Jet energy scale and resolution of jets with ParticleNet p_T regression using data collected by the CMS experiment for partial Run 3

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ML4Jets

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CMS

Jet p_T Regression in CMS

Jet p_T regression aims at estimating the truth-level jet p_T while at the same time improving the p_T resolution

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DNN-based b-jet energy regression used in multiple H→bb analyses in Run 2 (e.g. HH4b Phys. Rev. Lett. 129, 081802, VHbb Phys. Rev. D 109, 092011)

Phys. Rev. D 101, 056019

ParticleNet (**PNet**), a Graph Neural Network that performs jet-tagging and flavour aware jet p_T regression and jet energy resolution estimation

arXiv:2202.03772

UParT, a Particle Transformer model performing similar tasks to PNet (see Uttiya's talk for more details)

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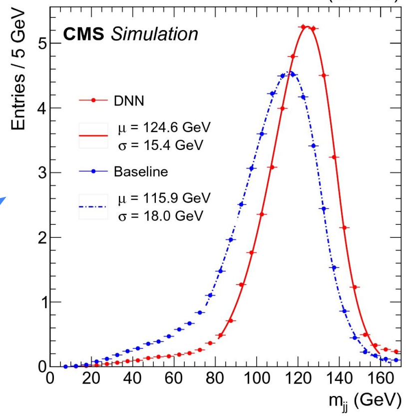

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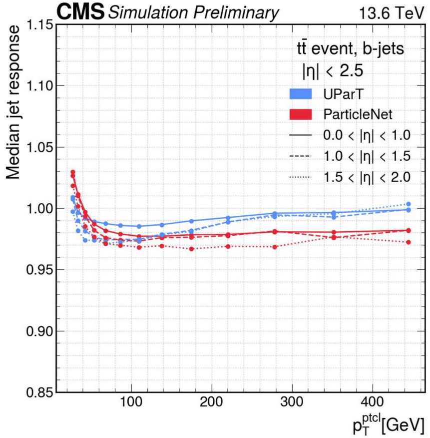
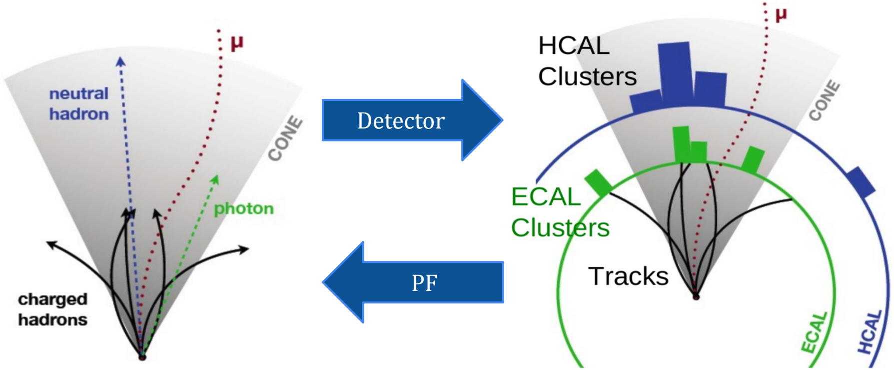


Jet Reconstruction in CMS

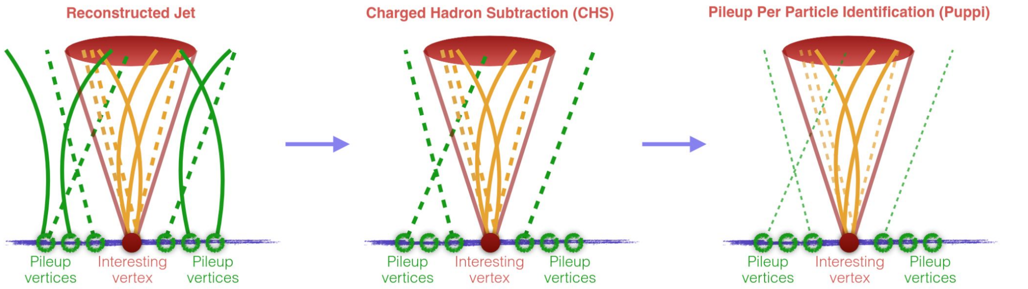
[JINST 12 P10003](#)

- The following results are shown for jets composed of **Particle Flow** (PF) candidates reconstructed by combining various sub-detectors information
- The jets are clustered using the **anti-k_T** algorithm with $R = 0.4$



