UNIVERSITY OF HELSINKI

HELSINKI INSTITUTE OF PHYSICS

CMS

Compact Muon Solenoid

Jet Performance in CMS

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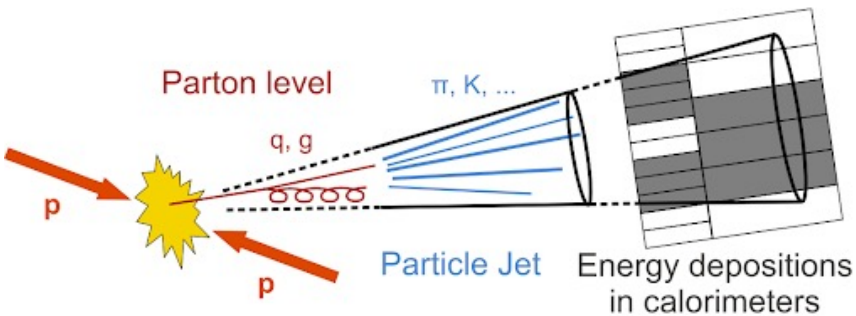
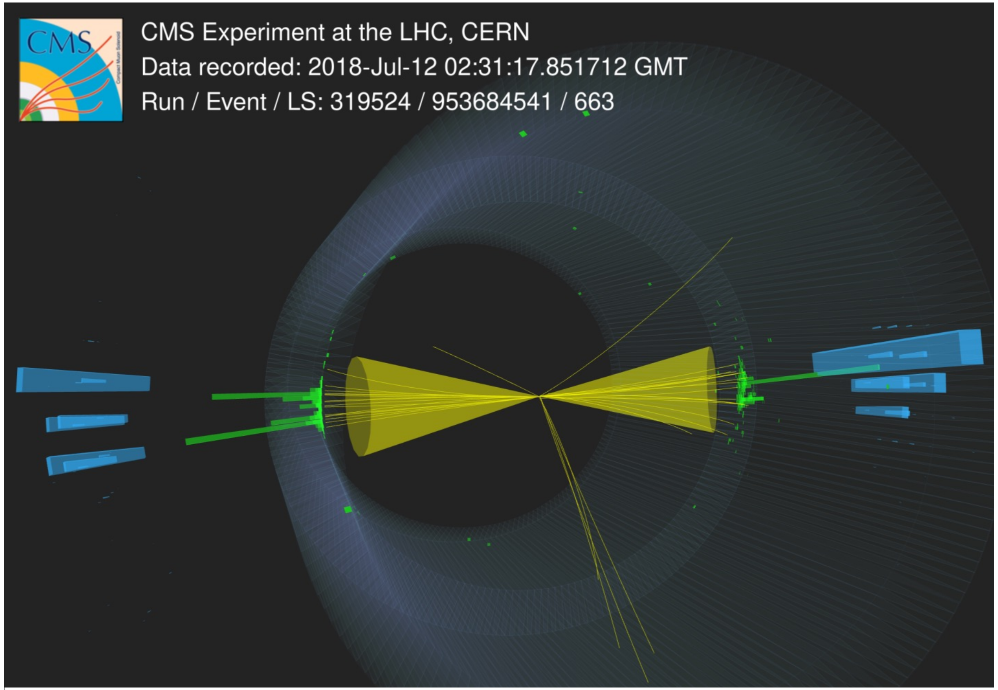
Particle Physics Days 2024

28 November 2024

Jet

Stream of hadrons originating from quarks/gluons





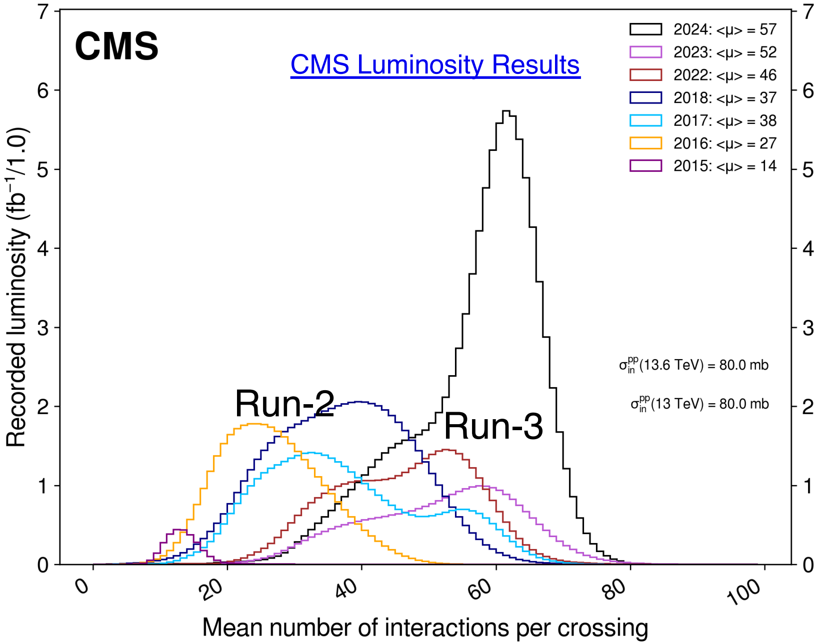
Link

Jets at CMS

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

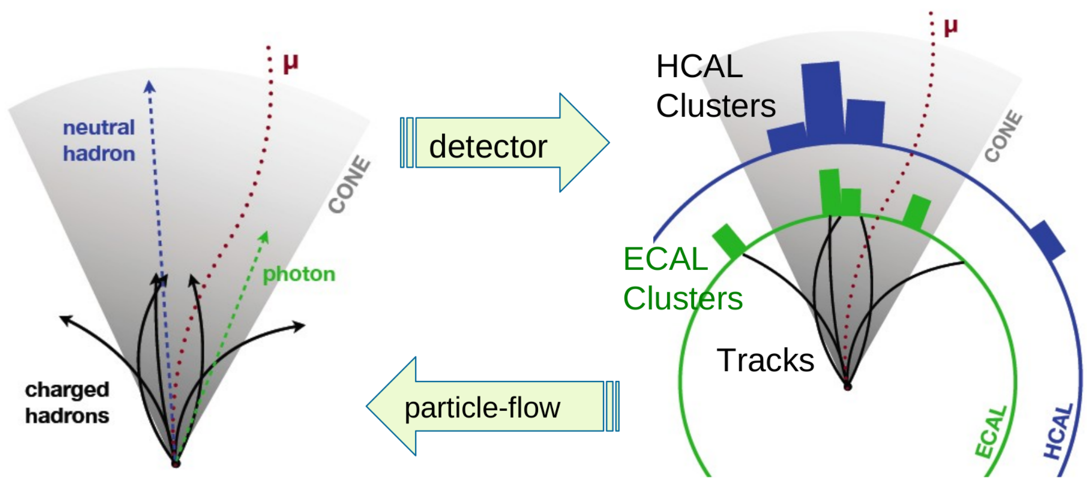
- Need optimum reconstruction & precise calibration.

