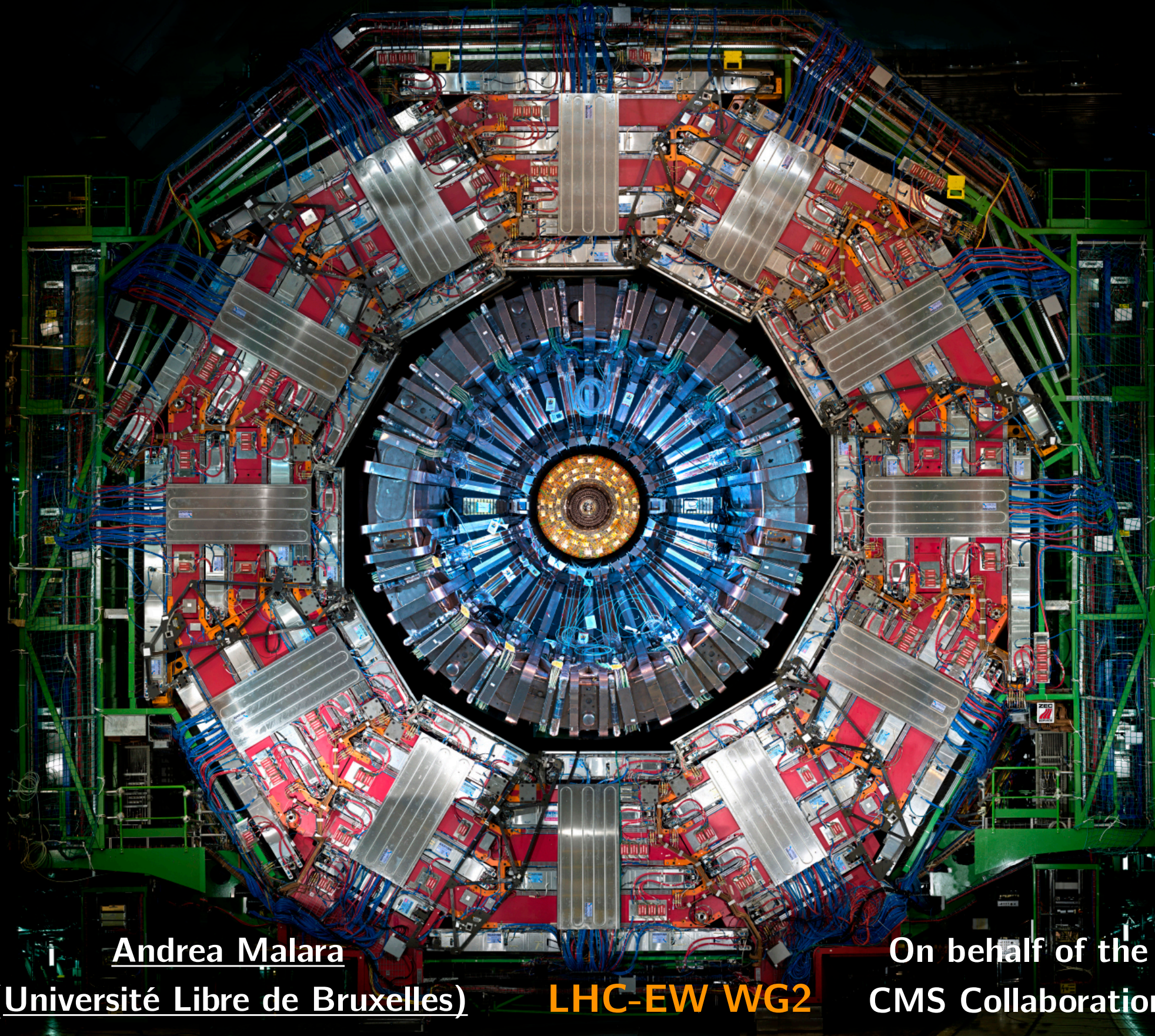


Reconstructing and calibrating jets



ULB

Andrea Malara
(Université Libre de Bruxelles)

LHC-EW WG2

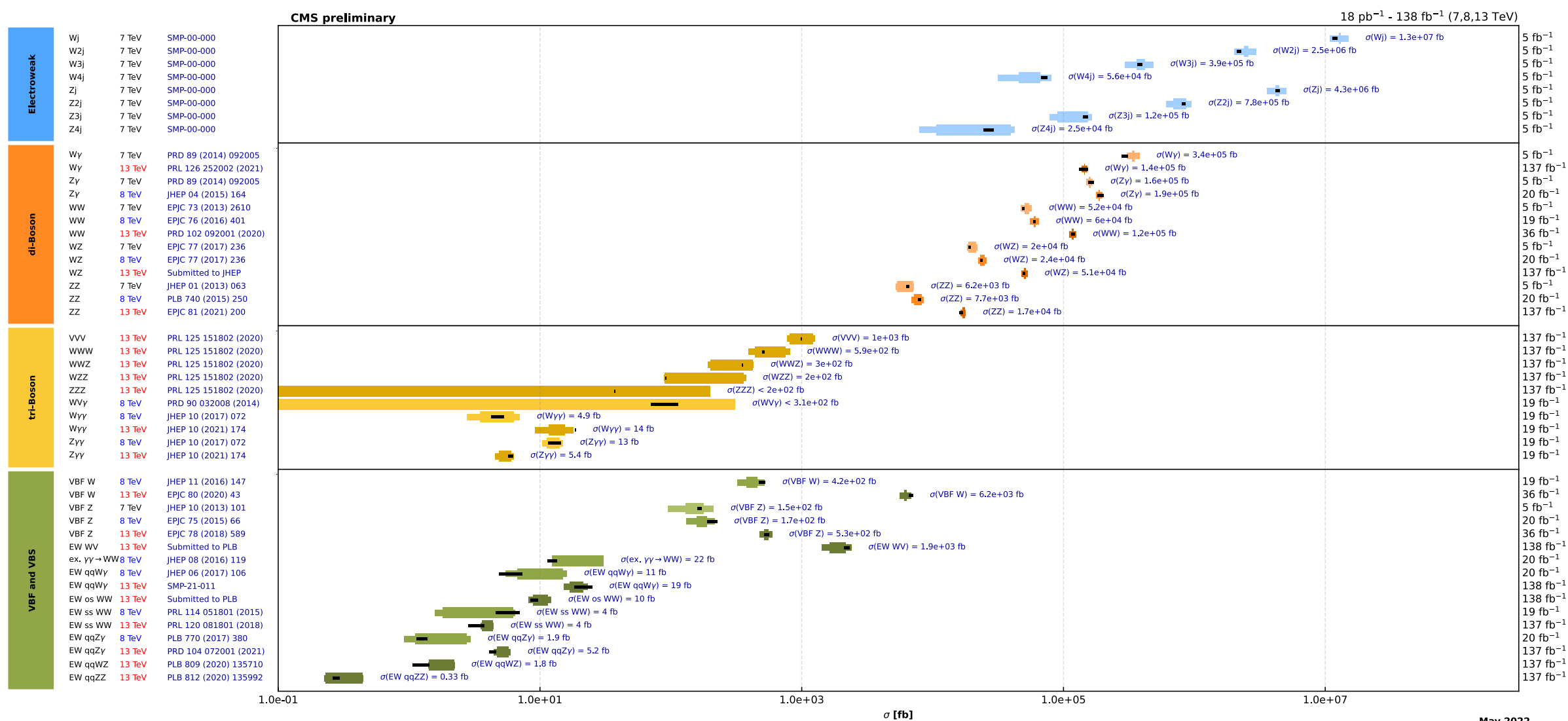
On behalf of the
CMS Collaboration



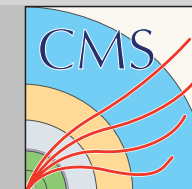
07 August 2024

- ▶ Test the self-consistency of the Standard Model
- ▶ Huge variety of processes analysed
- ▶ Approximatively 7 orders of magnitudes of cross-sections measured
- ▶ Majority already systematics-dominated

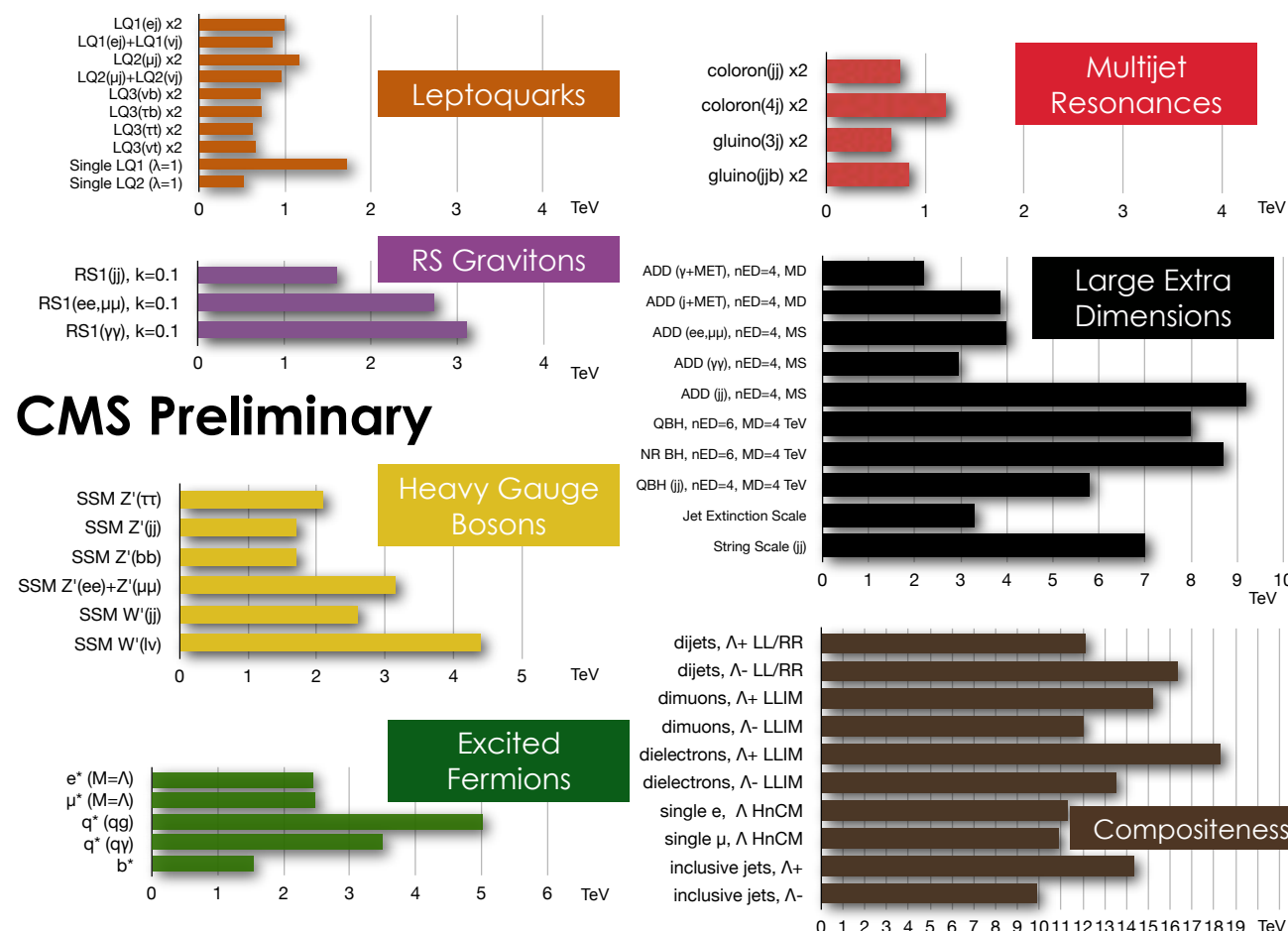
Overview of CMS cross section results



Physics programmes



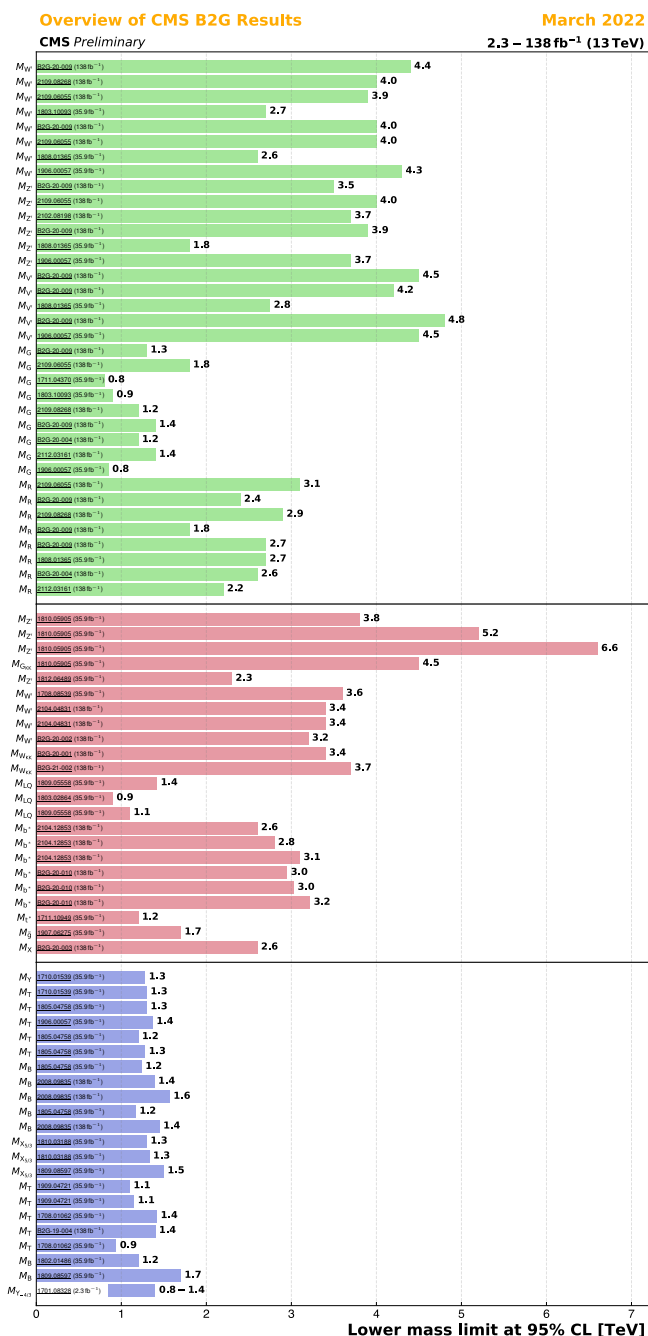
- ▶ Test the self-consistency of the Standard Model
- ▶ TeV energy frontier
- ▶ Enormous range of energy investigated (up to 10TeV)
- ▶ Multitude of different models studied



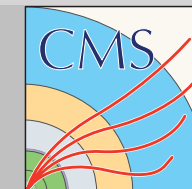
CMS Exotica Physics Group Summary – LHCP, 2016

CMS results

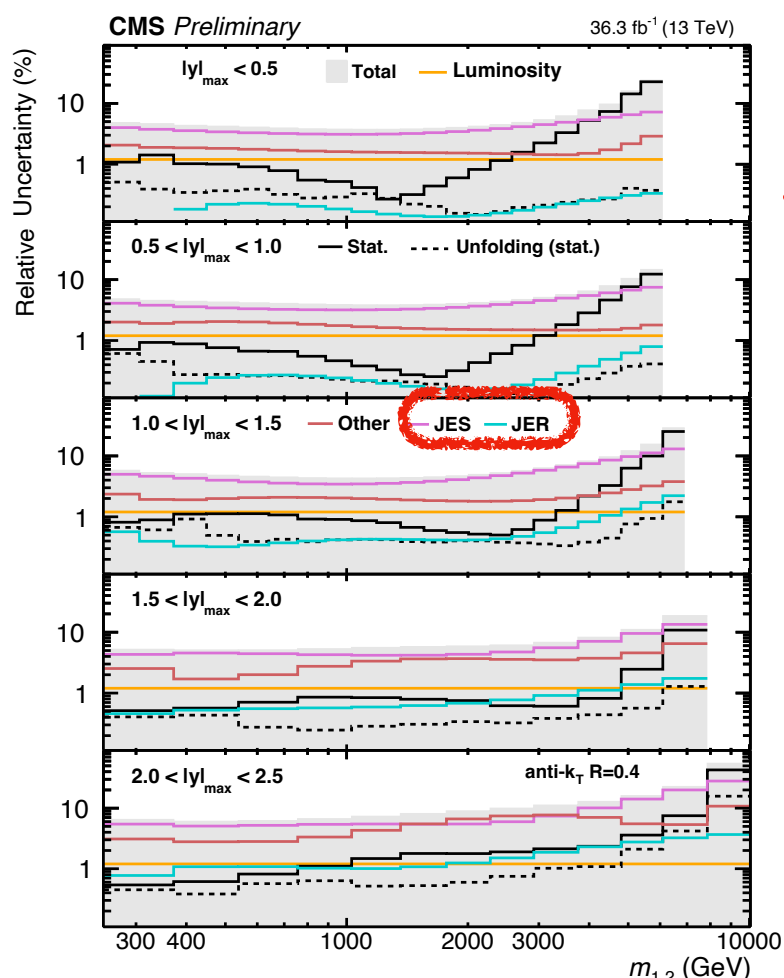
- W→WZ (qq̄q̄, HVT model B)
- W→WZ (vvq̄, HVT model B)
- W→WZ (lvq̄, HVT model B)
- W→WZ (ffq̄, HVT model B)
- W→WH (qq̄b̄, HVT model B)
- W→WH (lvb̄, HVT model B)
- W→WH (q̄q̄t̄, HVT model B)
- W (all final states, HVT model B)
- Z→WW (qq̄q̄, HVT model B)
- Z→WW (lvq̄, HVT model B)
- Z→ZH (ll, vv)bb̄, HVT model B)
- Z→ZH (qq̄b̄, HVT model B)
- Z→ZH (q̄q̄t̄, HVT model B)
- Z (all final states, HVT model B)
- V→VV (qq̄q̄, HVT model B)
- V→VH (qq̄b̄, HVT model B)
- V→VH (q̄q̄t̄, HVT model B)
- V→VV+VH (qq̄q̄, q̄q̄b̄, HVT model B)
- V (all final states, HVT model B)
- Bulk G→WW (qq̄q̄)
- Bulk G→WW (lvq̄)
- Bulk G→ZZ (ffvv)
- Bulk G→ZZ (ffq̄)
- Bulk G→ZZ (vvq̄)
- Bulk G→VV (qq̄q̄)
- Bulk G→HH (bb̄bb̄)
- Bulk G→HH (lvq̄q̄b̄, lvlvbb̄)
- Bulk G (all final states)
- Radion R→WW (lvq̄, λ=3 TeV)
- Radion R→WW (qq̄q̄, λ=3 TeV)
- Radion R→ZZ (vvq̄, λ=3 TeV)
- Radion R→ZZ (qq̄q̄, λ=3 TeV)
- Radion R→VV (qq̄q̄, λ=3 TeV)
- Radion R→HH (q̄q̄t̄, λ=3 TeV)
- Radion R→HH (bb̄bb̄, λ=3 TeV)
- Radion R→HH (lvq̄q̄b̄, lvlvbb̄, λ=3 TeV)
- Z→t̄t̄ (Γ/Mz=1%)
- Z→t̄t̄ (Γ/Mz=10%)
- Z→t̄t̄ (Γ/Mz=30%)
- G_K→t̄t̄ (Kaluza-Klein)
- Z→t̄t̄→t̄ZL, t̄Ht̄
- W→tb (l, RH)
- W→tb (0l, RH)
- W→tb (0l, LH)
- W→t̄b̄t̄ (M_W = 2/3M_W)
- W_K→RW→WWW (l)
- W_K→RW→WWW (0l + l)
- LQ₁→t̄tt̄
- LQ₁→t̄tt̄t̄
- LQ₁→b̄b̄bb̄
- b⁺→t̄W (0l, LH)
- b⁺→t̄W (0l, RH)
- b⁺→t̄W (0l, LH+RH)
- b⁺→t̄W (0l + 1l, LH)
- b⁺→t̄W (0l + 1l, RH)
- b⁺→t̄W (0l + 1l, LH+RH)
- t⁺→t̄g
- Stealth q̄→t̄t̄q̄ (γ + 2jets, M₂₁ = 0.2TeV)
- X→aa (bb̄bb̄, M_s = 0.1TeV, M_s/M_W = 8)
- YY→b̄b̄W
- TT→b̄b̄W
- TT→t̄Z
- TT→t̄HH
- TT (Singlet)
- TT (Doublet)
- BB→t̄W
- BB→b̄Z
- BB→b̄BH
- BB (Singlet)
- BB (Doublet)
- X₂₁₂X₂₁₂→t̄WW (Singlet)
- X₂₁₂X₂₁₂→t̄WW (Doublet)
- X₂₁₂→W (Singlet, Γ/M_s=30%)
- T→H (Singlet, Γ/M_s=10%)
- T→H (Singlet, Γ/M_s=30%)
- T→t̄Z (Singlet, Γ/M_s=10%)
- T→t̄Z (Singlet, Γ/M_s=30%)
- T→t̄Z (Doublet, Γ/M_s=10%)
- B→bH (Doublet, Γ/M_B=30%)
- B→t̄W (Doublet, Γ/M_B=30%)
- Y→q̄→b̄W



Era of precision physics

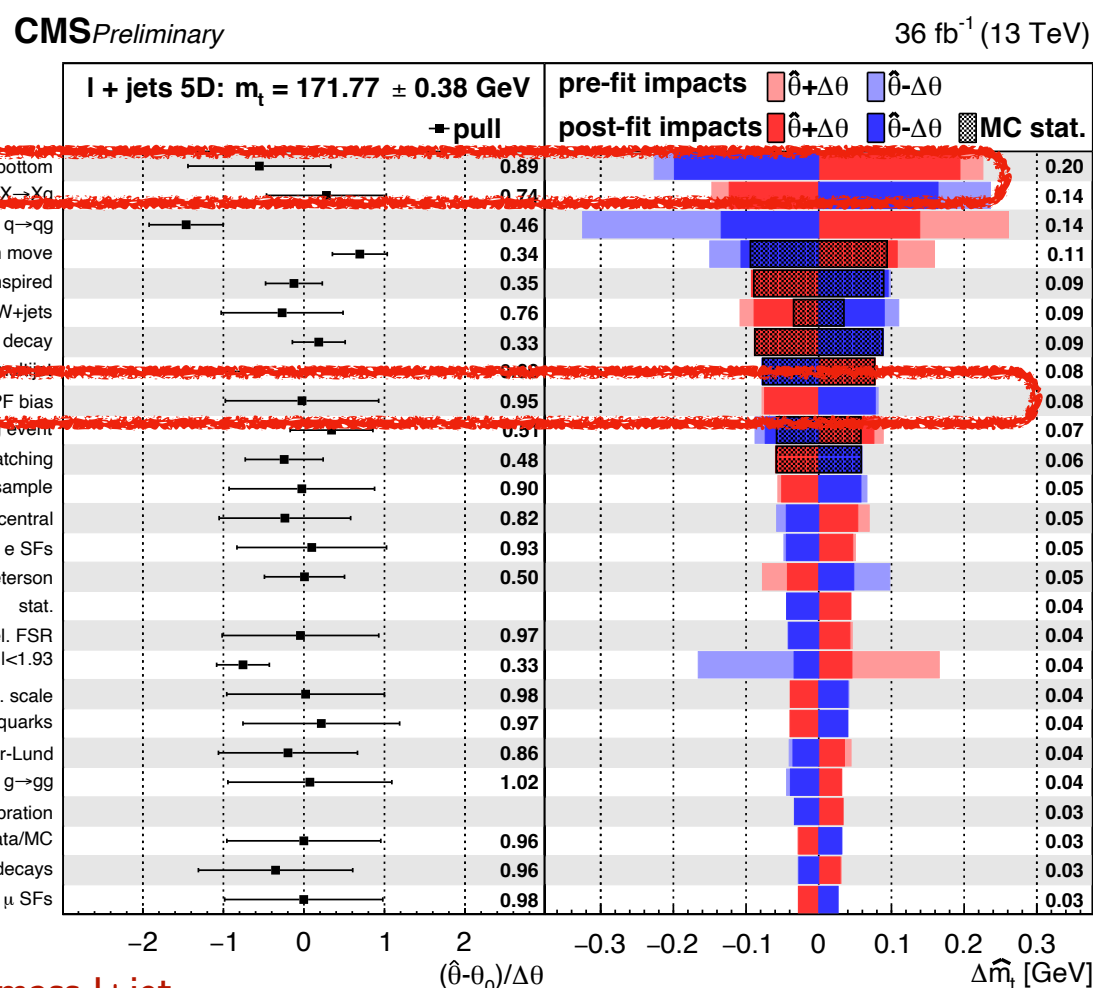


- ▶ Jet-related uncertainties are becoming a limiting factor in many analyses
 - ▶ Jets are abundant at the LHC -> hadronic decays, associated prod. with jets...
 - ▶ Jet energy scale -> impact on: top, Higgs, multijet analyses



Dijet cross section

Andrea Malara



Top mass I+jet

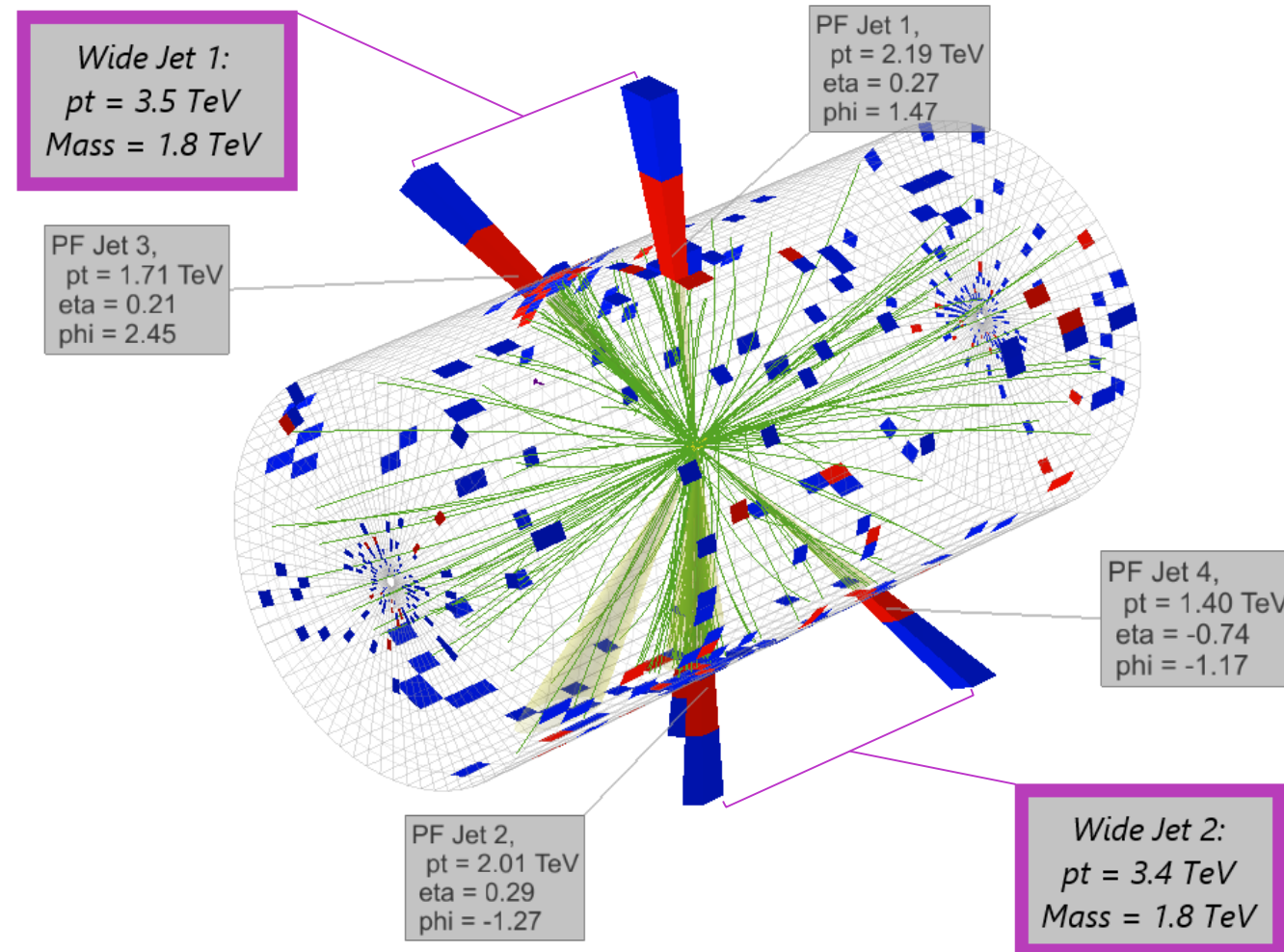
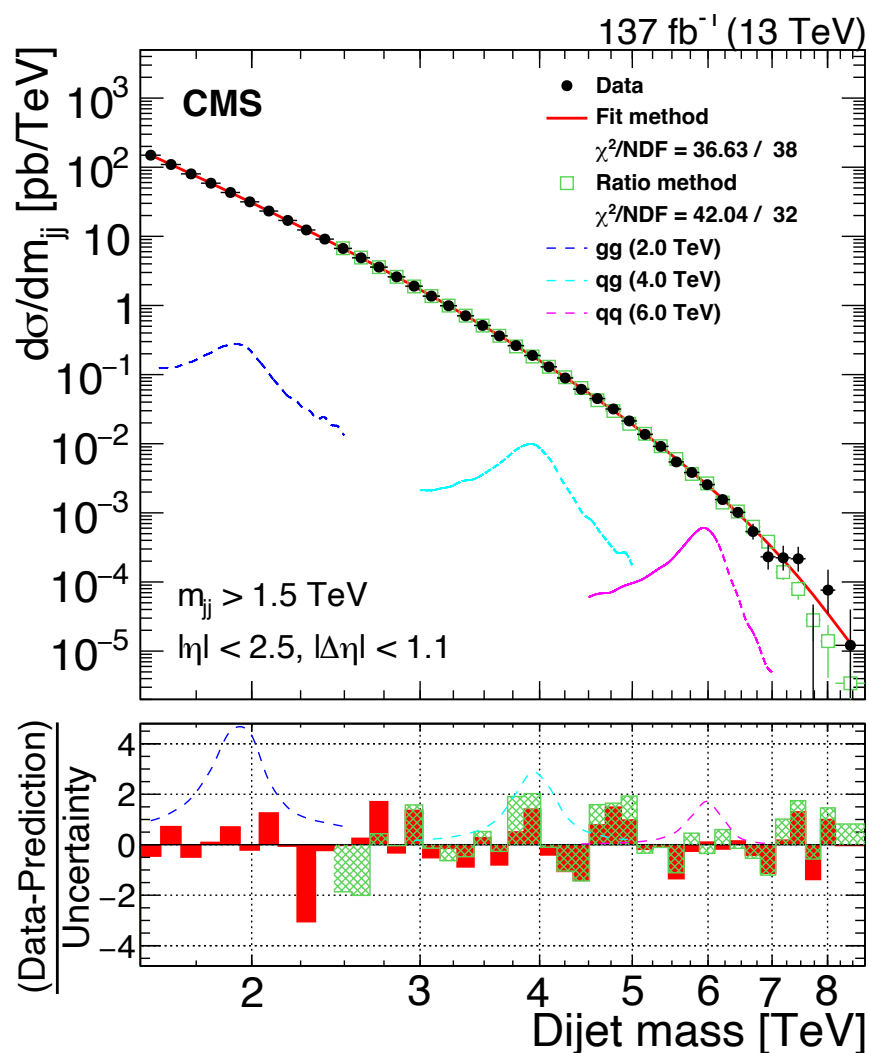
LHC-EW WG2

ttbar cross section dilepton

Source	Uncertainty [GeV]
Trigger	0.02
Lepton ident./isolation	0.02
Muon momentum scale	0.03
Electron momentum scale	0.10
Jet energy scale	0.57
Jet energy resolution	0.09
b tagging	0.12
Pileup	0.09
t \bar{t} ME scale	0.18
tW ME scale	0.02
DY ME scale	0.06
NLO generator	0.14
PDF	0.05
$\sigma_{t\bar{t}}$	0.09
Top quark p_T	0.04
ME/PS matching	0.16
UE tune	0.03
t \bar{t} ISR scale	0.16
tW ISR scale	0.02
t \bar{t} FSR scale	0.07
tW FSR scale	0.02
b quark fragmentation	0.11
b hadron BF	0.07
Colour reconnection	0.17
DY background	0.24
tW background	0.13
Diboson background	0.02
W+jets background	0.04
t \bar{t} background	0.02
Statistical	0.14
MC statistical	0.36
Total m_t^{MC} uncertainty	+0.68 -0.73

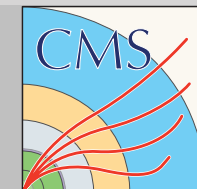
07 August 2024

- ▶ Jet-related uncertainties are becoming a limiting factor in many analyses
 - ▶ Jets are abundant at the LHC -> hadronic decays, associated prod. with jets...
 - ▶ Jet energy scale -> impact on: top, Higgs, multijet analyses
 - ▶ ... but also boosted searches -> merged decay products
 - ▶ Must be known very well for a wide range in energy and pseudorapidity



Dijet resonances

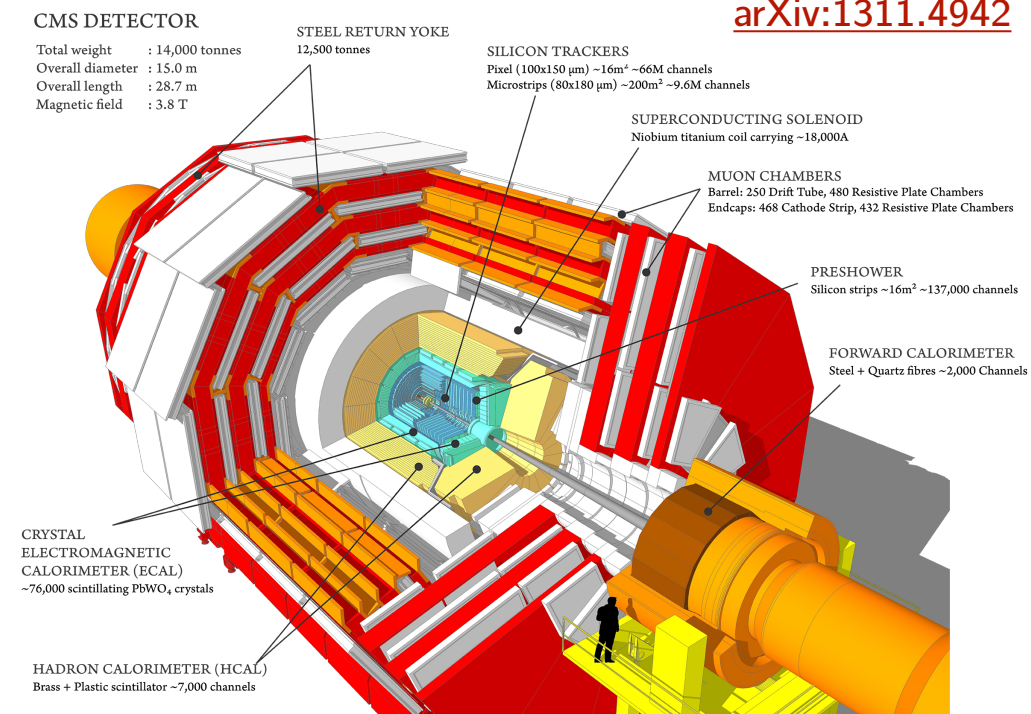
Experimental setup: CMS



[arXiv:1311.4942](https://arxiv.org/abs/1311.4942)

