Jet Reconstruction & Pileup Mitigation Performance in CMS

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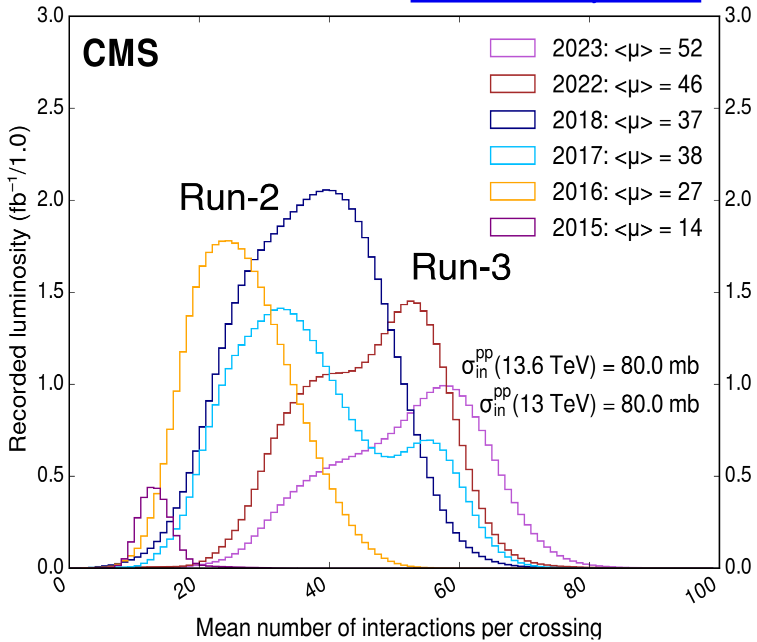
Introduction

- Jet reconstruction is integral to the CMS physics program.
  - ➢ Crucial signatures in SM measurements & BSM searches.

- Need optimum reconstruction & precise calibration.

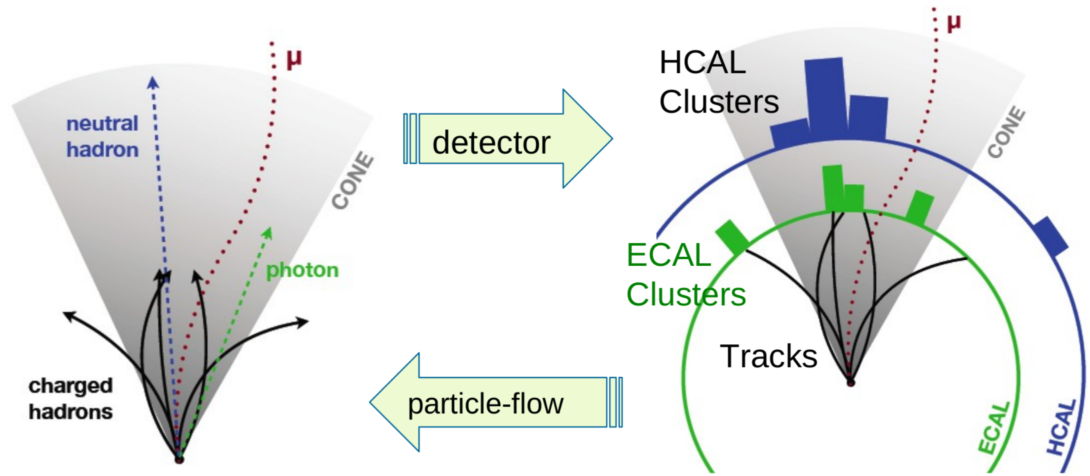
- Unprecedented number of Pileup in Run-3 datasets.
  - ➢ Pileup mitigation more important than ever to maintain jet performance.

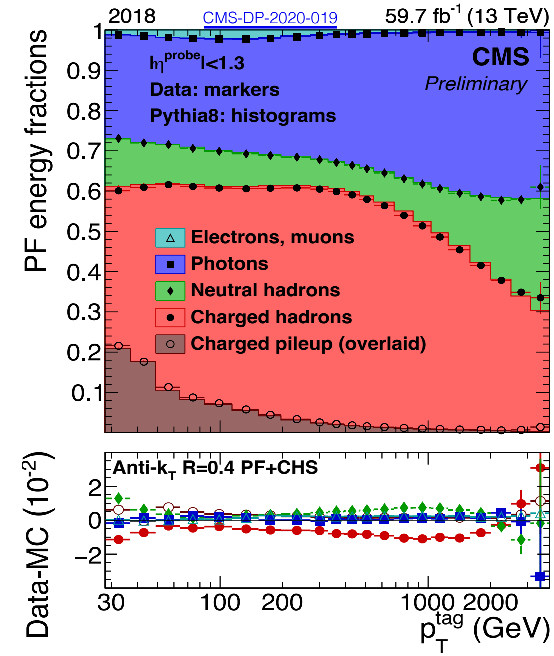
CMS Luminosity Results



Jet Reconstruction in CMS

Particle Flow (PF) Algorithm [JINST 12 (2017) P10003]





global event description by combining various sub-detectors information

"Standard" jet algorithms with PF candidates as inputs:

- Small-R jets: anti-k_T R = 0.4 [AK4]
- Large-R jets: anti-k_T R = 0.8 [AK8]

- AK or CA R=1.5 are sometimes used. Analysis specific.
- "Non-standard" jets also used (e.g Variable-R). See Gabriele Milella's poster & Donato Troiano's talk.