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

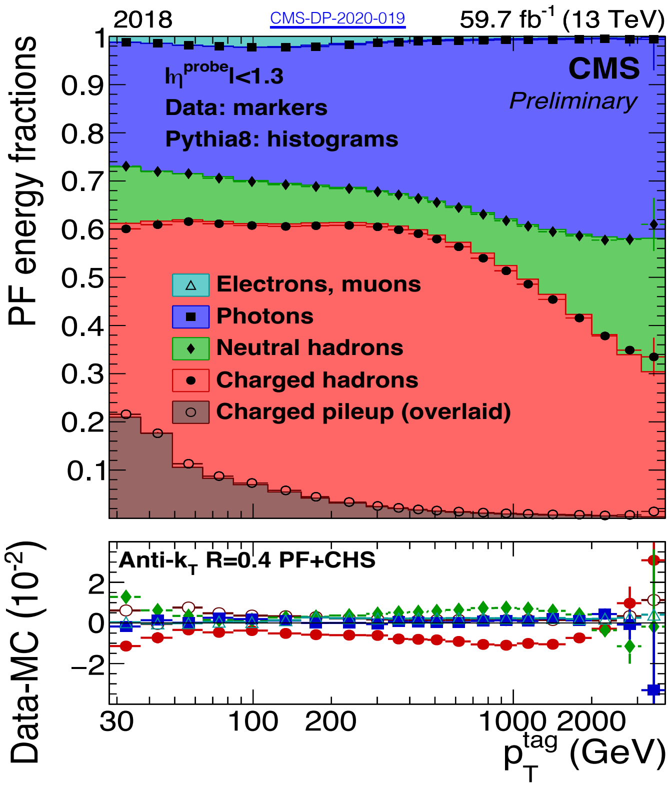


Particle Flow (PF) Algorithm

JINST 12 (2017) P10003



global event description by combining various sub-detectors information

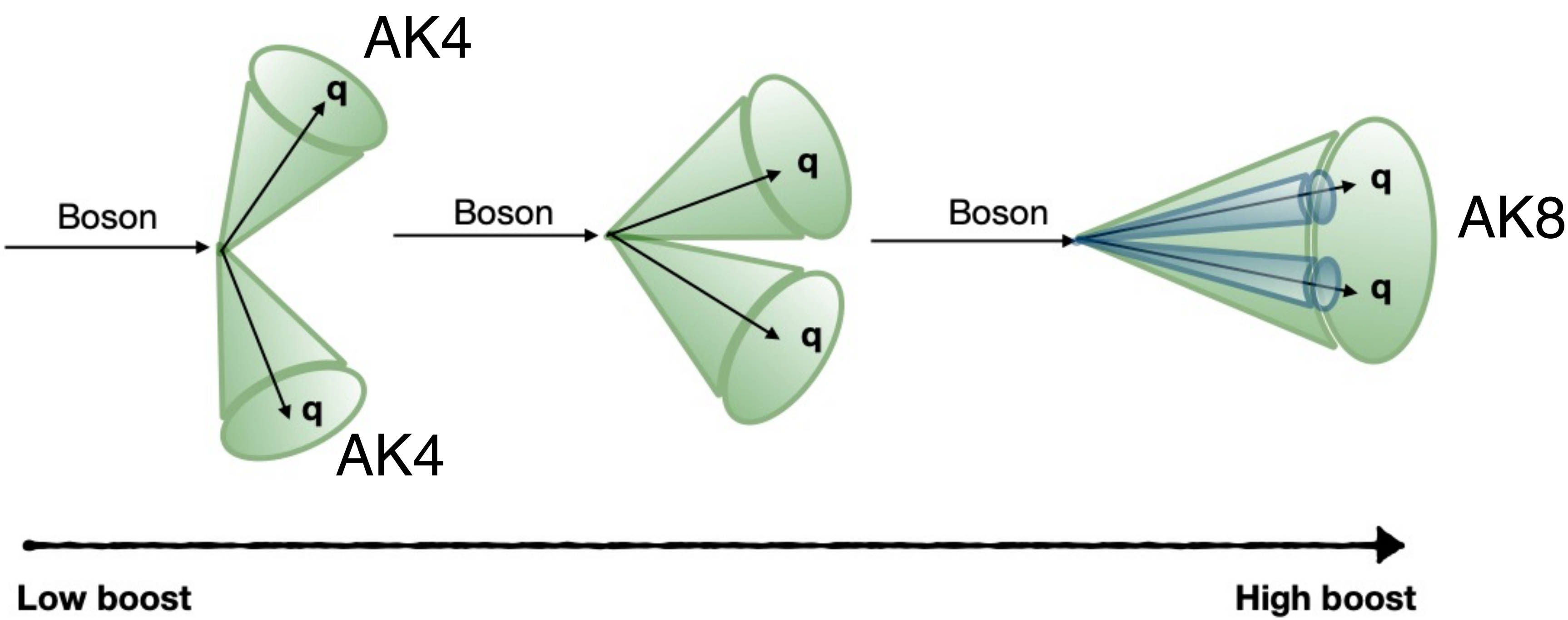


"Standard" jet algorithms with PF candidates as inputs:

- 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).

Why AK8?



Low momentum

High momentum

W/Z-boson ~ 240 GeV

Constituent-level Pileup Mitigation with PUPPI

Constituent-level Pileup Mitigation

JINST 15 (2020) P09018
DP-2021-001

CMS mitigates pileup at the constituent-level

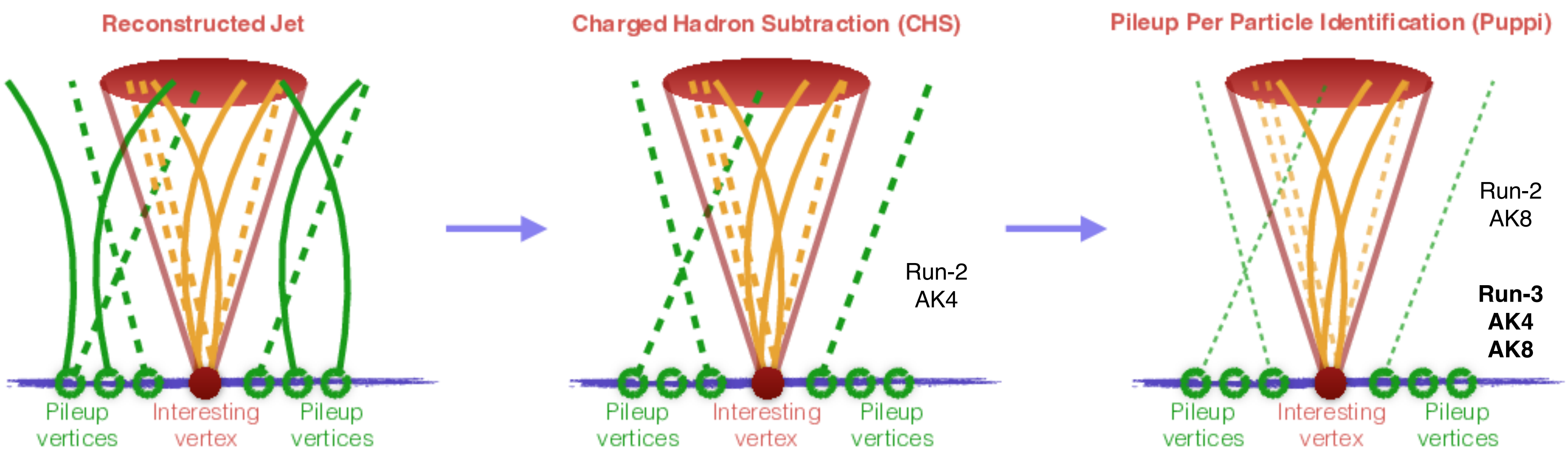


Figure by Andrea Malara

CHS

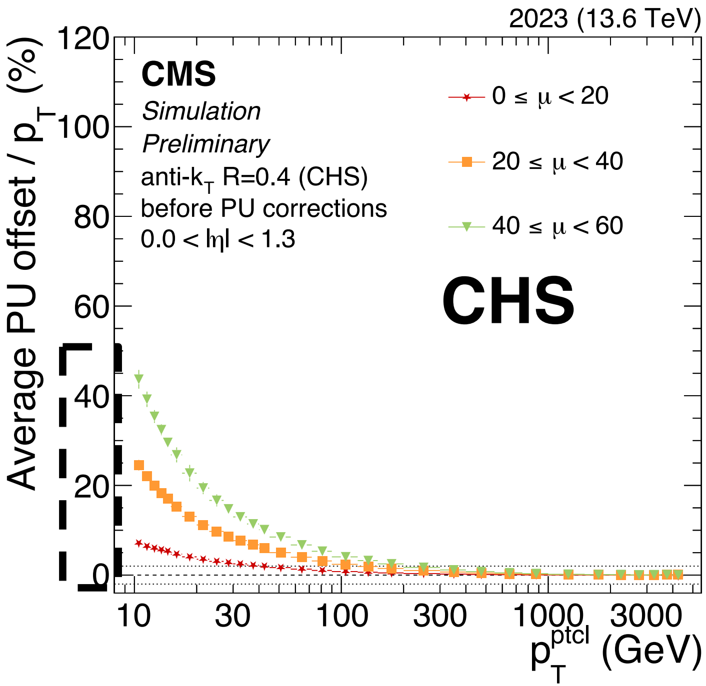
- Discard charged PF candidates from Pileup Vertices

PUPPI

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

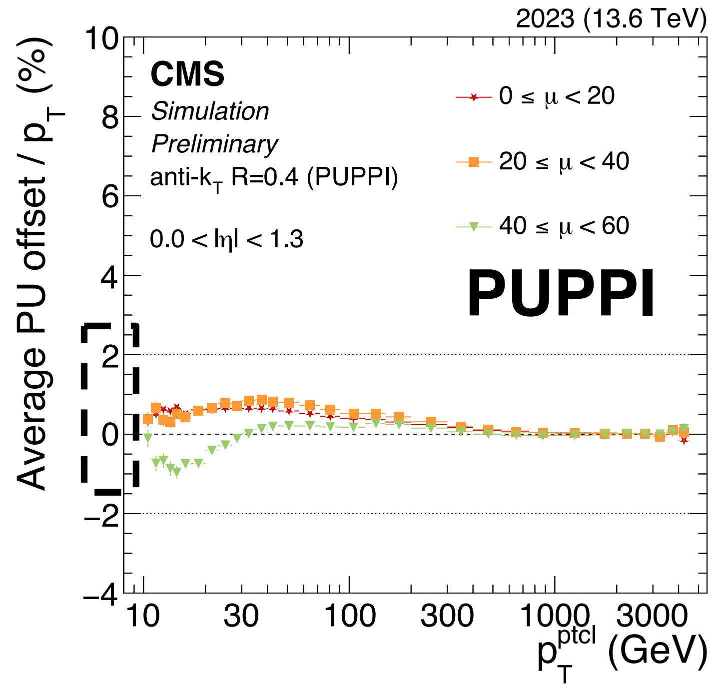
CHS vs PUPPI: Impact on jet energy

DP-2024-039



Large pileup contamination at low pT

Require dedicated step in jet energy corrections.



