Jet and MET results from CMS

Zeynep Demiragli [Boston University]
Andreas Hinzmann [Hamburg University]
and
Welcome to: Laurent Thomas [Univ. Libre de Bruxelles]

Prelude - A personal note …

- It has been a fantastic ride for the past 2 years!
  - At times (many times) it was exhausting and overwhelming but we have an amazing team of people which enabled all the physics we will discuss in the next slides (and for the next 2 days)

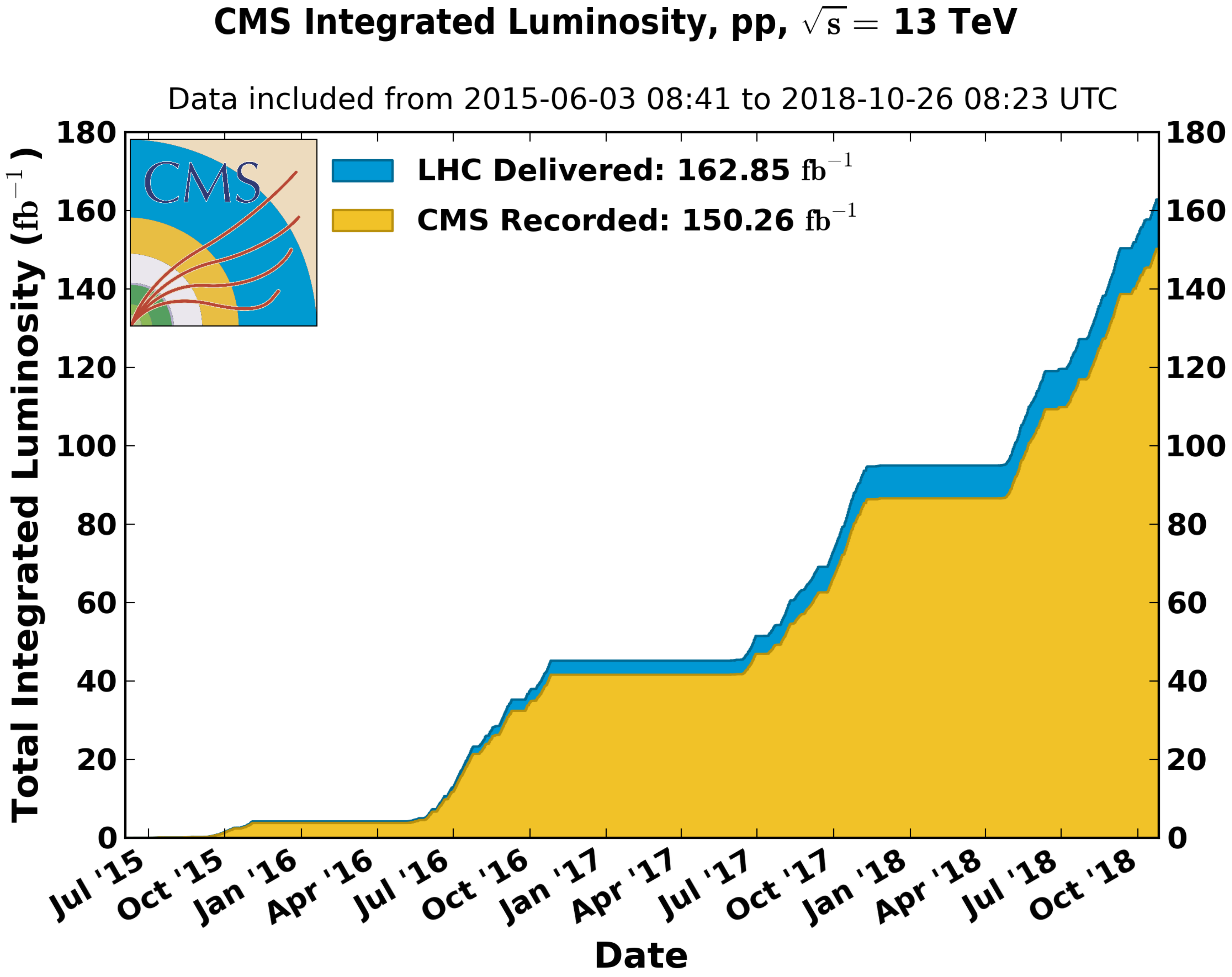
Prelude - A personal note …

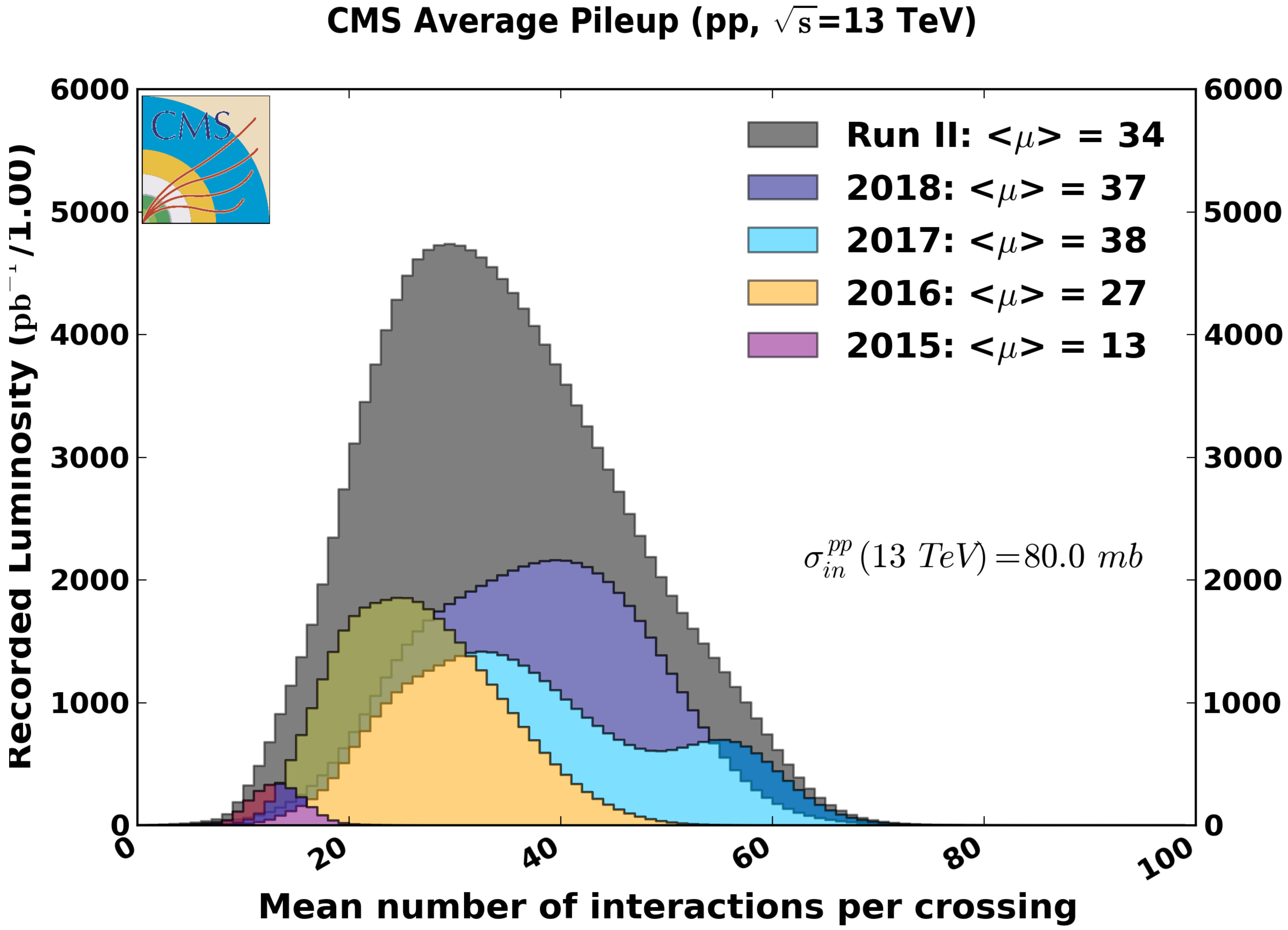
- It has been a fantastic ride for the past 2 years!
  - At times (many times) it was exhausting and overwhelming but we have an amazing team of people which enabled all the physics we will discuss in the next slides (and for the next 2 days)
  - These days, I am embarking on a slightly different journey, *motherhood*, which will probably be as exhausting and overwhelming at times… this is why I can't be there with you today…

… working on raising the next generation of JME collaborators :)

Prelude - A more scientific note …

As of ***today***, we have about **160/fb** of data from Run 2 at 13 TeV …
… with **average pile up of 34**!





Prelude - A more scientific note …

As of ***today***, we have about **160/fb** of data from Run 2 at 13 TeV …
… with **average pile up of 34**!

The challenge was/is to achieve best performance of the jet, MET objects while harmonizing data from different years. Every year came with unique features.

Run 3 is around the corner presenting a number of challenges!
Aging detector will likely be our biggest concern!

The Goal of this workshop is to ***reflect*** on what we learned from Run2 and to ***develop strategies*** for Run3!

Our Team

JME

Zeynep Demiragli
Andreas Hinzmann

JERC

Yi Chen
Giuseppe Latino

MET

Jordan Damgov
Laurent Thomas

JMAR

Clemens Lange
Marc Osherson

DQM

Okan Atakisi
Giuseppe Barbagli

TRIGGER

Aruna Nayak
Milos Djordjevic

Contacts

Generators
Haifa Rejeb Sfar
Radek Zlebcik
Alca
Sangeun Lee
Jet RECO
Gregor Kasieczka
Kevin Nash
Salvatore Rappoccio
MET RECO
Emilios Ioannou
TOP
Andrey Popov
Christoph Garbers
EXO
Eirini Tziaferi
Chad Freer
SMP
Jindrich Lidrych
SUS
Huilin Qu
Leonora Vesterbacka
HIG
Alejandro Gomez Espinosa
B2G
Christine McLean
Anna Benecke

BOSTON UNIVERSITY

Our Team

JME

Zeynep Demiragli
Andreas Hinzmann

JERC

Yi Chen
Giuseppe Latino

MET

...ge
Osherson

Atakisi
Giuseppe Barbagli

TRIGGER

Aruna Nayak
Milos Djordjevic

Contacts

Gener...

...Rappoccio

MET RECO
Emilios Ioannou
TOP
Andrey Popov
Christoph Garbers
EXO
Eirini Tziaferi
Chad Freer
SMP
Jindrich Lidrych
SUS
Huilin Qu
Leonora Vesterbacka
HIG
Alejandro Gomez Espinosa
B2G
Christine McLean
Anna Benecke

We are very proud to see that multiple members of our team has been promoted to Level-2 Positions!

Congratuations to: Yi Chen, Laurent Thomas, Clemens Lange

Also proud of Jet/MET Publications

"Performance of missing transverse momentum in pp collision at 13 TeV"
submitted to JINST! https://arxiv.org/abs/1903.06078

In the pipeline with 36/fb (Summer 2019 timescale):

- Jet energy scale and resolution at CMS in 13 TeV
- Pile Up mitigation at CMS in 13 TeV
- Heavy jet tagging algorithms in 13 TeV data

Many Physics Analysis Summaries and Detector Performance notes (PAS & DP):

- 2018 DP Jet trigger performance in 2018 at 13 TeV
- 2018 DP Jet energy scale and resolution performance with 13 TeV data collected by CMS in 2016
- 2017 DP Boosted jet identification using particle candidates and deep neural networks
- 2017 DP Missing transverse energy performance in high pileup data collected by CMS in 2016
- 2017 DP New Developments for Jet Substructure Reconstruction in CMS
- 2017 DP W and top tagging scale factors
- 2017 PAS Jet algorithms performance in 13 TeV data
- 2016 DP Performance of quark/gluon discrimination in 13 TeV data
- 2016 DP Jet energy scale and resolution performances with 13TeV data
- 2016 DP Trigger performance plots with 13 TeV data
- 2016 DP ETmiss performance in events with Gamma, Z and dijets using 0.8 fb-1 of 2016 Data

BOSTON UNIVERSITY

Building Jet & MET from Bottom Up!

Algorithms, alignments and calibrations of all sub detectors

Linking of sub detector deposits and particle identification

Aging detector

Analysis

Calibration & Tagging

Jets / MET

Particle Flow

Local Reconstruction

BOSTON UNIVERSITY

Building Jet & MET from Bottom Up!

Algorithms, alignments and calibrations of all sub detectors

Linking of sub detector deposits and particle identification

Aging detector

Analysis

Calibration & Tagging

Jets / MET

Particle Flow

Local Reconstruction

Pile up subtraction at PF (CHS & PUPPI)

Jet types (PF, Calo), algorithms (AK, CA) cones (0.4, 0.8, 1.5)

Huge validation efforts!

BOSTON UNIVERSITY

Building Jet & MET from Bottom Up!

Algorithms, alignments and calibrations of all sub detectors

Linking of sub detector deposits and particle identification

Aging detector

Jet energy scale and resolution

Flavor and heavy object tagging algorithm development

Huge validation efforts!

Analysis

Calibration & Tagging

Jets / MET

Particle Flow

Local Reconstruction

Huge validation efforts!

Pile up subtraction at PF (CHS & PUPPI)

Jet types (PF, Calo), algorithms (AK, CA) cones (0.4, 0.8, 1.5)

BOSTON UNIVERSITY

CMS

Building Jet & MET from Bottom Up!

Algorithms, alignments and calibrations of all sub detectors

Linking of sub detector deposits and particle identification

Aging detector

Local Reconstruction

Particle Flow

Huge validation efforts!

Jets / MET

Pile up subtraction at PF (CHS & PUPPI)

Jet types (PF, Calo), algorithms (AK, CA) cones (0.4, 0.8, 1.5)

Jet energy scale and resolution

Flavor and heavy object tagging algorithm development

Calibration & Tagging

Huge validation efforts!

Analysis

Comparison of Data & Simulation

Residual corrections and scale factors

Who forgot to take the trash out? Go back to step 1

BOSTON UNIVERSITY

Building Jet & MET from Bottom Up!

Algorithms, alignments and calibrations of all sub detectors

Linking of sub detector deposits and particle identification

Aging detector

Local Reconstruction

Particle Flow

Huge validation efforts!

Jets / MET

Pile up subtraction at PF (CHS & PUPPI)

Jet types (PF, Calo), algorithms (AK, CA) cones (0.4, 0.8, 1.5)

Jet energy scale and resolution

Flavor and heavy object tagging algorithm development

Calibration & Tagging

Huge validation efforts!

Analysis

Comparison of Data & Simulation

Residual corrections and scale factors

Who forgot to take the trash out? Go back to step 1

Jets & Calibration: Overview

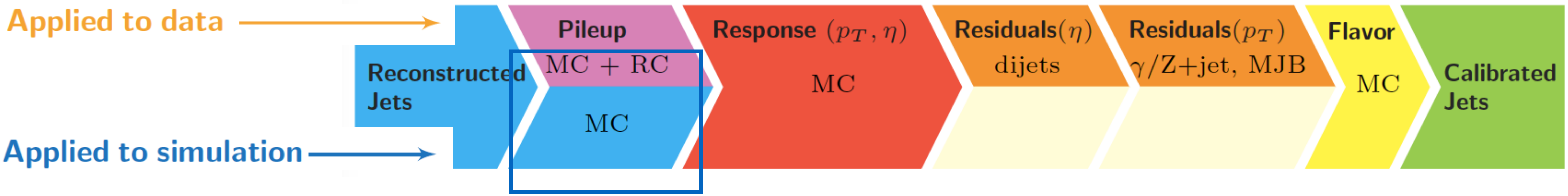
Strategy: Factorized approach to JEC

- Pileup corrections to correct the offset energy
- Correction to particle level jet vs. (pT ,η) from simulation
- Residuals correction to data: pile-up, relative vs η, absolute vs pT

Simulation based corrections are derived for:

- Anti-kT Jets: PF, PF+CHS, PF+PUPPI
- Jets with cone size of 0.4 and 0.8.

Jets & Calibration: Applied to Simulation



Pileup Correction (Offset)

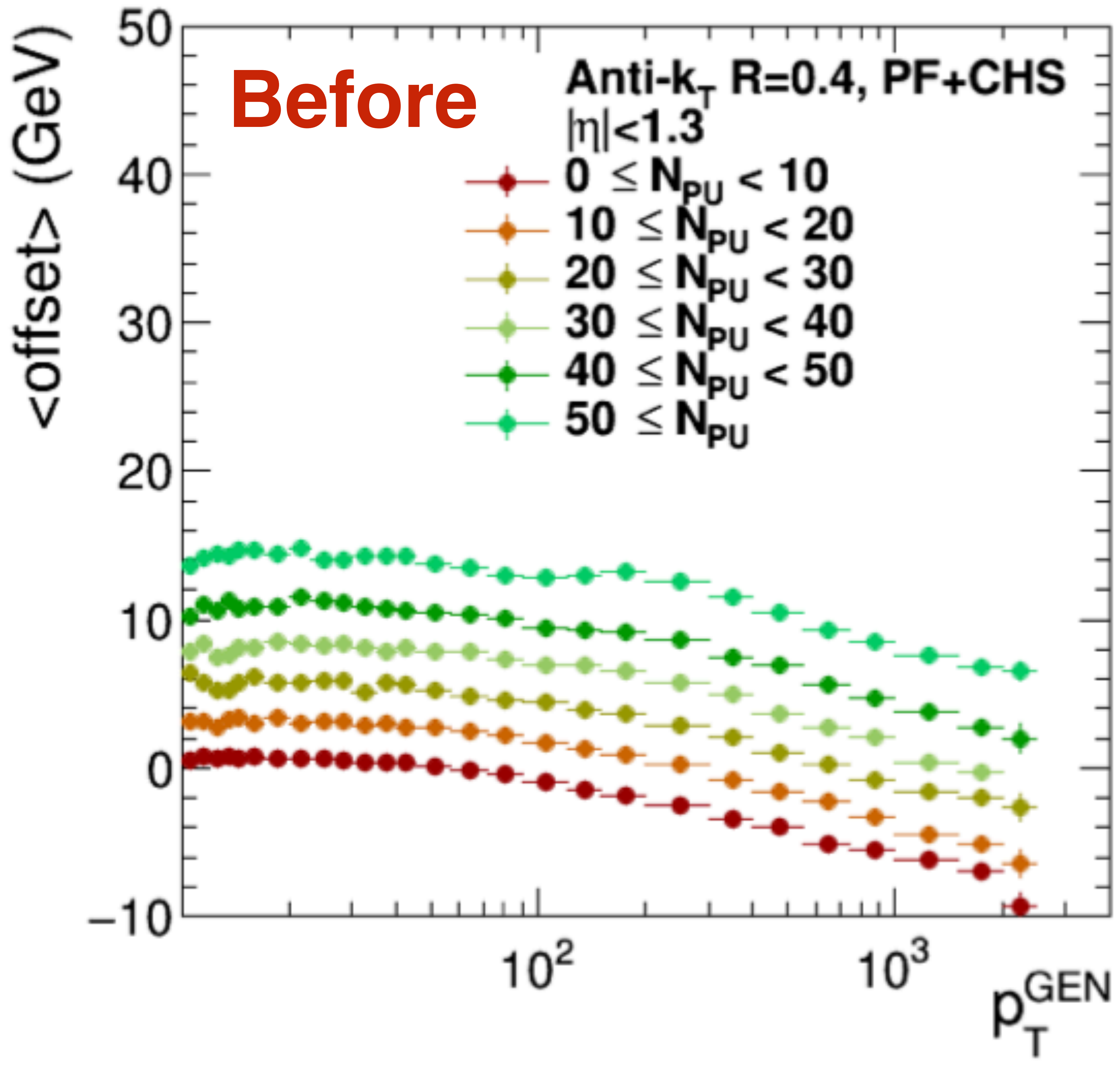
<Offset> derived by comparing same jets reconstructed in the same event with and without PU:

<offset> = <pT,jet(event w/ PU) - pT,jet(event w/o PU)>

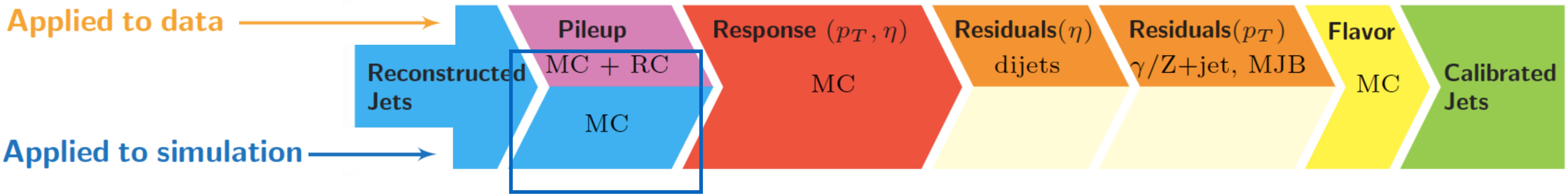
parametrized in ([η],pT,ρ)

Non-linear effects:

- Changes in the local reconstruction between with/ without PU



Jets & Calibration: Applied to Simulation



Pileup Correction (Offset)

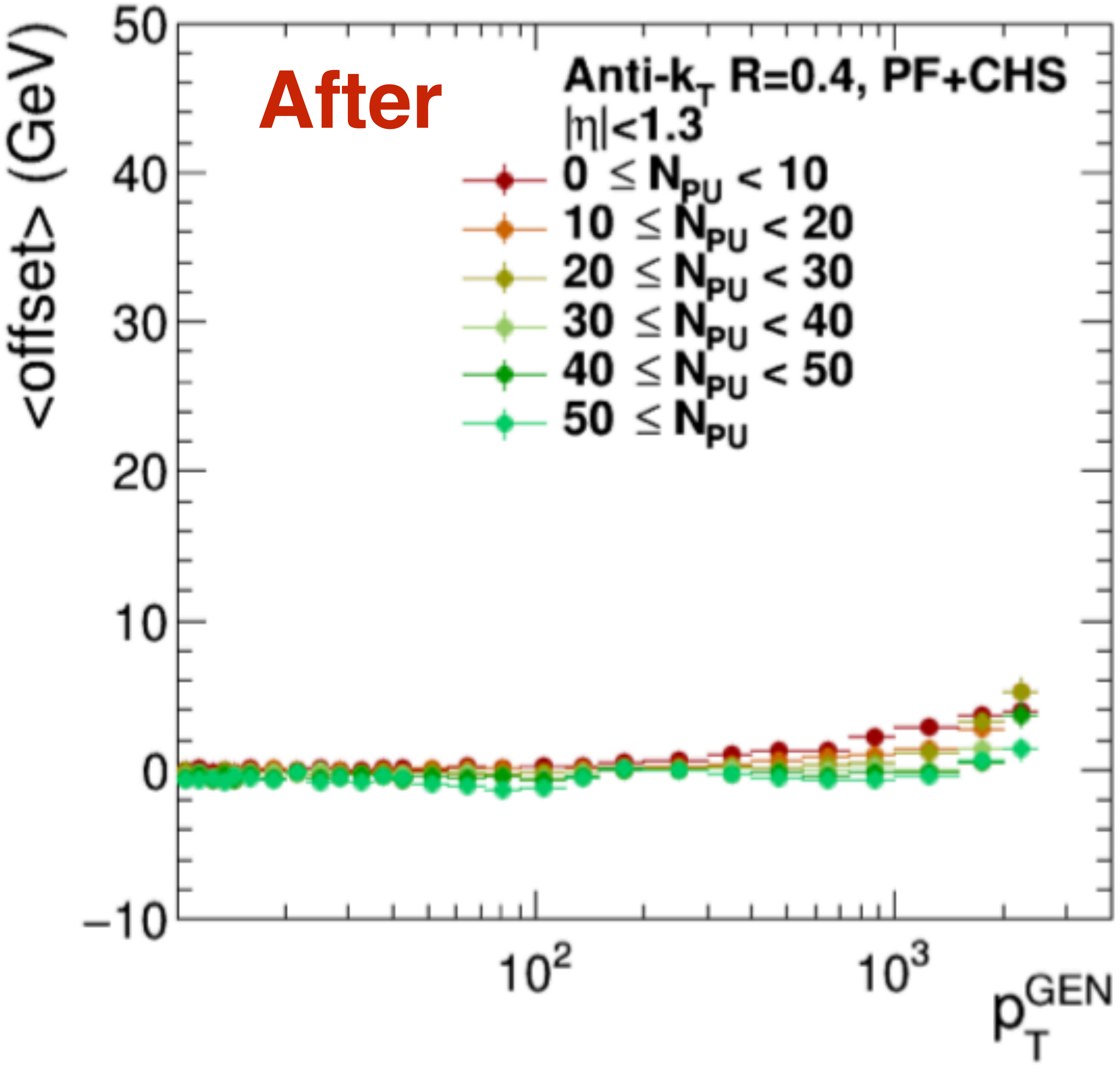
<Offset> derived by comparing same jets reconstructed in the same event with and without PU:

<offset> = <pT,jet(event w/ PU) - pT,jet(event w/o PU)>

parametrized in ([η],pT,ρ)

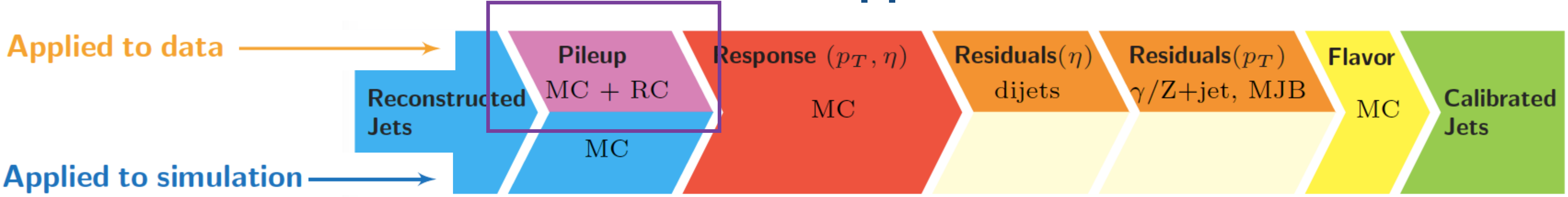
Non-linear effects:

