# Jet performance and pileup mitigation in CMS

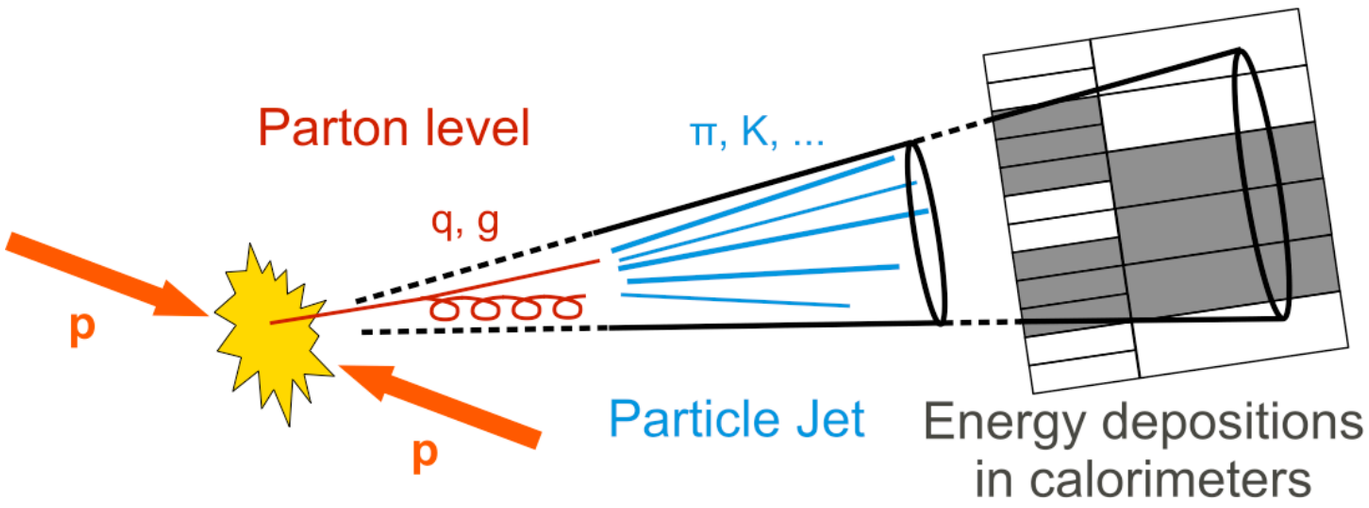
Garvita Agarwal (University at Buffalo)

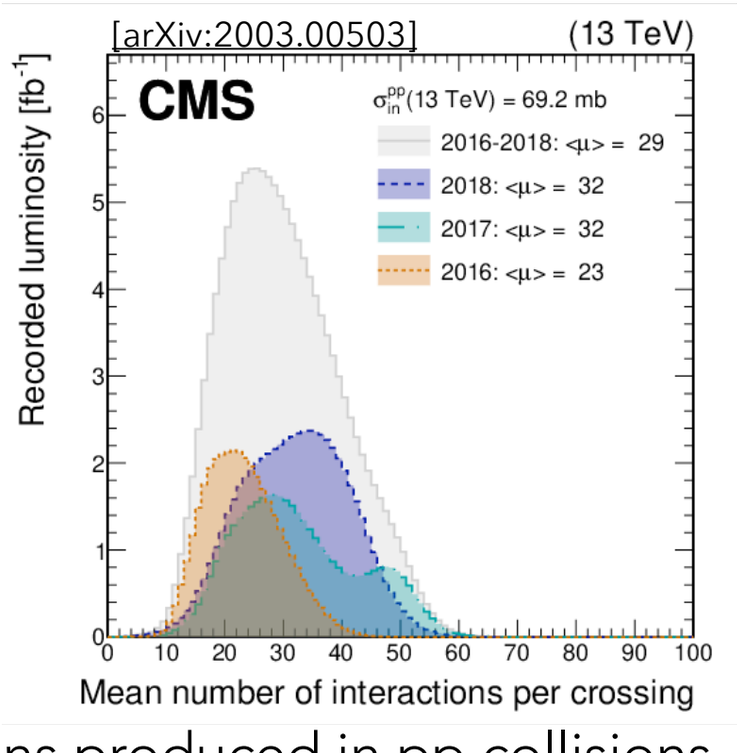
on behalf of the CMS Collaboration

Aug 18th, 2022

BOOST 2022 Hamburg

# Motivation

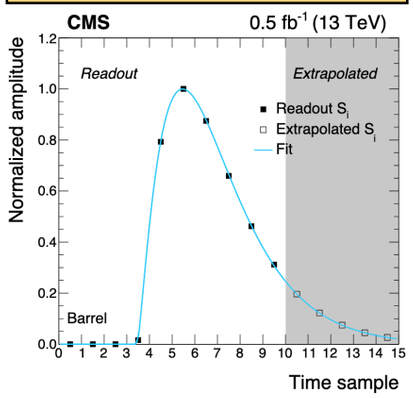


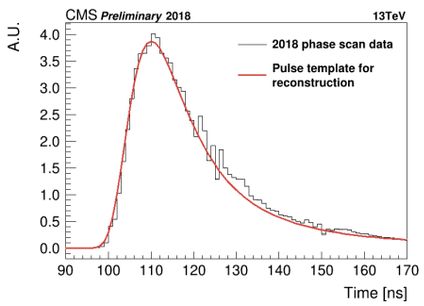

- Jets are the experimental signatures of quarks and gluons produced in pp collisions
- Jet production cross-section is several orders of magnitude higher than that of other processes
- Proper jet calibration is crucial for the majority of SM and BSM analyses and their associated systematic uncertainties e.g. top-mass measurements
- High event pileup (PU) presents a challenge for jet calibration and measurement. Average of 30 pp interactions per bunch crossing in Run2.

# Jet and MET reconstruction

ECAL pulse reconstruction

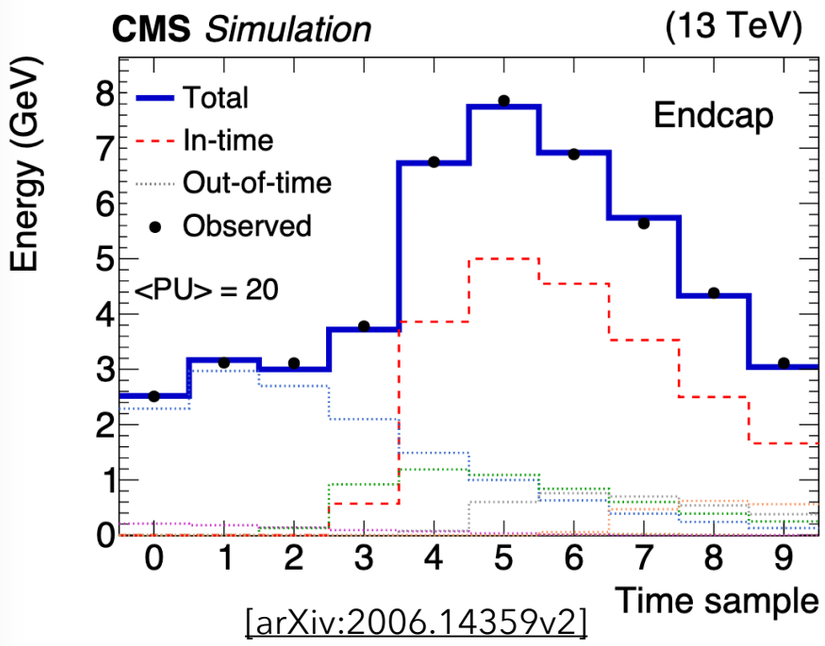



HCAL pulse reconstruction



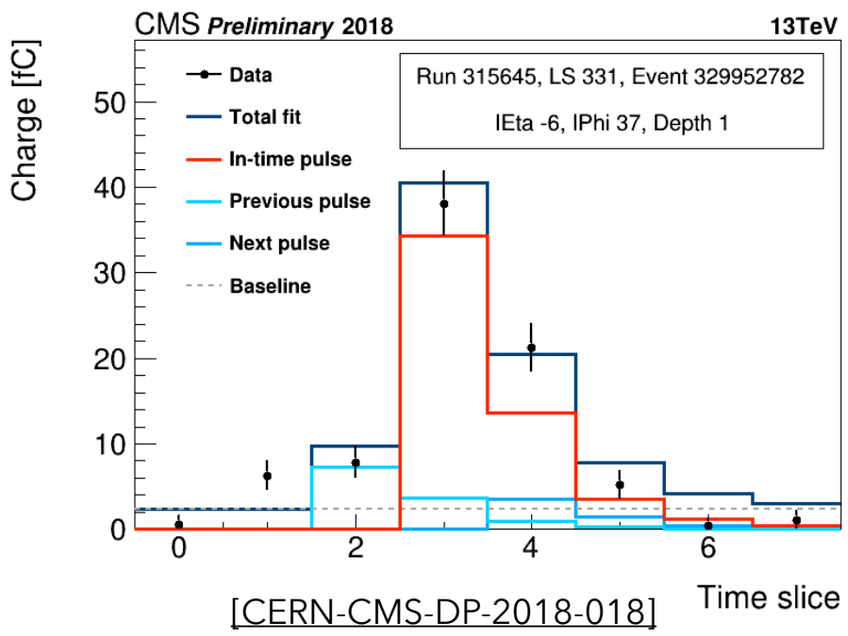

Track reconstruction

ECAL




[arXiv:2006.14359v2]

HCAL

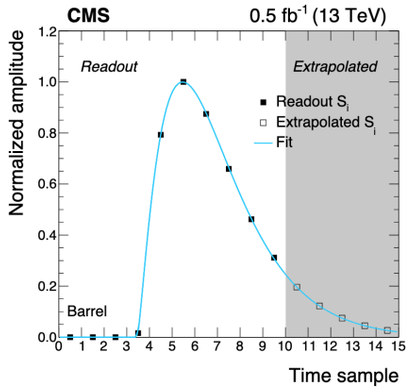



[CERN-CMS-DP-2018-018]

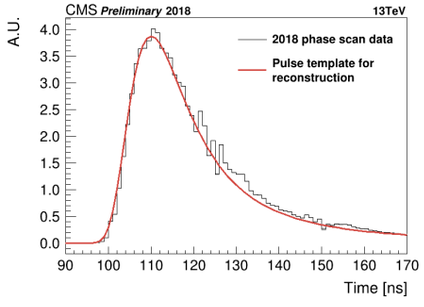
Multiple pulse shapes are fitted simultaneously to subtract OOT-PU.

# Jet and MET reconstruction

ECAL pulse reconstruction



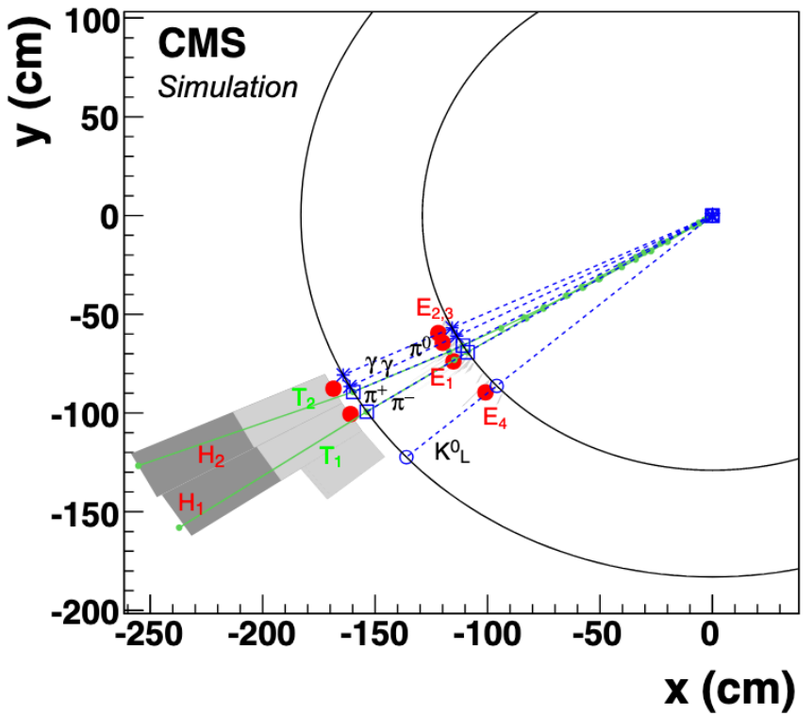

HCAL pulse reconstruction




Track reconstruction

PF cluster reconstruction and calibration

PF linking and global event reconstruction



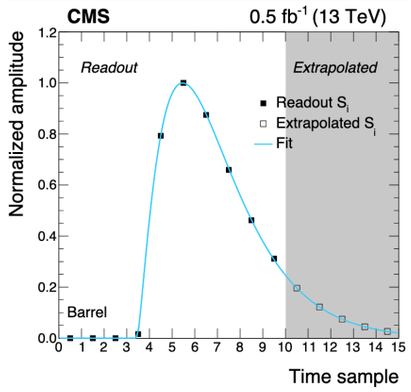

**Particle Flow (PF) algorithm** provides a global event description by combining information from various sub-detectors.

