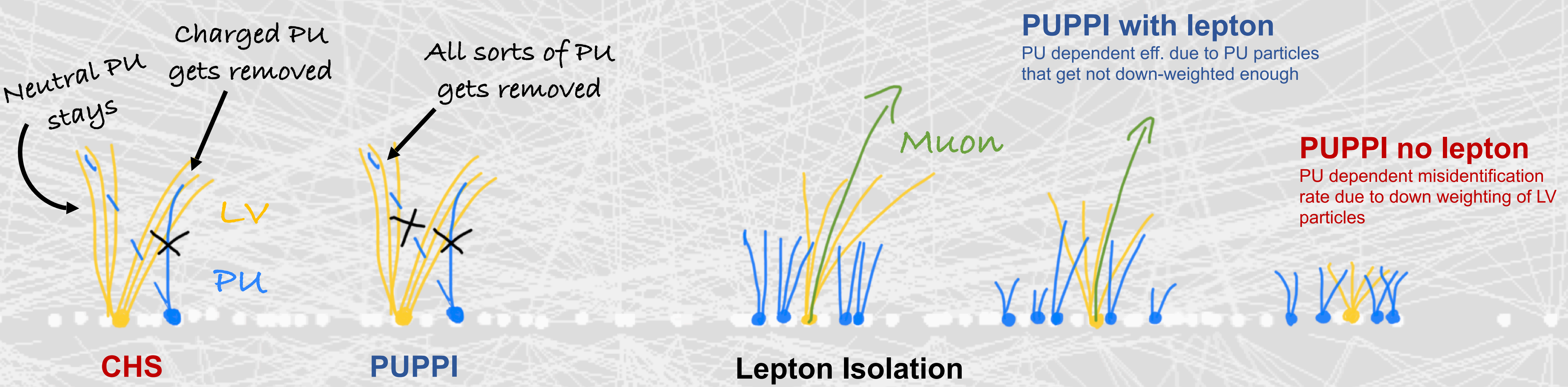
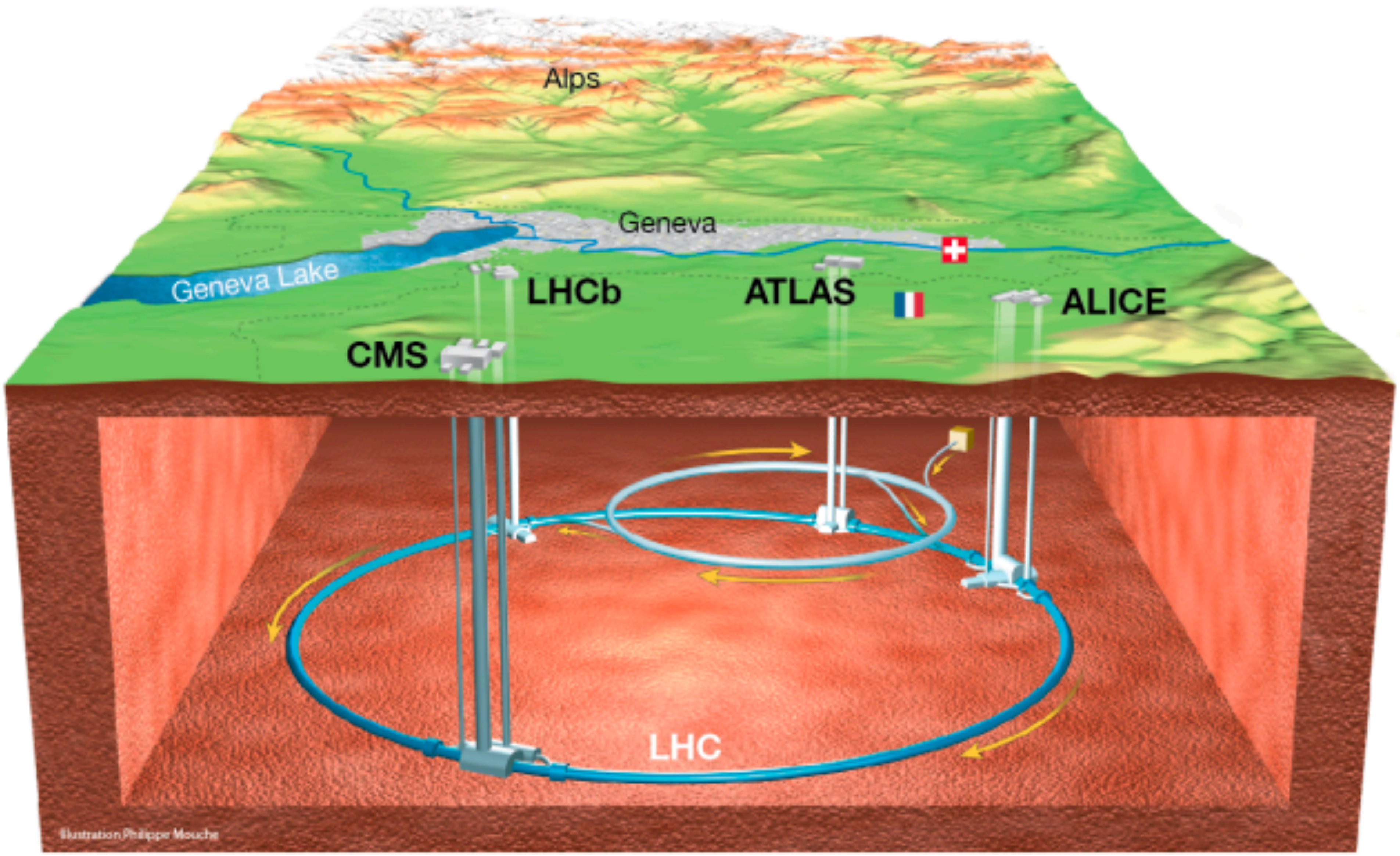
How CMS weeds out particles that pile up

Anna Benecke
UCLouvain



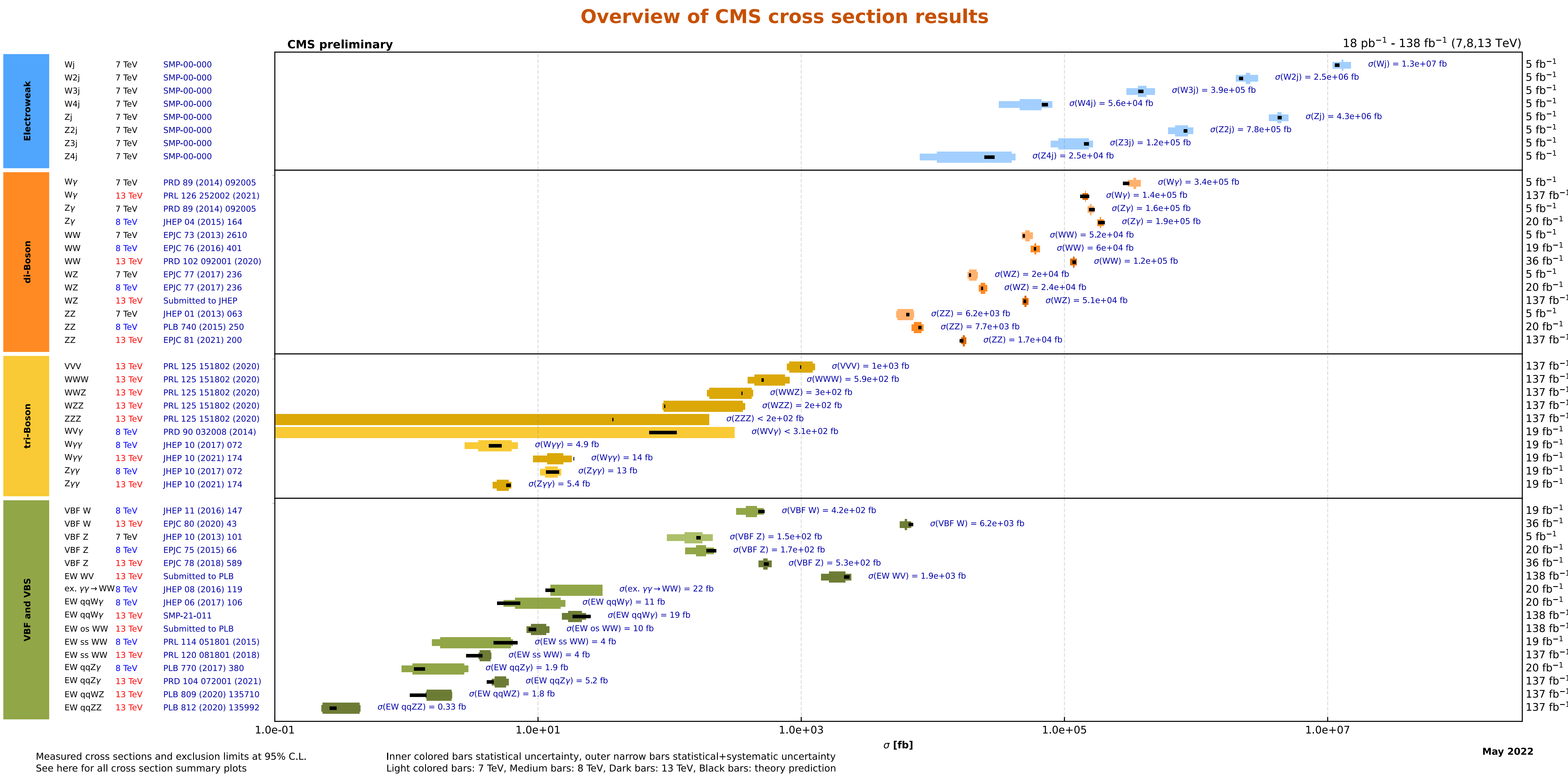
Experimental setup: LHC



Source: CERN

Physics program

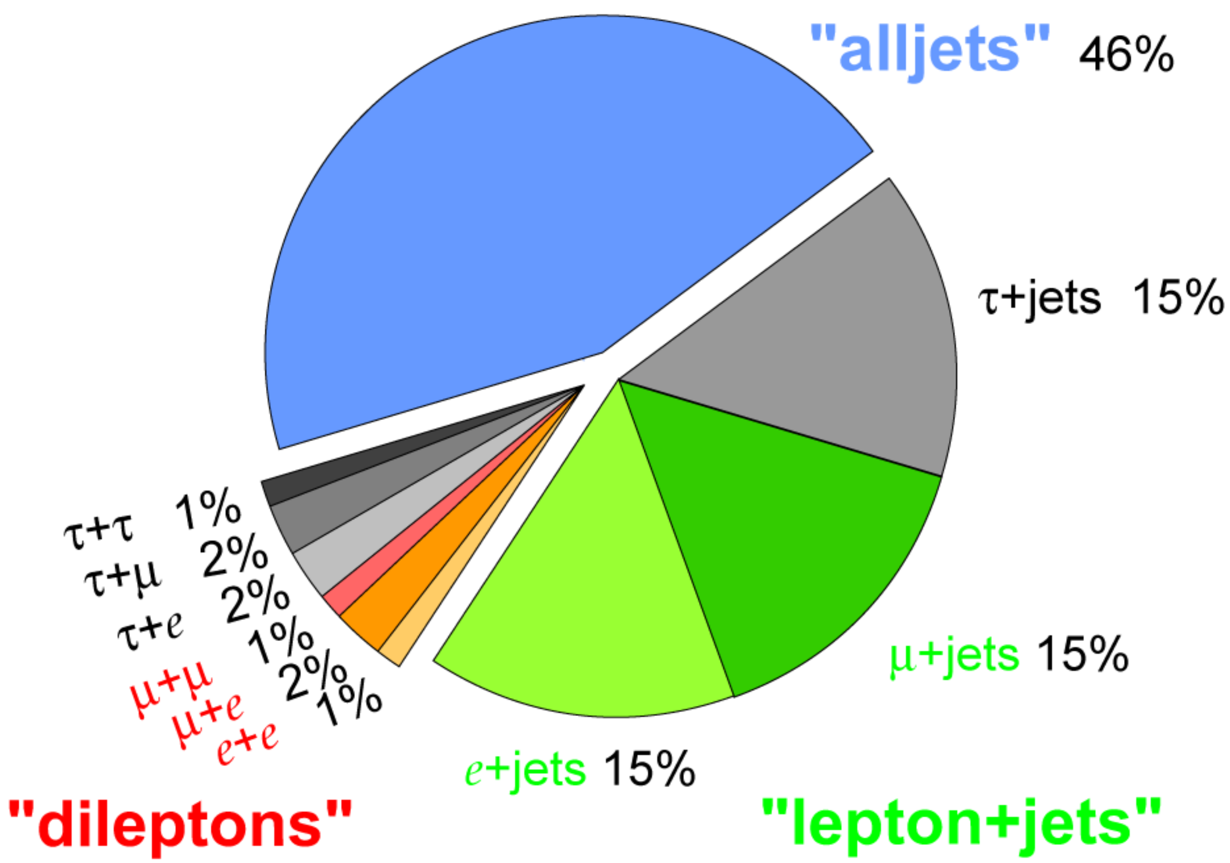
Test the self-consistency of the Standard Model of particle physics



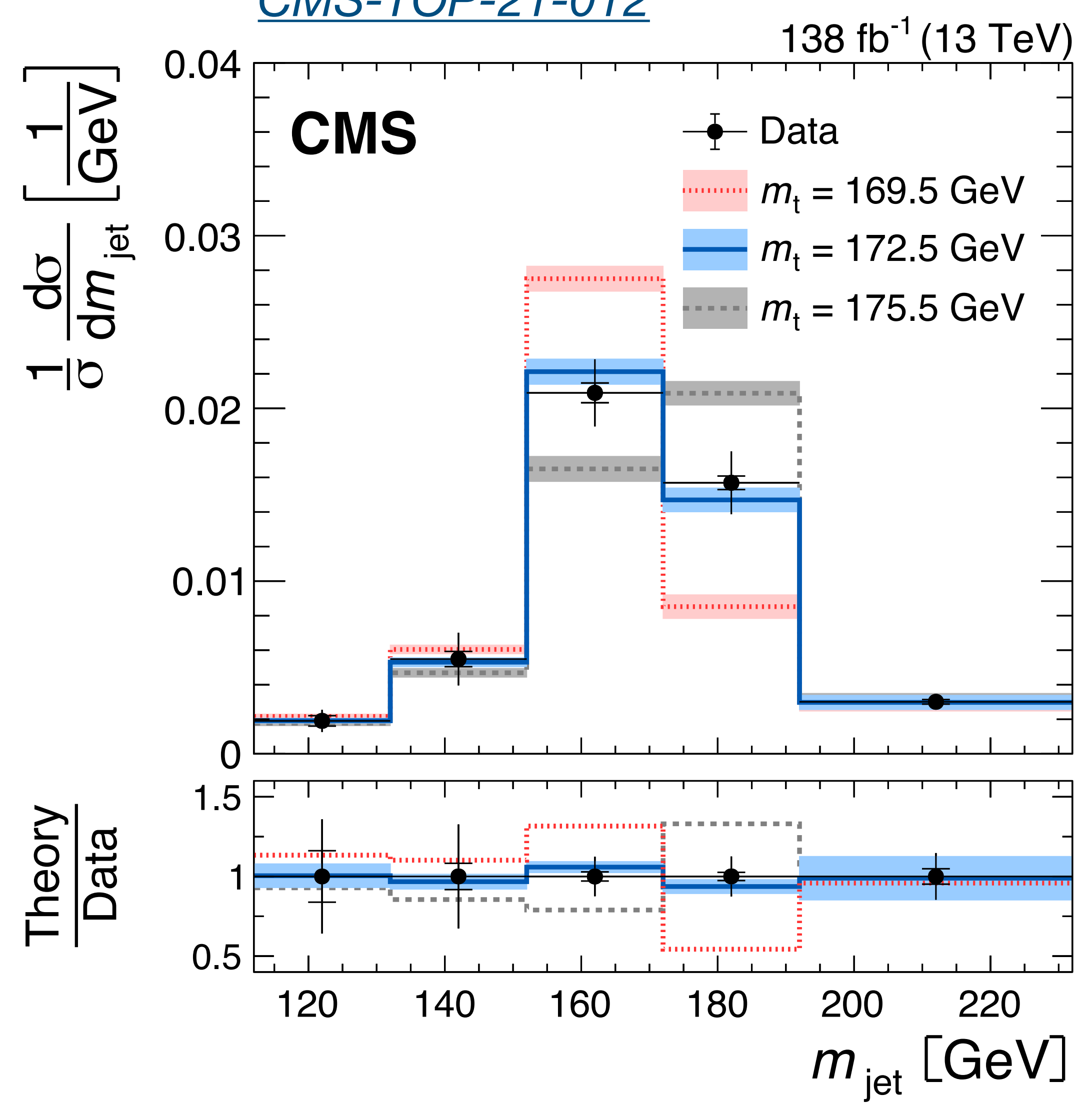
CMS cross section results

Era of precision physics

Reference

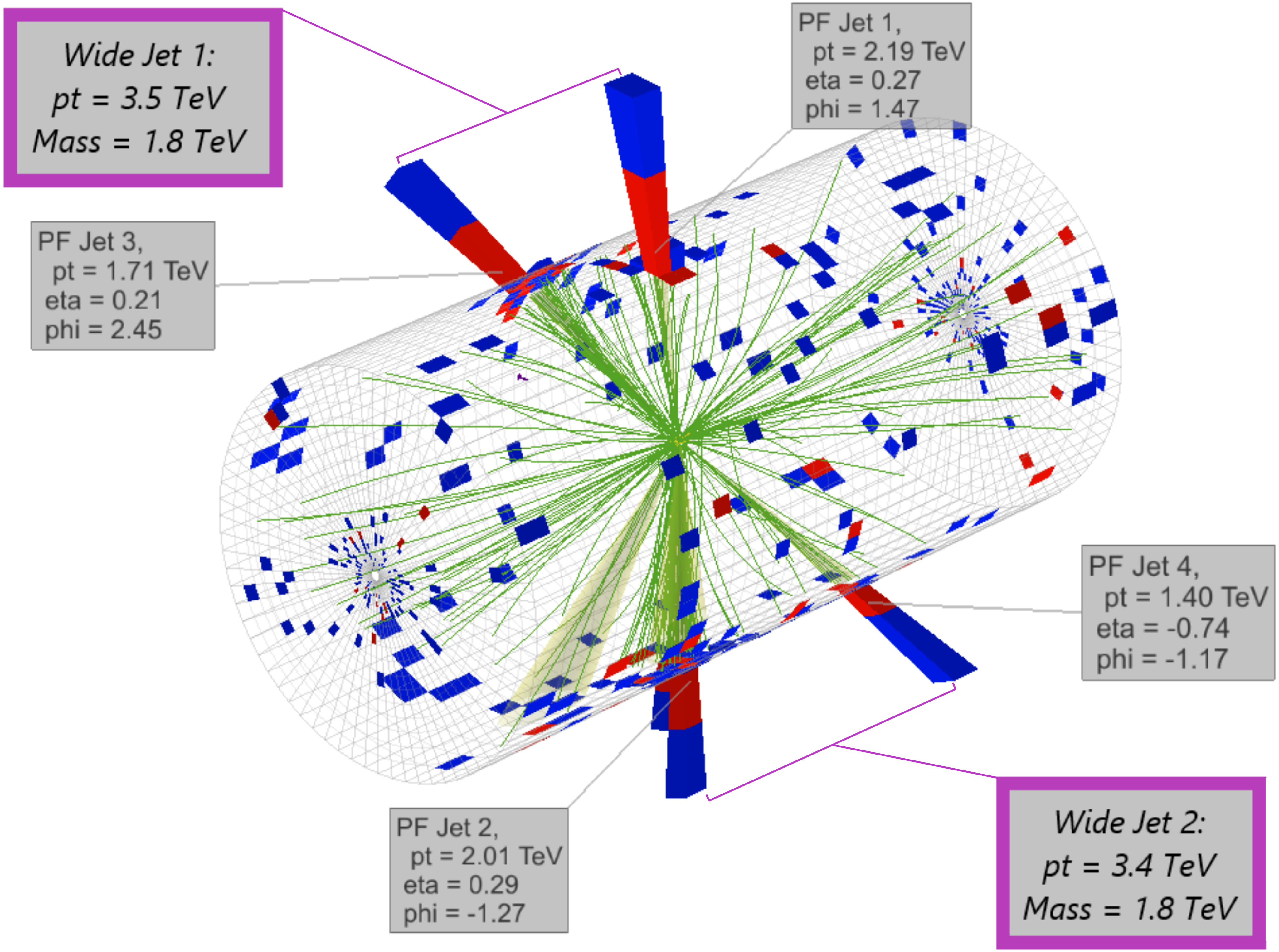


CMS-TOP-21-012

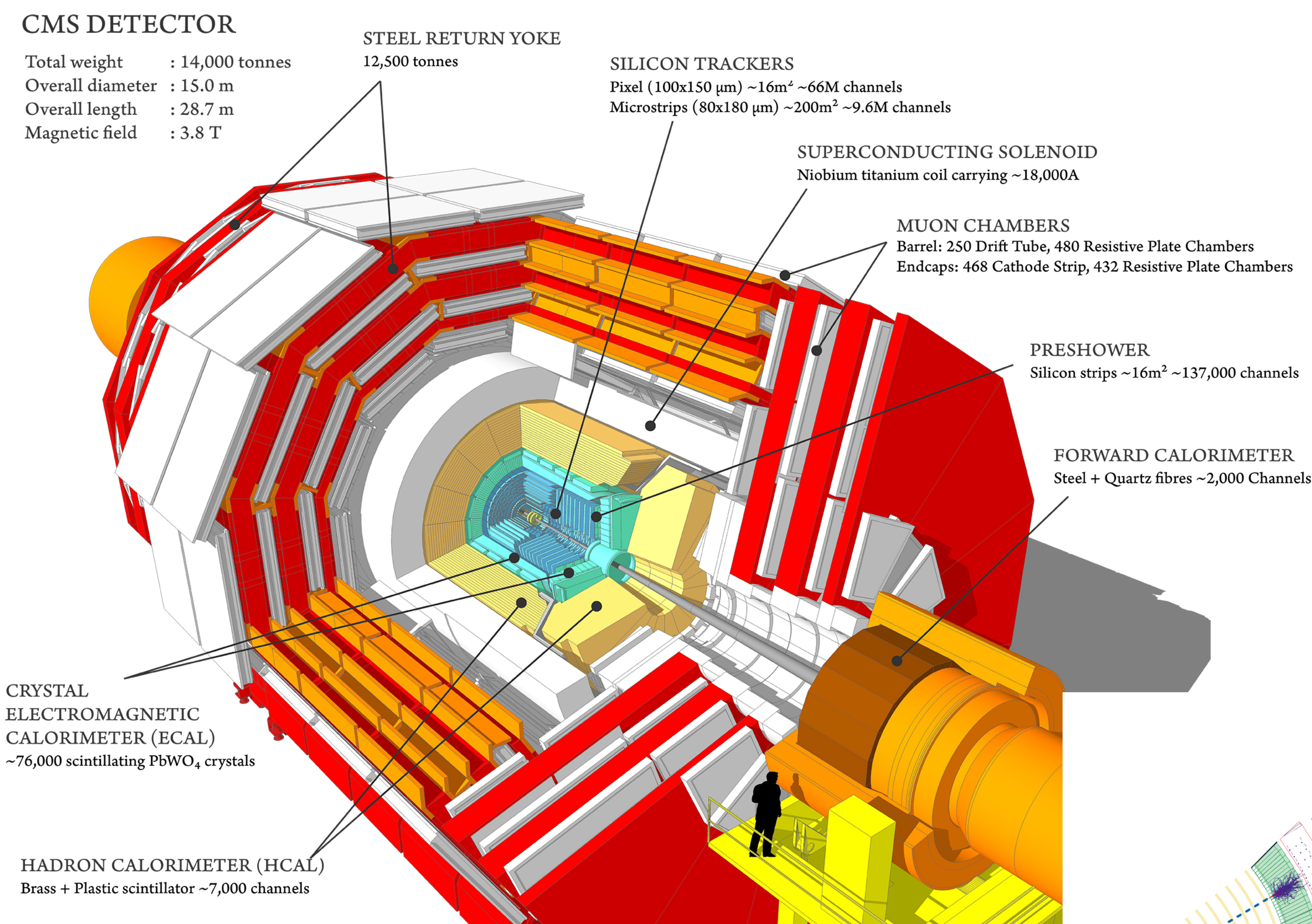


- Events with leptons, especially muons are more clean and precise
- However, hadronic decays offer more statistics
- First measurement of the top quark mass with hadronic boosted tops with Full Run2 data: $m_t = 173.06 \pm 0.84$ GeV

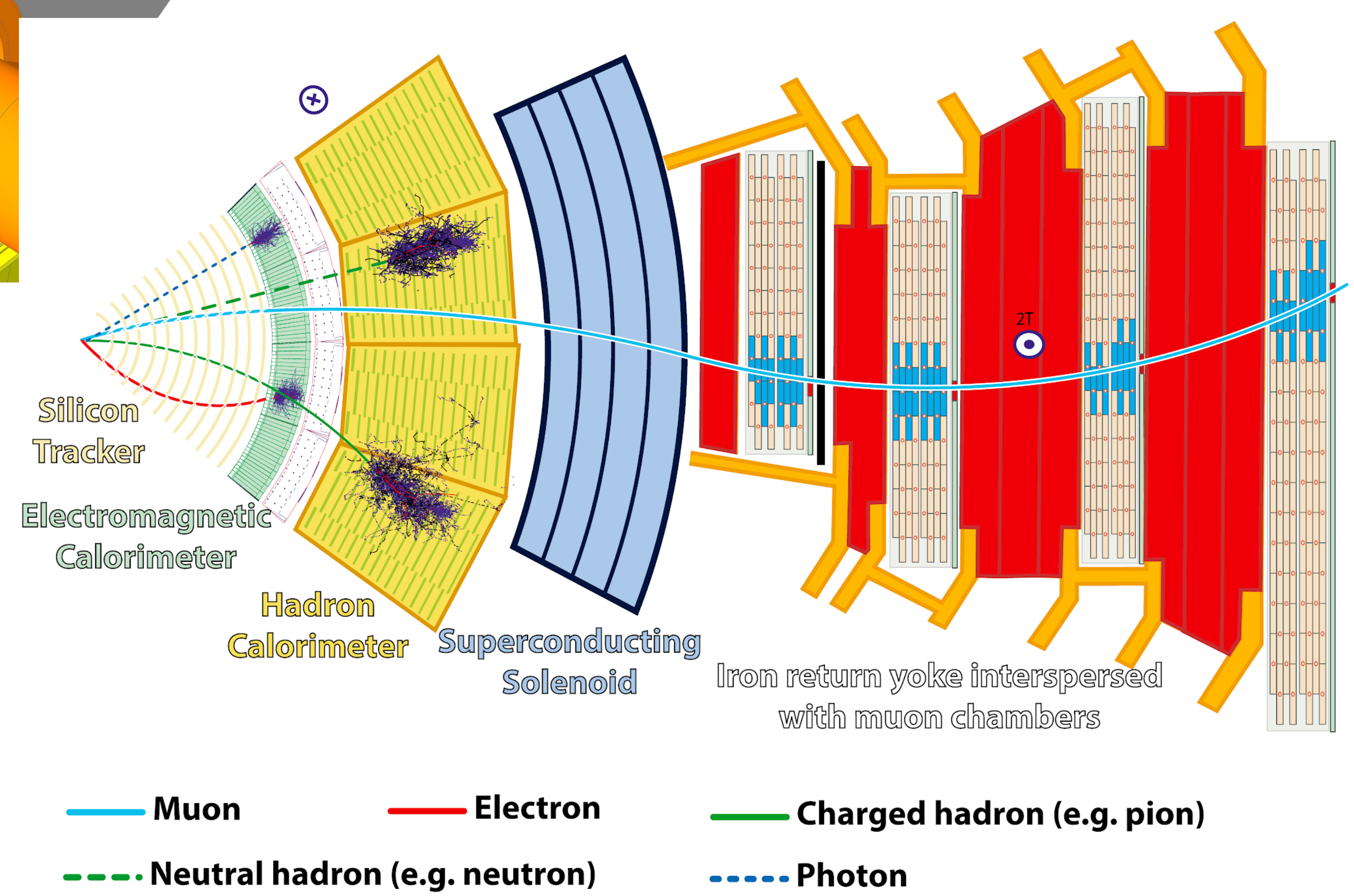
Search for BSM physics



Experimental setup: CMS



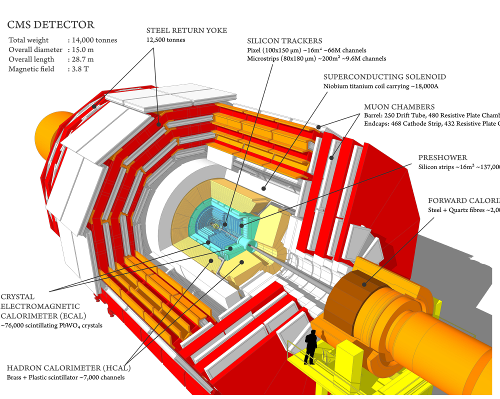
Source: CMS



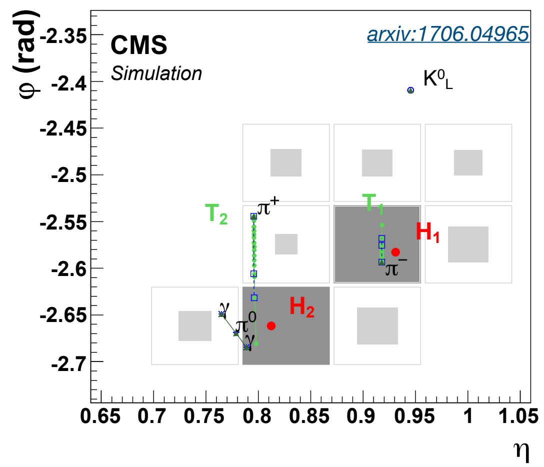
From detector signals to jet calibration