Negligible pileup contamination

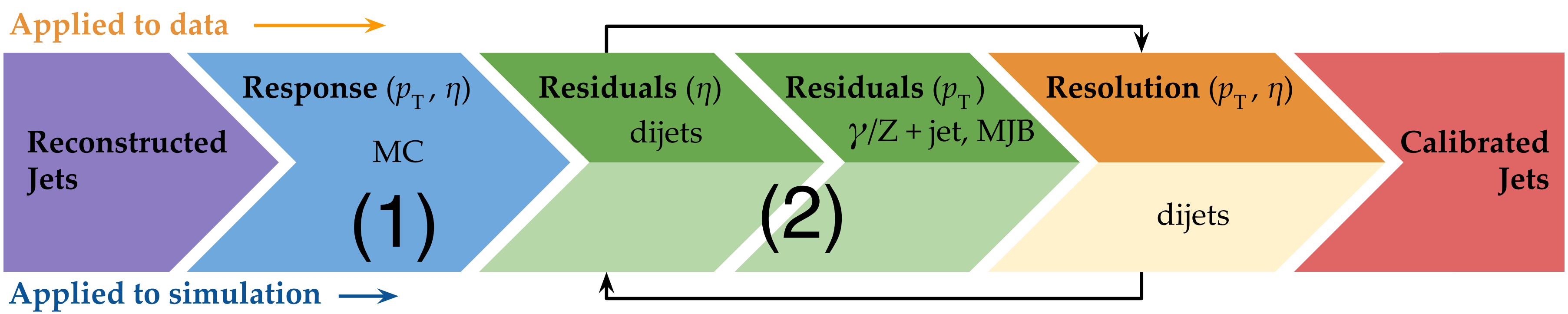
Not used for jet energy corrections. Monitor pileup.

Jet Energy Scale & Resolution Calibration

Early Run-3 datasets

Jet Energy Scale & Resolution Calibration

DP-2024-039

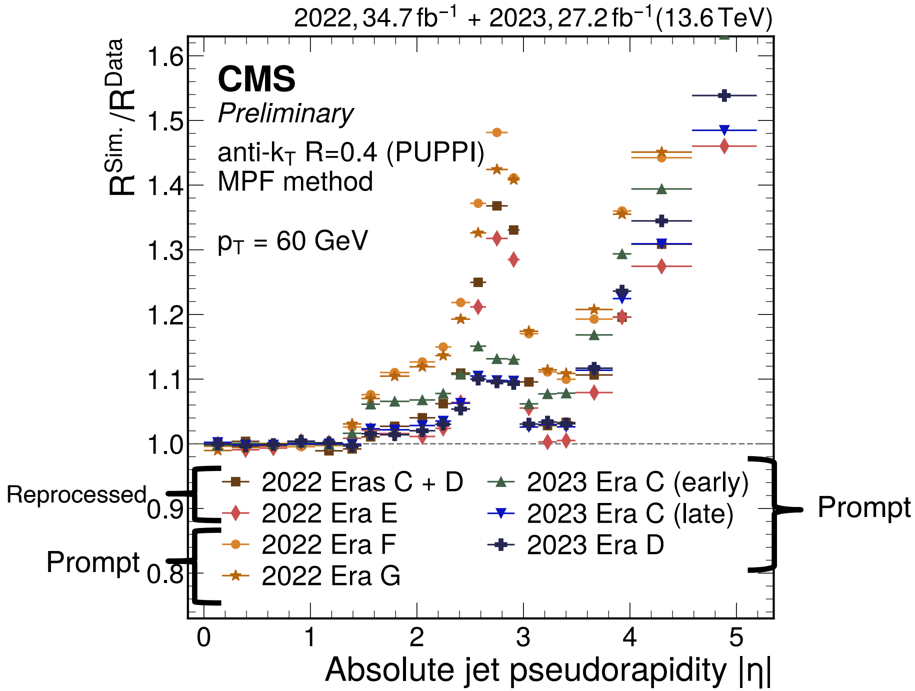


- Factorized approach to jet energy calibration.
- <u>Jet Energy Scale (JES)</u>:
  1) MC "truth" corrections: correct to particle-level jet scale.
  2) Residual corrections: correct for residual differences between simulation & data.
- <u>Jet Energy Resolution (JER)</u>:
  - ➢ Smear jet energy in simulation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