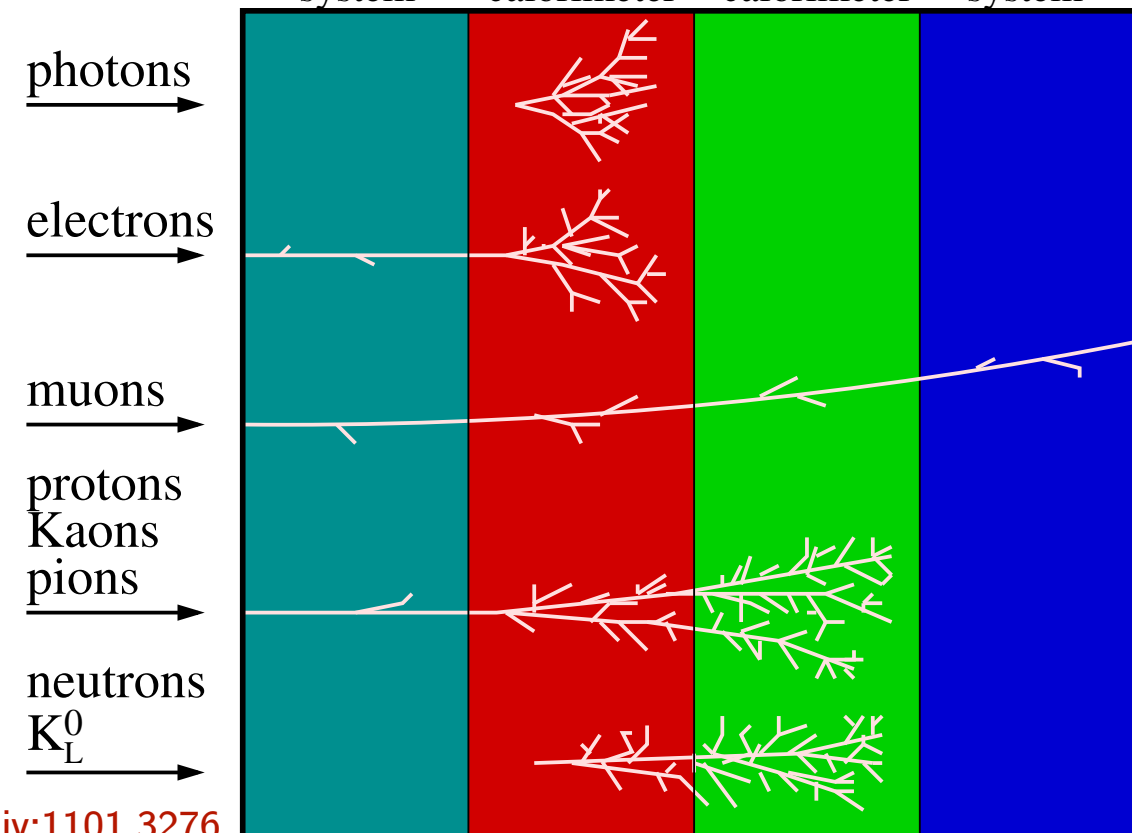
- ▶ Multi-purpose detector
- ▶ Layered structure
- ▶ Tracker
- ▶ Electromagnetic calorimeter
- ▶ Hadron calorimeter
- ▶ Solenoid
- ▶ Muon chambers

- ▶ Particle reconstruction
 - ▶ Detector signals -> physics objects
 - ▶ Based on ParticleFlow algorithm
- ▶ Operational since 2010, this talk focuses on:
 - ▶ Run2 data (2016-2018), $\sqrt{s} = 13$ TeV
 - ▶ Run3 data (2022-ongoing), $\sqrt{s} = 13.6$ TeV [arXiv:1101.3276](https://arxiv.org/abs/1101.3276)

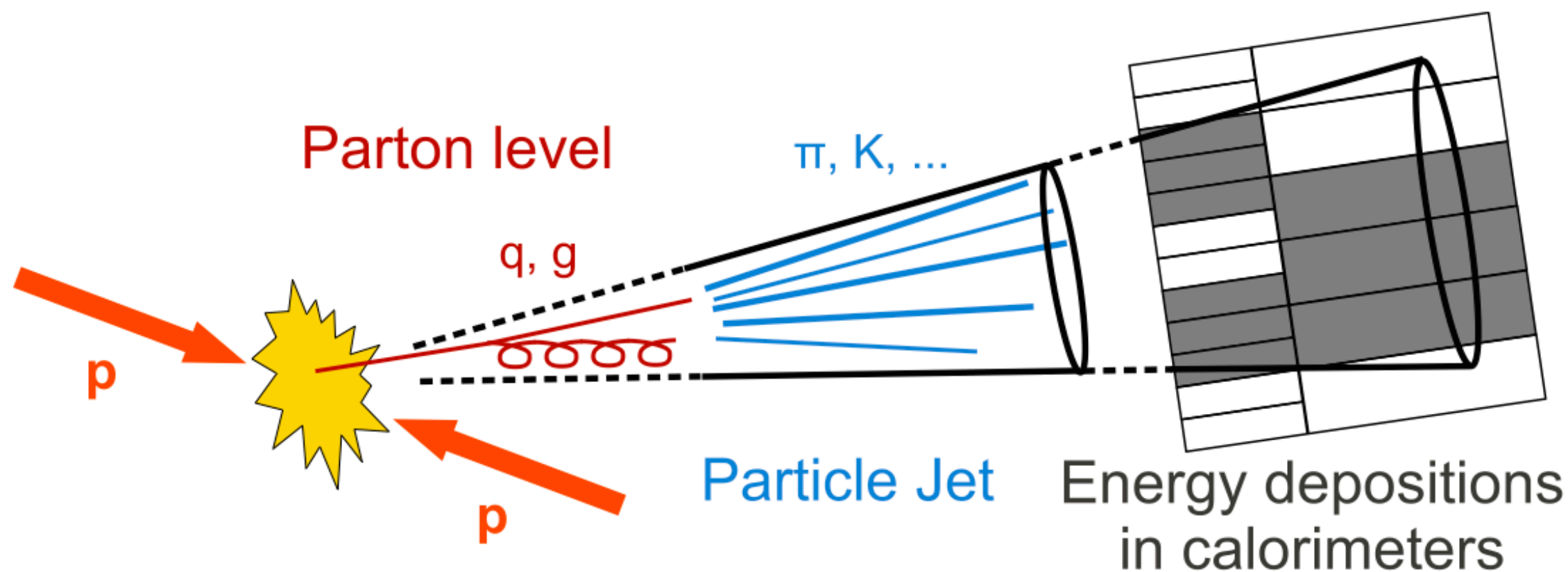


innermost layer \longrightarrow outermost layer

tracking system electromagnetic calorimeter hadronic calorimeter muon system



- ▶ As a consequence of the hadronisation of quarks and gluons produced in pp collisions, a collimated shower of hadrons (jet) is produced.



Local reconstruction:
Tracks, ECAL, HCAL



- ▶ Information from sub-detectors
- ▶ Similar method online but less detail

Local reconstruction:
Tracks, ECAL, HCAL

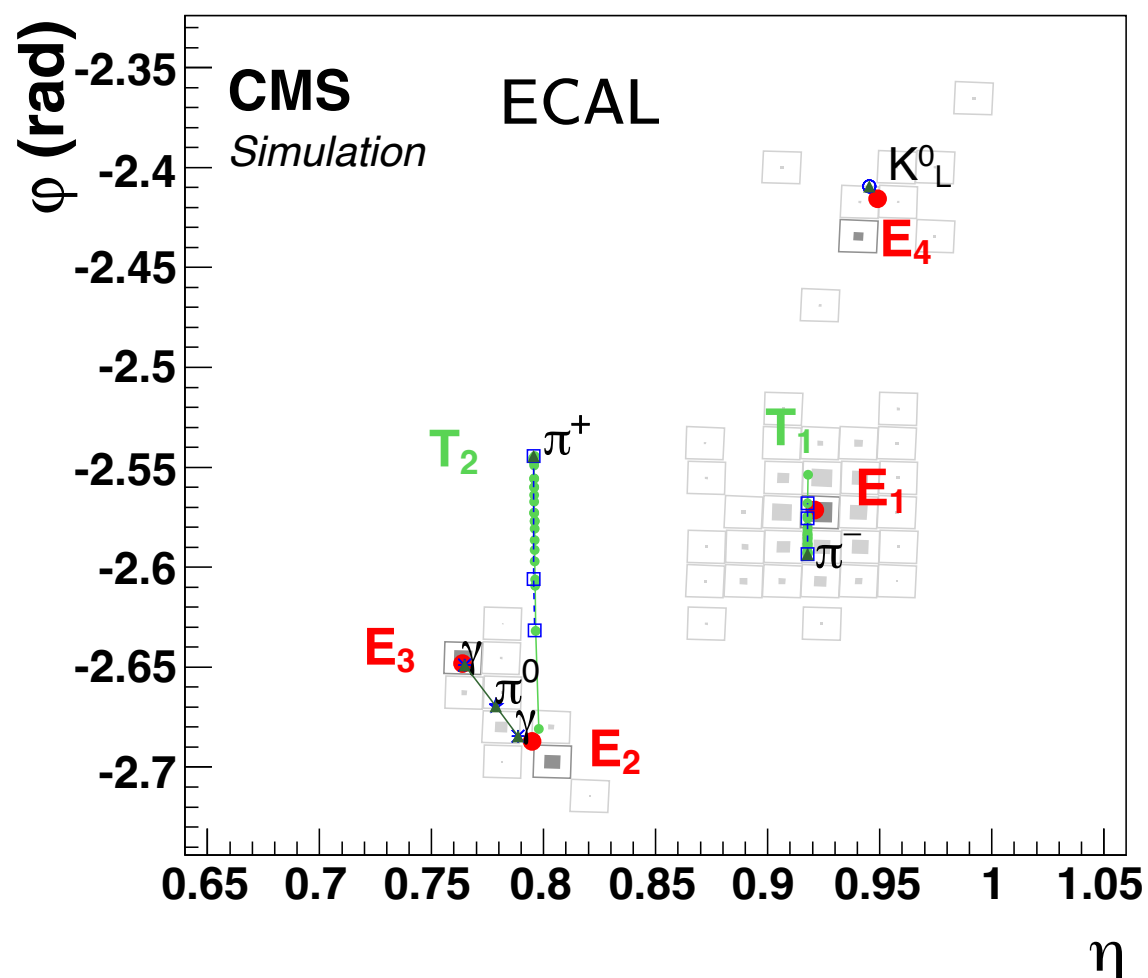


- ▶ Information from sub-detectors
- ▶ Similar method online but less detail

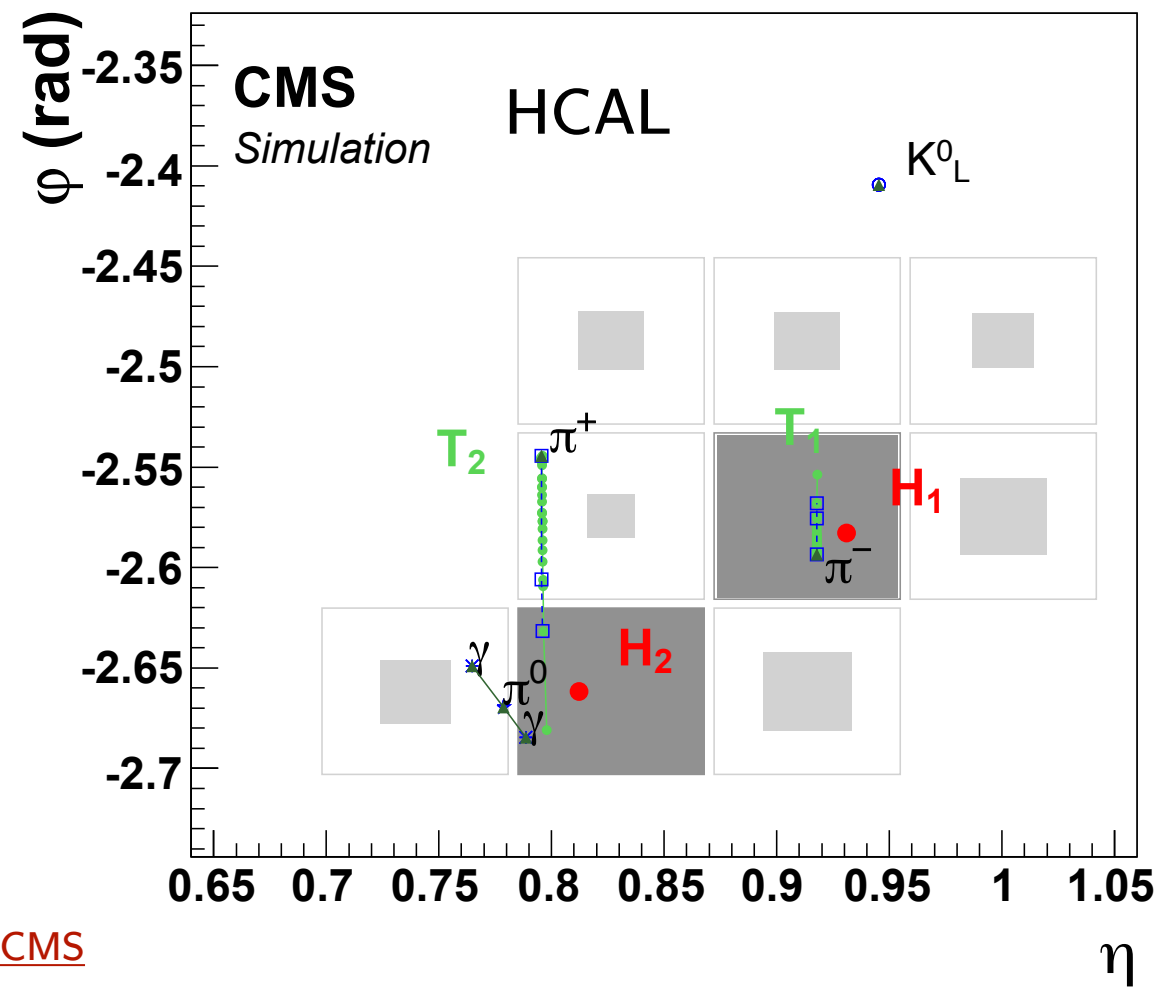
Particle flow (PF)



- ▶ Link tracks and calorimeter signals
- ▶ Particle identification



Particle Flow in CMS



Local reconstruction:
Tracks, ECAL, HCAL



- ▶ Information from sub-detectors
- ▶ Similar method online but less detail

Particle flow (PF)



- ▶ Link tracks and calorimeter signals
- ▶ Particle identification

Pileup mitigation



- ▶ Charge hadron subtraction (CHS)
- ▶ Pileup Per Particle Identification (Puppi)

Local reconstruction:
Tracks, ECAL, HCAL



- ▶ Information from sub-detectors
- ▶ Similar method online but less detail

Particle flow (PF)



- ▶ Link tracks and calorimeter signals
- ▶ Particle identification

Pileup mitigation



- ▶ Charge hadron subtraction (CHS)
- ▶ Pileup Per Particle Identification (Puppi)

Jet clustering



- ▶ Algorithms (AK, CA, HOTVR, Xcone)
- ▶ Cone radii (0.4, 0.8, 1.5, VR)

Local reconstruction:
Tracks, ECAL, HCAL



- ▶ Information from sub-detectors
- ▶ Similar method online but less detail

Particle flow (PF)



- ▶ Link tracks and calorimeter signals
- ▶ Particle identification

Pileup mitigation



- ▶ Charge hadron subtraction (CHS)
- ▶ Pileup Per Particle Identification (Puppi)

Jet clustering



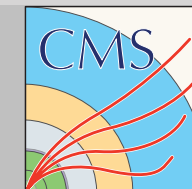
- ▶ Algorithms (AK, CA, HOTVR, Xcone)
- ▶ Cone radii (0.4, 0.8, 1.5, VR)

Jet calibration



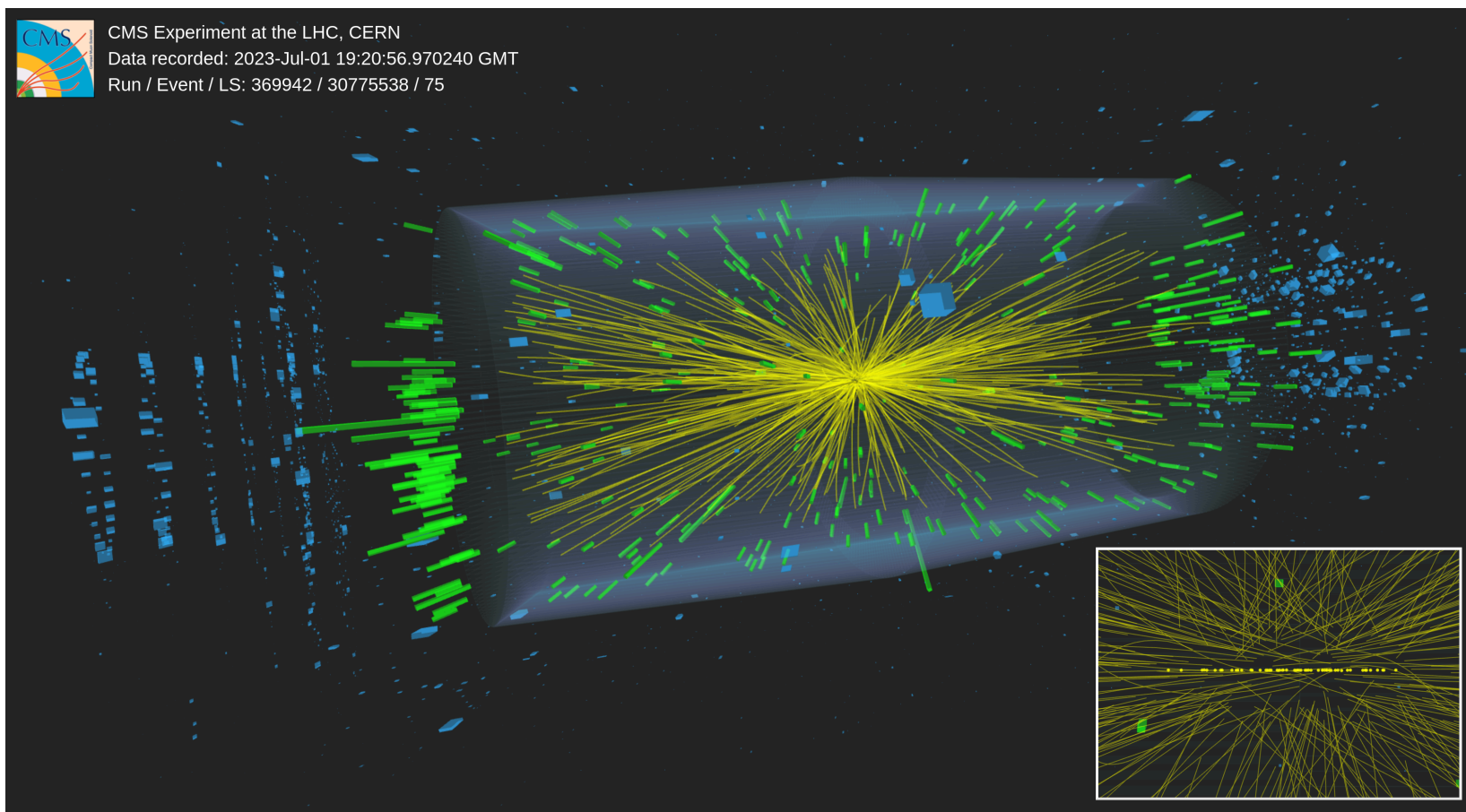
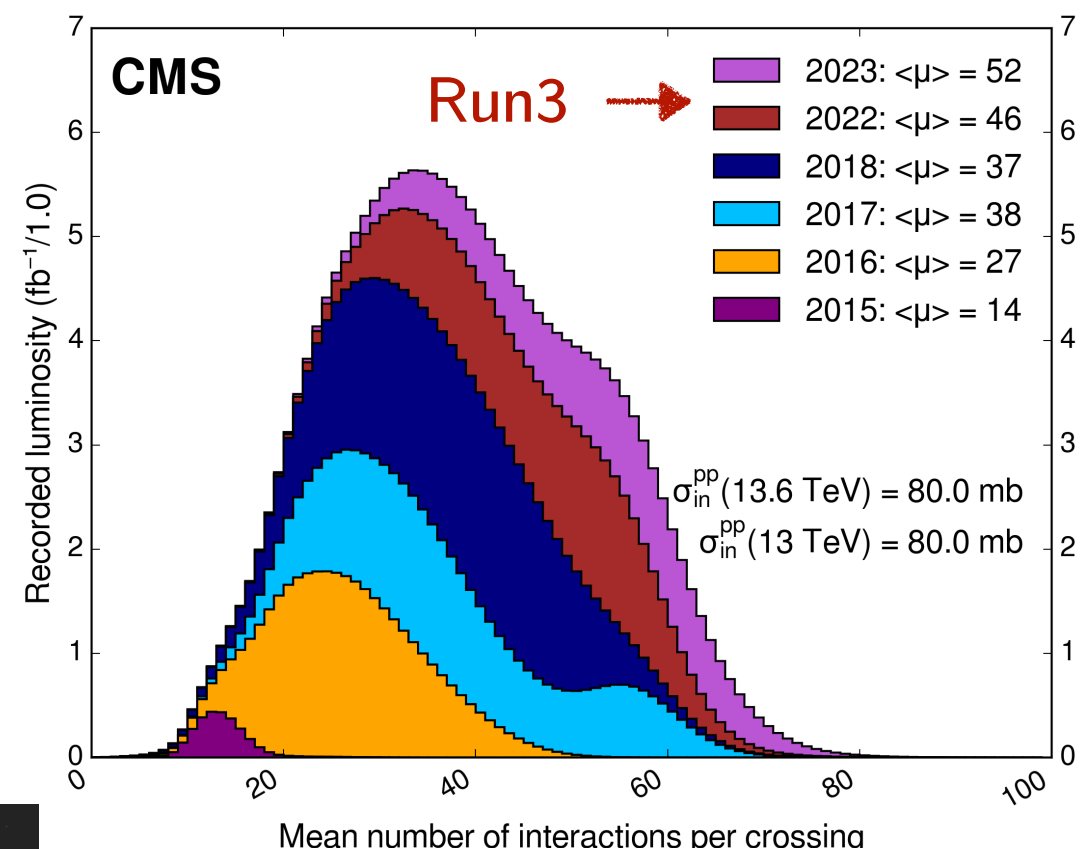
- ▶ Jet energy scale & resolution
- ▶ Jet mass scale & resolution

Proton-proton collision @ LHC

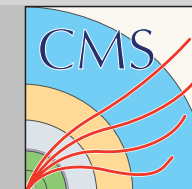


Pileup

- ▶ Challenging environment for LHC physics
- ▶ Additional interactions (pileup)
- ▶ Average of 30 interactions in Run 2
- ▶ Average of 50 interactions in Run 3 (so far...)

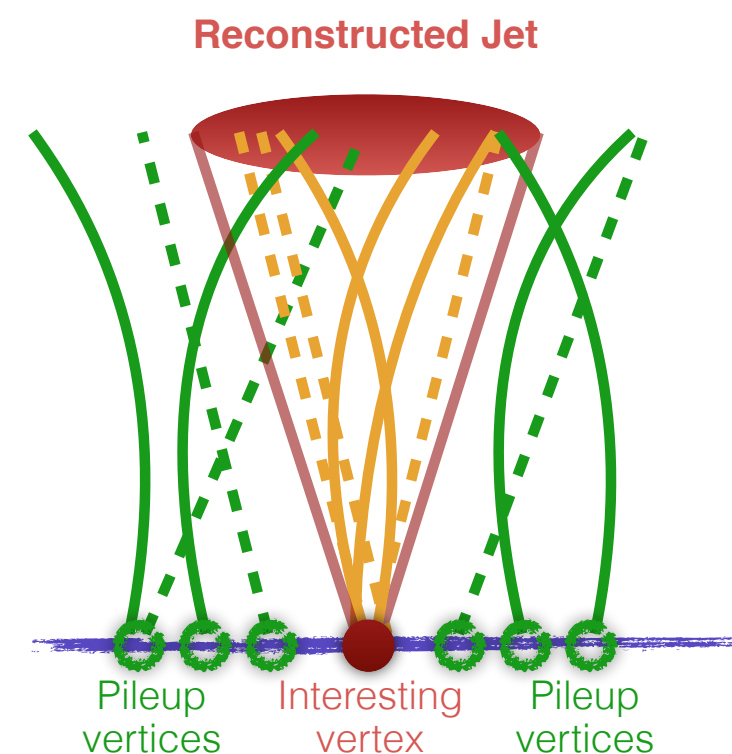
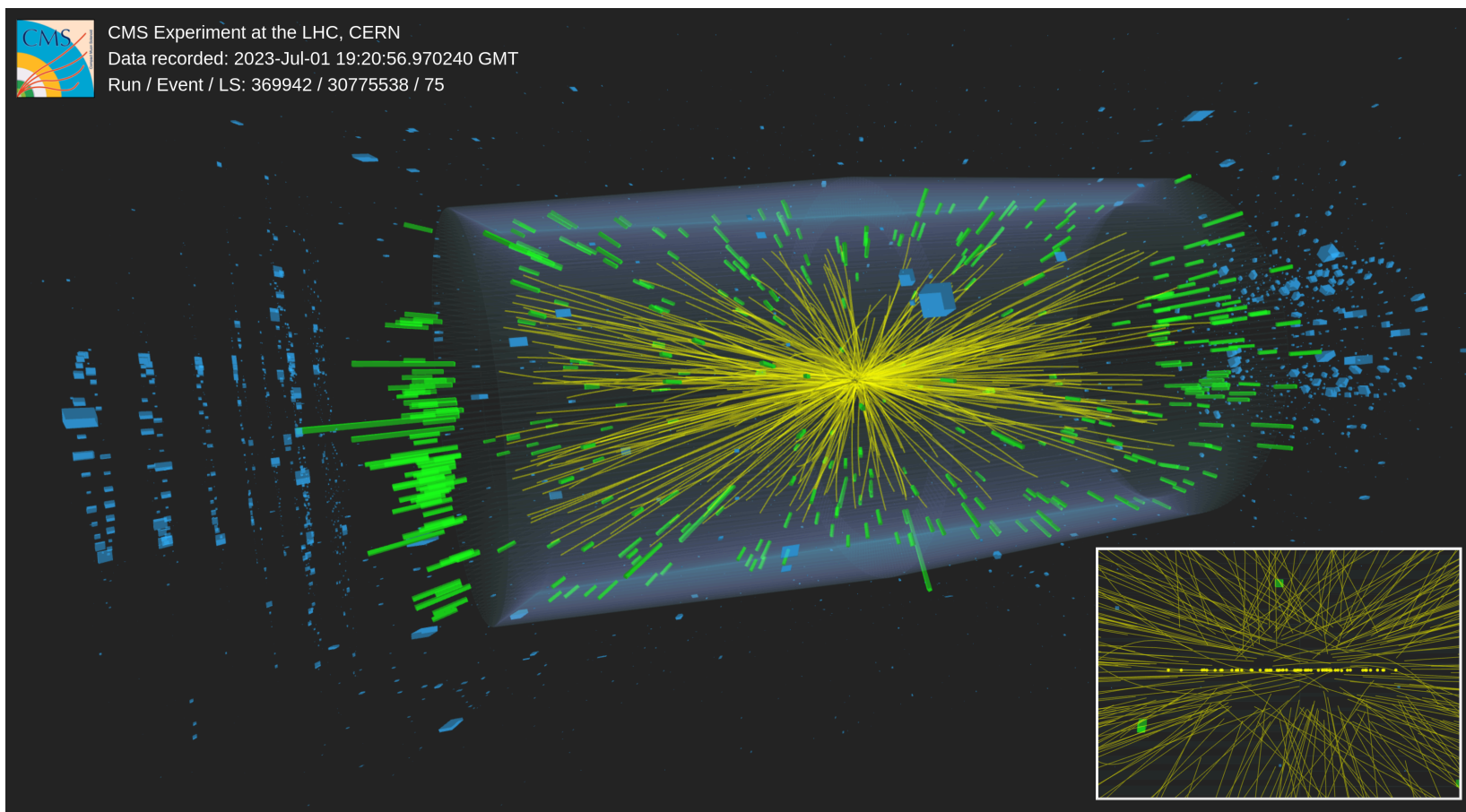
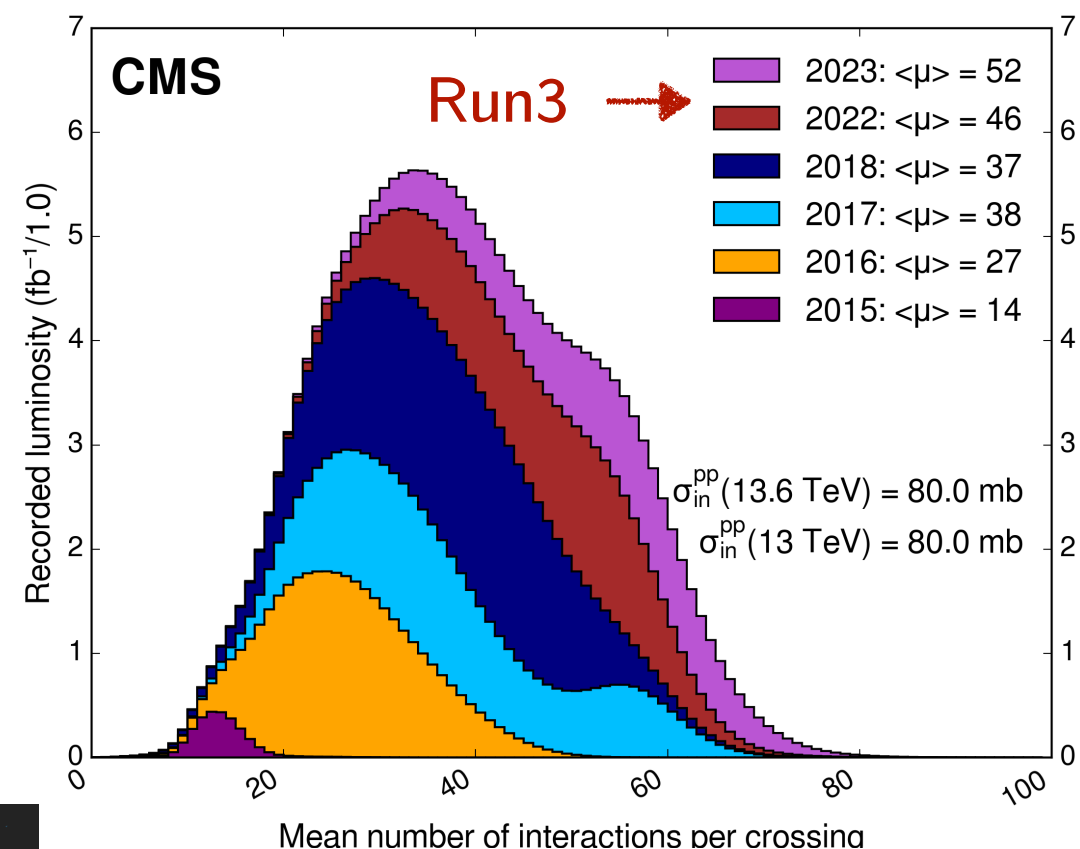


Proton-proton collision @ LHC

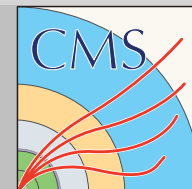


Pileup

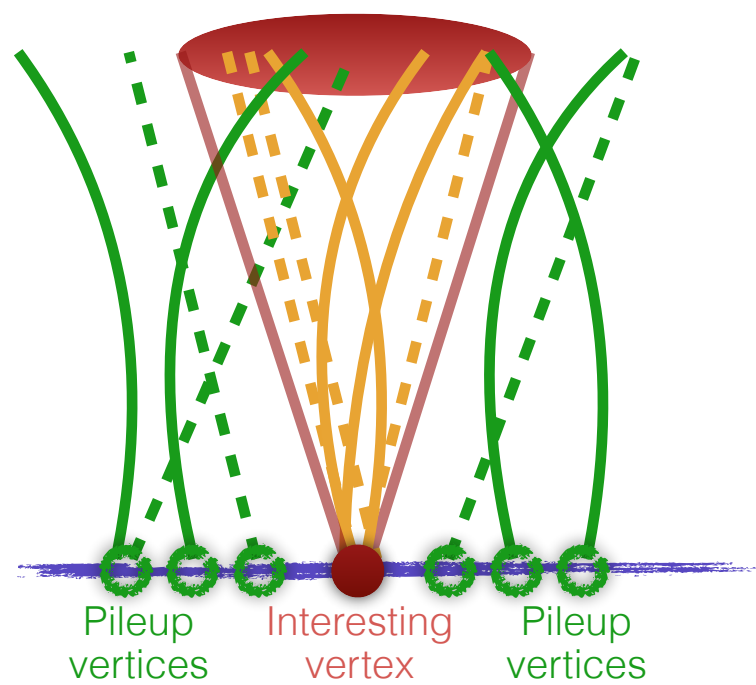
- ▶ Challenging environment for LHC physics
- ▶ Additional interactions (pileup)
- ▶ Average of 30 interactions in Run 2
- ▶ Average of 50 interactions in Run 3 (so far...)
- ▶ **Additional particles** deteriorate measurements
- ▶ Several approaches to cope with it



