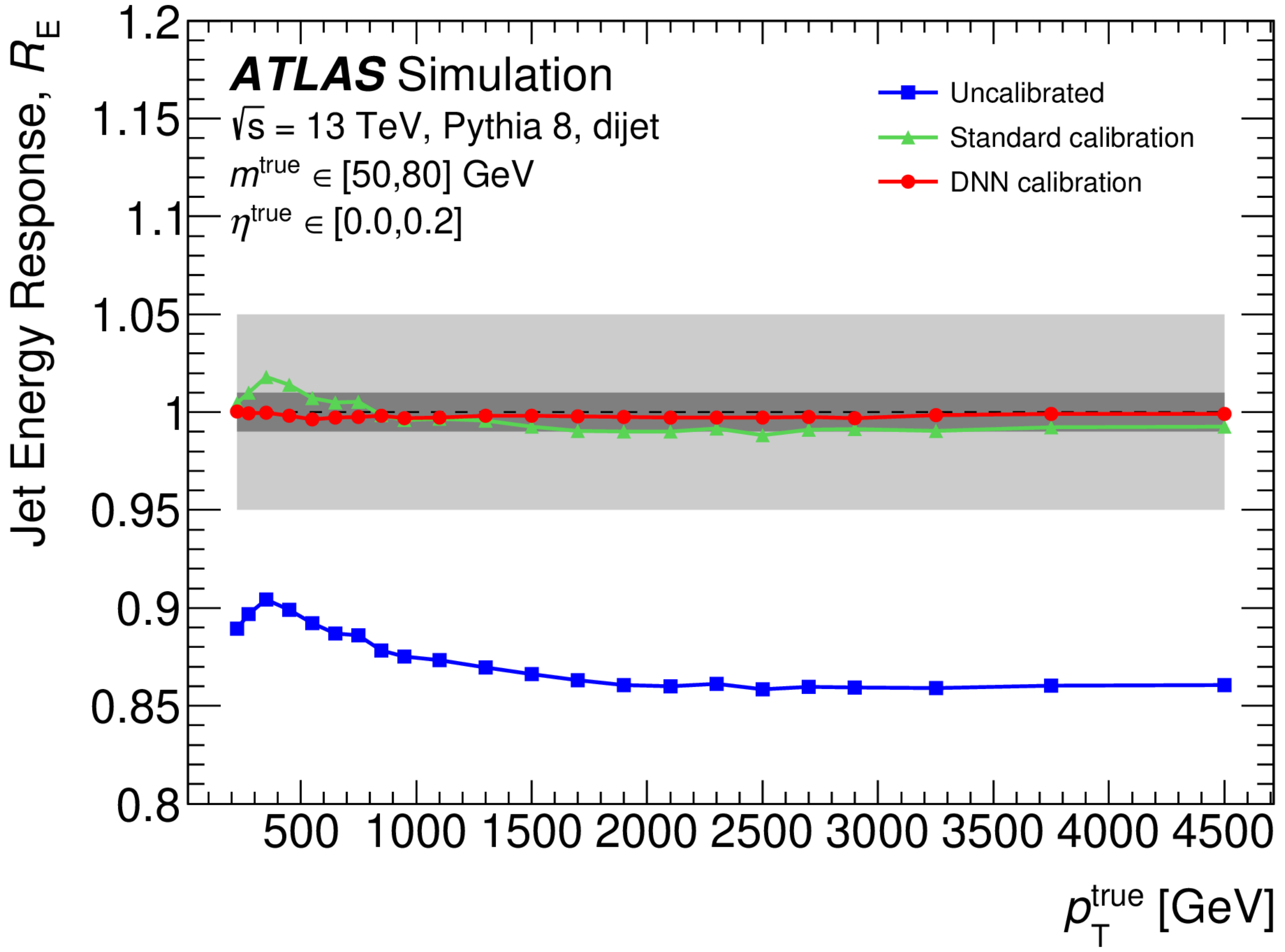
✓ We can constraint 40% better the noise term N and 20% the stochastic S





Energy and Mass calibration of Large-R jets using a DNN

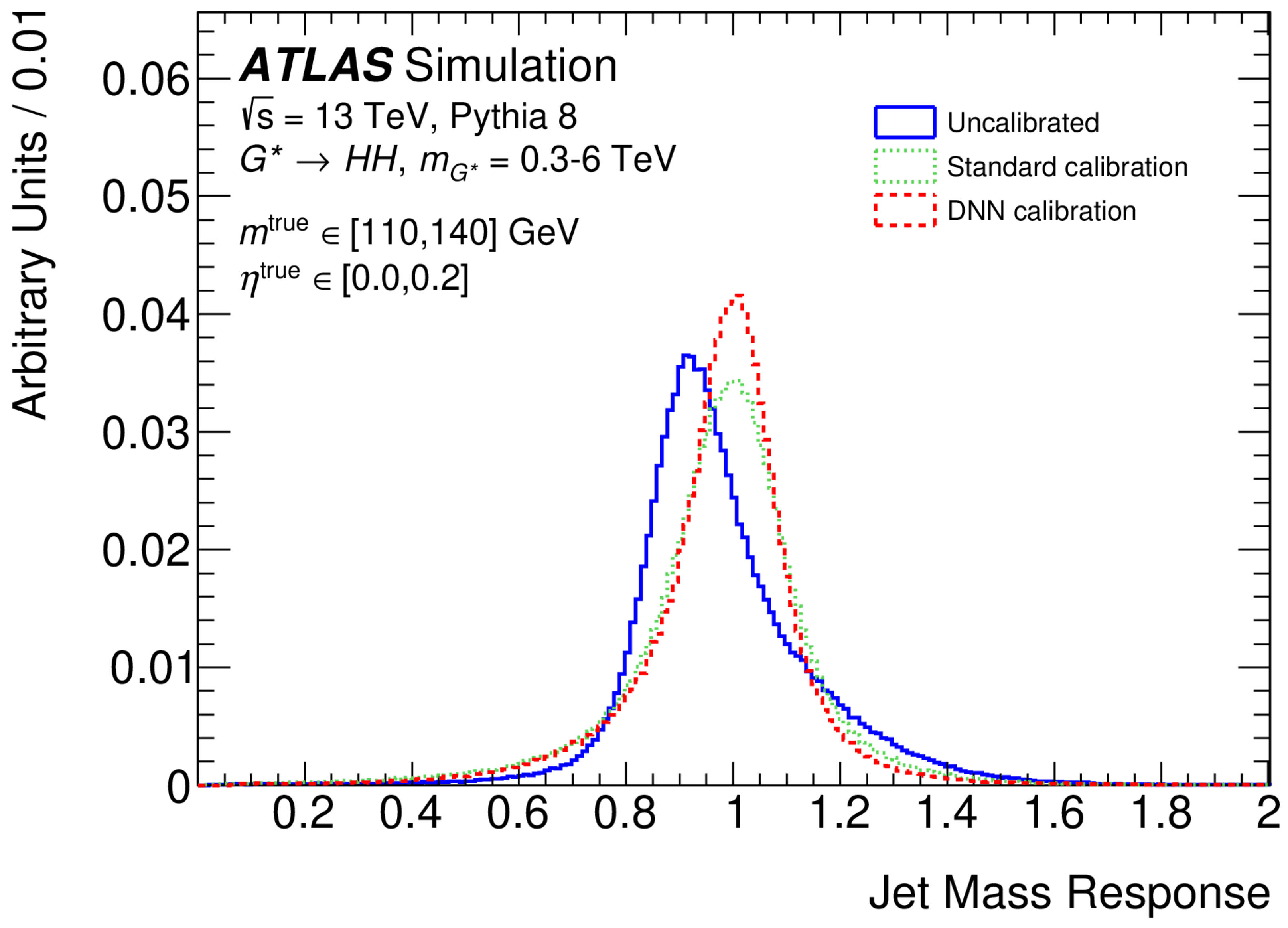
- Simultaneous calibration of **energy and mass** of **Large-R** jets using a Deep Neural Network
  - ML is suitable for a multidimensional problem like this
  - Motivated by the work on Small-R calibration using a DNN [2303.17312]
- Complex DNN containing:
  - Feature annotation: encodes the η distribution of the detector
  - Residual connection layers: improve the mass task

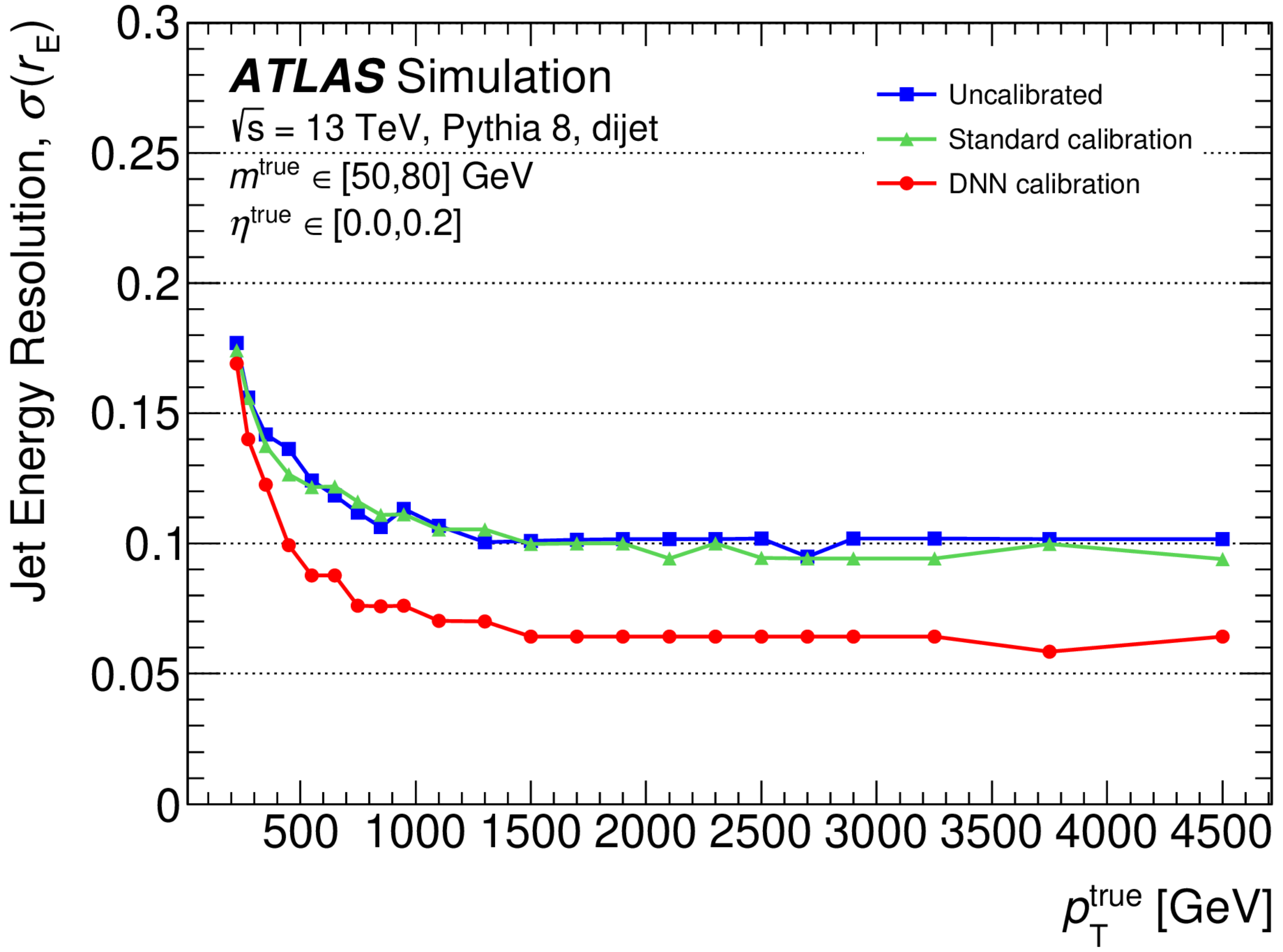


[2311.08885]

