Performance of Jet and Missing Transverse Energy Reconstruction with CMS in pp Collisions at $\sqrt{s}=7$ TeV

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On behalf of the CMS collaboration

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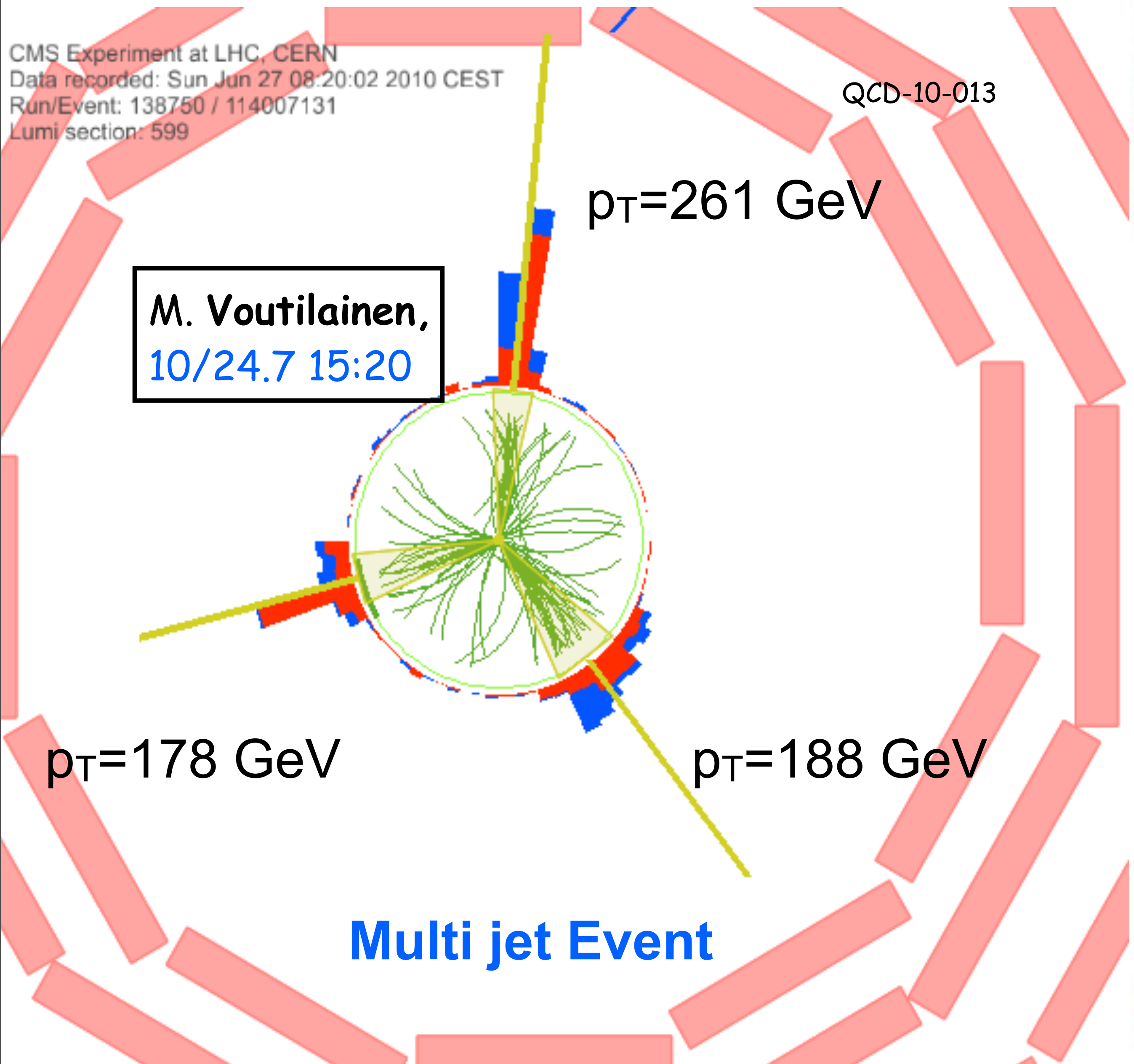
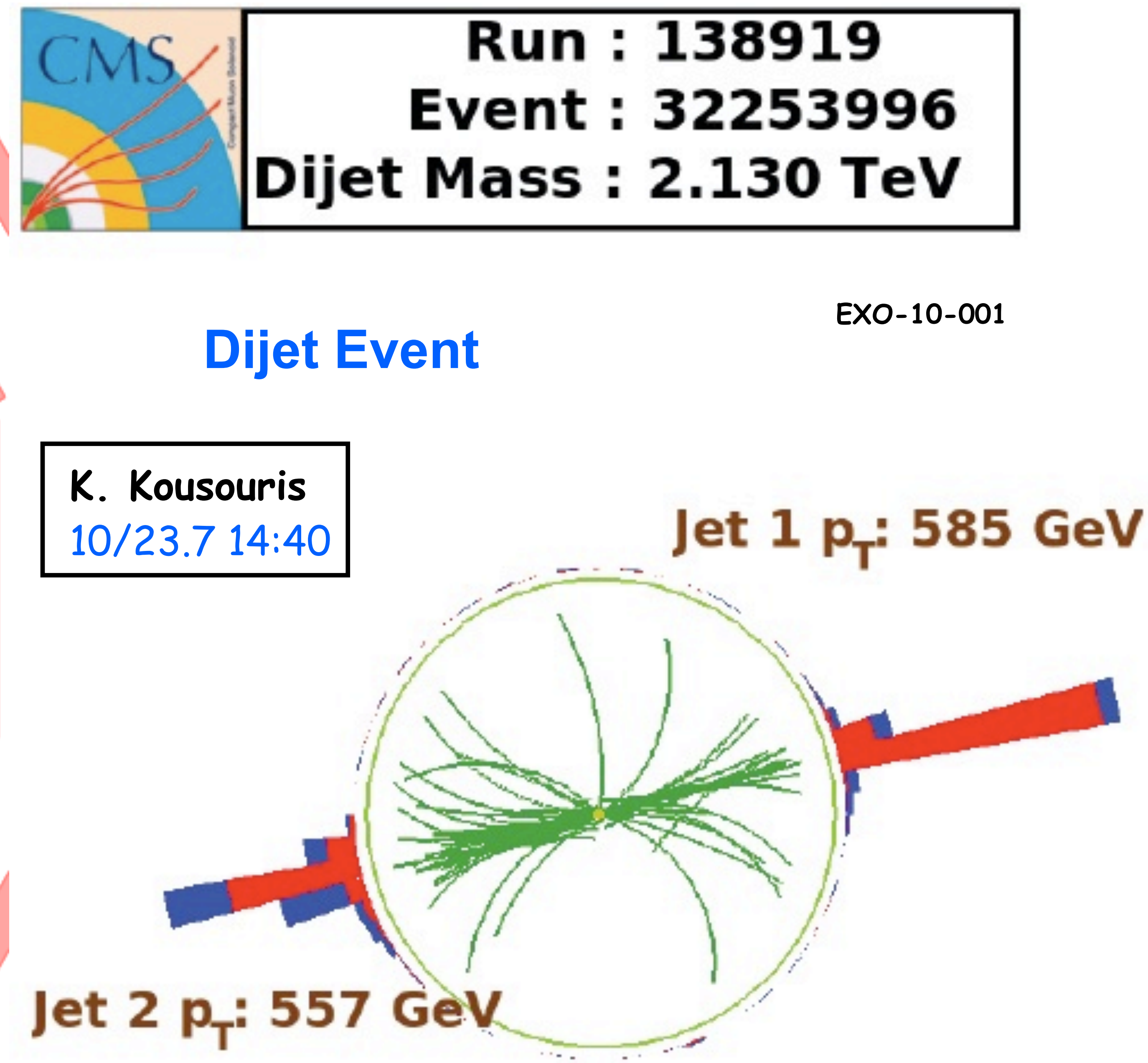
Motivation

Jets and MET crucial for many measurements and also important for searches





From "Hadronic Event Shapes in pp Collisions at at √s=7TeV", **CMS PAS QCD-10-013**

From "Search for Dijet Resonances in the Dijet Mass Distribution in pp Collisions at √s=7TeV", **CMS PAS EXO-10-001**

The CMS Detector

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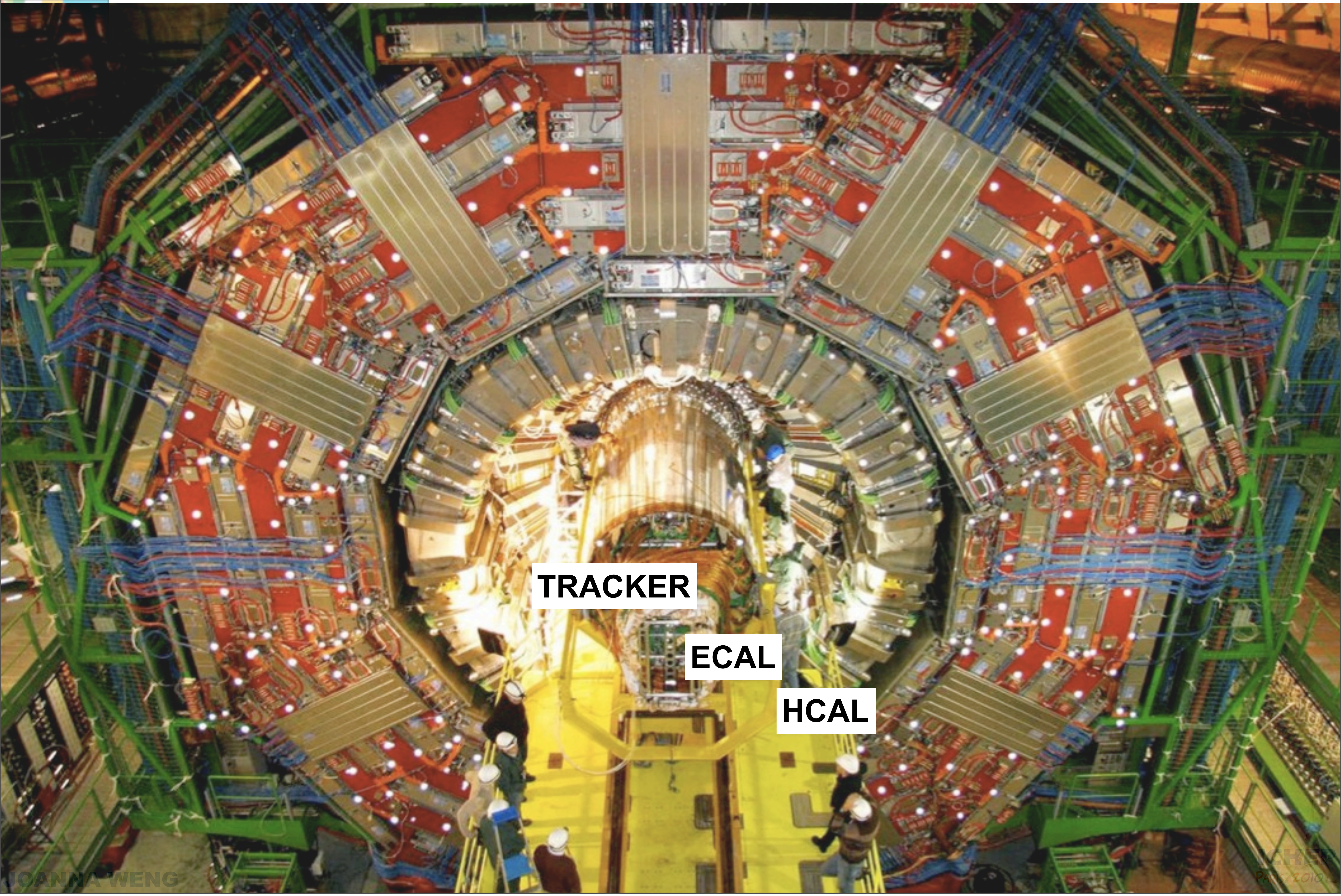


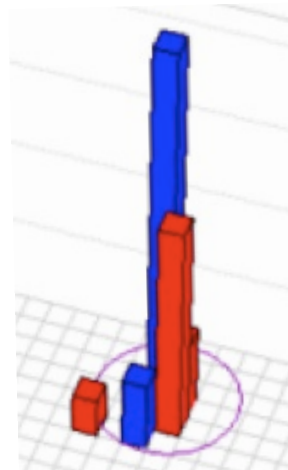
Jet/MET Types in CMS

Default Jet Clustering Algorithm : Anti K_T with R=0.5

Calorimeter Jets

Jets clustered from ECAL and HCAL deposits (Calo Towers)
Accordingly:

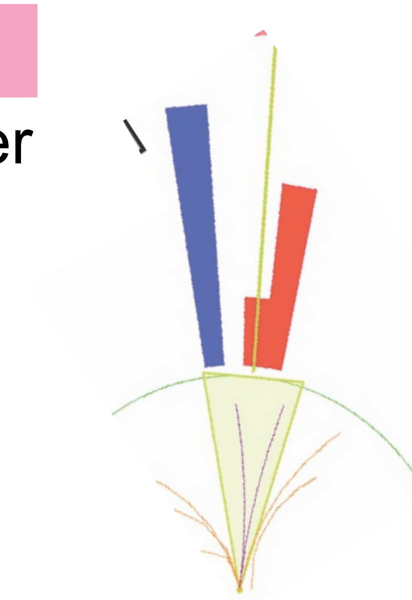
Calo MET



Jet-Plus-Track Jets (JPT)

Subtract average calorimeter response from CaloJet and replace it with the track measurement
Accordingly:

Tc MET



Particle Flow Jets (PF)

Cluster Particle Flow objects:
Unique list of calibrated particles "a la Generator Level"
Accordingly:

PF MET

F. Beaudette
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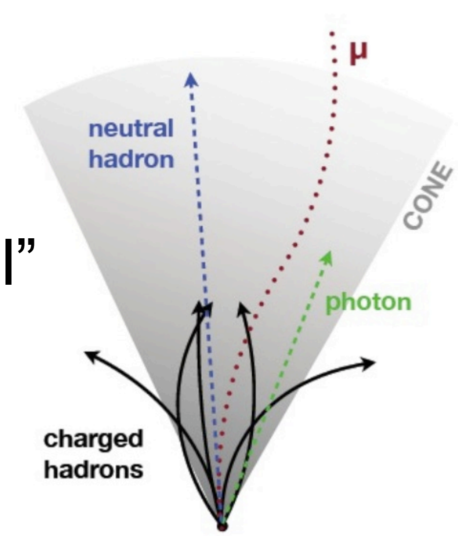
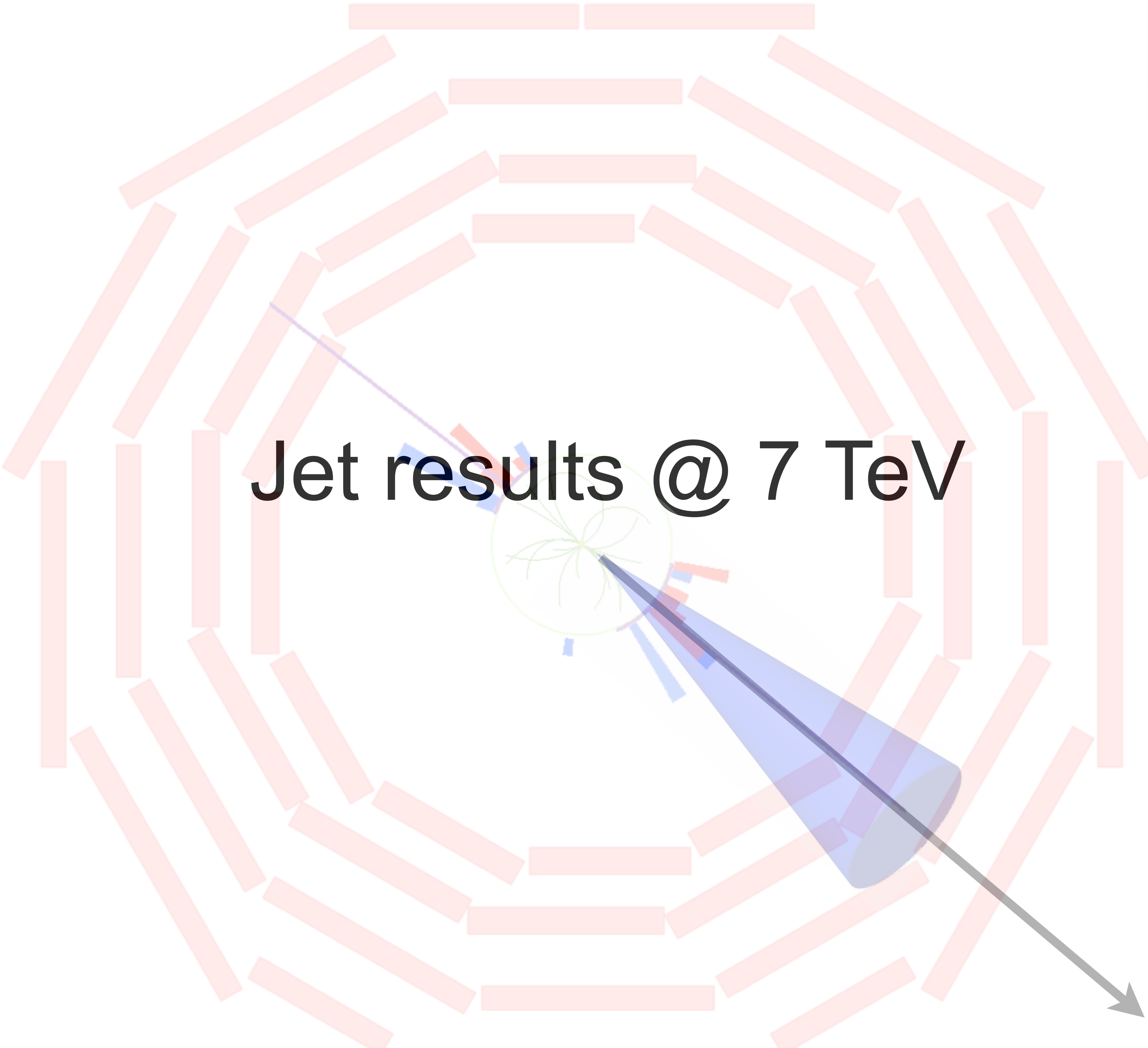


Track Jets

Reconstructed from tracks of charged particles, independent from calorimetric jet measurements

=> Using different inputs allows CMS to study and constrain experimental systematics

Jet results @ 7 TeV



How well do we understand
Jet Energy Scale and Jet Resolution ?