Hadronisation of quarks and gluons leads to collimated showers (jets) in the detector

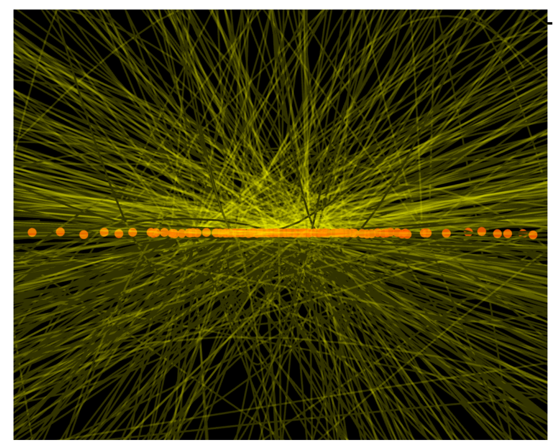
Detector



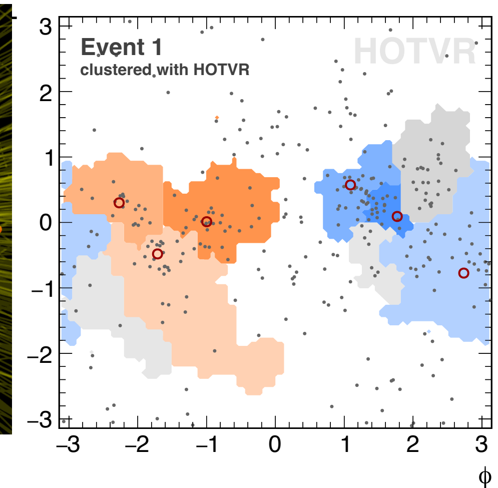
Reconstruction



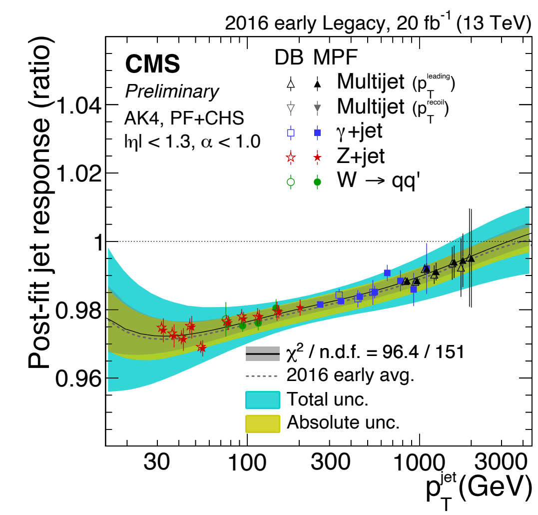
Pileup

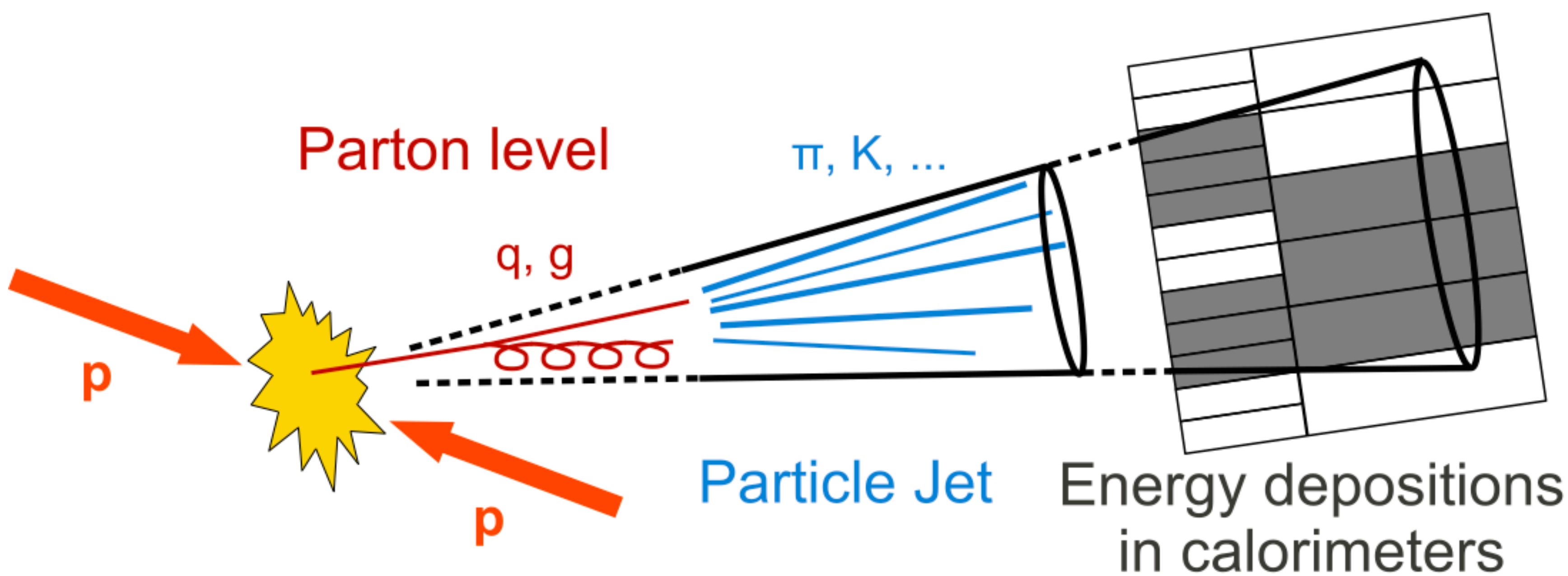


Clustering

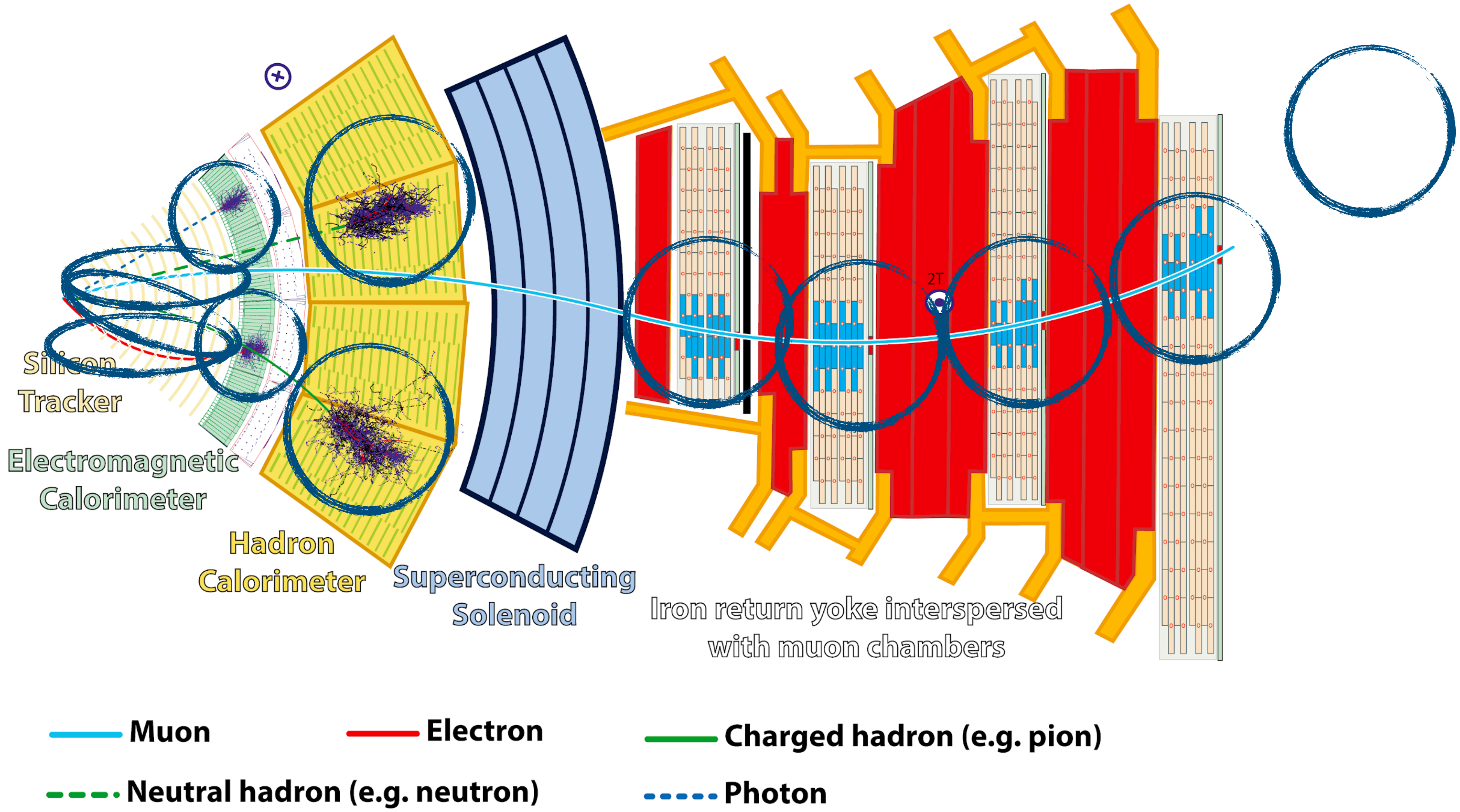


Calibration



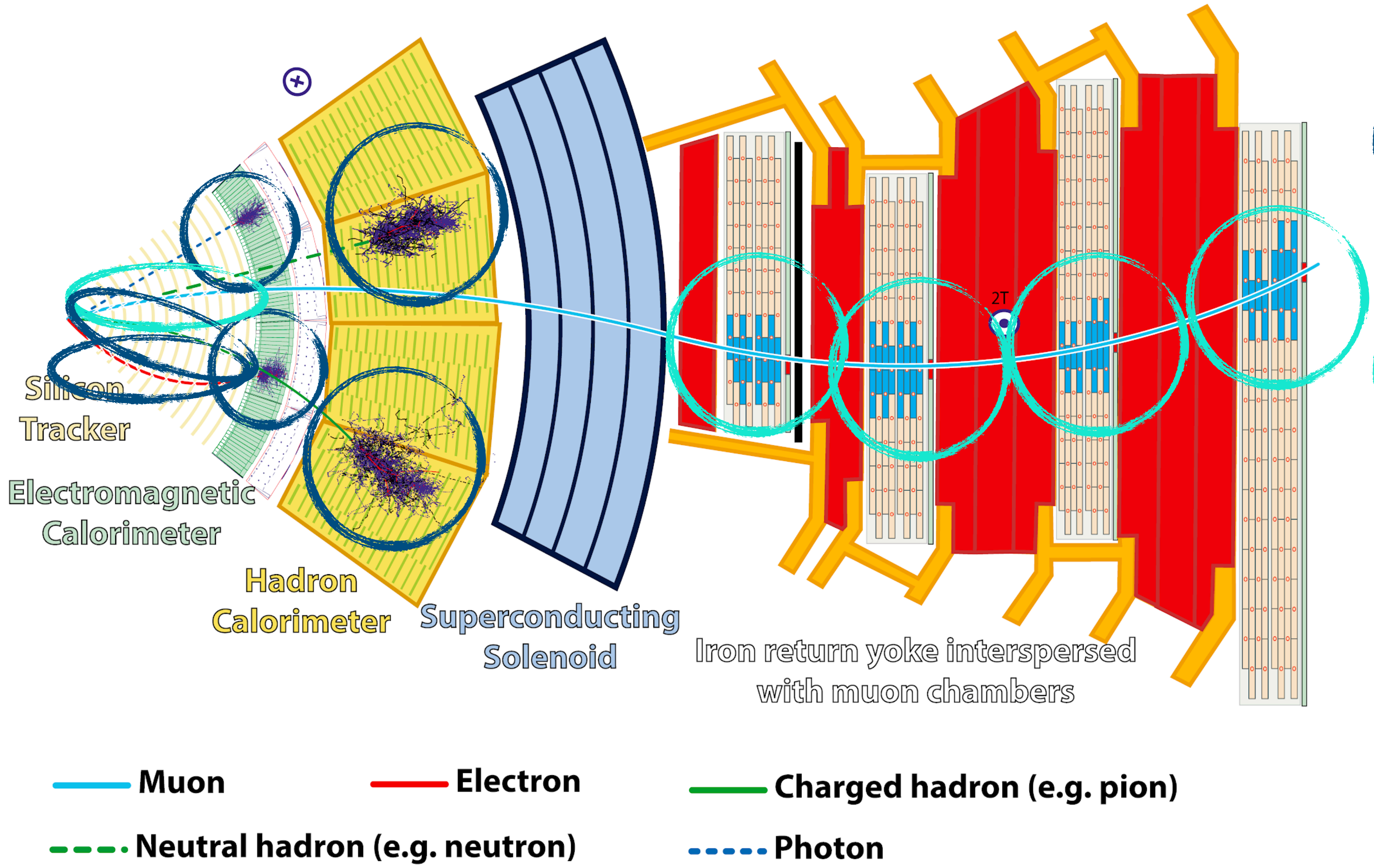


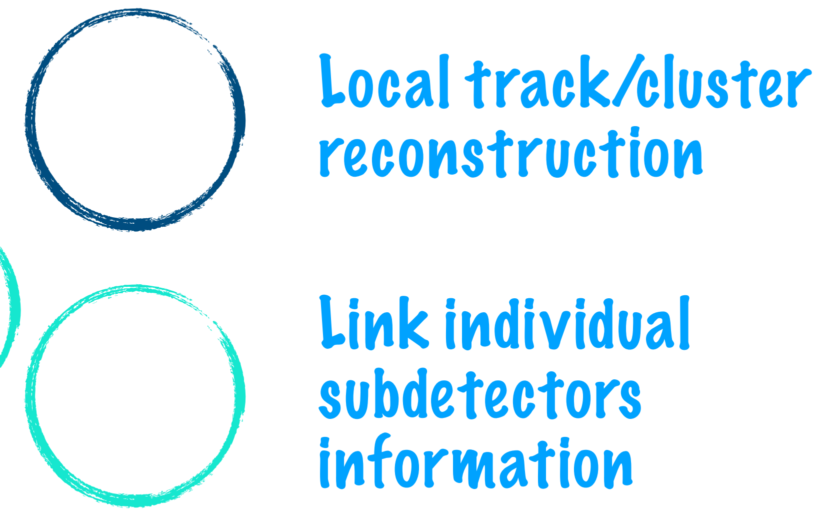
Experimental setup: CMS



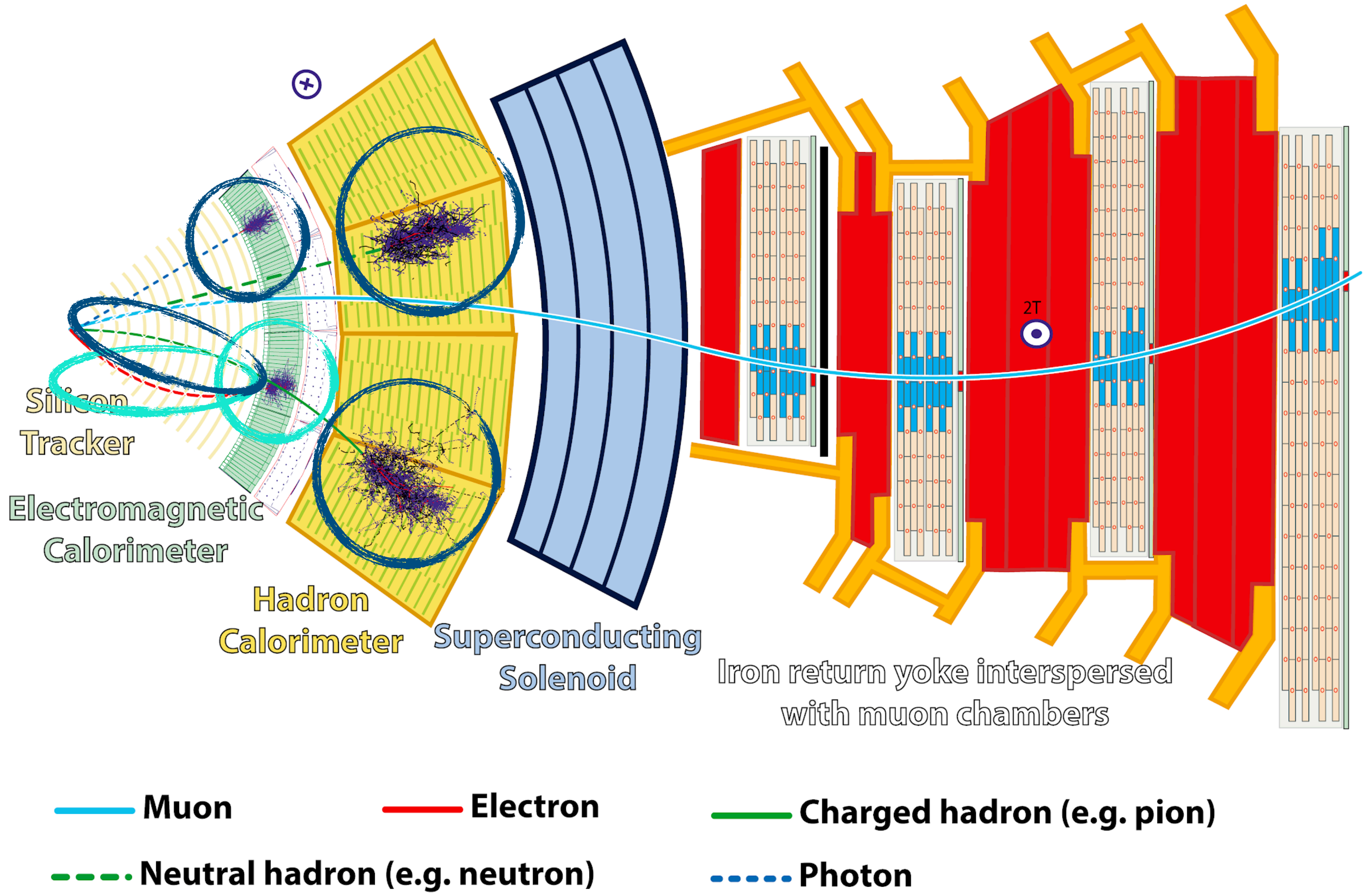
Local track/cluster reconstruction

Experimental setup: CMS





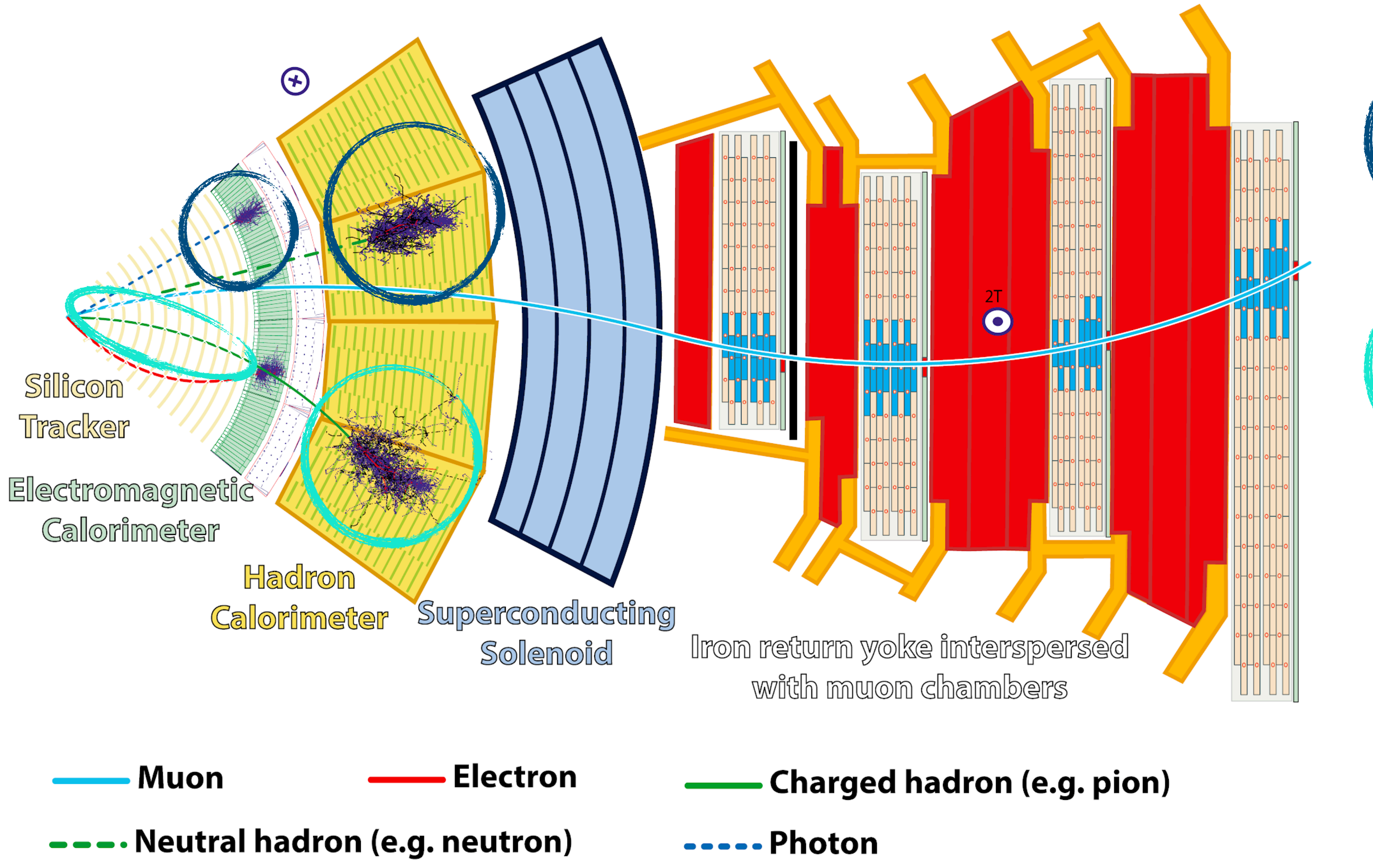
Experimental setup: CMS



Local track/cluster reconstruction

Link individual subdetectors information

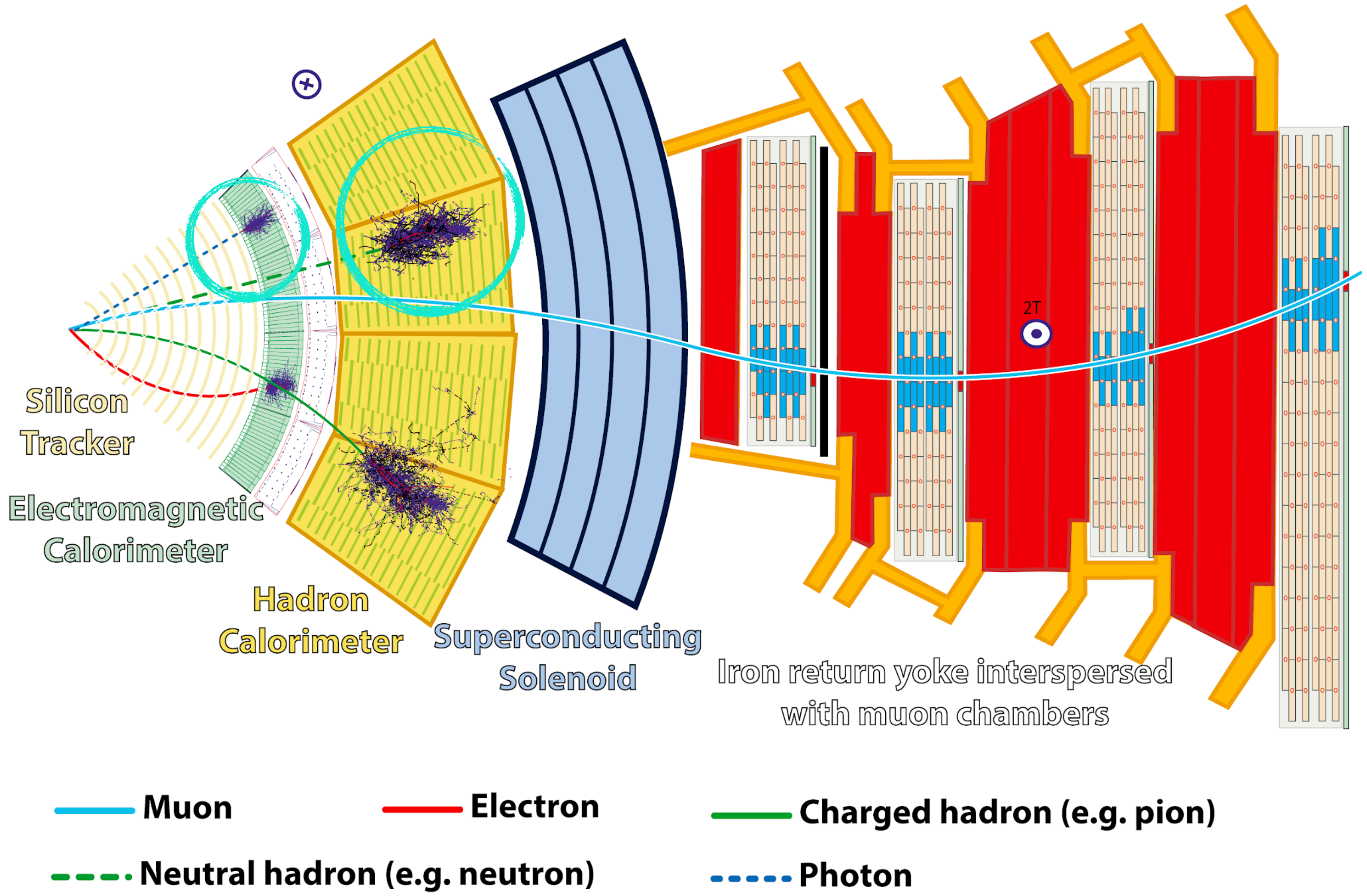
Experimental setup: CMS



Local track/cluster reconstruction

Link individual subdetectors information

Experimental setup: CMS

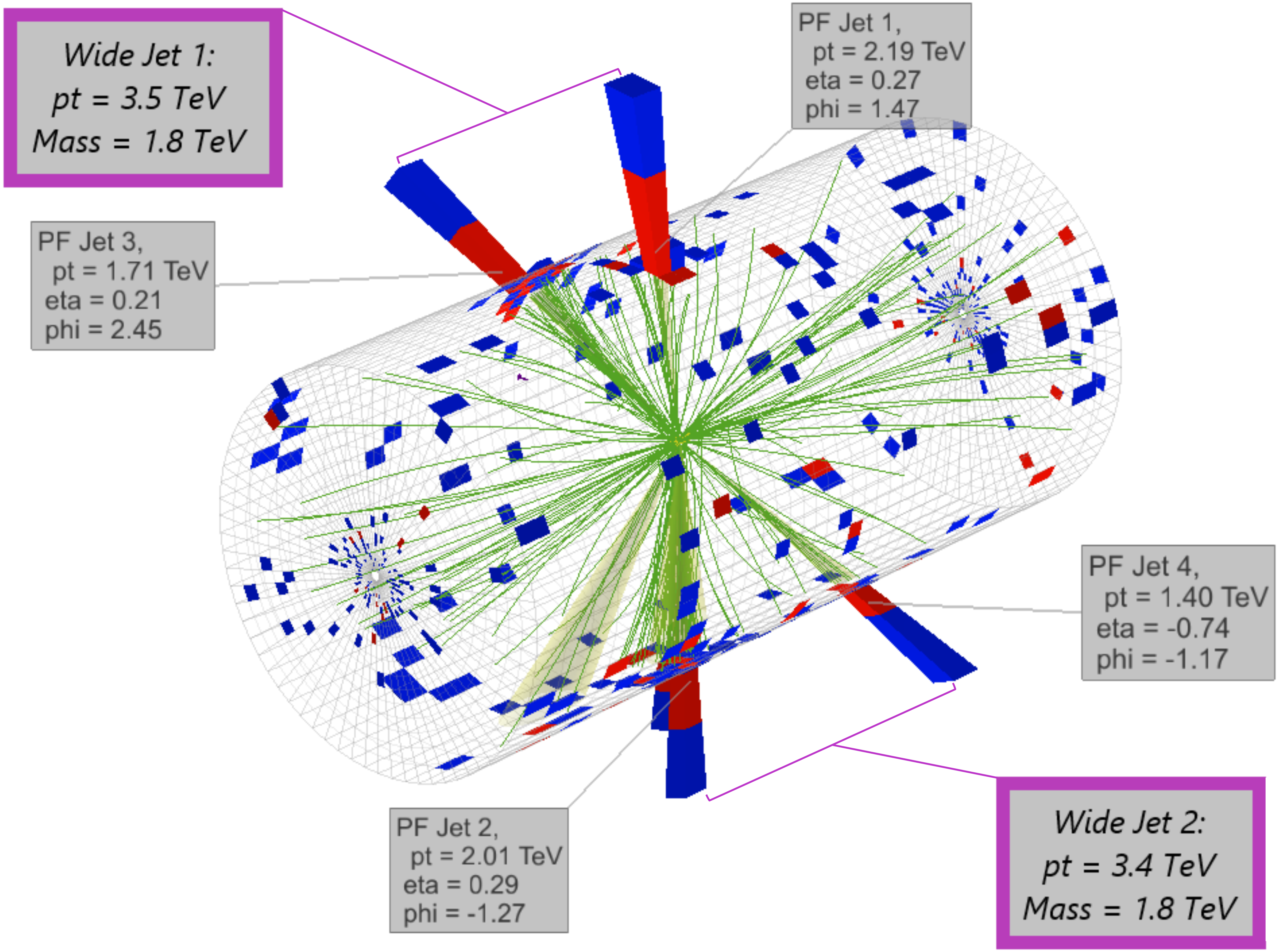


Local track/cluster reconstruction

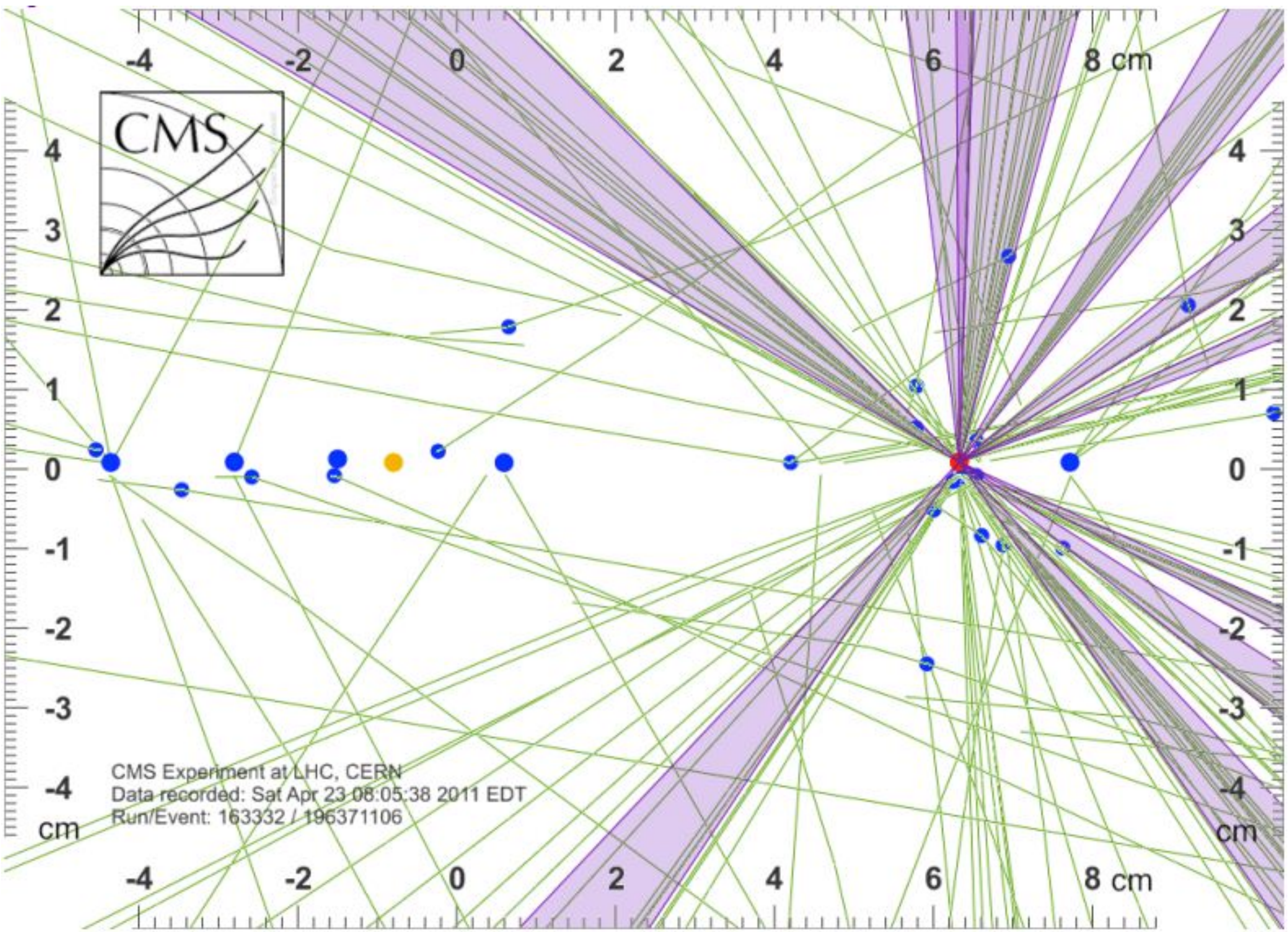
Link individual subdetectors information

