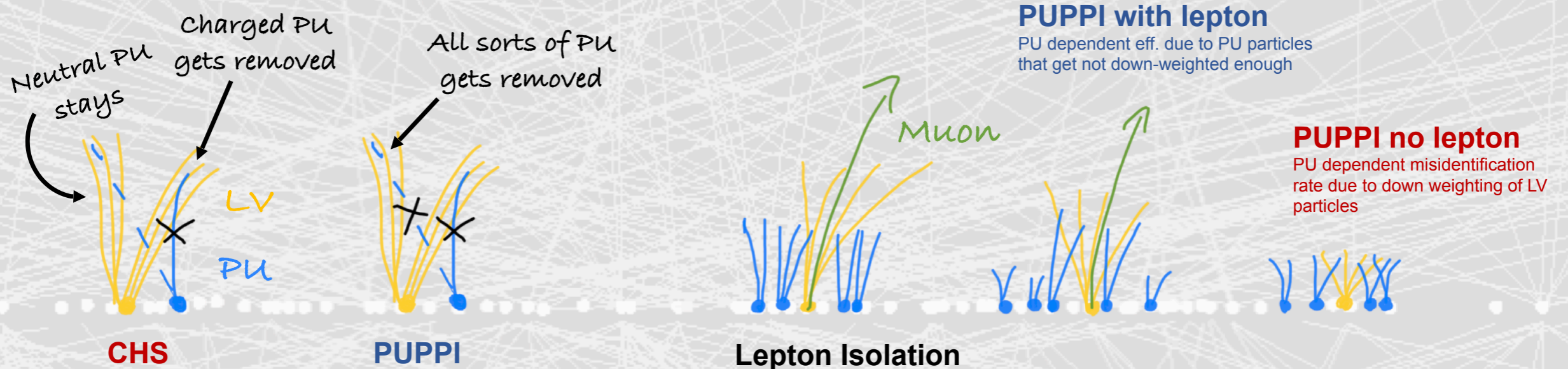


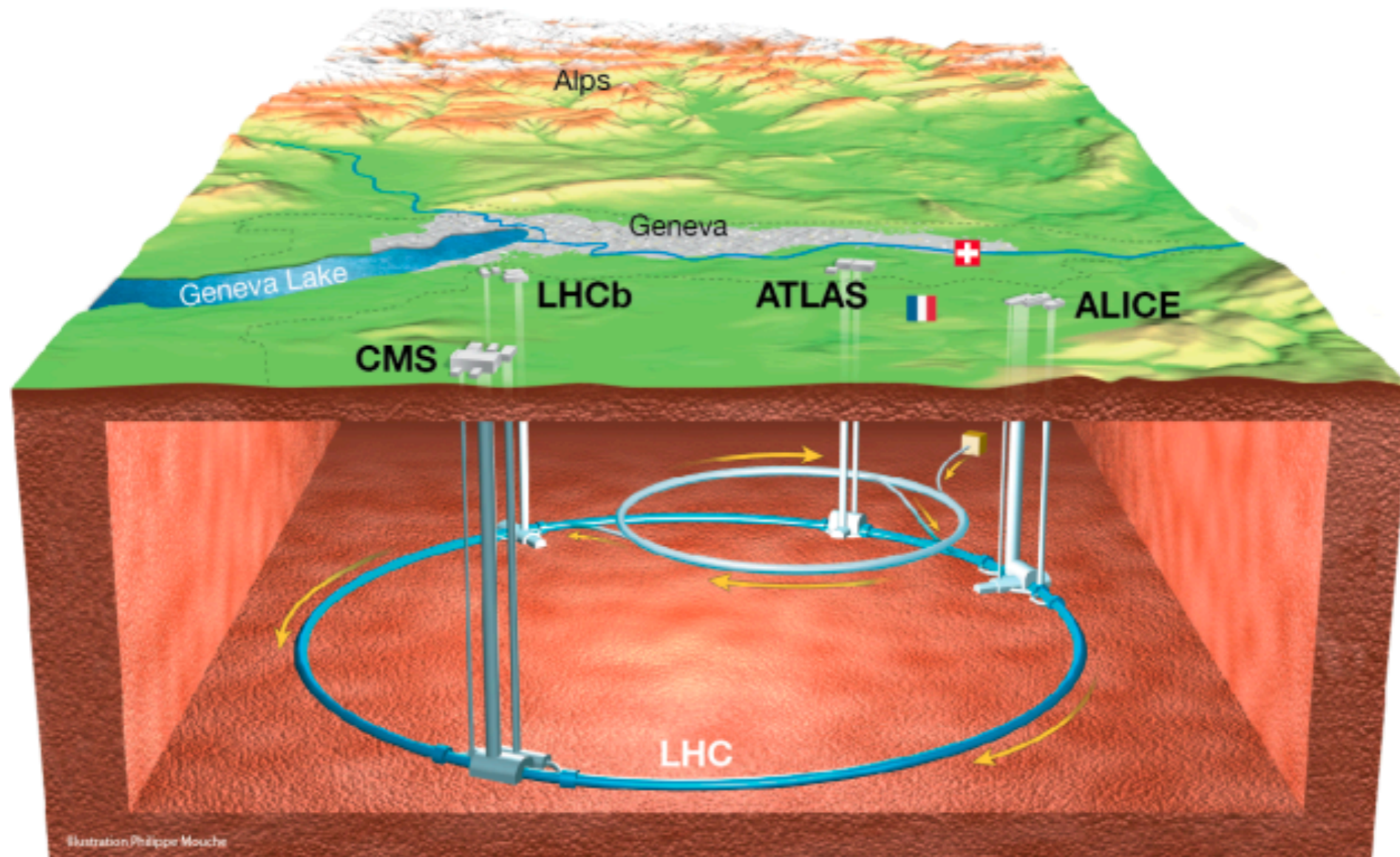


# How CMS weeds out particles that pile up

Anna Benecke  
UCLouvain



# Experimental setup: LHC

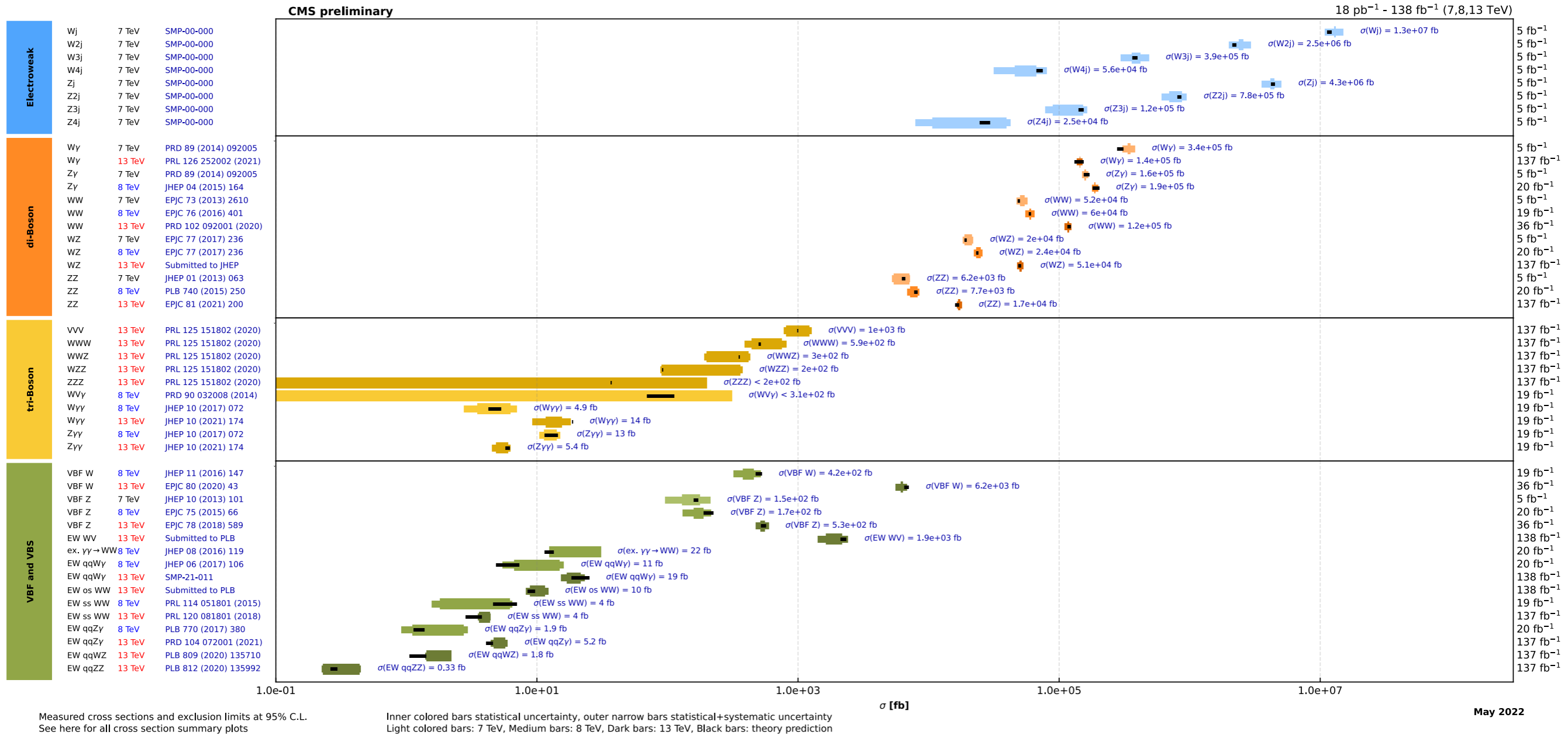


Source: CERN

# Physics program

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

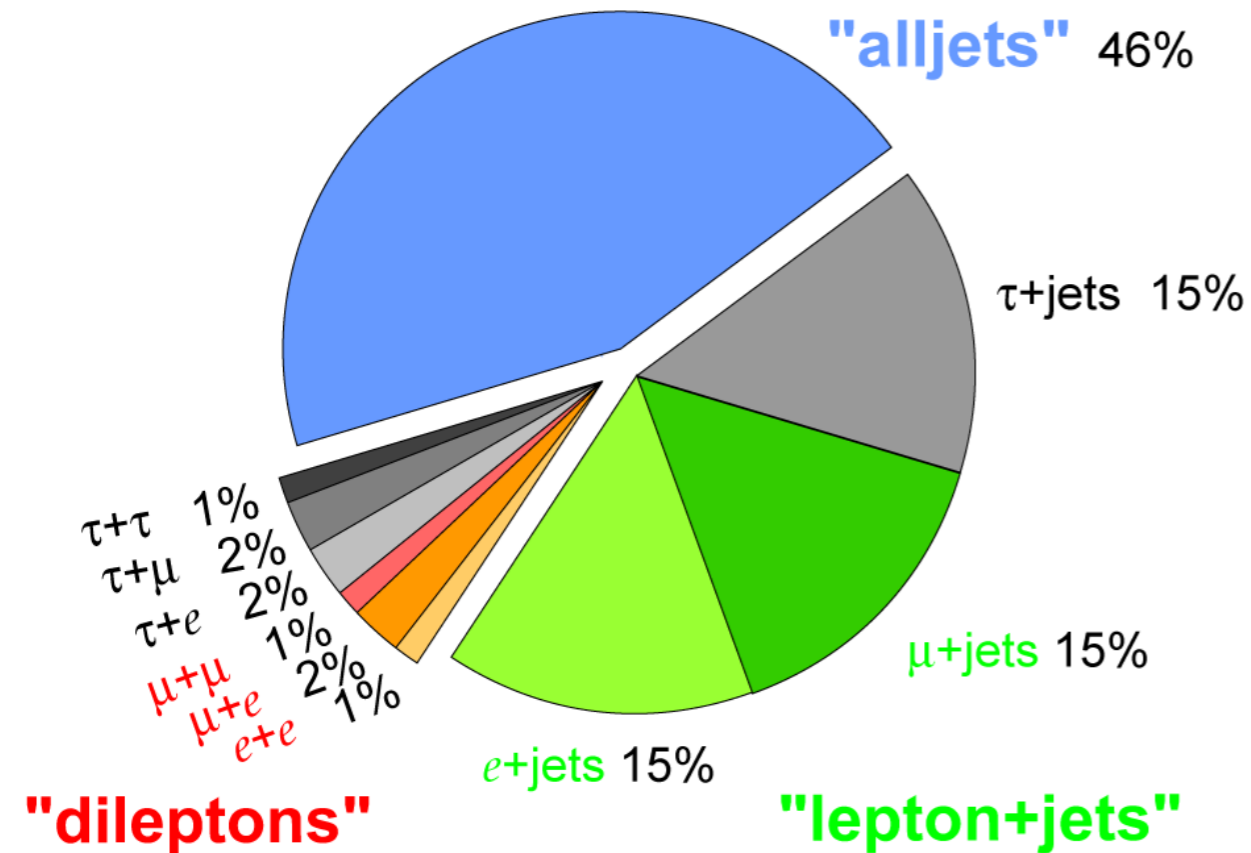
## Overview of CMS cross section results



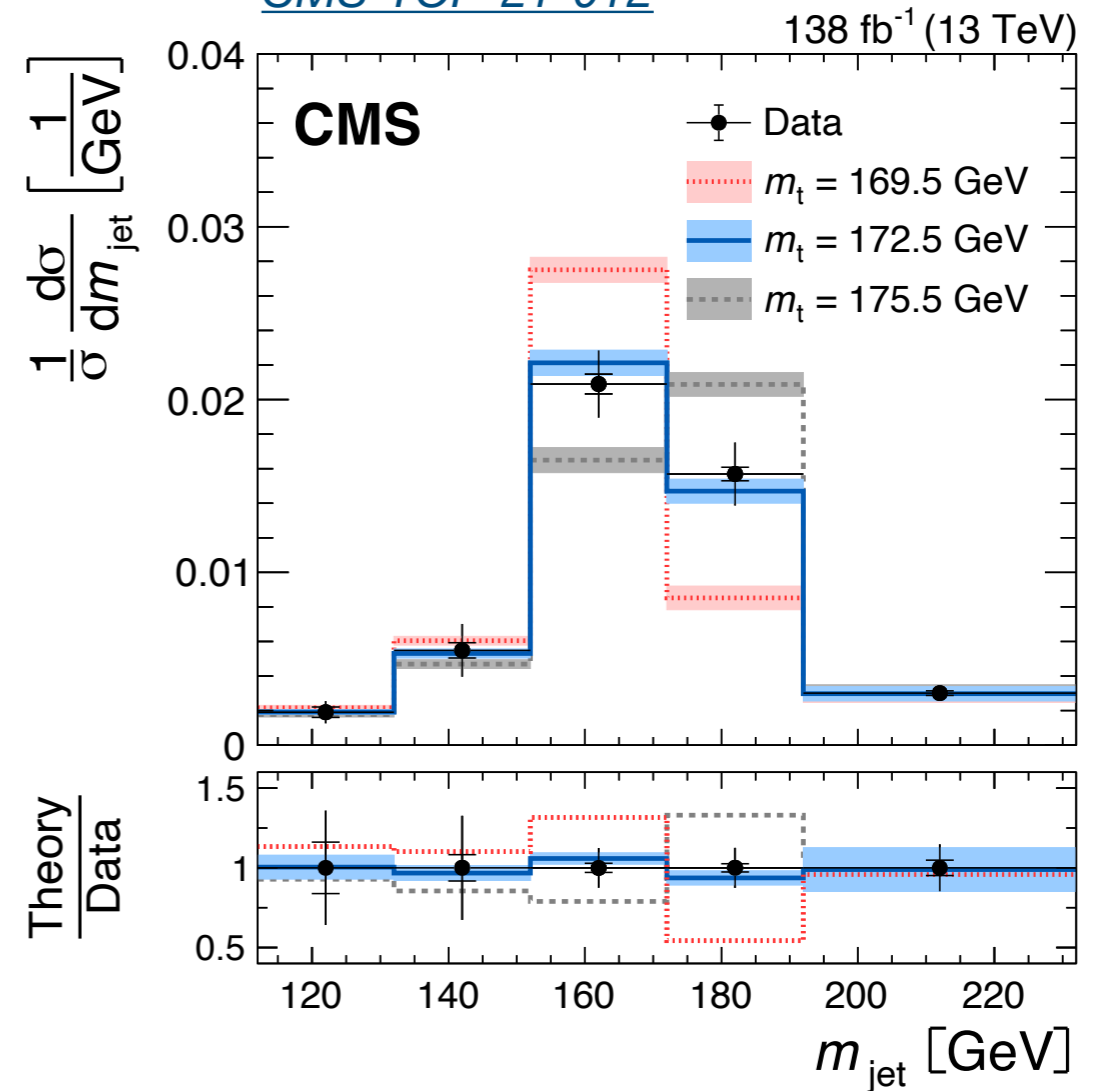
*CMS cross section results*

# Era of precision physics

Reference

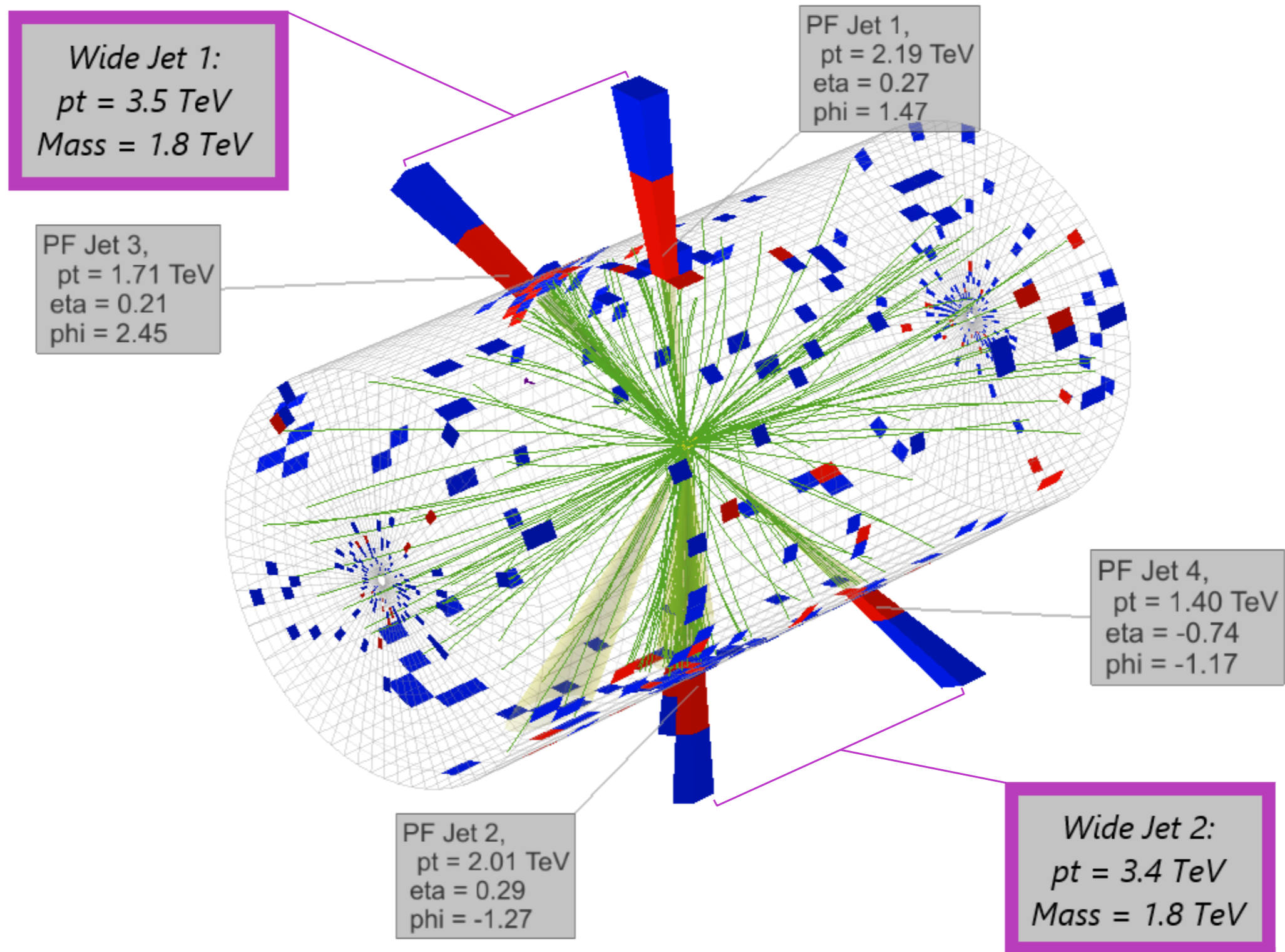


CMS-TOP-21-012



- 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

## CMS DETECTOR

Total weight : 14,000 tonnes  
 Overall diameter : 15.0 m  
 Overall length : 28.7 m  
 Magnetic field : 3.8 T

STEEL RETURN YOKE  
 12,500 tonnes

SILICON TRACKERS  
 Pixel (100x150  $\mu\text{m}$ )  $\sim 16\text{m}^2 \sim 66\text{M}$  channels  
 Microstrips (80x180  $\mu\text{m}$ )  $\sim 200\text{m}^2 \sim 9.6\text{M}$  channels

SUPERCONDUCTING SOLENOID  
 Niobium titanium coil carrying  $\sim 18,000\text{A}$

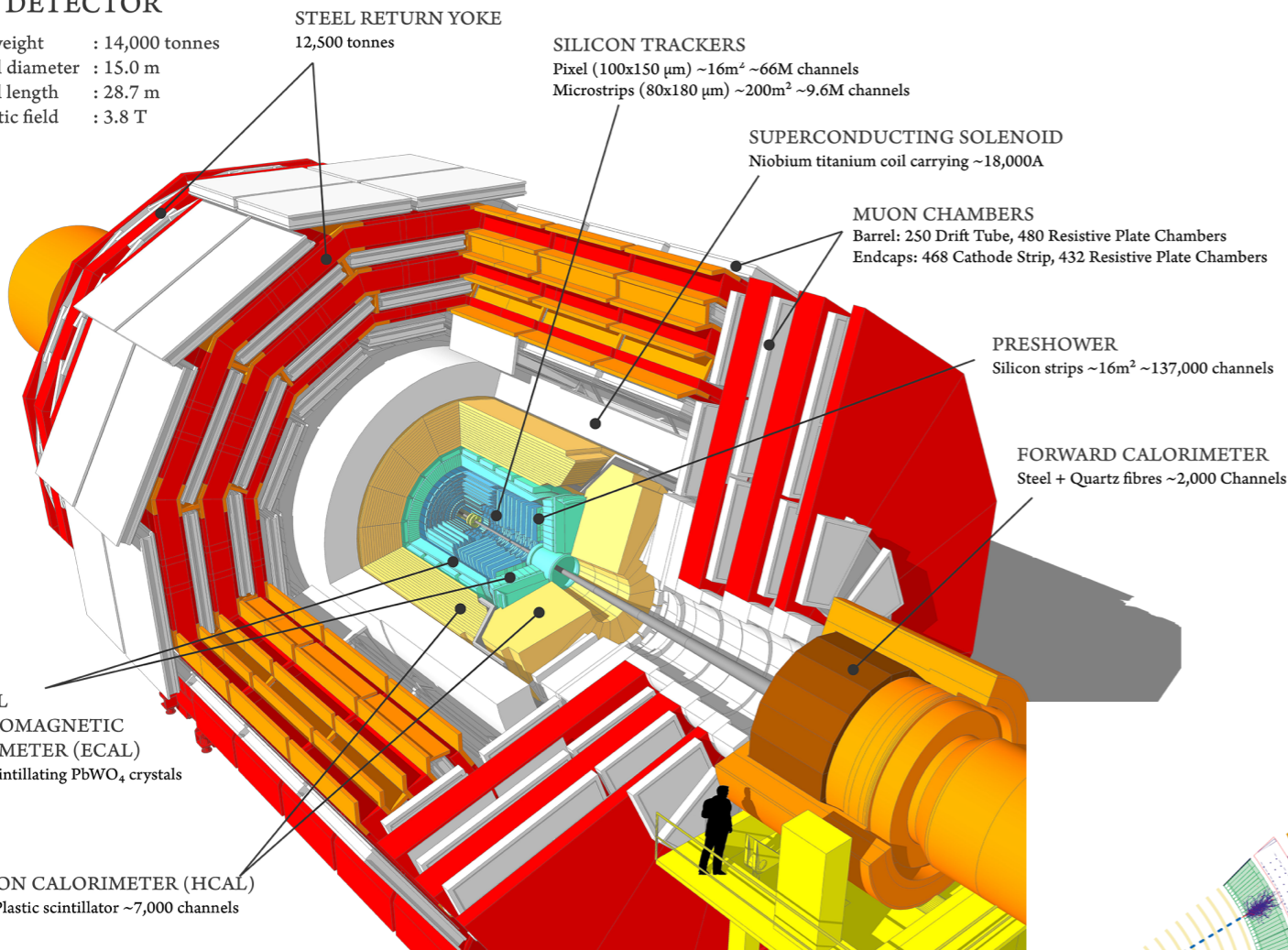
MUON CHAMBERS  
 Barrel: 250 Drift Tube, 480 Resistive Plate Chambers  
 Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers

PRESHOWER  
 Silicon strips  $\sim 16\text{m}^2 \sim 137,000$  channels

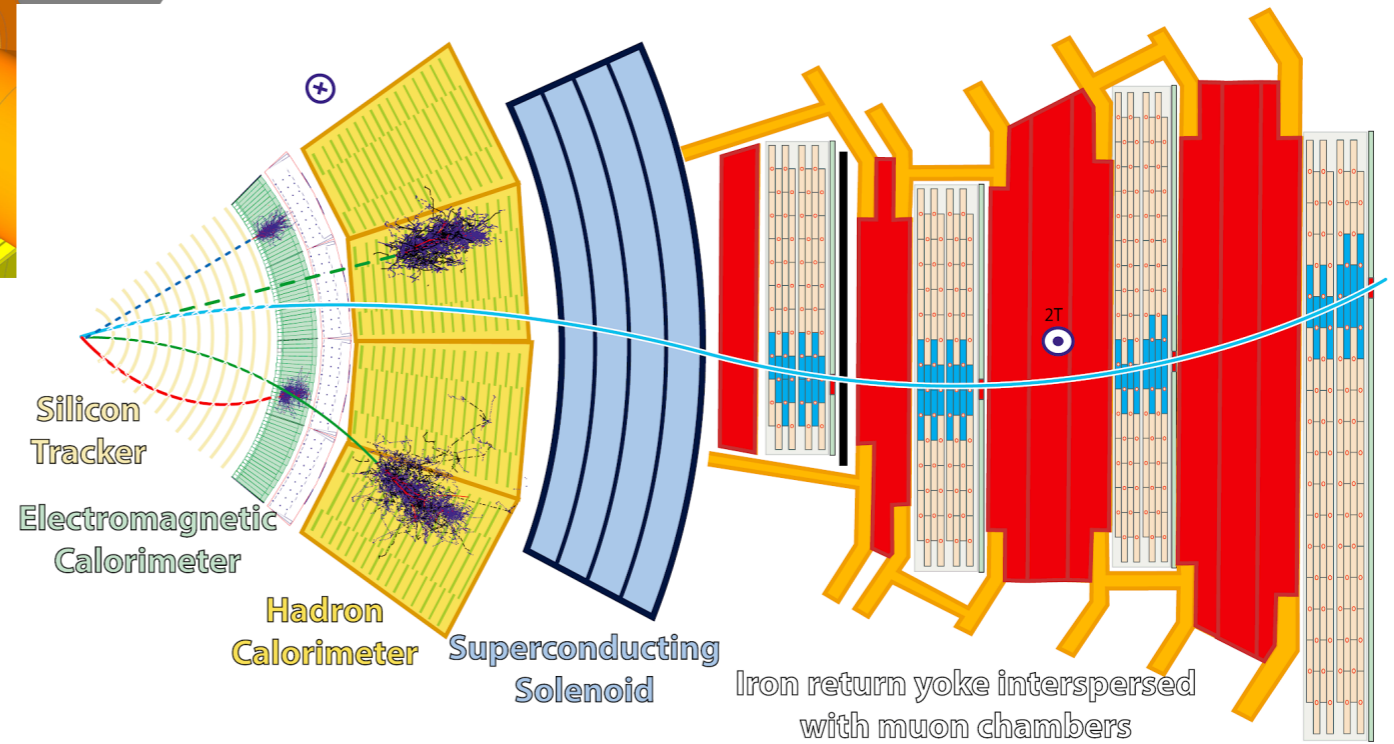
FORWARD CALORIMETER  
 Steel + Quartz fibres  $\sim 2,000$  Channels

CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)  
 $\sim 76,000$  scintillating  $\text{PbWO}_4$  crystals

HADRON CALORIMETER (HCAL)  
 Brass + Plastic scintillator  $\sim 7,000$  channels



Source: CMS

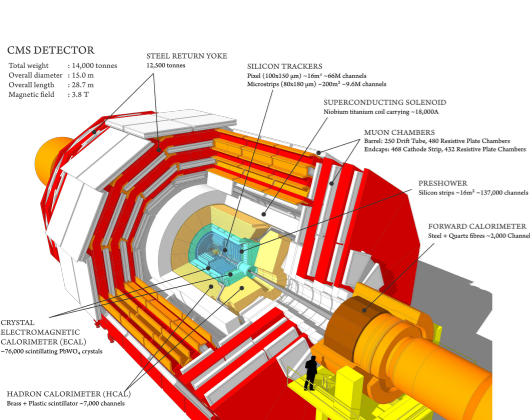


— Muon      — Electron      — Charged hadron (e.g. pion)  
 - - - Neutral hadron (e.g. neutron)      - - - Photon

