Reconstructing jets at the LHC

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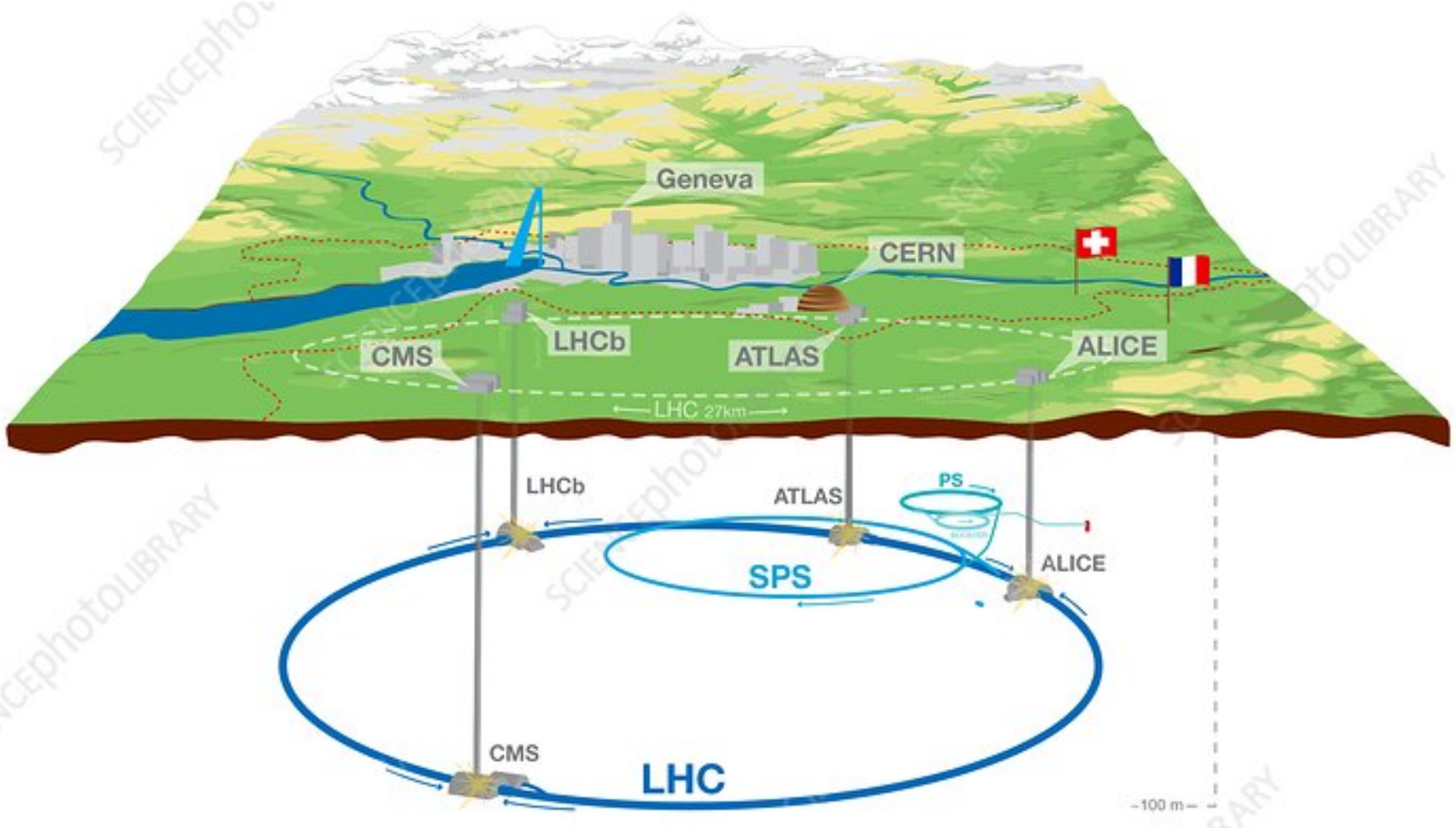
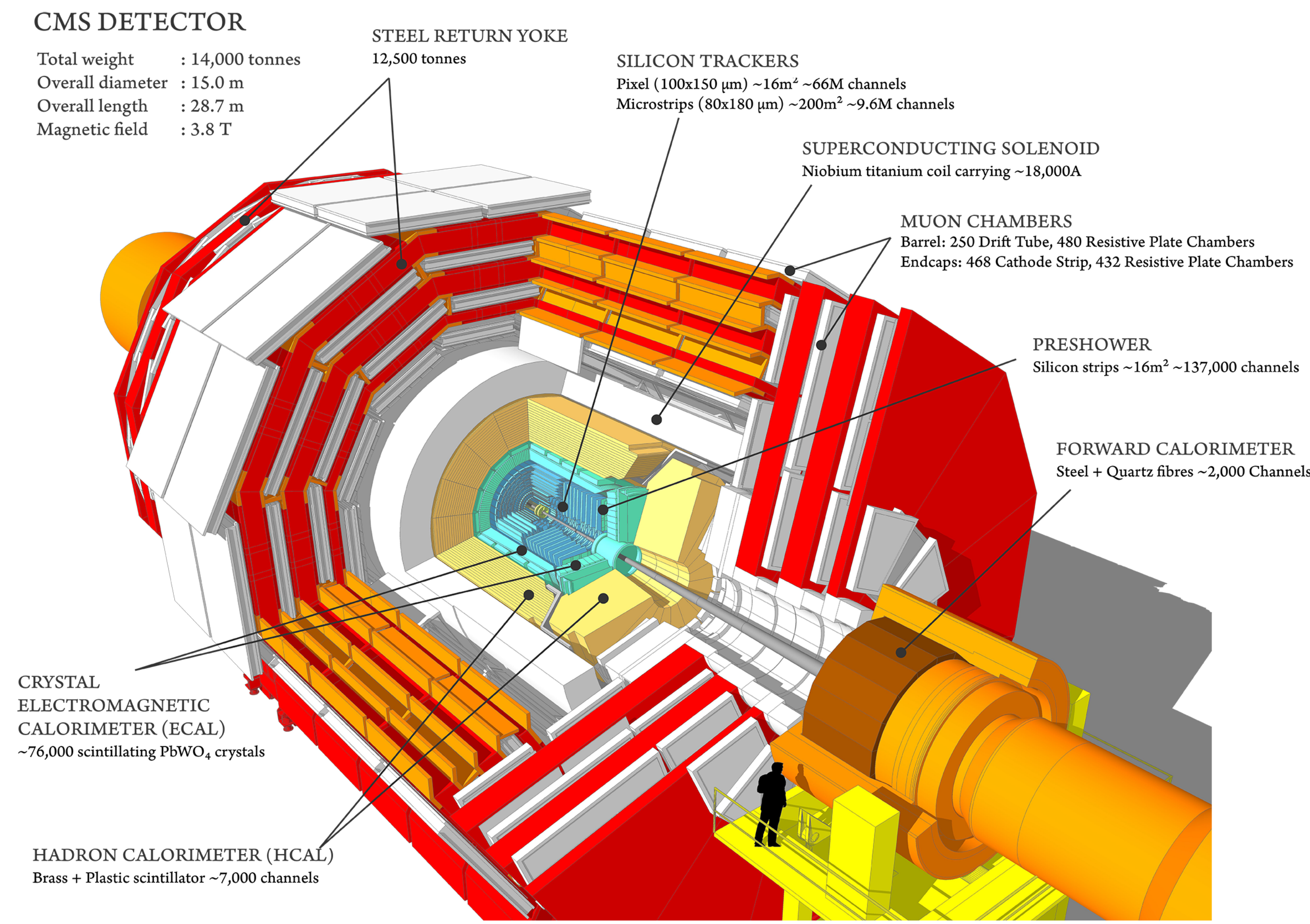
Experimental setup: LHC

- Proton-proton collider
  - 27 km circumference
  - Up to $\sqrt{s} = 14$ TeV
- Host of 4 large experiments (+ several others)
  - ATLAS
  - CMS
  - LHCb
  - ALICE
- Vast physics programme
  - Standard Model physics
  - Higgs/top physics
  - TeV energy frontier
  - New physics

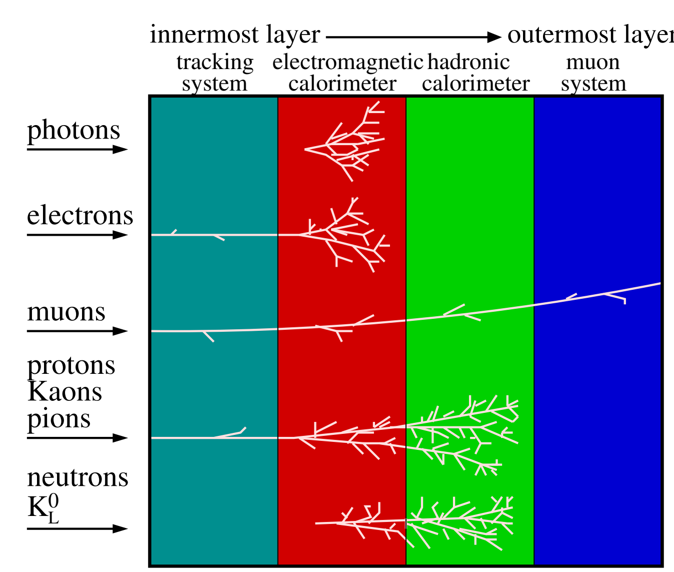


Experimental setup: CMS

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

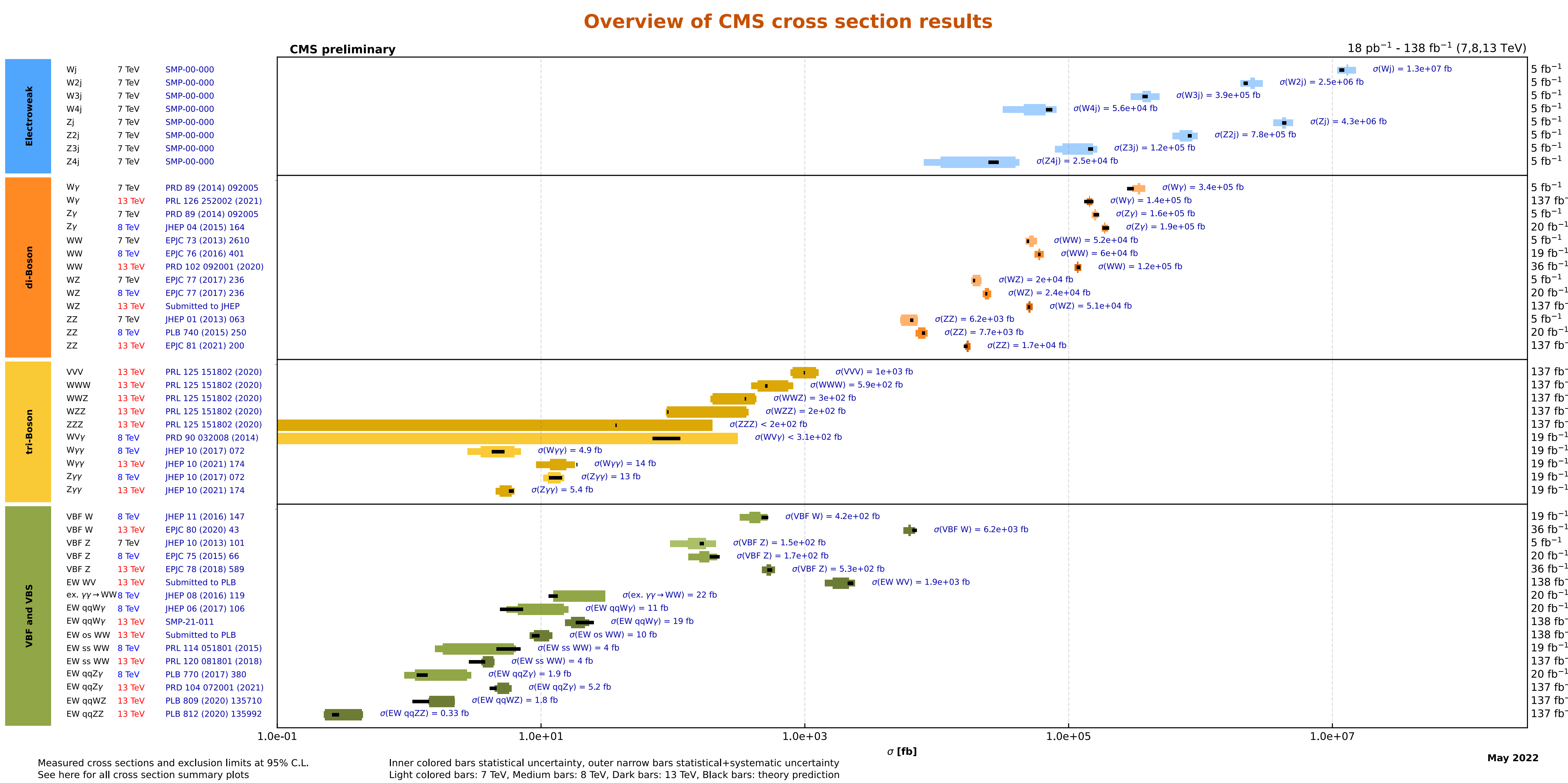


- Particle reconstruction
  - Detector signals → physics objects
  - Based on ParticleFlow algorithm
- Operational since 2010, this talk focuses on:
  - Run2 data (2016-2018), $\sqrt{s}$ = 13 TeV
  - Run3 data (2022-ongoing), $\sqrt{s}$ = 13.6 TeV



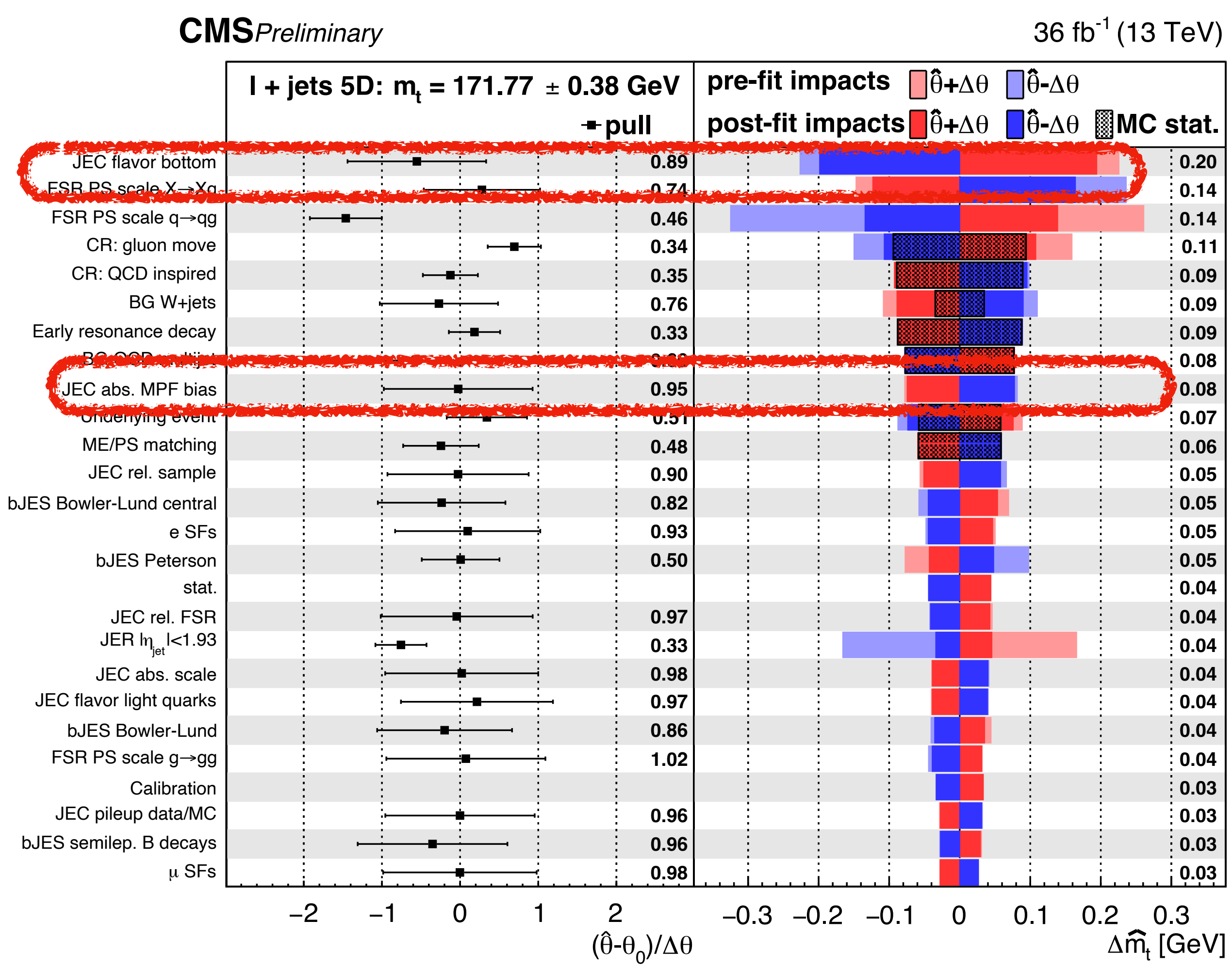
Physics program

- Test the self-consistency of the Standard Model
  - Huge variety of processes analysed, across multiple final states
  - Majority of analyses already systematics-dominated
- TeV energy frontier
  - Enormous range of energy investigated (up to 10TeV), several models studied



Era of precision physics

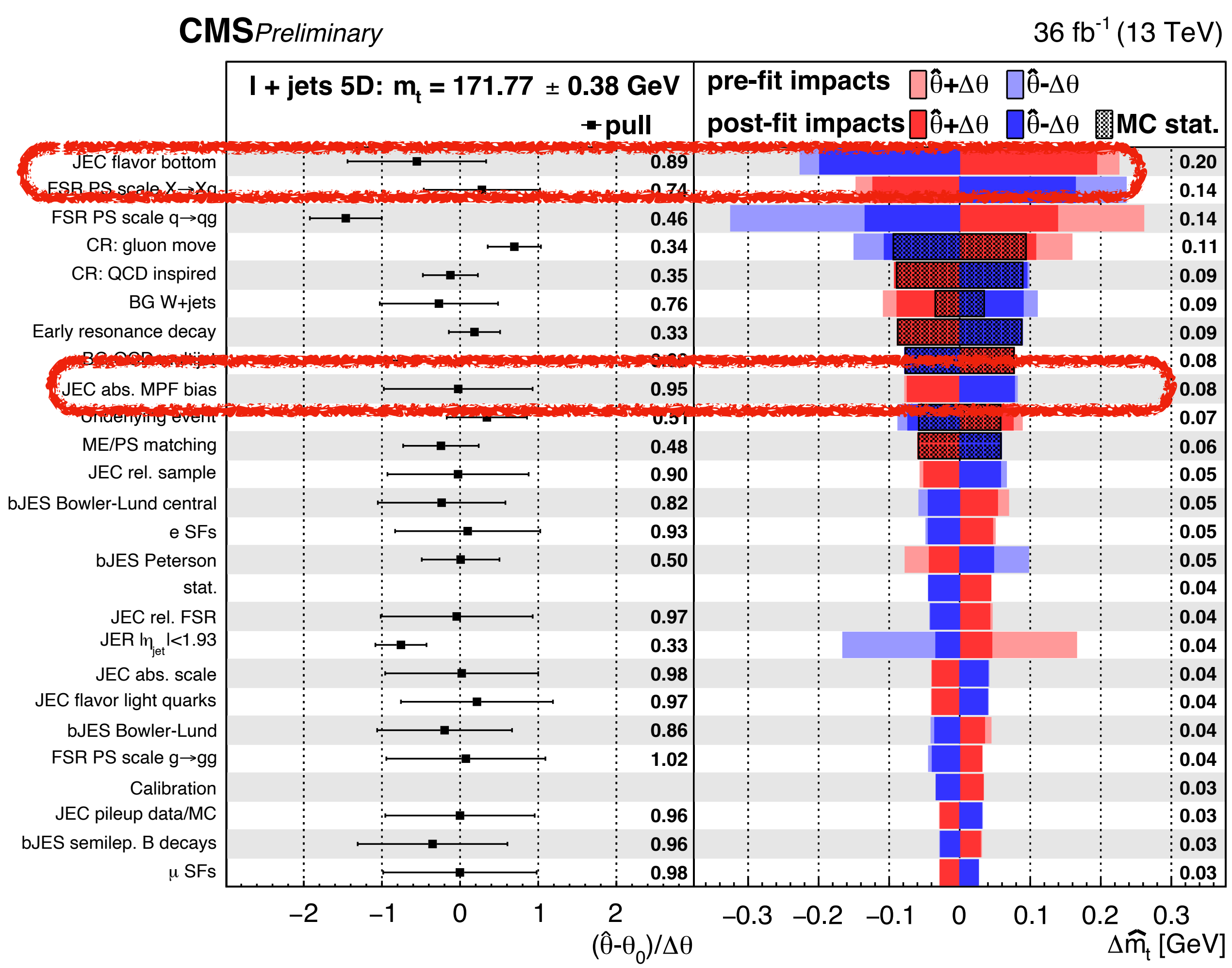
- Jet-related uncertainties are becoming a limiting factor in many analyses
  - Jets are abundant at the LHC -> hadronic decays, associated prod. with jets, ...
  - Jet energy scale → impact on: top, Higgs, multi-jets analyses



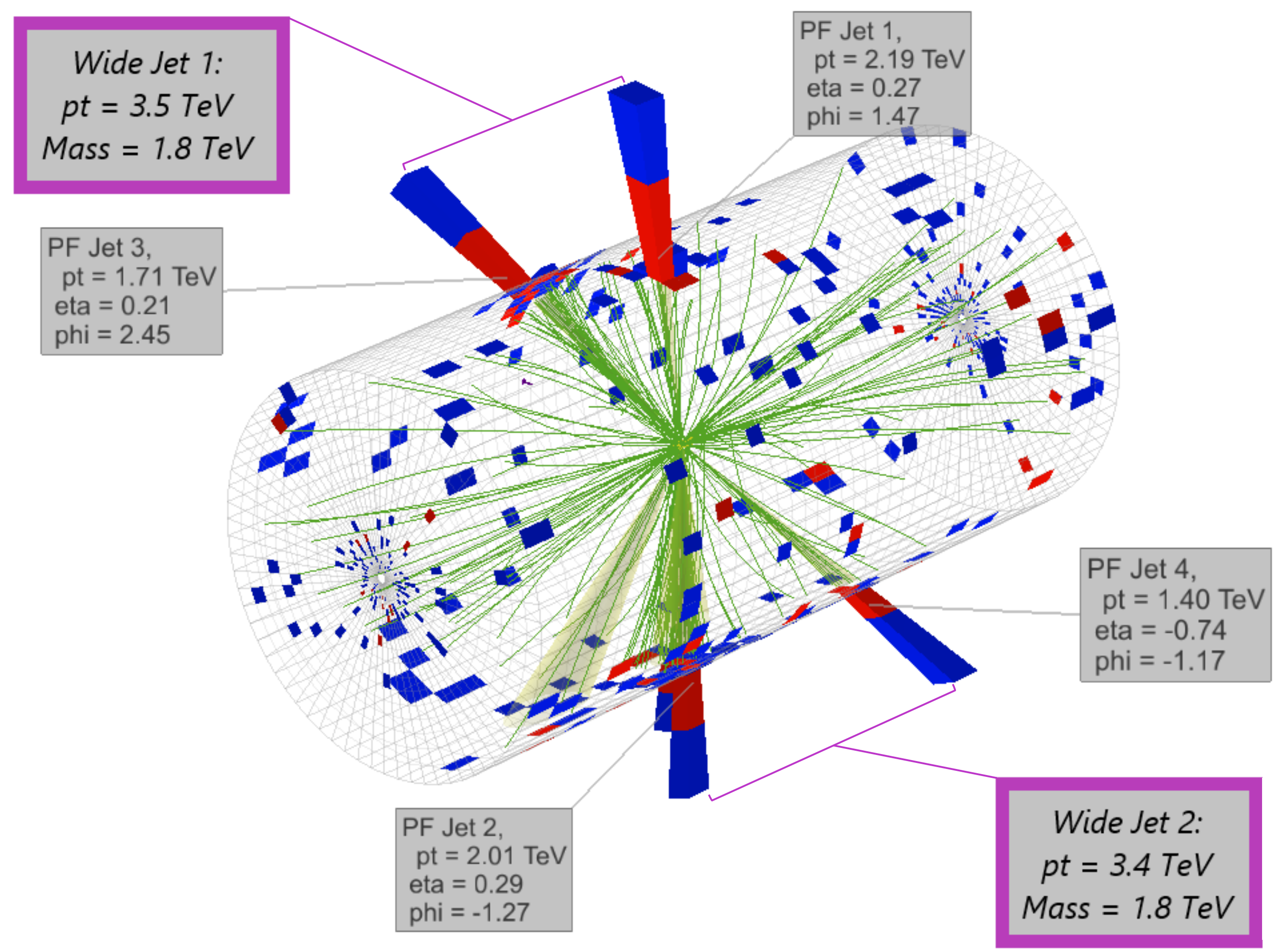
Top mass l+jet

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, multi-jets analyses
  - ... but also boosted searches -> merged decay products
  - Must be known well for a wide range in energy and pseudo rapidity