Pileup mitigation techniques

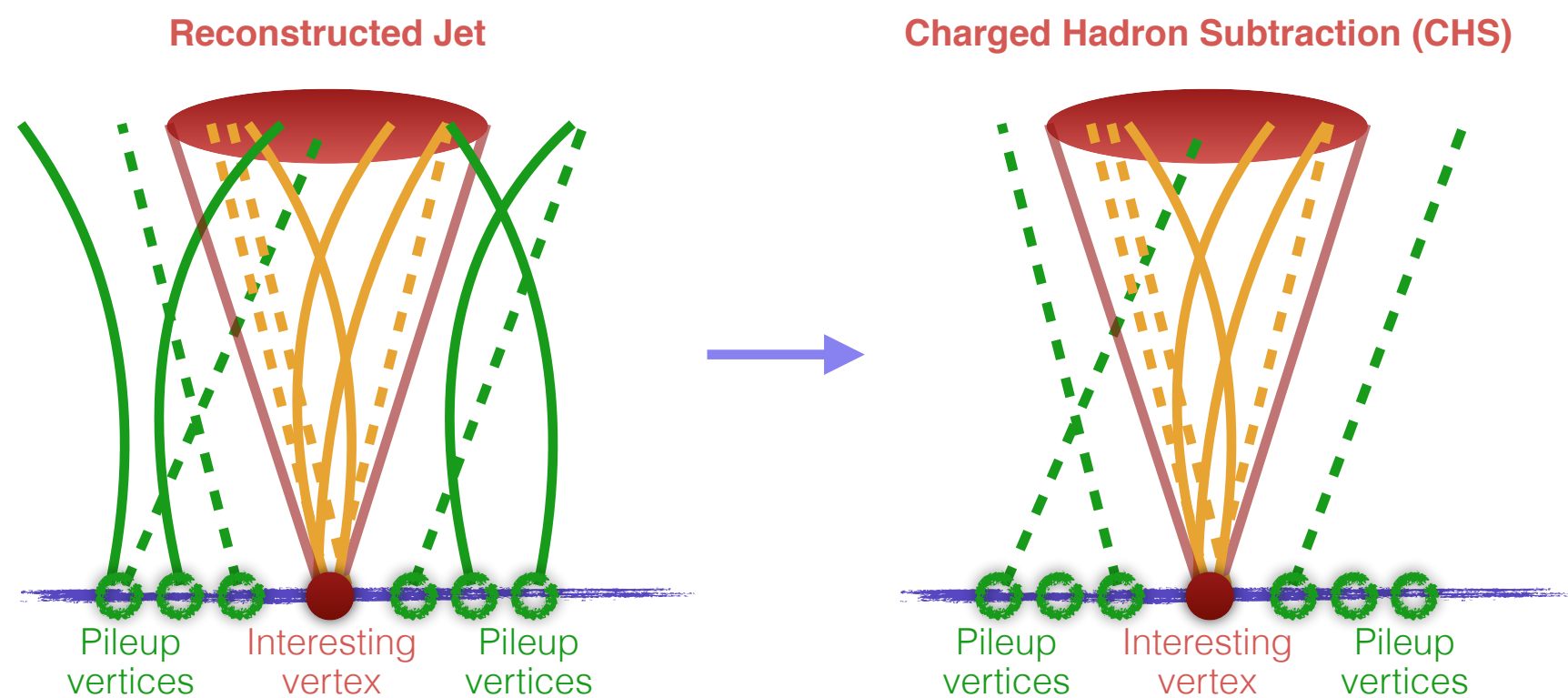


Reconstructed Jet

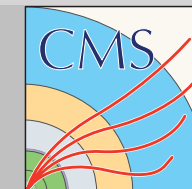


Charged Hadron Subtraction (CHS)

- ▶ Tracker information to remove charged particles associated to PU
- ▶ Neutral particles energy subtracted
- ▶ Applicable for $|\eta| < 2.4$



Pileup mitigation techniques



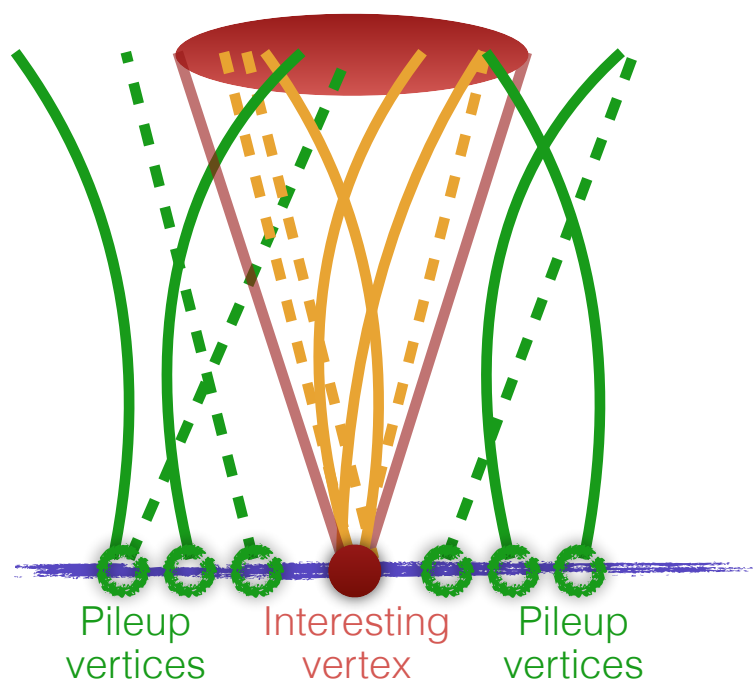
Charged Hadron Subtraction (CHS)

- ▶ Tracker information to remove charged particles associated to PU
- ▶ Neutral particles energy subtracted
- ▶ Applicable for $|\eta| < 2.4$

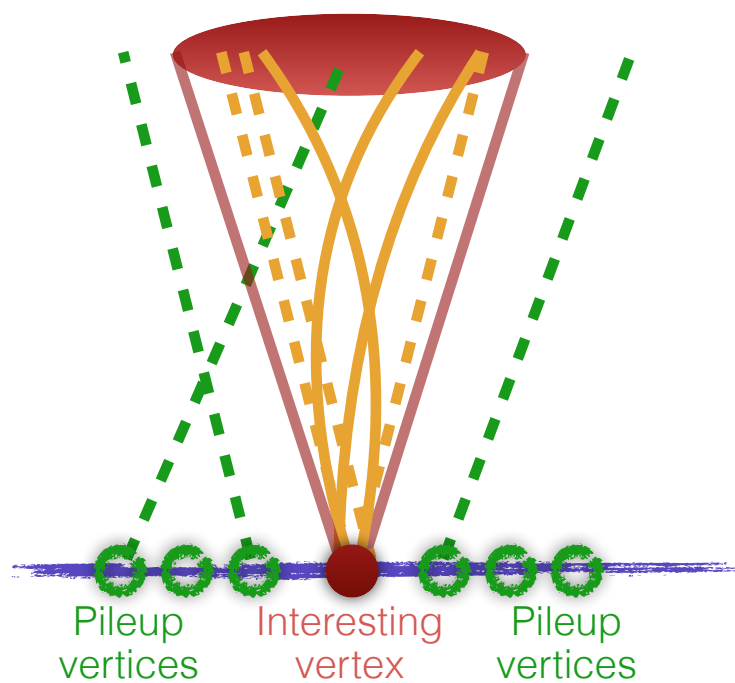
Pileup Per Particle Identification (Puppi) [Puppi in CMS](#)

- ▶ Per-particle weight
- ▶ Scale 4-momentum before clustering
- ▶ Charged particles similar to CHS
- ▶ Redefined track-vertex association

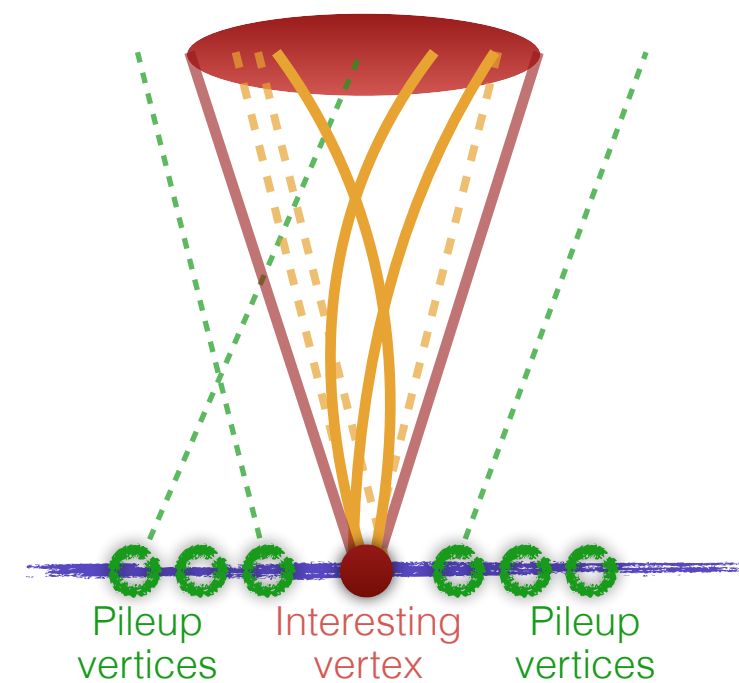
Reconstructed Jet



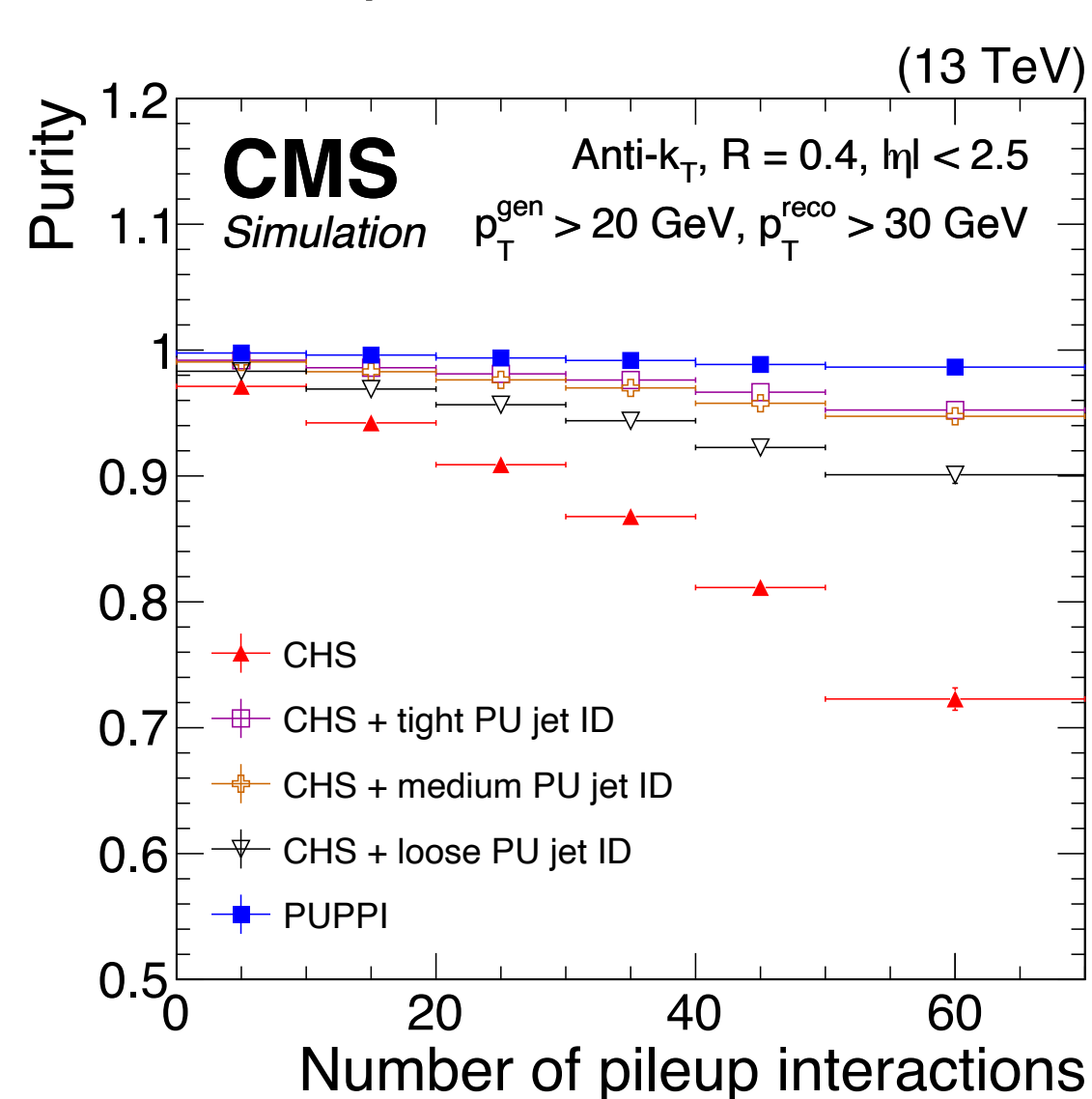
Charged Hadron Subtraction (CHS)



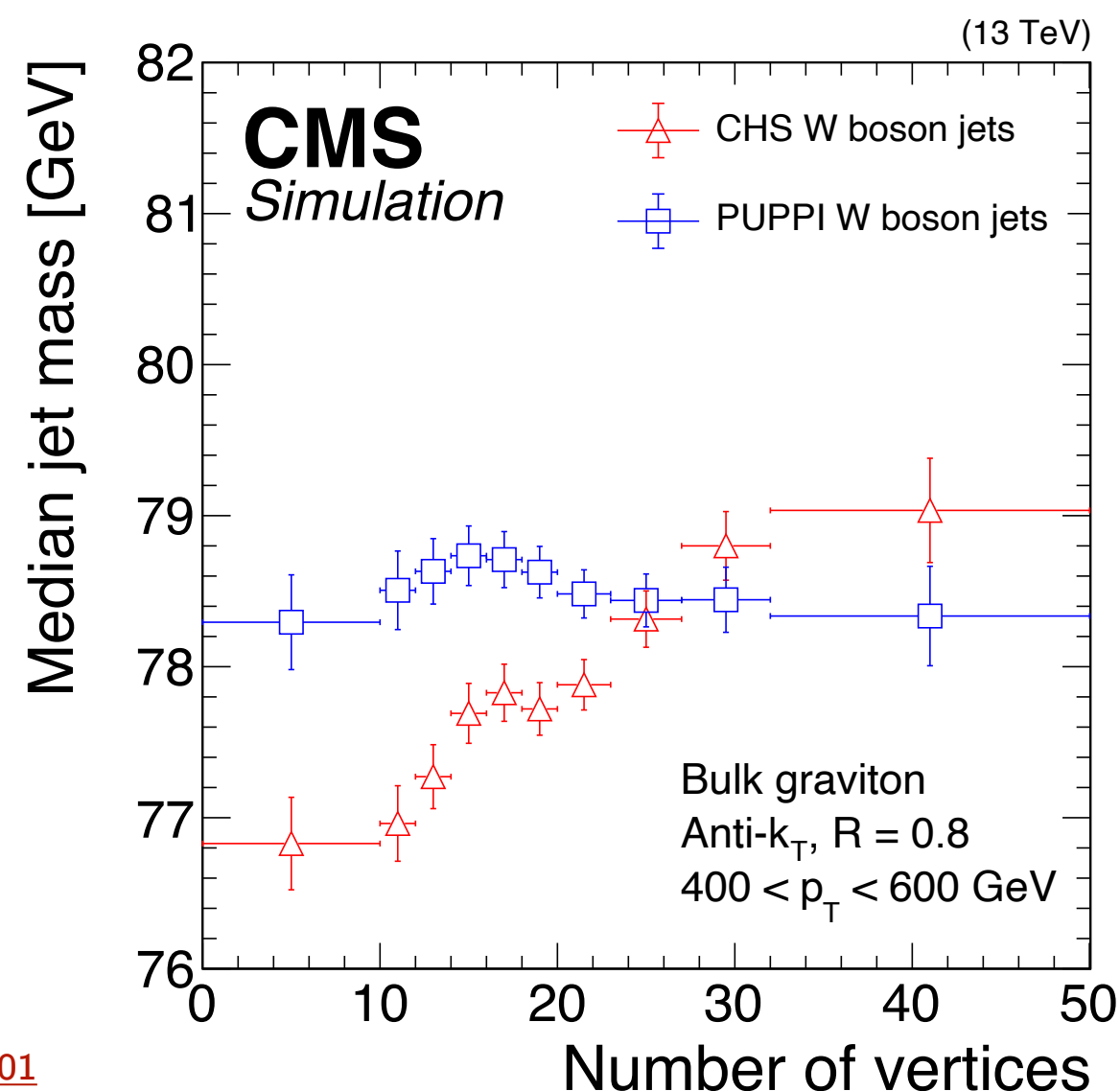
Pileup Per Particle Identification (Puppi)



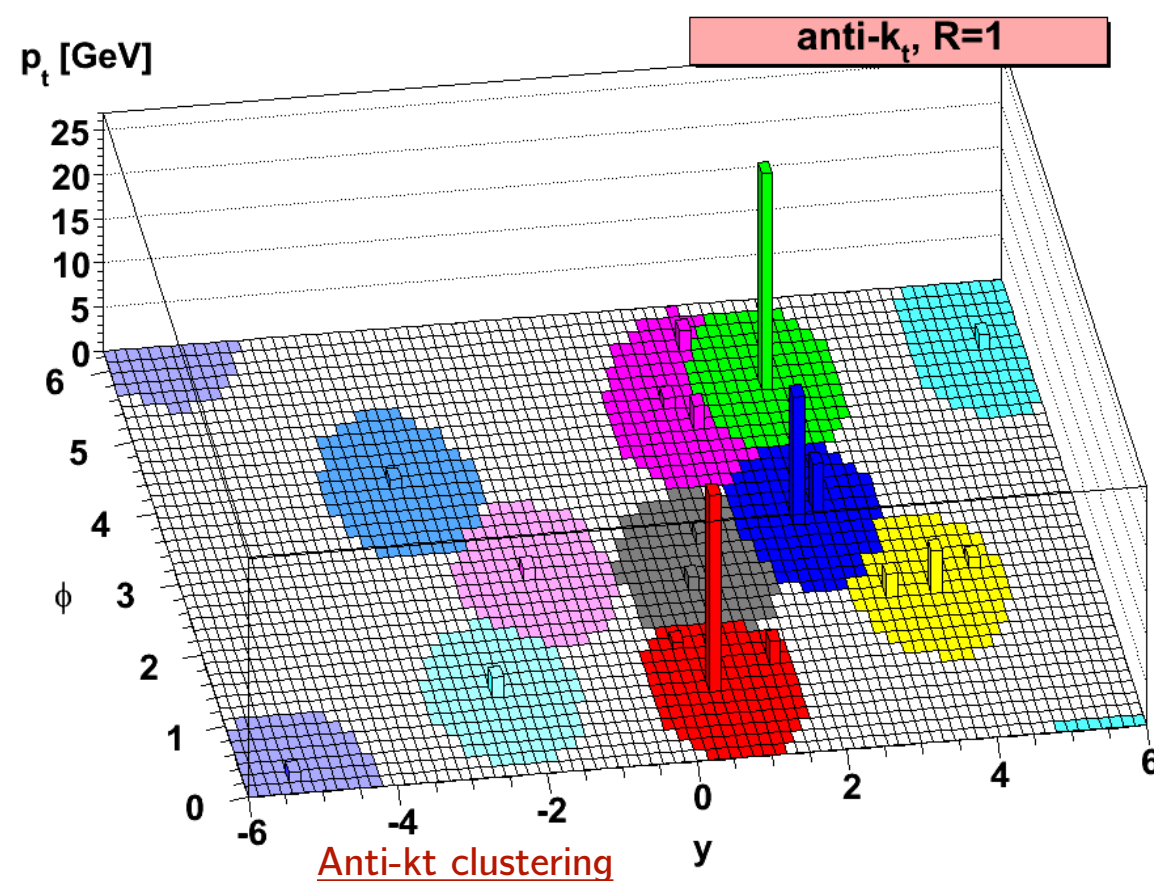
- ▶ Widely used in Run 2, default in Run 3
- ▶ Improved all jet-related variables
 - ▶ Jet efficiency and purity (matched to generator-level jets)
 - ▶ Jet substructure
 - ▶ New optimisation to include hadronic tau reconstruction: [CMS-DP-2024-043](#)



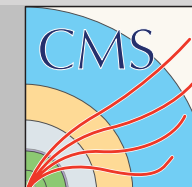
[CMS-DP-2021-001](#)



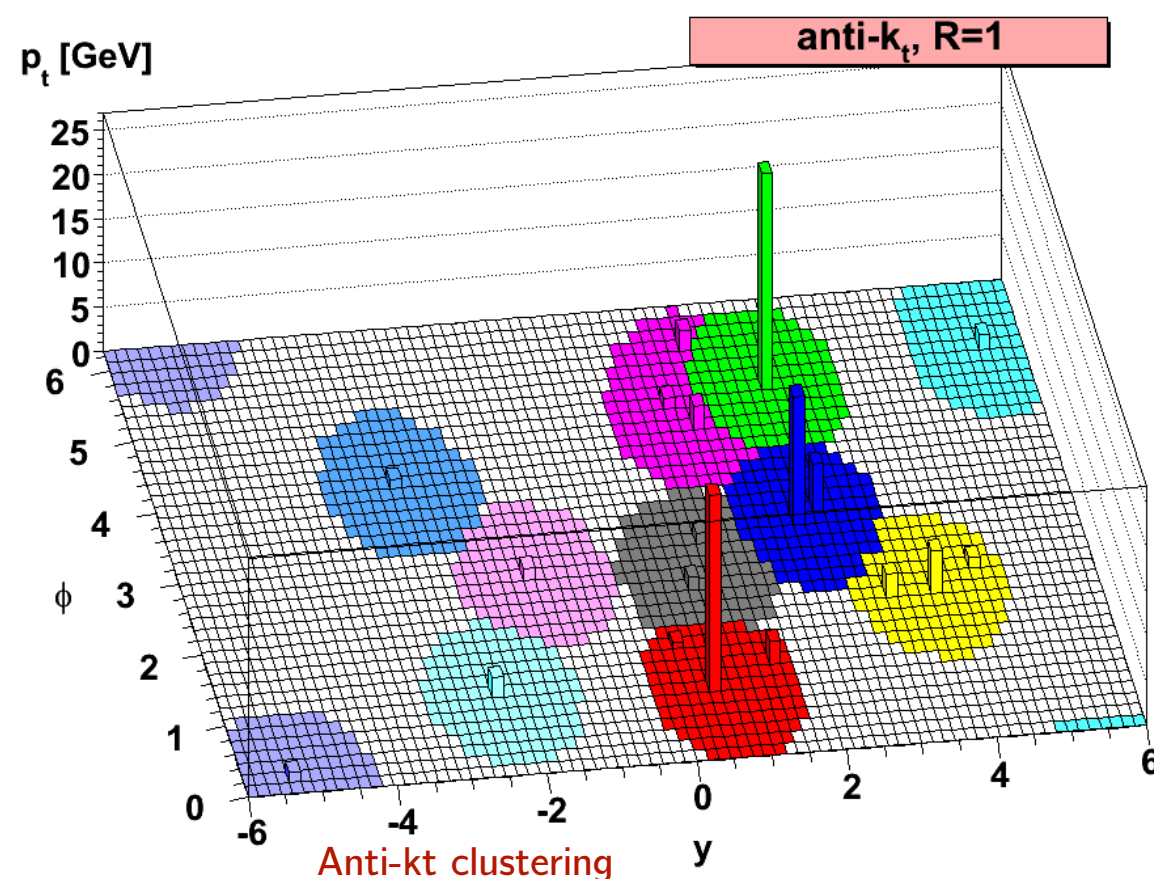
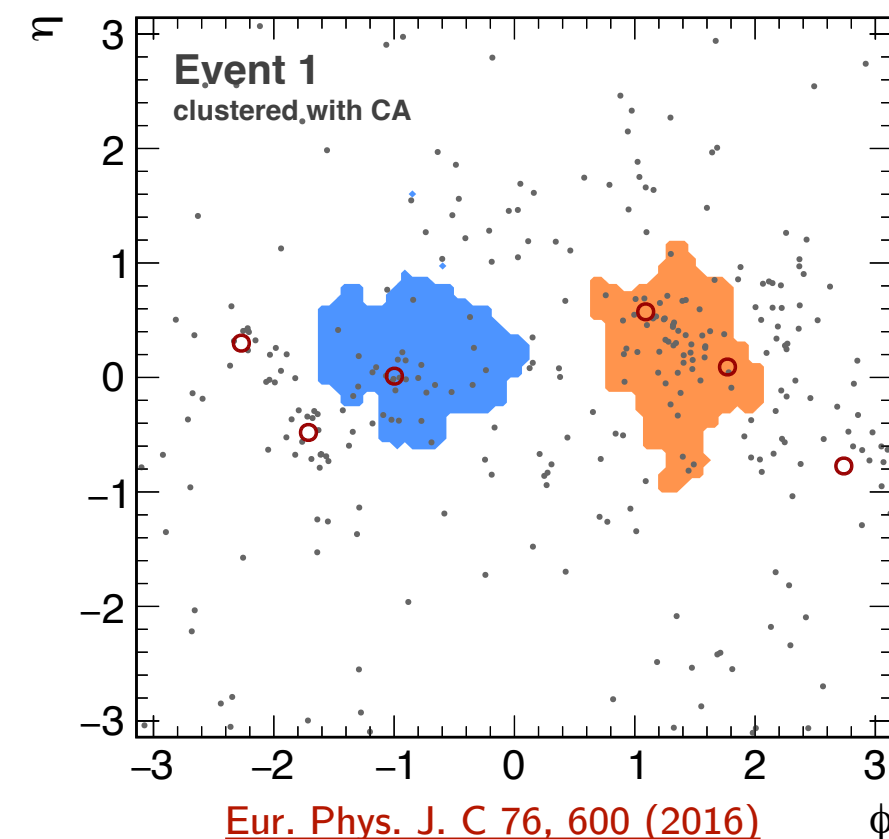
- ▶ Anti- k_T as default algorithm
 - ▶ small radius: $R=0.4$ (AK4)
 - ▶ large radius: $R=0.8$ (AK8)



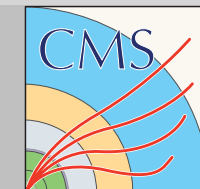
Jet reconstruction



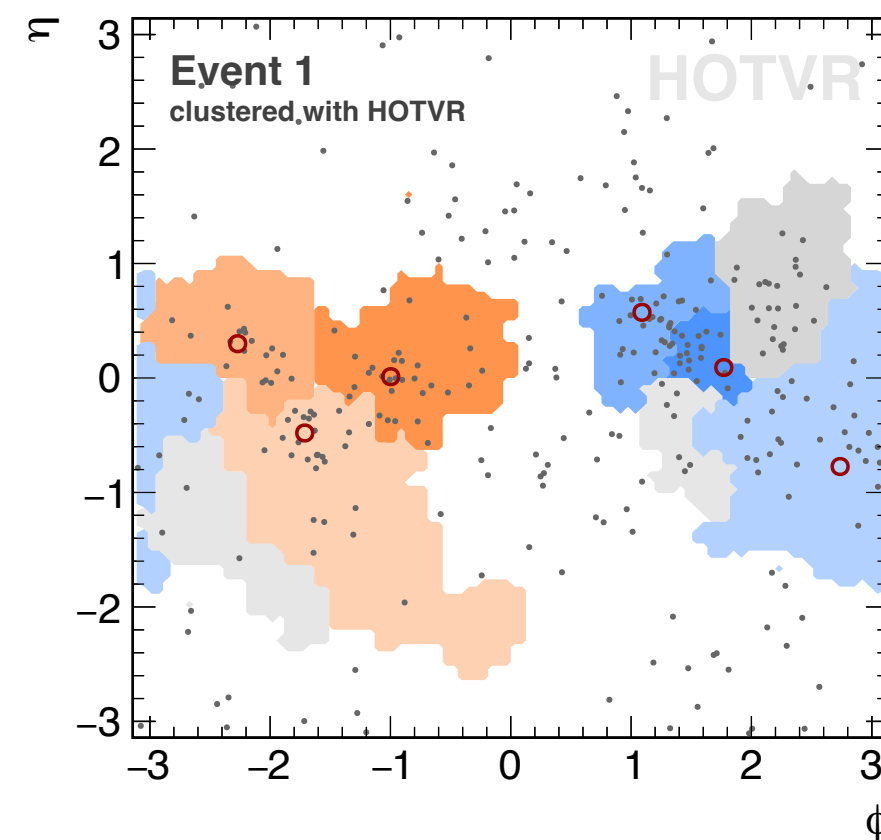
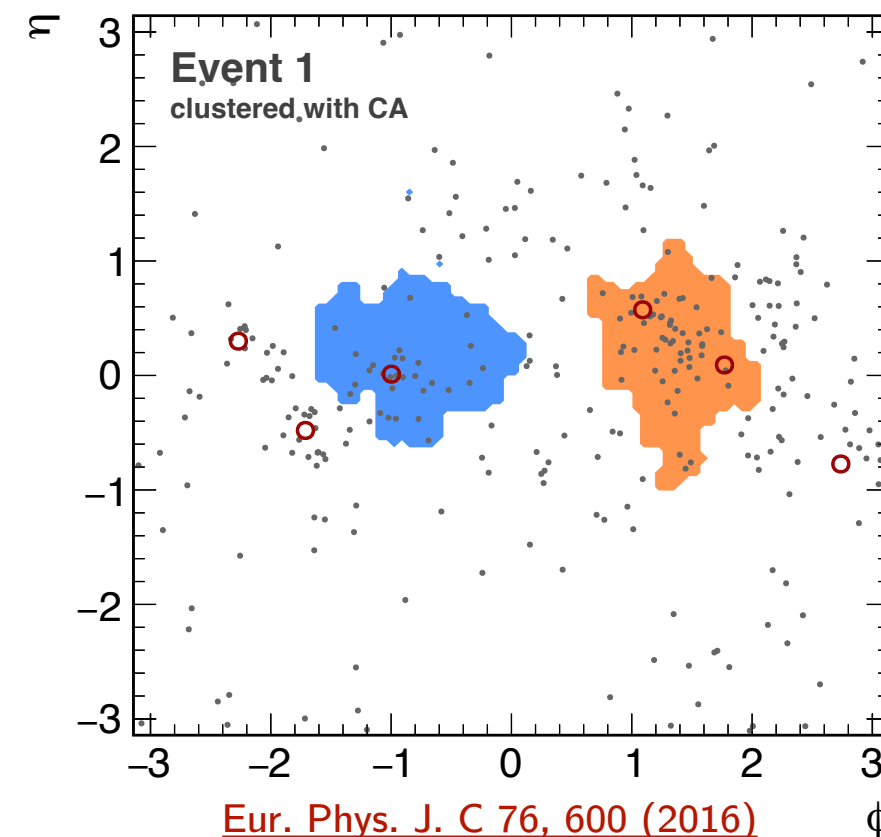
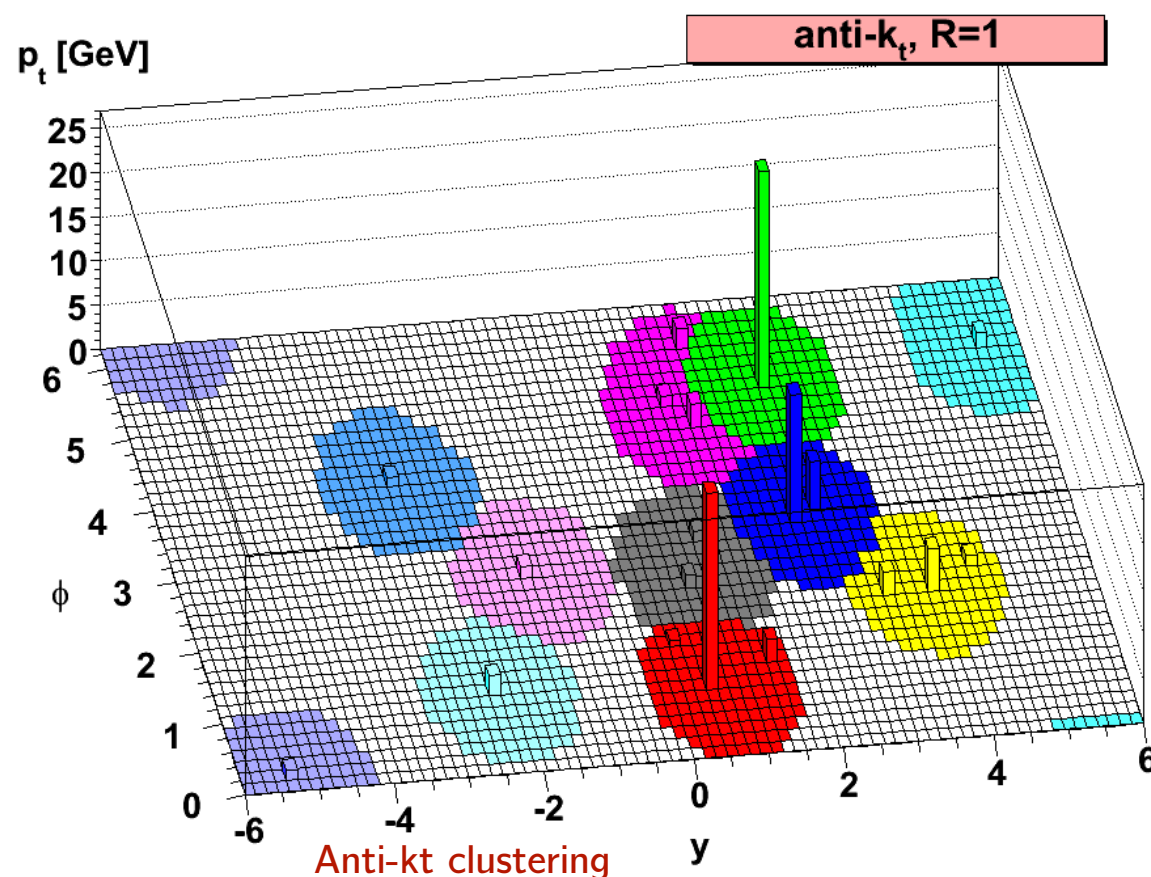
- ▶ Anti- k_T as default algorithm
 - ▶ small radius: $R=0.4$ (AK4)
 - ▶ large radius: $R=0.8$ (AK8)
 - ▶ alternative algorithms: CA, HOTVR, XCone