Constituent-level Pileup Mitigation with PUPPI

Constituent-level Pileup Mitigation

JINST 15 (2020) P09018
DP-2021-001

CMS mitigates pileup at the constituent-level

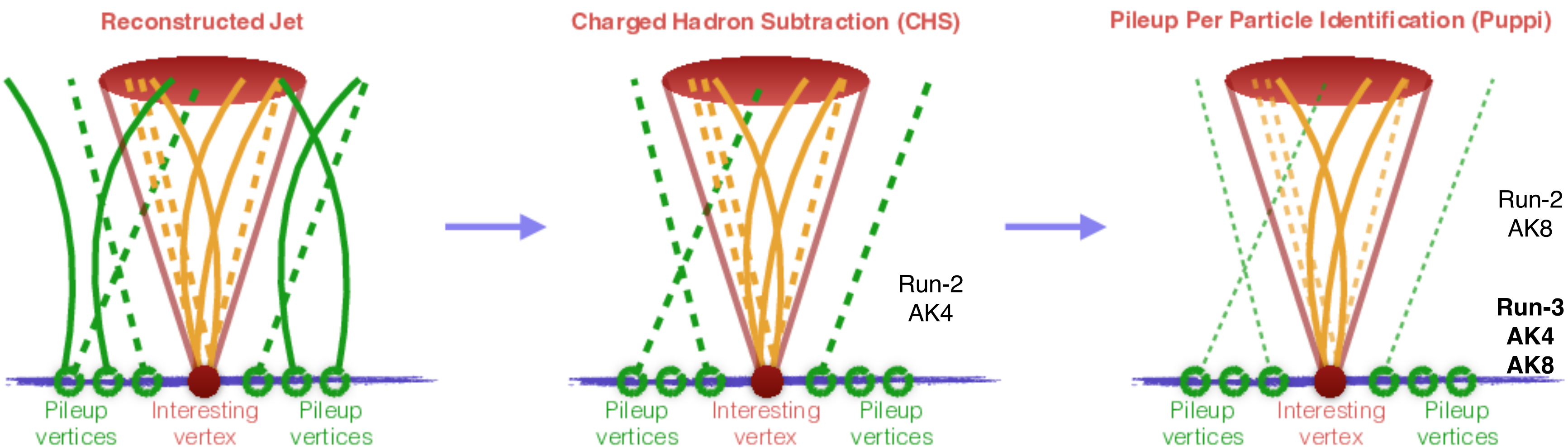


Figure by Andrea Malara

CHS

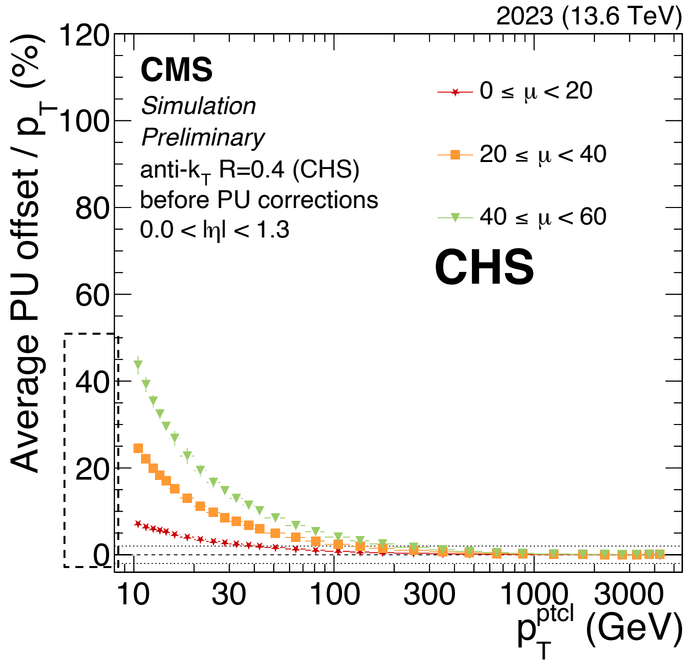
- Discard charged PF candidates from Pileup Vertices

PUPPI

- More refined treatment of charged PF candidates, depends on vertex association.
- Apply weights to neutral PF candidates four-vector.

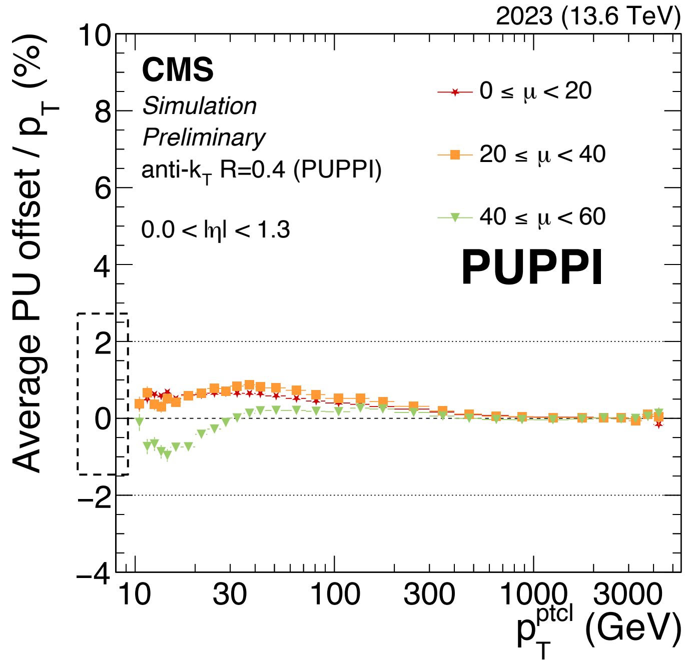
CHS vs PUPPI: Impact on jet energy

DP-2024-039



Large pileup contamination at low pT

Require dedicated step in jet energy corrections.



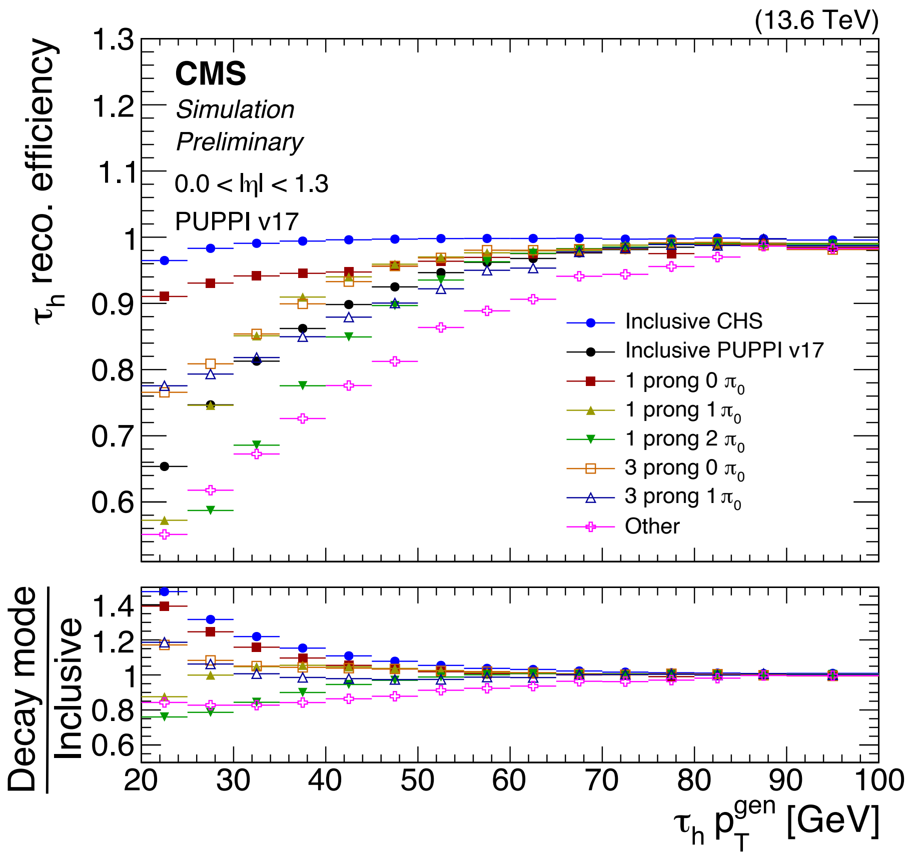
Negligible pileup contamination

Not used for jet energy corrections. Monitor pileup.