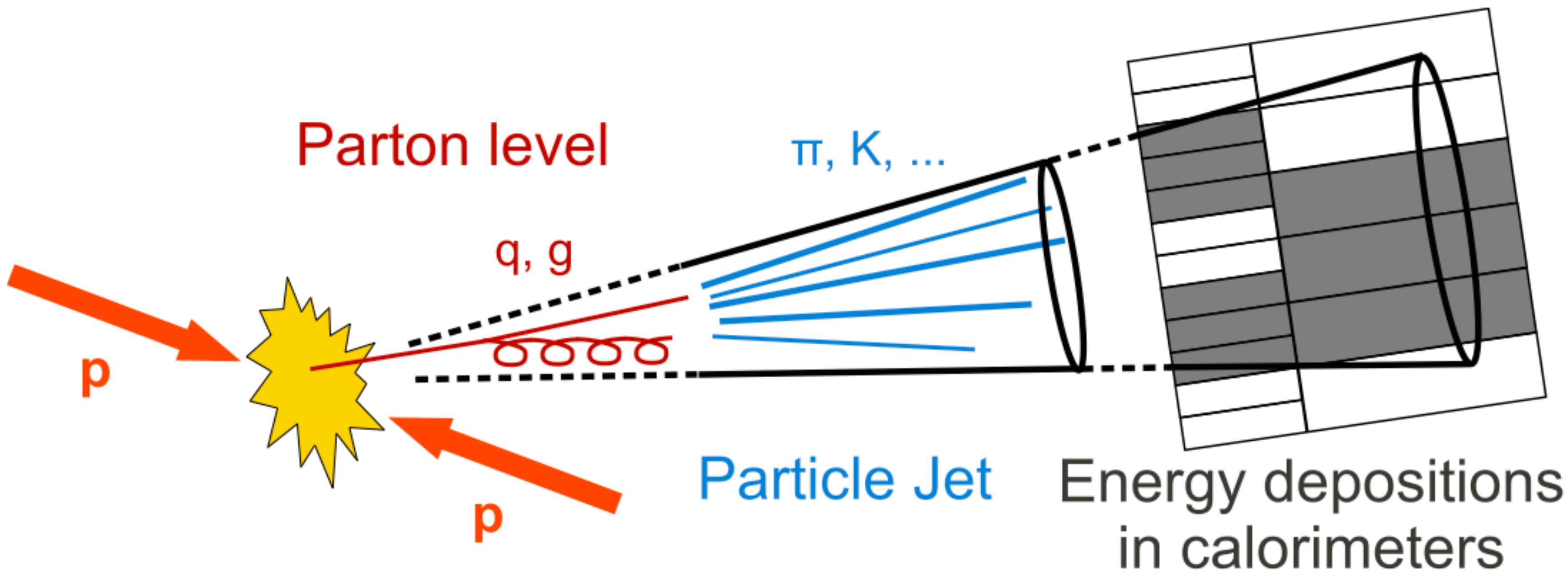


Top mass l+jet



Dijet resonances

From detector signals to jet calibration



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

From detector signals to jet calibration

Local reconstruction:
Tracks, Calorimeter clusters

→

- Information from all sub-detectors

From detector signals to jet calibration

Local reconstruction:
Tracks, Calorimeter clusters →
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Particle flow (PF) →
- Link tracks and calorimeter signals
- Particle identification

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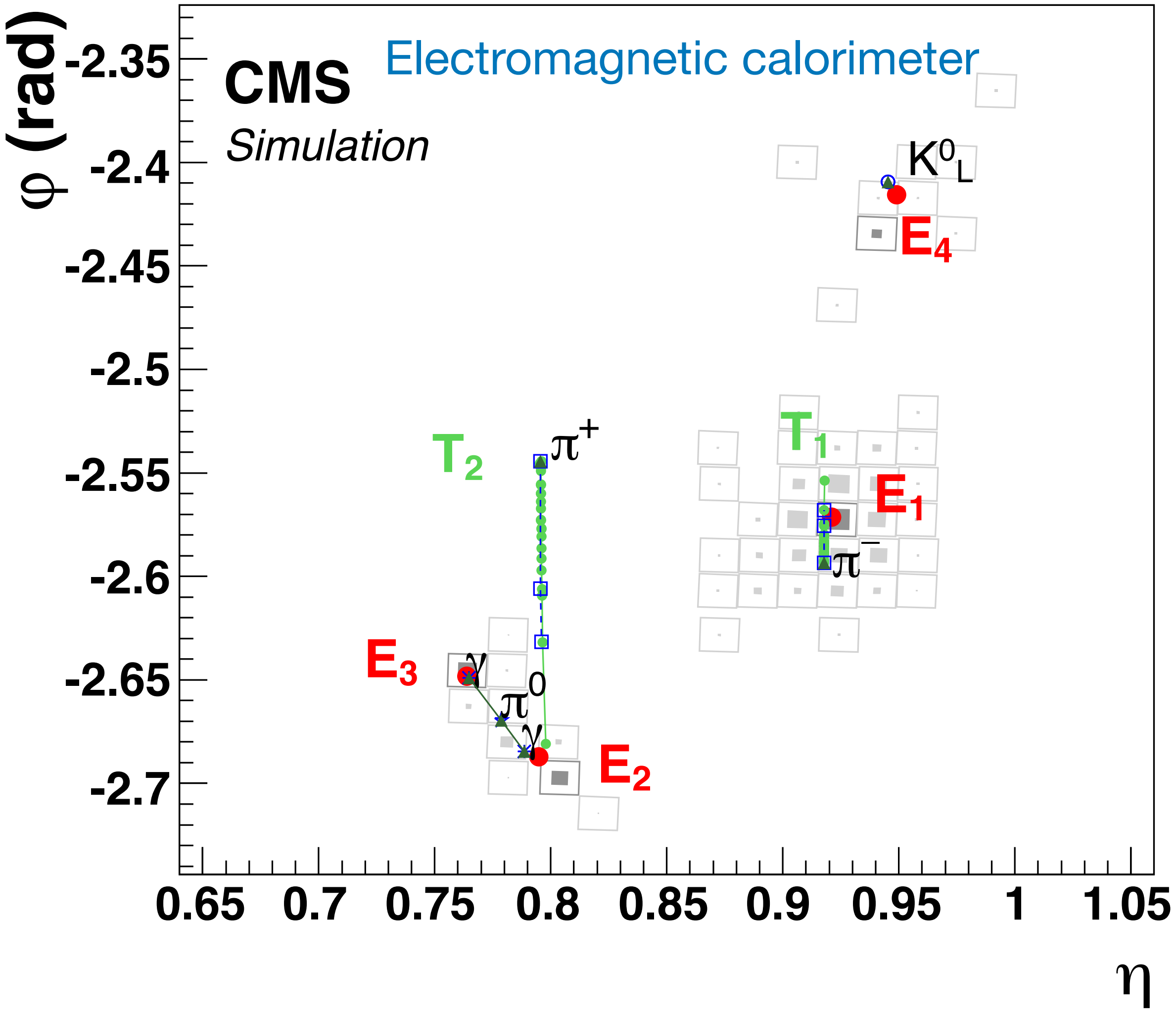

From detector signals to jet calibration

Local reconstruction:
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Particle flow (PF)

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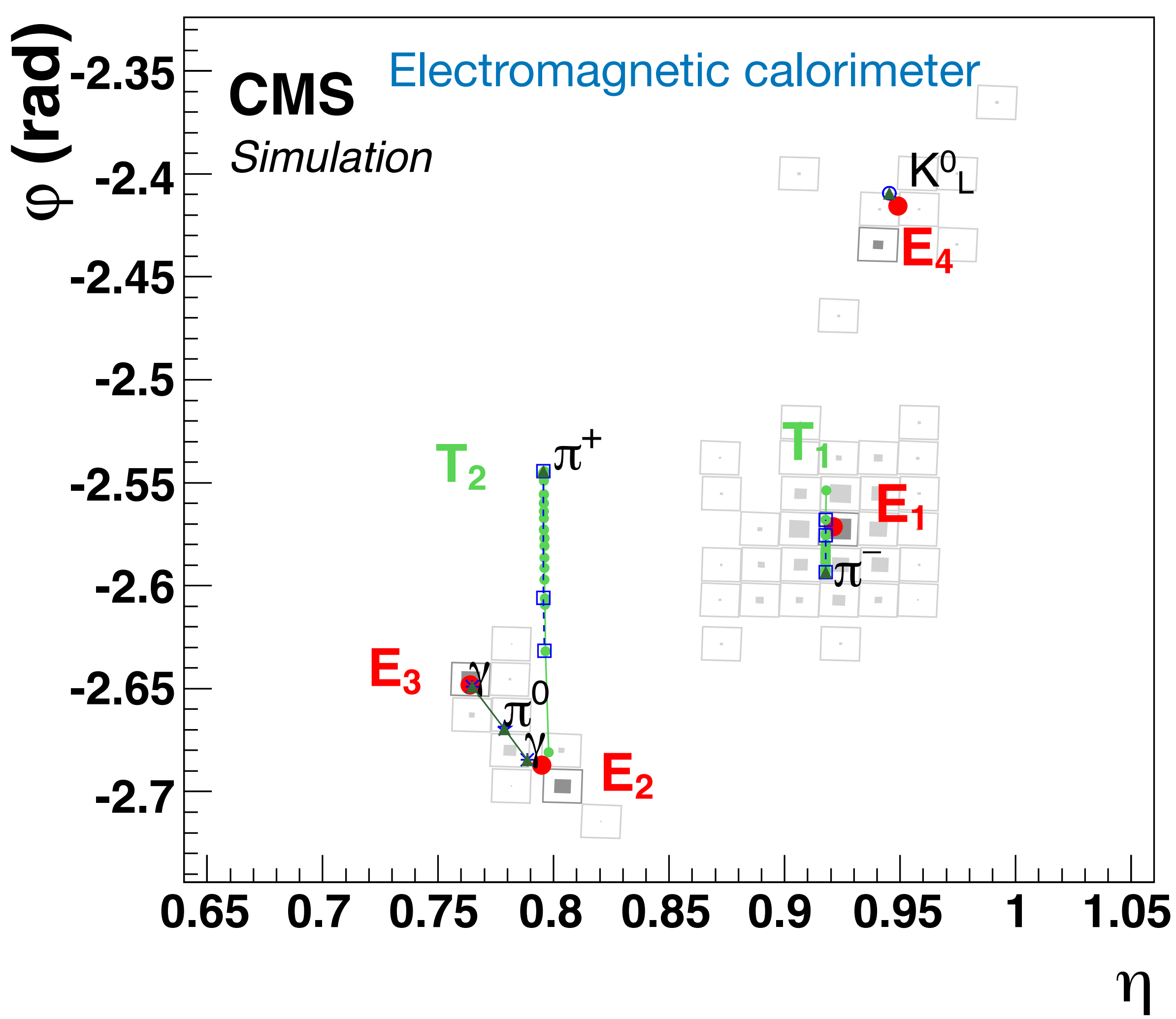

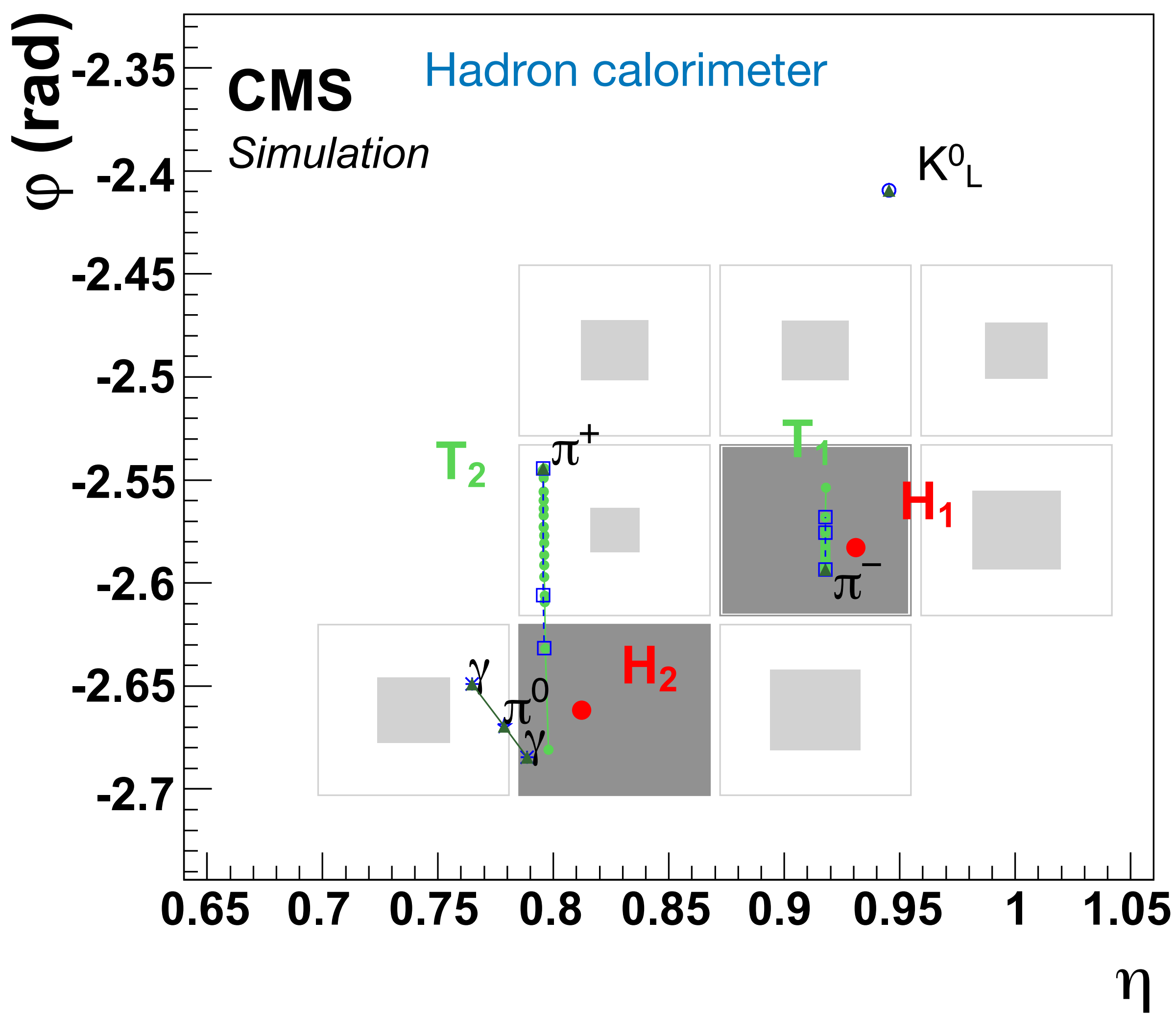

From detector signals to jet calibration

Local reconstruction: Tracks, Calorimeter clusters →
- Information from all sub-detectors

Particle flow (PF) →
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- Particle identification

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

From detector signals to jet calibration

Local reconstruction: Tracks, Calorimeter clusters →	▶ Information from all sub-detectors
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Jet clustering →	▶ Algorithms (AK, CA, HOTVR, Xcone) ▶ Cone radii (0.4, 0.8, 1.5, variable)

From detector signals to jet calibration

Local reconstruction: Tracks, Calorimeter clusters →	▶ Information from all sub-detectors
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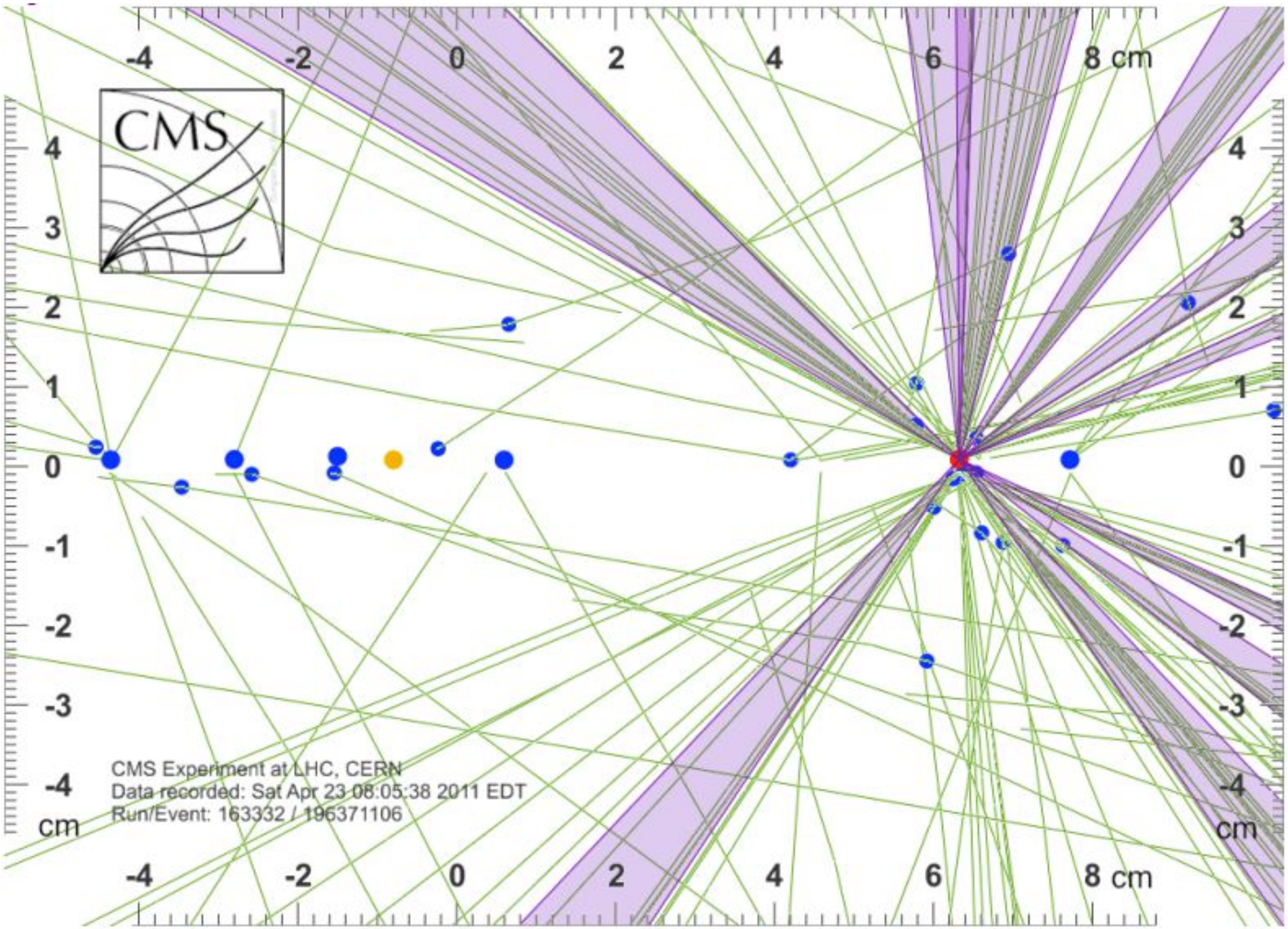
Jet clustering →	▶ Algorithms (AK, CA, HOTVR, Xcone) ▶ Cone radii (0.4, 0.8, 1.5, variable)
Jet calibration →	▶ Jet energy scale & resolution ▶ Jet mass resolution

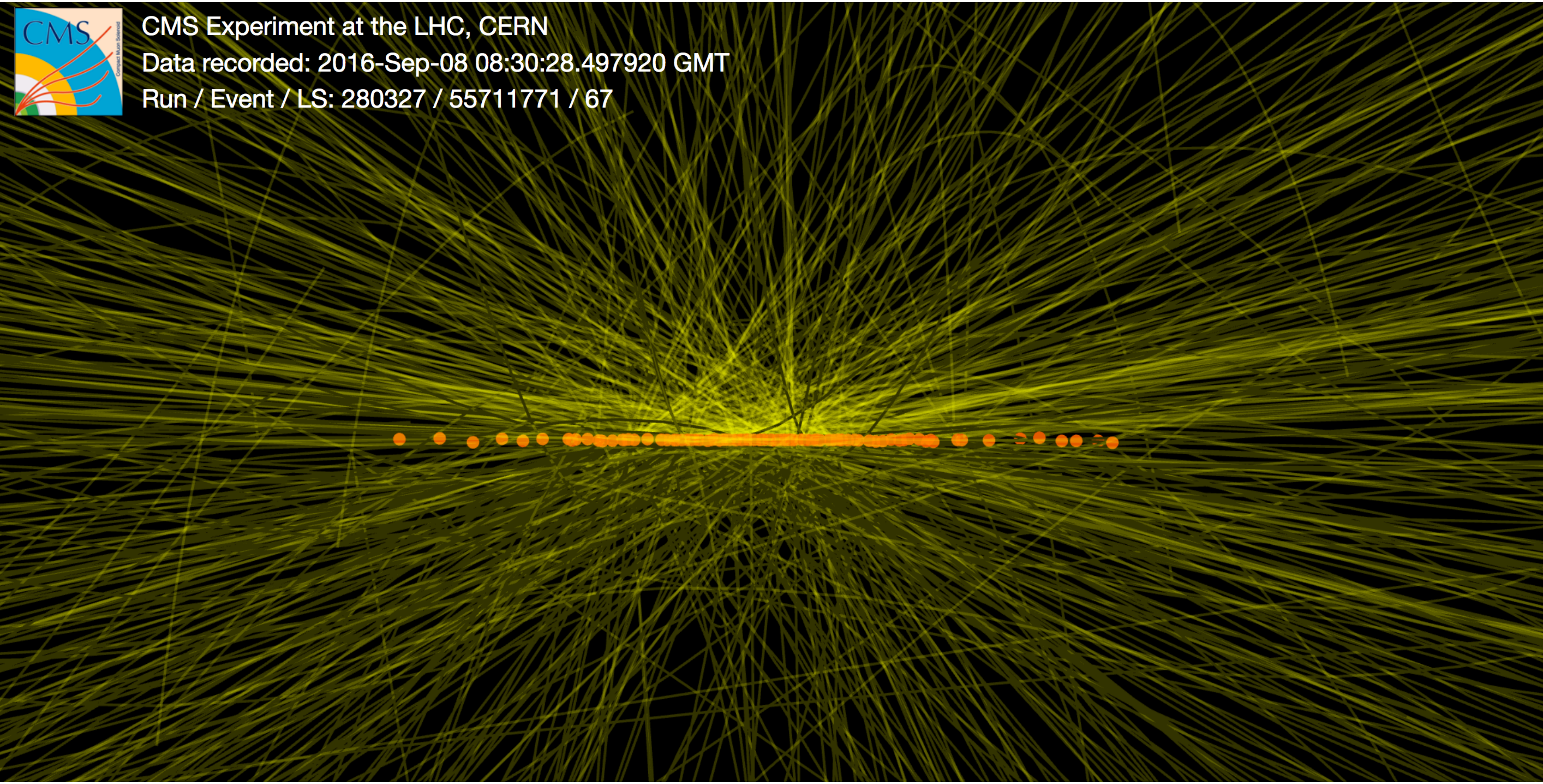
Proton-Proton collisions @ LHC



http://cds.cern.ch/record/1357882

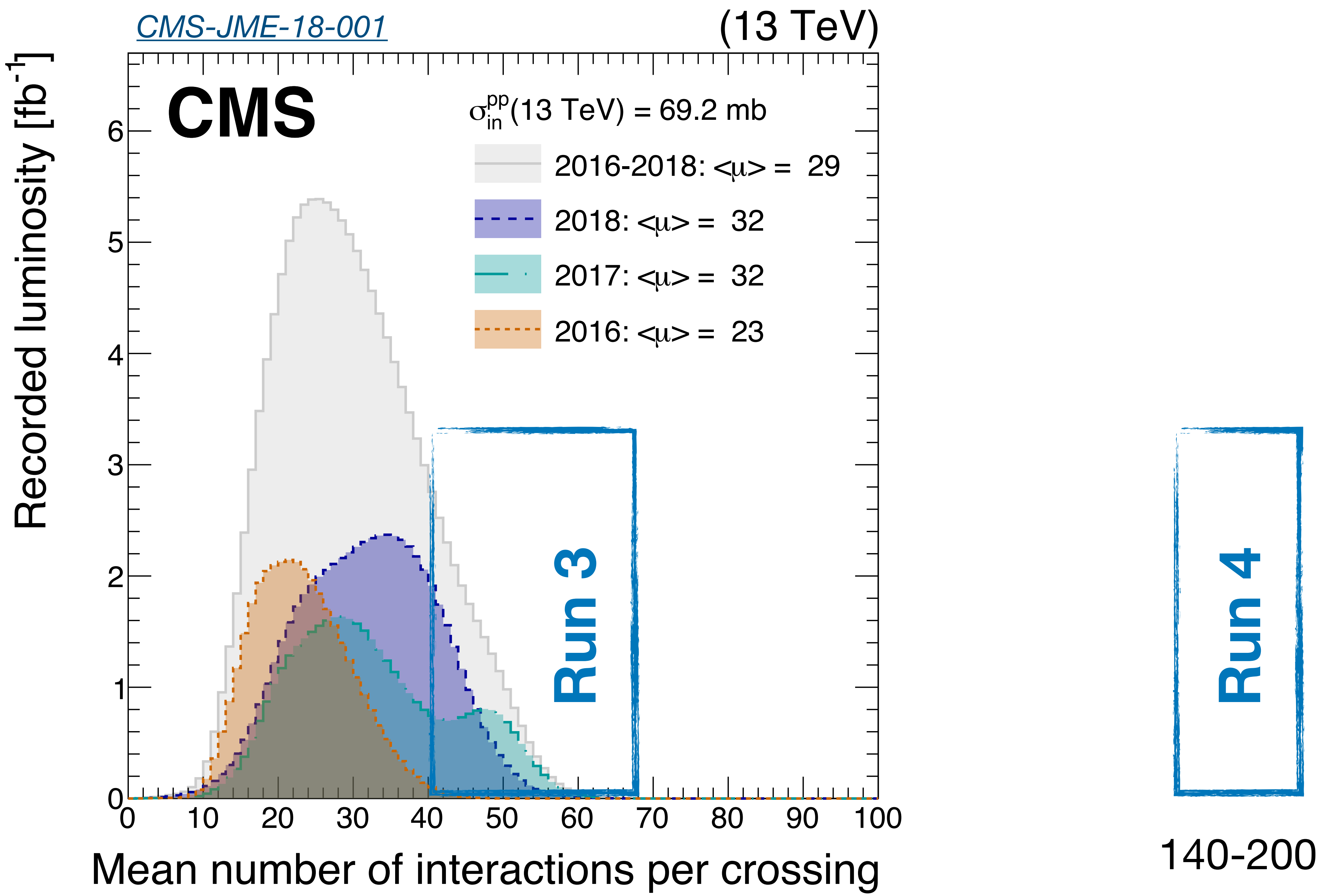
Pileup adds additional energy to the whole detector

