Run 3 detector performance and object reconstruction at CMS

September 23, 2024

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On behalf of the CMS collaboration

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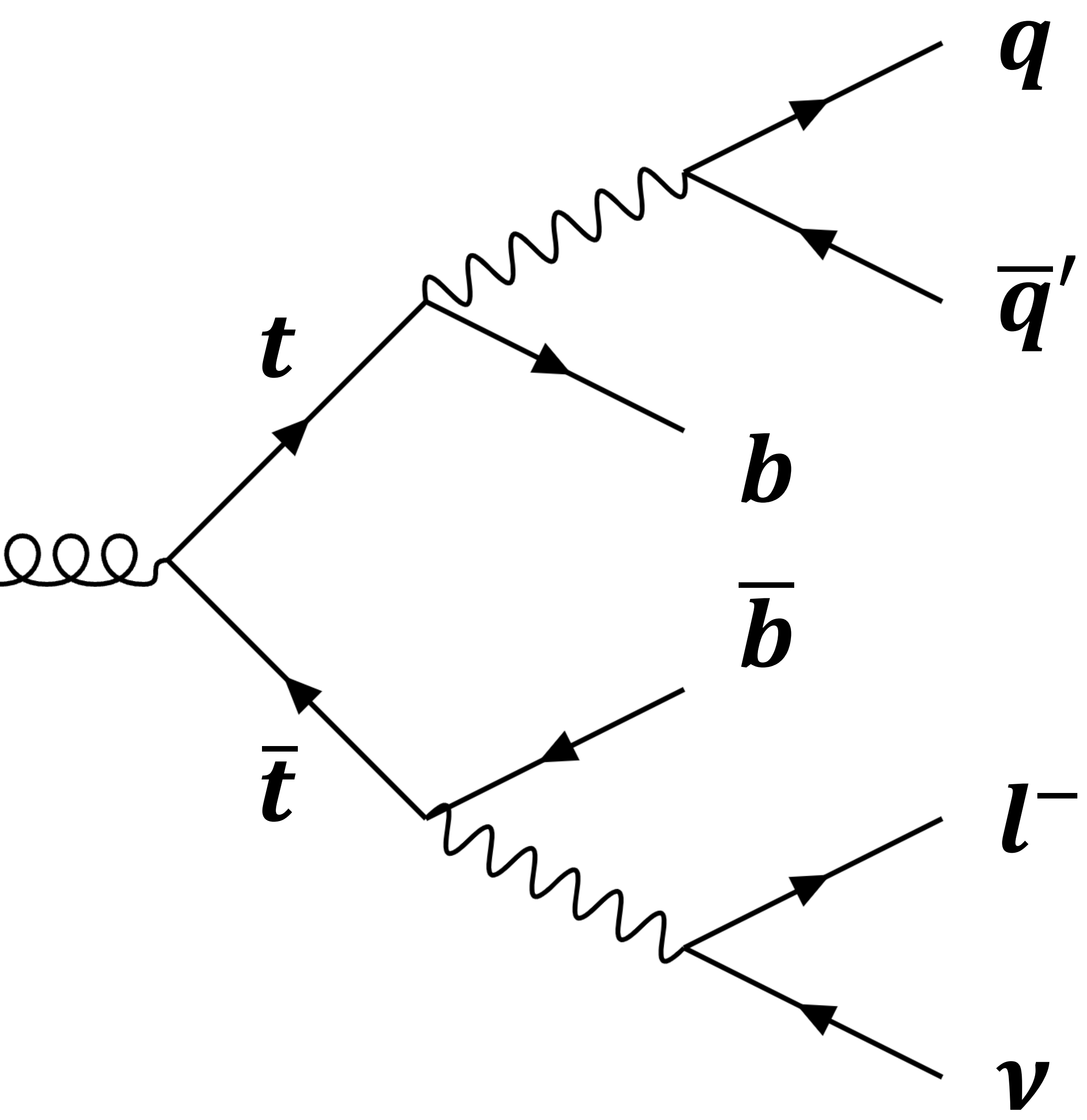
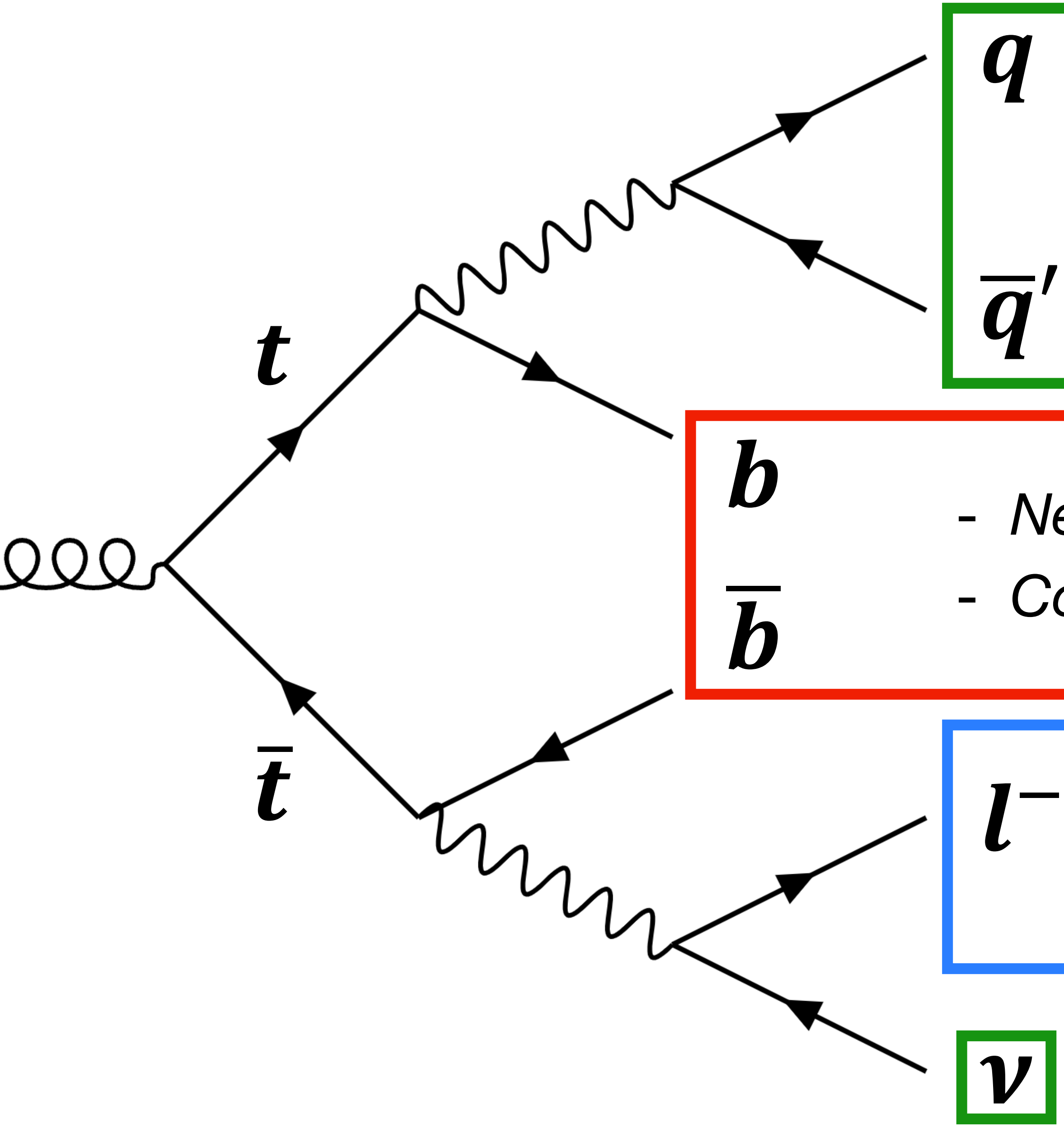
Outline



Outline



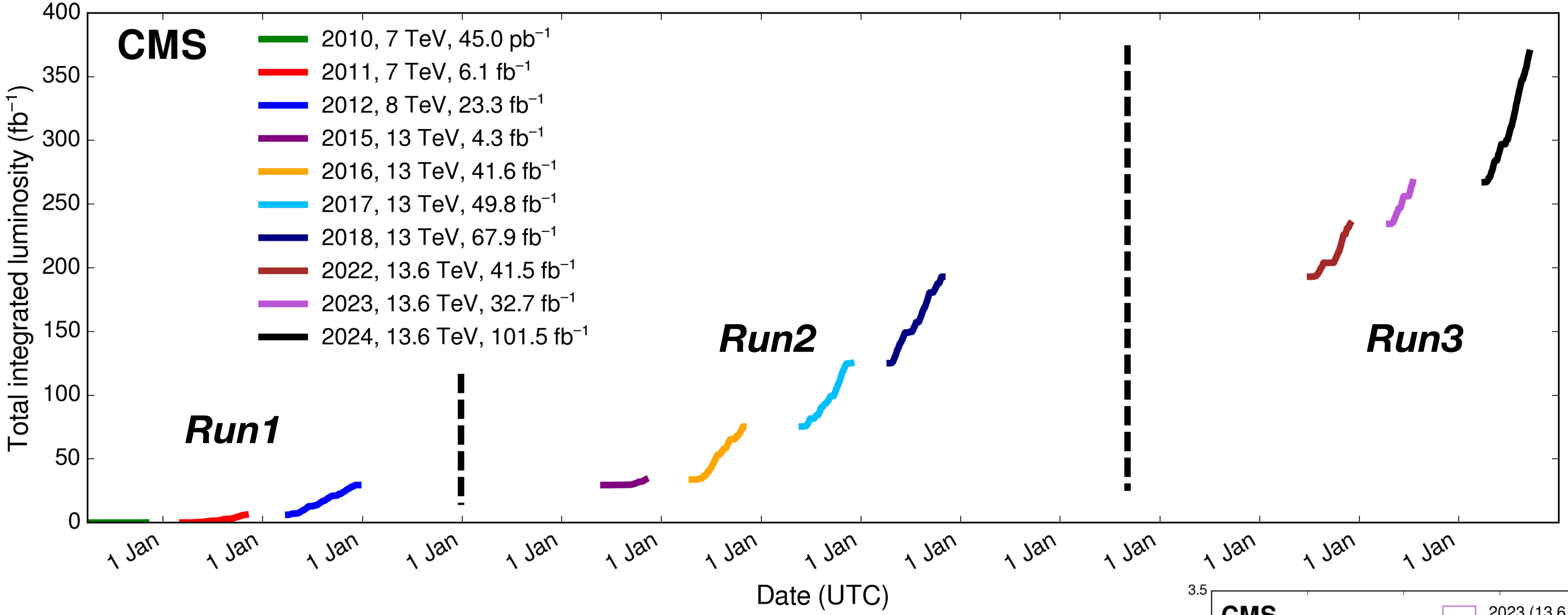
- PUPPI Jet
- Jet Energy Scale
- Jet Energy Resolution

- Next Generation Heavy Flavor tagger
- Commissioning and Calibration

- Lepton performance

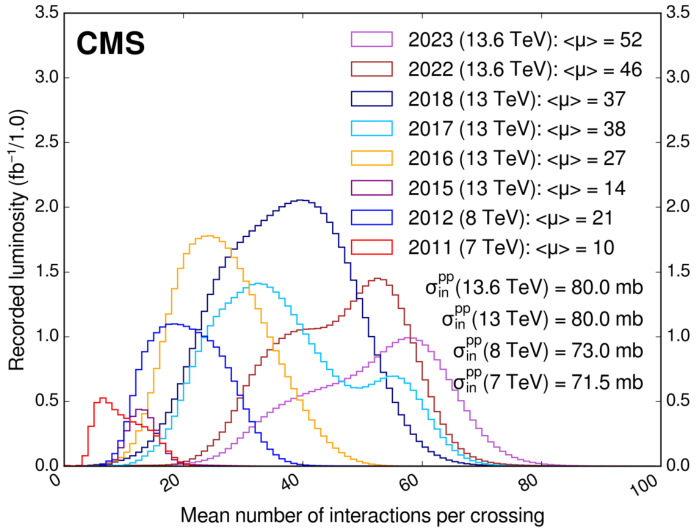
Where we are at data taking

CMSPublic/LumiPublicResults
CMS-DP-2024-068



Cumulative luminosity in CMS

- Luminosity delivered to CMS by the end of Run2 is > 190 /fb
- Luminosity delivered in Run3 is > 160 /fb
  - 1.3% of uncertainty in 2023
- Average number of pp interactions per crossing in Run3 is > 50

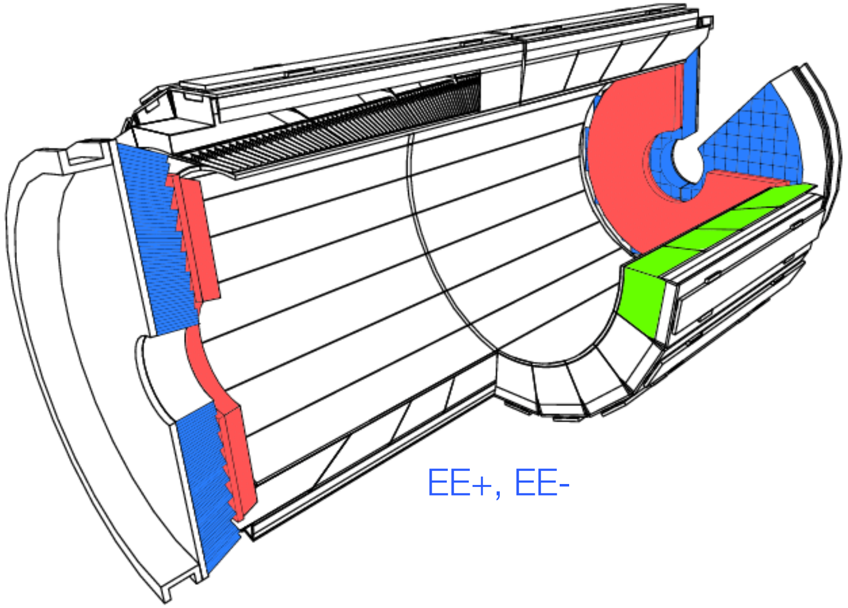


The Known Issues in Run 3

Pictures taken from
2019 J. Phys.: Conf. Ser. 1162 012007
CERN-LHCC-2012-016

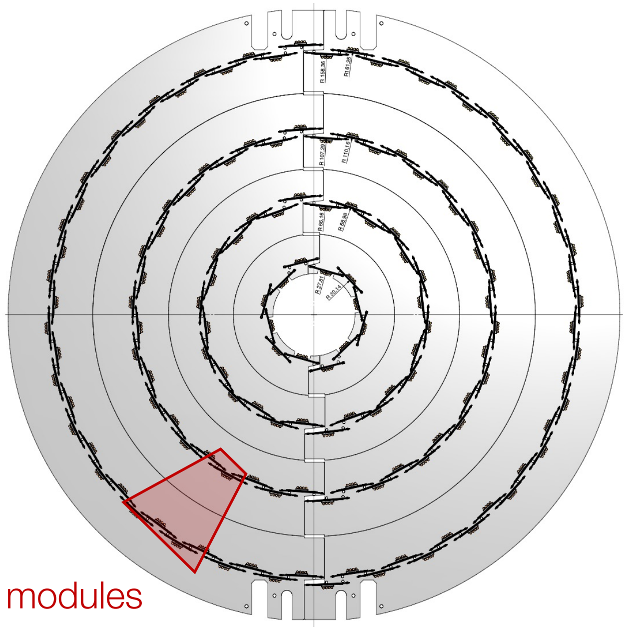
“ECAL power cooling issue”