PUPPI: Optimization for hadronic τ reconstruction

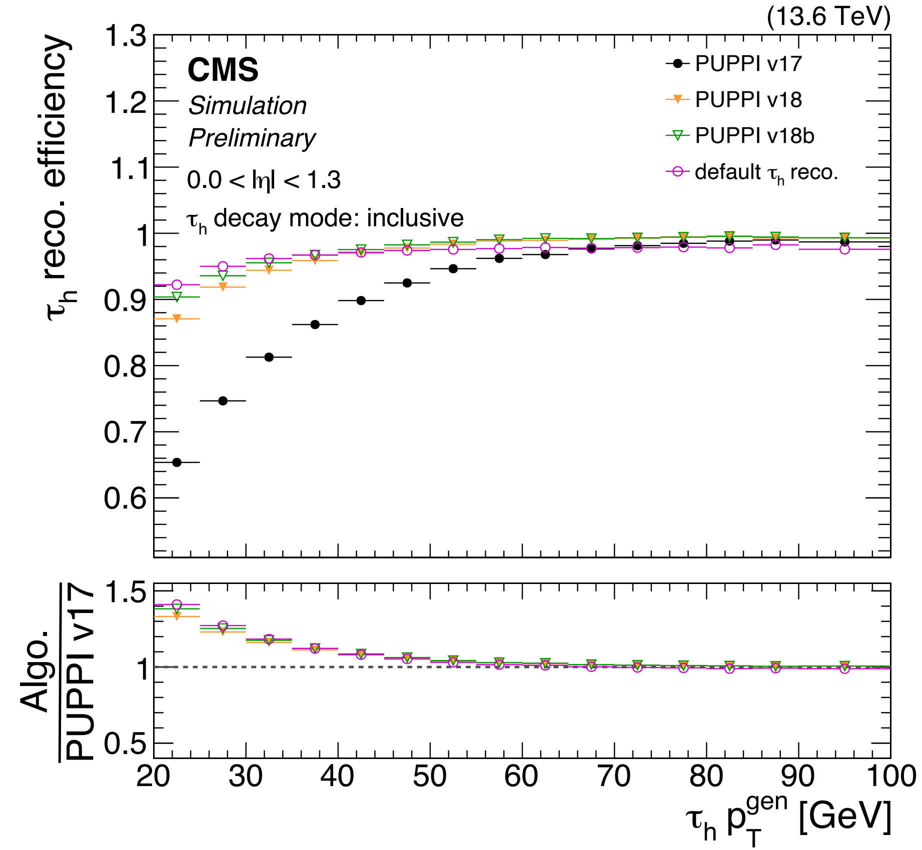
DP-2024-043

- Hadronically-decaying τ-lepton reconstruction uses AK4 CHS jets as seeds. JINST 13 (2018) P10005
- Natural to switch to **PUPPI jets** but observed a lower reconstruction efficiency.
- Due to the different treatment of charged PF candidates associated to Pileup Vertices between CHS and PUPPI.
  - ➢ specifically ones not associated to any vertex.



DP-2024-043

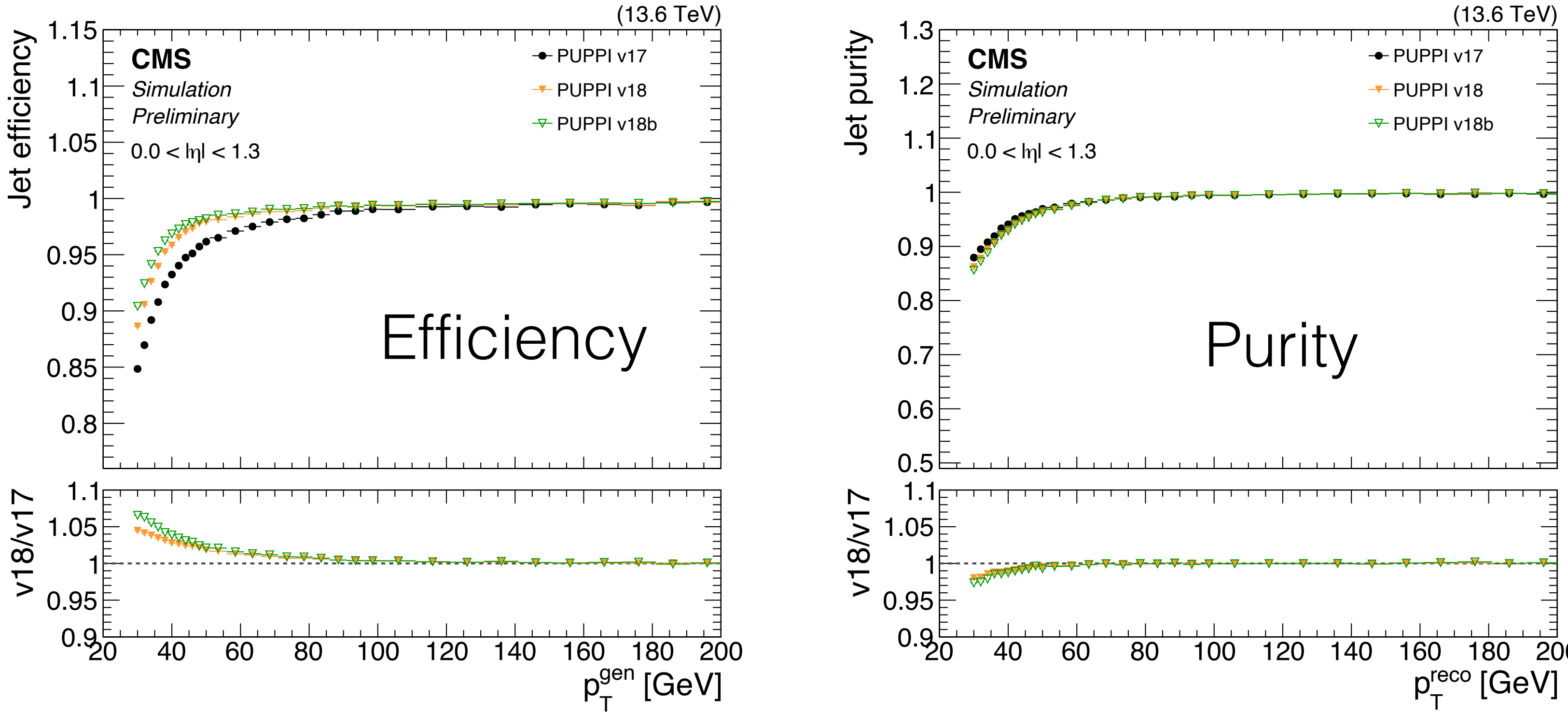
- CHS: retains charged PF candidates <u>not associated</u> to any vertices.
- PUPPI: retains if $p_T > 20$ GeV but assign a weight if lower.
- Update PUPPI algorithm (V18): retains if $p_T > 4$ GeV.
  - ➢ **Substantial** efficiency recovery.