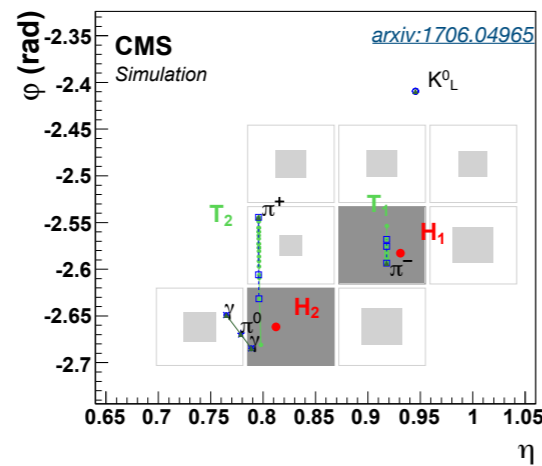
# From detector signals to jet calibration

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

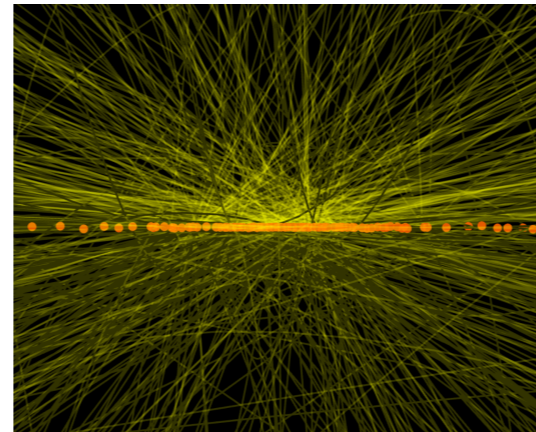
## Detector



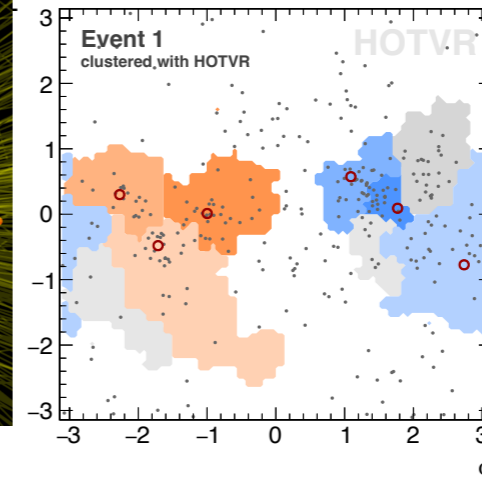
## Reconstruction



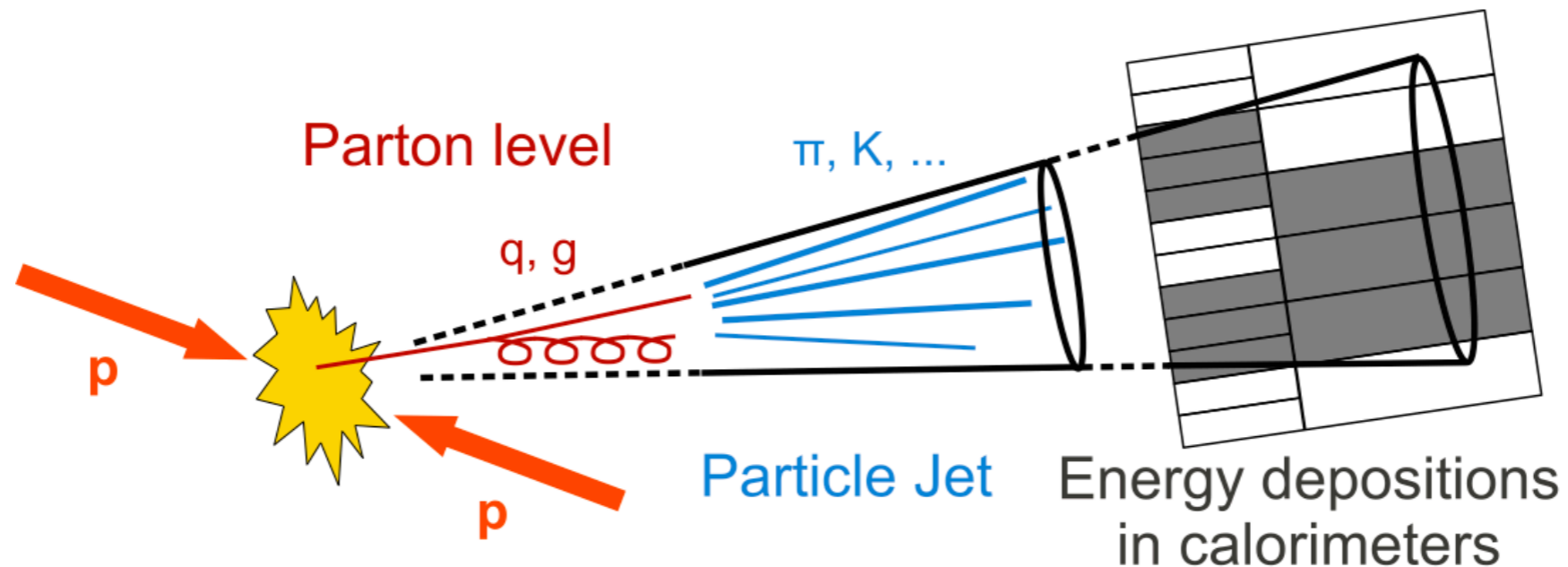
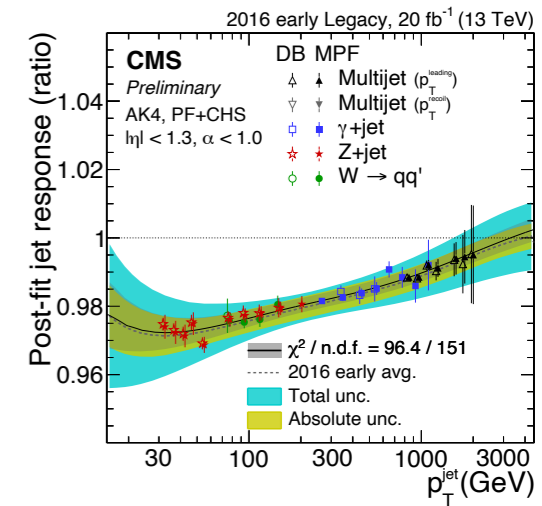
## Pileup



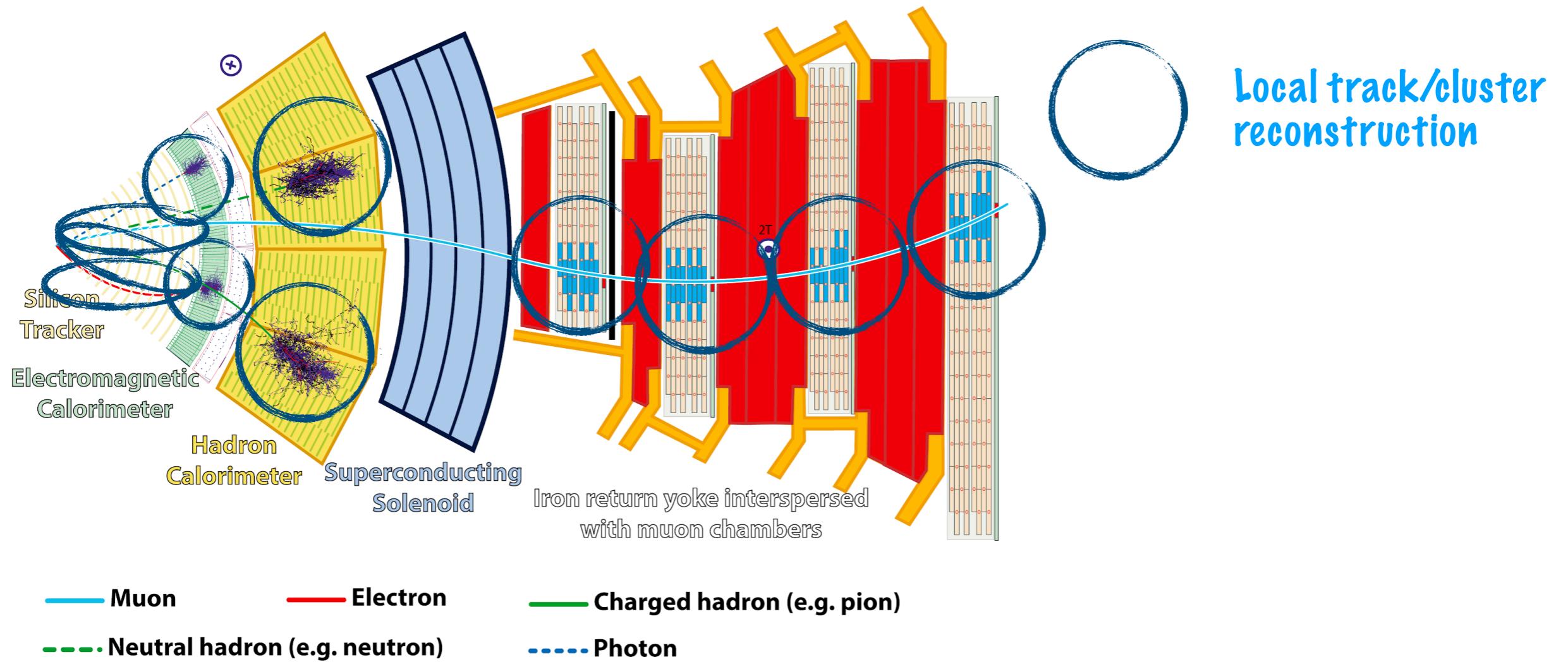
## Clustering



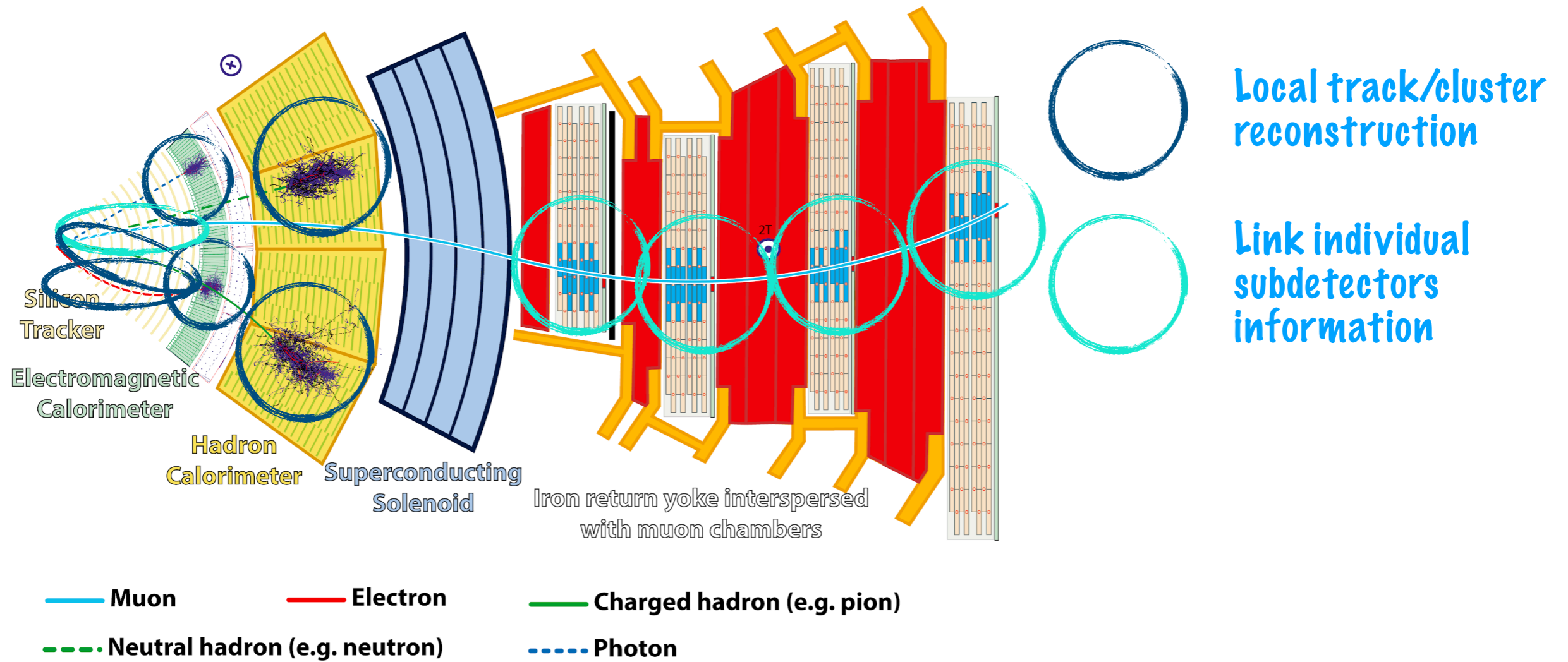
## Calibration



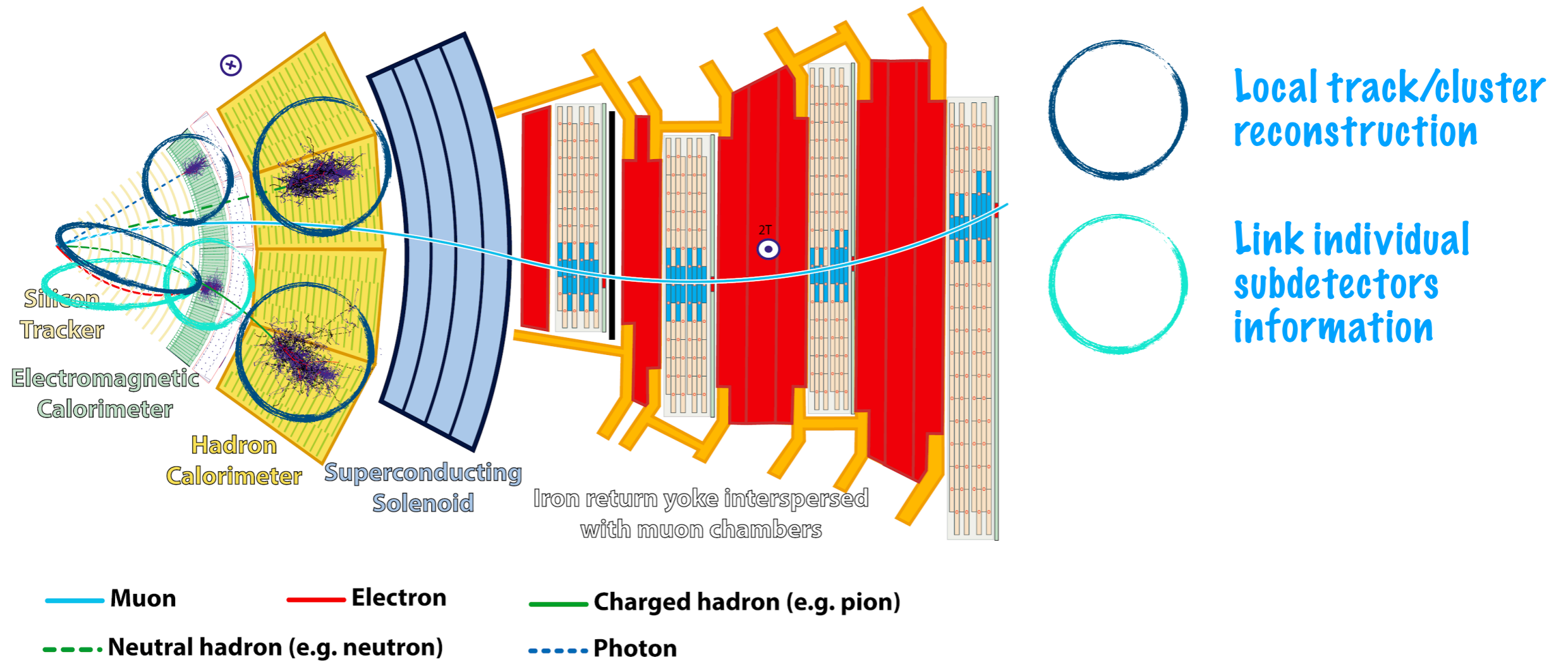
# Experimental setup: CMS



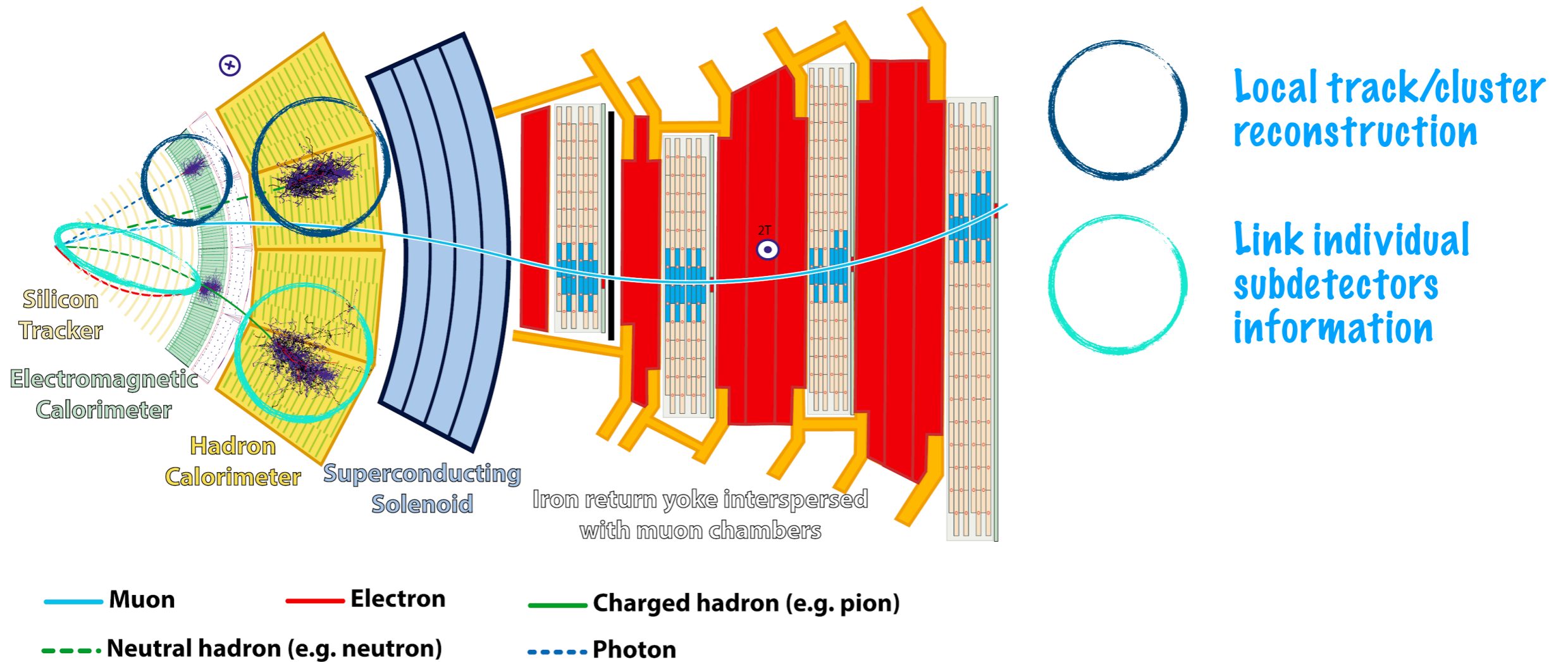
# Experimental setup: CMS



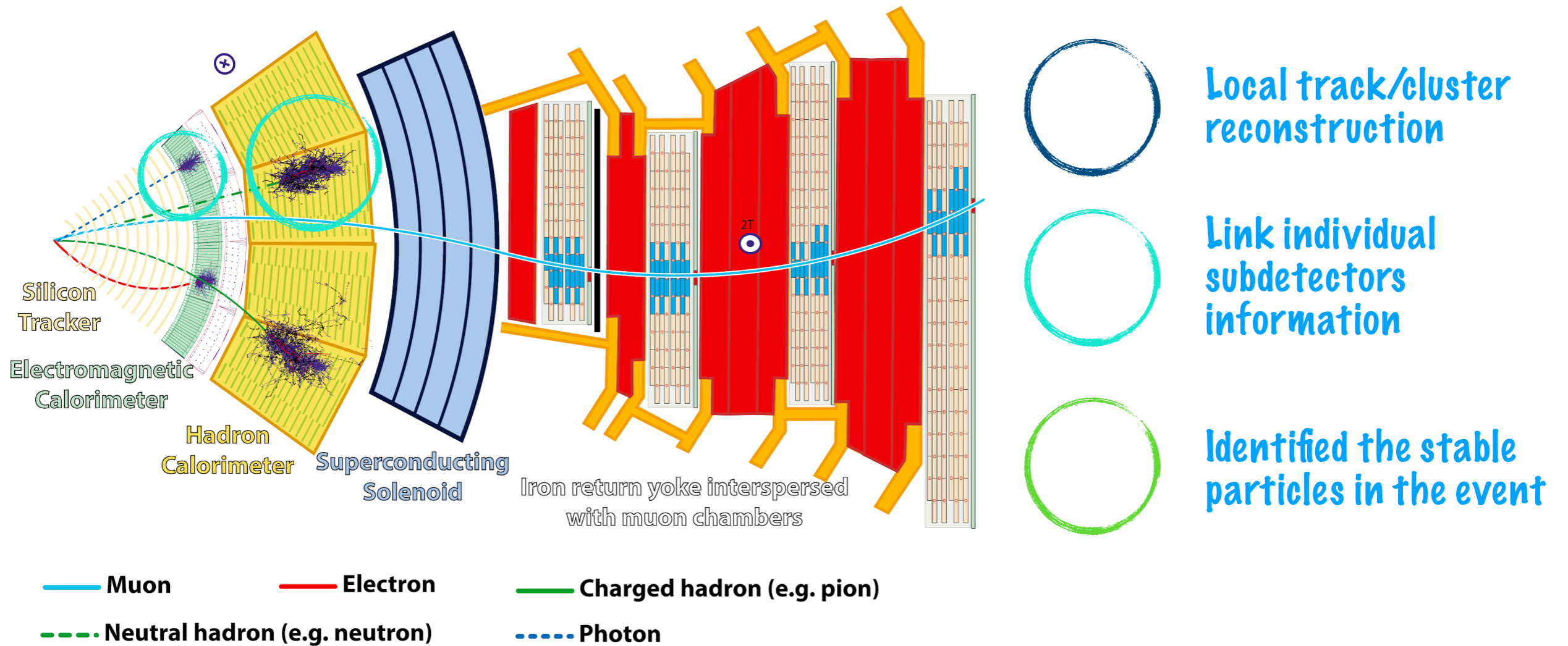
# Experimental setup: CMS



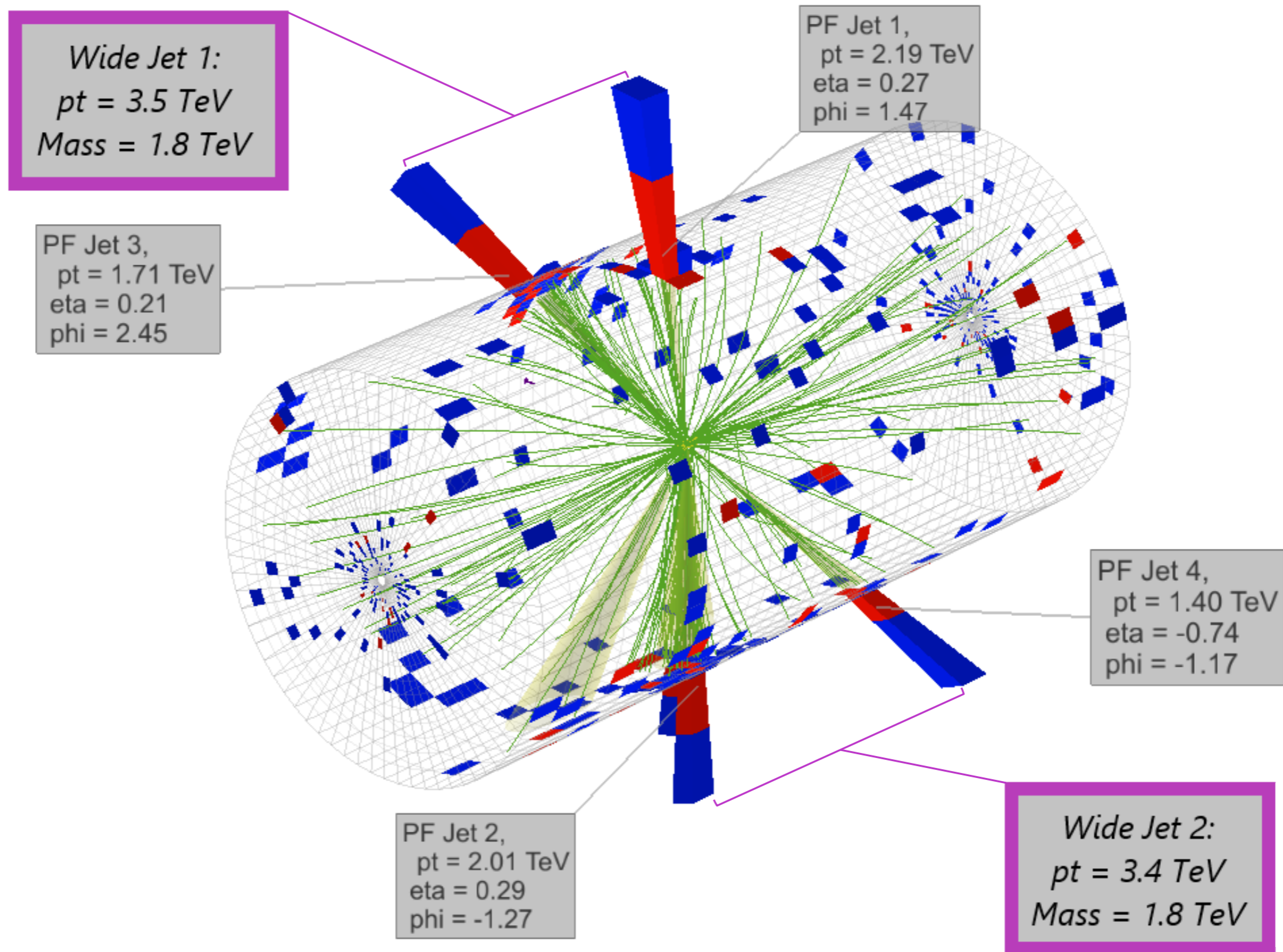
# Experimental setup: CMS



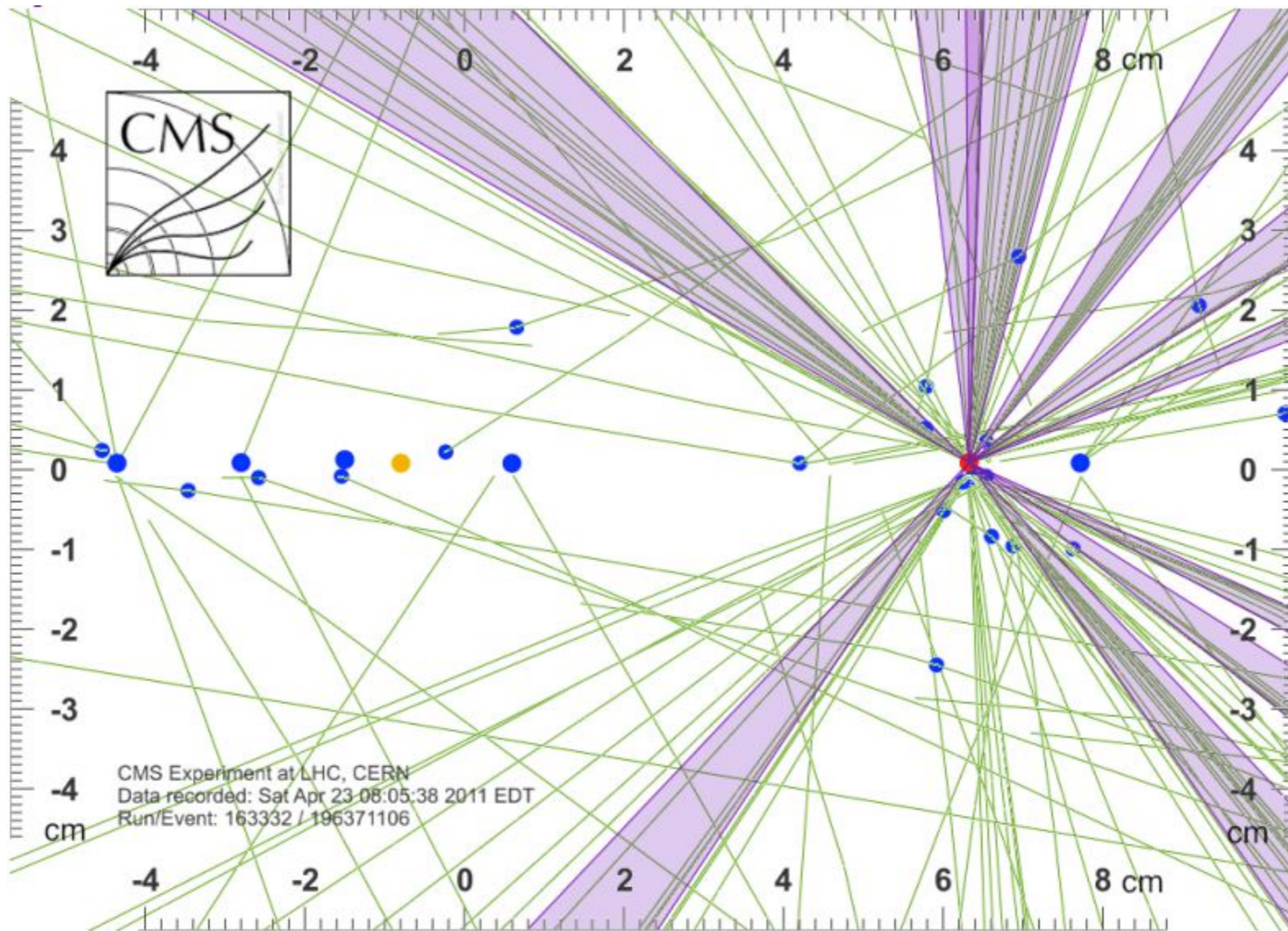
# Experimental setup: CMS



# Event display



# Proton-Proton collisions @ LHC



# Proton-Proton collisions @ LHC

[CMS-PHO-EVENTS-20216-008](#)