✓ Overall better performance in both tasks

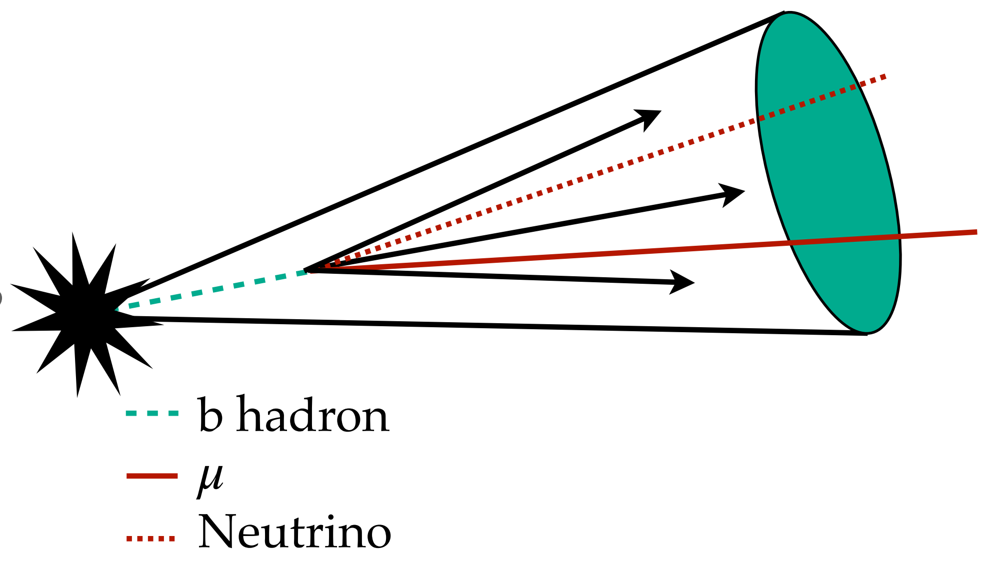
✓ **Energy resolution ~30% better for $p_T > 500$ GeV**





Transformer for constituent-based b-jet calibration

- **b-jets** are important on many analyses such as $t\bar{t}$ and Higgs
    - They give a distinguished signature, often containing leptons and neutrinos

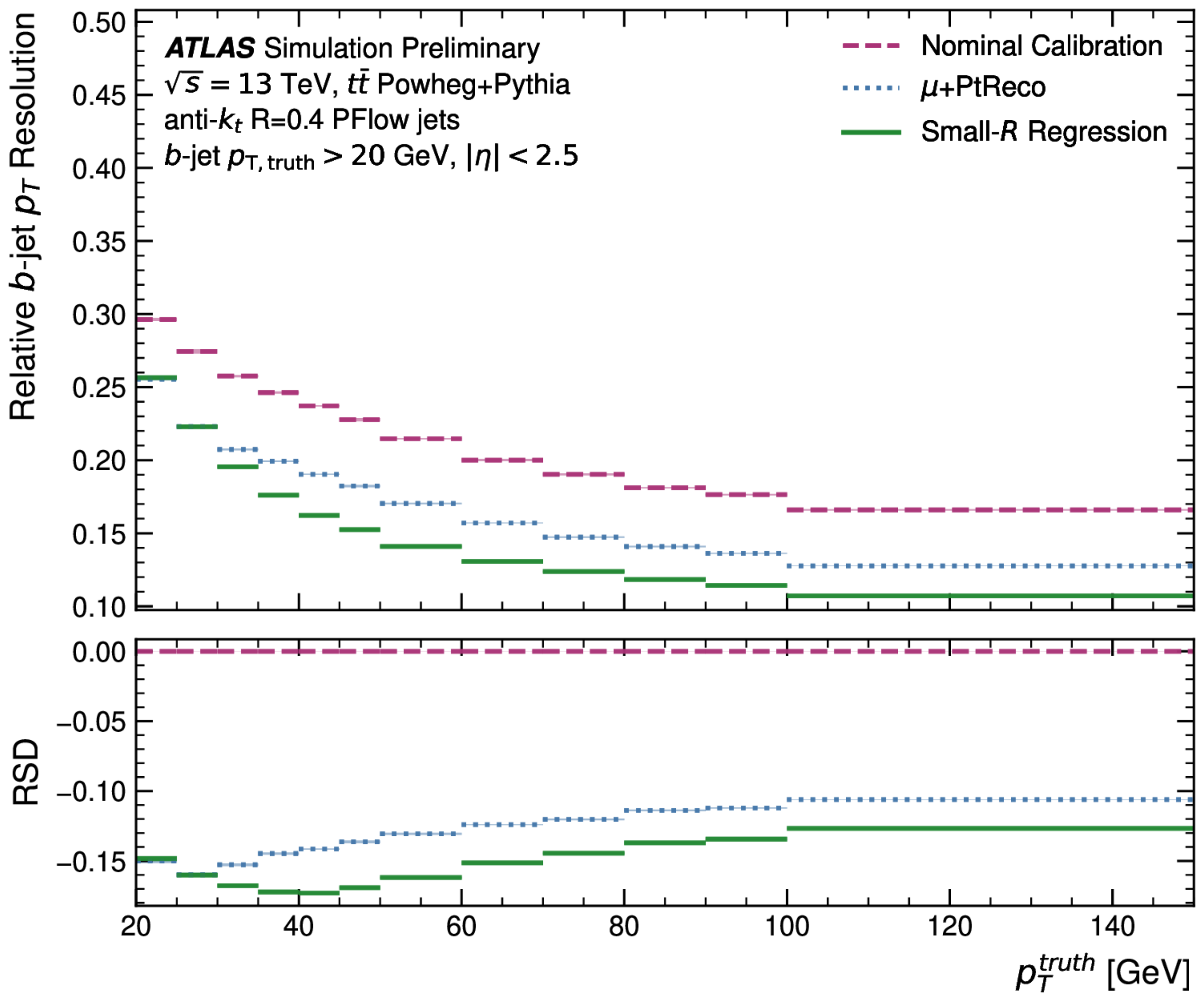


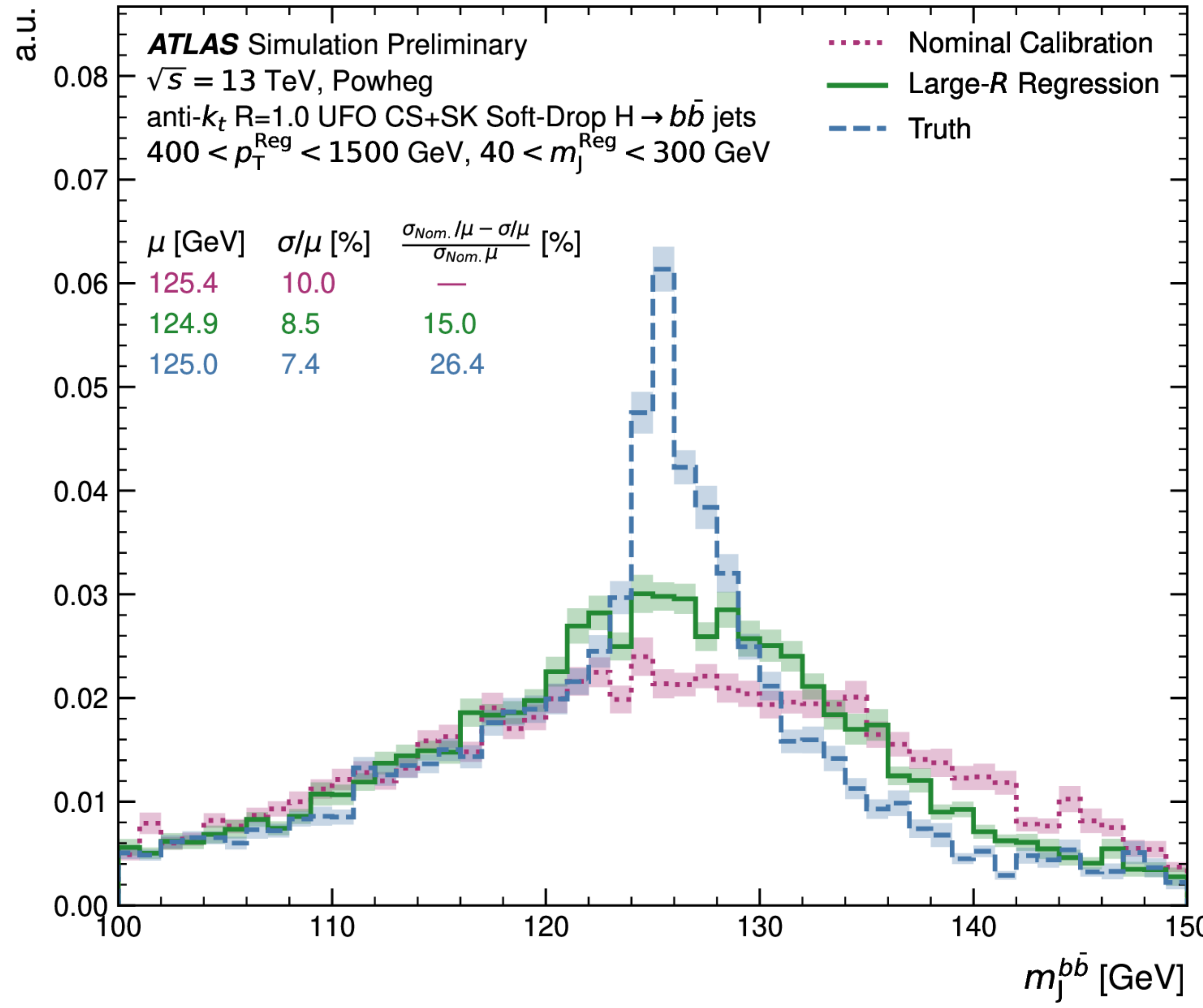
- Some analyses use *muon-in-jet* and *PtReco* methods for Small-R jets, comparisons to this methods and Nominal Calibration are performed
- Two **transformers** (called Regression) based on GN2 and GN2X (flavour tagging)