- Early September 2022
- ~7% of the positive side of the ECAL (EE+ water leak region) had turned off
- Due to cooling limitations caused by a water leak
    - problems-and-solutions-ecal-leak-story



“BPix issue”

- 19-24 June 2023 (After Technical Stop 1)
- 27 modules (~1.5%) in the Barrel Pixel Layers 3 and 4 became inoperable
- They cover a sector spanning approximately 0.4 radius (~23 degrees) in phi at negative pseudorapidity
- Due to issue in distributing the LHC clock signals

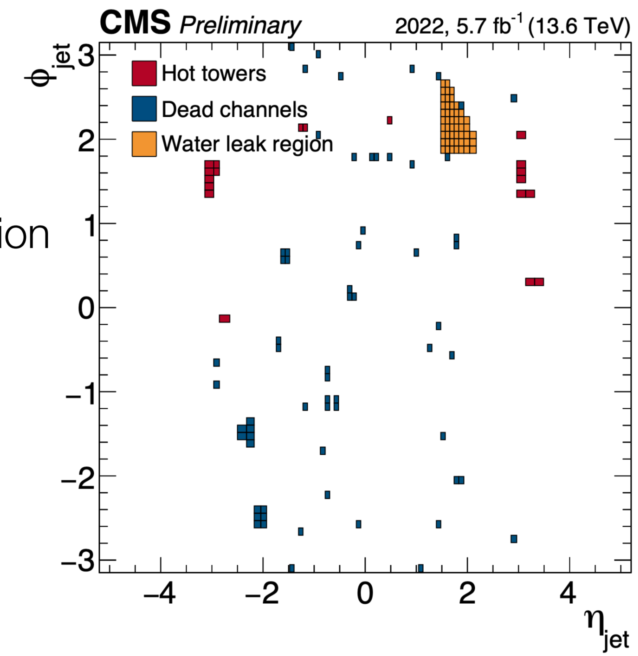


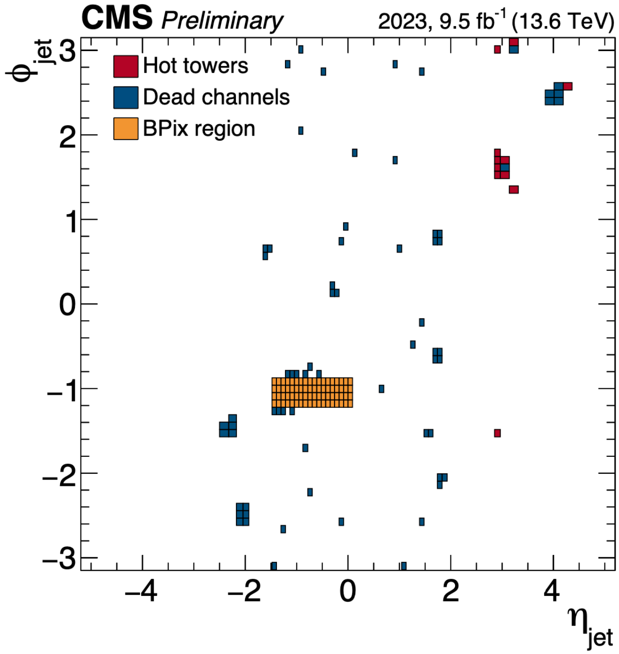
From known issues to Jet

[CMS-DP-2023-045](#)
[CMS-DP-2024-039](#)

Affected regions in Jet

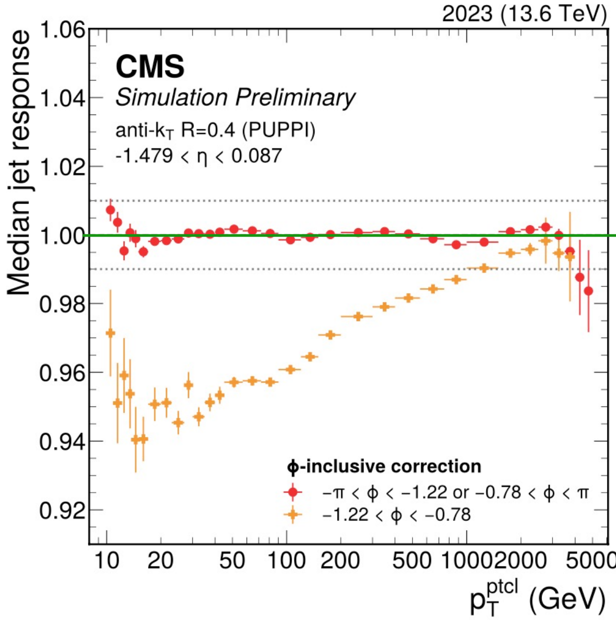
- ECAL power cooling issue
  - mis-reconstruction of electrons and jets in the affected region
  - Events to be vetoed
- BPix issue
  - Inefficiency in the track reconstruction in a small region with implications for the jet energy scale (JES)
  - Events to be included

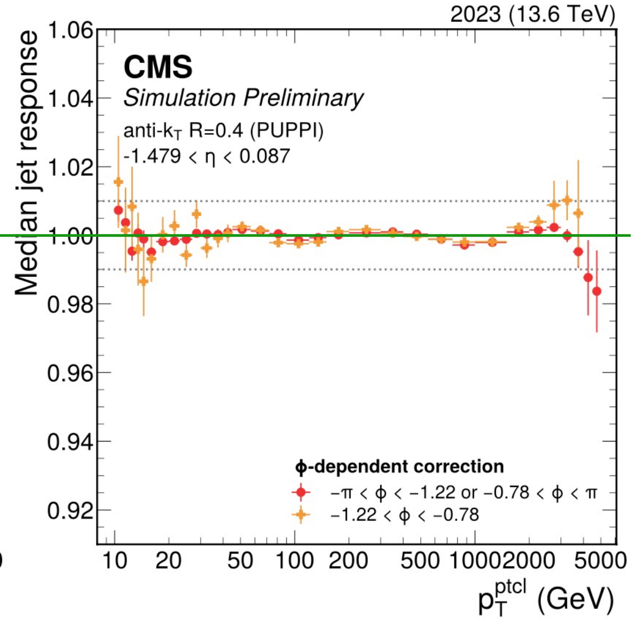




Addressing BPix issue to JES

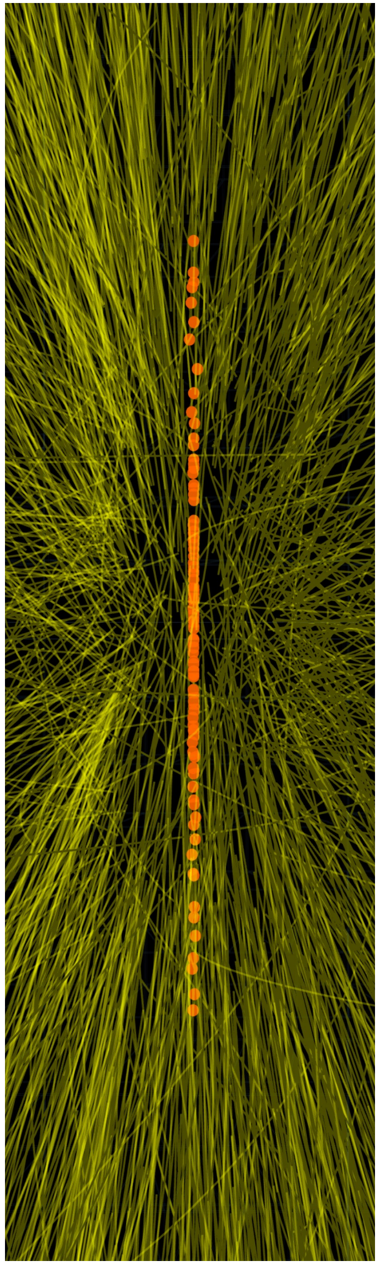
- Comparison from ϕ-dependent vs inclusive correction
  - ϕ-inclusive corrections
    - a drop in the response of up to 6% is observed in the affected ϕ region
  - ϕ-dependent corrections
    - -1.22 < ϕ < -0.78
    - a closure within 1% is obtained in most of the analyzed phase space

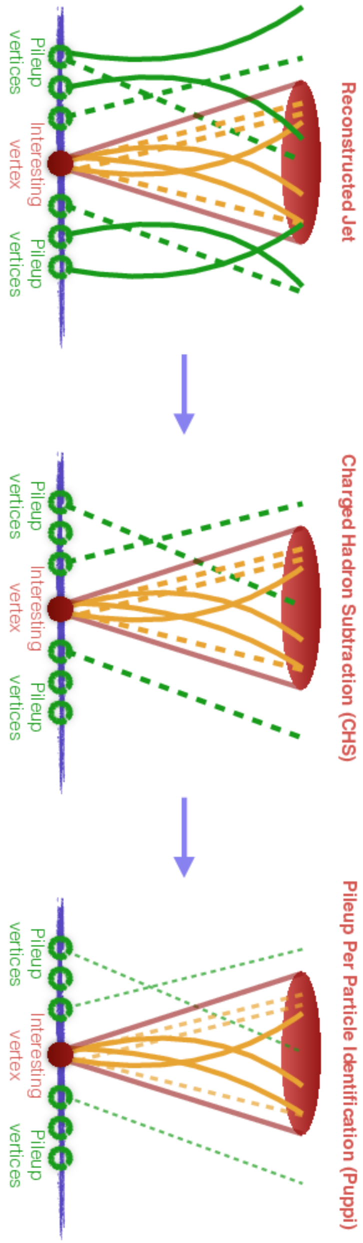




Jet Energy Performance

CMS-PHO-EVENTS-2016-008
PoS ICHEP2020 (2021) 752
CMS-DP-2021-001
CMS-DP-2024-043





PileUp mitigation

- Pileup (PU) particles can overlap with jet candidates

Charged Hadron Subtraction (CHS) ; Run2 default

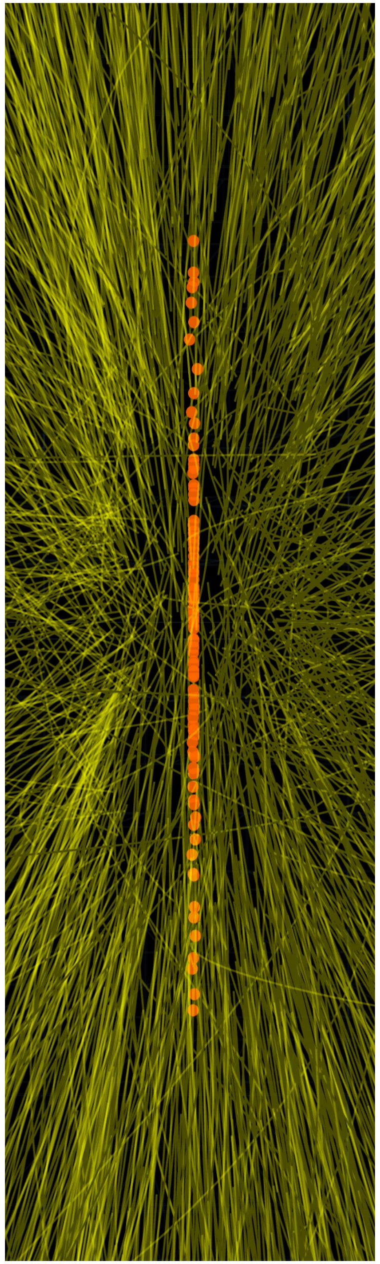
- A majority of PU is from charged particles!
- Removed charged particles originating from PU vertices
- Only works within the tracker covered region
- Does not remove neutral PU contribution

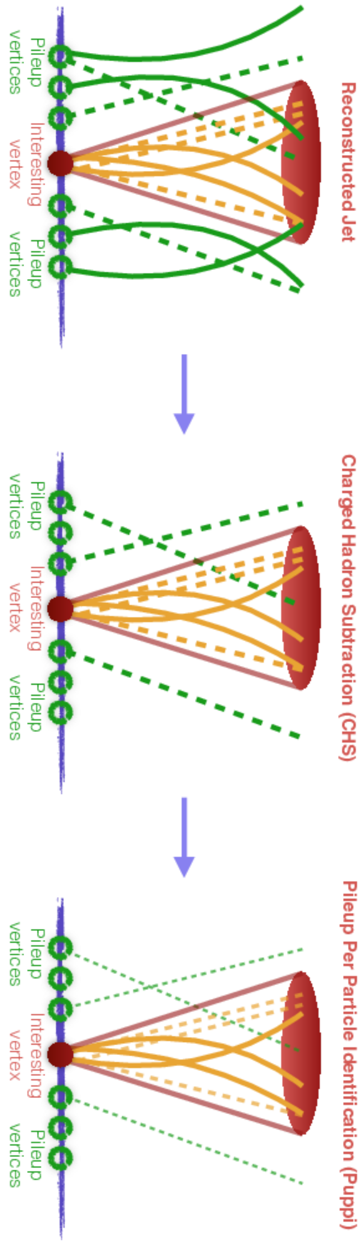
PileUp Per Particle Identification (PUPPI) ; Run3 default