Identify stable final state particles as: **photons, electrons, neutral hadrons, charged hadrons, muons.**

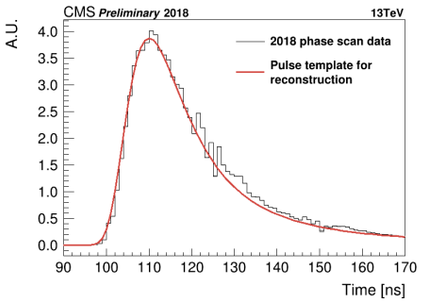
[arXiv:1706.04965v2]

# Jet and MET reconstruction

ECAL pulse reconstruction



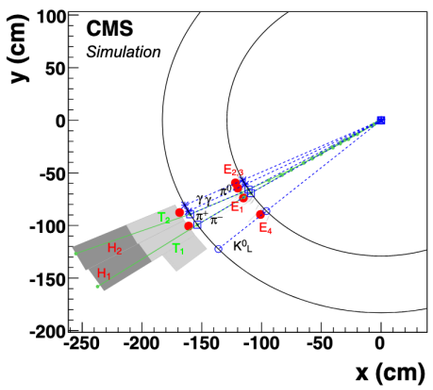

HCAL pulse reconstruction




Track reconstruction

PF cluster reconstruction and calibration

PF linking and global event reconstruction



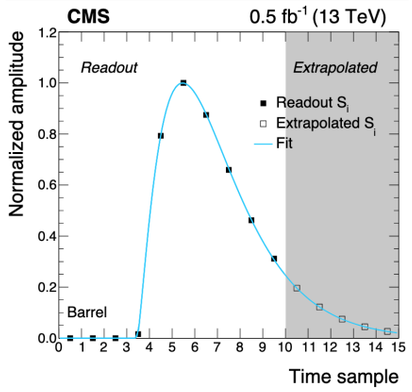

Pileup mitigation

Pileup mitigation **at the level of PF candidates**:

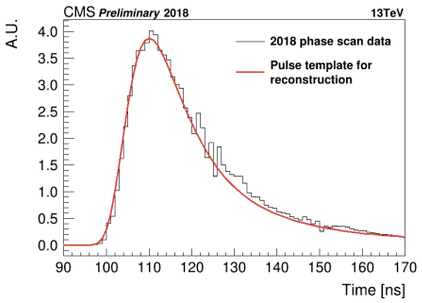
- Charged Hadron Subtraction (CHS)
- PileUp Per Particle Identification (PUPPI)

# Jet and MET reconstruction

ECAL pulse reconstruction



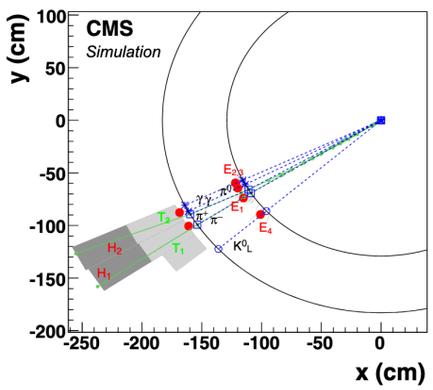

HCAL pulse reconstruction




Track reconstruction

PF cluster reconstruction and calibration

PF linking and global event reconstruction



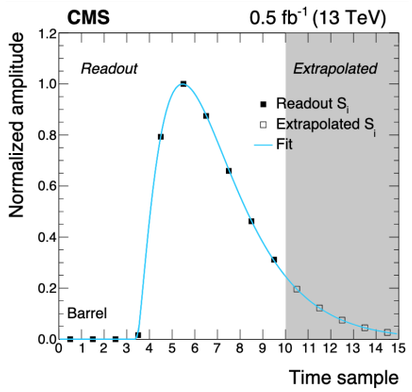

Pileup mitigation

MET

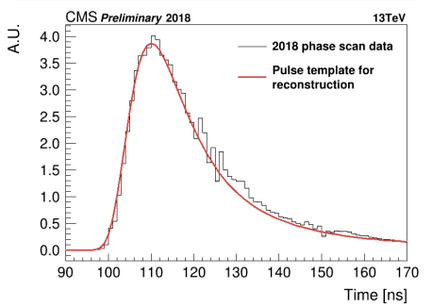
MET is the imbalance in the transverse momentum of all visible final state particles in an event.

# Jet and MET reconstruction

ECAL pulse reconstruction



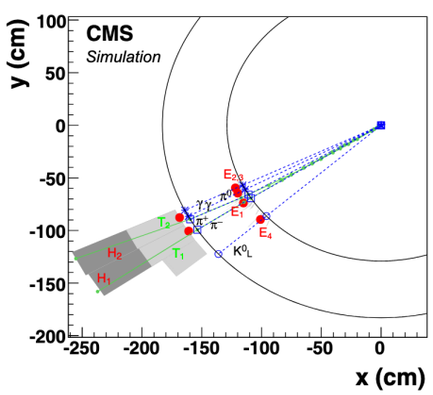

HCAL pulse reconstruction




Track reconstruction

PF cluster reconstruction and calibration

PF linking and global event reconstruction




Pileup mitigation

Jet clustering

MET

CMS standard for Run2:

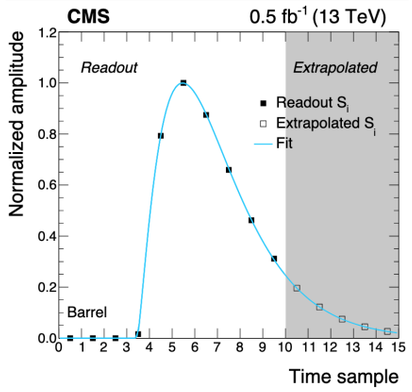
- Anti-kT jets with CHS for R = 0.4
- Anti-kT jets with PUPPI for R = 0.8

Default for Run3:

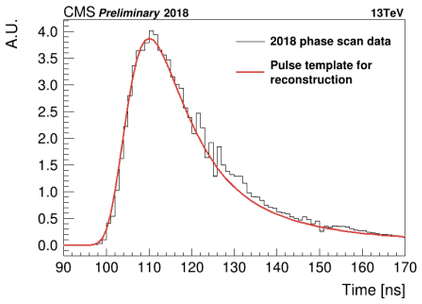
Anti-kT jets with PUPPI for R = 0.4, 0.8

# Jet and MET reconstruction

ECAL pulse reconstruction



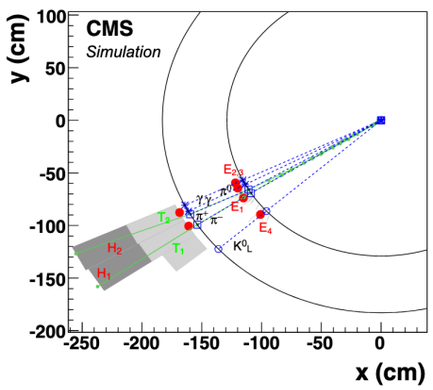

HCAL pulse reconstruction




Track reconstruction

PF cluster reconstruction and calibration

PF linking and global event reconstruction




Pileup mitigation

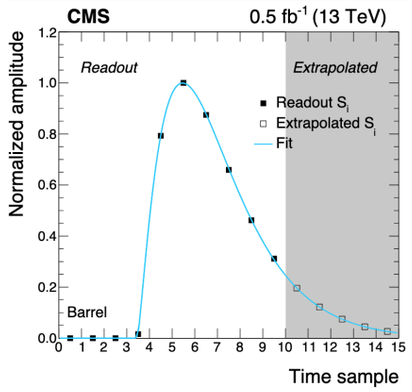
MET

Jet clustering

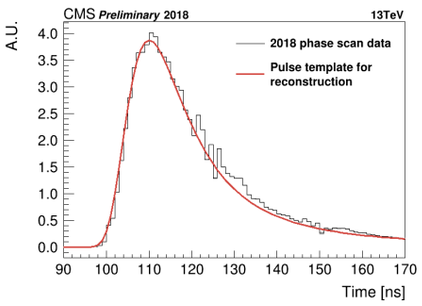
Jet and MET calibrations

# Jet and MET reconstruction

ECAL pulse reconstruction



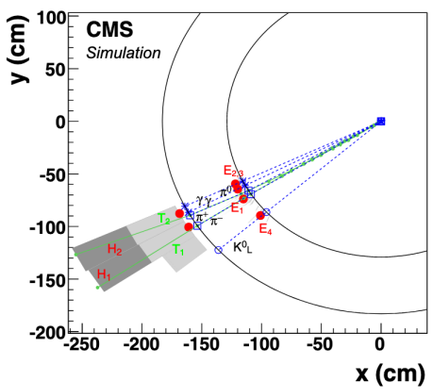

HCAL pulse reconstruction




Track reconstruction

PF cluster reconstruction and calibration

PF linking and global event reconstruction




Pileup mitigation

MET

Jet clustering

Jet and MET calibrations

PU Jet ID

Flavor tagging

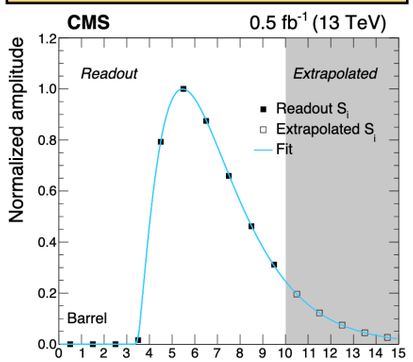
Quark-gluon jet ID

W/t/Z/H tagging

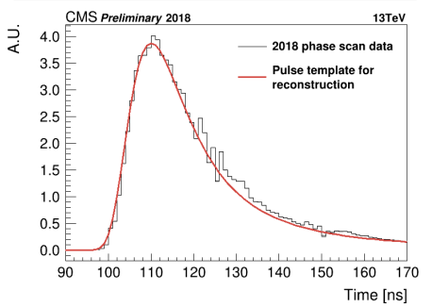
- Poster on jet tagging at CMS by Brendan Regnery

# Jet and MET reconstruction

ECAL pulse reconstruction



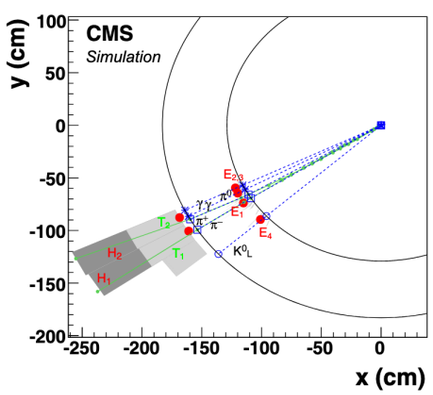

HCAL pulse reconstruction




Track reconstruction

PF cluster reconstruction and calibration

PF linking and global event reconstruction




Pileup mitigation

MET

Jet clustering

PU Jet ID

Flavor tagging

Jet and MET calibrations

Quark-gluon jet ID

W/t/Z/H tagging

Type-I corrections

# PU mitigation techniques

- *Pileup(PU):* Multiple pp collisions in the same and neighbouring bunch crossing. Produces additional unwanted tracks and calorimeter deposits
- *Charge Hadron Subtraction (CHS):* removes charged particles originating from PU vertices. Drawbacks:
  - Only works within tracker coverage
  - Only removes charged contribution
- *Pileup Per Particle Identification (PUPPI):* uses local shape information to reduce pileup on jet variables by deriving per-particle weights. Weights used to scale 4-momenta before clustering

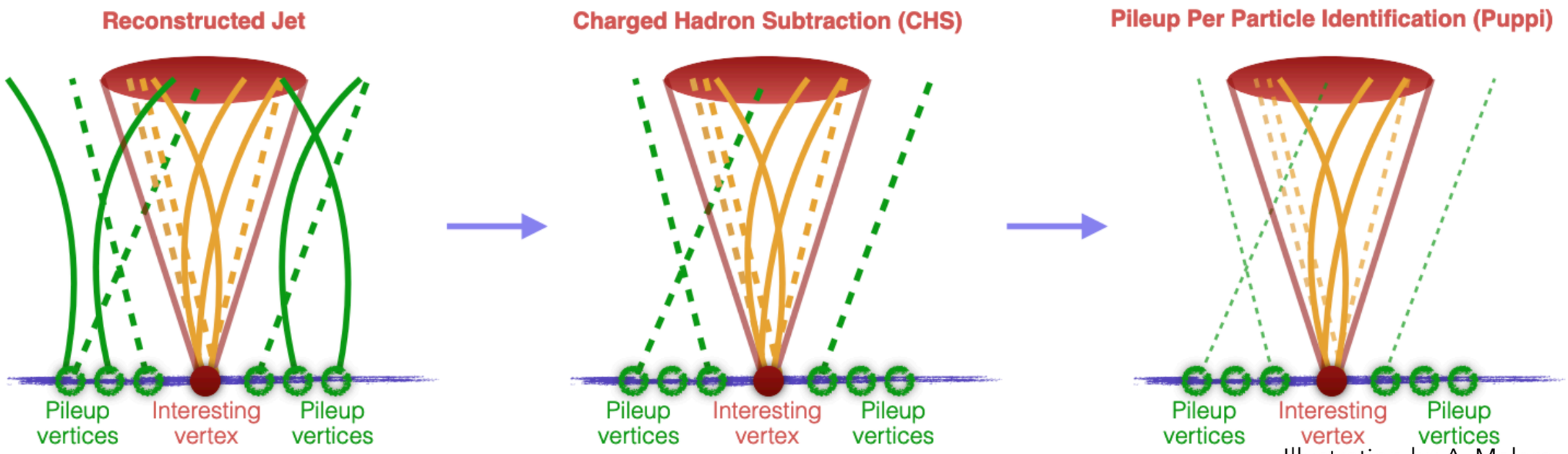
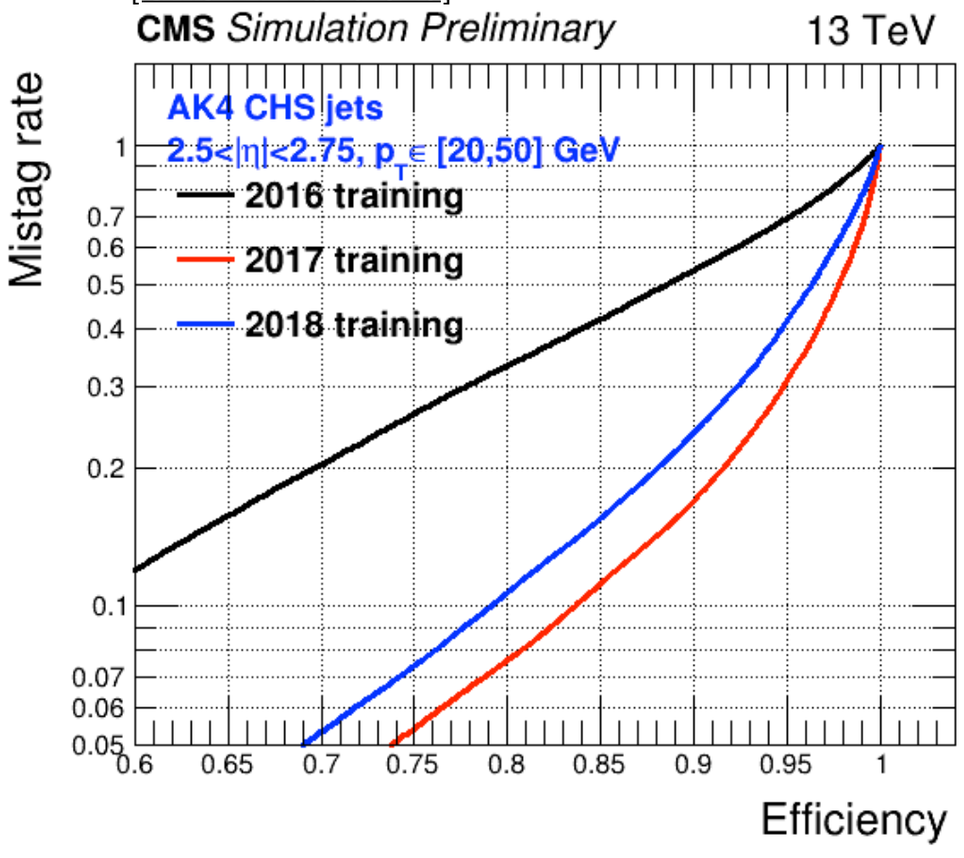