CMS Experiment at the LHC, CERN

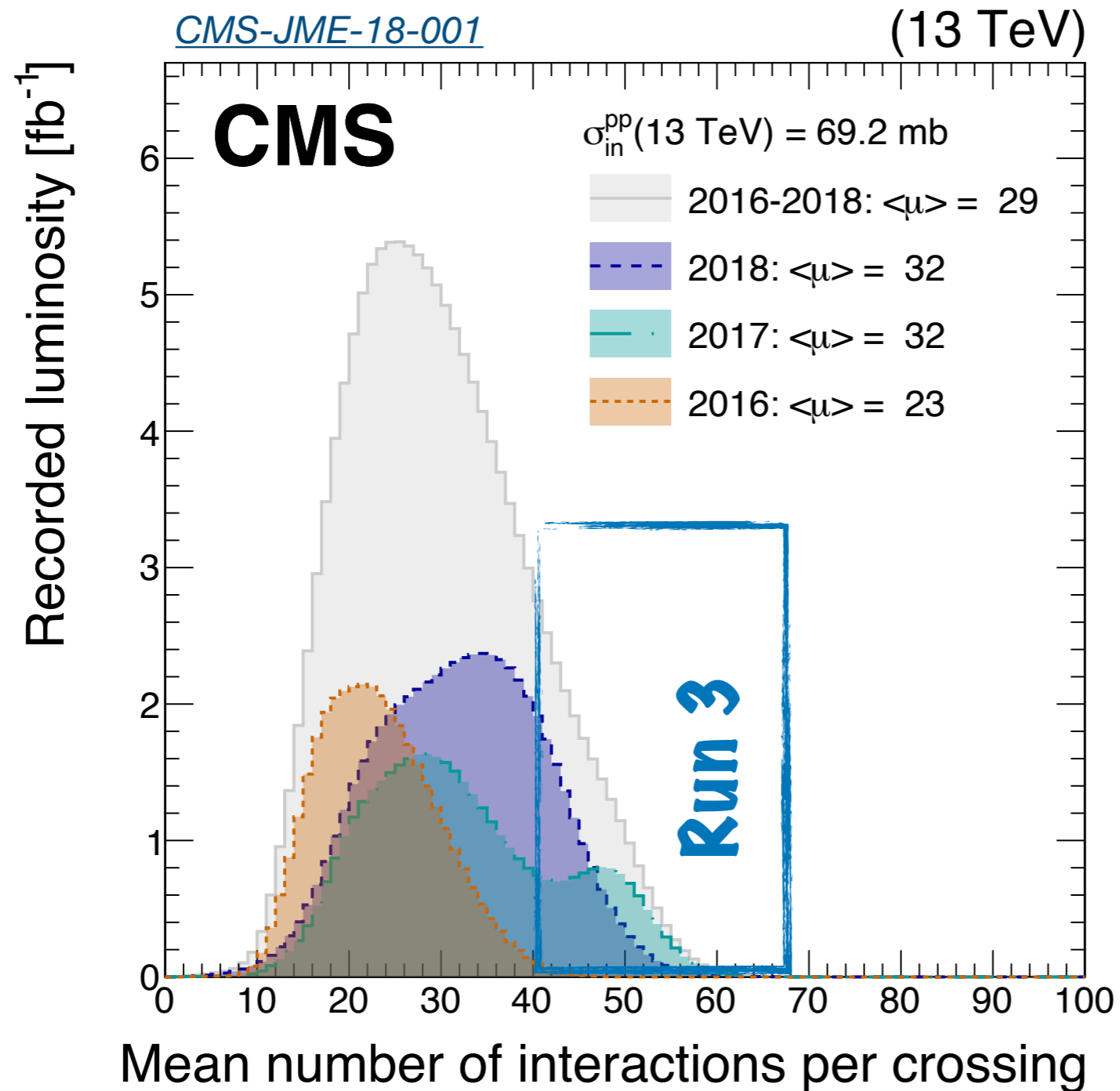
Data recorded: 2016-Sep-08 08:30:28.497920 GMT

Run / Event / LS: 280327 / 55711771 / 67

[CMS-PHO-EVENTS-20216-008](#)

**Pileup adds additional energy to the whole detector**

# More data, more pileup



**Run 4**  
140-200

# 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

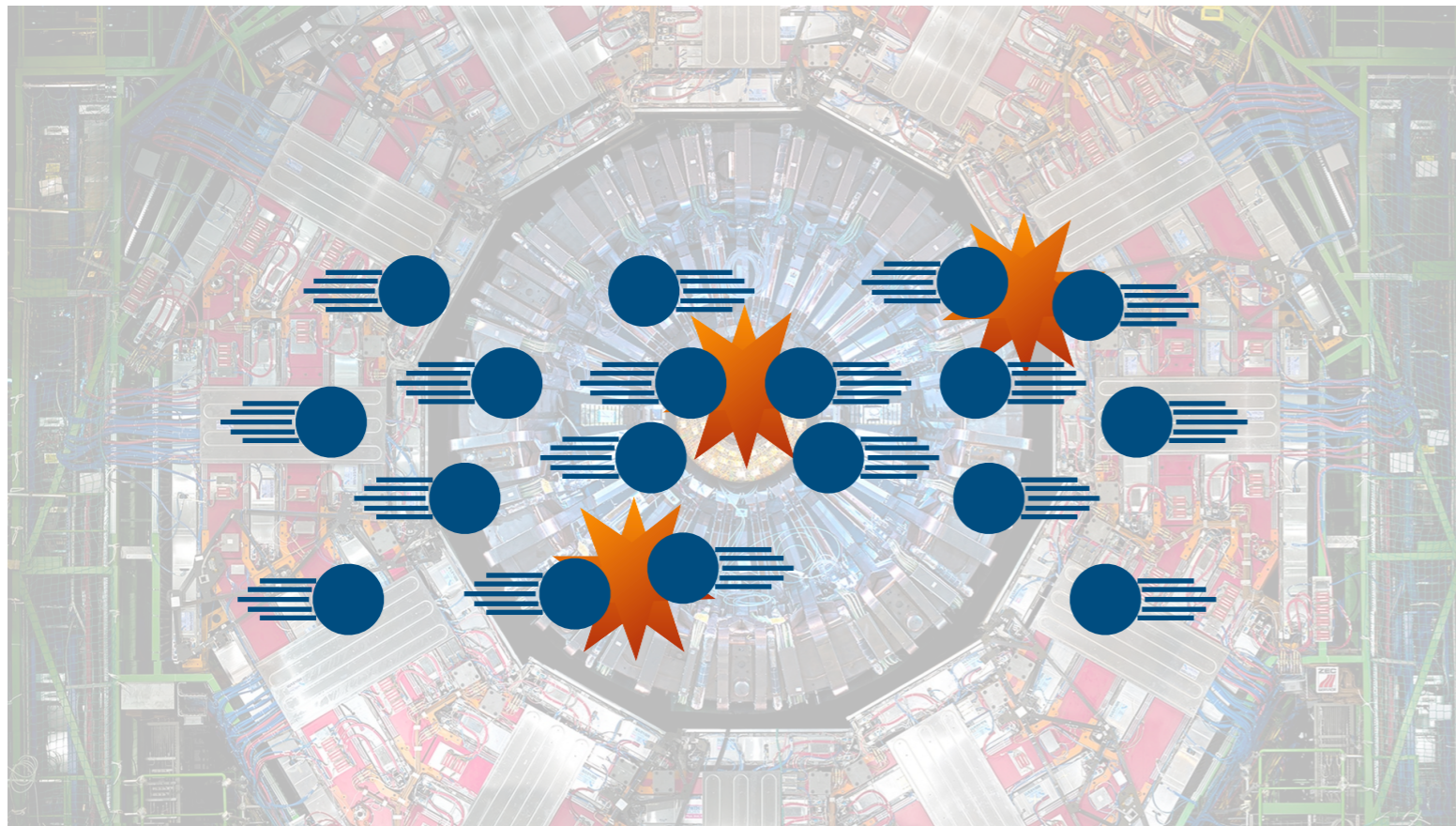
# More data, more pileup

$$N_{\text{Events}} = \sigma \int L dt \quad L = \frac{f N_1 N_2}{4\pi \sigma_x \sigma_y}$$

frequency  
40 MHz

Number of protons

Size of the beam



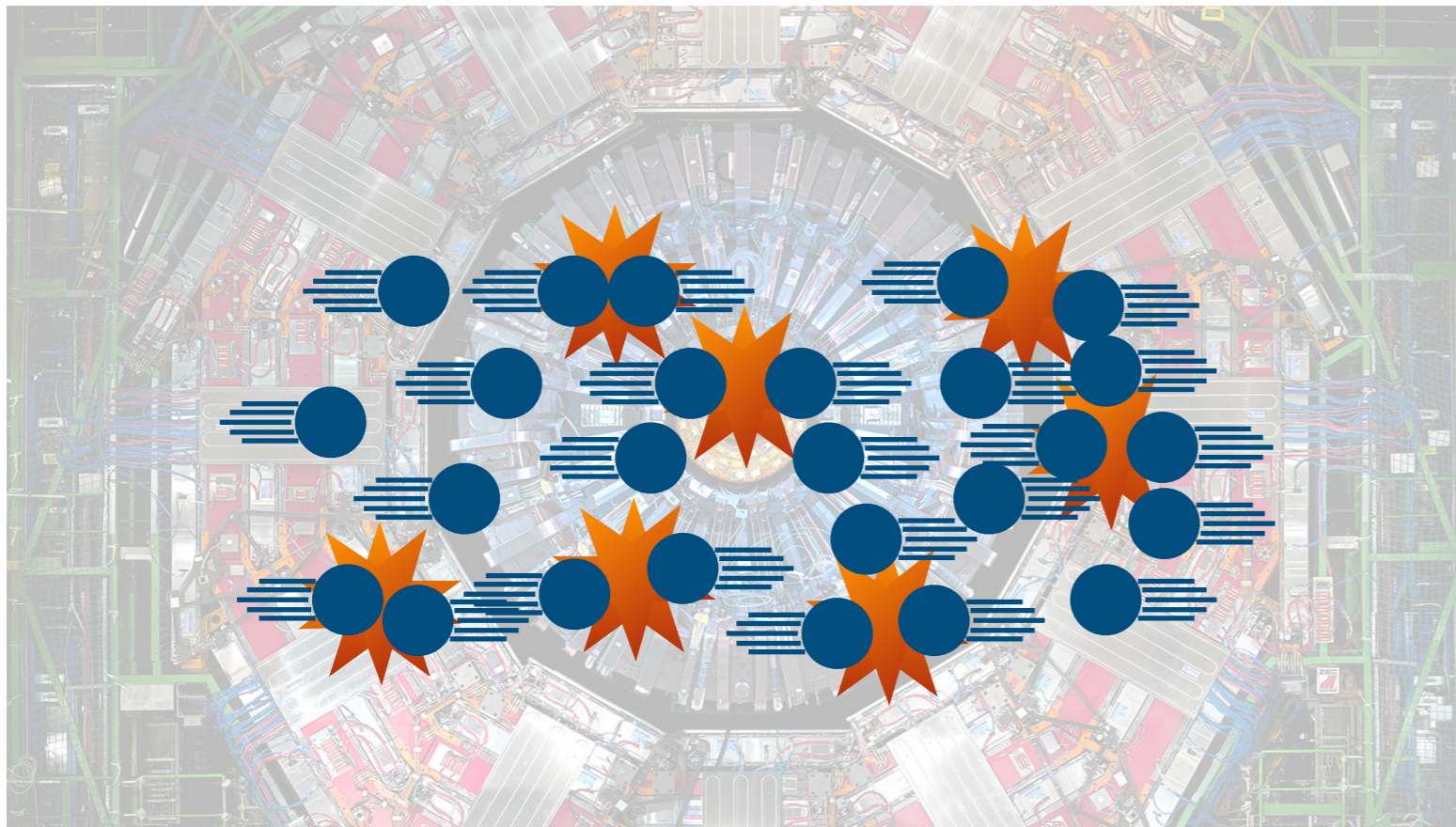
# More data, more pileup

$$N_{\text{Events}} = \sigma \int L dt \quad L = \frac{f N_1 N_2}{4\pi\sigma_x\sigma_y}$$

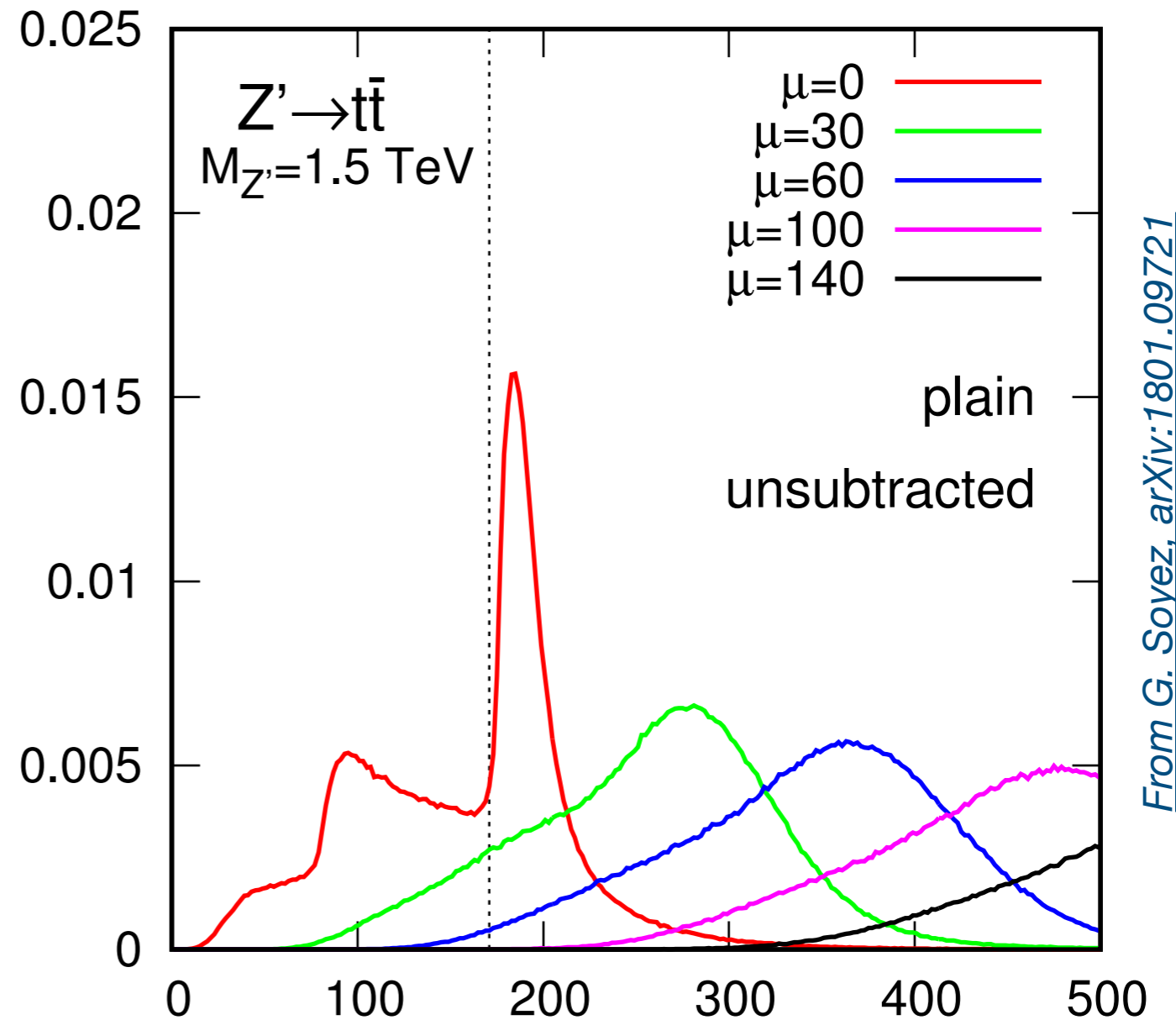
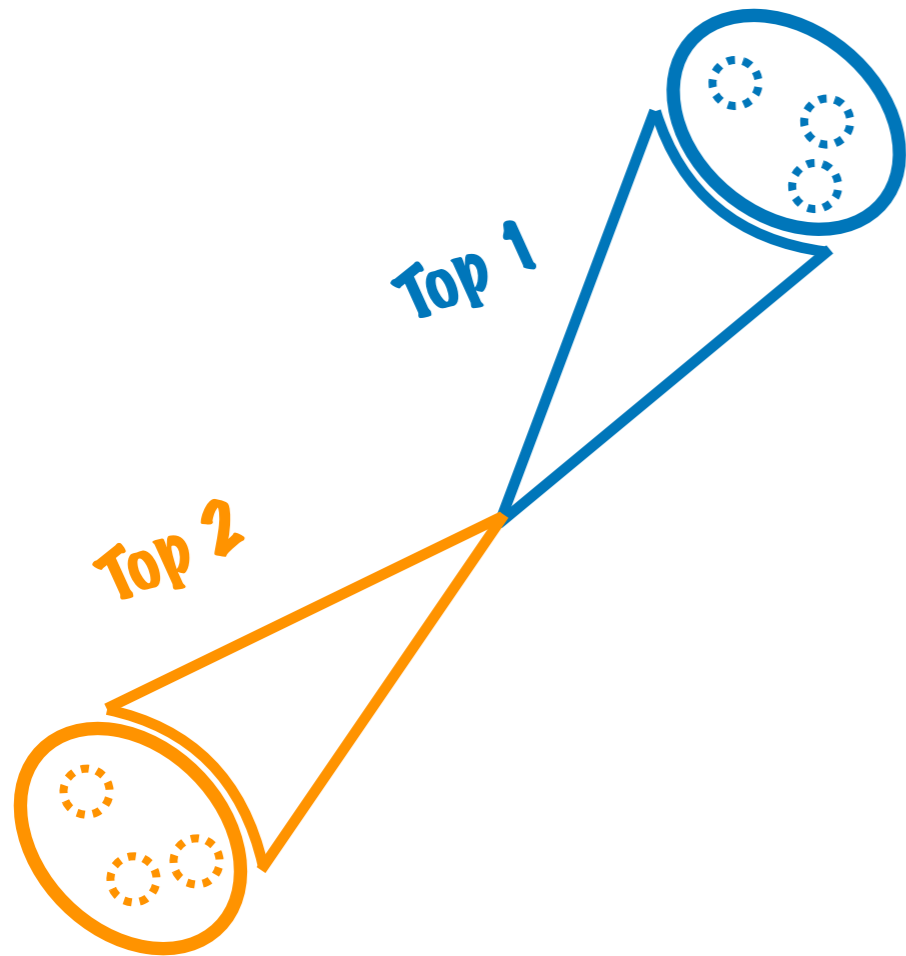
frequency  
40 MHz

Number of protons

Size of the beam



# Challenges with pileup



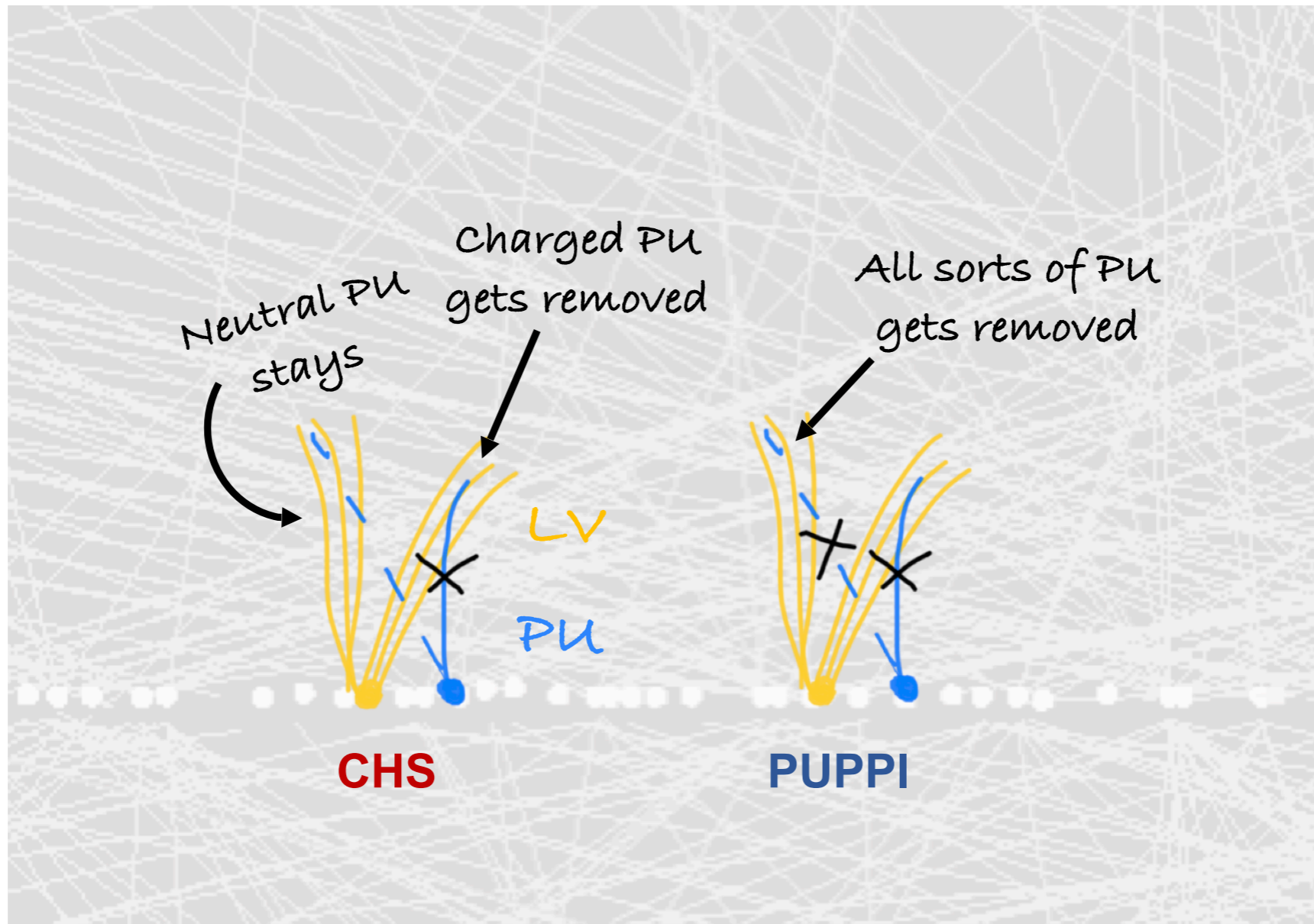
From G. Soyez, arXiv:1801.09721

(a) raw, ungroomed jets

PU affects jet substructure, jet counting, lepton isolation...

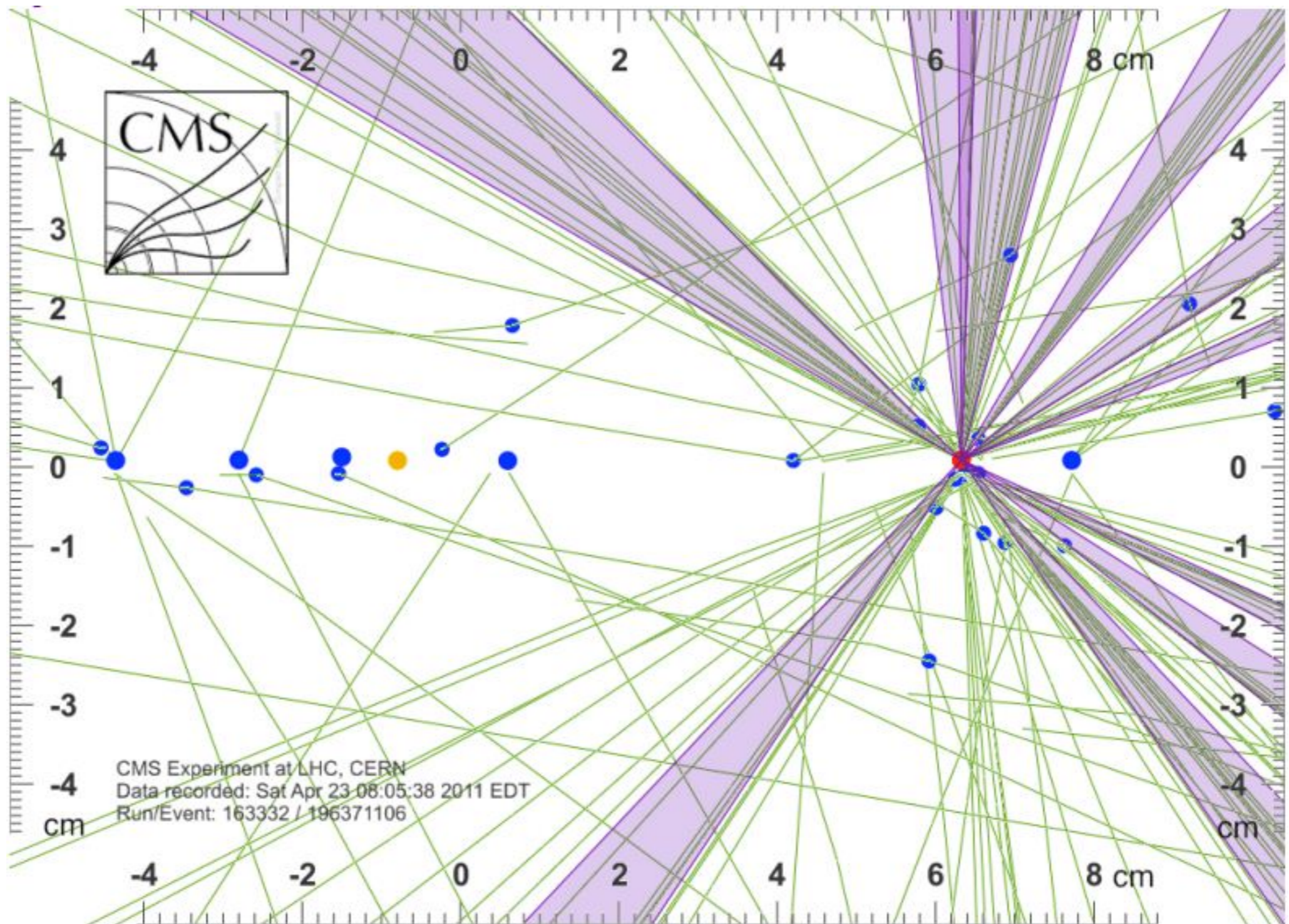
# Pileup mitigation in CMS

[Click me](#)