Example: Dijets Δφ in Data/MC

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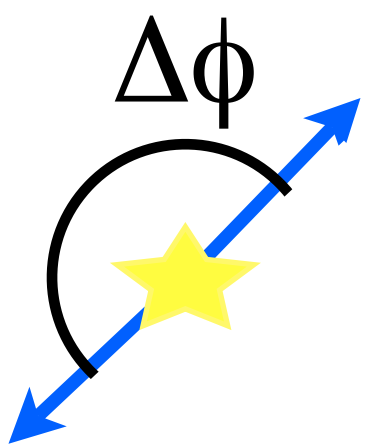
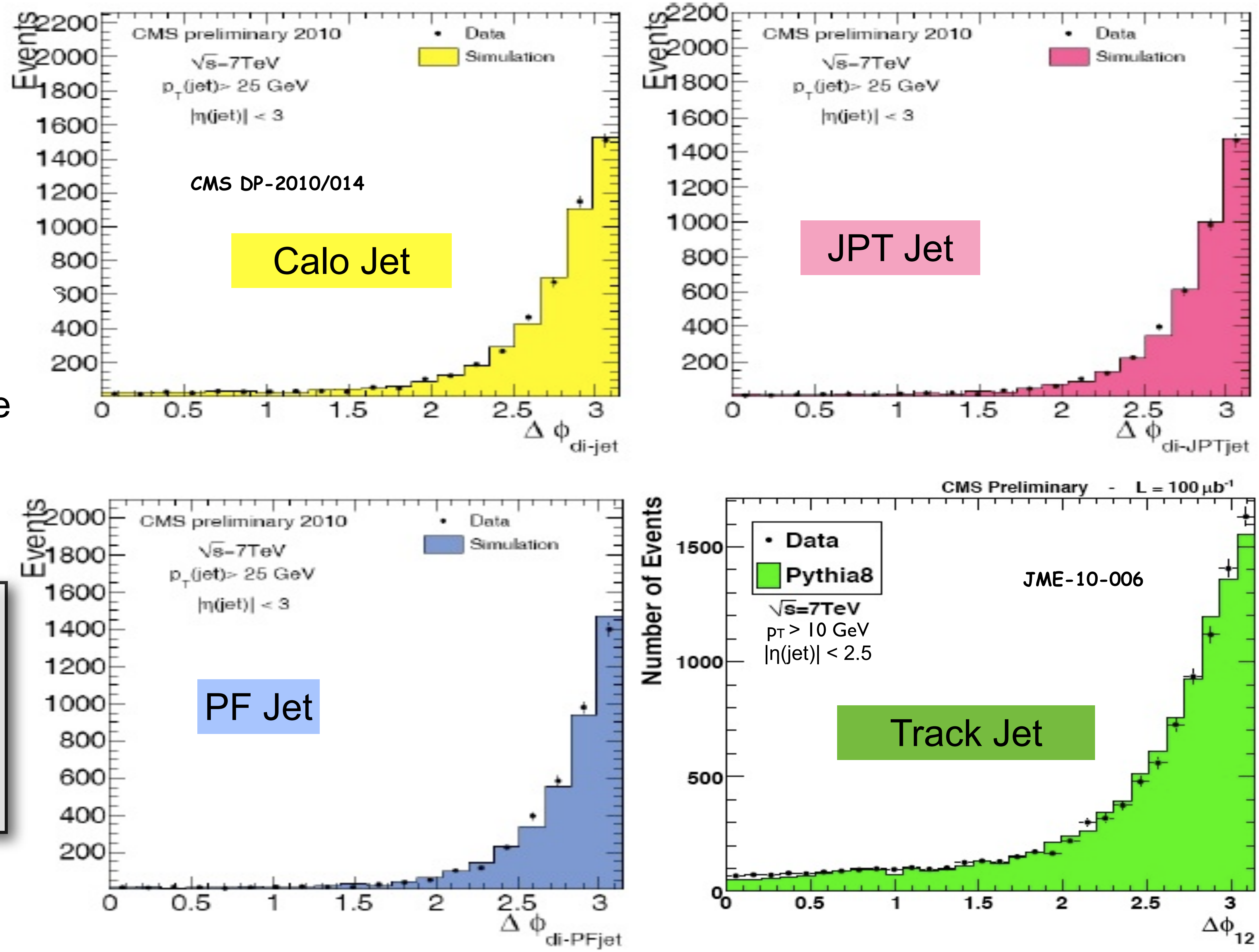


Important variable to select a clean dijet sample

=> Good agreement for all jet types between data and MC

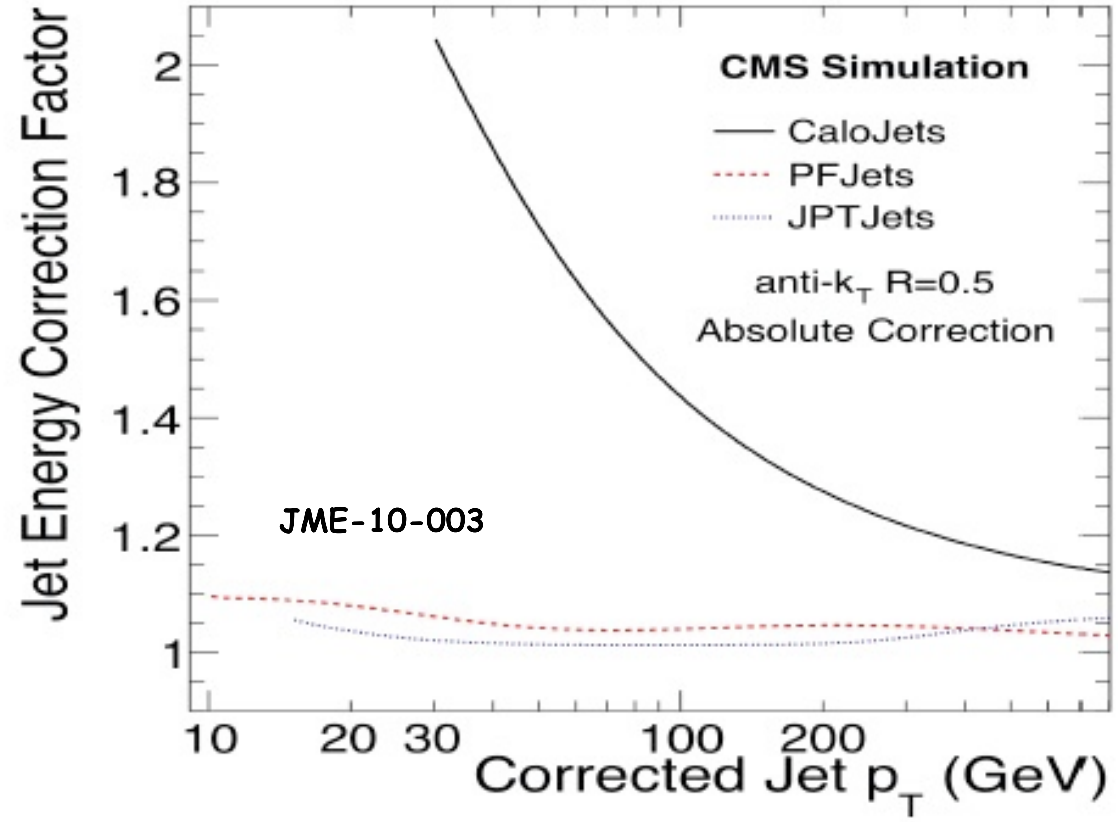


Jet Energy Corrections (JEC)

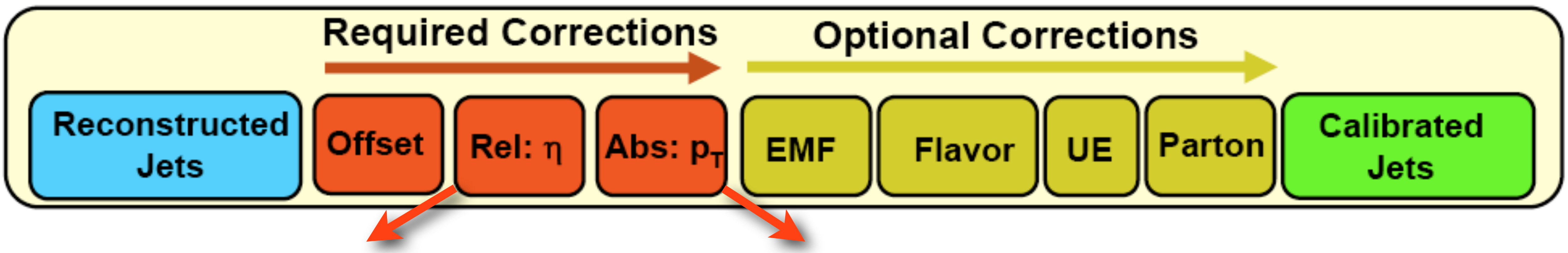
Two Strategies:

MC-truth JEC and In-situ JEC

- Majority of CMS physics analyses currently use **MC-truth** JEC
- MC corrections are derived from PYTHIA QCD dijet MC events
- **In-situ JEC** sub-corrections will replace **MC-truth** corrections when available



Factorized approach:



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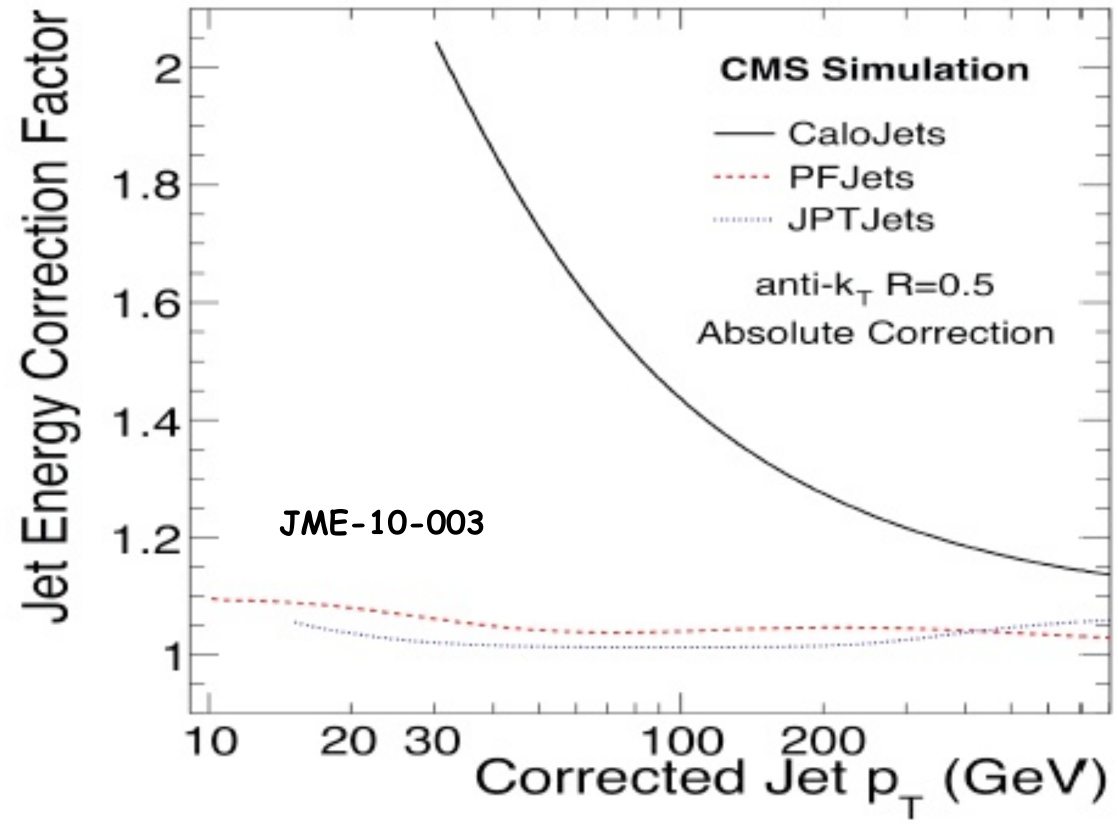
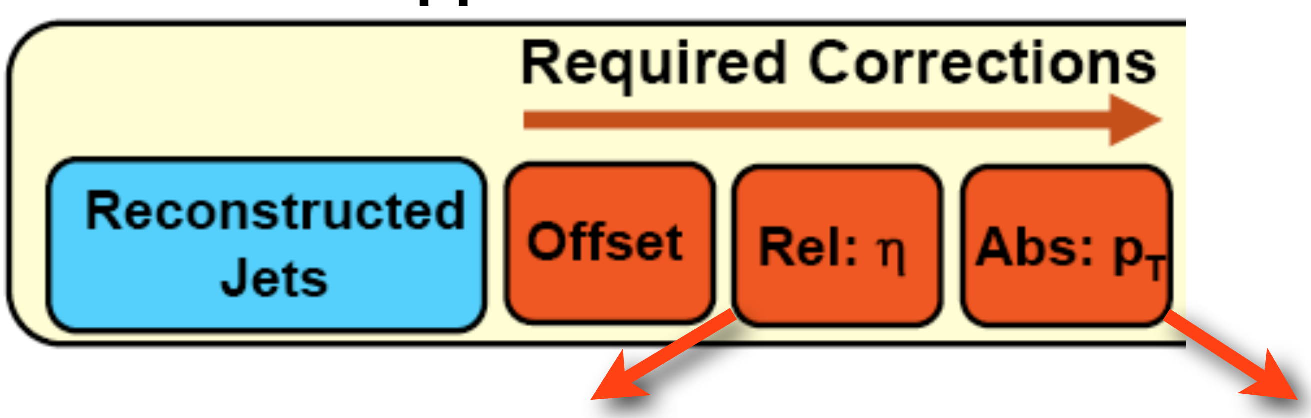


Factorized approach:



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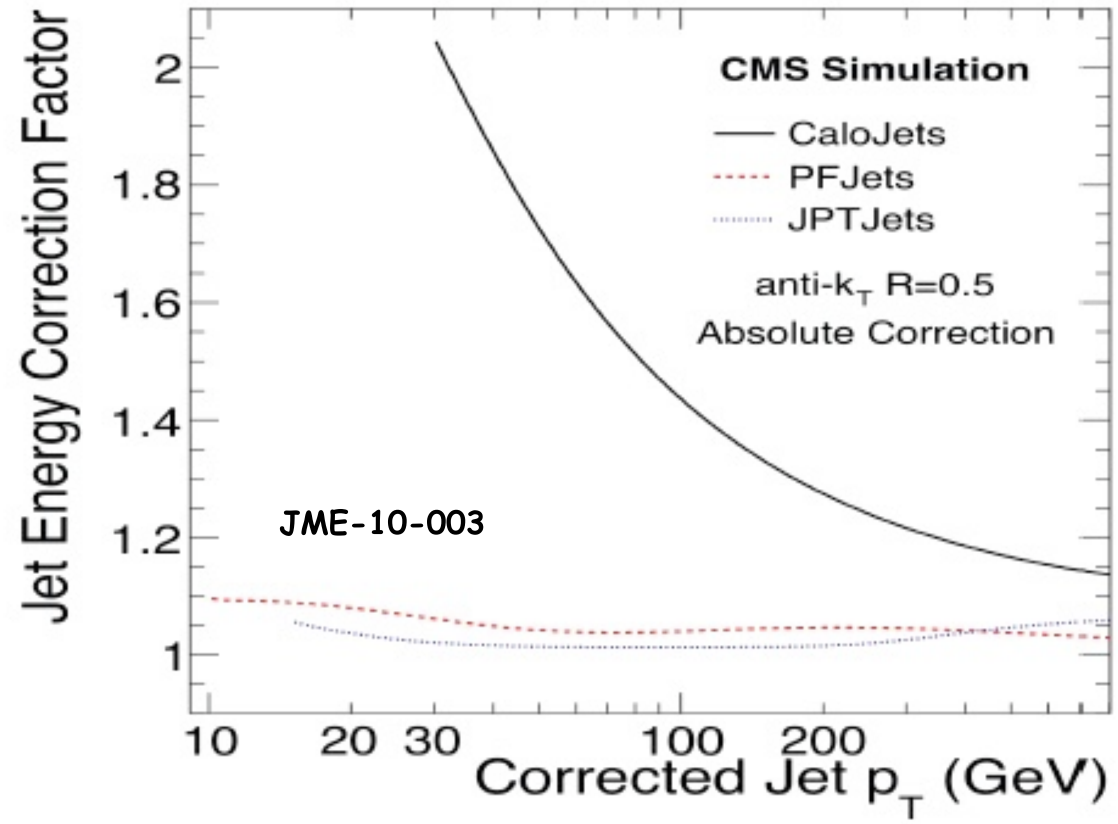

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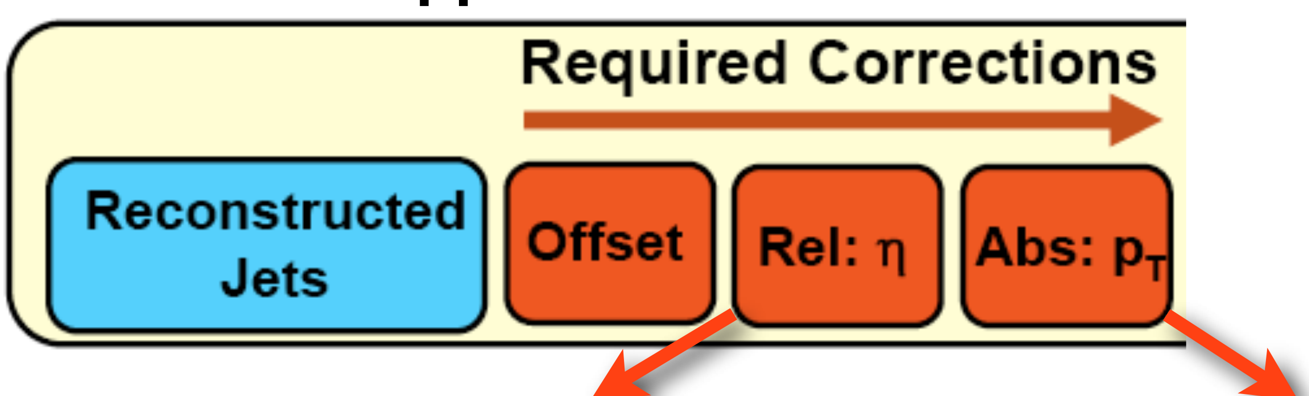

Relative: Correct to make calorimeter response uniform in η
In-situ method:
Dijet p_T balance

Absolute: Correct absolut energy scale
In-situ method:
Photon+jet p_T balance
MPF method

Jet Energy Corrections (JEC)