- Changes in the local reconstruction between with/without PU

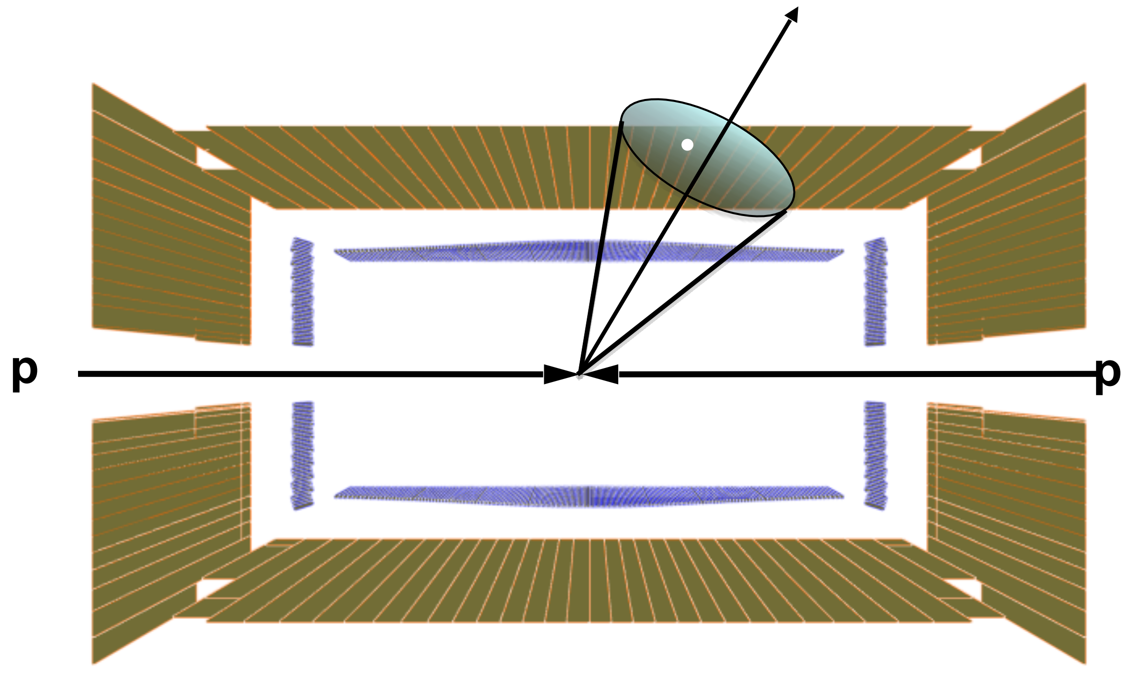


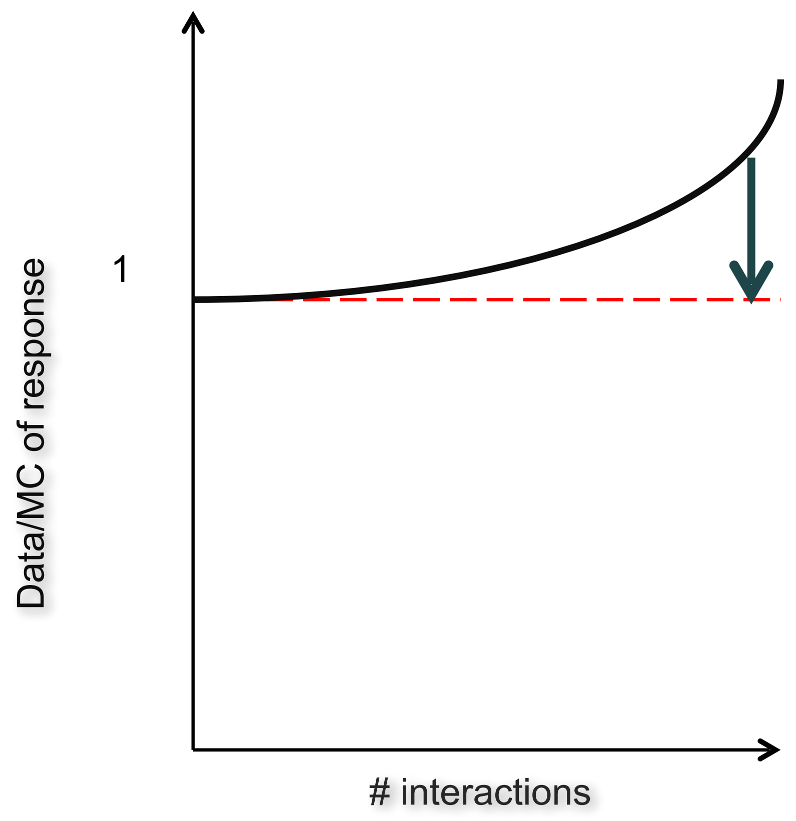
Zeynep Demiragli - JetMET Workshop. April 2019

Jets & Calibration: Applied to Data



Residual Pileup Correction

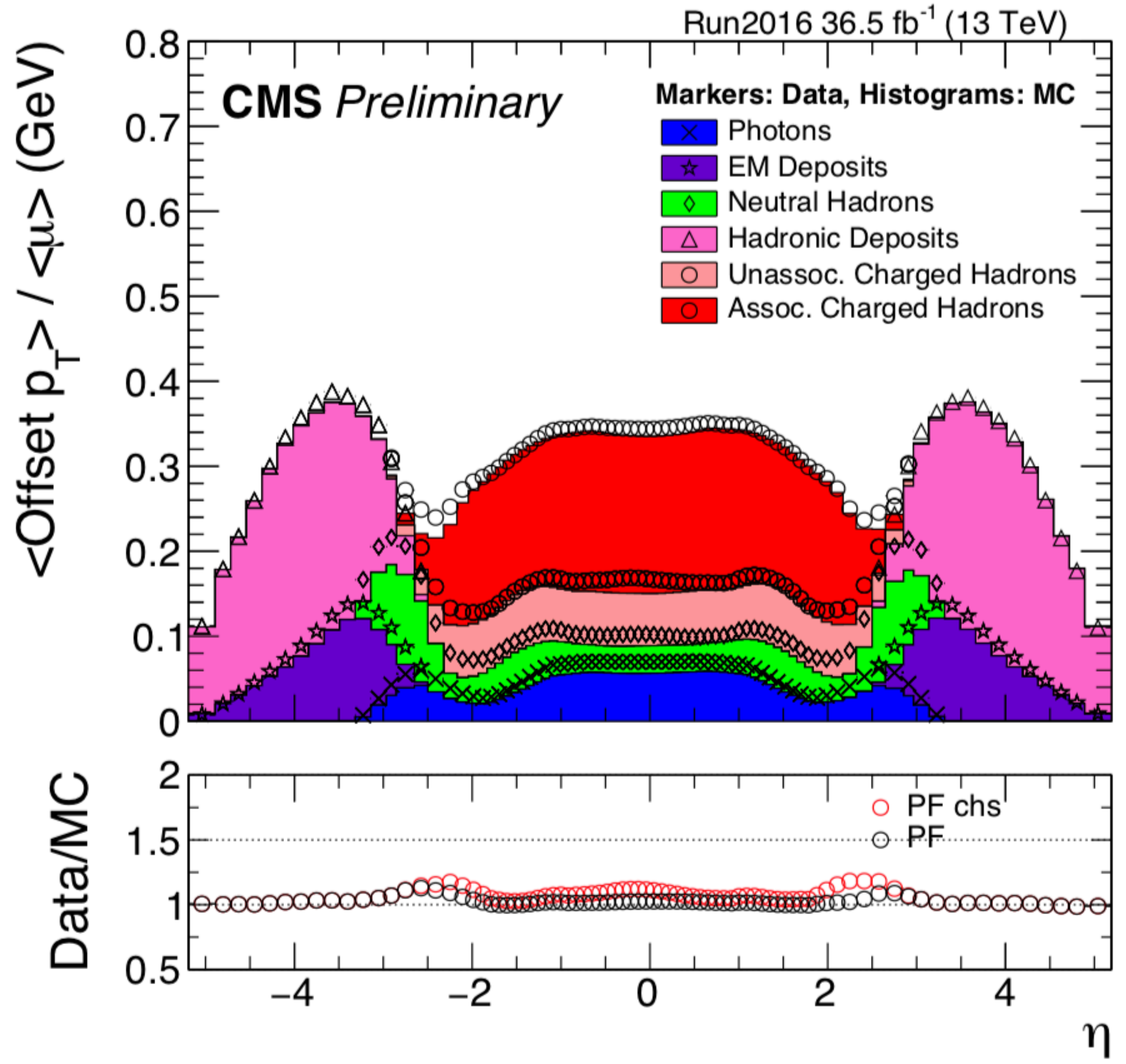




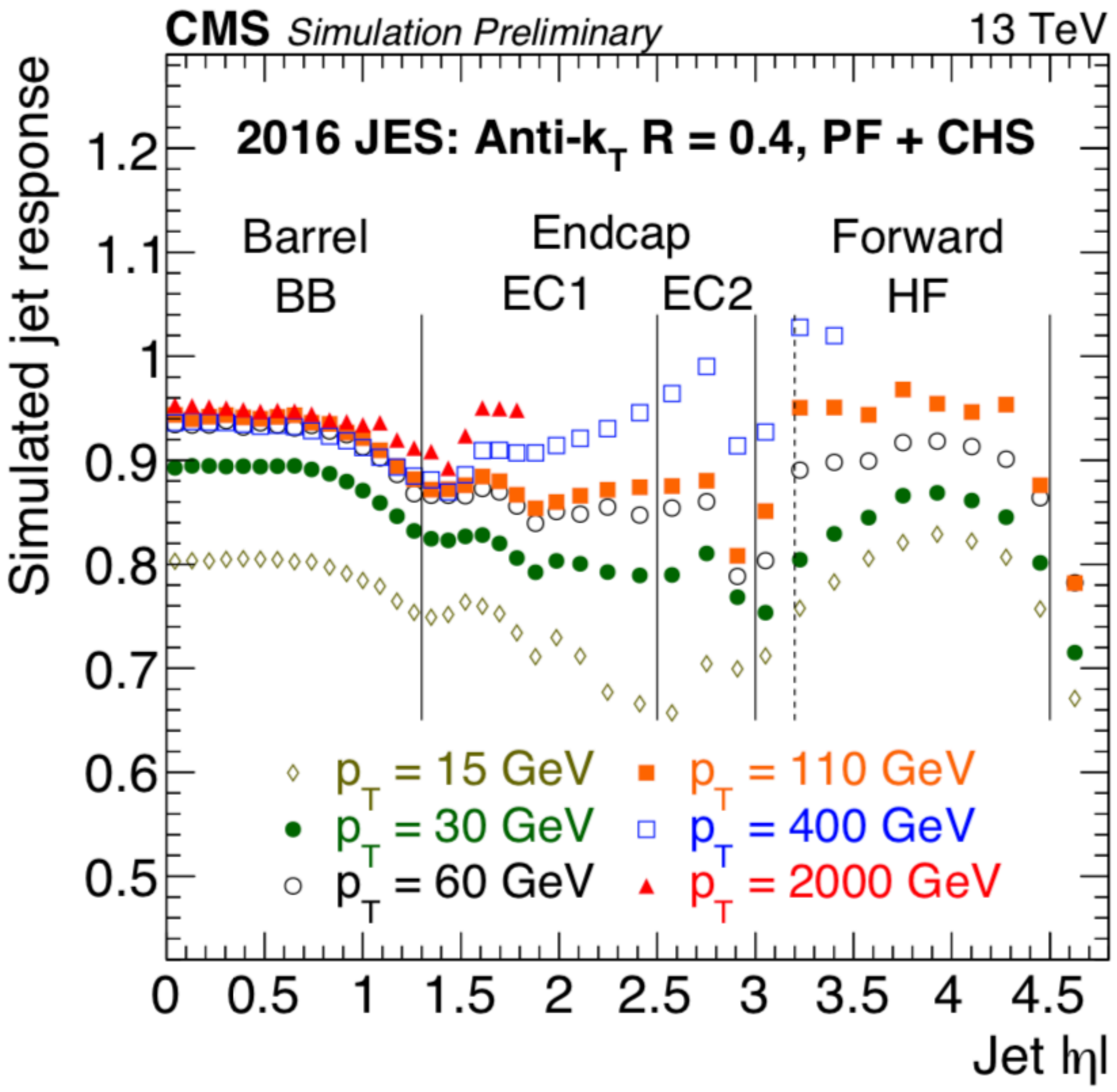
Goal: Data/MC comparison for the average offset per additional pileup interaction (μ), that is calculated for each type of PF particles!

Has excellent capability of detecting changes / degradation of each of the sub detector as a function of time!

Susceptibel to “zero suppression”



Jets & Calibration: Applied to Simulation



Response Correction

$$\frac{\langle p_T^{RECO} \rangle}{\langle p_T^{ptcl} \rangle}(p_T^{ptcl}, \eta) = 1$$

Stable in the barrel (tracker coverage)

- Response of 95% due to neutral hadrons response of 60% (makes up 15% of the particle jet energy)
- Drop below pT<30 GeV due to HCAL acceptance

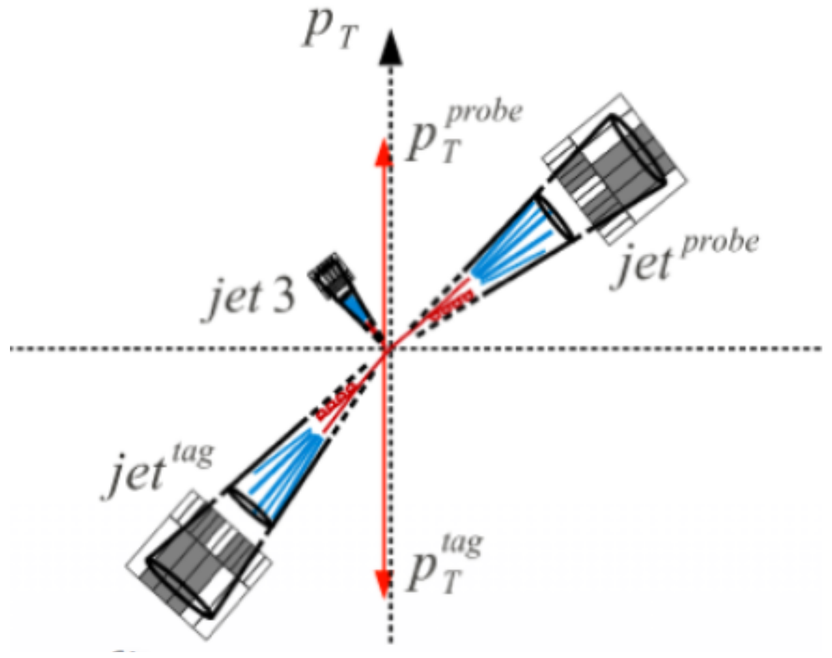
Larger variations outside tracker coverage

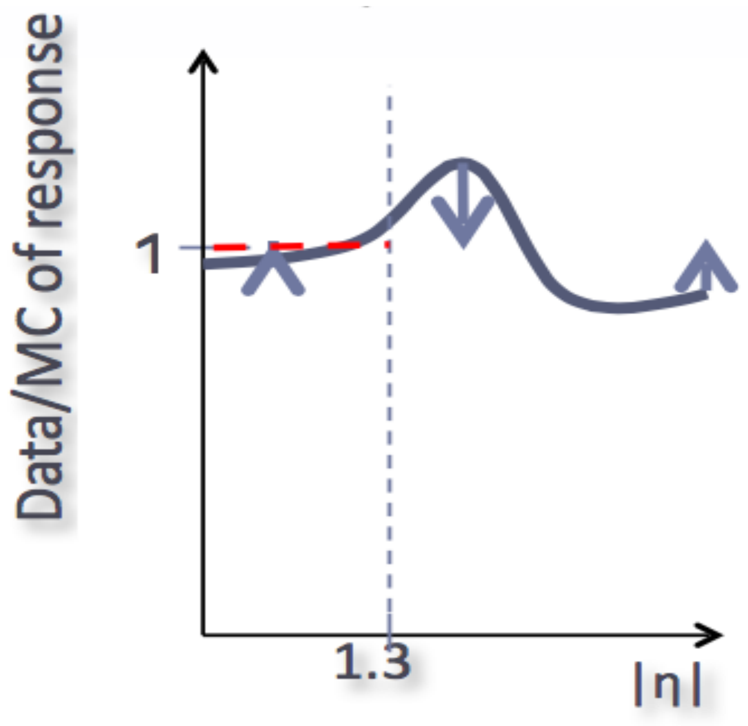
- 3.0<|η|<3.2 due to detector transition
- |η|>4.5 due to acceptance

BOSTON UNIVERSITY

Jets & Calibration: Applied to Data

Residual Corrections (eta)



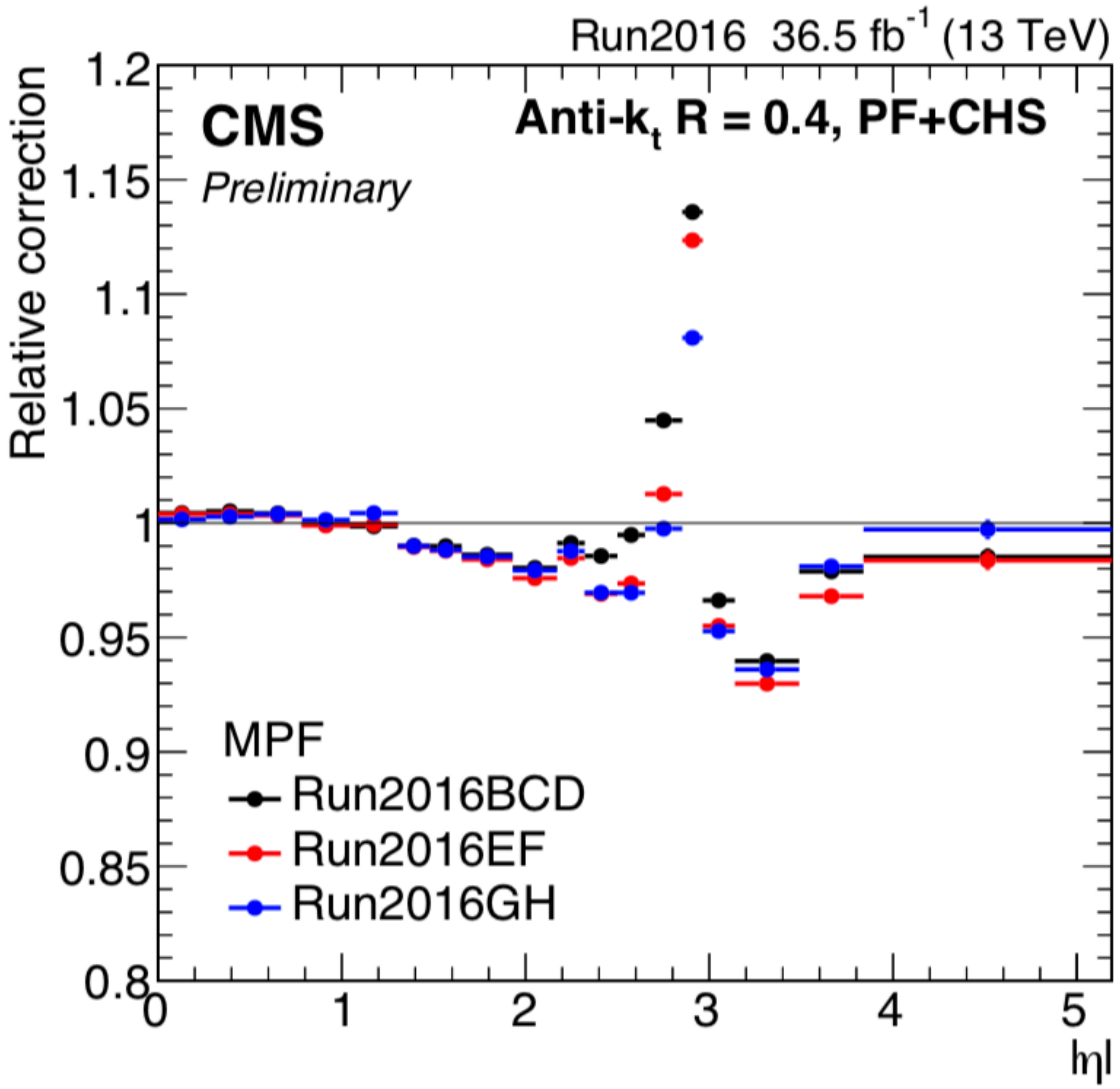


Jets are different beasts at different η:

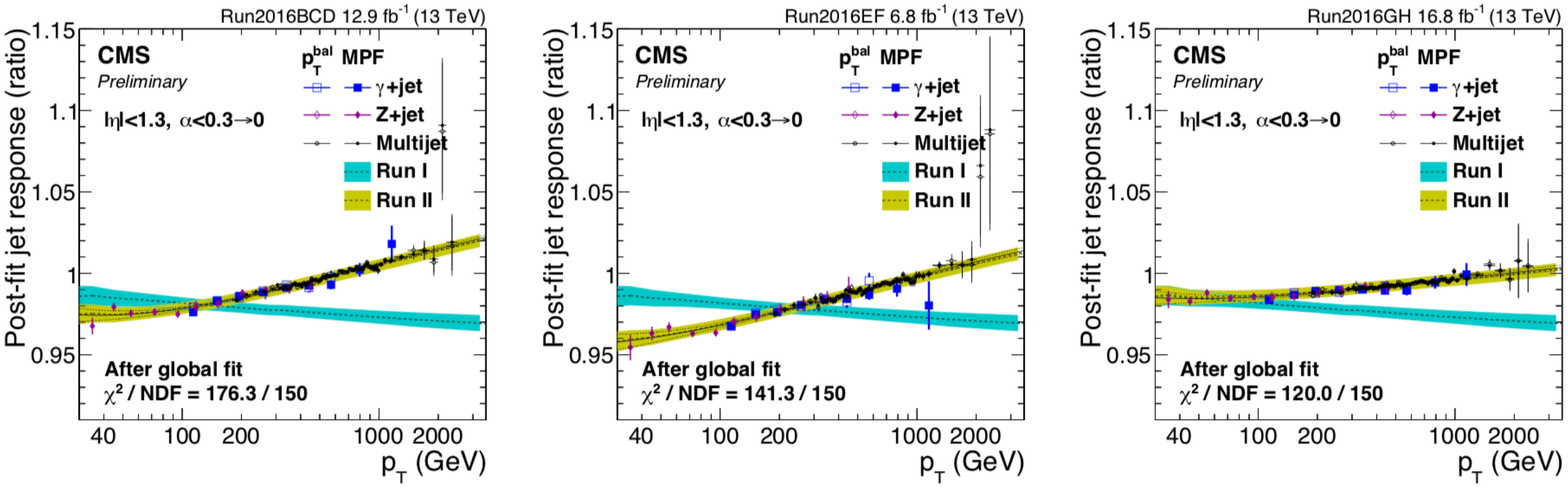
- intrinsic resolution of each sub detector is “sampled” with this analysis

At the detector transition regions, the residual corrections are no longer “small”

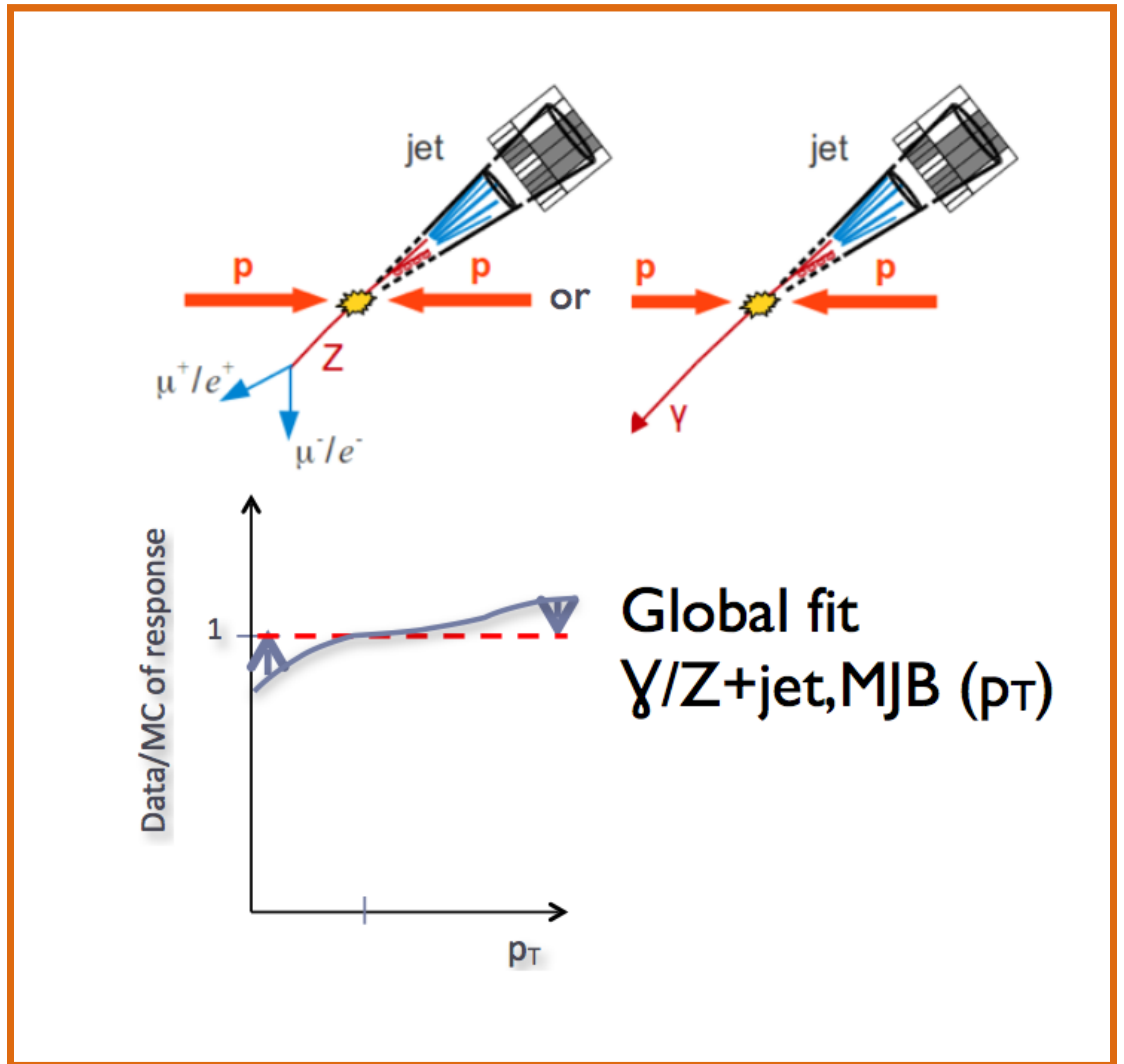
Going to lower pTs with this method is difficult due to trigger thresholds.