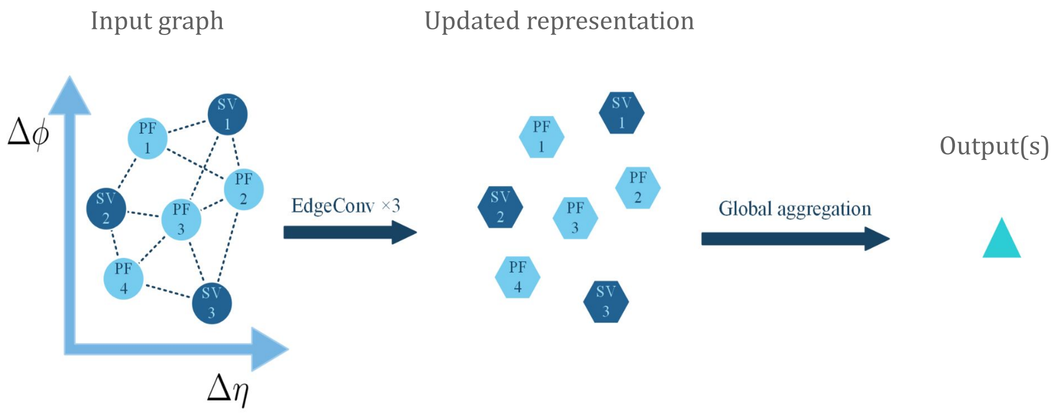
[JINST 15 P09018](#)

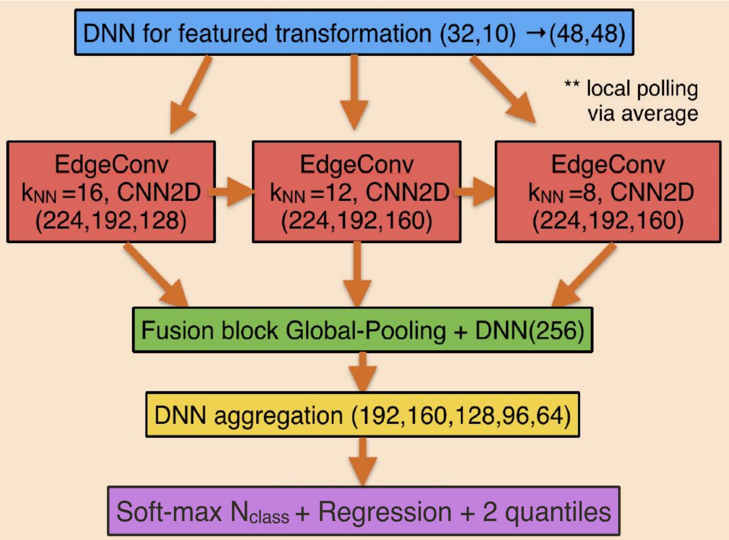
- The **Pileup Per Particle Identification** (PUPPI) algorithm is applied to **mitigate the pileup** (PU)
  - Instead of removing charged particles originating from PU as the Charged Hadron Subtraction (CHS) algorithm, PUPPI derives per-particle weights used to scale the 4-momenta before clustering



ParticleNet Architecture

- PNet is a **Dynamic Graph Convolutional Neural Network** developed for jet flavor classification
- Jets are treated as a ***particle cloud*** composed of:
  - PF candidates
  - Reconstructed Secondary Vertices (SVs)





ParticleNet Tasks

PartilceNet performs multiple tasks:

- **Jet flavour classification**
  - Identification of b, c, uds, g, τ_h, e, μ
- **Jet energy regression**
  - Correct the **raw jet p_T** to the **truth-level jet p_T**
  - Prediction of the ratio between the truth-level jet p_T and the raw jet p_T
  - Factorized contribution to **account for neutrinos**
- **Jet energy resolution**
  - Estimate the 84% and 16% quantiles of the jet resolution distribution

Jet Energy Corrections

- **Jet Energy Scale** calibration is presented, based on data collected in pp collisions at $\sqrt{s}$ = 13.6 TeV by the CMS experiment in **2022** and **2023**
- Jets are calibrated sequentially with what are referred to as **Jet Energy Corrections (JEC)**:
  - Detector response correction from simulation (**Response Correction**)
  - Residual correction for differences between data and detector simulation (**Relative and Absolute Residual Corrections**)
- JEC for PNet p_T regression:
  - Dedicated Response Correction has been derived
  - Performance of the existing Residual Corrections have been assessed
  - Final efforts for the complete calibration of the PNet p_T regression are in progress, to potentially make this new baseline in CMS for Run 3