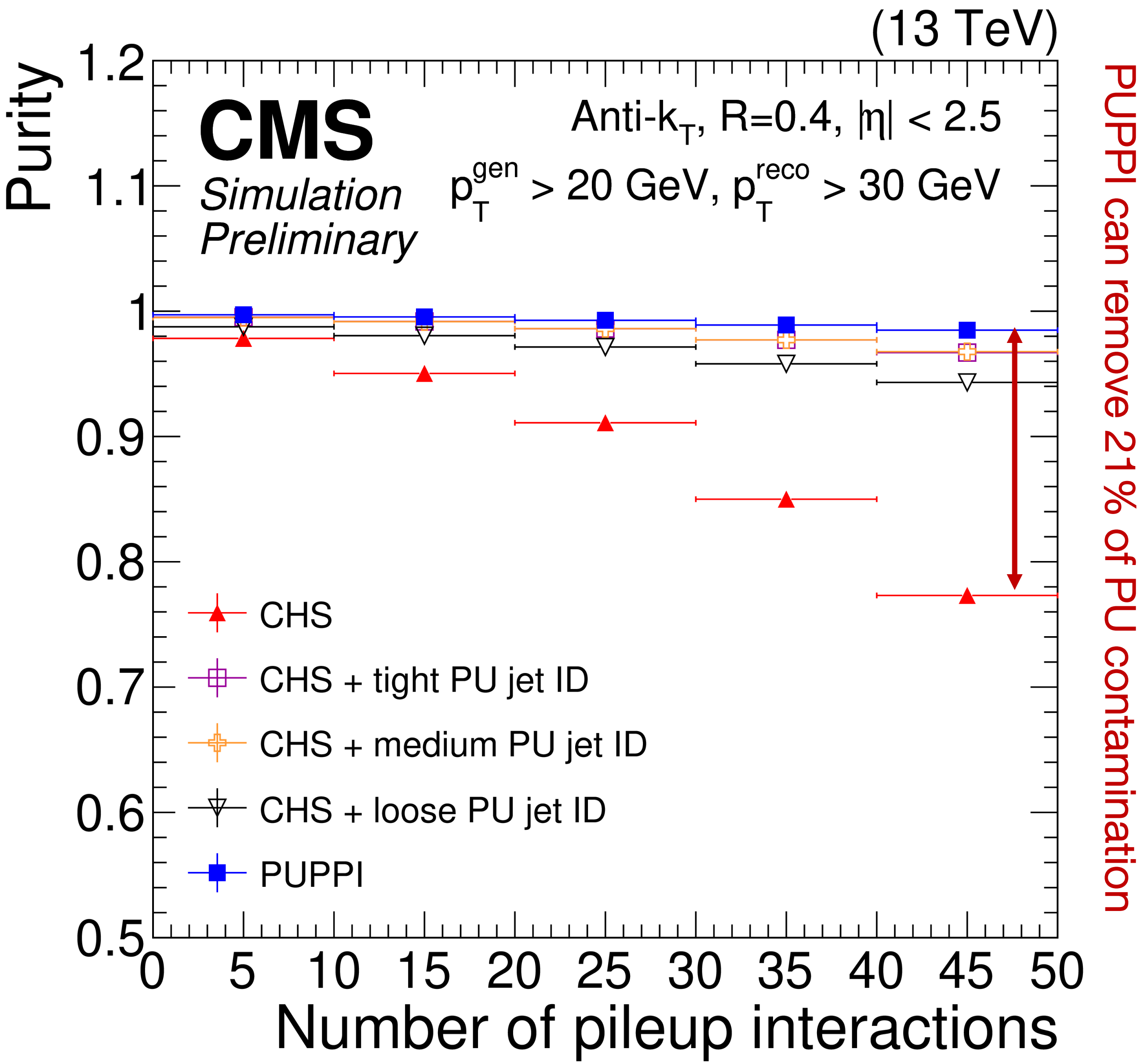
- Intended to remove PU + identify PU at particle level
- Event-by-event basis weights for each particle if they are PU-like
- Used to re-scale the four momenta of the particles
- Jet+MET, jet substructure variables are expected to be less susceptible to PU

Jet Energy Performance

CMS-PHO-EVENTS-2016-008
PoS ICHEP2020 (2021) 752
CMS-DP-2021-001
CMS-DP-2024-043





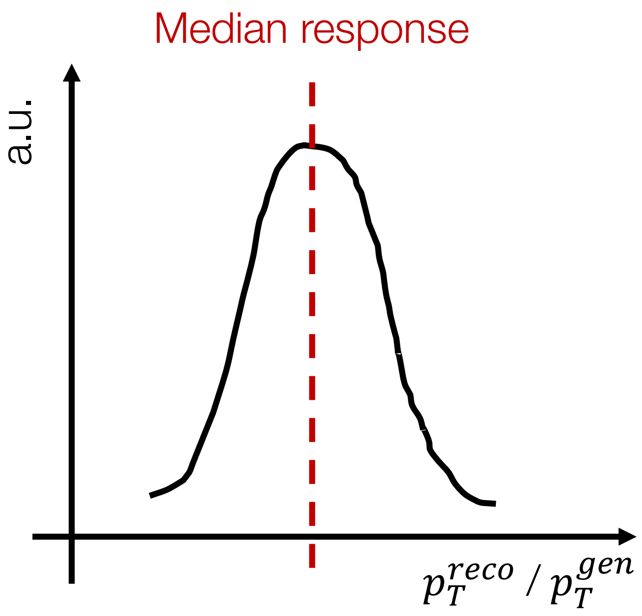


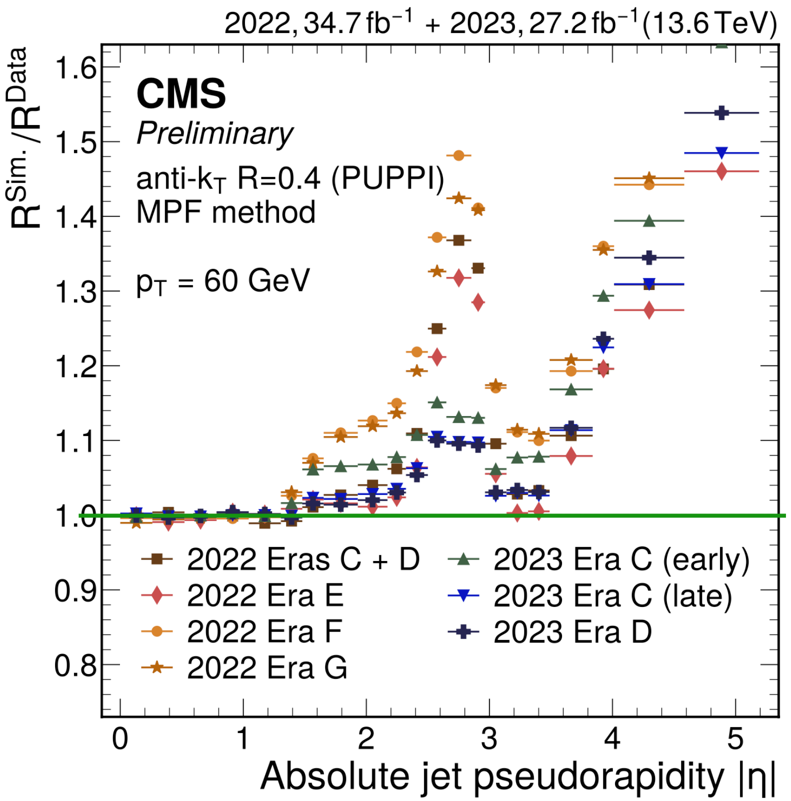
Jet Energy Scale

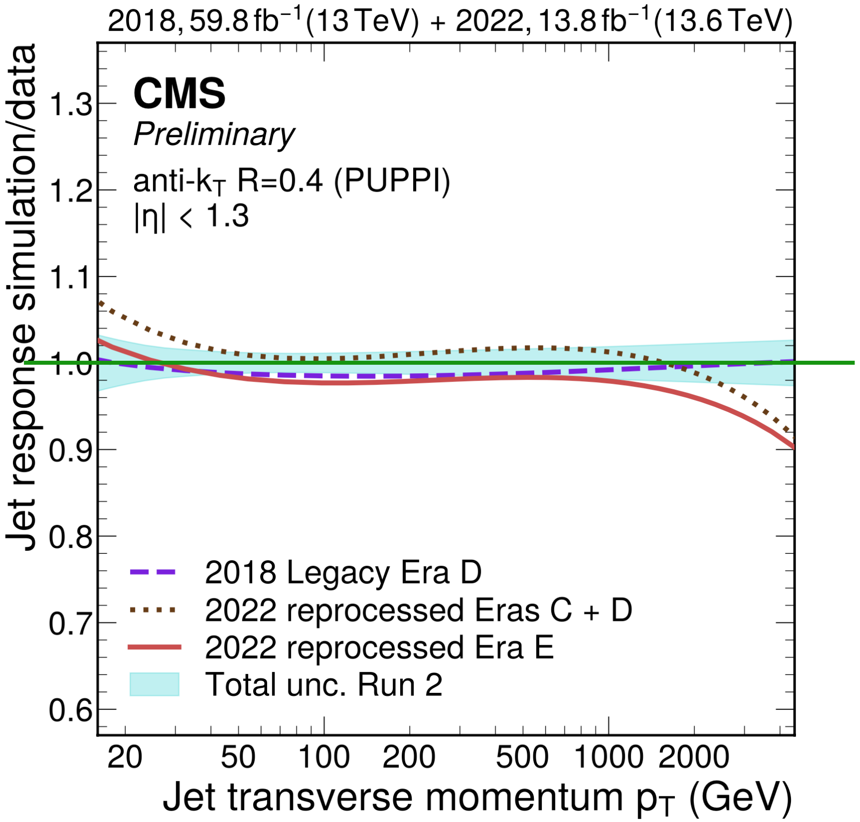
CMS-DP-2024-039

Residual correction

- Jet energy corrections are applied to the reconstructed-level jets
  - η-dependent correction (different response from each subdetector) + p_T-dependent correction (scale difference in central)
- Great performance in the barrel region (correction < 2%)
- Stable difference between data and simulation in 2022
  - Similar performance to Run 2 legacy reconstruction in $50 < p_T < 500$ GeV





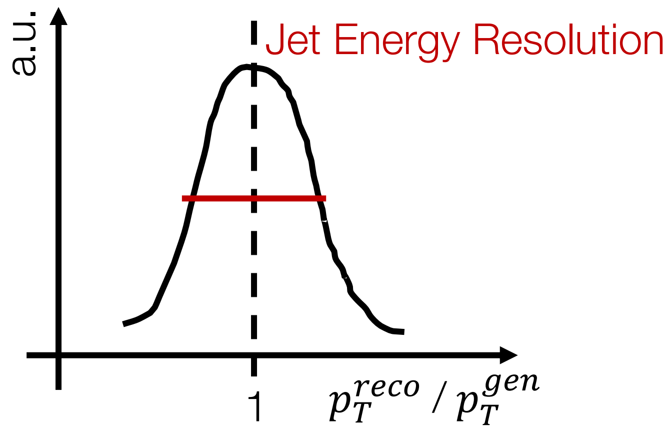


Jet Energy Resolution

CMS-DP-2024-039
CMS-DP-2024-064

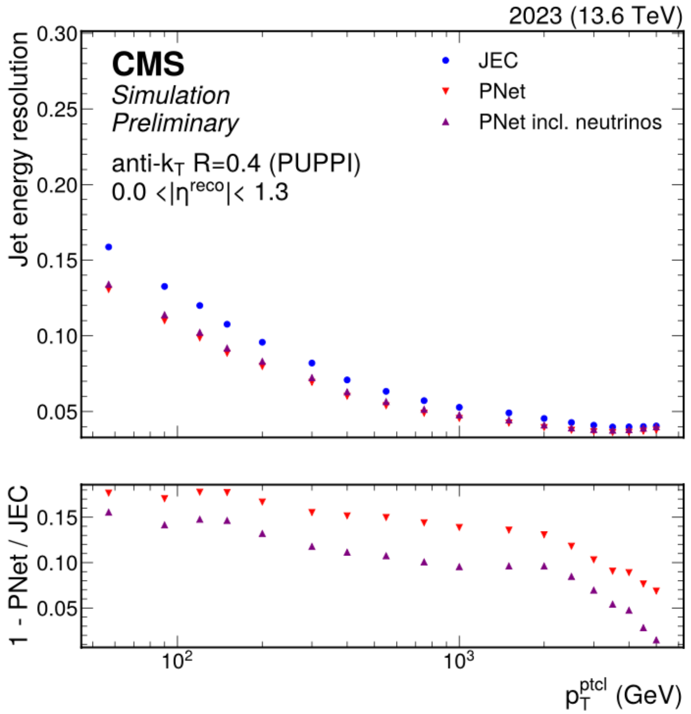
Smearing

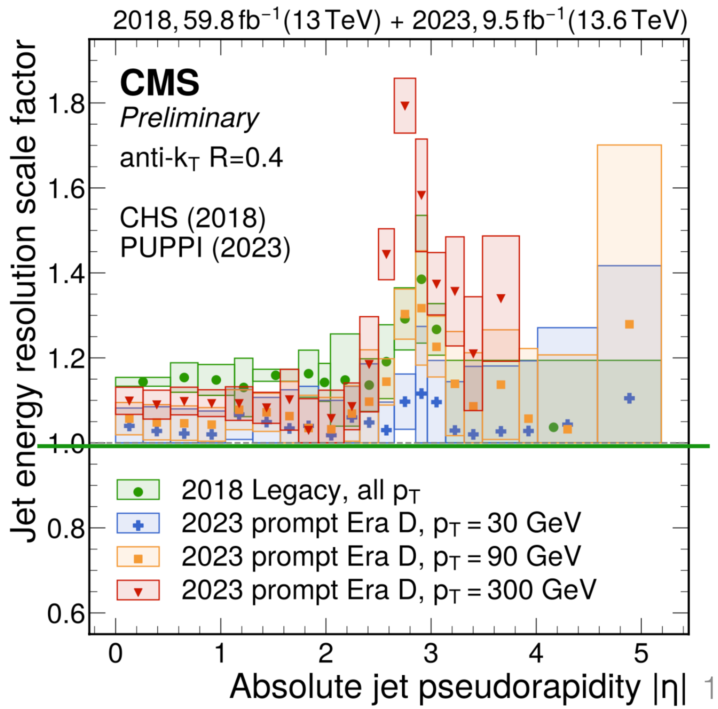
- Jet energy resolution (JER) in simulation needs to be smeared to match that of data
  - Defined as the spread of the response distribution; gaussian fit
  - SFs are extracted using data-based methods
- Prompt construction in $|\eta| < 2.5$ outperforms legacy Run2
- The imperfect calibration of overlapping sub-detectors ($2.5 < |\eta| < 3$) leads to larger SFs