PUPPI: Optimization for hadronic τ reconstruction

DP-2024-043

Impact on real jets from hard-scatter vertex

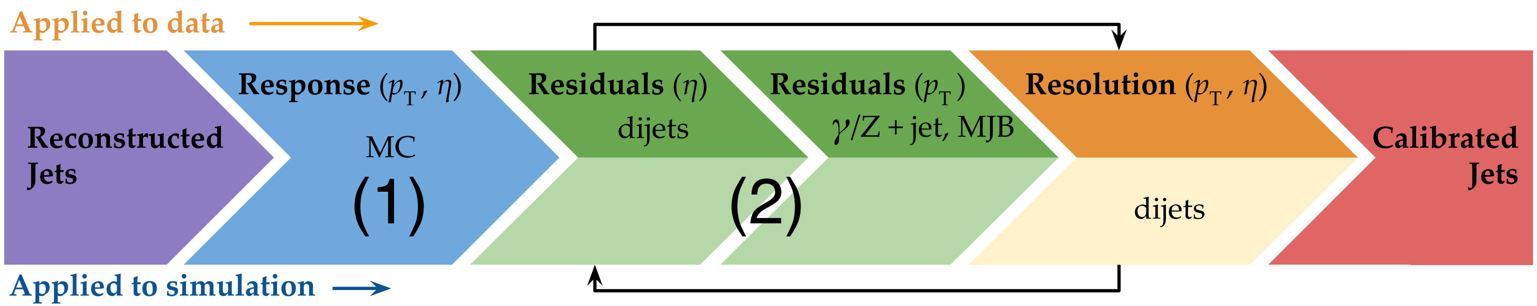


Improve efficiency, small reduction in purity

Jet Energy Scale & Resolution Calibration for Run-3 Datasets

Jet Energy Scale (JES) & Resolution (JER) Calibration

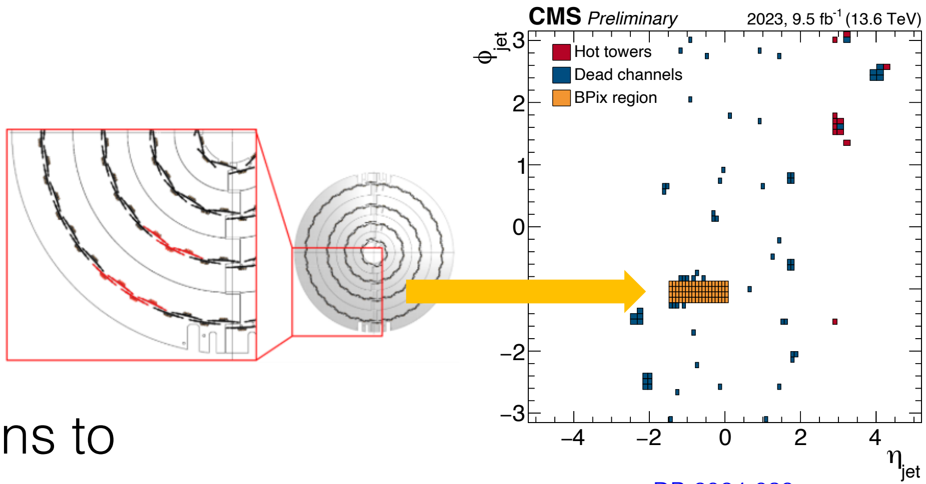
DP-2024-039



- Factorized approach to jet energy calibration.
- Jet Energy Scale (JES) calibration:
  1) MC "truth" corrections: correct to particle-level jet scale.
  2) Residual corrections: correct for residual differences between simulation & data.
- Jet Energy Resolution (JER) calibration:
  - ➢ Smear jet energy in simulation to match that in data.

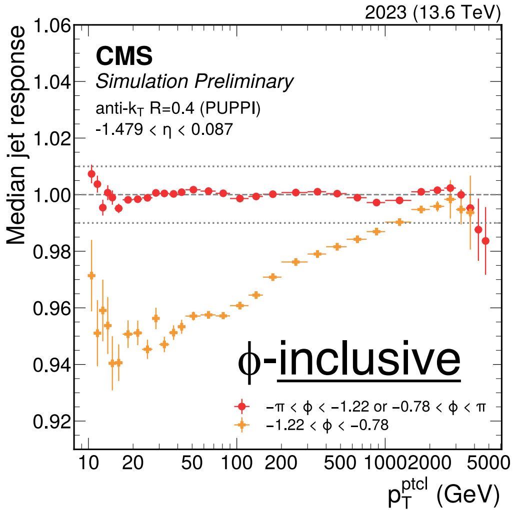
ϕ-dependent JES Corrections

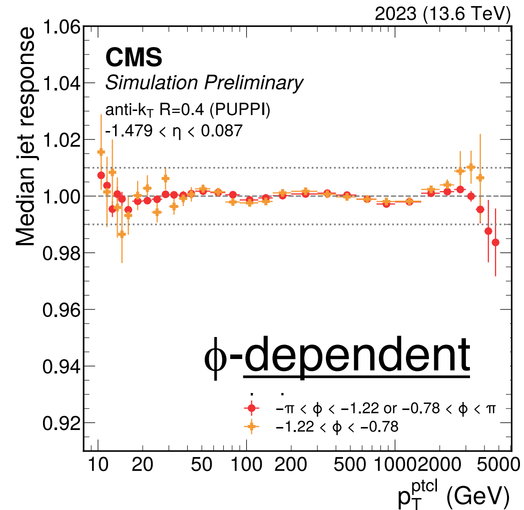
- Partial failure of a portion of the Barrel Pixel sub-detector (BPix) occurred during 2023 data-taking.
  - ➢ Track reconstruction efficiency loss, affects jet energy scale.



DP-2024-039

- Introduce ϕ-dependent JES corrections to minimize impact of BPix inefficiency.