# PUPPI in Detail

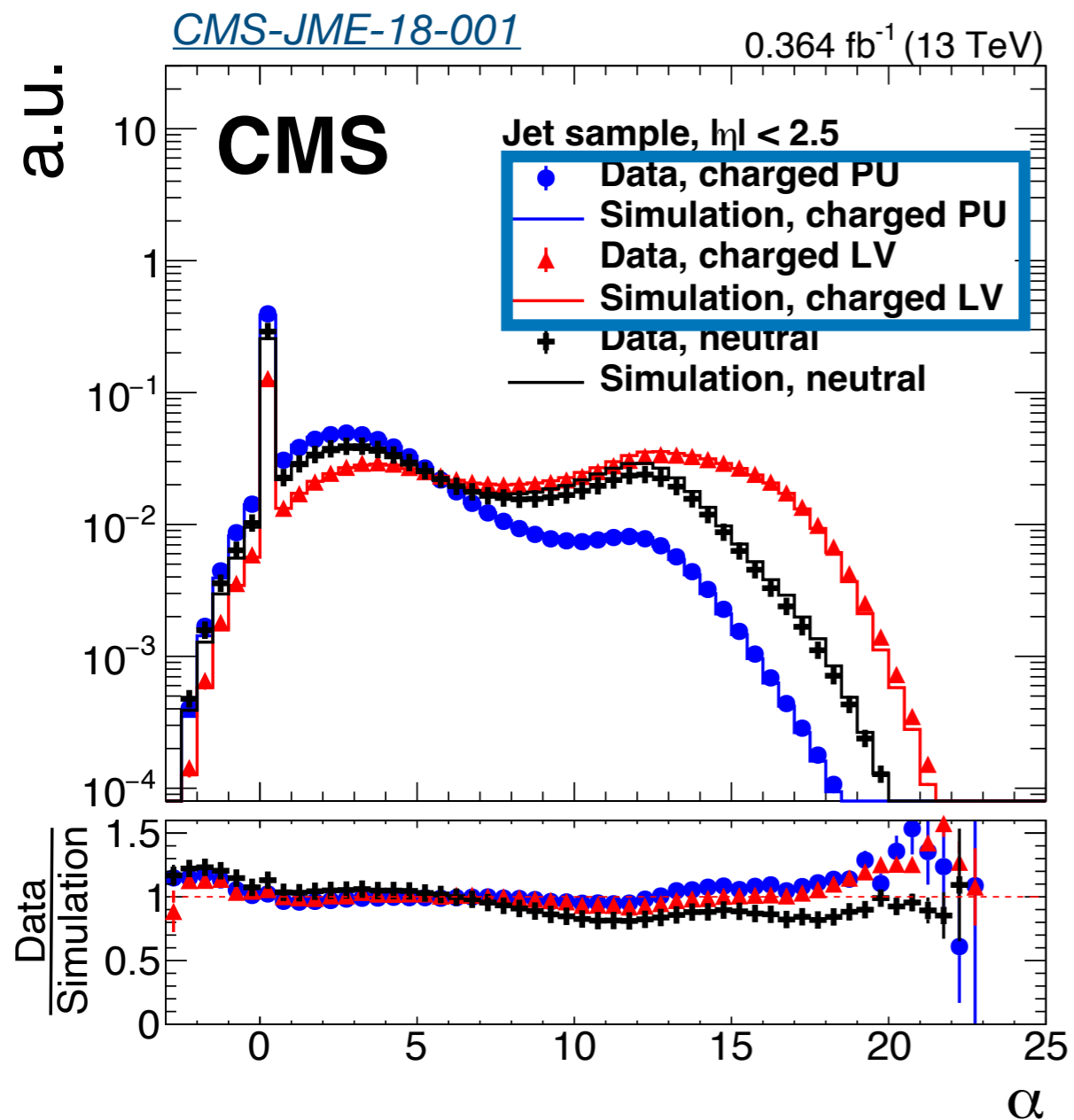




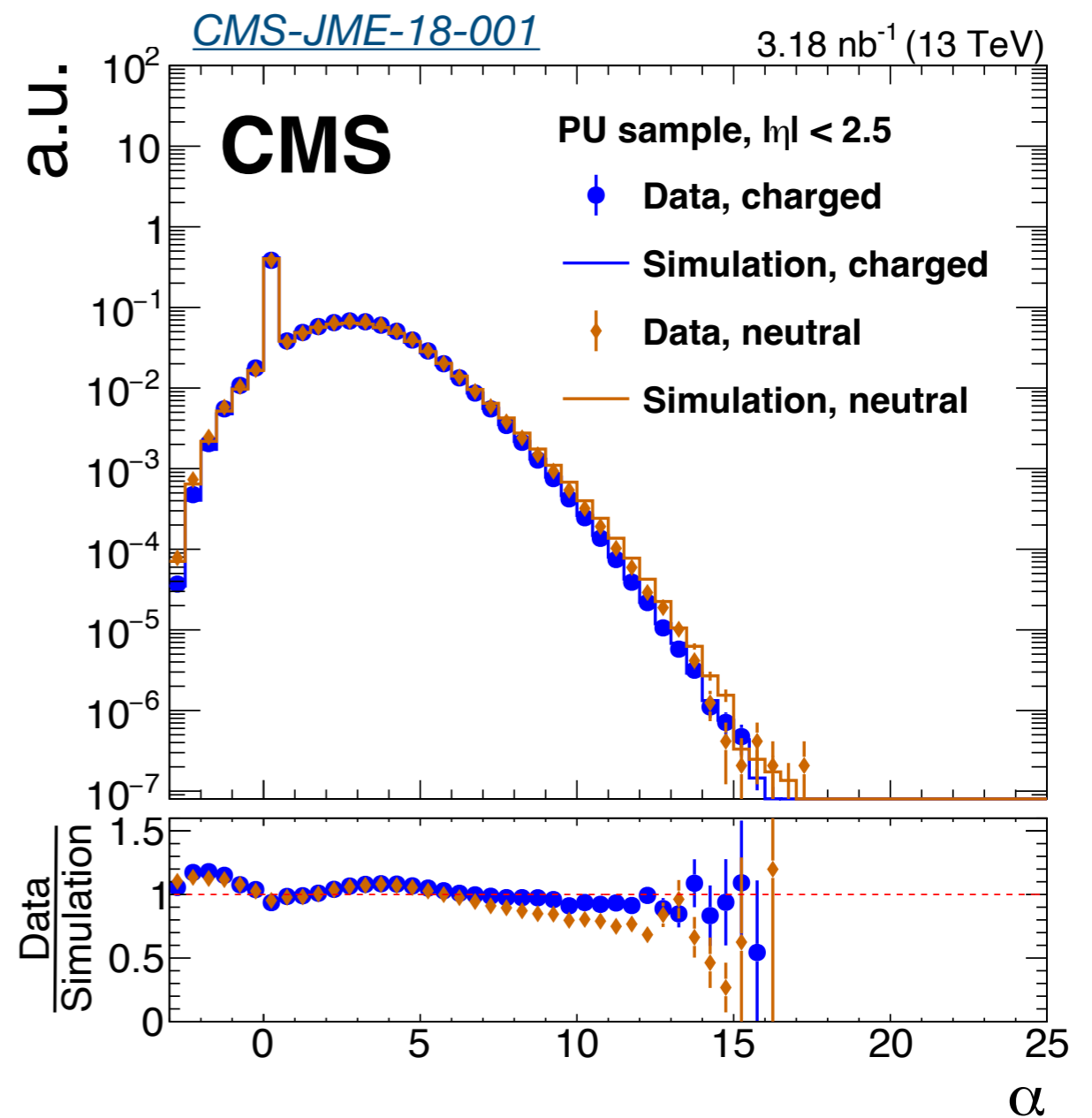
<http://cds.cern.ch/record/1357882>

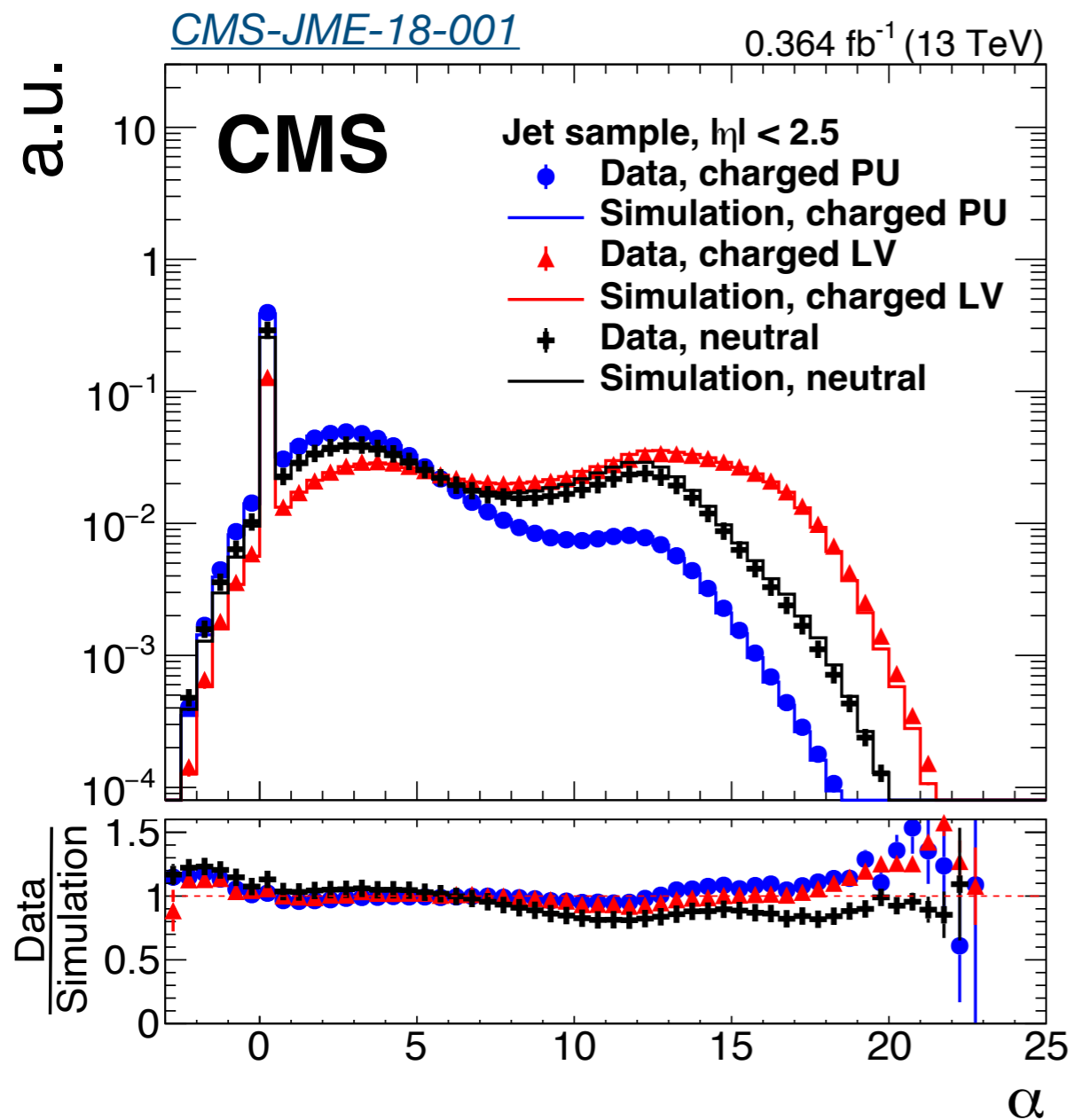


$$\alpha_i = \log \sum_{j \neq i, \Delta R_{ij} < R_0} \left( \frac{p_{Tj}}{\Delta R_{ij}} \right)^2 \begin{cases} \text{for } |\eta_i| < 2.5, & j \text{ are charged particles from leading vertex} \\ \text{for } |\eta_i| > 2.5, & j \text{ are all kinds of reconstructed particles} \end{cases}$$



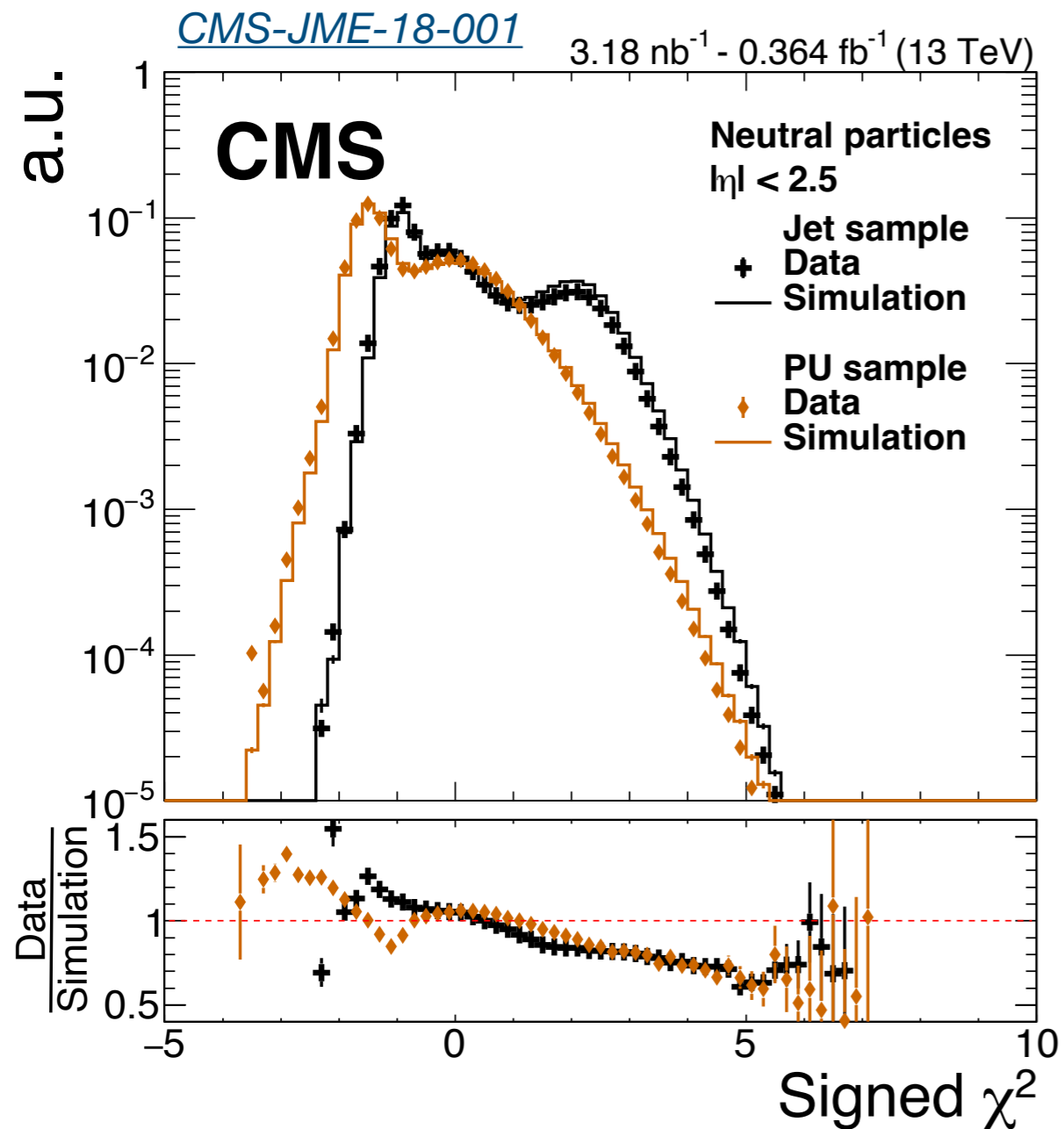
$$\alpha_i = \log \sum_{j \neq i, \Delta R_{ij} < R_0} \left( \frac{p_{Tj}}{\Delta R_{ij}} \right)^2 \begin{cases} \text{for } |\eta_i| < 2.5, & j \text{ are charged particles from leading vertex} \\ \text{for } |\eta_i| > 2.5, & j \text{ are all kinds of reconstructed particles} \end{cases}$$





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

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

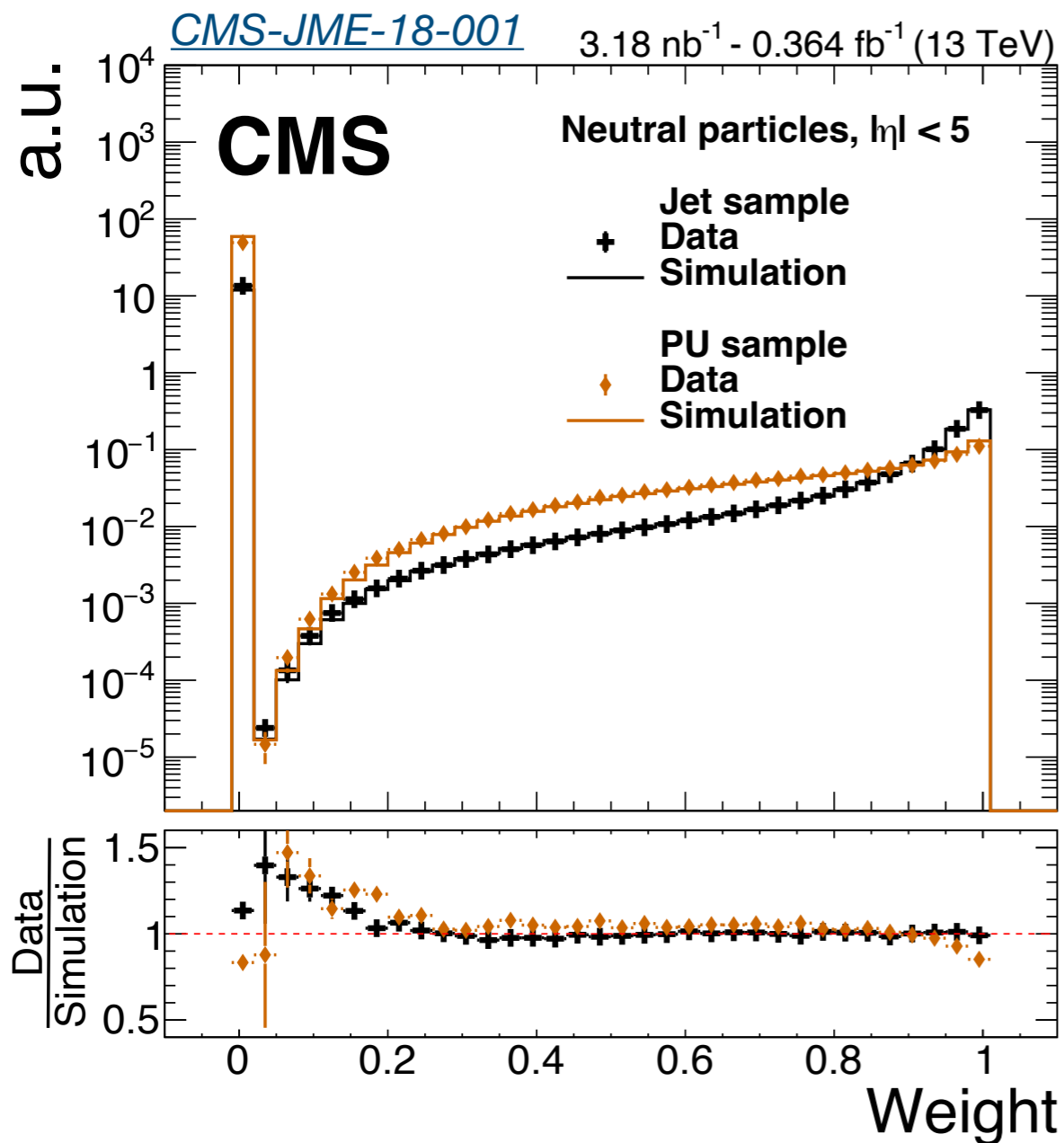


1. Calculate Median and RMS of charged PU shape (blue)

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

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

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

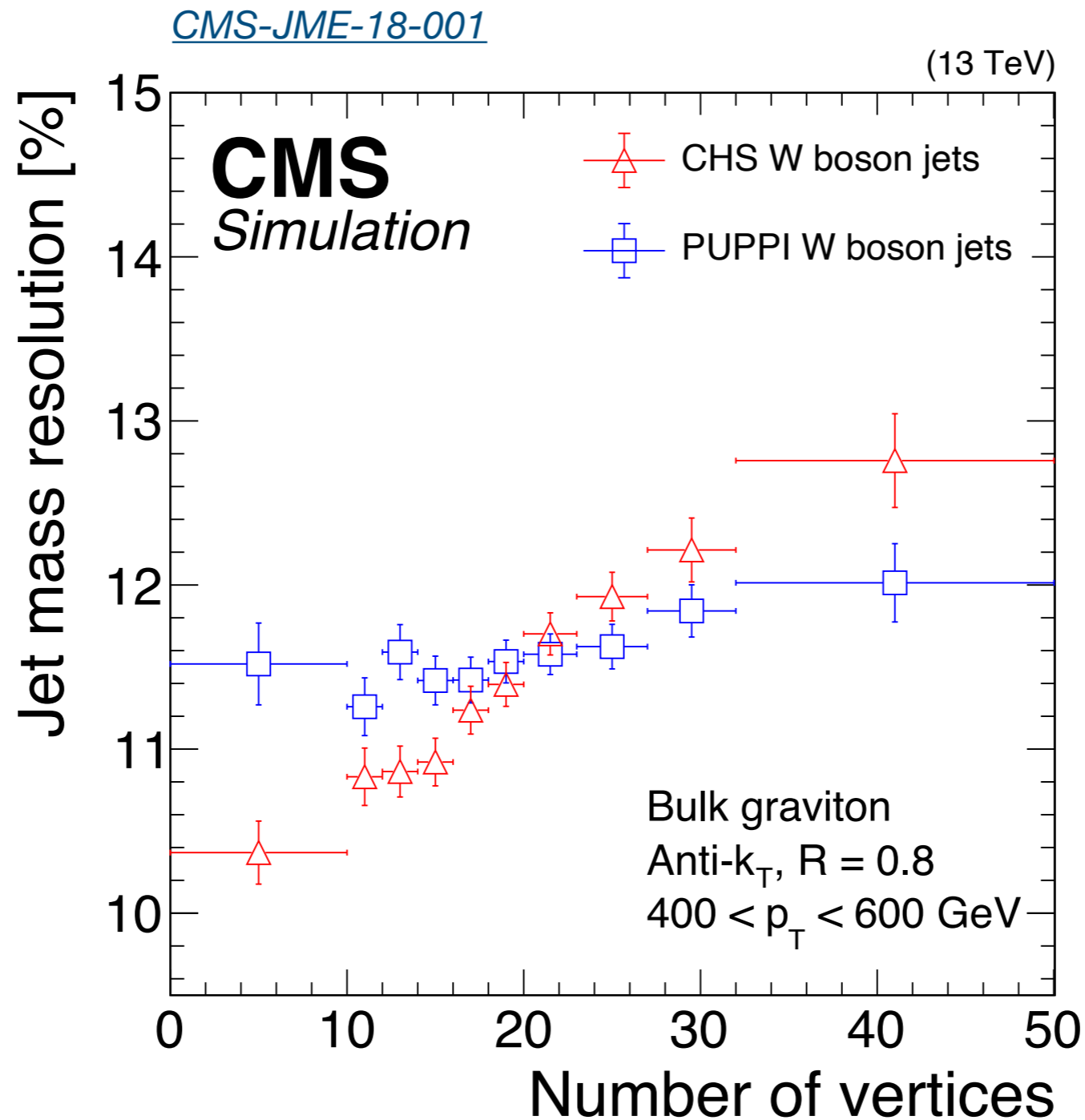
3. Assign a weight to each particle

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

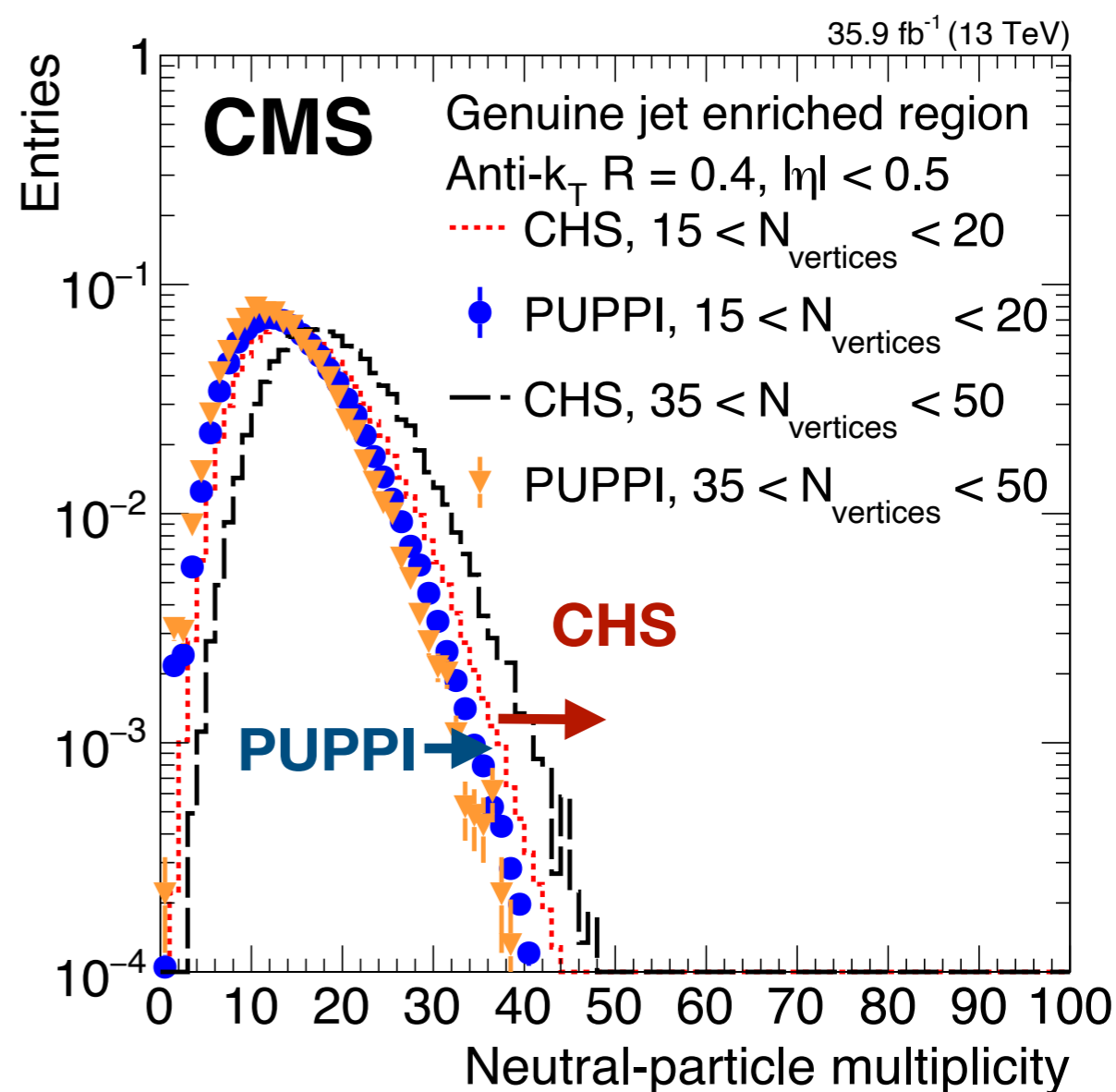
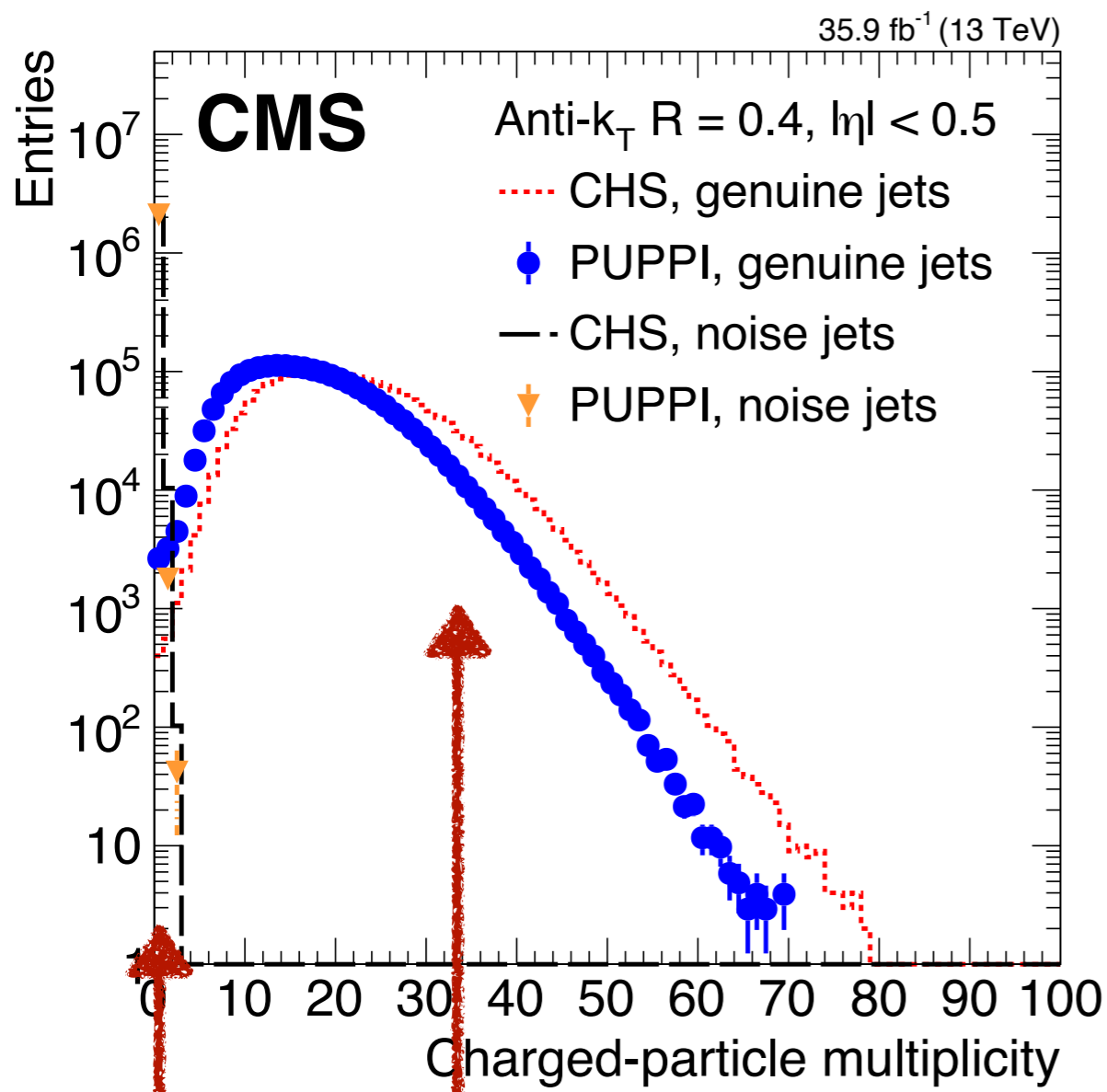
Pileup  $\longrightarrow$  Hard scattering

# Validation of PUPPI

Performances of PUPPI jets/MET were extensively studied and compared to CHS jets/PF MET in [JME-18-001](#)