p_T regression

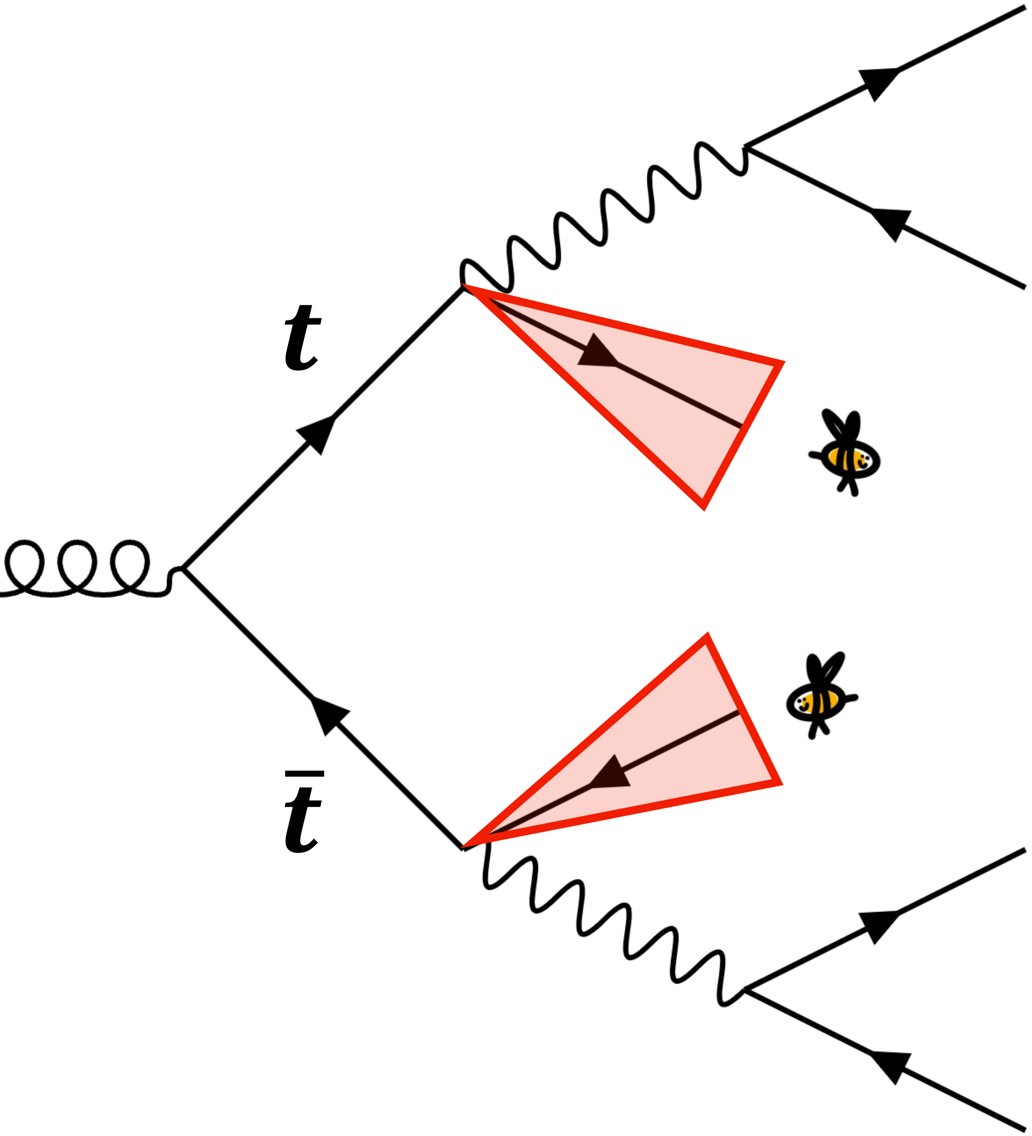
- ML based algorithm ParticleNet
  - Jet classification
  - Jet p_T regression
  - Jet energy resolution estimation
- First full calibration of flavor-aware regressed p_T for small-cone jets
  - Correcting raw jet p_T to the truth-level
- Significant resolution improvement ~ 15%
- Calibration with data gives a non-closure of 2-5 % in $|\eta| < 2.5$





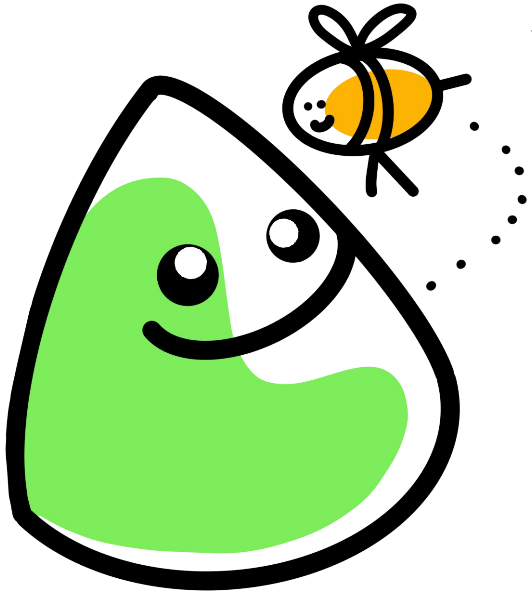
Heavy flavor tagging in CMS

Picture taken from
[2018 JINST 13 P05011]

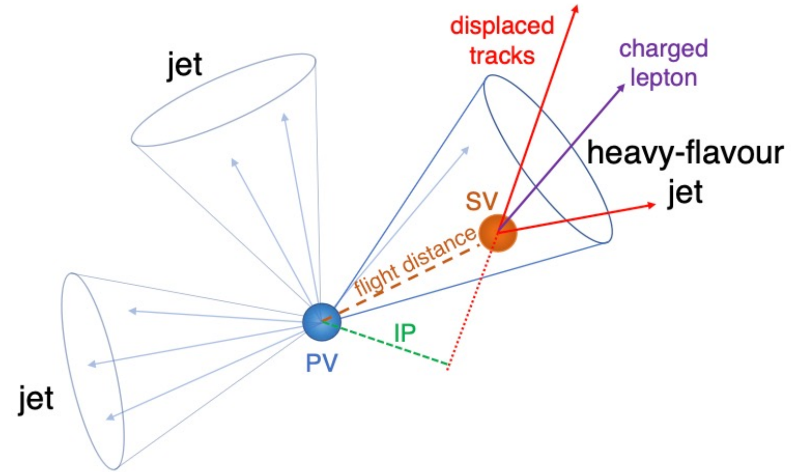


Heavy flavor jet in Top topology

- Quarks and gluons hadronized and form particle jets



- Top quarks decay before hadronization
  - Almost exclusively t→bW decays
  - Final state determined by W boson decays



- B hadrons live long enough to resolve decay
  - Exceptional signature
    - displaced vertices, soft lepton insides..
  - Significant improvement in machine learning based tagging algorithms
  - Performs beyond the heavy flavor tagging (s, tau-jets)

The evolution of Jet taggers

arXiv:2202.03772
CMS-DP-2024-066

Run 2

- Shallow ML: BDTs or feedforward NNs
- Deep ML: sequence-based deep NNs

Run 3

- Particle Clouds: Graph Neural Networks
- Transformers: Attention model

2015 — Combined secondary vertex v2 (CSVv2), ***MLP***

2016

2017 — DeepCSV, ***DNN***

2018 — DeepJet, ***CNN+RNN***

2022

2023 — ParticleNet, ***DGCNN***; RobustParT, ***Multi Head Attention***

2024 — ***UParT***

Extension to a unified approach

- From Transformer Model (Particle Transformer)
  - Based on the “Attention” model designed for particles
  - Not only single particle information, but also pair-wise features
- To Unified Particle Transformer (UParT)
  - b / c jet identification
  - Hadronic tau + s-tag (!)
  - Simultaneous flavor aware jet energy/resolution regression

Discriminators are determined:

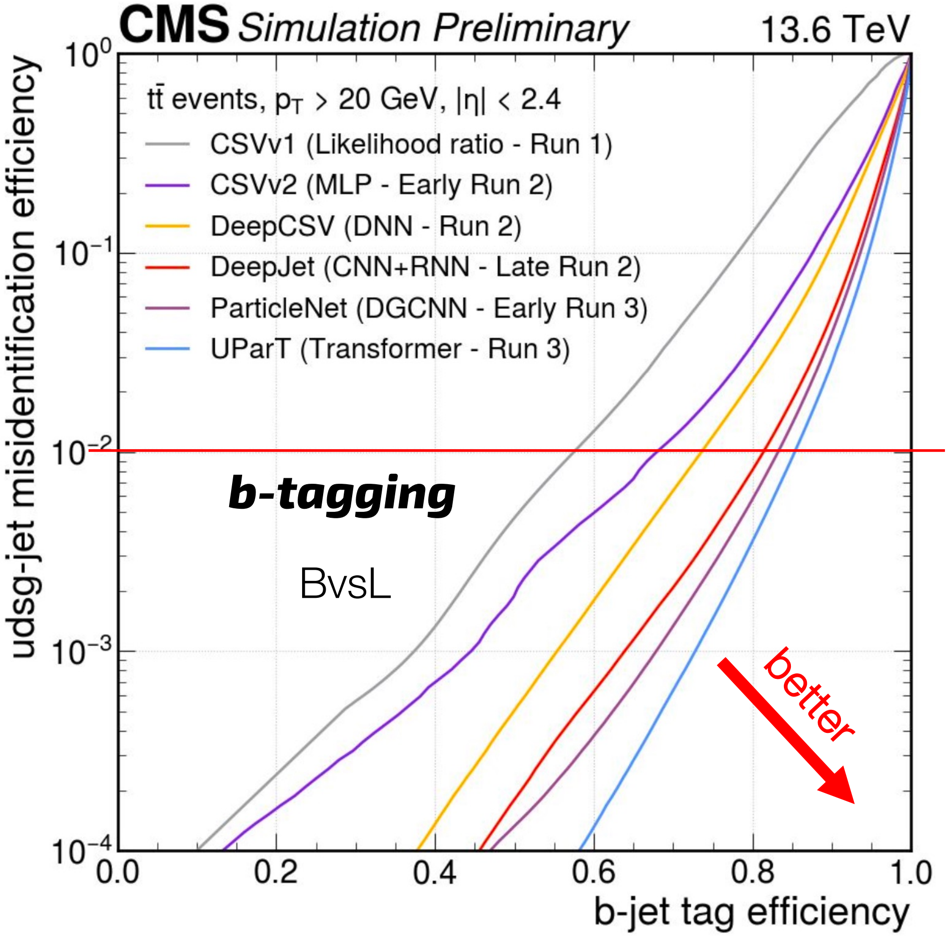
$$\mathrm{XvsY} = \frac{\mathrm{P(X)}}{\mathrm{P(X)+P(Y)}}$$

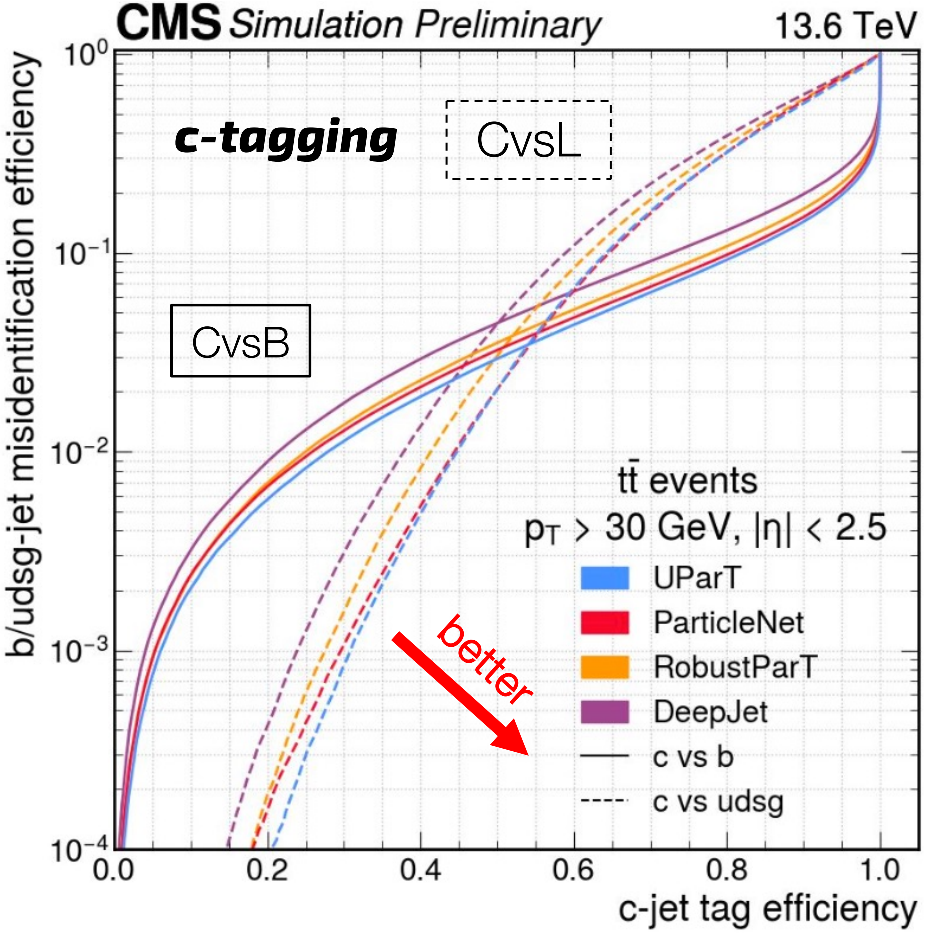
Flavor Tagging Performance

CMS-DP-2024-066

b/c-tagging performance

- Promising performance compared to previous taggers
  - ~5% better b-tag efficiency than DeepJet having the same misidentification rate at 1%
  - The highest/comparable c-tag efficiencies compared to the previous taggers





Fla Tagging Performance

CMS-D -066

b/ forn

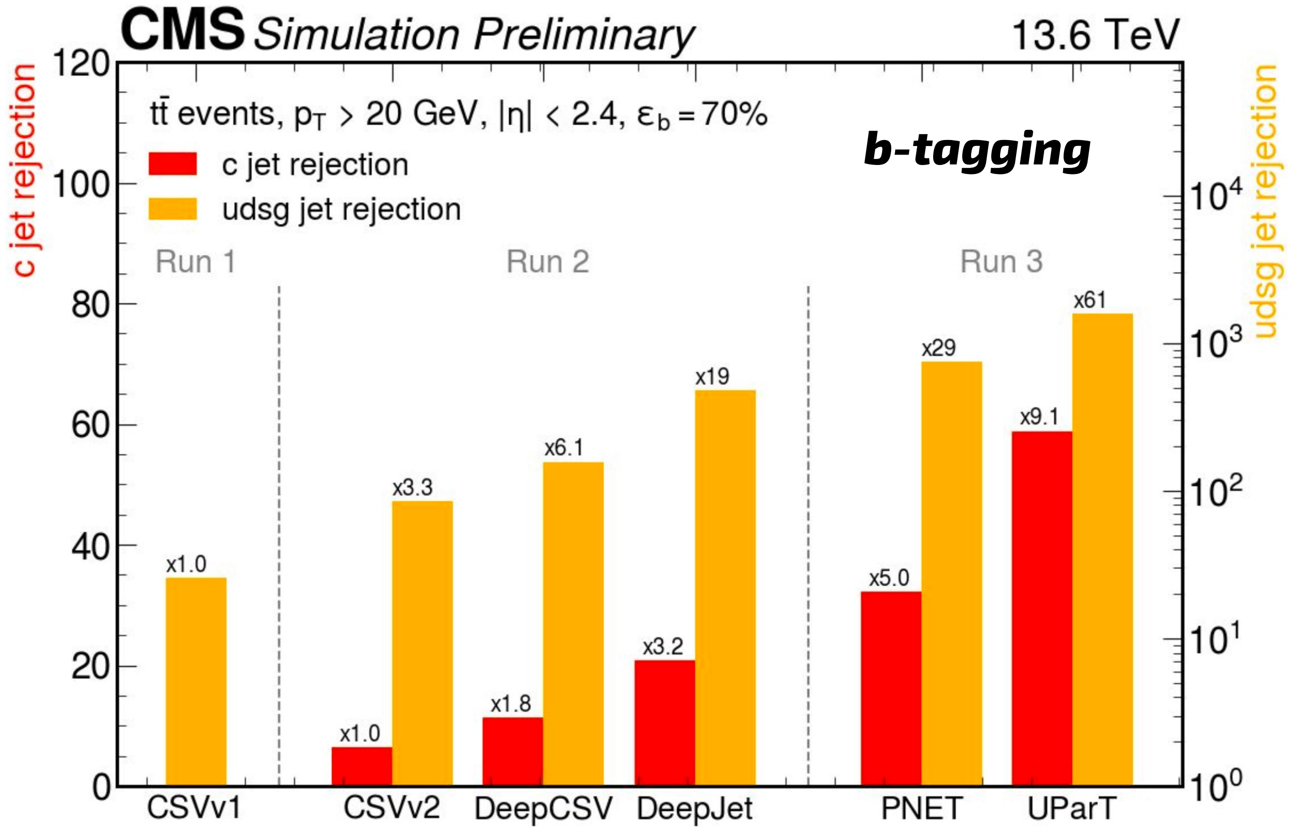
~10% more $t\bar{t}$ than Run2 !