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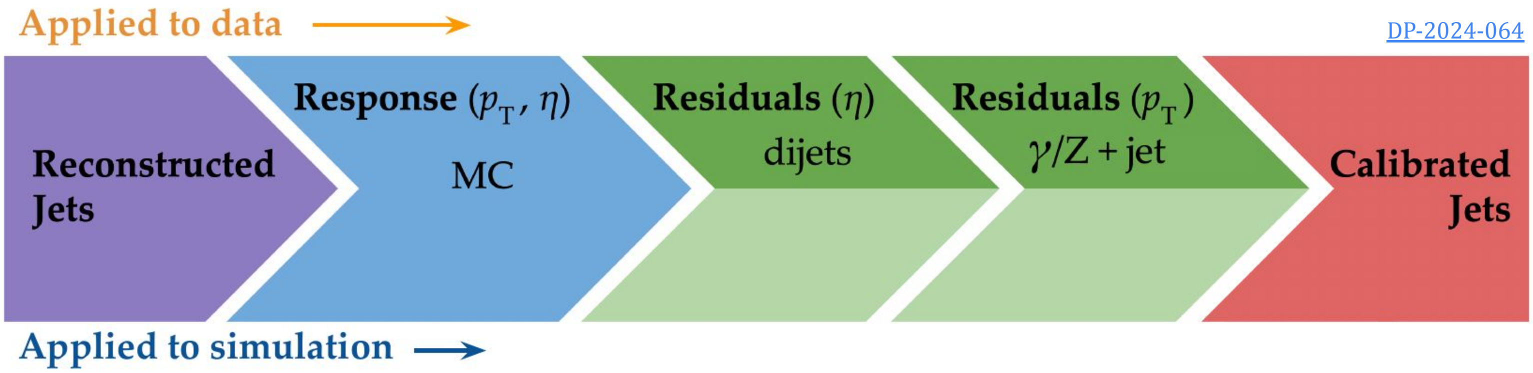

Response Correction - Experimental Techniques

- The correction in simulation is derived by **matching reconstructed and particle-level jets** by requiring $\Delta R = \sqrt{\Delta\eta^2 + \Delta\varphi^2} < 0.2$
- Two different definitions of generator-level jets are used:
  - Particle-level jets are clustered from **visible** particles, referred to as particle (**ptcl**) jets. These jets are used as default when comparing to reconstructed (**reco**) jets
  - When comparing the p_T of the reconstructed jets after applying the PNet p_T regression that account for the presence of neutrinos, the particle-level jets include also **generator-level neutrinos**
- The PNet training and evaluation is performed using only jets with $\boldsymbol{p_T^{raw} > 15}$ **GeV** for now
  - To avoid biasing the corrections, only jets with $\boldsymbol{p_T^{ptcl} > 50}$ **GeV** are considered
  - The evaluation threshold will be lowered for the next reprocessing
- Correction compute using QCD multijet simulated samples dominated by light quark and gluon jets

Response Correction - Derivation

$$\text{Response} = \frac{p_T^{reco}}{p_T^{ptcl}}$$

- Raw (before jet energy corrections) p_T^{reco}
- Standard jet energy corrected p_T^{reco}
- PNet-regressed jet p_T^{reco} w/o neutrino correction
- PNet-regressed jet p_T^{reco} w/ neutrino correction

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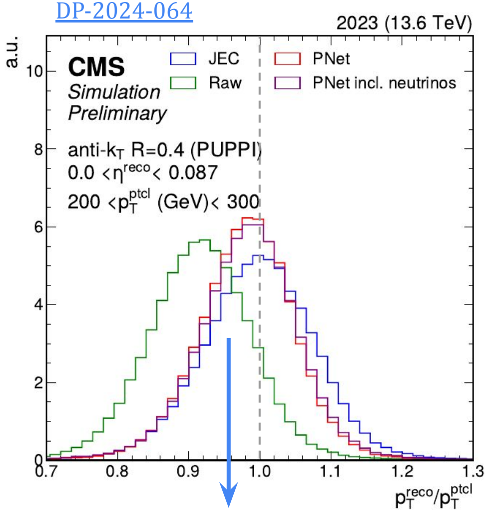
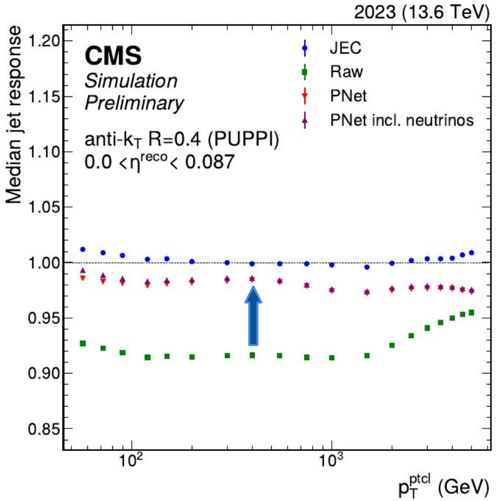