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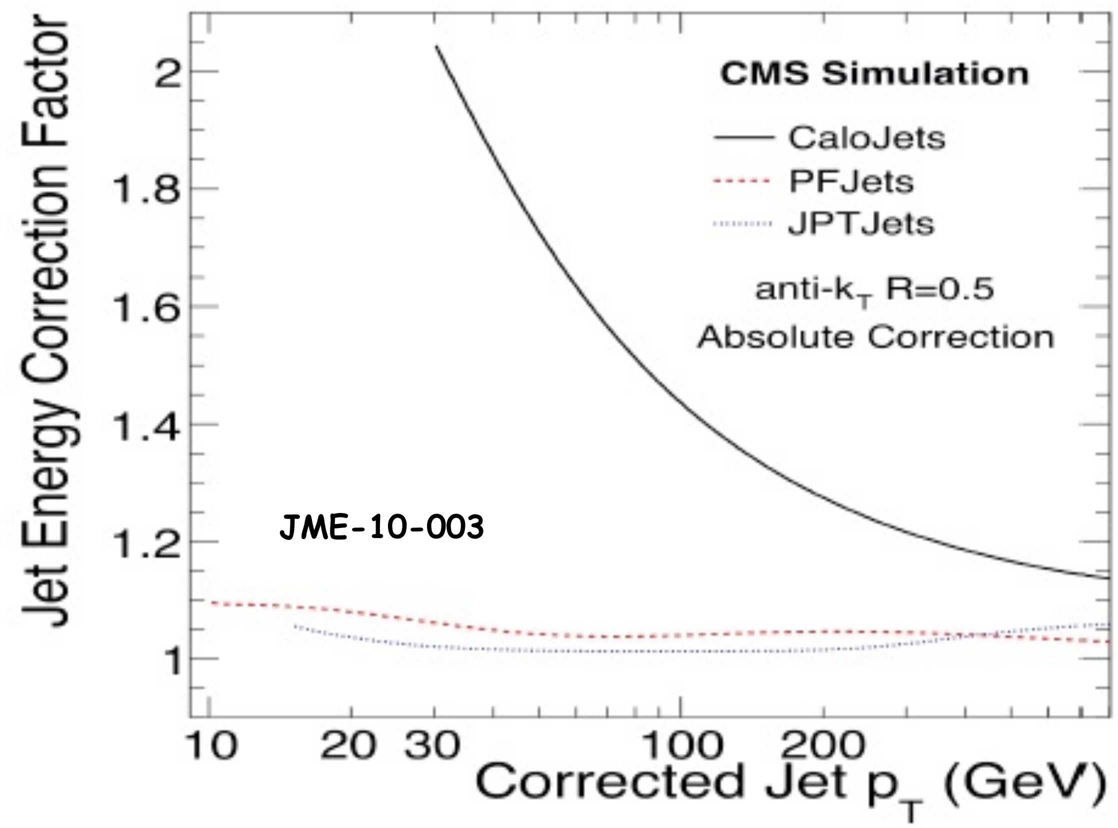
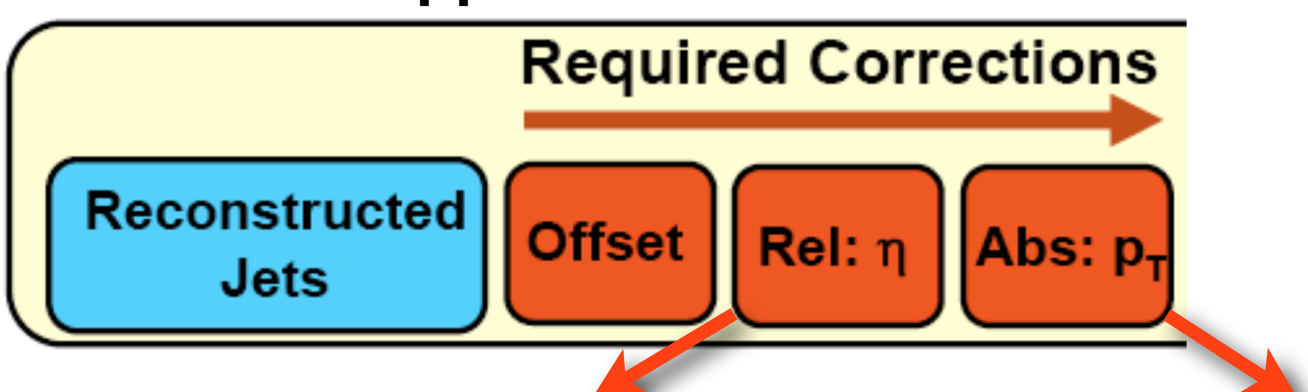


Factorized approach:



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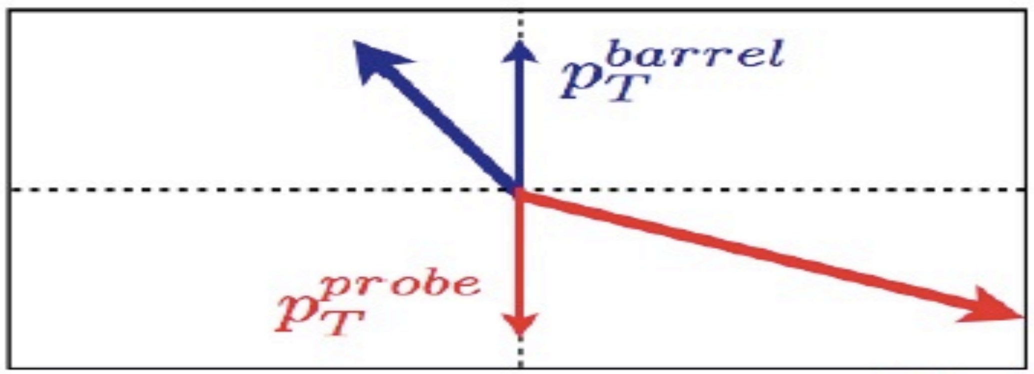
Photon+jet p_T balance
MPF method

Relative JEC: dijet p_T balance

Relative JEC removes jet response variation in η
A priori estimate of uncertainty: ±2% x |η|

Barrel Jet



Probe Jet

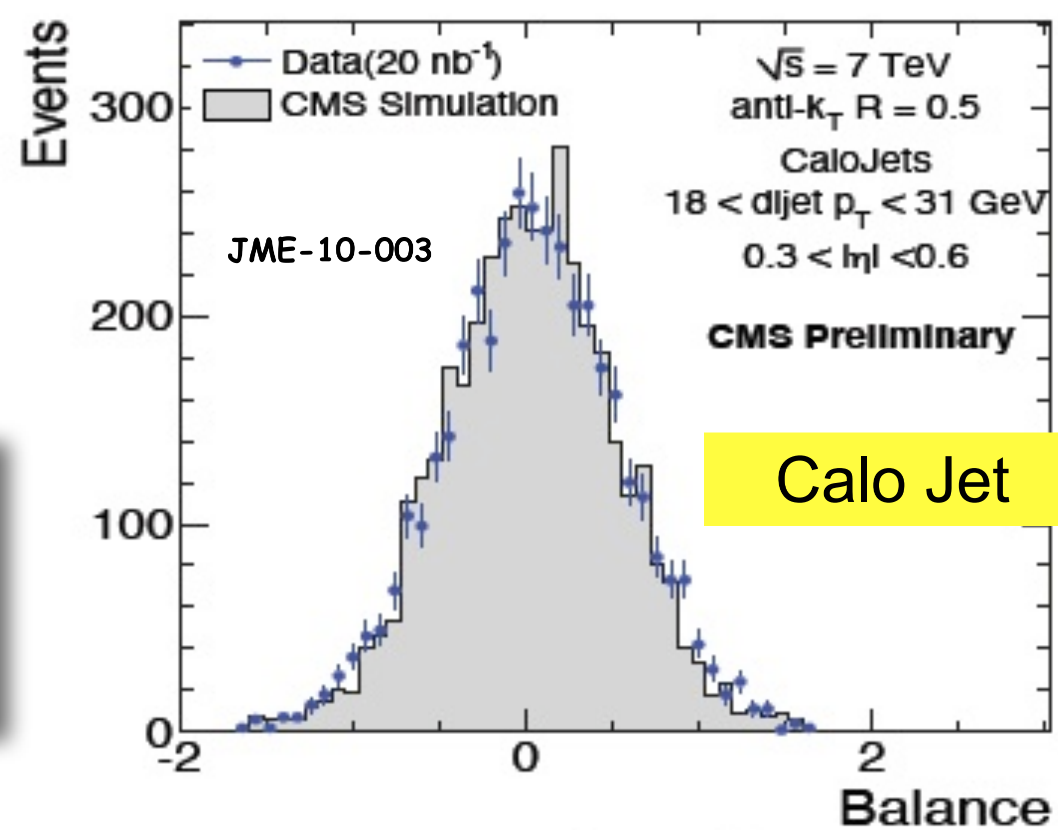
$$p_T^{dijet} = \frac{p_T^{probe} + p_T^{barrel}}{2}$$

$$B = \frac{p_T^{probe} - p_T^{barrel}}{p_T^{dijet}}$$

$$r = \frac{2 + \langle B \rangle}{2 - \langle B \rangle}$$

r:= relative response in a given (p_T^{dijet}, |η|) bin

- Require at least 2 jets, one jet in the barrel region |η|<1.3
- Azimuthal separation ΔΦ > 2.7
- Third jet veto $p_T^{3rd}/p_T^{dijet} < 0.2$



=> Measure distributions of balance variable B in representative (p_T^{dijet}, |η|) bins for all jet types

Relative JEC: Data/MC

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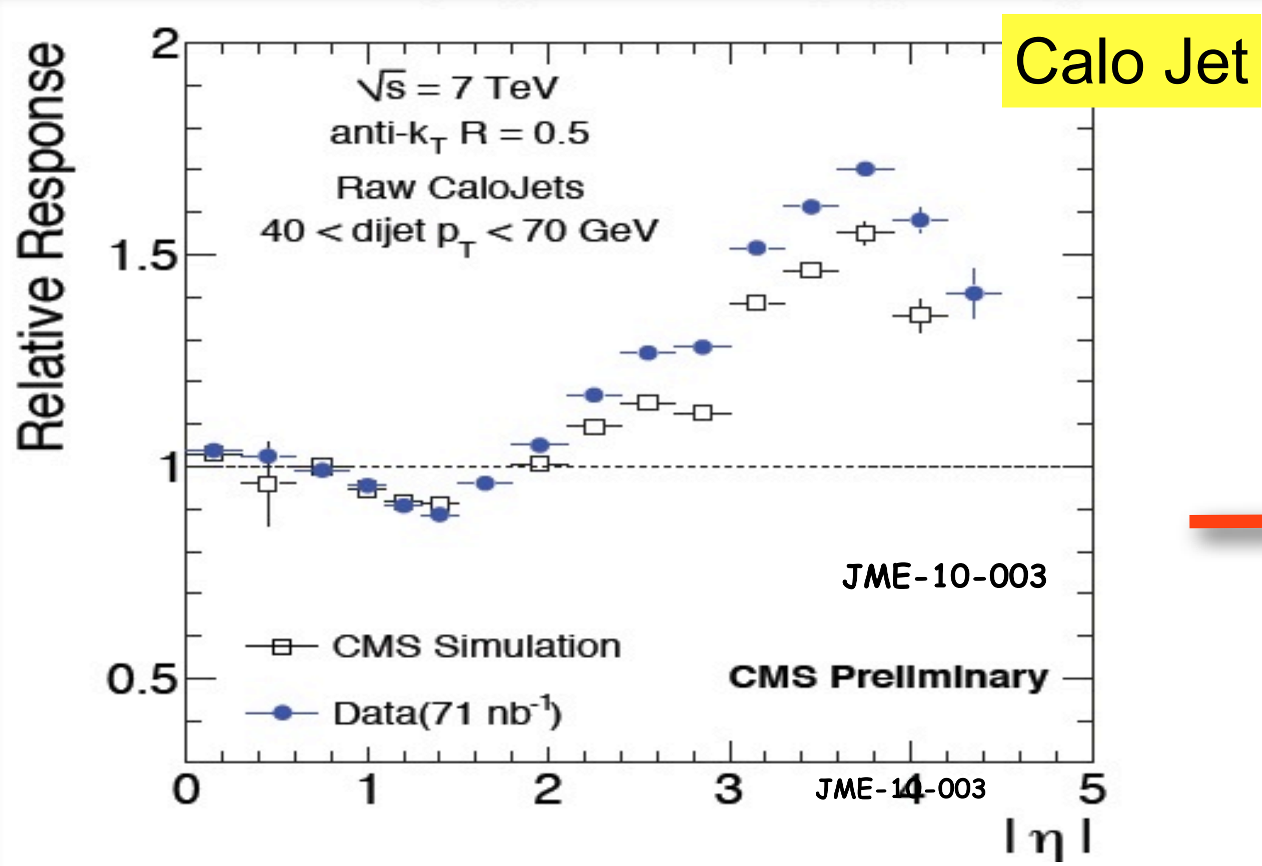
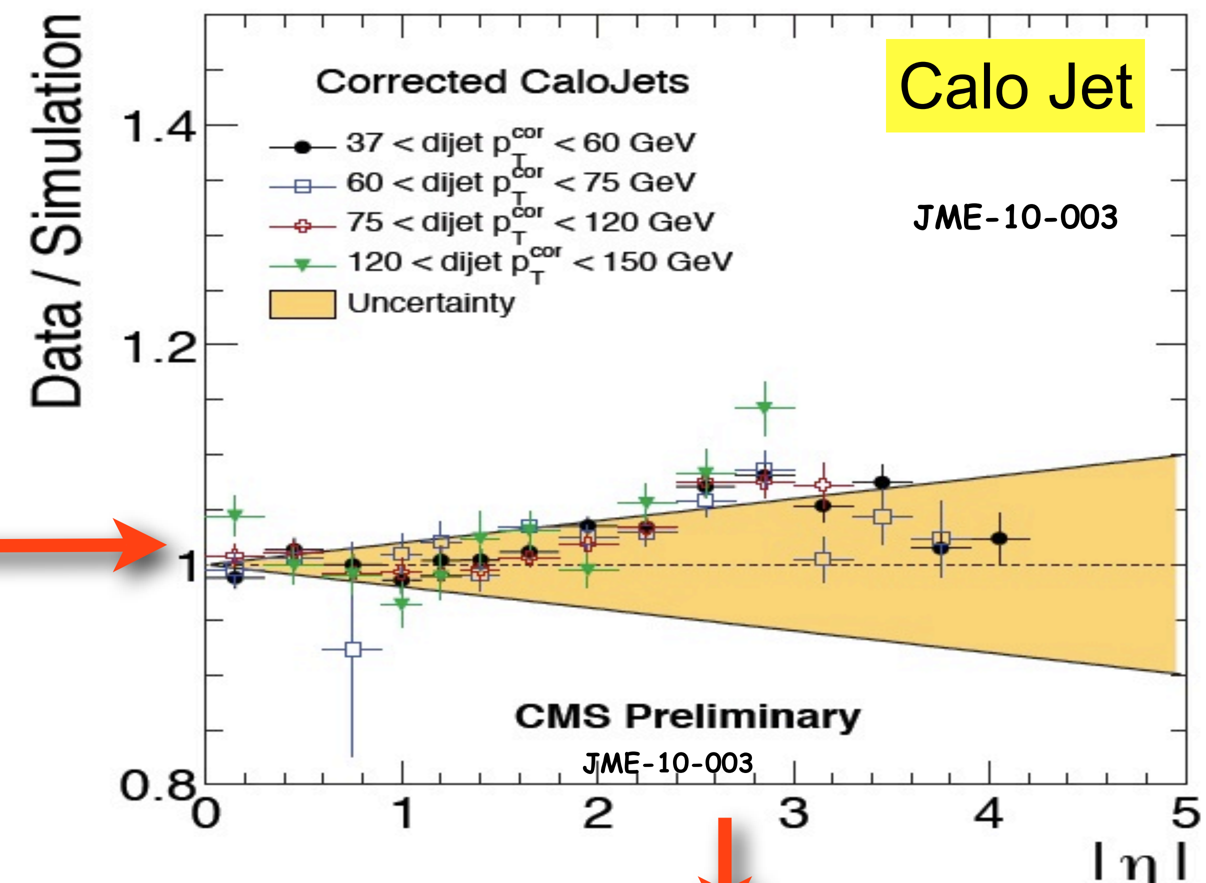
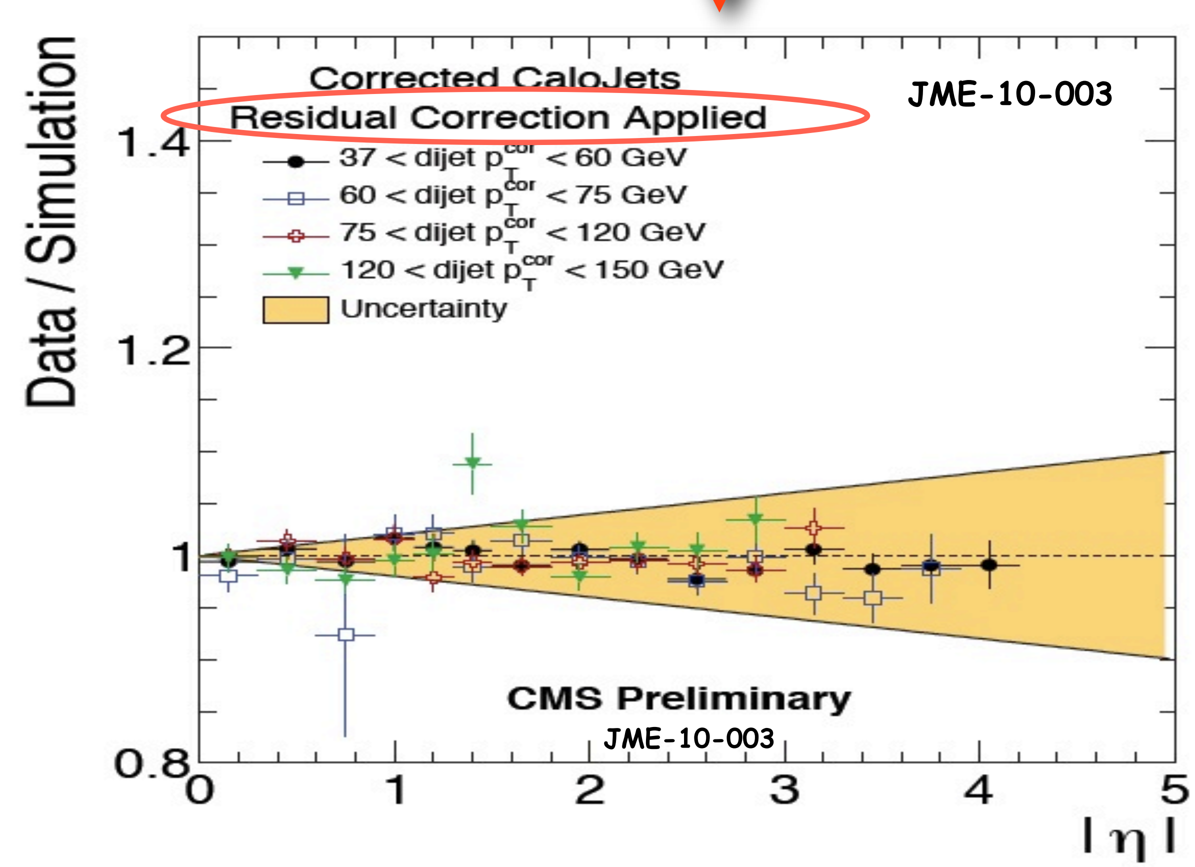