Jets & Calibration: Applied to Data



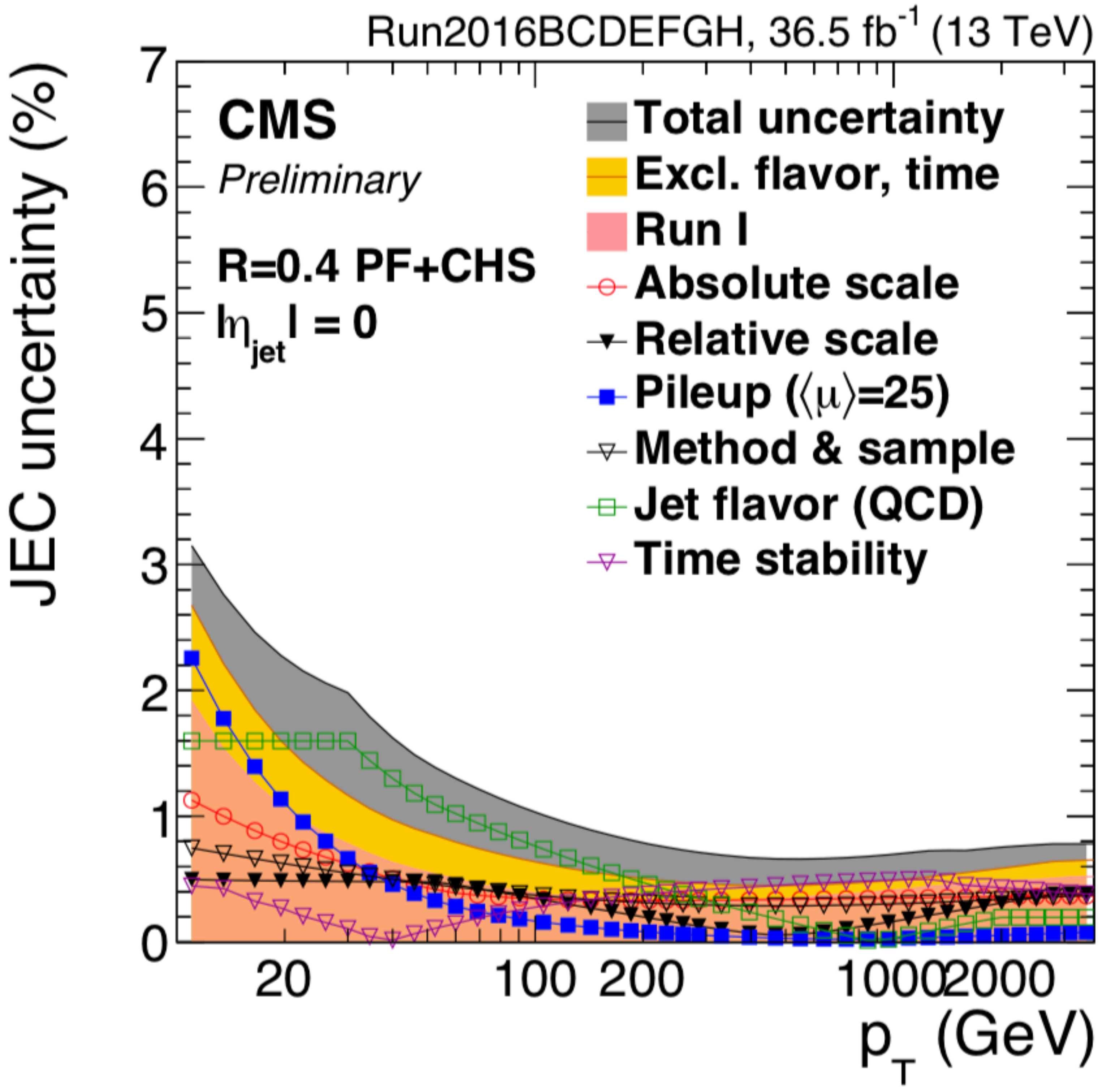
Residual Corrections (pt)

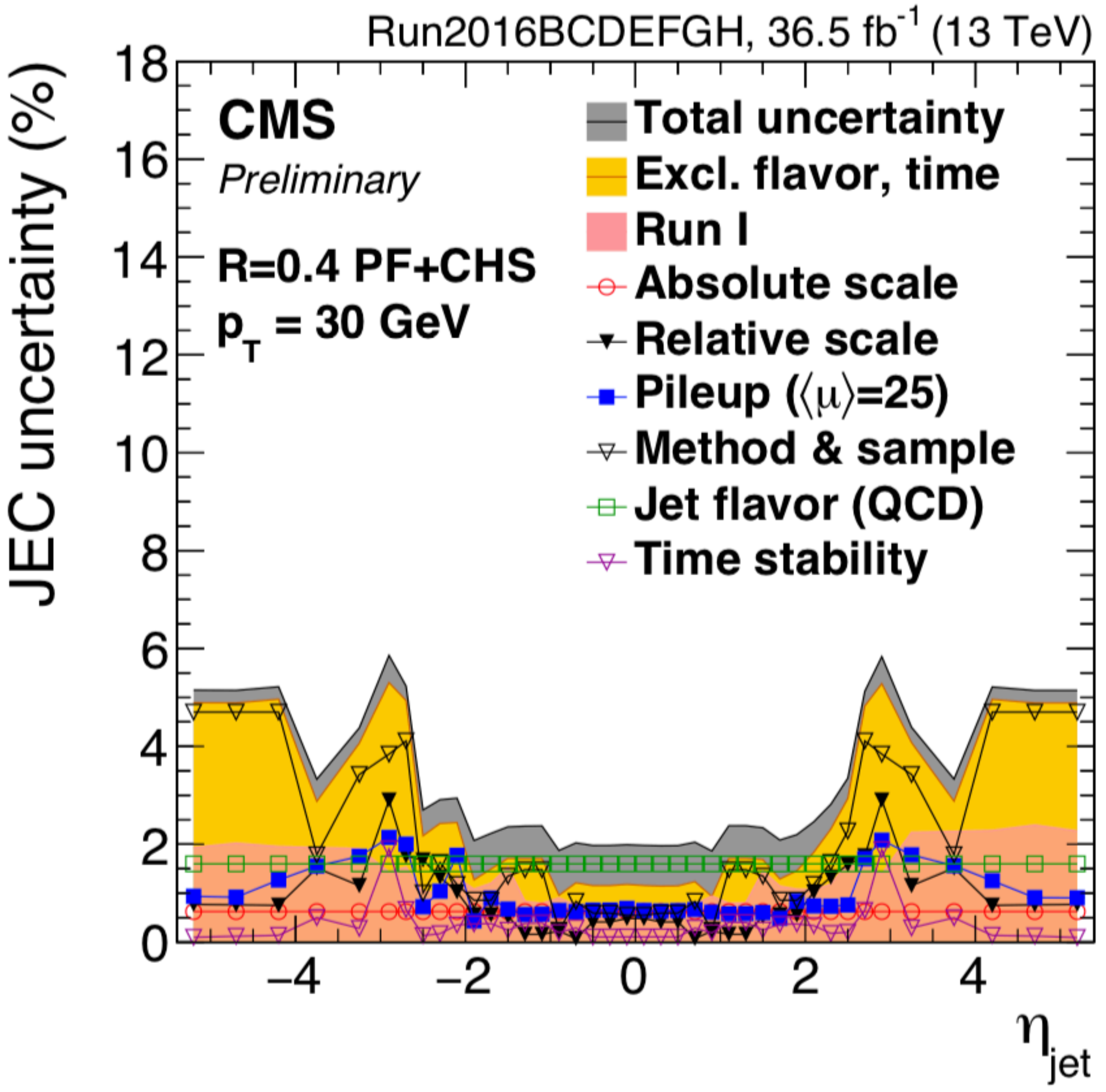


Data/MC comparison for the jet response dependency on the jet pT using well measured vector bosons!

Even within a single year, large variations between the detector response was observed!

Jets & Calibration: Uncertainties and Outlook





Large residual corrections lead to large uncertainties..

In comparison to Run1, our uncertainties have increased by x1.5 (x2-5) in barrel (endcap).

- **Time stability:** Accounts for the differences seen in residual corrections in different eras after applying corrections and comparing to JEC derived on the full sample

- **Method & Sample:** Accounts for the biases (large pT dependences) seen in the residual measurements

Jets & Calibration: Uncertainties and Outlook

2016 Problems:

- Dynamic pixel inefficiency - loss of performance in charged hadrons as a function of time with the
- ECAL gain switch issues - mis measurement of high energy electrons/γ

2017 Problems:

- Loss of transparency of the ECAL end-caps
- Pre-firing problem in L1 in the ECAL endcap detectors

2018 Problems:

- Local reconstruction issues with HCAL (Negative energy filter)
- Loss of 2 Sectors in the HCAL Endcap

Jets & Calibration: Uncertainties and Outlook

2016 Problems:

- Dynamic pixel inefficiency - loss of performance in charged hadrons as a function of time with the
- ECAL gain switch issues - mis measurement of high energy electrons/γ

2017 Problems:

- Loss of transparency of the ECAL end-caps
- Pre-firing problem in L1 in the ECAL endcap detectors

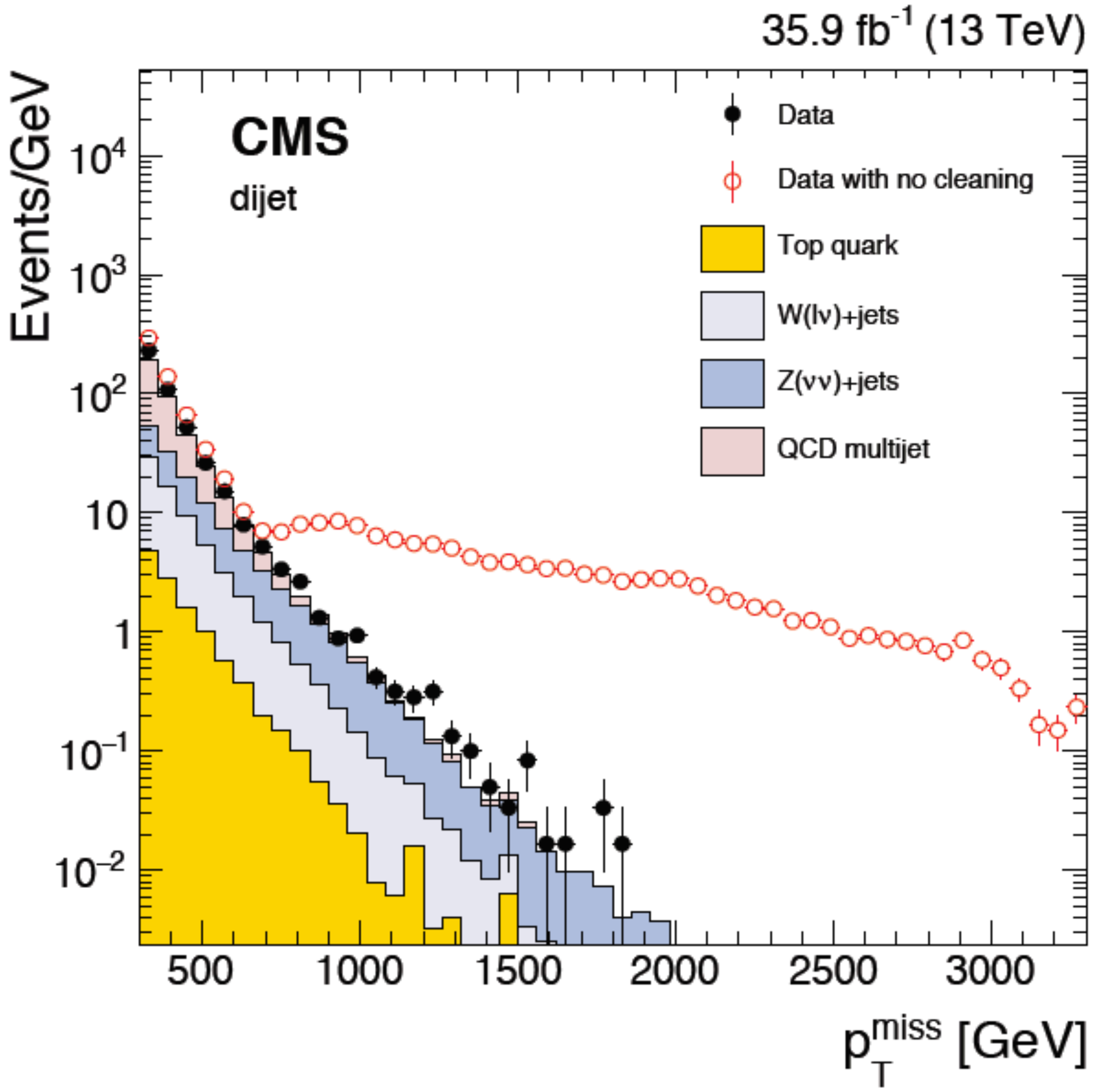
2018 Problems:

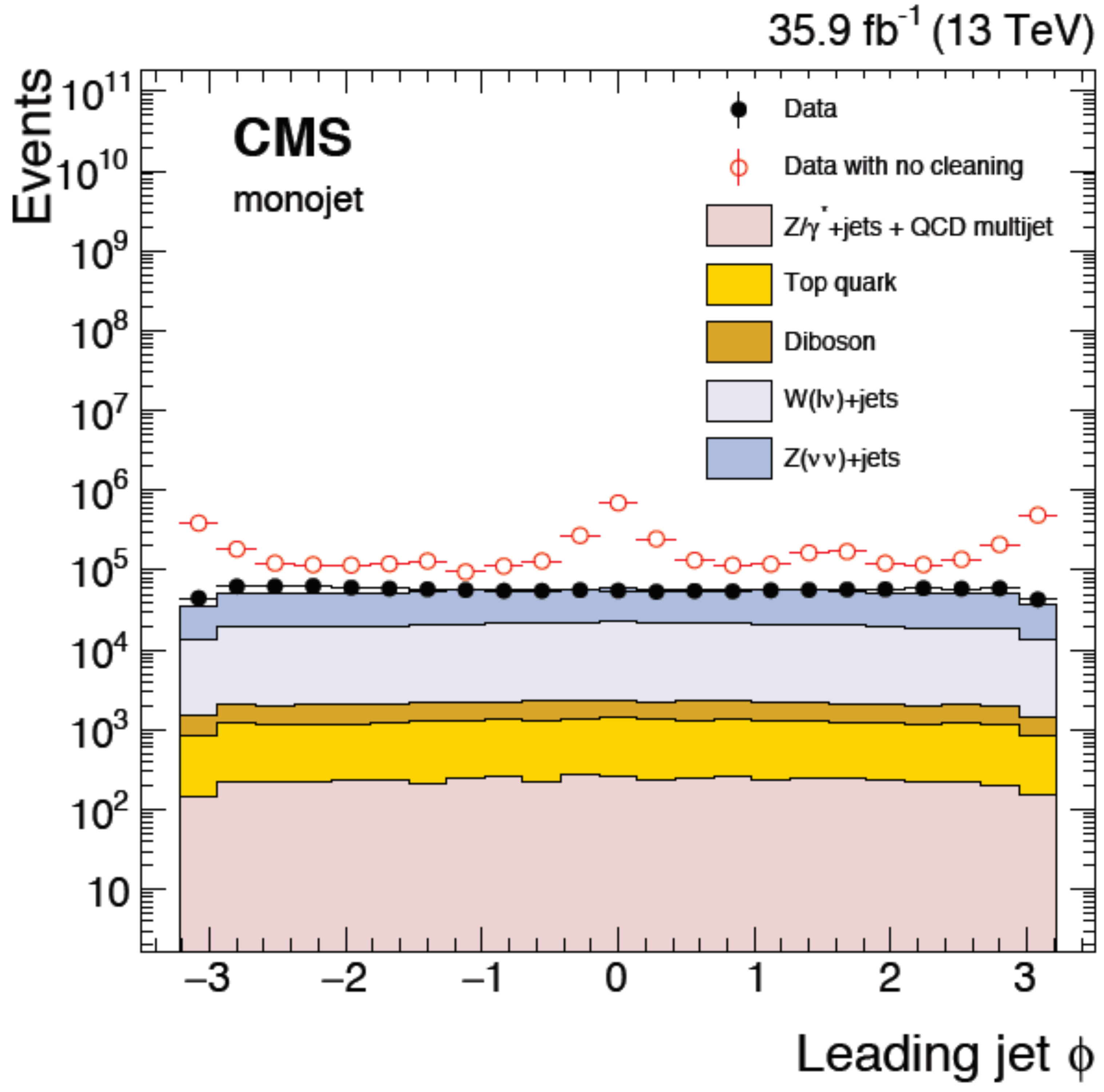
- Local reconstruction issues with HCAL (Negative energy filter)
- Loss of 2 Sectors in the HCAL Endcap

Never ending battle: How do we move forward? For precision Run2, for Run3?

- Time dependent MC? Can this reduce the uncertainties due to non-harmonized data?
- Streamlining the JEC analysis. Can this help coping with unprecedented amount of data is being analyzed - we need to be faster than all CMS analyzers!
- Increasing the dimensionality of the corrections? Detector started having phi-dependent problems..

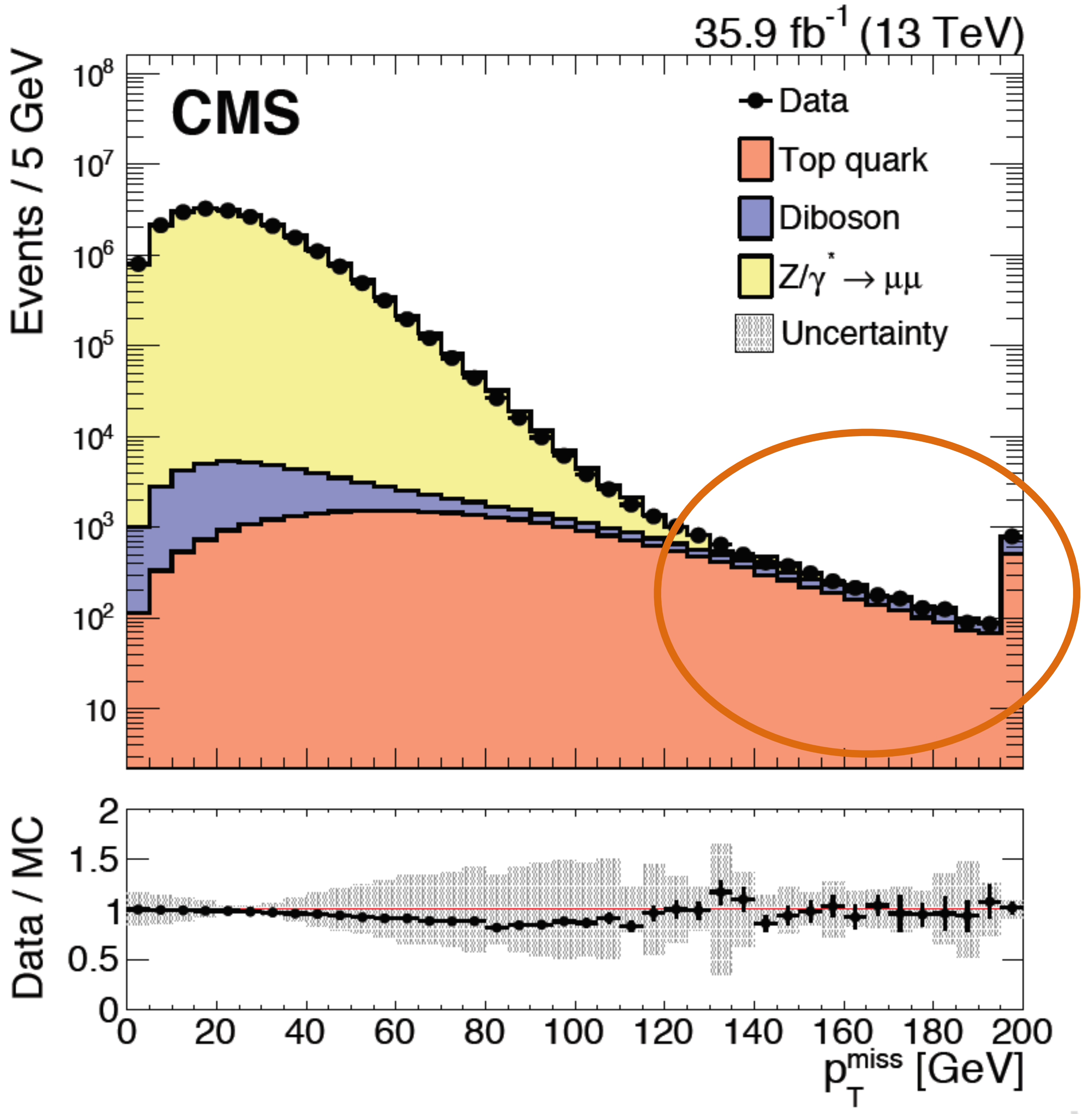
Missing Transverse Momentum: Prerequisites



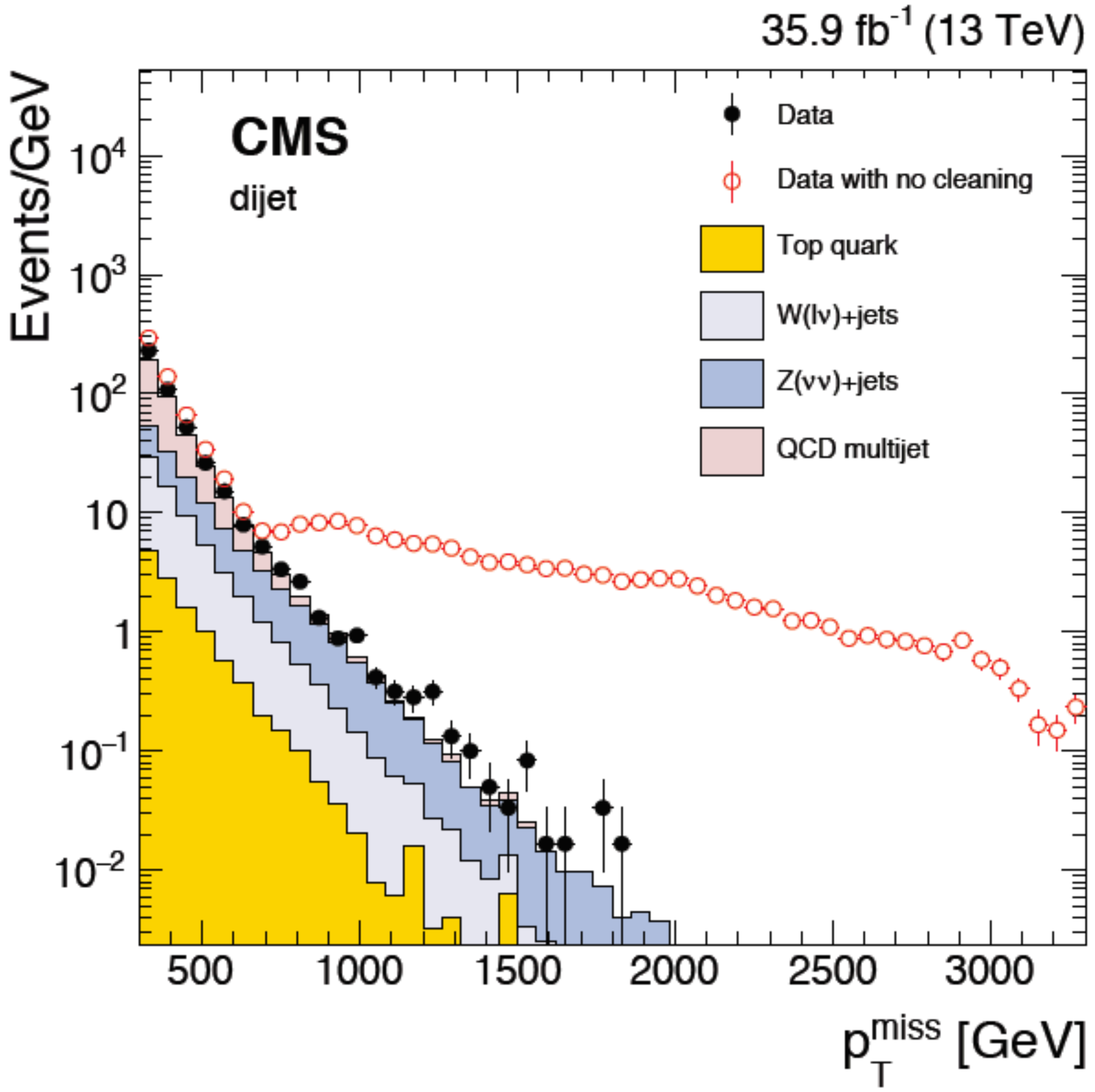


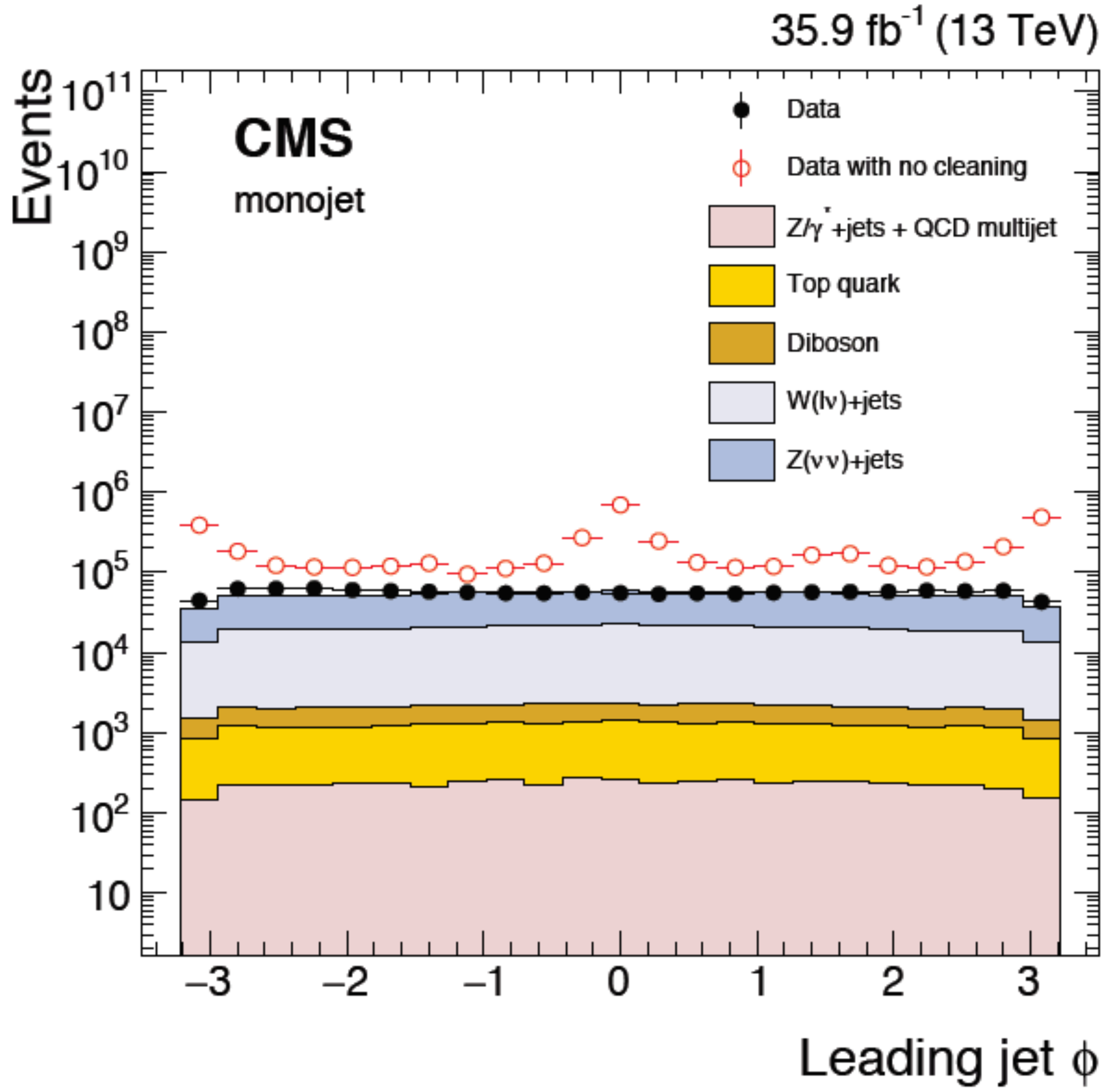
Step 1) Clean your data from anomalous sources! -> MET Tails