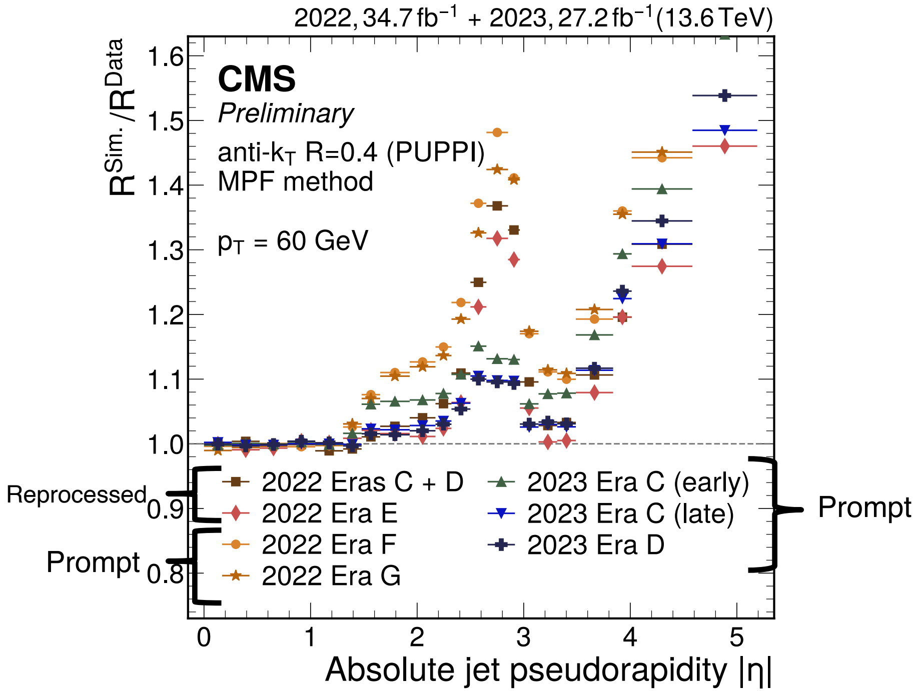




JES & JER SF

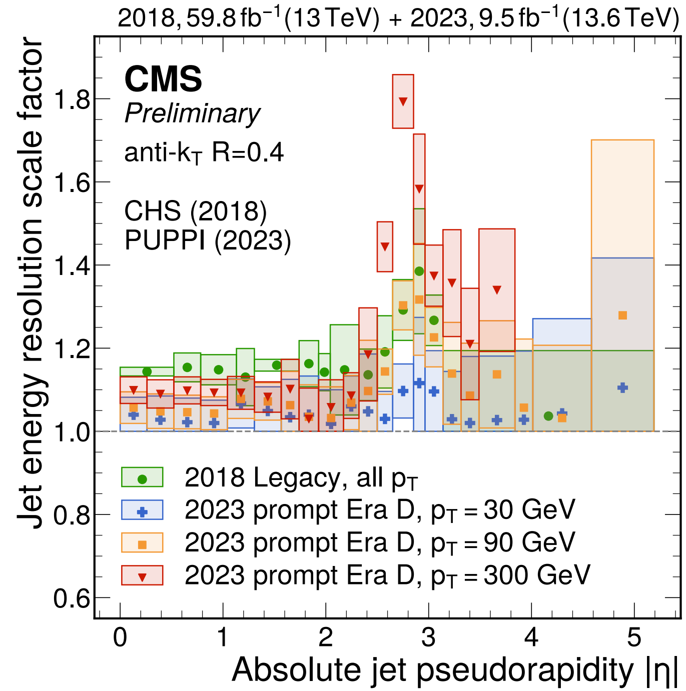
DP-2024-039

JES residual corrections



Significant improvement of the reprocessed 2022 & prompt 2023 data compared to prompt 2022 data

JER (Data/Simulation) SF



- Run-3 prompt reconstructed data is better than Run-2 legacy.
- Observed pT dependence for Run-3 dataset.

Jet p_T regression with ParticleNet

Jet p_T regression with ParticleNet

ParticleNet

Phys. Rev. D 101, 056019 (2020)

Graph NN with PF constituents & Secondary Vertices as inputs.

- First used for boosted resonance tagging with **AK8 jets.** DP-2020-002 CMS-PAS-BTV-22-001
- Extended for **AK8** jet **mass regression**. DP-2021-017
- Commissioned for **AK4** jet flavor tagging & p_T regression.

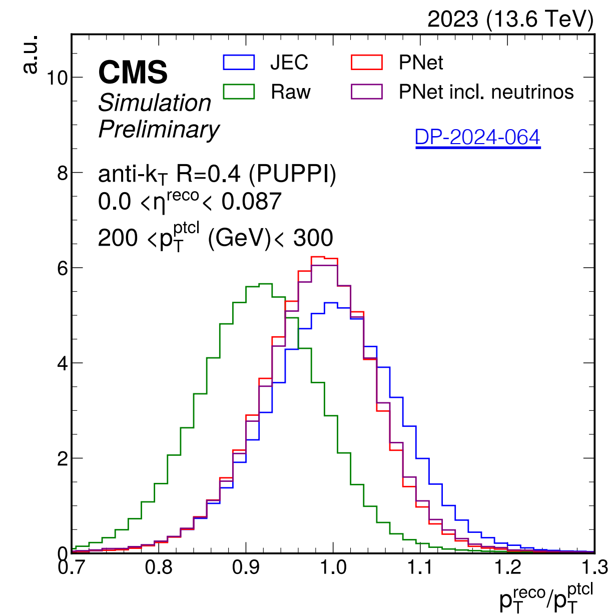
DP-2024-066

Classification | *Regression* | *Quantile regression (resolution estimation)*

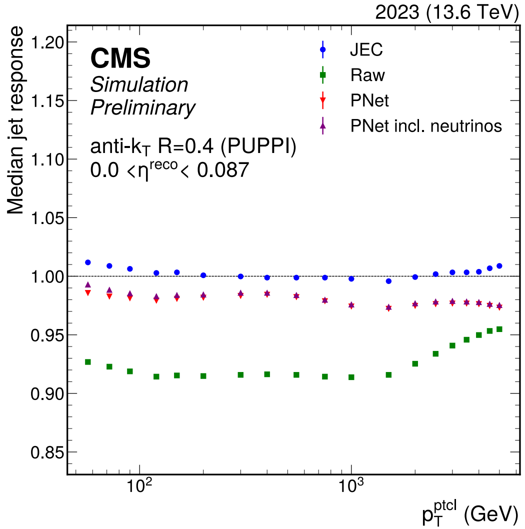
$$L = CatEntropy(x, x_{truth}) + \gamma_{regr} \cdot log(cosh(y - y_{truth})) + \gamma_{quantile} \cdot [p_{0.16}(z - z_{truth}) + p_{0.84}(z - z_{truth})]$$

Two types of target p_T regression

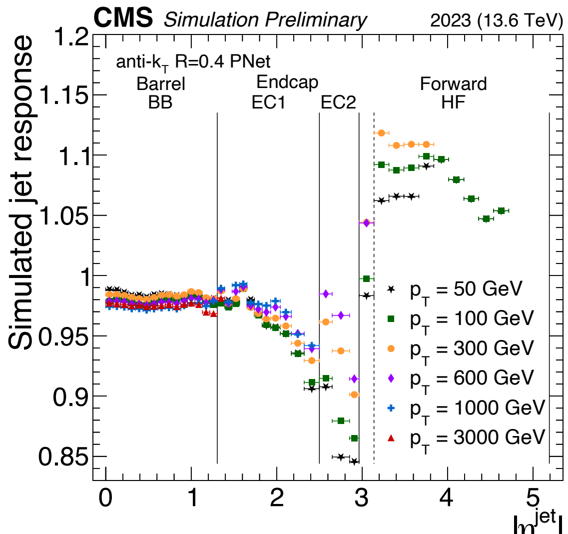
without & with neutrino contribution



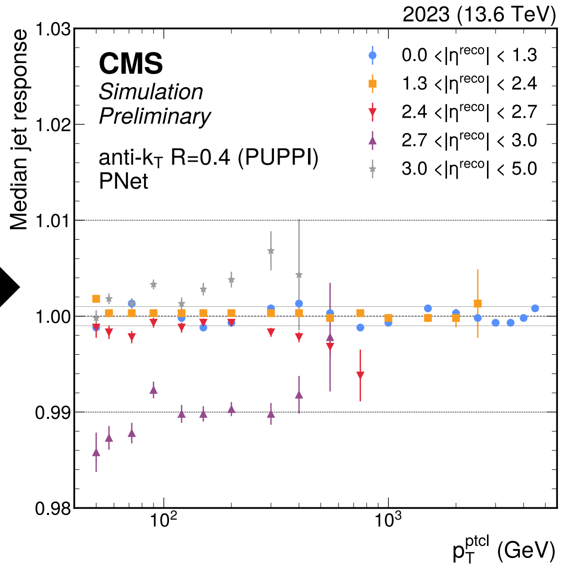
DP-2024-064



- Regressed p_T response closer to 1 compared to raw p_T for central jets.
- Derive MC-truth corrections, achieve response closure within 1% (similar level to JEC).