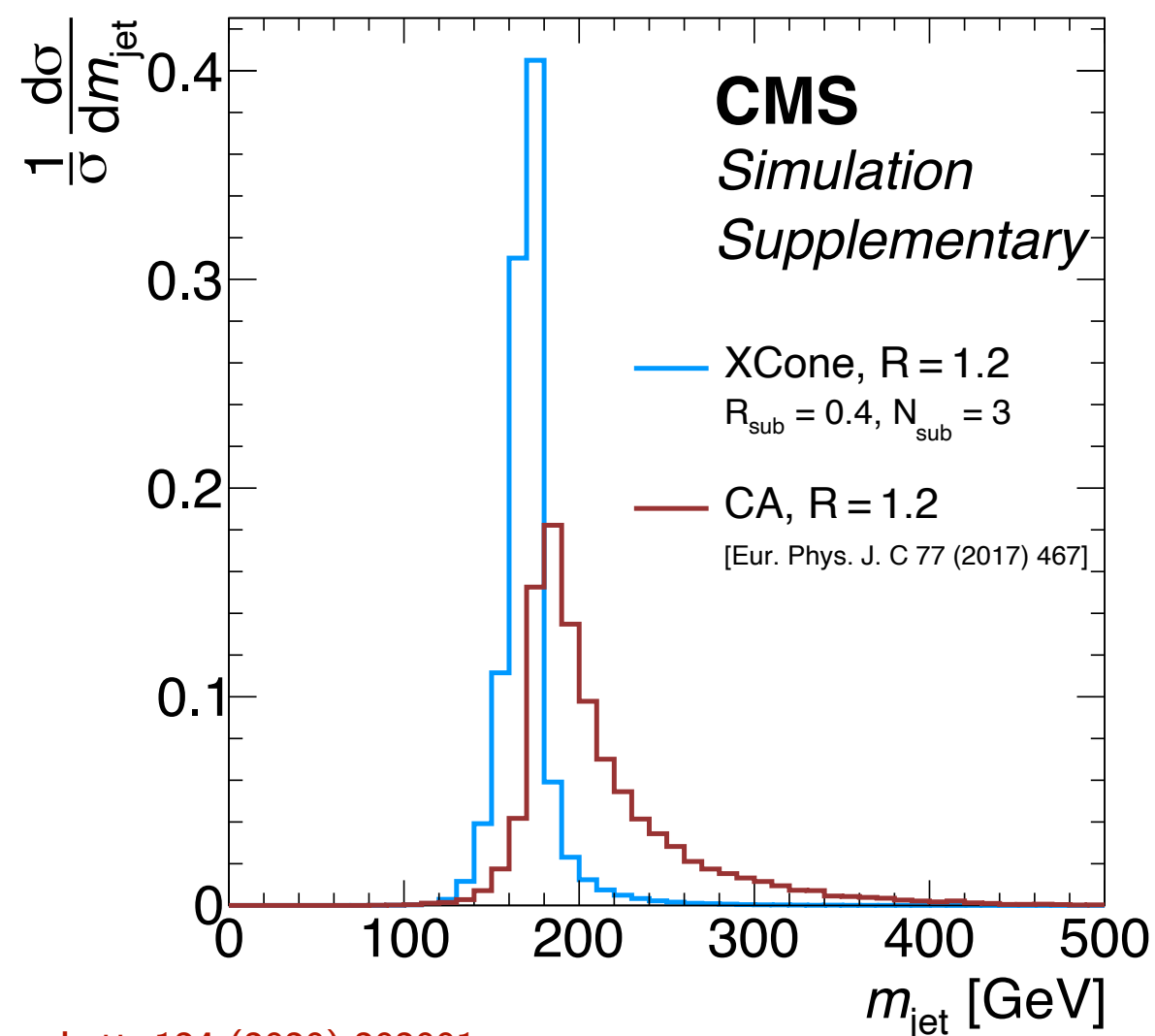
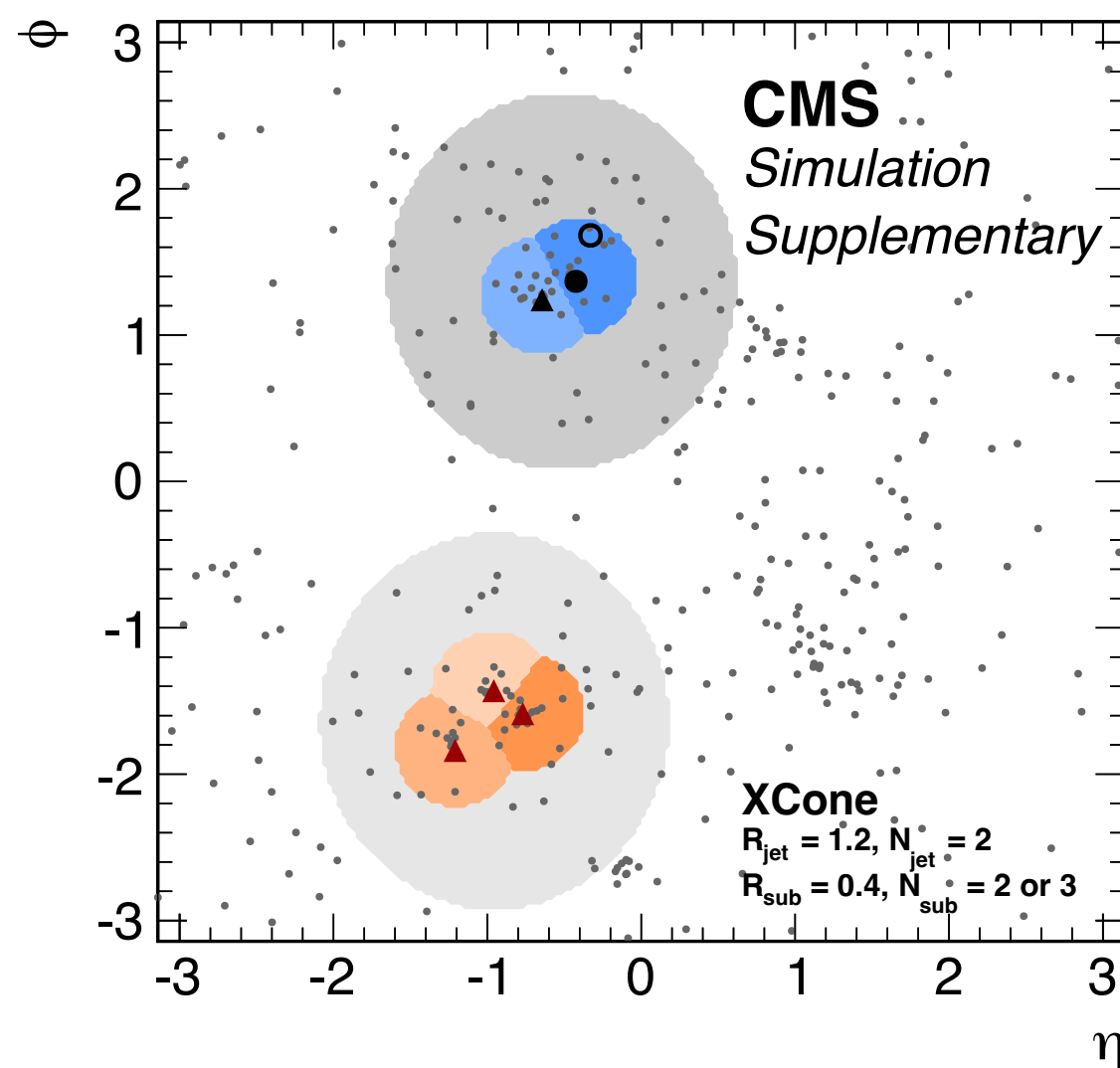
Jet reconstruction



- ▶ Anti- k_T as default algorithm
 - ▶ small radius: $R=0.4$ (AK4)
 - ▶ large radius: $R=0.8$ (AK8)
 - ▶ alternative algorithms: CA, HOTVR, XCone

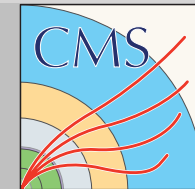


- ▶ Event signature defines clustering
- ▶ Return exactly N jets
- ▶ Examples from top-mass measurement
- ▶ Large improvement for the jet mass resolution

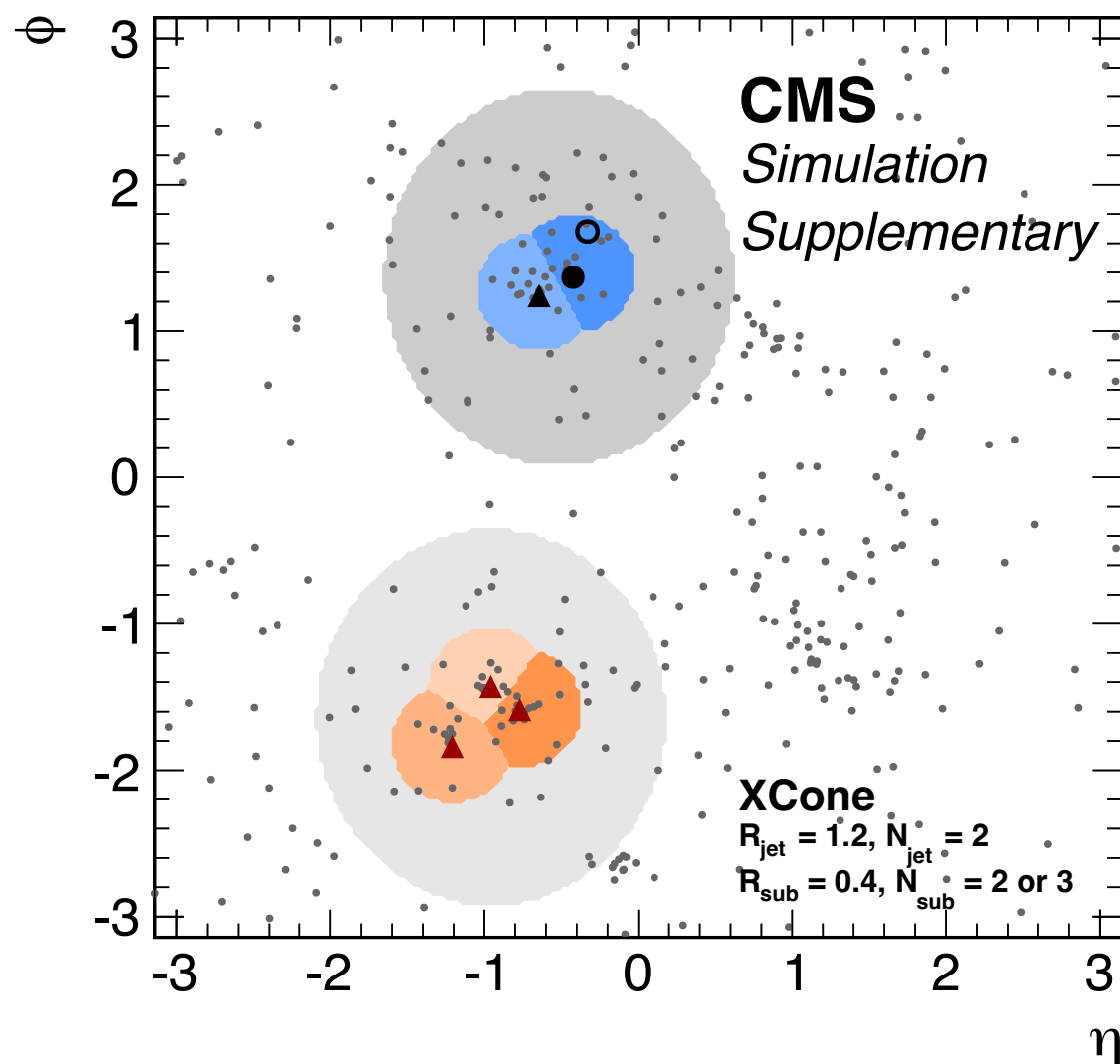


[Phys. Rev. Lett. 124 \(2020\) 202001](#)

Jet reconstruction – XCone



- ▶ Event signature defines clustering
- ▶ Return exactly N jets
- ▶ Examples from top-mass measurement
- ▶ Large improvement for the jet mass resol



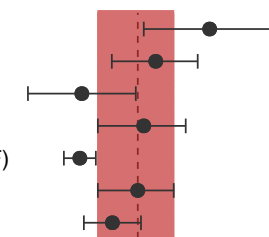
CMS

[arxiv:2403.01313](https://arxiv.org/abs/2403.01313)

Lagrangian mass extractions

Pole mass from cross section

- Inclusive $t\bar{t}$ 7 TeV, NNLO \otimes CT10
- Inclusive $t\bar{t}$ 7+8 TeV, NNLO \otimes CT14
- Inclusive $t\bar{t}$ 13 TeV, NNLO \otimes CT14
- Inclusive $t\bar{t}$ 13 TeV, NNLO \otimes CT14
- Differential $t\bar{t}$ 13 TeV, NLO + 3D fit ($m_t^{pole}, \alpha_s, PDF$)
- Dilepton 7+8 TeV, ATLAS+CMS cross section
- Differential $t\bar{t}$ +jet 13 TeV, NLO \otimes CT18



stat. total

--- ATLAS+CMS combination $m_t^{pole} = 173.4^{+1.8}_{-2.0}$ GeV [JHEP 07 (2023) 213]

--- CMS 7+8 TeV comb. $m_t^{MC} = 172.52 \pm 0.42$ GeV [arXiv:2402.08713]

--- CMS 7+8 TeV comb. stat. uncertainty

$m_t^{pole} = 177.0^{+3.6}_{-3.3}$ (tot) GeV [PLB 728 (2014) 496]

$m_t^{pole} = 174.3^{+2.1}_{-2.2}$ (tot) GeV [JHEP 08 (2016) 029]

$m_t^{pole} = 170.6 \pm 2.7$ (tot) GeV [JHEP 09 (2017) 051]

$m_t^{pole} = 173.7^{+2.1}_{-2.3}$ (tot) GeV [EPJC 79 (2019) 368]

$m_t^{pole} = 170.5 \pm 0.8$ (tot) GeV [EPJC 80 (2020) 658]

$m_t^{pole} = 173.4^{+1.8}_{-2.0}$ (tot) GeV [JHEP 07 (2023) 213]

$m_t^{pole} = 172.13 \pm 1.43$ (tot) GeV [JHEP 07 (2023) 077]

\overline{MS} mass from cross section

- Inclusive $t\bar{t}$ 13 TeV, NNLO \otimes CT14

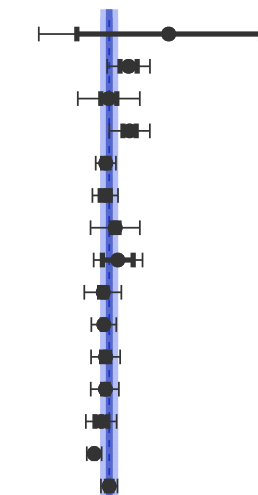


$m_t(m_t) = 165.0^{+1.8}_{-2.0}$ (tot) GeV [EPJC 79 (2019) 368]

Direct measurements

Full reconstruction

- Dilepton 7 TeV, KINb and AMWT
- Lepton+jets 7 TeV, 2D ideogram
- Dilepton 7 TeV, AMWT
- All-jets 7 TeV, 2D ideogram
- Lepton+jets 8 TeV, Hybrid ideogram
- All-jets 8 TeV, Hybrid ideogram
- Dilepton 8 TeV, AMWT
- Single top quark 8 TeV, Template fit
- Dilepton 8 TeV, $M_{bl} + M_{T2}^{bb}$ Hybrid fit
- Lepton+jets 13 TeV, Hybrid ideogram
- All-jets 13 TeV, Hybrid ideogram
- Dilepton 13 TeV, m_{bl} fit
- Single top quark 13 TeV, $\ln(m_t / 1 \text{ GeV})$ fit
- Lepton+jets 13 TeV, Profile likelihood
- Combination 7+8 TeV



$m_t^{MC} = 175.5 \pm 4.6$ (stat) ± 4.6 (sys) GeV [JHEP 07 (2011) 04]

$m_t^{MC} = 173.49 \pm 0.43$ (stat) ± 0.98 (sys) GeV [JHEP 12 (2012) 105]

$m_t^{MC} = 172.5 \pm 0.4$ (stat) ± 1.5 (sys) GeV [EPJC 72 (2012) 2202]

$m_t^{MC} = 173.54 \pm 0.33$ (stat) ± 0.96 (sys) GeV [EPJC 74 (2014) 2758]

$m_t^{MC} = 172.35 \pm 0.16$ (stat) ± 0.48 (sys) GeV [PRD 93 (2016) 072004]

$m_t^{MC} = 172.32 \pm 0.25$ (stat) ± 0.59 (sys) GeV [PRD 93 (2016) 072004]

$m_t^{MC} = 172.82 \pm 0.19$ (stat) ± 1.22 (sys) GeV [PRD 93 (2016) 072004]

$m_t^{MC} = 172.95 \pm 0.77$ (stat) $^{+0.97}_{-0.93}$ (sys) GeV [EPJC 77 (2017) 354]

$m_t^{MC} = 172.22 \pm 0.18$ (stat) $^{+0.89}_{-0.93}$ (sys) GeV [PRD 96 (2017) 032002]

$m_t^{MC} = 172.25 \pm 0.08$ (stat) ± 0.62 (sys) GeV [EPJC 78 (2018) 891]

$m_t^{MC} = 172.34 \pm 0.20$ (stat) ± 0.70 (sys) GeV [EPJC 79 (2019) 313]

$m_t^{MC} = 172.33 \pm 0.14$ (stat) $^{+0.66}_{-0.72}$ (sys) GeV [EPJC 79 (2019) 368]

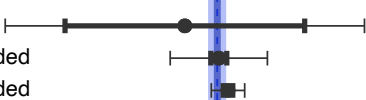
$m_t^{MC} = 172.13 \pm 0.32$ (stat) $^{+0.69}_{-0.71}$ (sys) GeV [JHEP 12 (2021) 161]

$m_t^{MC} = 171.77 \pm 0.04$ (stat) ± 0.37 (sys) GeV [EPJC 83 (2023) 963]

$m_t^{MC} = 172.52 \pm 0.14$ (stat) ± 0.39 (sys) GeV [arXiv:2402.08713]

Boosted measurements

- Boosted 8 TeV, C/A jet mass unfolded
- Boosted 13 TeV, XCone jet mass unfolded
- Boosted 13 TeV, XCone jet mass unfolded



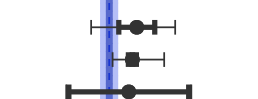
$m_t^{MC} = 170.9 \pm 6.0$ (stat) ± 6.7 (sys) GeV [EPJC 77 (2017) 467]

$m_t^{MC} = 172.6 \pm 0.4$ (stat) ± 2.4 (sys) GeV [PRL 124 (2020) 202001]

$m_t^{MC} = 173.06 \pm 0.24$ (stat) ± 0.80 (sys) GeV [EPJC 83 (2023) 560]

Alternative measurements

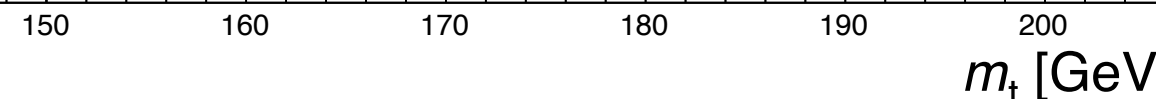
- Dilepton 7 TeV, Kinematic endpoints
- 1+2 leptons 8 TeV, Lepton + secondary vertex
- 1+2 leptons 8 TeV, Lepton + J/ψ



$m_t = 173.9 \pm 0.9$ (stat) $^{+1.7}_{-2.1}$ (sys) GeV [EPJC 73 (2013) 2494]

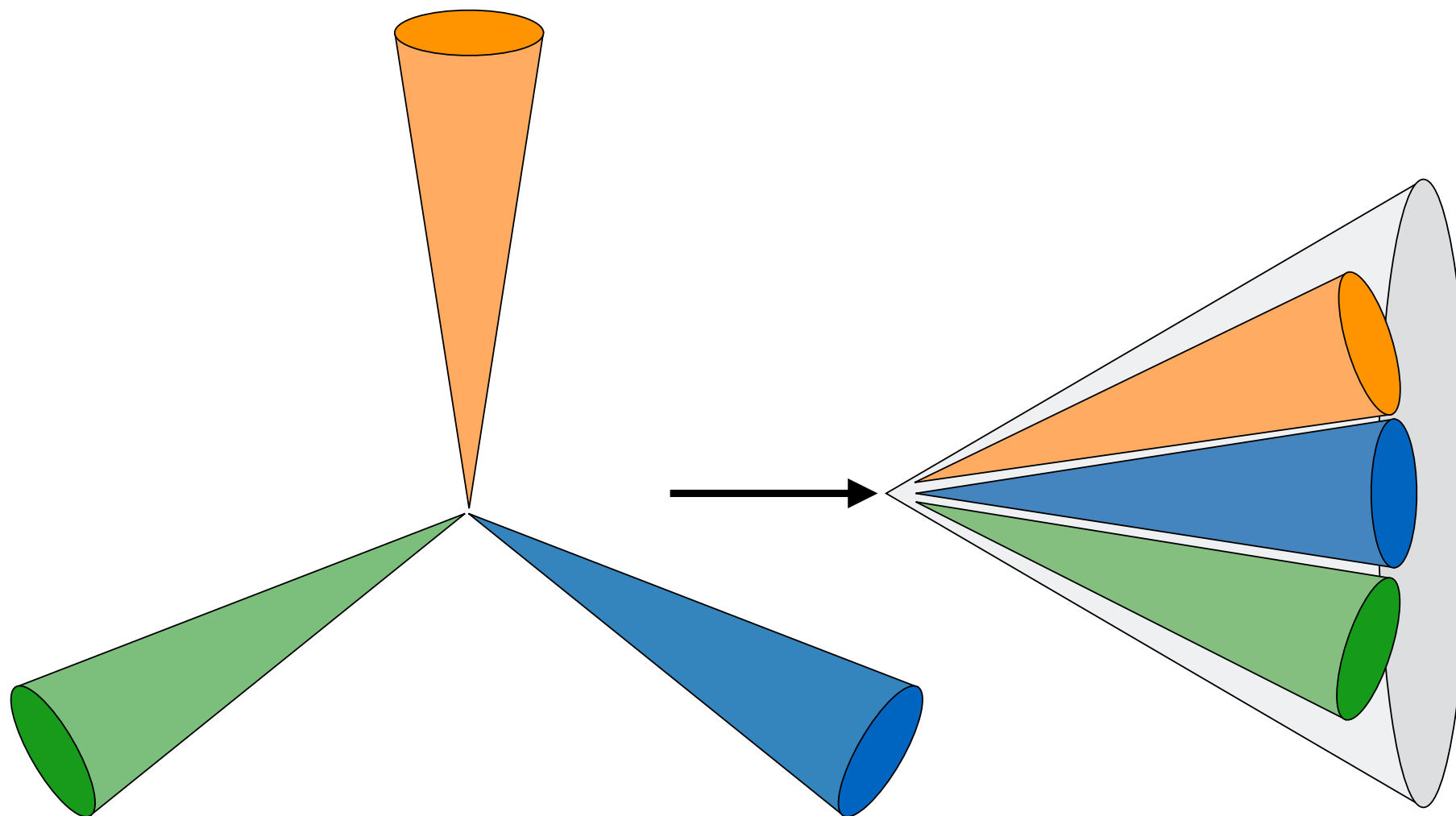
$m_t^{MC} = 173.68 \pm 0.20$ (stat) $^{+1.58}_{-0.97}$ (sys) GeV [PRD 93 (2016) 092006]

$m_t^{MC} = 173.5 \pm 3.0$ (stat) ± 0.9 (sys) GeV [JHEP 12 (2016) 123]

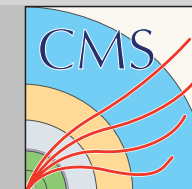


Tagging

- ▶ Type of elementary particle that initiated the jet
- ▶ Boosted topology -> Collimated decay products reconstructed as multi-prong objects

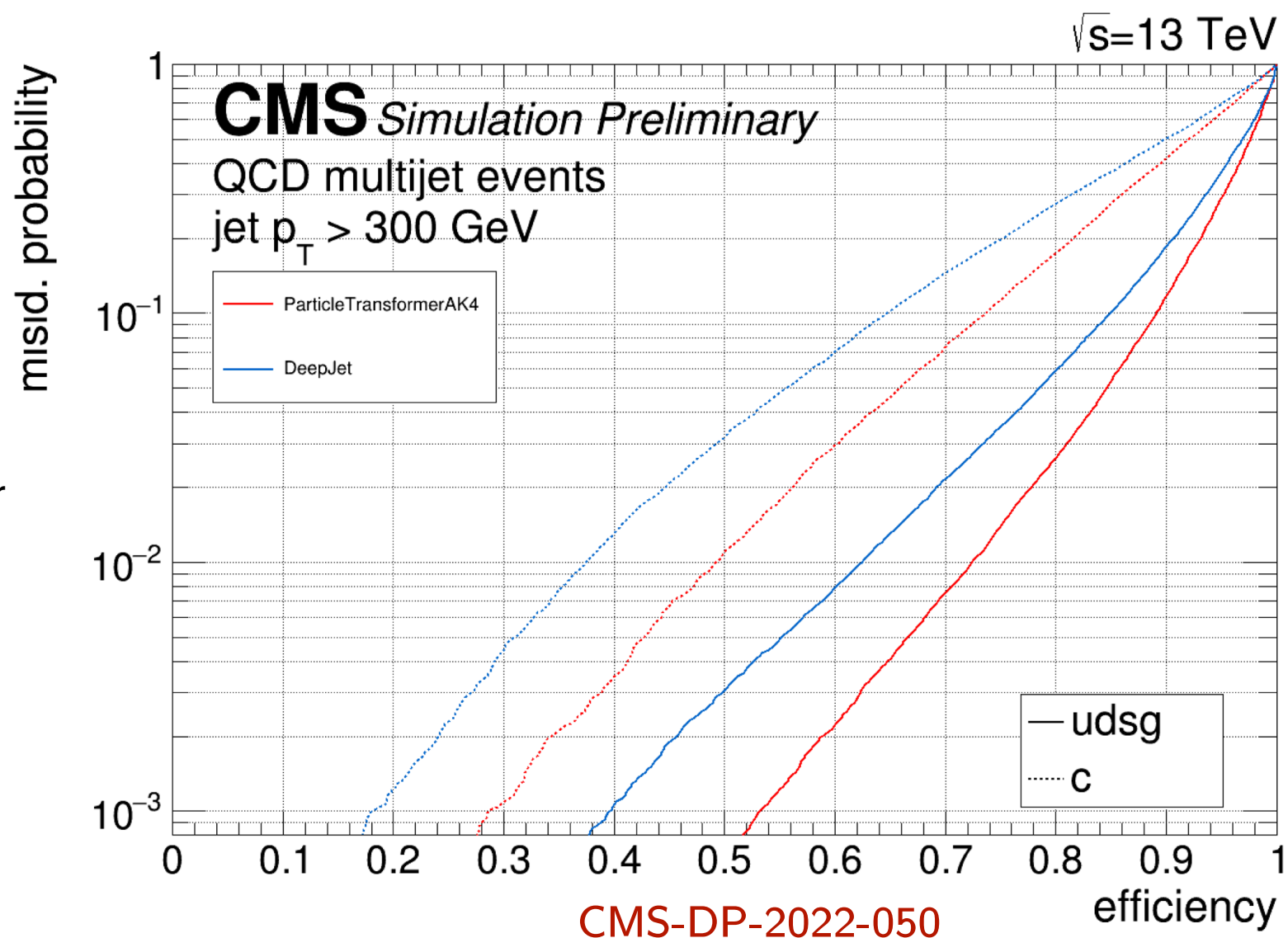
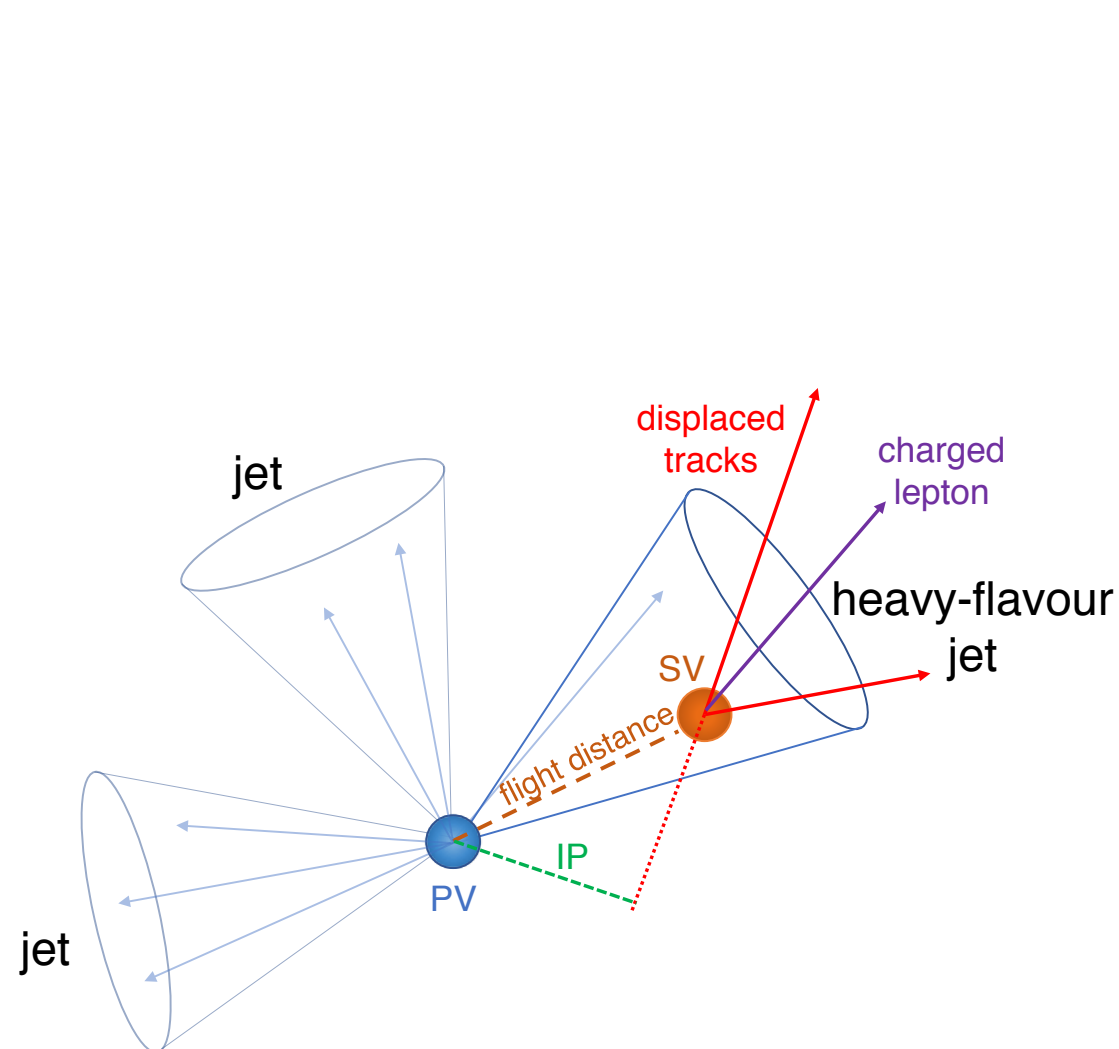


Jet identification (“tagging”)

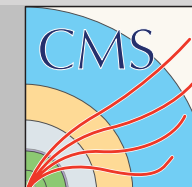


Tagging

- ▶ Type of elementary particle that initiated the jet
 - ▶ Boosted topology -> Collimated decay products reconstructed as multi-prong objects
- ▶ Jet flavor (b vs light, b vs c, ...)