Identified the stable particles in the event

Event display



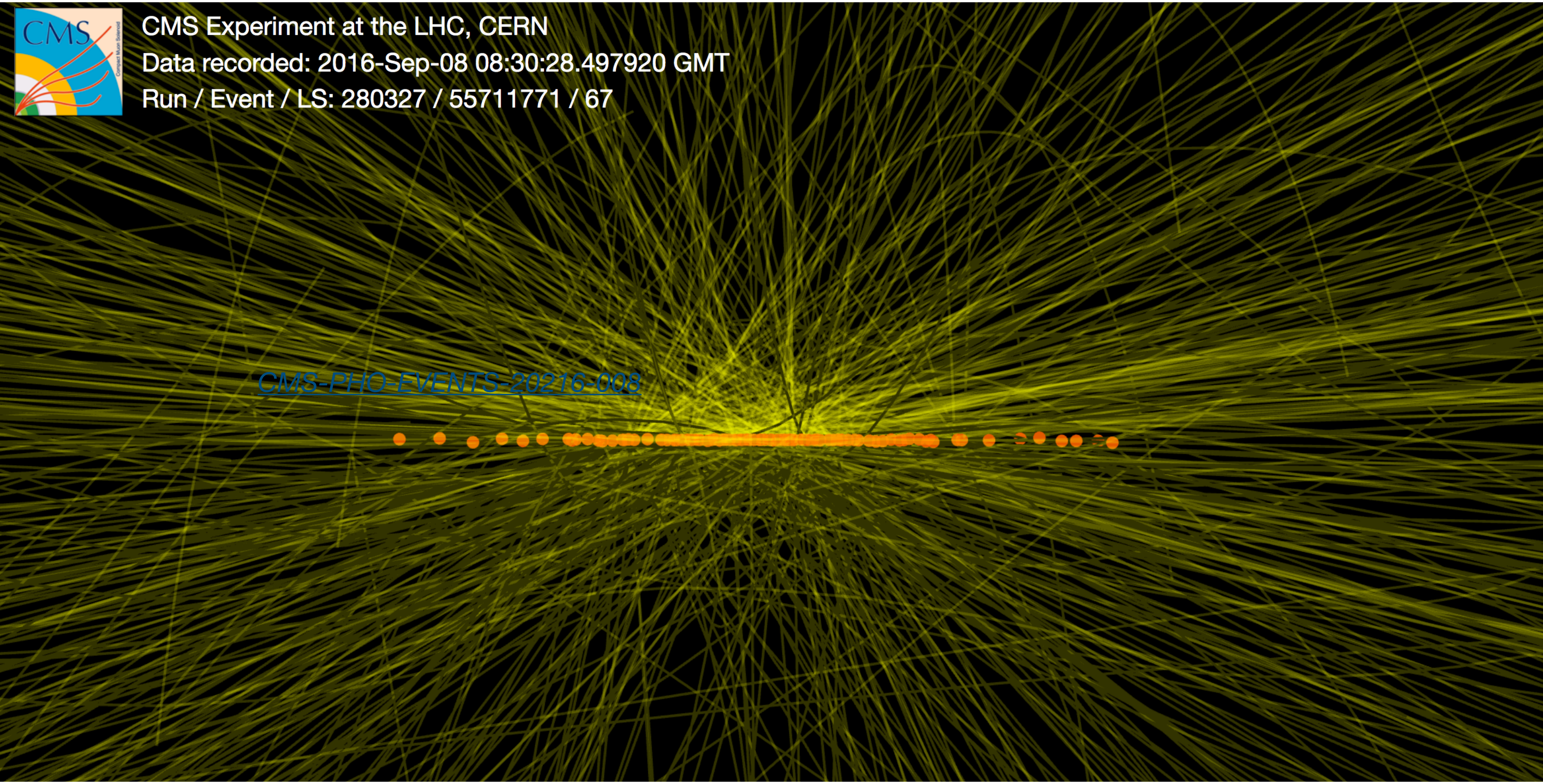
Proton-Proton collisions @ LHC



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

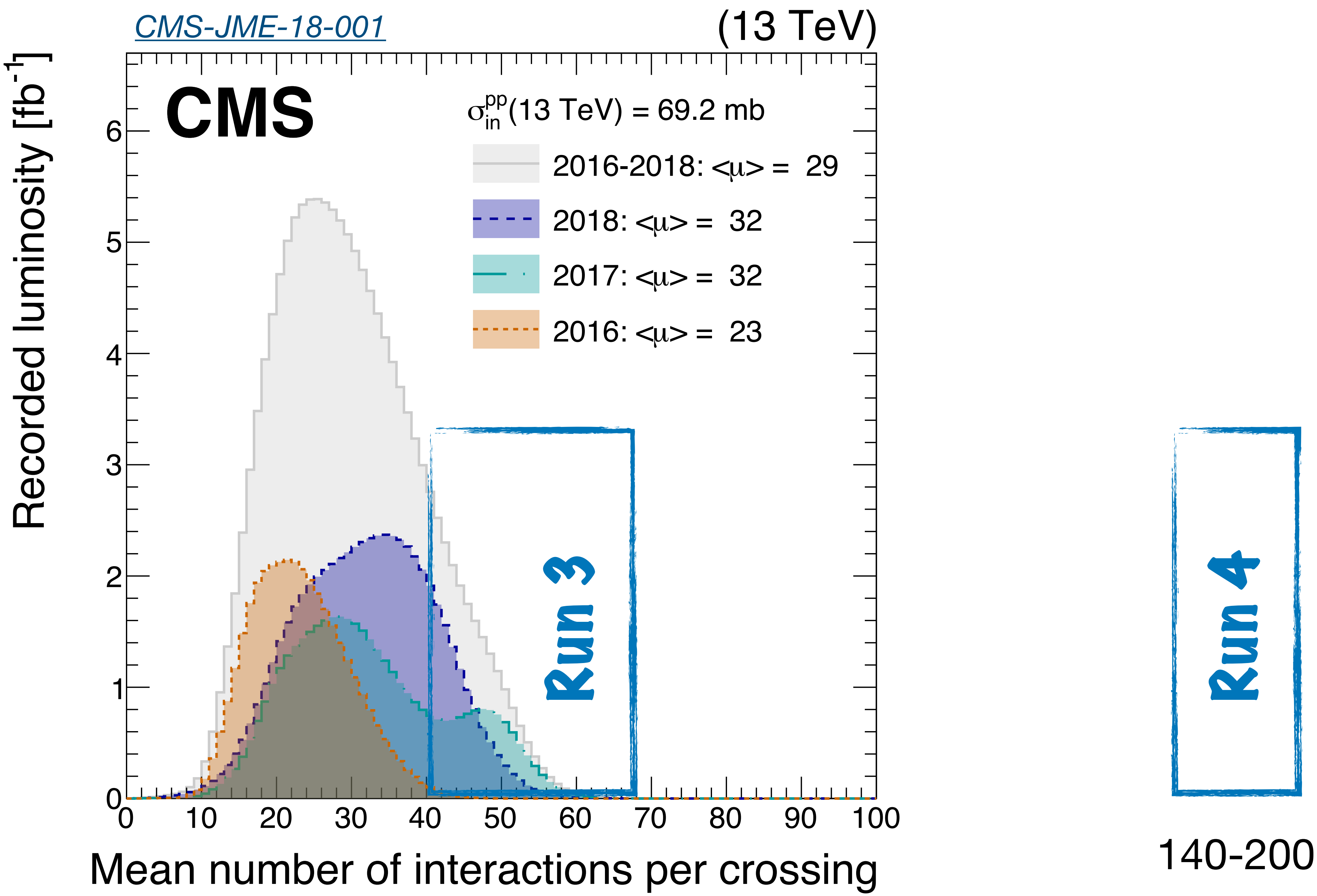
Proton-Proton collisions @ LHC

CMS-PHO-EVENTS-20216-008



Pileup adds additional energy to the whole detector

More data, more pileup



More data, more pileup

$$N_{\text{Events}} = \sigma \int L dt$$

$$L = \frac{f N_1 N_2}{4\pi\sigma_x\sigma_y}$$

frequency
40 MHz

Number of protons

Size of the beam

More data, more pileup

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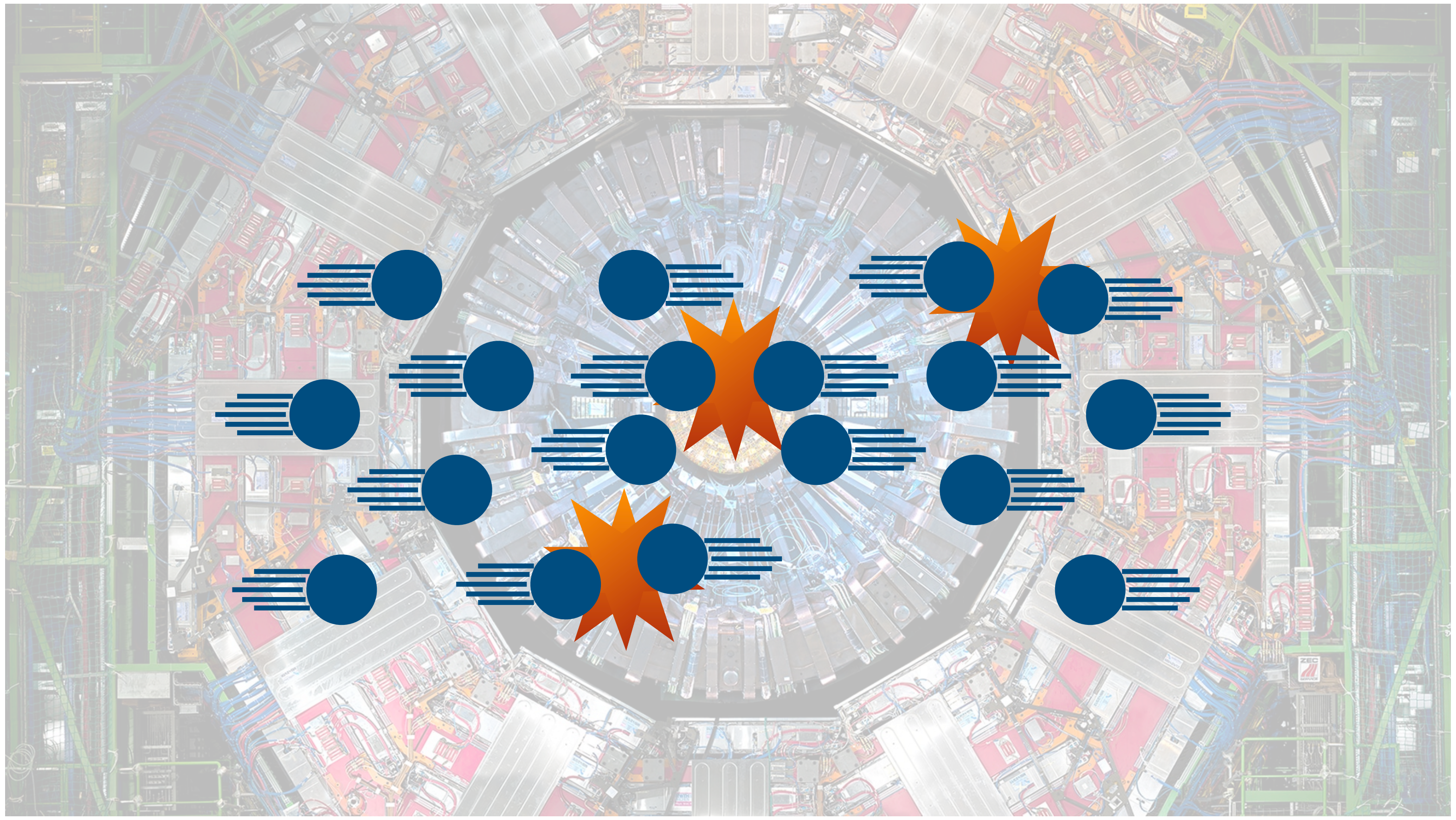

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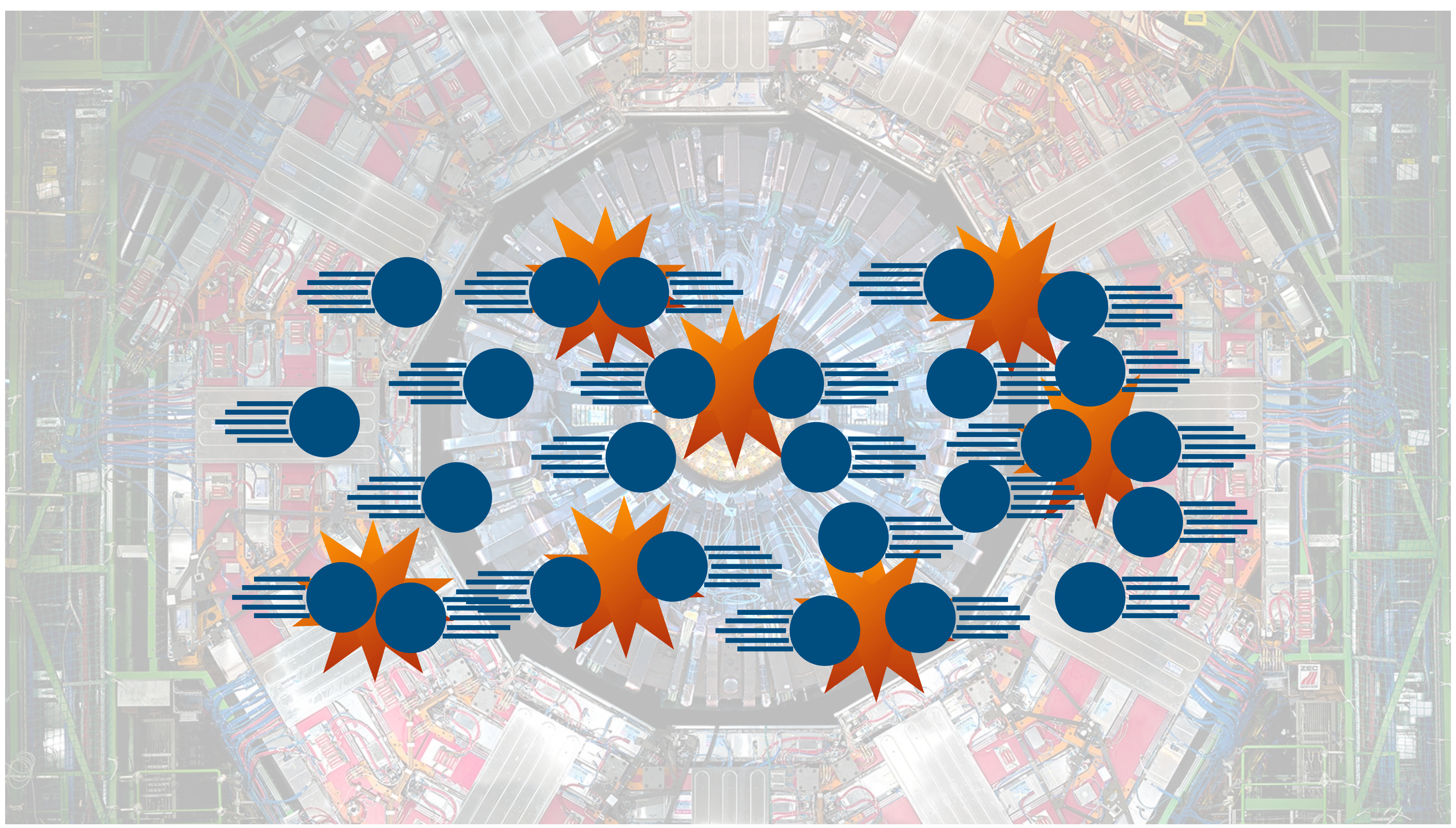
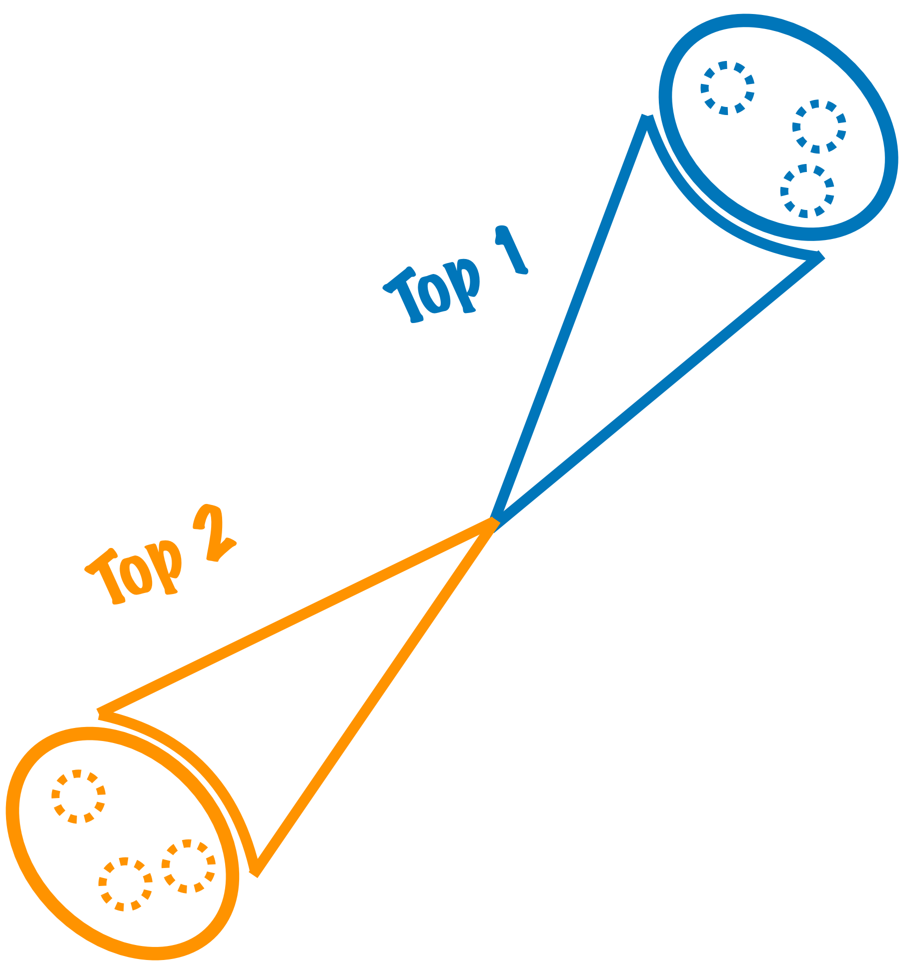
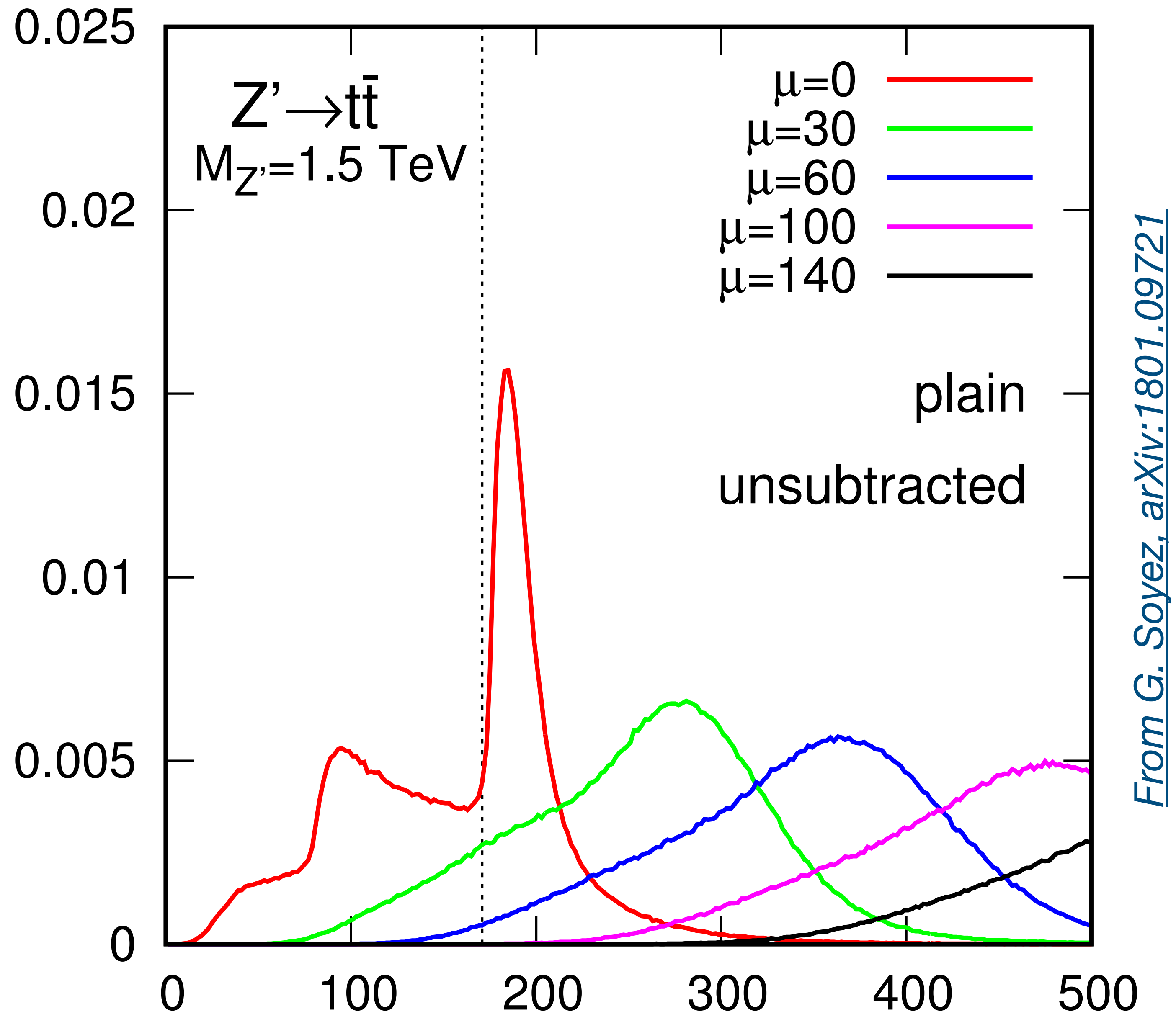