- Good agreement up to |η| =2
- Relative response in data ~10% higher compared to simulation for |η| > 2





=> Data/MC close to unity after the residual correction
=> Data/MC deviations are covered by conservative η-dependent systematic uncertainty of **±2% x |η|**

Single Particle Response

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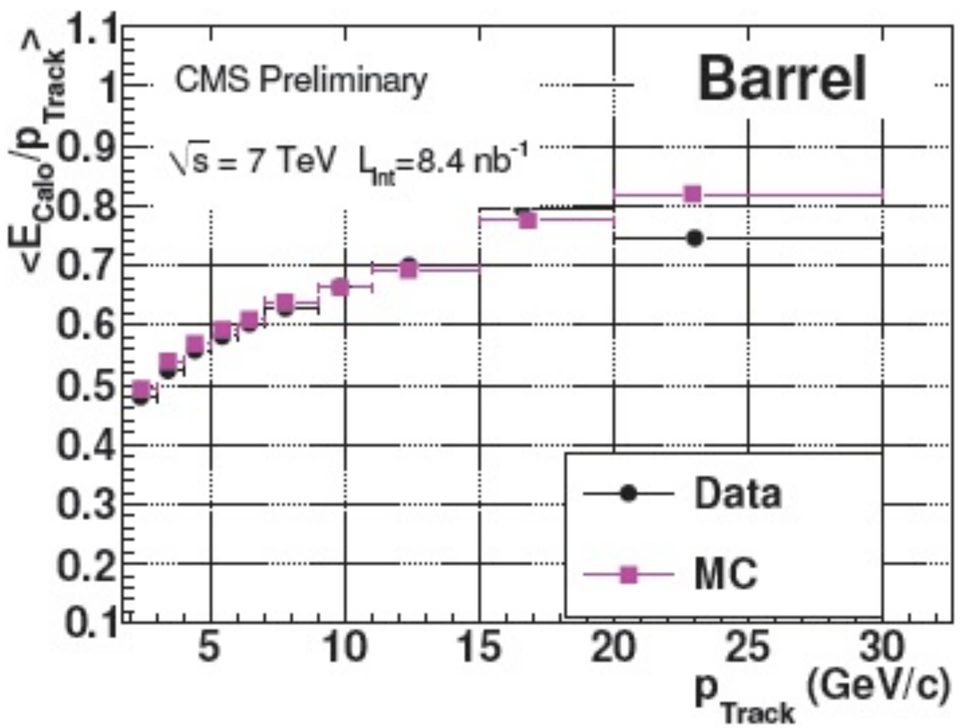
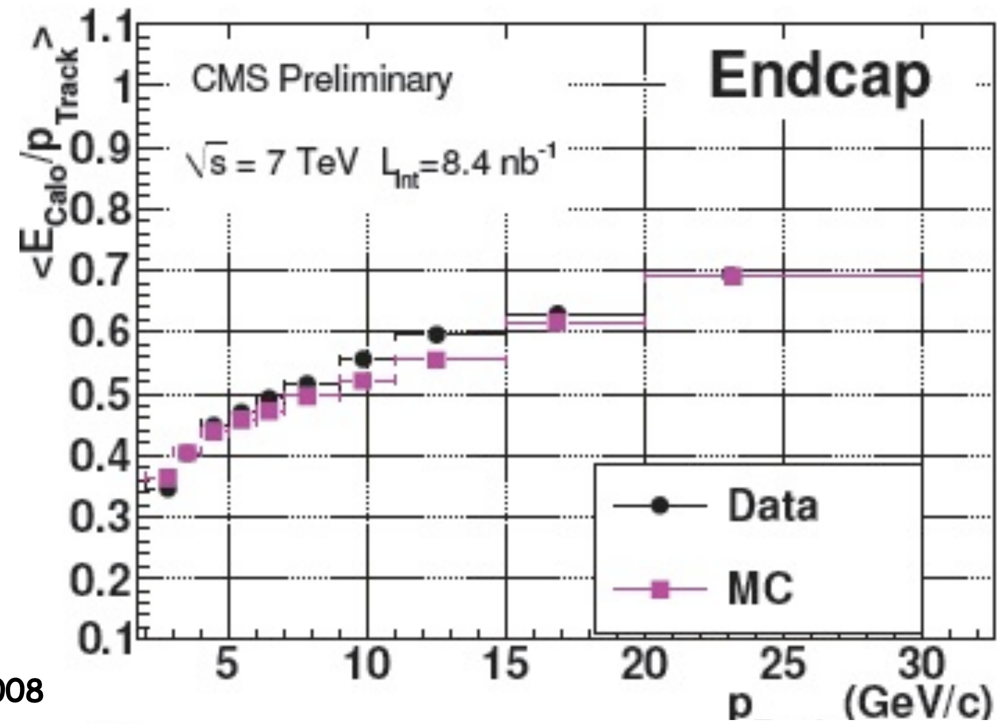
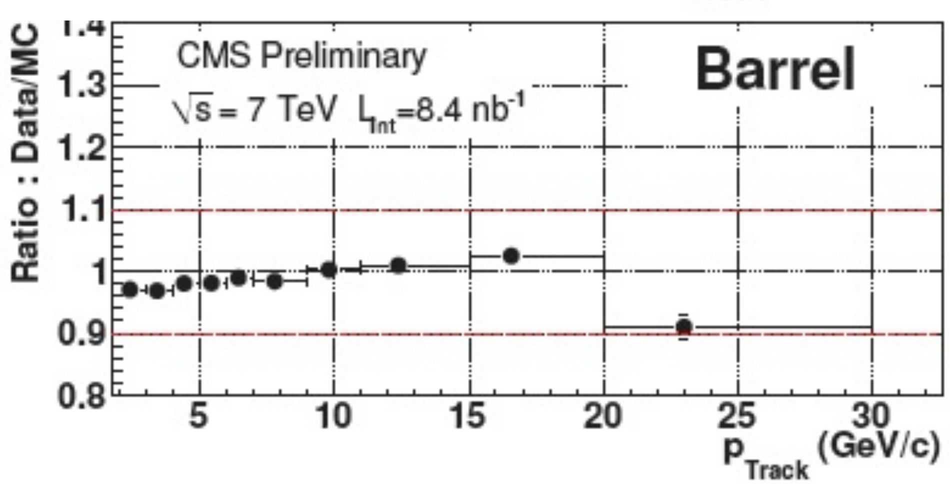
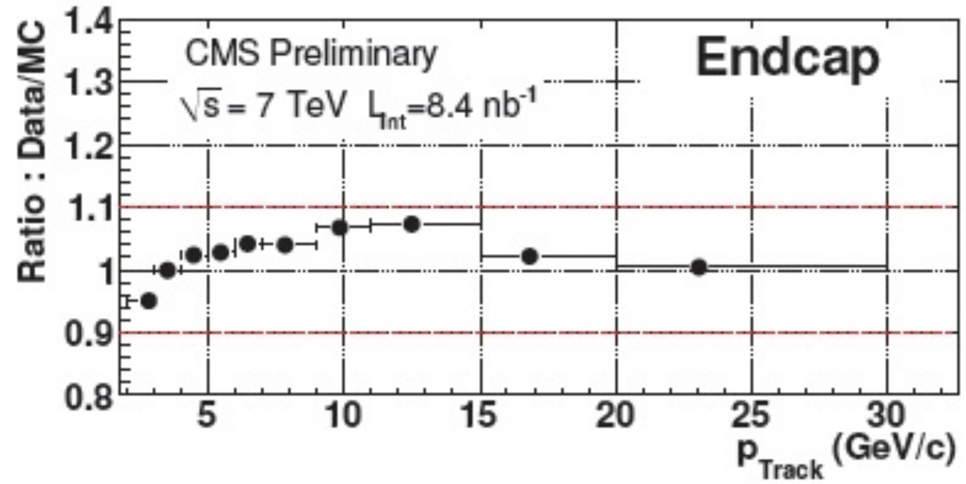
Compare response of isolated tracks in MinBias events with single pions from MC





JME-10-008

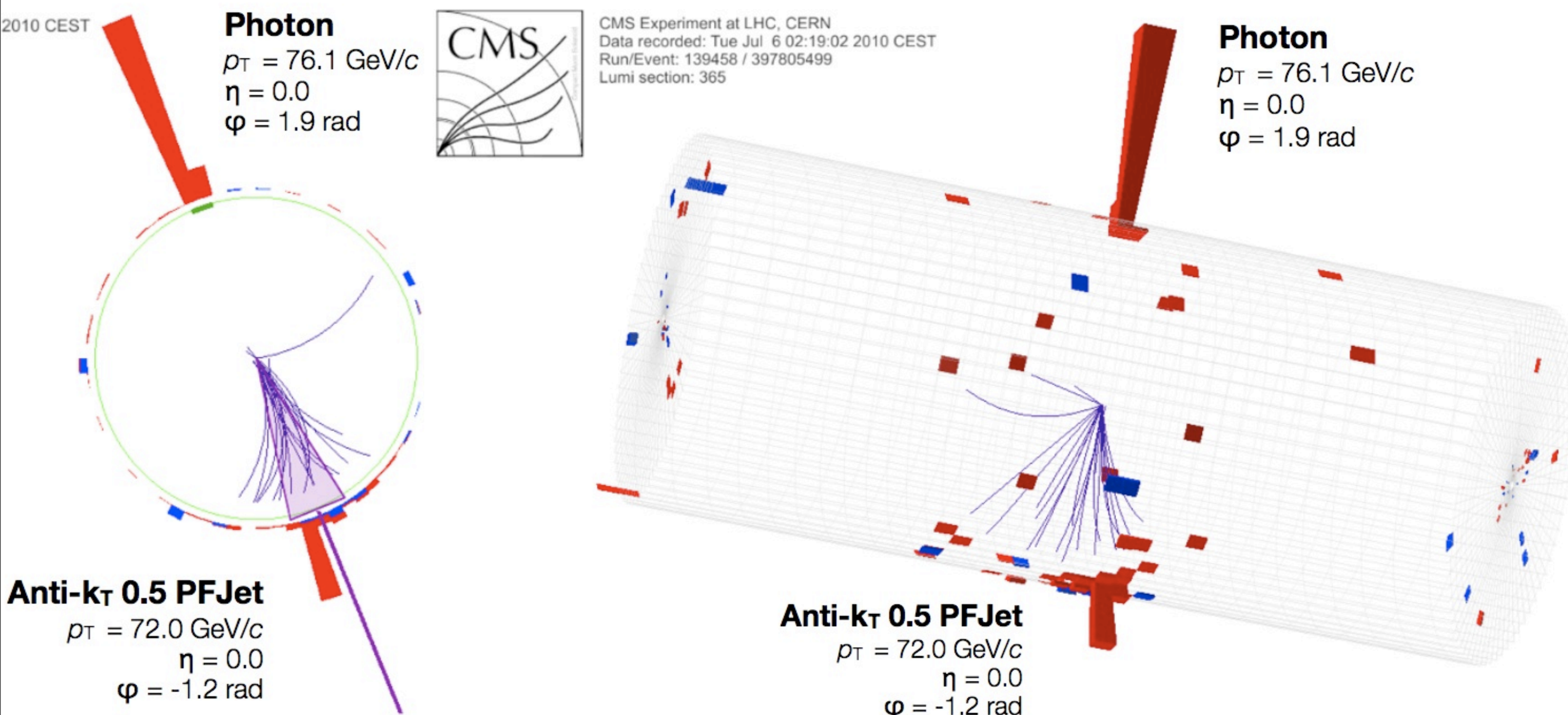




=> Mean response in Data and MC agrees within **2-3 %** in **barrel region**
In endcap, the simulated response is systematically lower than data (**~ 4%**)

Absolute JEC: photon+jet balance

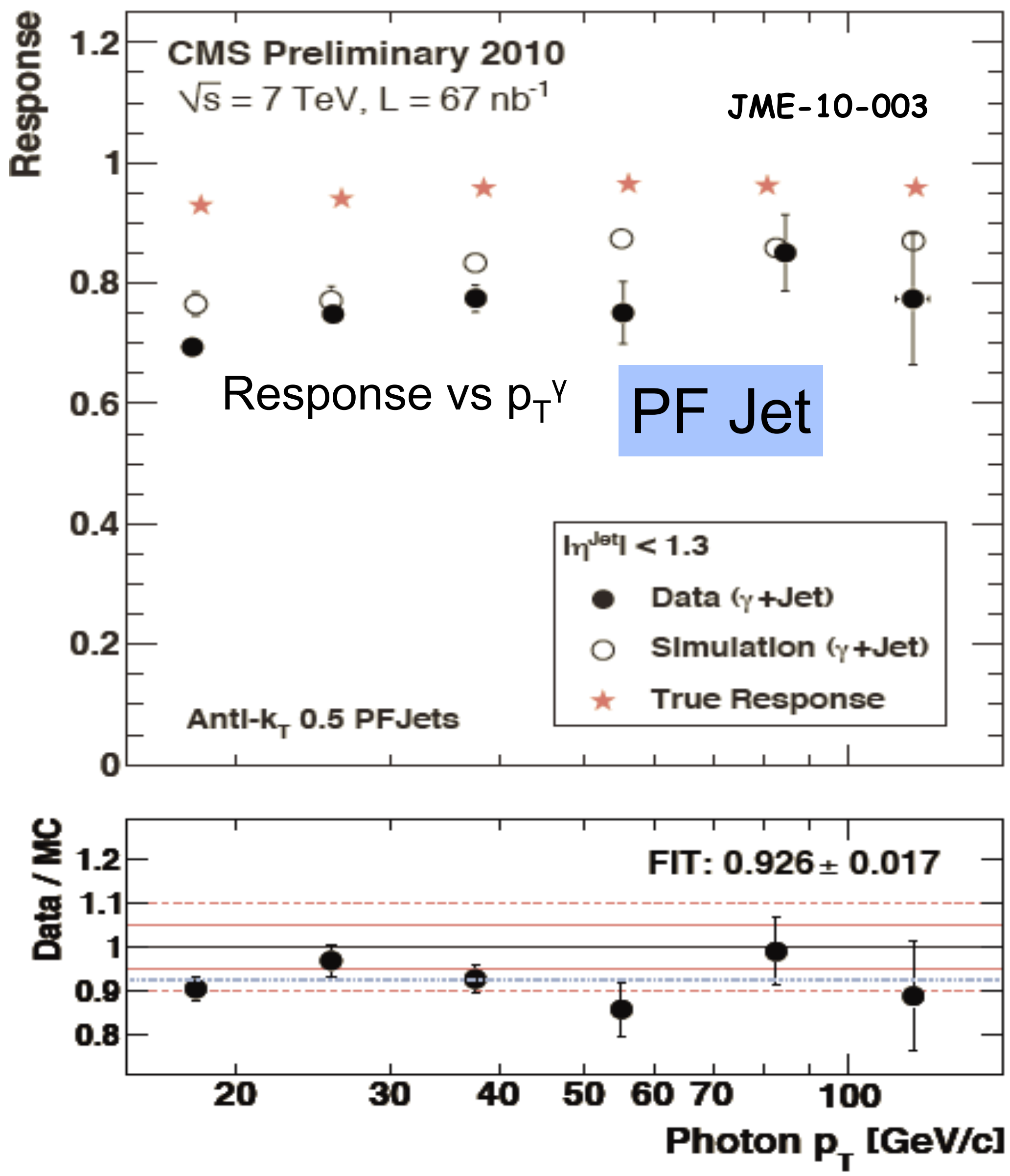
A-priori estimate of JEC uncertainty in barrel 5% for tracking-based jets (JPT, PFJets, track jets), 10% for CaloJets

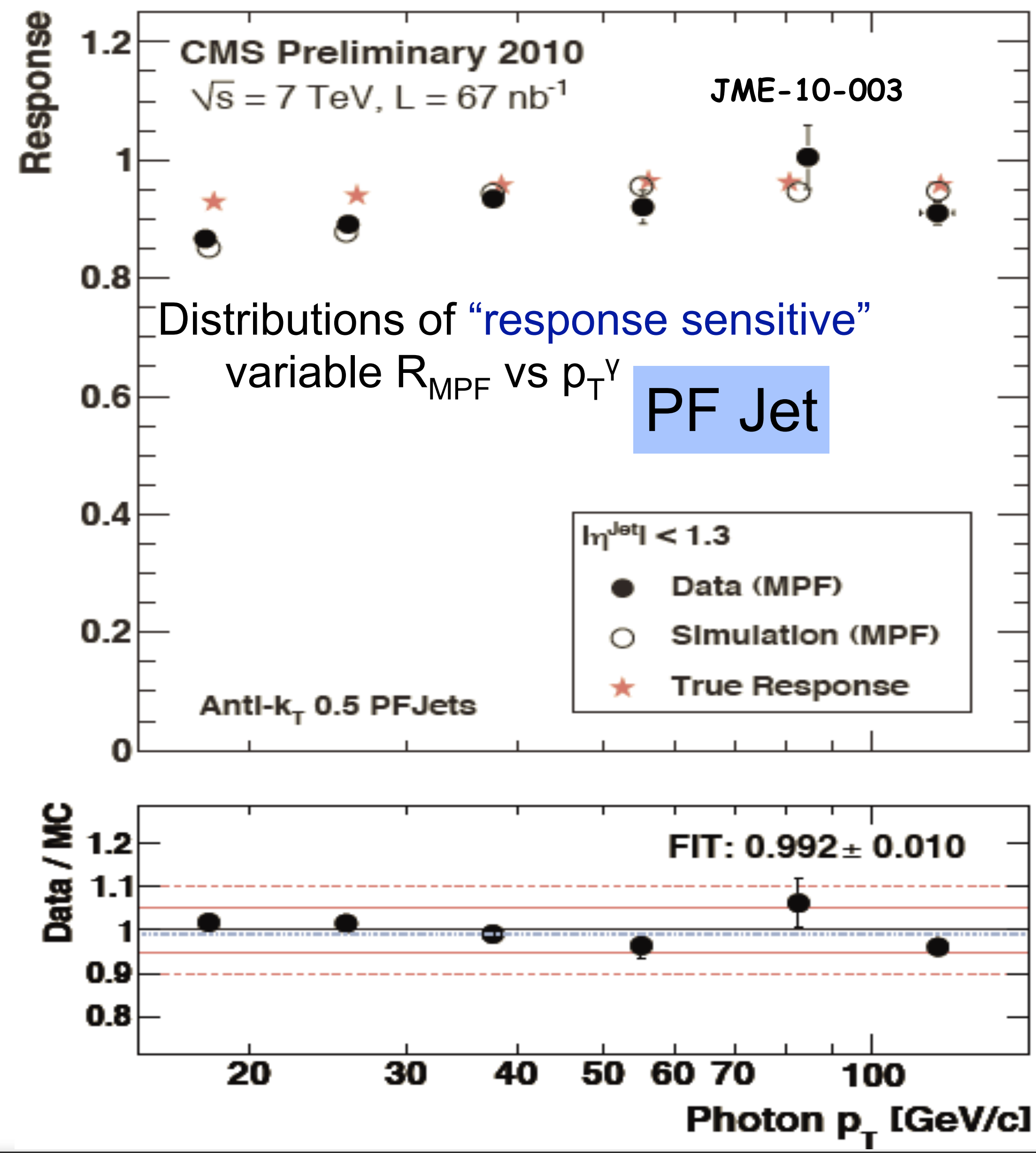


- Method employs p_T balance in back-to-back photon+jet events (well measured photon as a reference object)
- Use photon trigger and isolated photons p_T>15 GeV and |η|<1.3