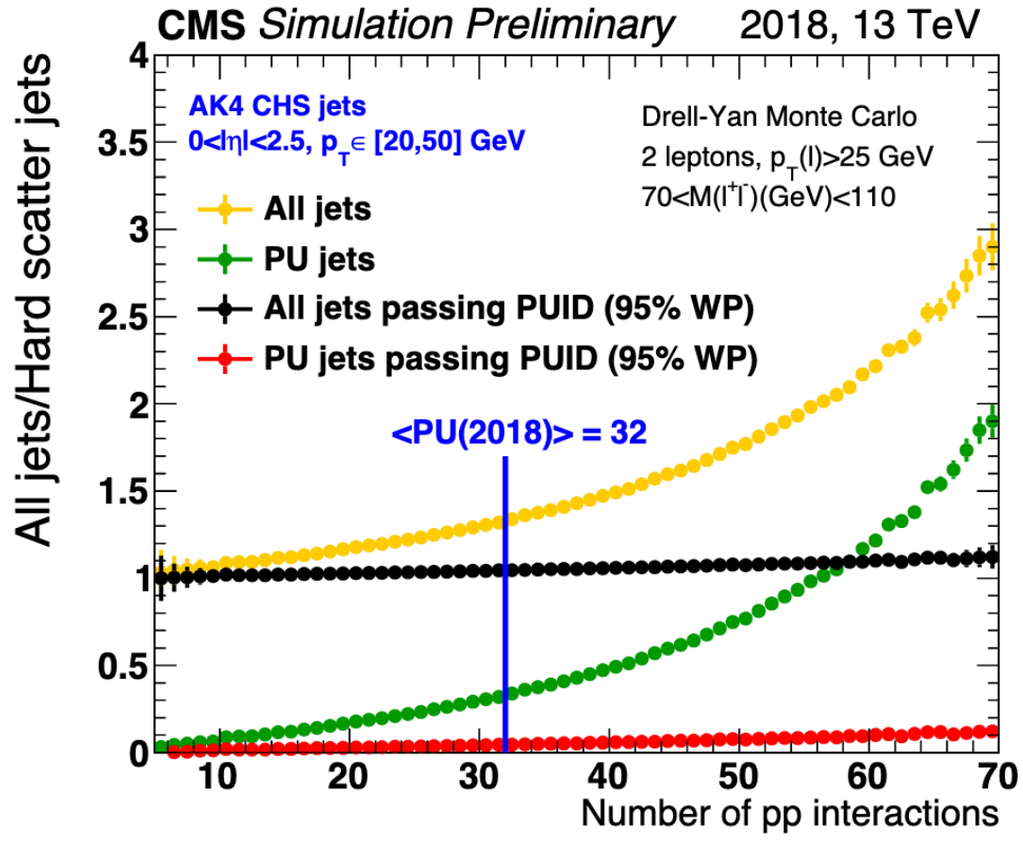

Illustration by A. Malara

# PU jet ID

- Multi-variant technique to identify and reject low $p_T$ jets coming from PU. Identification based on:
  - PU jets contain more tracks from PU vertices than from the leading vertex
  - PU jets more diffuse
- Large improvements from the new pixel detector: $|\eta|$ coverage extended to 2.7 from 2.5
- Loose working point corresponding to a 95% efficiency provides low mistag rate and high rejection power.

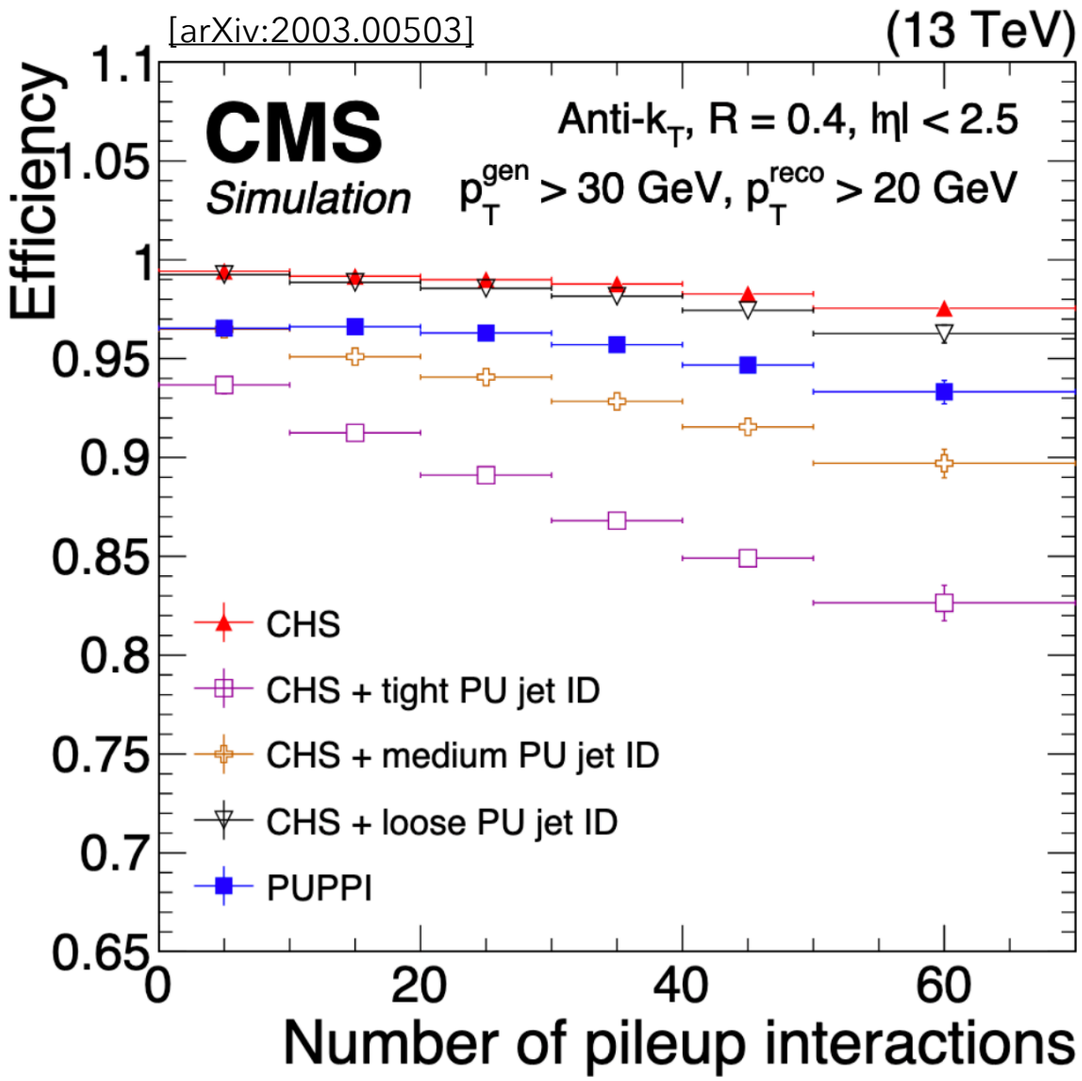
[CMS-DP-2020-020]

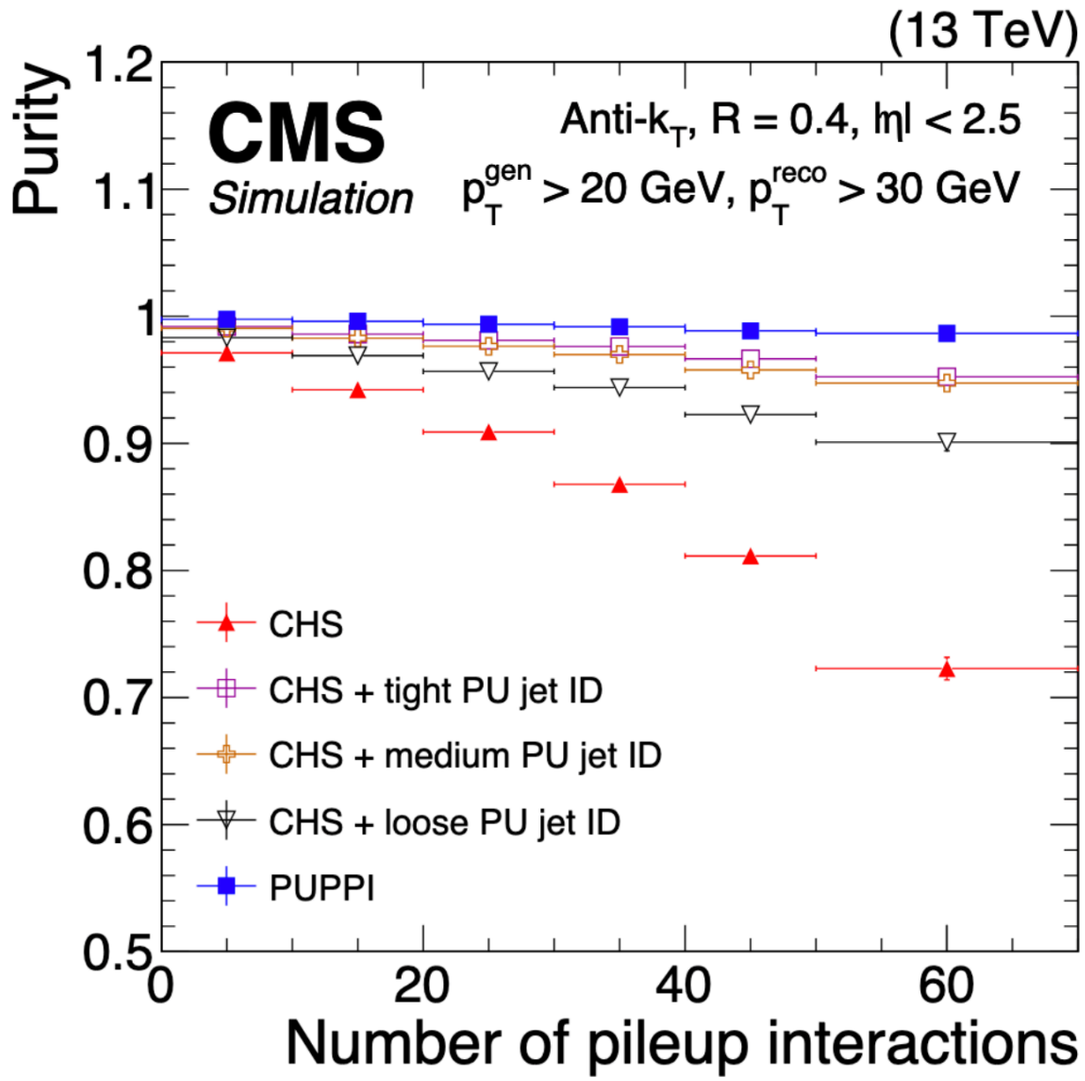


# CHS vs PUPPI

[arXiv:2003.00503]

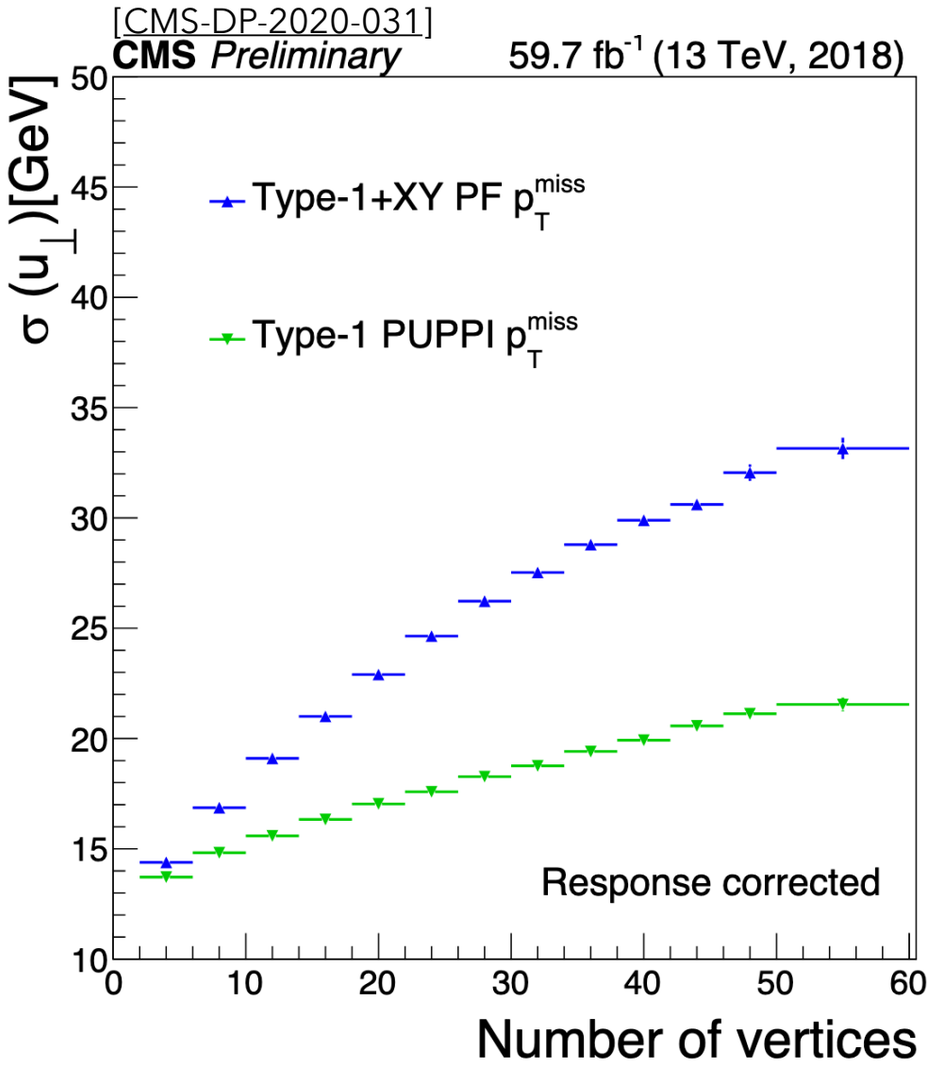



- CHS efficiency is close to100% but purity impacted in high PU scenarios
- CHS + PU jet ID improves the purity
- PUPPI has a good performance in both efficiency and purity