Proton-Proton collisions @ LHC

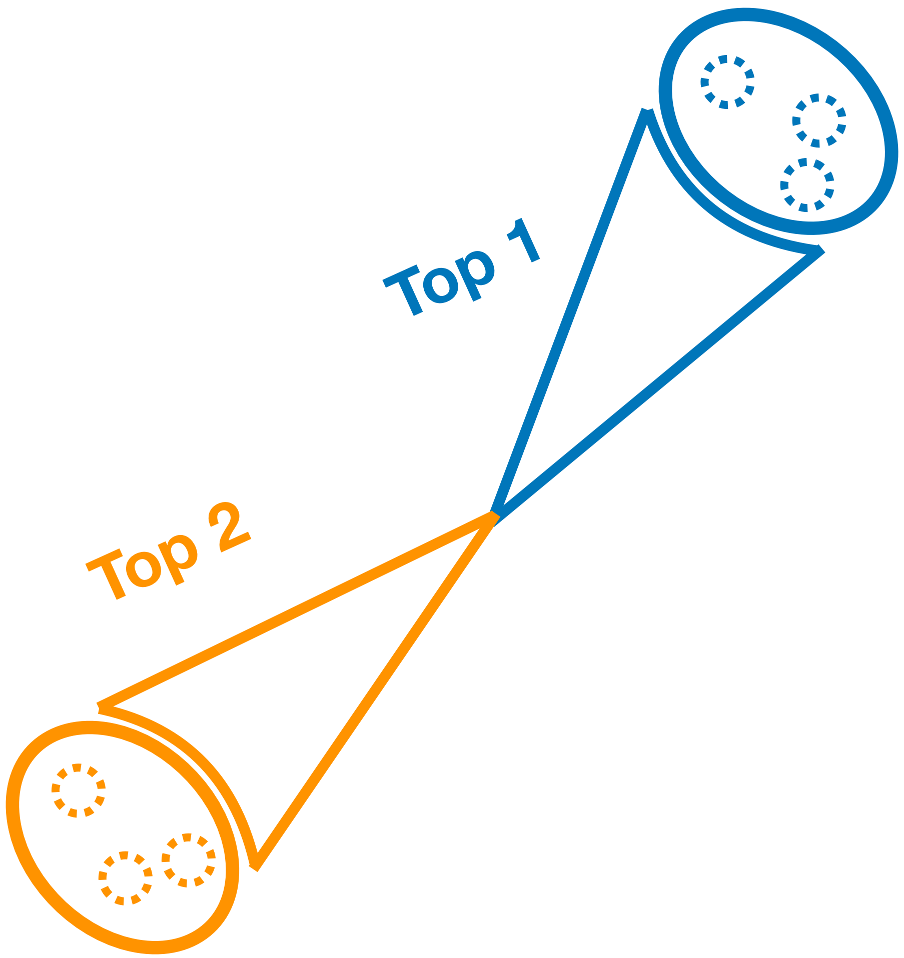


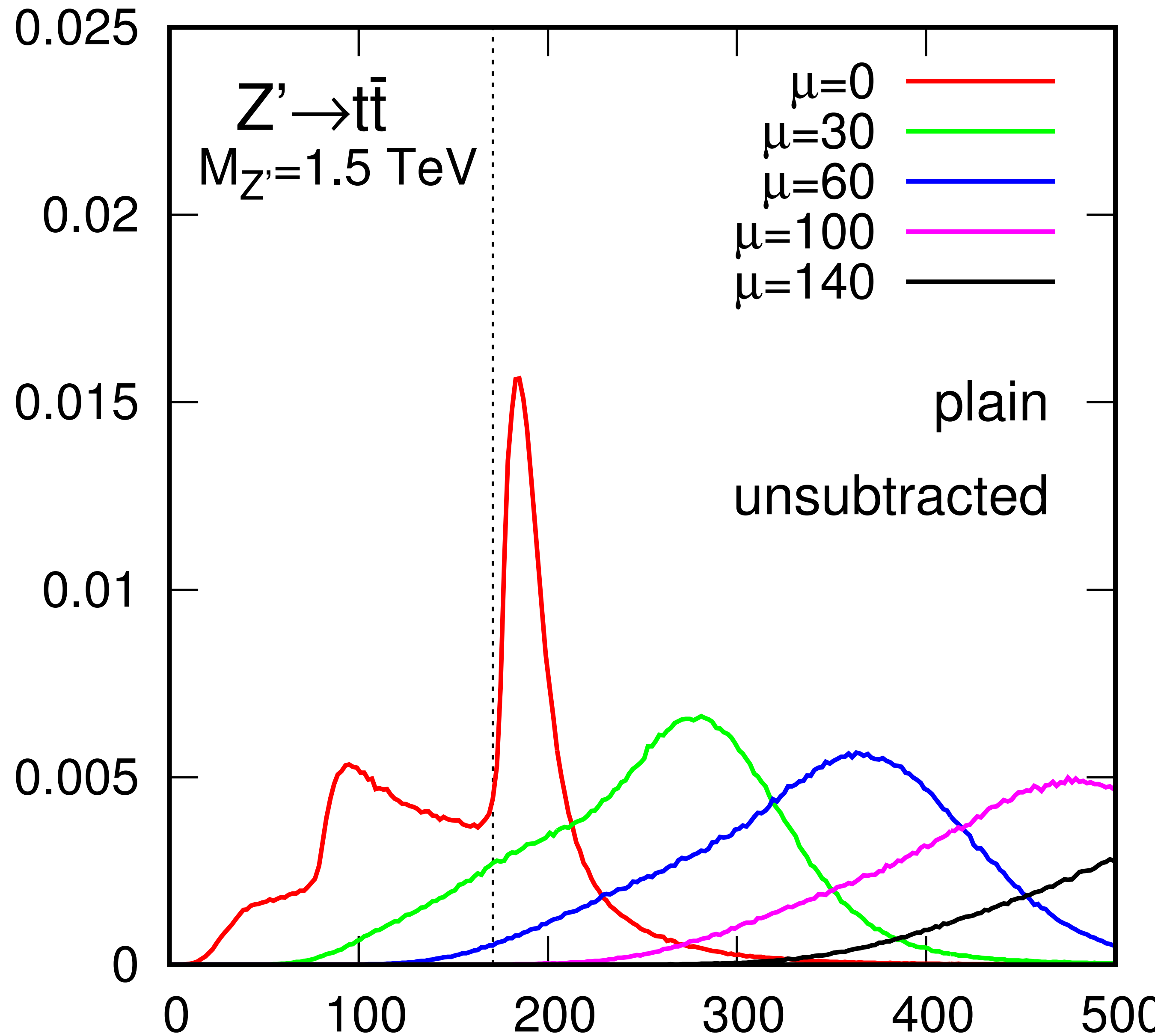
Pileup adds additional energy to the whole detector

More data, more pileup



Challenges with pileup





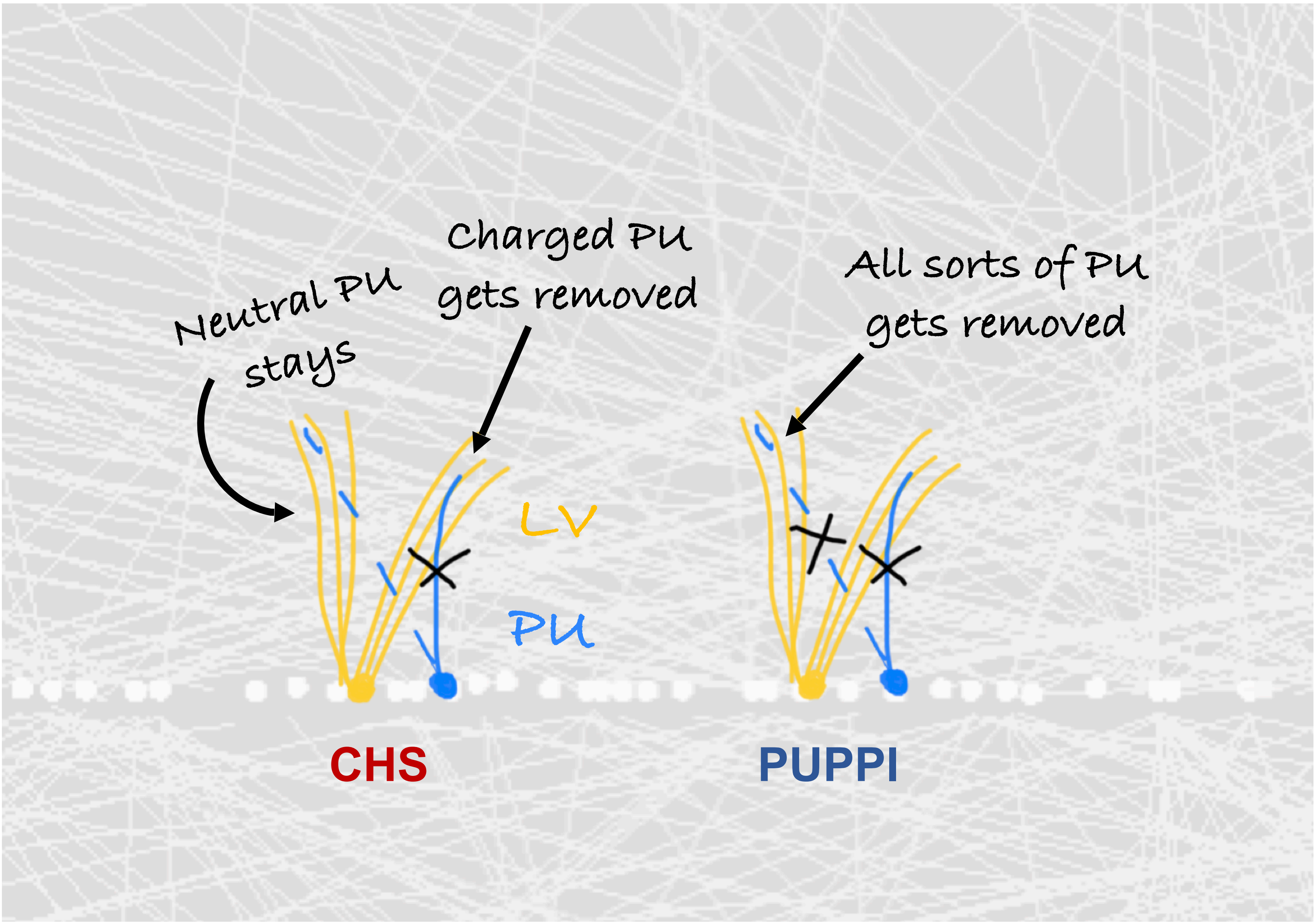
(a) raw, ungroomed jets

From G. Soyez, arXiv:1801.09721

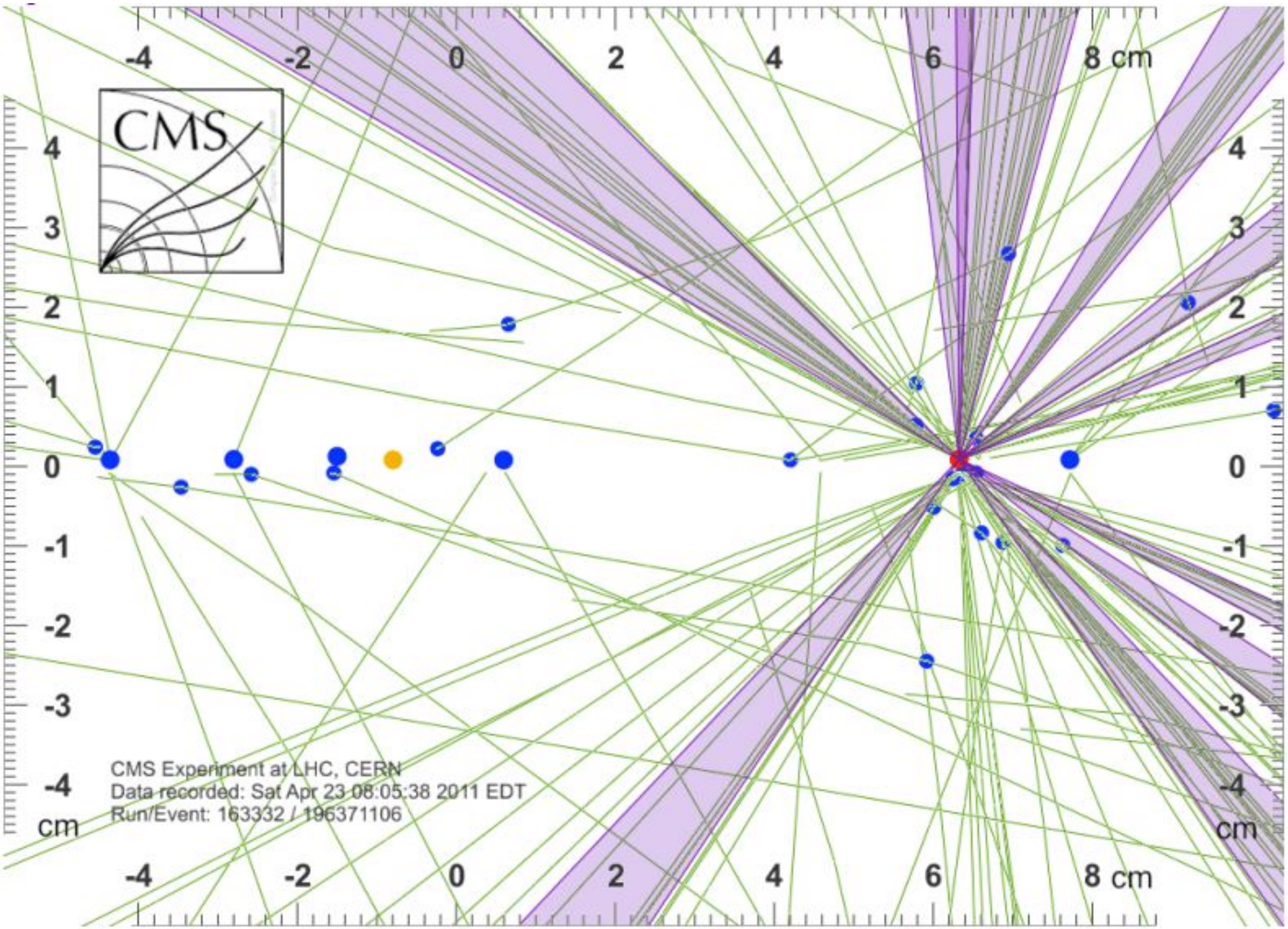
PU affects jet substructure, jet counting, lepton isolation…

Pileup mitigation in CMS

Click me

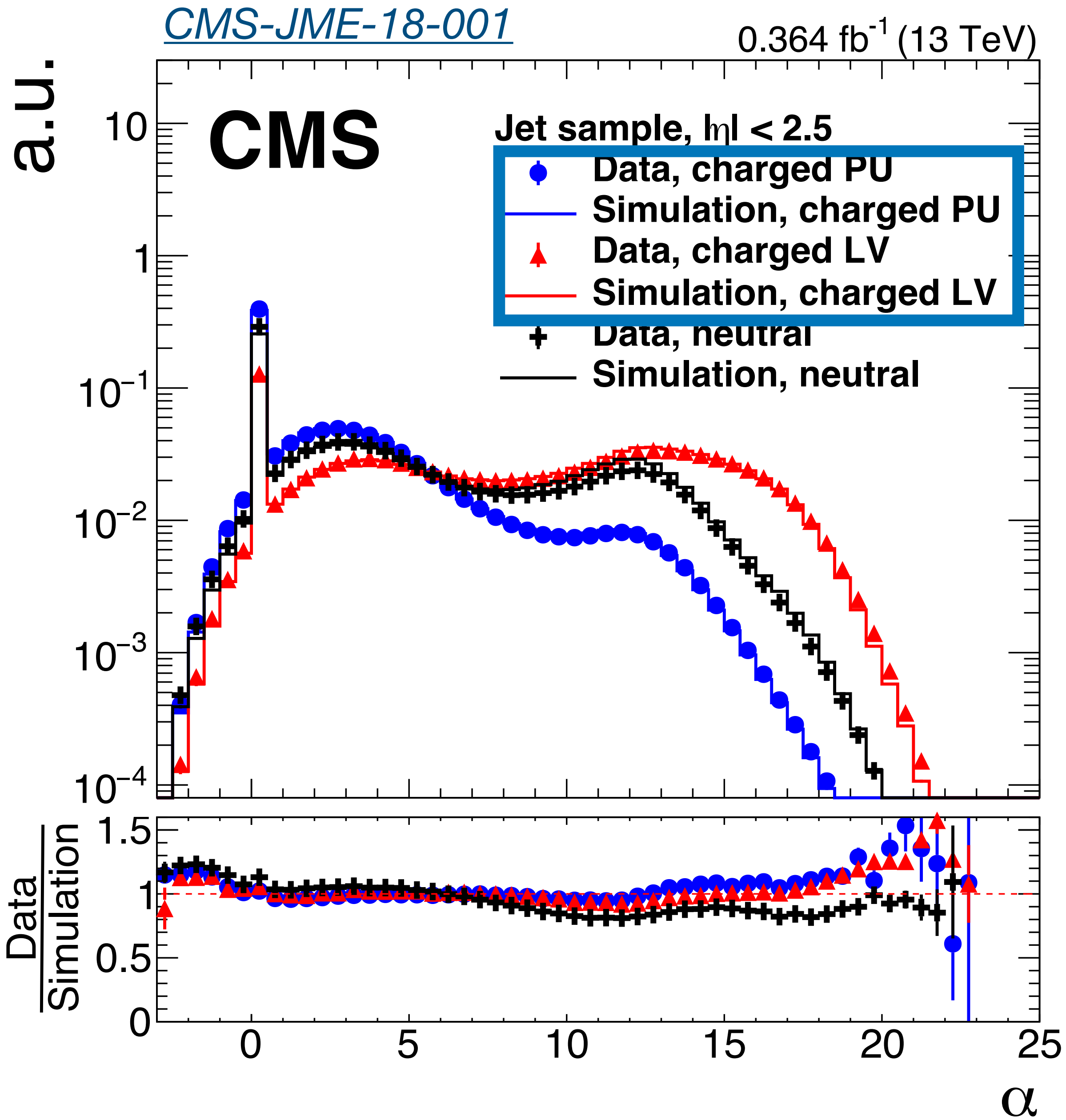


PUPPI in Detail



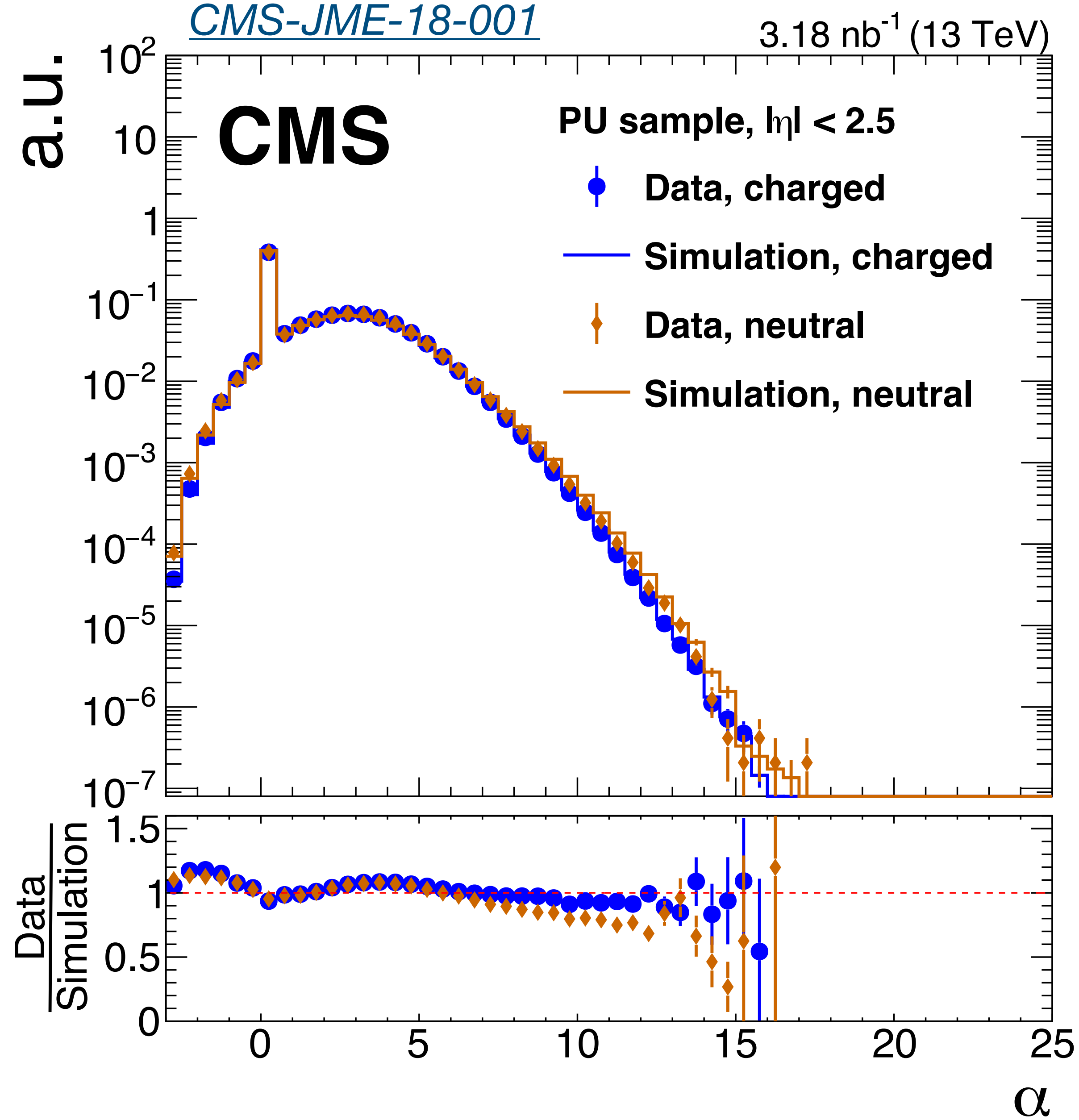
http://cds.cern.ch/record/1357882

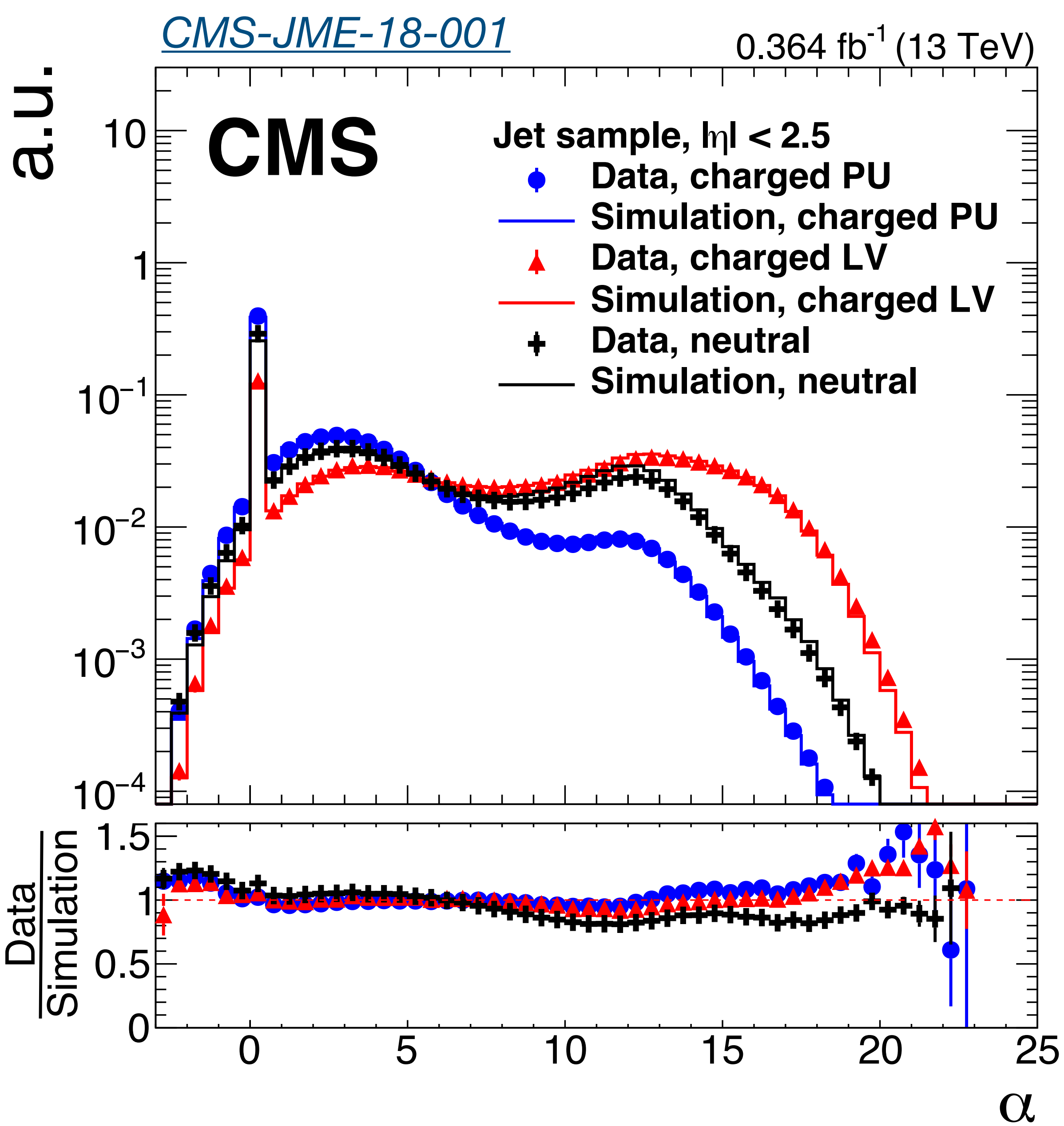
$$\alpha_i = \log \sum_{j \neq i, \Delta R_{ij} < R_0} \left(\frac{p_{Tj}}{\Delta R_{ij}} \right)^2 \begin{cases} \text{for } |\eta_i| < 2.5, & j \text{ are charged particles from leading vertex} \\ \text{for } |\eta_i| > 2.5, & j \text{ are all kinds of reconstructed particles} \end{cases}$$