Absolute JEC: photon+jet balance

Photon+jet balance: Bias due to soft veto on second jet → Missing-E_T projection fraction method (**MPF**, from D0) uses MET to measure the balance and is less sensitive to QCD radiation





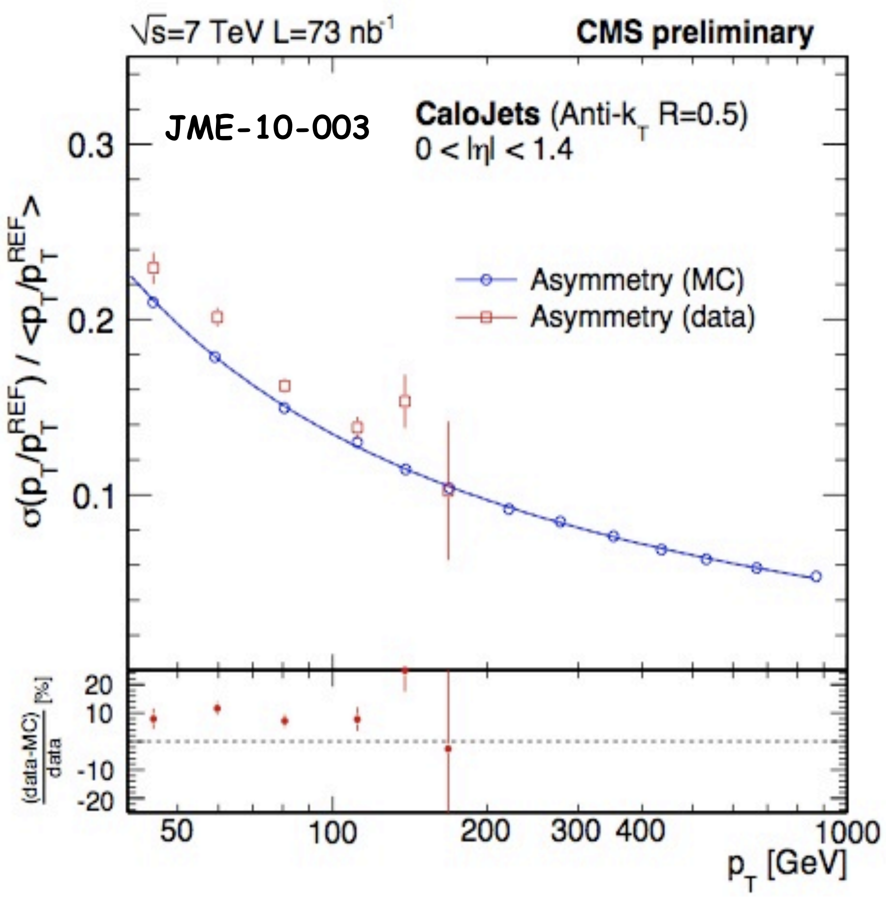
=> Mostly good agreement when same method applied to MC and Data
=> Direct evidence from MPF supports **5%/10% JEC uncertainty** as conservative

Jet p_T resolutions

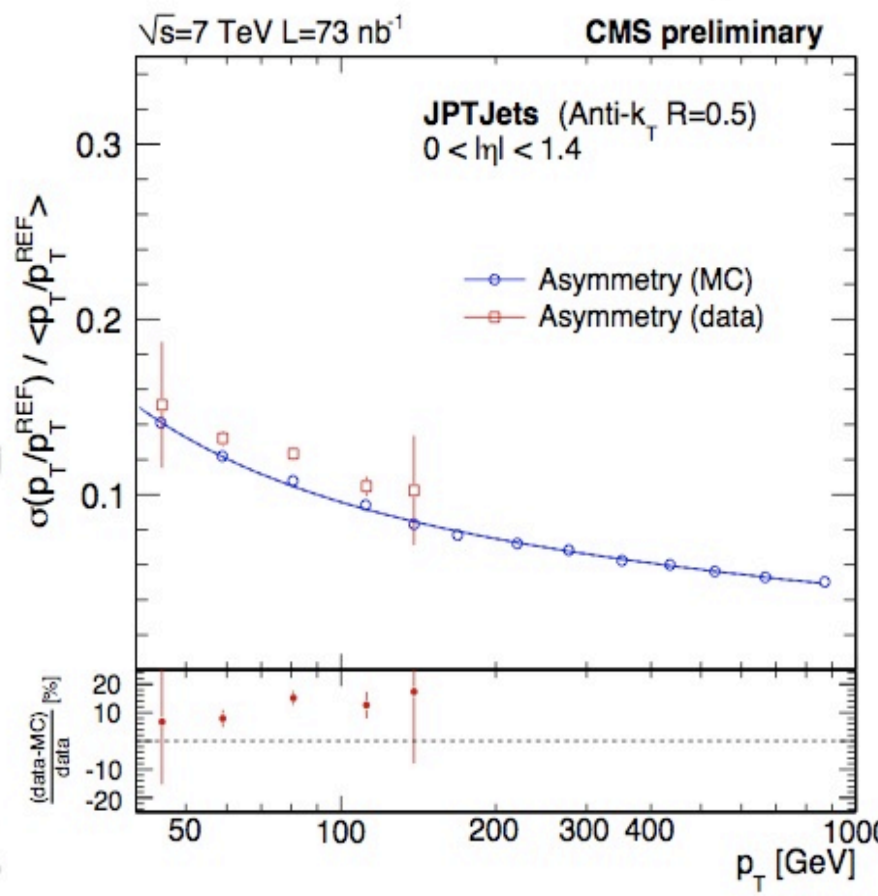
Extracted from Pythia QCD sample (MC) and Dijet Asymmetry method (In Situ)

- Define pT asymmetry of the two leading jets in back-to-back dijet events: $A = \dfrac{p_T^{jet1} - p_T^{jet2}}{p_T^{jet1} + p_T^{jet2}}$
- For approximately equal value of the jet p_T's: $\dfrac{\sigma(p_T)}{p_T} = \sqrt{2}\,\sigma_A$

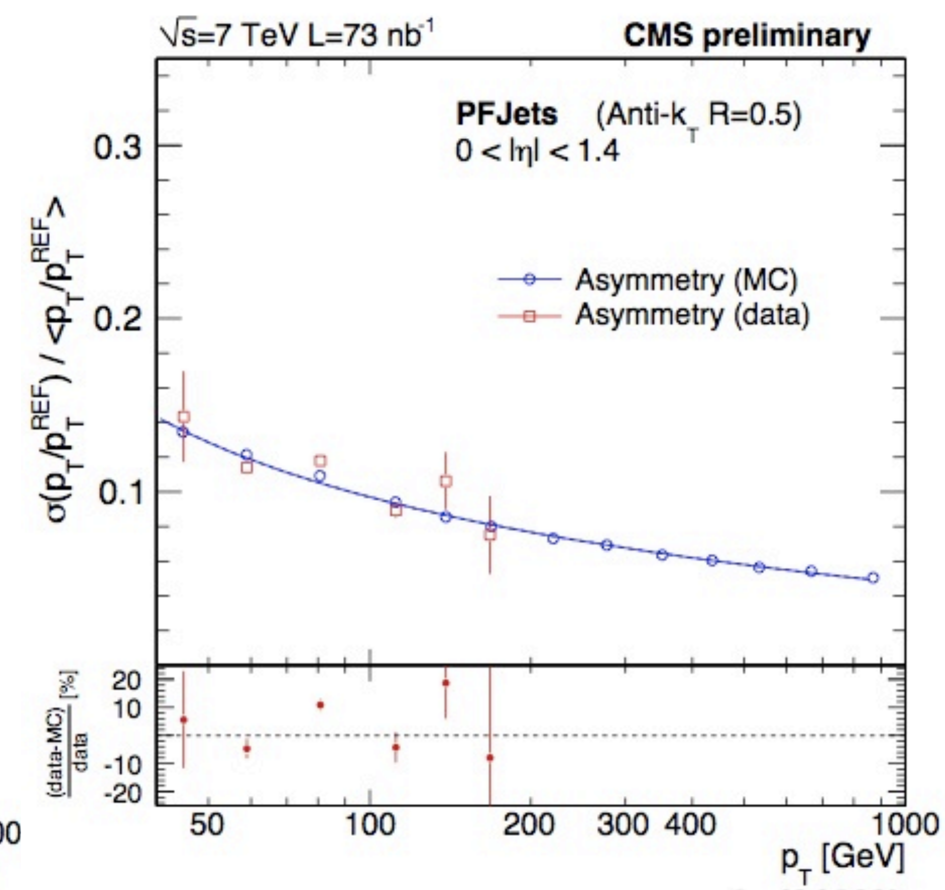
Calo Jet



JPT Jet



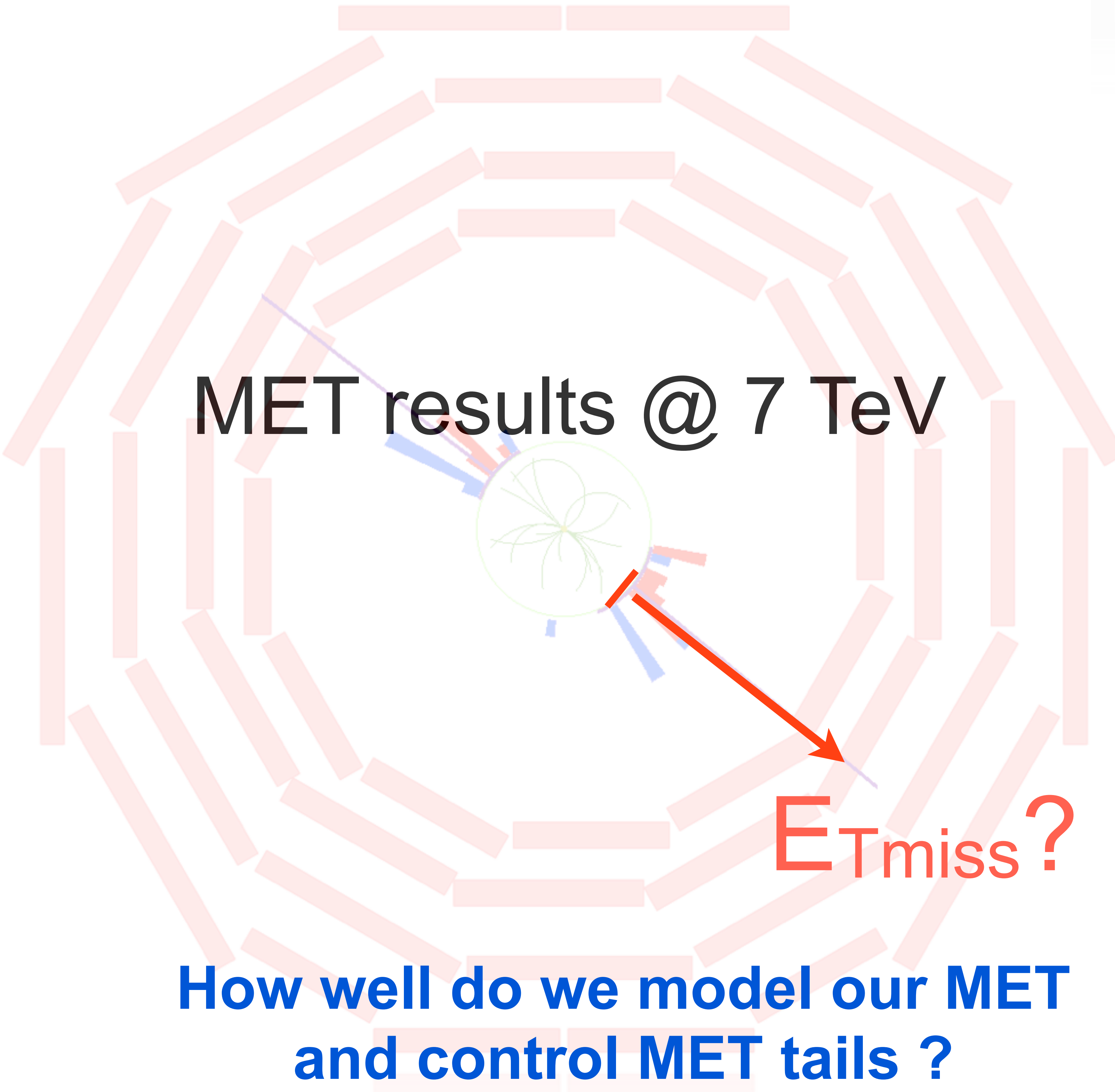
PF Jet



- Full chain of Dijet Asymmetry method applied to data and MC to extract jet p_T resolutions

=> Observed data/MC agreement within a priori **~10% uncertainty**

MET results @ 7 TeV



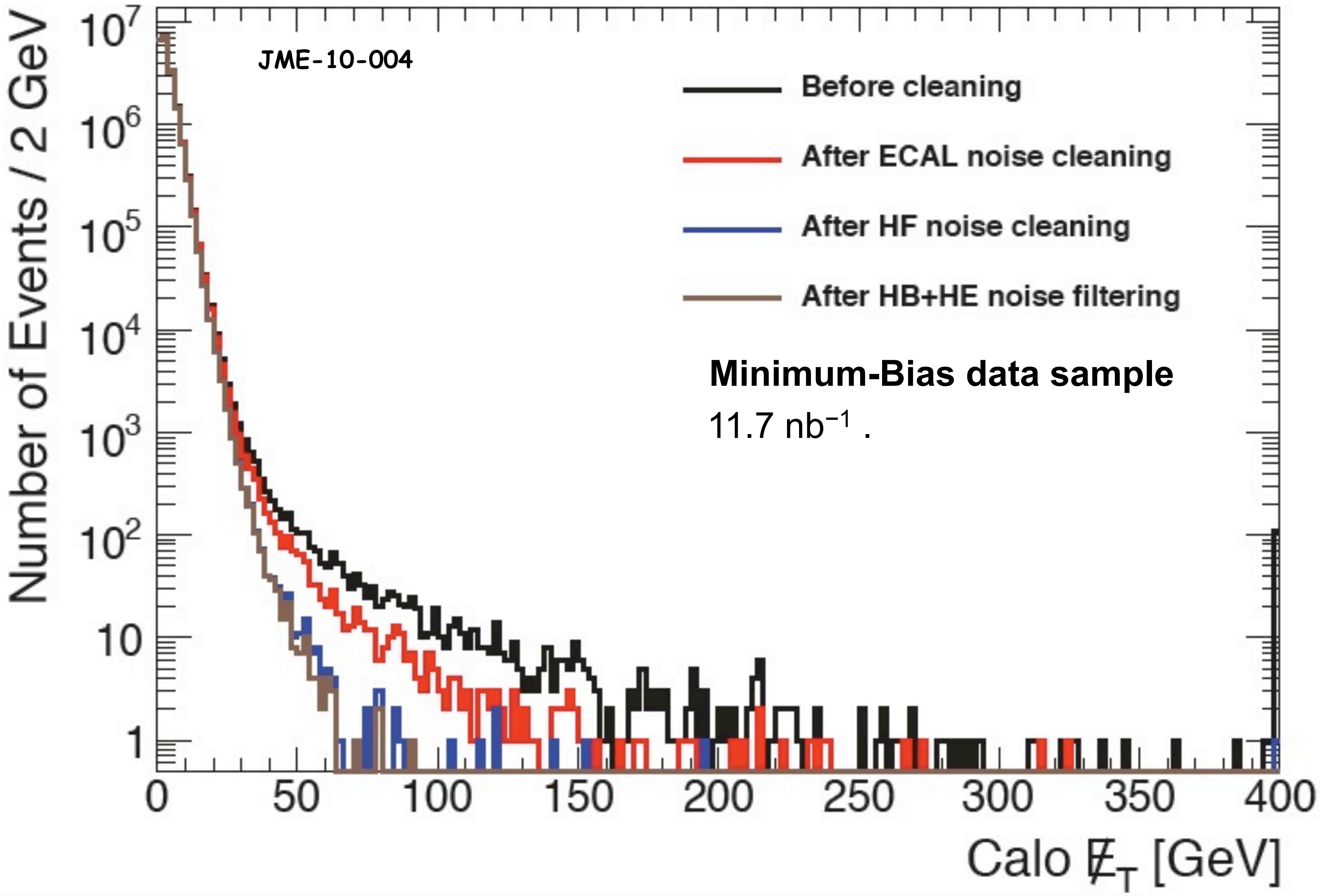
How well do we model our MET and control MET tails ?