Challenges with pileup



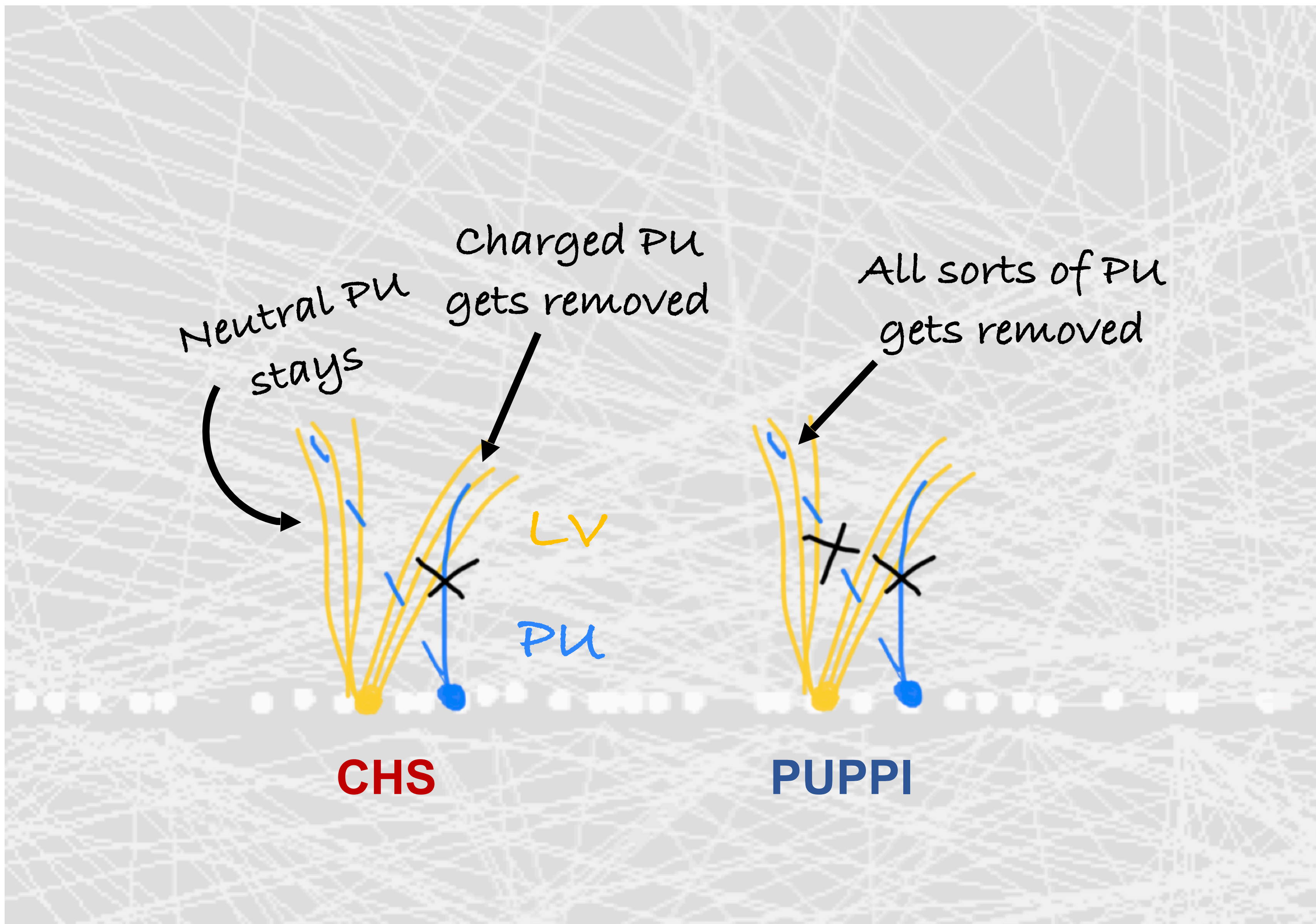


(a) raw, ungroomed jets

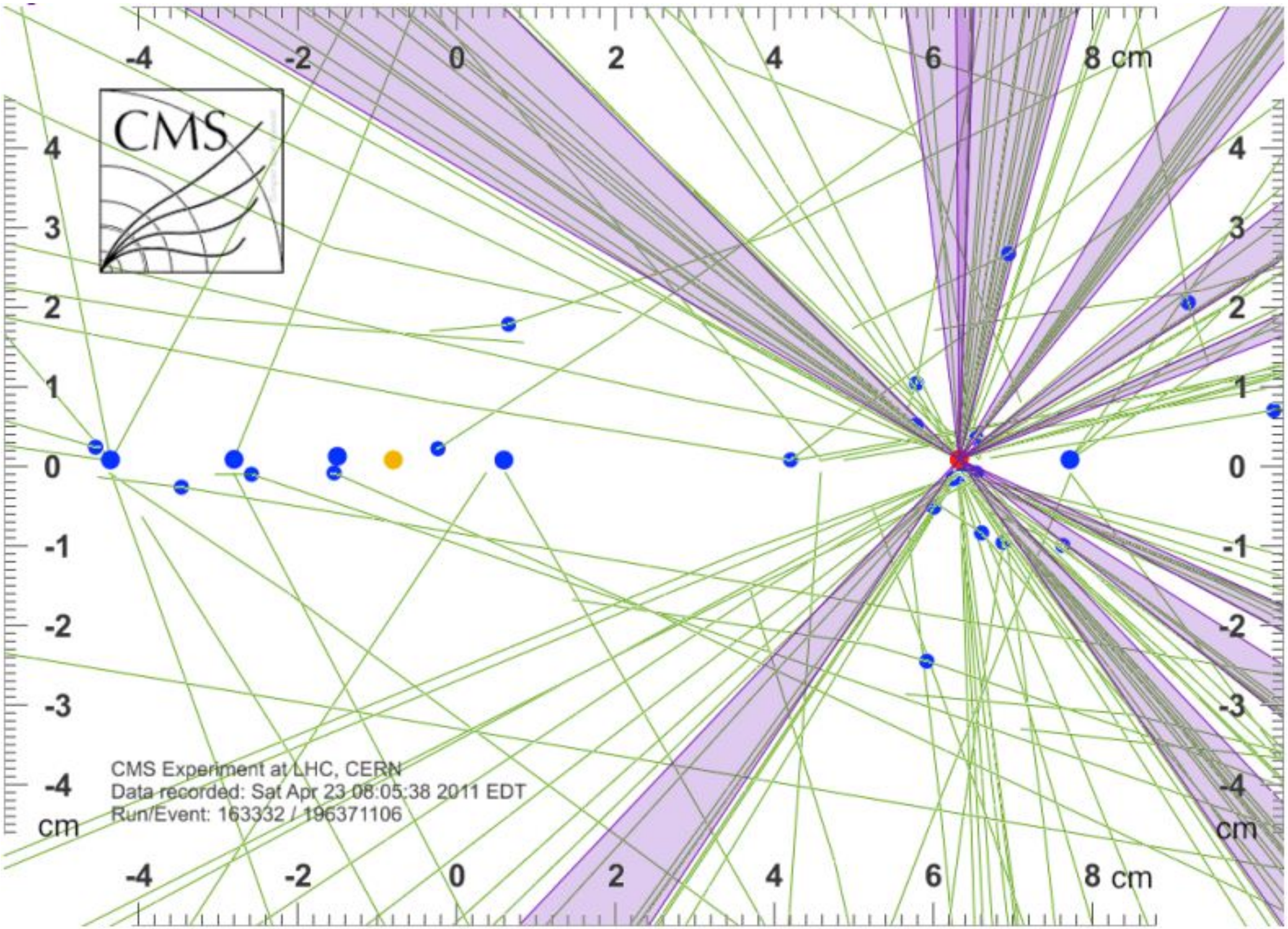
PU affects jet substructure, jet counting, lepton isolation…

Pileup mitigation in CMS

Click me



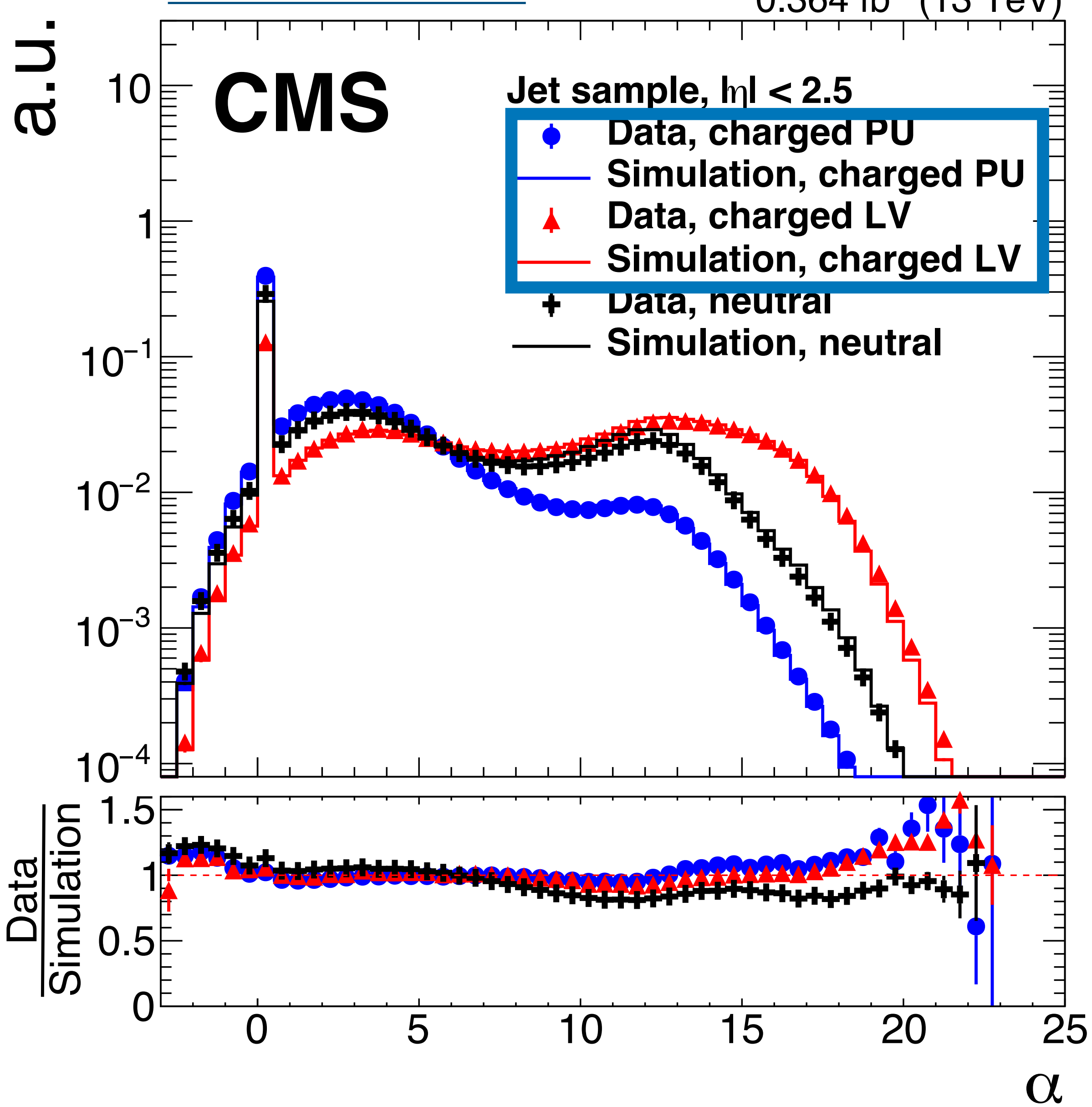
PUPPI in Detail



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

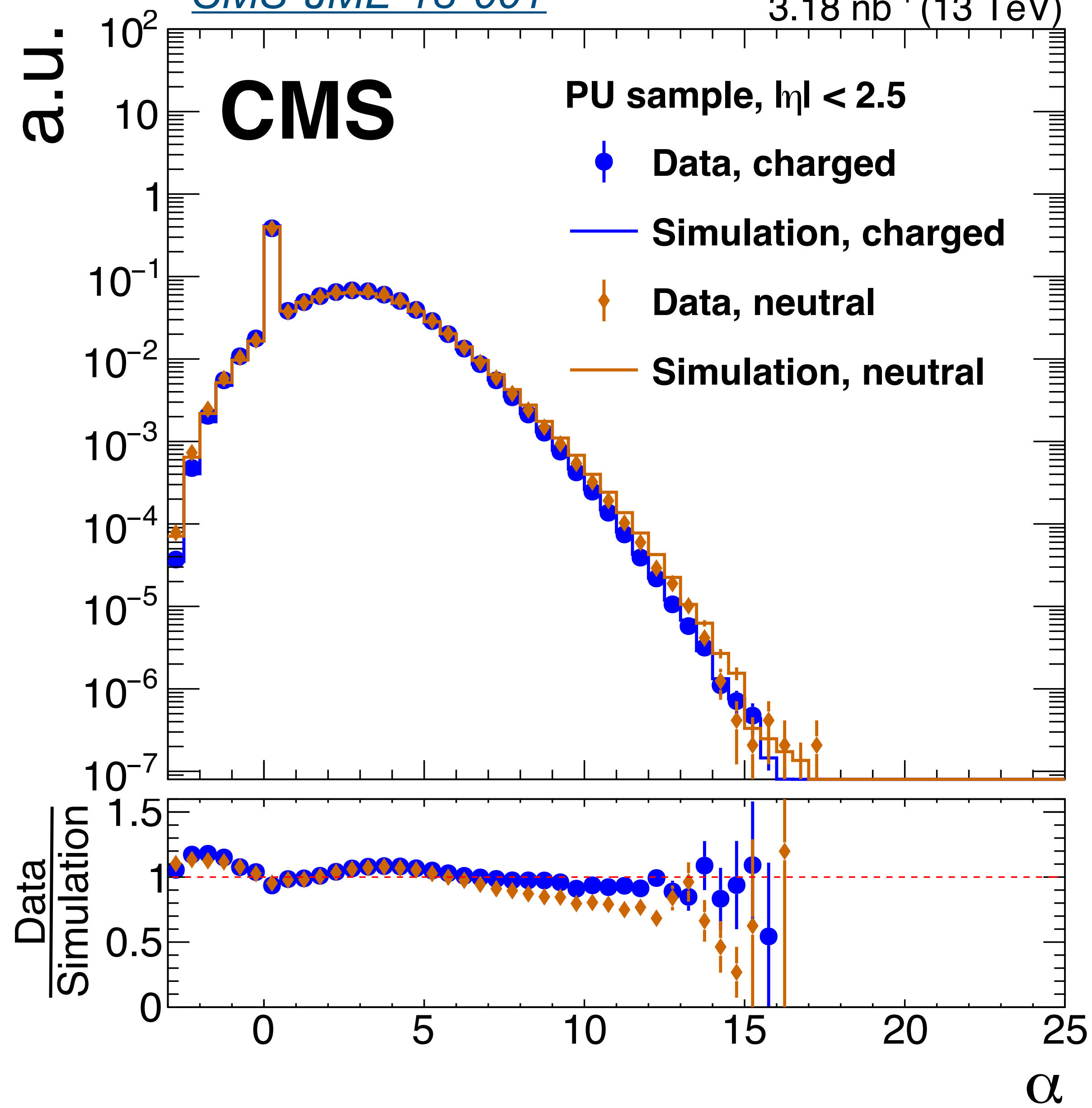
$$\alpha_i = \log \sum_{j \neq i, \Delta R_{ij} < R_0} \left(\frac{p_{Tj}}{\Delta R_{ij}} \right)^2 \begin{cases} \text{for } |\eta_i| < 2.5, & j \text{ are charged particles from leading vertex} \\ \text{for } |\eta_i| > 2.5, & j \text{ are all kinds of reconstructed particles} \end{cases}$$

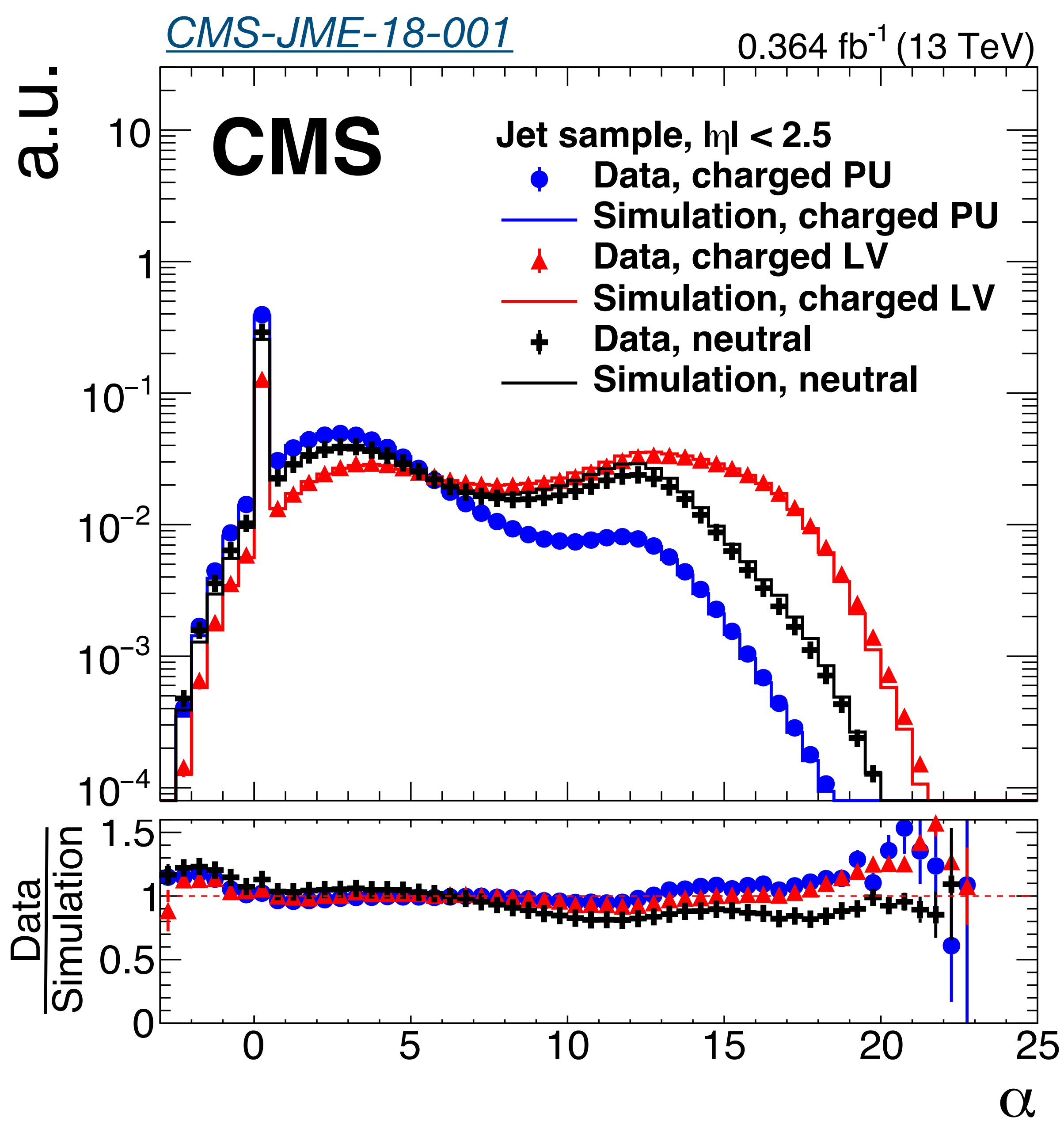
CMS-JME-18-001



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

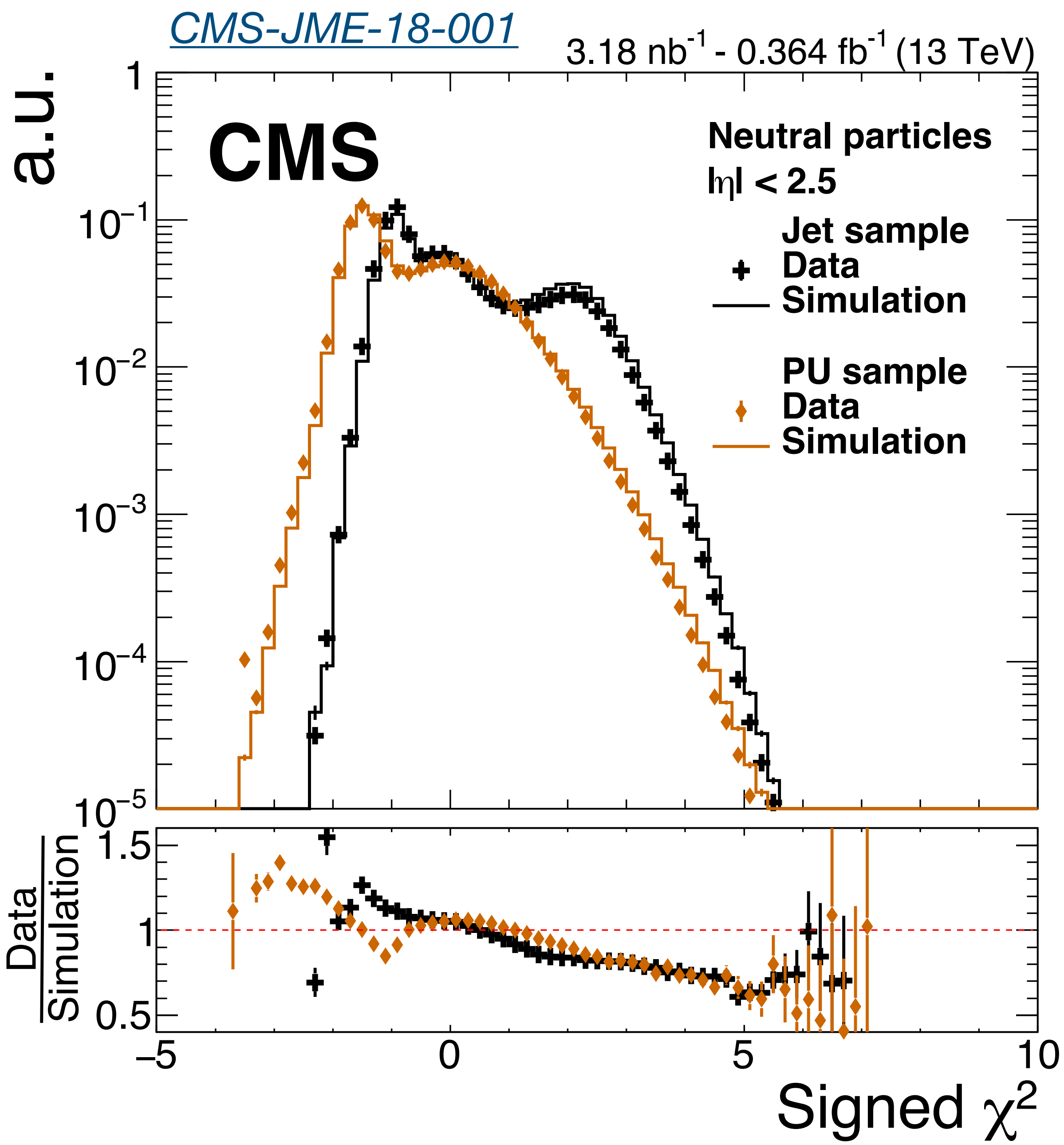
[CMS-JME-18-001](CMS-JME-18-001)