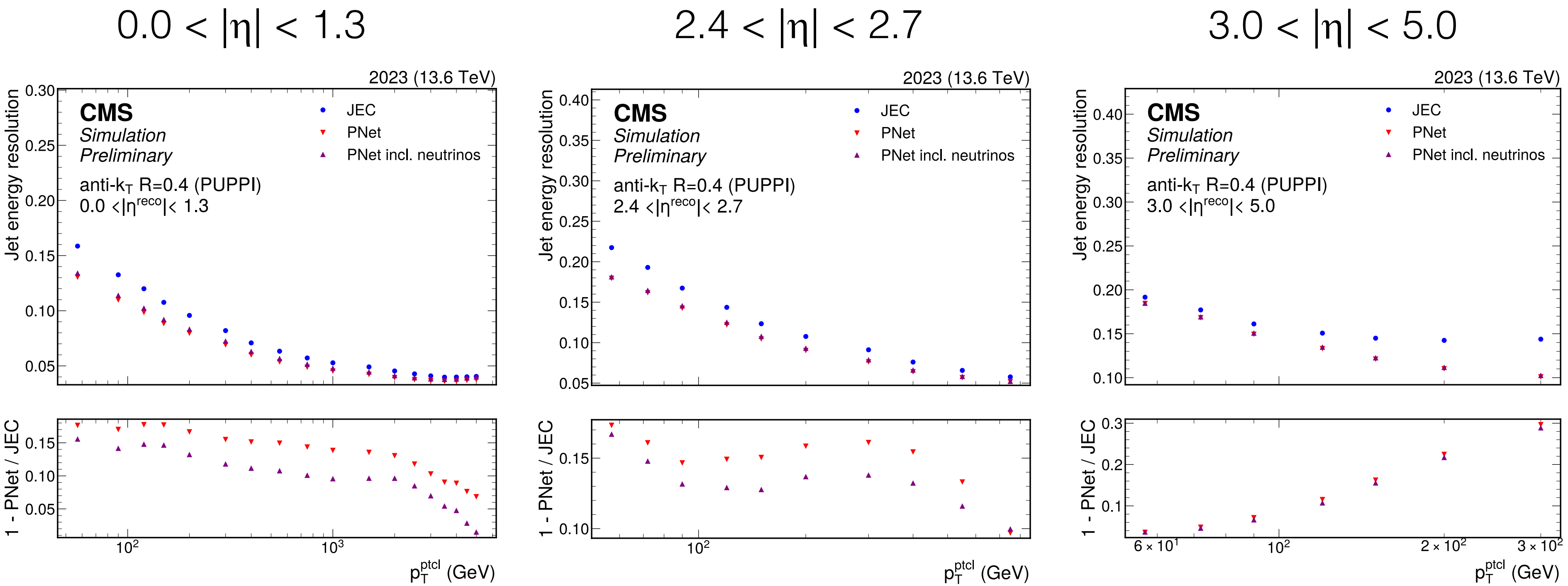


Apply corrections



Jet p_T regression with ParticleNet (Resolution)

DP-2024-064



Clear improvement in JER
across the jet p_T range, even for forward jets.

Unified Particle Transformer (UParT)

- CMS investigated several Transformer models for flavour tagging:

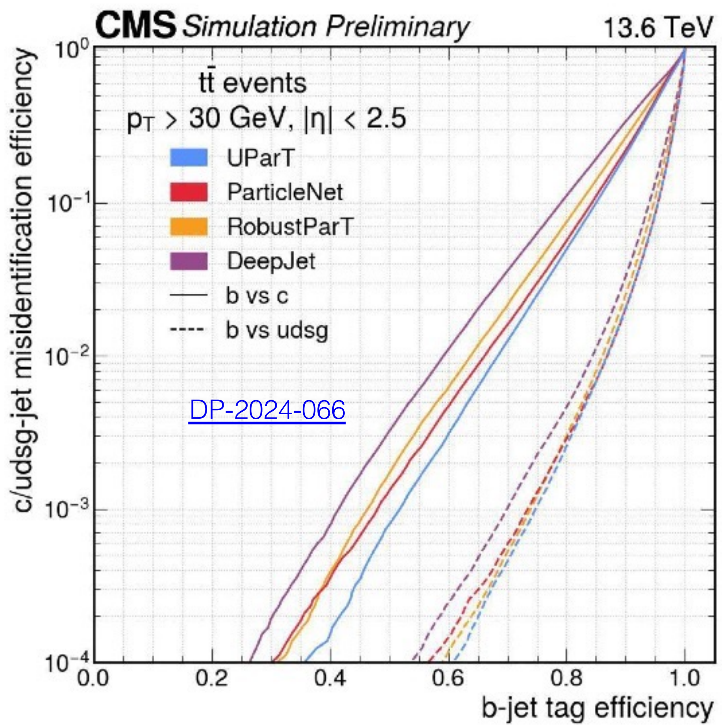
➢ ParticleTransformerAK4 2202.03772 DP-2022-050

➢ RobustParT: Utilize adversarial training to enhance model robustness against simulation mismodeling. DP-2024-025

Unified Particle Transformer (UParT)

- Extended class: extending from b & c jet tagging to include s & hadronic τ (one per final state) tagging.

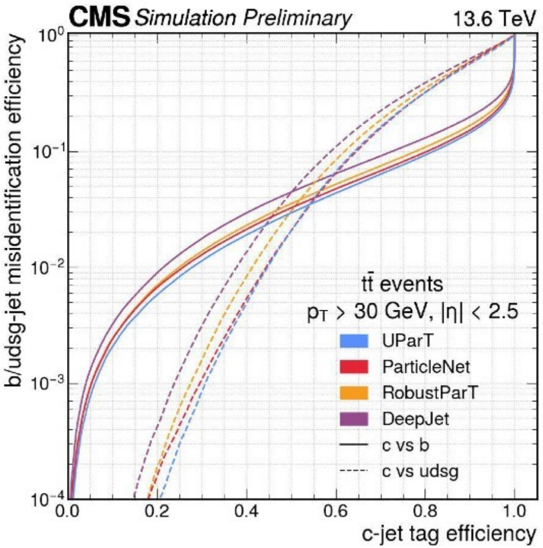
- Extended regression: simultaneous flavor aware **jet energy & resolution regression**