# PF MET and PUPPI MET

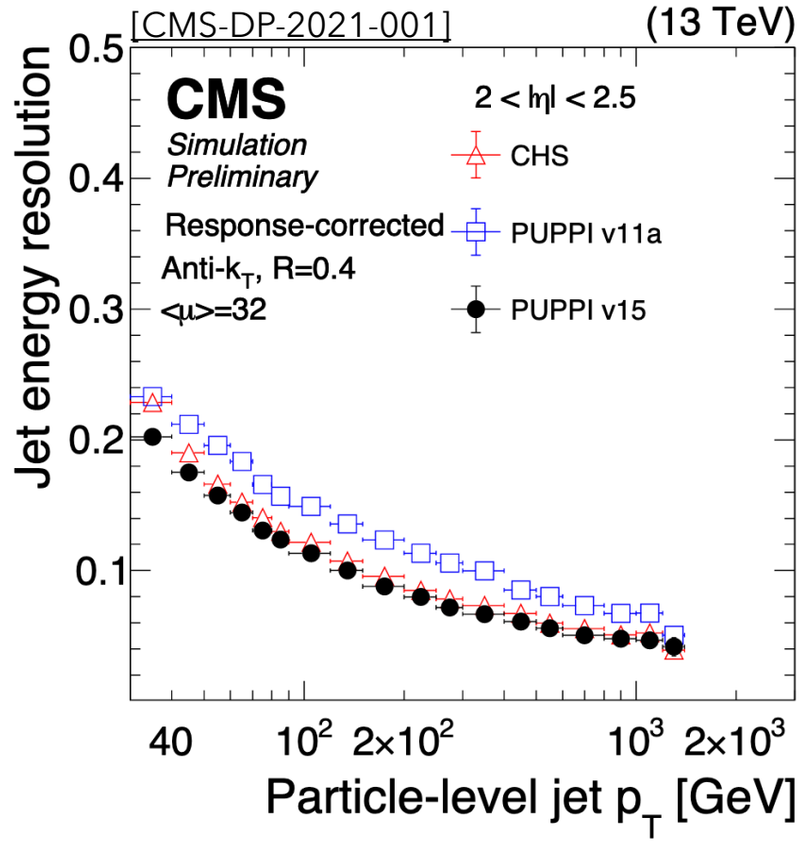
- **PF MET**
  - the negative vector sum of the pT of all the PF candidates in an event
  - used in the majority of the CMS analysis in Run 2
  - provides a simple, robust MET reconstruction
- **PUPPI MET**
  - calculated using the PUPPI weighted momenta of PF candidates

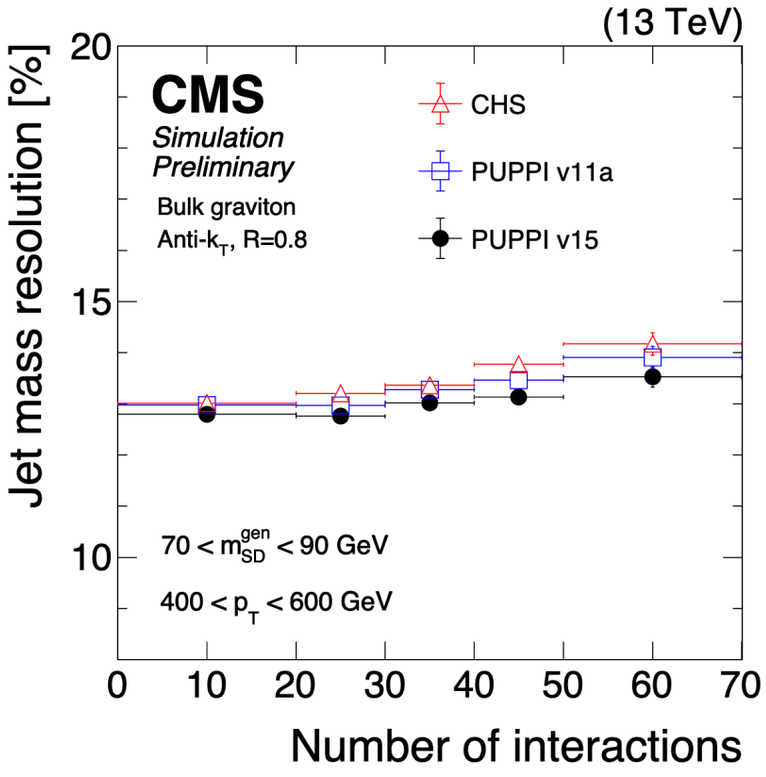


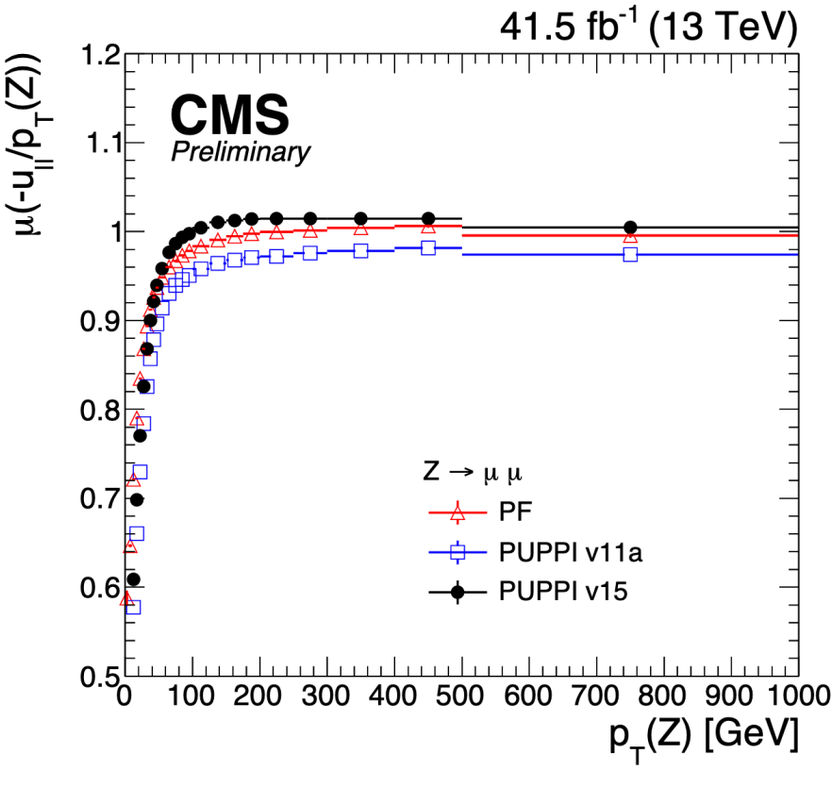

- MET is improved by correcting the scale of the jets to the particle level using the jet energy corrections and propagating these corrections to MET

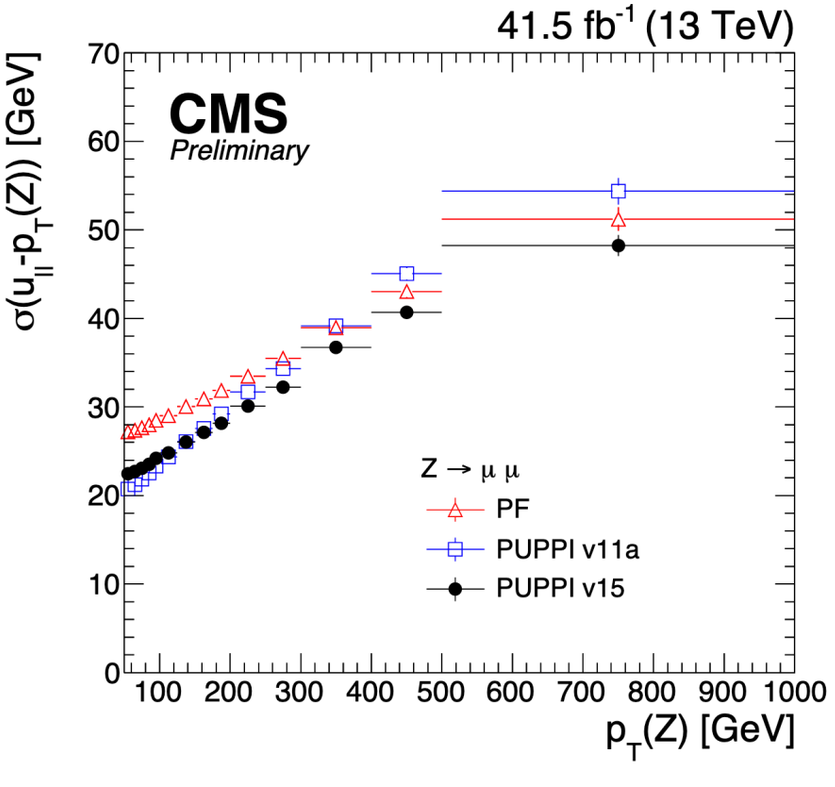
# PUPPI for Run3

- PUPPI v11a used widely in Run2
- New iteration of PUPPI (v15) aimed to improve JER for high $p_T$ jets
- Used in Run2 UL reconstruction and default in Run3
- Substructure variables like soft drop mass and mass resolution stable against pileup.
- Improved PUPPI MET resolution compared to PF MET for hadronic recoils up to more than 500 GeV.

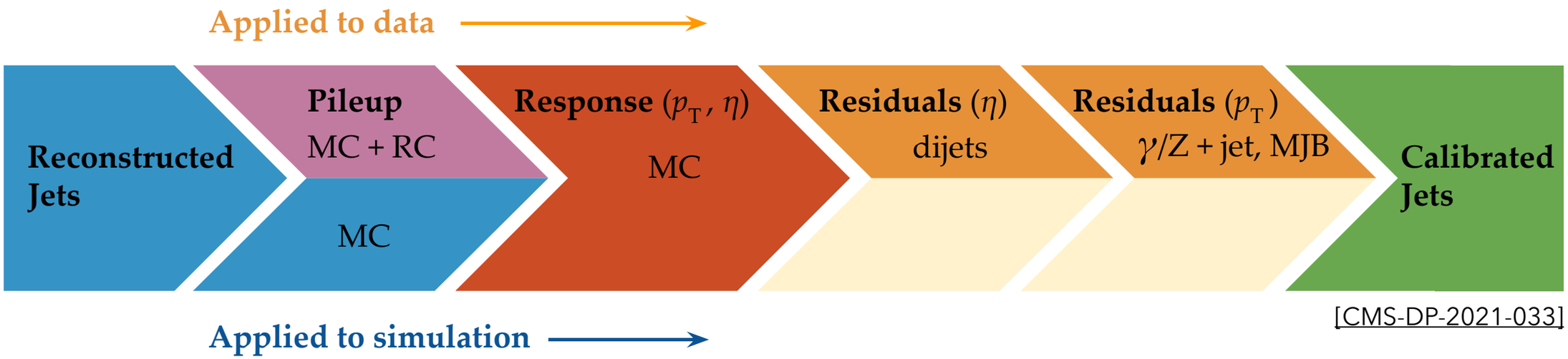


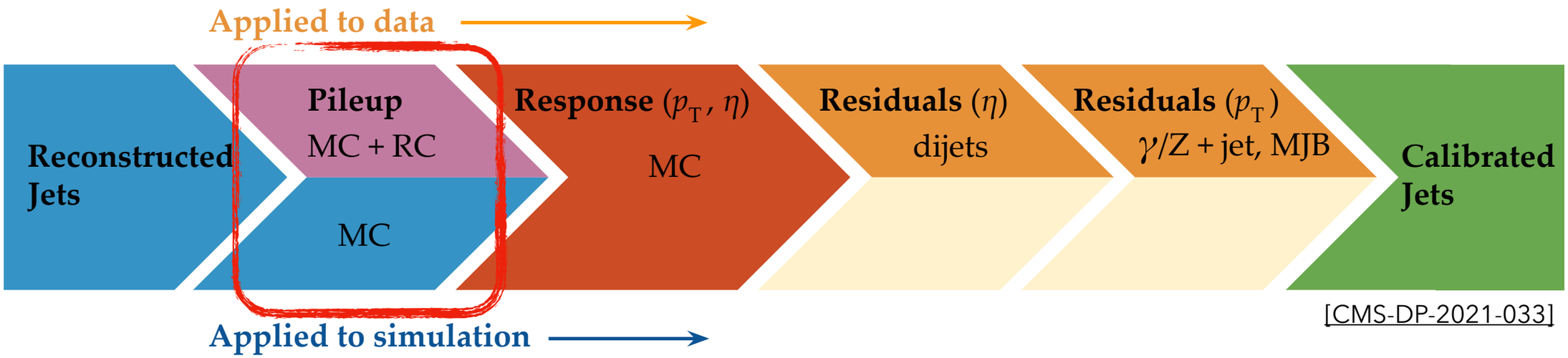
# Jet calibration at CMS




[CMS-DP-2021-033]

- CMS follows a factorised approach to correct the energy of reconstructed jets to match that of the particle-level jet

# Jet calibration at CMS

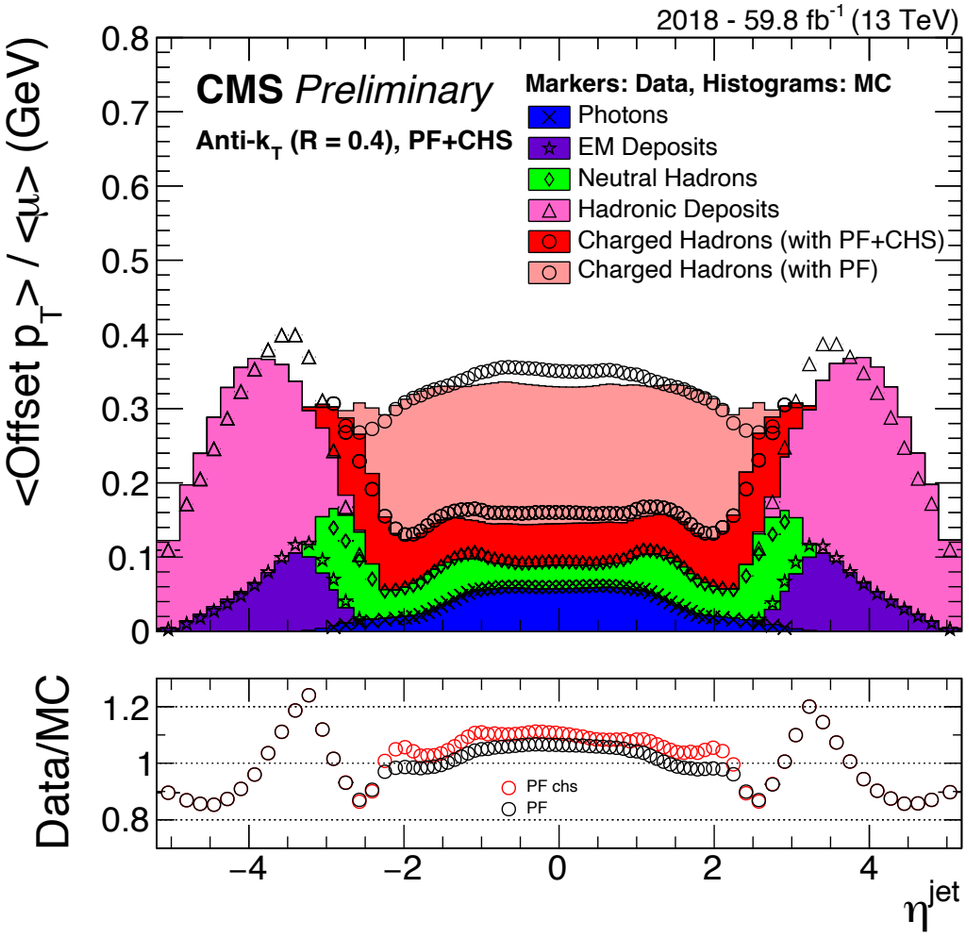



[CMS-DP-2021-033]