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

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

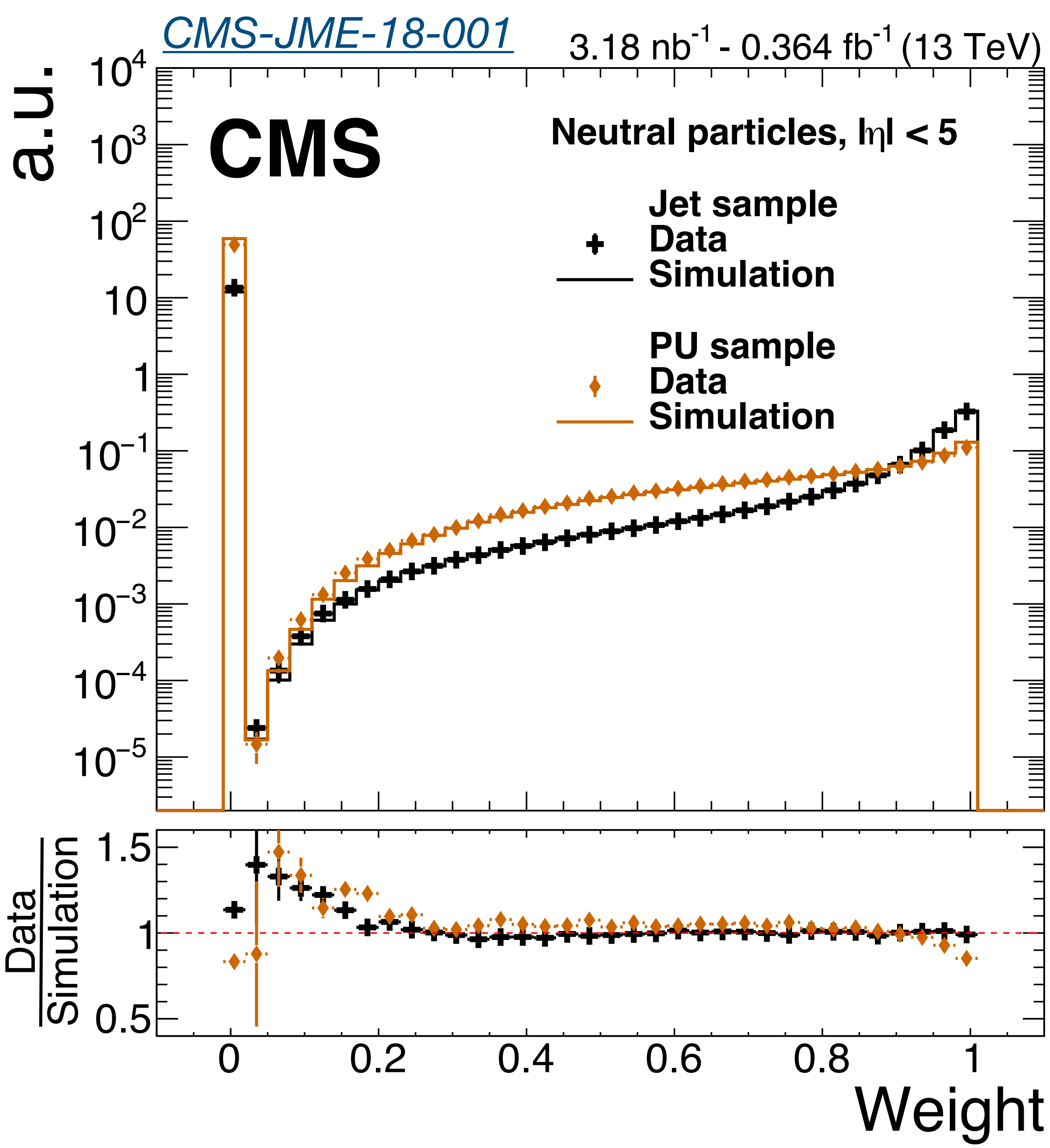


1. Calculate Median and RMS of charged PU shape (blue)

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

2. For each particle calculate

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



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

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

2. For each particle calculate

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

3. Assign a weight to each particle

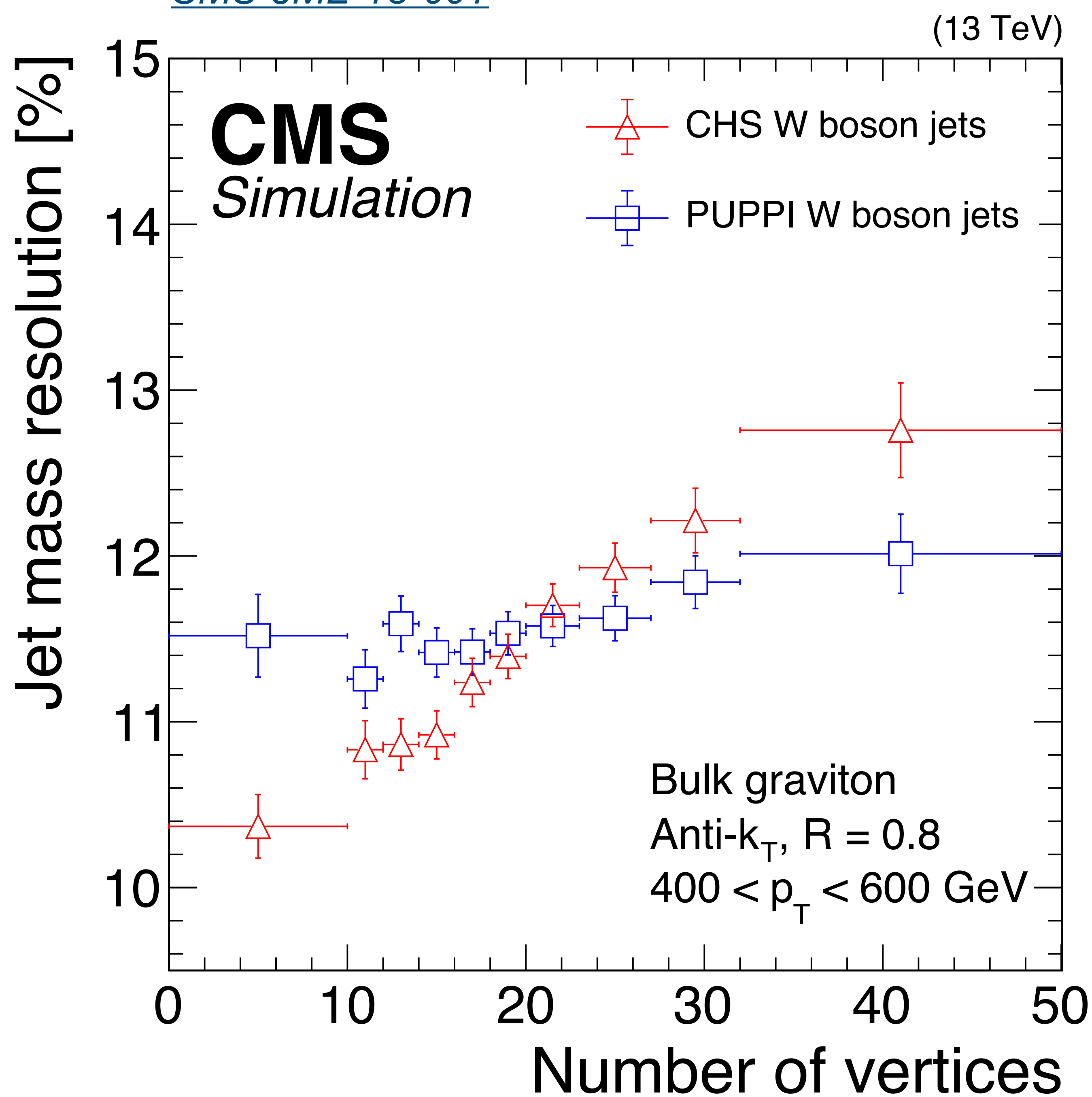
$$w_i = F_{\chi^2, NDF=1}(\chi_i^2)$$

Pileup → Hard scattering

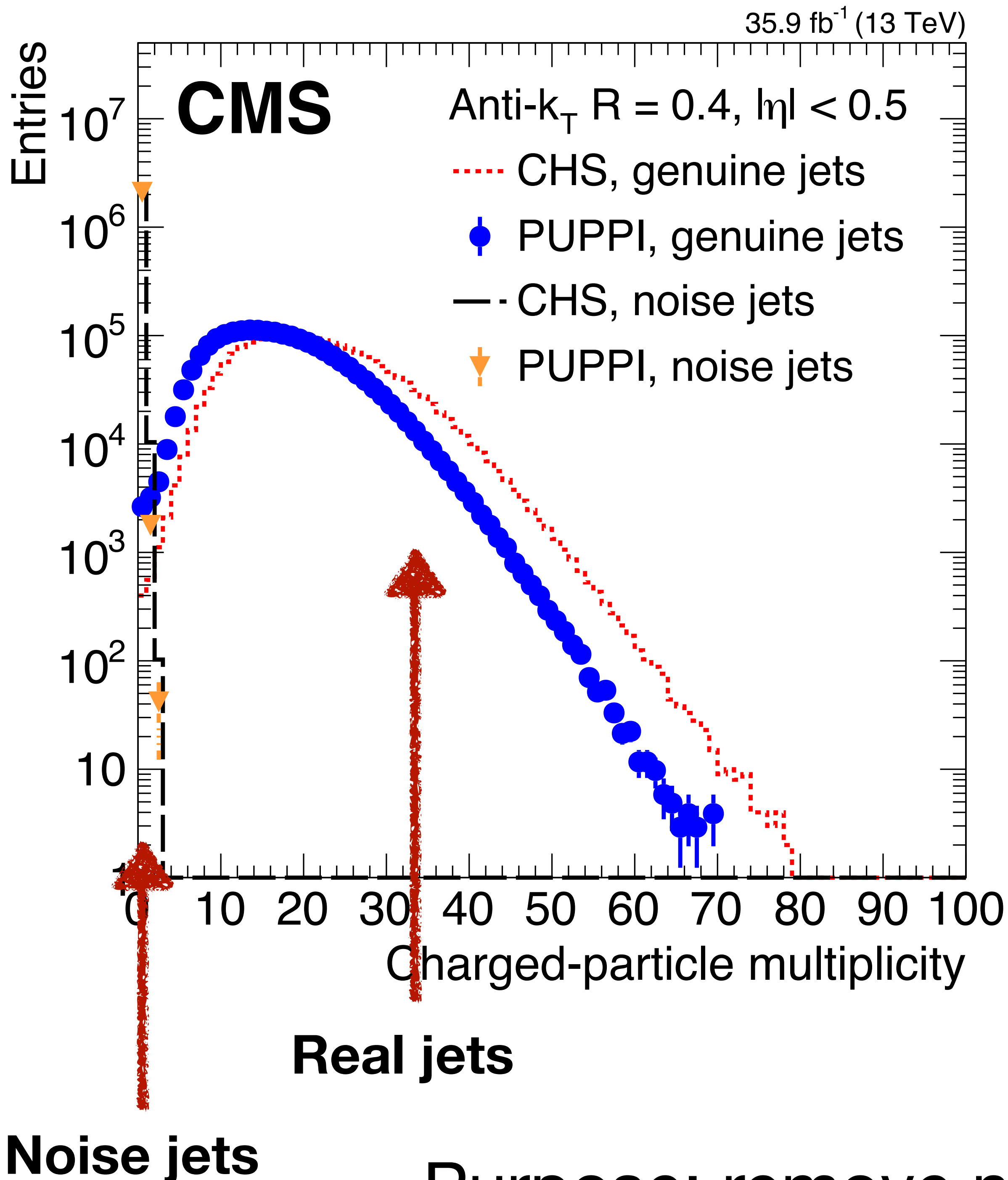
Validation of PUPPI

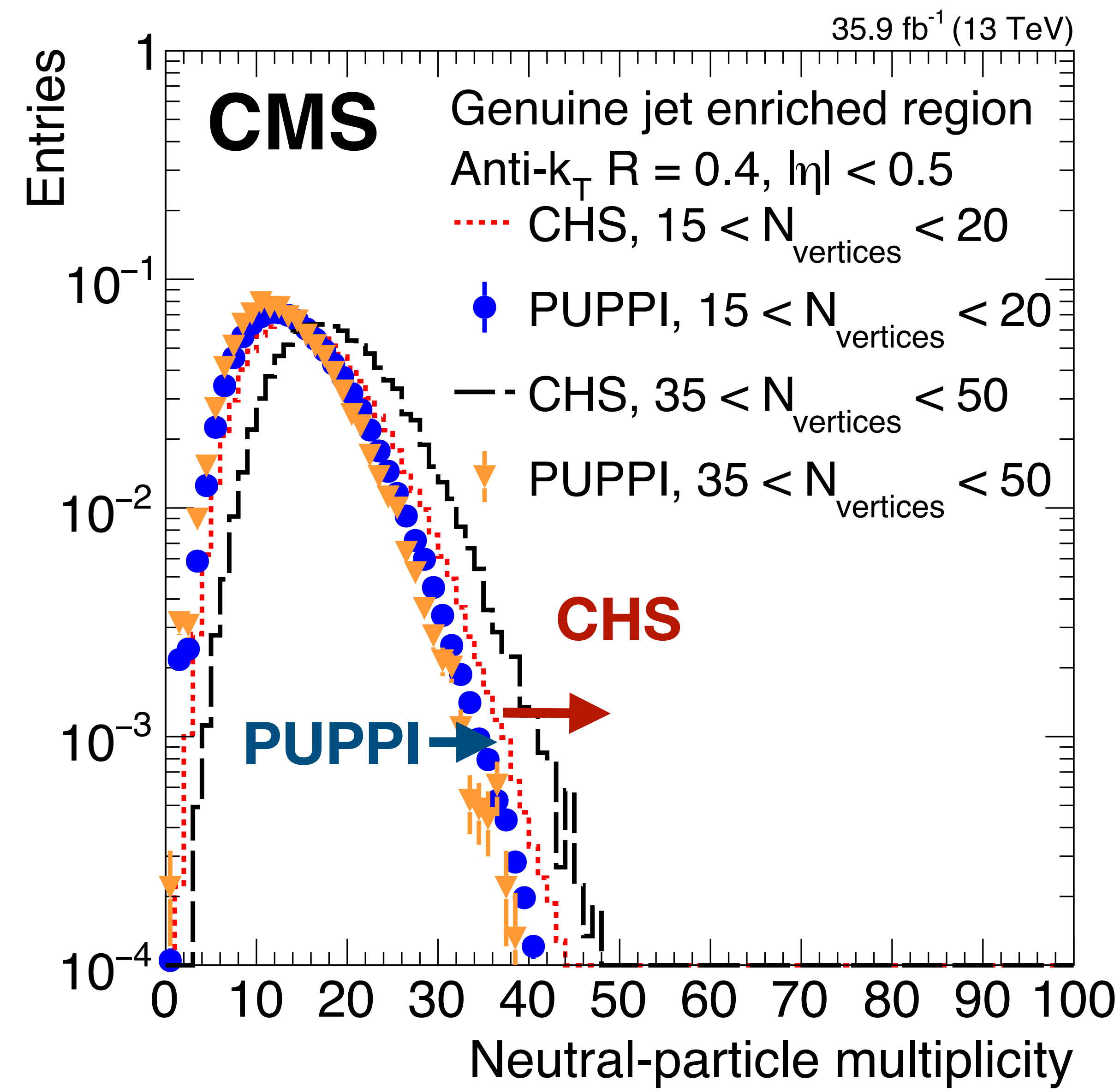
Performances of PUPPI jets/MET were extensively studied and compared to CHS jets/PF MET in JME-18-001

CMS-JME-18-001



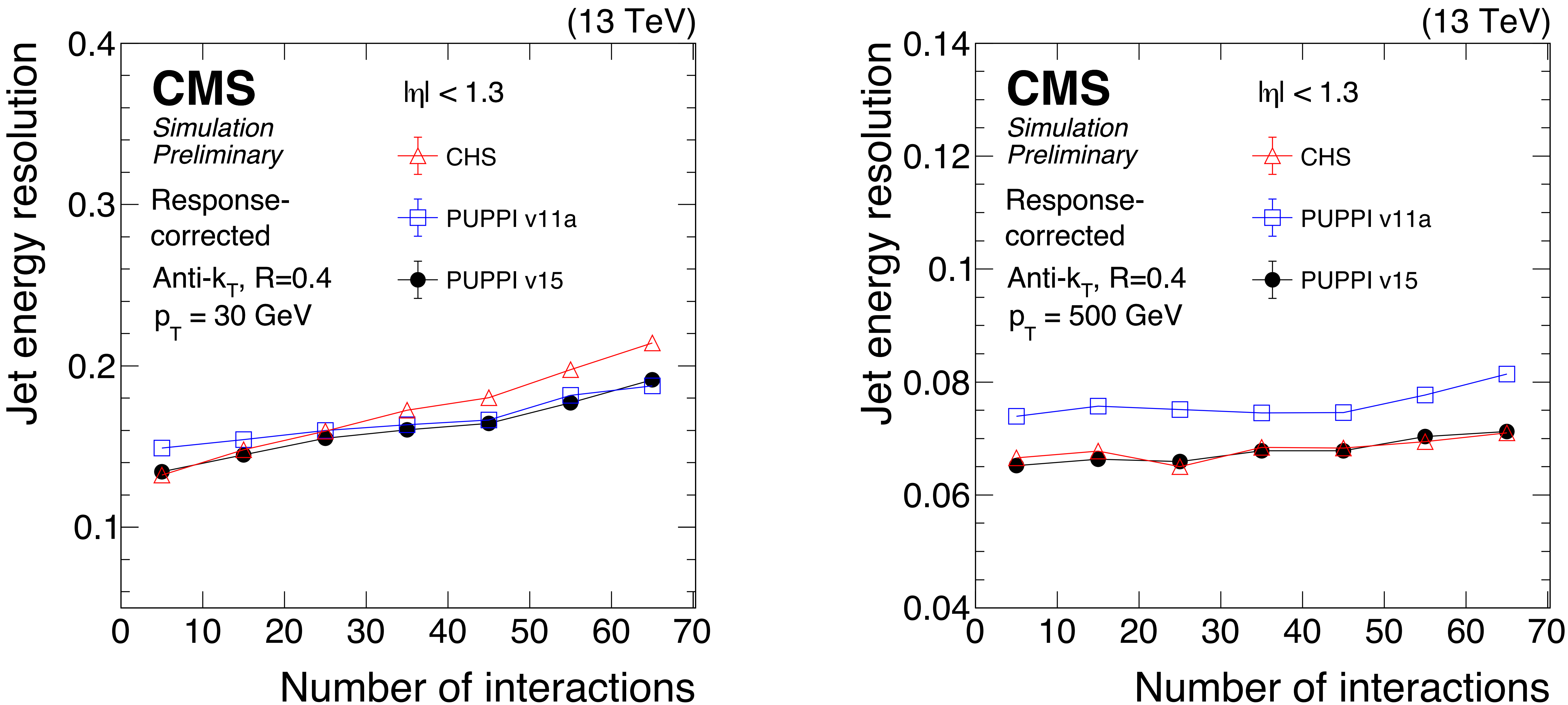
Noise Jet ID





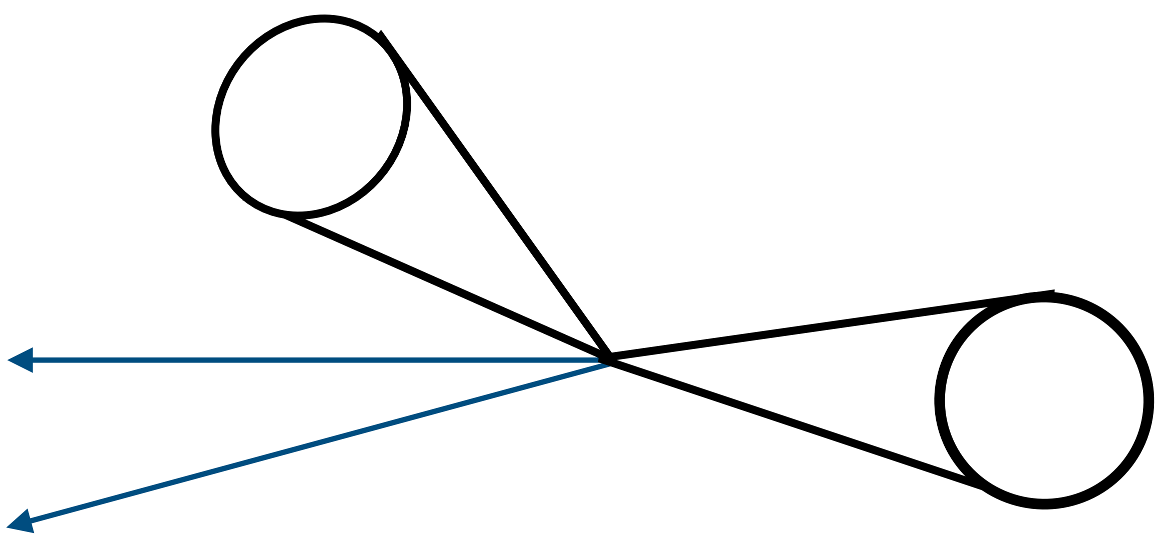
Purpose: remove noise from HCAL & ECAL by retaining ~98% of the real jets

Jet energy resolution



Efficiency & purity in Z+jets

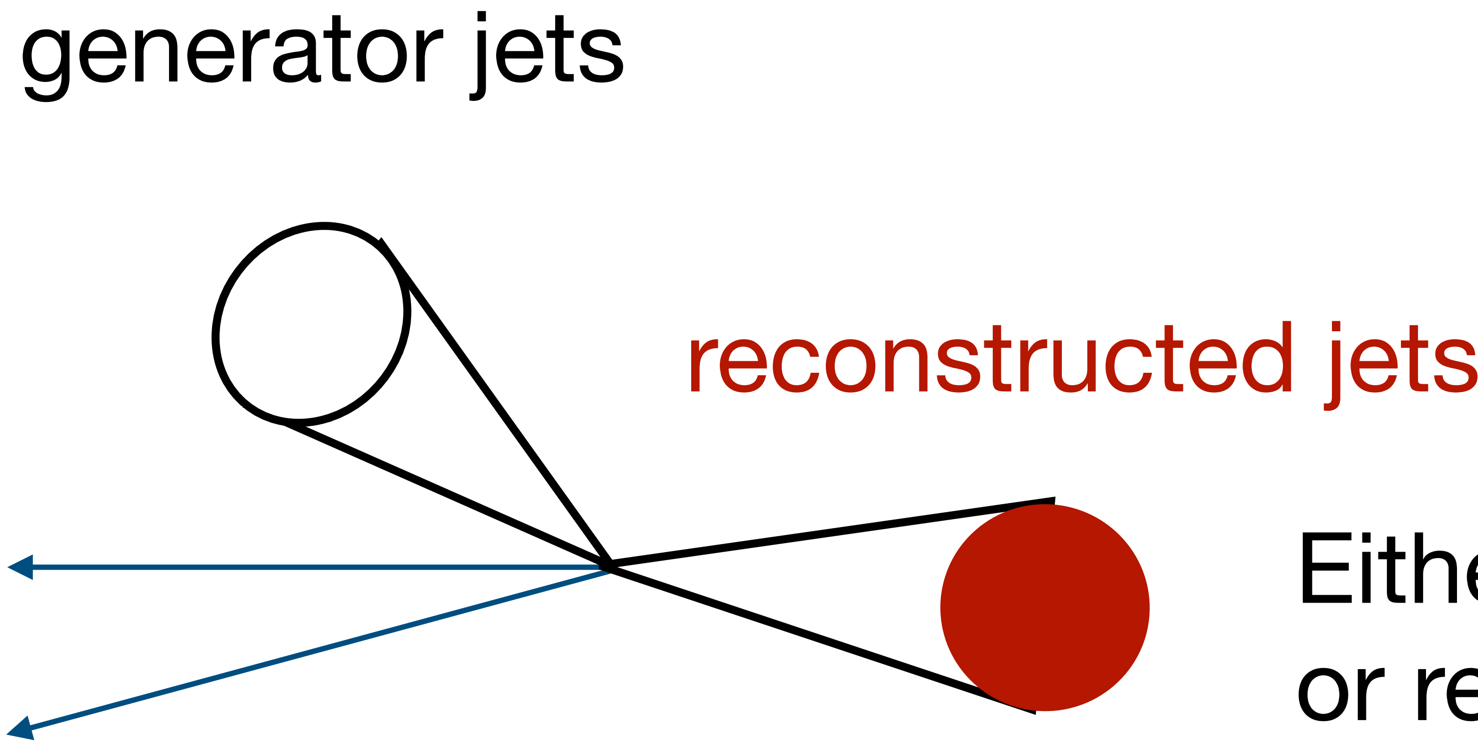
generator jets



Efficiency

Simulation only study

Efficiency & purity in Z+jets



Either not reconstructed or rejected:

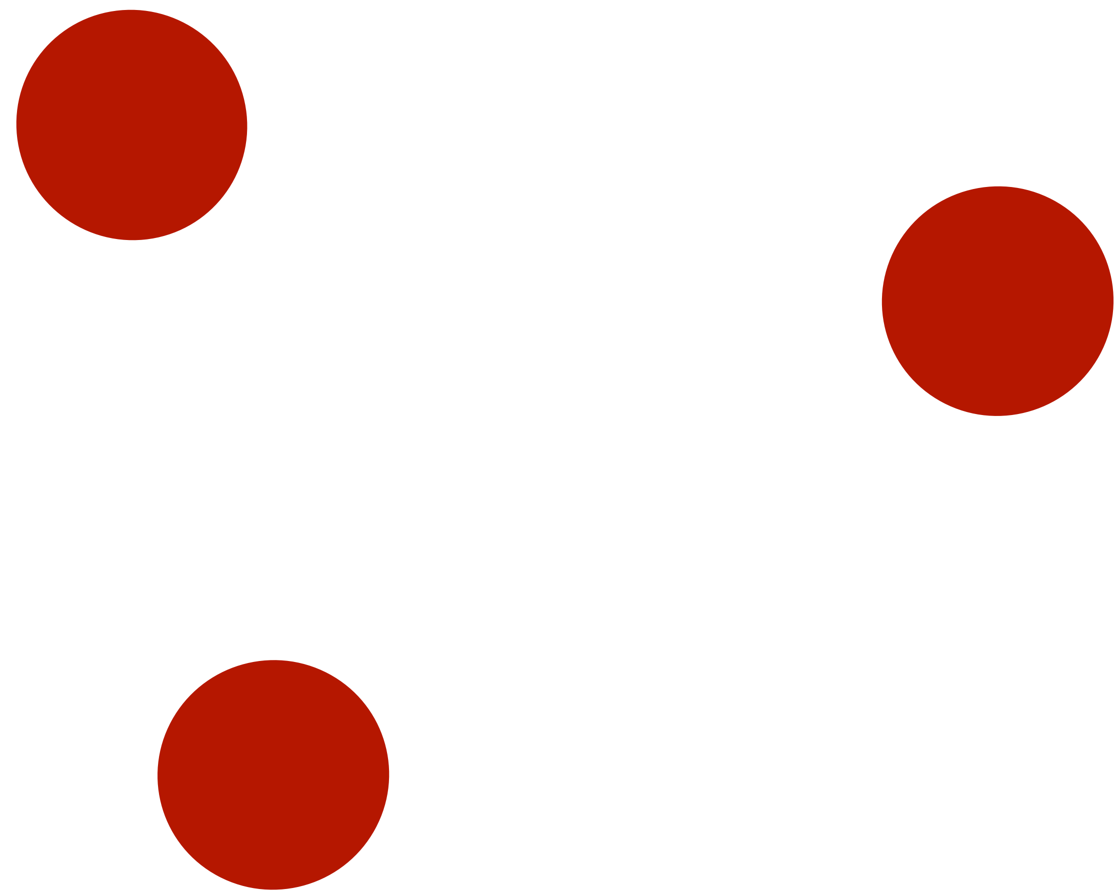
- Pileup Jet ID
- down weighted particles from PUPPI
- …

Efficiency

Simulation only study

Efficiency & purity in Z+jets

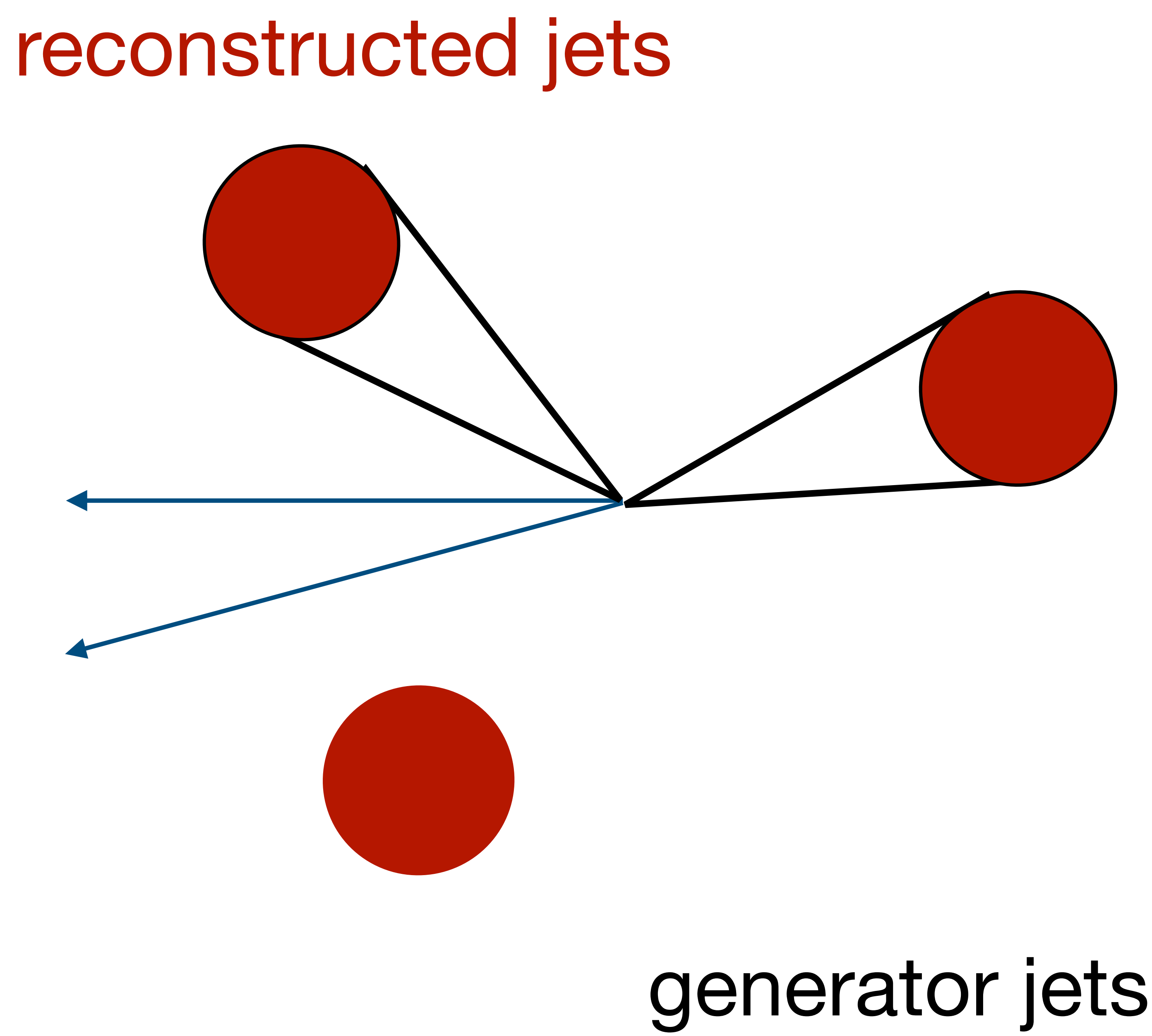
reconstructed jets



Purity

Simulation only study

Efficiency & purity in Z+jets



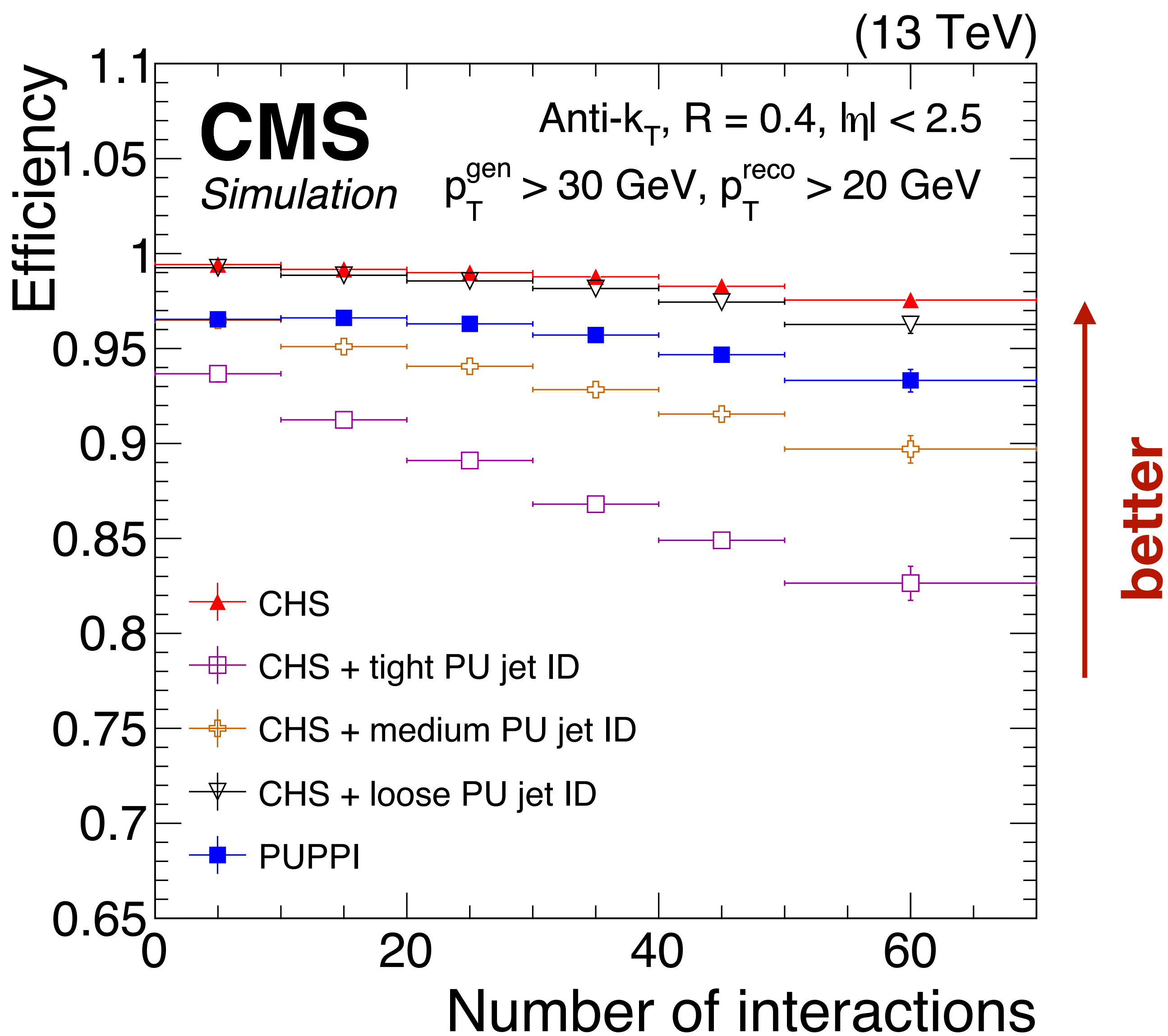
Most likely PU Jets did not get rejected:

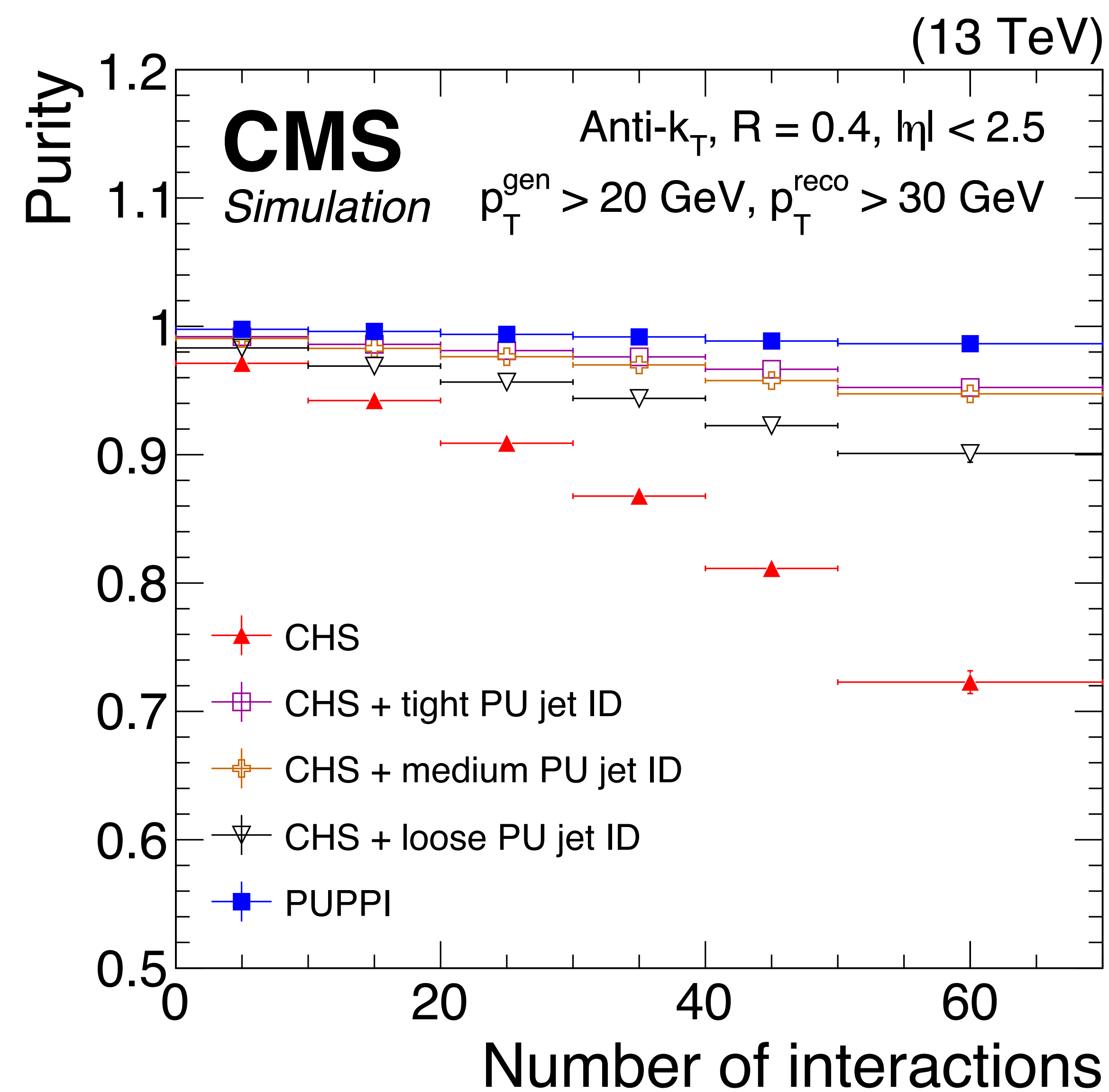
- CHS does not remove enough jets
- PUPPI does not remove enough particles
- …