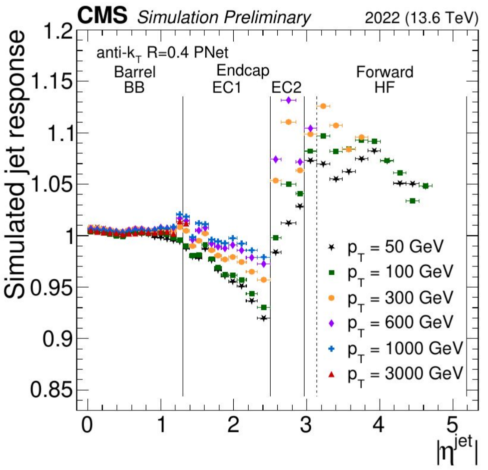
Response corrections are obtained by fitting the [median jet response]$^{-1}$ in each η^{reco} bin as a function of the mean p_T^{reco} in each bin of p_T^{ptcl}

PNet-regressed p_T jets show a response distribution which peaks closer to 1 and is narrower compared to the raw p_T response

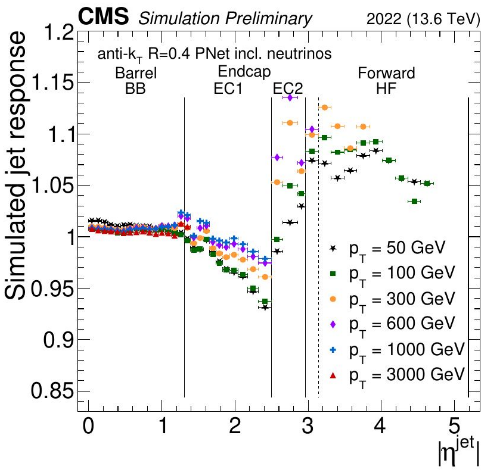
Response Correction from Simulation (2022)

- Jet response for PNet-regressed p_T shows significant improvement compared to the nominal jet response across the entire detector phase-space
  - PNet-regressed p_T shows stable response in the barrel ($|\eta|$ < 1.3), changes within ~ 2% compared to 8% for nominal jet response
  - Stronger momentum dependence in endcaps and forward regions w.r.t. barrel

PNet without neutrino



PNet incl. neutrinos



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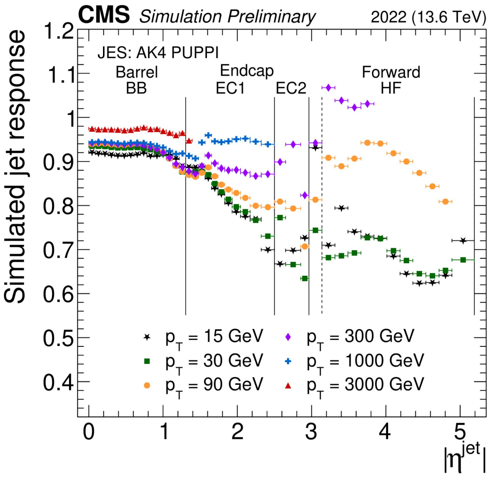
Nominal jet response



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Response Correction from Simulation (2023)