# Noise Jet ID

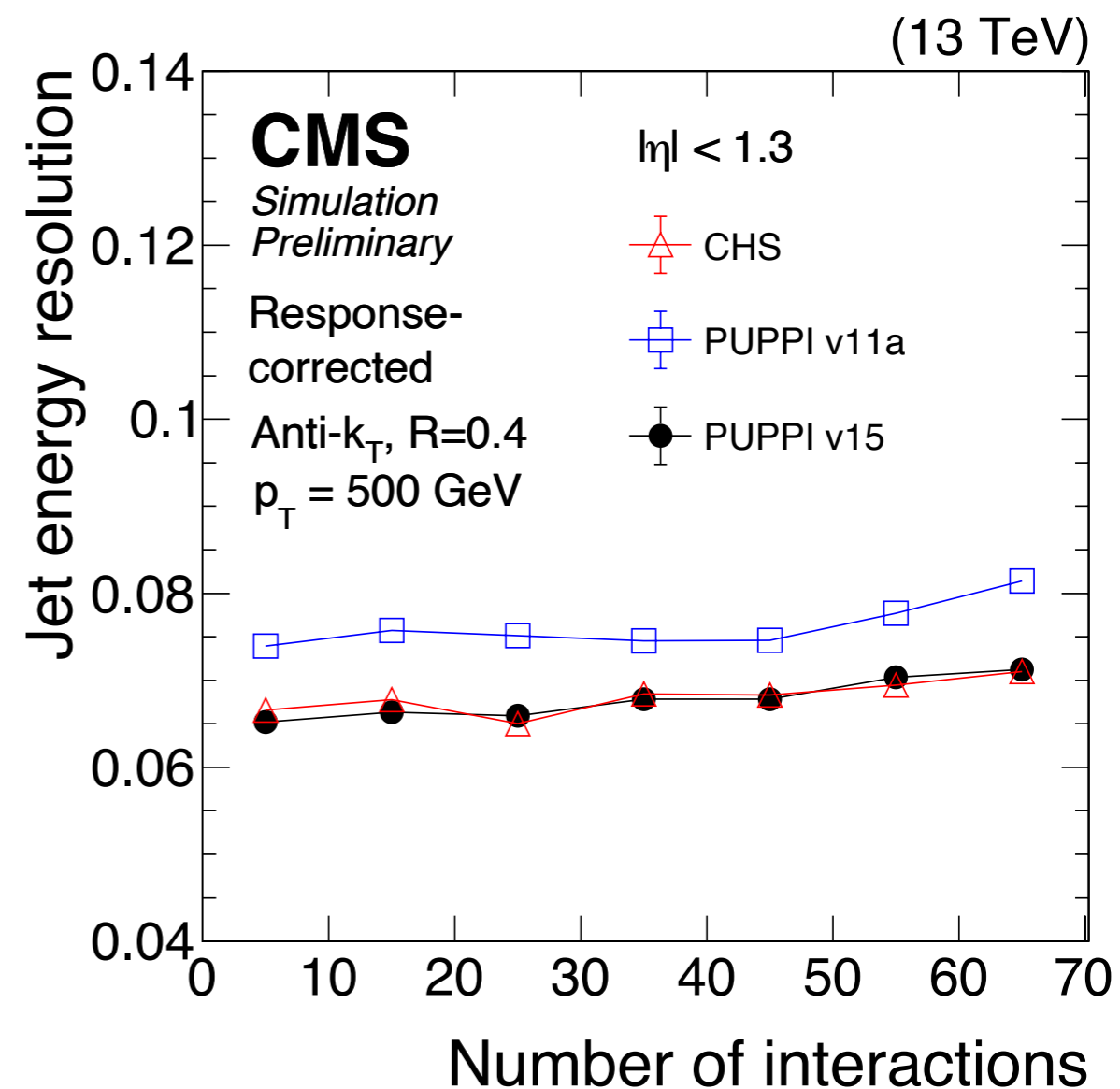
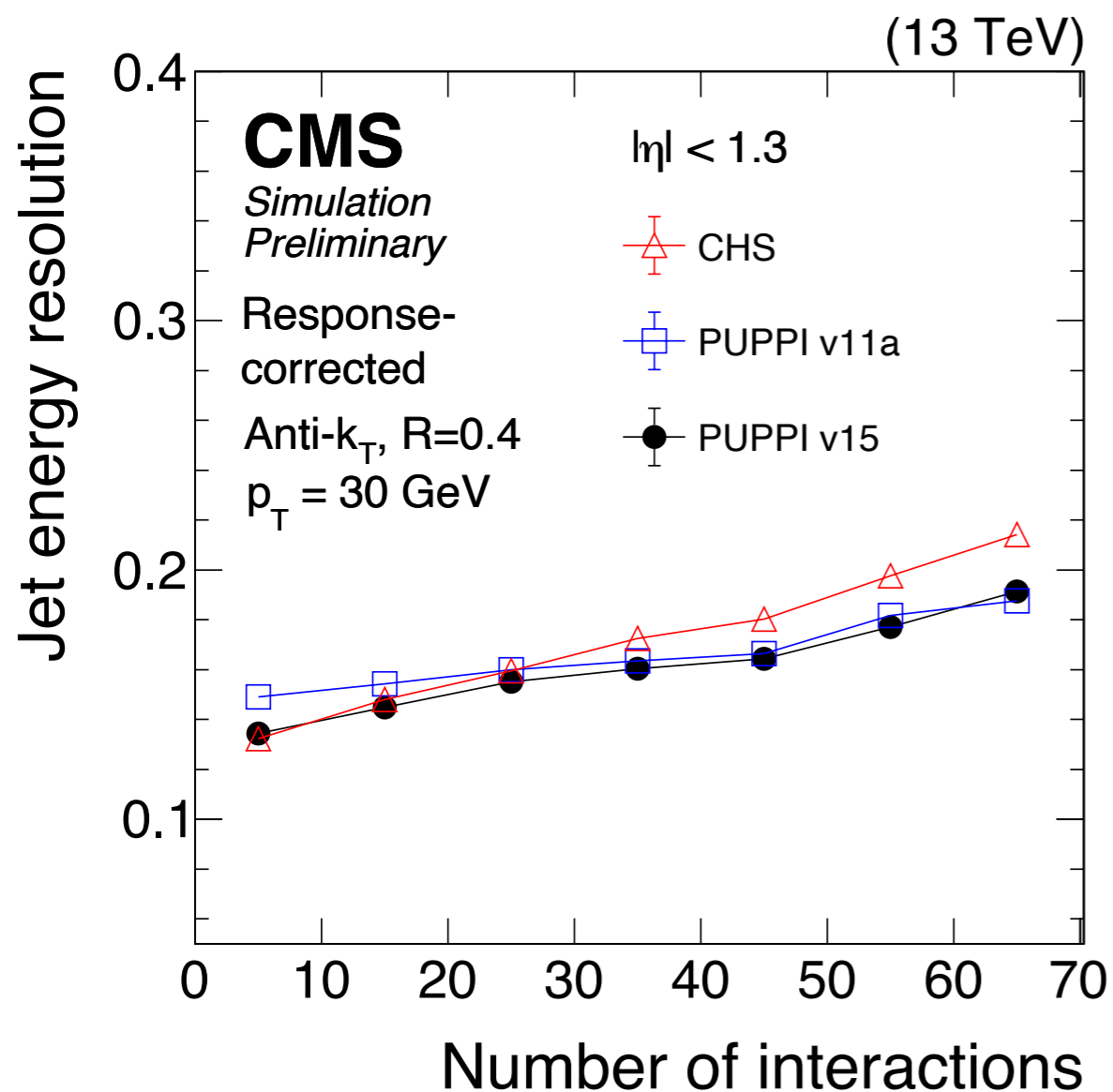


Real jets

Noise jets

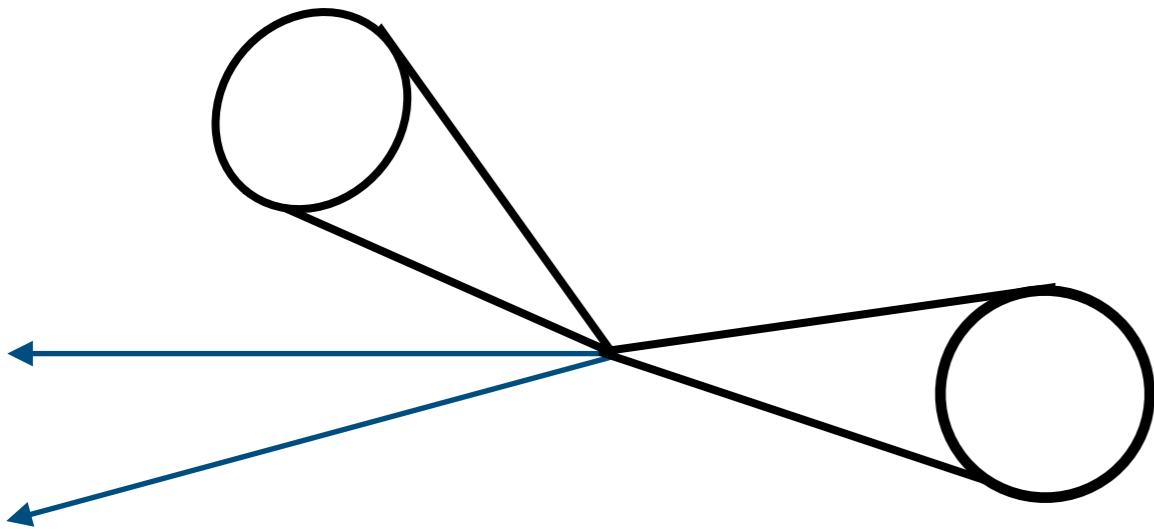
Purpose: remove noise from HCAL & ECAL by retaining ~98% of the real jets

# Jet energy resolution



# Efficiency & purity in Z+jets

generator jets

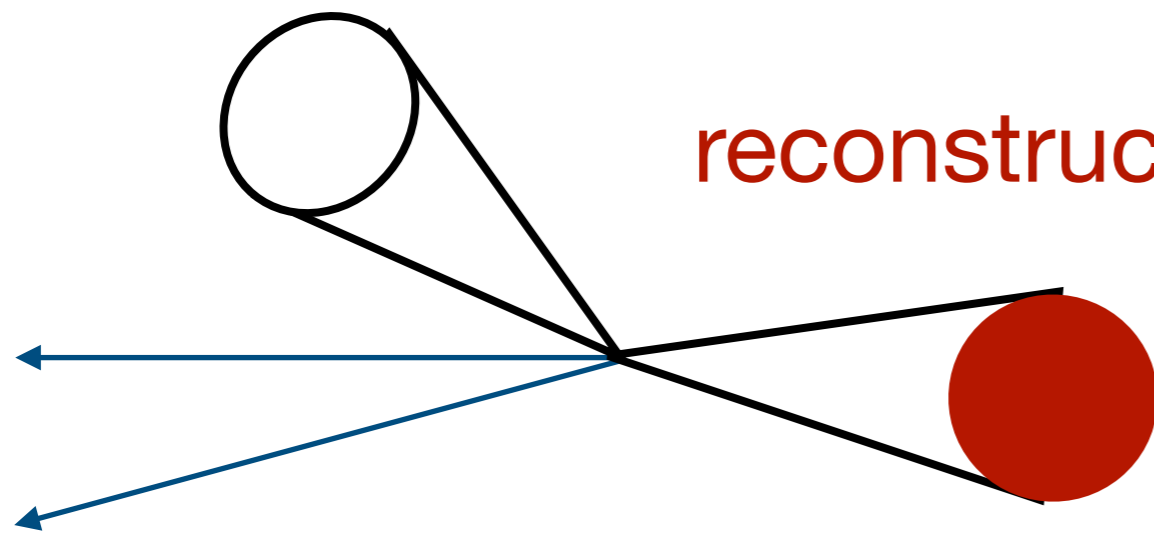


## Efficiency

Simulation only study

# Efficiency & purity in Z+jets

generator jets



reconstructed jets

Either not reconstructed or rejected:

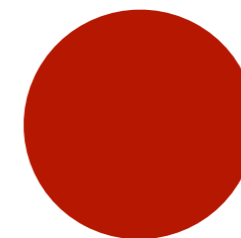
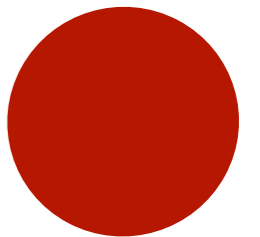
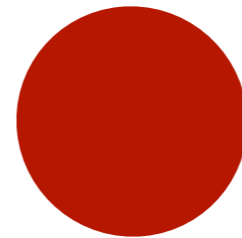
- Pileup Jet ID
- down weighted particles from PUPPI
- ...

## Efficiency

Simulation only study

# Efficiency & purity in Z+jets

reconstructed jets

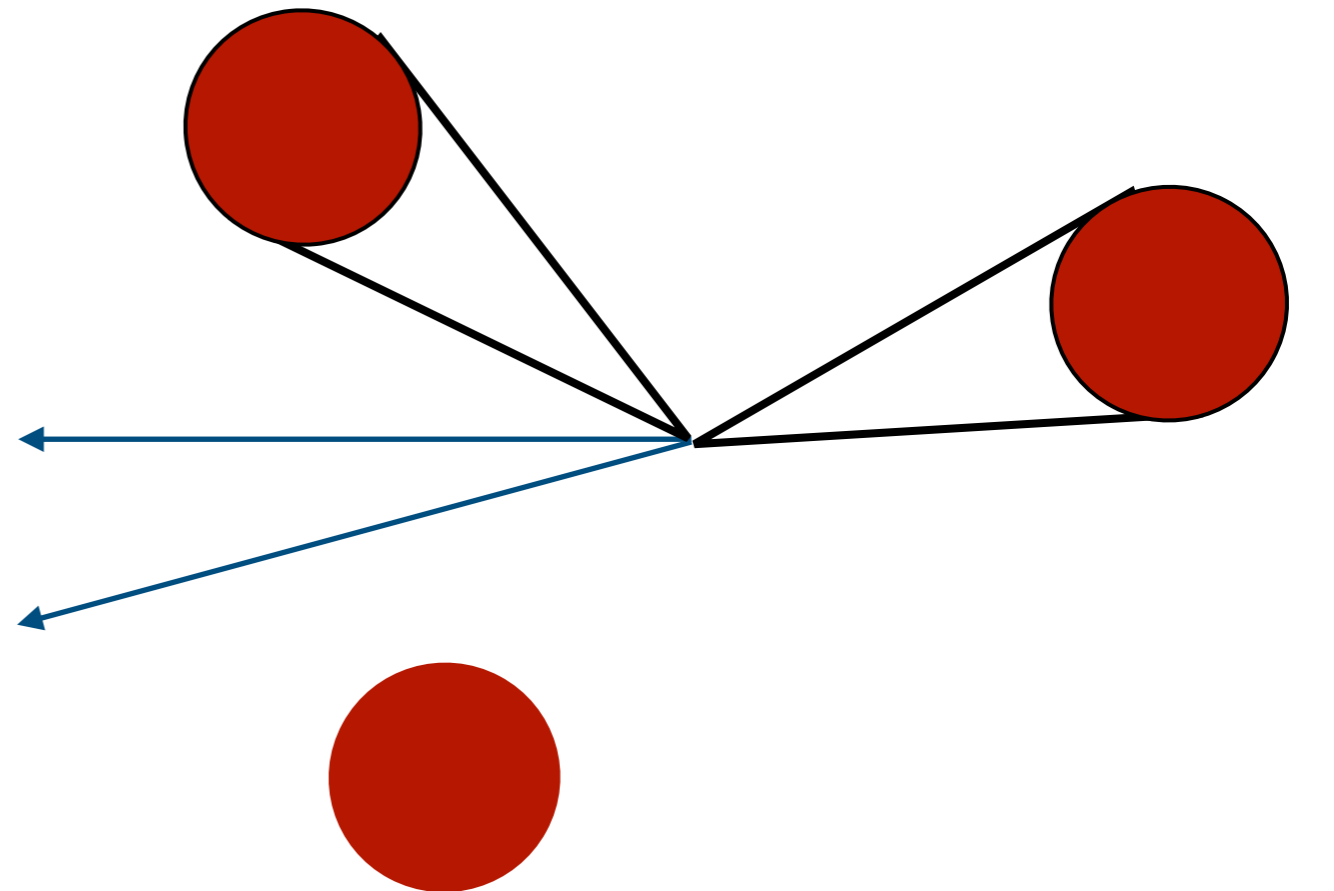


Simulation only study

**Purity**

# Efficiency & purity in Z+jets

reconstructed jets



generator jets

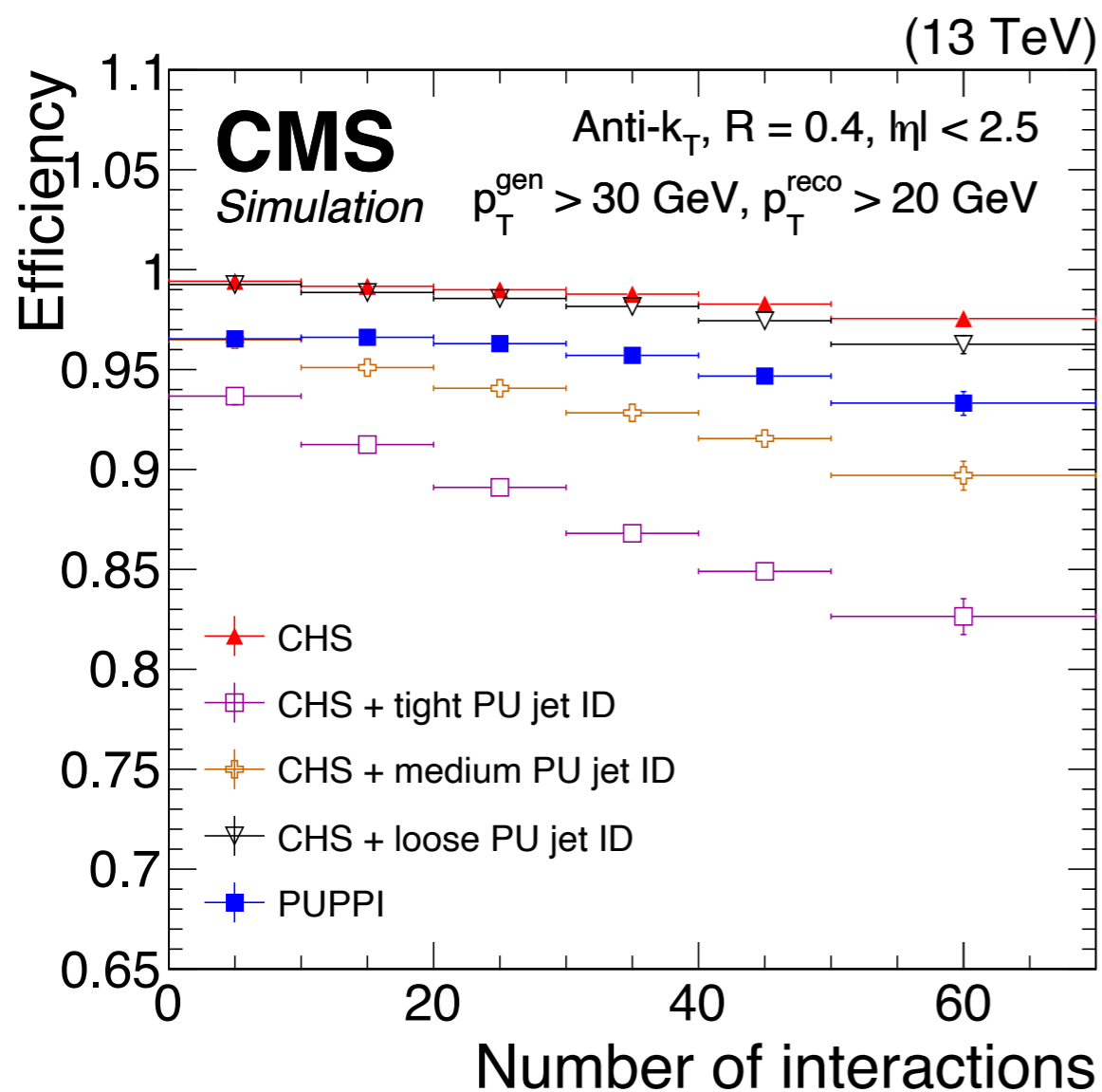
Most likely PU Jets did not get rejected:

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

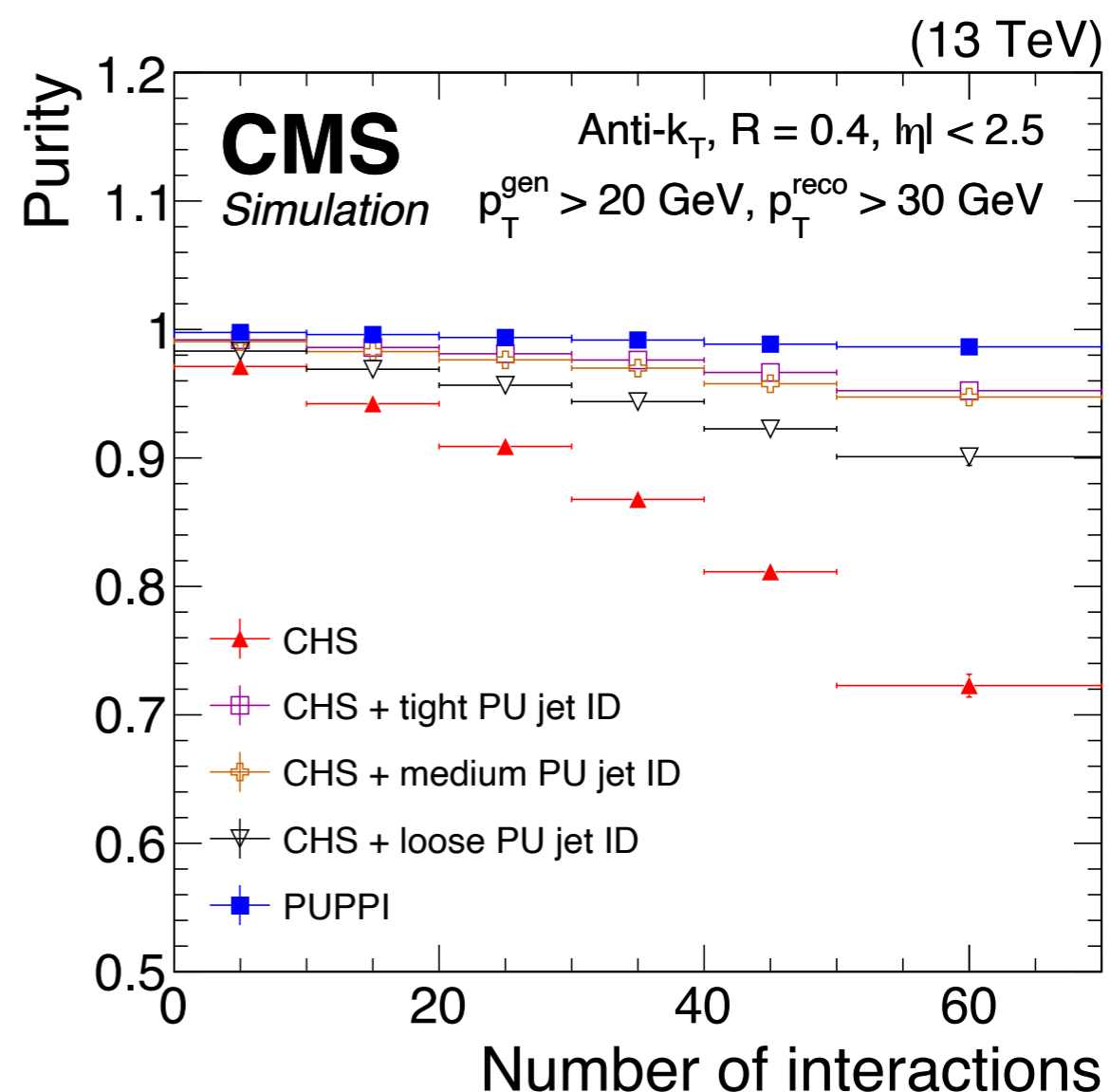
Simulation only study

**Purity**

# Efficiency and purity

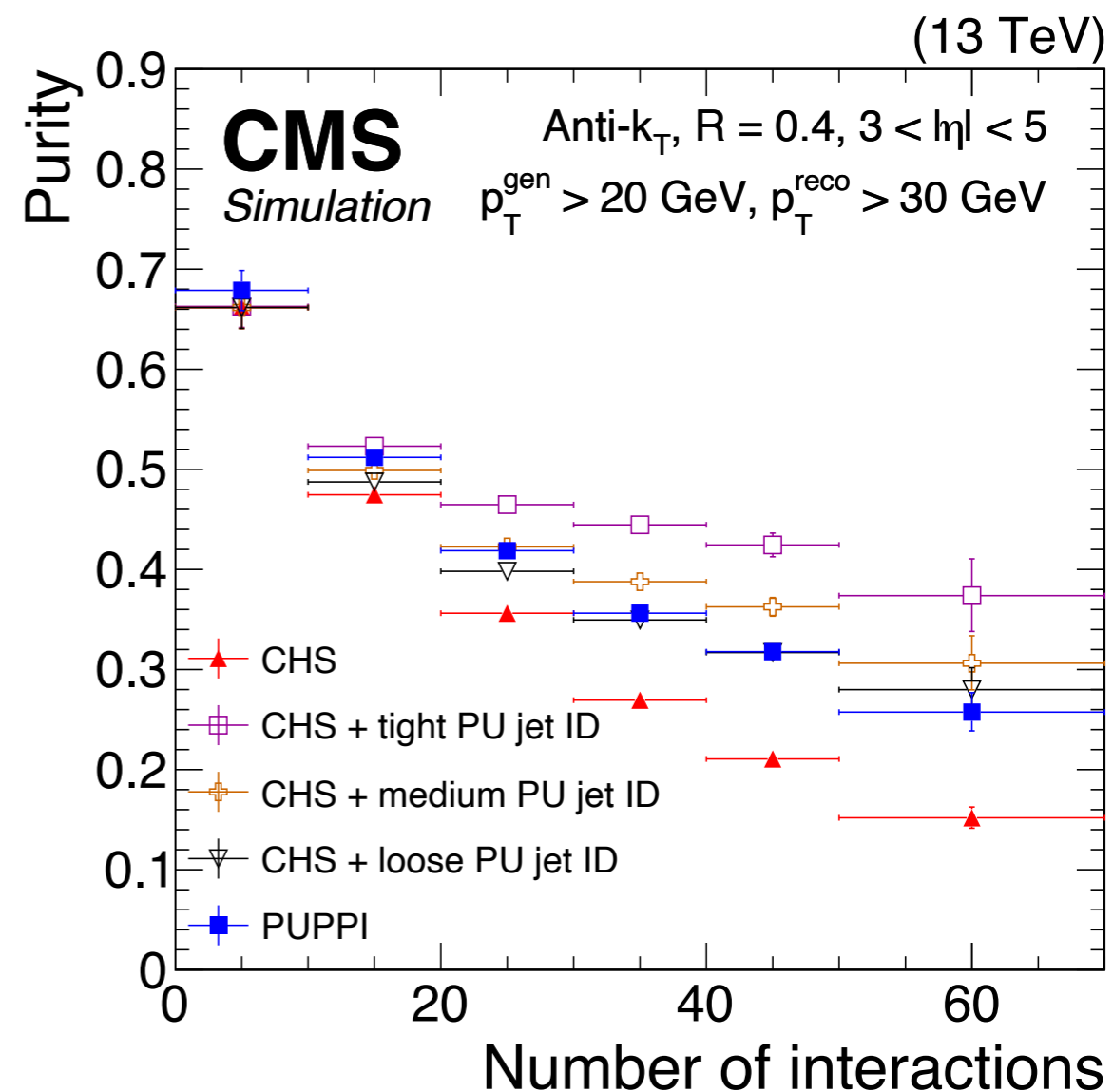
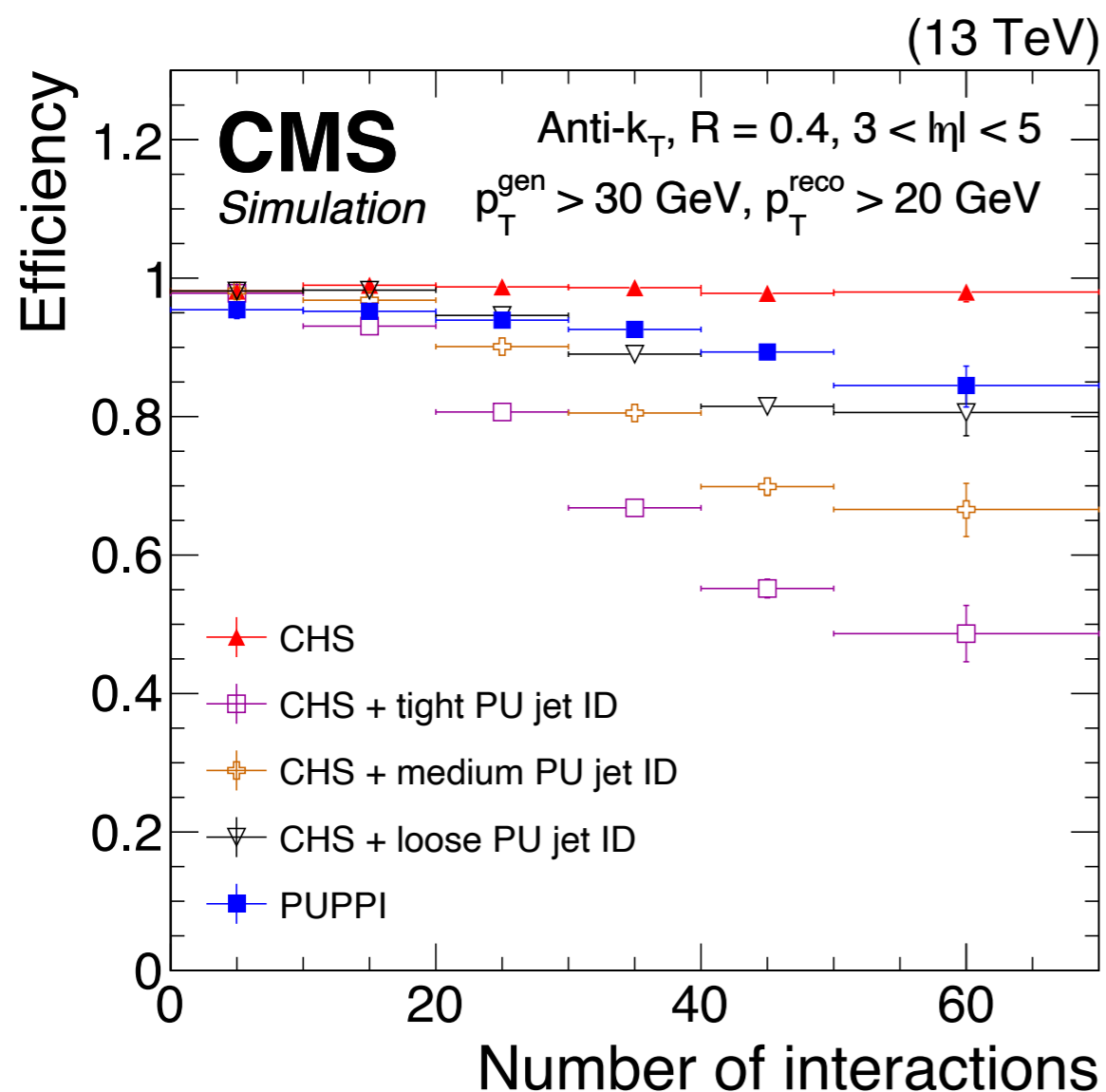