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

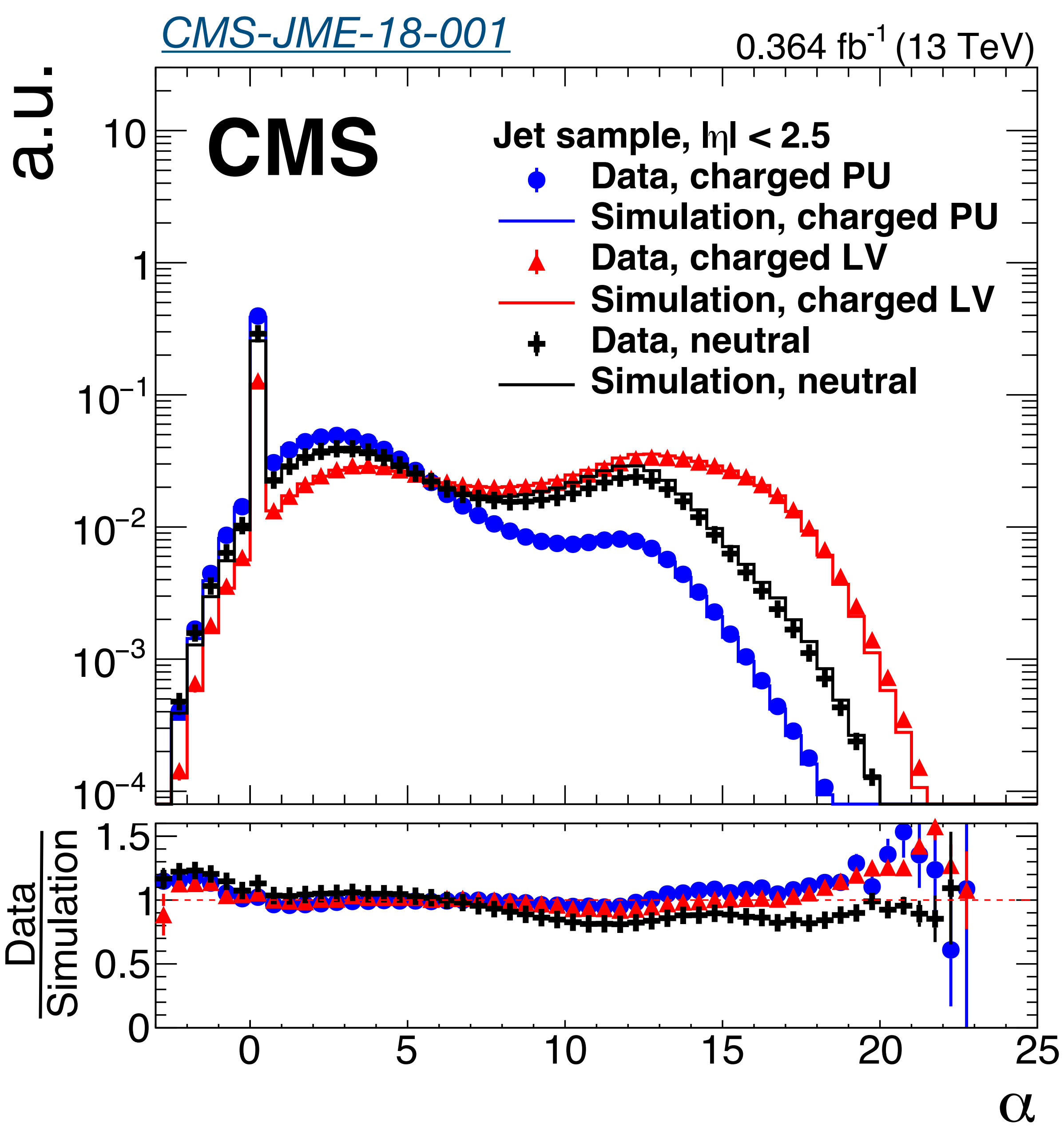
CMS-JME-18-001





1. Calculate Median and RMS of charged PU shape (blue)

$$\bar{\alpha}_{PU},\ RMS_{PU}$$

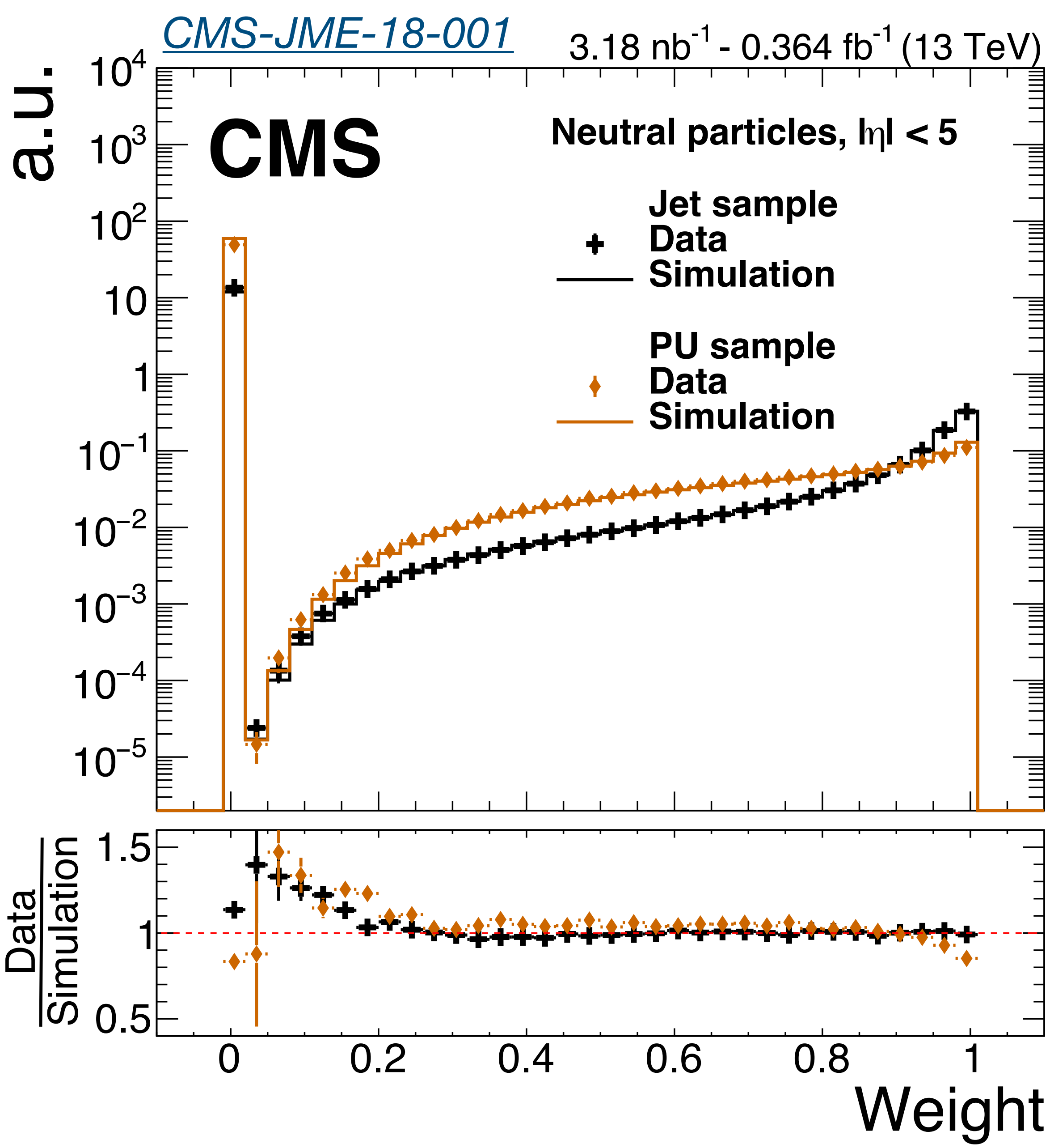


1. Calculate Median and RMS of charged PU shape (blue)

$$\bar{\alpha}_{PU},\ RMS_{PU}$$

2. For each particle calculate

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



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$$\bar{\alpha}_{PU},\ RMS_{PU}$$

2. For each particle calculate

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

3. Assign a weight to each particle

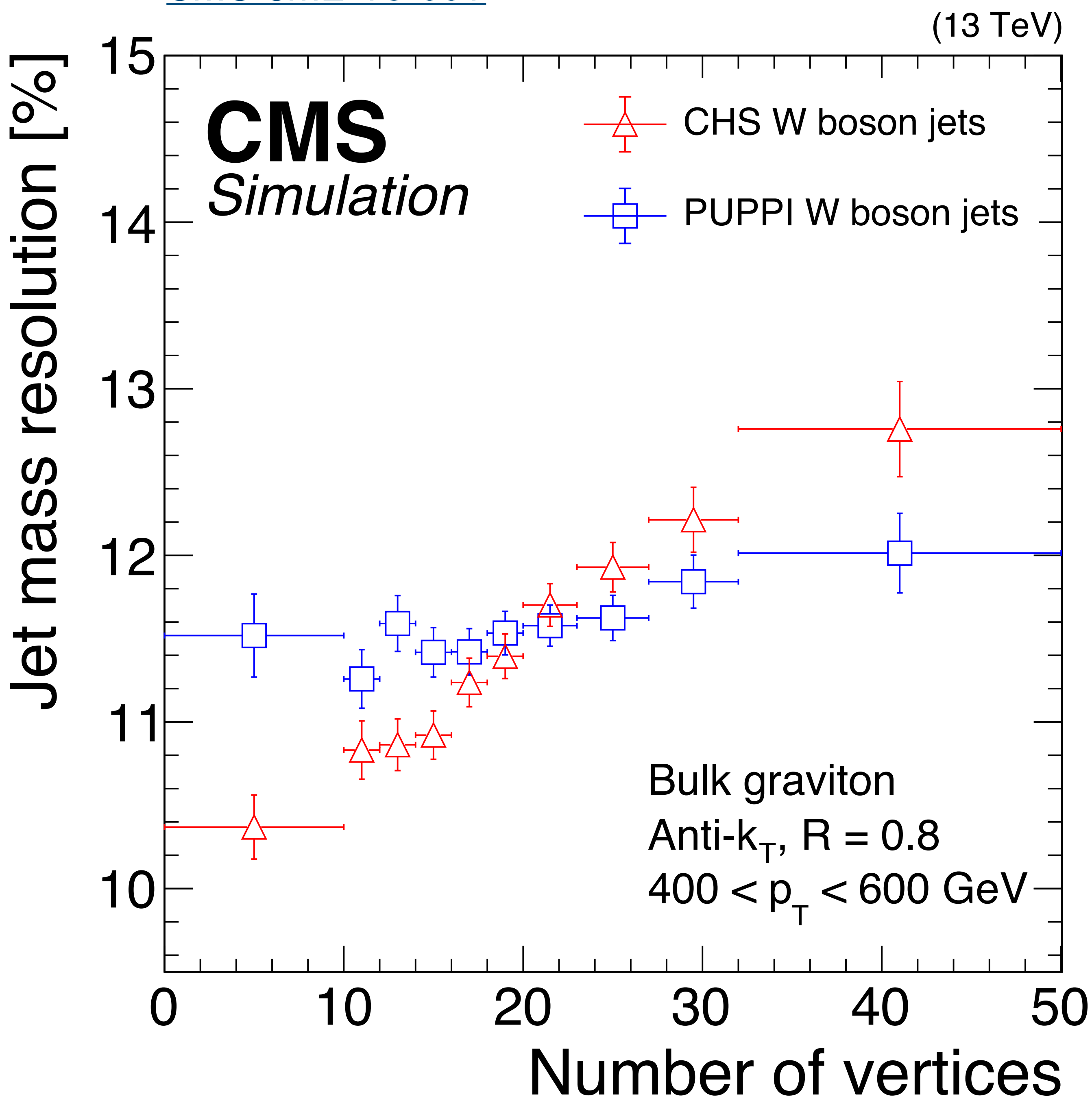
$$w_i = F_{\chi^2, NDF=1}(\chi_i^2)$$

Pileup ⟶ Hard scattering

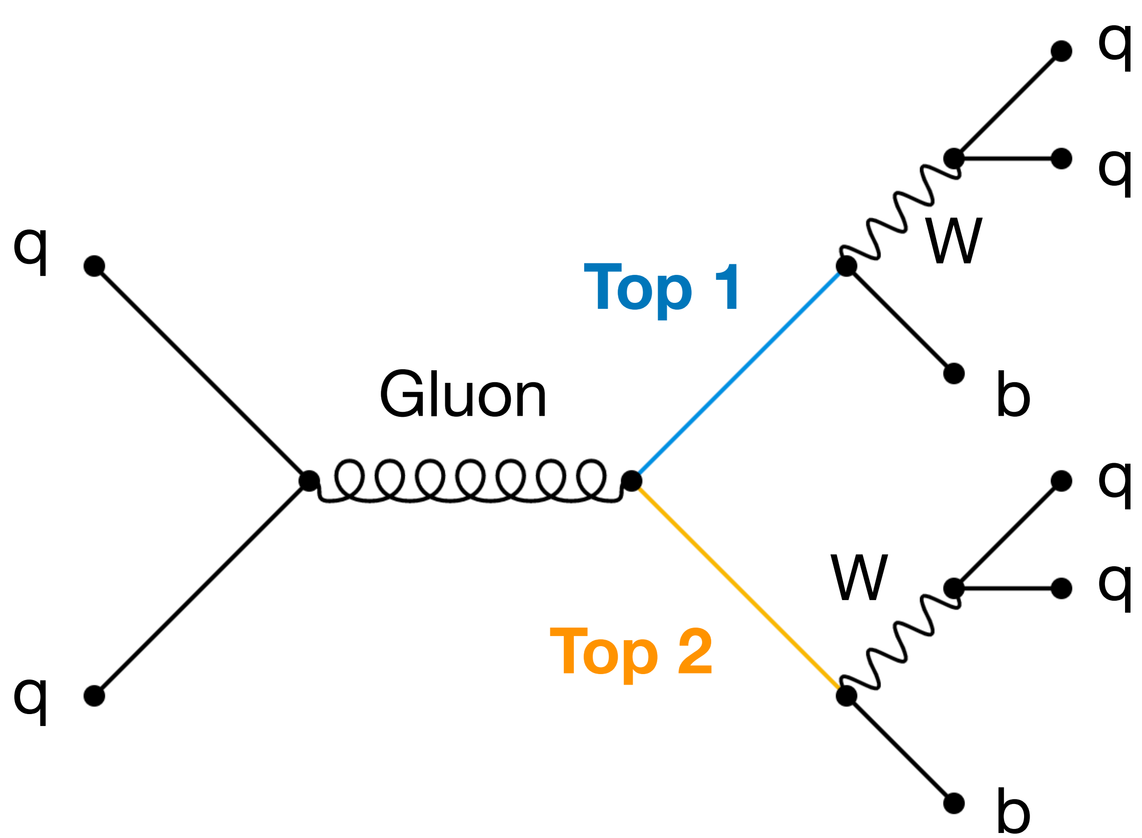
Validation of PUPPI

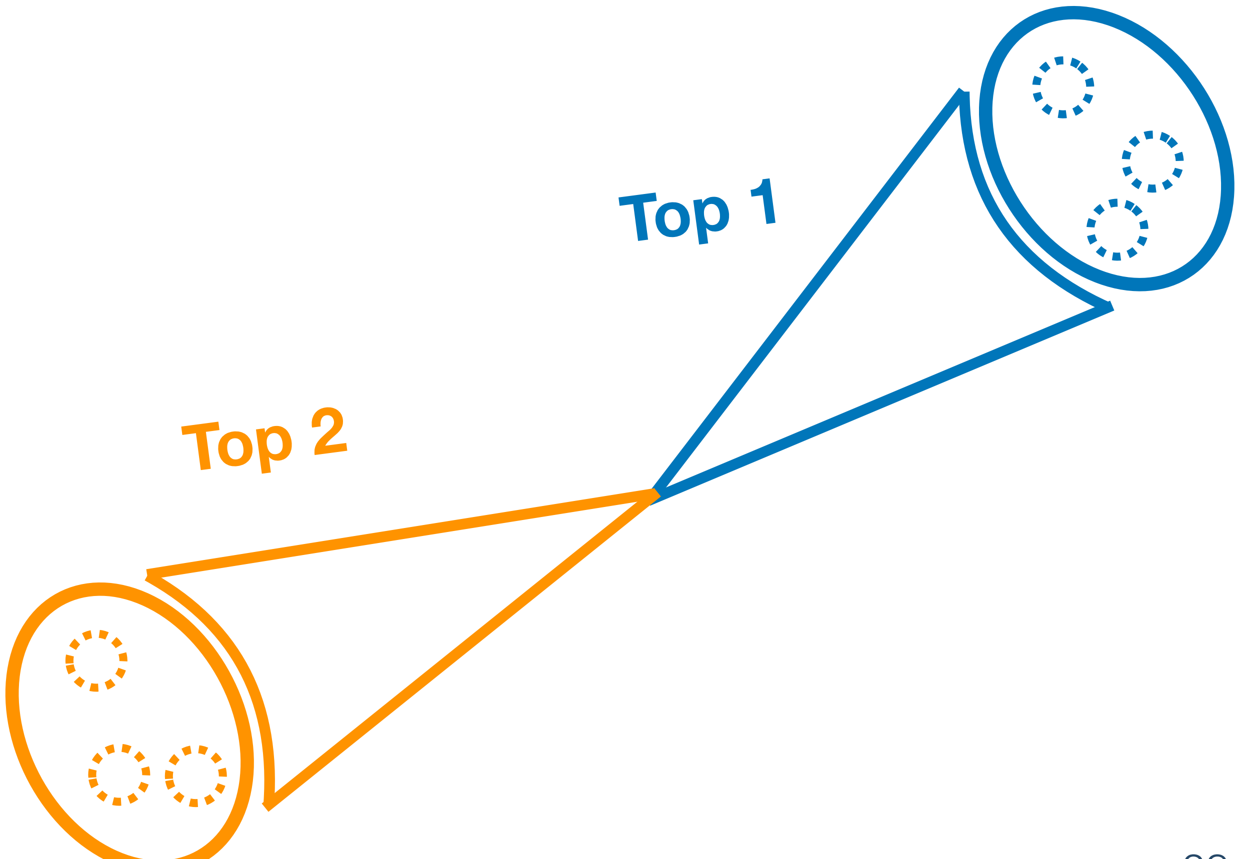
Performances of PUPPI jets/MET were extensively studied and compared to CHS jets/PF MET in JME-18-001