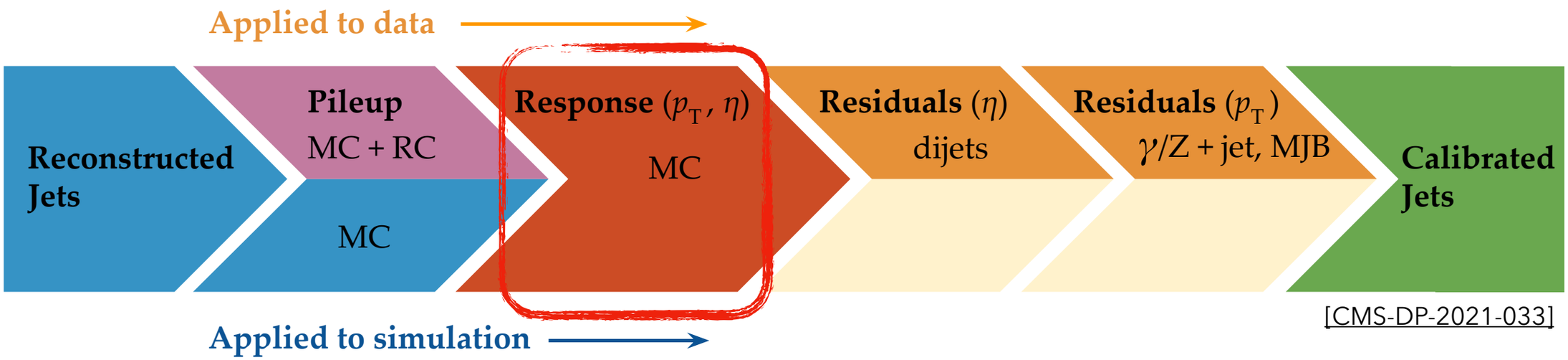
## *Pileup offset correction*

- Pileup offset in simulation - calculated by taking the average difference in $p_T$ between matched jets in simulated samples with and without pileup overlay

- Residual offset correction using data are derived using Random Cone (RC) method



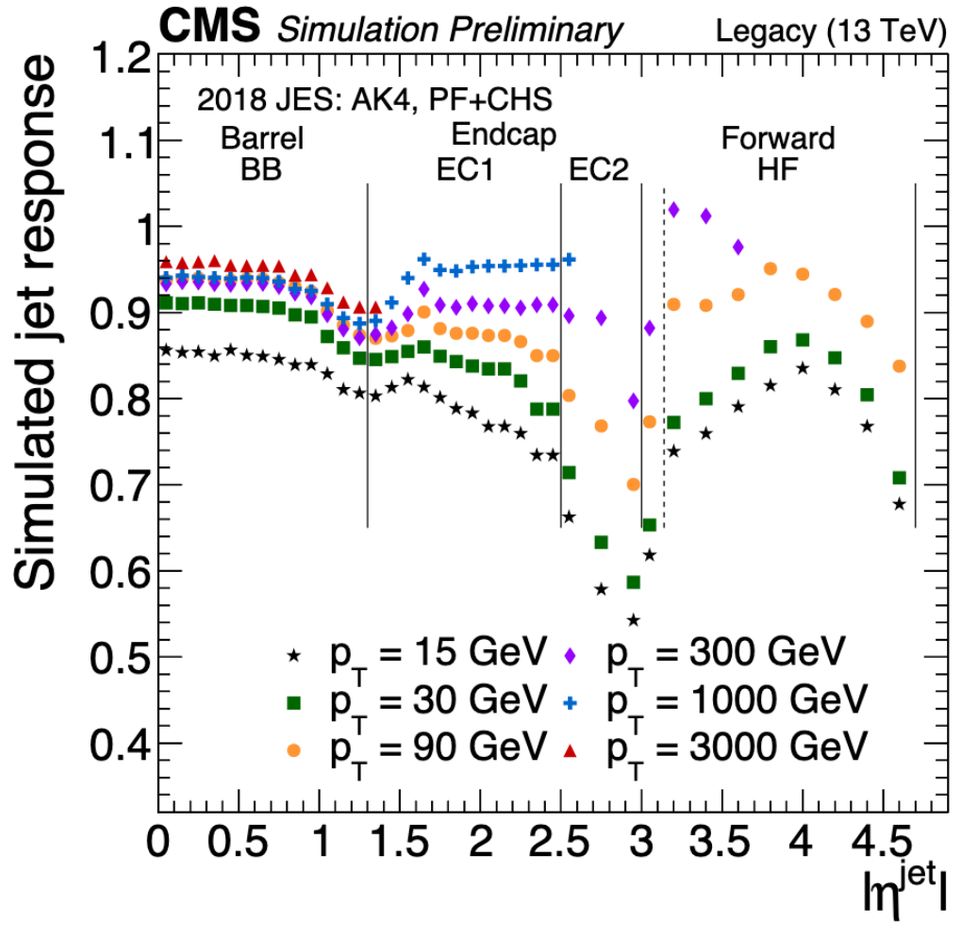
# Jet calibration at CMS



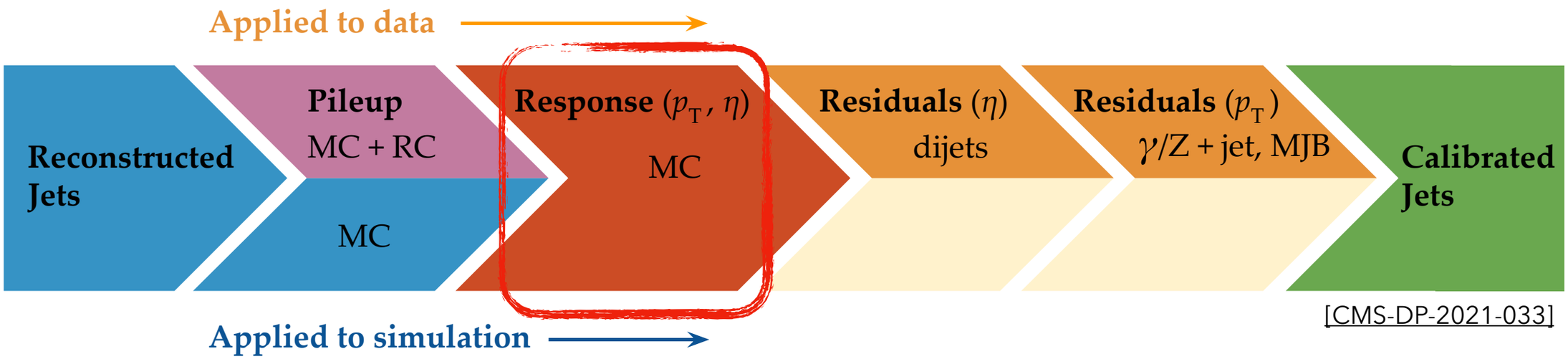

[CMS-DP-2021-033]

## *Jet response calibration*

- Addresses the non-uniformity of the detector response as a function of $p_T$ and $\eta$ of the jet
- Derived from jets that are already corrected for pileup offset
- Change in performance at high $|\eta|$ and low $p_T$ due to detector acceptance



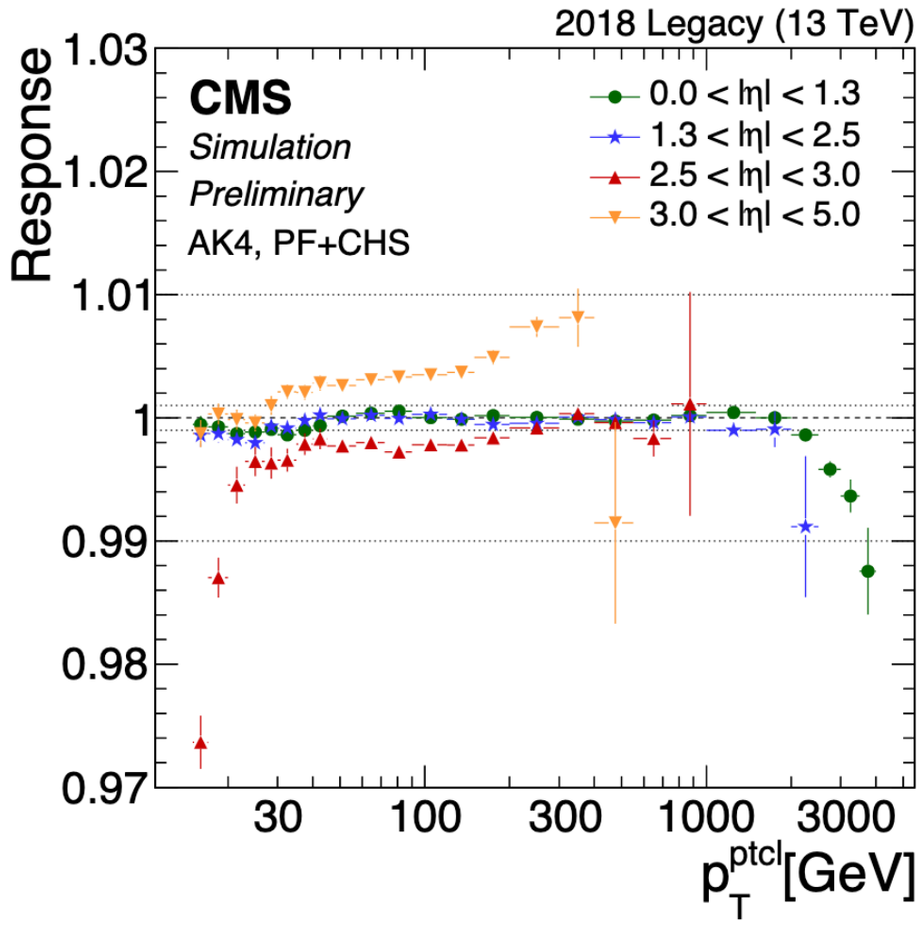
# Jet calibration at CMS



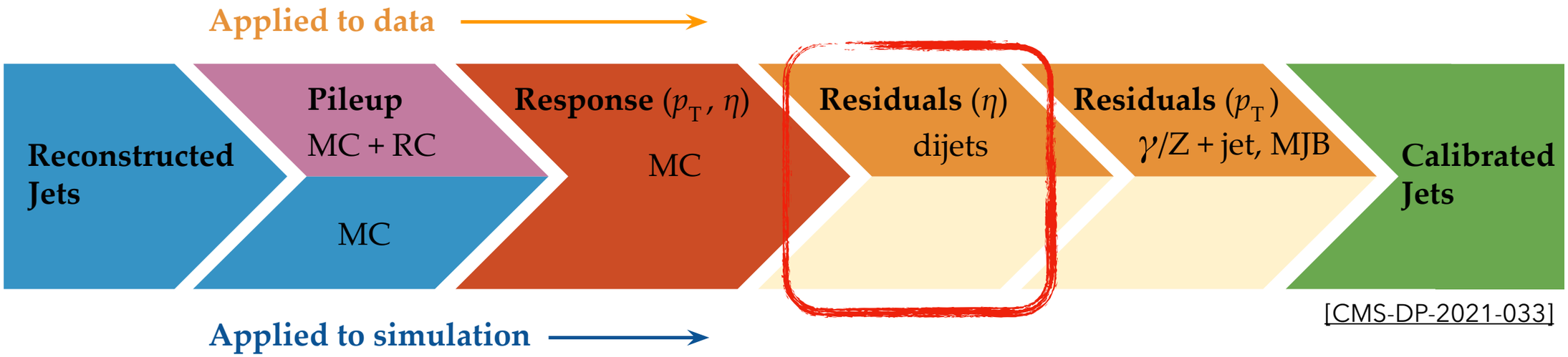

[CMS-DP-2021-033]

## *Jet response calibration*

- Addresses the non-uniformity of the detector response as a function of $p_T$ and $\eta$ of the jet
- Derived from jets that are already corrected for pileup offset
- Change in performance at high $|\eta|$ and low $p_T$ due to detector acceptance



# Jet calibration at CMS

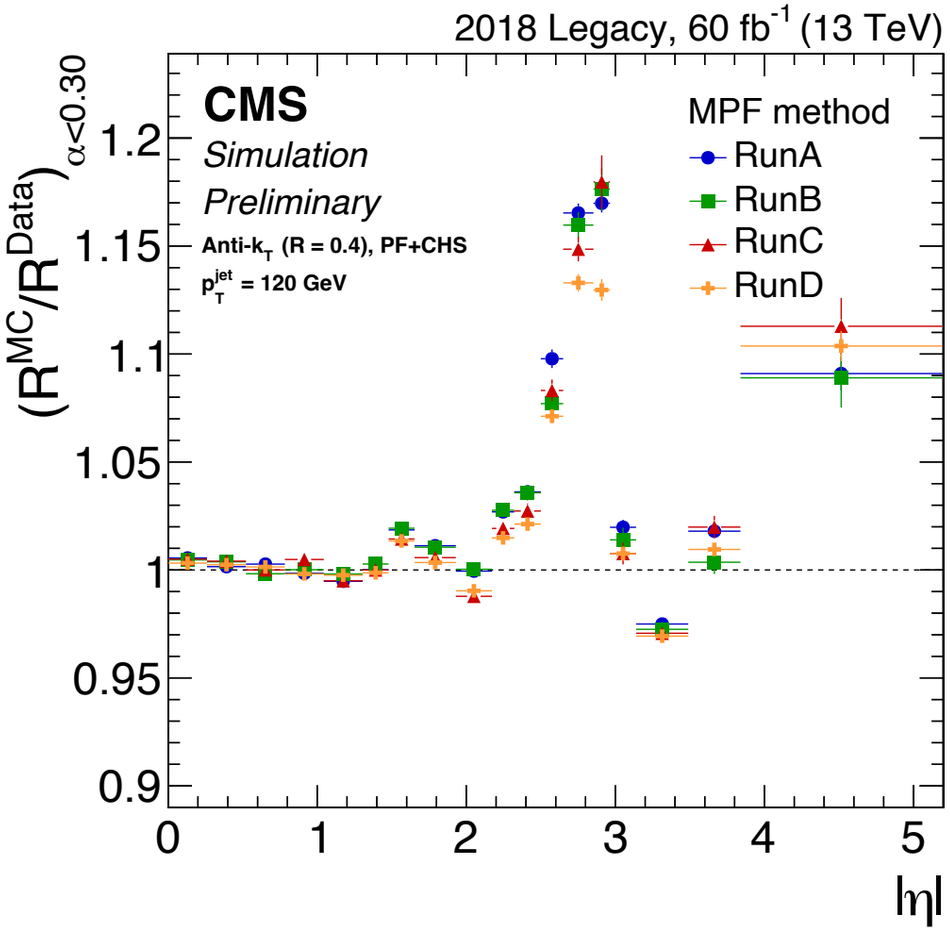



[CMS-DP-2021-033]

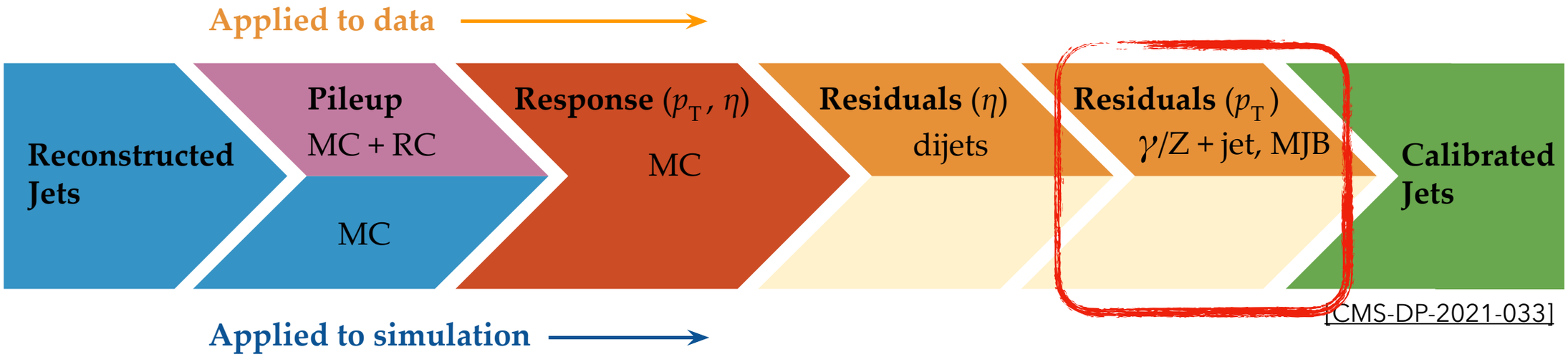
## *Residual response corrections vs. η*

- Residual corrections for data as a function of jet η are determined with dijet events.