✓ Regression models bring the median closer to the true value

✓ **Resolution** of Small-R p_T and Large-R p_T and m **improves ~30%**

✓ **Higgs and Z mass** resolution improves by **~22% on Small-R** and by **~15% on Large-R**





[ATL-PHYS-PUB-2024-015]

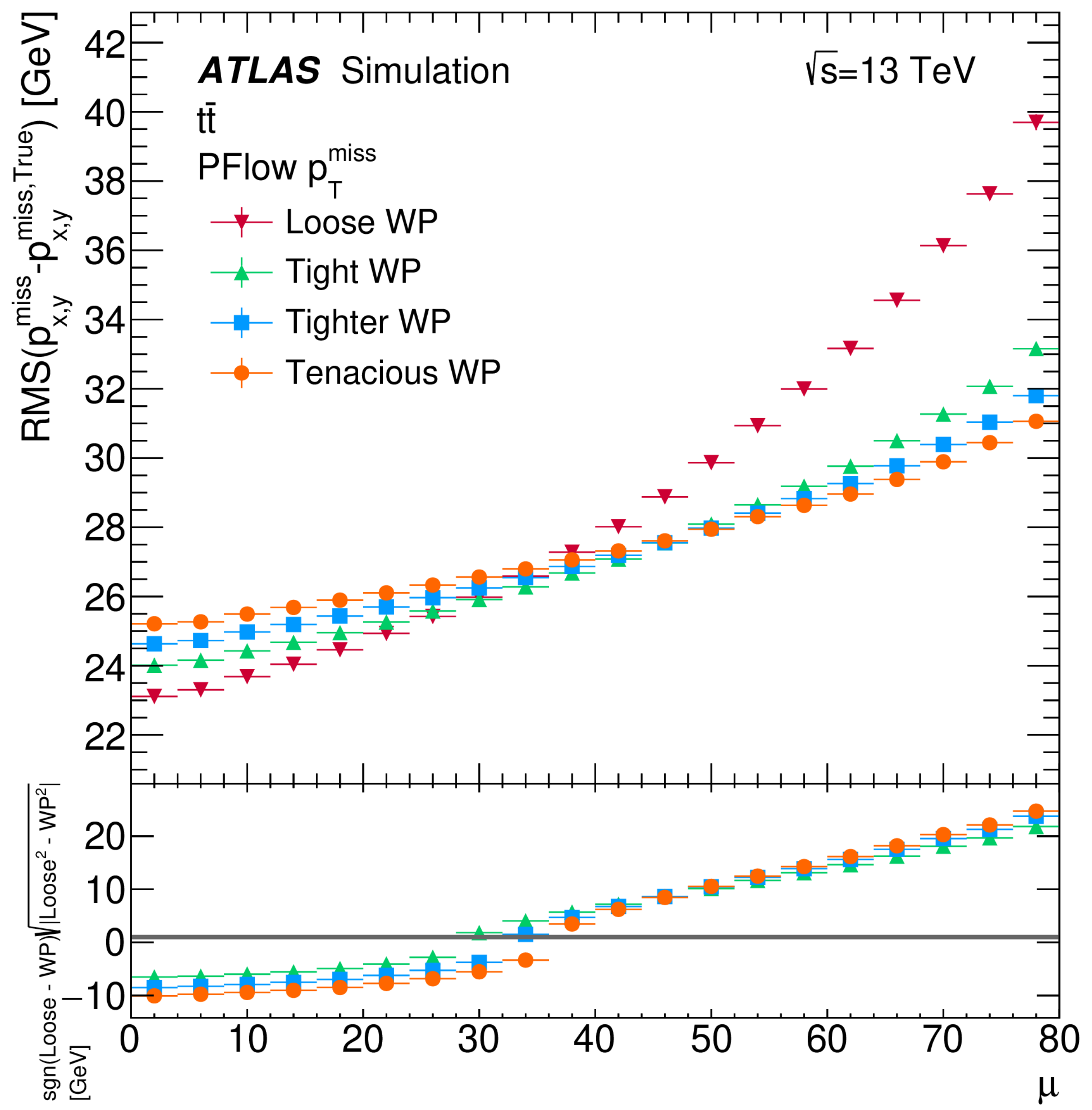
Performance of missing transverse momentum

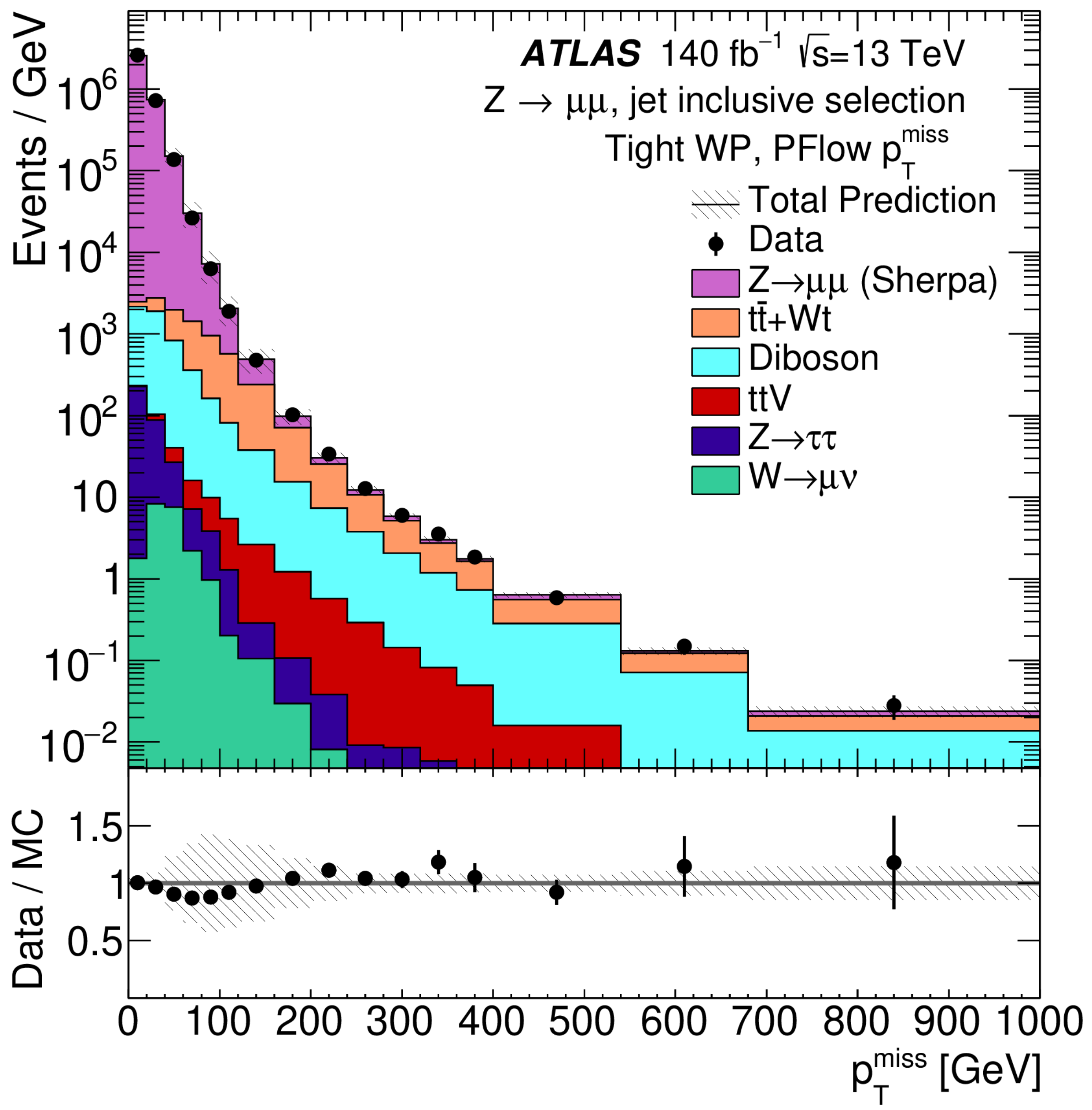
[2402.05858]

- p_T^{miss} is a key quantity to study SM processes with neutrinos and BSM with e.g. dark matter candidates

$$p_T^{miss} = -\left(\sum p_T^{e} + \sum p_T^{\gamma} + \sum p_T^{\tau} + \sum p_T^{\mu} + \sum p_T^{jet} + \overbrace{\sum p_T^{unused\ track}}^{\text{track soft term}}\right)$$

- First time studying the performance with the p_T^{miss} WPs: Loose to Tenacious
    - On $t\bar{t}$ sample, containing real p_T^{miss}: need for supporting the different WPs which might give better resolution in different phase space
    - These results are the current method of p_T^{miss},with **Tight** being the default WP





Performance of missing transverse momentum

- p_T^{miss} is a key quantity to study SM processes with neutrinos and BSM with e.g. dark matter candidates