CMS-JME-18-001



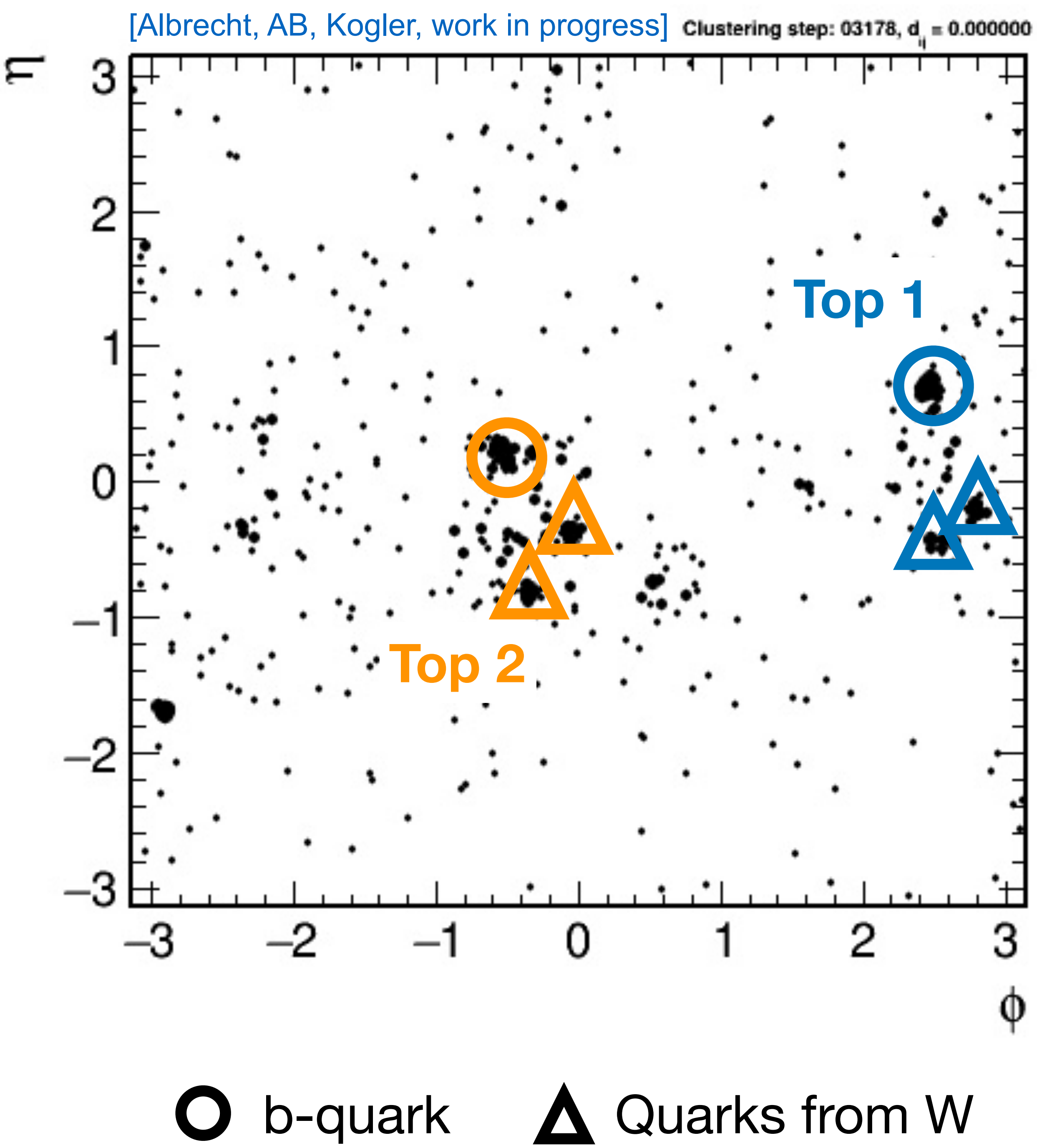
Jet reconstruction



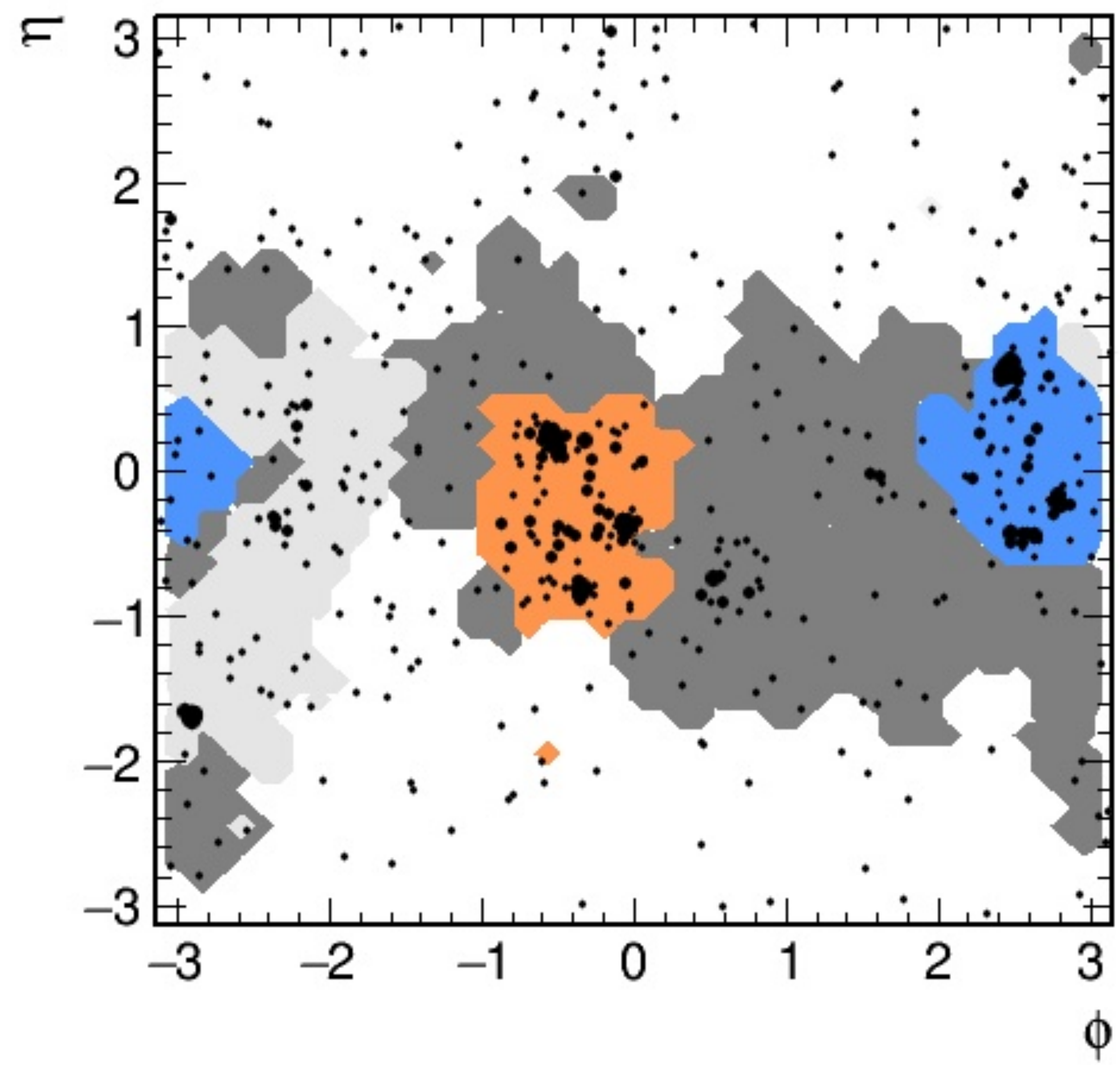


Jet reconstruction

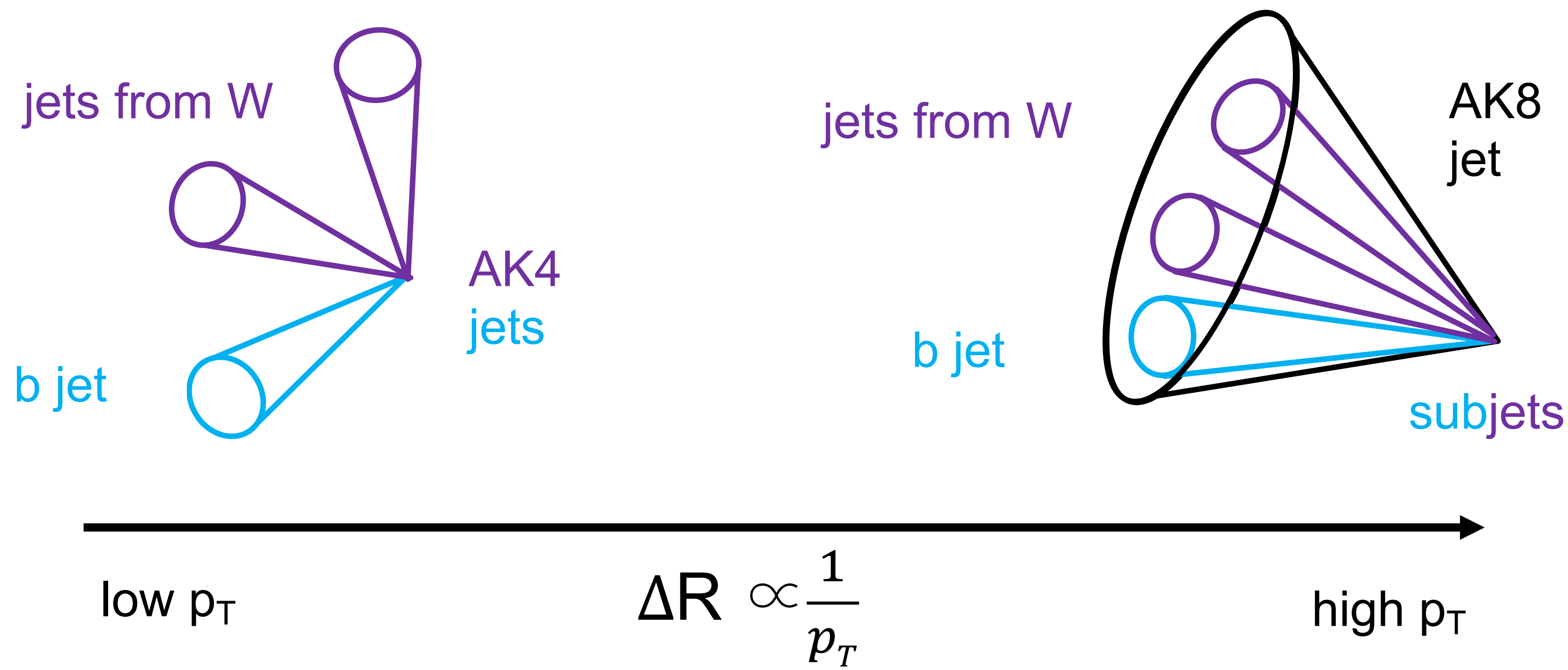
Starting point: cleaned PF candidates



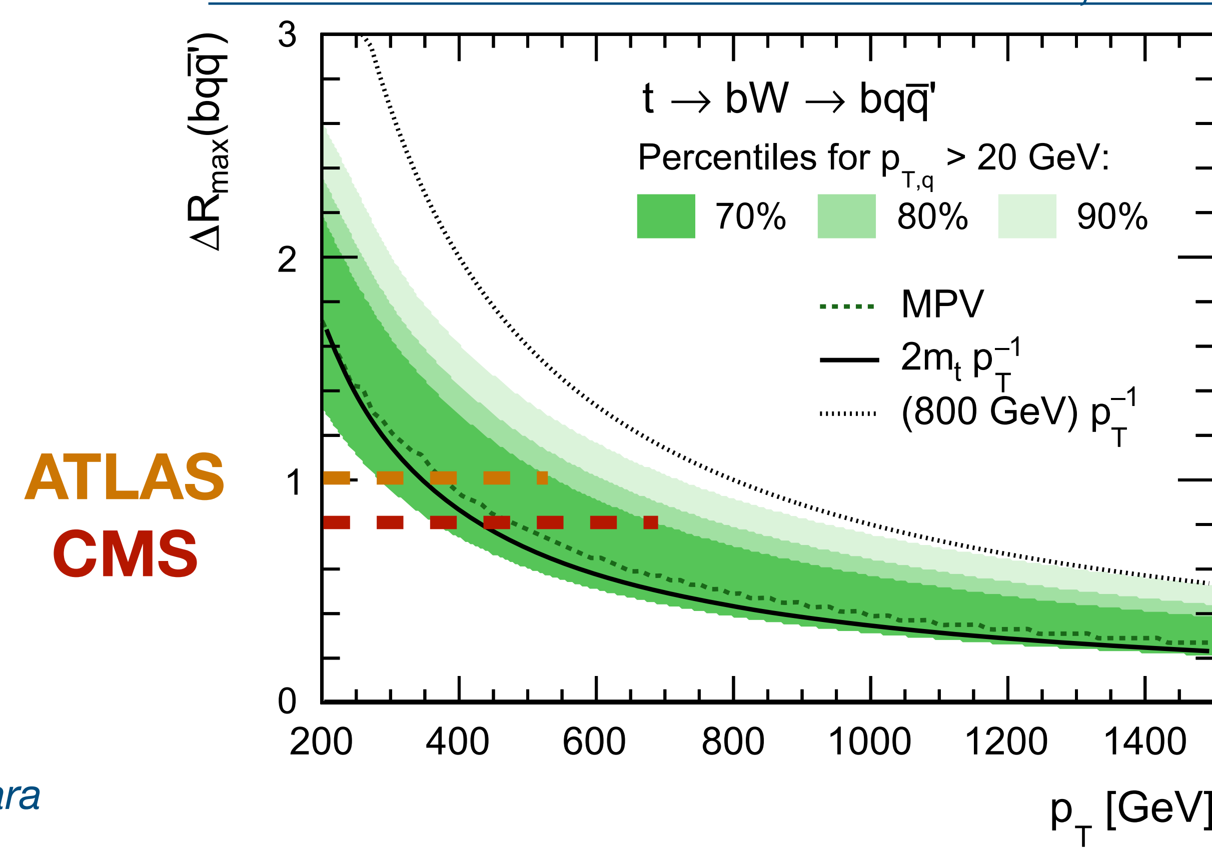
End point: two jets representing the top quark kinematics



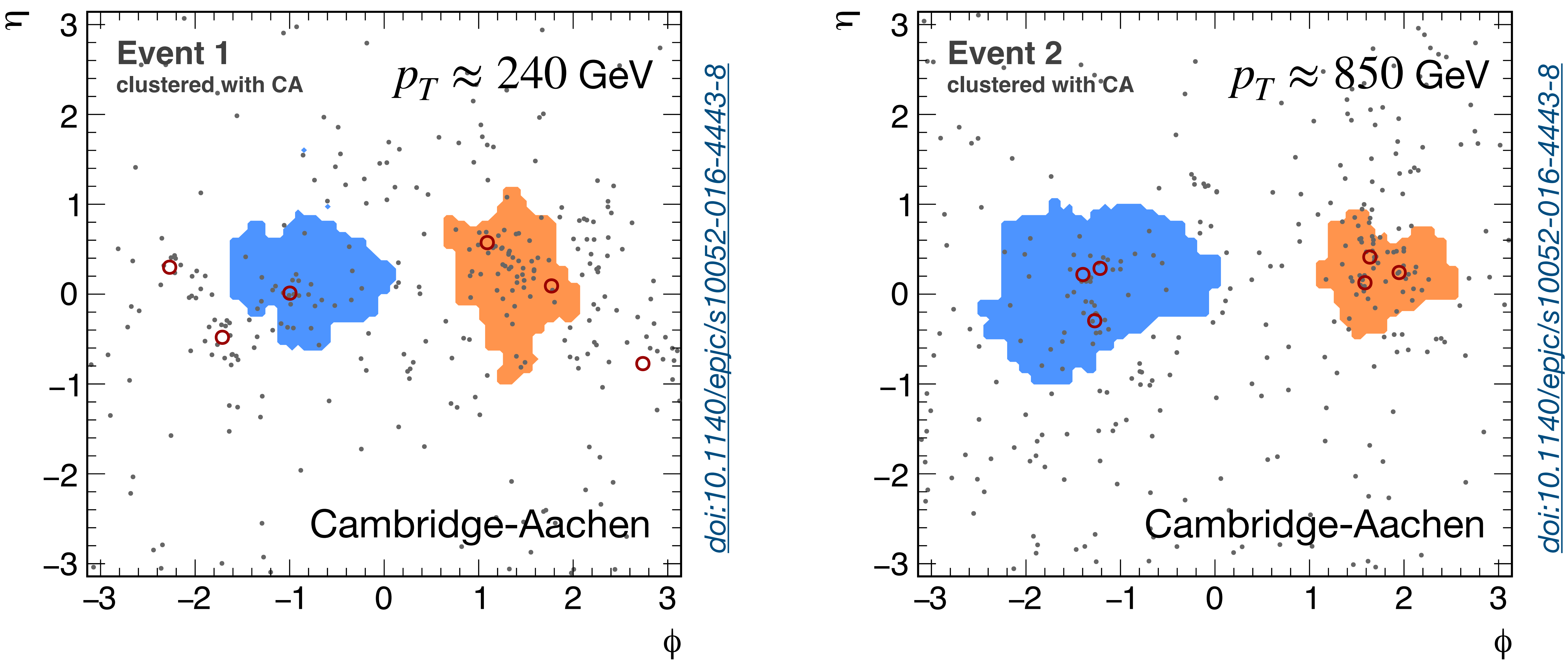
Jet reconstruction



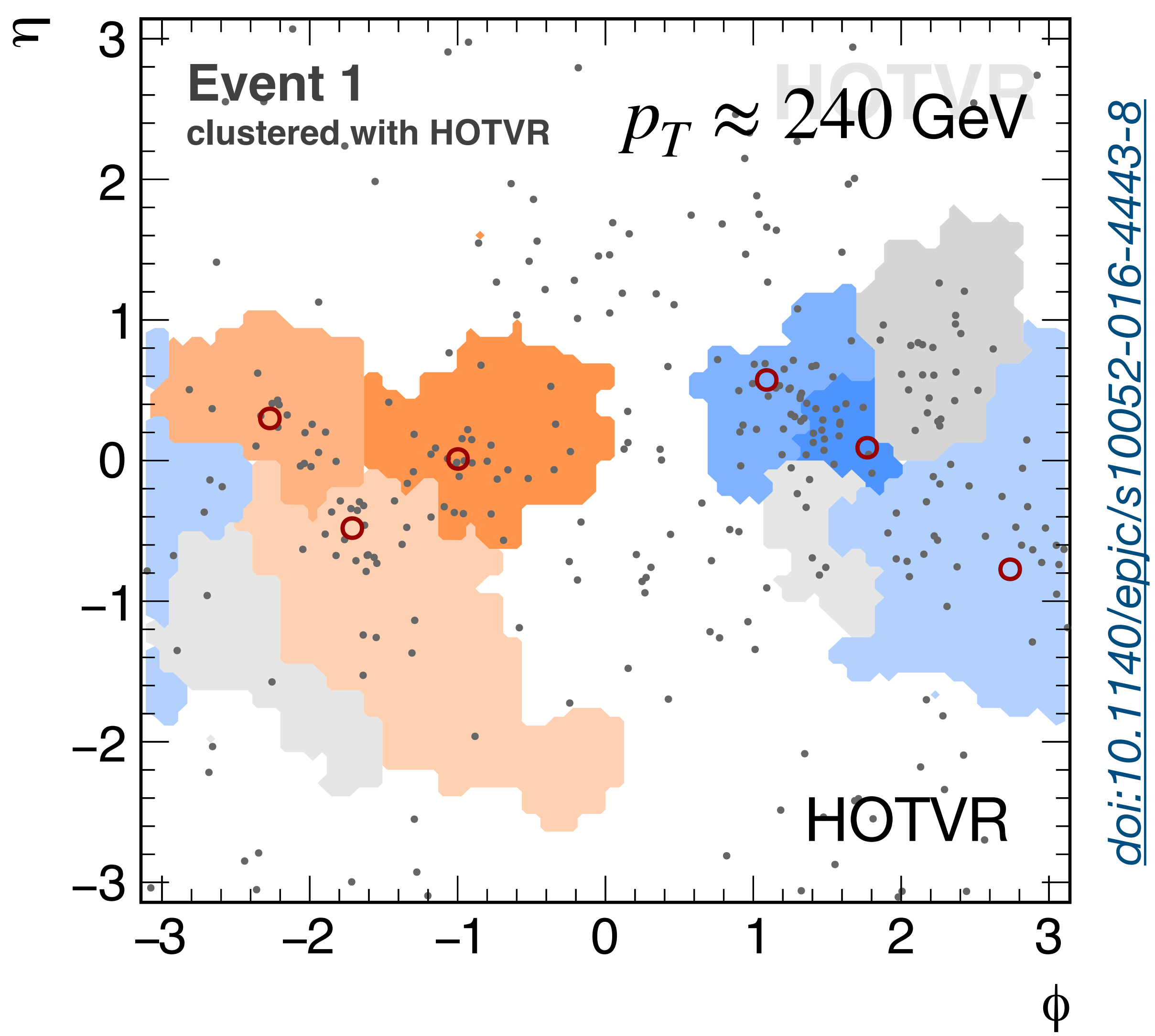
Advances in Jet Substructure at the LHC, R. Kogler