Purity

Simulation only study

Efficiency and purity

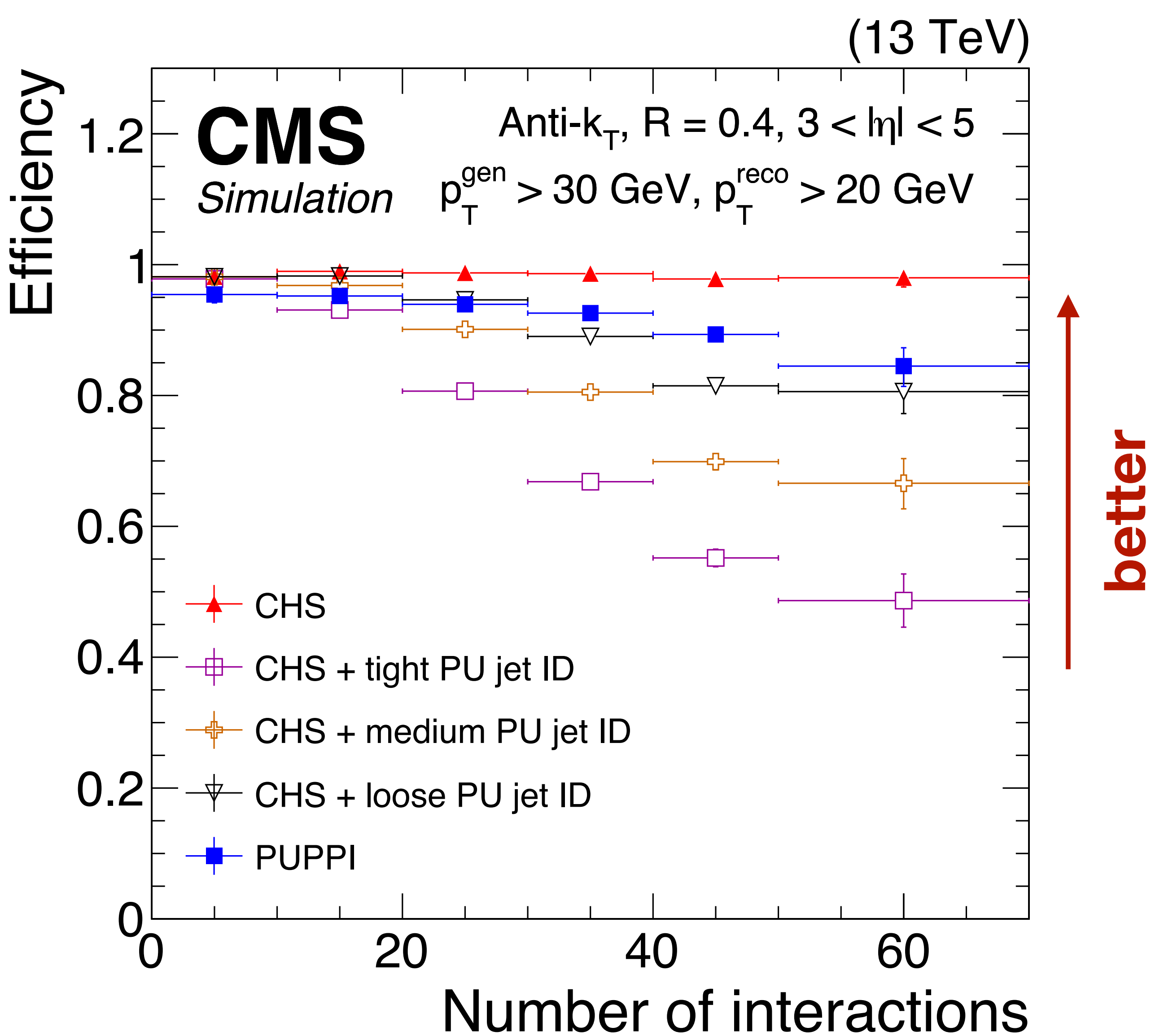


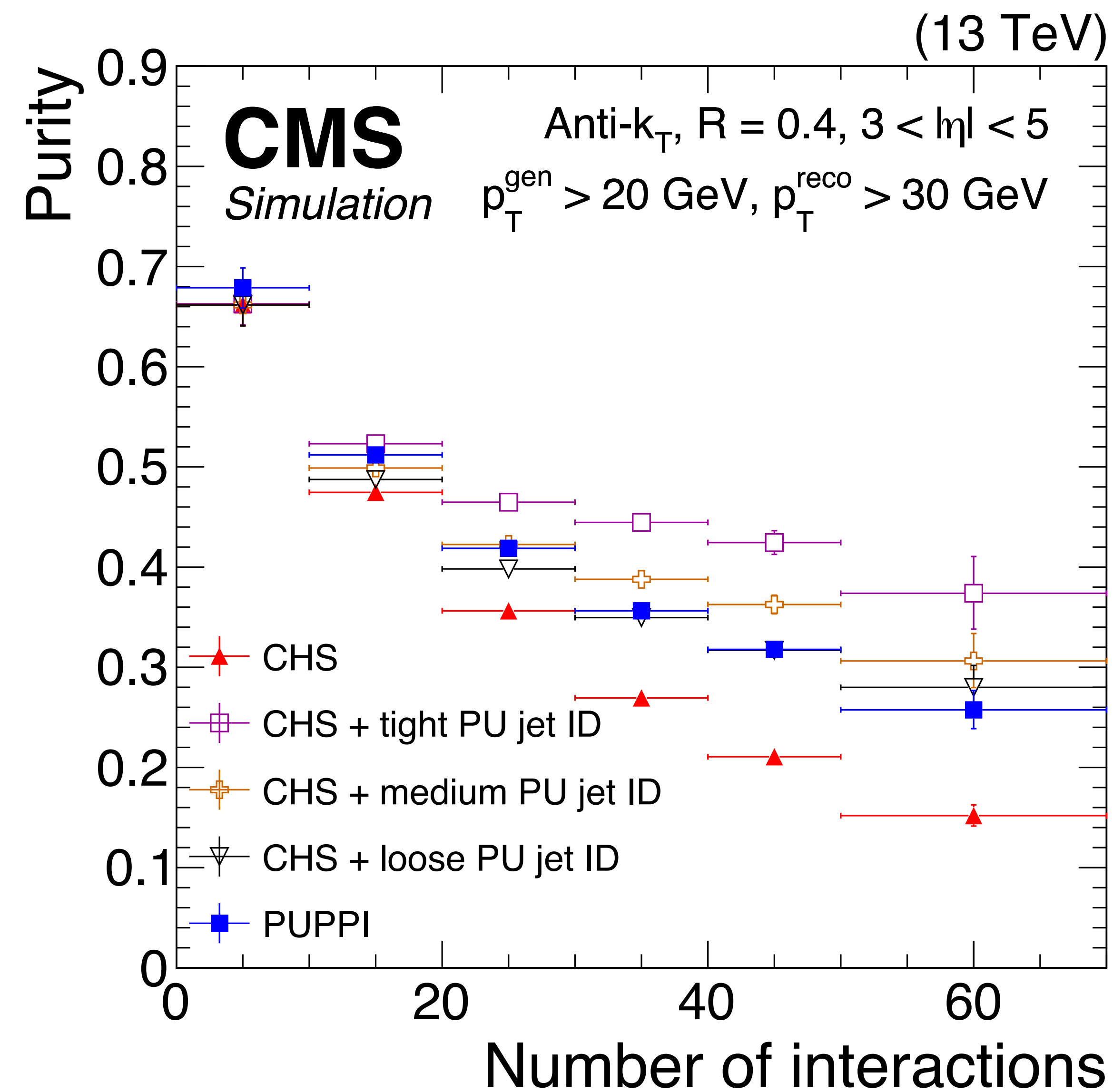


PUPPI better than **CHS+loose/medium** pileup jet ID

CMS-JME-18-001

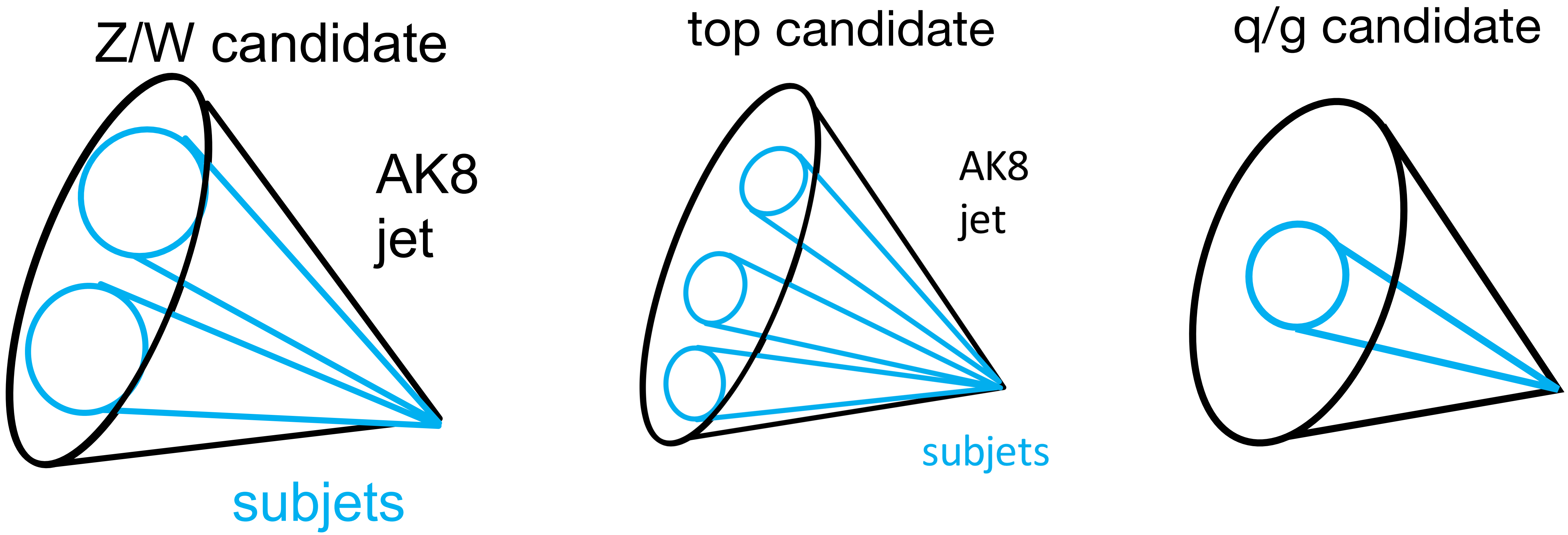
Efficiency and purity





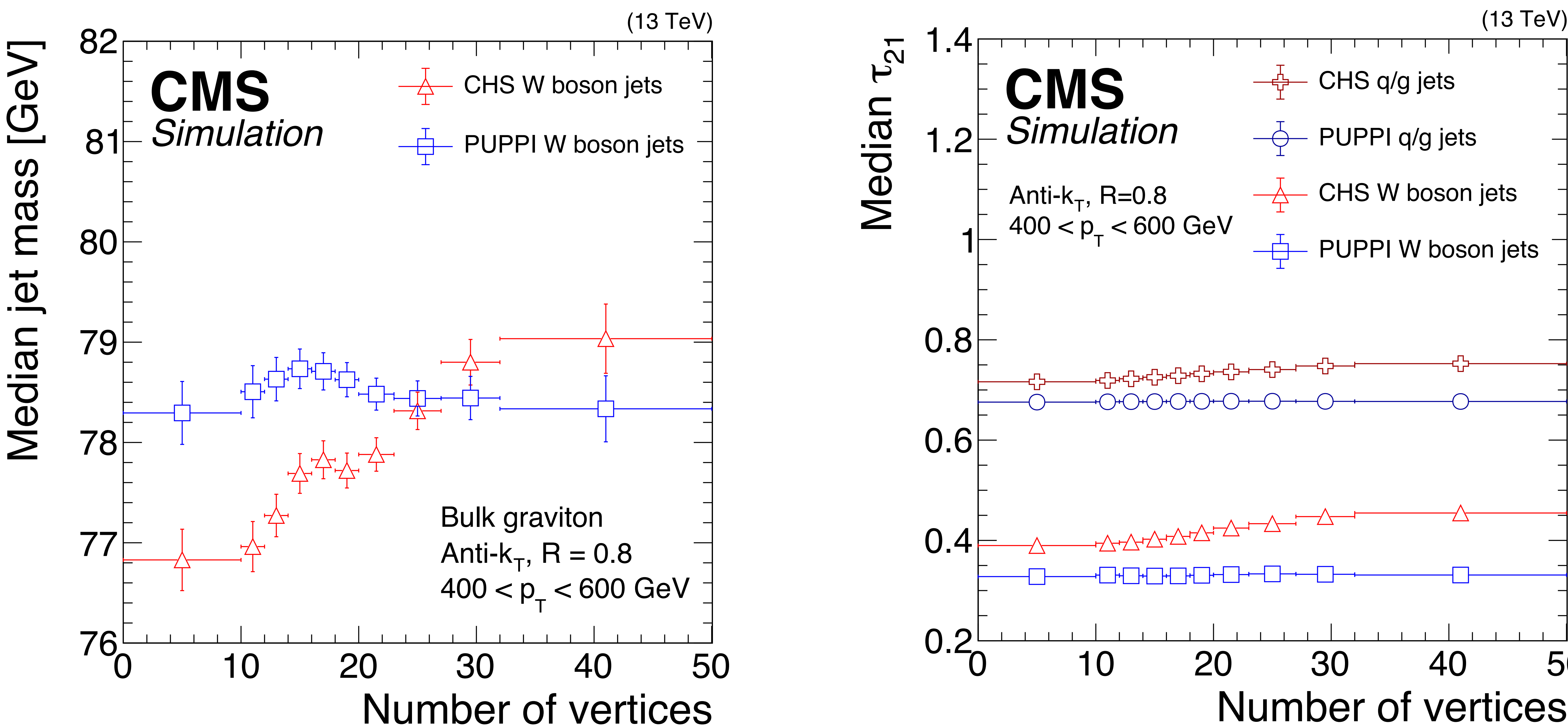
PUPPI better than **CHS+loose/medium** pileup jet ID

Identifying W bosons

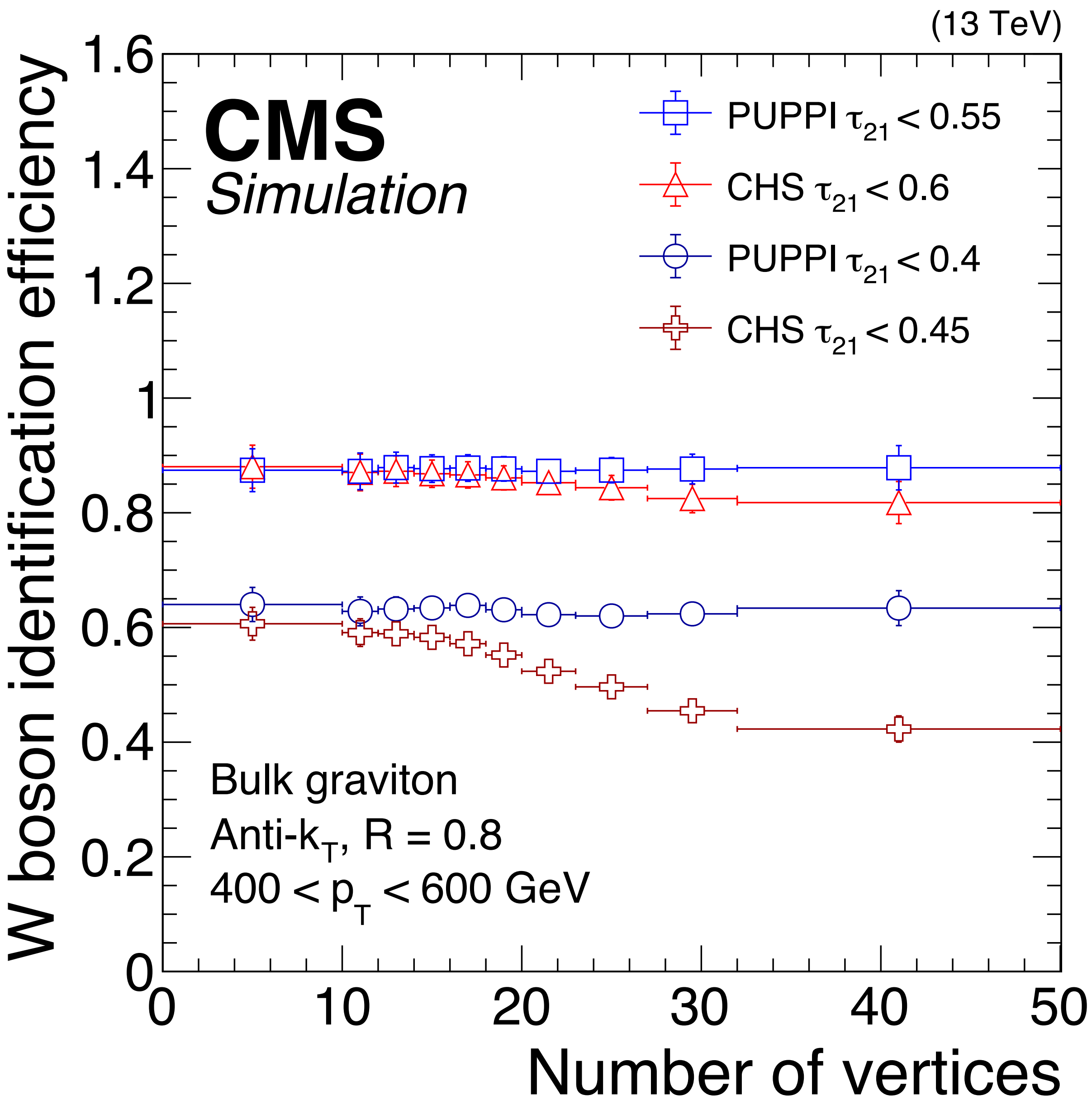


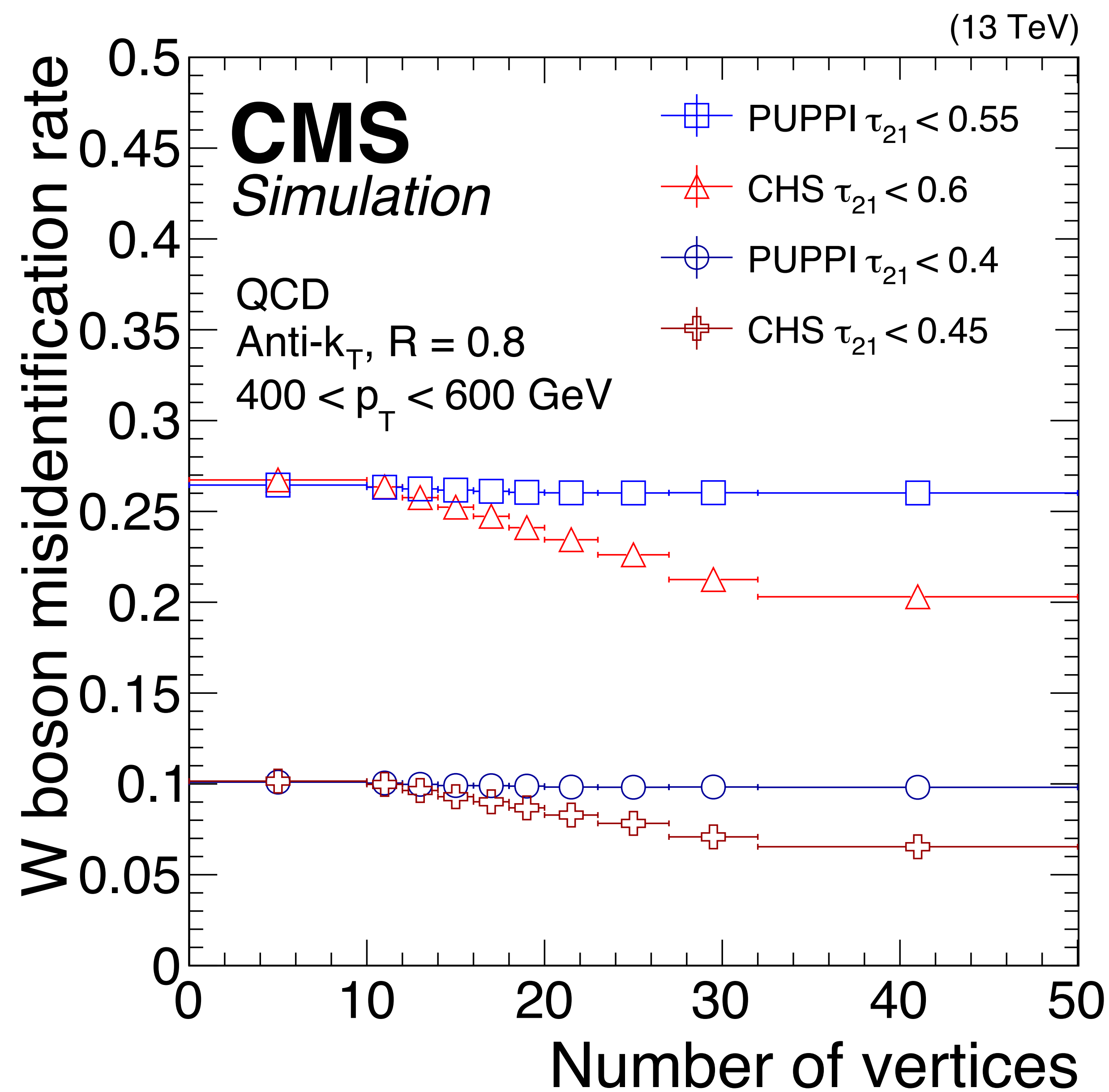
Identified through SD mass, n-subjettiness, subjet b-tagging, ...