↑  
**better**



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

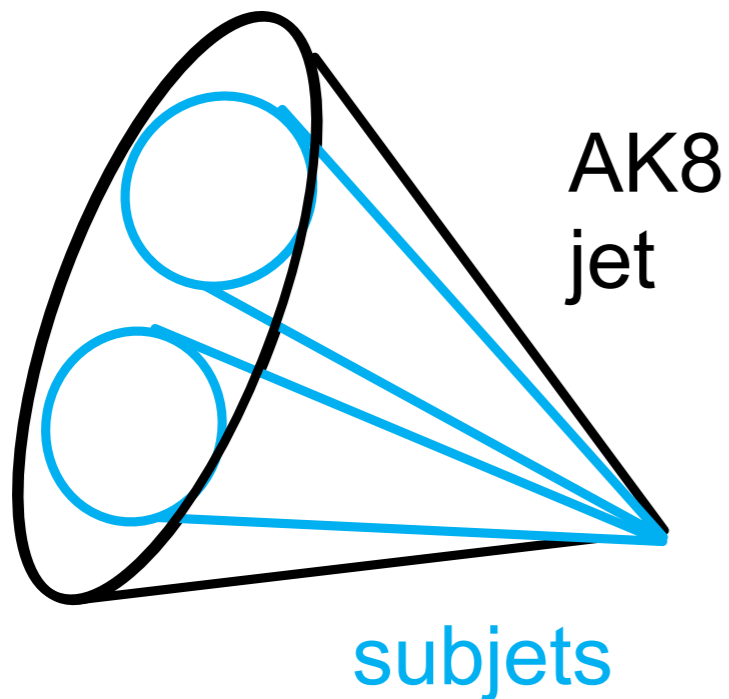
# Efficiency and purity



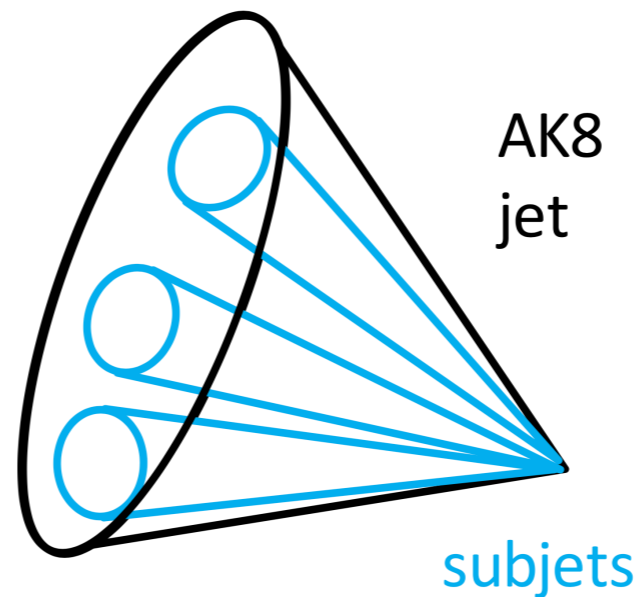
**PUPPI** better than **CHS+loose/medium** pileup jet ID

# Identifying W bosons

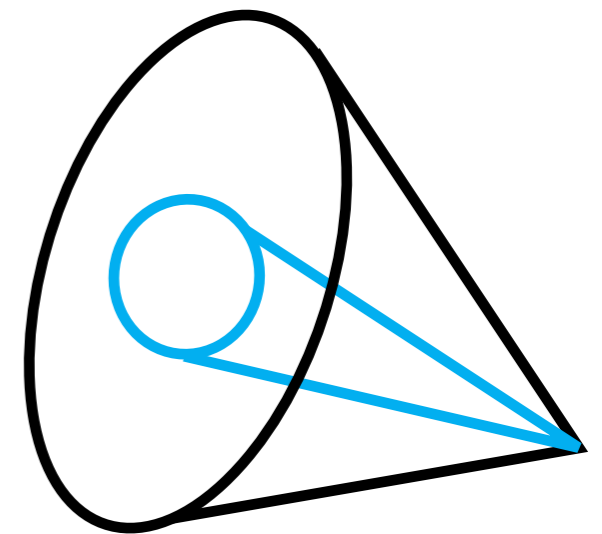
Z/W candidate



top candidate

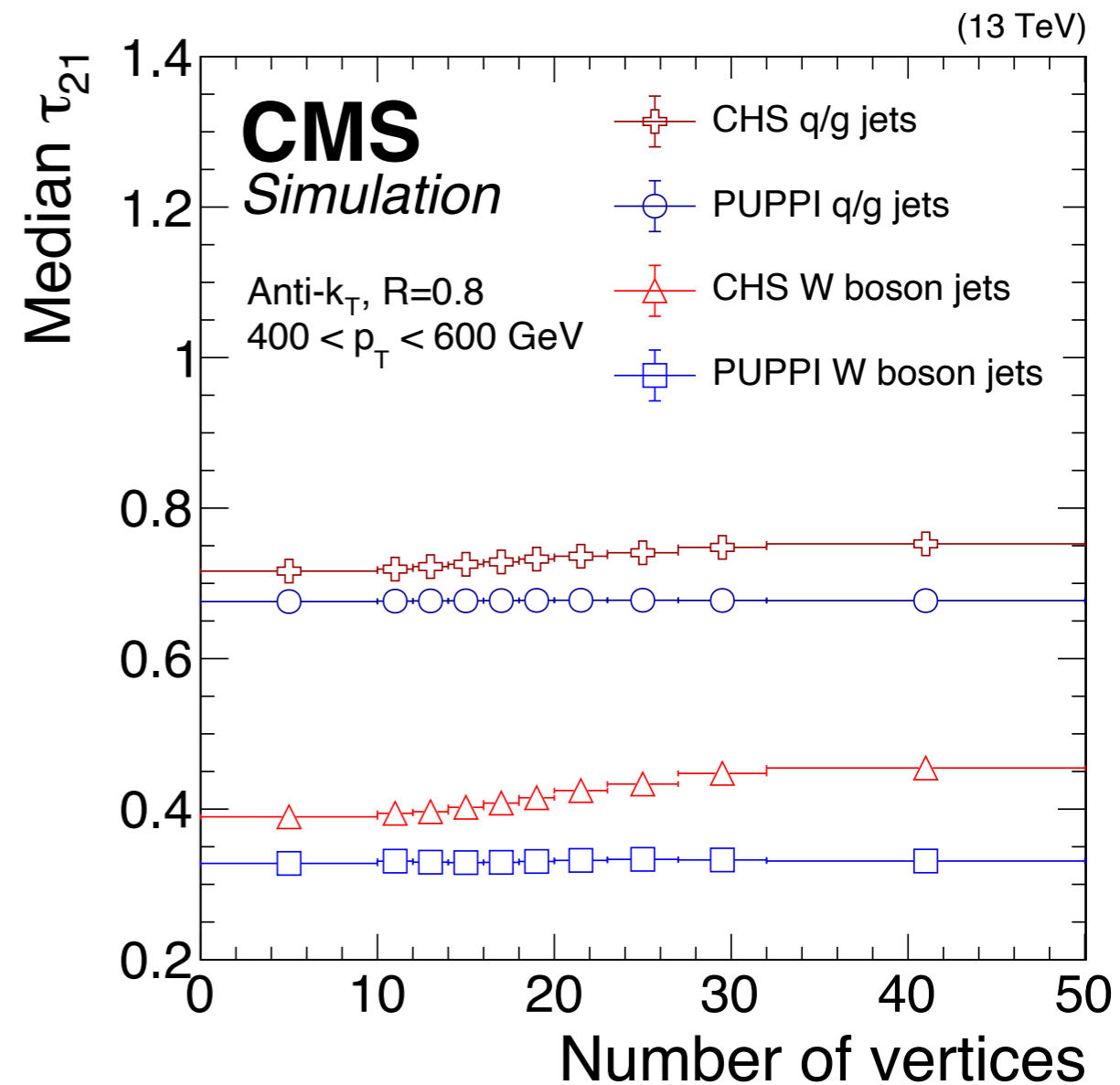
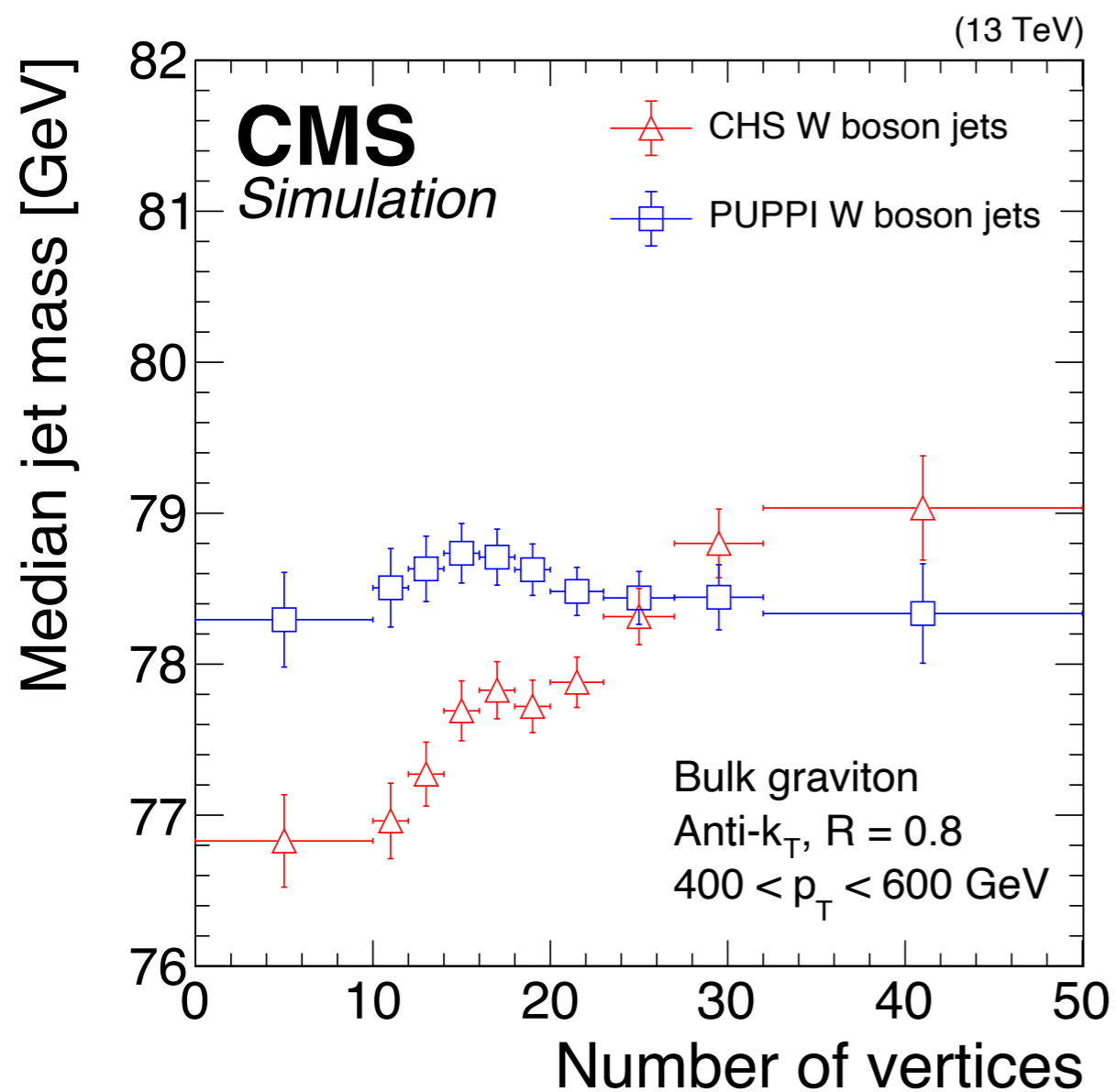


q/g candidate

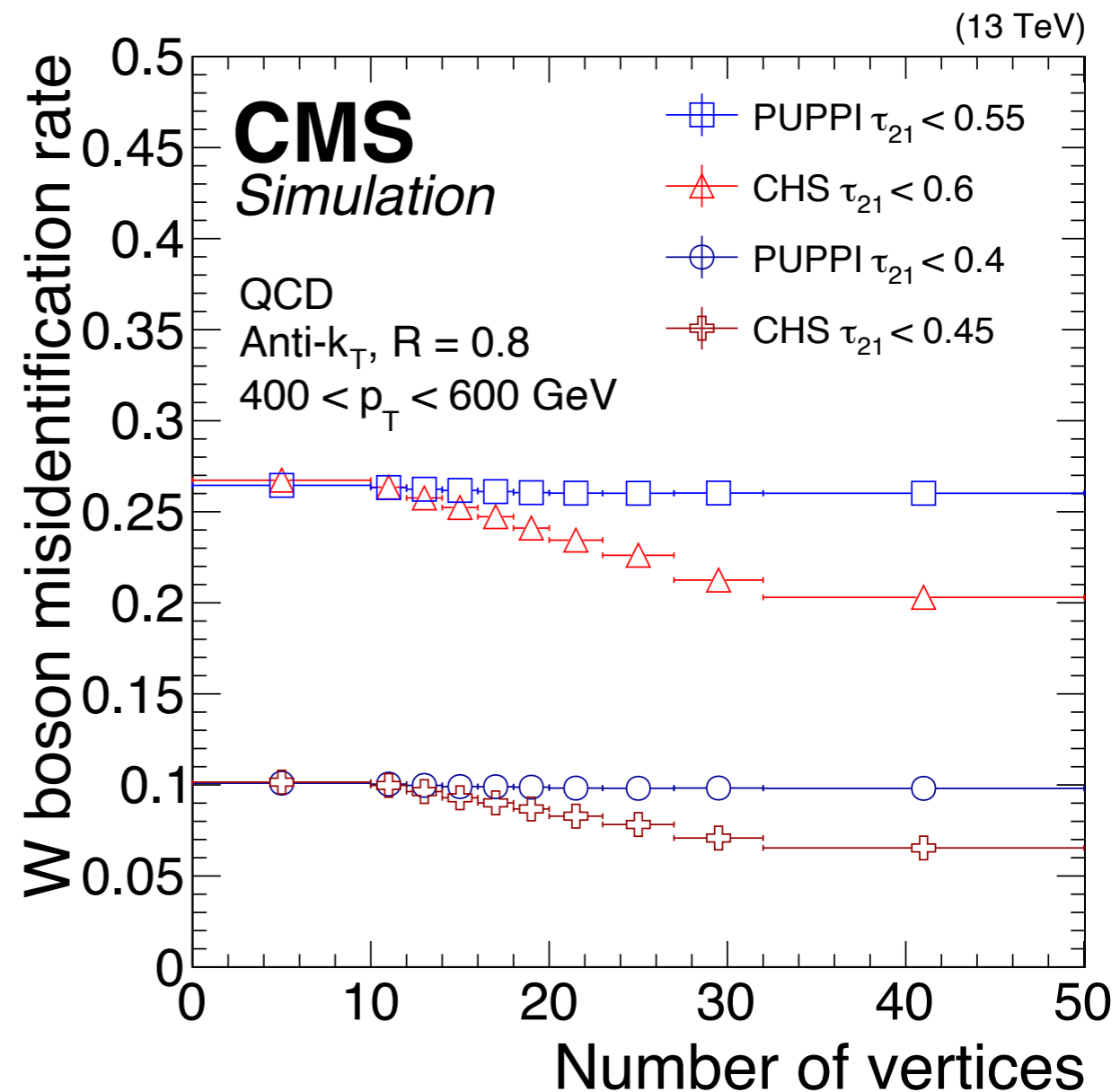
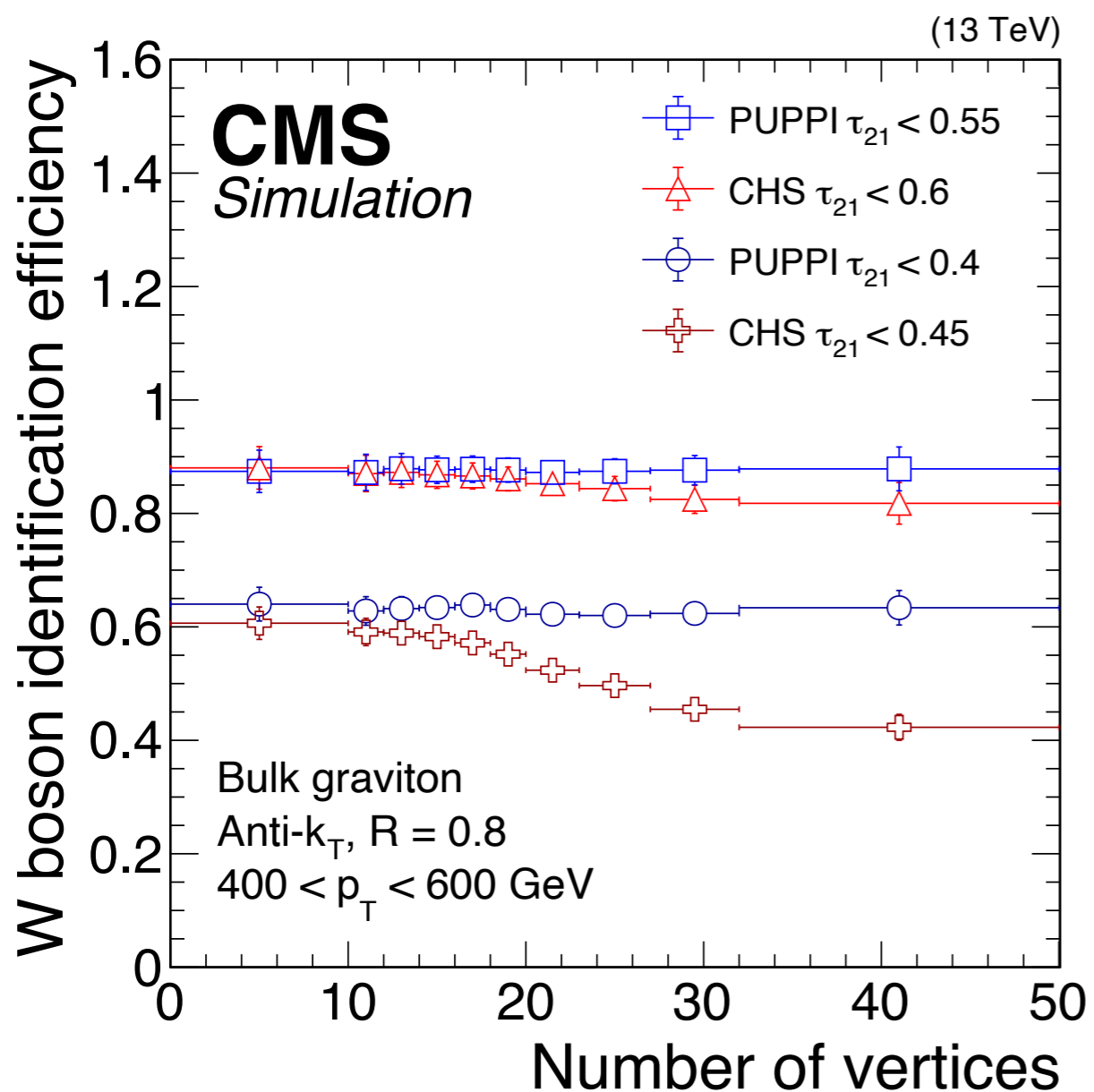


Identified through SD mass, n-subjettiness, subjet b-tagging, ...

# Identifying W bosons



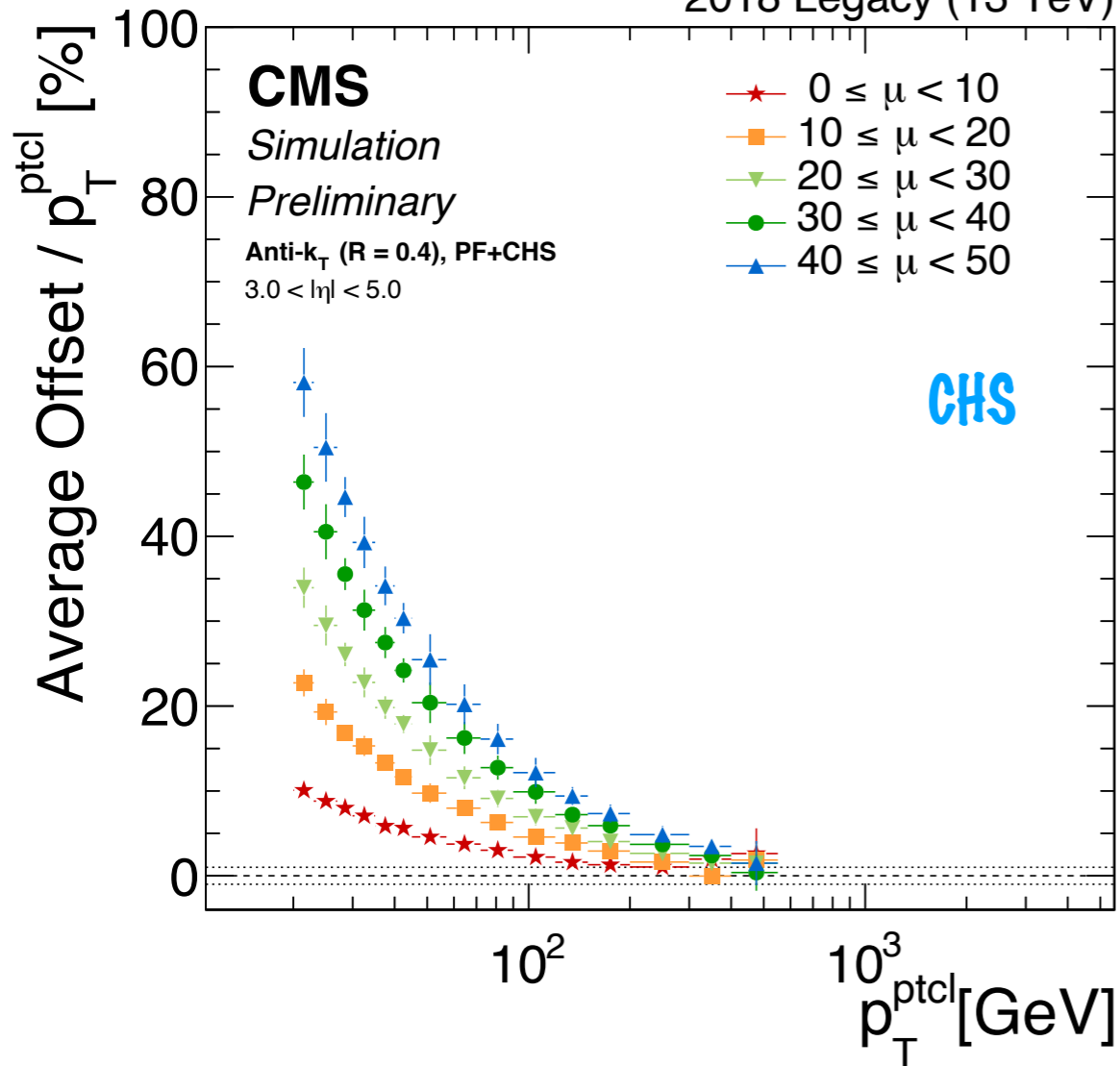
# Identifying W bosons



# Quick look into Run3

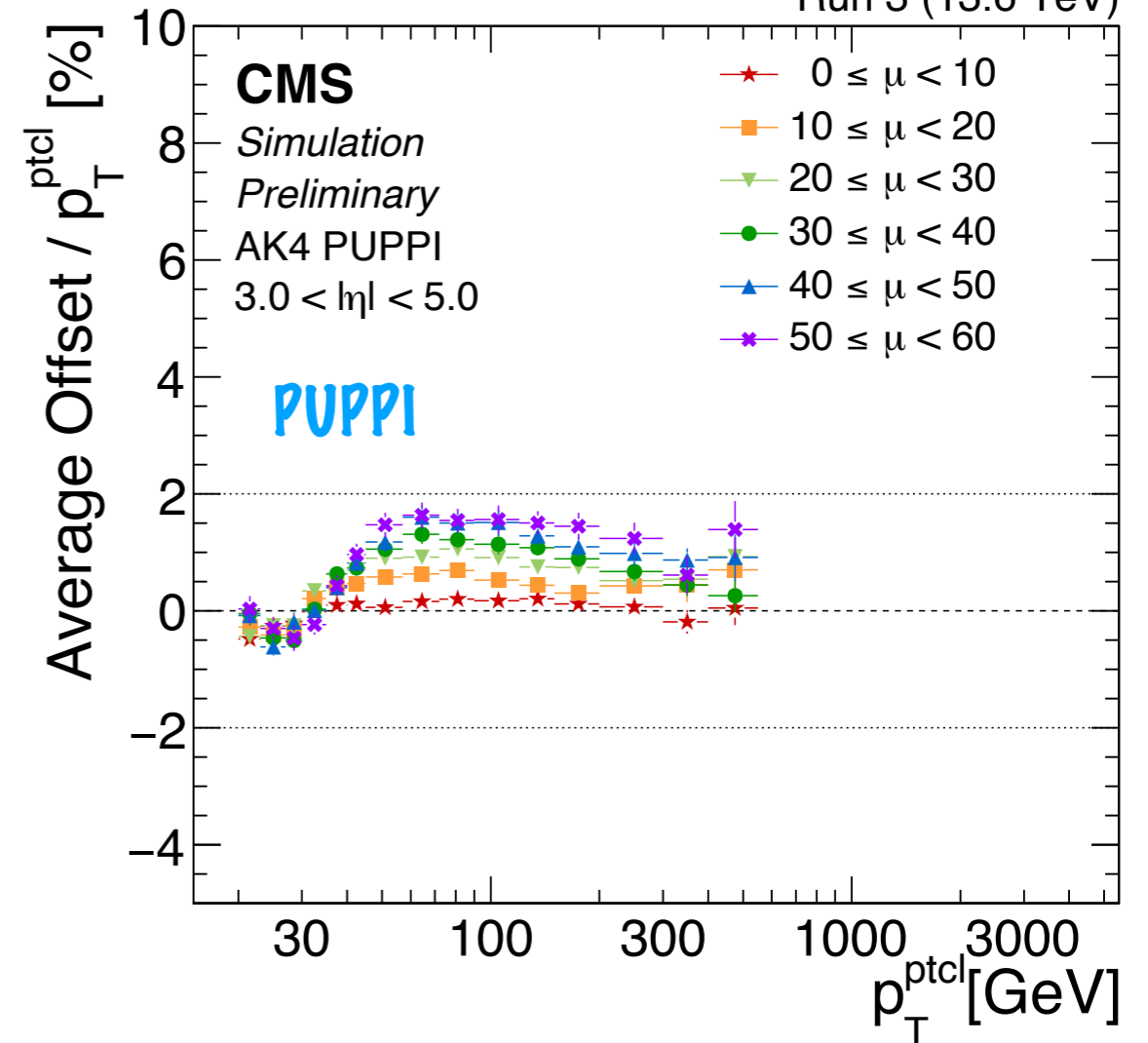
[CMS-DP-2021-033](#)

2018 Legacy (13 TeV)



[CMS-DP-2022-054](#)