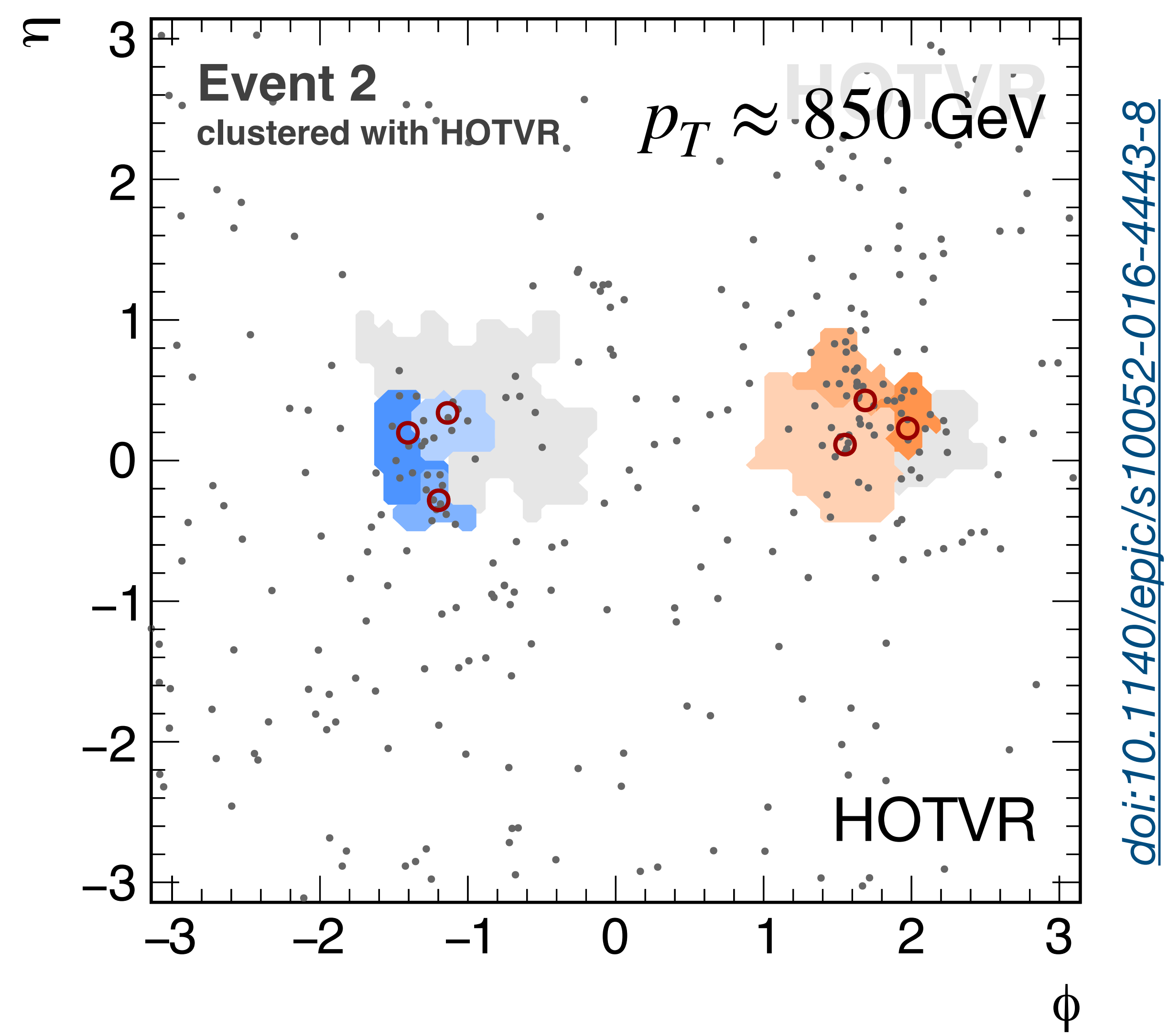


Fixed R clustering

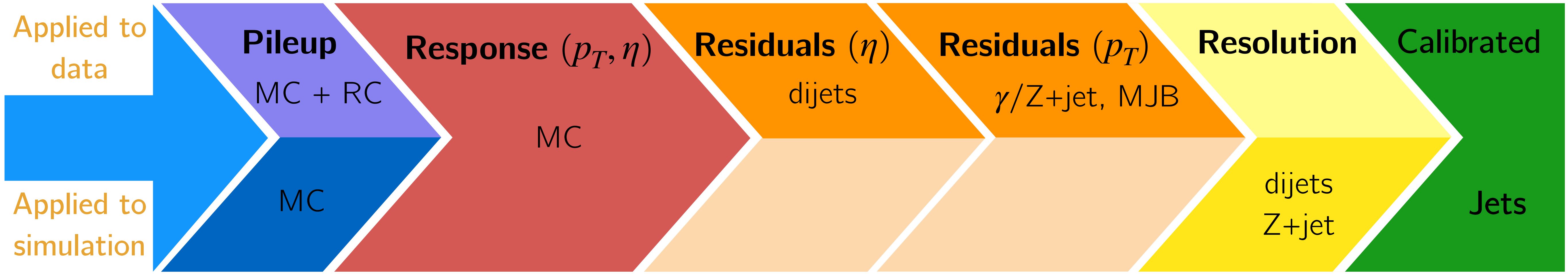


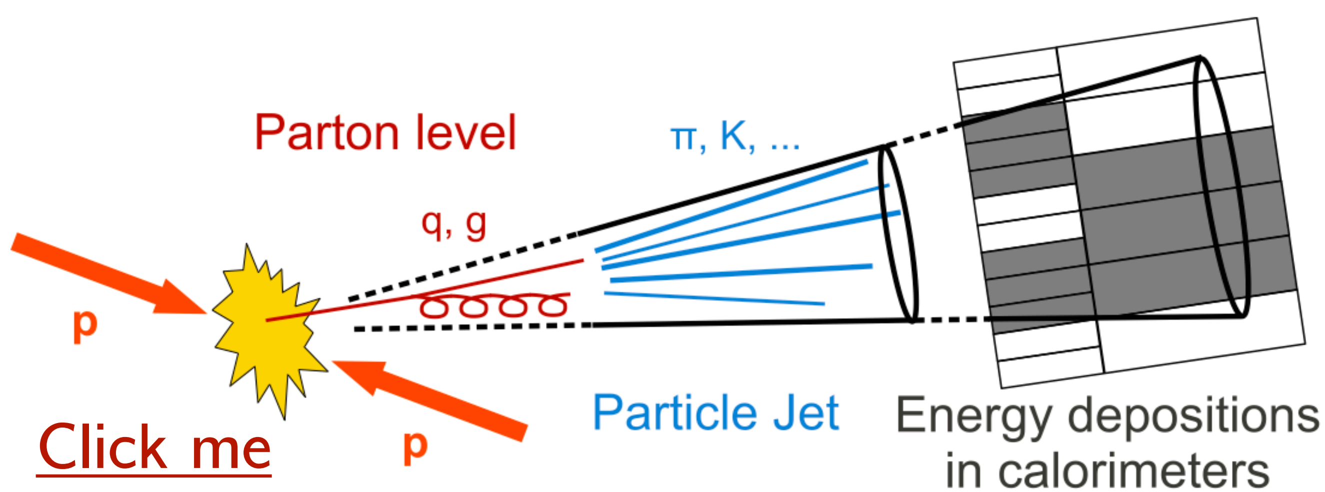
Variable R jet clustering



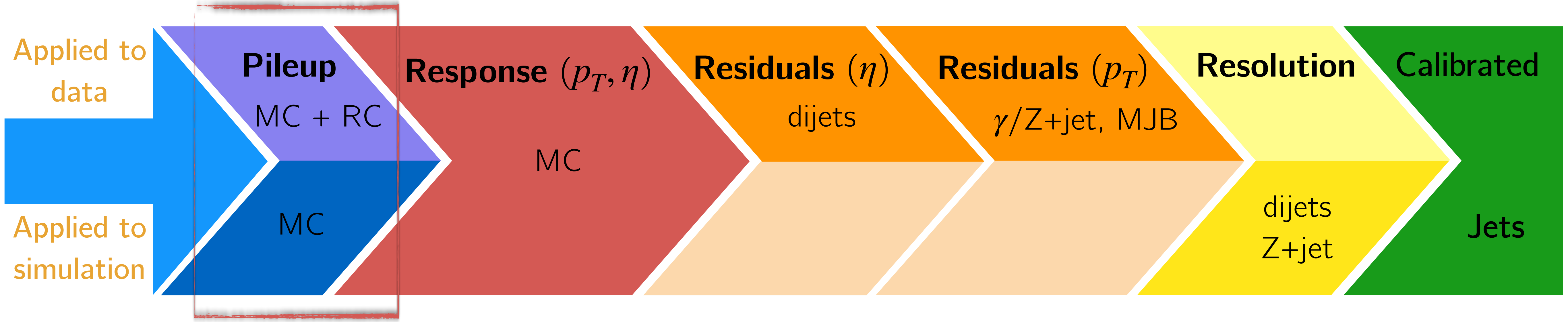


Jet Calibration





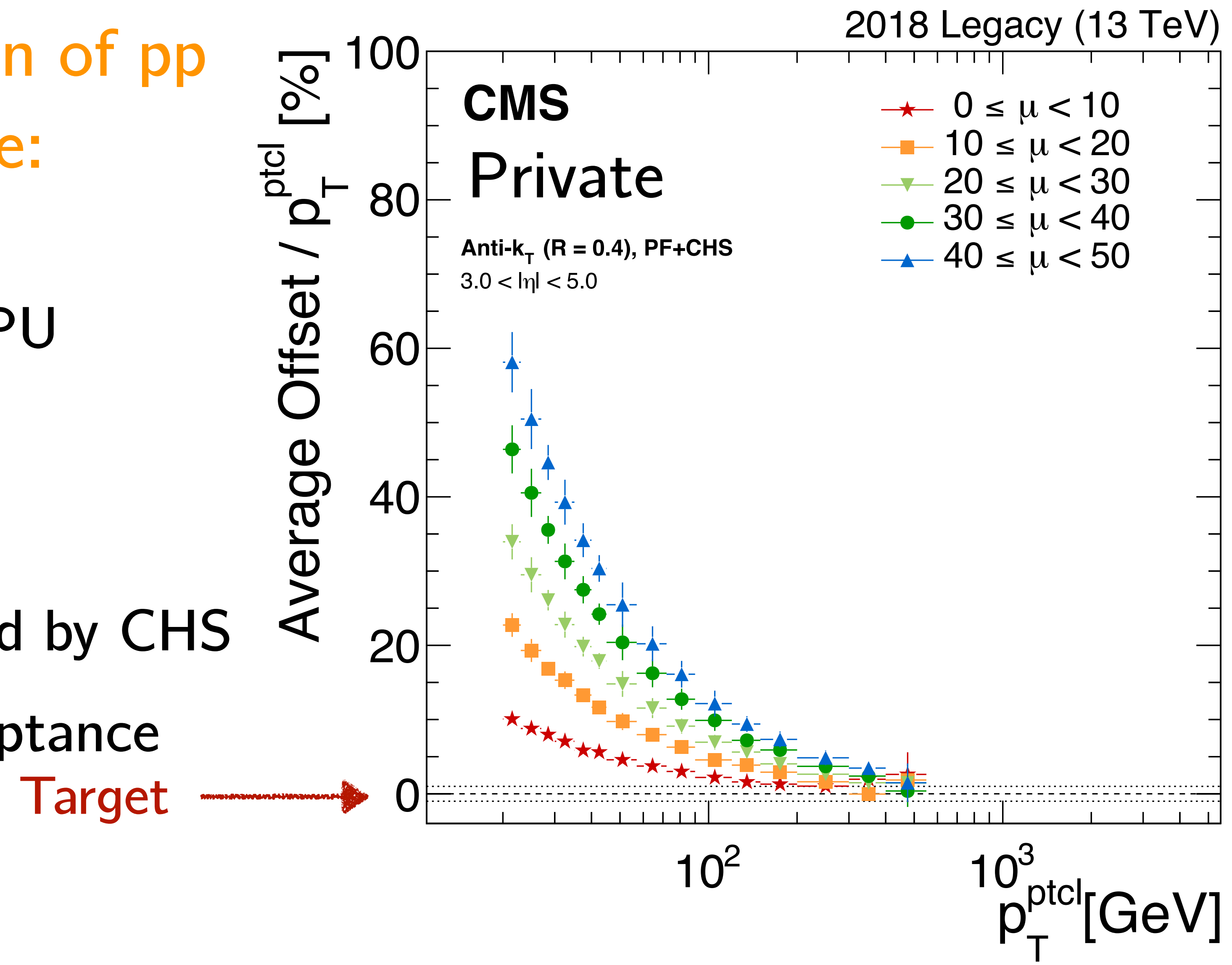
Jet Calibration



Corrections based on simulation of pp collisions and detector response:

PU subtraction

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



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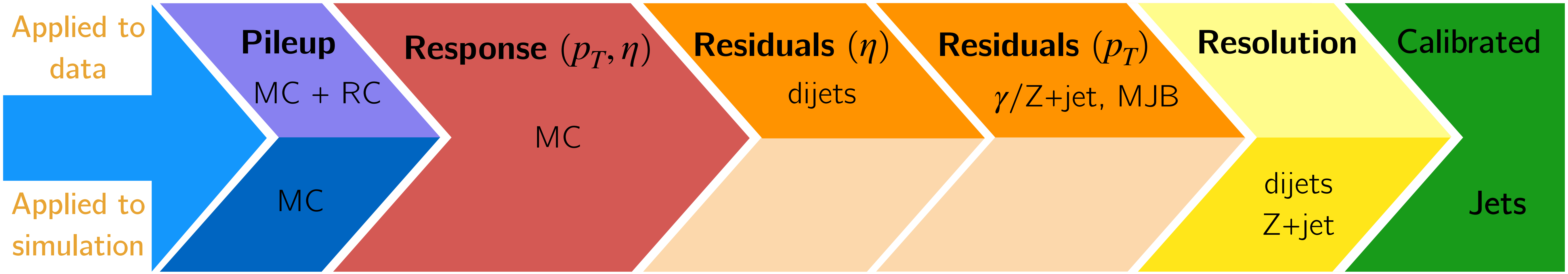

Corrections based on simulation of pp collisions and detector response:

PU subtraction

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- Approx. 0.5 GeV extra energy per jet
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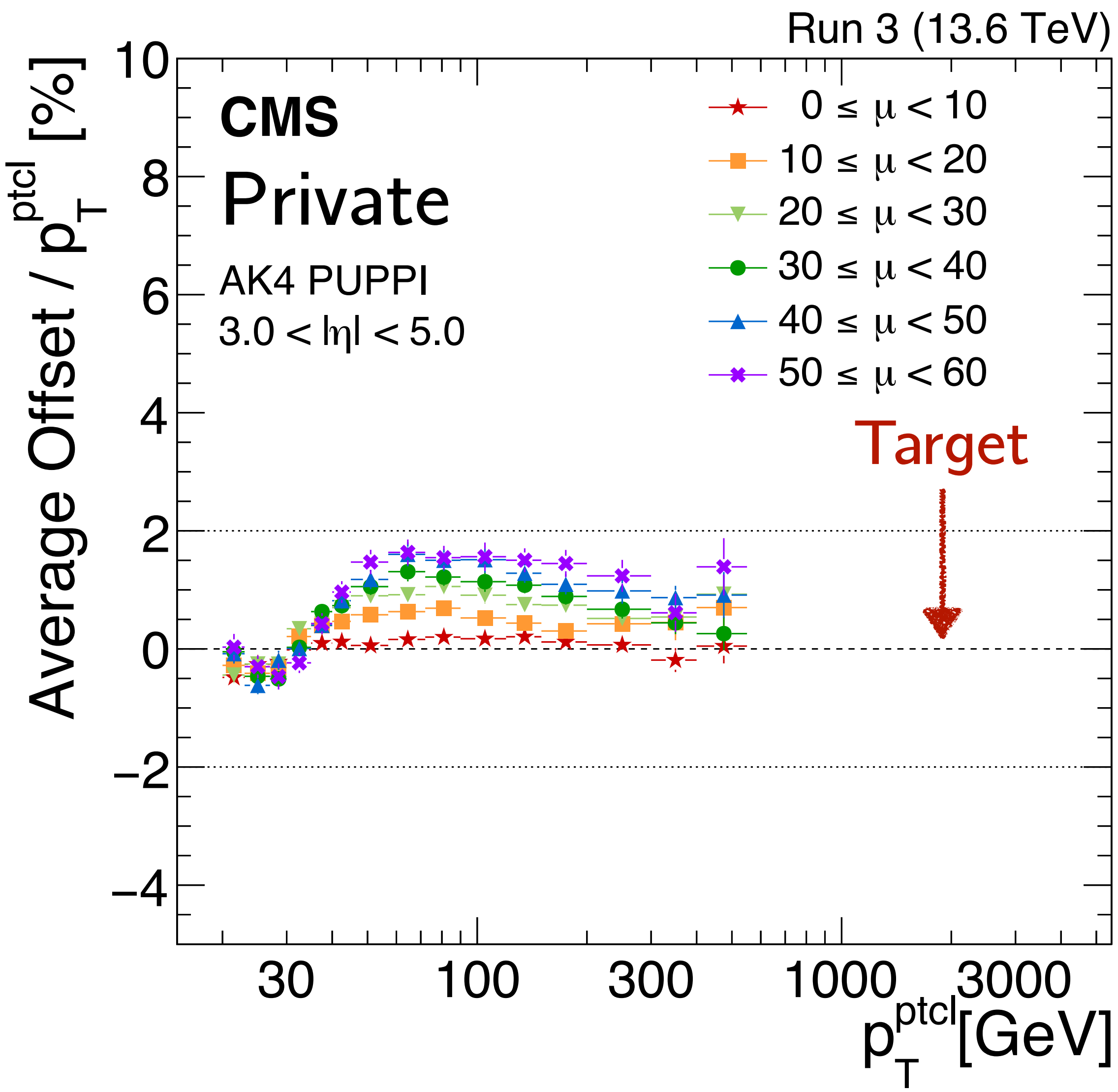
- Neutral component not removed by CHS
- Significant outside tracker acceptance
- Not needed for Puppi



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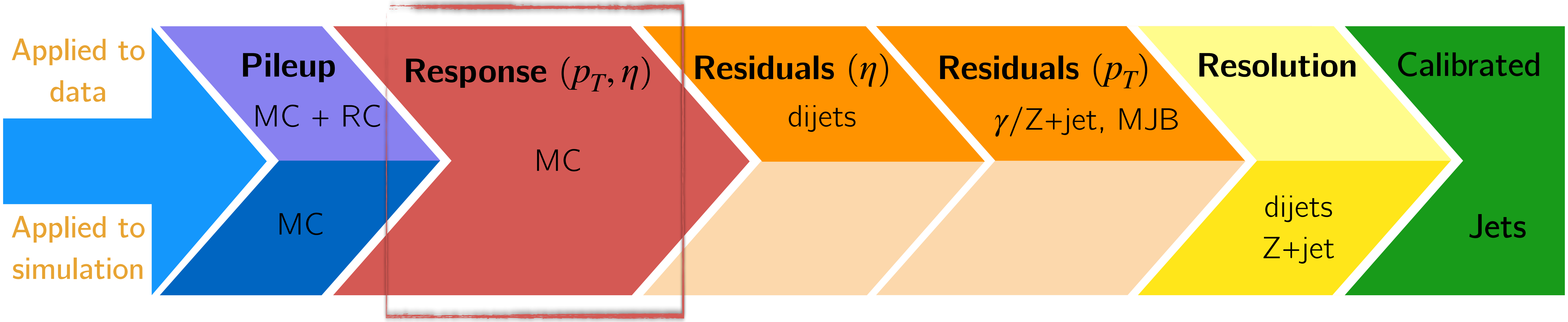
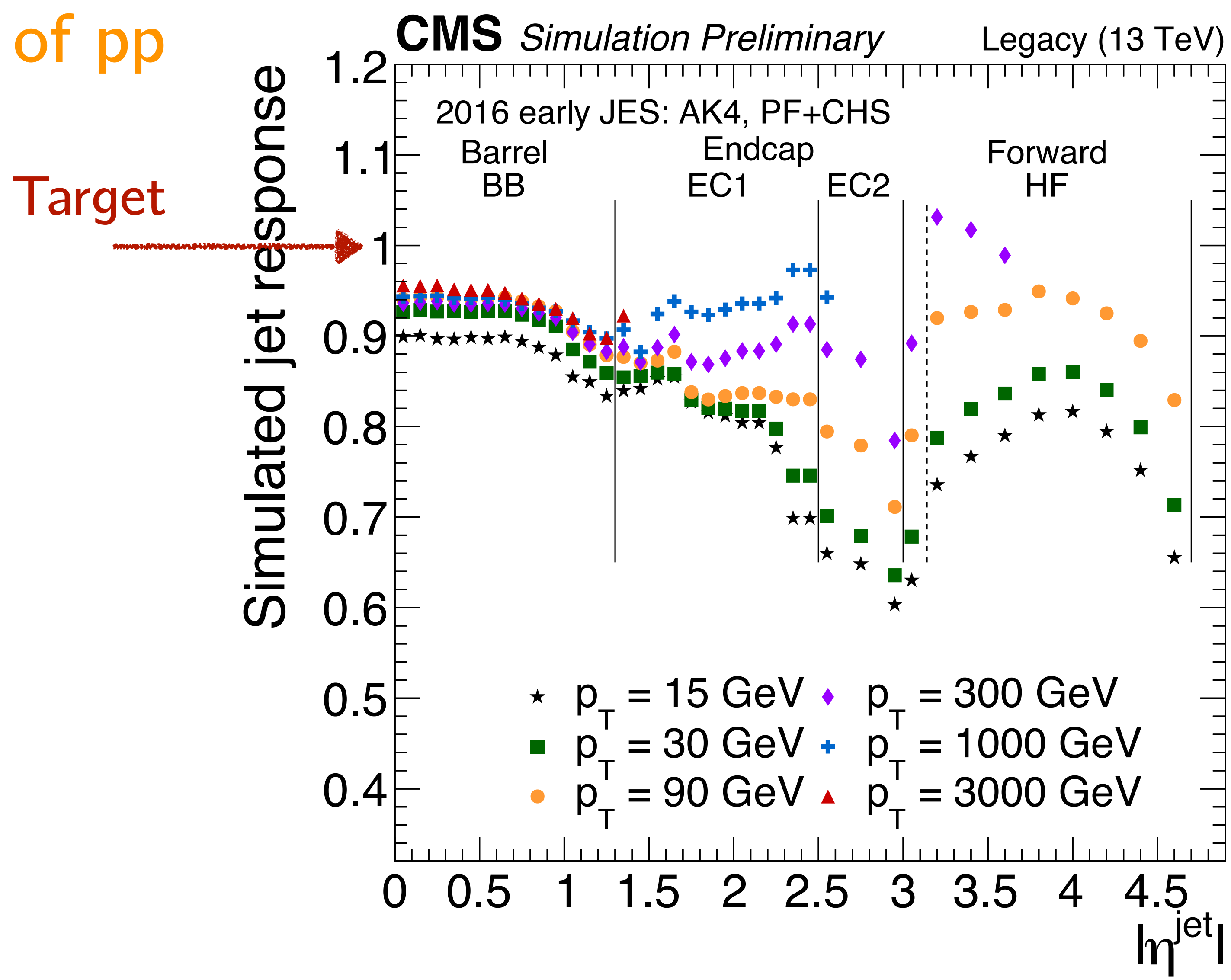


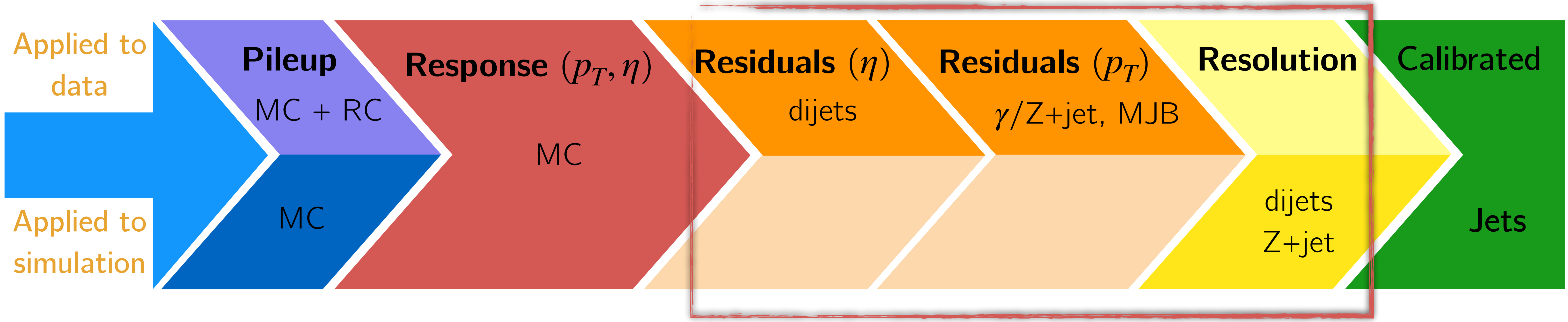
Corrections based on simulation of pp collisions and detector response:

Jet response calibration



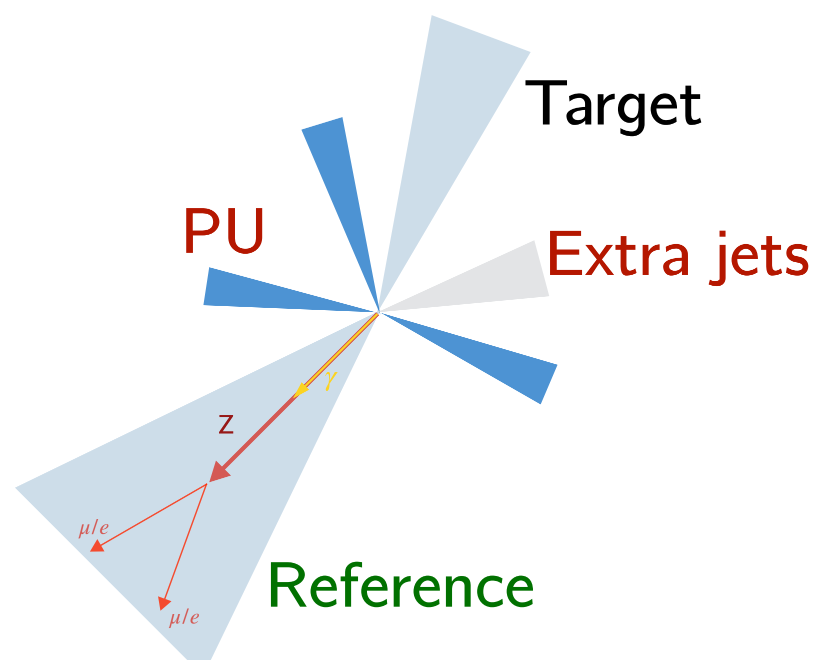
- Core of the calibration
- Simulation-based
- Accounts for detector effects
  - change in performance due to detector acceptance

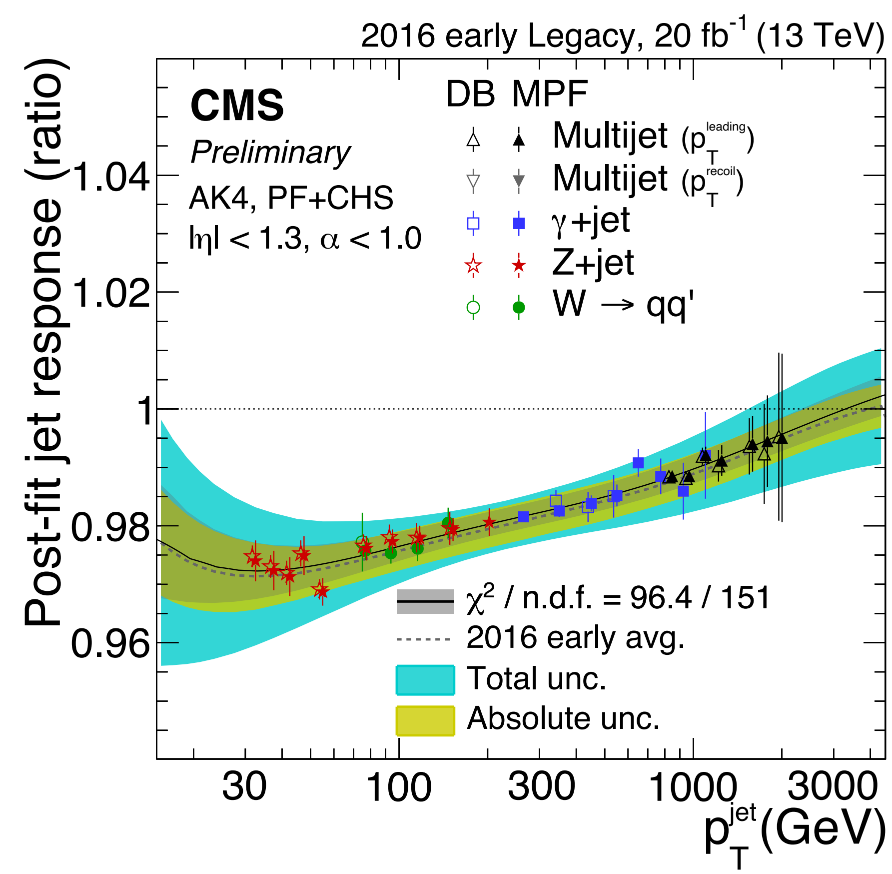
Jet Calibration



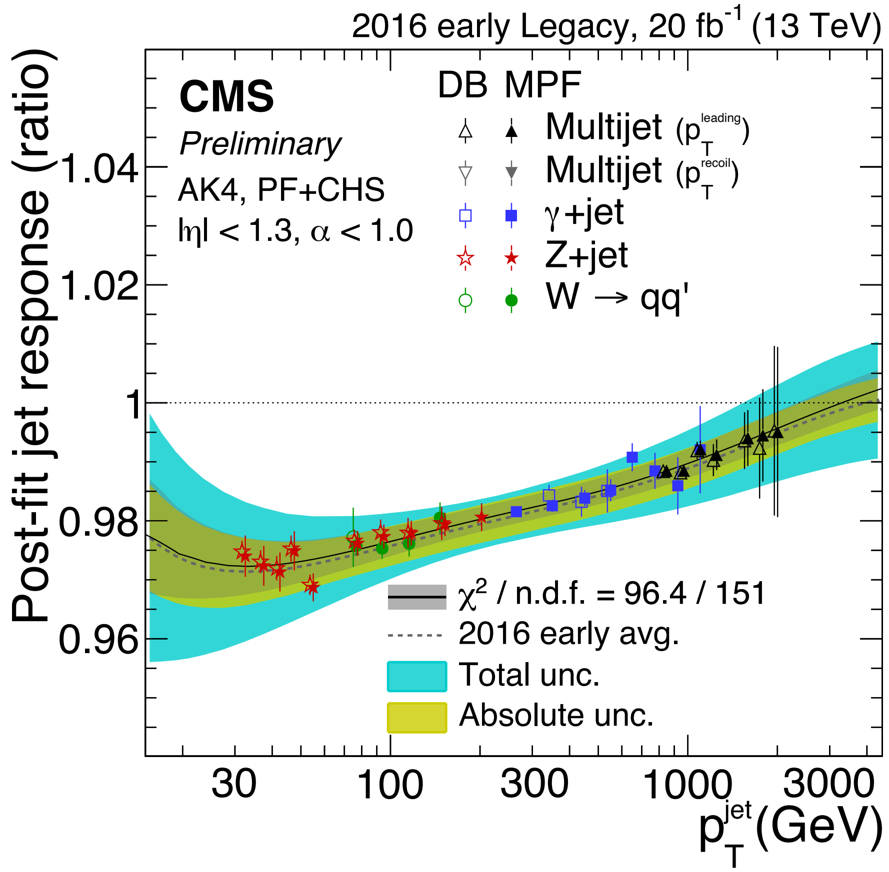
Corrections derived from data

- Based on precision of other reference objects
  - Electrons, photons, muons, other jets...
- Address different response in each sub-detector
  - usually small corrections except in transition regions