Each year, new sources pop up. MET filters are the main deliverable



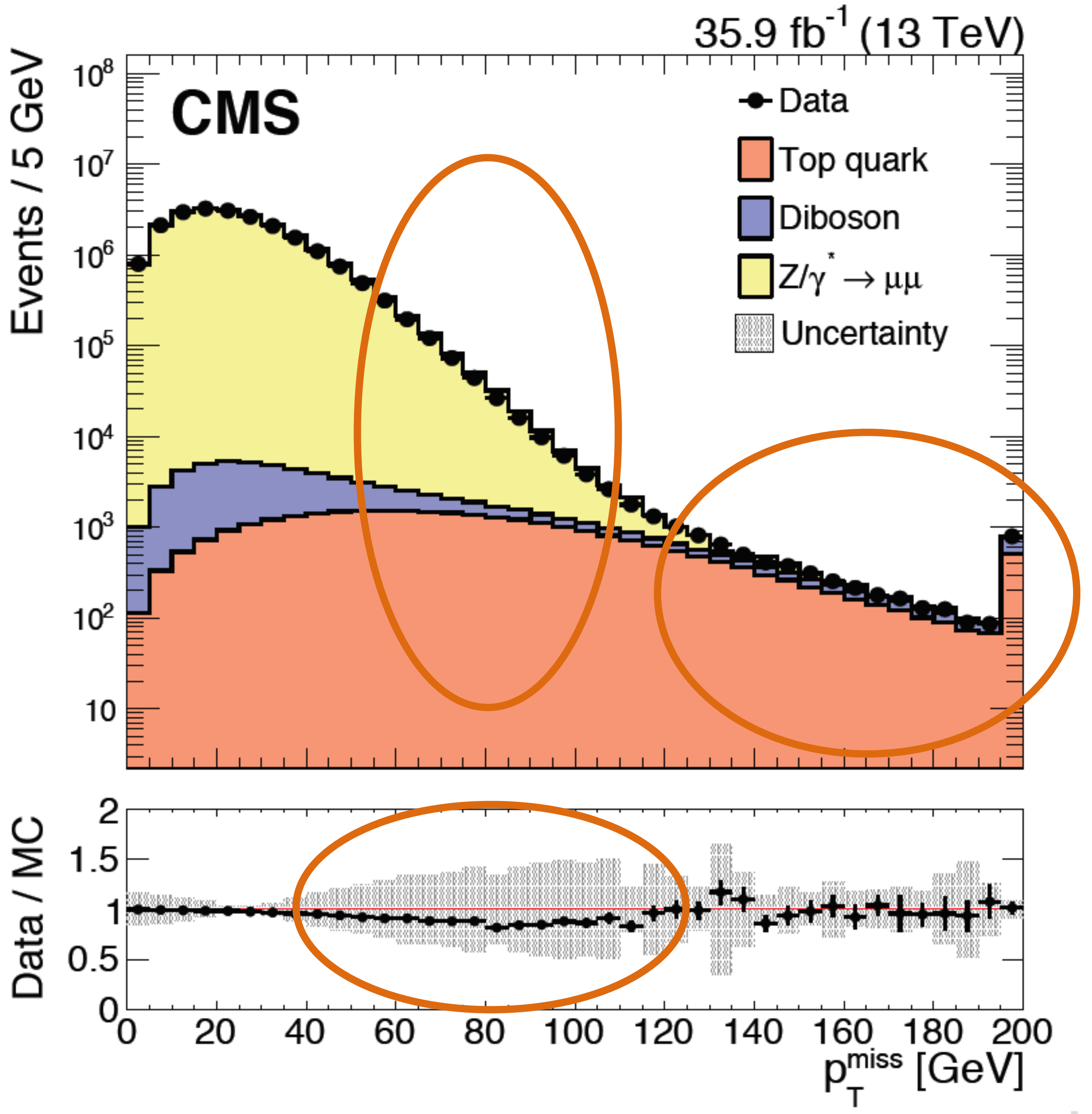
Missing Transverse Momentum: Prerequisites





Step 1) Clean your data from anomalous sources! -> MET Tails

Each year, new sources pop up. MET filters are the main deliverable



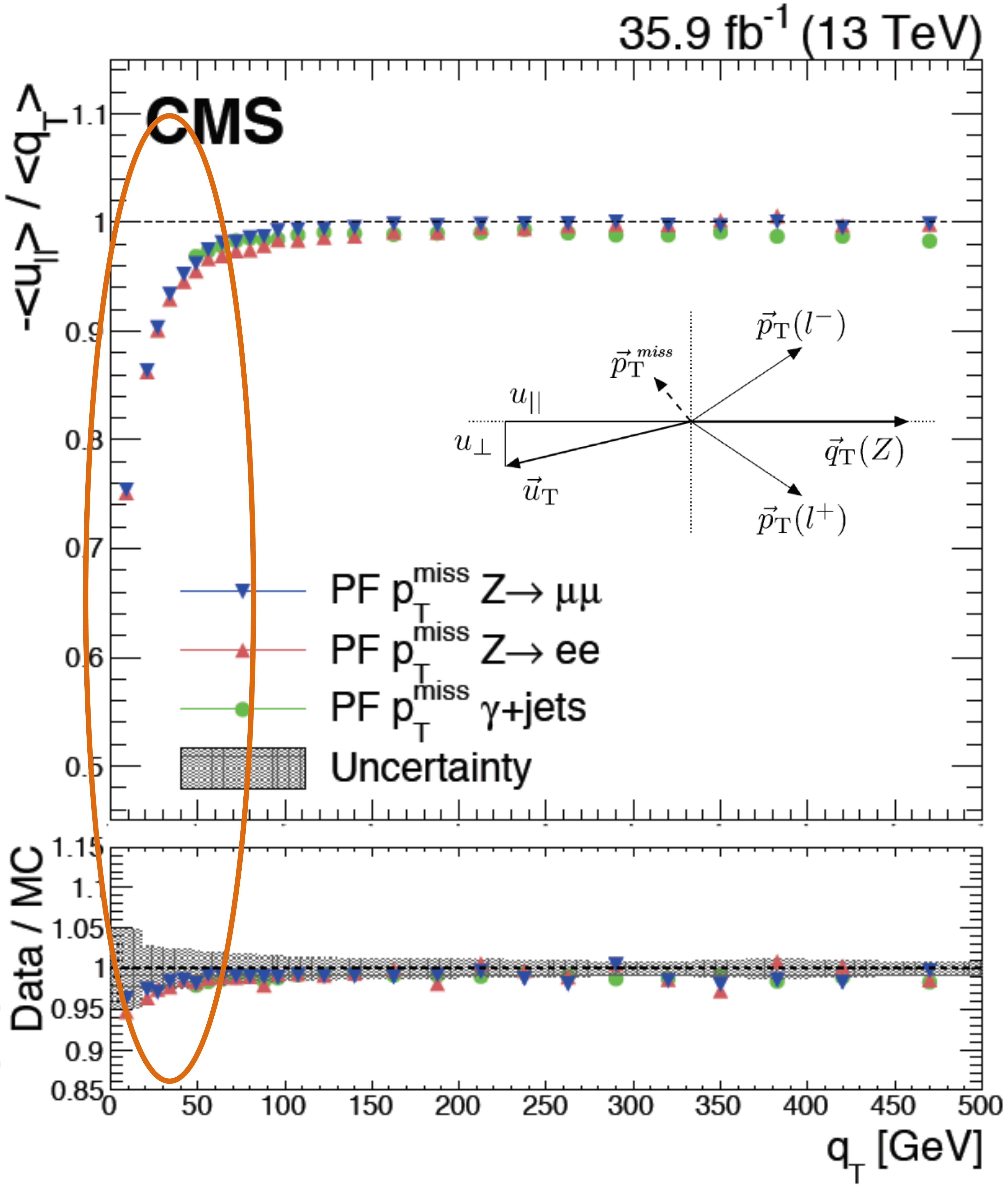
Step 2) Clean your data **more** from reconstructed physics object due to "noise":

- This is a new problem we are facing due to aging detectors and degraded performance -> effects MET resolution

Step 3) Model the pile up well

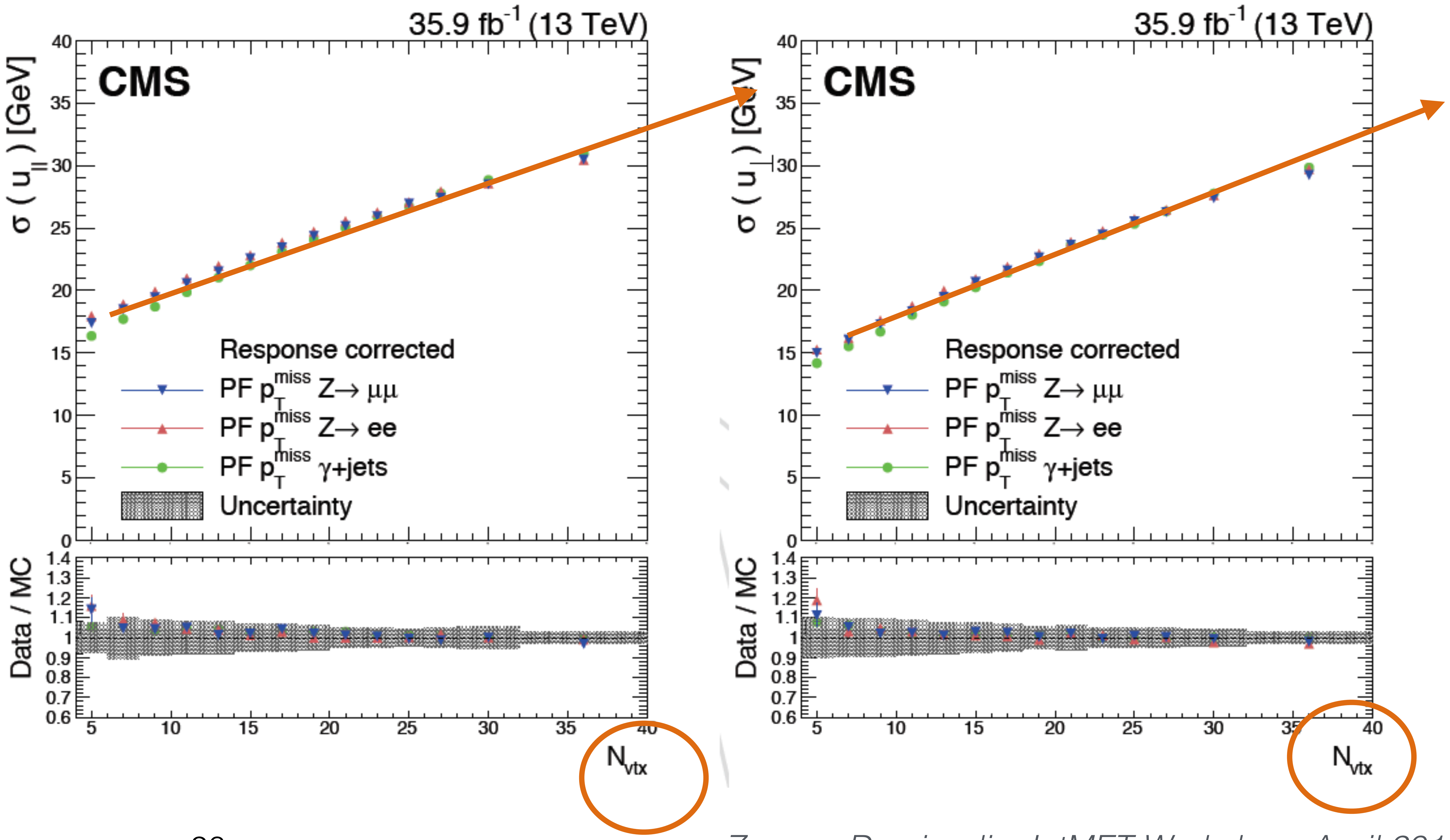
- Getting increasingly hard -> effects MET resolution

Missing Transverse Momentum: Performance



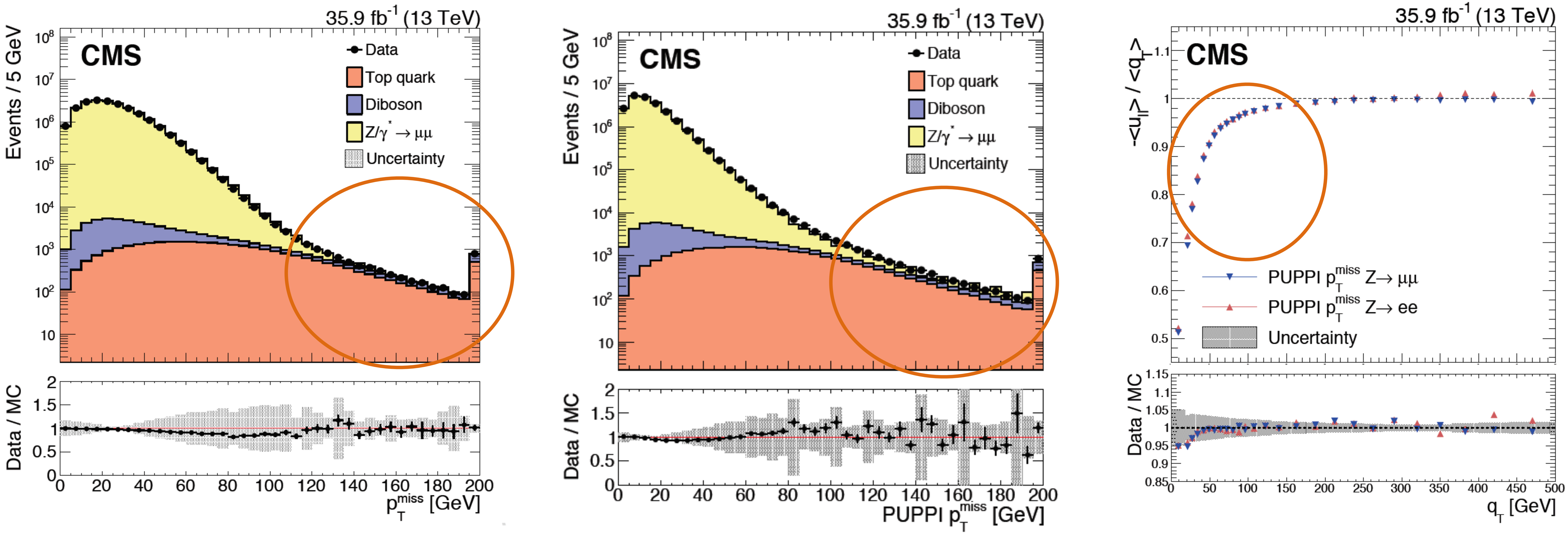
Measured in 3 channels, and yield good agreement.

Room for improvement is in the sharply rising shoulder of the scale at low boson pT



Missing Transverse Momentum: Advanced Algorithms

Comes to the rescue, PUPPI Algorithm: in simplest terms it is a re-weighting of the neutral candidates according to PU probability

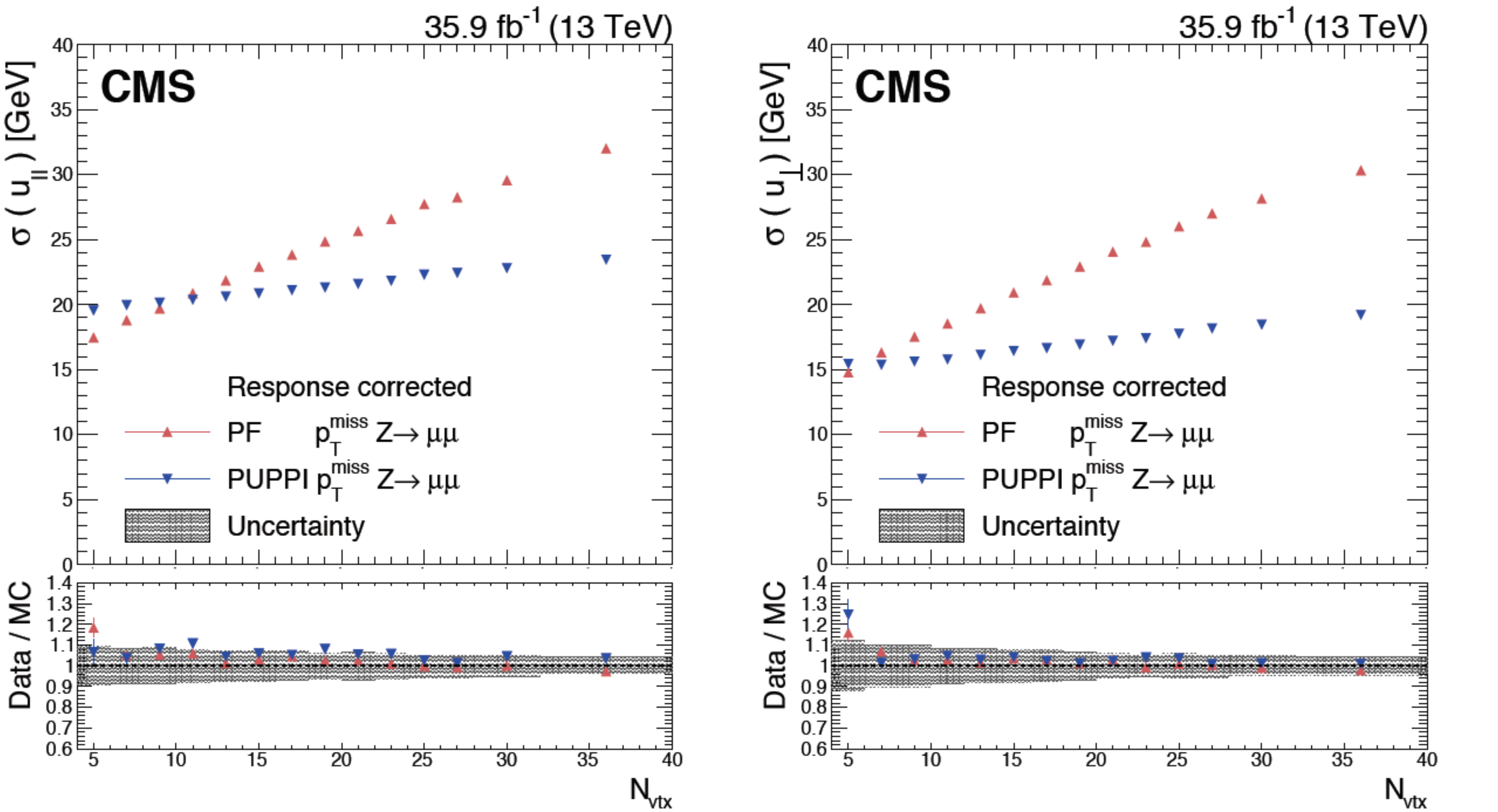


Danger: Any wrong weight assignment could lead to fake MET -> larger tails and slower turn-on in MET scale

BOSTON UNIVERSITY

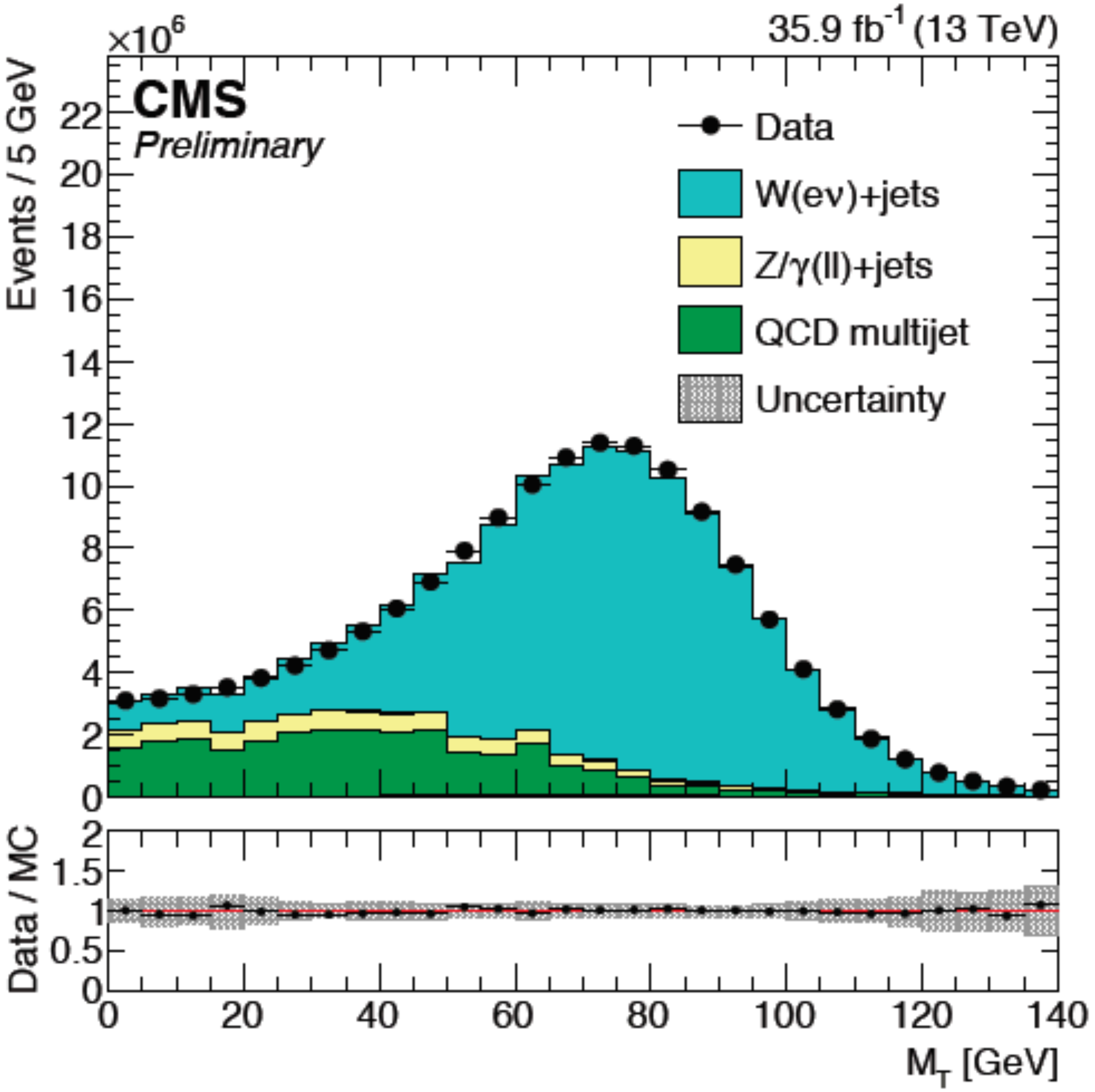
Missing Transverse Momentum: Advanced Algorithms

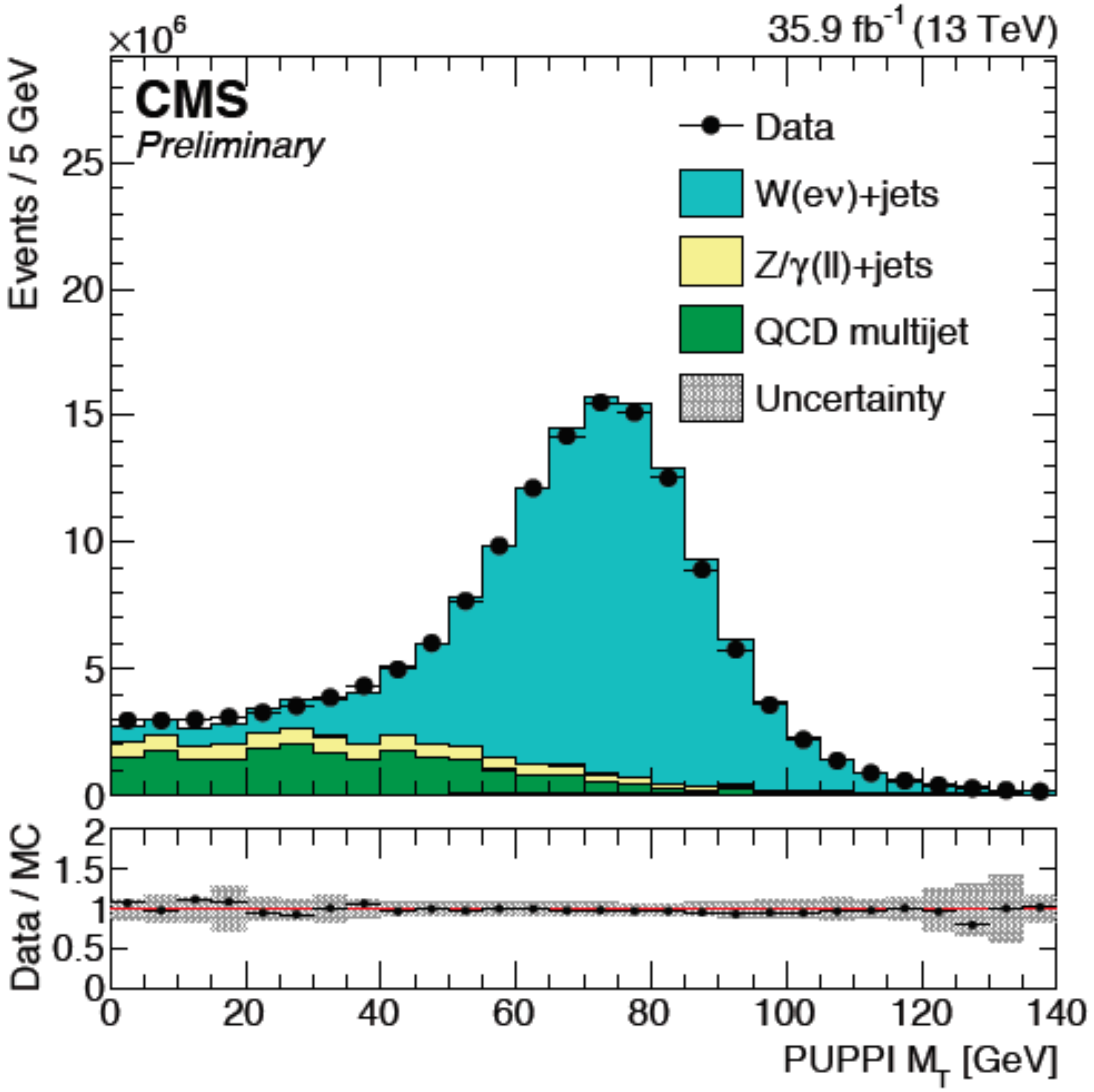
HUGE gains in MET resolution - stability against pile up! Very close to holy grail?