Cleaning of MET Tails

No large MET for Minimum-bias / QCD jet events expected

Basic cleaning strategy: identify anomalous signals based on :

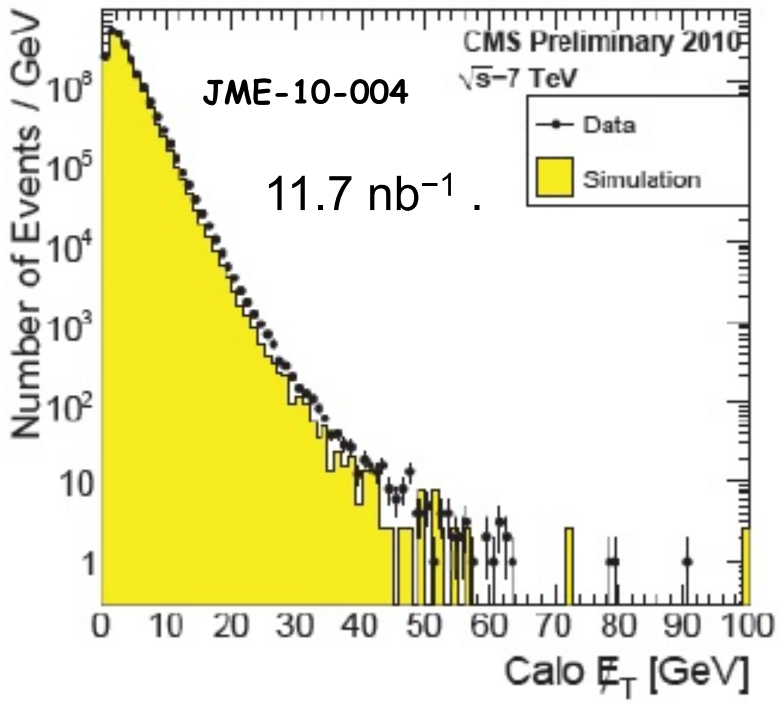
- Unphysical charge sharing of neighboring channels
- Timing/pulse shape information

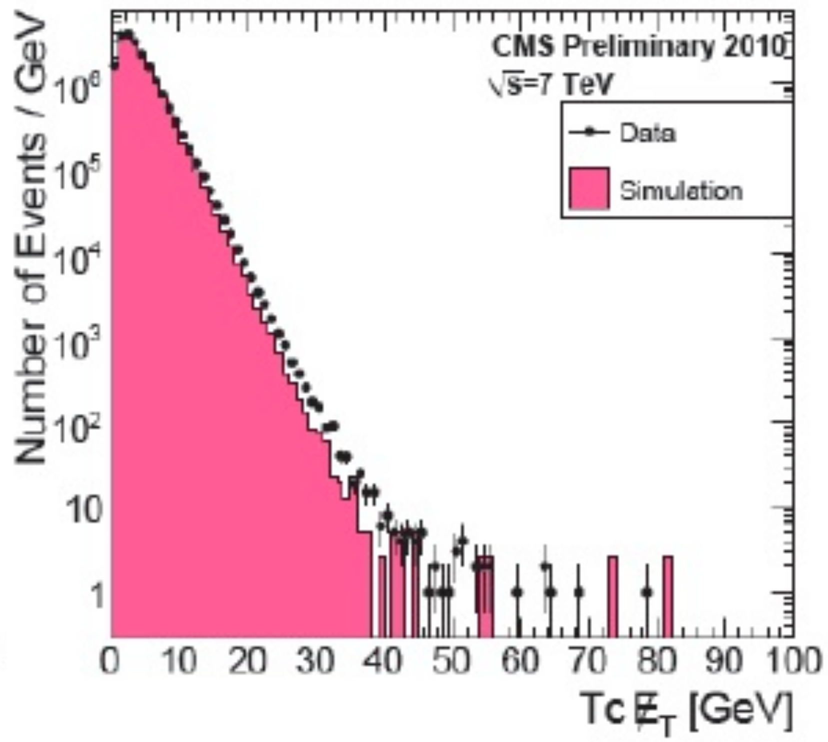


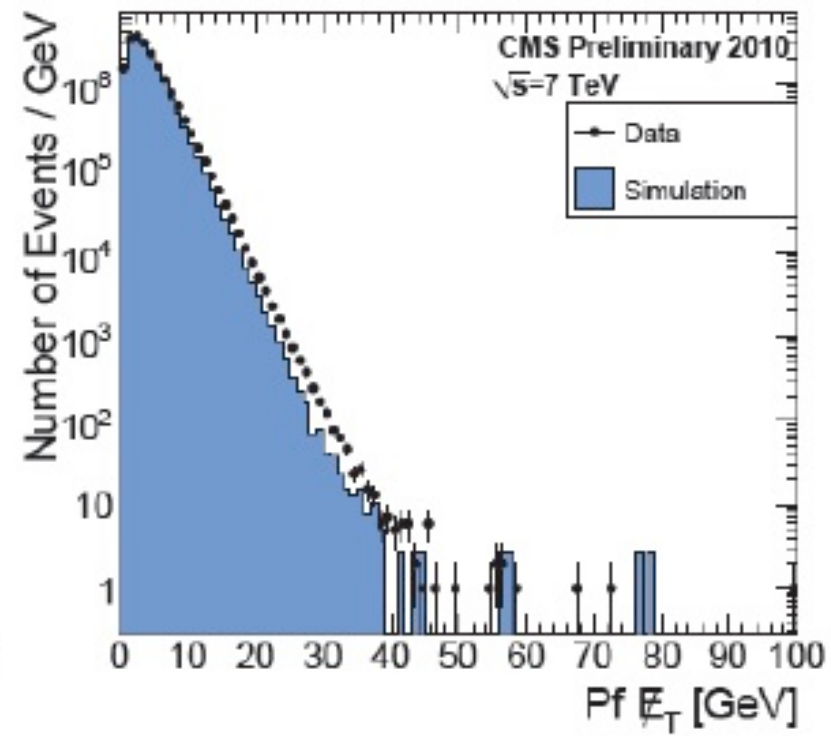
=> Cleaning is very effective
=> After cleaning, MET tail is no longer dominated by anomalous signals

MET in Data /MC

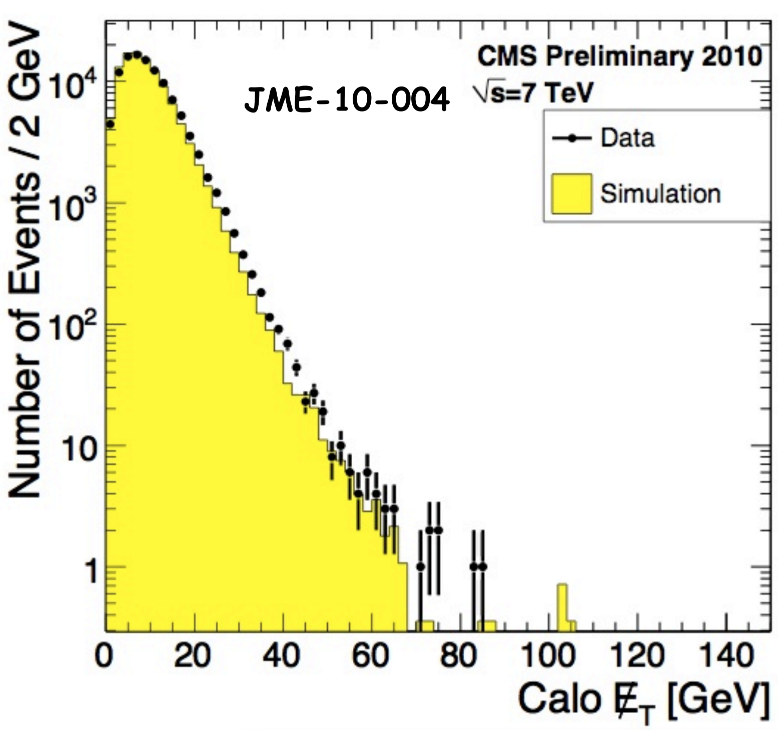
Minimum Bias: Calo MET | tc MET | PF MET

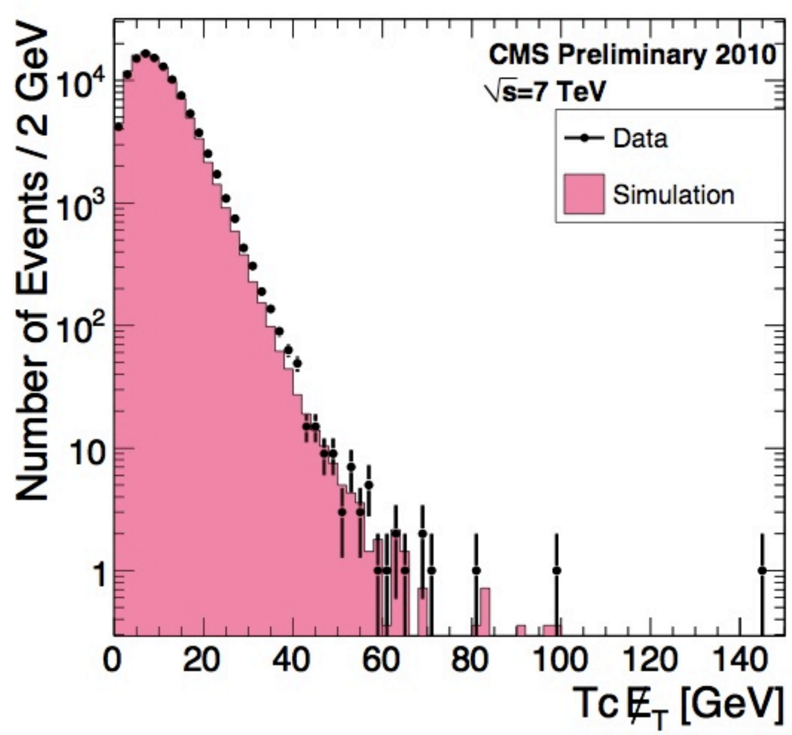


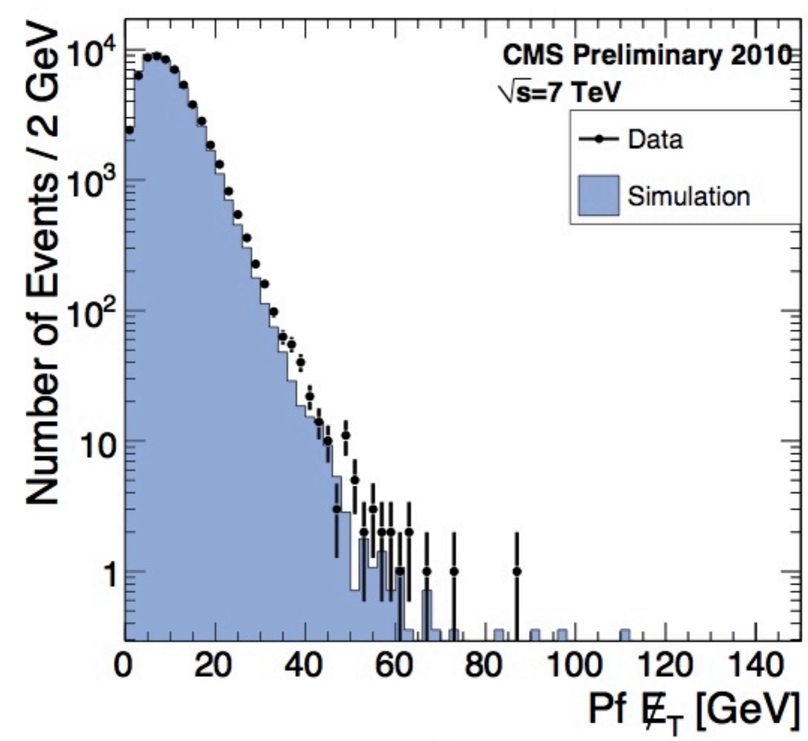




Dijet events with corr. $p_T^{1,2}$>25 GeV, $|\eta_{1,2}|$<3:



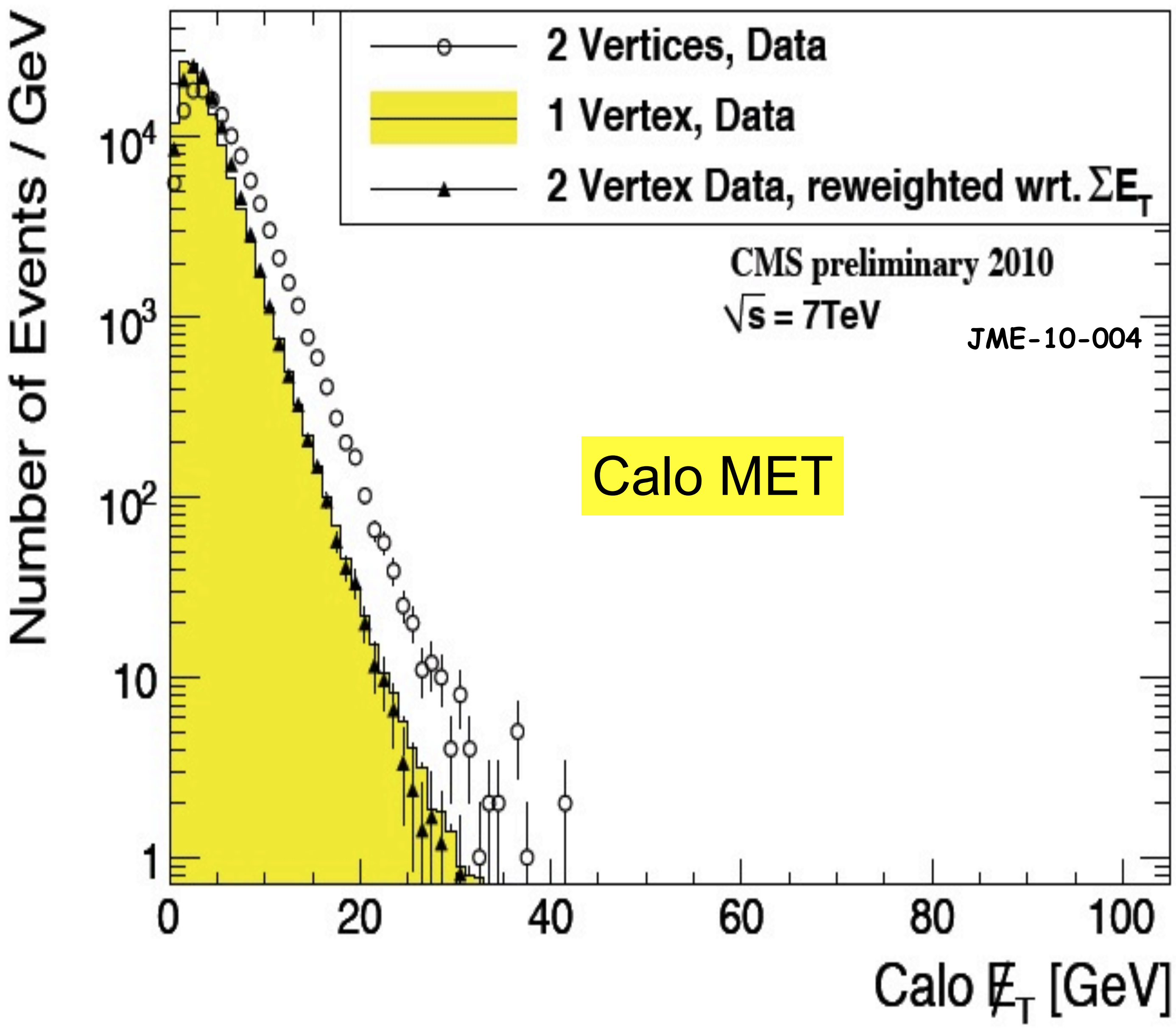




=> General Agreement between Data and MC

MET in Pile Up Events

Study of MET distribution in 1-and 2-vertex events in minimum-bias

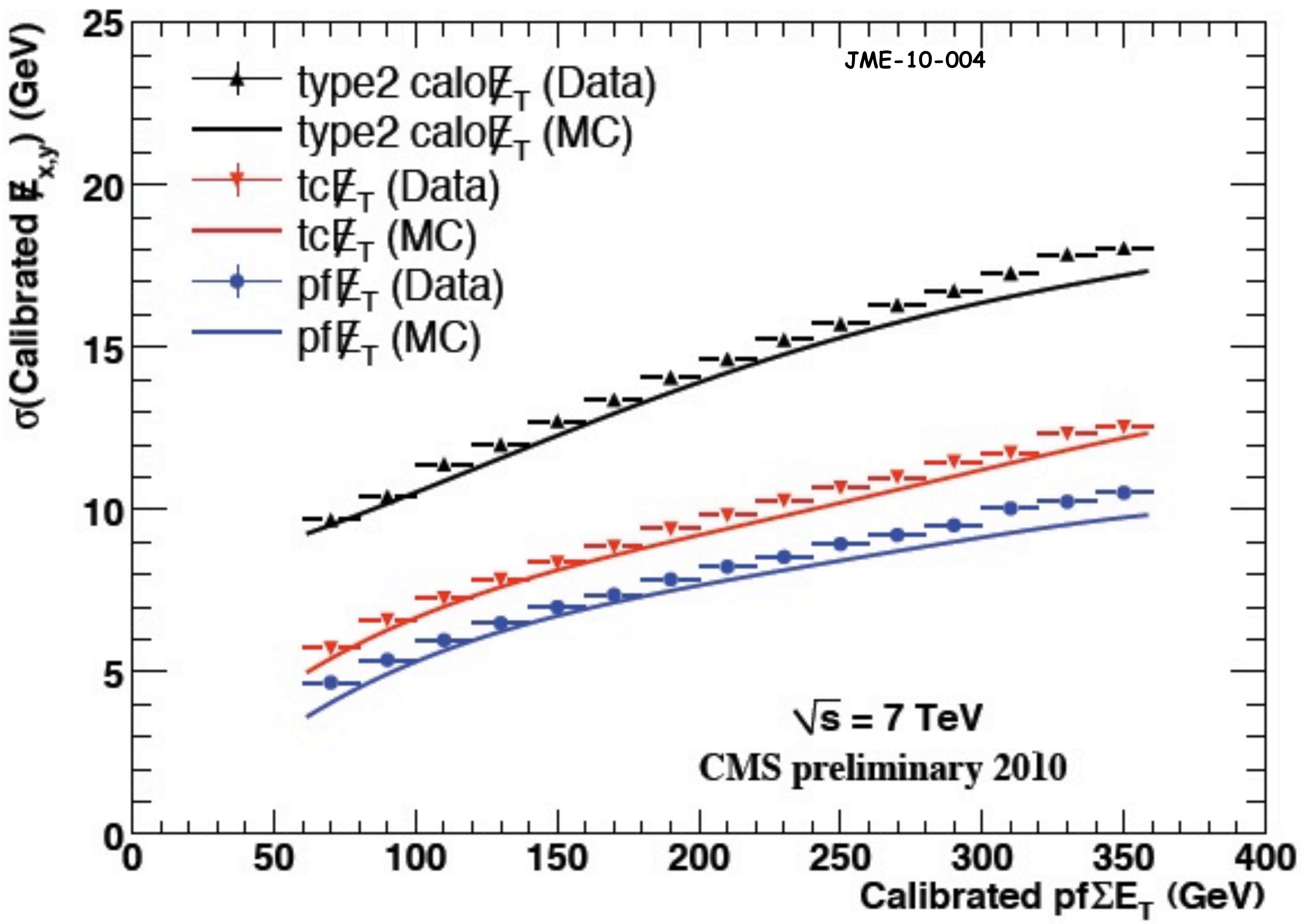


- MET distributions wider in 2-vertex events
- Reweight 2-vertex events so that the SumE_T distribution matches that of the 1-vertex events
- After reweighting, MET distribution agrees between 1-vertex and 2-vertex events