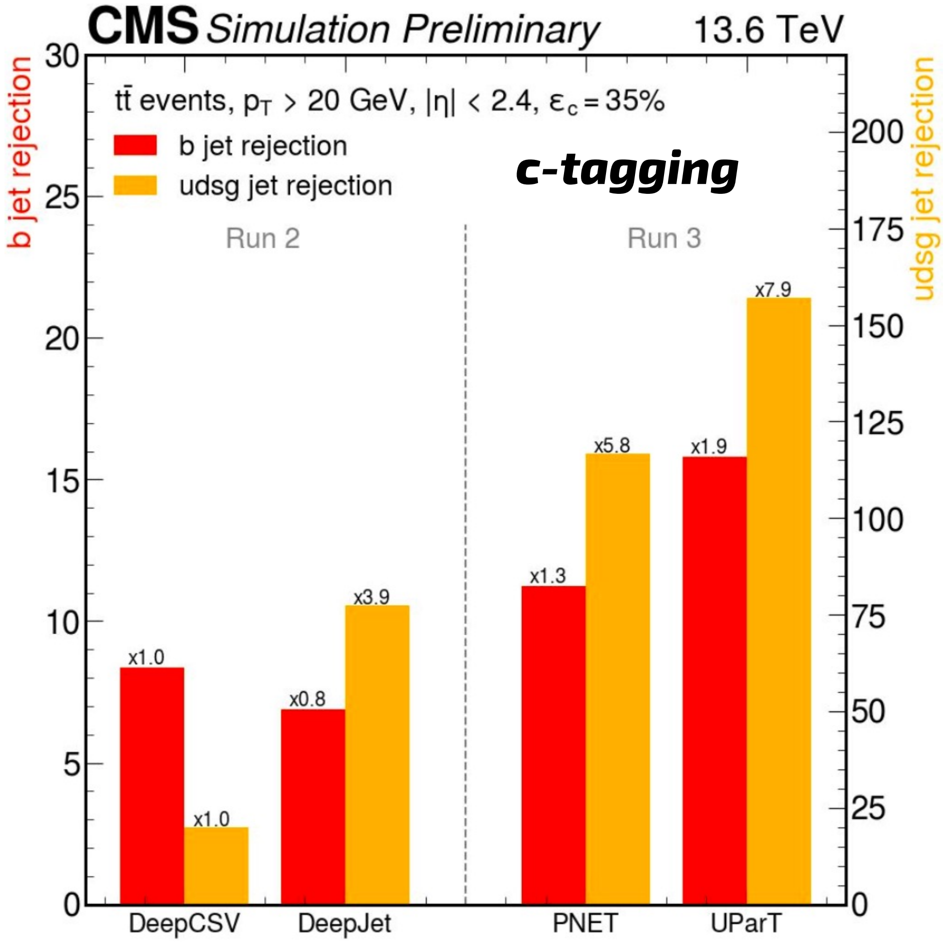
Flavor Tagging Performance

CMS-DP-2024-066

b/c-tagging performance

- Promising performance compared to previous taggers
  - ×3 better light jet rejection (at b-jet eff 70%) than DeepJet
  - ×2 better light rejection + ×2 better b-jet rejection (at c-jet eff 35 %) than DeepJet



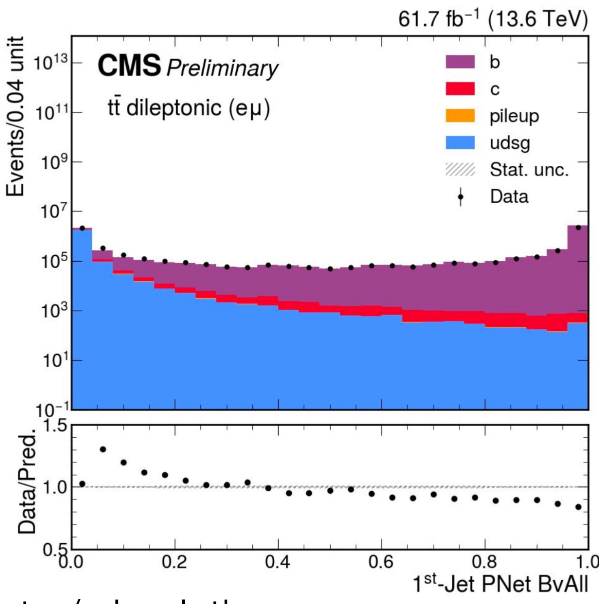


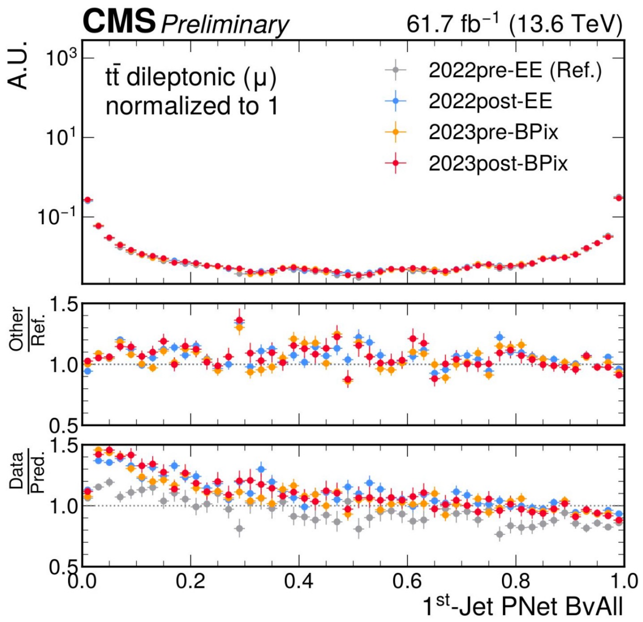
Data vs Simulations

CMS-DP-2024-024
CMS-DP-2024-025
arXiv:211.03027

Commissioning

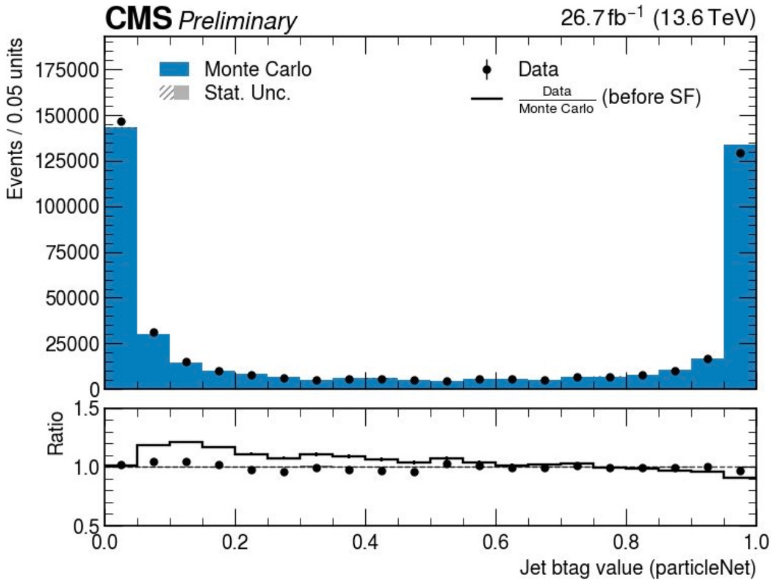
- Disagreement due to mismodelling in simulations
  - input variables → output discriminator
- Prone to changes in the calibration of the detector alignment
- Only small differences in b-tag output discriminator for different data taking period in Run3
  - Performed in CvsL and CvsB as well

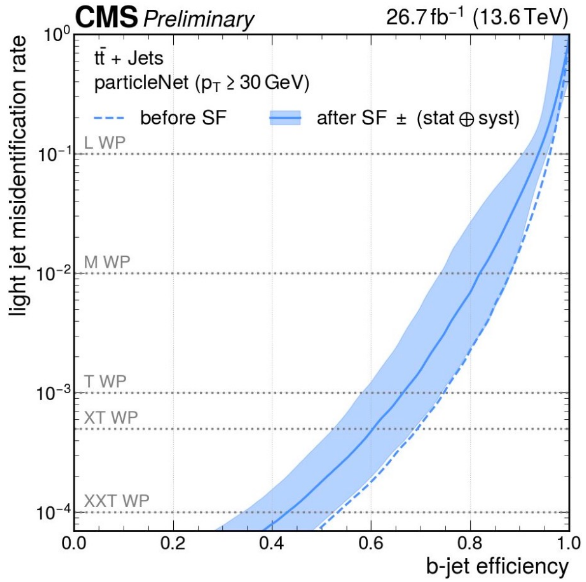




Calibrations

- Scale-Factors defined from efficiencies for a jet with flavor in data / simulation
- Define heavy flavor enriched data for SF derivation
  - Phase space dedicated to class
- Good Data vs MC closure after applying SFs
- Performance changed after SFs application
- No public results in c-tagging yet



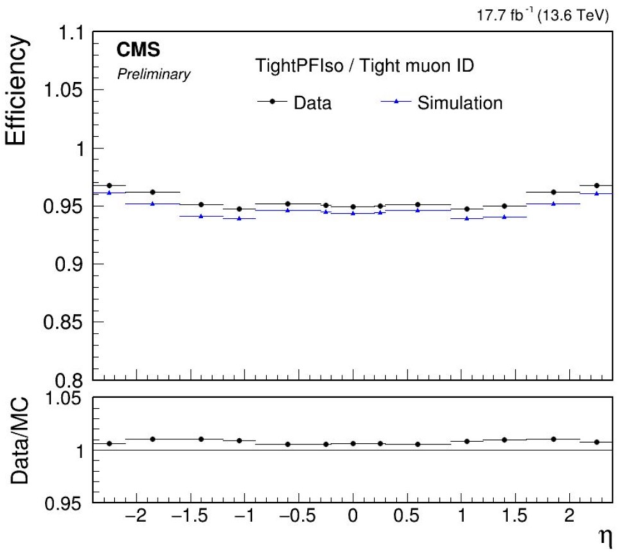


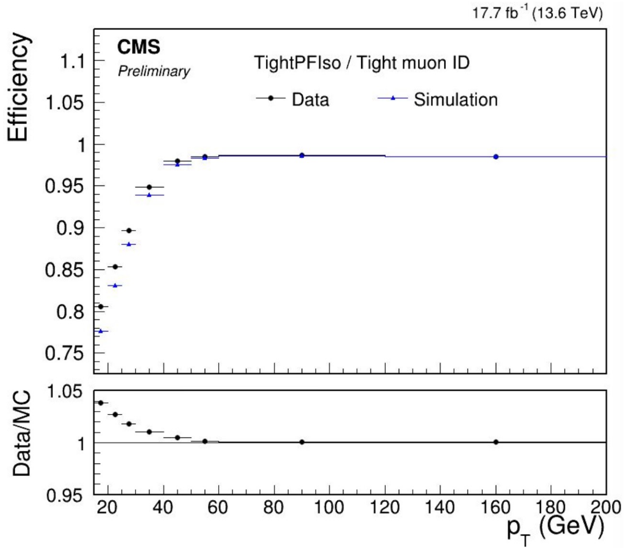
Lepton Performance

CMS-DP-2024-023
CMS-DP-2024-052

Muon performance

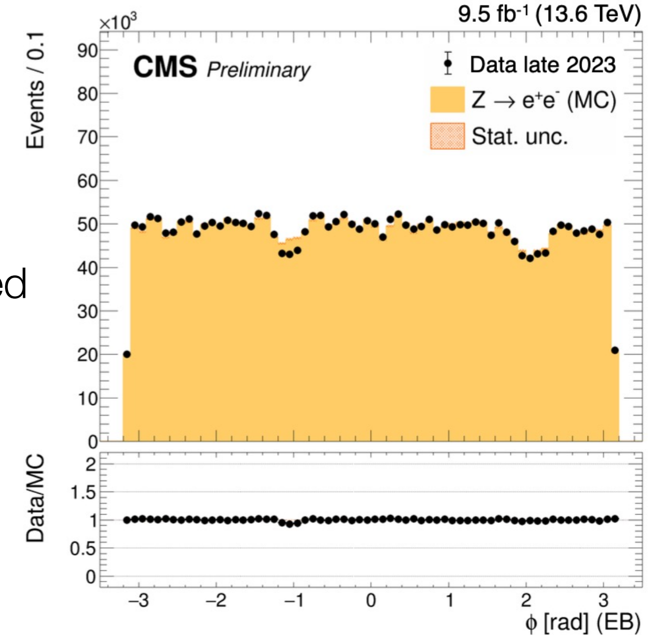
- Good data-to-simulation performance for Muon identification
- Stable isolation performance