Missing Transverse Momentum: Advanced Algorithms

Resolution improvements particularly impressive for the W events…
20% improvement in RMS and stability of the mean mass value in all PU

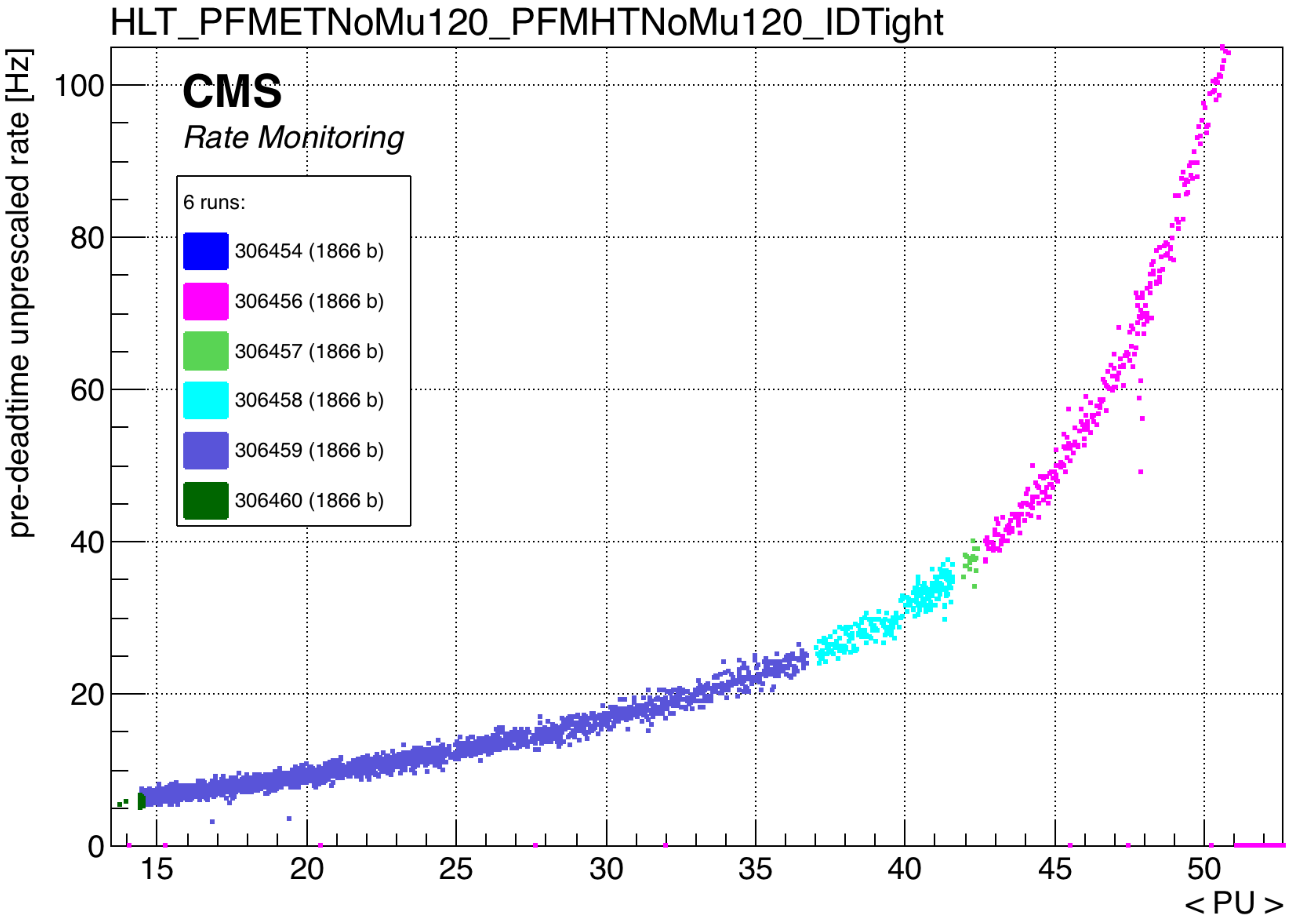




Missing Transverse Momentum: Triggers & Outlook

It is a struggle to keep low thresholds at the Trigger level for jet/MET objects..
Lowest MET/MHT path is at 120-140 GeV, lowest pure MET is at 250-300 GeV

- The efficiency turn-on reaches ~100% at 250 GeV
  - Limited bandwidth: thresholds are dictated by the rate of the trigger!
- To sustain low thresholds:
  - Pile up mitigation algorithms have be introduced
  - Zero-suppression for detectors @ HLT



Jet Tagging: Pileup mitigation

CHS Algorithm : Removes charged particles associated to PU vertex.

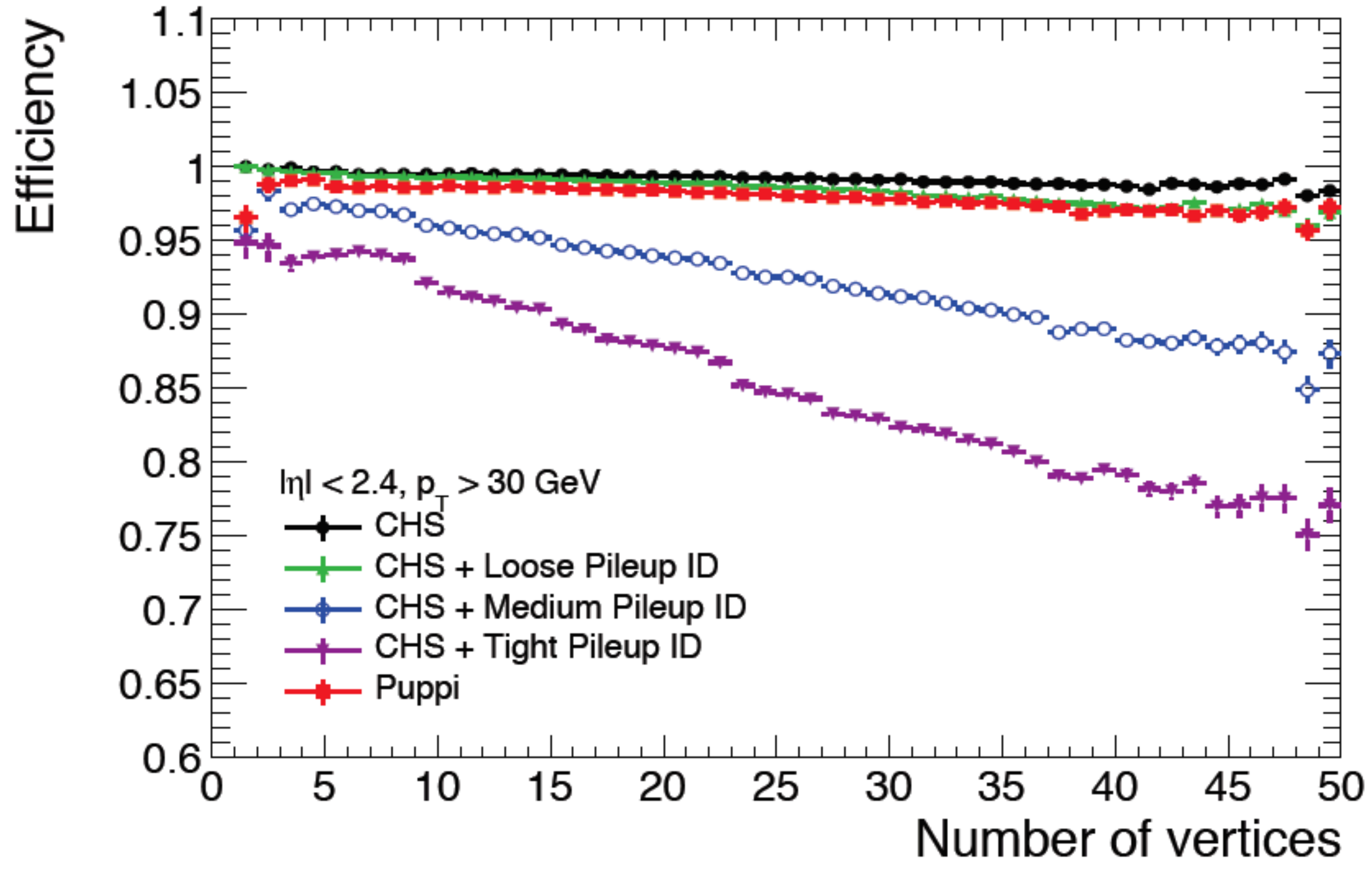
Optimized for early Run2 and can be further improved with the improved tracker coverage.

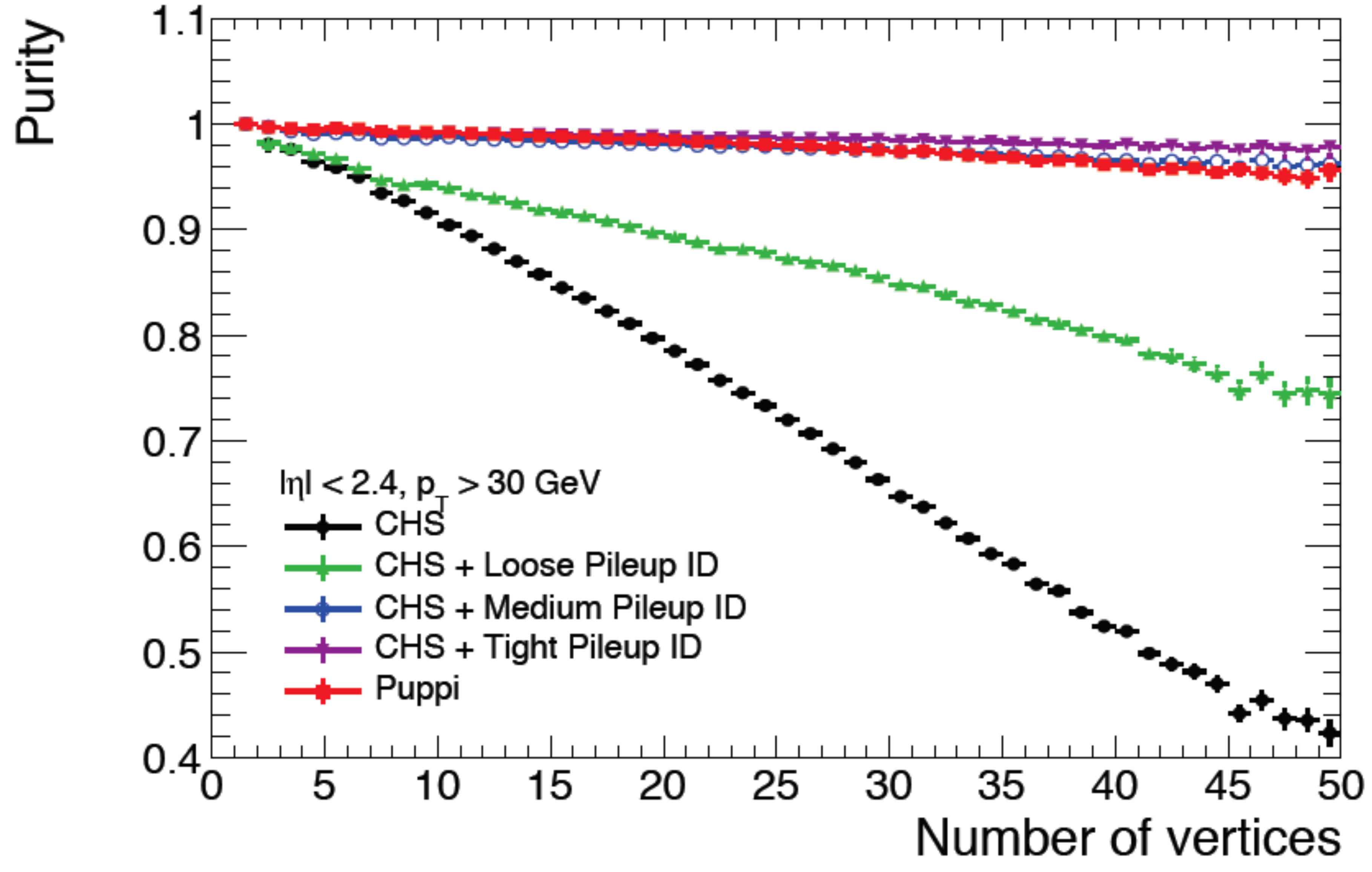
PU Jet id: Multi-variant technique to reject PU jets. It is applied on CHS Jets.

Total of 12 variables used: differences in jet shapes, and tracking related quantities, q/g variables

Puppi Algorithm: Calculate weight for each neutral particle based on the "shape" of PU

$$\alpha_i = \log \sum_{j \neq i, \Delta R_{ij} < 0.4} \left(\frac{p_{Tj}}{\Delta R_{ij}} \right)^2 \begin{cases} \text{for } |\eta_i| < 2.5, & \text{j = charged} \\ \text{for } |\eta_i| > 2.5, & \text{j = all} \end{cases}$$



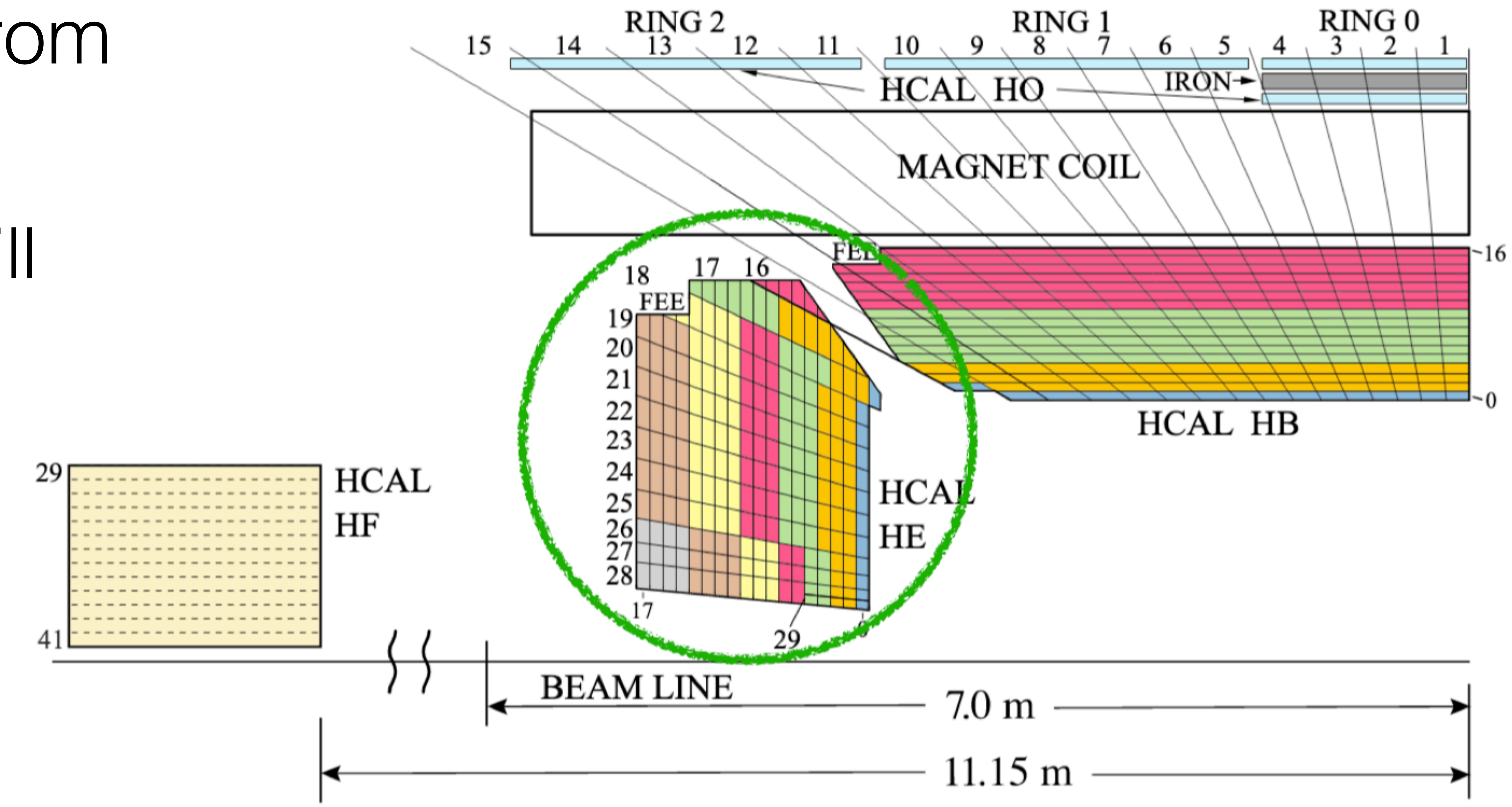


Future improvements: HCAL Depth Segmentation

In 2018, HE **layers** were increased from **3 to up to 7!**

Longitudinal shower profile information will be helpful in discriminating hard interaction from pileup.

Currently this information is not used in the reconstruction of jets



PUPPI

$$\alpha_i = \log \sum_{j \in \text{event}} \xi_{ij} \times \Theta(R_{\min} \leq \Delta R_{ij} \leq R_0),$$

$$\text{where } \xi_{ij} = \frac{p_{Tj}}{\Delta R_{ij}}.$$

↓

$$\chi_i^2 = \Theta(\alpha_i - \bar{\alpha}_{\text{PU}}) \times \frac{(\alpha_i - \bar{\alpha}_{\text{PU}})^2}{\sigma_{\text{PU}}^2},$$

↓

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

PUPPI+depth

$$\alpha_i, d_i$$

↓

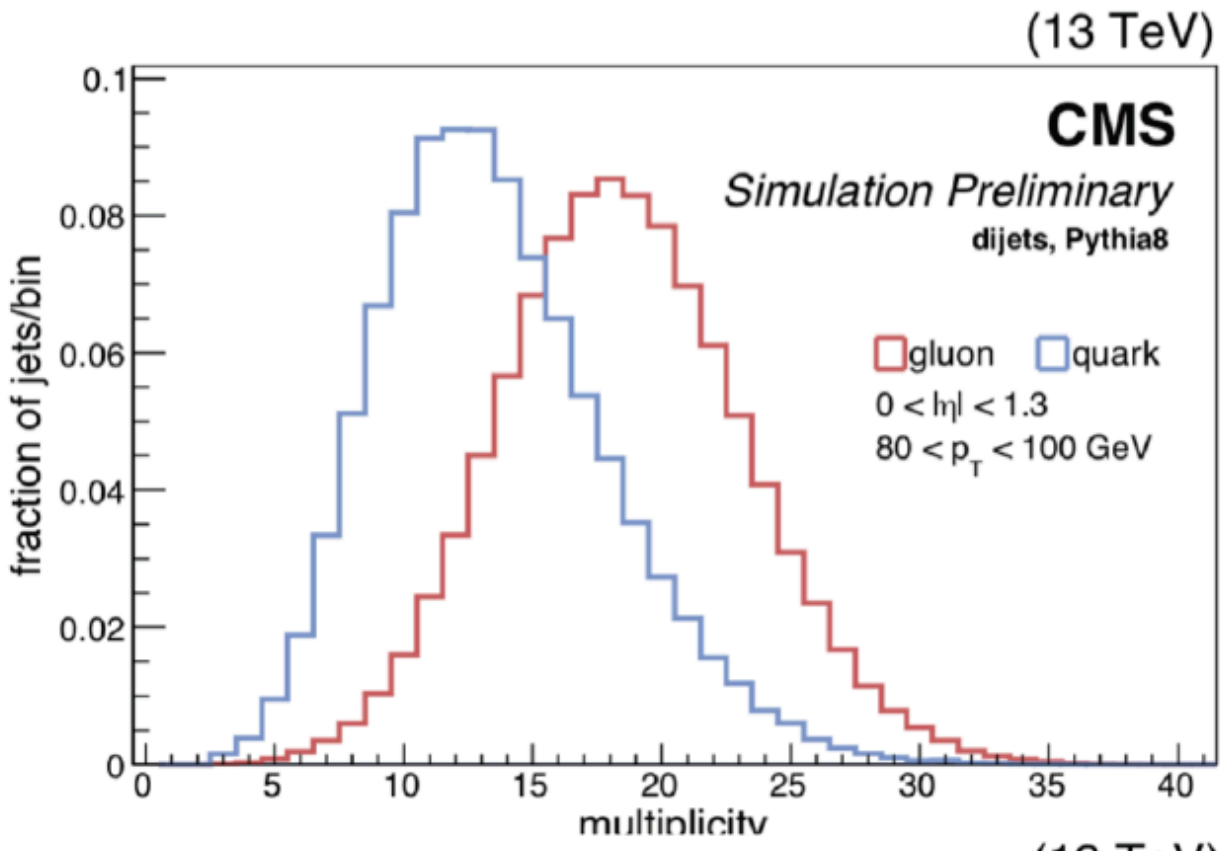
$$\chi_i^2, f(d_i)$$

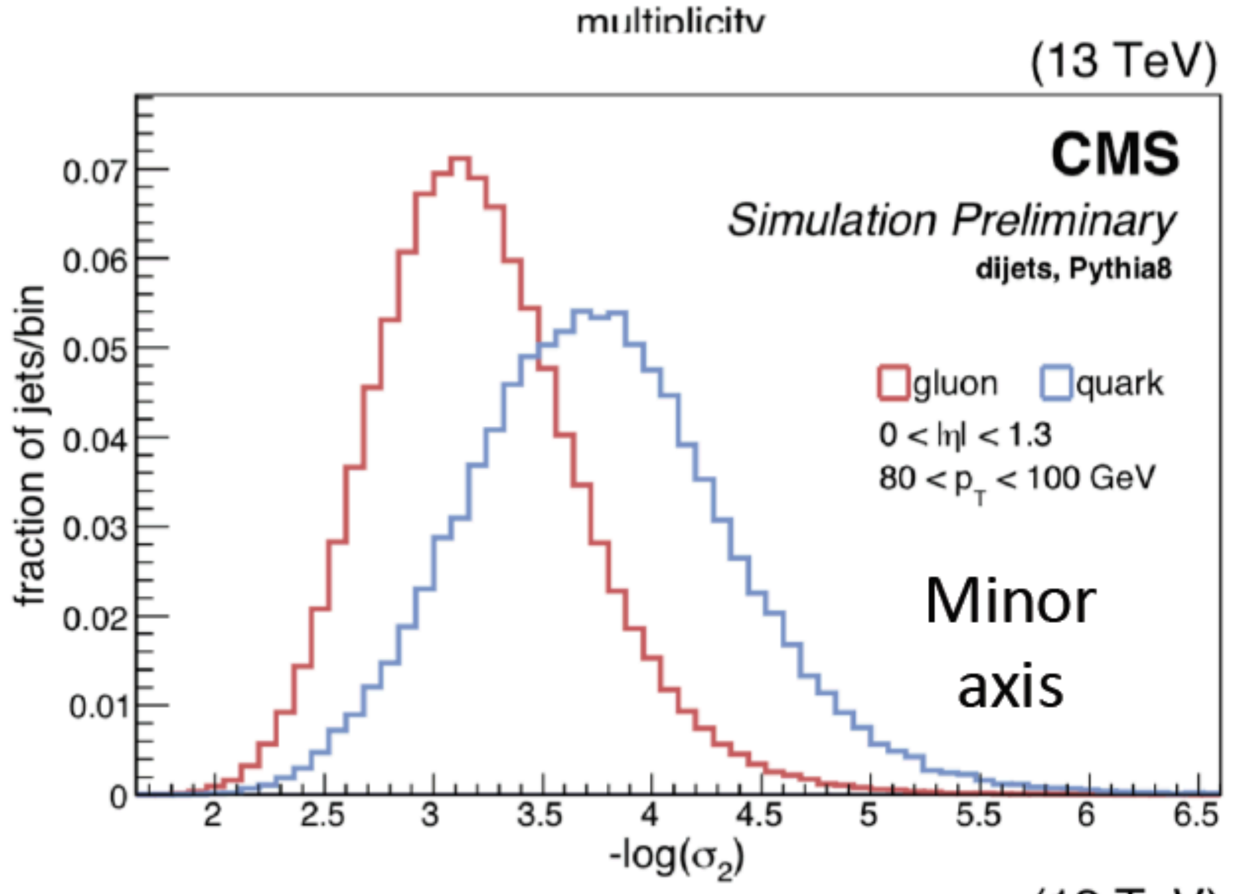
↓

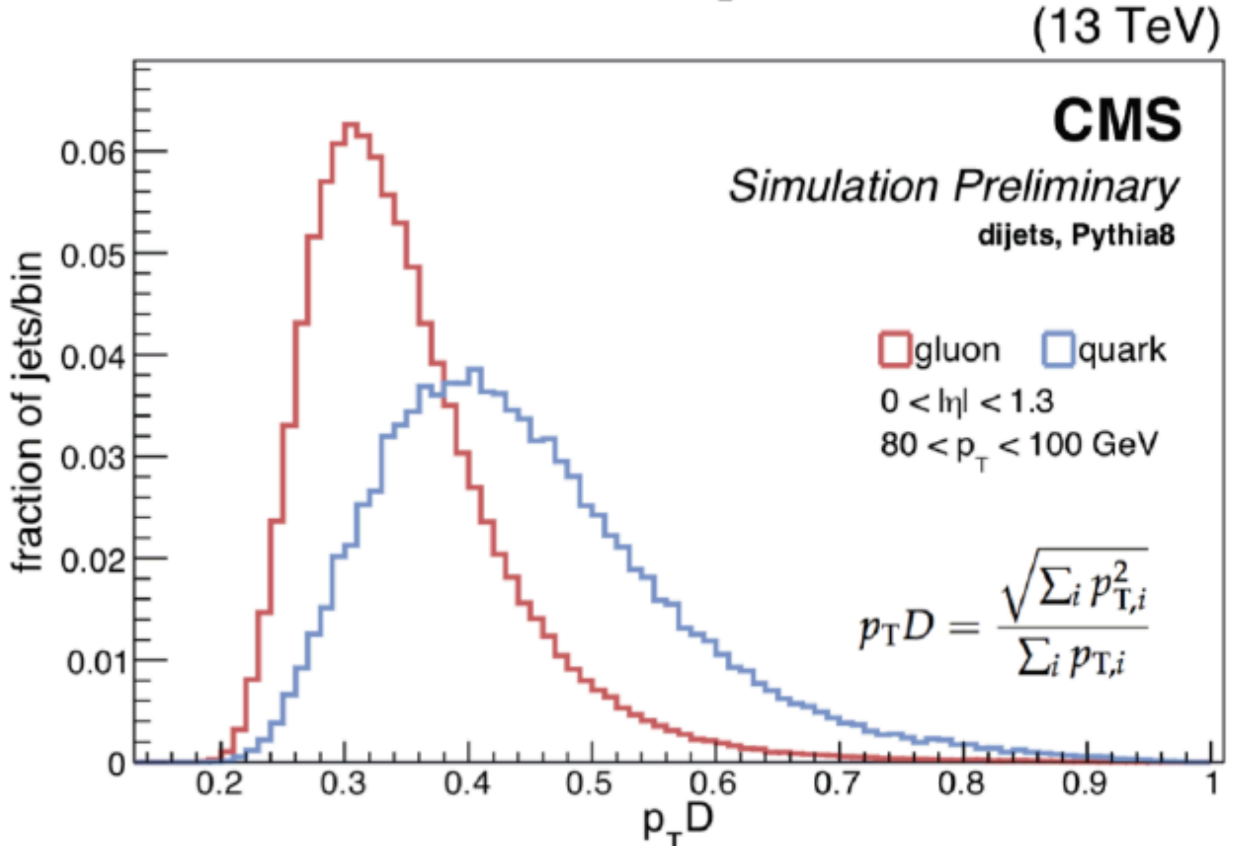
$$w_i = F_{\chi^2,\text{NDF}=2}(\chi_i^2, f(d_i))$$