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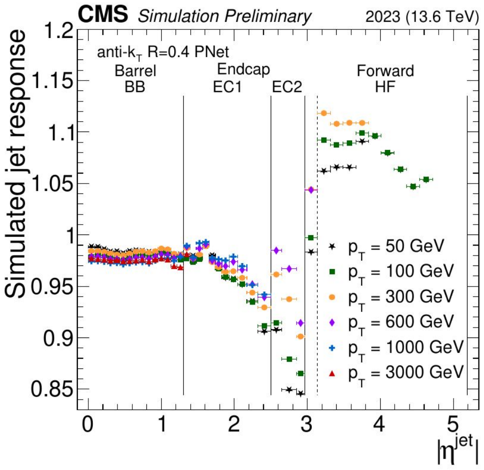
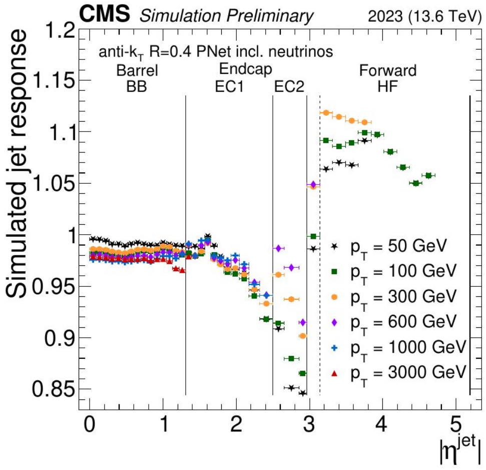
- PNet-regressed p_T shows better response compared to the nominal jet response
- Observed ~ **5%** difference in jet response compared to 2022 in the barrel region and ~ **20-30%** difference in the endcaps

PNet without neutrino



PNet incl. neutrinos



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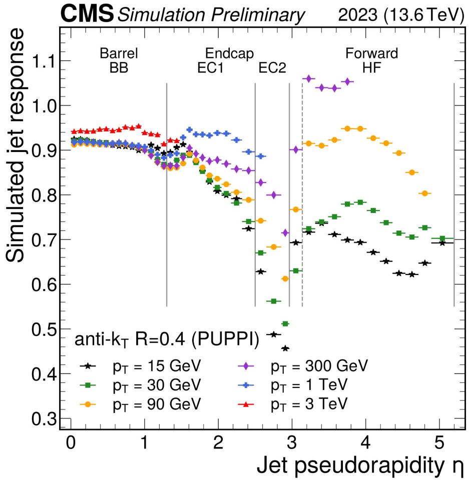
Nominal jet response



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Response Correction - Closure (2023)*

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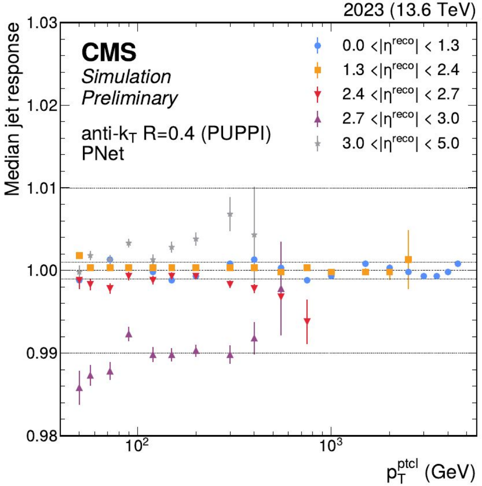
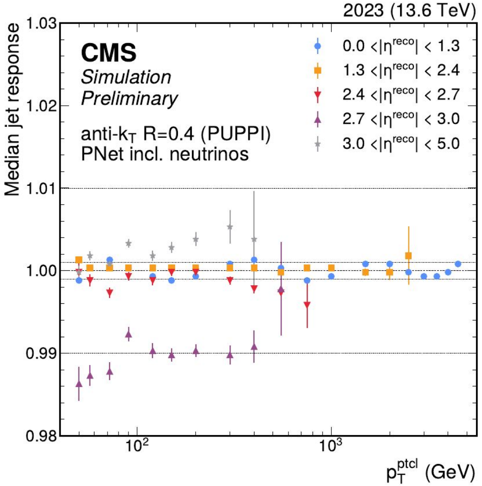
- The median jet energy response in simulation, after jets are corrected for JES, is shown
- The level of residual non-closure after the application of the Response corrections for PNet-regressed p_T is within **0.1%** for $|\eta^{reco}| < 2.4$
- Outside tracker acceptance ($|\eta^{reco}| > 2.4$), the non-closure is within **1.5%**, which is better than the nominal jet response for which it reaches 4%