JES & JER with early Run-3 dataset

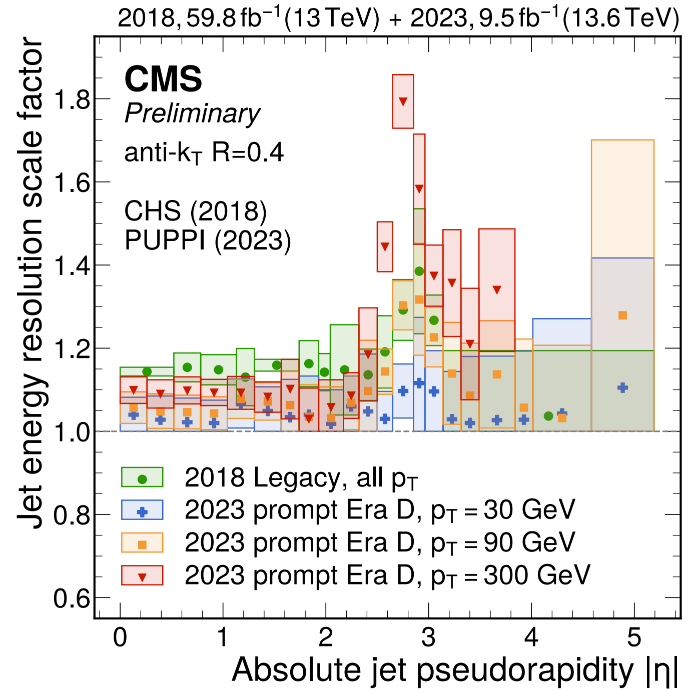
DP-2024-039

JES residual corrections



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

JER (Data/Simulation) SF



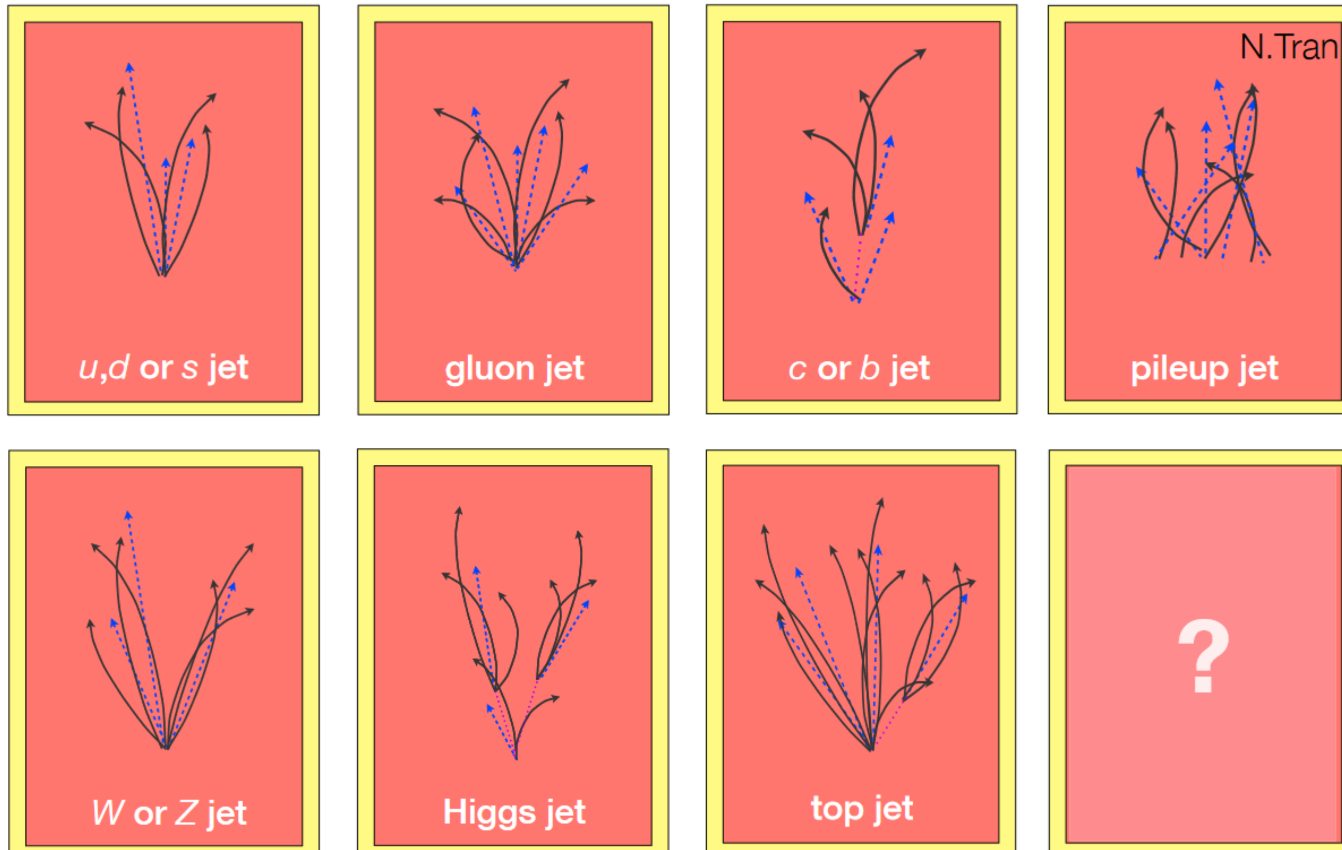
- Run-3 prompt reconstructed data is better than Run-2 legacy.
- Observed p_T dependence for Run-3 dataset.

Jet tagging

Run-3 developments

What is Jet tagging?

Determine origin of a jet

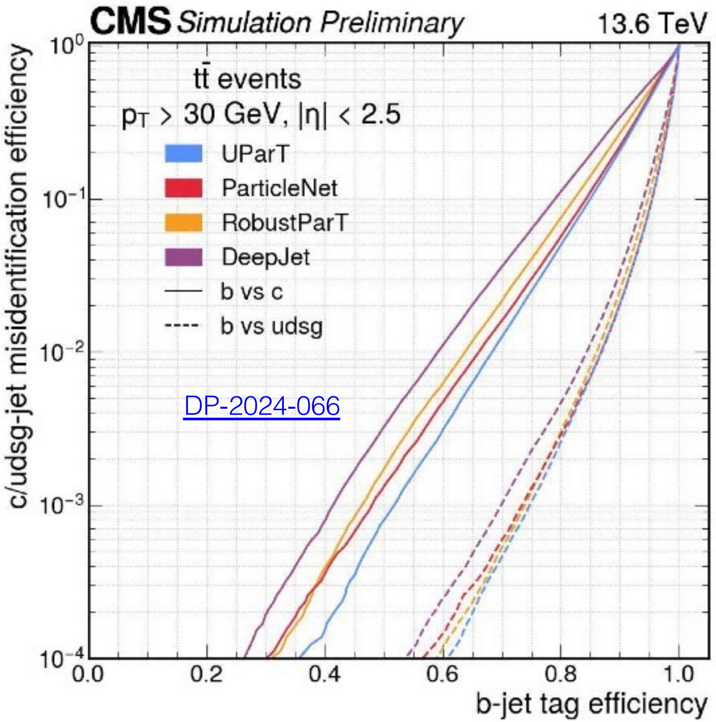


AK4: (Unified) Particle Transformer

- 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)

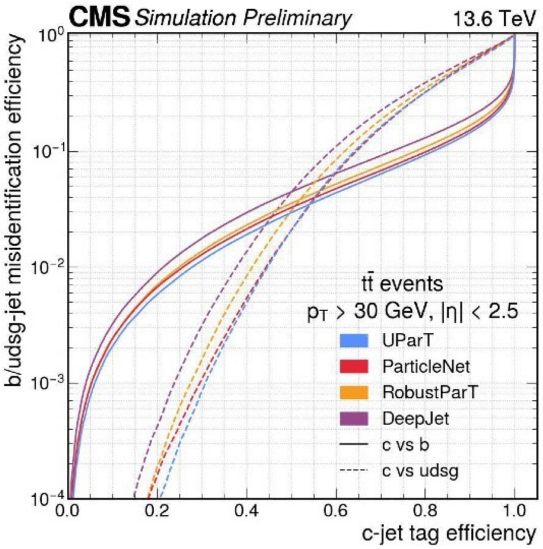
- Extended class: extending from b & c jet tagging to include s & hadronic τ (one per final state) tagging.
- Extended regression: simultaneous flavor aware **jet energy & resolution regression**