We can improve the PUPPI algorithm by defining a discriminator using shower shape profile for the PF candidates in the end cap! ***Stay tuned…***

Quark Gluon Identification



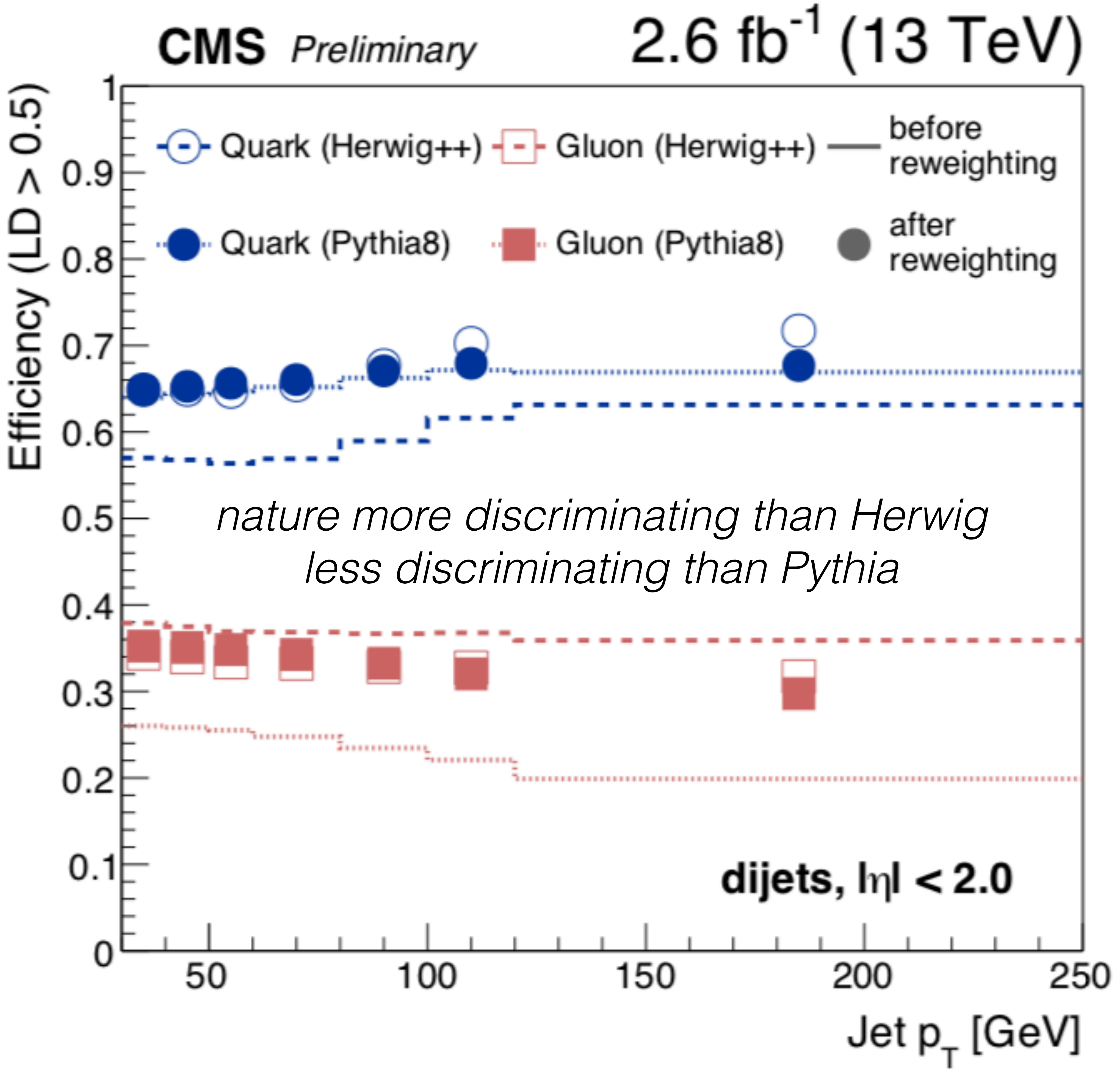




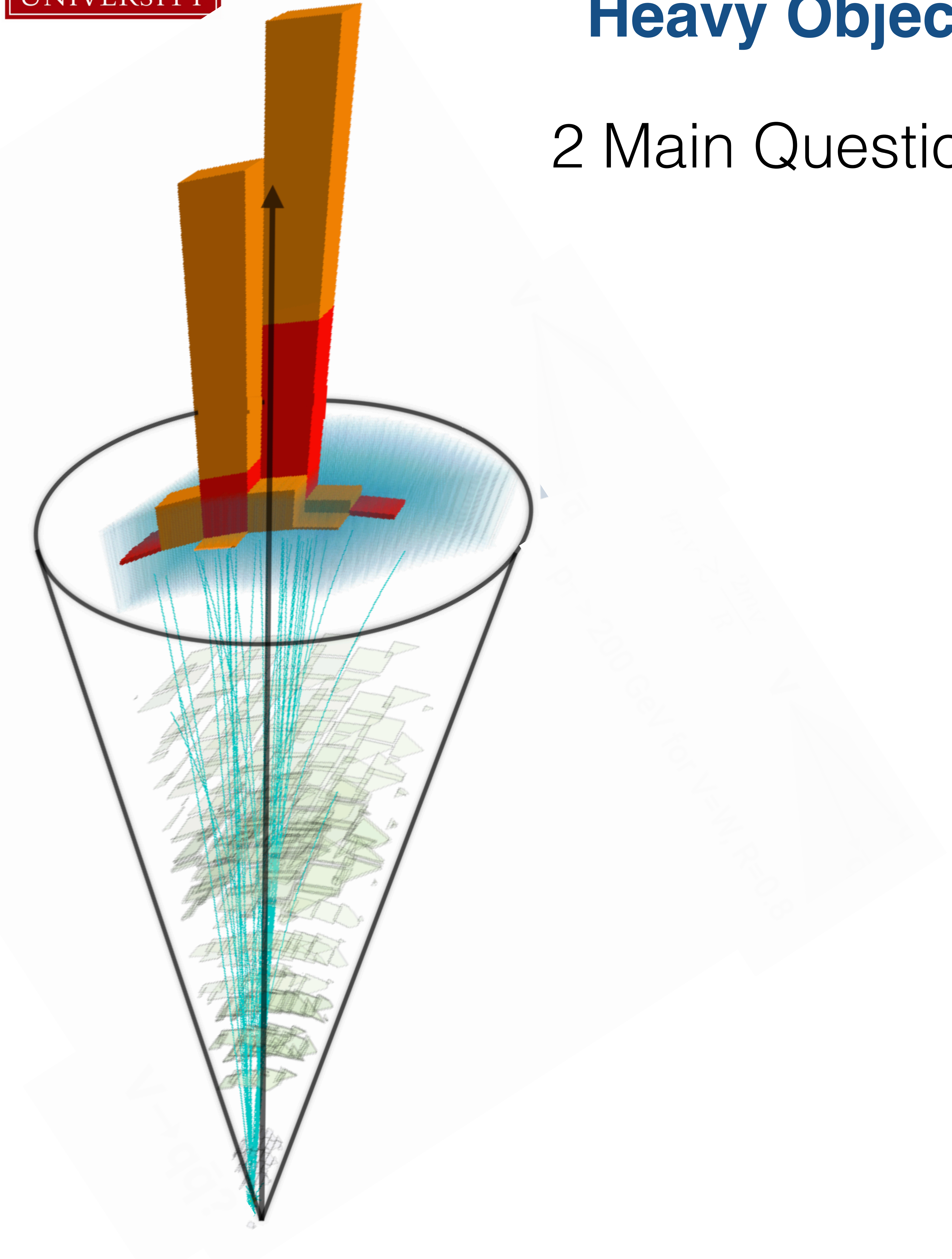
Likelihood discriminant using 3 variables:
ptD,σ2, multiplicity

Data/MC scale factors extracted from dijet and Z+jet events, used for systematic reshaping

- Effect of reshaping <1% for quarks, up to 10% for gluons
- Improves agreement between Pythia and Herwig



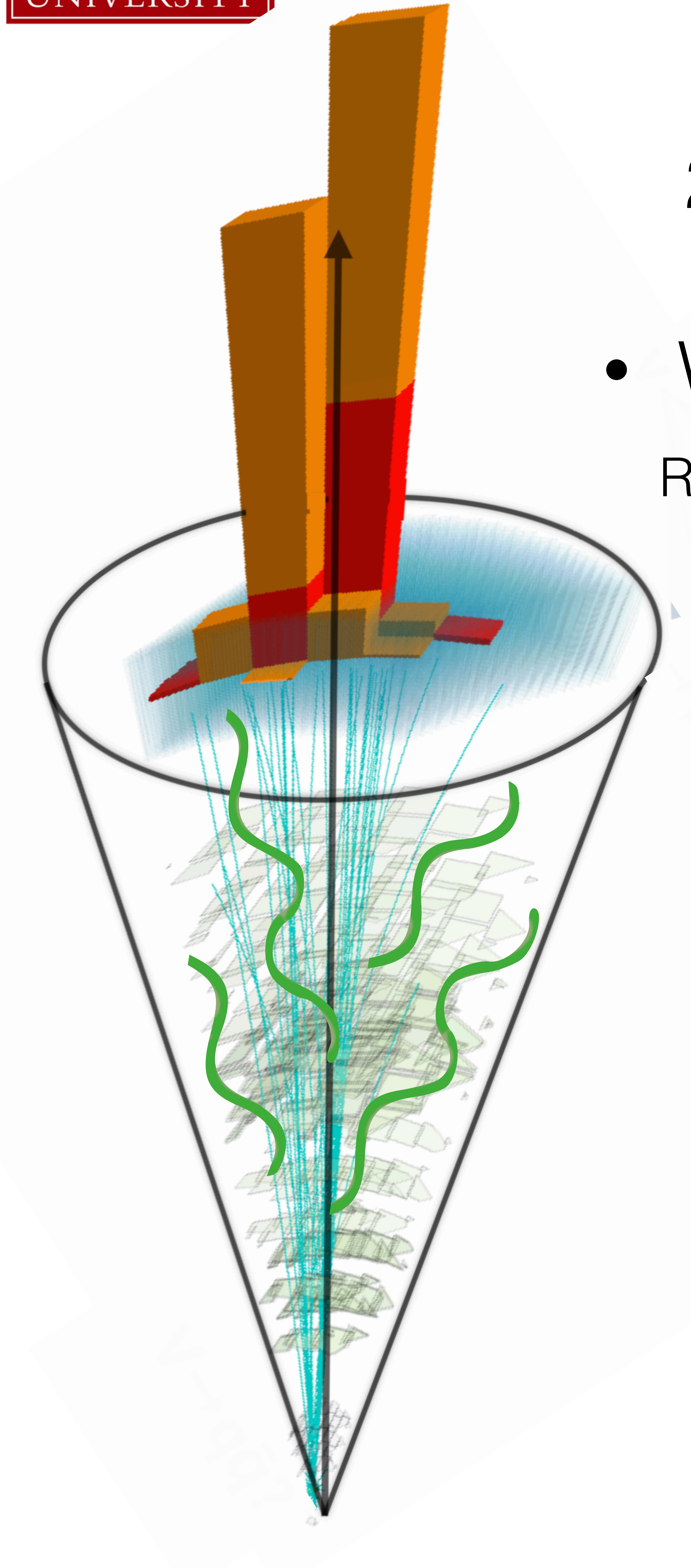
Heavy Object Tagging: “Traditional Way”



2 Main Questions you can ask to this “picture”

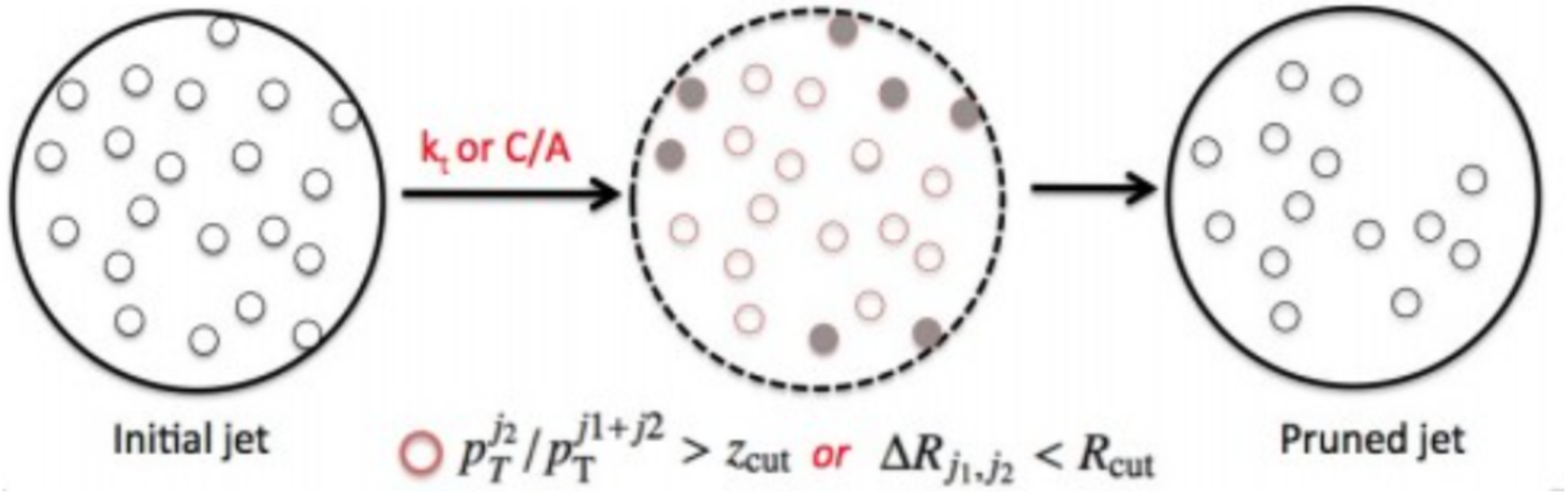
Heavy Object Tagging: “Traditional Way”

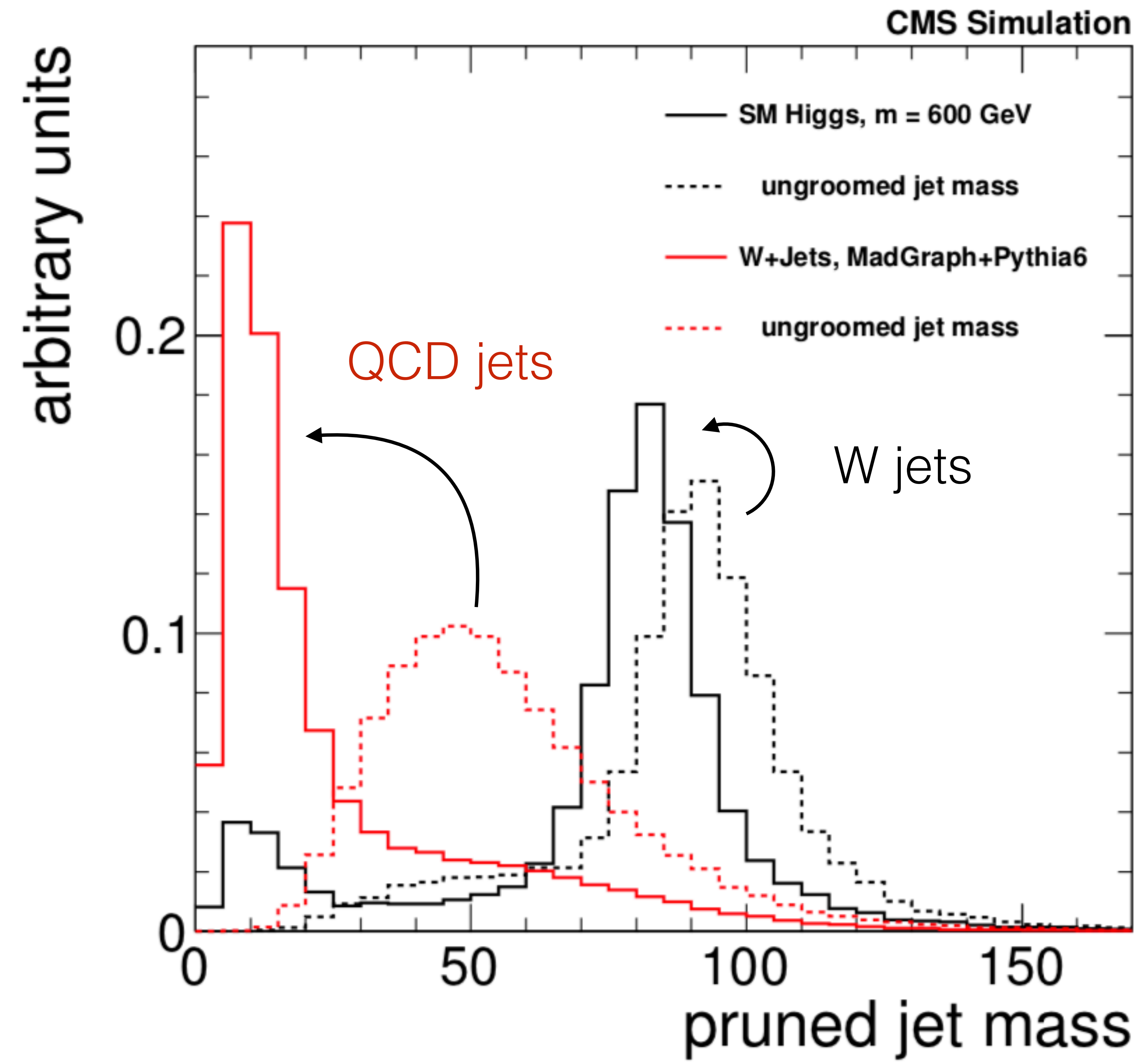
2 Main Questions you can ask to this “picture”

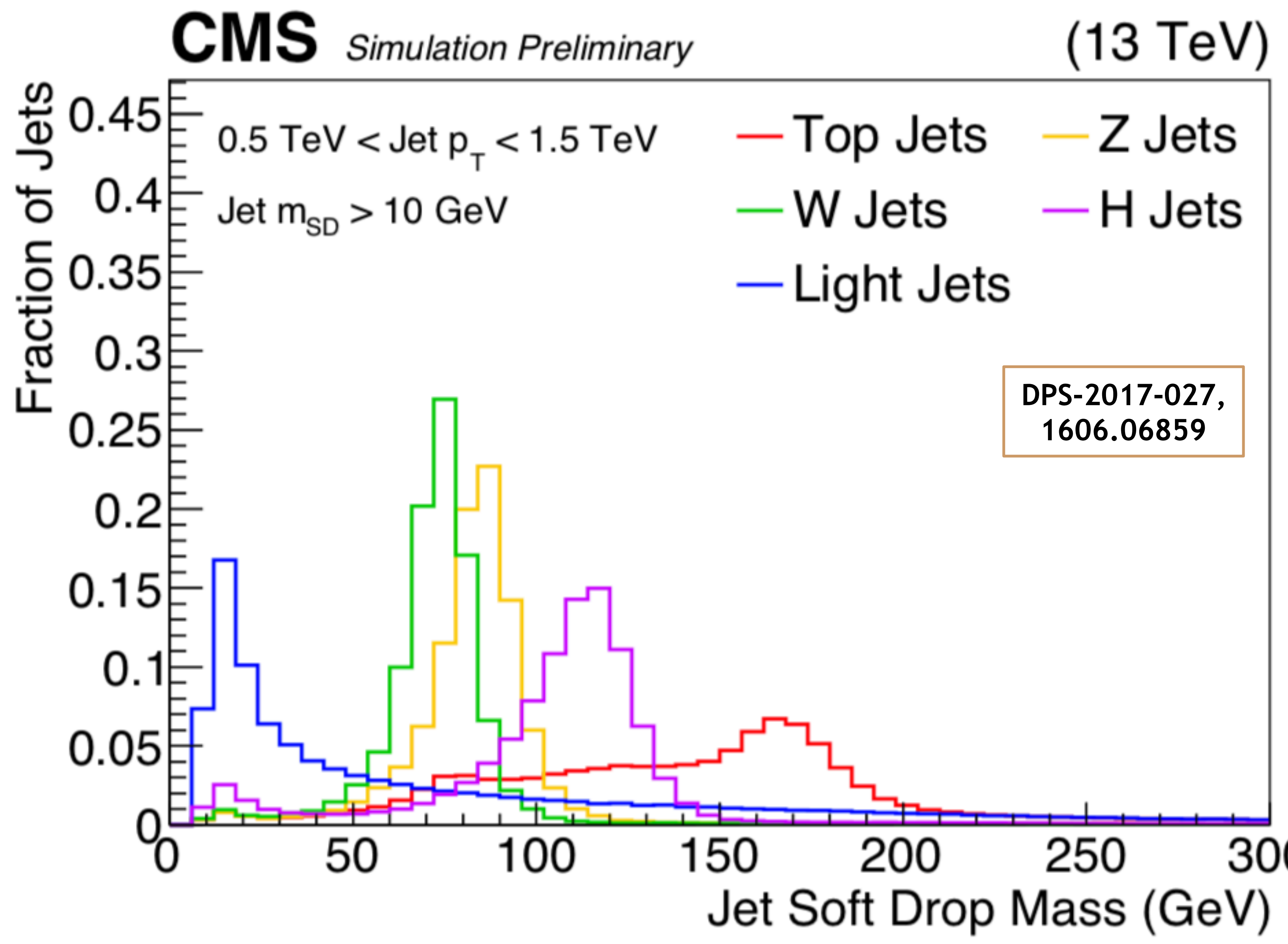


- What is the mass of this object?