- The response is derived using the Missing transverse momentum Projection Fraction (MPF) method



# Jet calibration at CMS

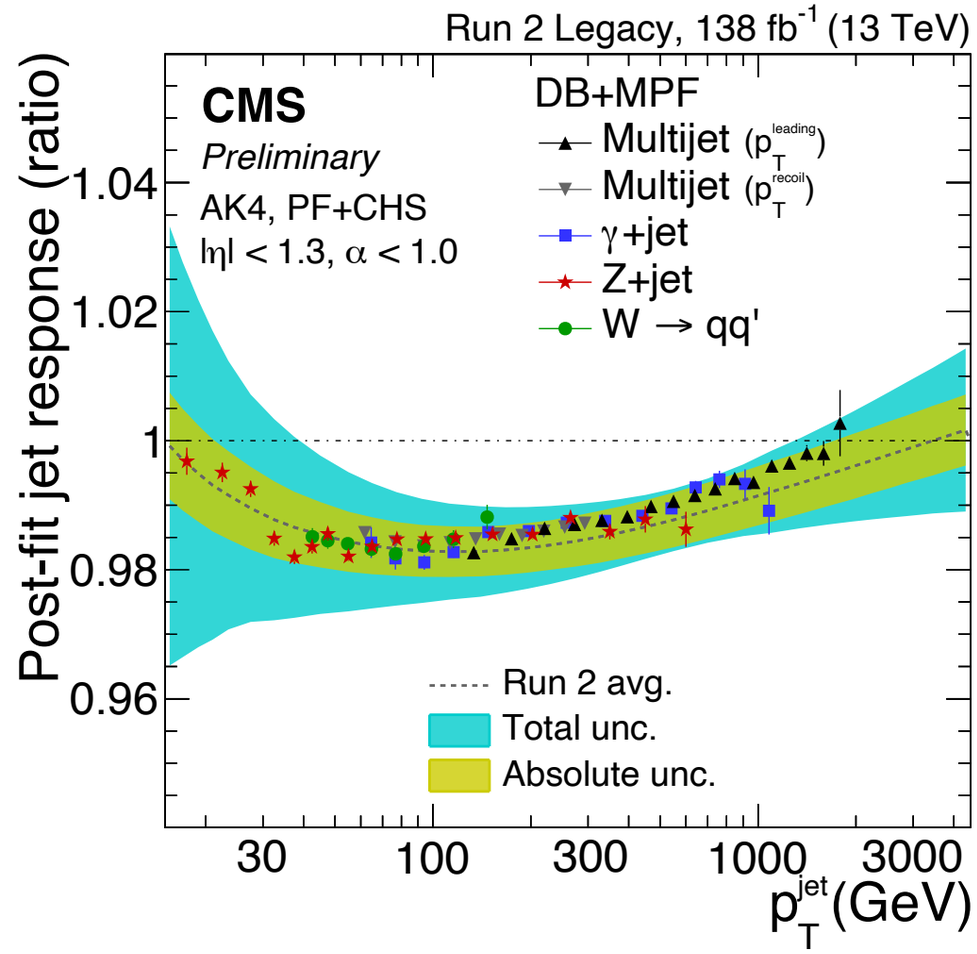



[CMS-DP-2021-033]

## *Residual response corrections vs. $p_T$*

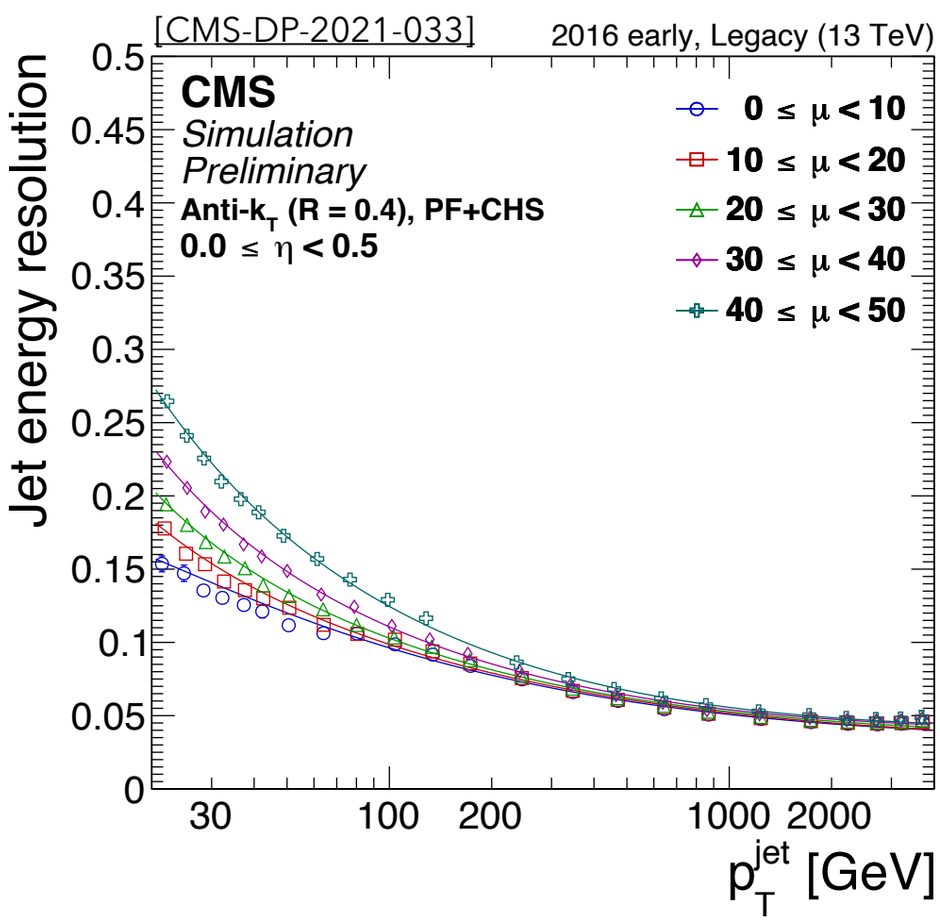
- Residual corrections for data as a function of jet $p_T$ derived by exploiting the $p_T$ balance between the jet to be calibrated and a precisely calibrated reference object

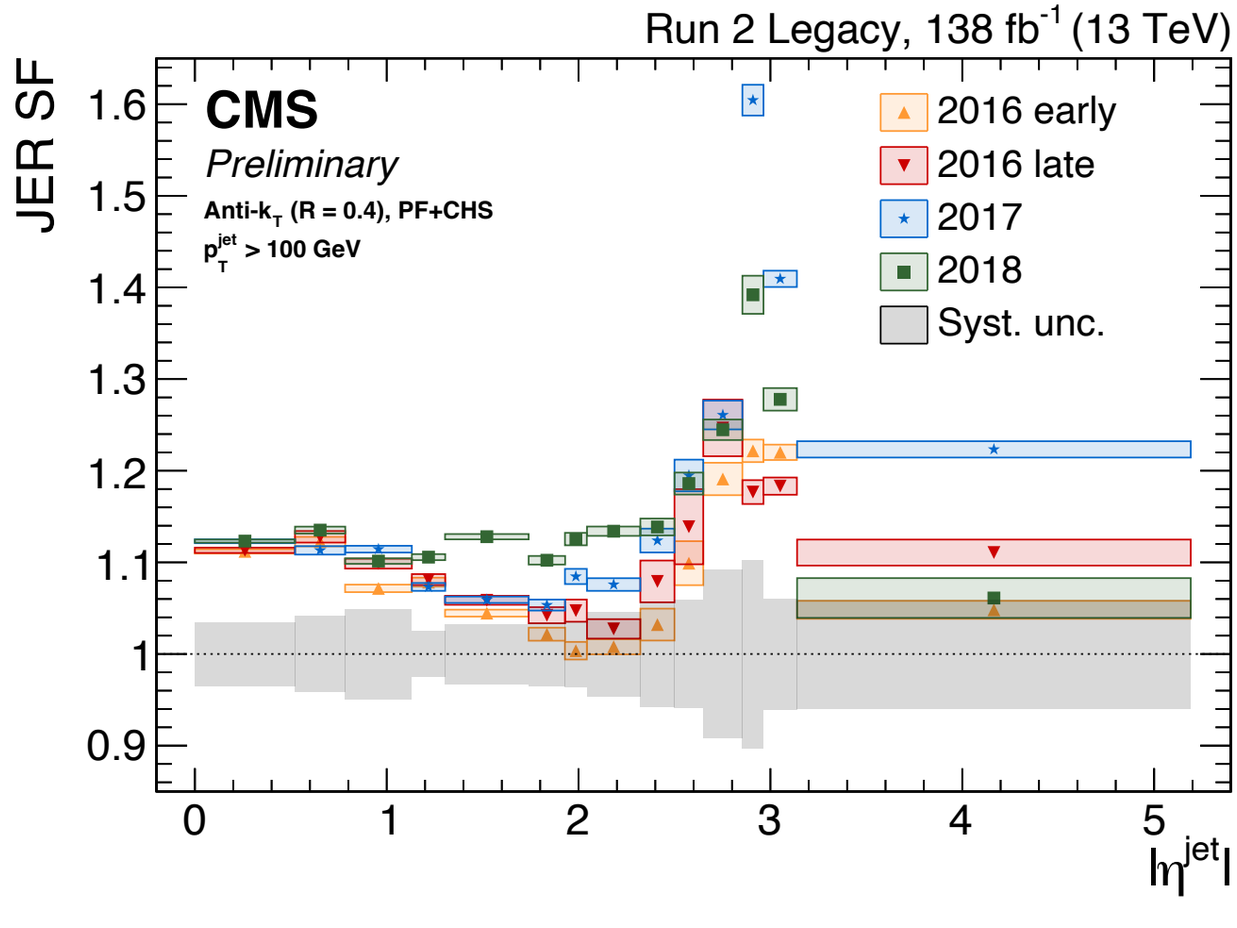
- The absolute $p_T$ scale is then fitted simultaneously, combining the results from $p_T$ balance and MPF methods



# Jet momentum resolution

- Jet energy resolution (JER) is determined using simulation and is the width of the gaussian fit to the particle-level response ($p_T/p_{T,ptcl}$)
- Data-to-simulation scale factors (SFs) are extracted using data-based methods and are applied to simulation to match jet resolution in data

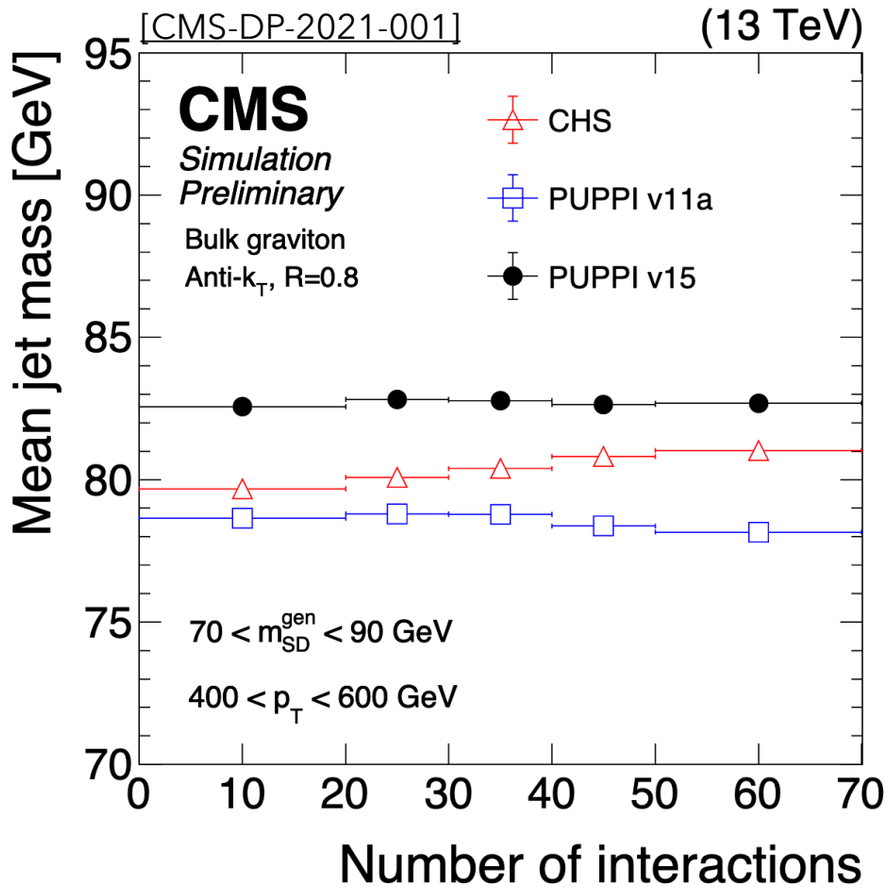


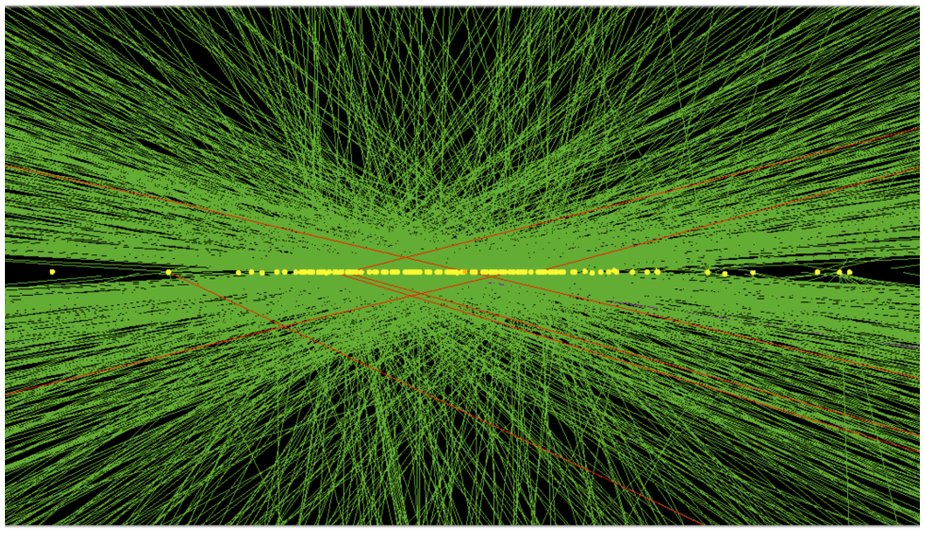




JER vs. $p_T$ in barrel for varying levels of pileup (left),
JER scale factors as a function of |η| (right)