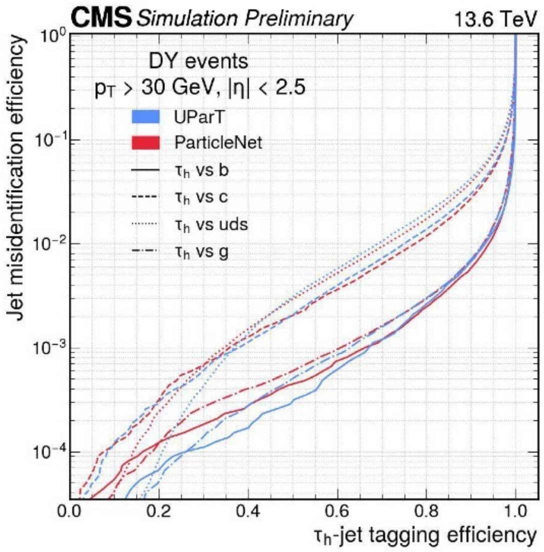
AK4: (Unified) Particle Transformer

DP-2024-066

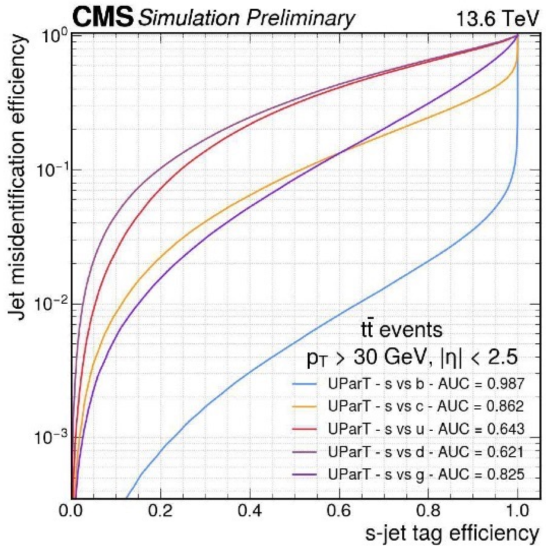
charm-jet



hadronic τ

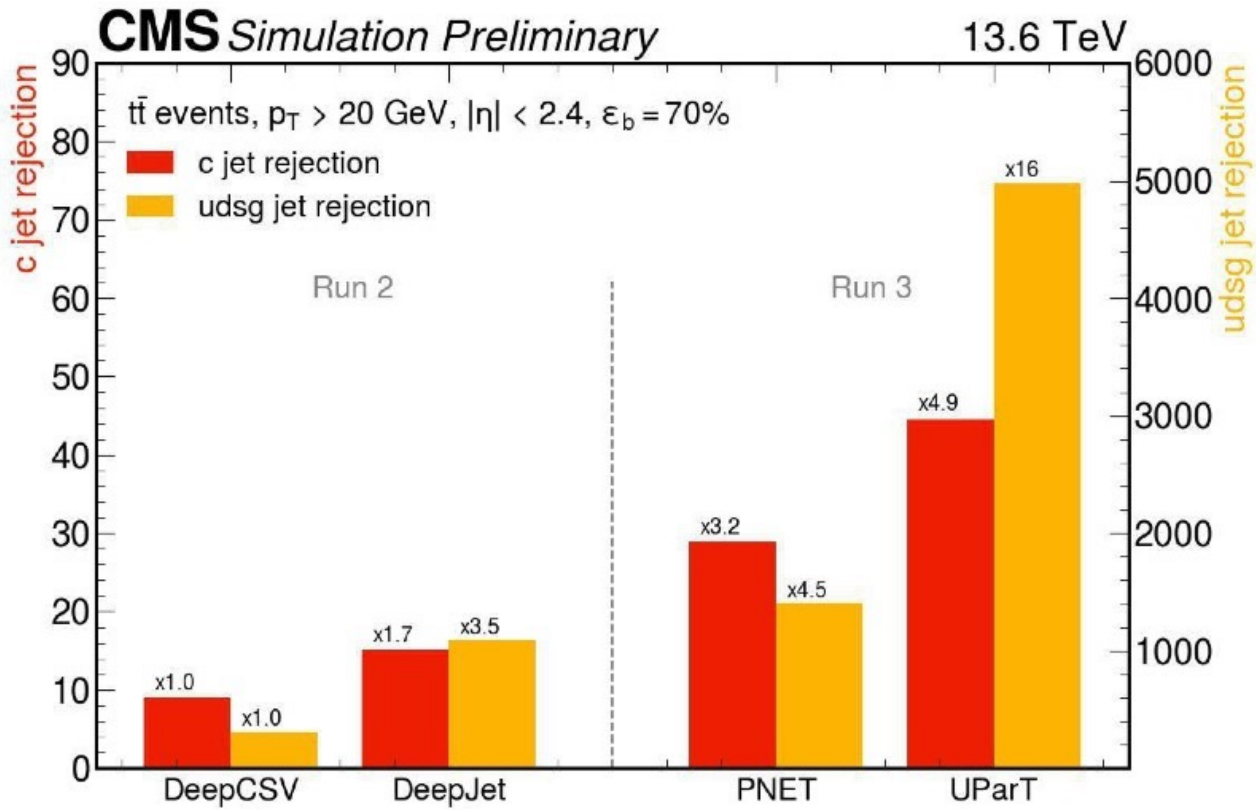


strange-jet



First attempt at strange-jet tagging in CMS!

DP-2024-066



Impressive advancement of jet tagging within ~decade.

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

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.

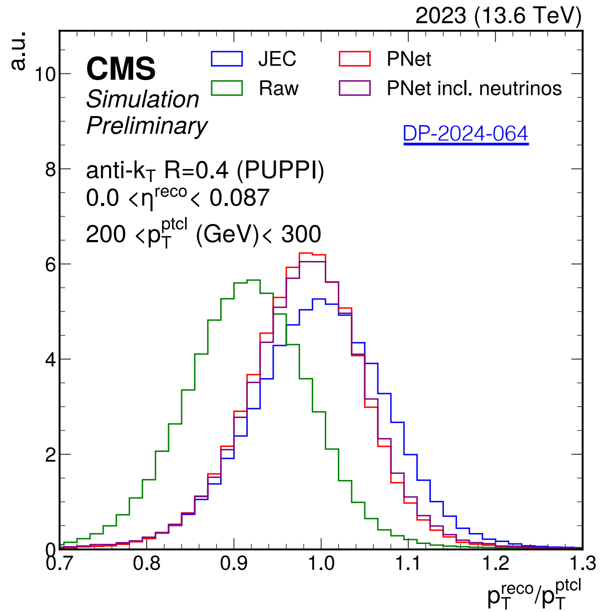
DP-2024-066

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

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

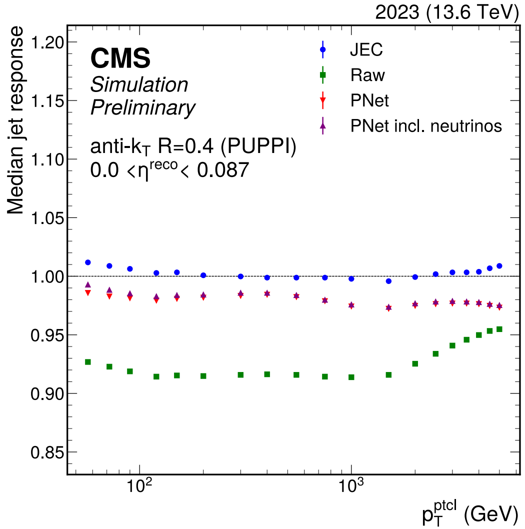
Two types of target p_T regression

without & with neutrino contribution

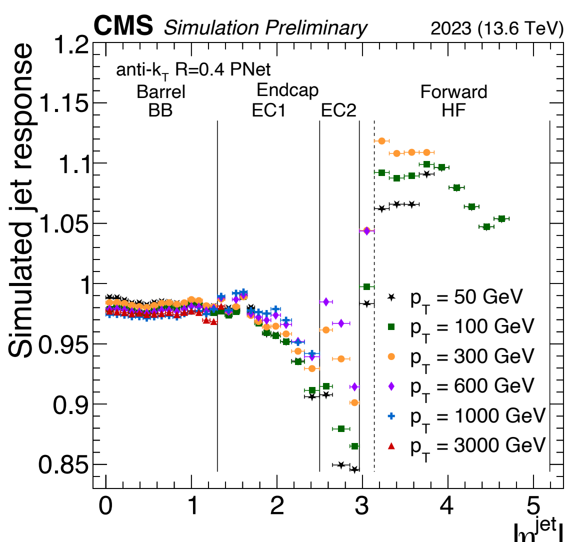


AK4 p_T regression with ParticleNet (Response)

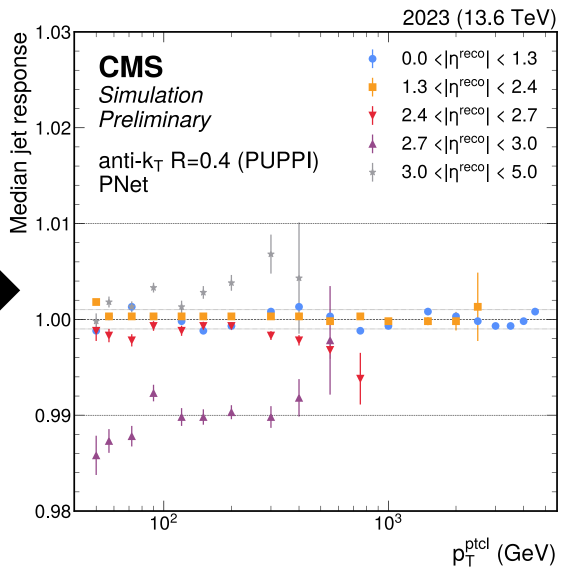
DP-2024-064



- 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).