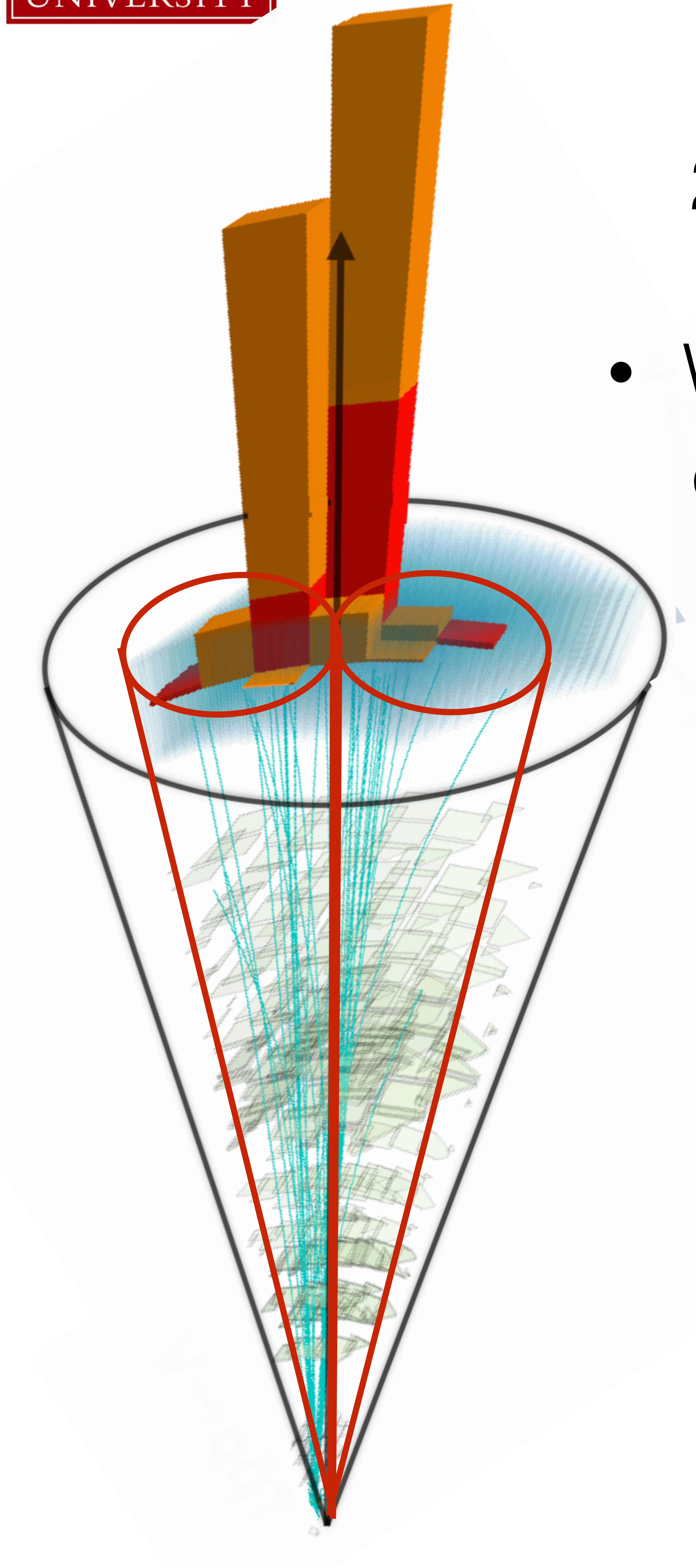
Remove softer constituents (QCD radiation)







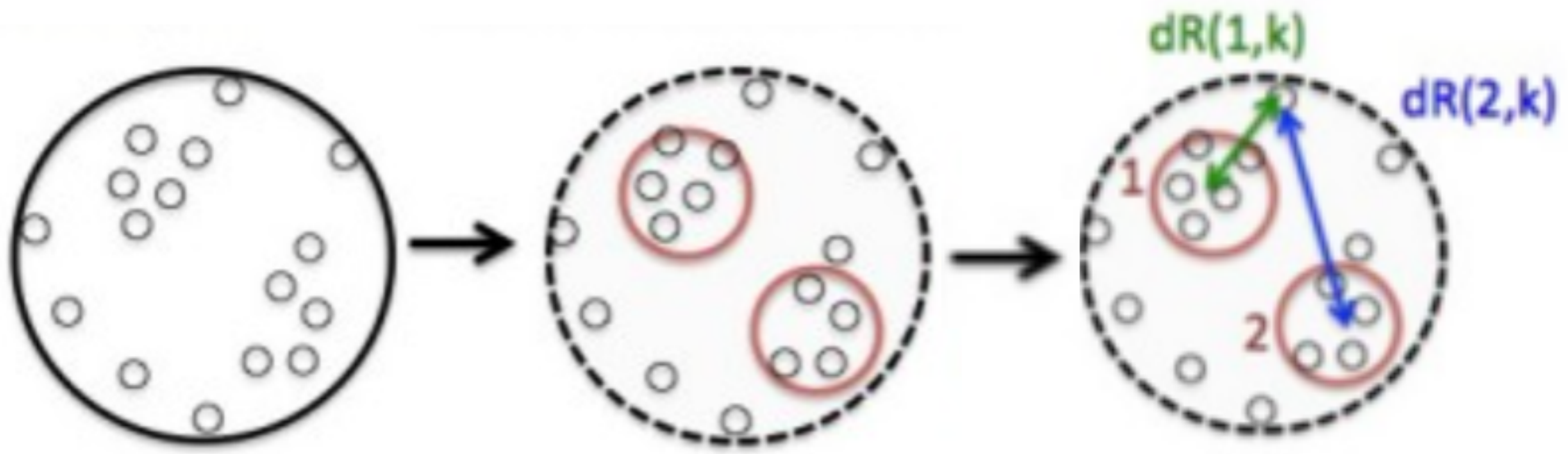
Heavy Object Tagging: "Traditional Way"

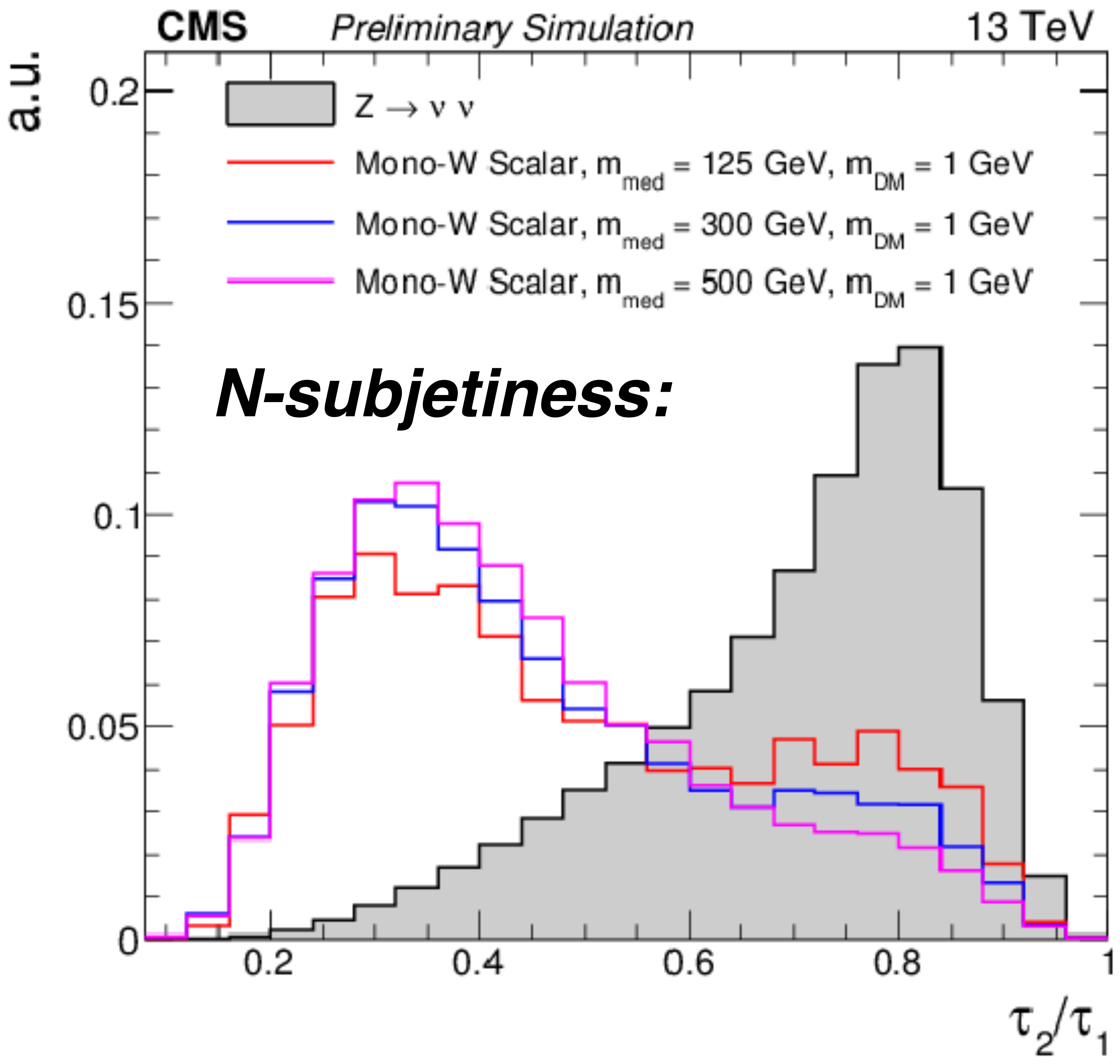


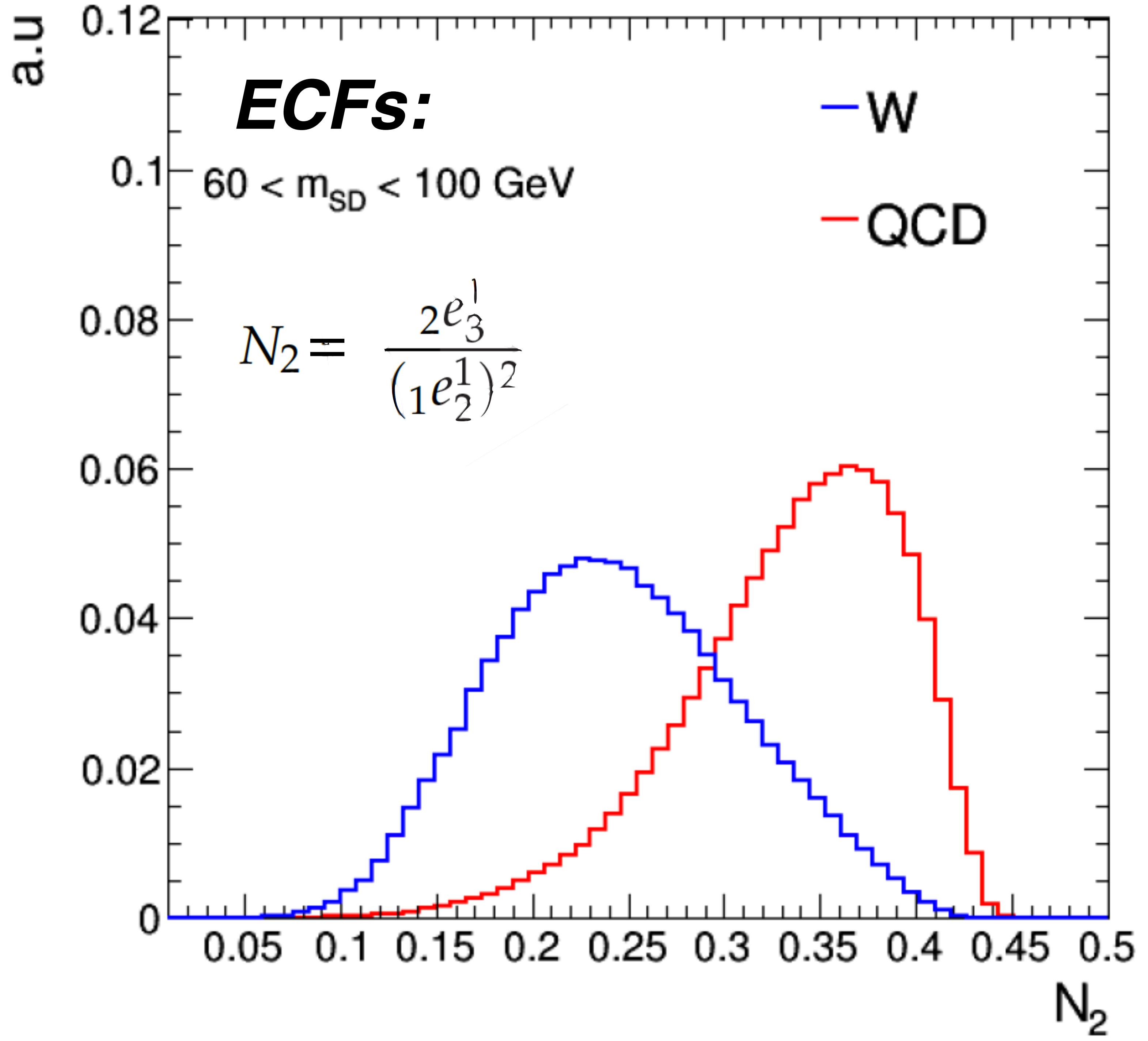
2 Main Questions you can ask to this "picture"

- What is inside this object?

Quantify how well a jet can be subdivided into sub-jet



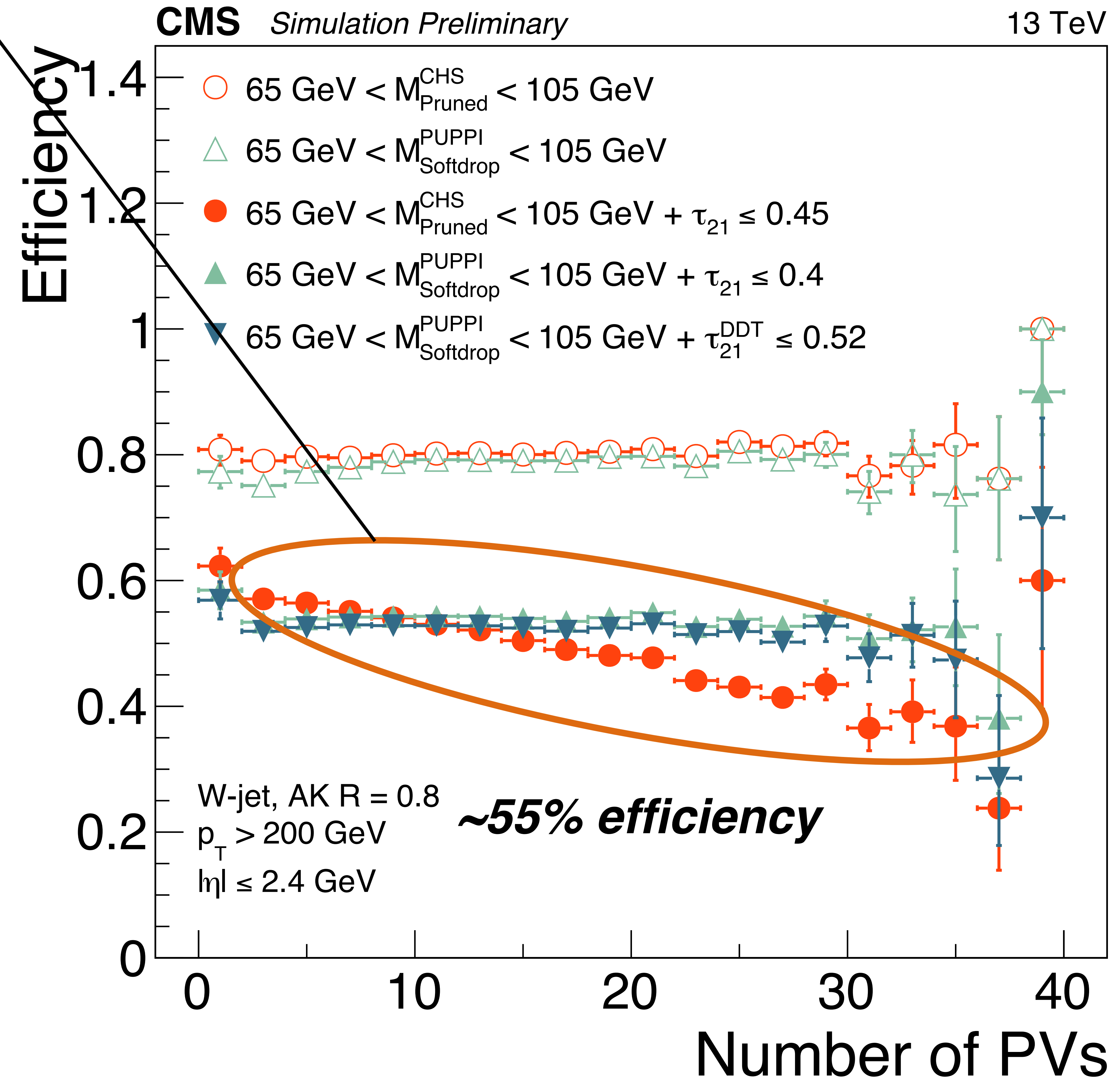


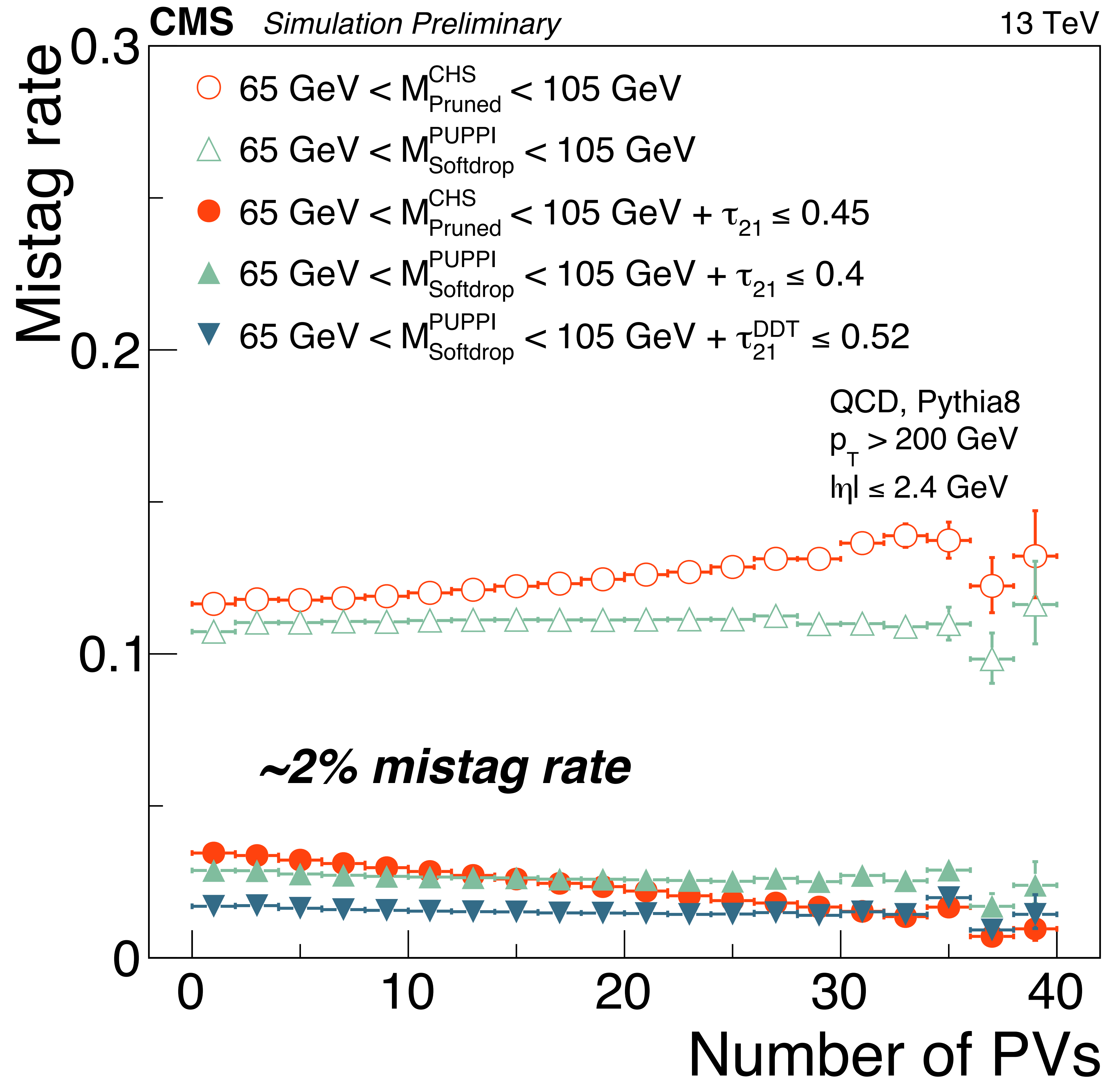


Heavy Object Tagging: “Traditional Way”

For various working points and jet algorithms, SFs are derived regularly with ~O(10%) uncertainty

PU dependency reduced with Puppi!





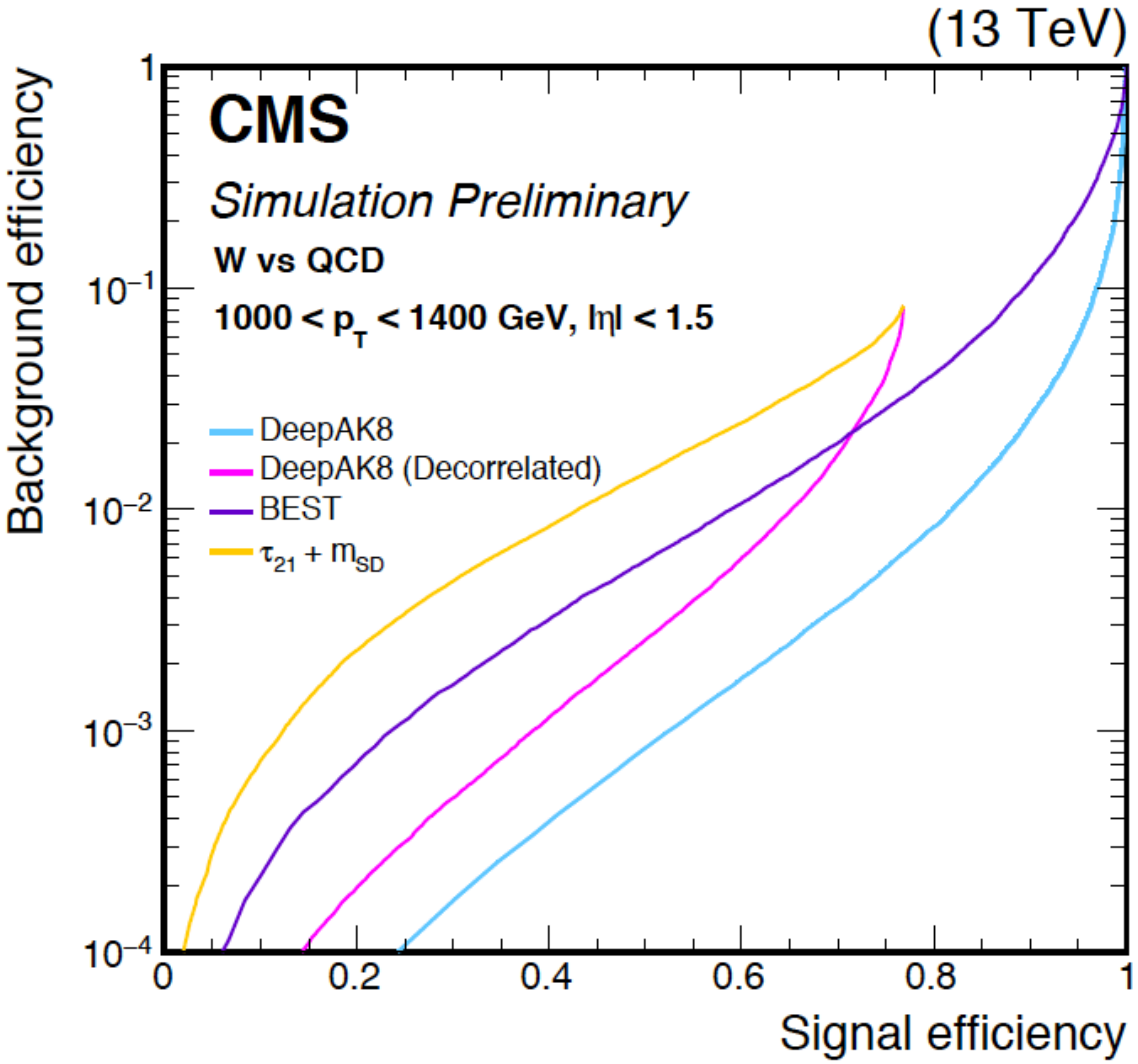
Heavy Object Tagging: “New Generation”

Many taggers based on various ML methods are being investigated:
https://cds.cern.ch/record/2275226/files/DP2017_027.pdf
Paper with data validation will be out this summer!

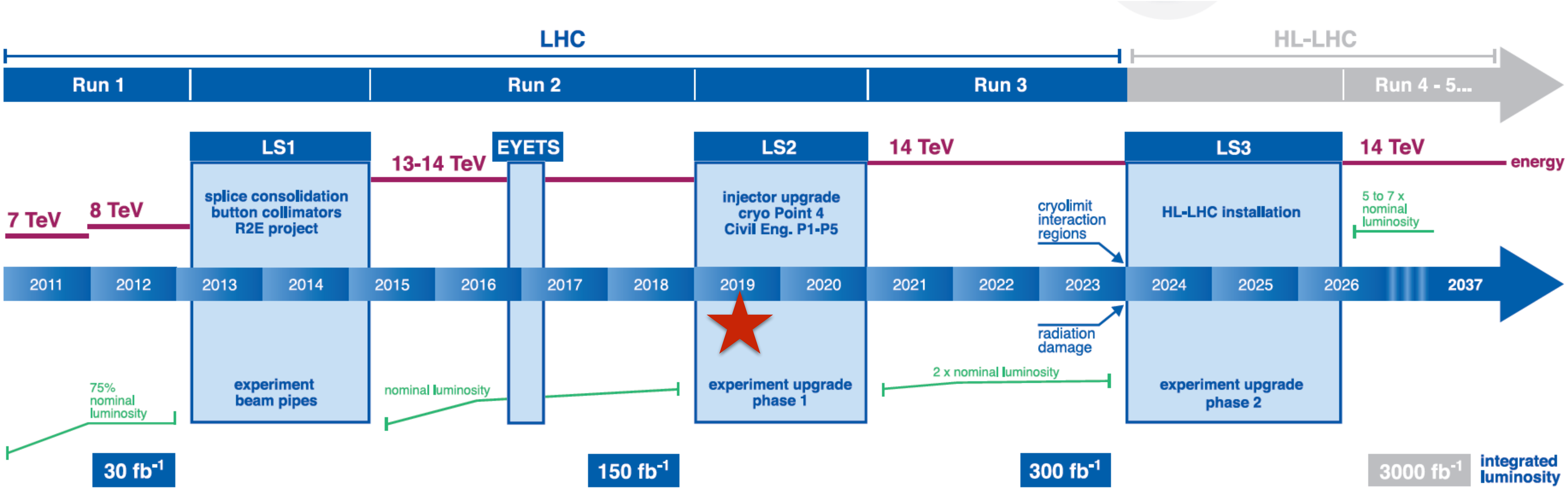
Deep Jet Classifier: Exploits particle-level information directly with customized Deep Neural Network (DNN).

Boosted Event Shape Tagger (BEST): Obtains discrimination on a jet-by-jet basis by transforming the entire set of jet constituents with a boost vector obtained by assuming the jet originated from one of the heavy objects.

Are they correlated with mass? Can we reproduce this performance in data? Pileup dependence?
Stay tuned!!



LHC Schedule & Run 3



Two main objectives:

- Answer as many of the questions asked in this talk in time for Ultra legacy of the full Run2 data (only a month away)
- Learn from the experience and prepare for Run3 (only a year away)

Summary & Outlook

Run2 experience: For accurate, and precise Jet/MET object performance:
(1) reliable local reconstruction
(2) stable particle flow (i.e. global event description)

These *almost* came for free easy in the past…
Now detectors are aged and most will not be replaced for Run3…

In the mean time … LHC is discussing increasing the pile up for Run3
(up to pile up 60)

We have to be smarter:
Port our knowledge to online reconstruction
Invest efforts to stabilize the global event description and pile up modeling

BOSTON UNIVERSITY

Summary & Outlook

Run2 experience: For accurate, and precise Jet/MET object ... nce:

(1) reliable local reconstruction

(2) stable particle flow (i.e. global ev...