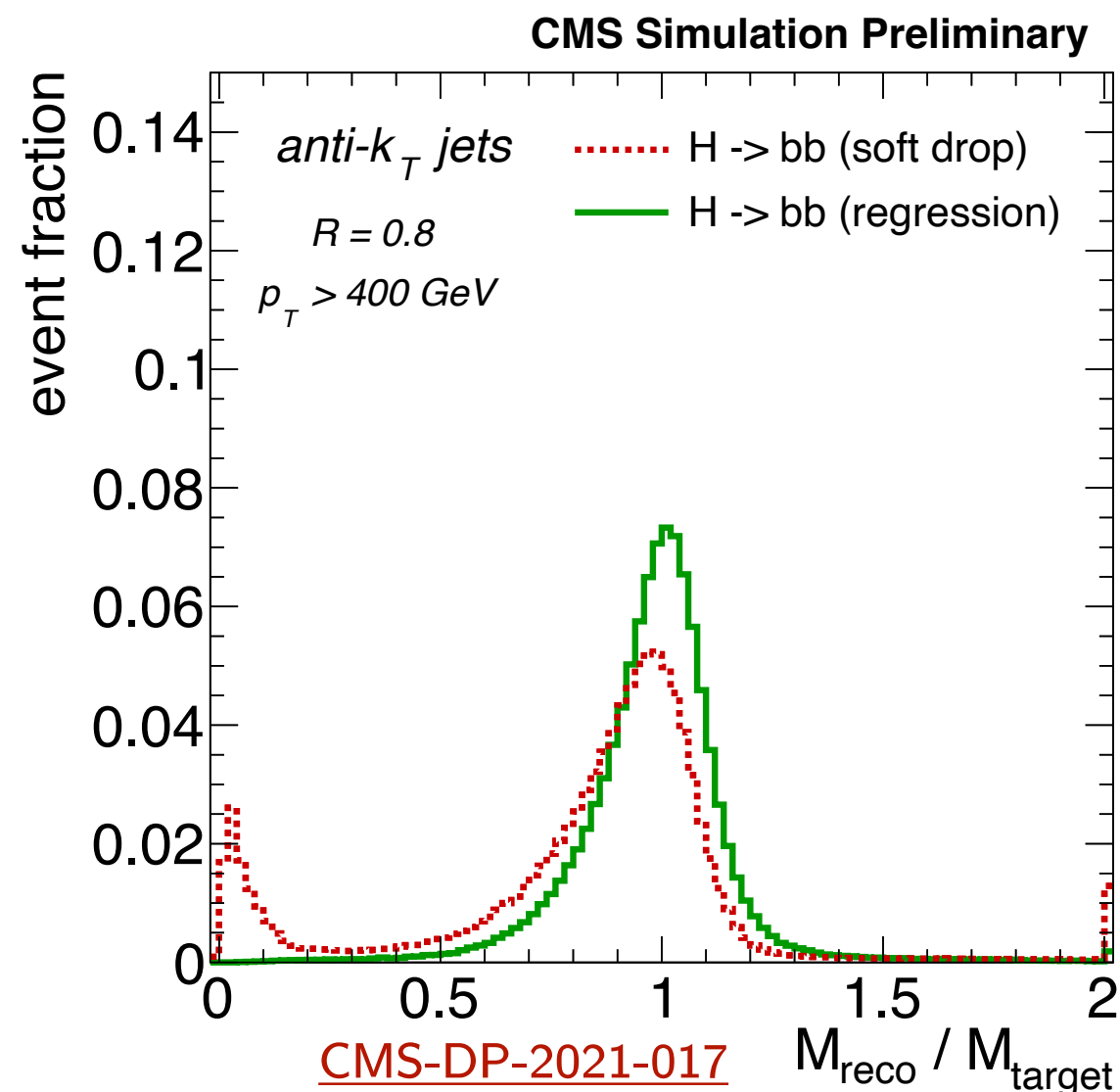
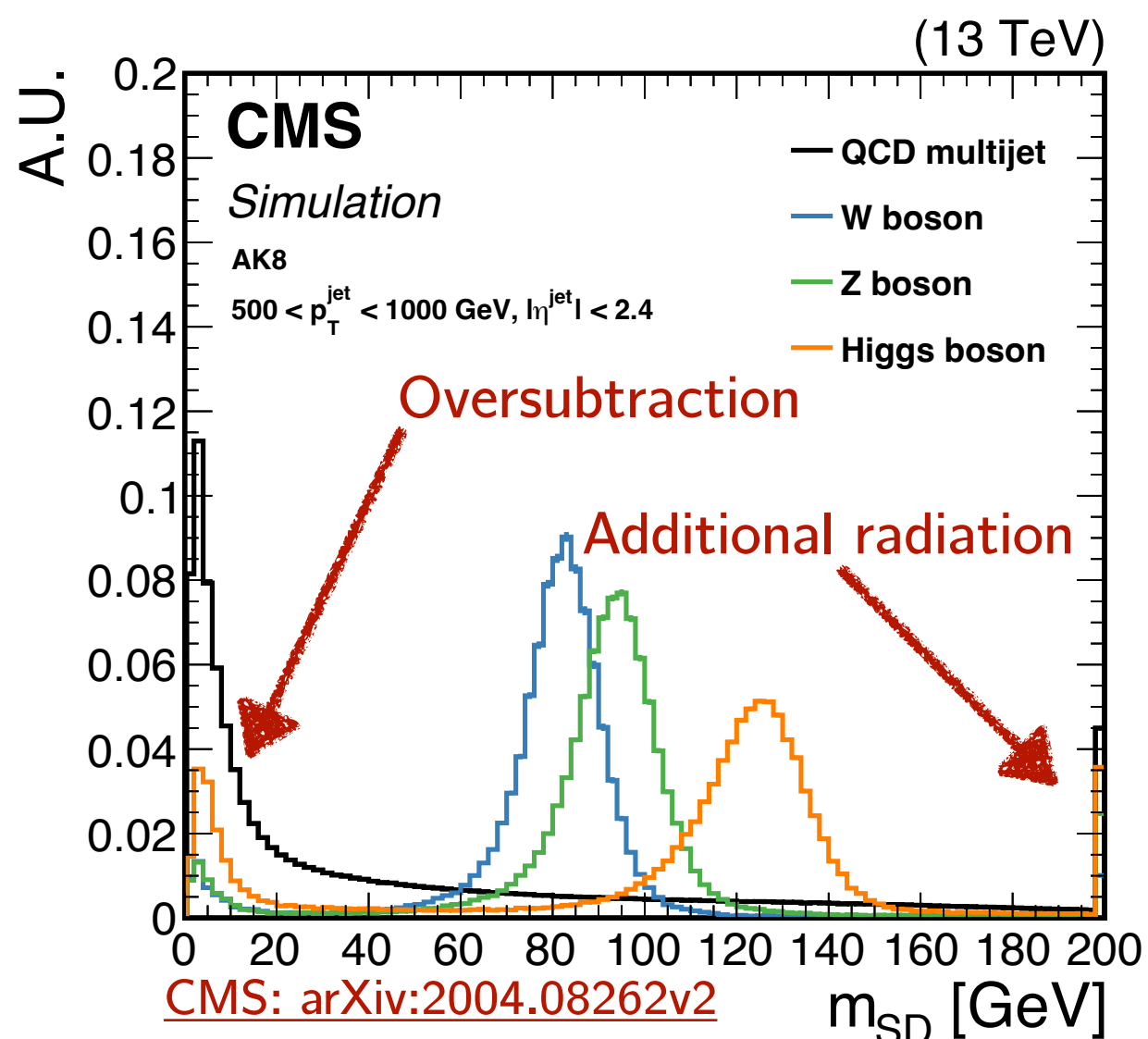


Jet identification (“tagging”)

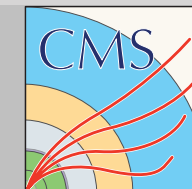


Tagging

- ▶ Type of elementary particle that initiated the jet
 - ▶ Boosted topology -> Collimated decay products reconstructed as multi-prong objects
- ▶ Jet flavor (b vs light, b vs c, ...)
- ▶ Jet mass (ML with regression)

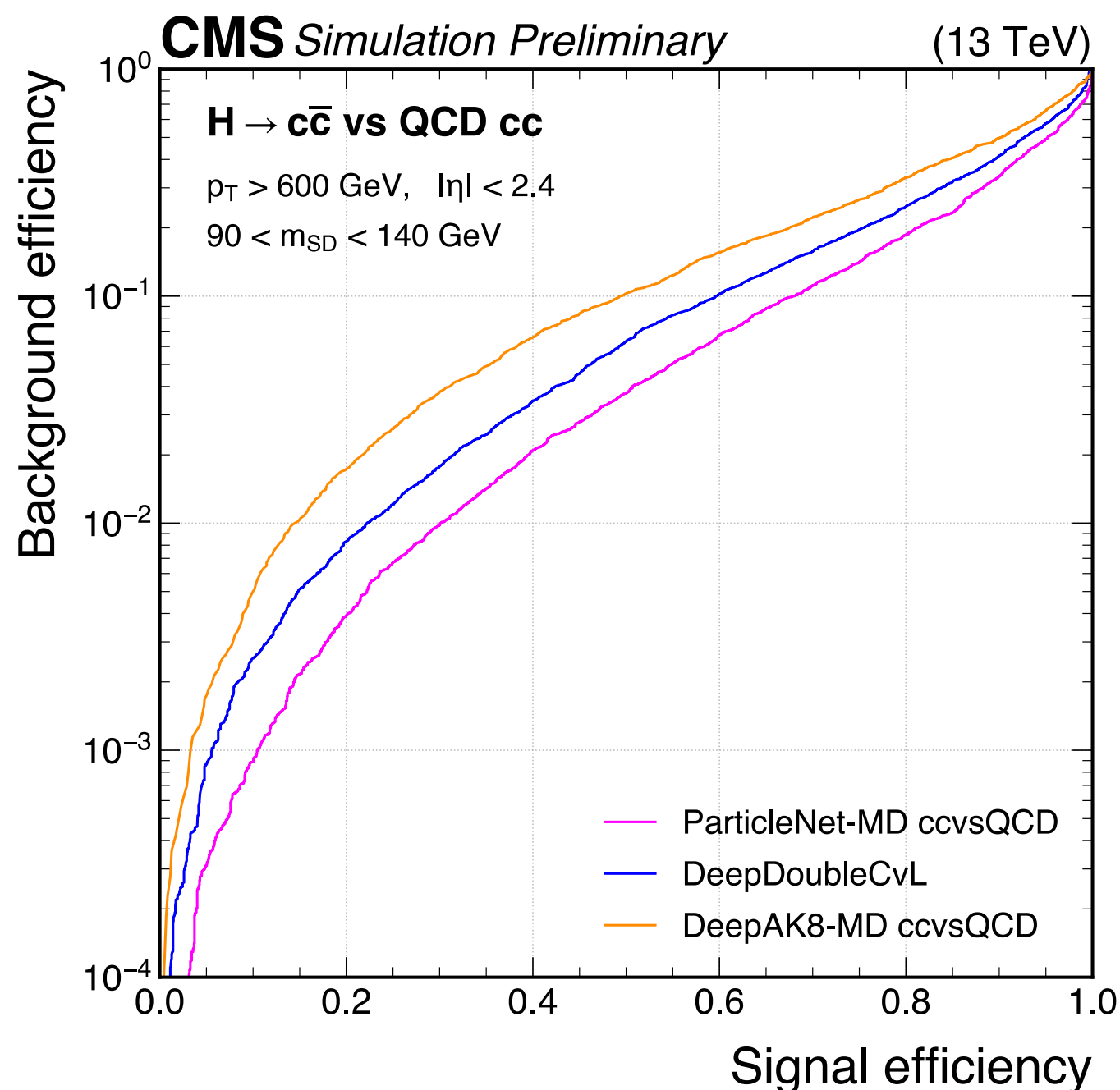
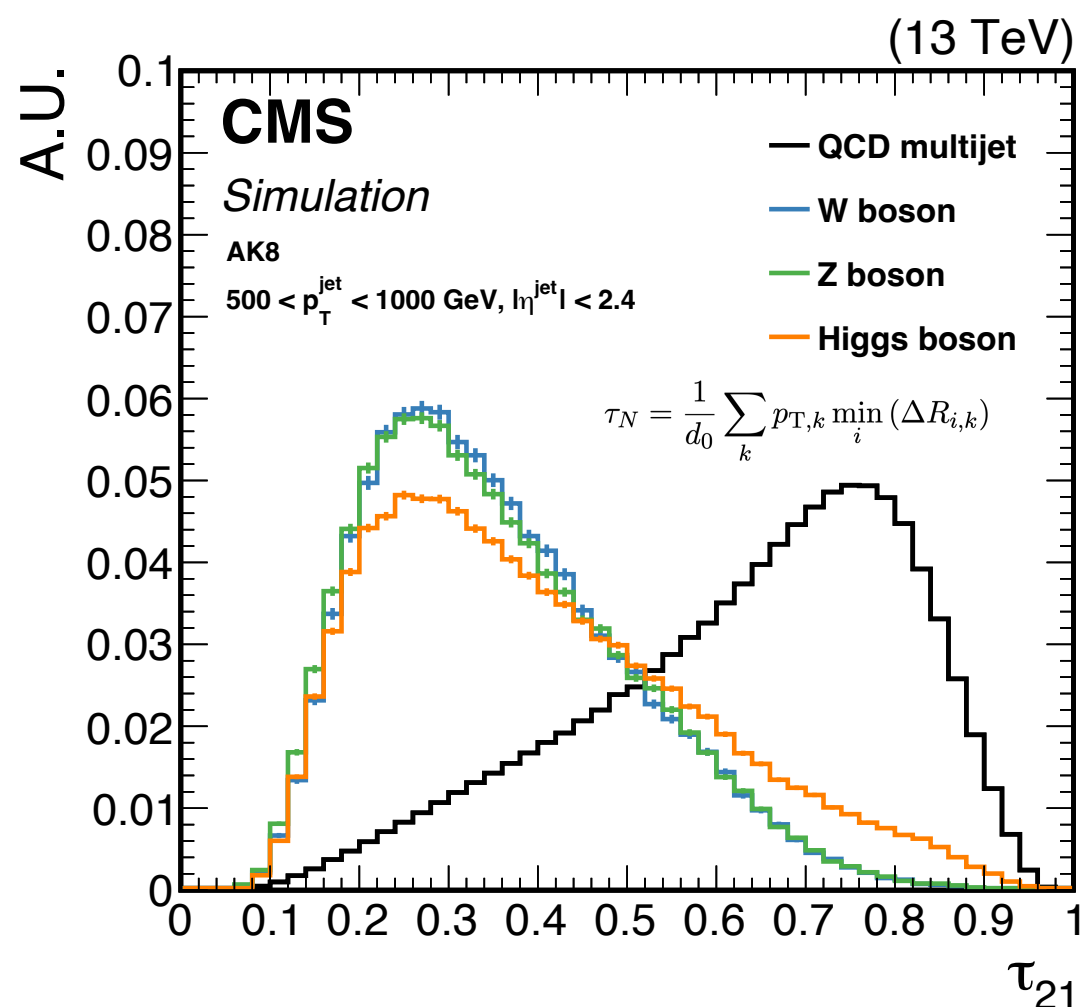


Jet identification (“tagging”)



Tagging

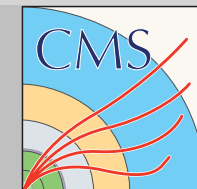
- ▶ Type of elementary particle that initiated the jet
 - ▶ Boosted topology -> Collimated decay products reconstructed as multi-prong objects
- ▶ Jet flavor (b vs light, b vs c, ...)
- ▶ Jet mass (ML with regression)
- ▶ Jet substructure



Jet identification (“tagging”)

CMS-DP-2024-038

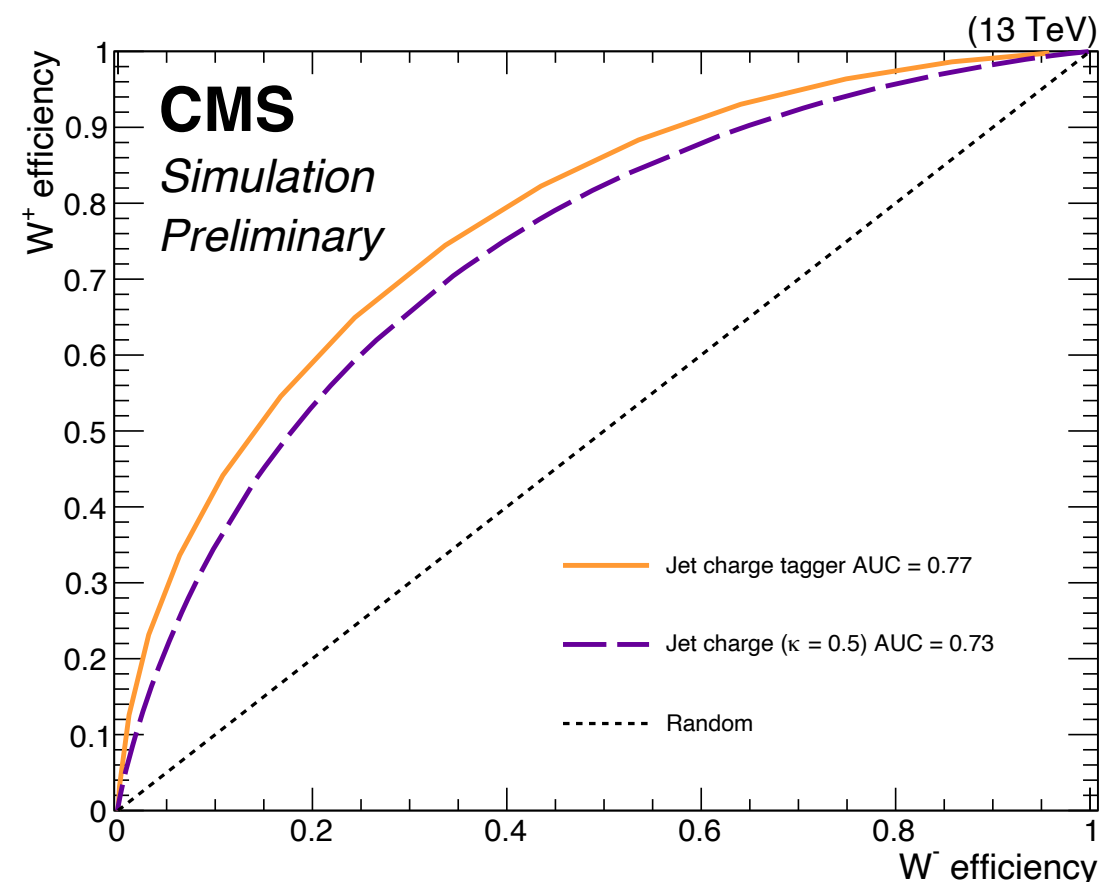
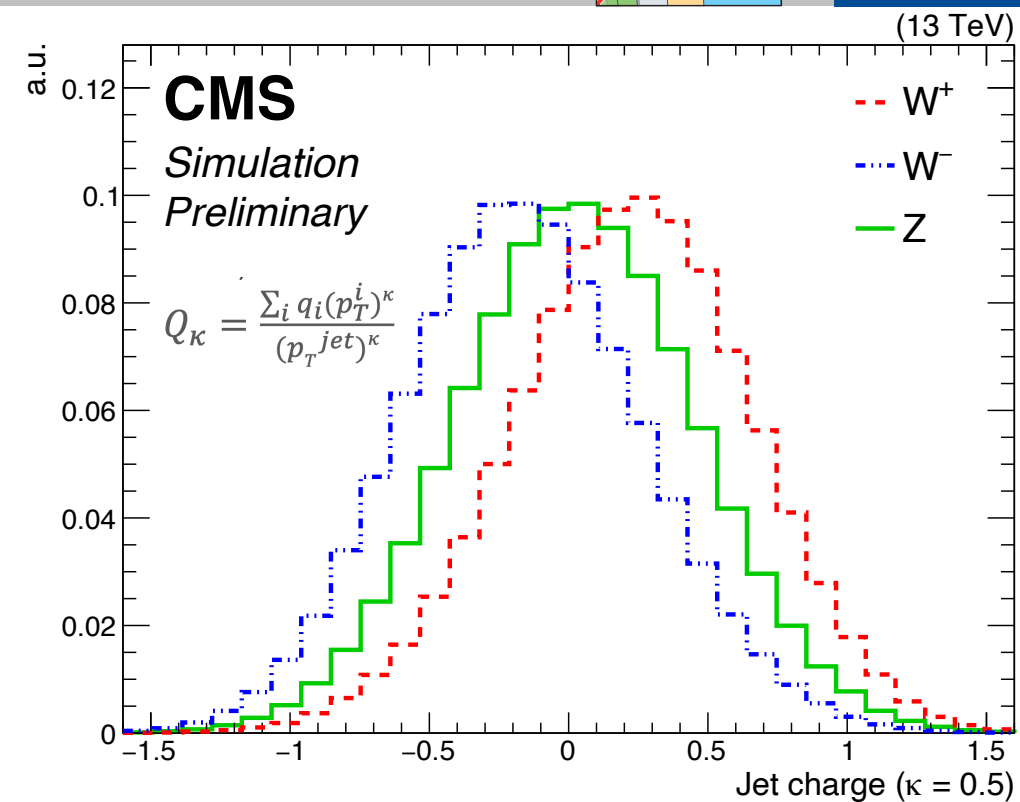
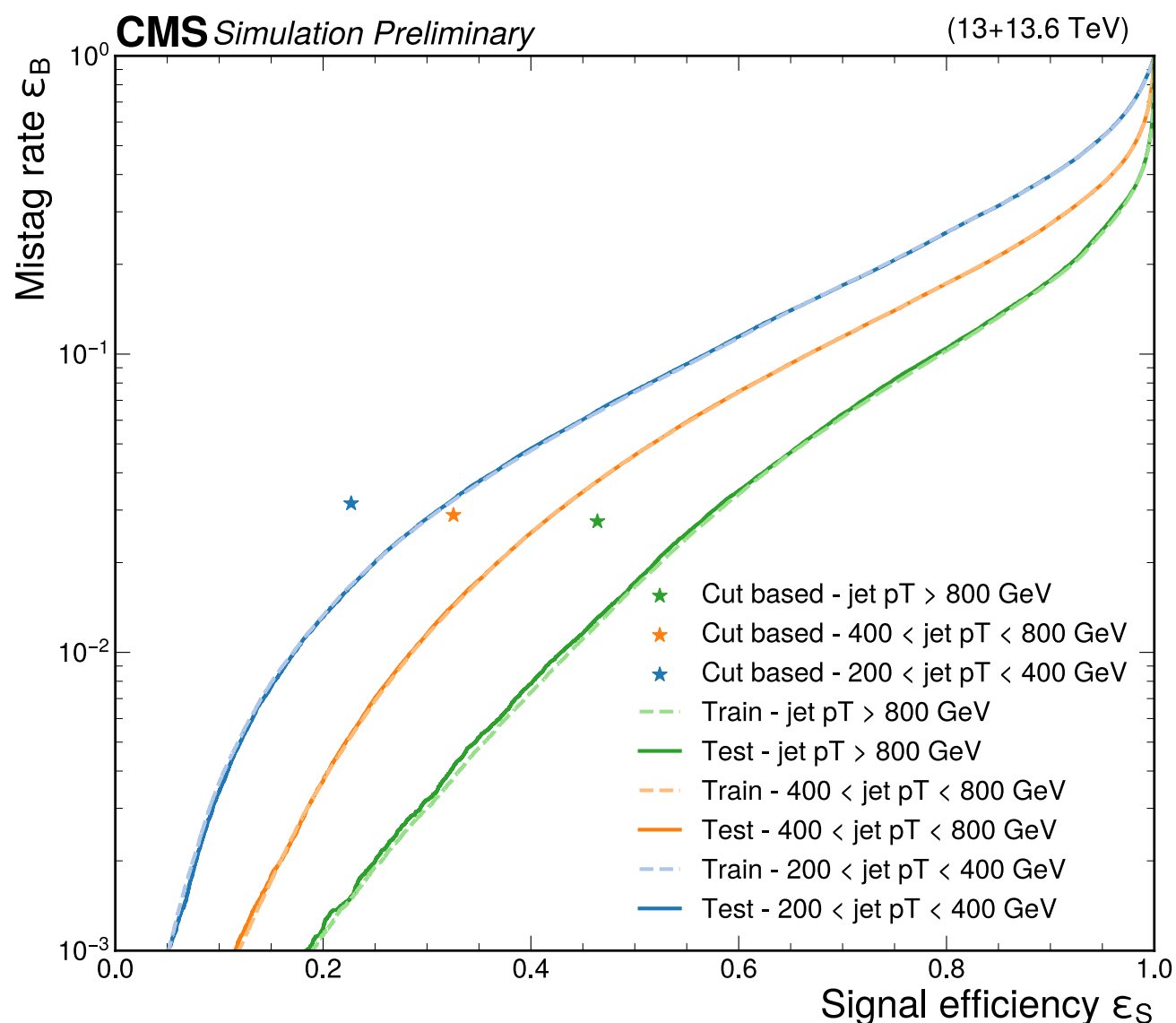
CMS-DP-2024-044



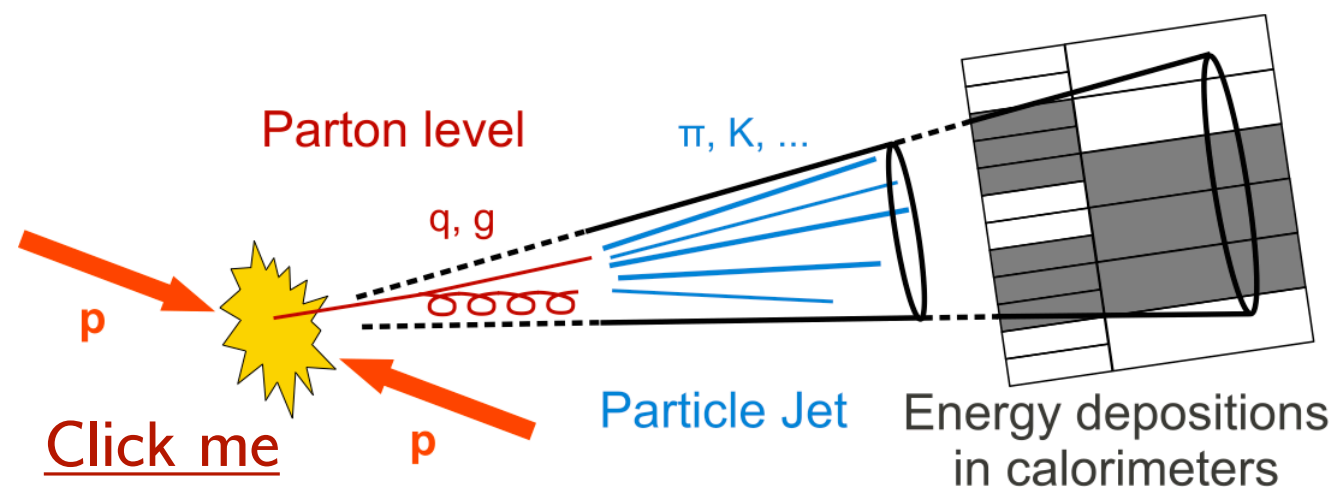
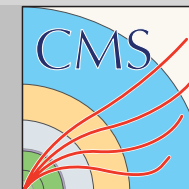
ULB

Tagging

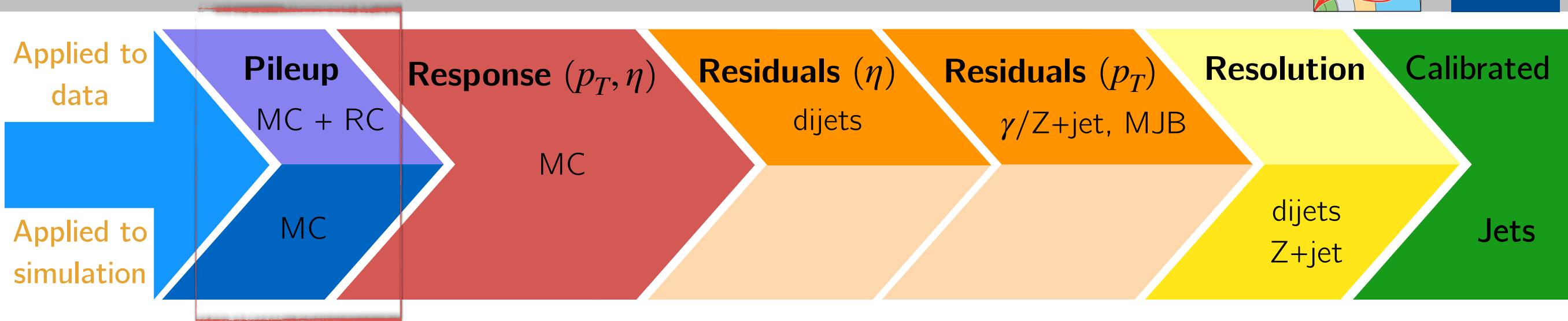
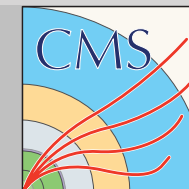
- ▶ New ML developments with:
 - ▶ HOTVR + BDT
 - ▶ Vector boson charge tagger



Jet calibration

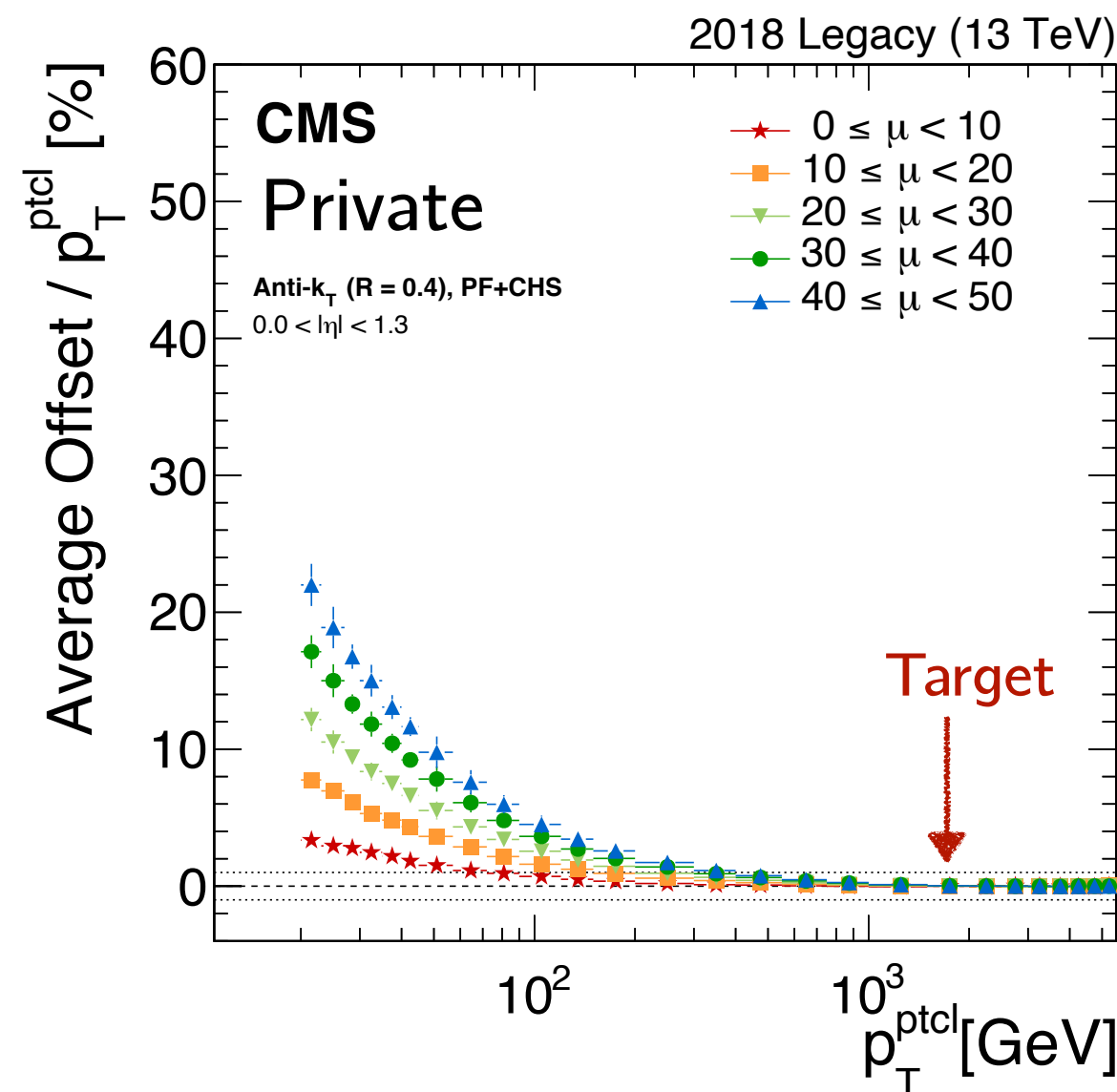


Jet calibration

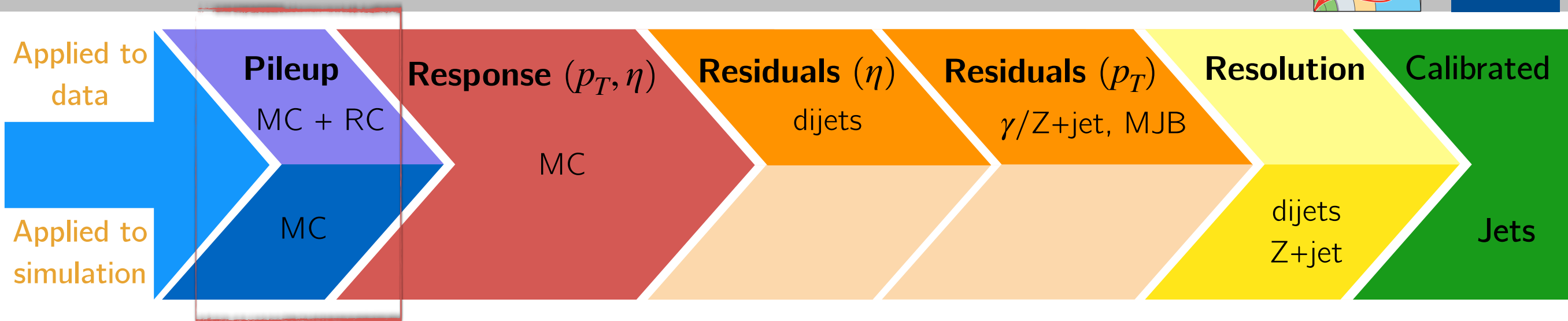


MC truth correction: PU subtraction

- ▶ Remove average offset due to PU
- ▶ Approx. 0.5 GeV extra energy per jet
- ▶ Neutral component not removed by CHS