# Outlook

- High PU and evolving detector pose a challenge for jet calibrations
- PUPPI as the default for Run 3 to cope with high expected PU
  - better jet resolution with PUPPI v15
  - substructure variables more stable against pileup compared to CHS
- Higher JES precision in Run 2 achieved by employing improved techniques
  - Run 2 legacy corrections planned with <1% JEC uncertainties
  - Documentation in the upcoming jet performance paper
- Harsher conditions expected in HL-LHC with PU~200 interactions
  - new detector, PUPPI as a good starting point, several new techniques in the works



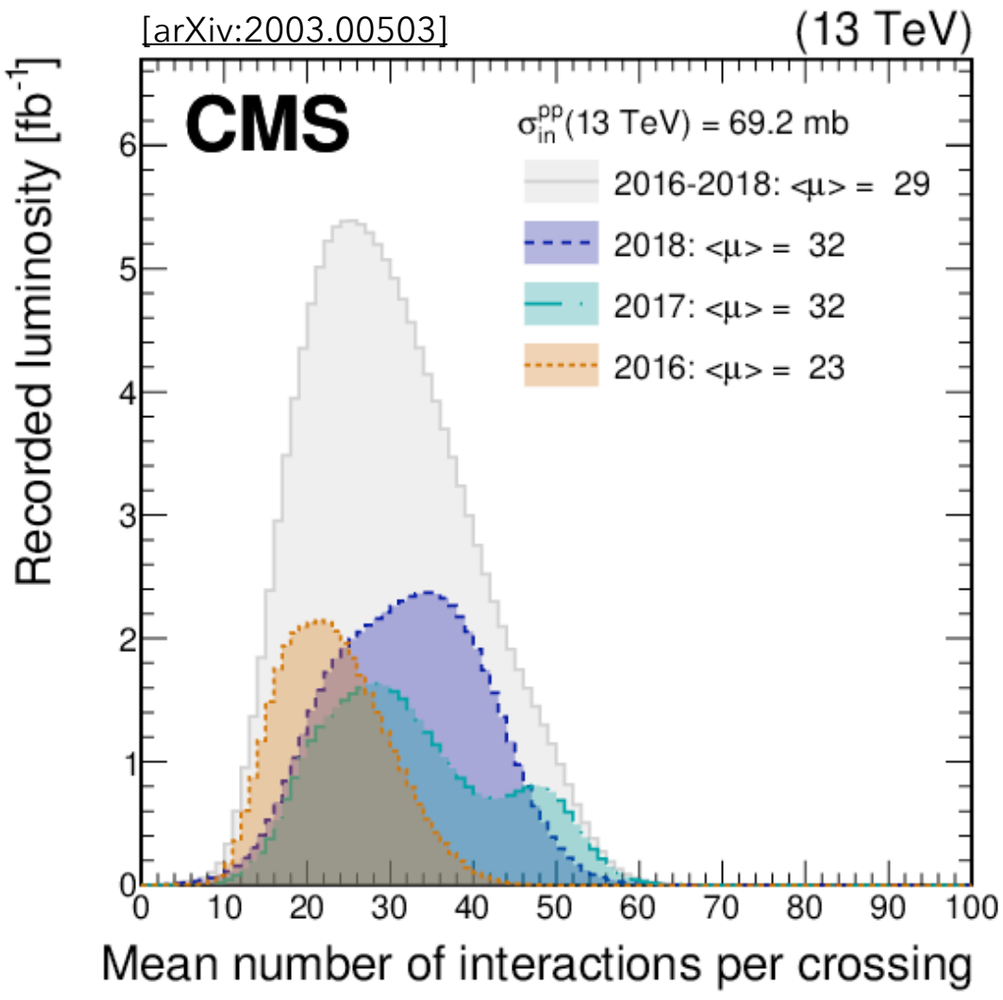



Exiting times ahead!

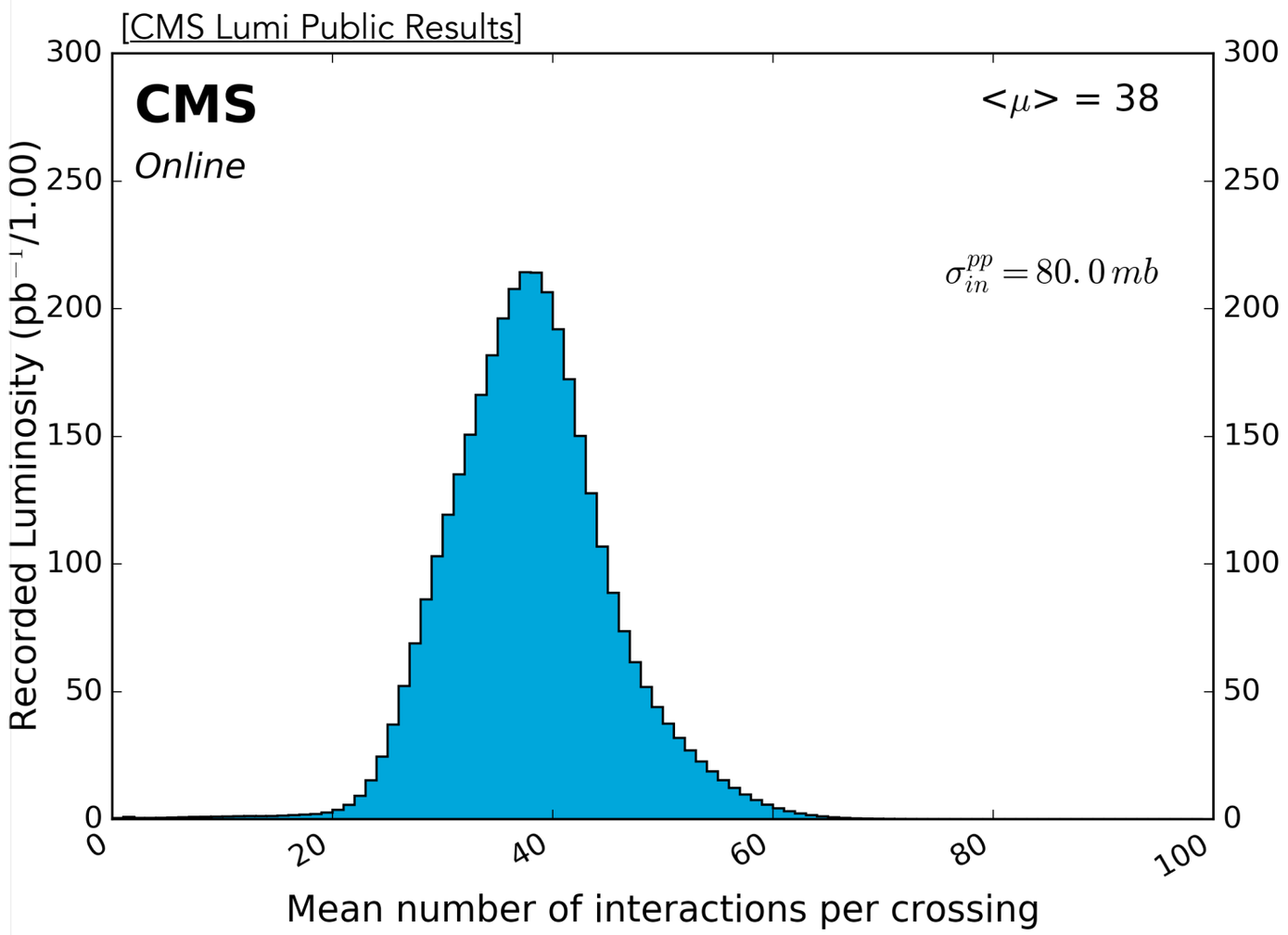
# BACKUP

# Run2 and Run3 pileup profiles

[arXiv:2003.00503]




[CMS Lumi Public Results]



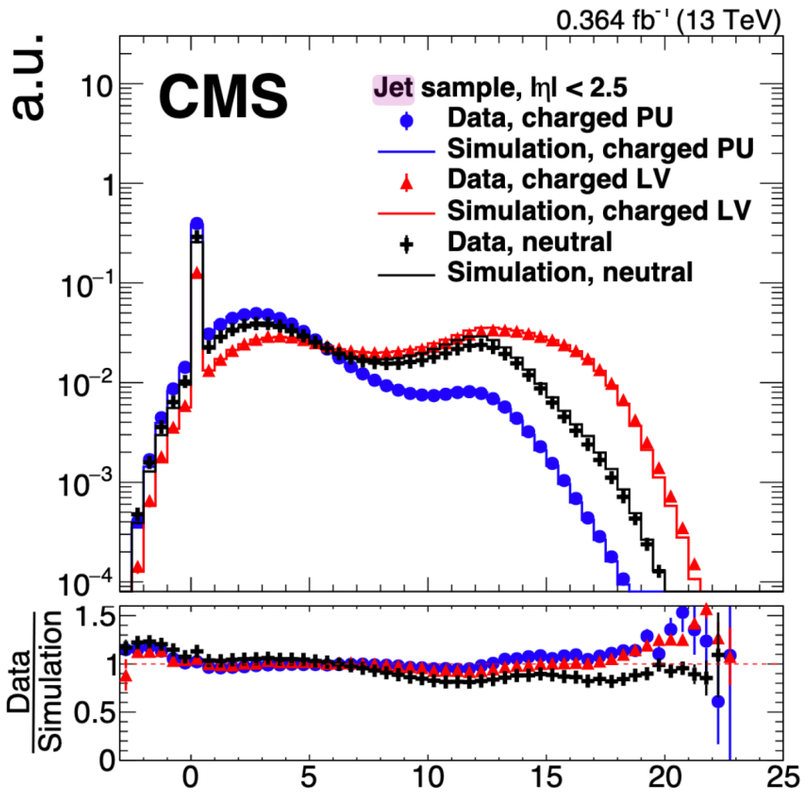
# PUPPI v15

- Uses the information of vertices reconstructed from charged-particle tracks

- PUPPI calculates an $\alpha$ value for each particle in the event:

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

For |η| < 2.5, j are charged particles from LV, whereas all particles with |η| > 2.5

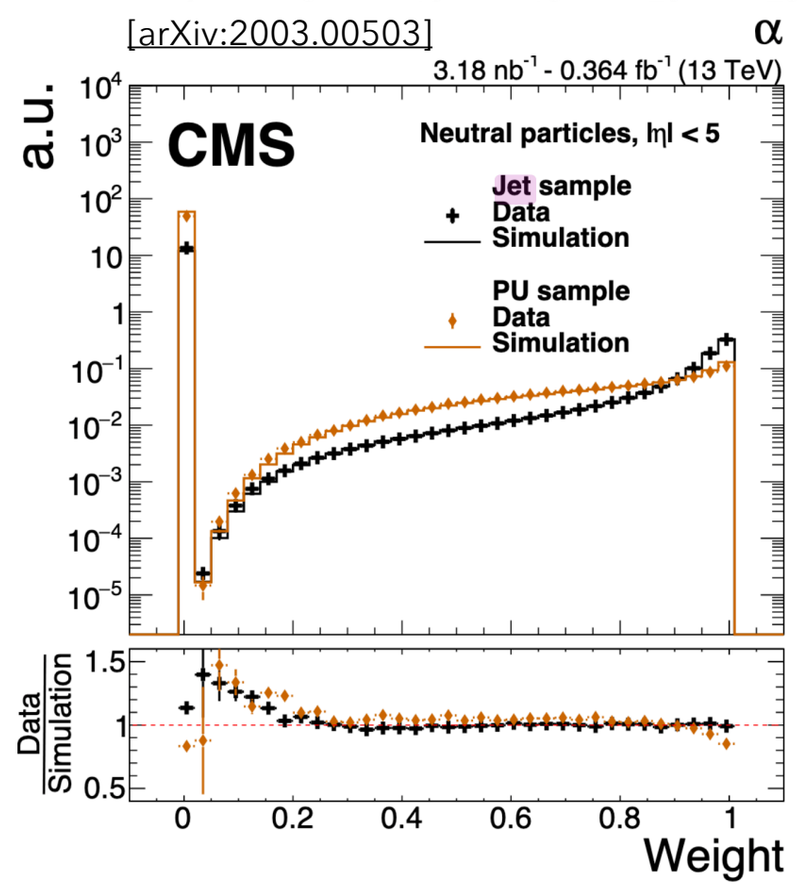



- Charged particles used in PU vertex fit are kept if they belong to the 1st or second PU vertex and |dz| < 0.2cm

- For charged particles not used in LV or PU vertex fit, if they have pT > 20 GeV they are kept.

  - For pT < 20GeV and inside tracking volume a PUPPI weight is calculated for them.