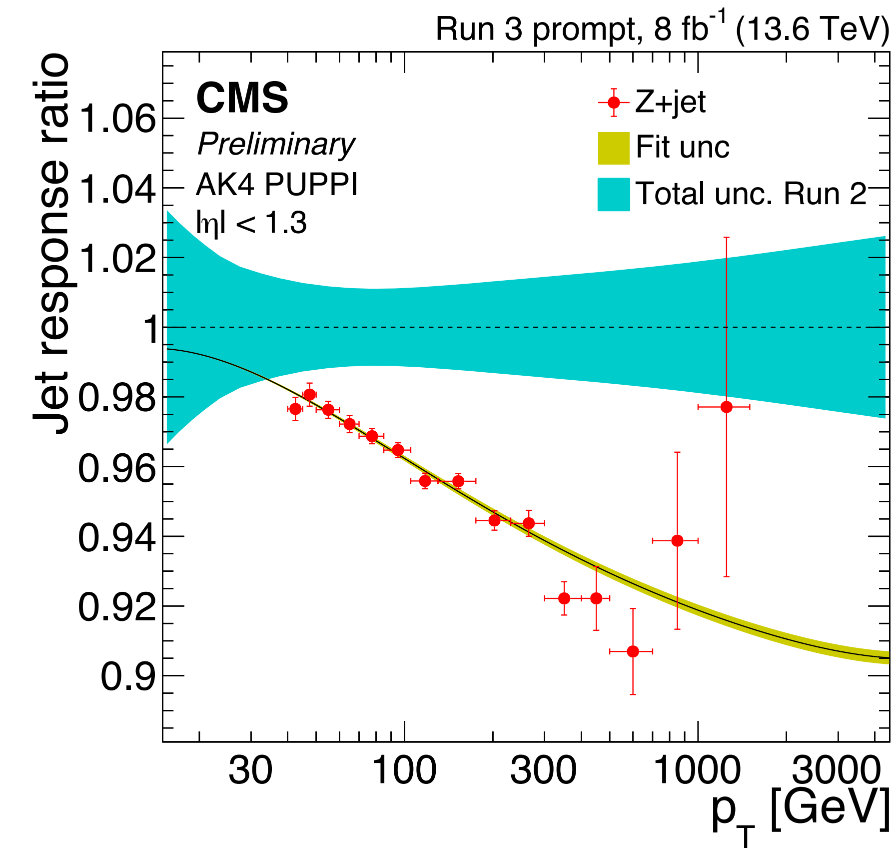




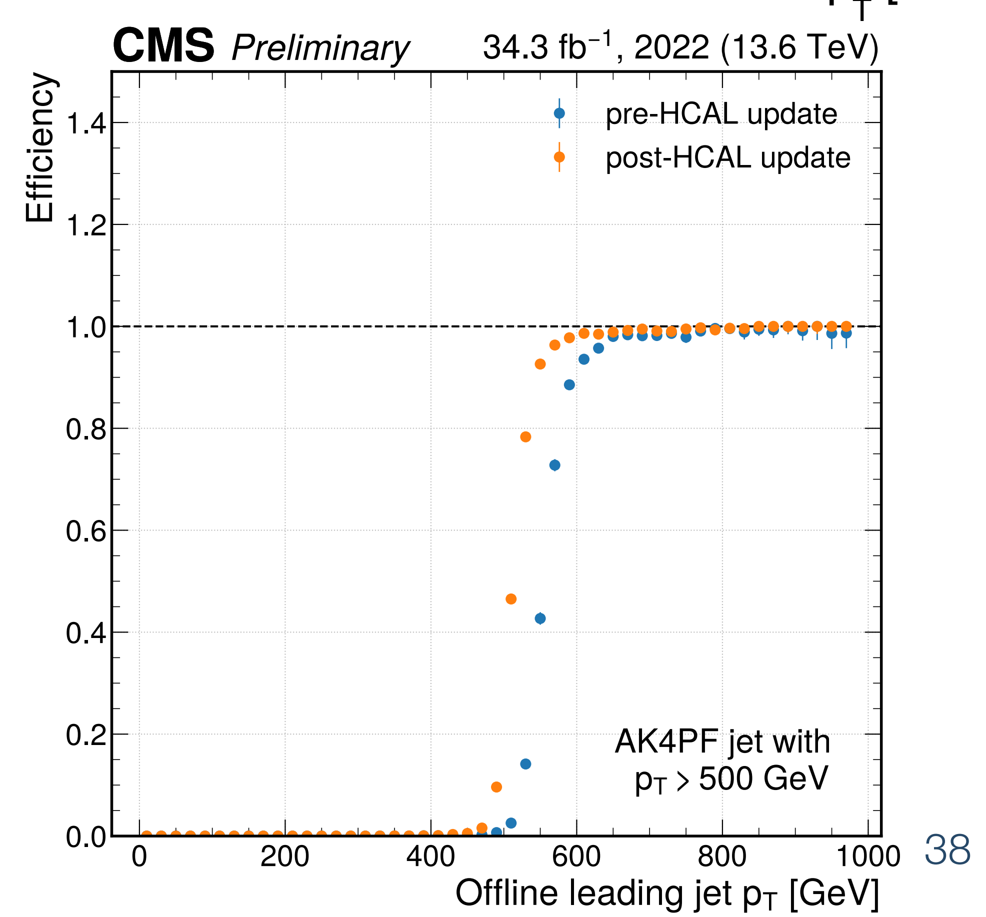
Jet Calibration in Run3



Run2 → **Run3**

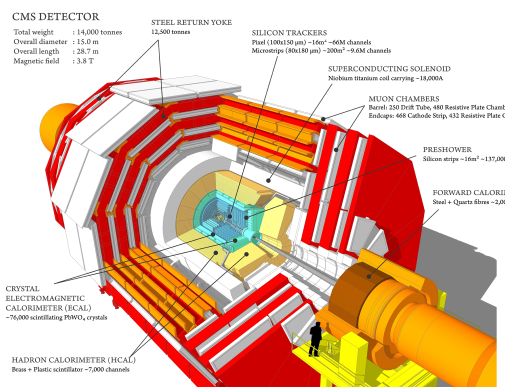


- Usually small corrections offline for data
  - means small effect on data online (trigger)
- Start of Run3:
  - underestimated corrections for calorimeter energy scale (downstream)
  - confirmed impact by jet energy scale (upstream)
  - small fraction of data collected less efficiently

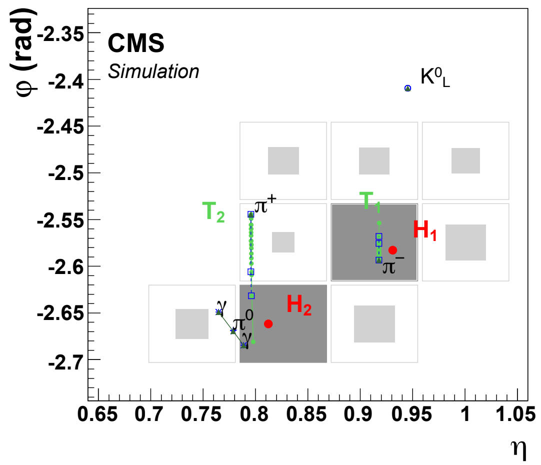


Summary & Outlook

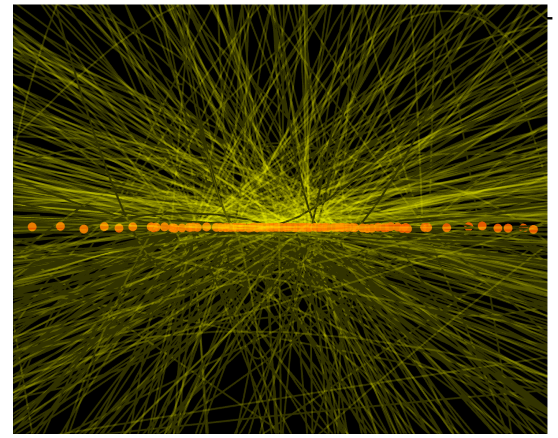
Detector



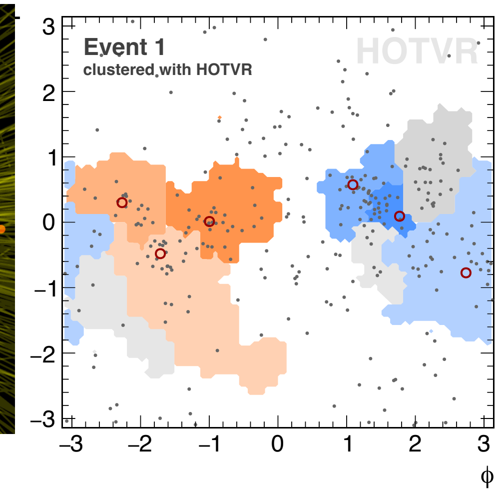
Reconstruction



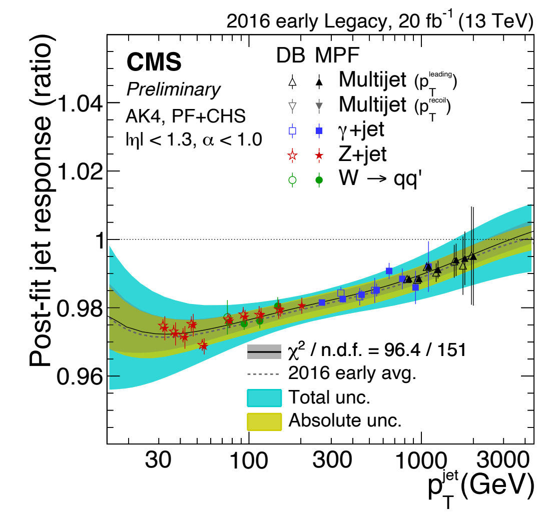
Pileup



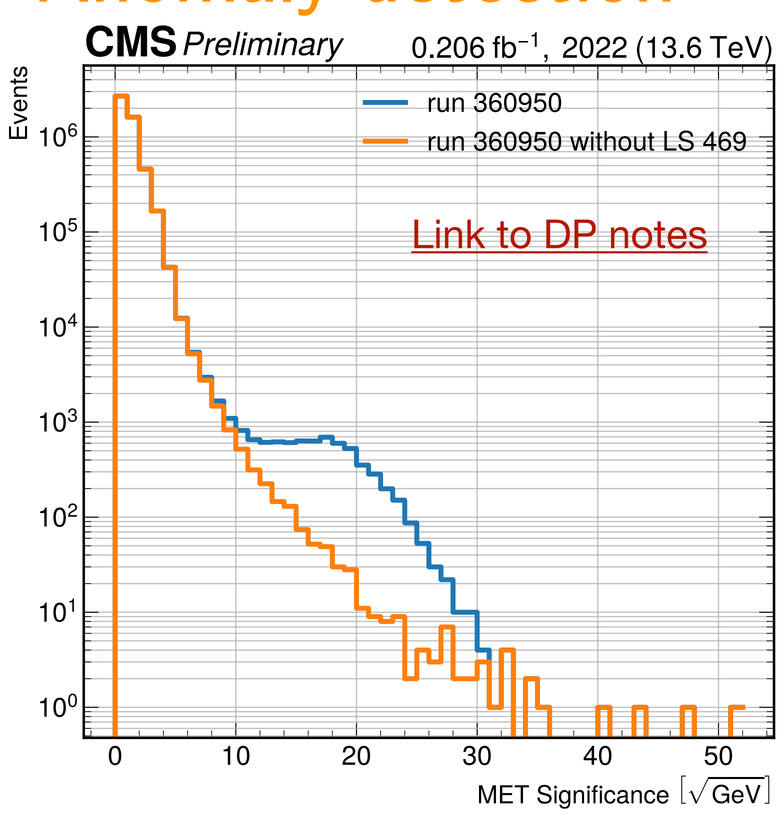
Clustering



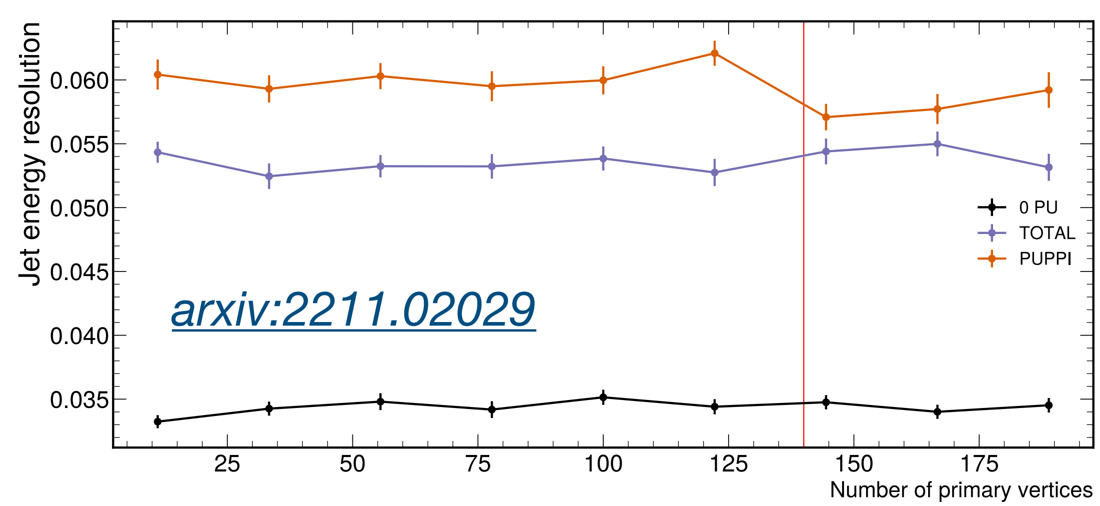
Calibration



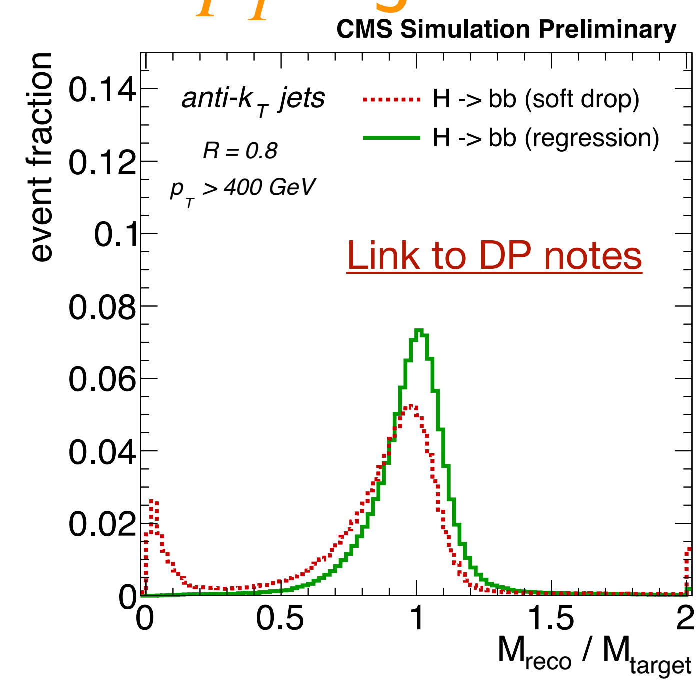
Anomaly detection



ML PU mitigation



ML p_T regression



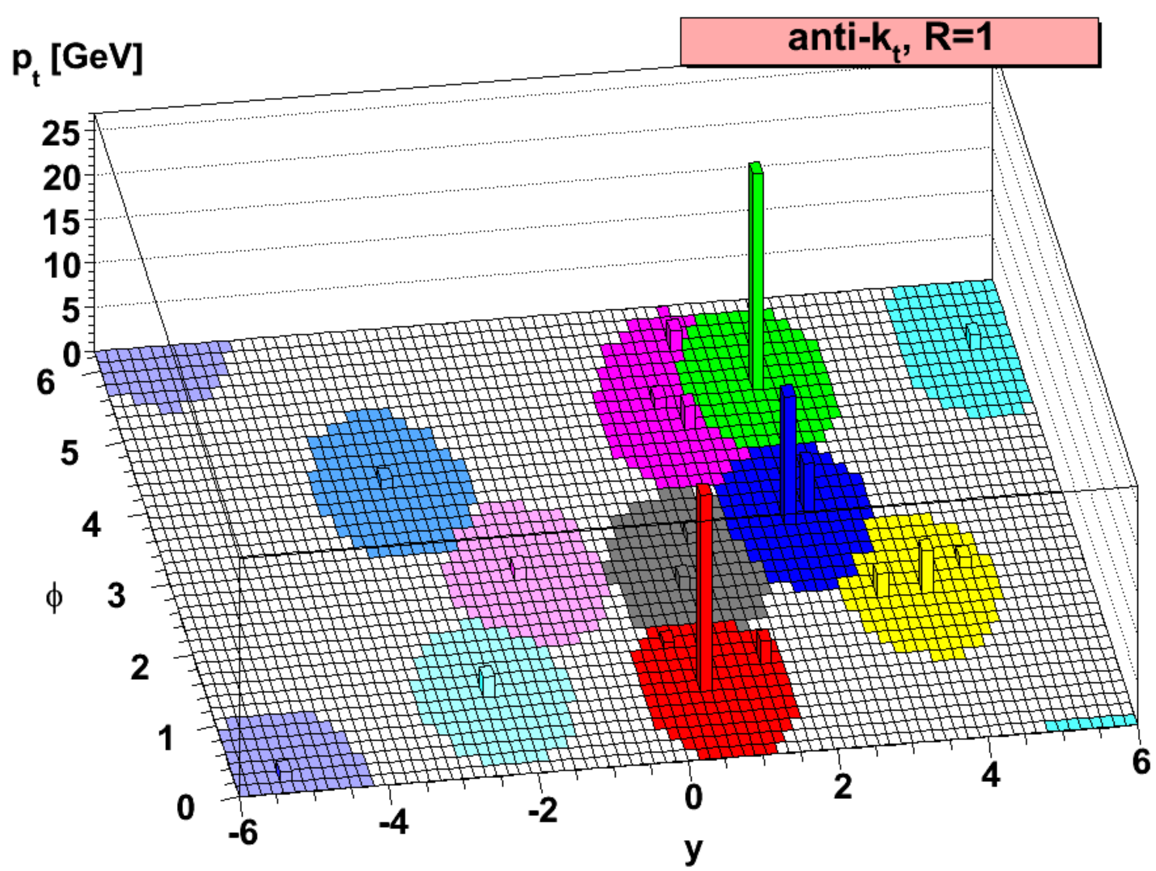
Anna Benecke & Andrea Malara

Successful **workshop** in Brussels!

Backup

Jet reconstruction

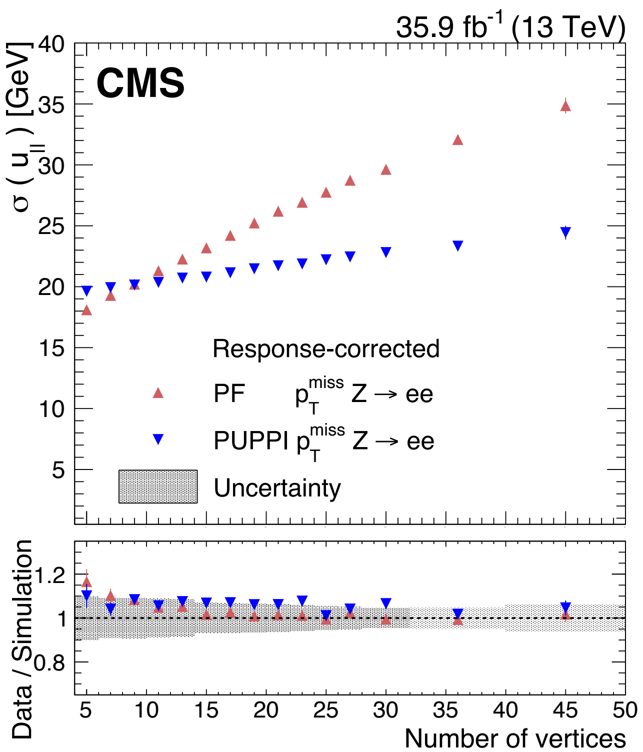
- Create particle-flow (PF) particles
  - link of tracks, calorimeter deposits, muon chamber hits
  - successfully used since Run1
  - Atlas only recently moved to a similar algorithm
- Anti-k_T algorithm to cluster together PF particles
  - small radius: R=0.4 (AK4)
  - alternative algorithms: CA, HOTVR, XCone



Validation of PUPPI

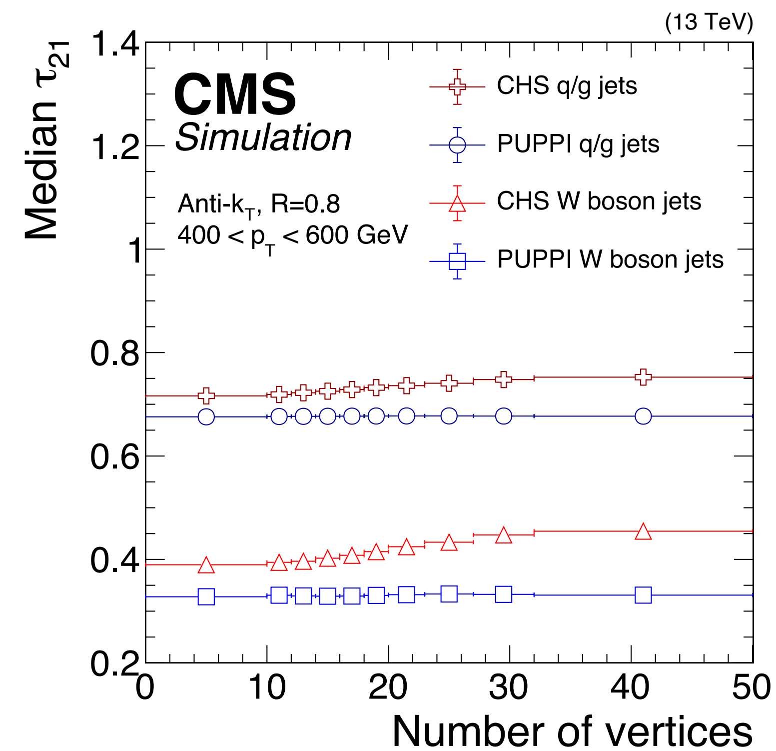
Performances of PUPPI jets/MET were extensively studied and compared to CHS jets/PF MET in JME-18-001

MET resolution

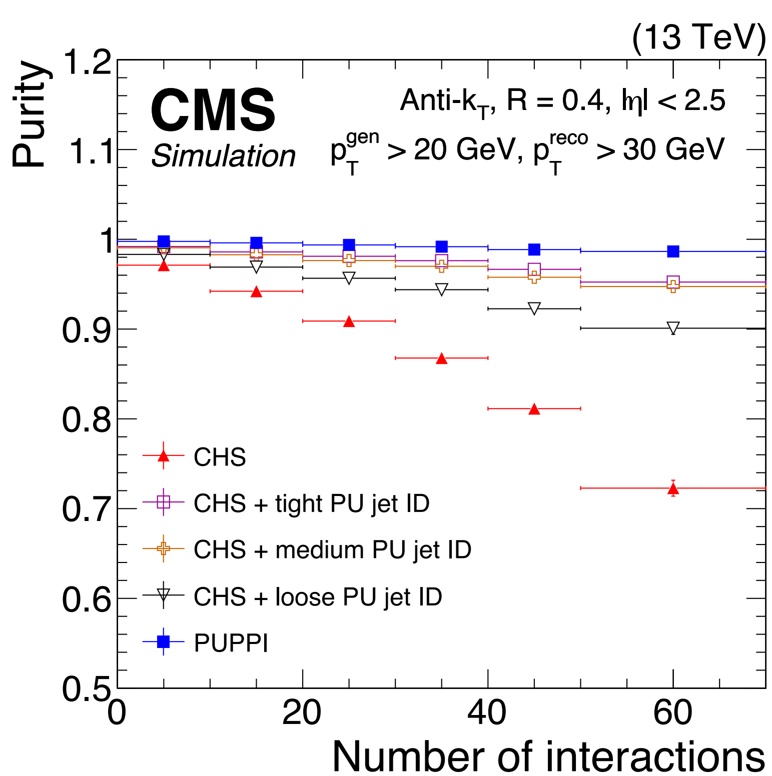


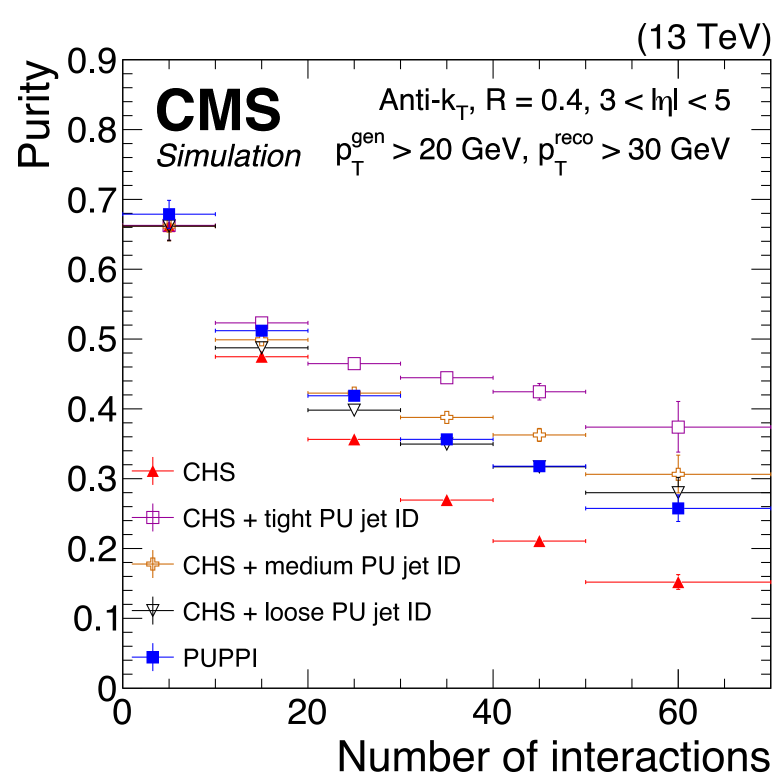
PUPPI has a better MET resolution and less fake MET.