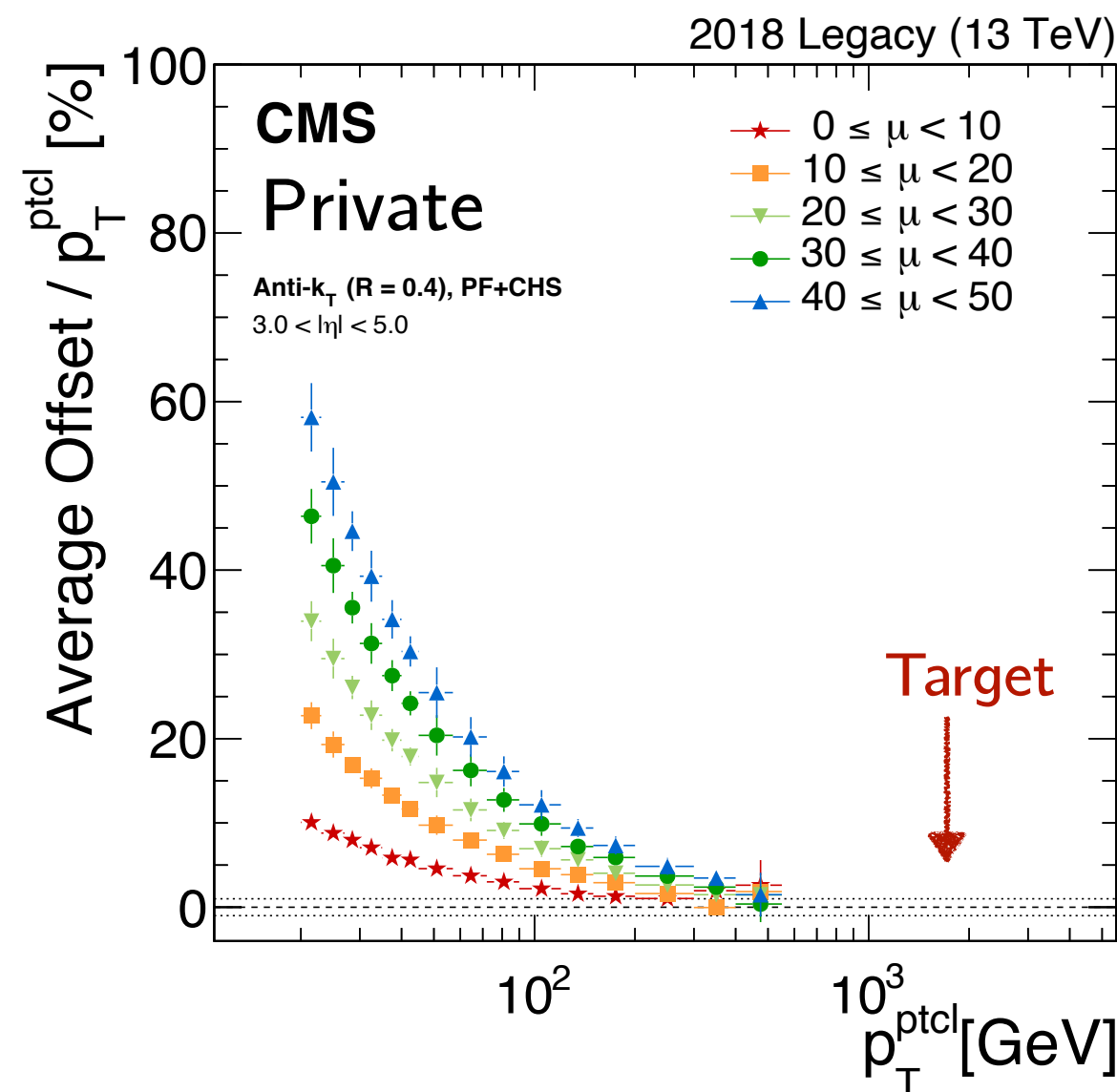


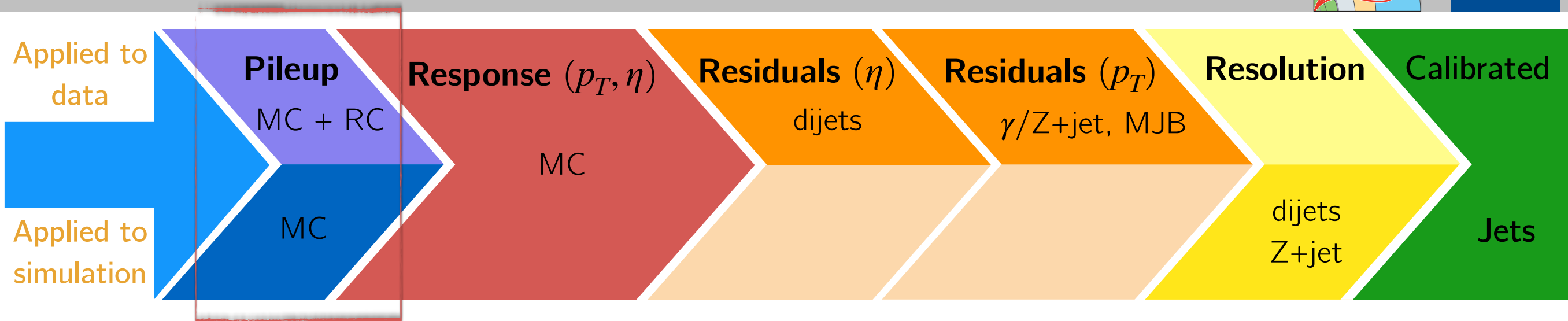
JEC DPNNotes Legacy



MC truth correction: PU subtraction

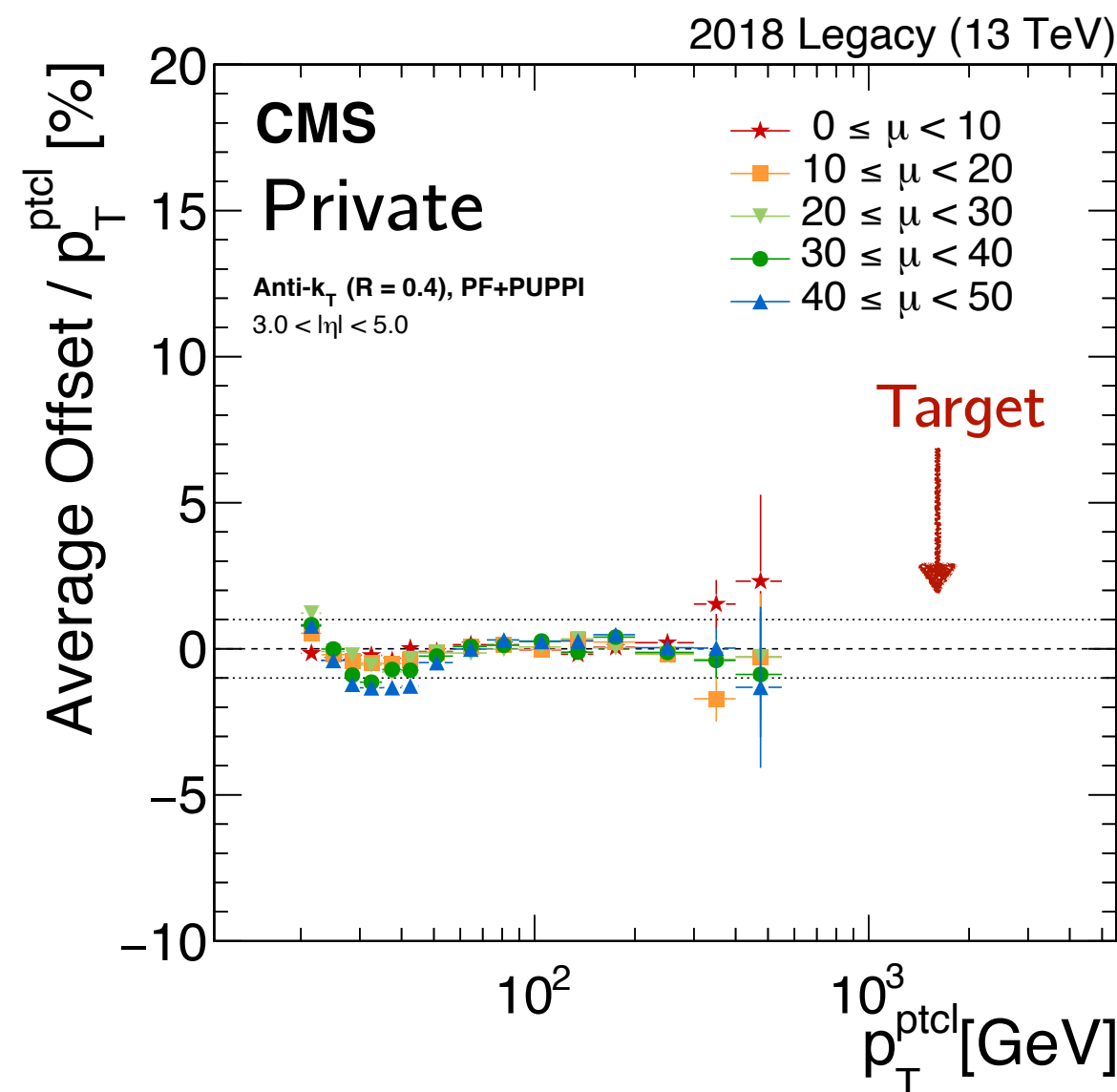
- ▶ Remove average offset due to PU
- ▶ Approx. 0.5 GeV extra energy per jet
- ▶ Neutral component not removed by CHS
- ▶ Significant outside tracker acceptance

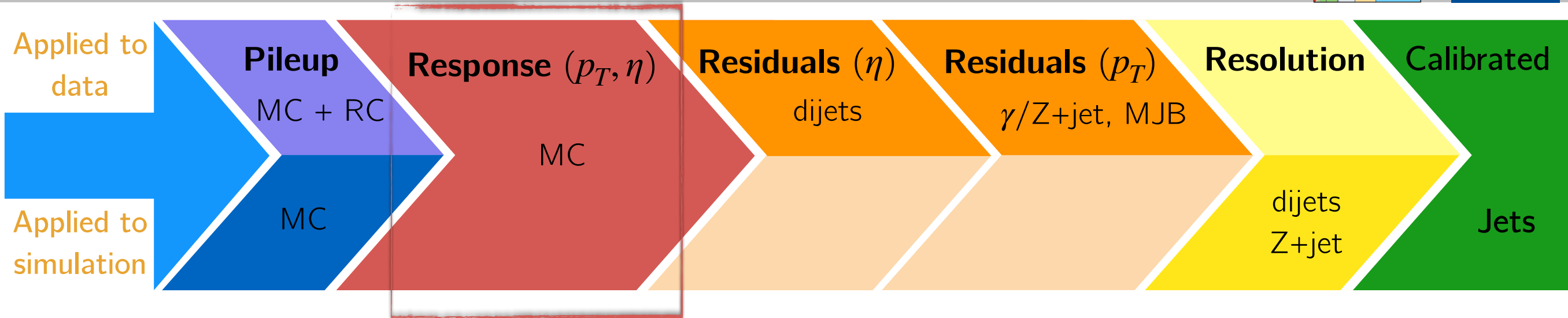




MC truth correction: PU subtraction

- ▶ Remove average offset due to PU
- ▶ Approx. 0.5 GeV extra energy per jet
- ▶ Neutral component not removed by CHS
- ▶ Significant outside tracker acceptance
- ▶ Not needed for Puppi



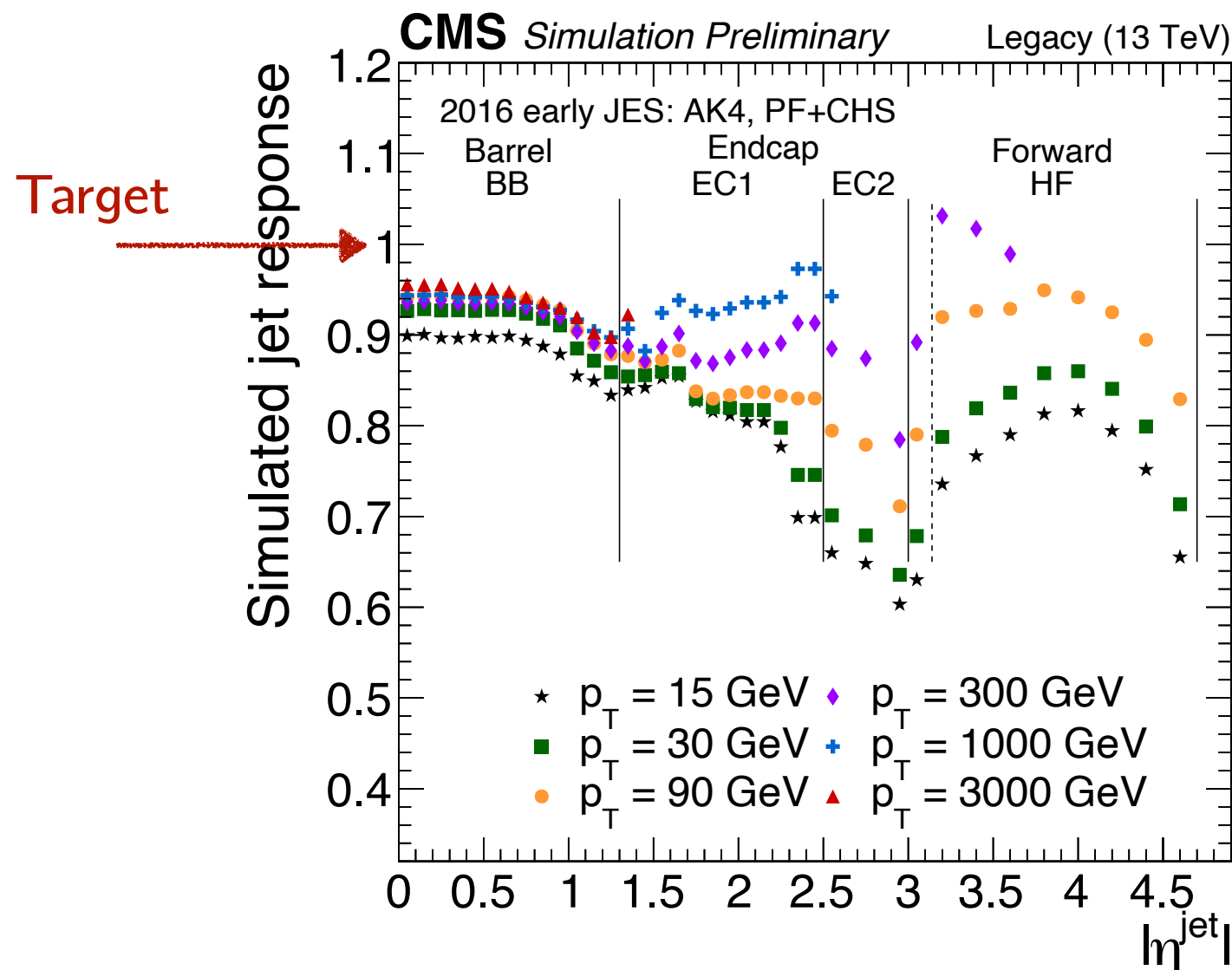


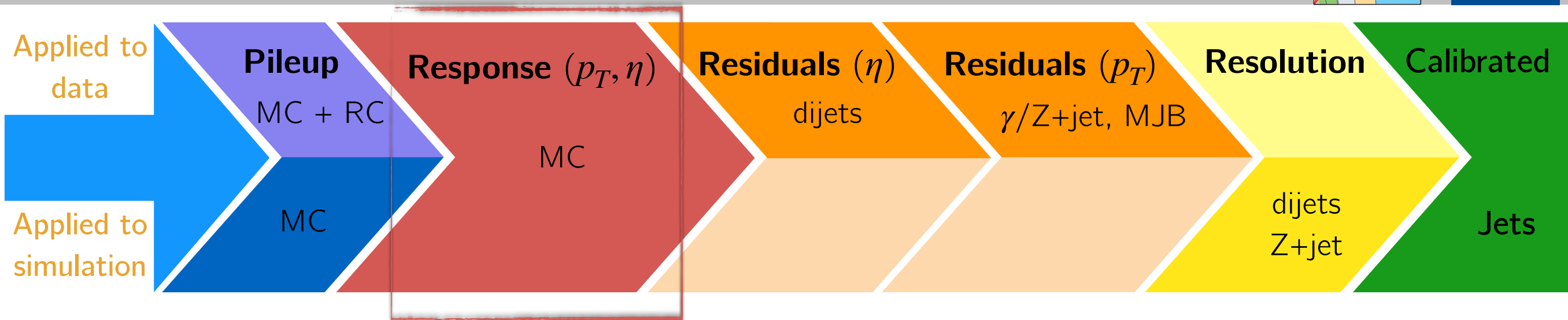
MC truth correction:

PU subtraction

Jet response calibration

- ▶ Core of the calibration
- ▶ Simulation-based
- ▶ Accounts for detector effects
- ▶ Change in performance due to detector acceptance



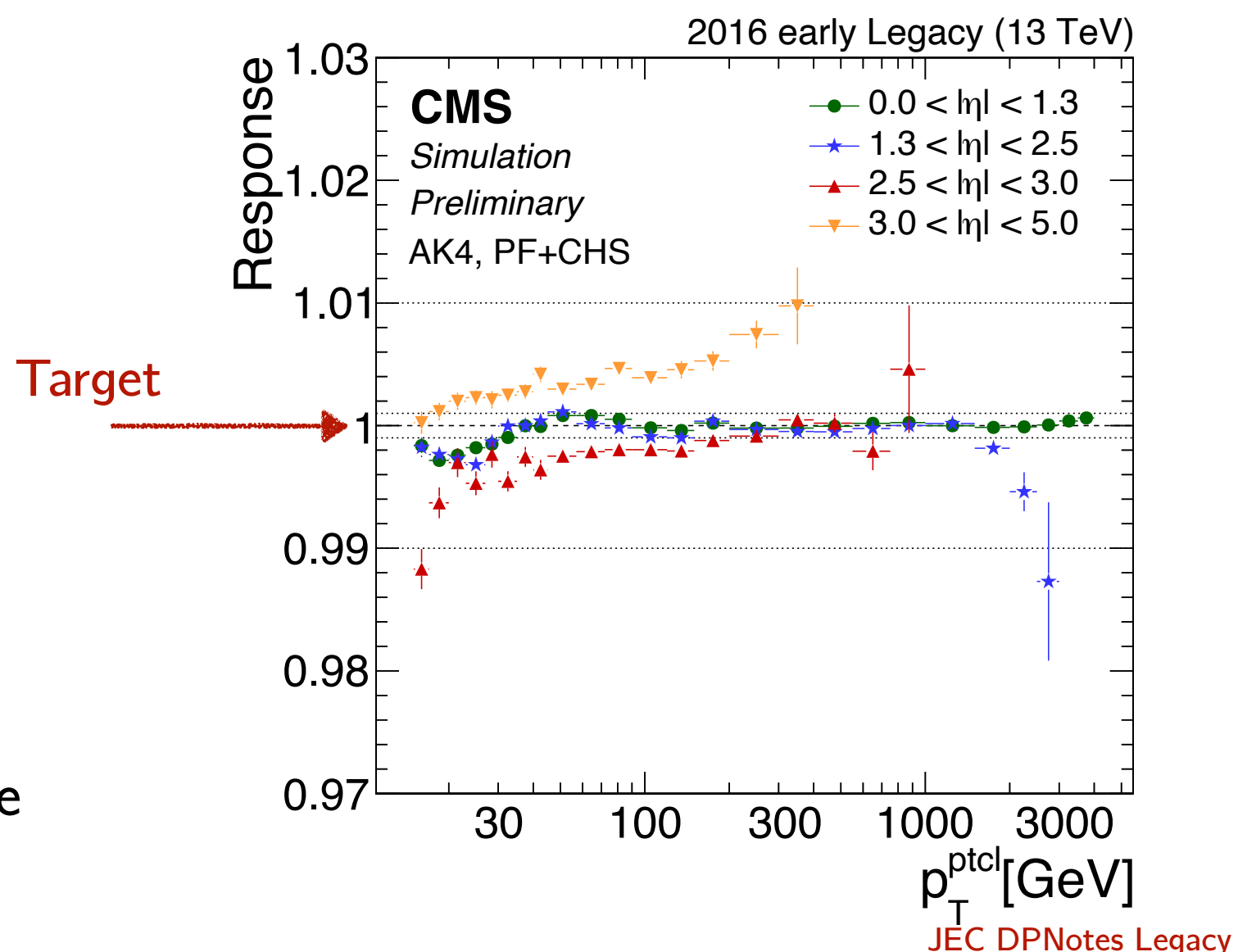


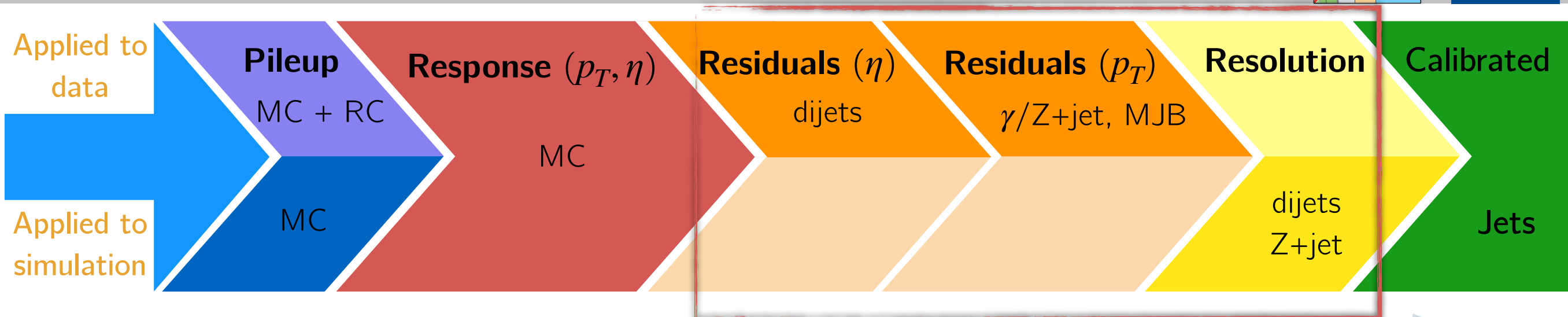
MC truth correction:

PU subtraction

Jet response calibration

- ▶ Core of the calibration
- ▶ Simulation-based
- ▶ Accounts for detector effects
- ▶ Change in performance due to detector acceptance
- ▶ Closure better than 1% everywhere (0.1% in central region)





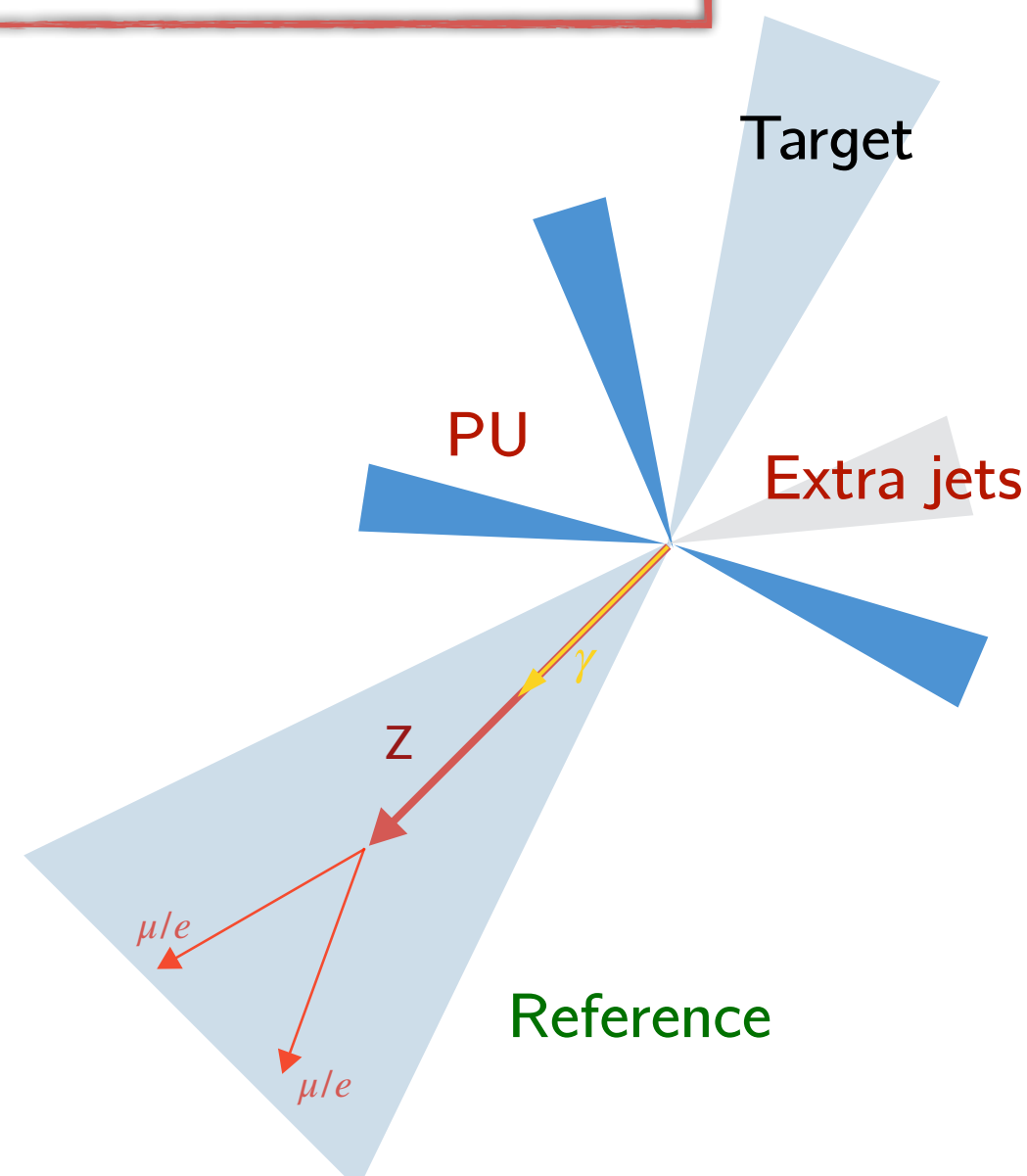
MC truth correction:

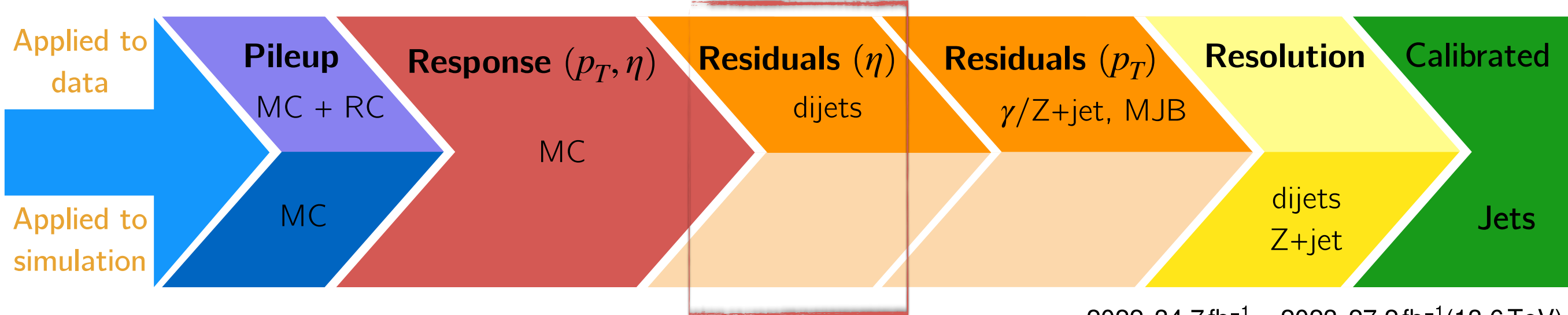
PU subtraction

Jet response calibration

Residual corrections

- ▶ Based on precision of other **reference** objects
 - ▶ Electrons, photons, muons, other jets...
- ▶ Truth level unknown
 - ▶ Data/Simulation to reduce bias
- ▶ Realistic events taken into account
 - ▶ Extra jets, additional interactions,...



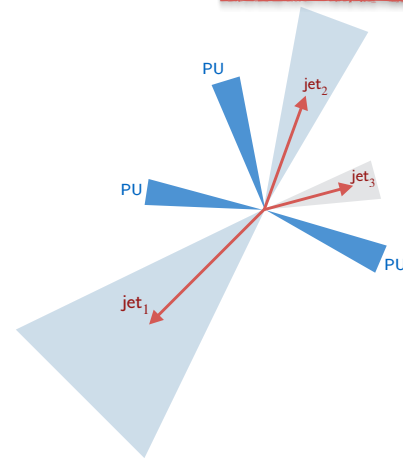


MC truth correction:

PU subtraction

Jet response calibration

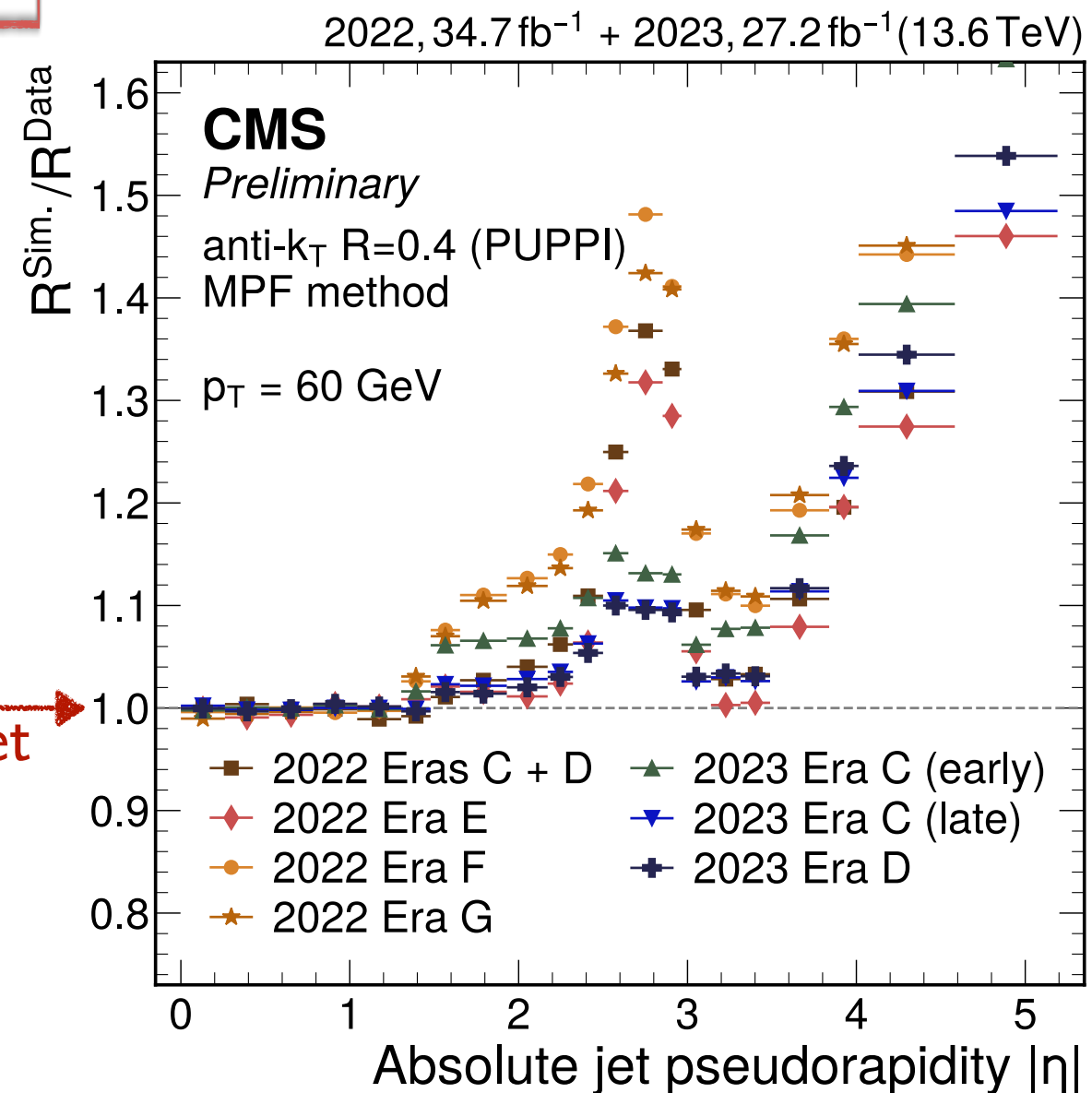
Residual corrections



▶ Small residual correction of jet response applied to data based on dijet topology

▶ Address different response in each sub-detector (η dep.)