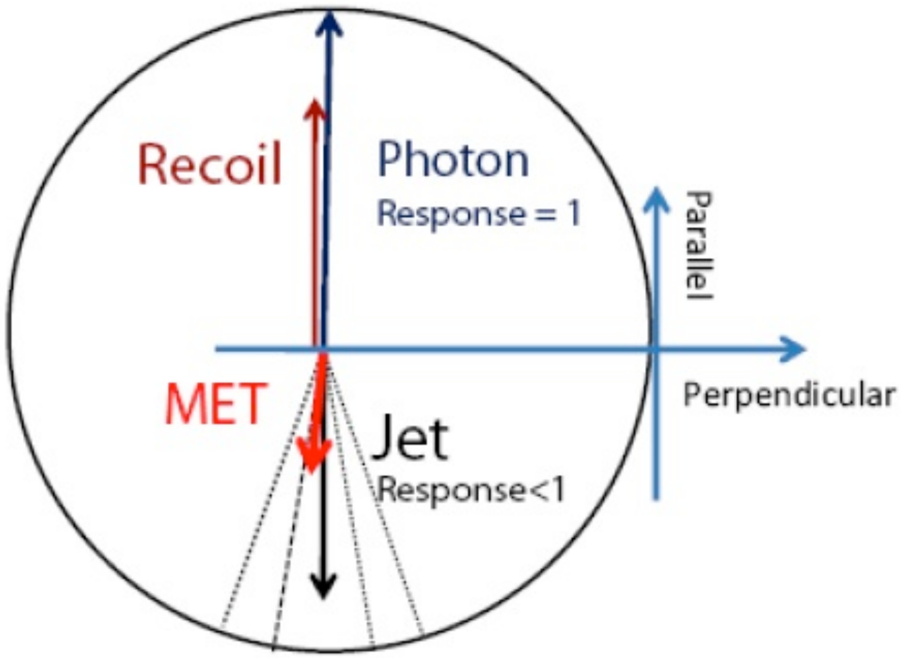
=> Widening of MET distribution in 2-vertex events due to transverse energy increase in events

MET Resolution vs SumE$_T$

Compare the resolution of different MET types at the same PF SumE$_T$ (closest to real sumE$_T$)



- PF SumE$_T$ is calibrated to generator level Sum E$_T$
- Observed MET sigma is calibrated using photon+jets MC events:



=> PF MET has the best resolution.
=> Tc MET also shows significant improvement w.r.t. Calo MET

Summary

First results of the Jet and Missing Transverse Energy performance were presented

Jets:

- General data/MC agreement for jet response and p_T resolutions
- Observations from current data support a priori estimates :
  - 10% (5%) JEC uncertainty for calorimeter jets (jets using tracking)
  - Additional 2% uncertainty per unit rapidity
  - 10% p_T resolution uncertainties for all three jet types

MET:

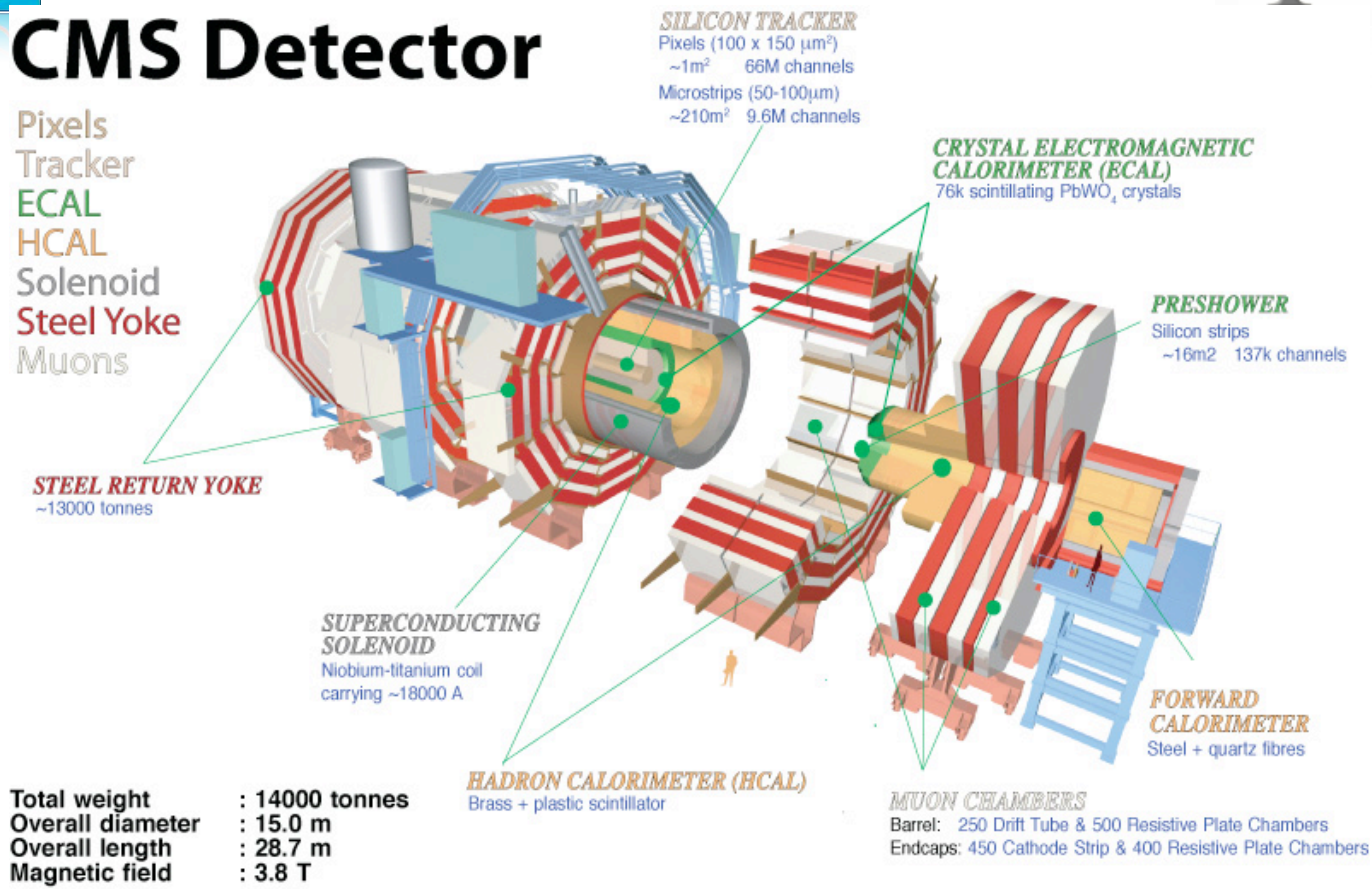
- Acceptable data/MC agreement
- Improved cleaning, tails are under control
- Tackling the challenge of MET commissioning with large pile up
- Tc MET, and especially PF MET, improve resolution **significantly**

Impressive Jet and MET understanding already after just 3 months of data taking at $\sqrt{s}$=7TeV !

References

- CMS DP-2010/014 -- Jet and MET Commissioning Results from 7 TeV Collision Data
- JME-10-006 -- Commissioning of Track Jets in pp Collisions at $\sqrt{s}$=7TeV
- JME-10-008 -- Single Particle Response in the CMS Calorimeters
- JME-10-003 -- CMS Jet Performance in pp Collisions at $\sqrt{s}$=7TeV
- JME-10-004 -- Missing Transverse Energy Performance in Minimum-Bias and Jet Events from Proton-Proton Collisions at $\sqrt{s}$=7TeV
- ME-10-006 -- Commissioning of Track Jets in pp Collisions at $\sqrt{s}$=7TeV
- JME-10-008 -- Single Particle Response in the CMS Calorimeters
- PFT-10-001 -- Commissioning of the Particle-flow Event Reconstruction with the first LHC Collisions recorded in the CMS detector
- PFT-10-002 -- Commissioning of the Particle-Flow reconstruction in Minimum-Bias and Jet Events from pp Collisions at $\sqrt{s}$=7TeV
- QCD-10-013 -- Hadronic Event Shapes in pp Collisions at $\sqrt{s}$=7TeV
- EXO-10-001 -- Measurement of the Dijet Mass Spectra in pp Collisions at $\sqrt{s}$=7TeV

Backup: CMS Parameters



Tracker: 66M pixel channels, ~10M Si microstrip channels,

Calorimetry: ~75k crystals, ~15k HCAL channels,

Muon System: 250 DT chambers (170k wires), 450 CSC chambers (~200k wires) , ~ 500 Barrel RPCs ~ 400 endcap RPCs,

Trigger System: muon and calorimeter trigger system, 40 kHz DAQ system (~ 10k CPU cores),

Grid Computing (~ 50 k cores), **Offline** (> 2M lines of source code).

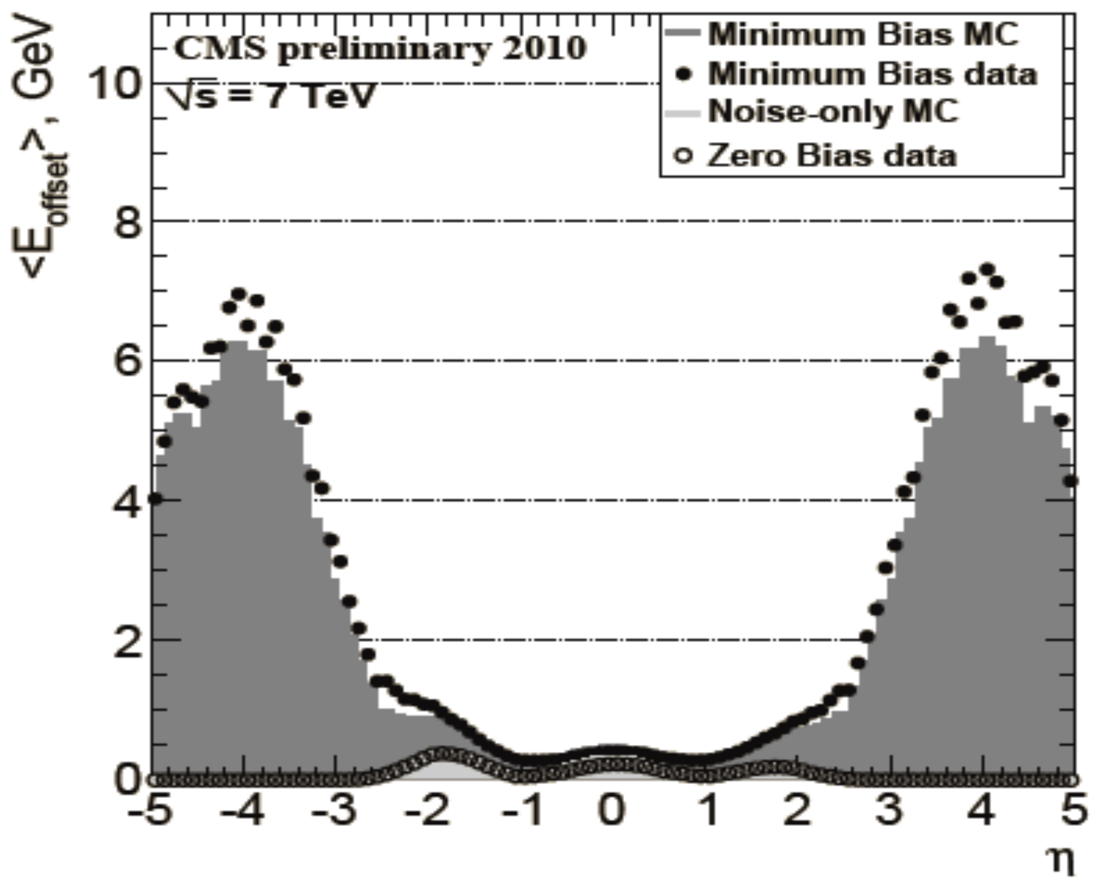
Backup : Anti K_T

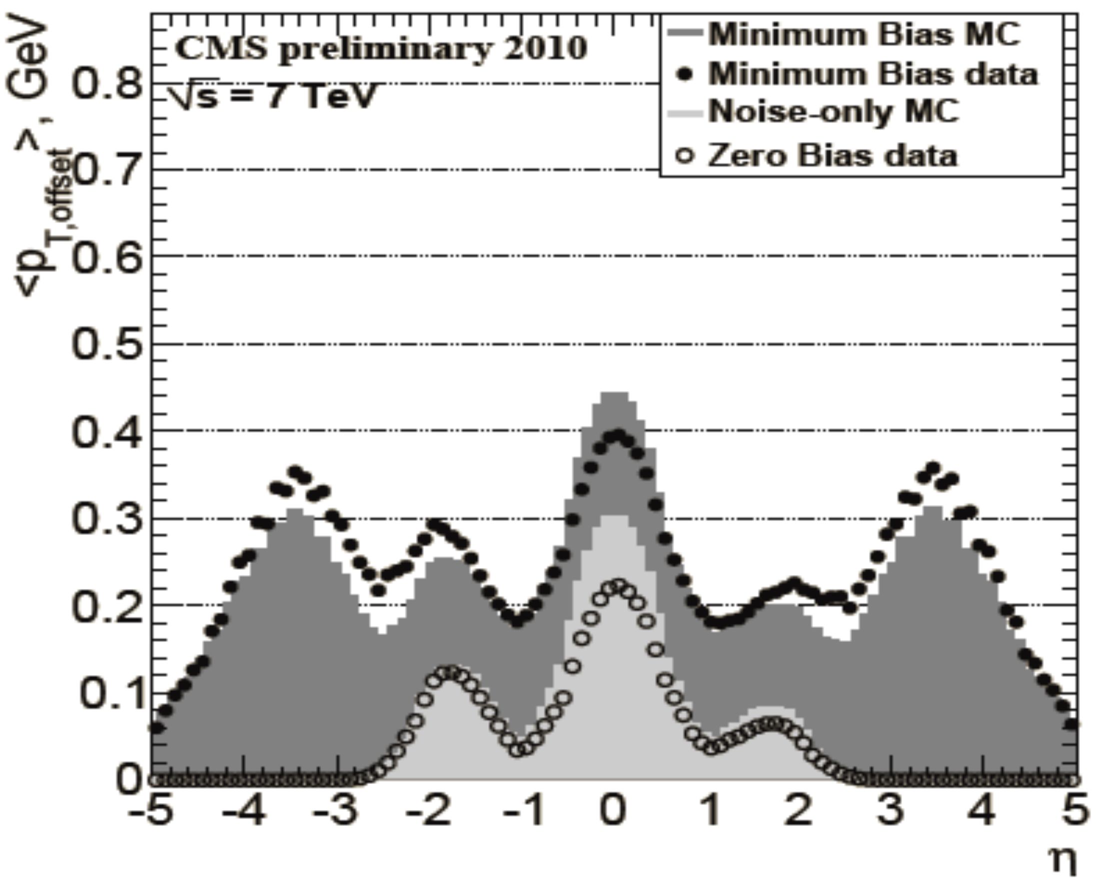
$$d_{ij} = min\left(k_{T,i}^{-2}, k_{T,j}^{-2}\right)\frac{\Delta R_{ij}^2}{R^2}$$

$$\Delta R_{i,j}^2 = (y_y - y_j)^2 + (\phi_i - \phi_j)^2$$

- New development in the jet clustering theory.
- Tends to cluster the energy around the hardest particles.
  - essentially behaves like a cone algorithm giving perfectly round jet areas
- Belongs to the "k_T" family.
  - merging of 4-vector pairs based on transverse momentum weighted distance in y-φ plane.
  - the clustering terminates when the weighted distance between particles is greater than a specific value **R** (resolution parameter).
  - the quantity **R** is of the order of unity.
- infrared and collinear safe (suitable for theory calculations).

Backup: Offset correction





- Offset from noise:
  - is below 400 (300) MeV in energy (p_T).
  - Simulation gives good description of noise in data.
- Offset from one pile-up event:
  - Up to 7 GeV in energy, but stays below 350 MeV in p_T
  - Pythia Minimum Bias (D6T tune) gives decent description of PU
- Probability of pile-up in 2010 data typically ~50% (was ~10% in earlier plots)

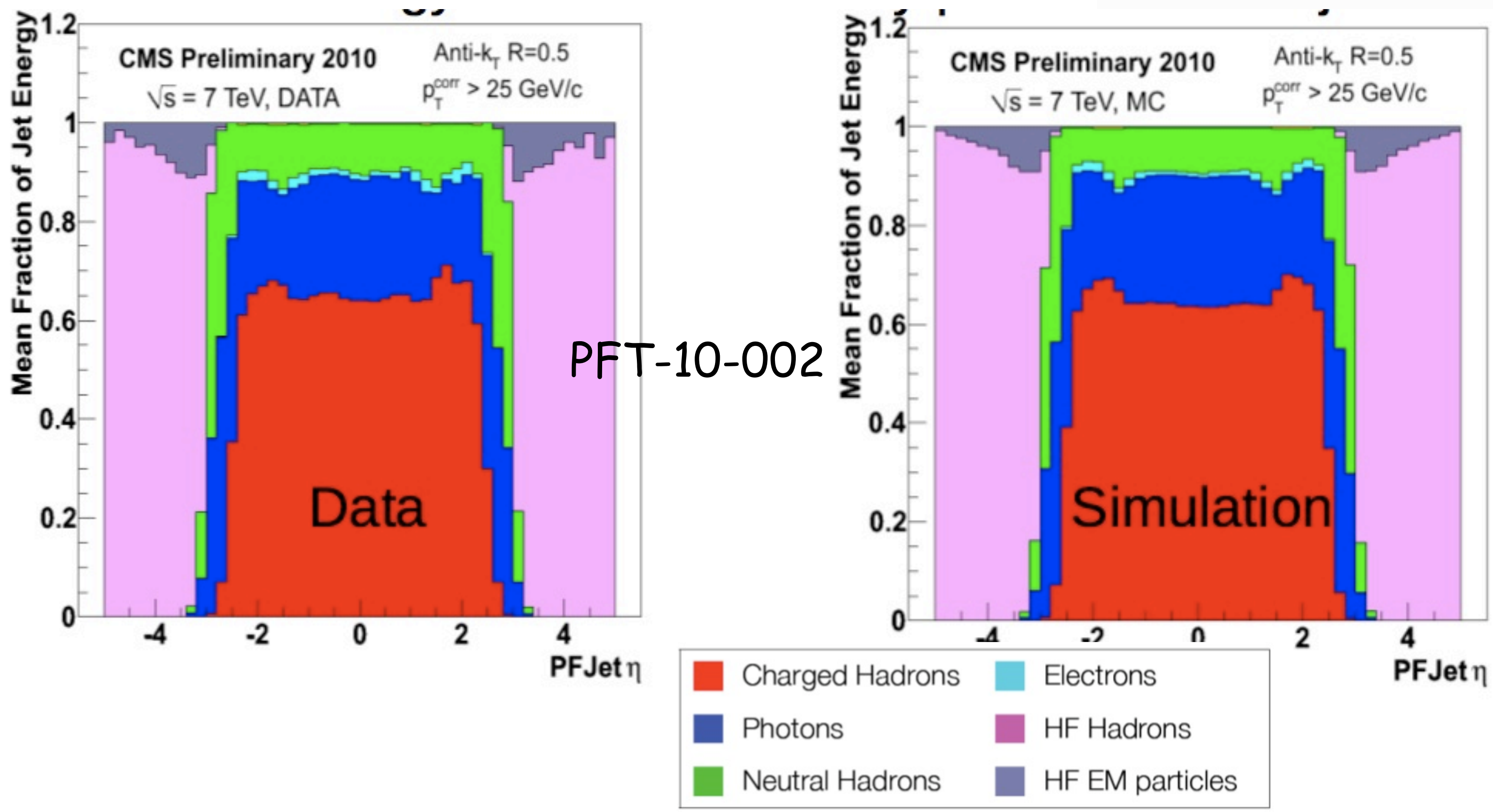
=> Total average offset contribution to jet p_T is small in the current data.
=> No offset correction is applied in the standard JEC chain.