Identifying W bosons



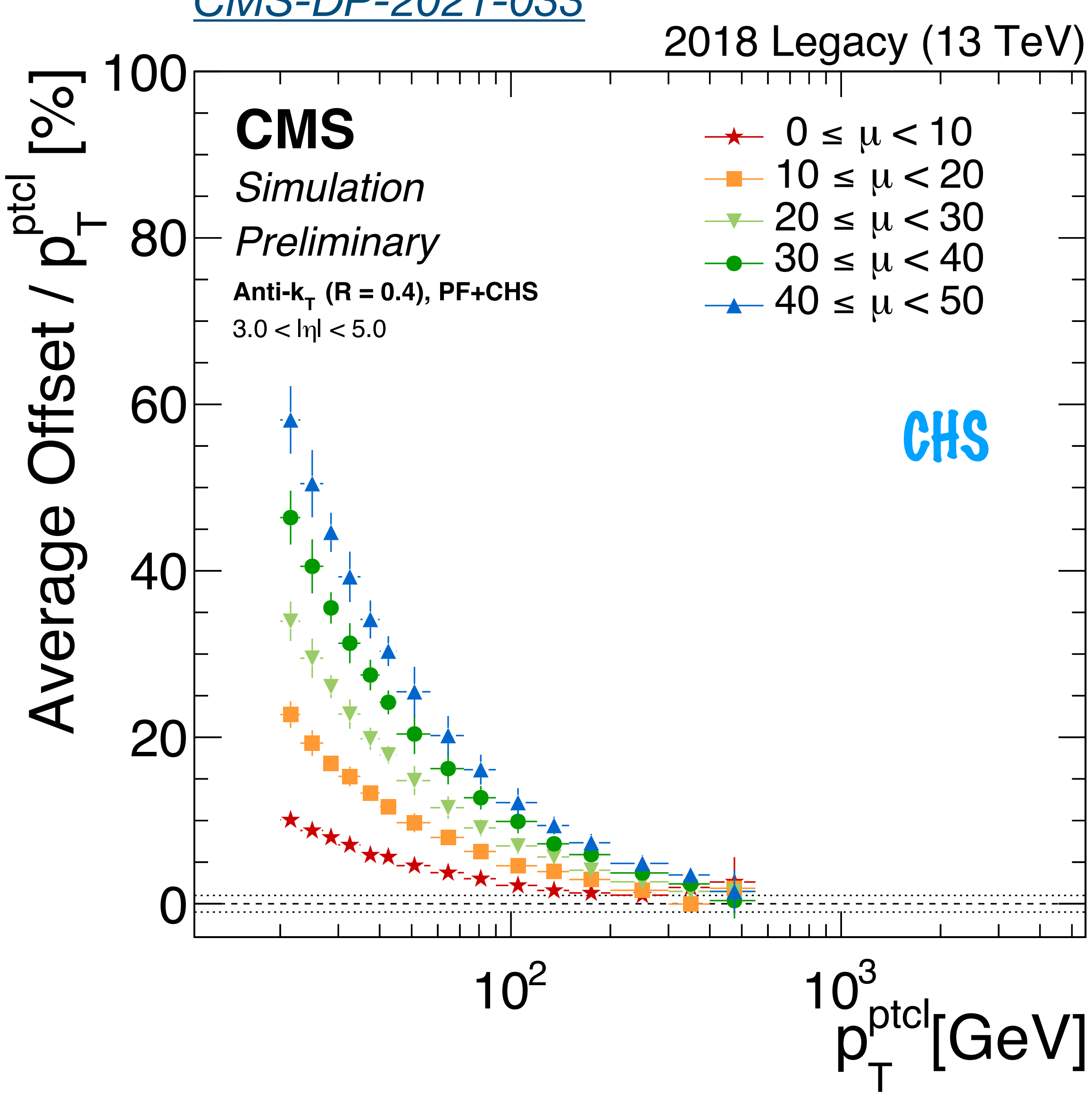
Identifying W bosons



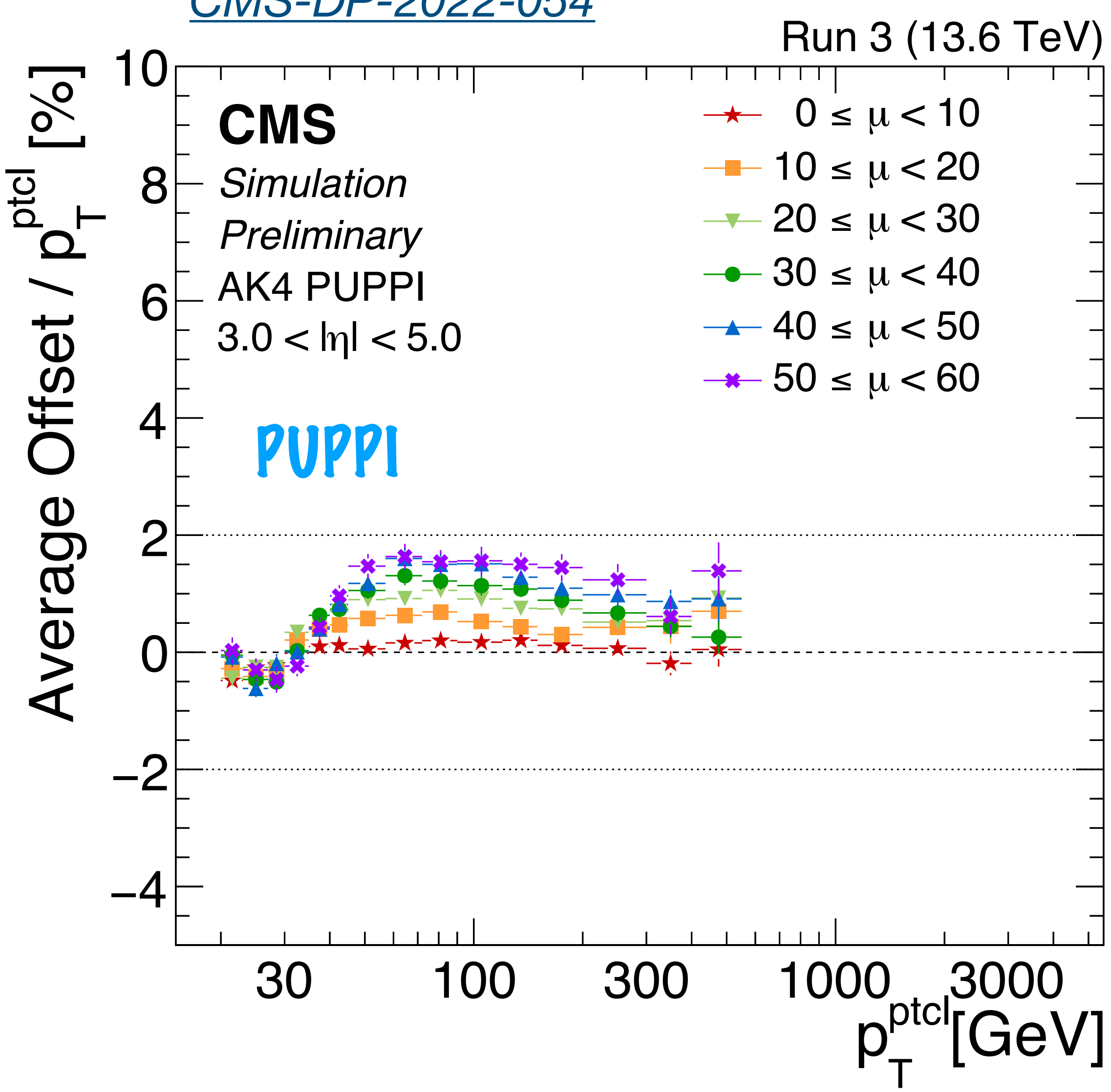


Quick look into Run3

CMS-DP-2021-033

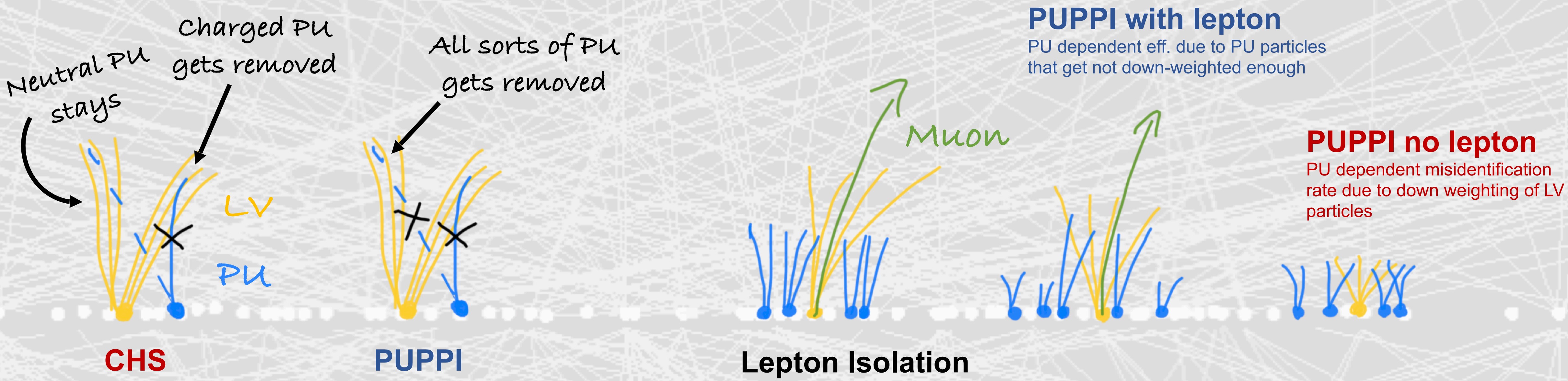


CMS-DP-2022-054



Significant reduction of the PU contribution with PUPPI in Run3

Pileup Mitigation Techniques in CMS



- full validation of PUPPI shows a good performance, especially at high PU

  CMS-JME-18-001

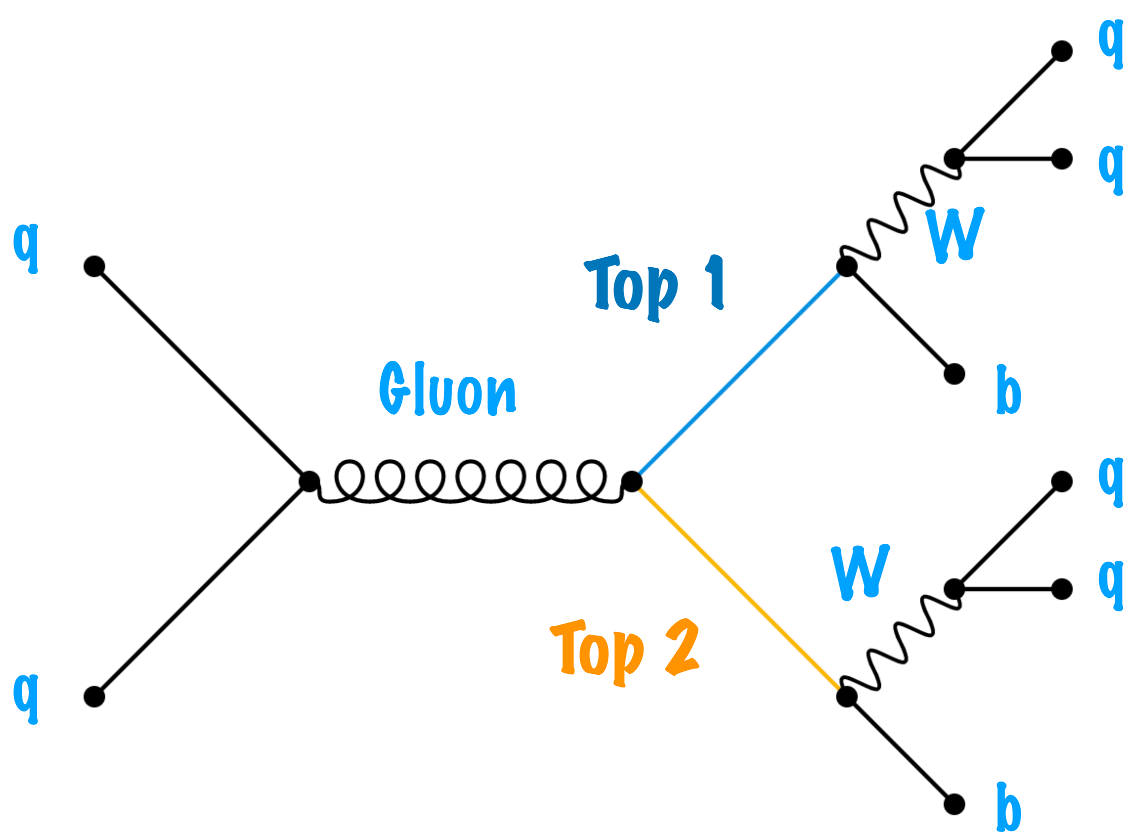
- PUPPI is the standard pileup mitigation technique for CMS in Run 3

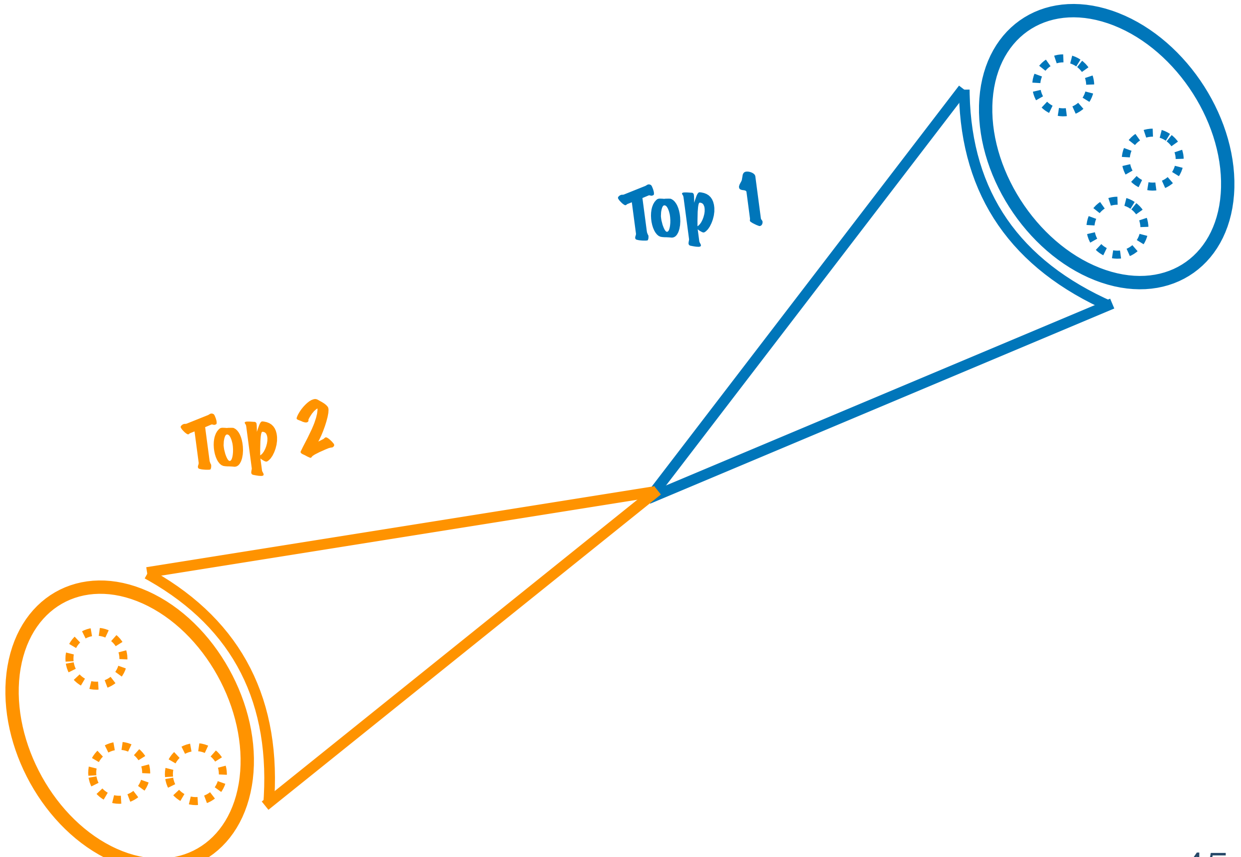
  CMS-DP-21-001

Backup

Jet reconstruction

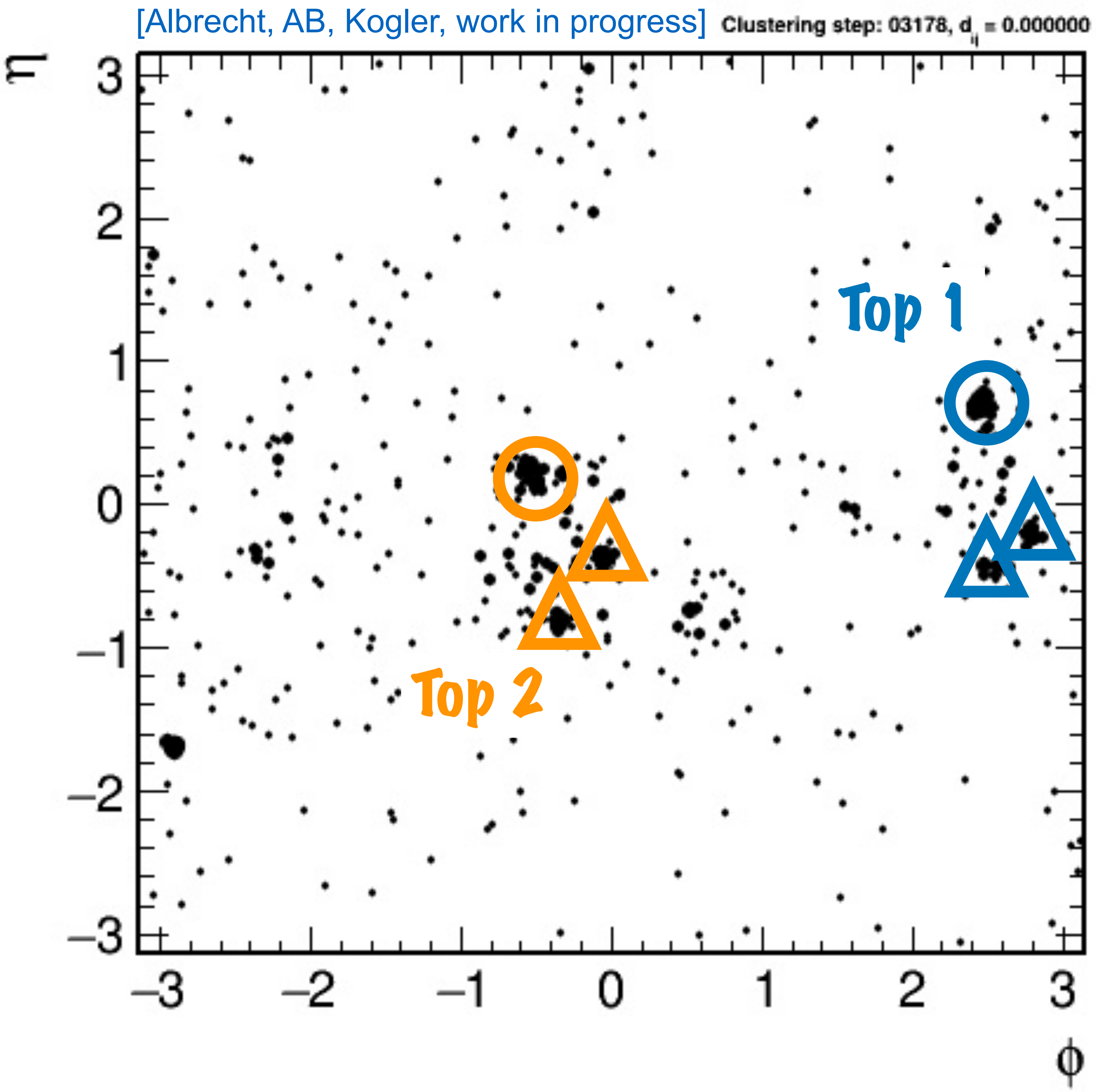
Jet reconstruction



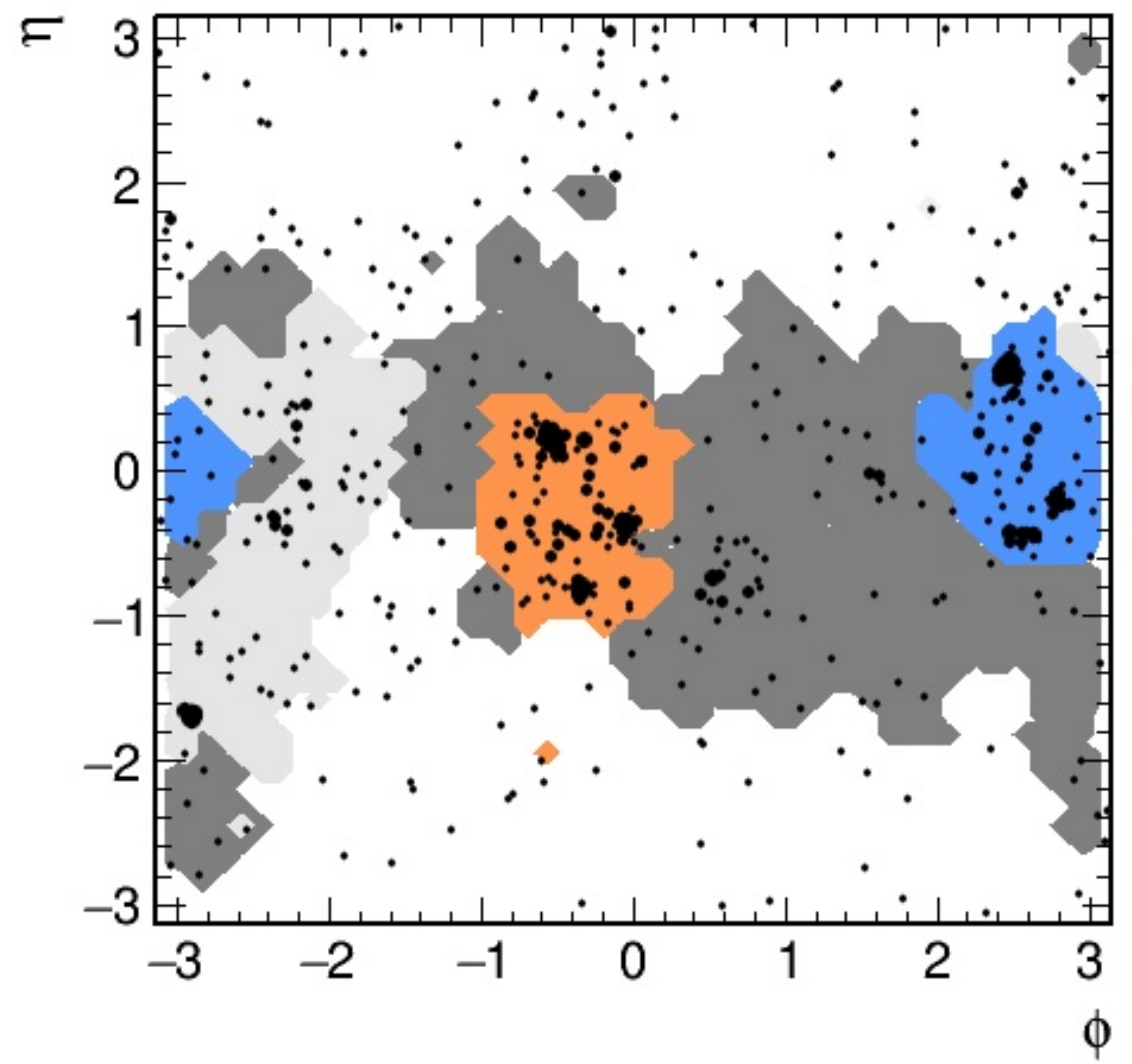


Jet reconstruction

Starting point: cleaned PF candidates

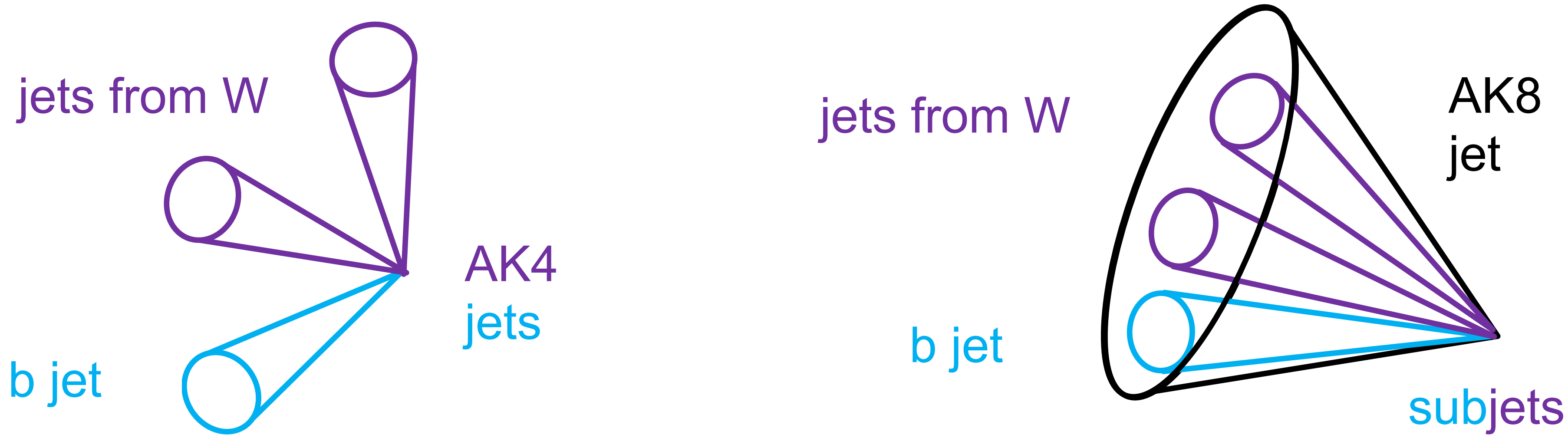


End point: two jets representing the top quark kinematics



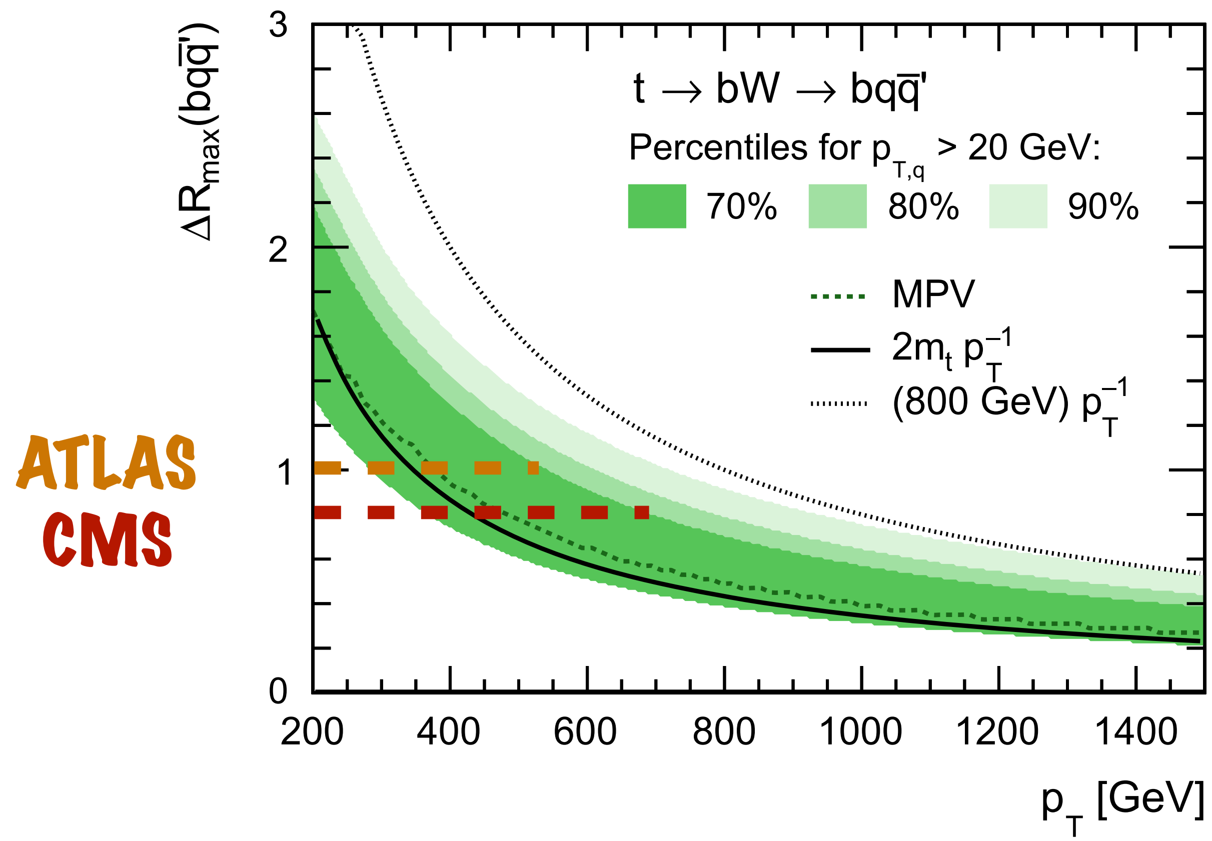
O b-quark
Δ Quarks from W

Jet reconstruction

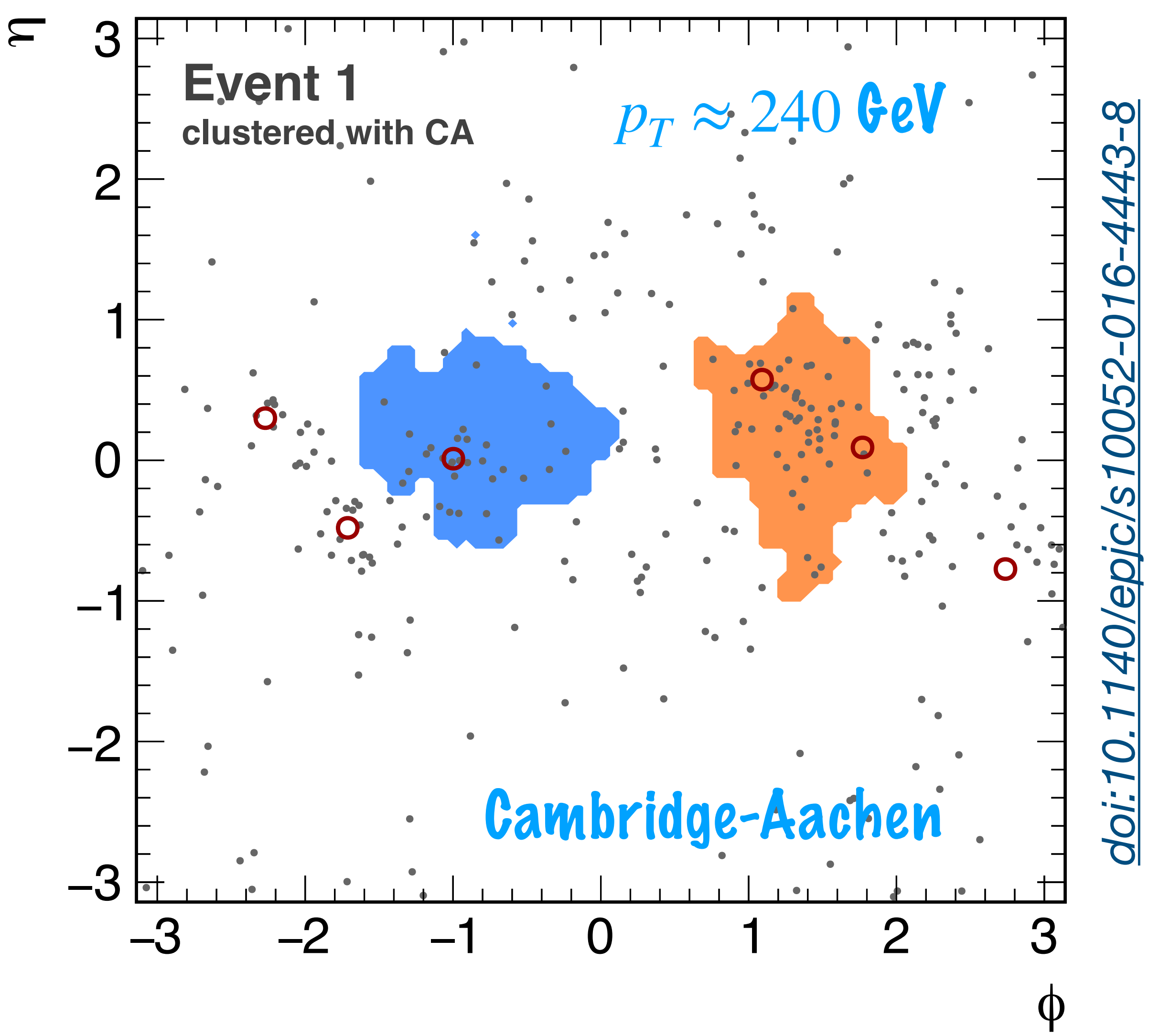


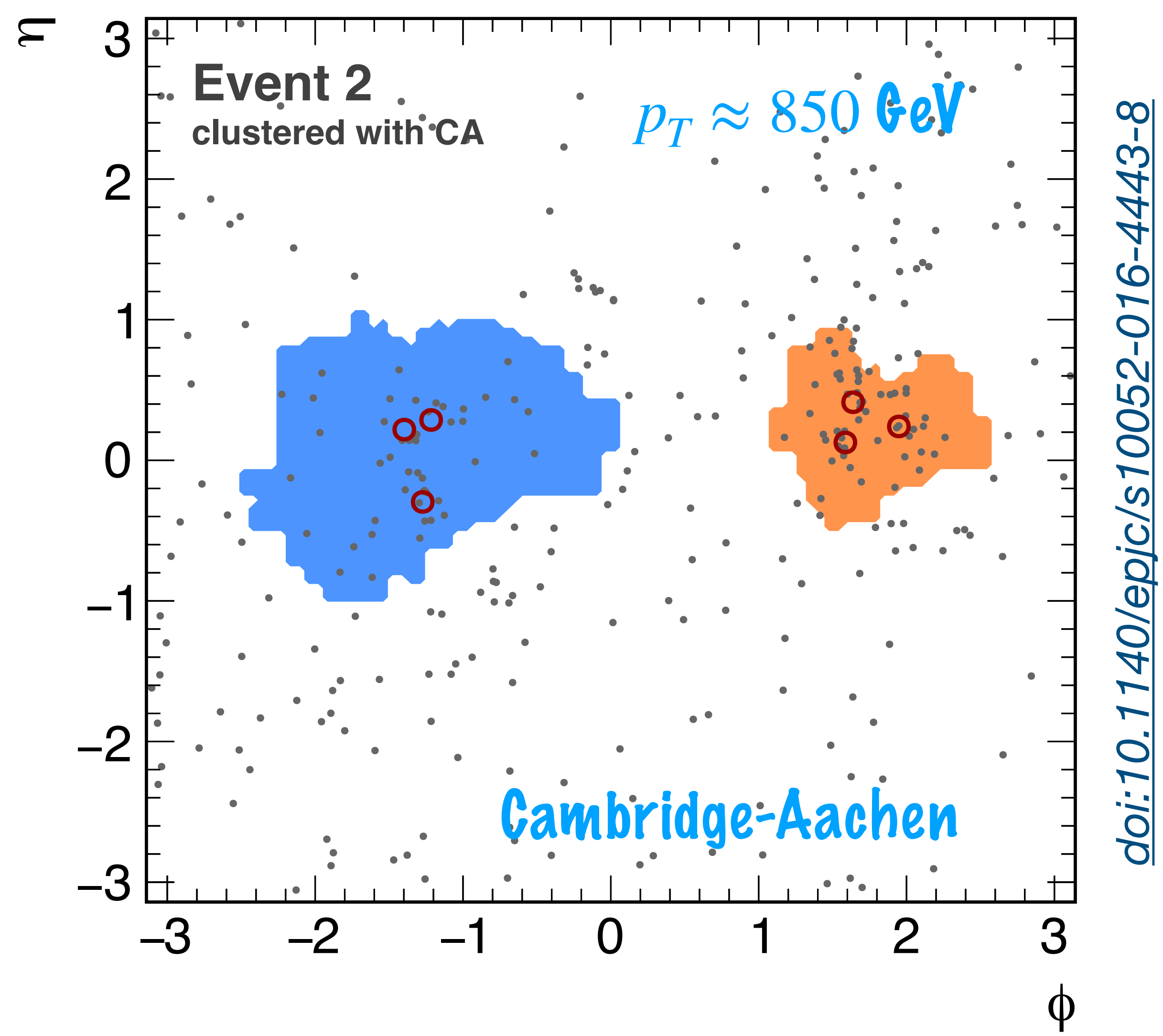
low p_T $\Delta R \propto \frac{1}{p_T}$ high p_T