Target



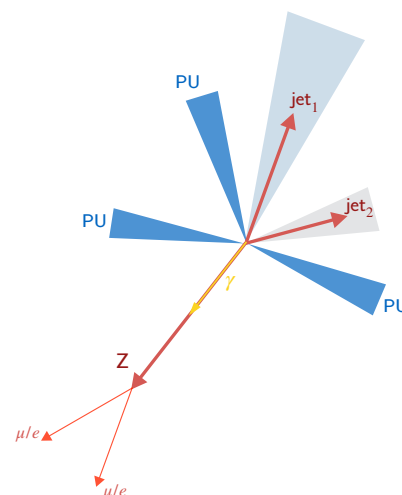


MC truth correction:

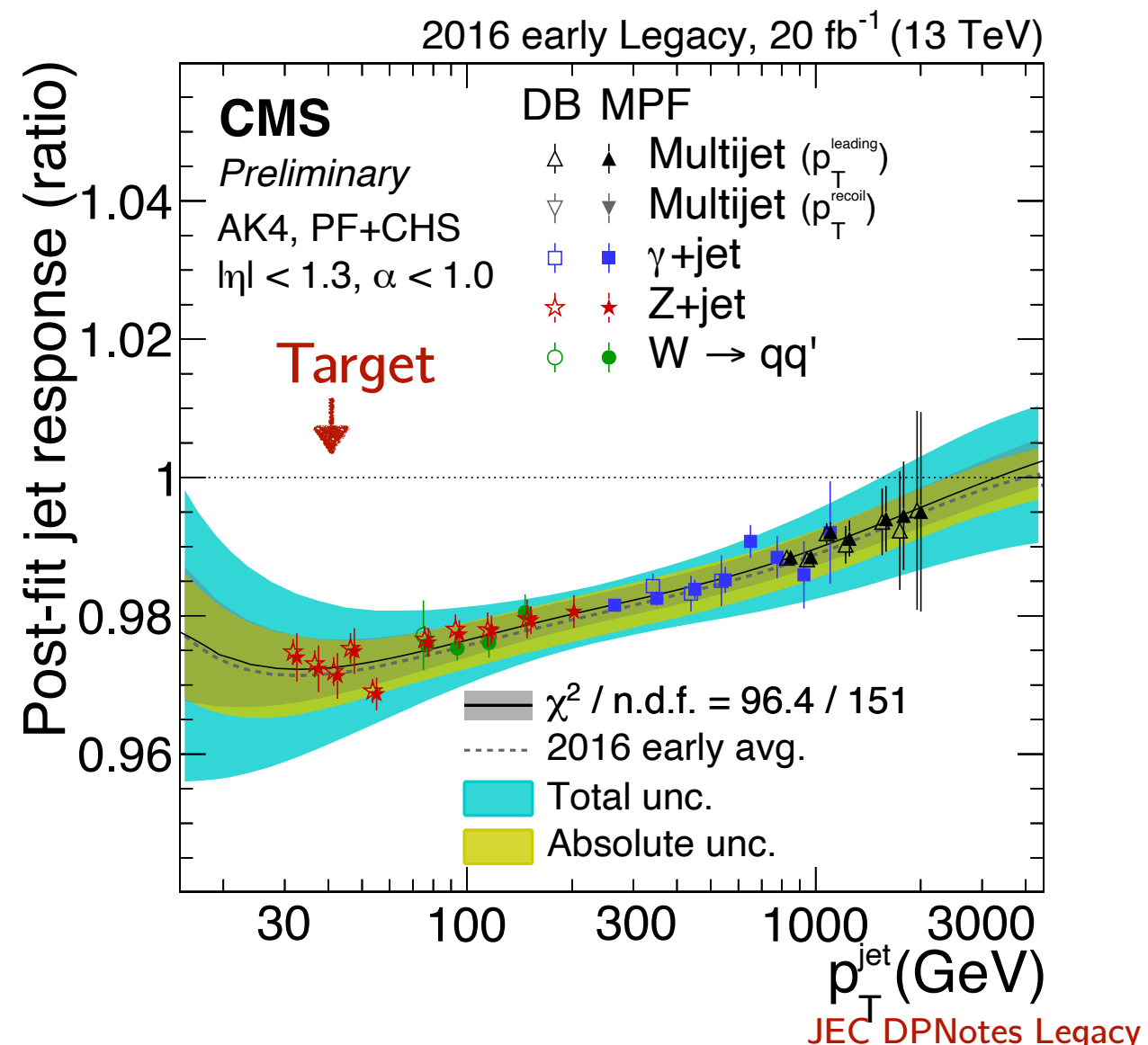
PU subtraction

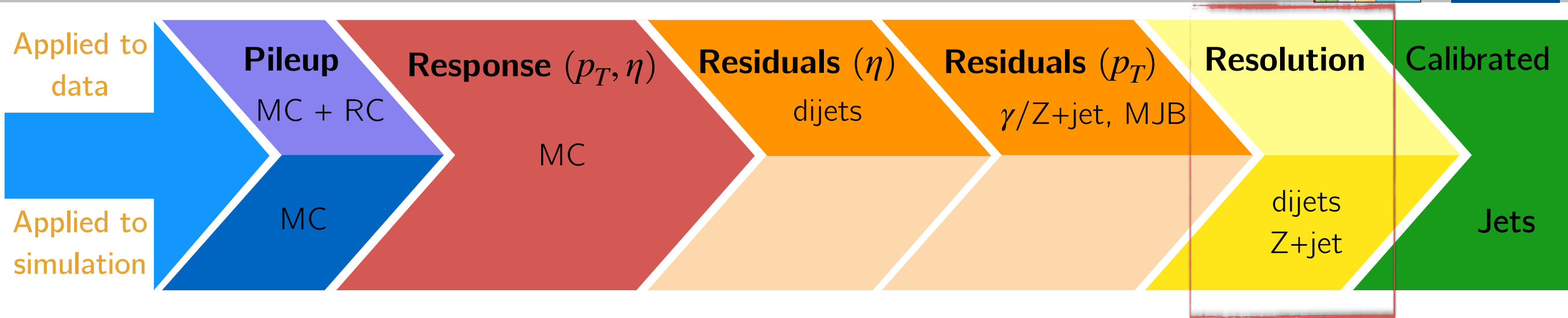
Jet response calibration

Residual corrections



- ▶ Additional p_T -dependent corrections accounting for absolute scale in barrel
- ▶ Determined relative to precisely measured reference objects (μ , e , γ , W)
- ▶ Channels combined in a global fit
 - ▶ Exploit individual precision in each phase-space





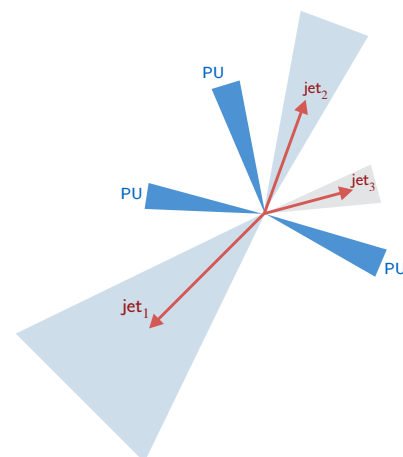
MC truth correction:

PU subtraction

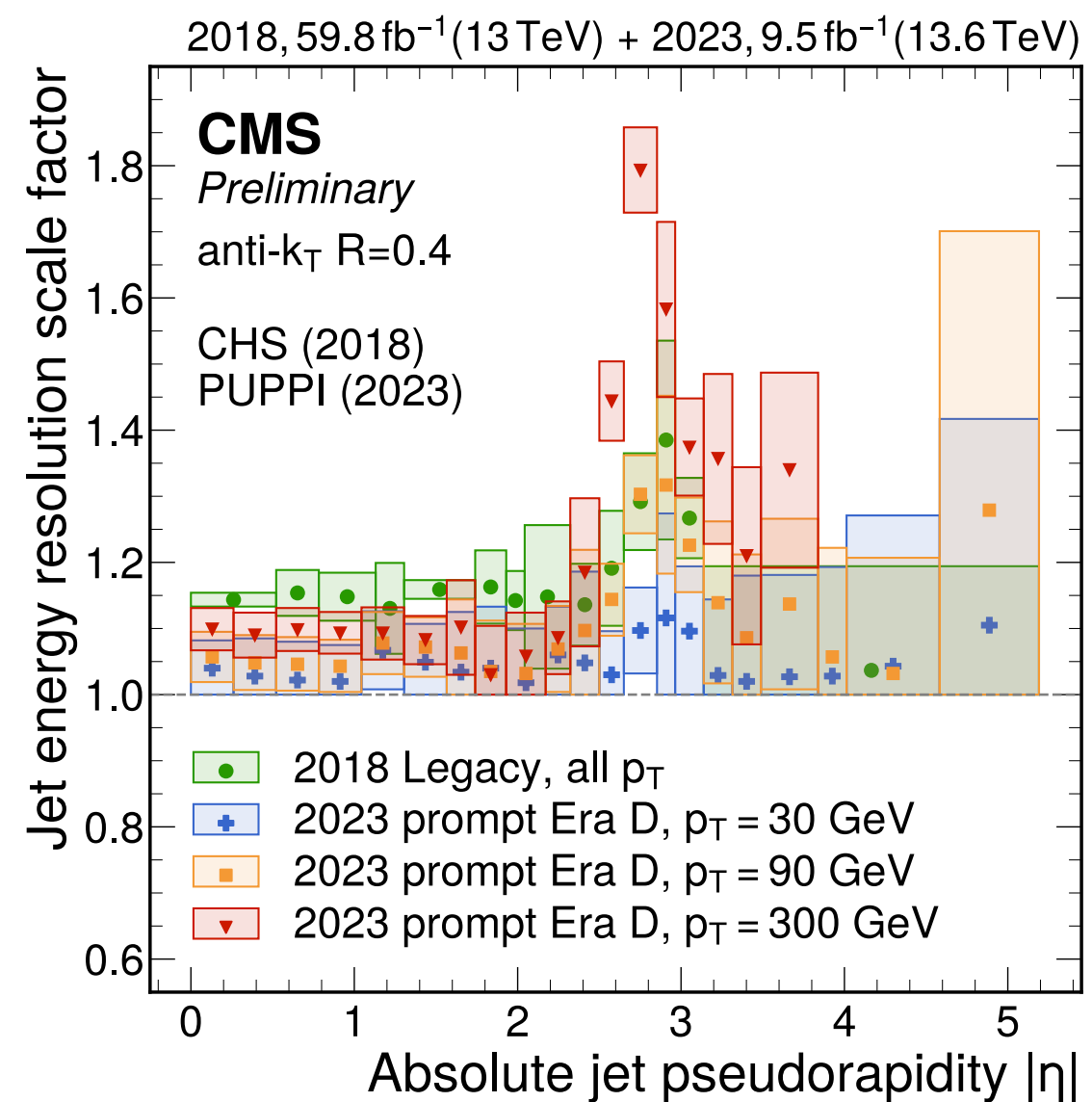
Jet response calibration

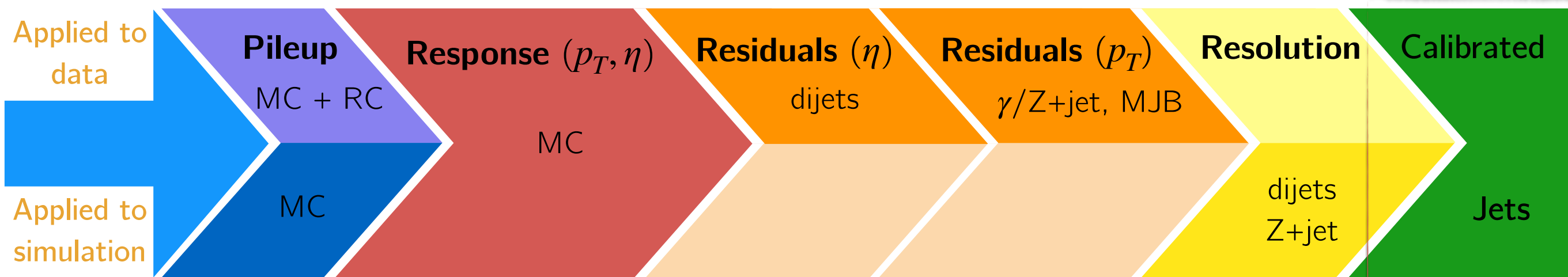
Residual corrections

Jet energy resolution smearing



- ▶ Scale factors (SFs) applied to simulation to match resolution in data
- ▶ Direct balance in dijet events
- ▶ Sensitive to detector changes/calibration





MC truth correction:

PU subtraction

Jet response calibration

Residual corrections

Jet energy resolution smearing

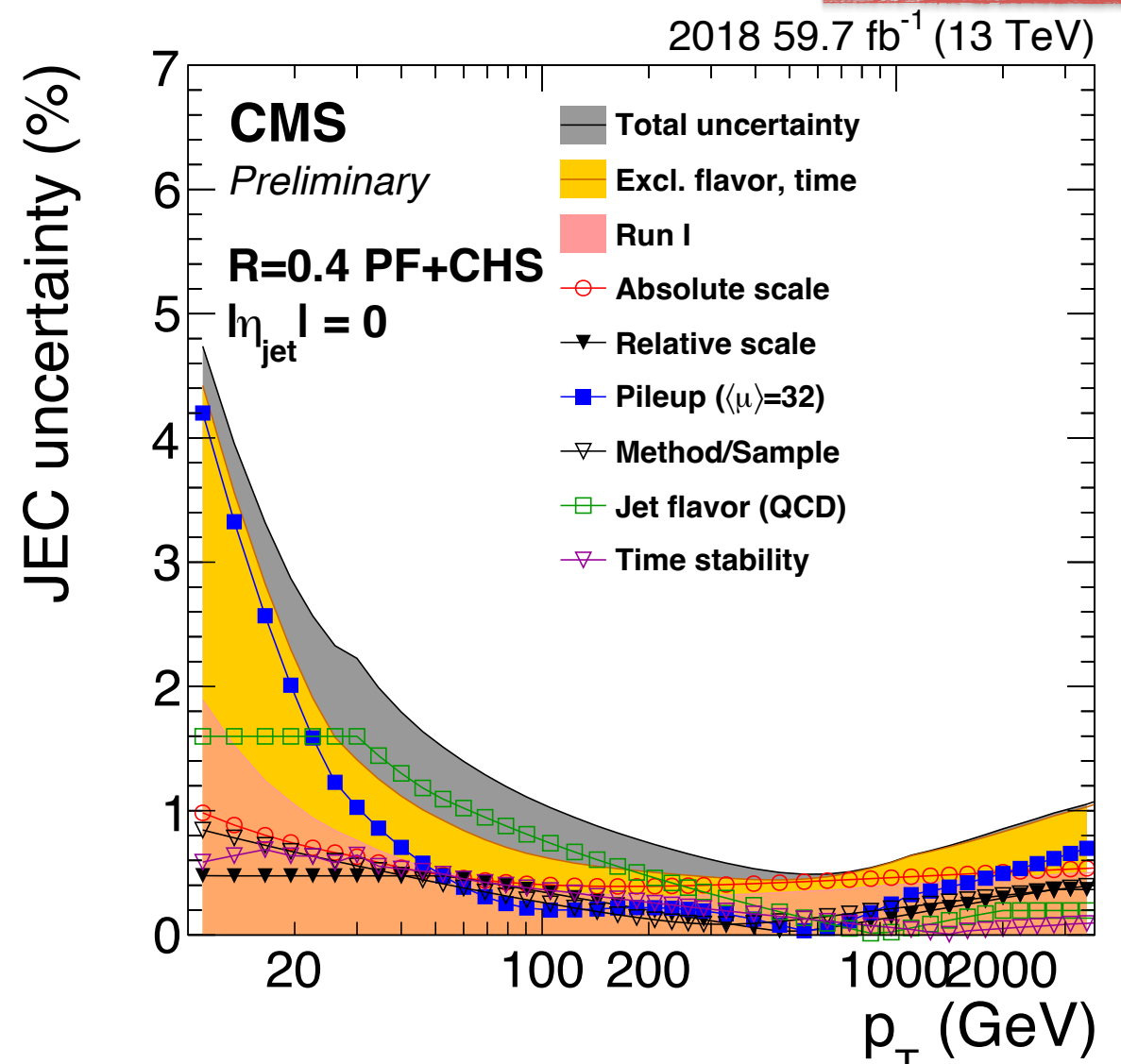
Jet energy scale uncertainties

► Uncertainty $\sim 1\%$ for jets $p_T > 100$ GeV

► Increasing contribution from PU

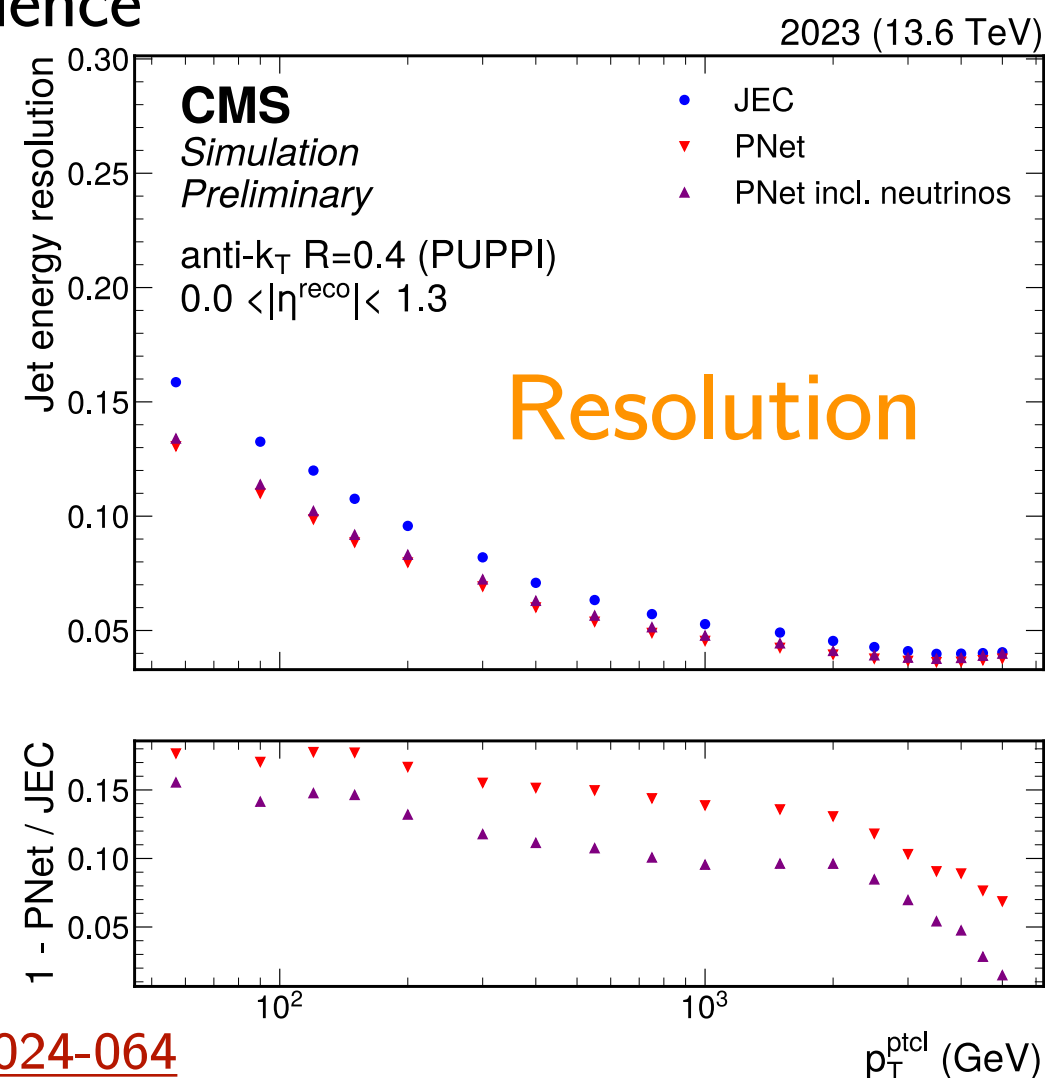
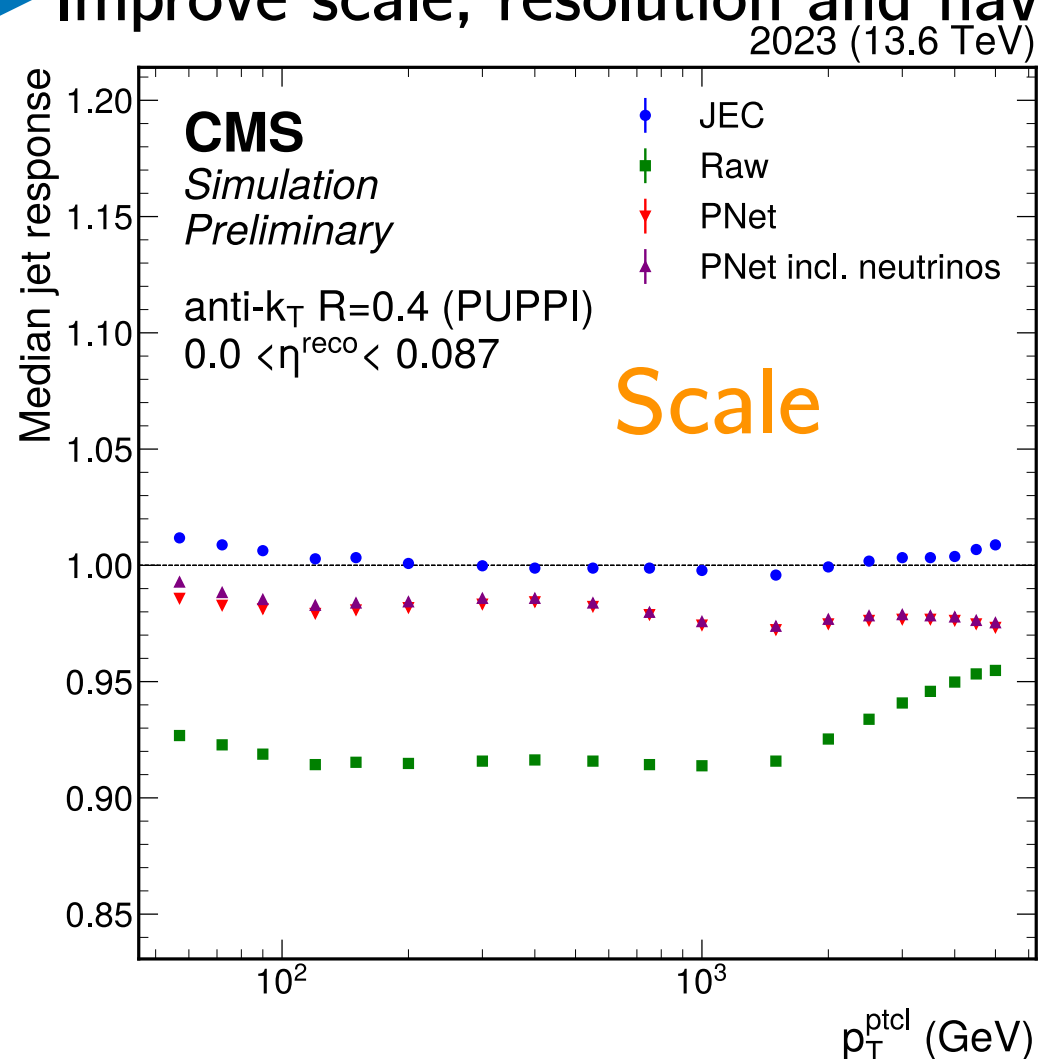
► Detector degradation:

► Ageing, damage, ...



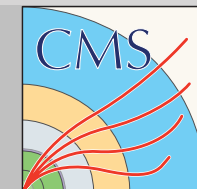
Machine learning:

- ▶ More performant wrt traditional algorithms
- ▶ Currently used for jet mass regression:
 - ▶ Direct effect on analyses's sensitivity
- ▶ Simultaneous training of tagging and regression for energy and mass:
 - ▶ Improve scale, resolution and flavour dependence

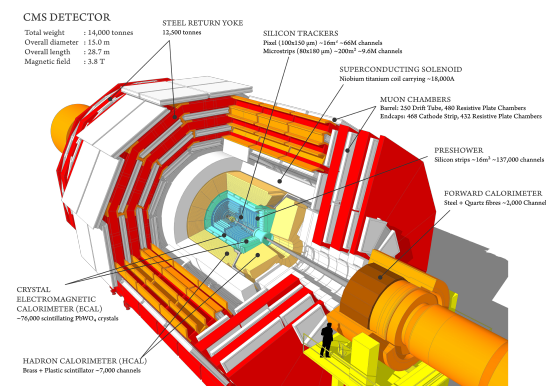


[CMS-DP-2024-064](#)