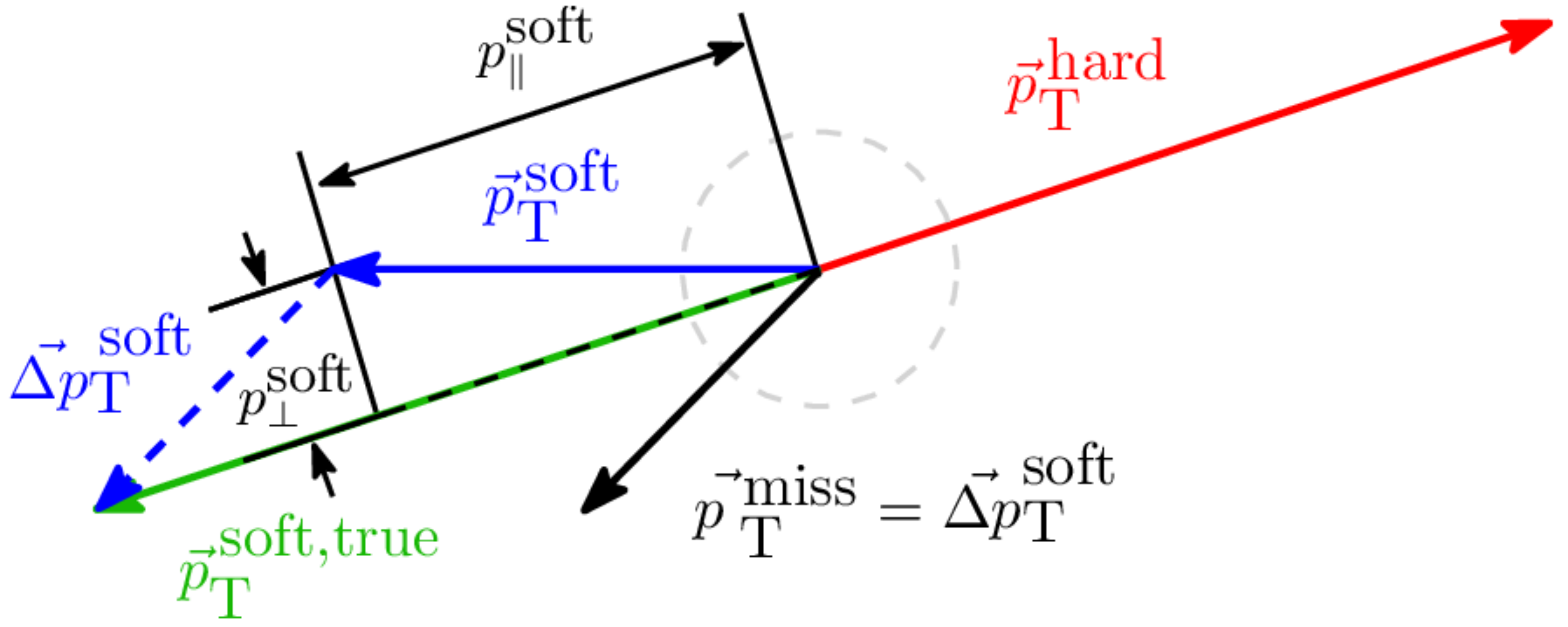
$$p_T^{miss} = -\left(\sum p_T^{e} + \sum p_T^{\gamma} + \sum p_T^{\tau} + \sum p_T^{\mu} + \sum p_T^{jet} + \overbrace{\sum p_T^{unused\ track}}^{\text{track soft term}}\right)$$

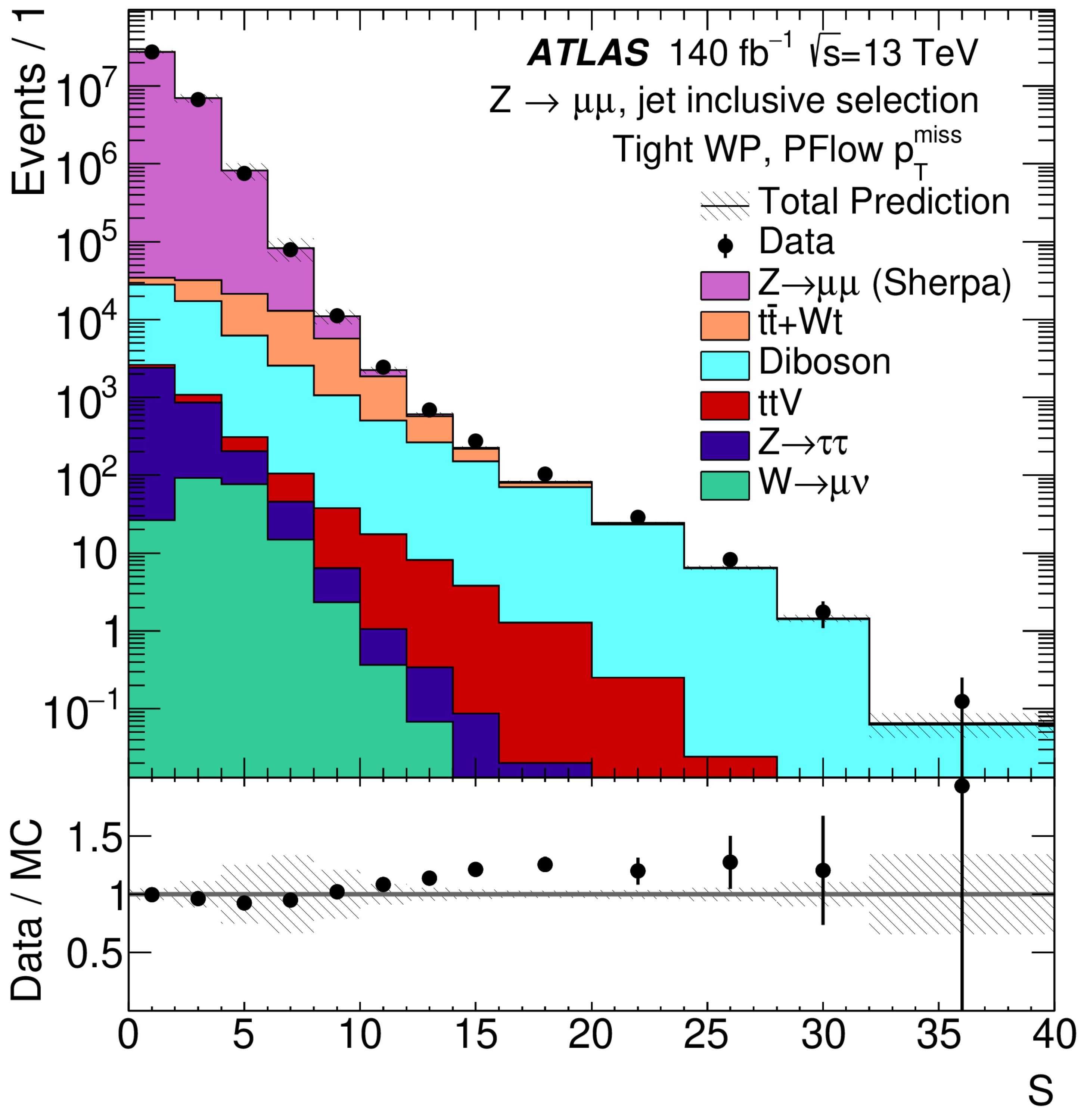
- First time studying the performance with the p_T^{miss} WPs: Loose to Tenacious
  - On $t\bar{t}$ sample, containing real p_T^{miss}: need for supporting the different WPs which might give better resolution in different phase space
  - These results are the current method of p_T^{miss},with **Tight** being the default WP

✓ **Scale and Resolution uncertainties are reduced by up to 76% and 51%** w.r.t. 2015 results, with more luminosity and computation of the systematic uncertainty from soft p_T^{miss}

- Soft term uncertainty is calculated by projecting it into the hard term

✓ Object-based Significance for fake $p_T^{miss} \rightarrow S(p_T^{miss})$ using the covariance matrix per each object





[2402.05858]

Conclusions

Towards higher precision in preparation of future HL-LHC

Pile-up mitigation with cell-time cut

Decreasing JES uncertainty with extended E/p single measurements

Using pile-up as statistical source for improving JER

ML methods to improve scale and resolution for b-jets and inclusive Large-R jets

Best p_T^{miss} performance with reduced uncertainty and supported WPs

- Further improvements are on their way

Back-up

Pipeline of standard jet calibration

- Small-R: JETM-2018-05

Reconstructed jets → **p_T-density-based pile-up correction** → **Residual pile-up correction** → **Absolute MC-based calibration** → **Global sequential calibration** → **Residual *in situ* calibration**

- **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.*

- Large-R: JETM-2018-02

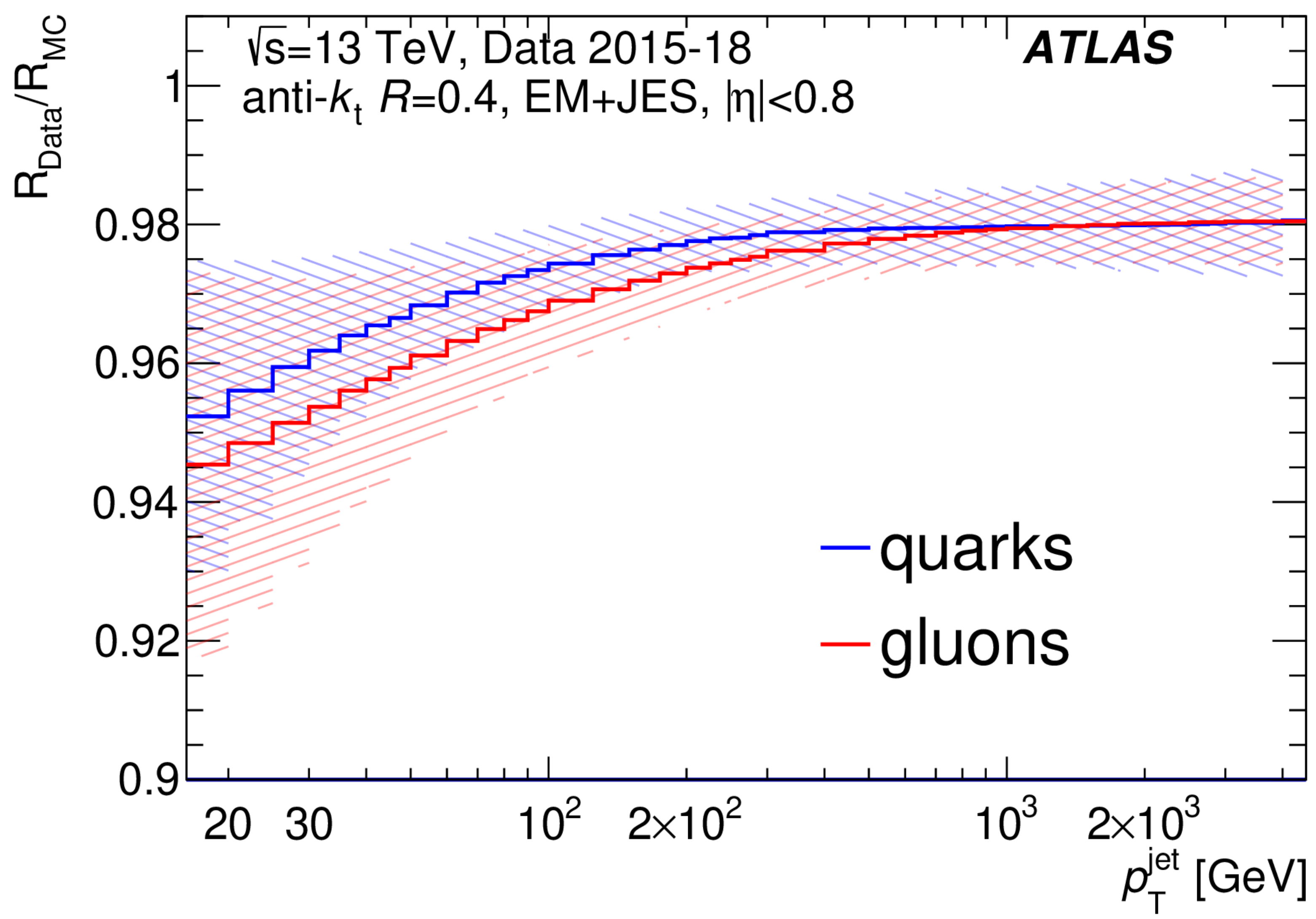
Calorimeter energy clusters (LCW scale) → **Large-*R* jet reconstruction** → **Ungroomed large-*R* jets (LCW scale)** → **Jet grooming** → **Groomed large-*R* jets (LCW scale)** → **E, η & m calibration** → **Residual *in situ* calibration** → **Groomed large-*R* jets (LCW+JES+JMS scale)**