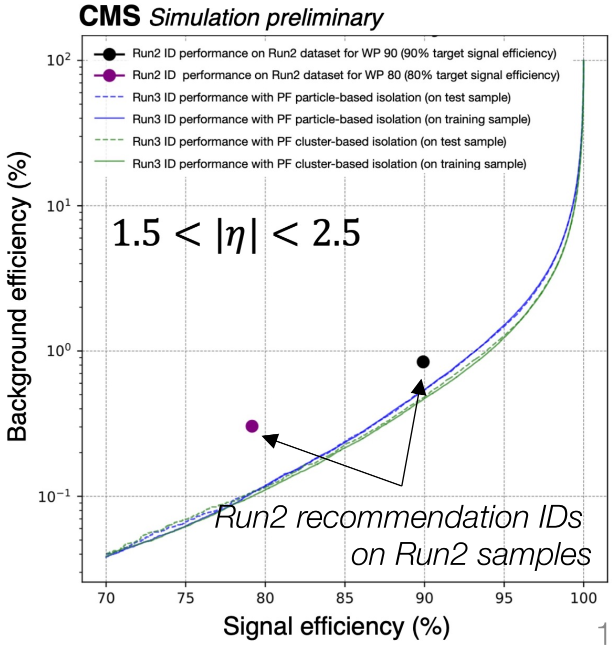




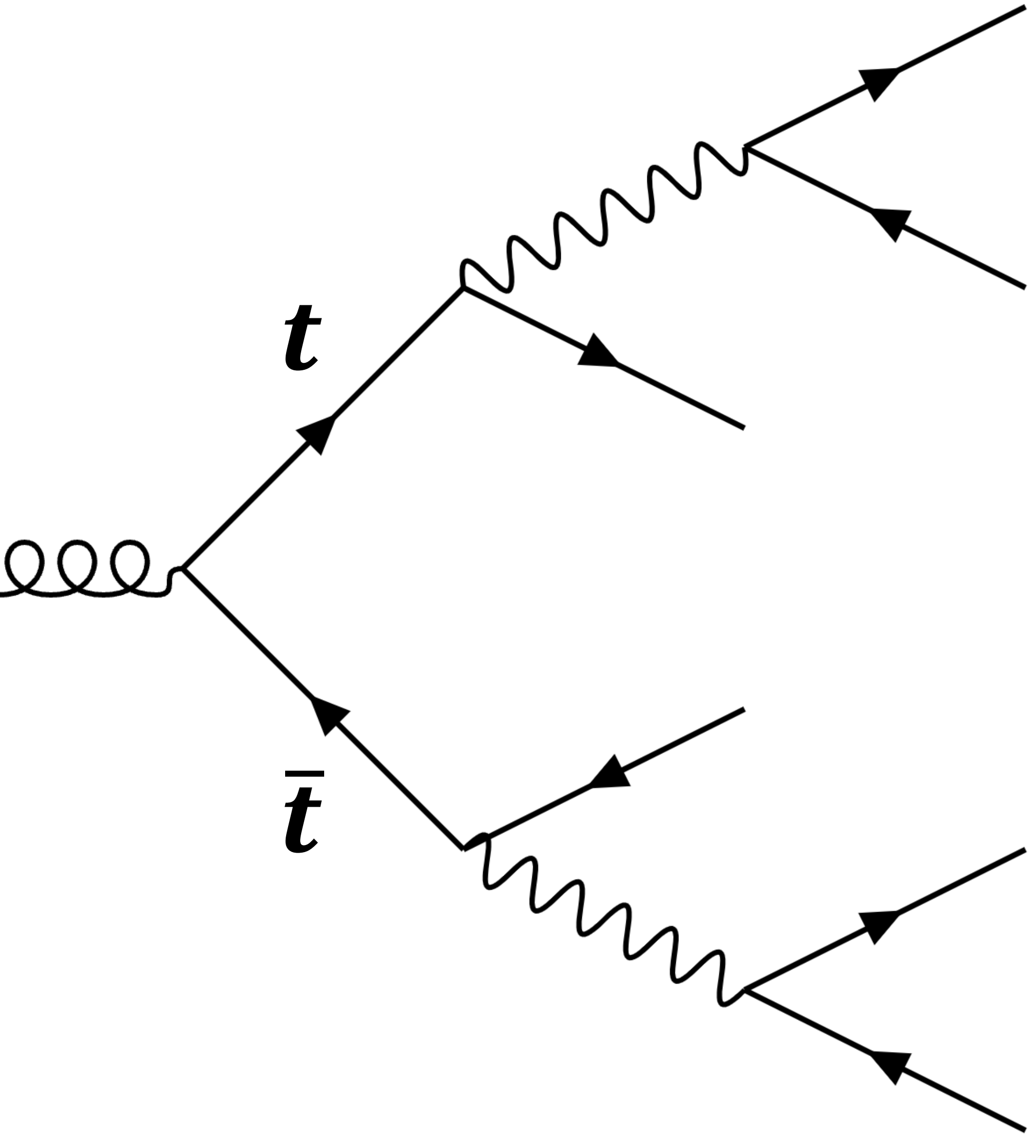
Electron Performance

- Minimal inefficiency in BPix failure region
- A BDT-based (XGBoost) multivariate optimization is performed to discriminate background electrons from signal ones
- The cut-based and MVA-based electron and photon IDs were tuned to ensure a better performance than the Run2





Summary



Jet+MET

- PUPPI as the default algorithm for pileup suppression in Run3
- JES: Excellent and stable performance in the barrel region
- JER: Run3 outperforming Run 2 legacy in $|\eta| < 2.5$
- Full calibration of flavor-aware pT regression for small-cone jets

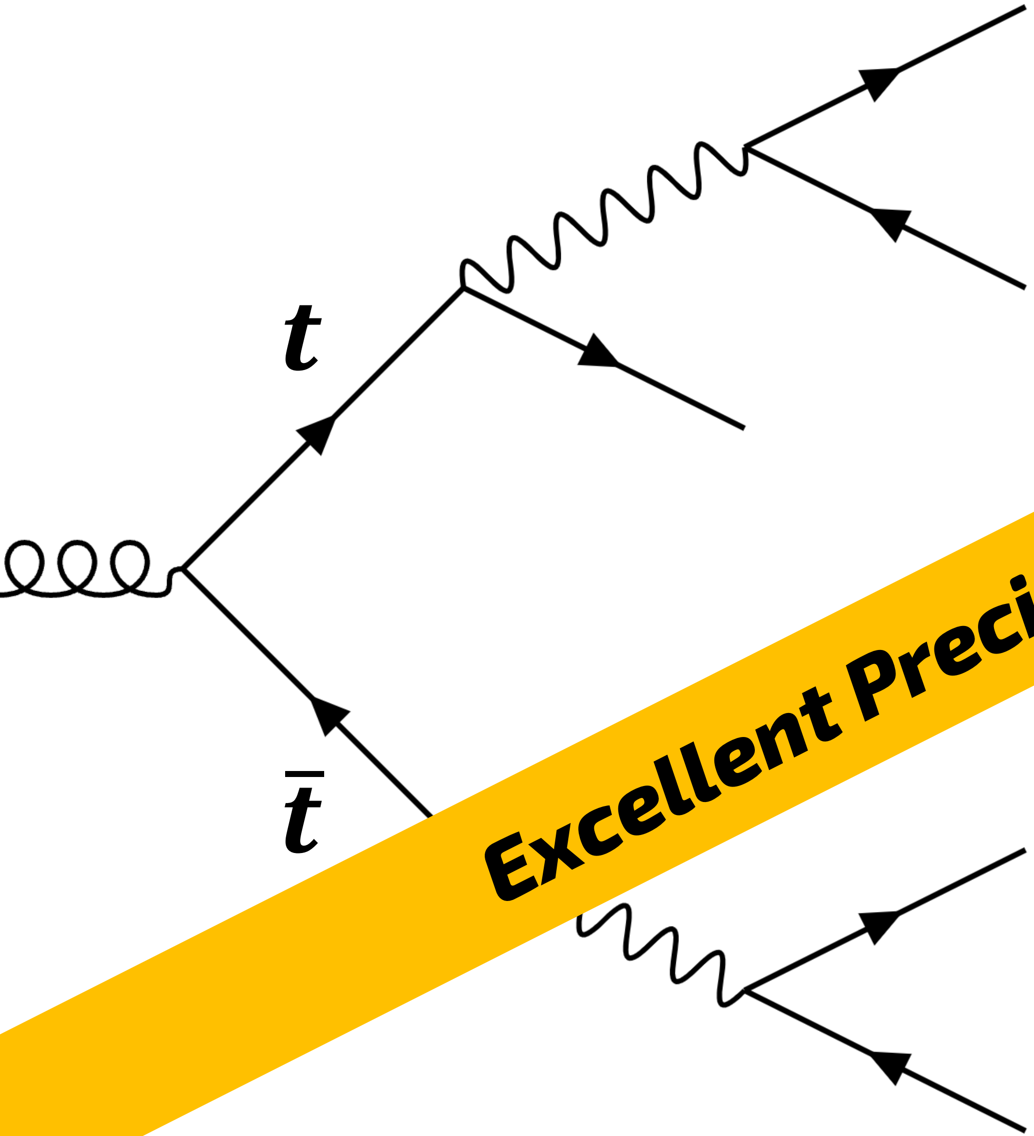
Heavy flavor tagging

- UParT shows promising performance in Run 3
- 5% better b-jet efficiency than DeepJet in Run2
  in the same light jet misidentification rate at 1%
- Good Data vs MC closure after applying SFs

Leptons

- Good and stable data-simulation performance in Muon
- Better Electron / Photon ID than in Run 2

Summary



Jet+MET

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He … tagging

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  in the same light jet misidentification rate at 1%
- Good Data vs MC closure after applying SFs

Leptons

- Good and stable data-simulation performance in Muon
- Better Electron / Photon ID than in Run 2

Excellent Precision for Top measurements!

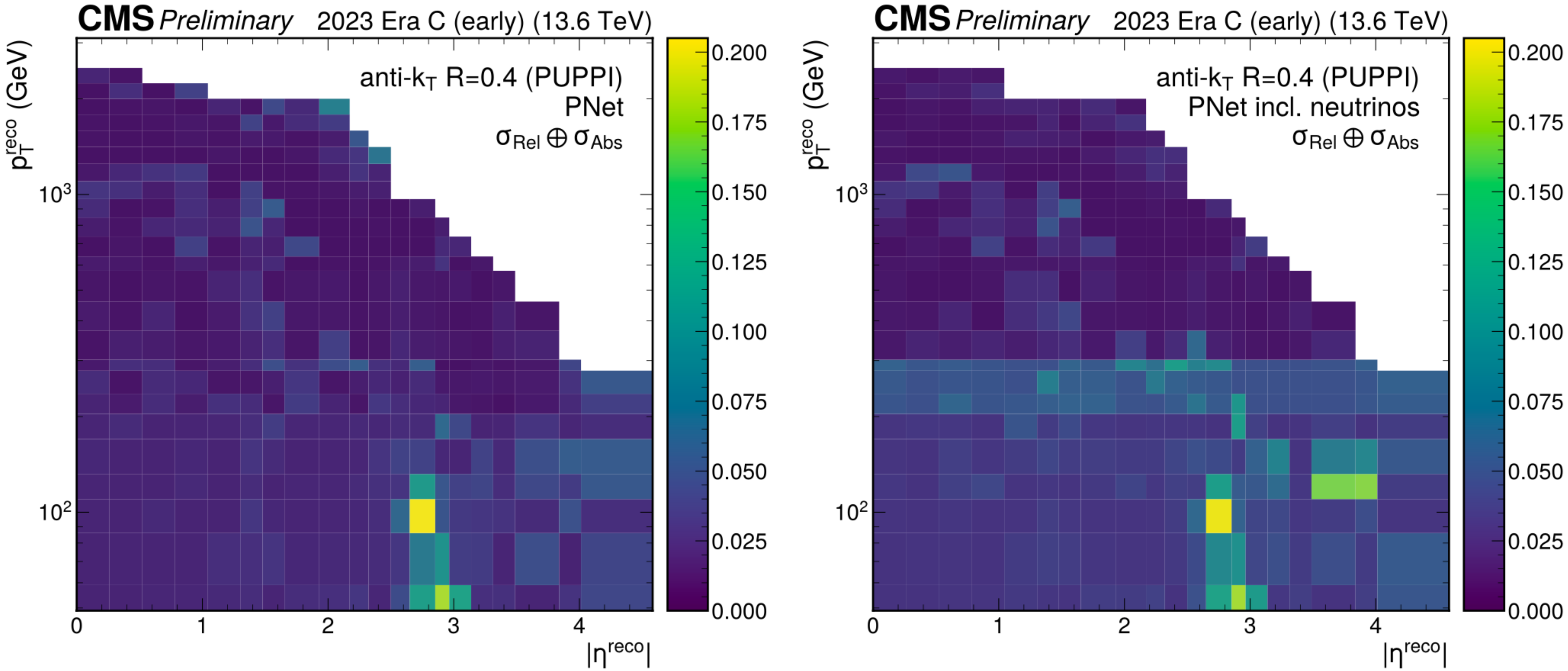
Backup

ParticleNet p_T regression

CMS-DP-2024-064

Residual corrections closure

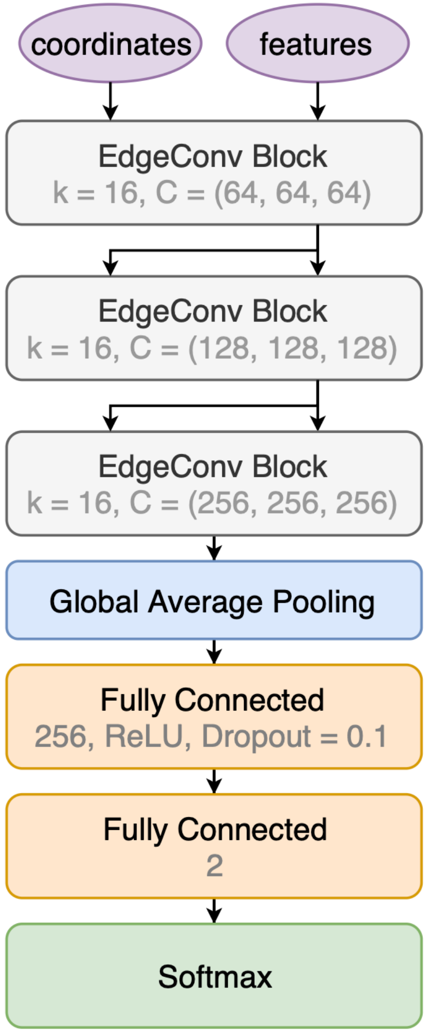
- Residual corrections are not recomputed for regressed p_T jets, but the standard ones are applied
- The level of non-closure is approximately up to 2-5% (2-8%) for PNet regressed p_T without (with) neutrinos in the barrel and higher in the endcap (up to 10-20%)