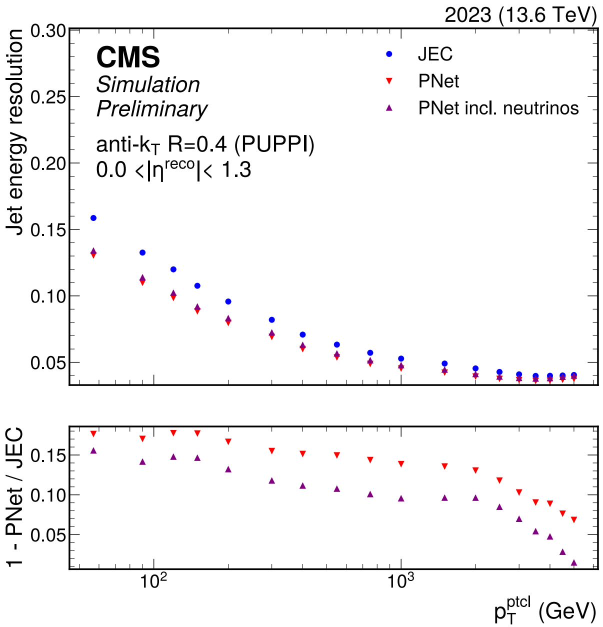


Apply corrections

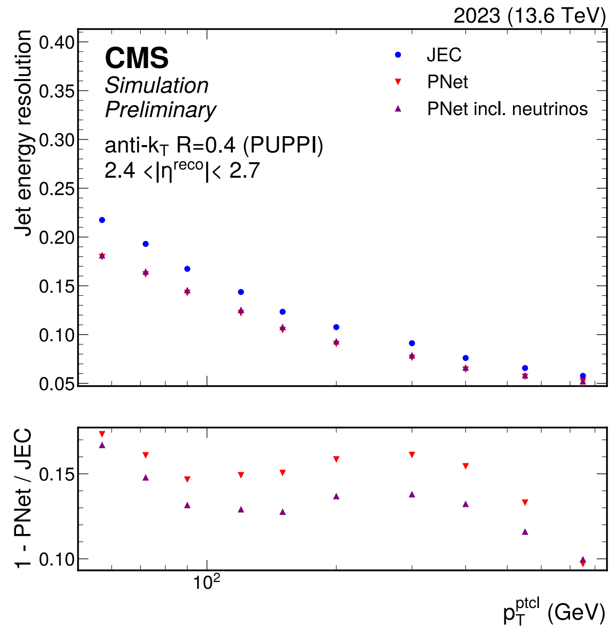


DP-2024-064

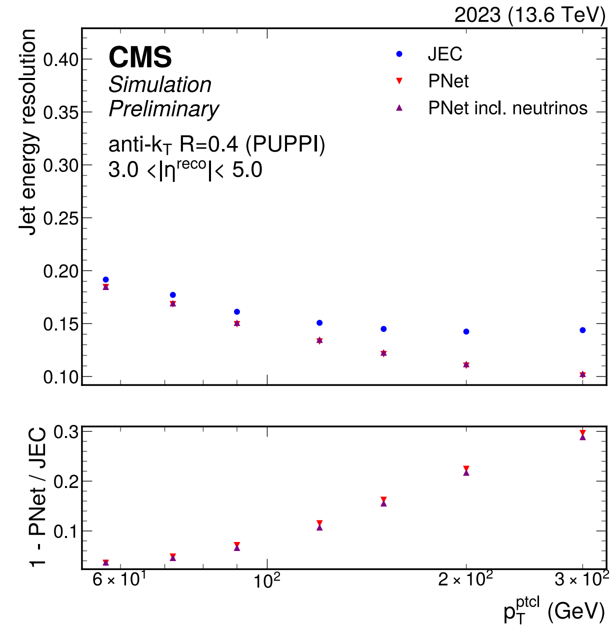
$0.0 < |\eta| < 1.3$



$2.4 < |\eta| < 2.7$



$3.0 < |\eta| < 5.0$



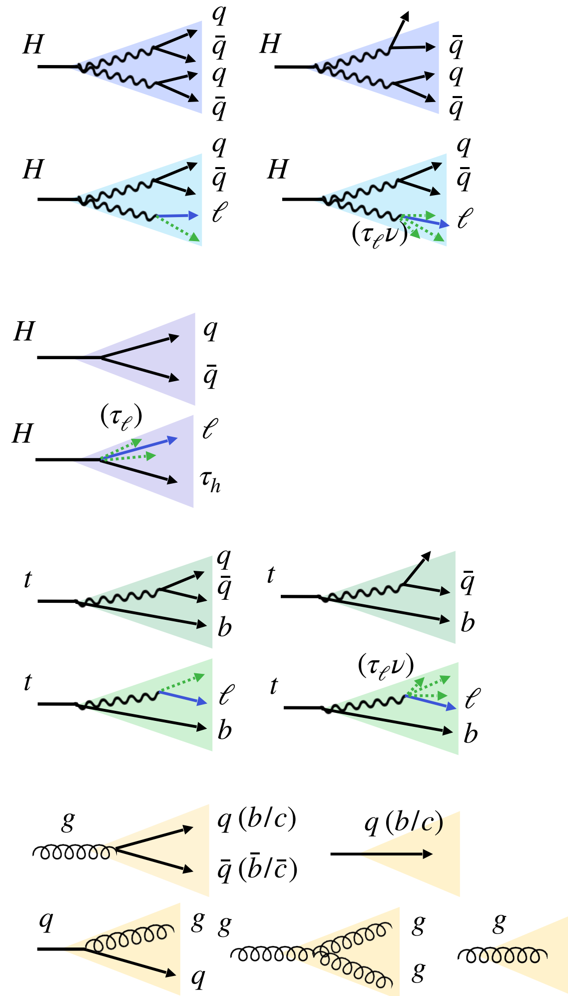
Clear improvement in JER

across the jet p_T range, even for forward jets.

AK8 Global Particle Transformer (GloParT)

CMS-PAS-HIG-23-012

Process	Final state/ prongness	heavy flavour	# of classes
H→VV (full-hadronic)	qqqq	0c/1c/2c	3
	qqq		3
H→WW (semi-leptonic)	$e\nu qq$	0c/1c	2
	$\mu\nu qq$		2
	$\tau_e\nu qq$		2
	$\tau_\mu\nu qq$		2
	$\tau_h\nu qq$		2
H→qq		bb	1
		cc	1
		ss	1
		qq (q=u/d)	1
H→ττ	$\tau_e\tau_h$		1
	$\tau_\mu\tau_h$		1
	$\tau_h\tau_h$		1
t→bW (hadronic)	bqq	1b + 0c/1c	2
	bq		2
t→bW (leptonic)	$be\nu$	1b	1
	$b\mu\nu$		1
	$b\tau_e\nu$		1
	$b\tau_\mu\nu$		1
	$b\tau_h\nu$		1
QCD		b	1
		bb	1
		c	1
		cc	1
		others (light)	1



- Cover as many decay modes as possible
- Include also semi-leptonic decays.

“Real-time” analysis at the trigger level

HLT Scouting

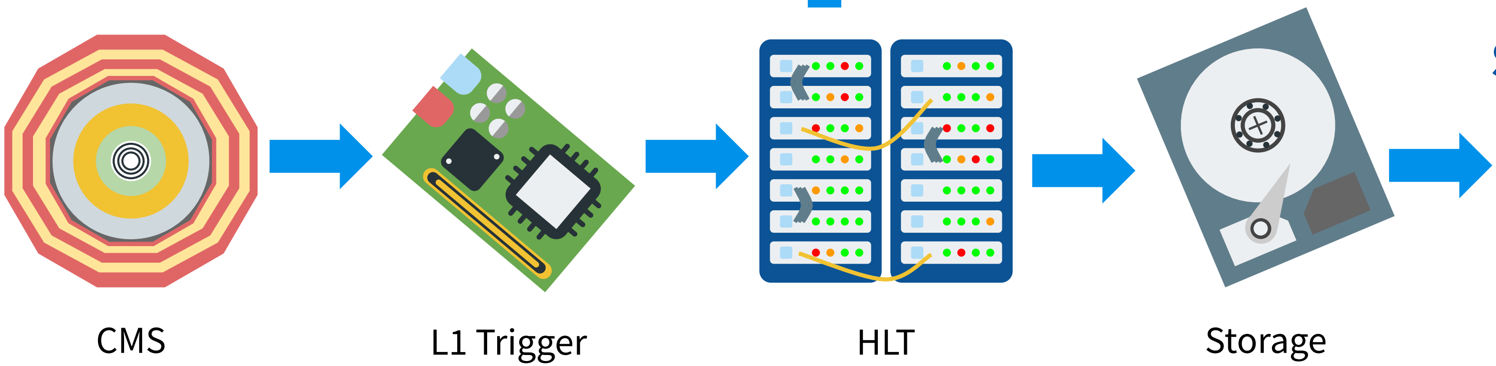
Comprehensive review: arXiv:2403.16134

The real bottleneck is data recording bandwidth (MB/sec), not event rate (event/sec)

Scouting Stream

Patin Inkaew

- reduced data format
- event size reduced by 100x
- event rate increased by 30x
- based on reconstruction at HLT (no offline reconstruction)



Standard Stream

- ~ 2.5 kHz
- ~ 1.1 MB/event
- full event
- reconstructed at Tier0 after 48 hours