These *almost* ca...

Now detectors are ... for Run3…

In the m... easing the pile up for Run3

... ile up 60)

We have to be smarter:

Port our knowledge to online reconstruction

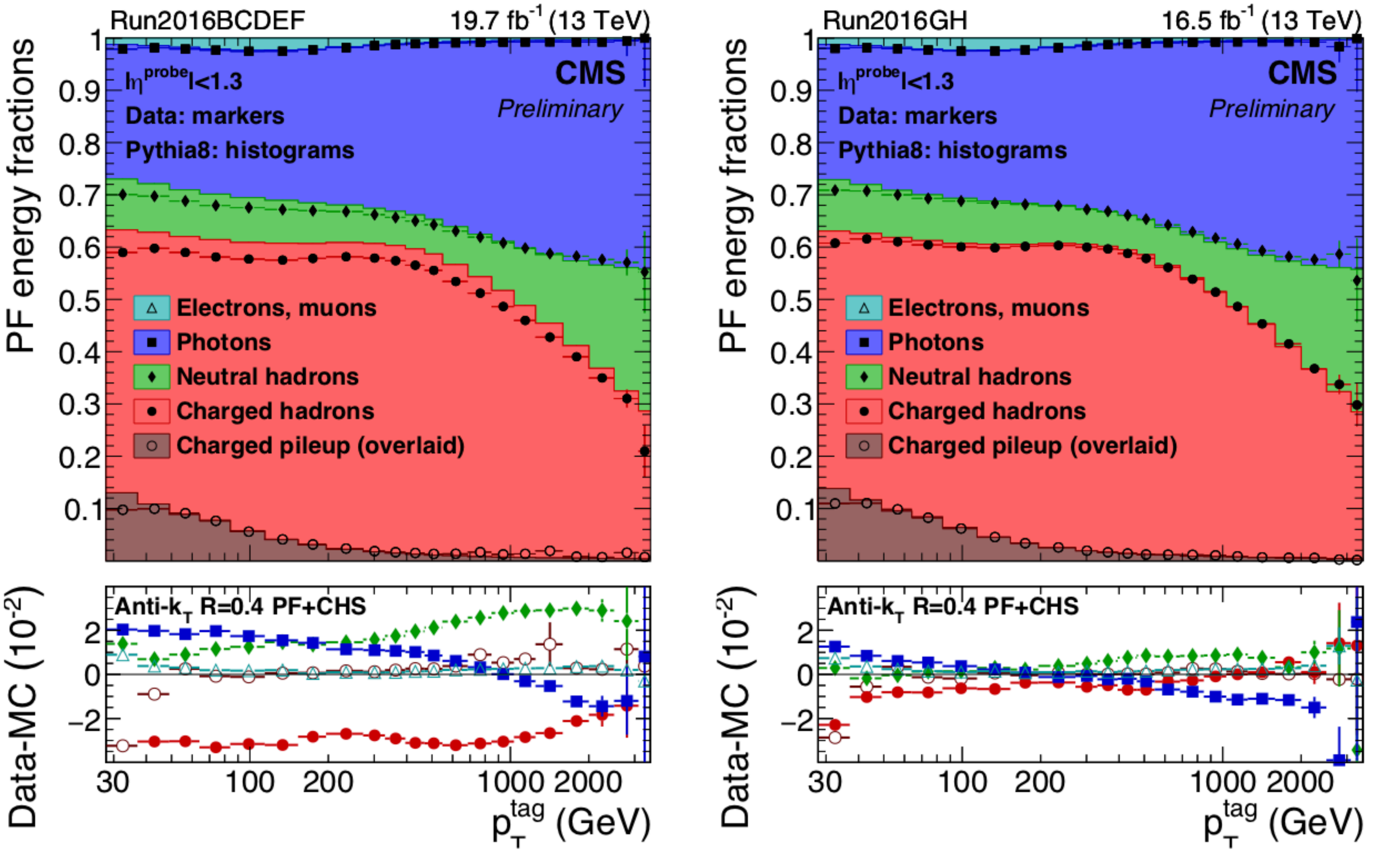
Invest ...orts to stabilize the global event description and pile up modeling

On that note…

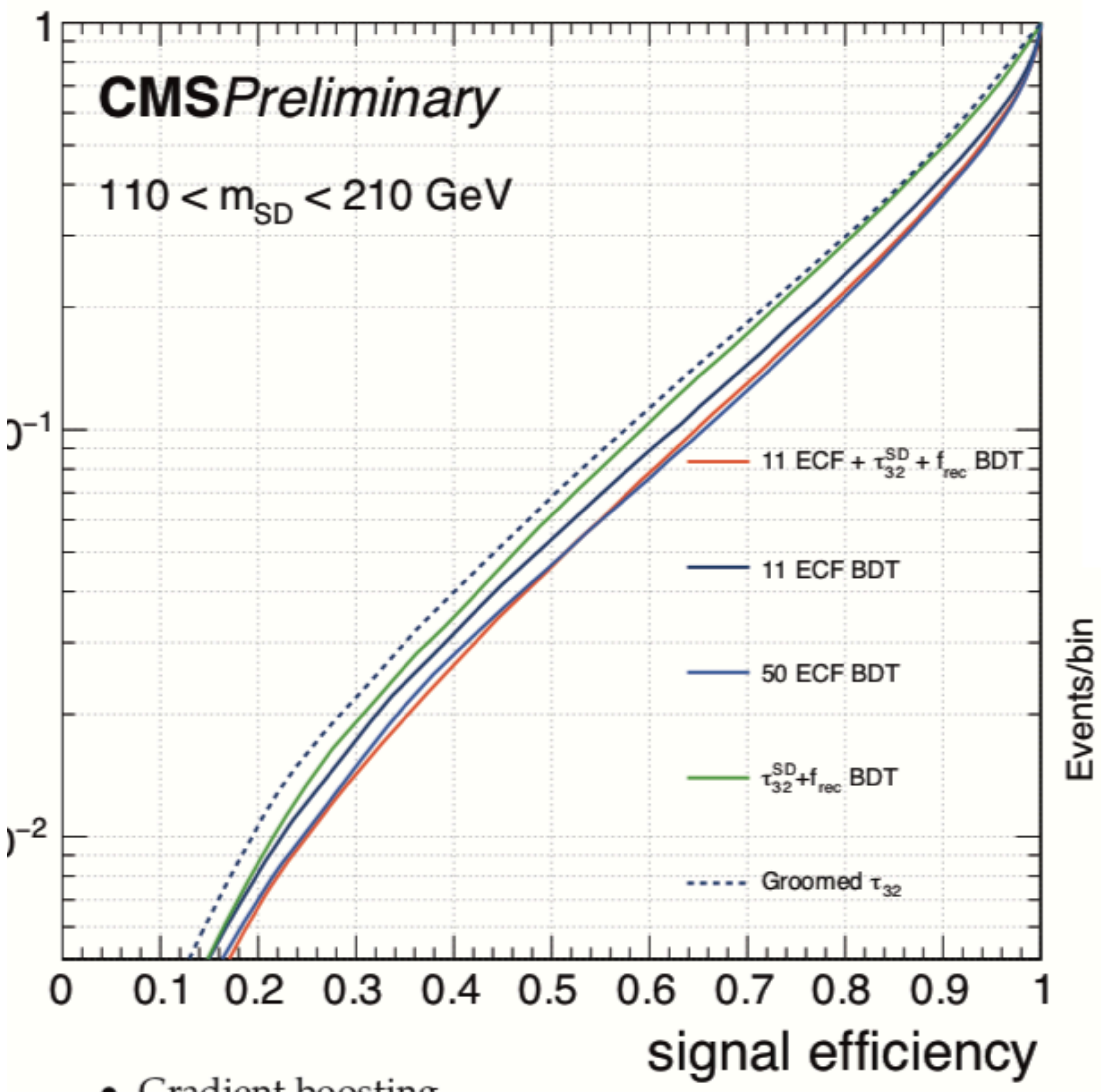
I want to thank the JME team for the frutiful, exciting 2 years! It was a lot of fun!

And I wish Andreas & Laurent all the best for the coming year! It will only get more fun :)

Back up

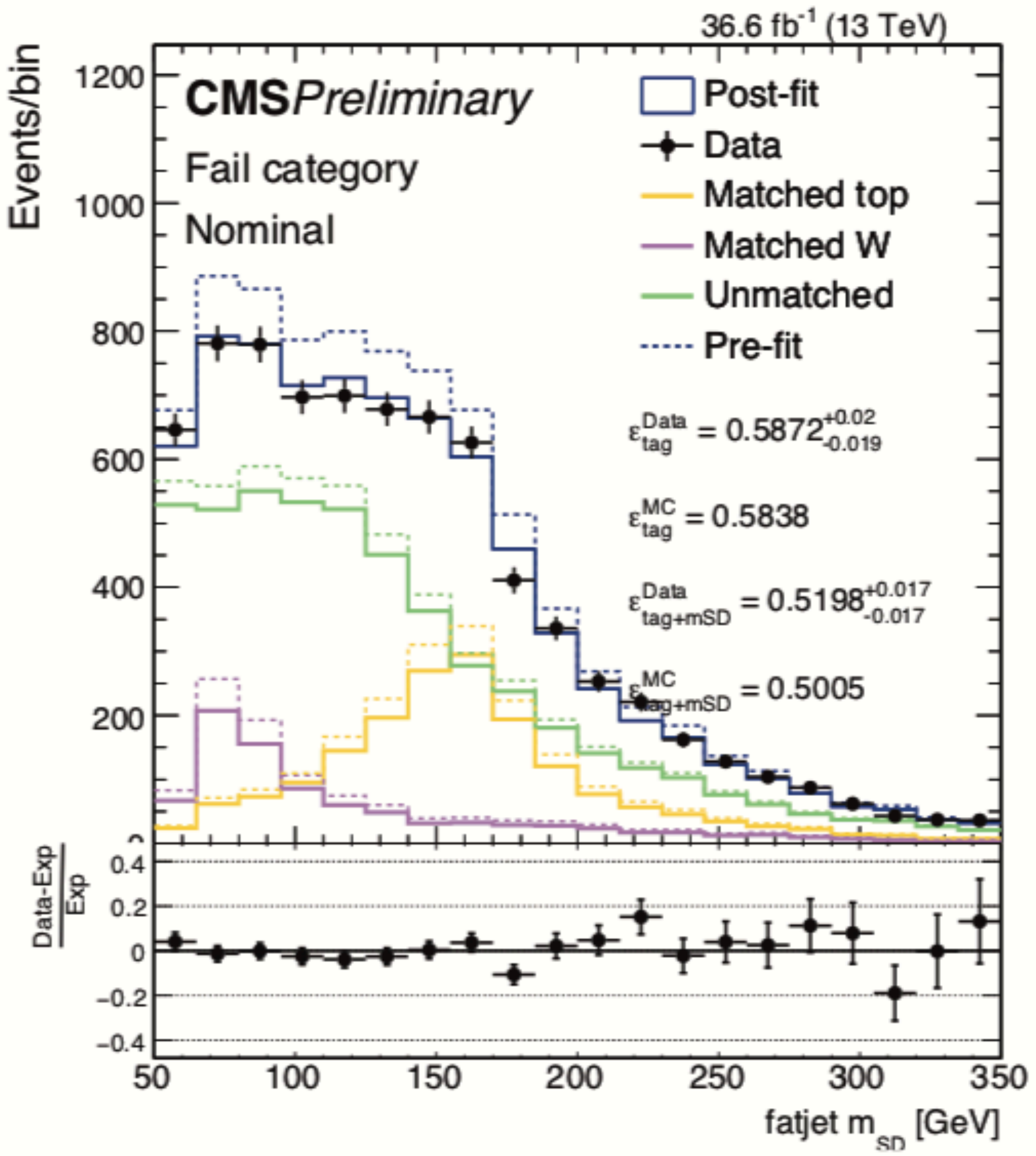


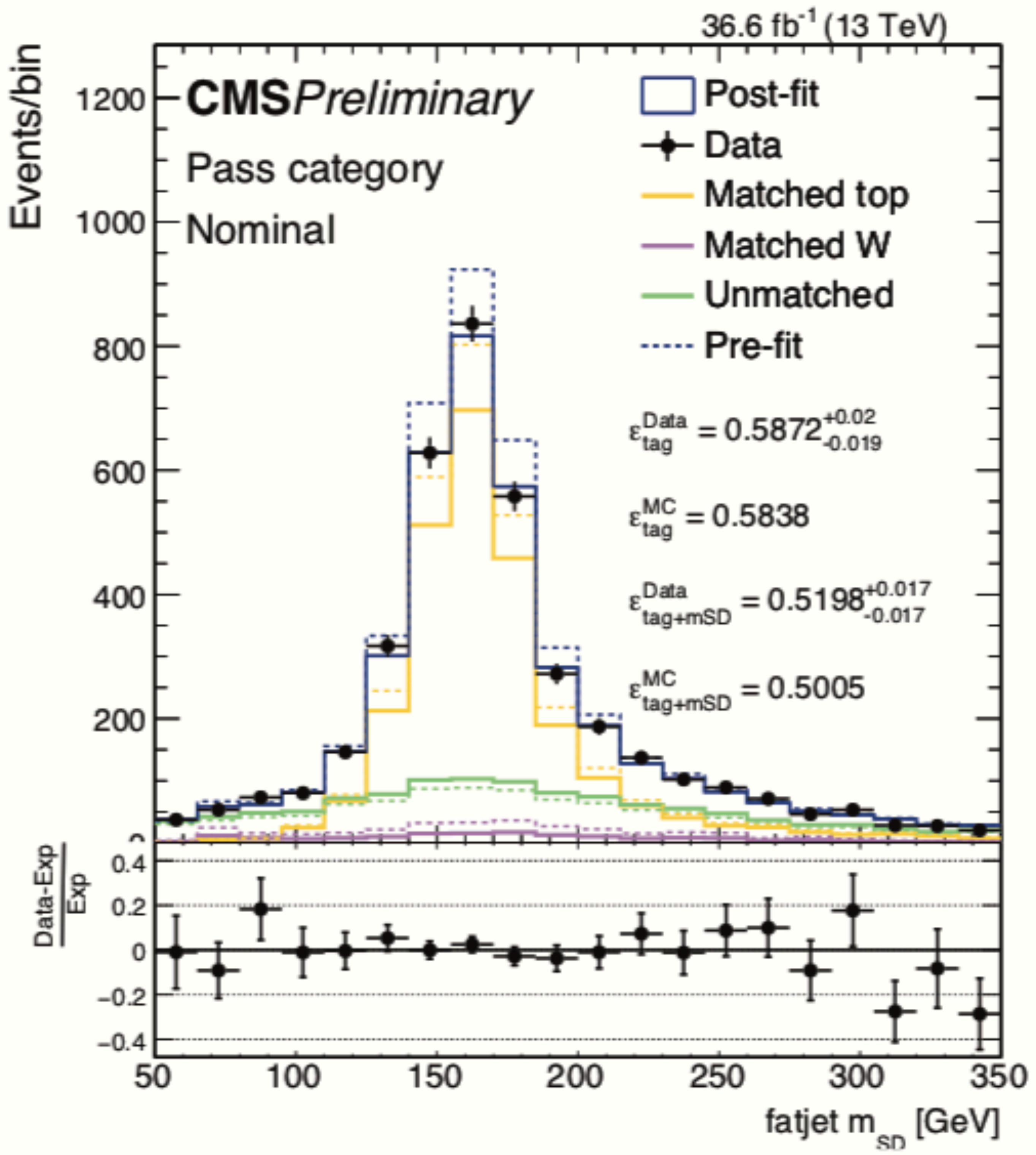
Run2016BCDEF
19.7 fb^{-1} (13 TeV)
CMS
Preliminary
$|\eta^{probe}|<1.3$
Data: markers
Pythia8: histograms
Electrons, muons
Photons
Neutral hadrons
Charged hadrons
Charged pileup (overlaid)
PF energy fractions
Anti-k$_T$ R=0.4 PF+CHS
Data-MC (10^{-2})
p_T^{tag} (GeV)
Run2016GH
16.5 fb^{-1} (13 TeV)



- Gradient boosting
- 300 trees
- Maximum depth of 5
- Minimum node size of 2.5% of the training sample
- Shrinkage factor of 0.3

$$e(o,N,\beta) \equiv {}_o e_N^\beta = \sum_{i_1<i_2<\cdots<i_N\in J} \left[\prod_{1\le k\le j} z_{i_k}\right] \times \min\left\{\prod_{k,l\in \text{pairs}\{i_1,\dots,i_N\}}^{o} \Delta R_{kl}^\beta\right\}$$





- ECF: Energy Correlation Functions
  - AJ Larkoski, GP Salam, J Thaler, *Energy Correlation Functions for Jet Substructure* JHEP 1306
  - I Moult, L Necib, J Thaler, *New Angles on Energy Correlation Functions*, JHEP 1612

$$N_i^{(\beta)} = \frac{{}_2e_{i+1}^{(\beta)}}{({}_1e_i^{(\beta)})^2}$$

$$N_2 = \frac{{}_2e_3^{(\beta)}}{({}_1e_2^{(\beta)})^2}$$

2 prong tagging

$$N_3 = \frac{{}_2e_4^{(\beta)}}{({}_1e_3^{(\beta)})^2}$$

3 prong tagging

$${}_ve_n^{(\beta)} = \sum_{1\le i_1<i_2<\cdots<i_n\le n_J} z_{i_1} z_{i_2} \dots z_{i_n} \prod_{m=1}^{v} \overset{(m)}{\min_{s<t\in\{i_1,i_2,\dots,i_n\}}} \left\{\theta_{st}^{\beta}\right\}$$

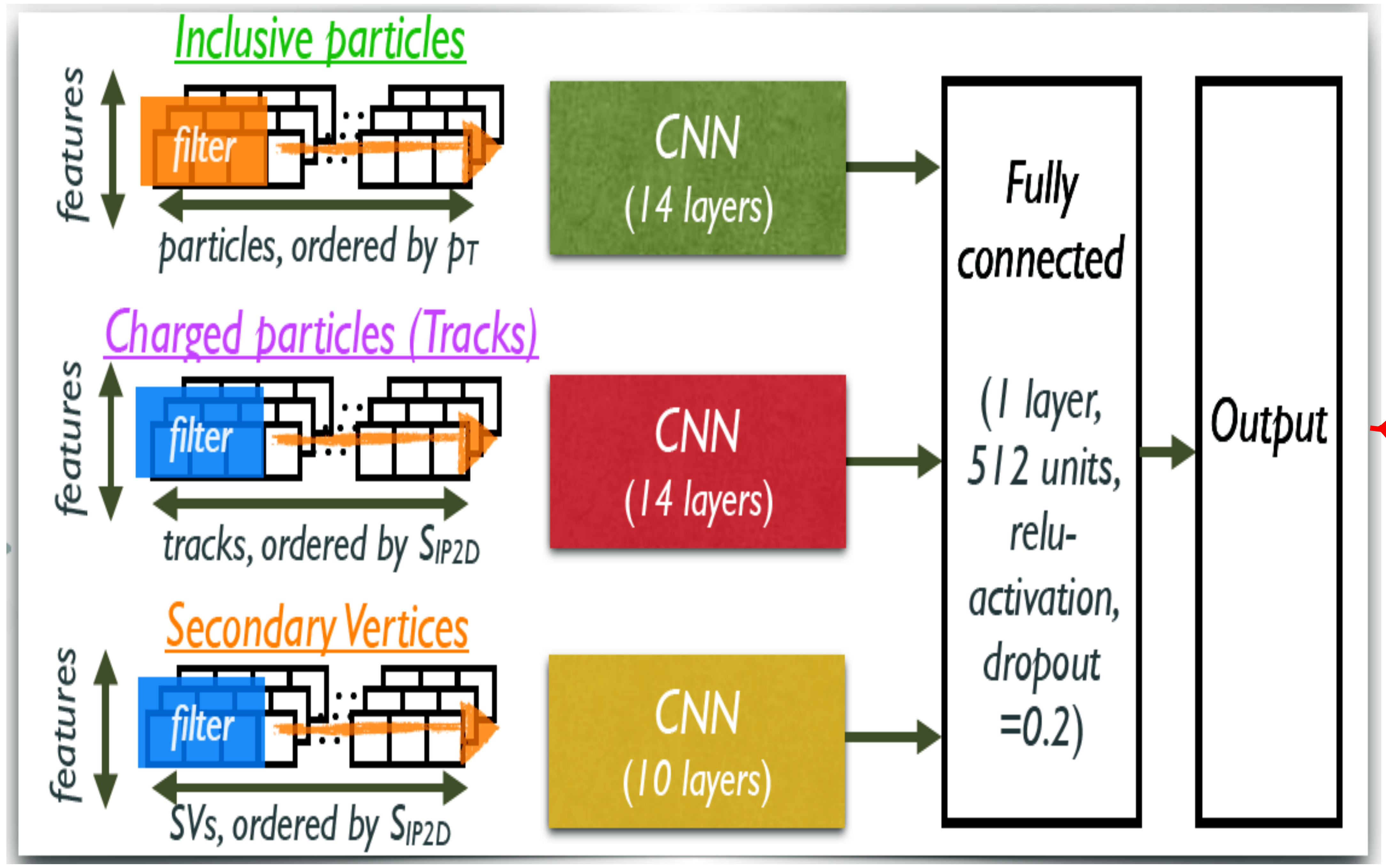
particles

angles

Example:

$${}_2e_3^{(\beta)} = \sum_{1\le i<j<k\le n_J} z_i z_j z_k \min\left\{\theta_{ij}^{\beta}\theta_{ik}^{\beta}\,,\theta_{ij}^{\beta}\theta_{jk}^{\beta}\,,\theta_{ik}^{\beta}\theta_{jk}^{\beta}\right\}$$

$$z_i \equiv \frac{p_{Ti}}{\sum_{j\in\text{jet}} p_{Tj}}\,, \qquad \theta_{ij}^2 \equiv R_{ij}^2 = (\phi_i - \phi_j)^2 + (y_i - y_j)^2\,,$$



Category	Label
Higgs	H (bb)
	H (cc)
	H (VV*→qqqq)
Top	top (bcq)
	top (bqq)
	top (bc)
	top (bq)
W	W (cq)
	W (qq)
Z	Z (bb)
	Z (cc)
	Z (qq)
QCD	QCD (bb)
	QCD (cc)
	QCD (b)
	QCD (c)
	QCD (others)

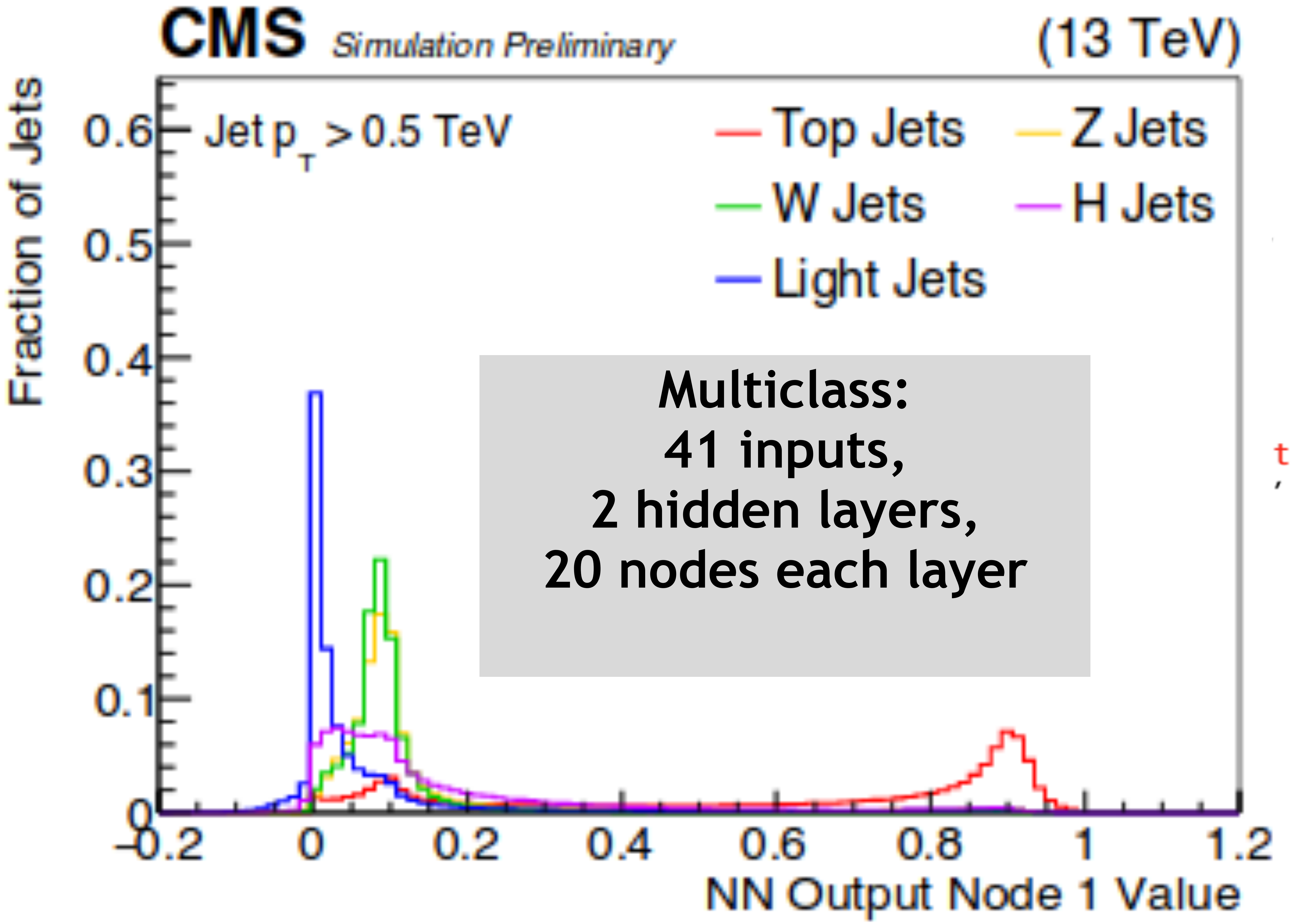
Inputs:

→ Up to 100 inclusive particles
10 features/particle

→ Up to 60 charged particles
60 features/particle

→ Up to 5 SV (14 features/SV)

A very versatile boosted jet tagger
-> various decay modes with different flavor content



Multiclass:
41 inputs,
2 hidden layers,
20 nodes each layer