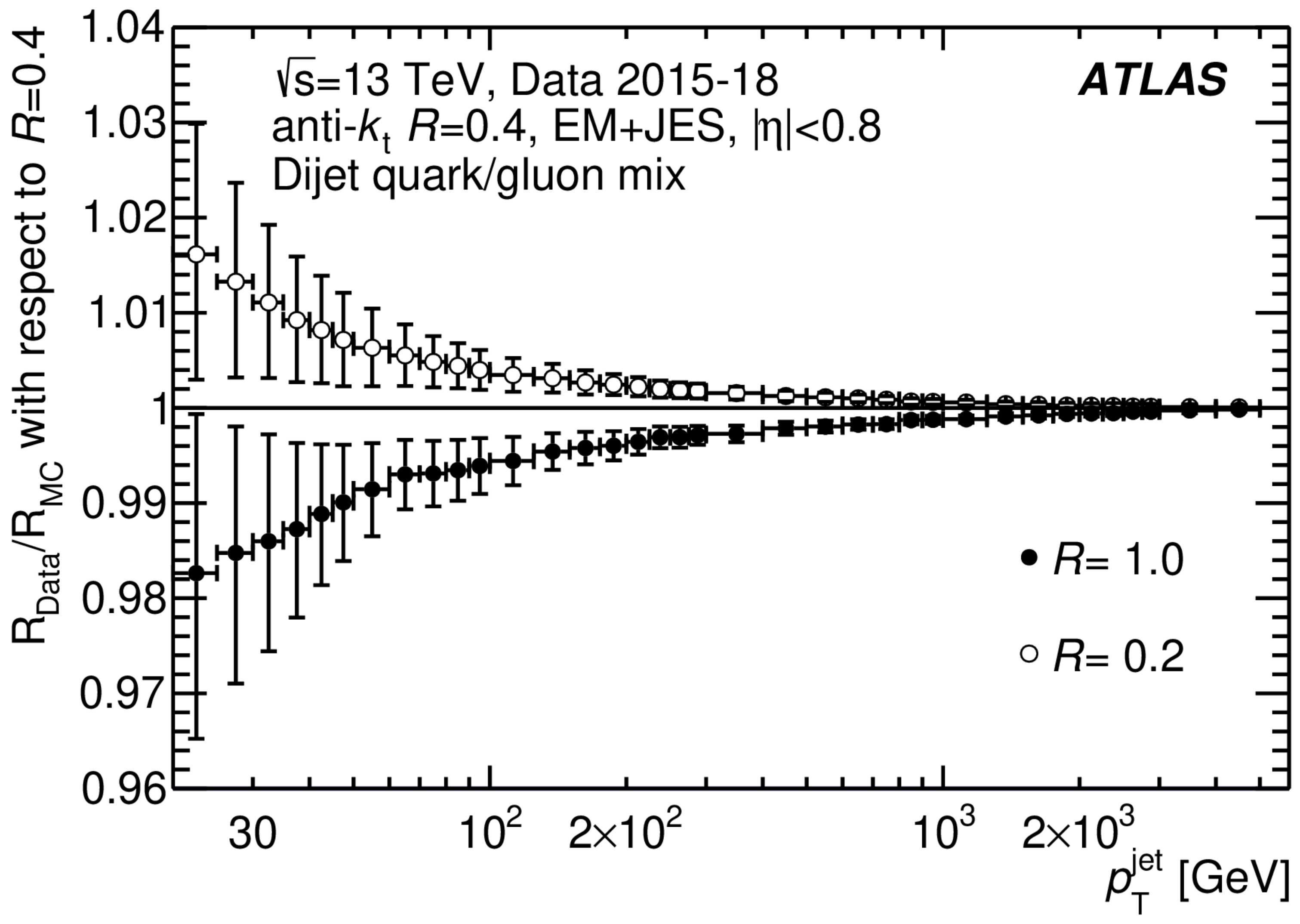
- **Large-*R* jet reconstruction**: Large-*R* jets are reconstructed using the anti-k_t algorithm with R = 1.0.
- **Jet grooming**: Soft subjets are removed from the reconstructed jets.
- **E, η & m calibration**: A correction to the jet energy, pseudorapidity and mass is derived from MC to bring the reconstructed jet to the particle jet scale.
- **Residual *in situ* calibration**: Residual correction determined using *in situ* measurements to bring data in agreement with MC. Applied only to data.

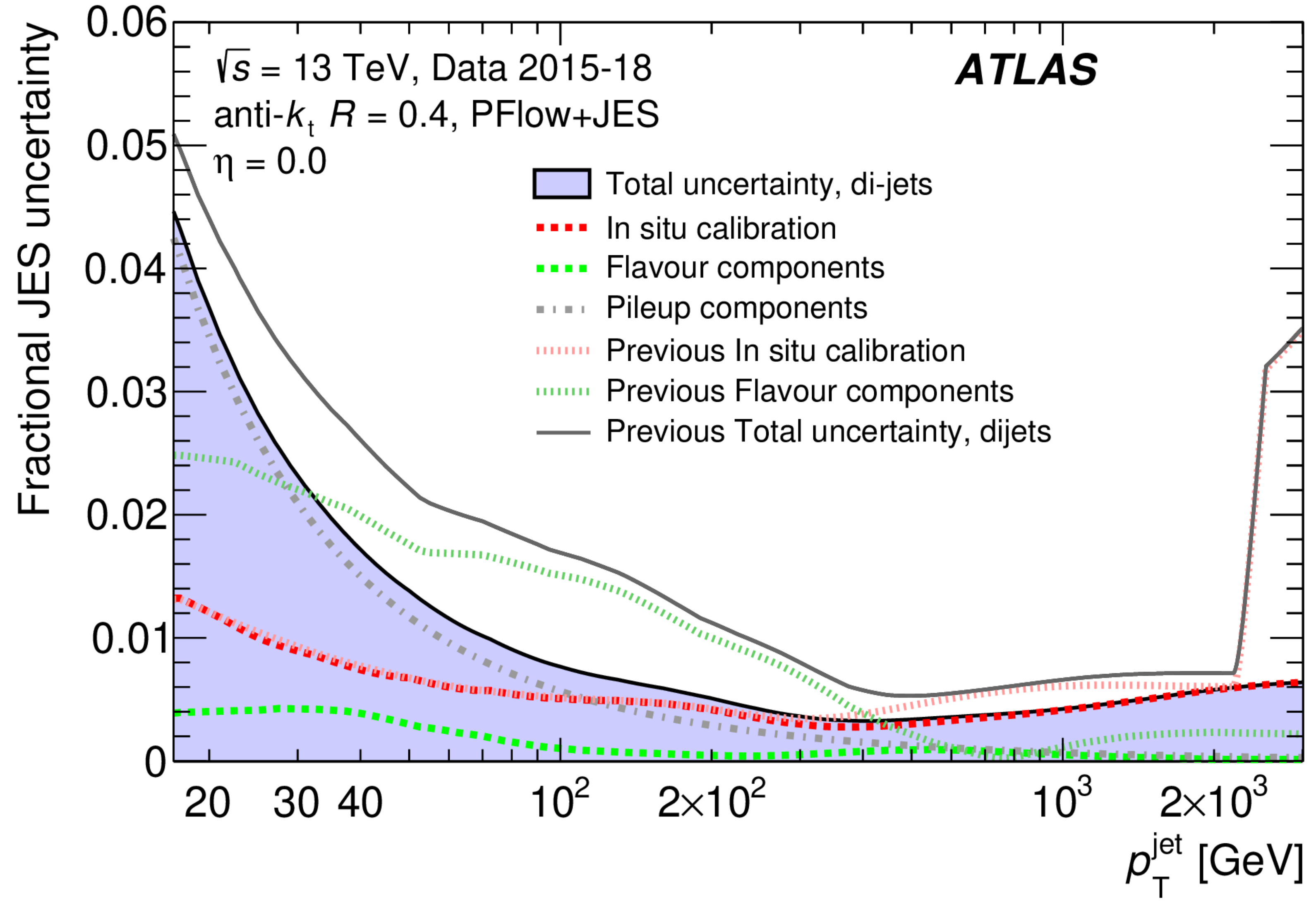
Precise measurement of JES using E/p single particles (details)

[2407.15627]

- In previous studies uncertainty was bigger than the p_T -balance method, so it was only used beyond kinematic reach of it
- E/p: ratio of the average energy deposited by an isolated charged particle in the calorimeter to the momentum of its inner detector track
- Electron and gamma uncertainties are reduced by using tag-and-probe in $Z \rightarrow e\bar{e}$ sample and extrapolating it to photons
- Extrapolation of single-particle response to very high p_T, two methods:
    1. Forced agreement up to $p_T = 175$ GeV, then the variation of the hadronic shower simulation is studied as function of p_T
    2. Using the JES response of the p_T-balance (up to 2 TeV) to constraint the JES derived by E/p measurements by scanning various assumed values of the out-of-range particle uncertainty
- Focus on R=0.4 EMTopo and PFlow, but can be used generic for different R values, and quark/gluon initiated jets