PNet without neutrino



PNet incl. neutrinos



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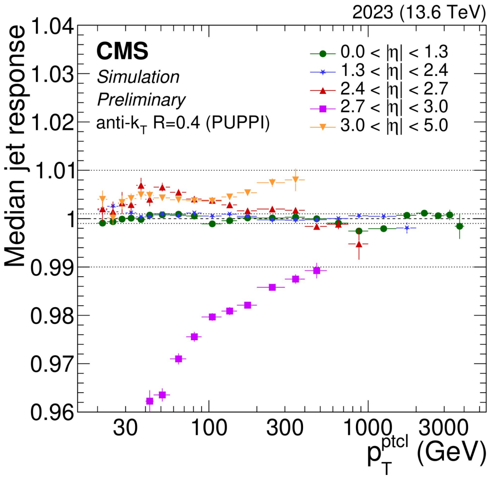
Nominal jet response



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* The closure is similar for 2022 and 2023 simulations

Response Resolution (2023)

After the application of the response correction, PNet p_T regression **improves the jet p_T response resolution of ~15%** w.r.t. the standard jet energy corrected p_T

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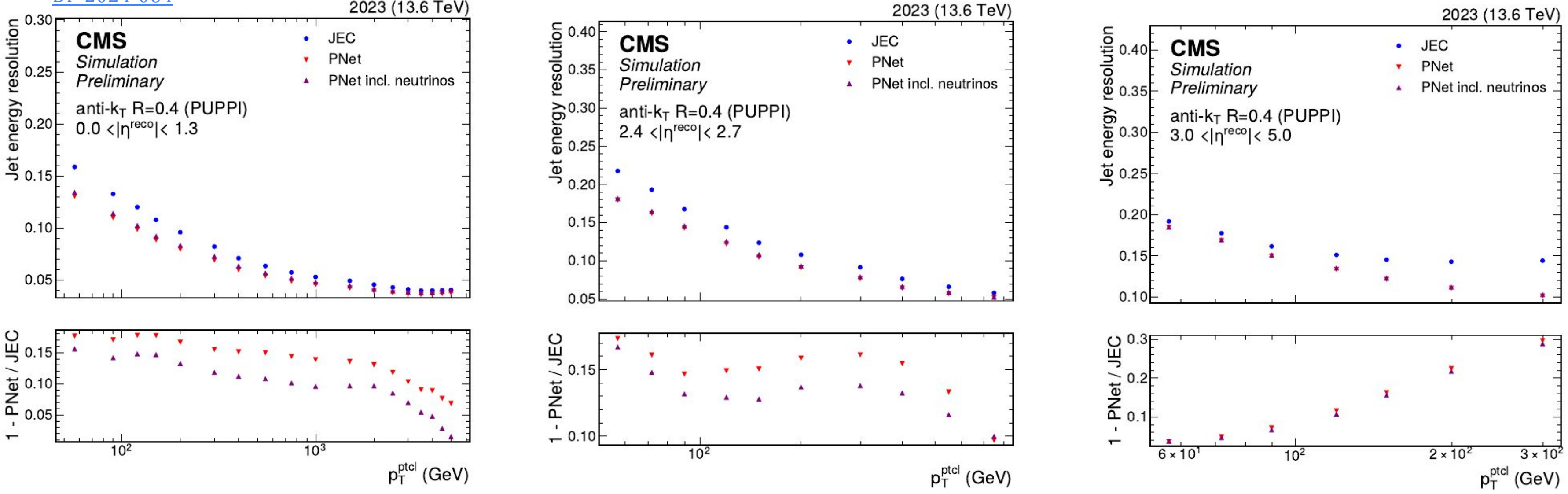

Residual Corrections - Closure

- **Relative (η-dependent) residual correction:** measured as a function of $|\eta|$ in **dijet** events with a reference jet in the barrel region ($|\eta| < 1.3$)
- **Absolute (p_T-dependent) residual correction**: determined in the barrel from **Z+jet, γ+jet**, and **multijet** events, using the Z boson, photon, or multijet recoil as a reference
- Residual corrections are not recomputed for PNet-regressed p_T jets, but the **standard residual corrections are applied on data and a closure test is performed**
- The residual non-closure of the relative corrections is provided in a **η-p_T jet heat map**. An additional term is also included in quadrature to account for the non-closure originated by the absolute correction.
- **The level of non-closure is approximately up to 2-5% (2-8%) for PNet-regressed p_T without (with) neutrinos in the barrel and up to 10-20% in the endcap**