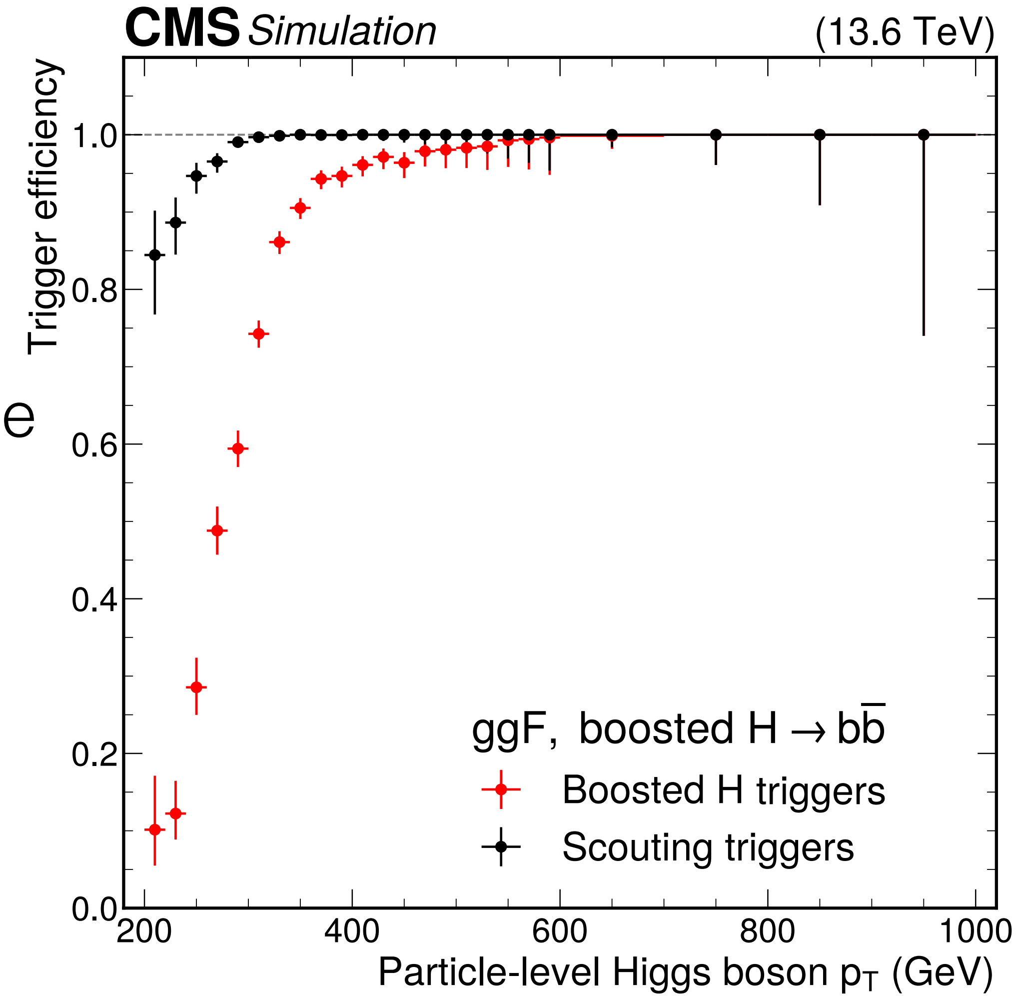
SMARTHEP
REAL-TIME ANALYSIS FOR SCIENCE AND INDUSTRY

- HLT Scouting strategy successful since 2011.
- Major updates in Run-3.

HLT Scouting

arXiv:2403.16134

- Access phase space not recorded with standard trigger strategy.
- Example: Search & measure boosted H->bb.
- Cover the entire Higgs pT spectrum.

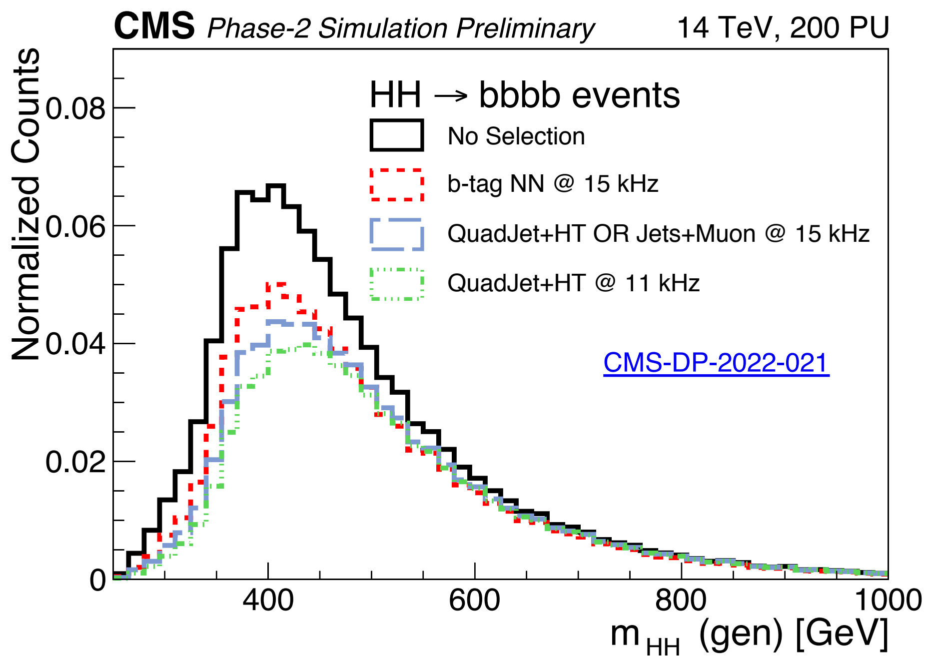


Jet Tagging at Level-1 Trigger at HL-LHC

- Phase-II major upgrades: High-Granularity Calorimeter & Tracking at Level-1 trigger.
  - ➢ PF at Level-1?
  - ➢ Tag jets at Level-1?

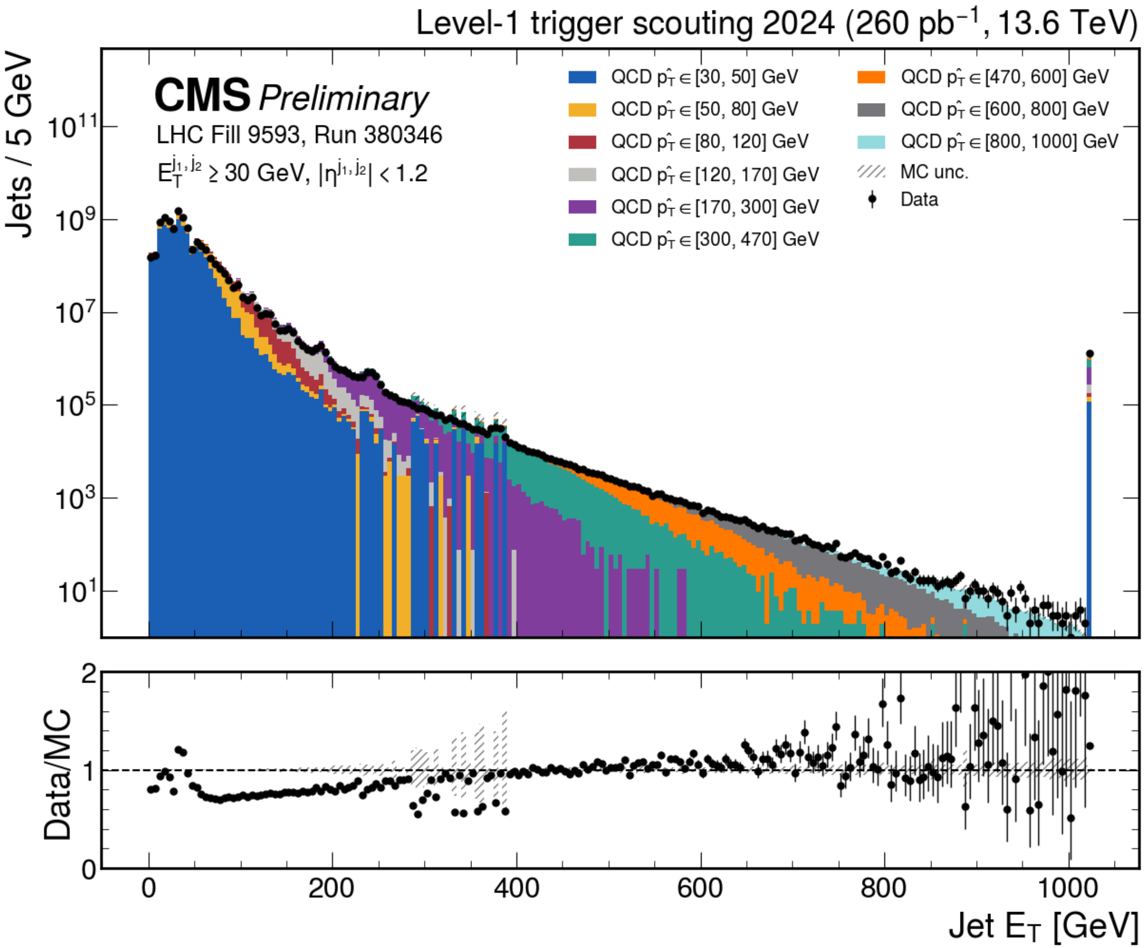
- Demonstrated it can be done.
  - ➢ Simplified PF(+Puppi).
  - ➢ NN for small-R jet tagging.