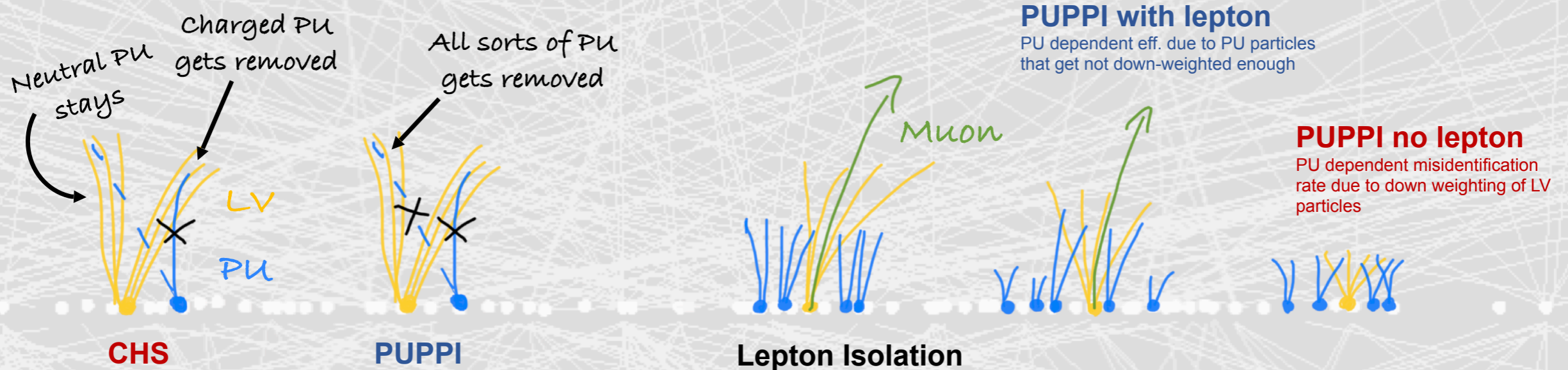
Run 3 (13.6 TeV)



Run2  Run3

Significant reduction of the PU contribution with PUPPI in Run3

# Pileup Mitigation Techniques in CMS

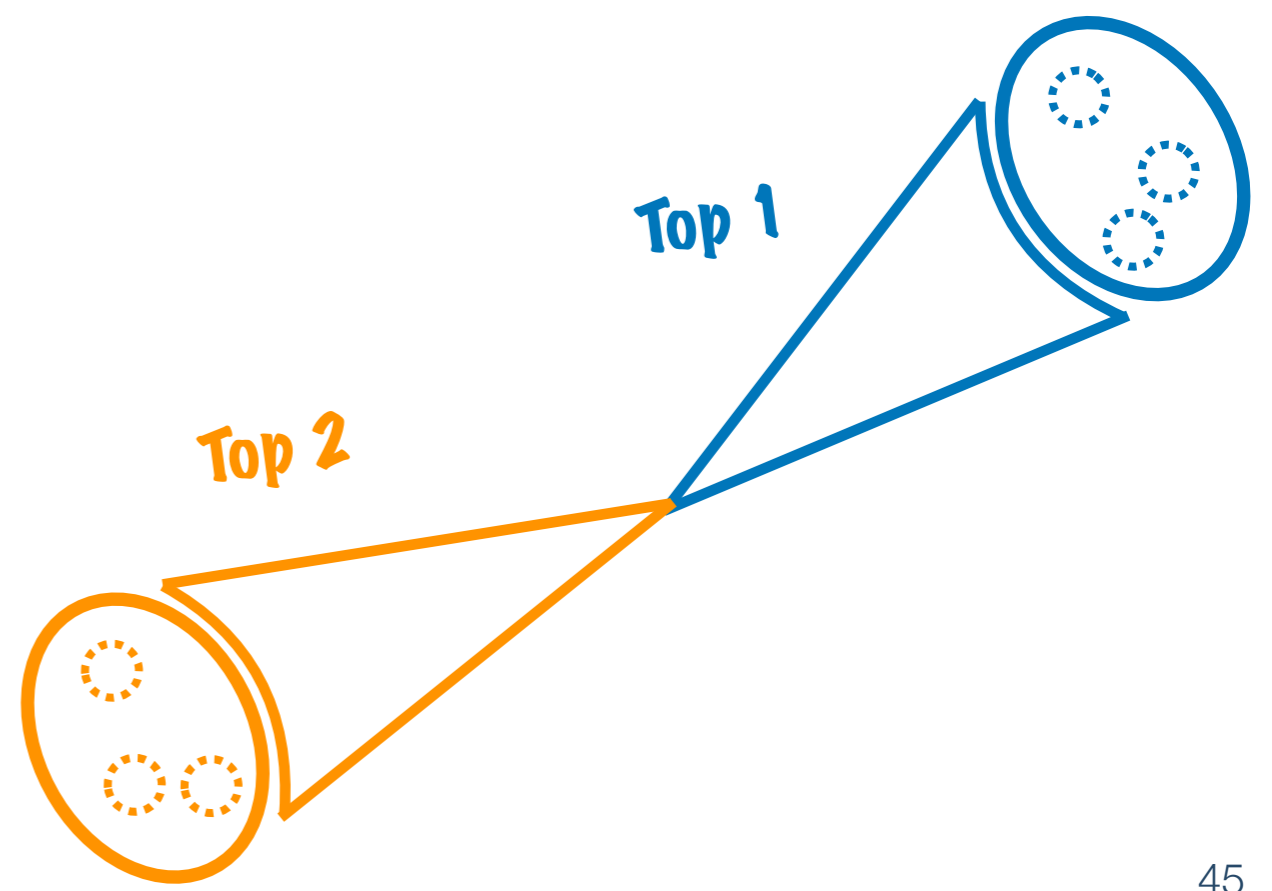
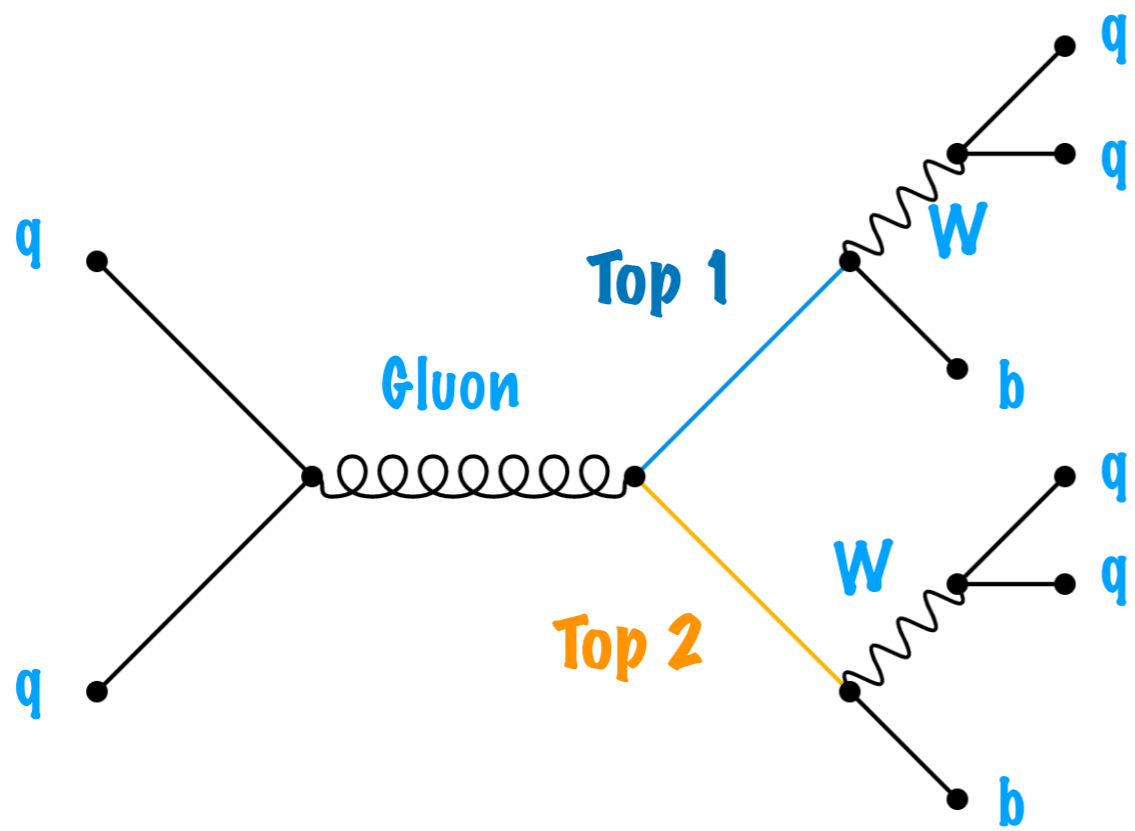


- full validation of PUPPI shows a good performance, especially at high PU  
[CMS-JME-18-001](#)
- PUPPI is the standard pileup mitigation technique for CMS in Run 3  
[CMS-DP-21-001](#)

# Backup

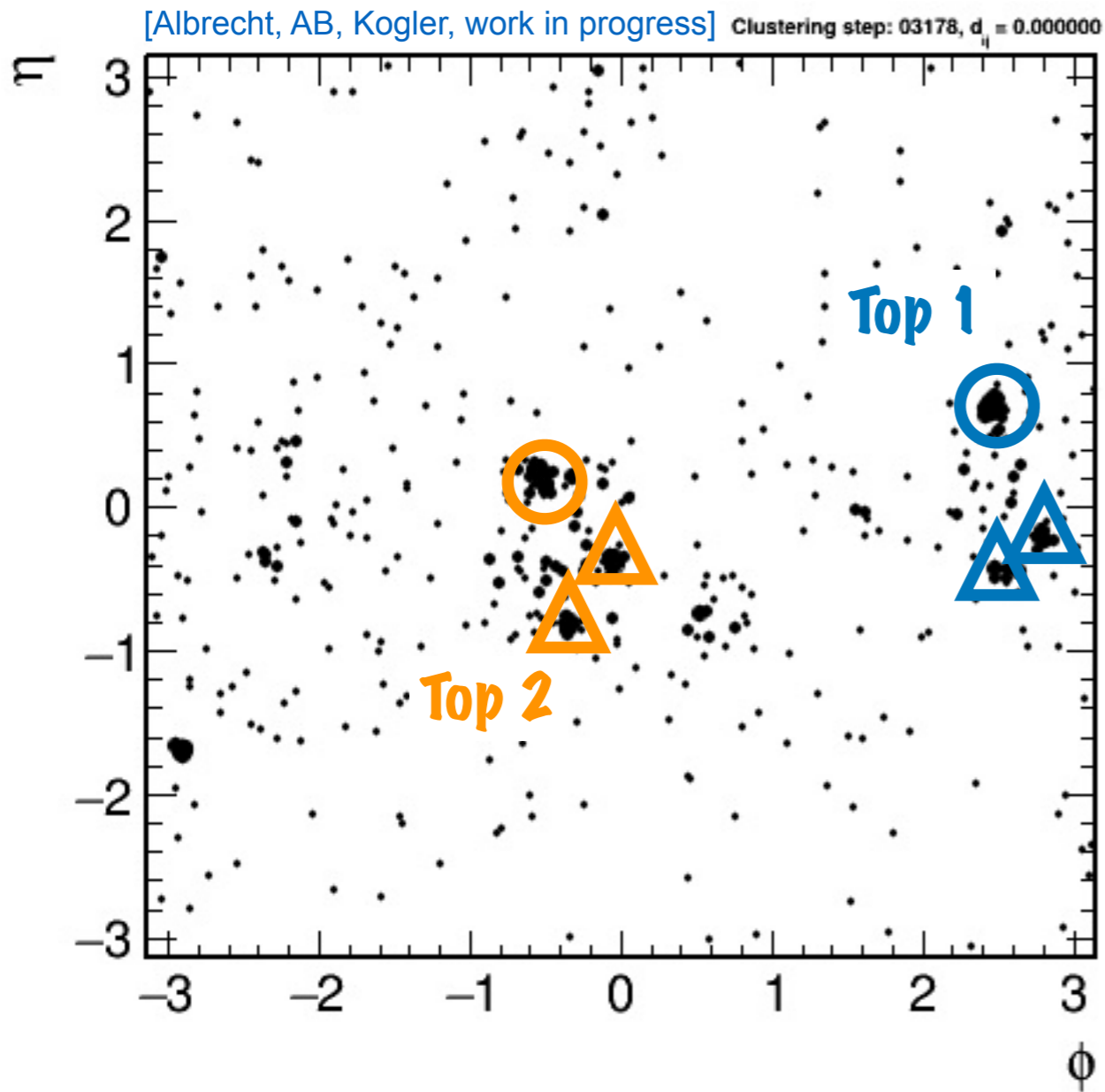
# Jet reconstruction

# Jet reconstruction

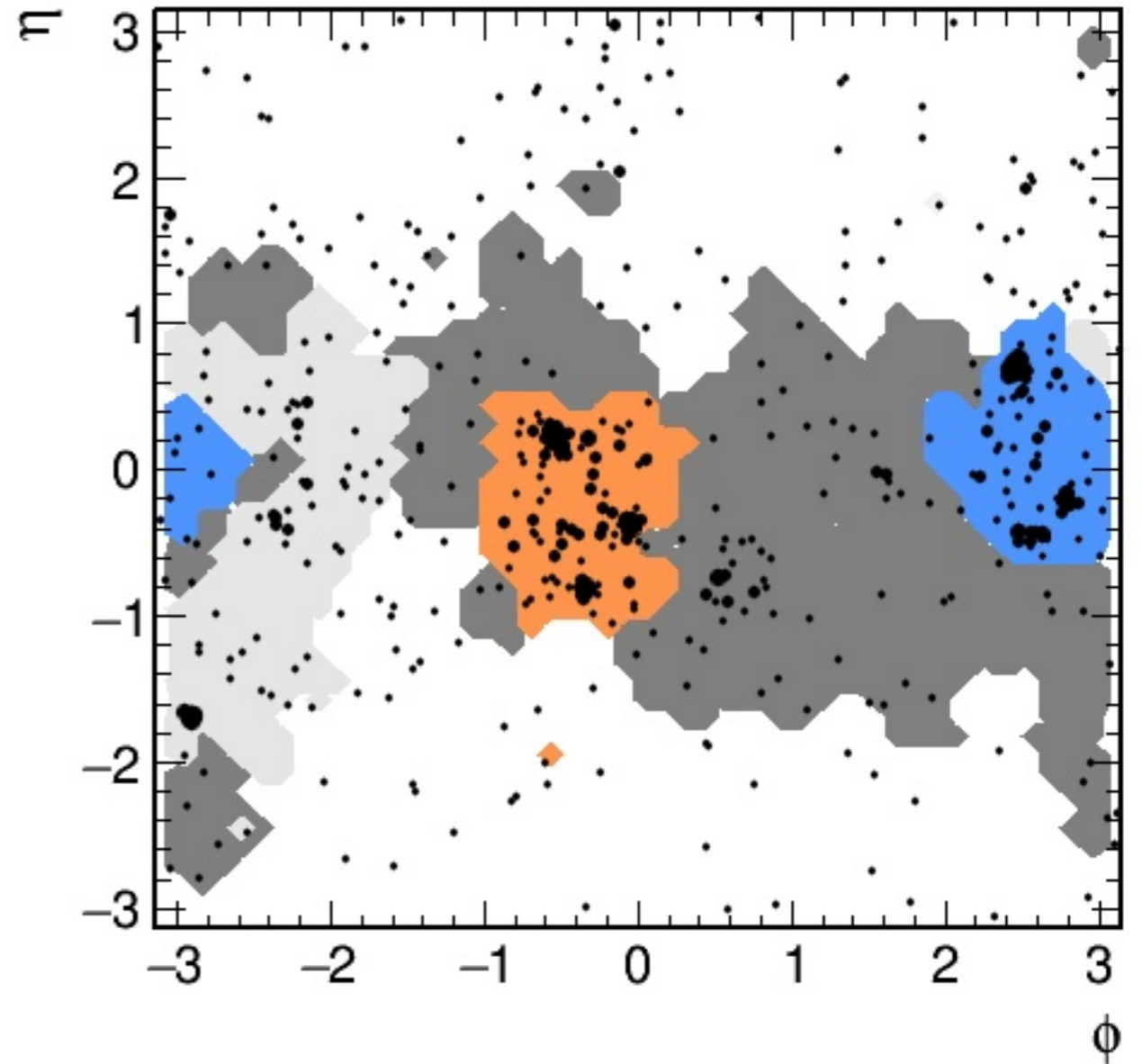


# Jet reconstruction

Starting point: cleaned PF candidates

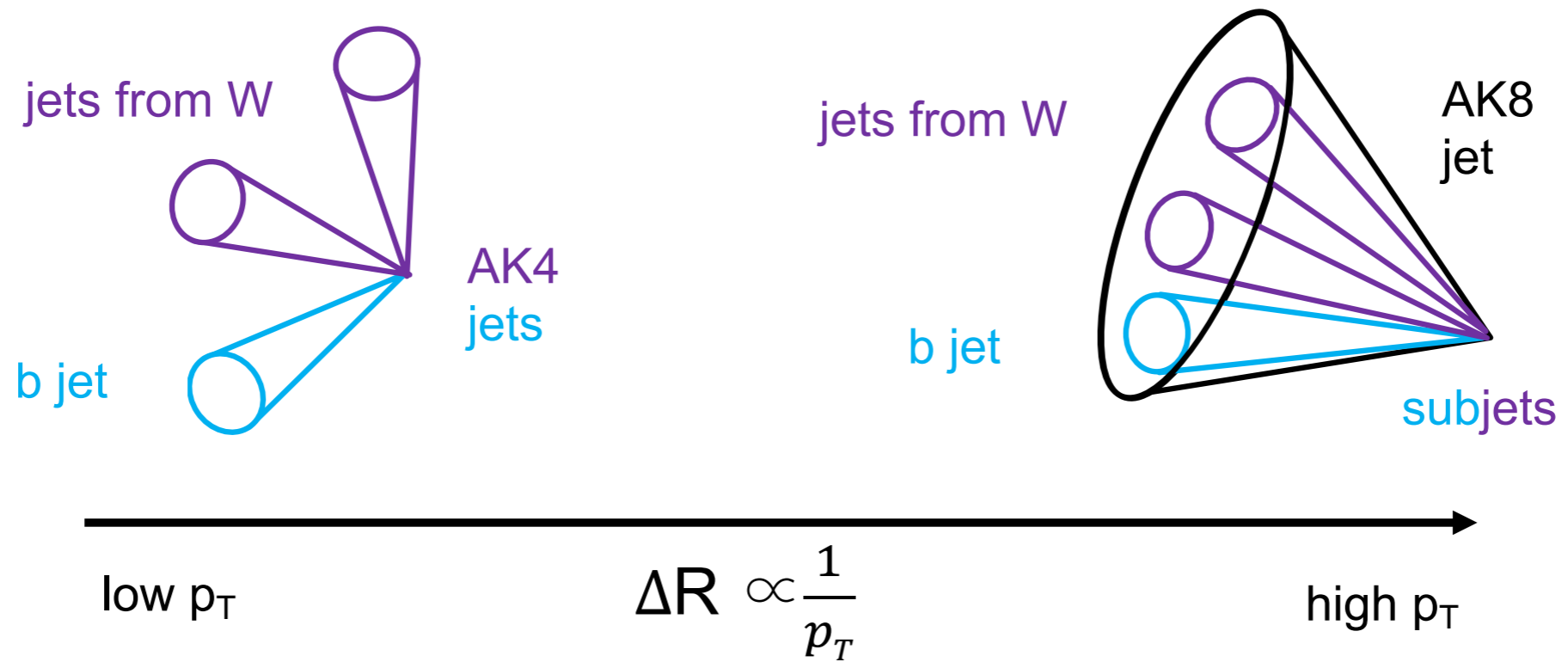


End point: two jets representing the top quark kinematics

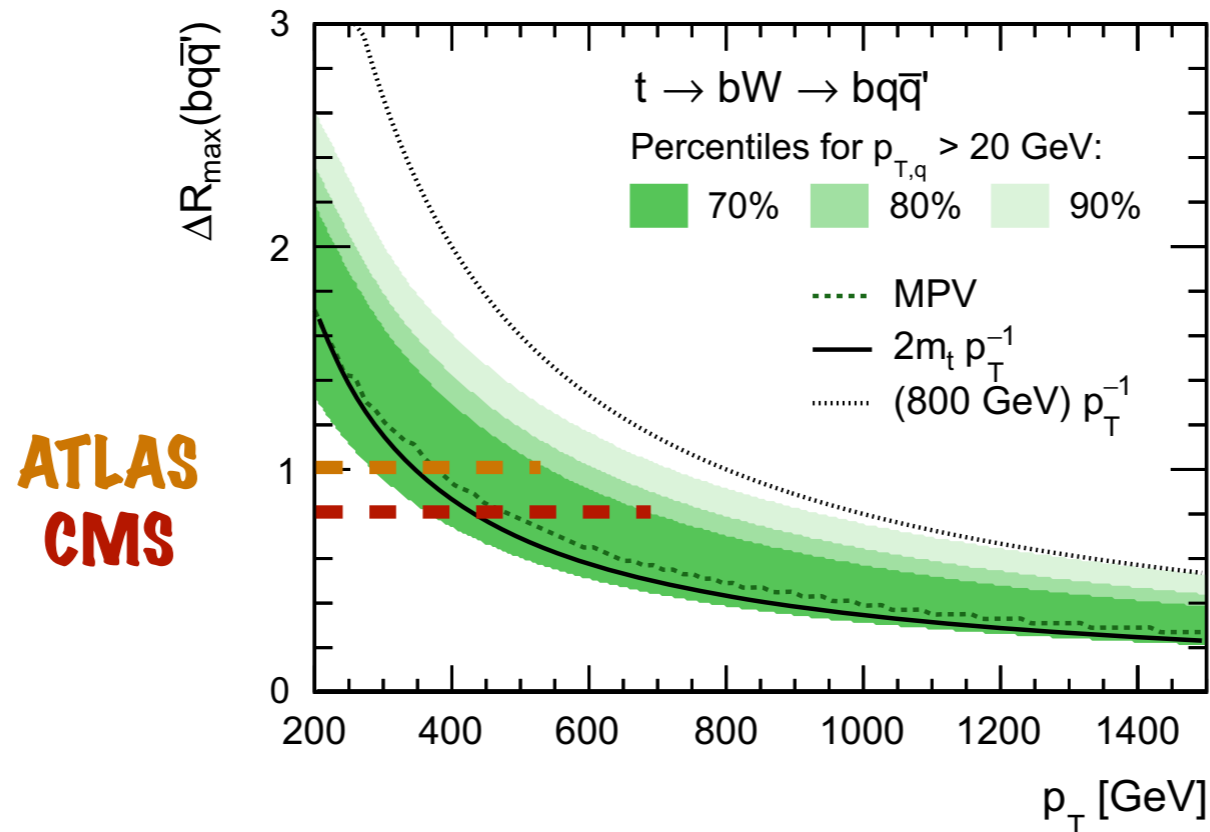


○ b-quark    △ Quarks from W

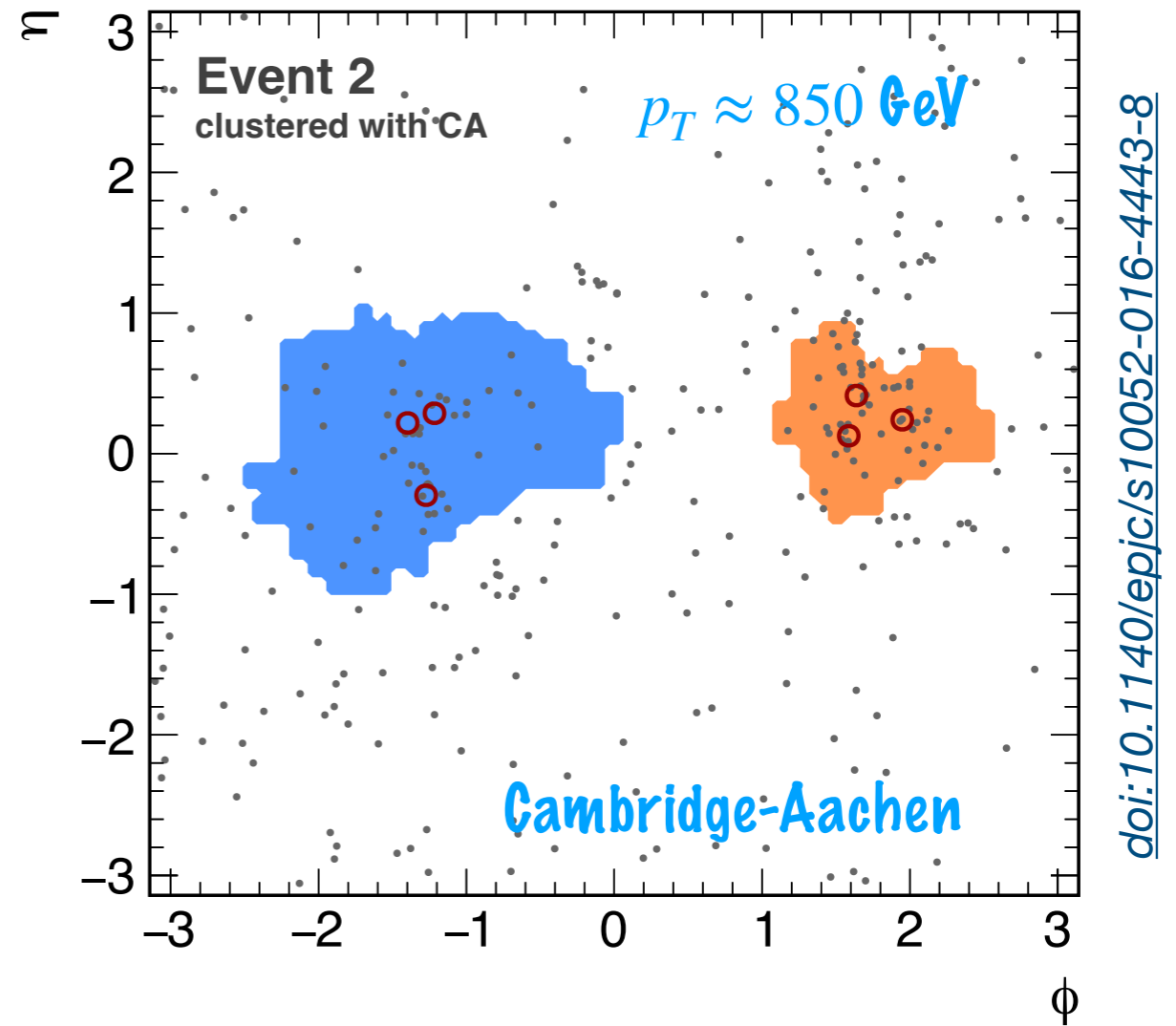
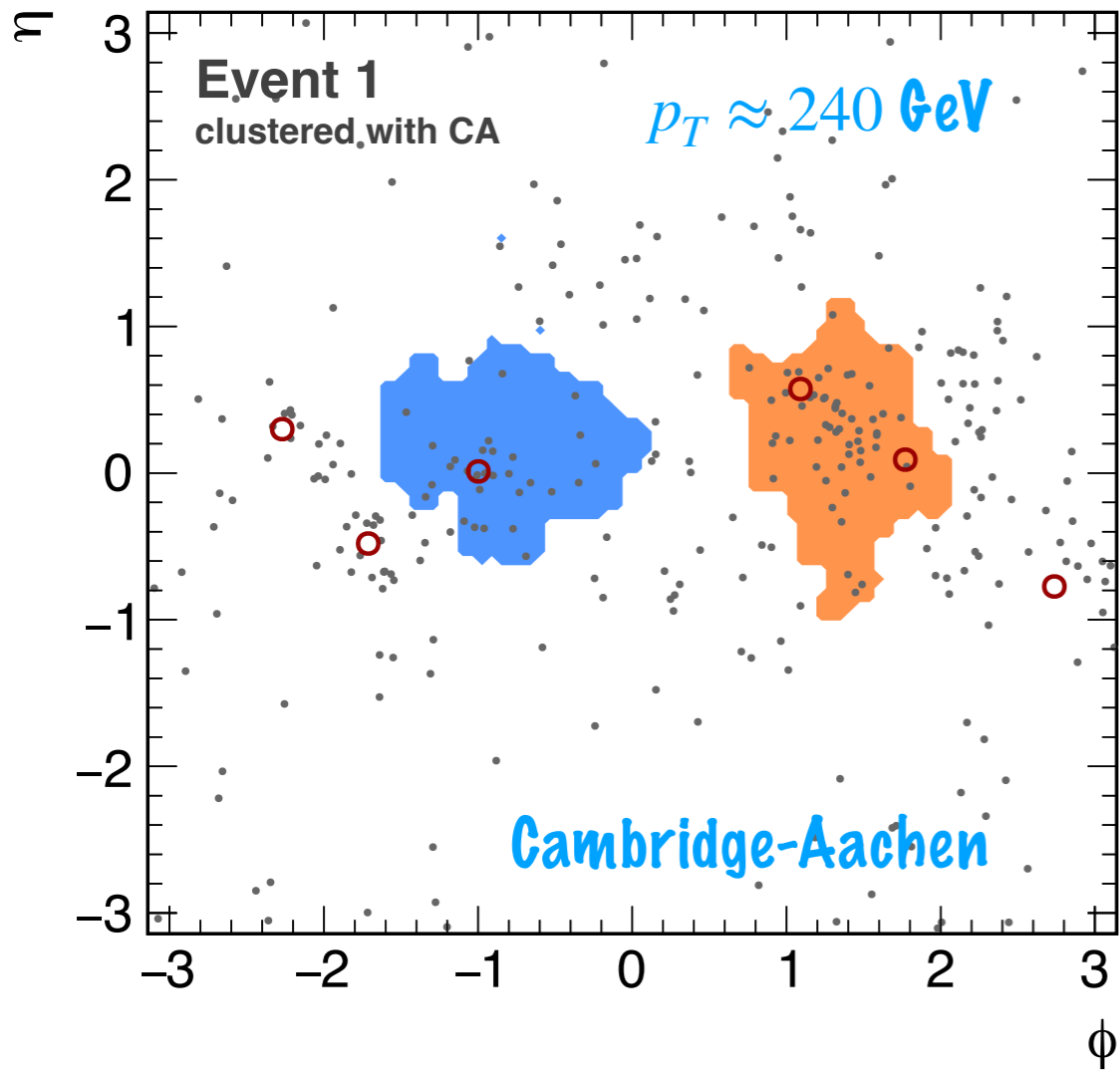
# Jet reconstruction