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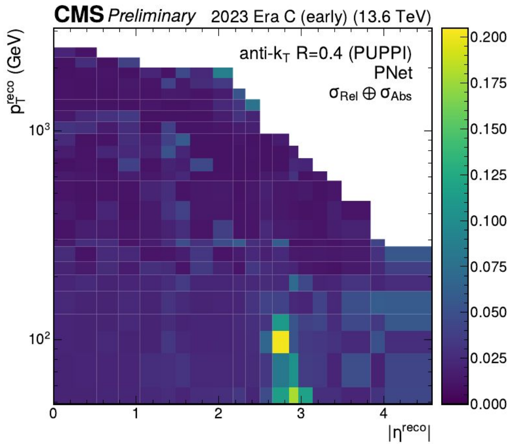
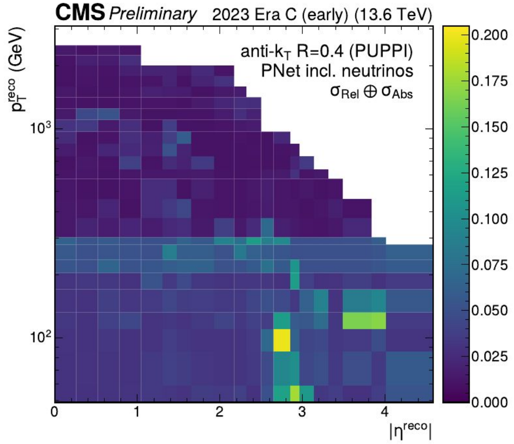




Summary and outlook

- **First simulation based response correction for PNet-regressed p_T**
- PNet p_T regression **improves resolution by ~15%** w.r.t. the standard jet energy corrected p_T
- Closure test was perform for jets with PNet-regressed p_T for the residual corrections
  - **No additional significant disagreement introduced by the regression**

Outlook

- **Lower the p_T threshold for the evaluation of PNet** to compute the corrections for low-p_T jets
- **Recompute the Residual Corrections for PNet-regressed p_T**
- **Compute the Jet Energy Resolution (JER)** correction
  - Smear jet energy in simulation to match that in data
- **Make PNet-regressed p_T the new baseline** in CMS for Run 3

Backup

ParticleNet - EdgeConv Operation

Node features $\mathbf{x}$:

- $\Delta\eta$
- $\Delta\phi$
- Energy
- Impact parameter
- …

EdgeConv operation

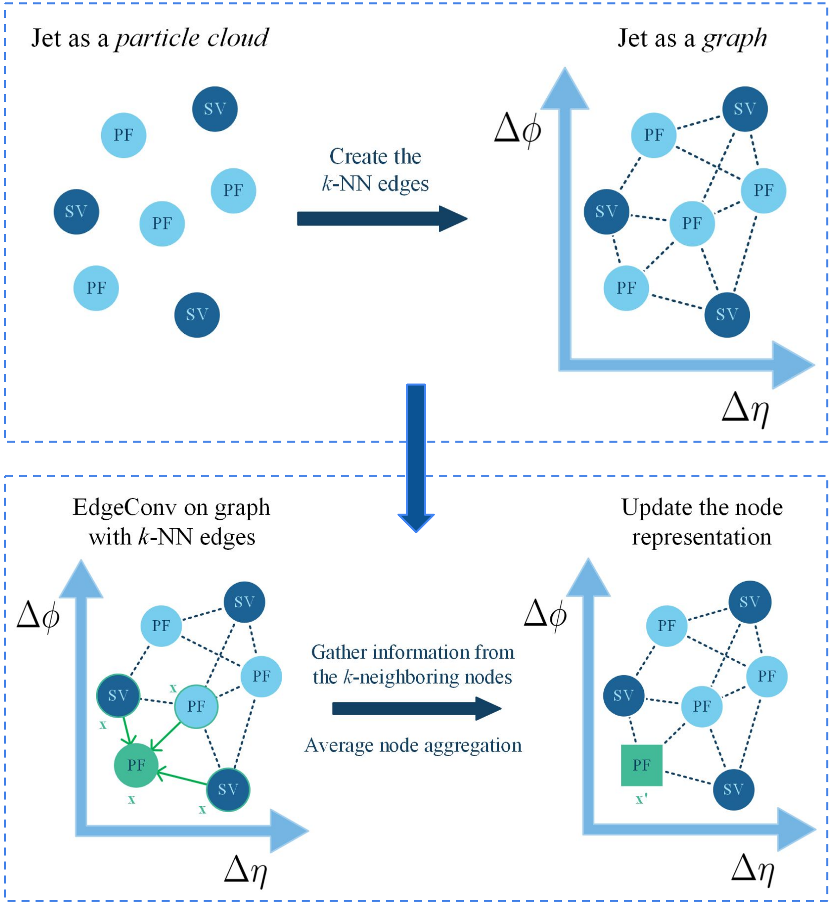
Function of learnable parameters

$$\mathbf{e}'_n = \bar{\phi}^e(\mathbf{x}_{rn}, \mathbf{x}_{rn} - \mathbf{x}_{sn})$$