- HIP-CMS effort to focus on “large-R” jets tagging at Level-1.
  - ➢ Level-1 Scouting?



Level-1 Scouting: The future is now!

[CMS-DP-2024-056]



Jets from Level-1 Scouting in 2024

Summary

- Jet performance at CMS for Run-3: Better than ever!

- Measured JES & JER for early Run-3 datasets.
  - HIP-CMS spearheading effort for 2024.

- Commissioned Transformer-based algorithms to tag jets & regress their p_T.

- HLT scouting program extends & complements physics reach with offline analysis.
  - More to come with Run-3 datasets.
  - Level-1 scouting for HL-LHC

EXTRA SLIDES

PUPPI

DP-2021-001

PUPPI calculates an α_i value for each particle in the event

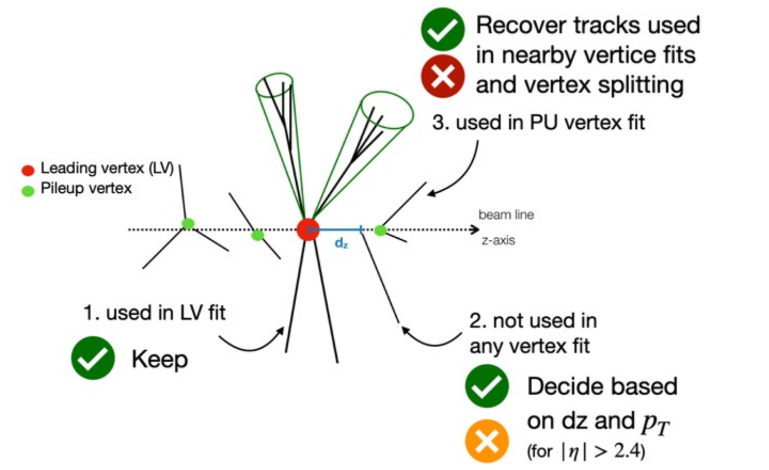
$$\alpha_i = \log \sum_{j \neq i, \Delta R_{ij} < R_0} \left(\frac{p_{T,j}}{\Delta R_{ij}} \right)^2$$

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:

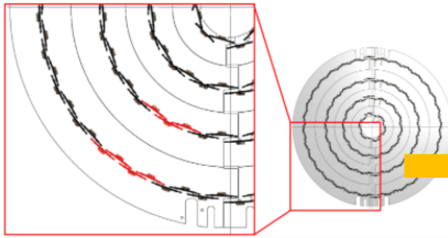
$$w_i = F_{\chi^2,\text{NDF}=1(\text{signed } \chi_i^2)}$$

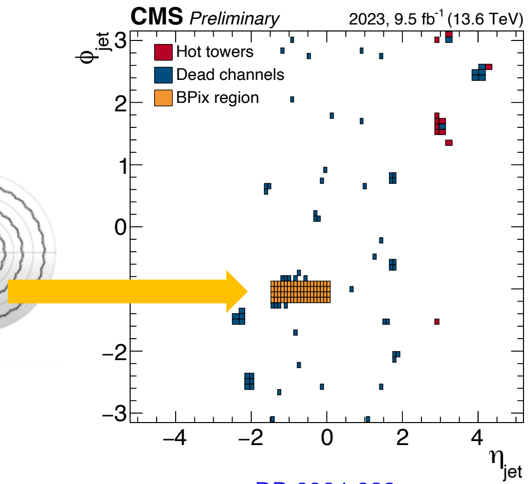


CHS keeps LV (✅) and unassociated (⊗) particles, PUPPI keeps LV (✅) but assigns a weight to unassociated particles (⊗).

ϕ-dependent JES Corrections

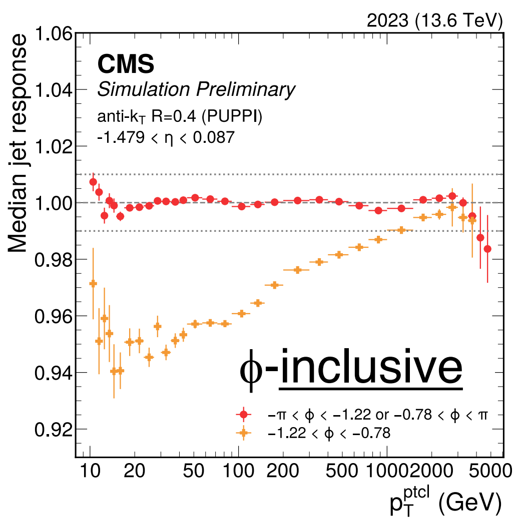
- Partial failure of a portion of the Barrel Pixel sub-detector (BPix) occurred during 2023 data-taking.
  - ➢ Track reconstruction efficiency loss, affects jet energy scale.

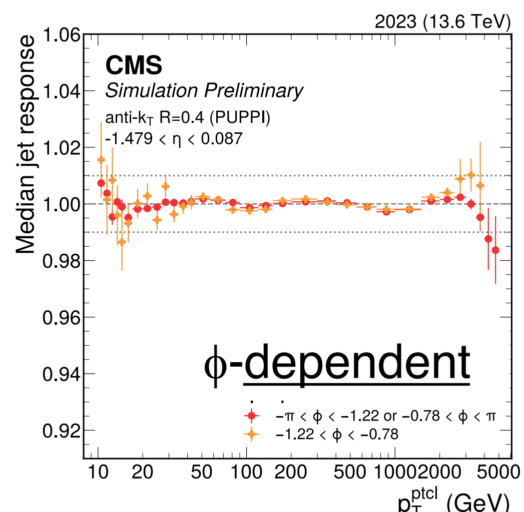




DP-2024-039

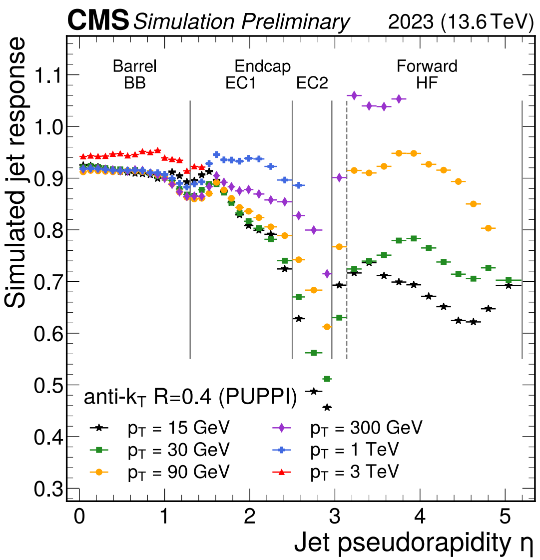
- Introduce ϕ-dependent JES corrections to minimize impact of BPix inefficiency.



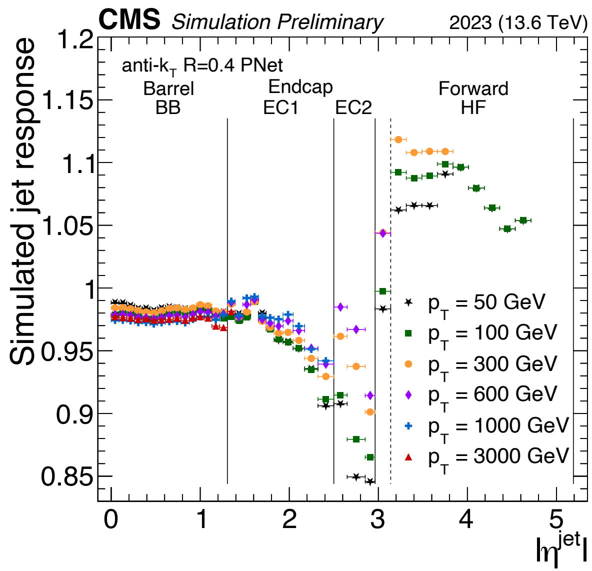


Jet p_T Response in Simulation (Raw vs Regressed)

Jet pT DP-2024-039



Regressed Jet p_T DP-2024-064



Regressed Jet p_T with Neutrinos