Advances in Jet Substructure at the LHC, R. Kogler

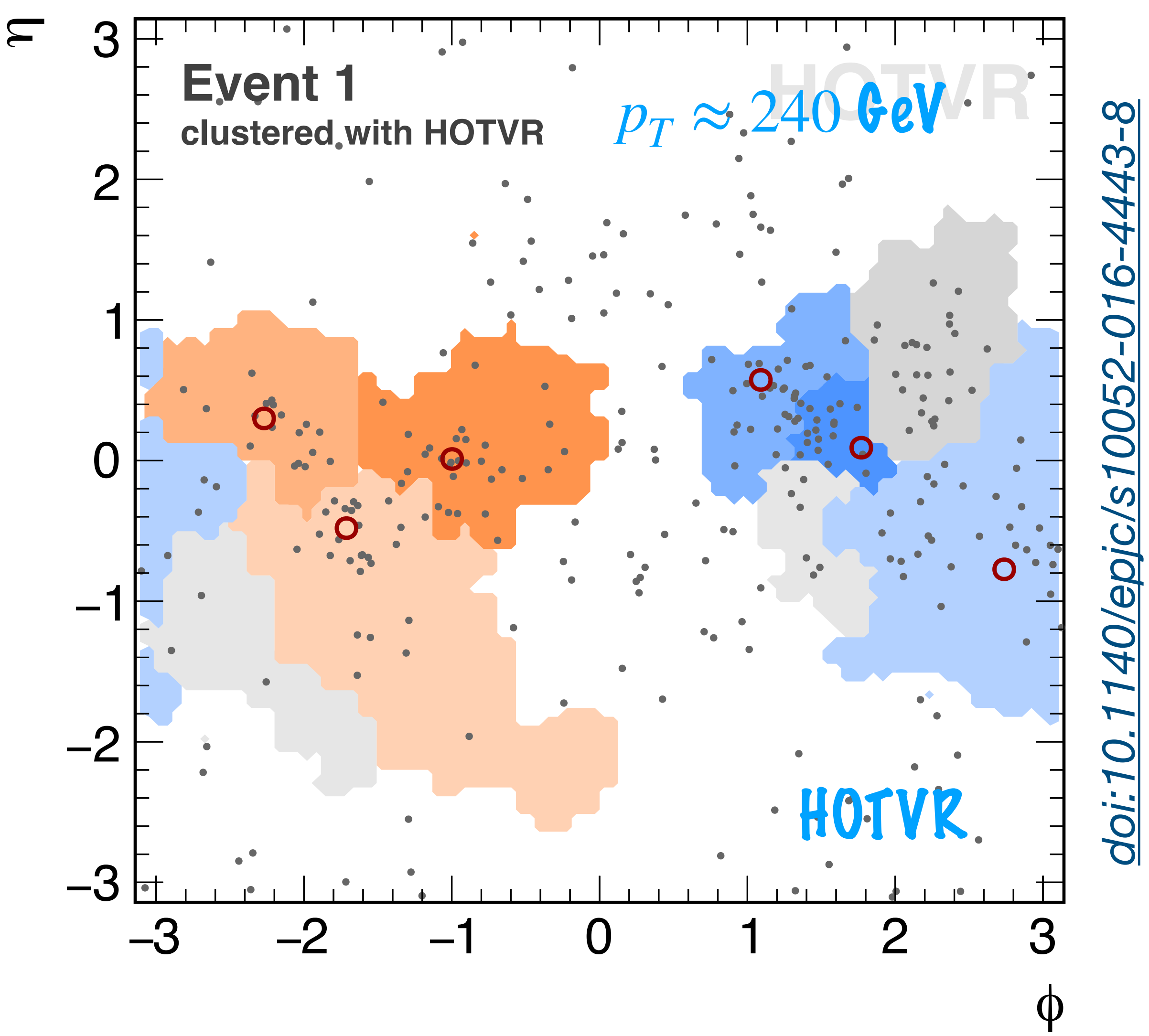


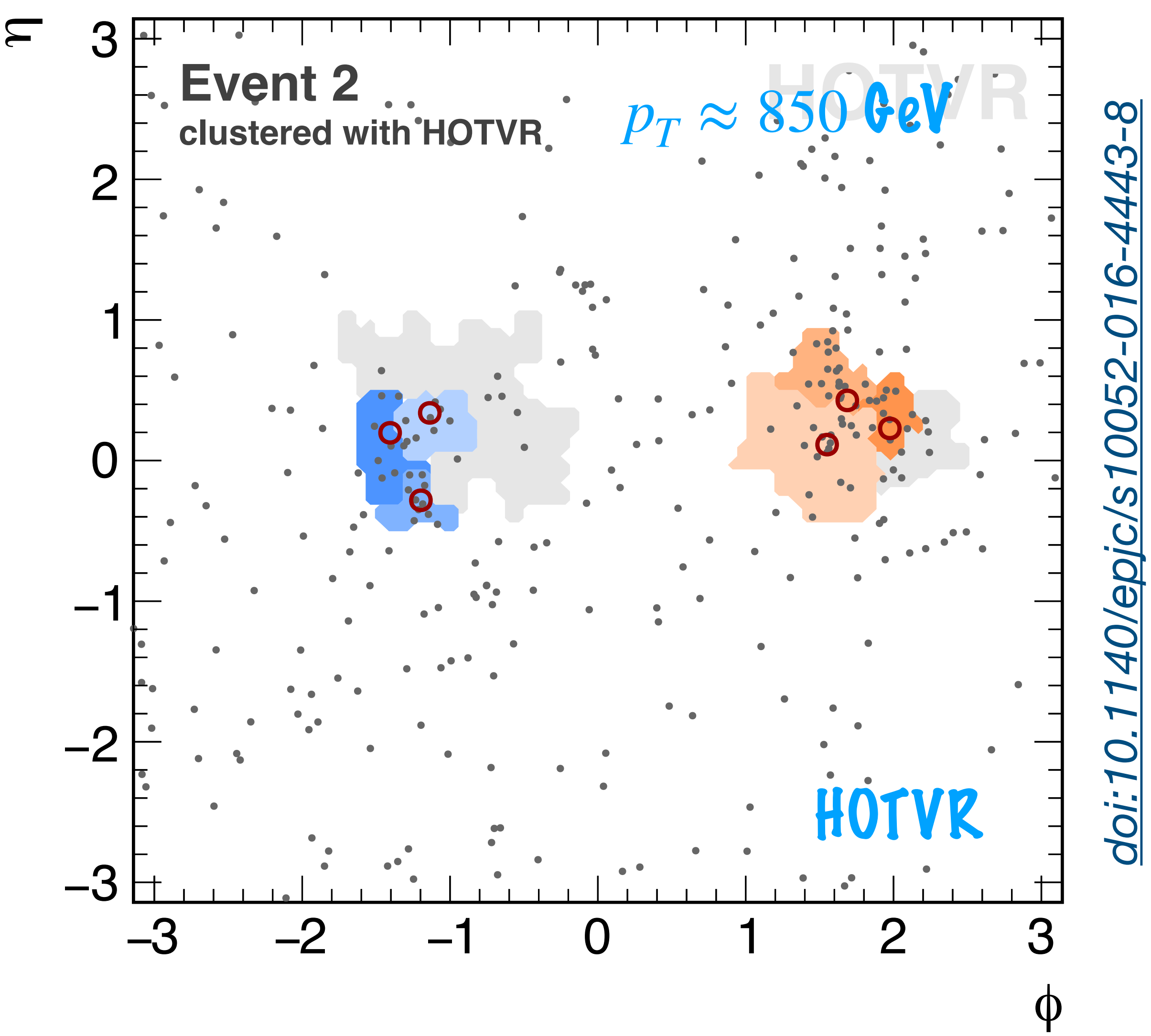
Fixed R clustering



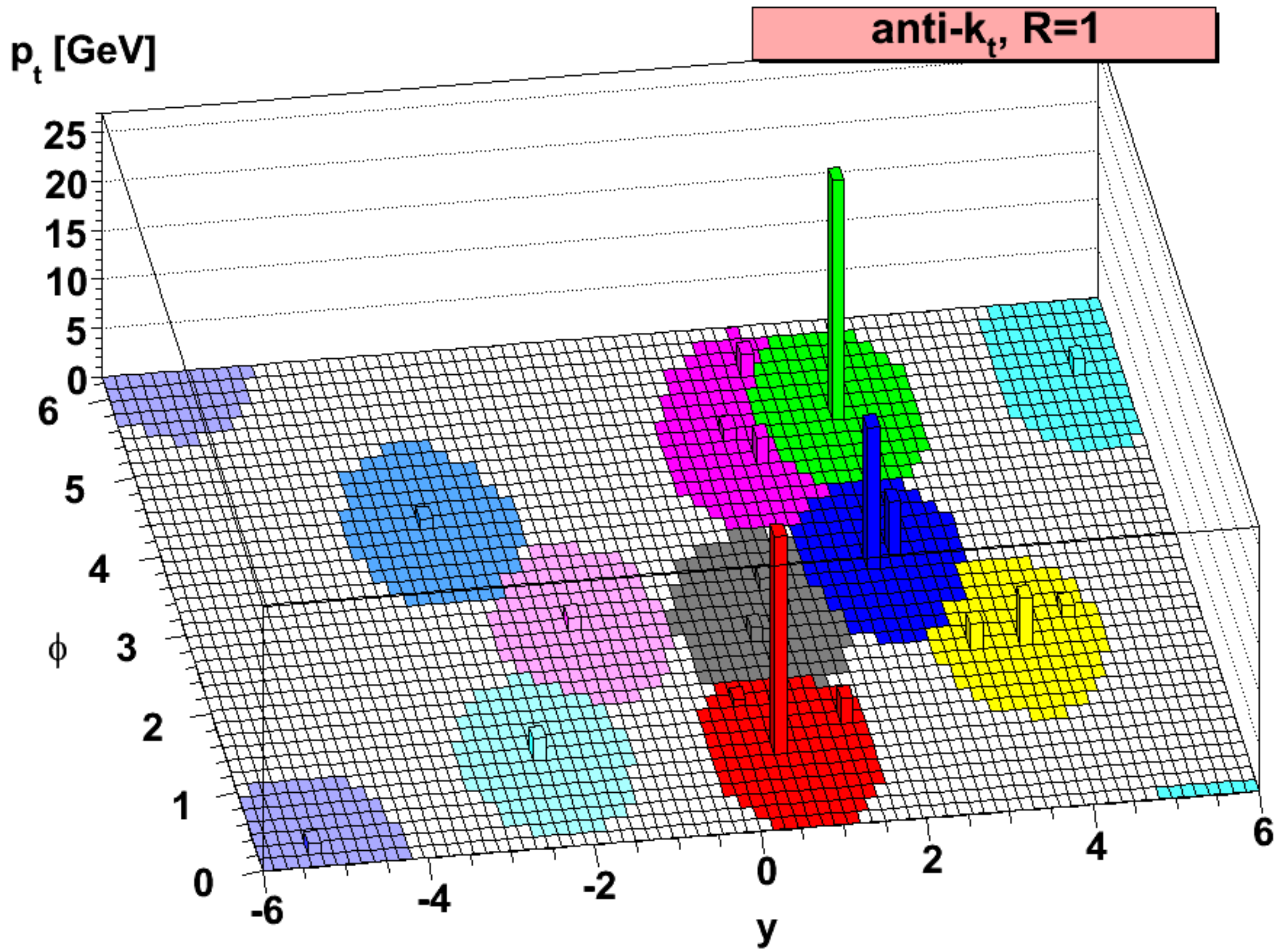


Variable R jet clustering





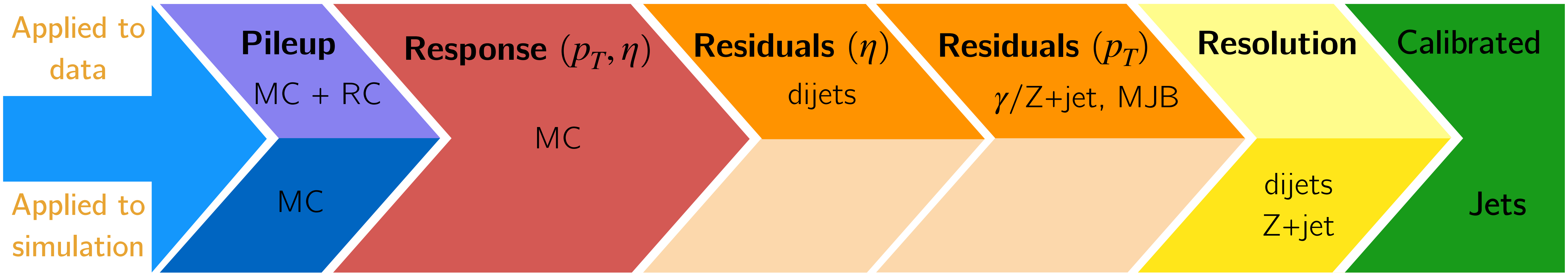
Jet reconstruction



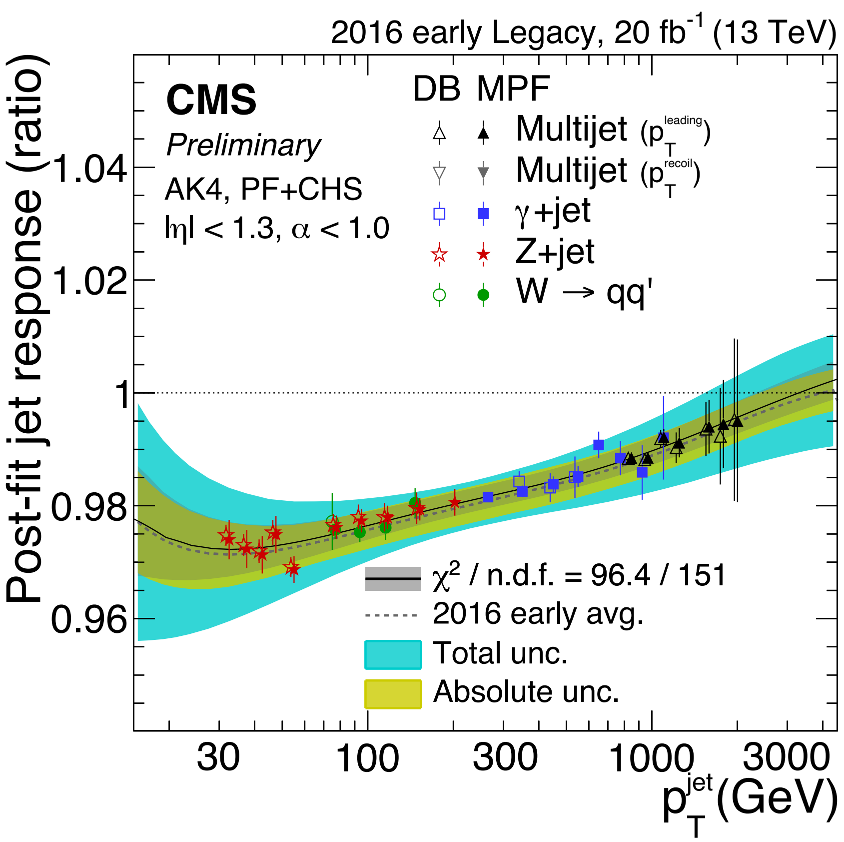
arxiv:0802.1189

Jet calibration

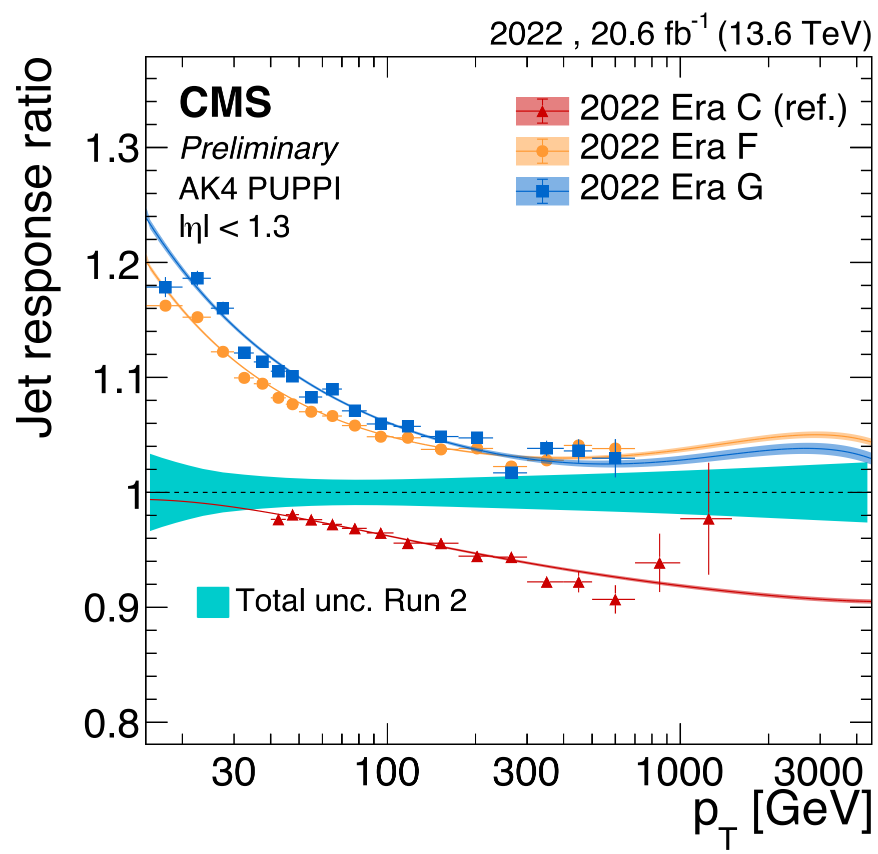
Jet Calibration in Run3



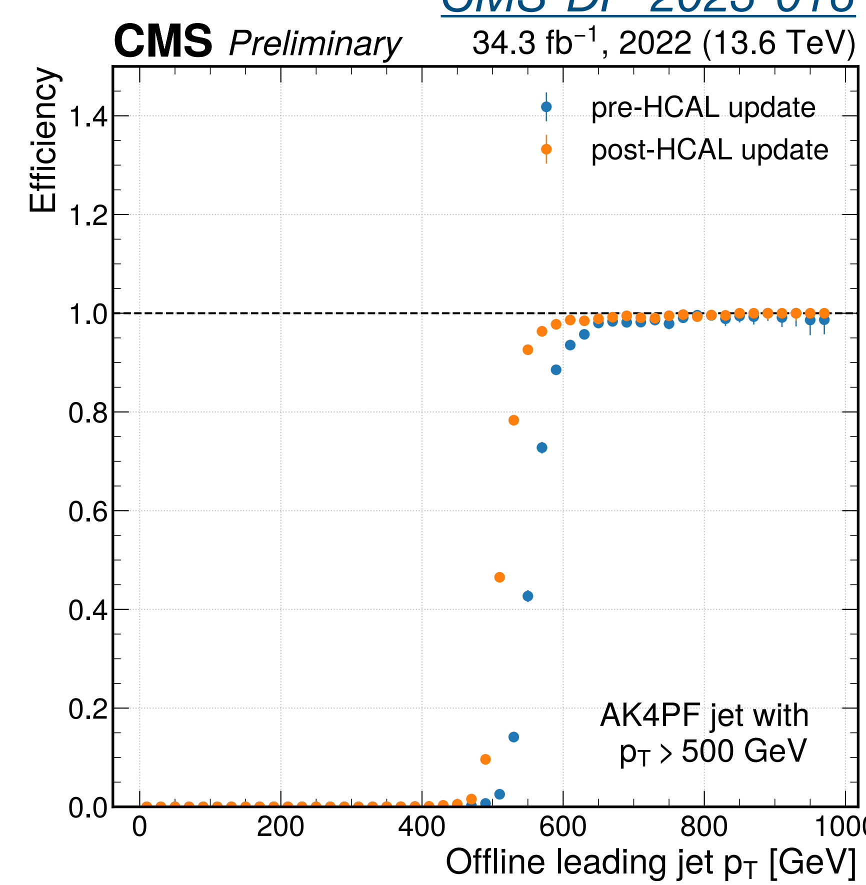
CMS-DP-2021-033



CMS-DP-2022-054



CMS-DP-2023-016

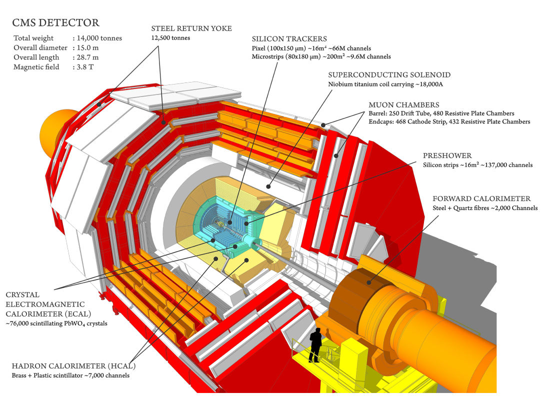


Run2 → **Run3**

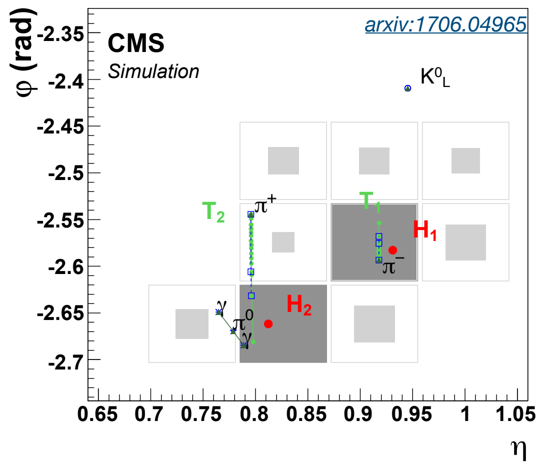
Anna Benecke

Summary & Outlook

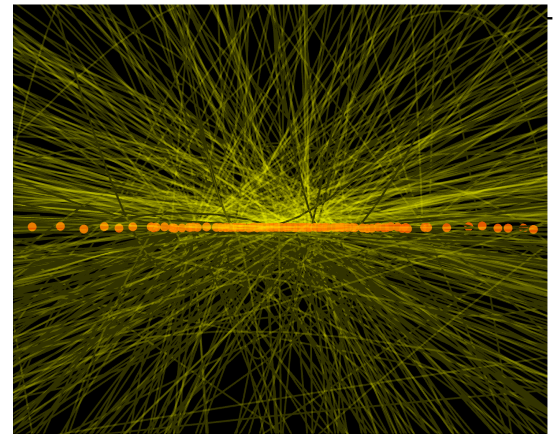
Detector



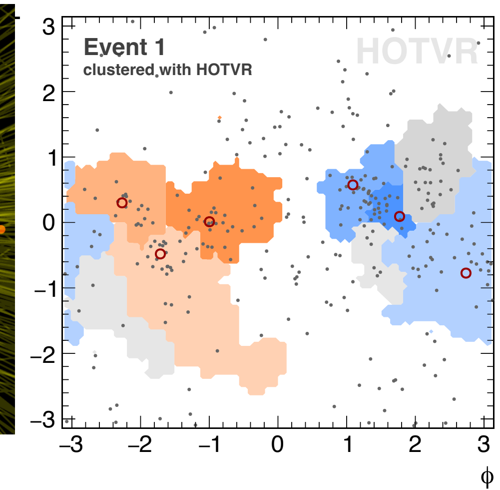
Reconstruction



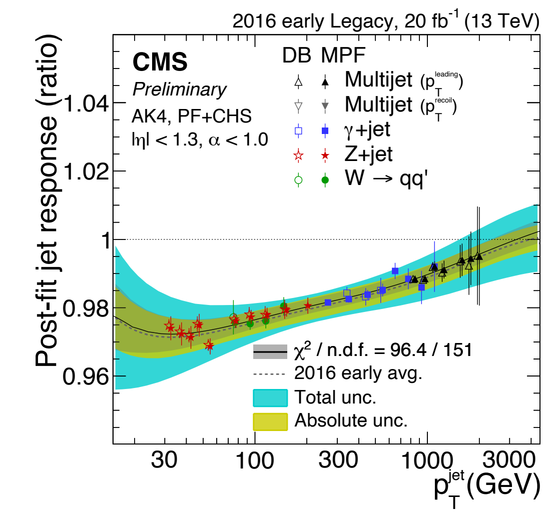
Pileup



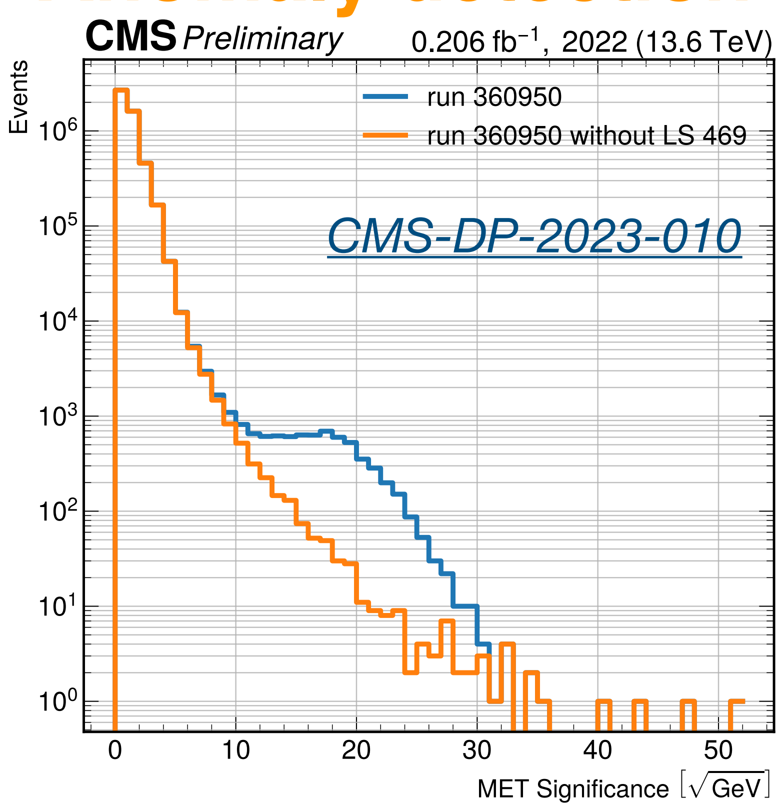
Clustering



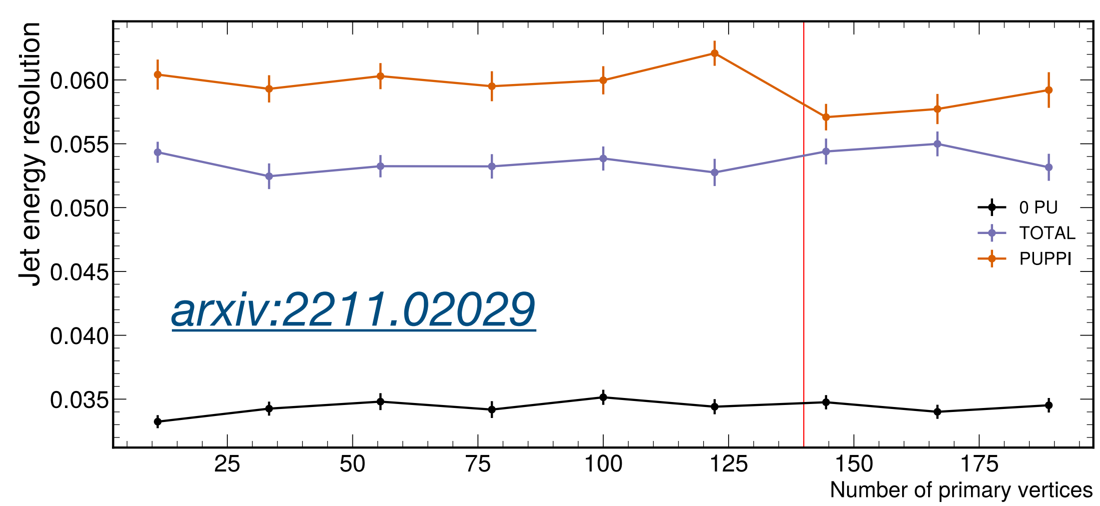
Calibration



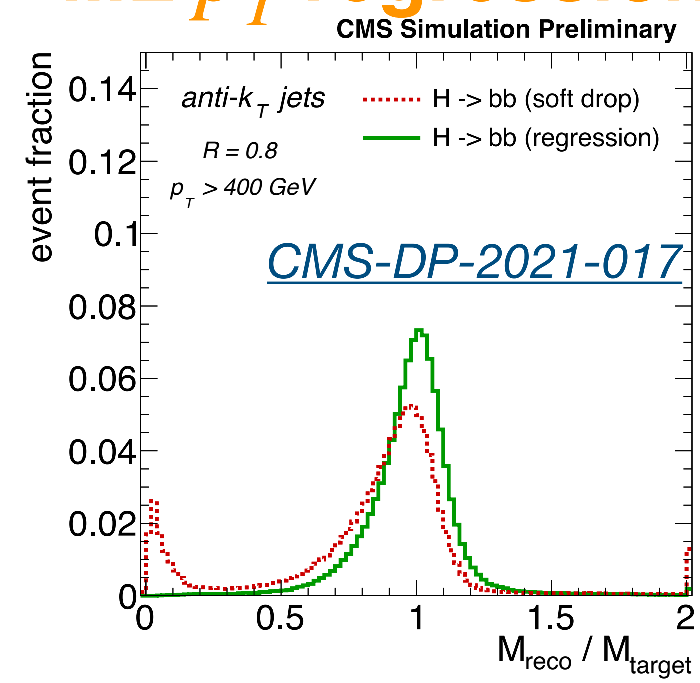
Anomaly detection



ML PU mitigation



ML p_T regression



HOTVR

[JME-18-002](JME-18-002)