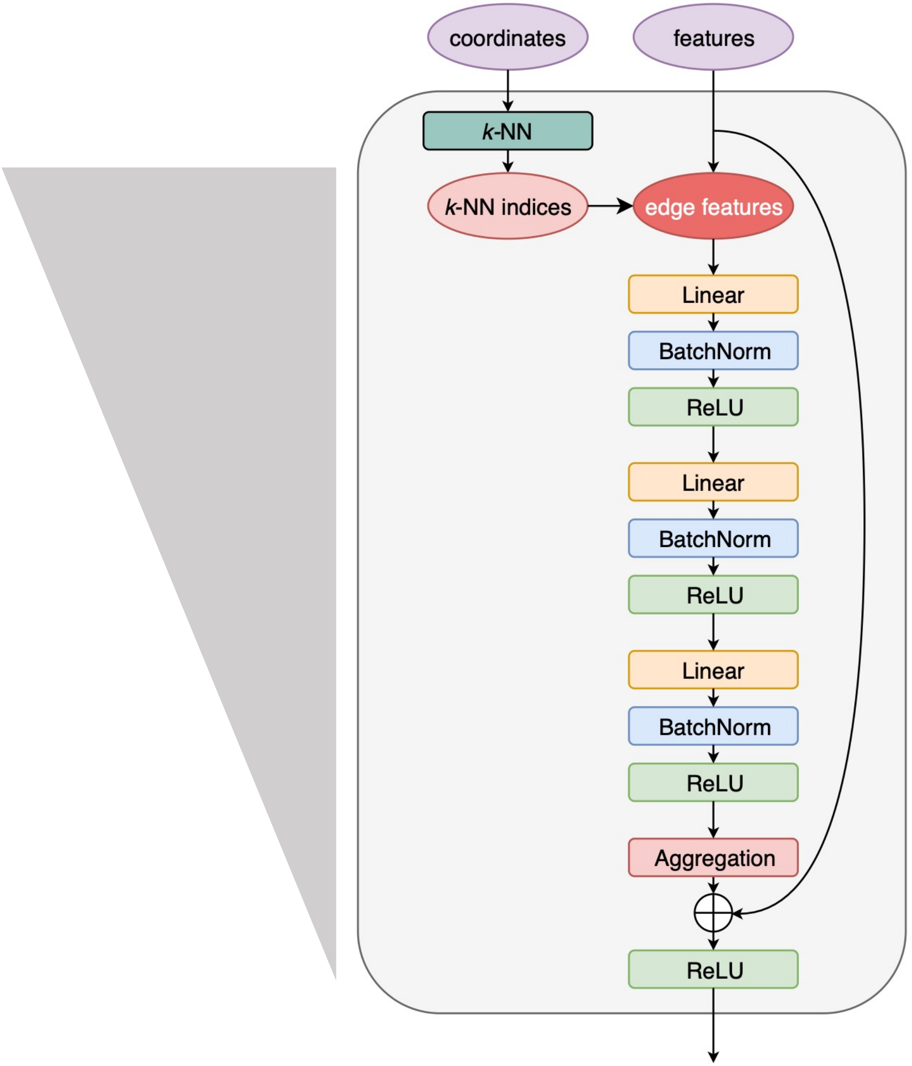
ML tagger Architectures

arXiv:1902.08570

ParticleNet



Architectures of the ParticleNet

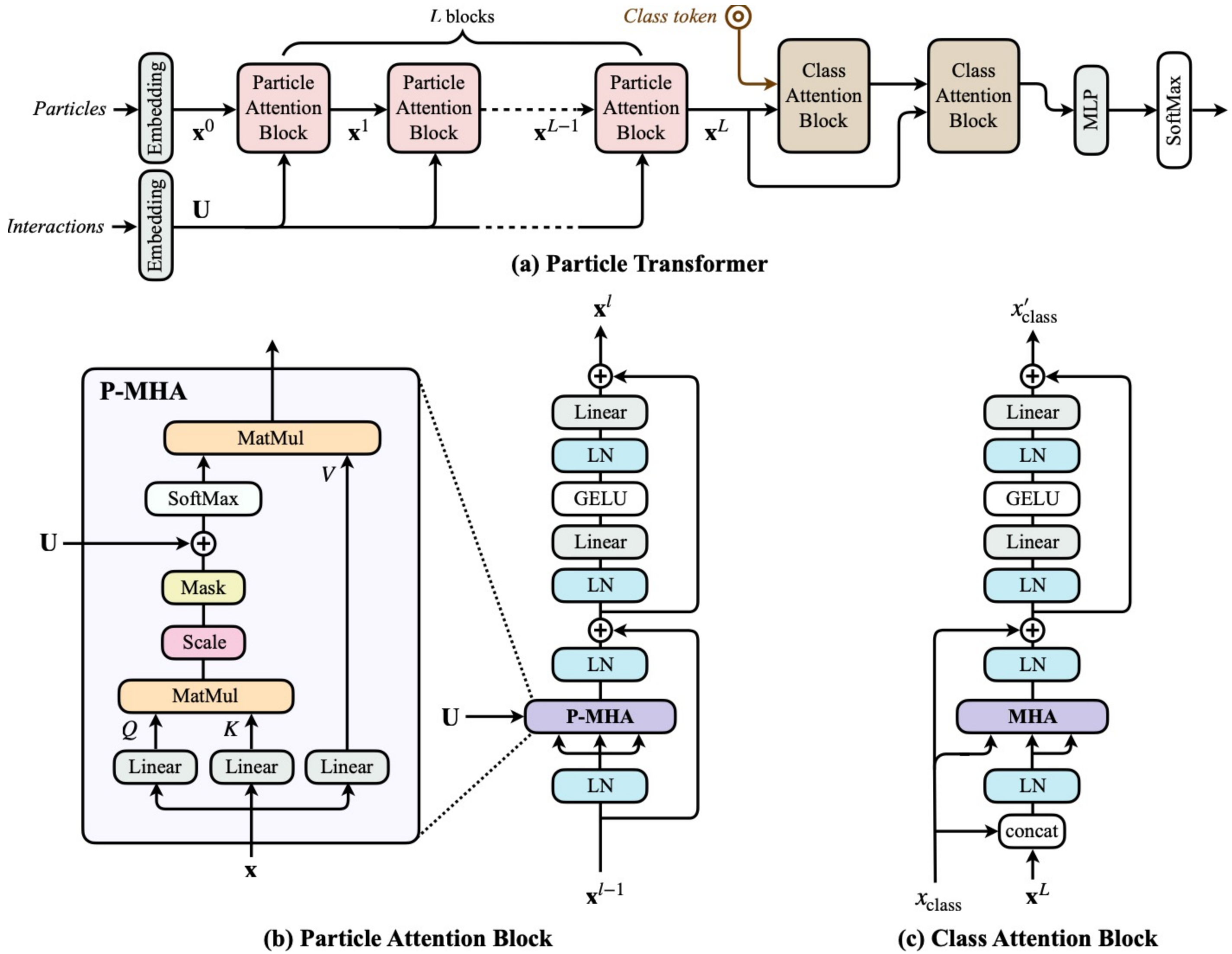


The structure of the EdgeConv block

ML tagger Architectures

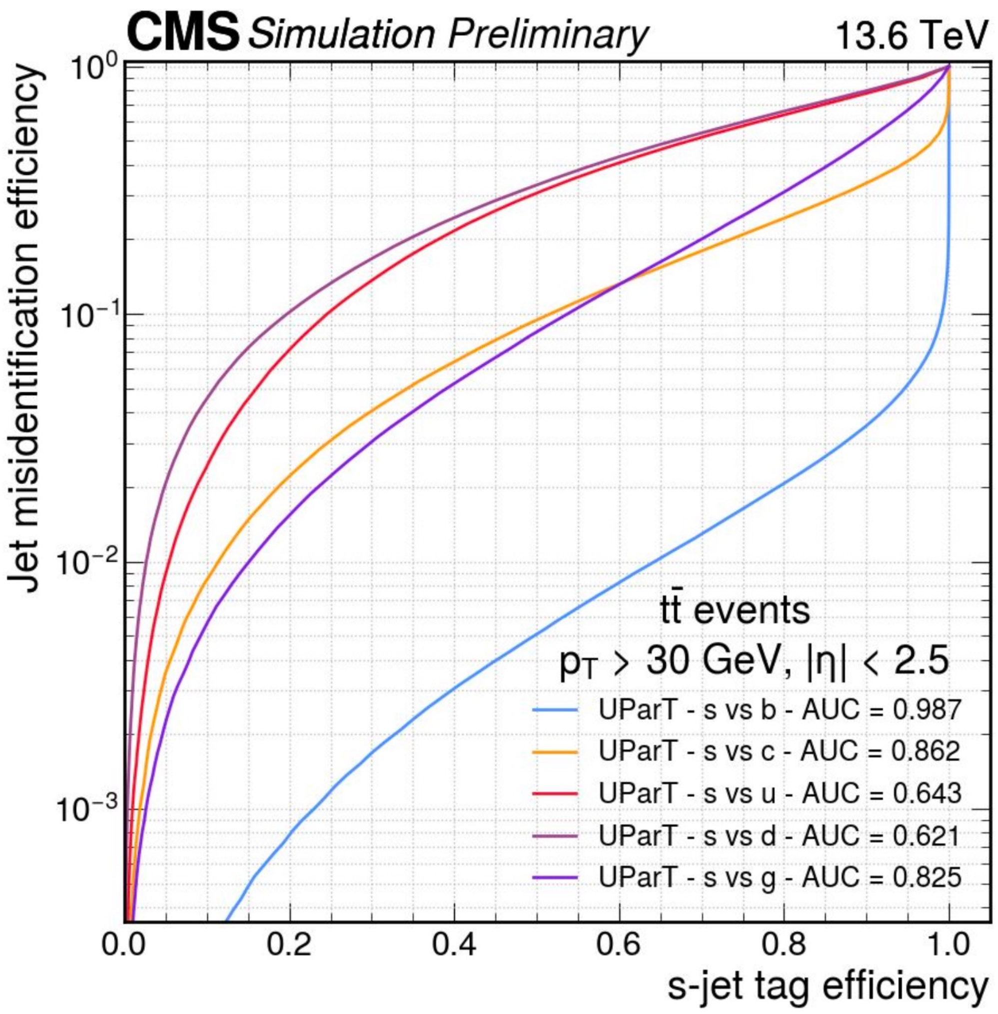
arXiv:2202.03772

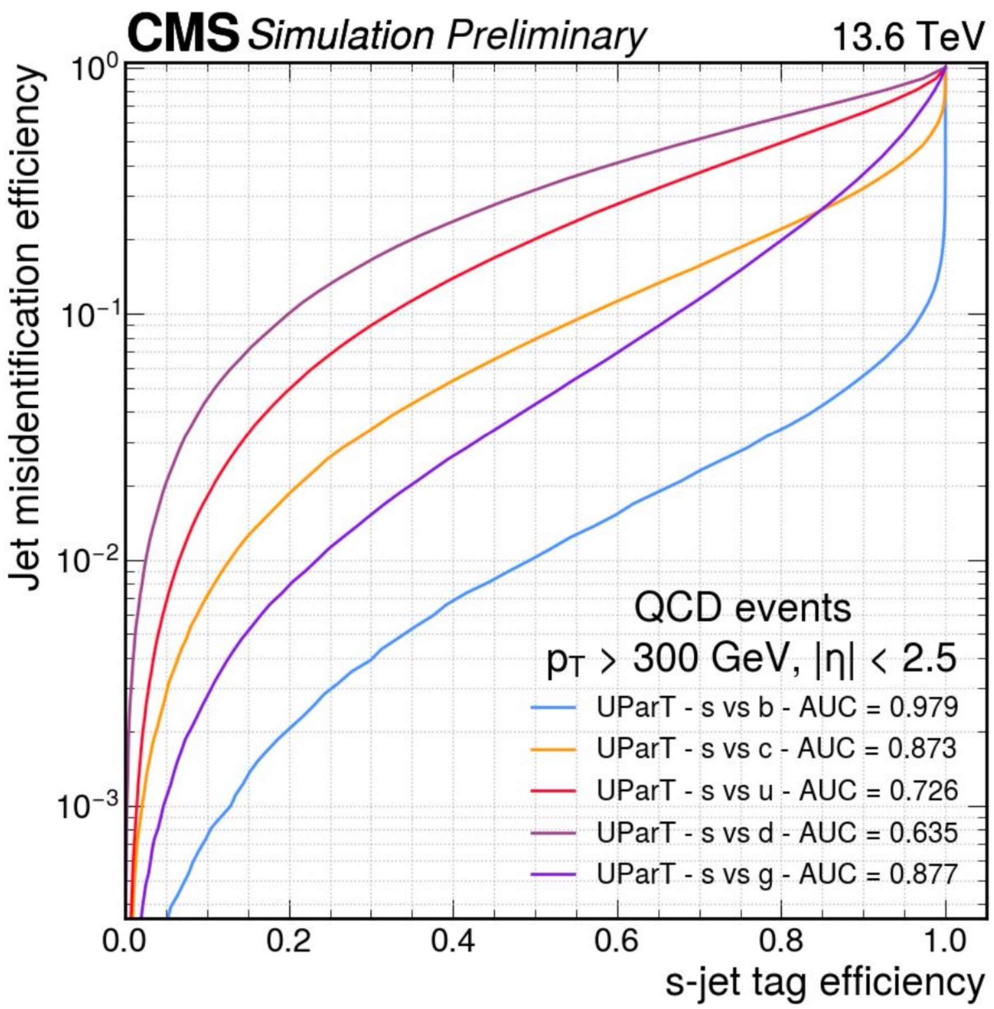
Particle Transformer



s-tagging Performance

CMS-DP-2024-066

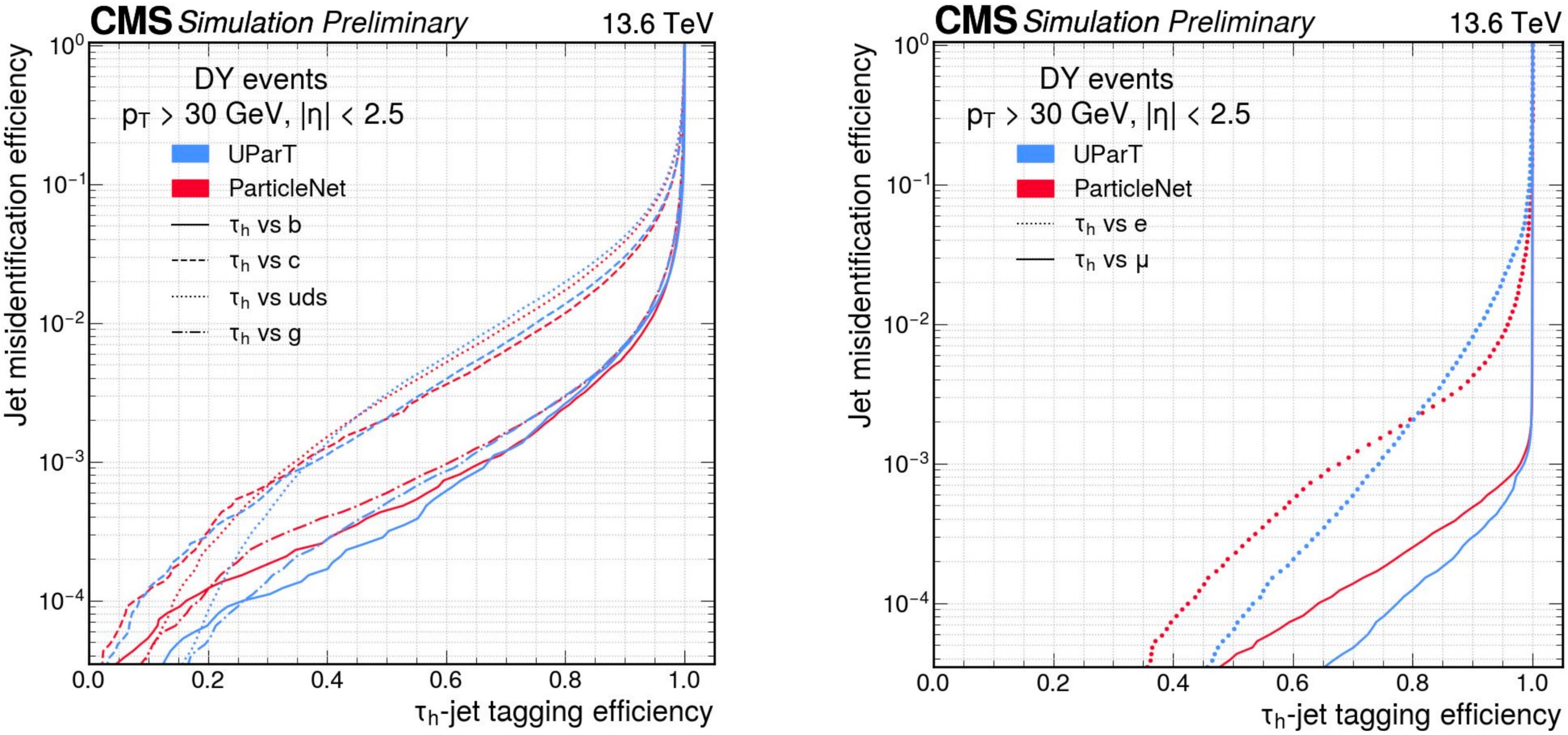




- The first time a specific s-node added to jet tagging algorithm
- Performance indicates we can achieve a low efficiency s-tagger