W boson identification



PUPPI is more stable in jet mass, jet mass resolution and τ_{21}.



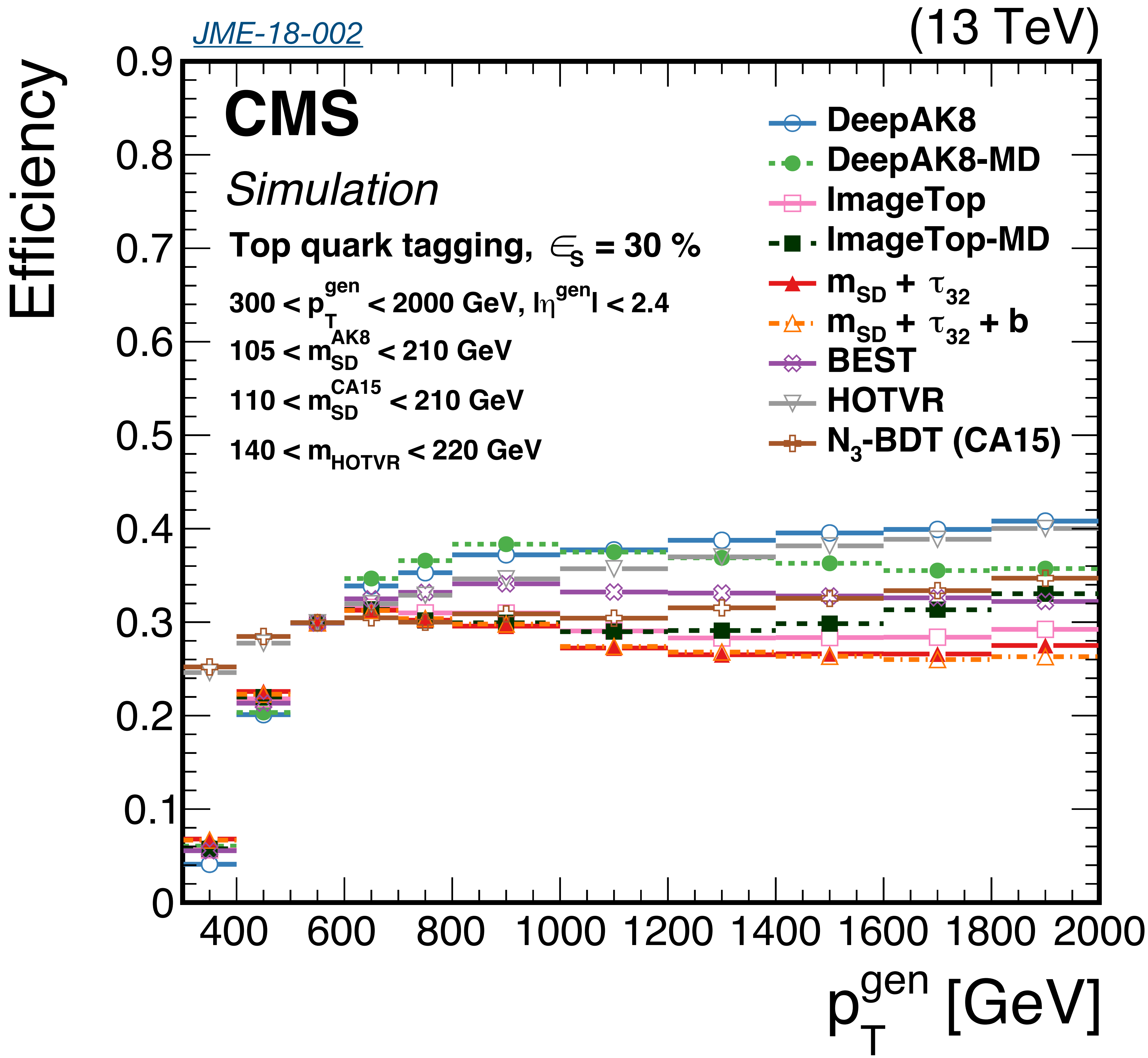


PU jets rejection

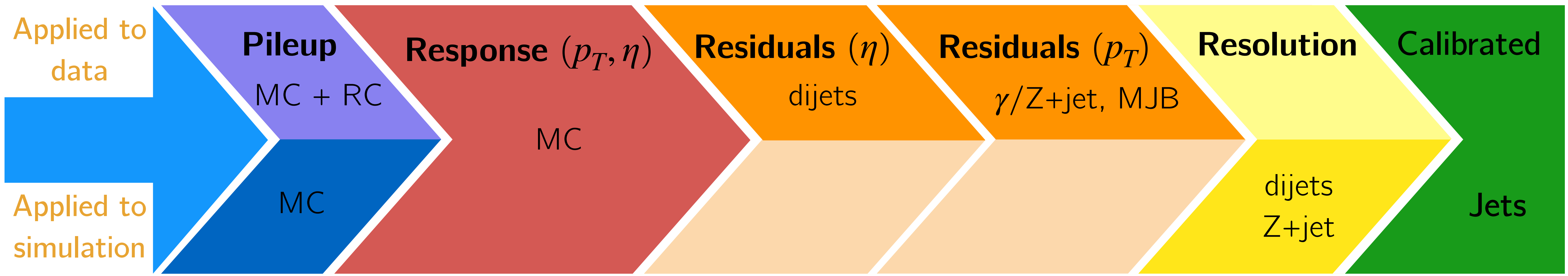
In $|\eta| < 2.5$ PUPPI rejects more PU jets than all other techniques

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

HOTVR

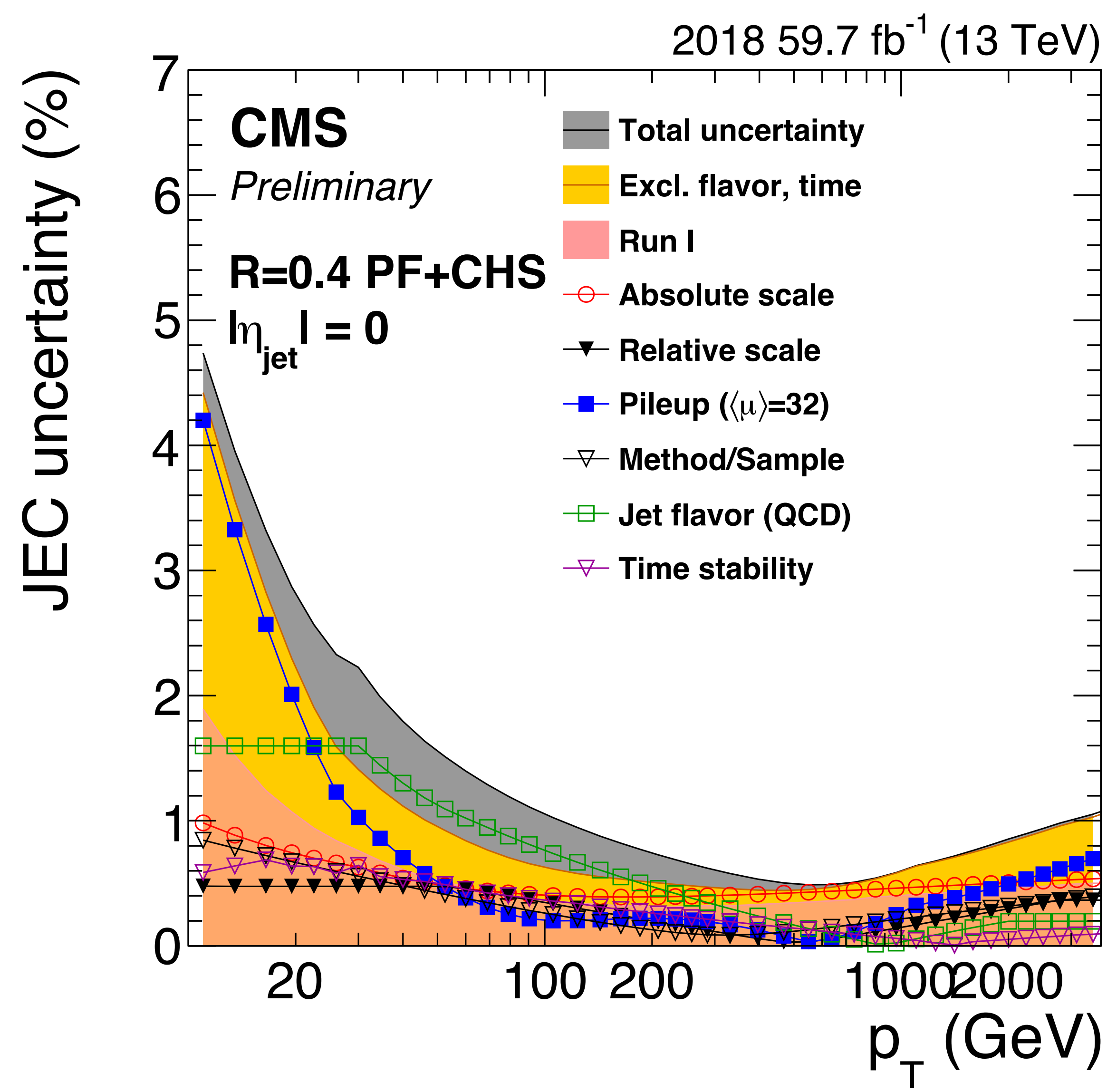

JME-18-002
(13 TeV)
CMS
Simulation
Top quark tagging, ϵ_S = 30 %
300 < p_T^{gen} < 2000 GeV, $|\eta^{gen}|$ < 2.4
105 < m_{SD}^{AK8} < 210 GeV
110 < m_{SD}^{CA15} < 210 GeV
140 < m_{HOTVR} < 220 GeV
DeepAK8
DeepAK8-MD
ImageTop
ImageTop-MD
m_{SD} + τ_{32}
m_{SD} + τ_{32} + b
BEST
HOTVR
N_3-BDT (CA15)
Efficiency
p_T^{gen} [GeV]

Jet Calibration

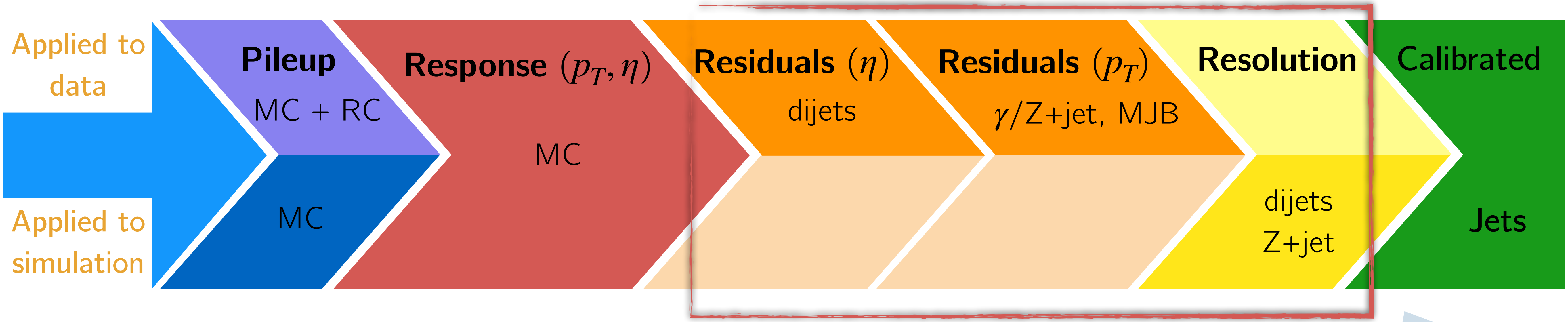


Jet energy scale uncertainties

- Uncertainty ~1% for jets pt >100 GeV
  - Primary goal it to bring down to 0.1%
  - Improve techniques, reduce biases, understand better our detector
- Increasing contribution from PU
- Detector degradation: Ageing, damage, ...

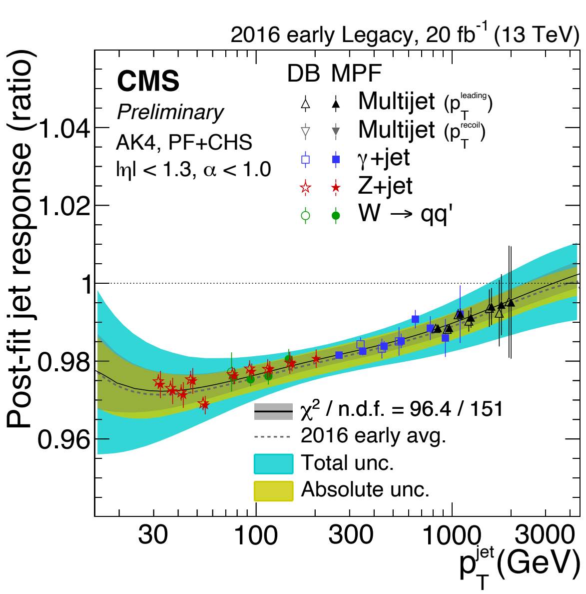


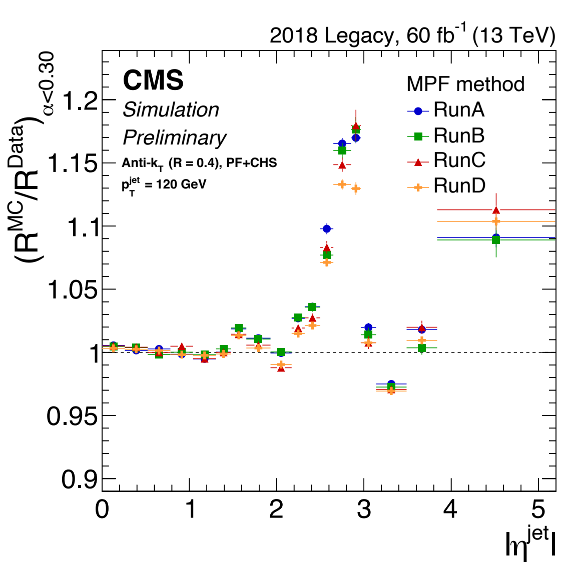
Jet Calibration

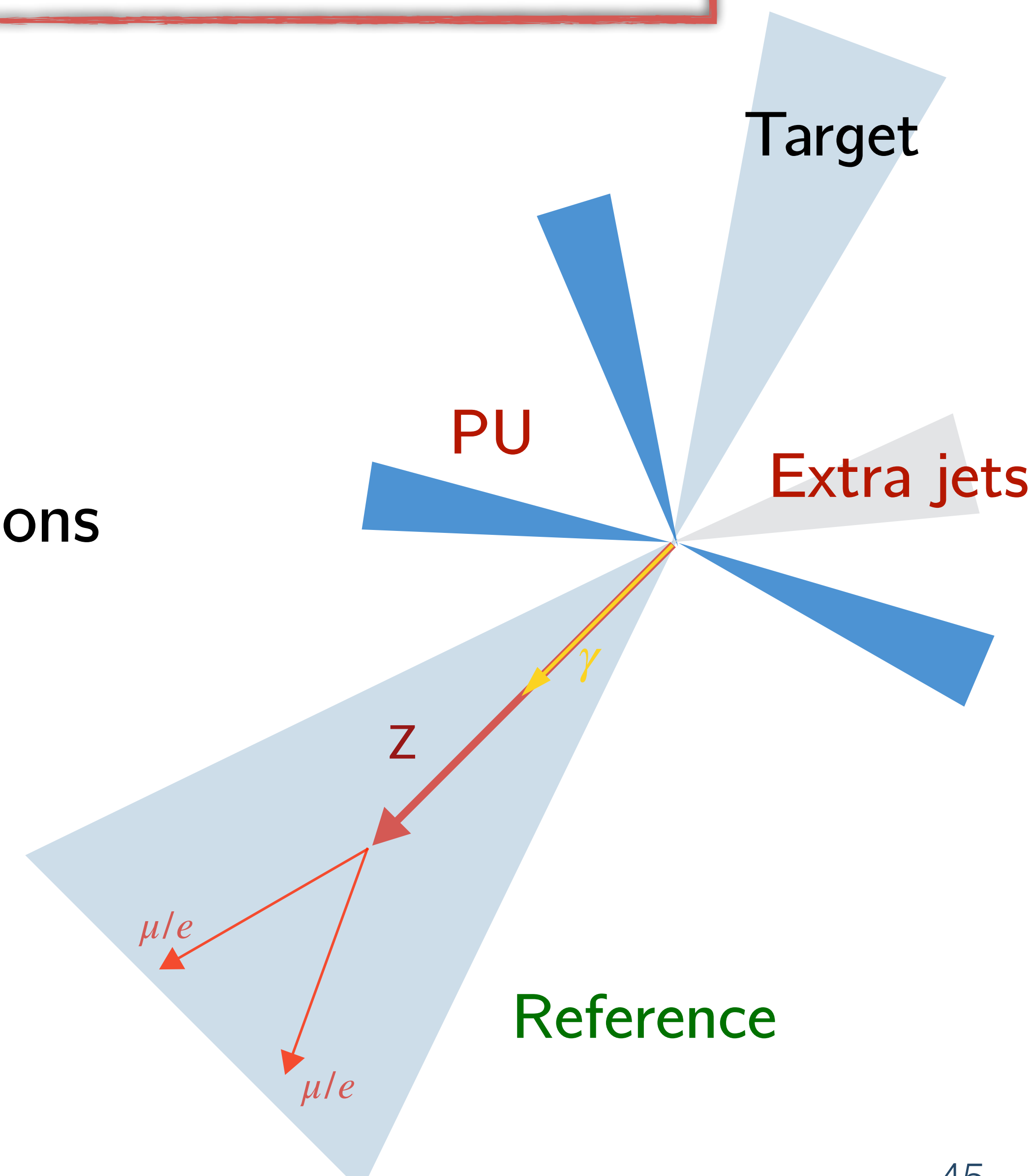


Residual corrections

- Based on precision of other reference objects
  - Electrons, photons, muons, other jets...
- Address different response in each sub-detector
  - usually small corrections except in transition regions

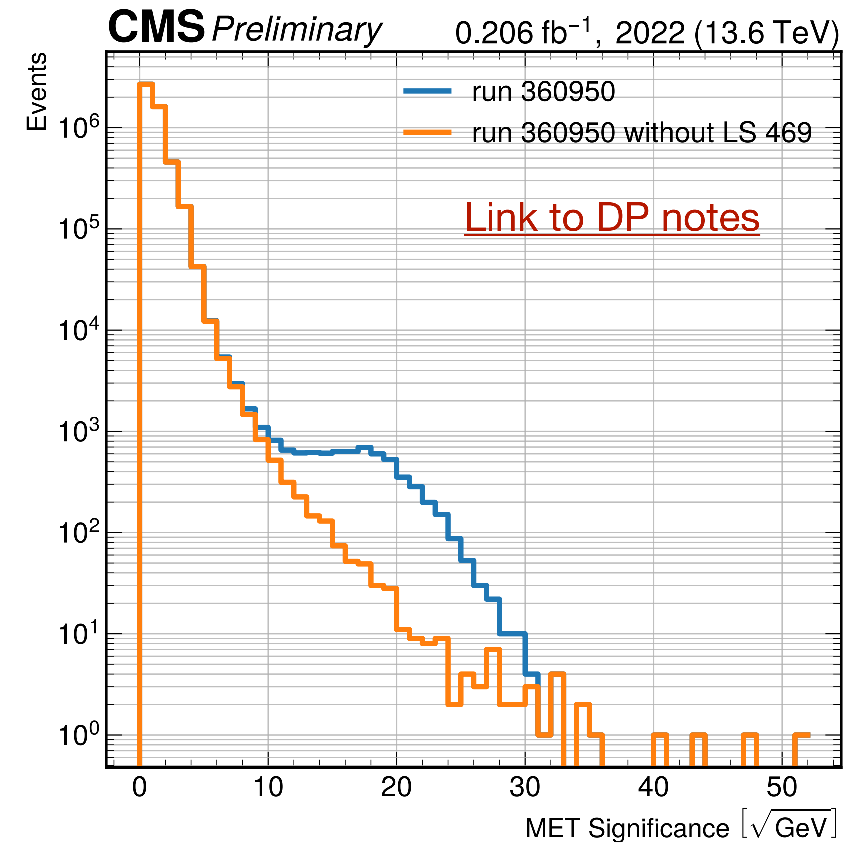






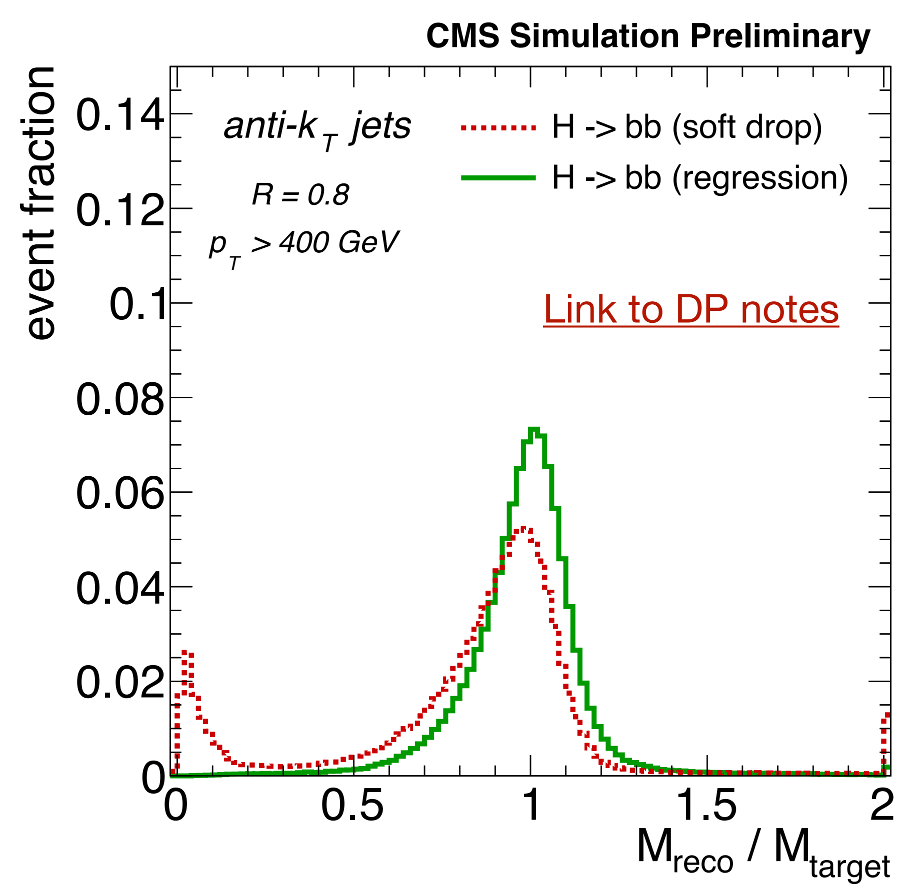
Machine learning: future perspective

Anomaly detection:



- Identify temporary problems in the detector
- Save time and increase data-taking efficiency

Regression for jet mass (and energy):



- More performant wrt traditional algorithms
- Currently used for jet mass
  - direct effect on analyses's sensitivity
- Planning on simultaneous training of tagging and regression for energy and mass
  - improve scale, resolution and flavour dependency