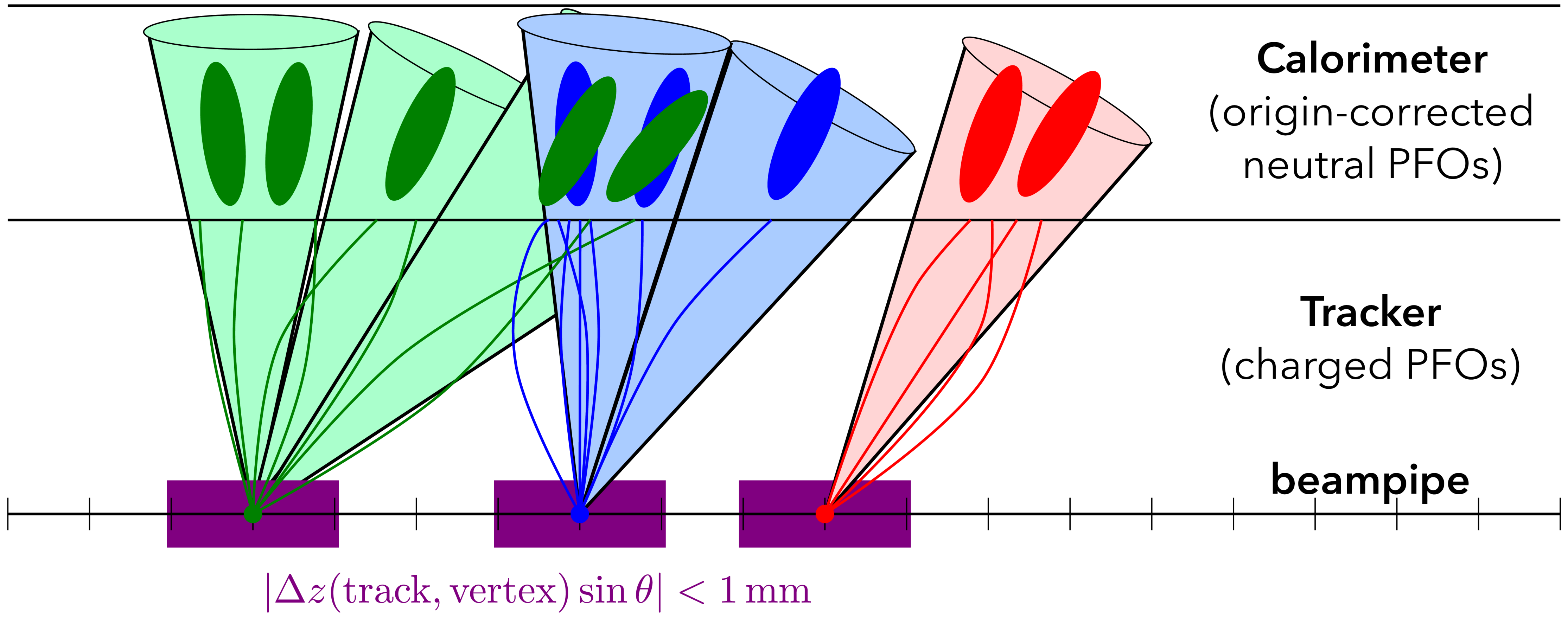


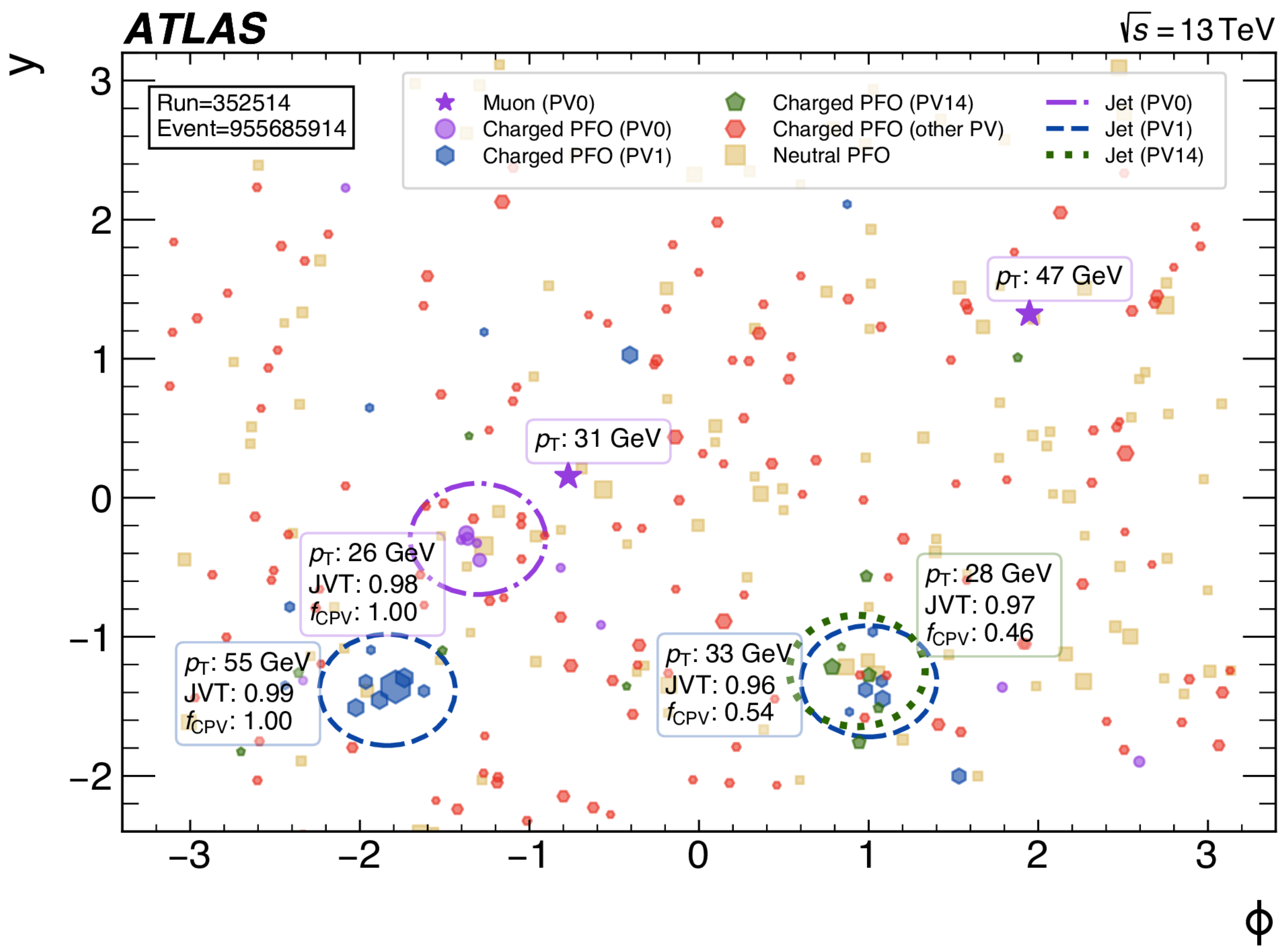
Using pile-up collisions as source of low-energy hadronic physics for JER (selection of PPV)

[2407.10819]

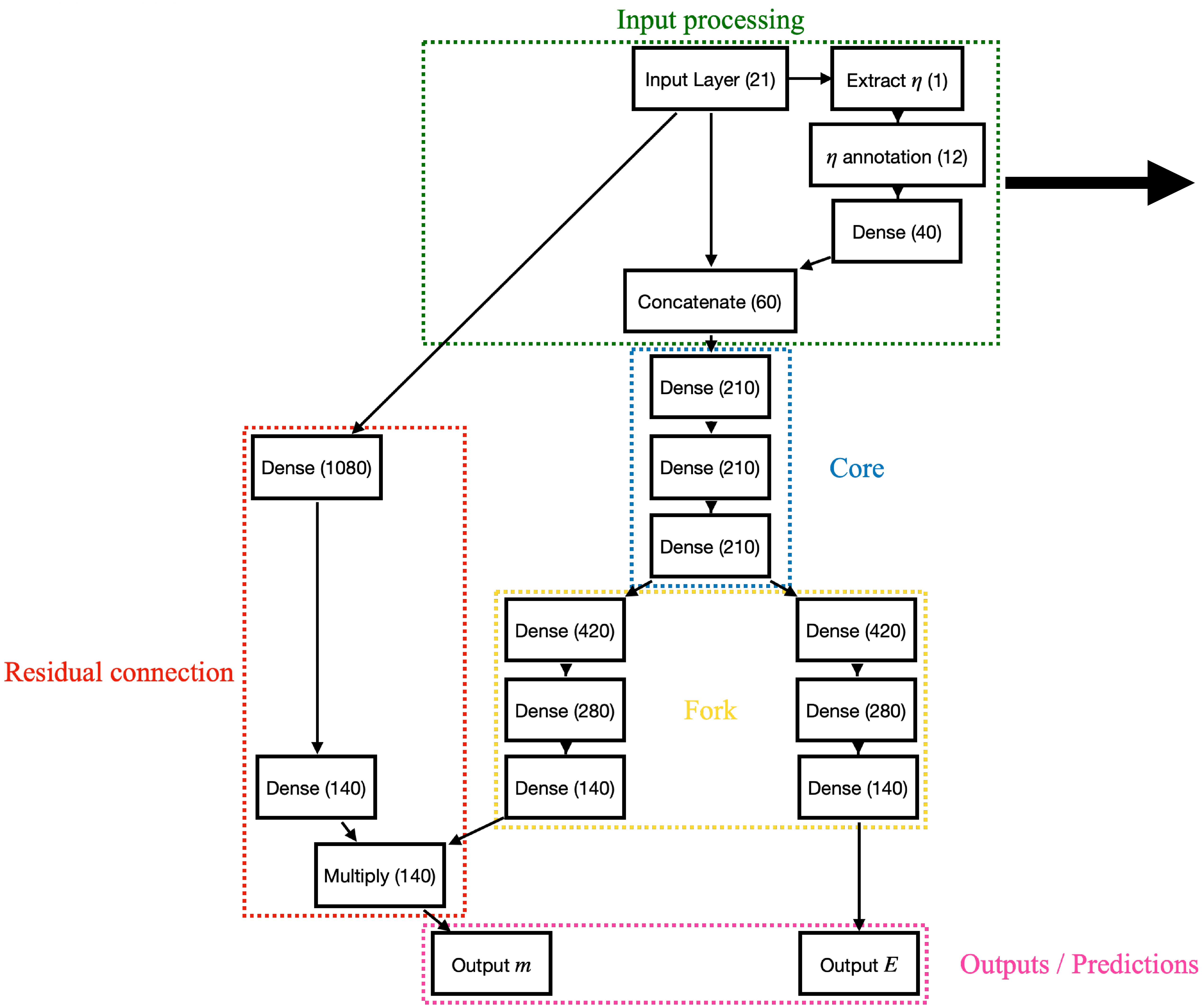
Select pile-up primary vertex:

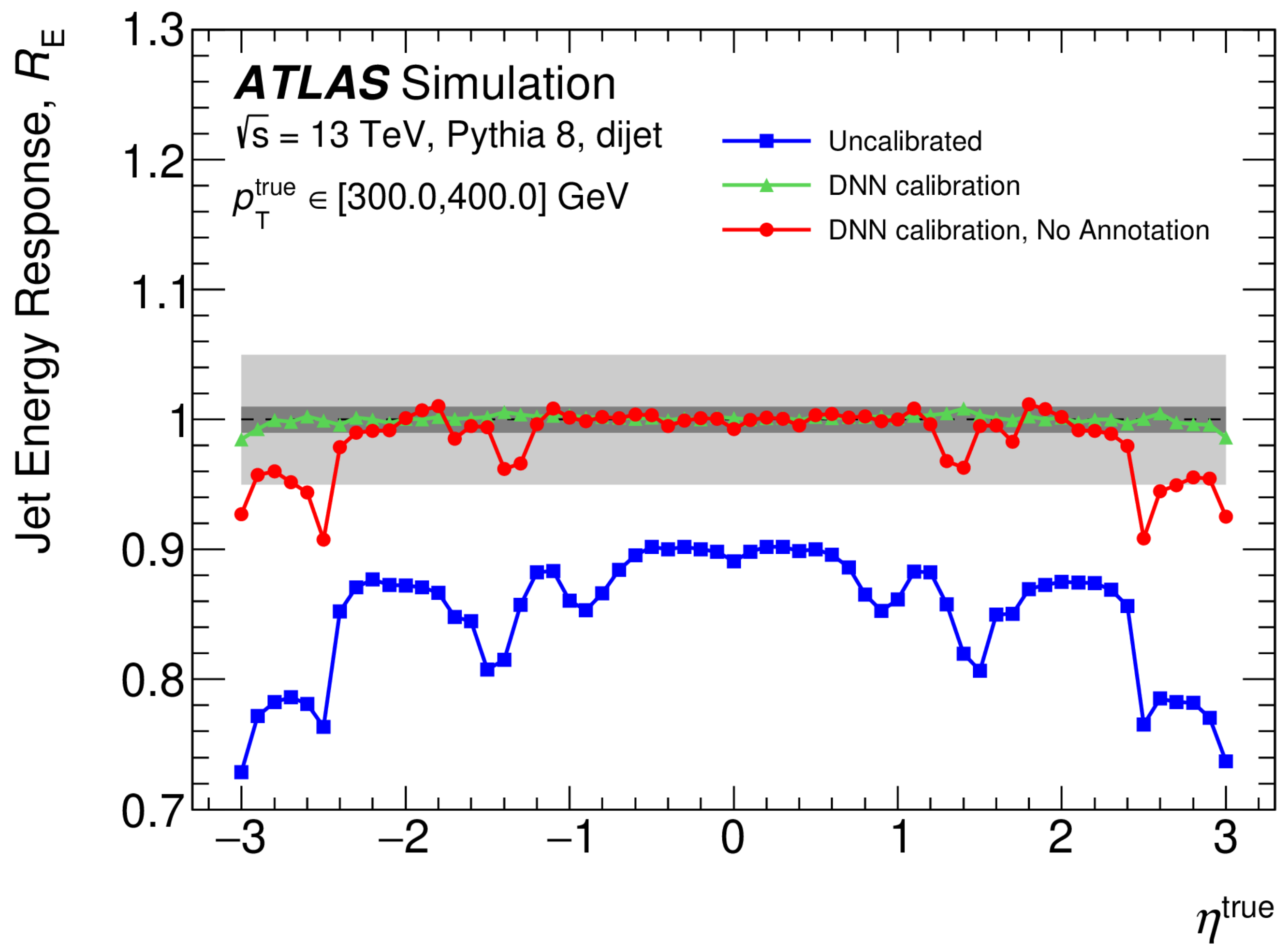
- Charged-particle tracks used to form PVs
    1. Select one PV
    2. Identified charged PFOs consistent with current PV
    3. Adjust all neutral PFO 4-vectors to point to the current PV
    4. Run FastJet clustering for the current PV
    5. Repeat the procedure for every PV (each charged PFO only match to one PV, all neutral PFOs are used on every PV)
- JVT provides substantial discrimination between jets originating from other PVs
- Mitigate overlapping high-momentum signals by $f_{jet}^{CPV} = \frac{p_T^{probe}}{p_T^{probe} + \sum p_T^{overlap}} = 1$
- PV associated to a trigger-matched electron or muon is removed from the RBC
- The total eff. having at least one PPV satisfying all selections in a given BC is 2.1%





Energy and Mass calibration of Large-R jets using a DNN (architecture and validation)





- η annotation encodes the region of the jet with additional features based on η

[2311.08885]

- Loss: Mixture-density-network finds the mode of the distr.

$$\mathscr{L}_{MDN} = \log(\sigma_{pred}) + \frac{1}{2}\frac{(r_E - \mu_{pred})^2}{\sigma^2_{pred}}$$

- Validations
  - Spectrum dependency: give flat $p_T \rightarrow$ similar performance
  - Pileup dependency: less gradient with NPV
  - Flavour dependency: better response
  - Generator dependency: less dependent than standard calibration

Energy and Mass calibration of Large-R jets using a DNN (input features)

ATLAS EXPERIMENT

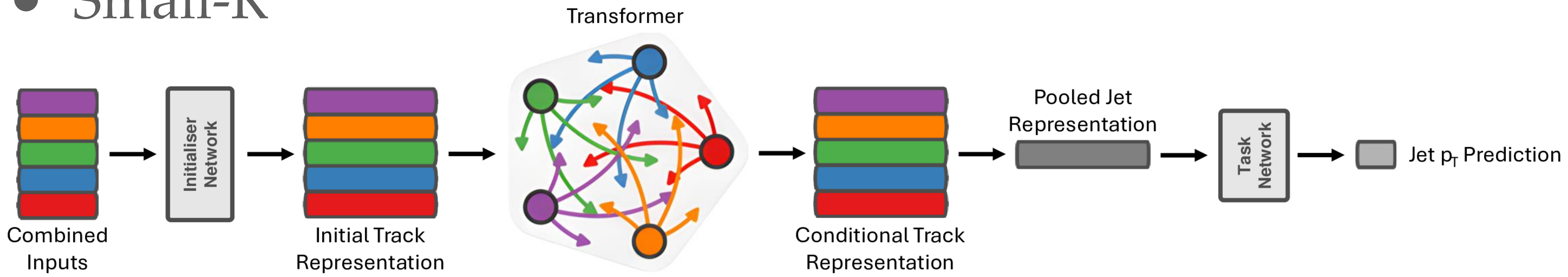
[2311.08885]

	Name	Definition
Jet level	E	Energy of the jet in GeV, $\log E$ is taken to reduce the spread of its distribution
	m	Mass of the jet in GeV, $\log m$ is taken to reduce the spread of its distribution
	η	Jet pseudorapidity
Substructure level	groomMRatio	Mass ratio of groomed to ungroomed jets
	Width	$\sum_i p_{\mathrm{T}i} \Delta R(i, \mathrm{jet}) / (\sum_i p_{\mathrm{T}i})$ where ΔR is the angular distance (sum over the jet constituents)
	Split12,Split23	Splitting scales at the 1st and 2nd exclusive k_T declusterings [34]
	C2, D2	Energy correlation ratios [35,36]
	τ_{21}, τ_{32}	N-Subjettiness ratios using WTA axis [37,38]
	Qw	Smallest invariant mass among the proto-jets pairs of the last 3 steps of a k_T reclustering sequence
Detector level	EMFrac	Energy fraction deposited in the electromagnetic calorimeter
	EM3Frac	Energy fraction deposited in the third layer of the electromagnetic calorimeter
	Tile0Frac	Energy fraction deposited in the 1st layer of the hadronic calorimeter
	EffNConsts	$(\sum_i E_i)^2 / (\sum_i E_i^2)$ (sum over the jet constituents)
	NeutralFrac	Energy fraction from neutral constituents
	ChargedPTFrac	p_{T} fraction from charged constituents
	ChargedMFrac	Mass fraction from charged constituents
Event level	μ	Mean number of interactions per bunch crossing
	NPV	Number of primary vertices per event

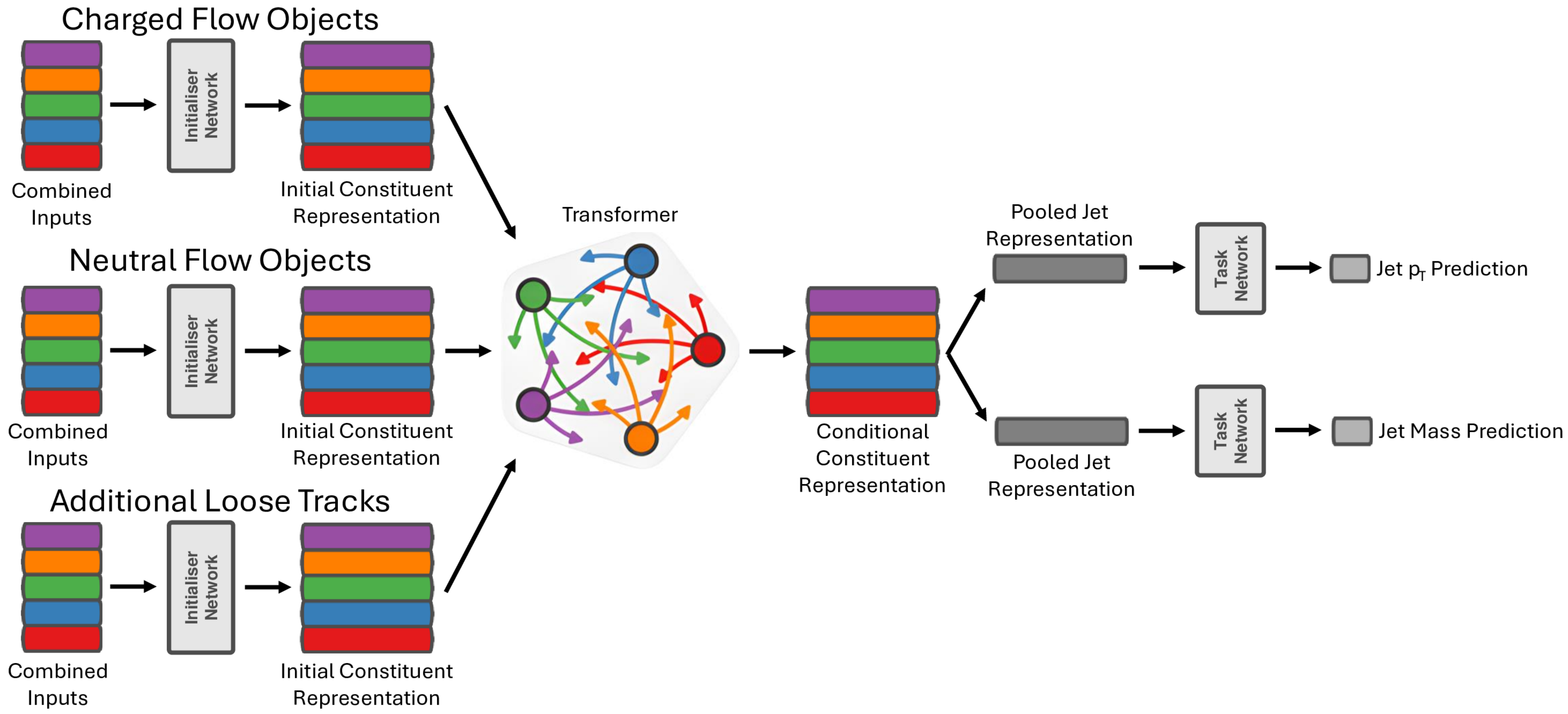
Transformer for constituent-based b-jet calibration (architecture and muon dependence)