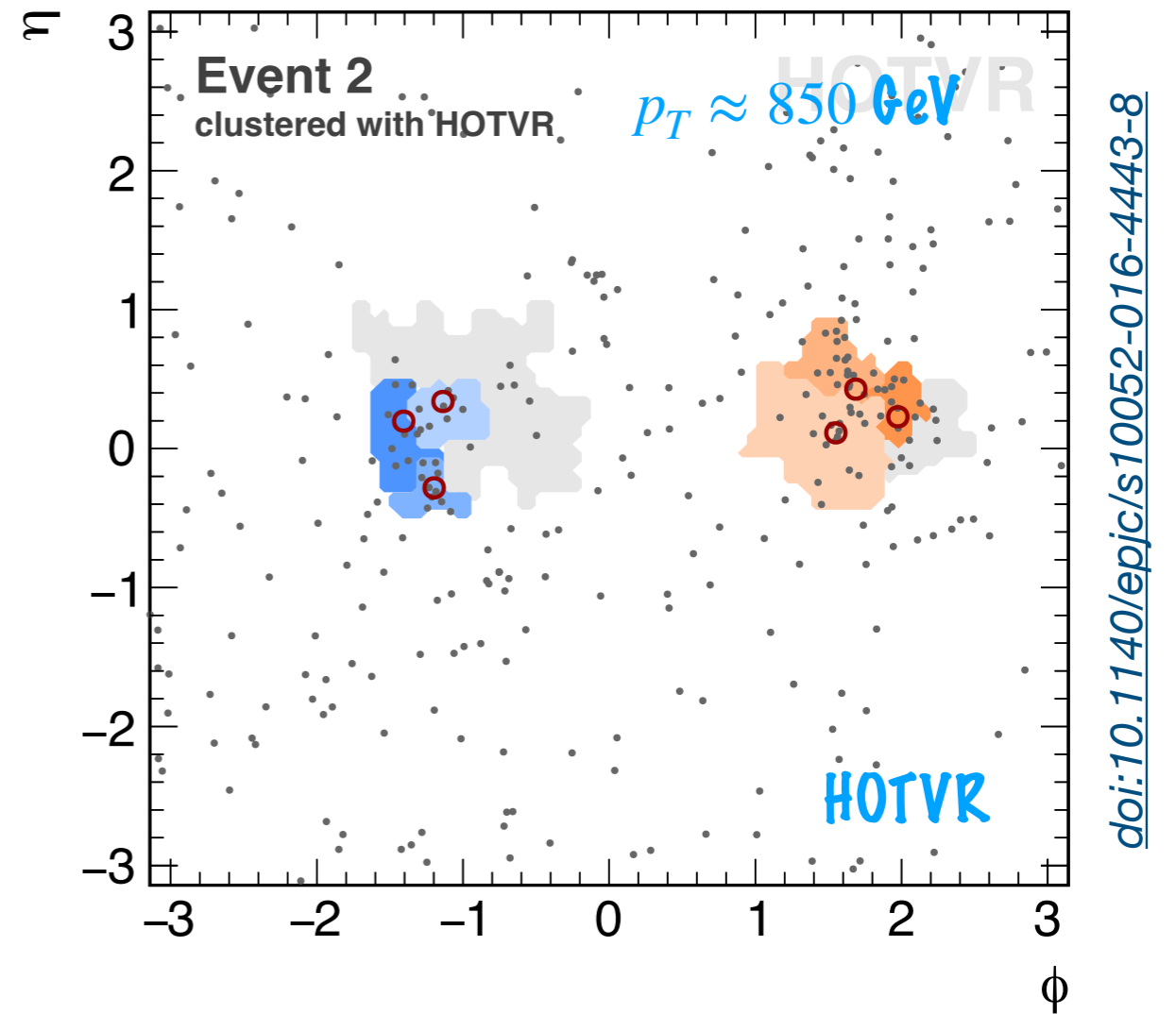
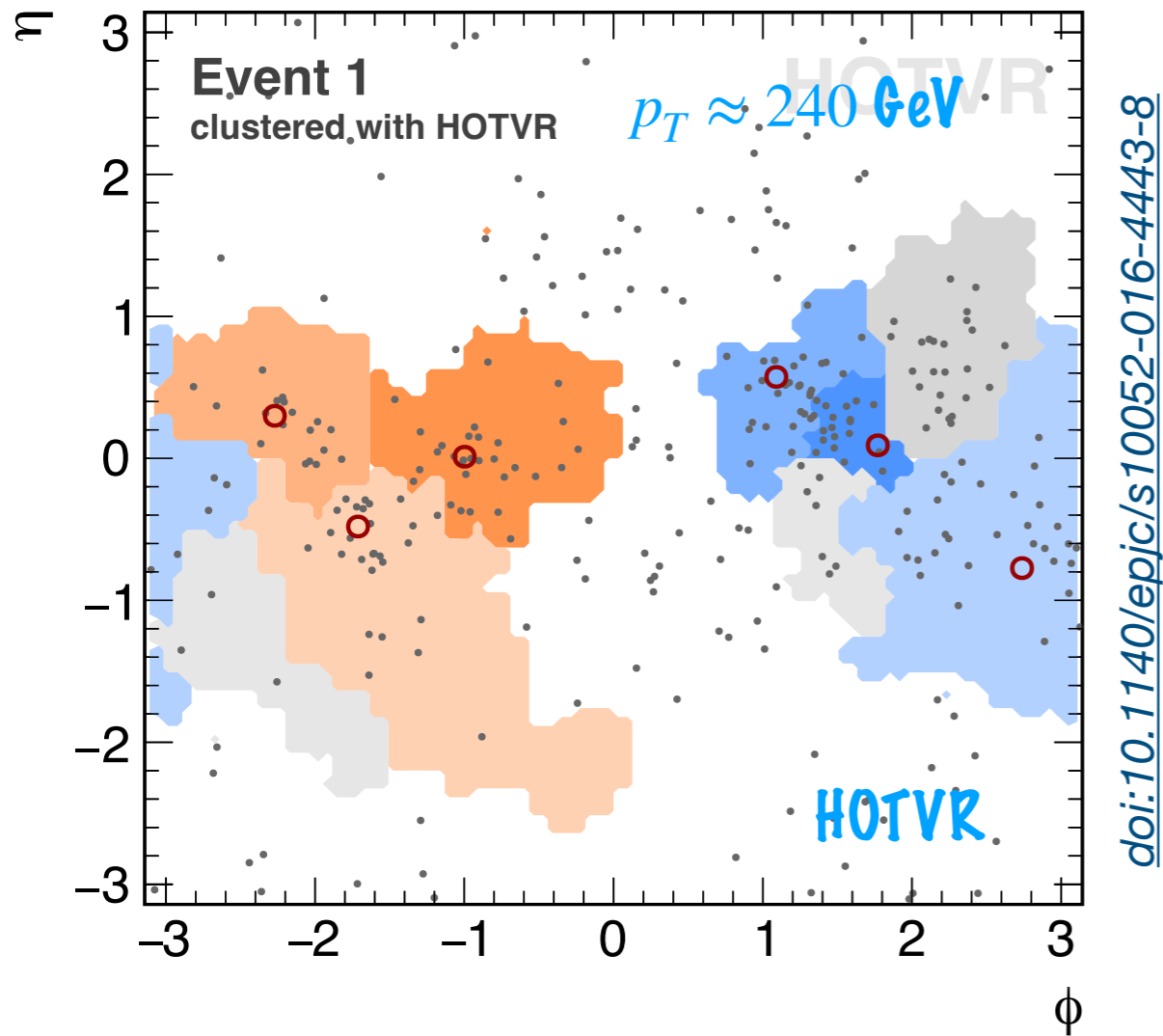
*Advances in Jet Substructure at the LHC, R. Kogler*



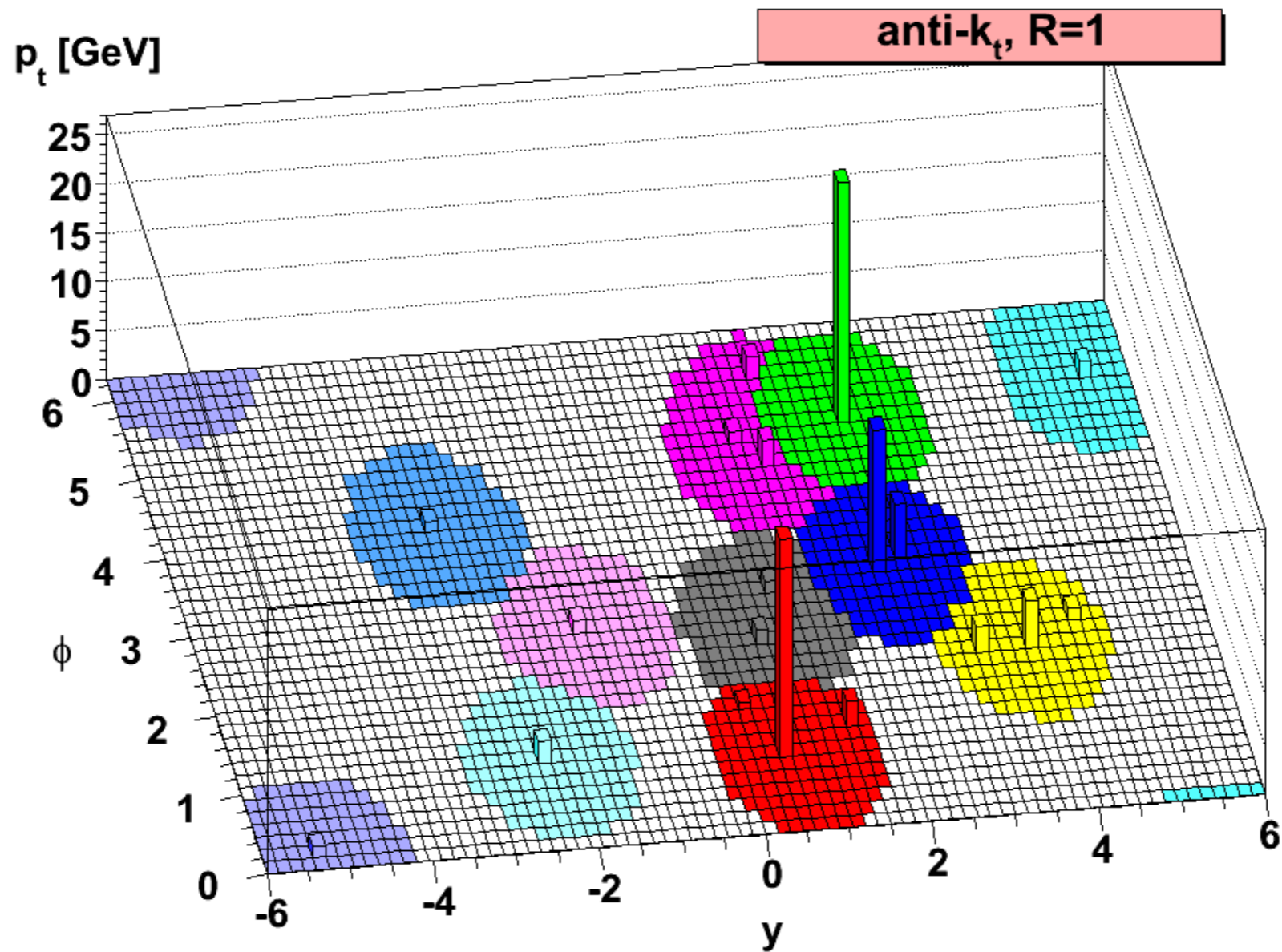
# Fixed R clustering



# Variable R jet clustering



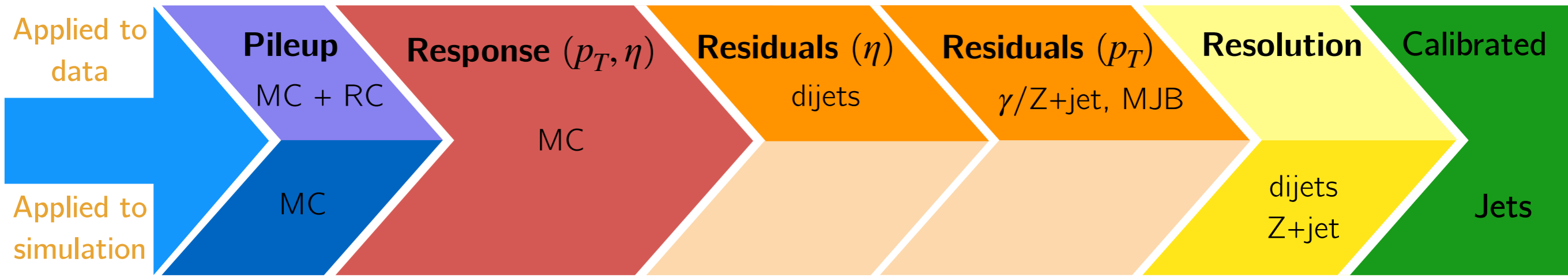
# Jet reconstruction



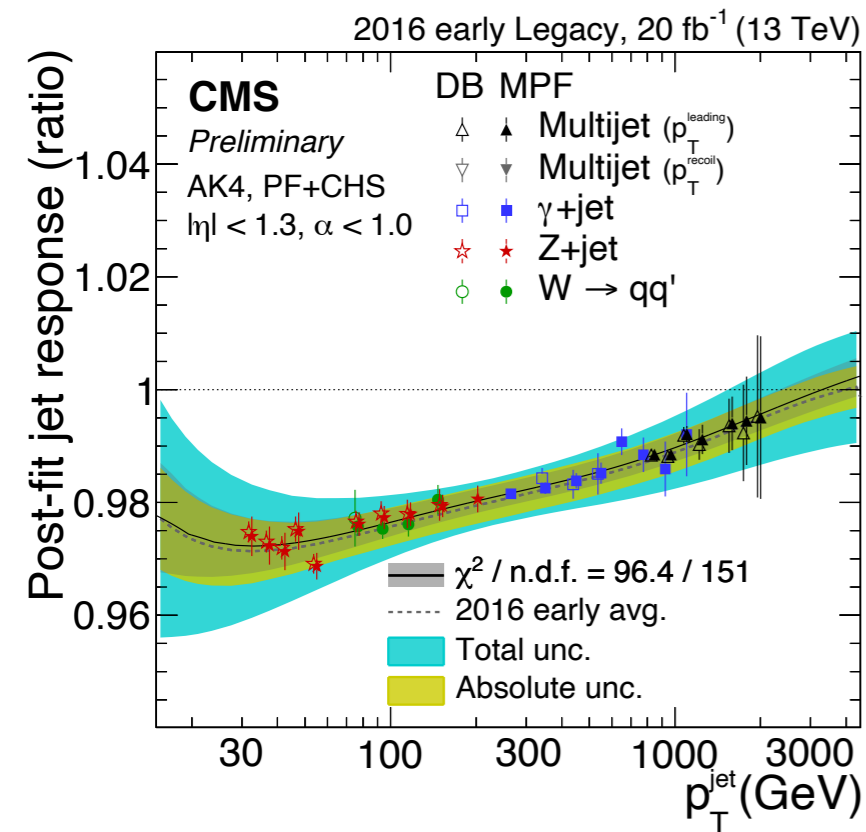
[arxiv:0802.1189](https://arxiv.org/abs/0802.1189)

# Jet calibration

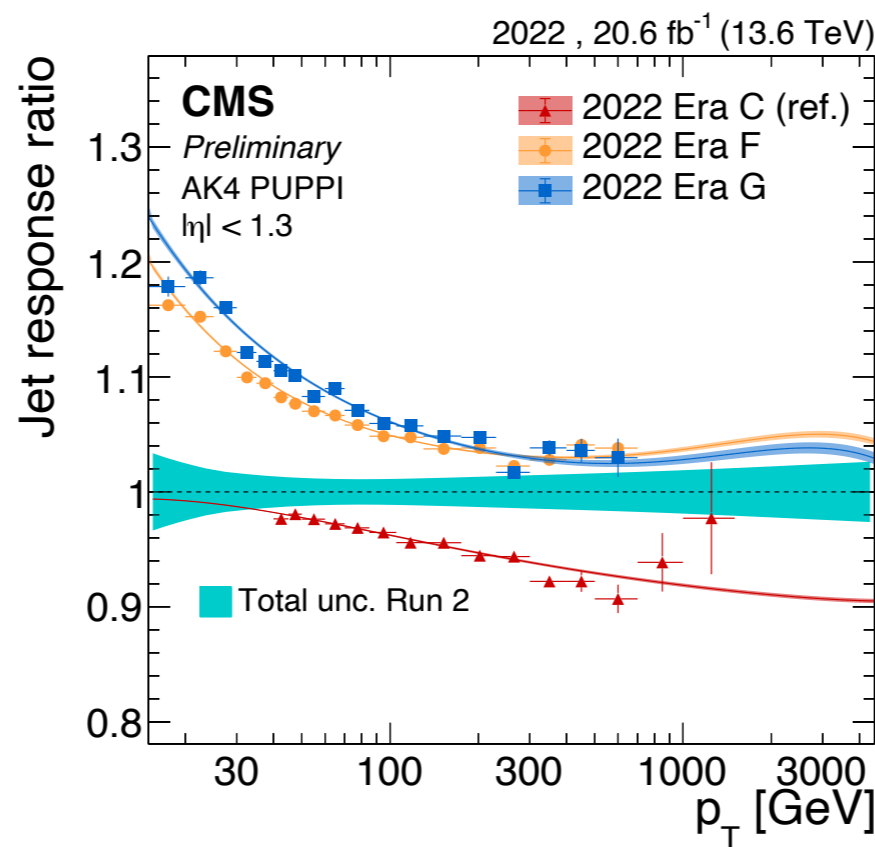
# Jet Calibration in Run3



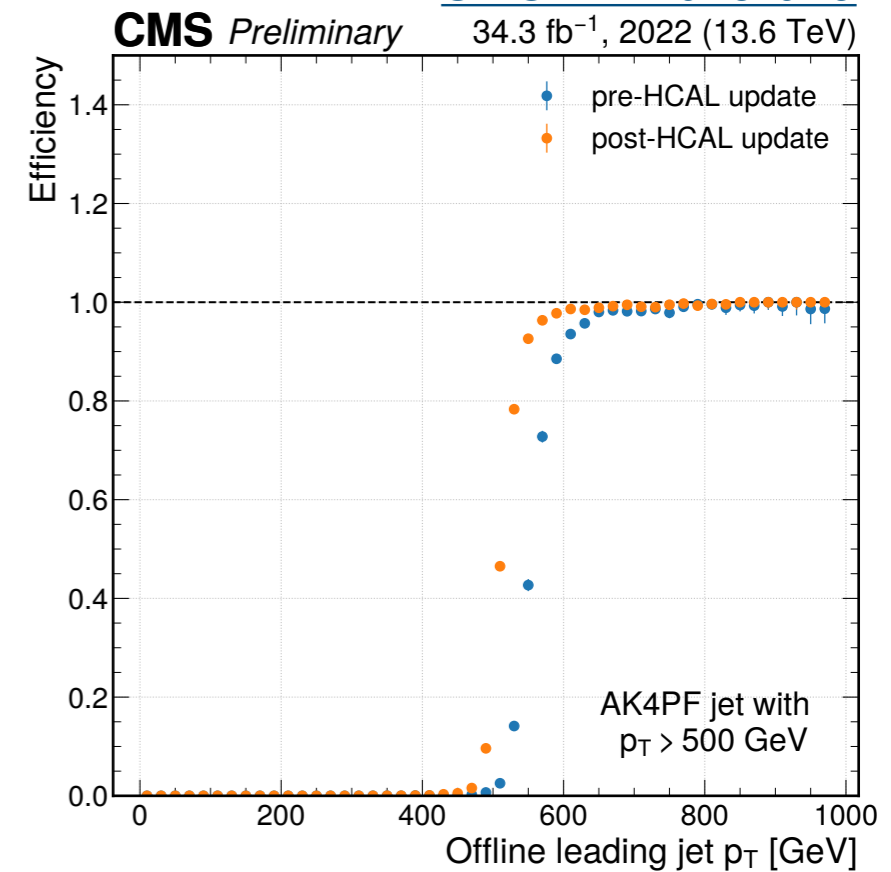
[CMS-DP-2021-033](#)



[CMS-DP-2022-054](#)



[CMS-DP-2023-016](#)



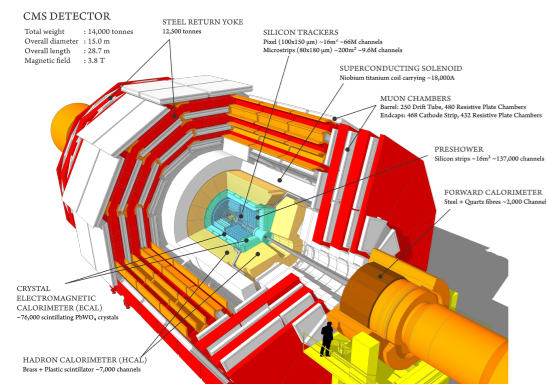
Run2



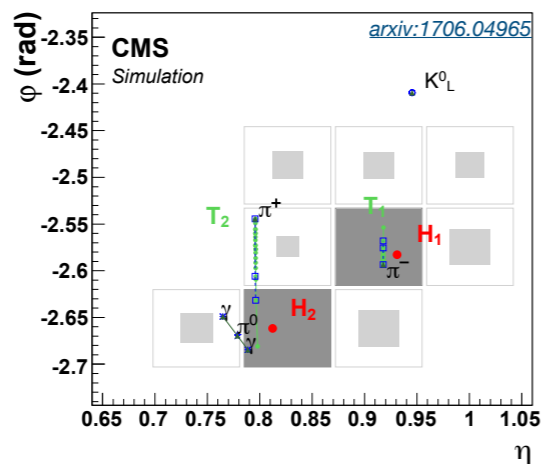
Run3

# Summary & Outlook

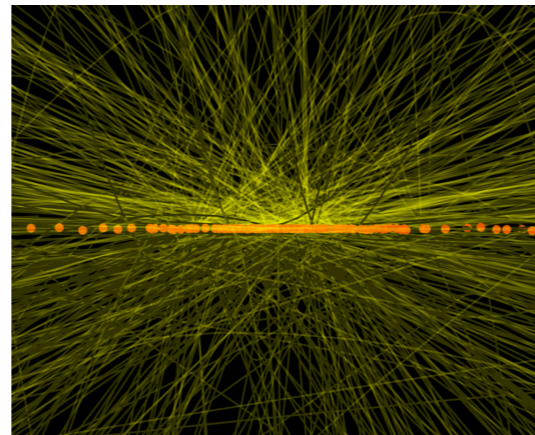
## Detector



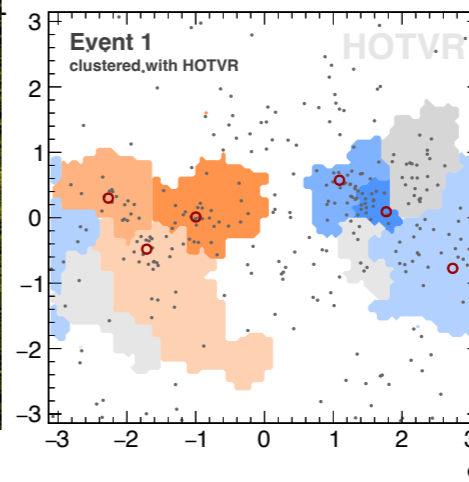
## Reconstruction



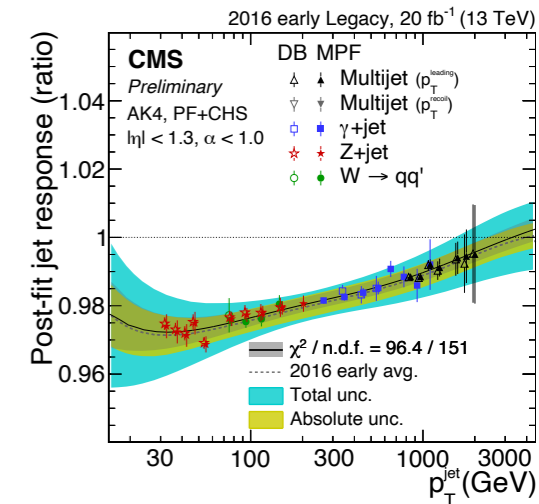
## Pileup



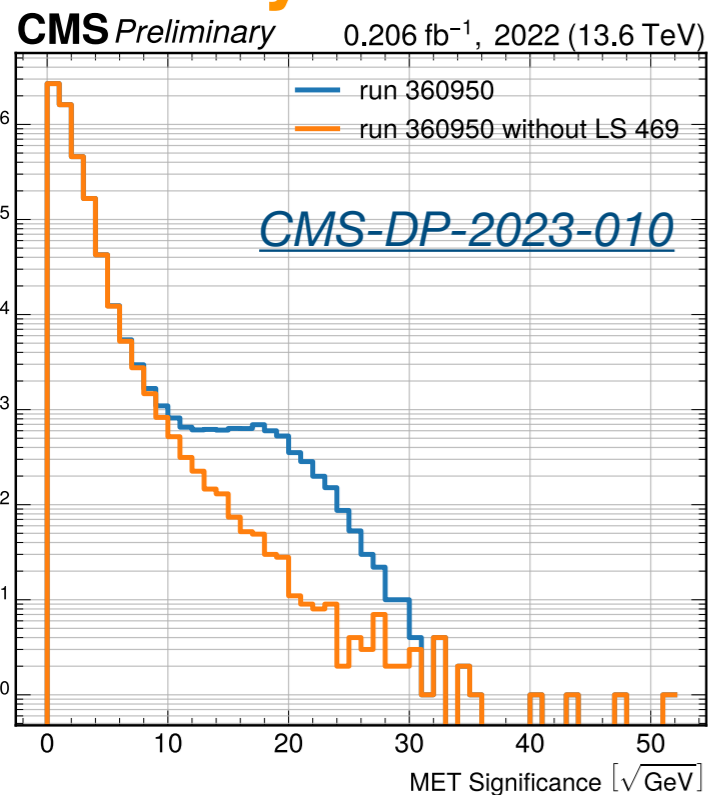
## Clustering



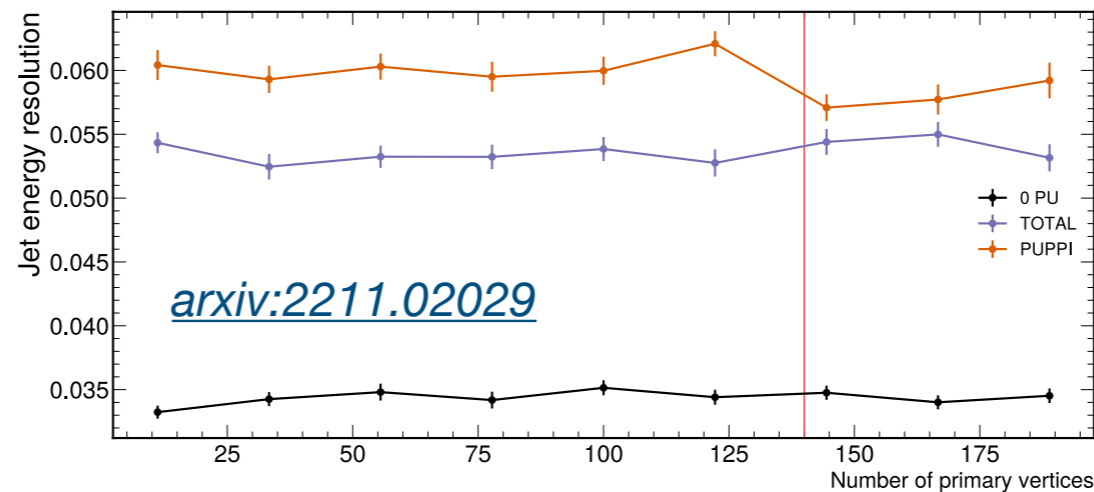
## Calibration



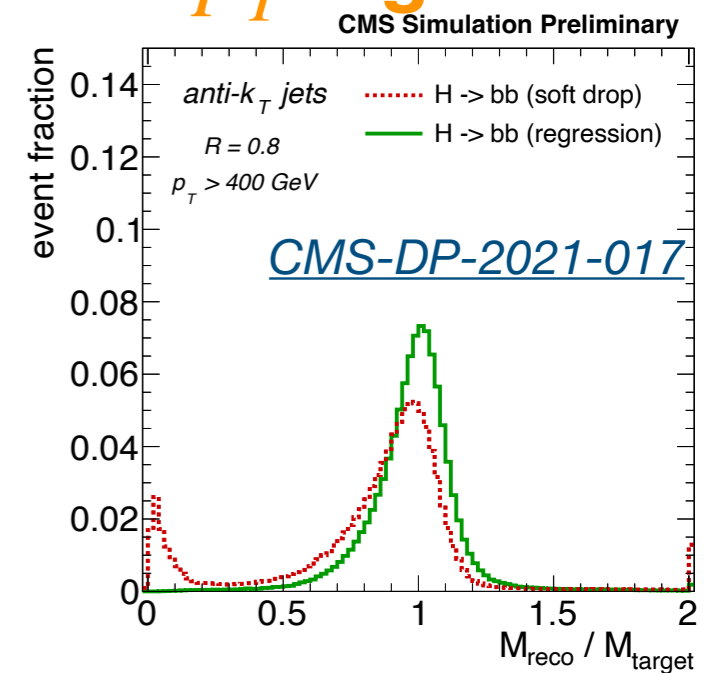
## Anomaly detection



## ML PU mitigation



## ML $p_T$ regression



# HOTVR