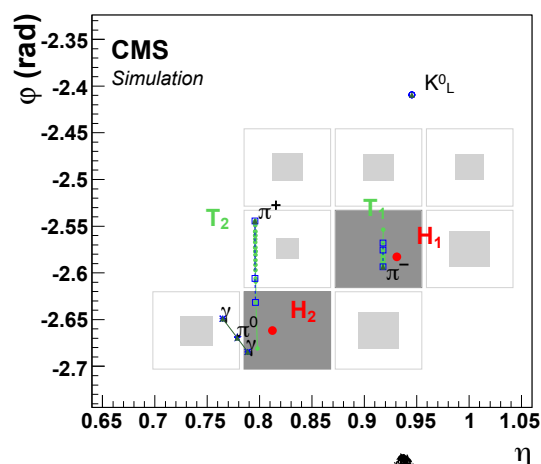
Summary and Outlook



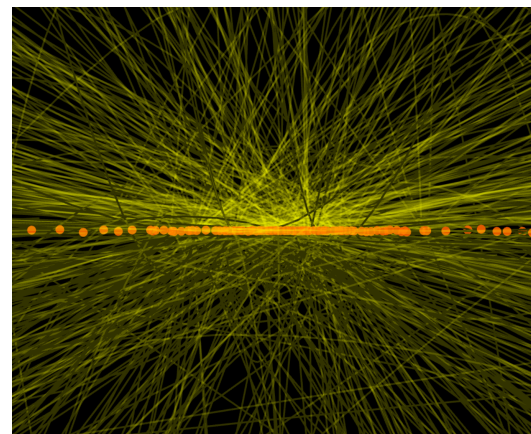
Detector



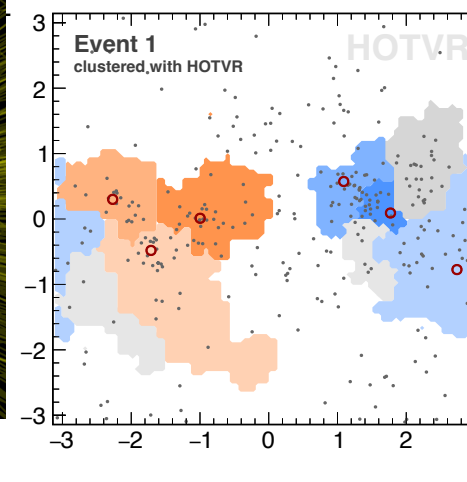
Reconstruction



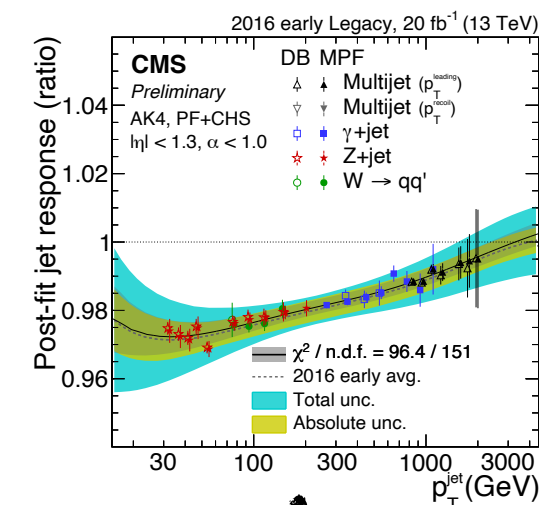
Pileup



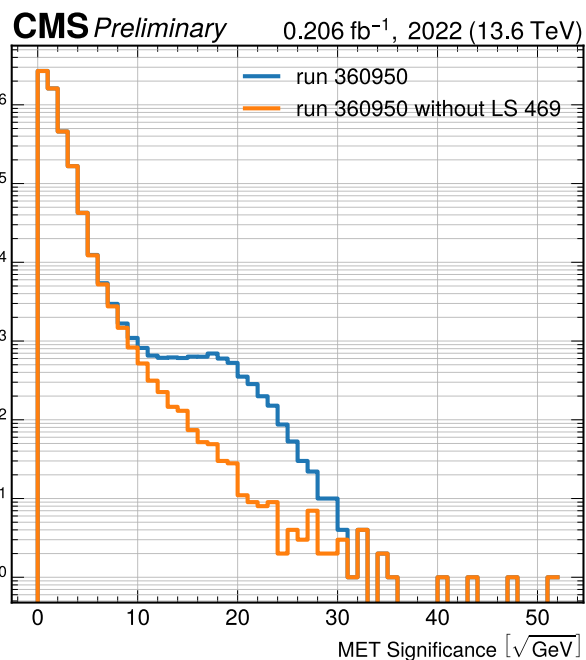
Clustering



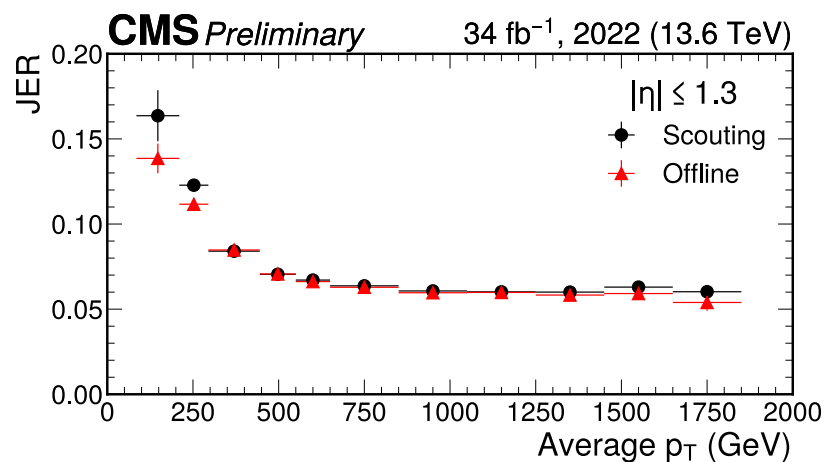
Calibration



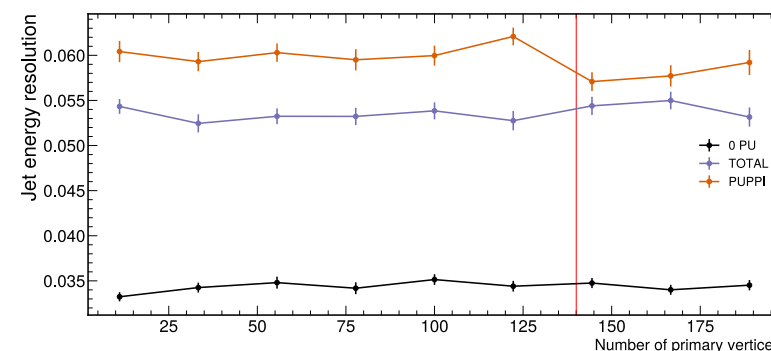
Anomaly detection



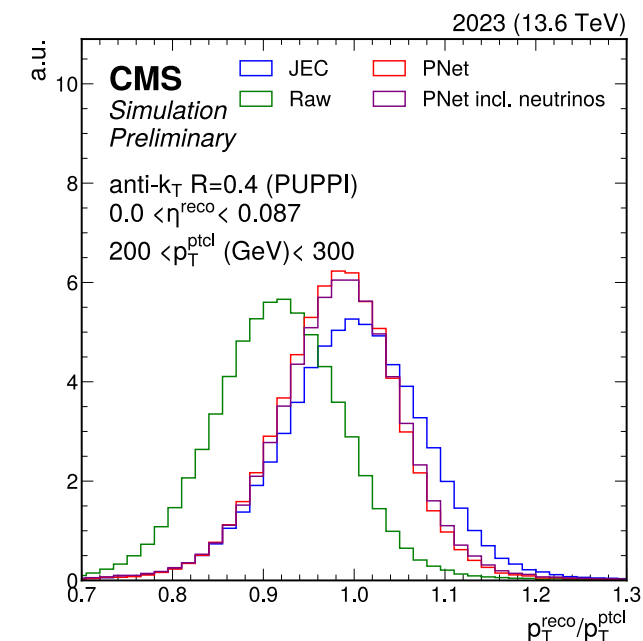
HLT scouting



ML for PU mitigation

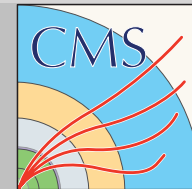


ML pT regression



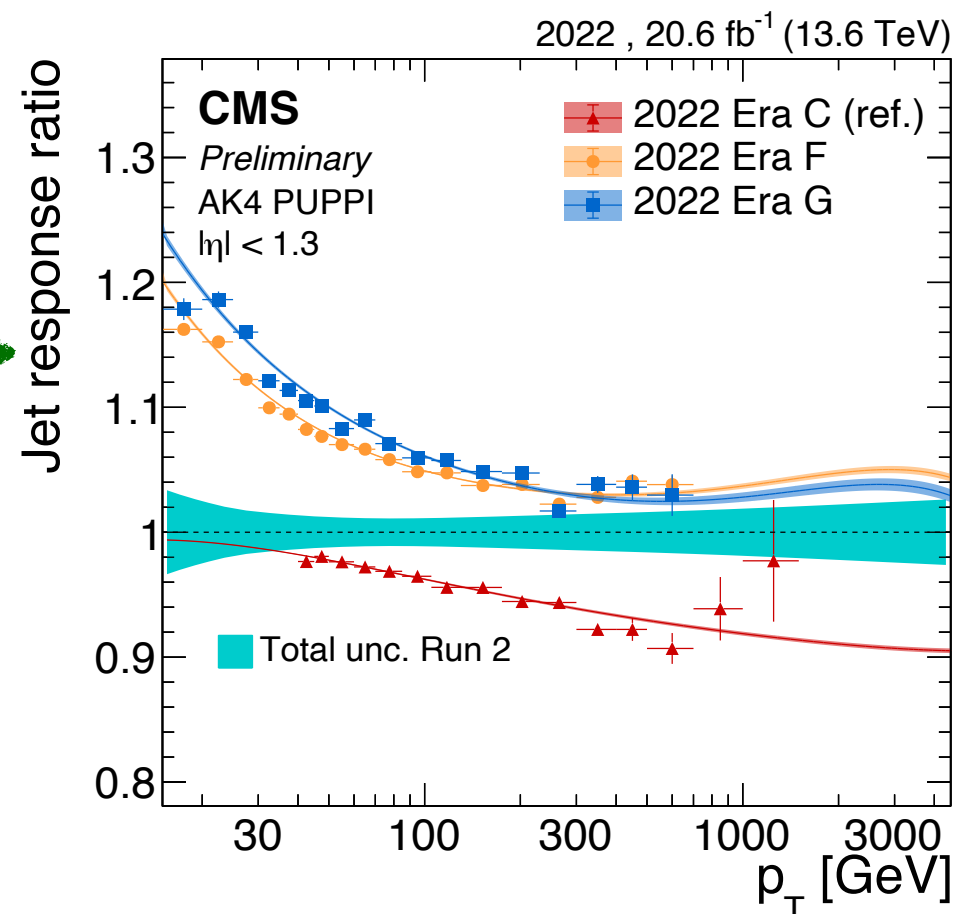
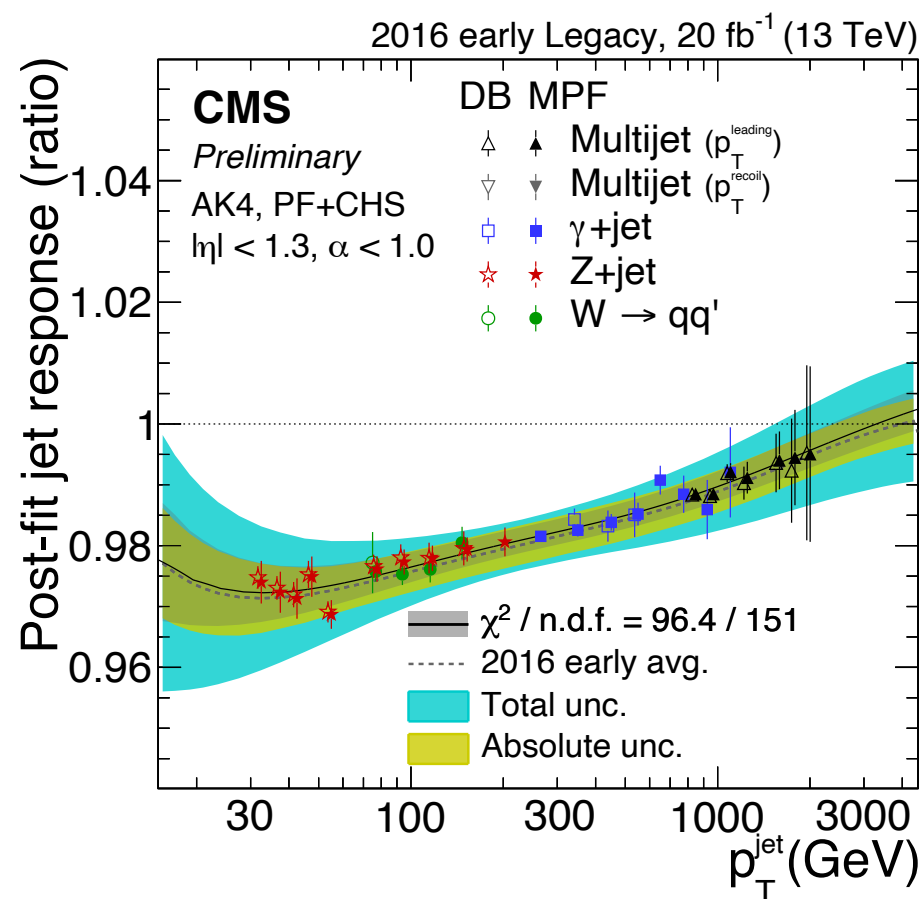
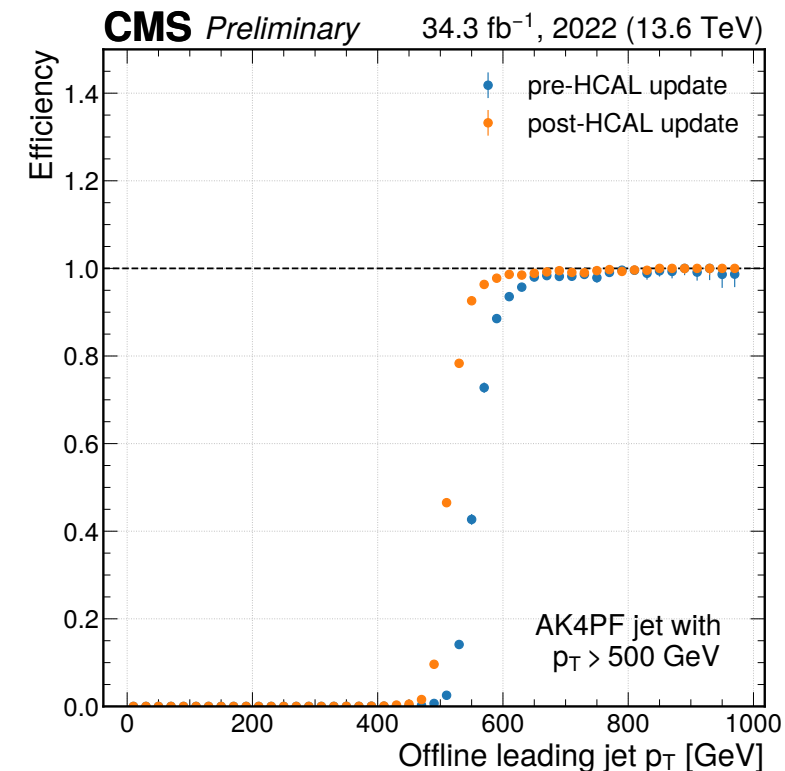

~~~ **Additional Material** ~~~

# Current and future developments



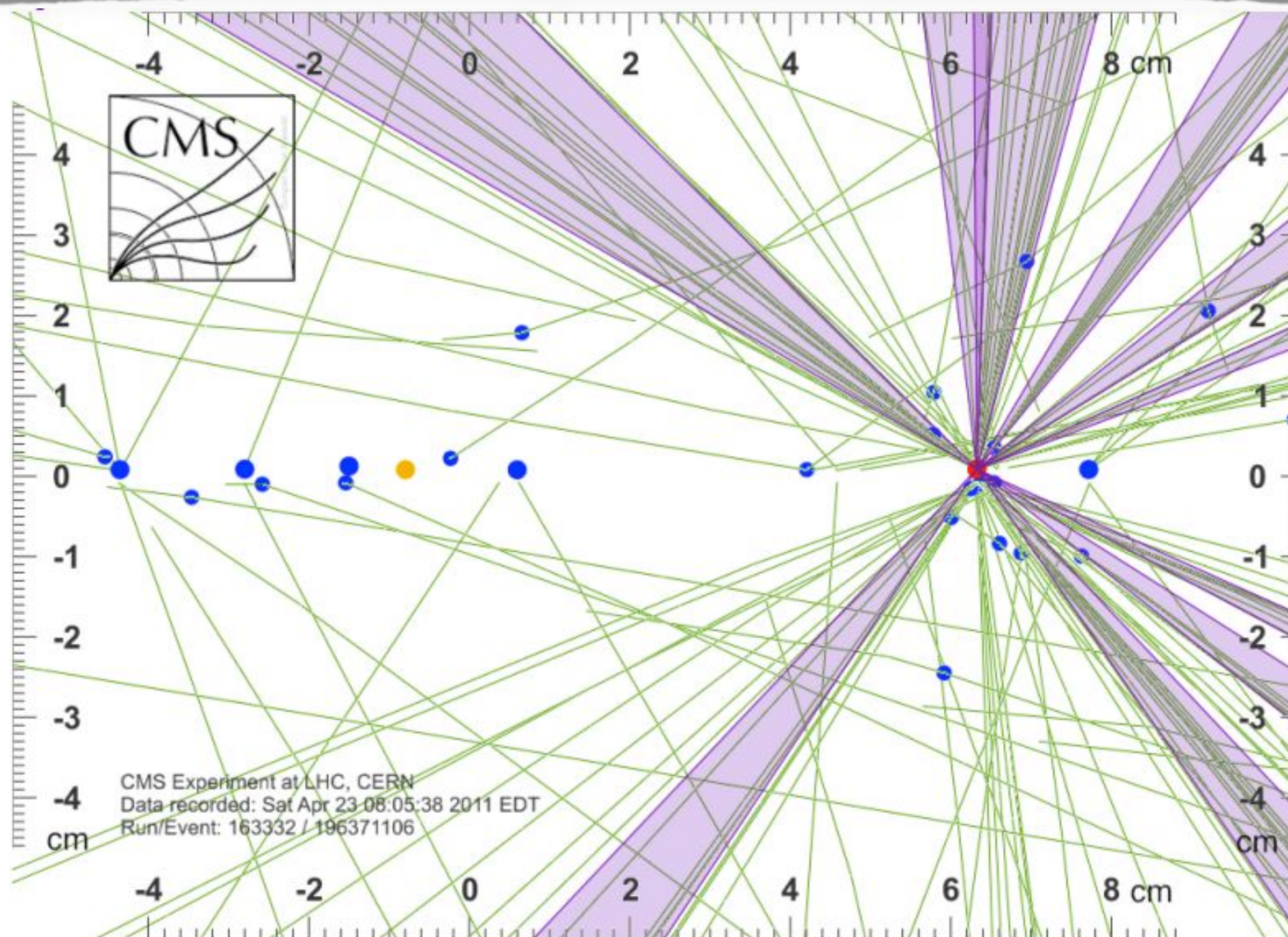
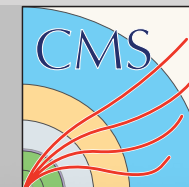
## Run3 calibration

- ▶ Usually small corrections for data offline...
- ▶ ... corresponds to small effect on data online (triggers)
- ▶ Run3:
  - ▶ Substantial corrections needed ( $\sim 10/20\%$ , up to x2 in endcaps)
  - ▶ Fraction of data collected less efficiently



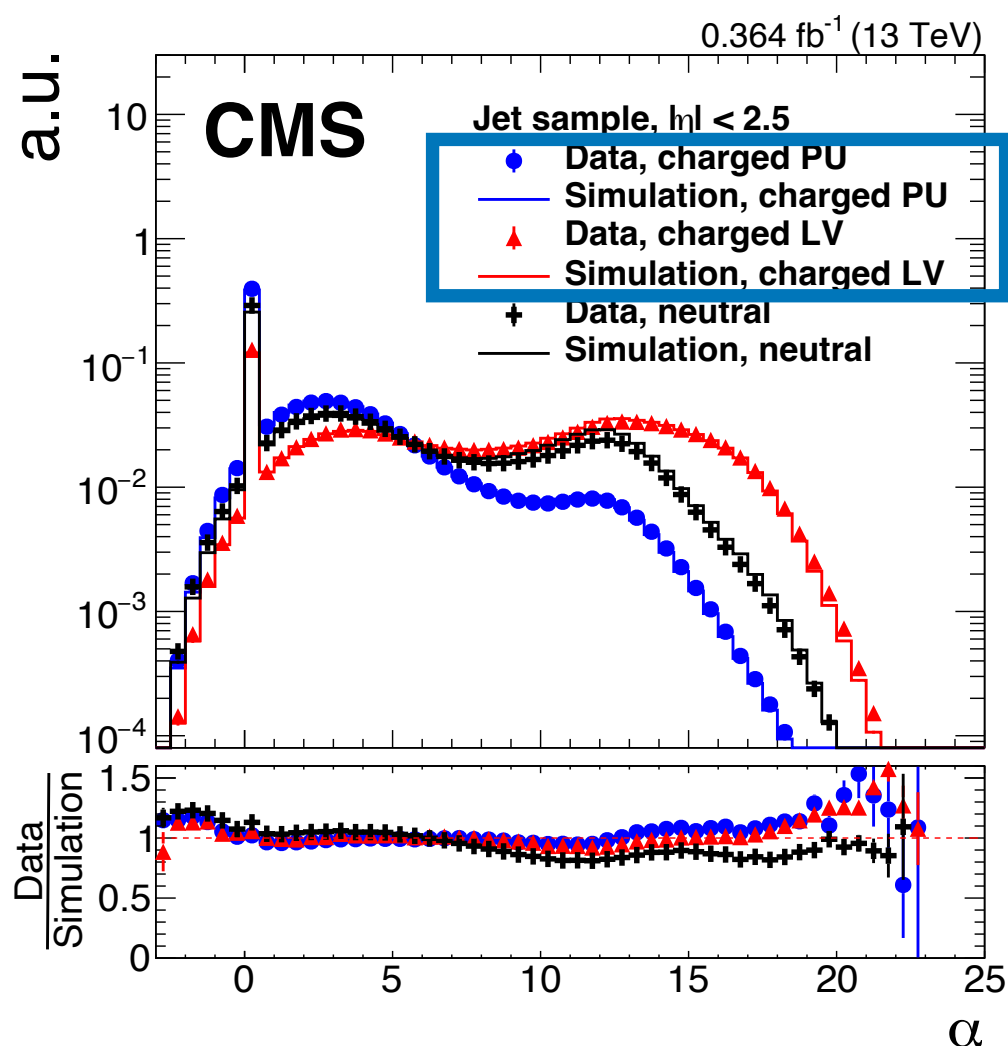


# PUPPI in Detail

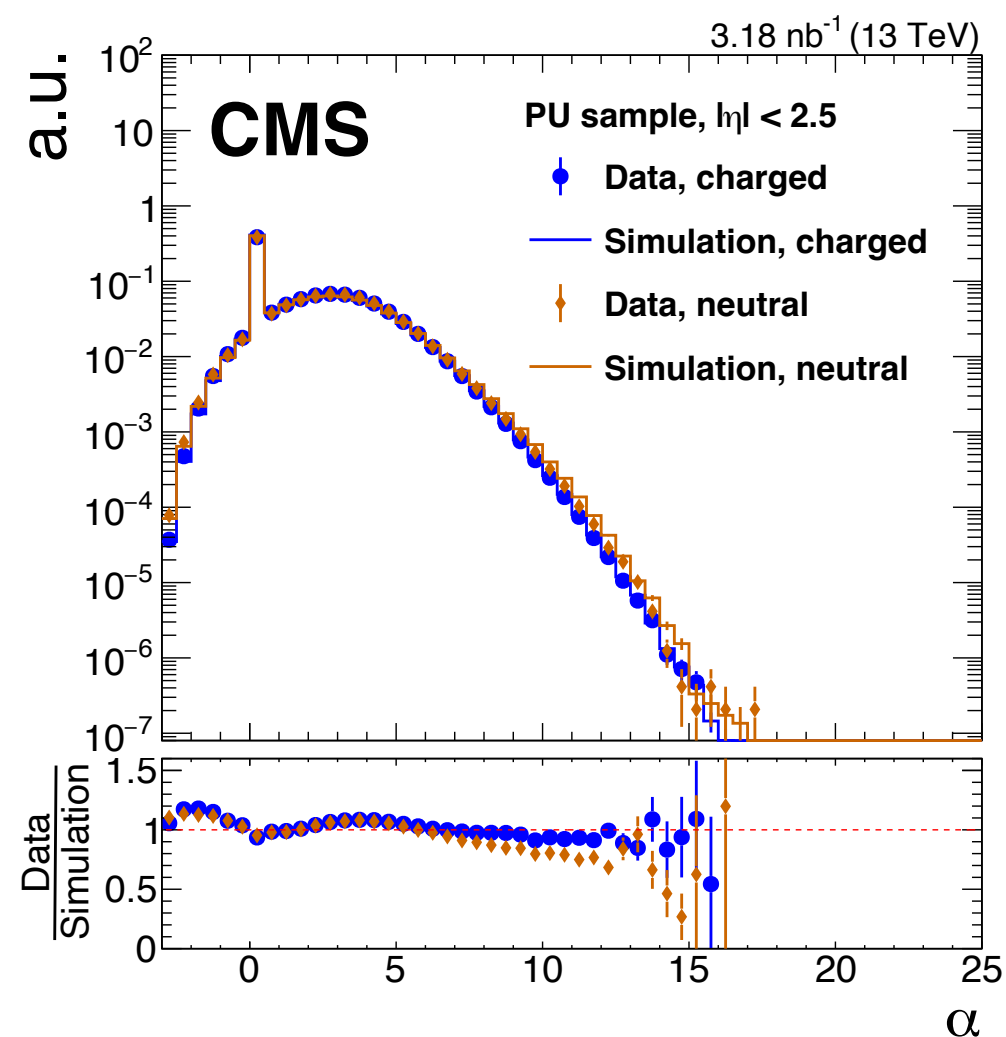


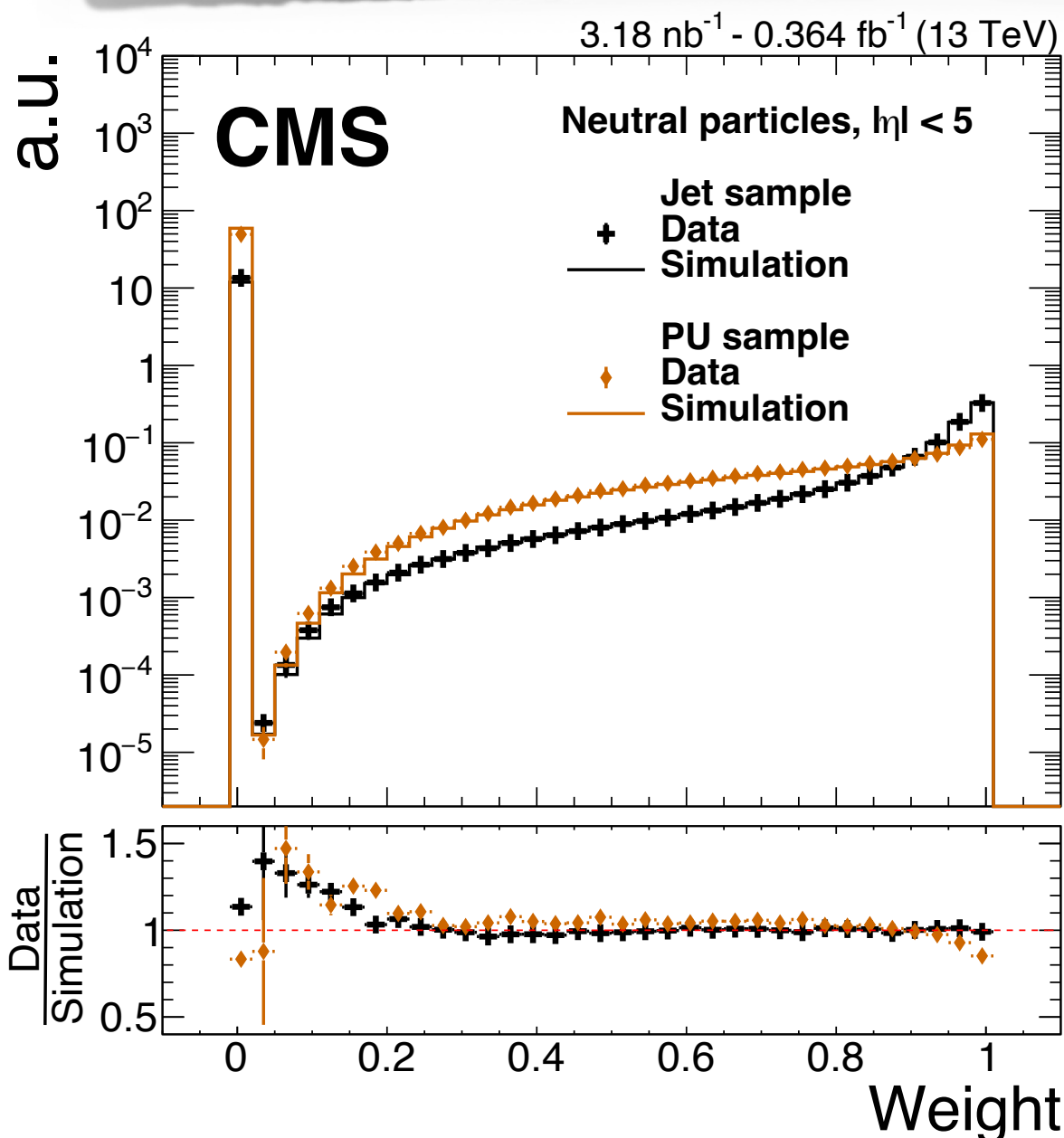


$$\alpha_i = \log \sum_{j \neq i, \Delta R_{ij} < R_0} \left( \frac{p_{Tj}}{\Delta R_{ij}} \right)^2 \begin{cases} \text{for } |\eta_i| < 2.5, & j \text{ are charged particles from leading vertex} \\ \text{for } |\eta_i| > 2.5, & j \text{ are all kinds of reconstructed particles} \end{cases}$$



$$\alpha_i = \log \sum_{j \neq i, \Delta R_{ij} < R_0} \left( \frac{p_{Tj}}{\Delta R_{ij}} \right)^2 \begin{cases} \text{for } |\eta_i| < 2.5, & j \text{ are charged particles from leading vertex} \\ \text{for } |\eta_i| > 2.5, & j \text{ are all kinds of reconstructed particles} \end{cases}$$





1. For each particle calculate

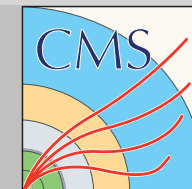
$$\chi_i^2 = \frac{(\alpha_i - \bar{\alpha}_{PU}) | \alpha_i - \bar{\alpha}_{PU} |}{RMS_{PU}^2}$$

2. Assign a weight to each particle

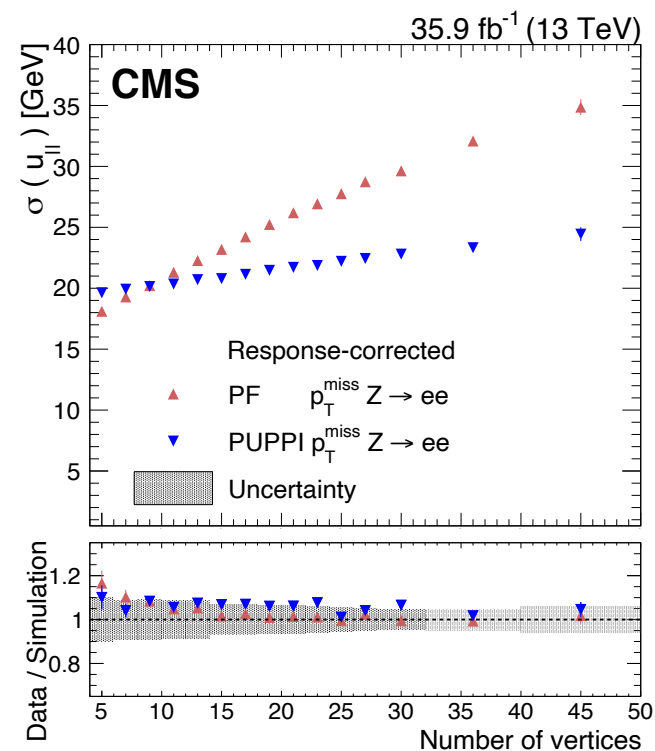
$$w_i = F_{\chi^2, NDF=1}(\chi_i^2)$$

Pileup  $\longrightarrow$  Hard scattering

# Validation of PUPPI

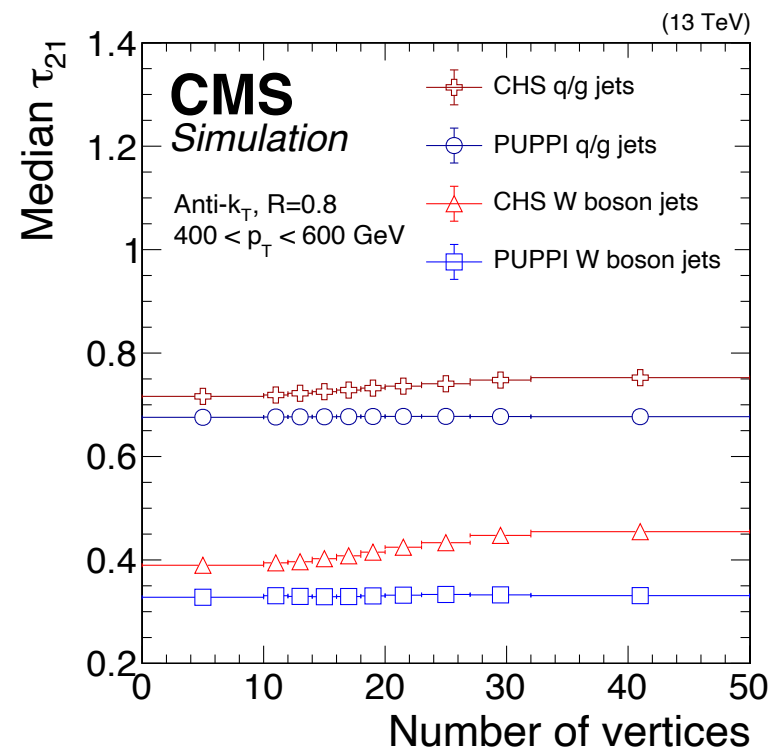


Performances of PUPPI jets/MET were extensively studied and compared to CHS jets/PF MET in JME-18-001



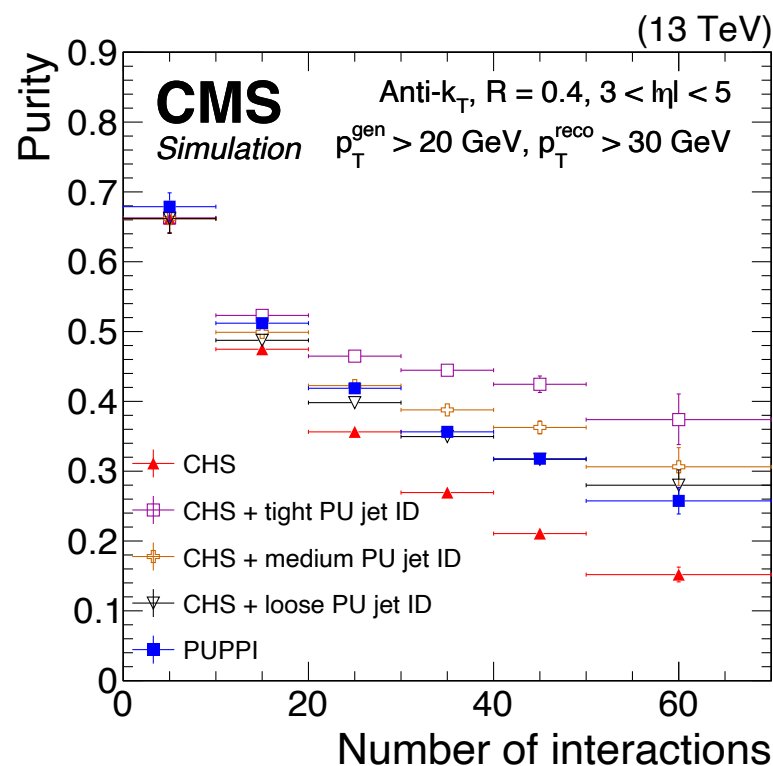
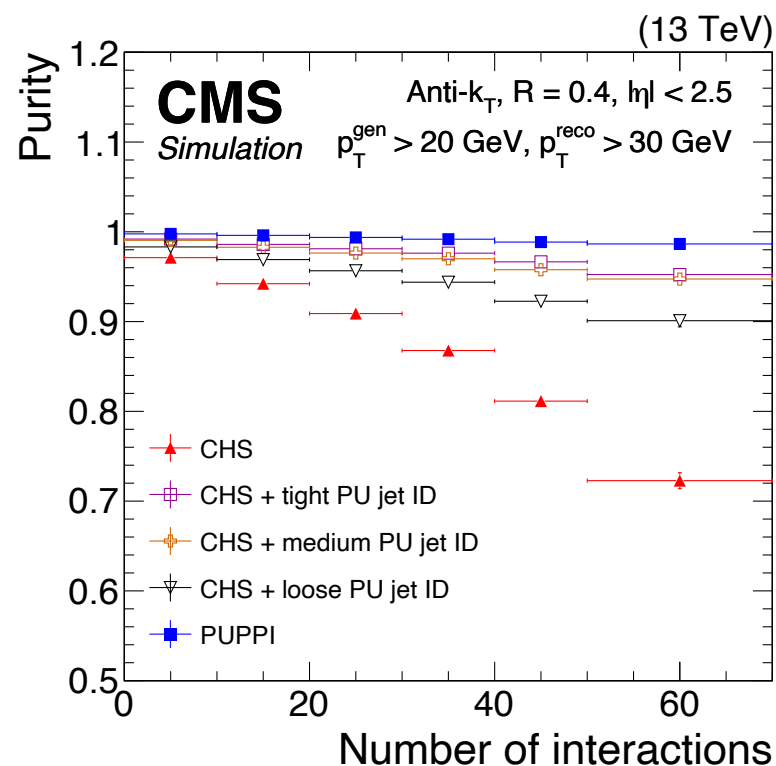
## MET resolution

PUPPI has a better MET resolution and less fake MET.



## W boson identification

PUPPI is more stable in jet mass, jet mass resolution and  $\tau_{21}$ .

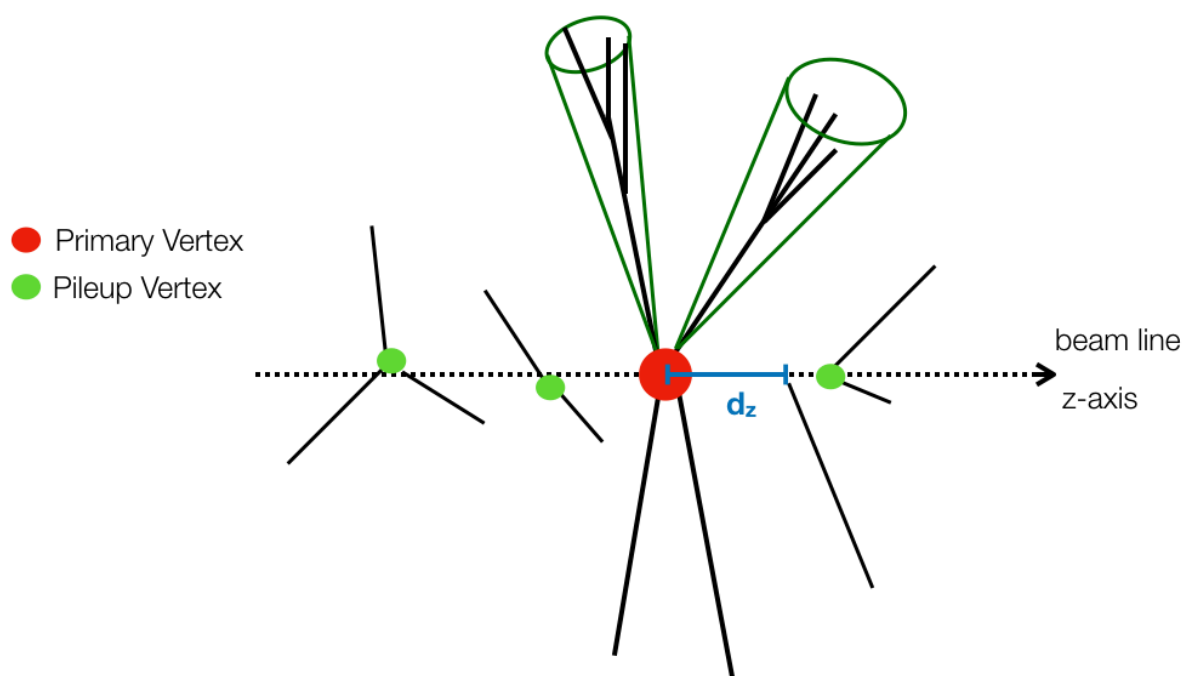


## PU jets rejection

In  $|\eta| < 2.5$  PUPPI rejects more PU jets than all other techniques

In  $|\eta| > 2.5$  PUPPI is compatible to CHS+PUJetID





| Charged particles         | CHS            | PUPPI v15                                                                                                                                                                                                                                                                                                                                                                            |  |                |                |                |      |                    |                |      |                                      |
|---------------------------|----------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--|----------------|----------------|----------------|------|--------------------|----------------|------|--------------------------------------|
| used in the LV fit        | keep           | keep                                                                                                                                                                                                                                                                                                                                                                                 |  |                |                |                |      |                    |                |      |                                      |
| used in the PU vertex fit | reject         | if 1st or 2nd PU vertex && $ d_z  < 0.2$ cm keep else reject                                                                                                                                                                                                                                                                                                                         |  |                |                |                |      |                    |                |      |                                      |
| not used in a vertex fit  | keep           | <table border="1"> <thead> <tr> <th></th> <th><math>p_T &gt; 20</math> GeV</th> <th><math>p_T &lt; 20</math> GeV</th> </tr> </thead> <tbody> <tr> <td><math> \eta  &lt; 2.4</math></td> <td>keep</td> <td>calculate a weight</td> </tr> <tr> <td><math> \eta  &gt; 2.4</math></td> <td>keep</td> <td>if <math> d_z  &lt; 0.3</math> cm keep else reject</td> </tr> </tbody> </table> |  | $p_T > 20$ GeV | $p_T < 20$ GeV | $ \eta  < 2.4$ | keep | calculate a weight | $ \eta  > 2.4$ | keep | if $ d_z  < 0.3$ cm keep else reject |
|                           | $p_T > 20$ GeV | $p_T < 20$ GeV                                                                                                                                                                                                                                                                                                                                                                       |  |                |                |                |      |                    |                |      |                                      |
| $ \eta  < 2.4$            | keep           | calculate a weight                                                                                                                                                                                                                                                                                                                                                                   |  |                |                |                |      |                    |                |      |                                      |
| $ \eta  > 2.4$            | keep           | if $ d_z  < 0.3$ cm keep else reject                                                                                                                                                                                                                                                                                                                                                 |  |                |                |                |      |                    |                |      |                                      |

Tab. 1: Categories for charged particles in CHS and PUPPI.

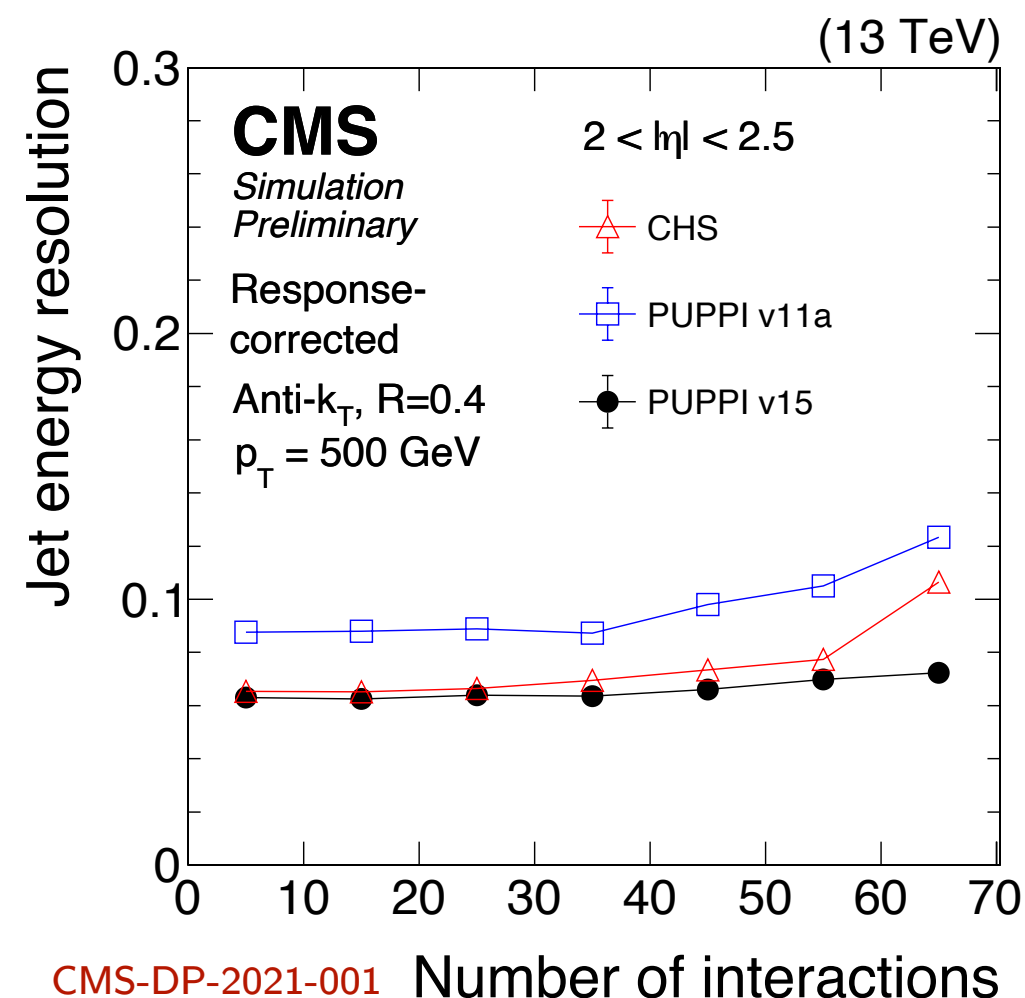
A charged particle can be either: used in the fit of the LV, used in the fit of a PU vertex or not used in any fit (see plot on the top left). The categories for CHS and PUPPI for each of the cases is shown in Tab. 1.

In order to recover tracks mistakenly used in the fit of another vertex (vertex splitting or track stealing by a nearby PU vertex), charged particles belonging to one of the first two PU vertices and with  $|d_z| < 0.2$  cm are kept.

|                | $p_T > 20 \text{ GeV}$ | $p_T < 20 \text{ GeV}$                          |
|----------------|------------------------|-------------------------------------------------|
| $ \eta  < 2.4$ | keep                   | calculate a weight                              |
| $ \eta  > 2.4$ | keep                   | if $ d_Z  < 0.3 \text{ cm}$ keep<br>else reject |

|                | $p_T > 20 \text{ GeV}$ | $p_T < 20 \text{ GeV}$                            |                                                             |
|----------------|------------------------|---------------------------------------------------|-------------------------------------------------------------|
|                |                        | $p_T > 4 \text{ GeV} \ \&\& \ \text{FromPV} == 2$ | else                                                        |
| $ \eta  < 2.4$ | keep                   | keep                                              | calculate a weight                                          |
| $ \eta  > 2.4$ | keep                   | keep                                              | if $ d_Z  < 0.3 \text{ cm}$ keep<br>else calculate a weight |

- ▶ Widely used in Run 2, default in Run 3
- ▶ Improved all jet-related variables
  - ▶ Jet efficiency and purity (matched to generator-level jets)
  - ▶ Jet substructure
  - ▶ Jet resolution (the lower the better)
- ▶ Improved performance also on lepton isolation, missing transverse energy, ...



Better