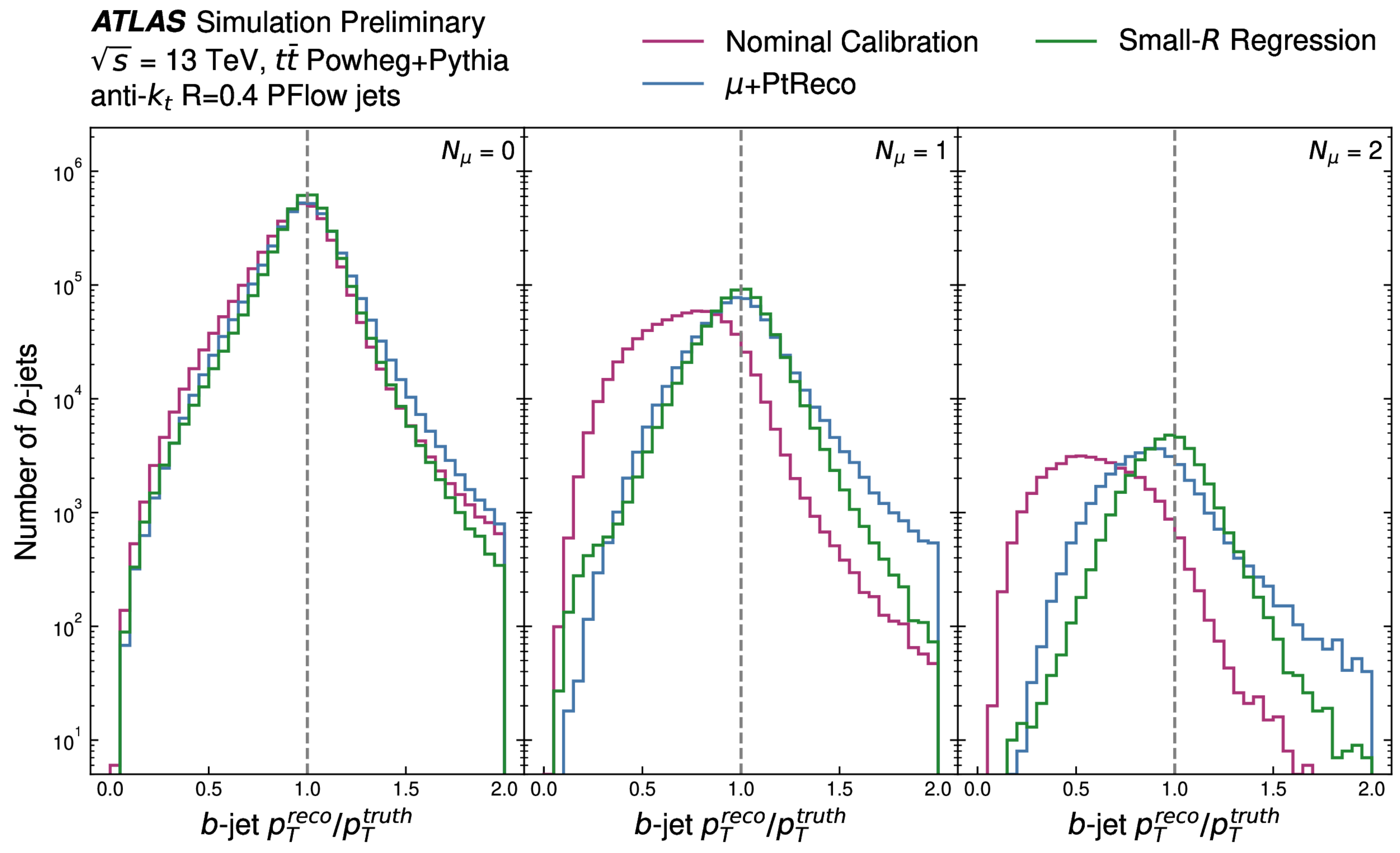
[ATL-PHYS-PUB-2024-015]

- Small-R



- Large-R





- Better response when muon comes from the jet
- *Muon-in-jet* starts failing if there is more than one muon

Transformer for constituent-based b-jet calibration (input features)

[ATL-PHYS-PUB-2024-015]

ATLAS EXPERIMENT

- †: only Small-R input
- ‡: only for Large-R input

Jet feature	Description
p_{T}	Transverse momentum
η	Signed pseudorapidity
m ‡	Jet mass

Track & charged UFO feature	Description
q/p	Track charge divided by reconstructed momentum
$\mathrm{d}\eta$	Pseudorapidity of track relative to the jet η
$\mathrm{d}\phi$	Azimuthal angle of the track, relative to the jet ϕ
d_0	Transverse IP: Closest distance from track to beam-line in the transverse plane
$z_0 \sin\theta$	Longitudinal IP: Closest distance from track to PV in the longitudinal plane
$\sigma(q/p)$	Uncertainty on q/p
$\sigma(\theta)$	Uncertainty on track polar angle θ
$\sigma(\phi)$	Uncertainty on track azimuthal angle ϕ
$s(d_0)$	Significance of transverse IP
$s(z_0 \sin\theta)$	Significance of longitudinal IP times the sin of the polar angle
nPixHits	Number of pixel hits
nSCTHits	Number of SCT hits
nIBLHits	Number of IBL hits
nBLHits	Number of B-layer hits
nIBLShared	Number of shared IBL hits
nIBLSplit	Number of split IBL hits
nPixShared	Number of shared pixel hits
nPixSplit	Number of split pixel hits
nSCTShared	Number of shared SCT hits
LeptonID †	Information on if the track was used in lepton reconstruction

Charged & neutral UFO feature	Description
$p_{\mathrm{T}}^{\mathrm{Flow}}$ ‡	Transverse momentum of charged flow constituent
E_{Flow} ‡	Energy of charged flow constituent
$\mathrm{d}\eta_{\mathrm{Flow}}$ ‡	Pseudorapidity of track relative to the large-R jet η
$\mathrm{d}\phi_{\mathrm{Flow}}$ ‡	Azimuthal angle of the track, relative to the large-R jet ϕ
$\mathrm{d}r_{\mathrm{Flow}}$ ‡	Angular distance of the track from the large-R jet direction

Only Small-R input →

Soft Muon Input	Description
p_{T}	Transverse momentum
η	Signed pseudorapidity
ϕ	Azimuthal angle
dR	Angular distance of the soft muon from the small-R jet axis
q/p	Muon charge divided by the reconstructed momentum
Momentum Balance Significance	Ratio of the difference in momentum measured by the ID and MS to the uncertainty on the energy loss measured by the calorimeters
Scattering Neighbour Significance	Sum of the significances of the angular difference $\Delta\phi$ between pairs of adjacent hits along the track, multiplied by the particle charge
$p_{\mathrm{T}}^{\mathrm{rel}}$	Orthogonal projection of the muon p_{T} onto the jet axis
d_0	Transverse IP: Closest distance from track to beam-line in the transverse plane
z_0	Longitudinal IP: Closest distance from track to PV in the longitudinal plane
$\sigma(d_0)$	Uncertainty on measurement of transverse IP
$\sigma(z_0)$	Uncertainty on measurement of longitudinal IP
$d_0/\sigma(d_0)$	Significance of transverse IP
$z_0/\sigma(z_0)$	Significance of longitudinal IP

Soft Electron Input	Description
$p_{\mathrm{T}}^{\mathrm{r}}$	Relative p_{T} of the electron with respect to the jet
dR	Angular separation between electron and jet axis
$p_{\mathrm{T}}^{\mathrm{iso}}$	Isolation variable
$\lvert\eta\rvert$	Absolute value of pseudorapidity
$s(d_0)$	Transverse IP: Closest distance from track to beam-line in the transverse plane
$z(d_0)$	Longitudinal IP: Closest distance from track to PV in the longitudinal plane
$s(d_0/\sigma_{d_0})$	Significance of the transverse IP
$\Delta\phi^{\mathrm{res}}$	The azimuthal angle difference $\Delta\phi$ between the cluster position in the middle layer and the track.
E/p	Ratio of the cluster energy to the track momentum
R_{had}	Ratio of E_{T} in the hadronic calorimeter to E_{T} of the EM cluster
R_{had1}	Ratio of transverse energy E_{T} in the first layer of the hadronic calorimeter to E_{T} of the EM cluster
E_{ratio}	Ratio of the energy difference between the largest and second-largest energy deposits in the cluster over the sum of these energies
$w_{\eta 2}$	Lateral shower width
R_{η}	Ratio of the energy in 3×7 cells over the energy in 7×7 cells centered at the electron cluster position
f_1	Ratio of the energy in the strip layer to the total energy in the EM accordion calorimeter
f_3	Ratio of the energy in the back layer to the total energy in the EM accordion calorimeter
p_{HF}	Probability of being from heavy flavour decay

Performance of missing transverse momentum (WPs details and soft term uncertainty)

[2402.05858]

- PFlow

Working point	p_T [GeV] for jets with: $\|\eta\| < 2.4$	$2.4 < \|\eta\| < 4.5$	JVT for jets with $\|\eta\| < 2.4$	fJVT for jets with $2.5 < \|\eta\| < 4.5$ & $p_T < 120$ GeV
	Selections			
Loose	> 20	> 20	> 0.5 for $p_T < 60$ GeV	-
Tight	> 20	> 30	> 0.5 for $p_T < 60$ GeV	-
Tighter	> 20	> 35	> 0.5 for $p_T < 60$ GeV	-
Tenacious	> 20	> 35	> 0.91 for $20 < p_T < 40$ GeV > 0.59 for $40 < p_T < 60$ GeV > 0.11 for $60 < p_T < 120$ GeV	< 0.5

- Object-based significance

$$S(p_T^{miss}) = \frac{p_T^{miss}}{\sqrt{\sigma_L^2(1-\rho_{LT}^2)}}$$

σ_L: longitudinal resolution

ρ_{LT}: correlation between transverse and longitudinal resolution to p_T^{miss}

For [30,35] GeV bin

- Parallel scale uncertainty reduced by 52%
- Parallel resolution uncertainty reduced by 43%
- Perpendicular resolution uncertainty reduced by 13%