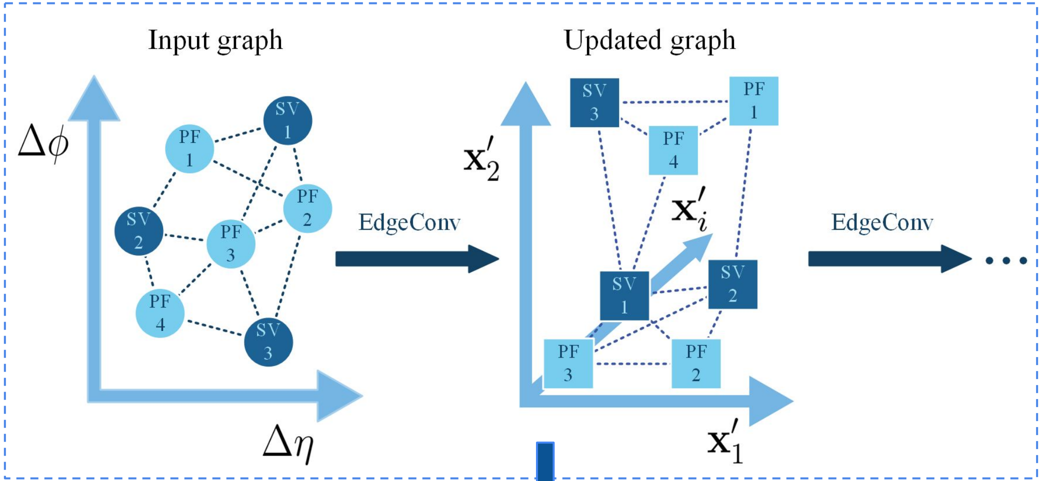
Edge features

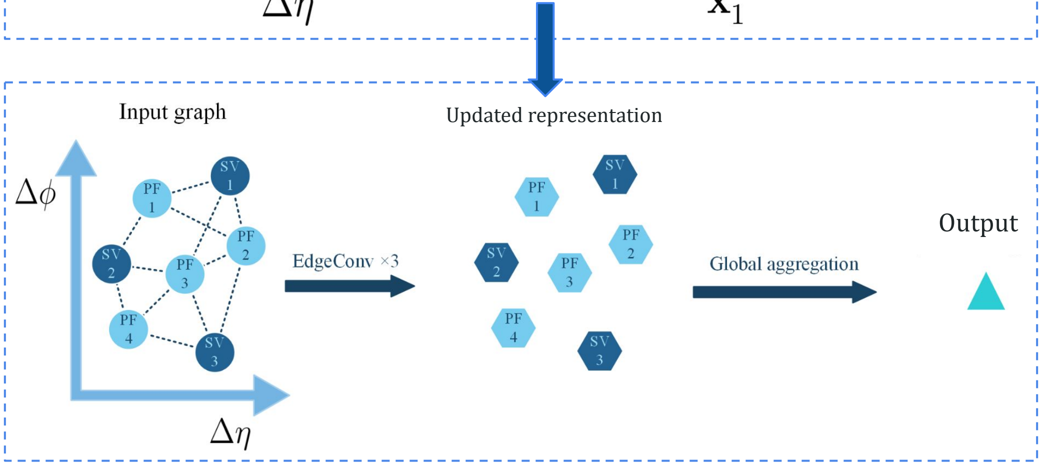
Sender node

Receiver node



ParticleNet - Information Flow





ParticleNet Loss

The loss function of PNet is composed of multiple terms, each corresponding to a different task:

$$p_\tau(z) = \begin{cases} \tau z, & \text{if } z > 0 \\ (\tau - 1) z, & \text{otherwise} \end{cases}$$

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Classification | Regression | Quantile regression (resolution estimation)

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

Jet flavour classification

Jet energy regression

Jet energy resolution

Jet p_T response resolution