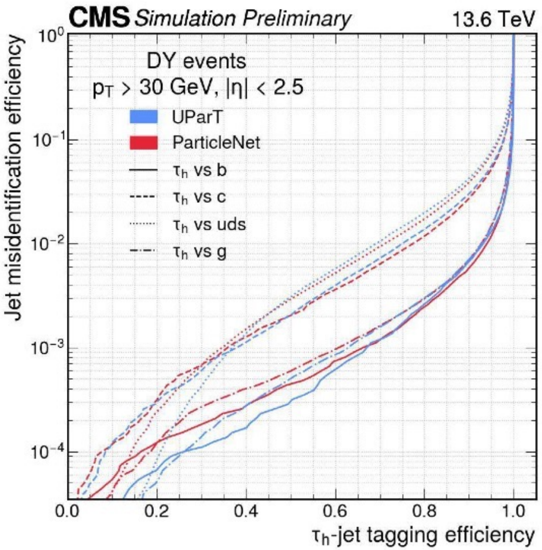
(Unified) Particle Transformer

DP-2024-066

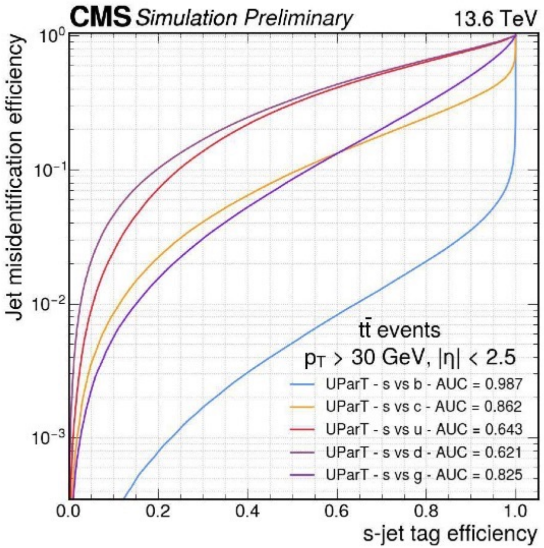
c-jet



hadronic τ



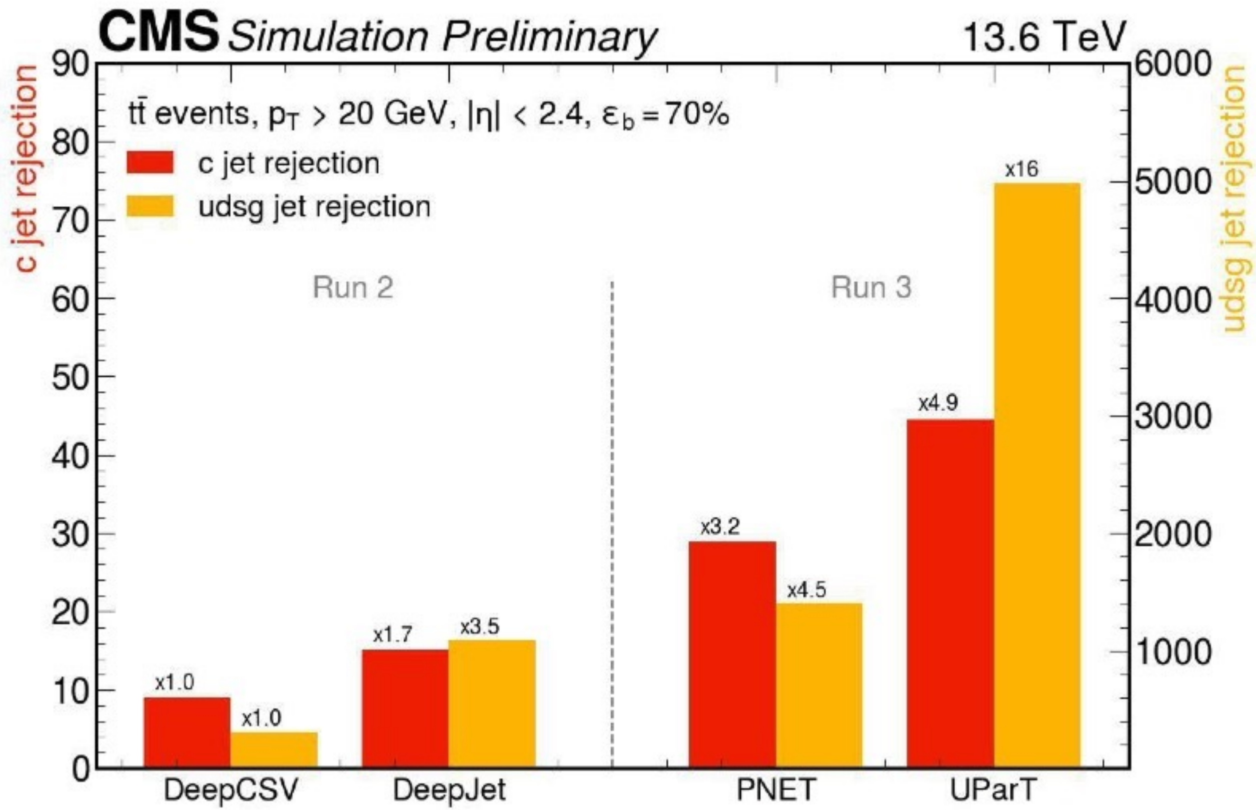
s-jet



First attempt at strange-jet tagging in CMS!

Progress of CMS flavour-tagging algorithms

DP-2024-066



Impressive advancement of jet tagging within ~decade.

Powered by state-of-the-art Machine Learning techniques!

Summary

- Updated PUPPI algorithm to maintain hadronic τ reconstruction efficiency.
  - ➢ Towards unified jet & τ reconstruction.

- Measured JES & JER for Run-3 datasets.
  - ➢ JER SF as good (even better) than Run-2 legacy in Run-3 prompt data.

- Extended ParticleNet architecture to include jet p_T regression
  - ➢ Substantial JER improvement.

- Commissioned **Unified Particle Transformer** tagger for AK4 jets.
  - ➢ Extended flavour-tagging capabilities & perform p_T regresssion at the same time!

EXTRA SLIDES

PUPPI

DP-2021-001

PUPPI calculates an α_i value for each particle in the event

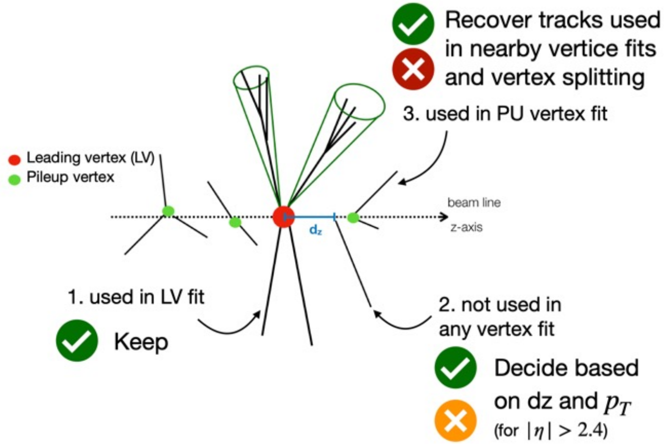
$$\alpha_i = \log \sum_{j \neq i, \Delta R_{ij} < R_0} \left(\frac{p_{T,j}}{\Delta R_{ij}} \right)^2$$

for $|\eta_i| < 2.5$, j are charged particles from LV and for $|\eta_i| > 2.5$, j are all kinds of reconstructed particles. The median ($\bar{\alpha}_{PU}$) and RMS (α_{PU}^{RMS}) are calculated from the charged PU α distribution. Based on that each neutral particle receives a signed χ^2

$$\text{signed } \chi_i^2 = \frac{(\alpha_i - \bar{\alpha}_{\text{PU}})\,|\,\alpha_i - \bar{\alpha}_{\text{PU}}\,|}{\left(\alpha_{\text{PU}}^{\text{RMS}}\right)^2}$$