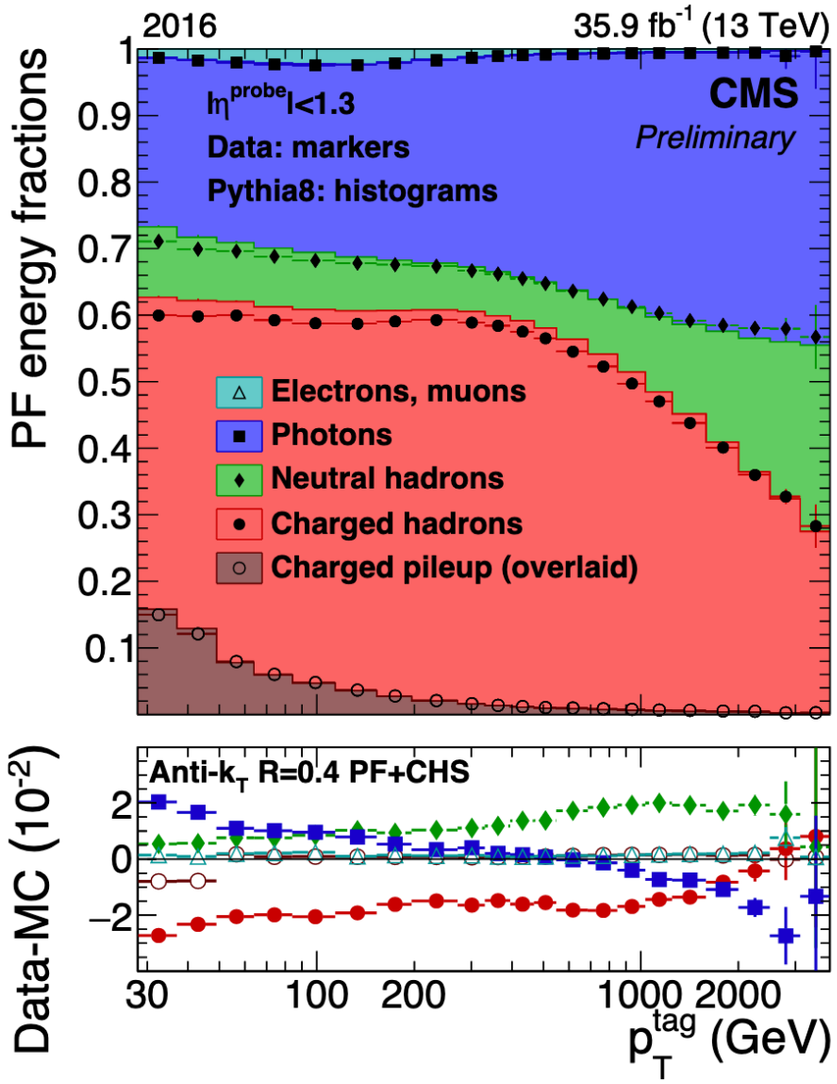
  - For pT < 20GeV and outside tracking volume and |dz| < 0.3 cm keep the particle, otherwise reject.

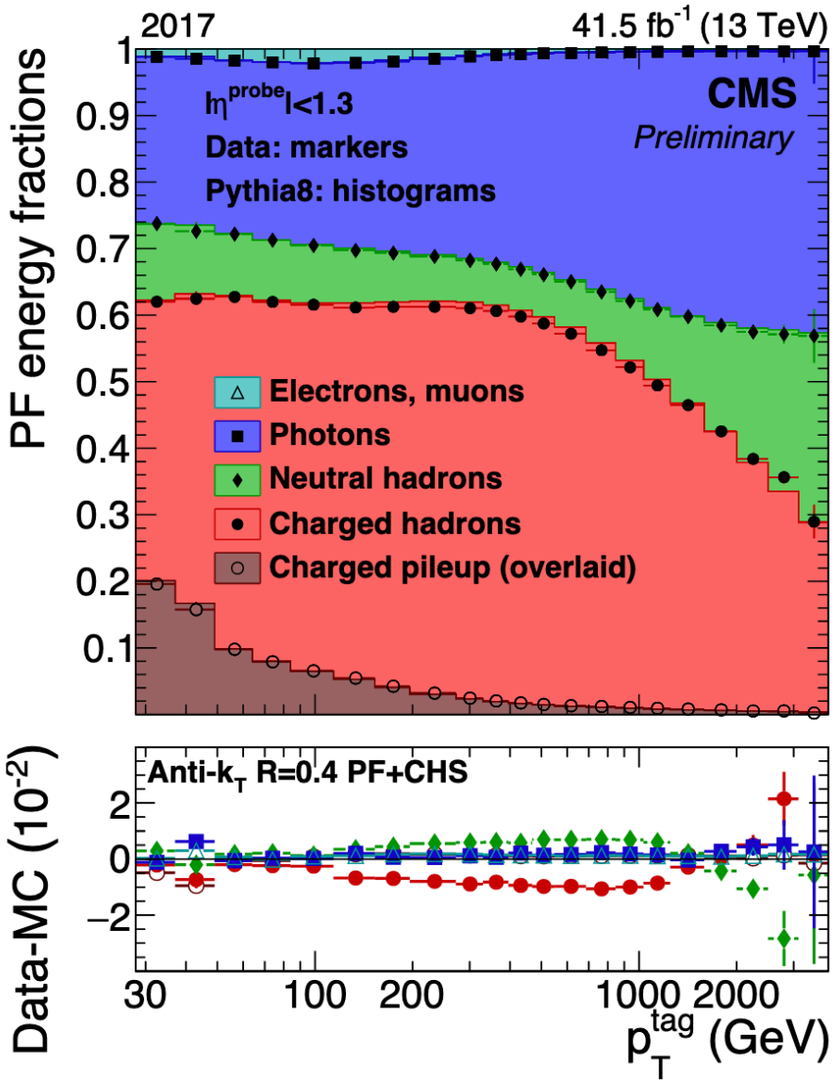


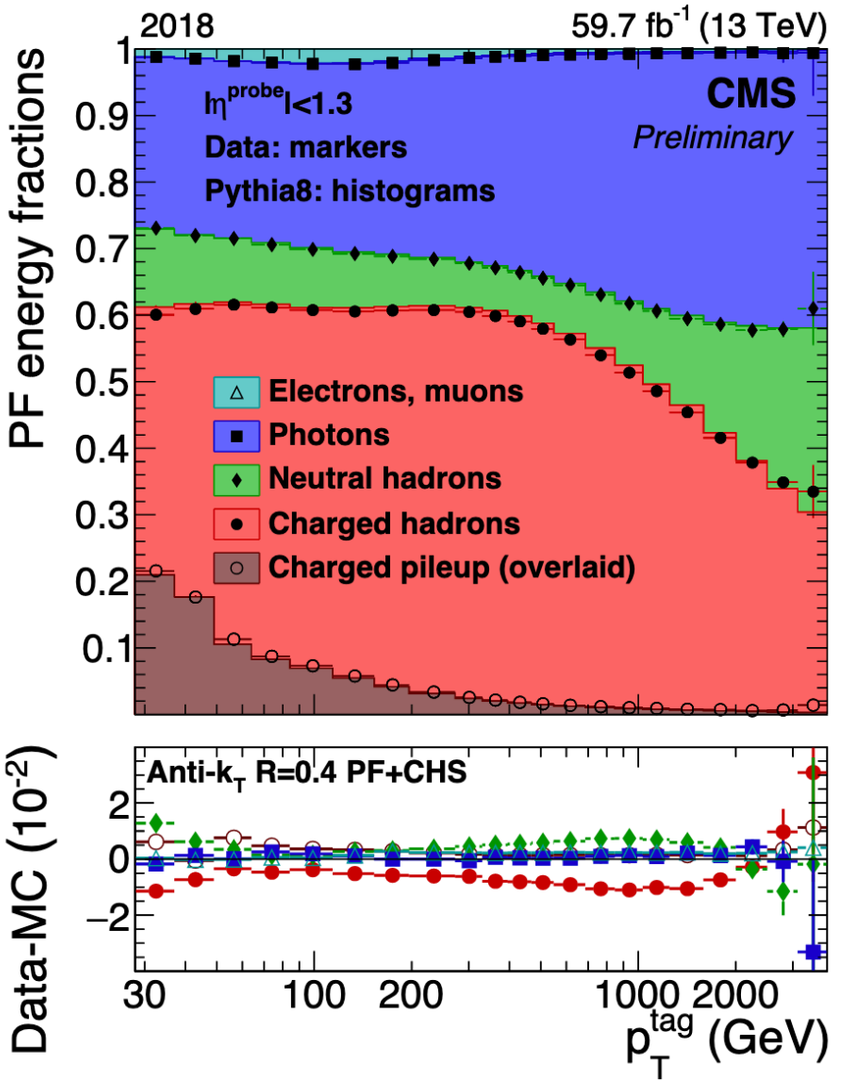
# Jet PF composition

[CMS-DP-2020-019]

EOY plots – will be updated for Legacy Run2 in the upcoming JERC paper



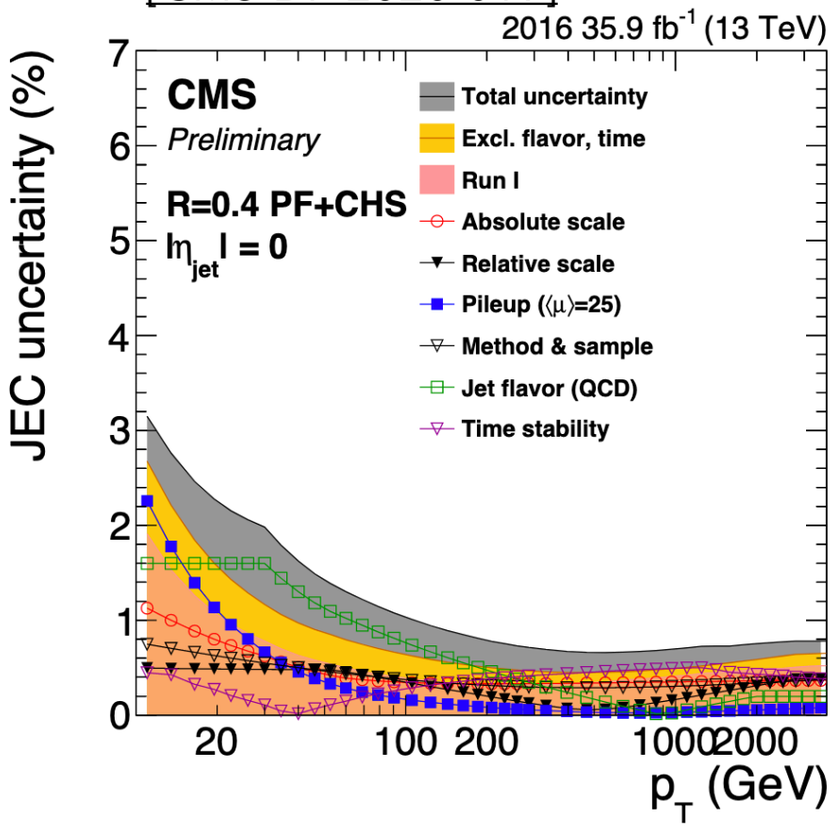



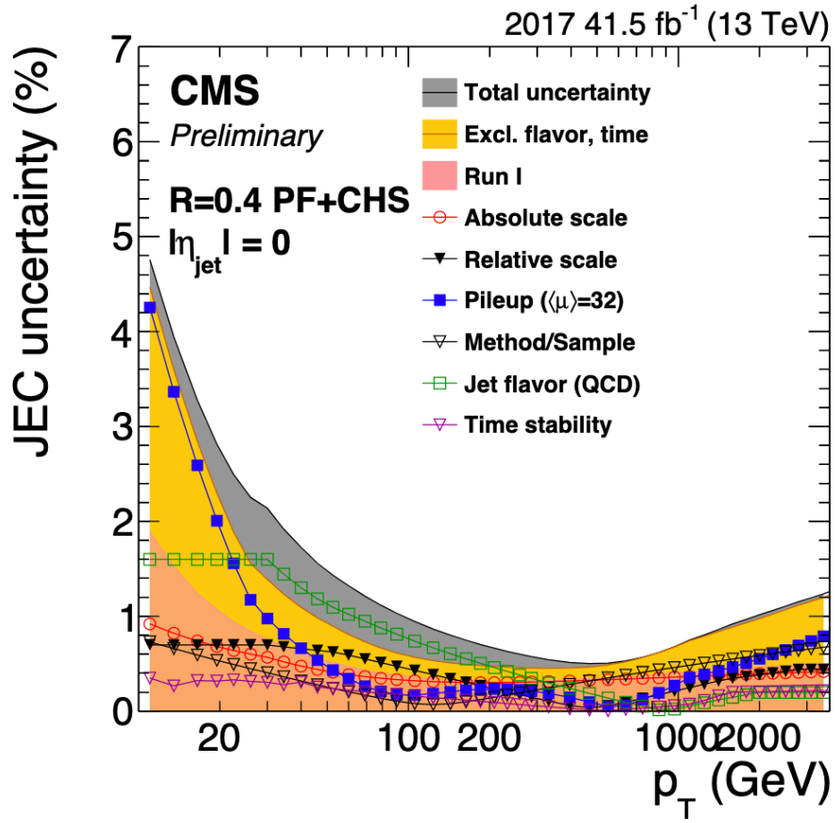



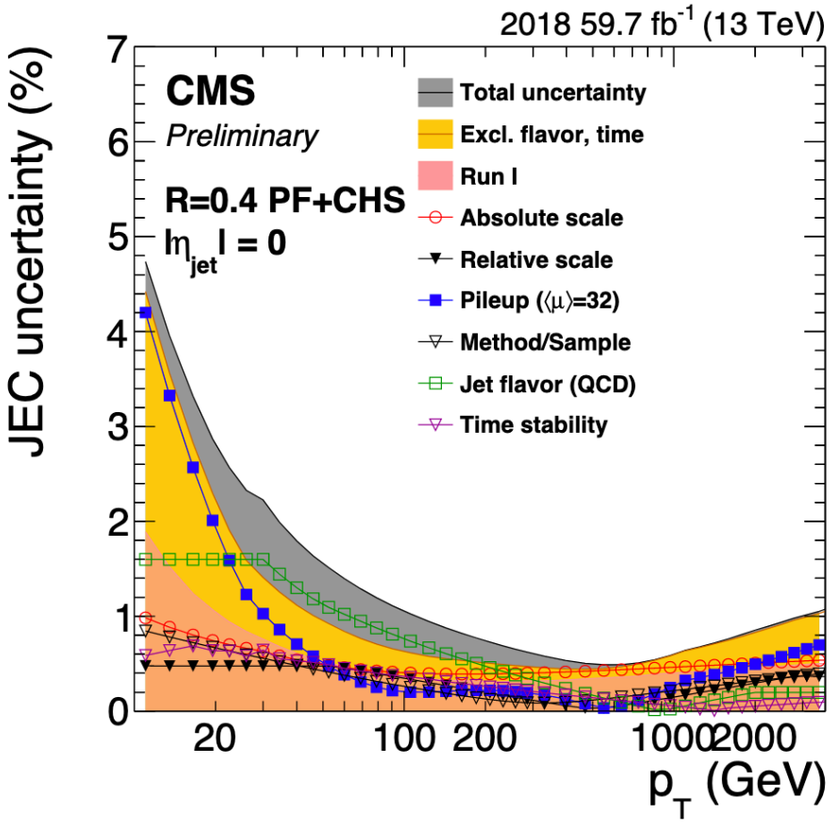
# JES Uncertainties

[CMS-DP-2020-019]

EOY plots – will be updated for Legacy Run2 in the upcoming JERC paper




- JES uncertainty sources and total uncertainty (quadratic sum of individual uncertainties)