τ_h-tagging Performance

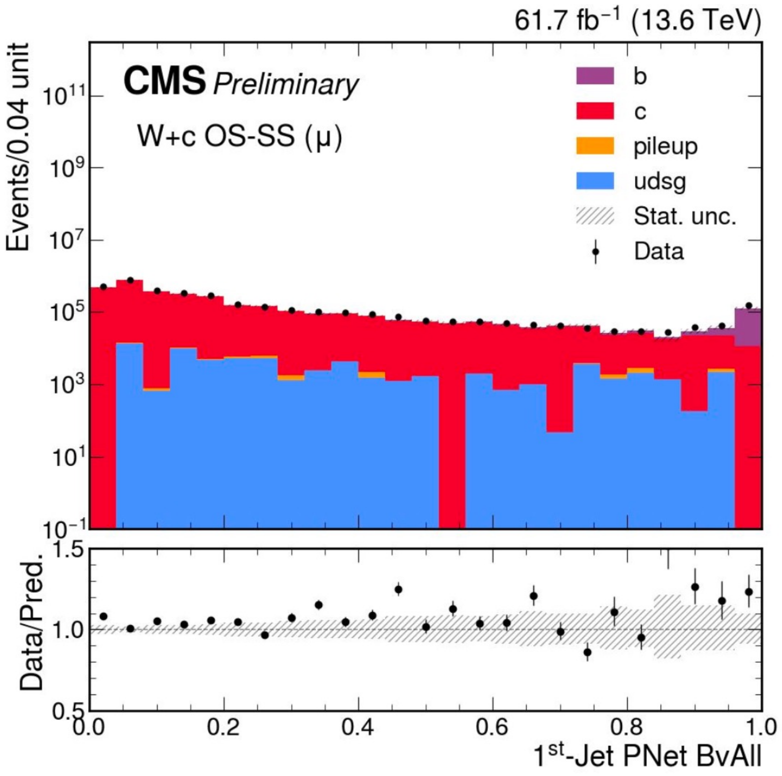
CMS-DP-2024-066

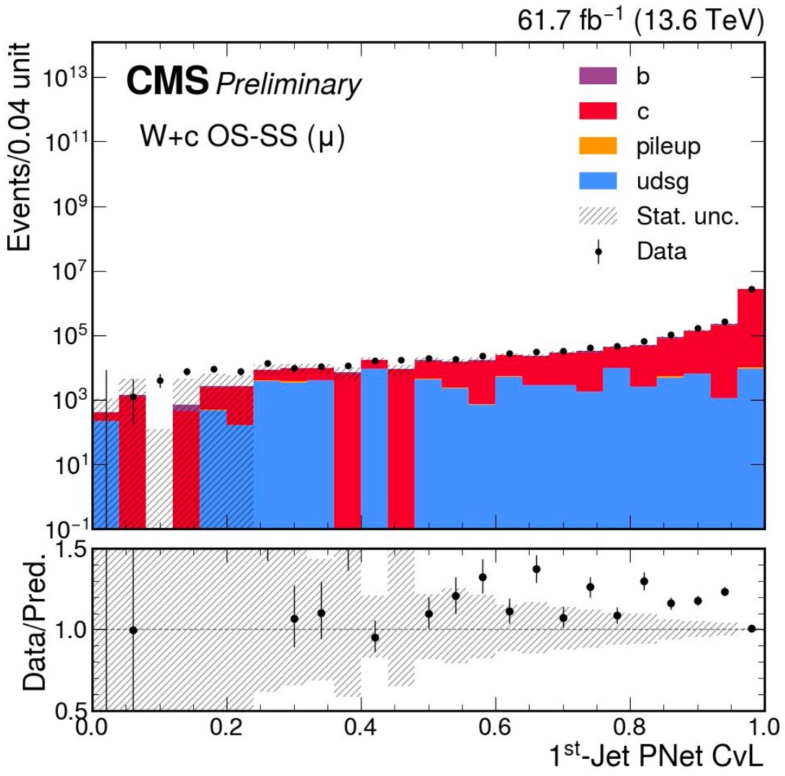


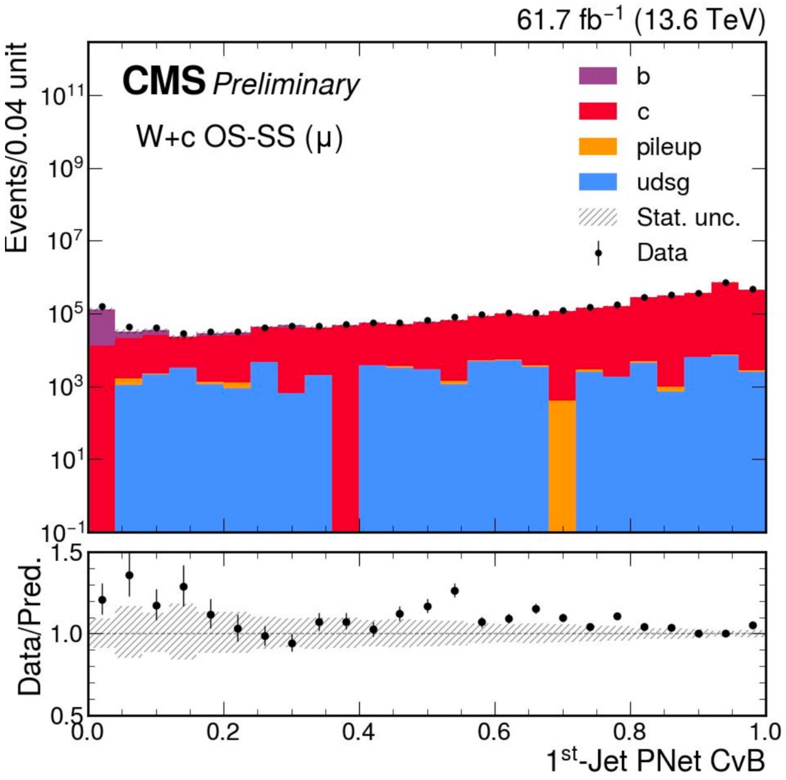
- ParticleNet and UParT show similar performances
- ParticleNet performs better at high misidentification rate and UParT at lower rate

Commissioning in c-tagging

CMS-DP-2024-066



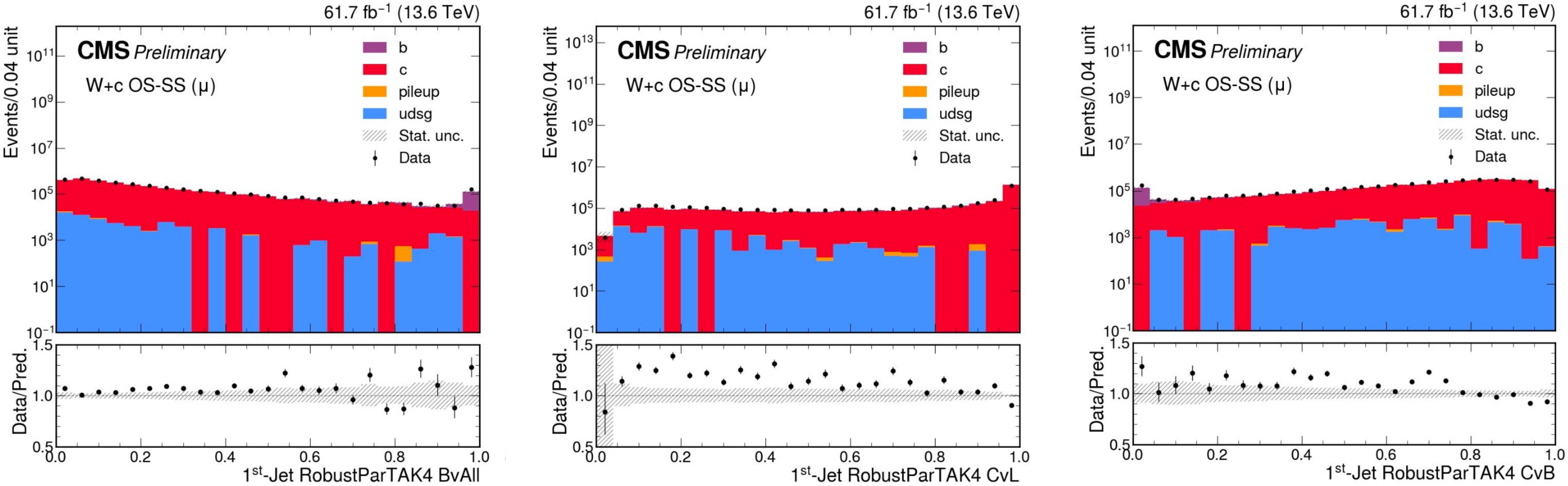




- Performed in W+c phase space

Commissioning in c-tagging

CMS-DP-2024-066



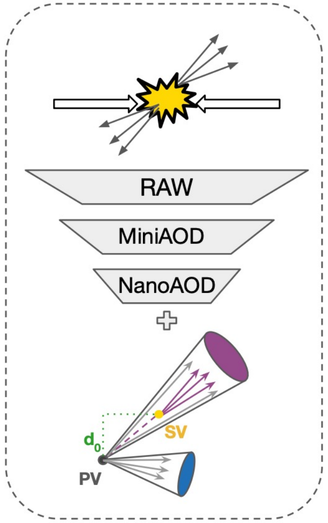
- Performed in W+c phase space

FTAG Frameworks

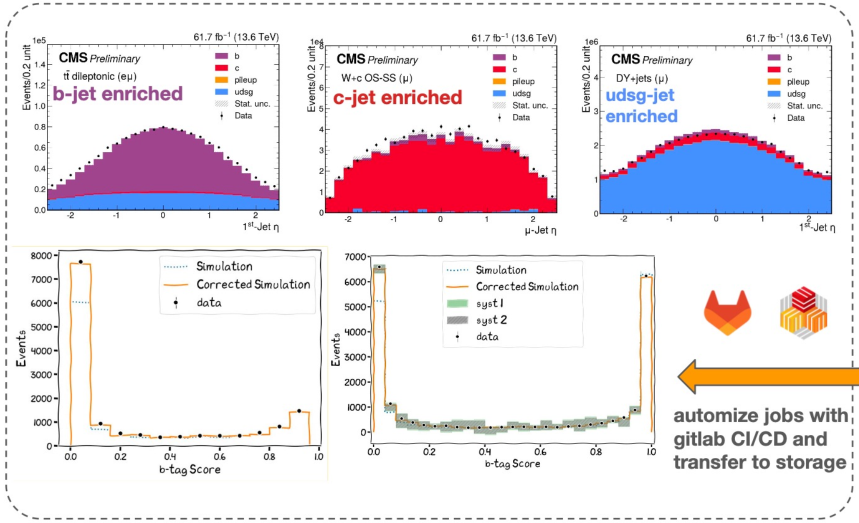
CMS-DP-2024-020
CMS-DP-2024-024

Commissioning workflows

- BTVNanoCommissioing
  - Fast and efficient
  - Python array based manipulation instead of loops
  - Automatized using Gitlab Continuous integration
  - Monitor performance in regular intervals



ntuplize (NanoAOD)

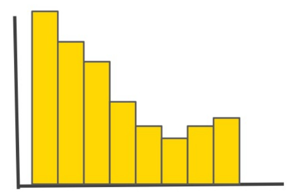


Common BTV framework(coffea)

arrays(ROOT, awkward)

jet pT	jet η	SV pT	SV d0	score
96	1.4	53	0.58	0.8
58	0.5	0	0	0.03
28	0.8	2.5	0.3	0.03
61	-0.6	8.8	0.9	0.98
68	1.5	10	0.1	0.41
...	...	...	...	...

histograms(coffea, ROOT)



plots, other framework

Training

- b-hive
  - Framework dedicated for training
  - Easily customizable to introduce your own model

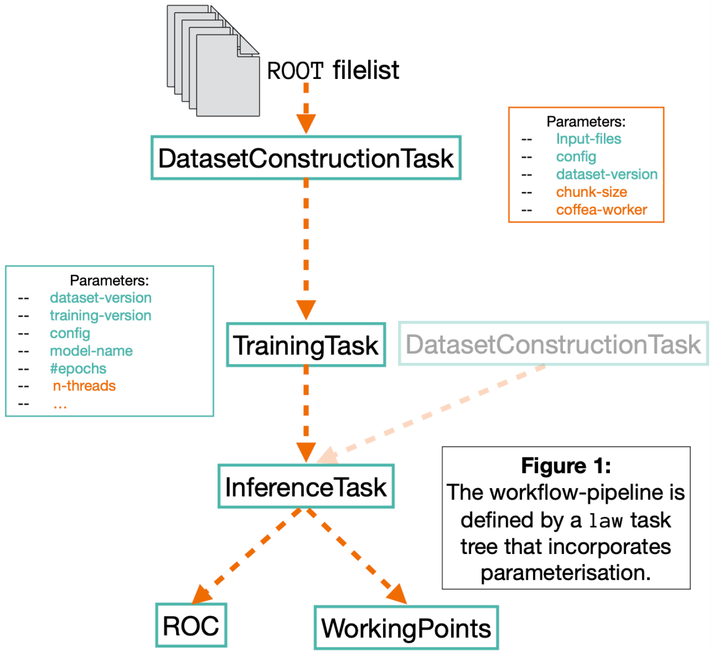


Figure 1: The workflow-pipeline is defined by a law task tree that incorporate parameterisation.