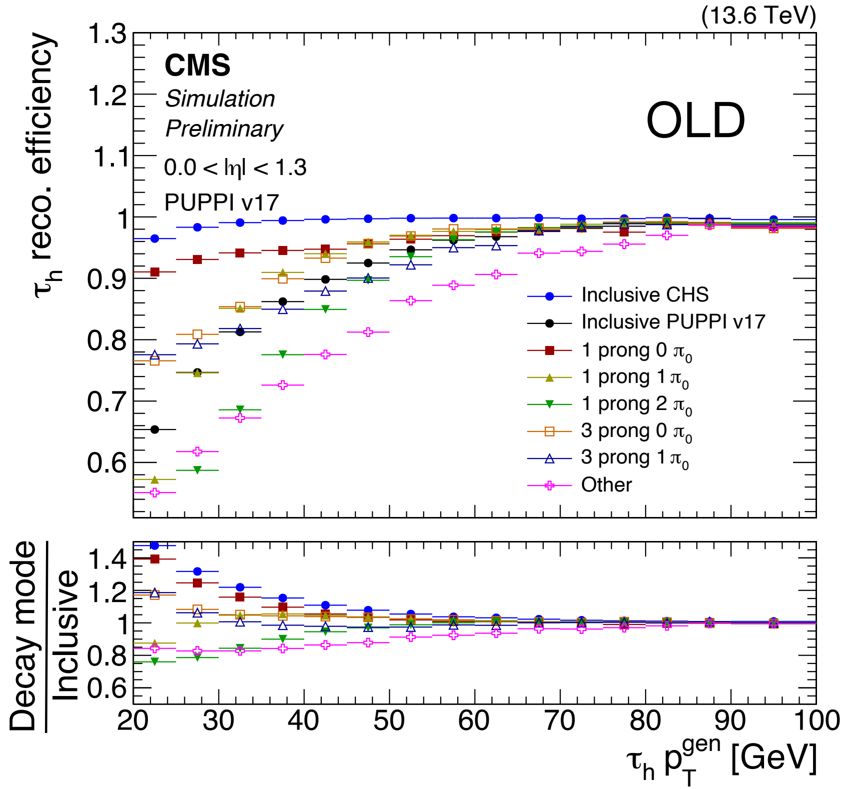
The weight for each neutral particle is calculated with a cumulative distribution function and multiplied to the four-momentum of the particle:

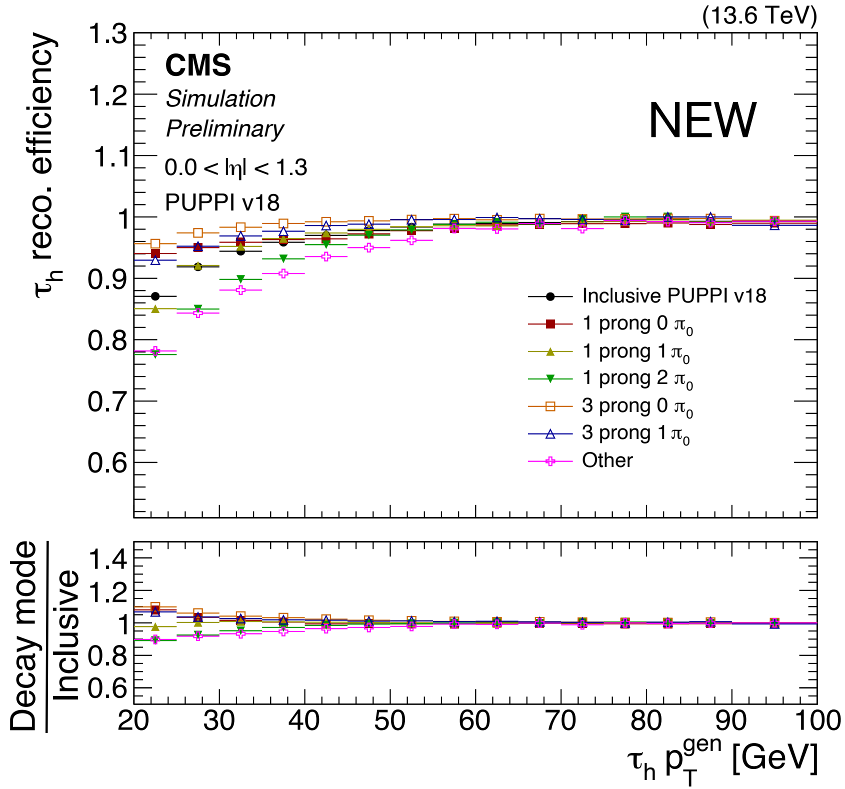
$$w_i = F_{\chi^2,\text{NDF}=1(\text{signed } \chi_i^2)}$$



CHS keeps LV (✔) and unassociated (✖) particles, PUPPI keeps LV (✔) but assigns a weight to unassociated particles (✖).

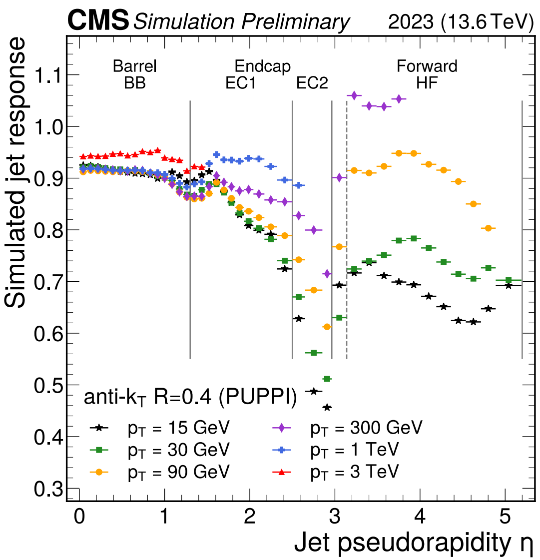
τ reconstruction efficiency (PUPPI v17 vs v18)



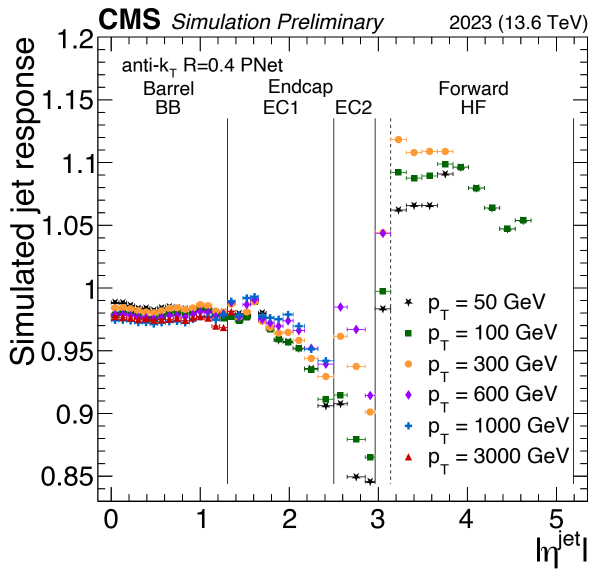


Jet p_T Response in Simulation (Raw vs Regressed)

Jet pT [DP-2024-039]



Regressed Jet p_T [DP-2024-064]



Regressed Jet p_T with Neutrinos