Backup : Absolute JES

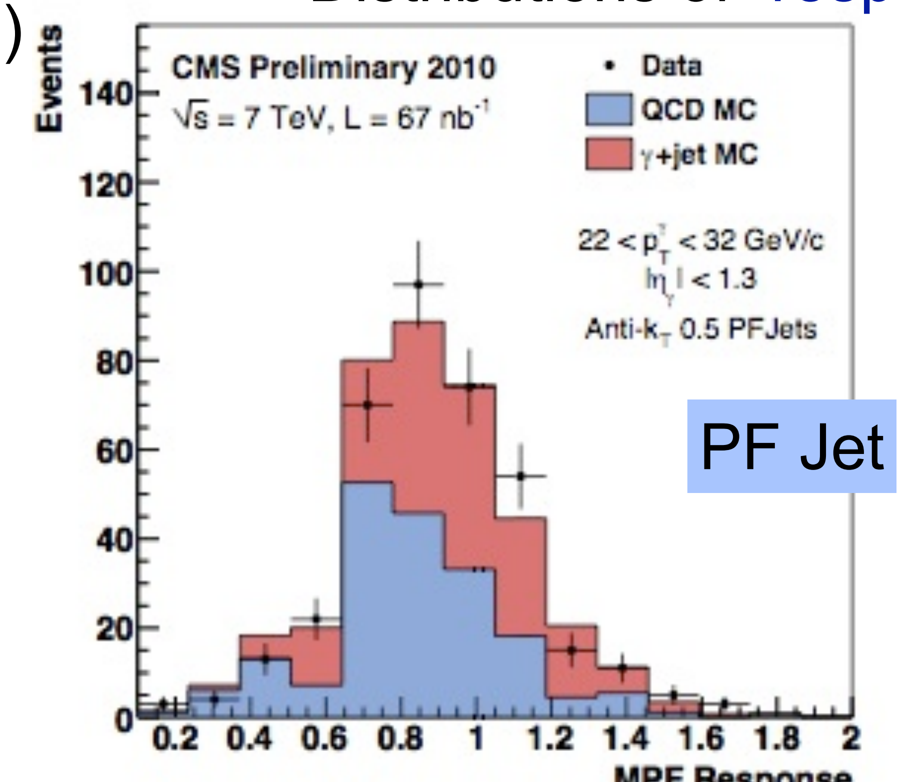
- A-priori estimate of JEC uncertainty in barrel 5% for tracking-based jets (JPT, PFJets, track jets), 10% for CaloJets

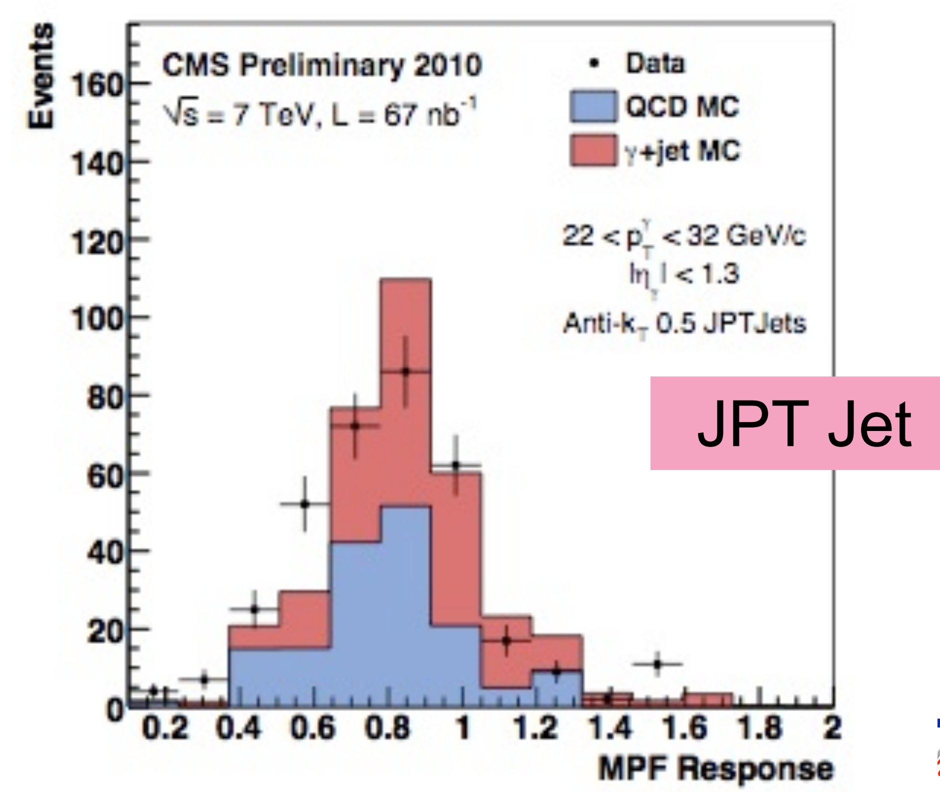
- Constraints from test beam, jet composition studies and "first principles" (single pion response, π^0 mass peak, tracker resonances)

- Direct evidence from Missing-ET projection fraction method (MPF) supports **5%/10% JEC uncertainty** as conservative

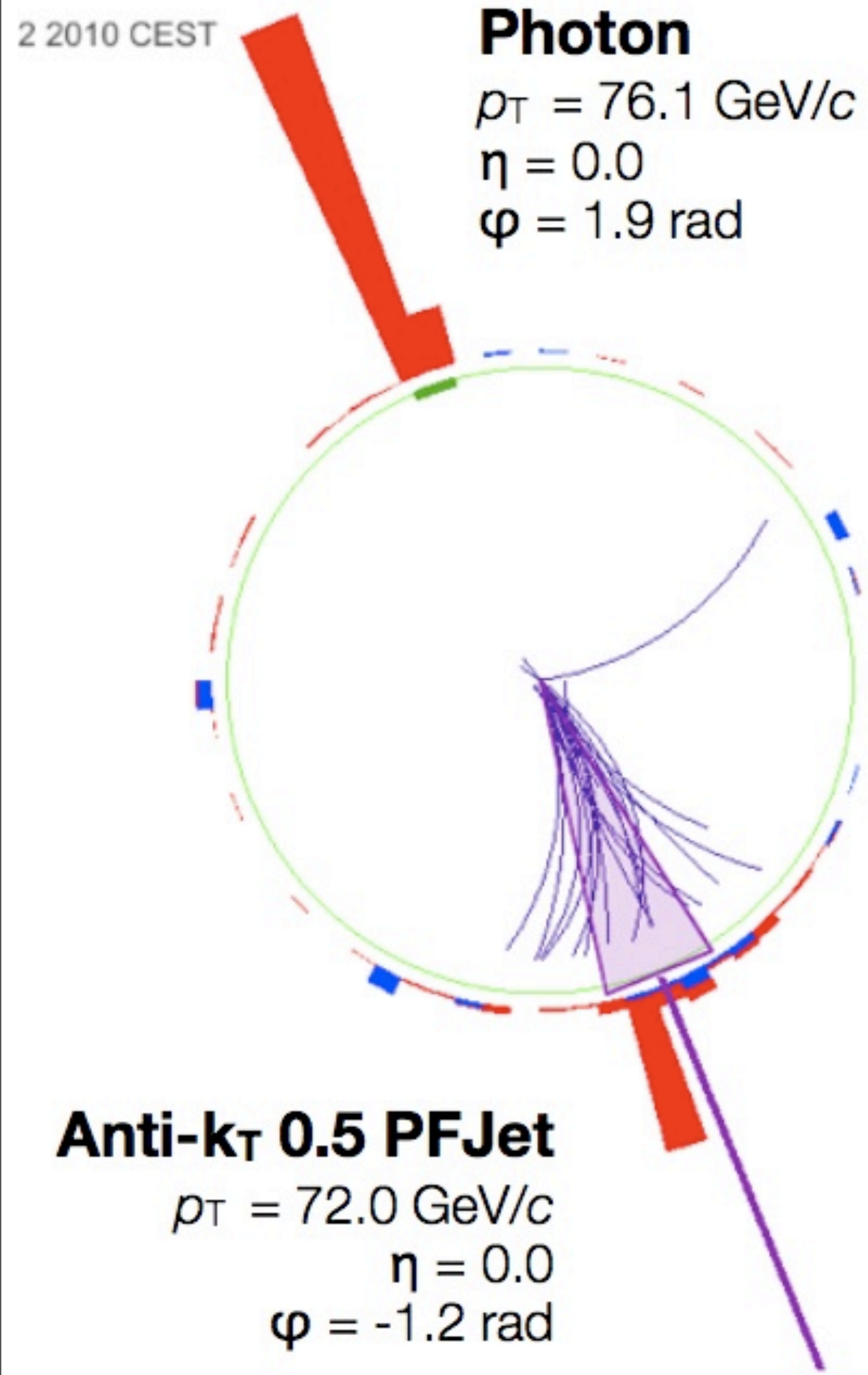


Distributions of "response-sensitive" variable R_{MPF}





Backup : Absolute JES

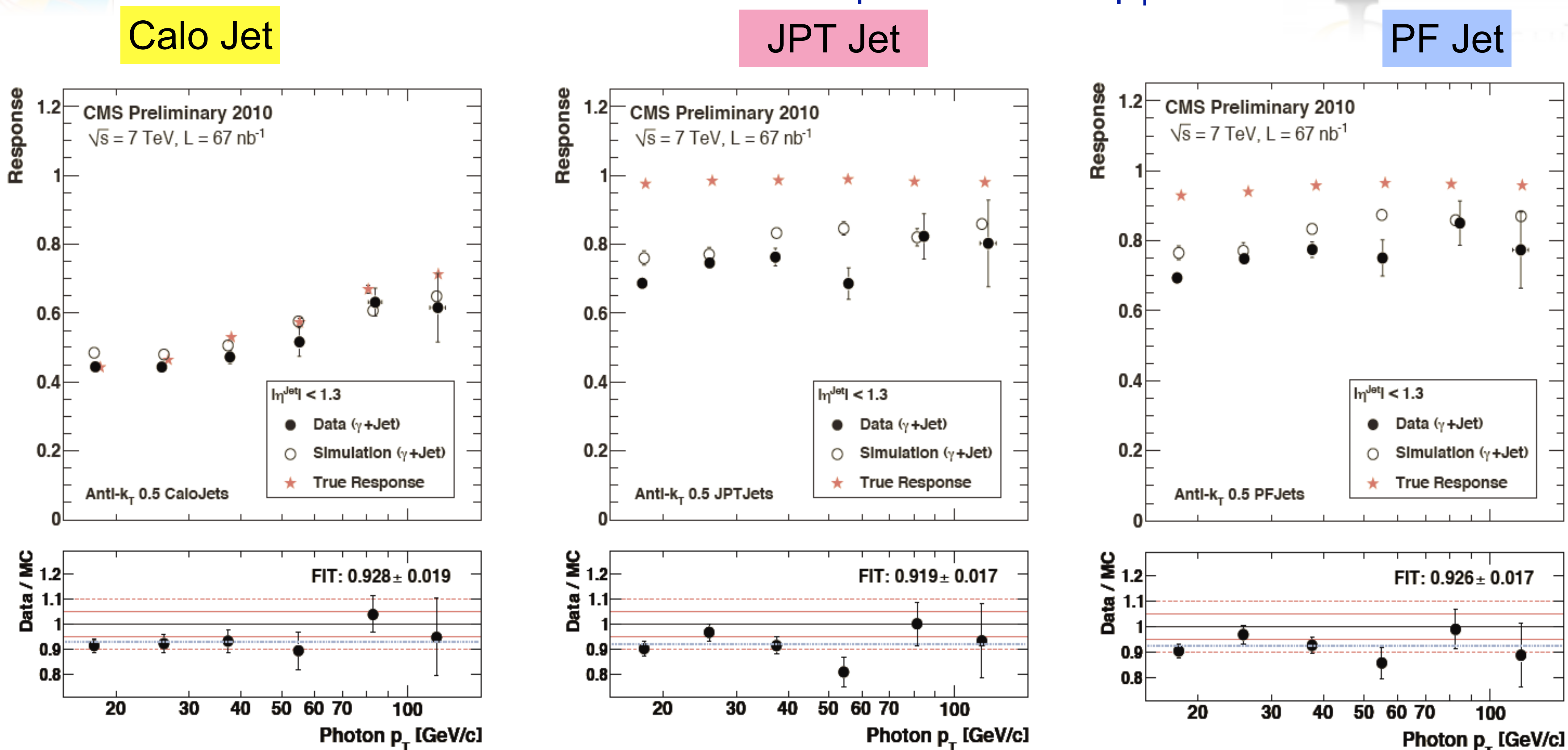


- Photon is looking even better:

	VALUE	ALLOWED RANGE
Cluster Minor Axis	0.22	0.15 ÷ 0.3
Cluster Major Axis	0.29	0.15 ÷ 0.35
ECAL GT Isolation (ΔR<0.4)	$1.7\% \cdot E_\gamma$	$< 5\% \cdot E_\gamma$
HCAL Isolation (ΔR<0.4)	$0.4\% \cdot E_\gamma$	$< 5\% \cdot E_\gamma$
Sum p_T Tracks (ΔR<0.35)	0	$< 10\% \cdot p_{T,\gamma}$
Number of Tracks (ΔR<0.35)	0	< 3

Backup: Absolute JEC

Balance "Response" versus p_T^γ



- Measured "response" is lower than MC-truth response
  - Loose second jet veto ($p_T^{2nd} < 0.5\ p_T^\gamma$) violates photon-jet p_T balancing and produces downward bias in the measurement.
- Reasonable data/MC agreement when the same p_T balance method is applied to data and simulation
- Pileup test in backups: ~no change with PV=1 cut

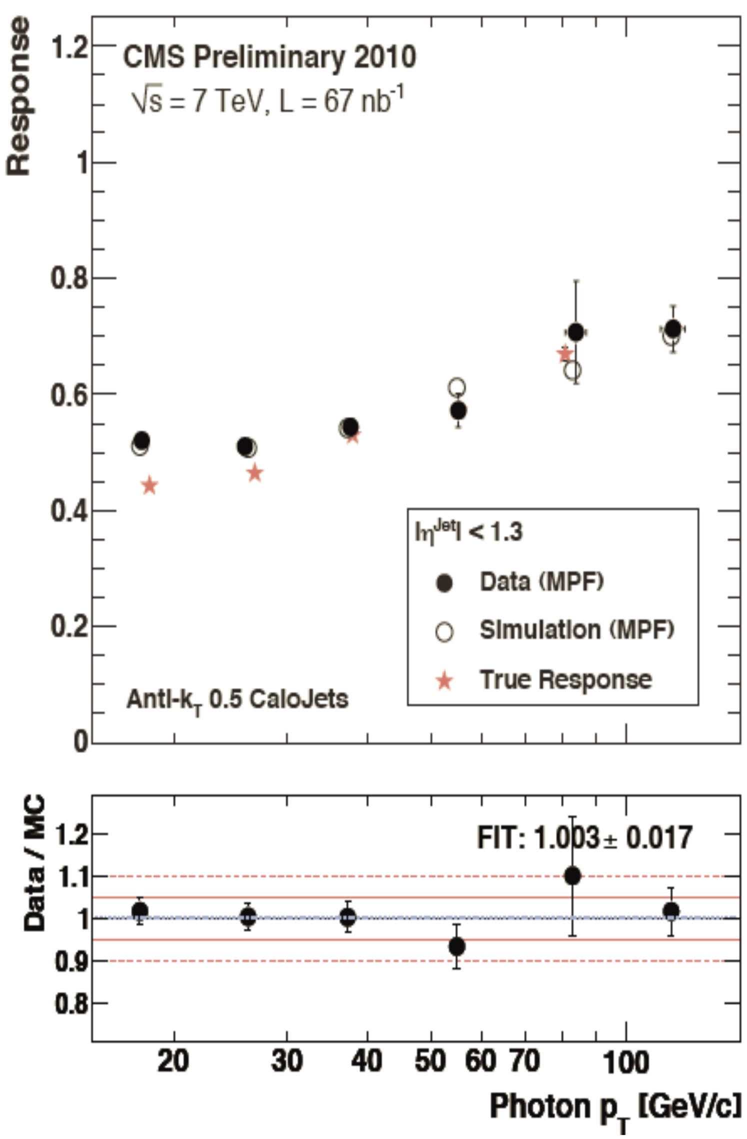
Backup: MPF

- Basics of MPF (Missing Momentum Fraction; AN-2010/218)
  - Ideally: $\vec{p}_{\rm T}^{\,\gamma} + \vec{p}_{\rm T}^{\,\rm recoil} = \vec{0}$
  - Add in the detector: $R_\gamma \vec{p}_{\rm T}^{\,\gamma} + R_{\rm recoil} \vec{p}_{\rm T}^{\,\rm recoil} = -\vec{E}_{\rm T}^{\rm miss}$
  - Solving: $R_{\rm recoil}/R_\gamma = 1 + \frac{\vec{E}_{\rm T}^{\rm miss} \cdot \vec{p}_{\rm T}^{\,\gamma}}{|\vec{p}_{\rm T}^{\,\gamma}|^2} \equiv R_{\rm MPF}$
  - ➡ R_{MPF} is assigned as the response of the recoil jet
- Advantage of MPF: Low sensitivity to extra radiation
  - ➡ Smaller error bars: Widths of distributions are narrower thanks to less fluctuations from the impact of extra radiation
  - ➡ Smaller bias wrt MC-truth than p_T^{jet}/p_T^{γ} for current very loose cuts on extra radiation
  - ➡ Helps to fully exploit the accuracy of PF method
- MPF method demonstrates the accuracy of JES for different types of jets more clearly than γ-jet balancing method does

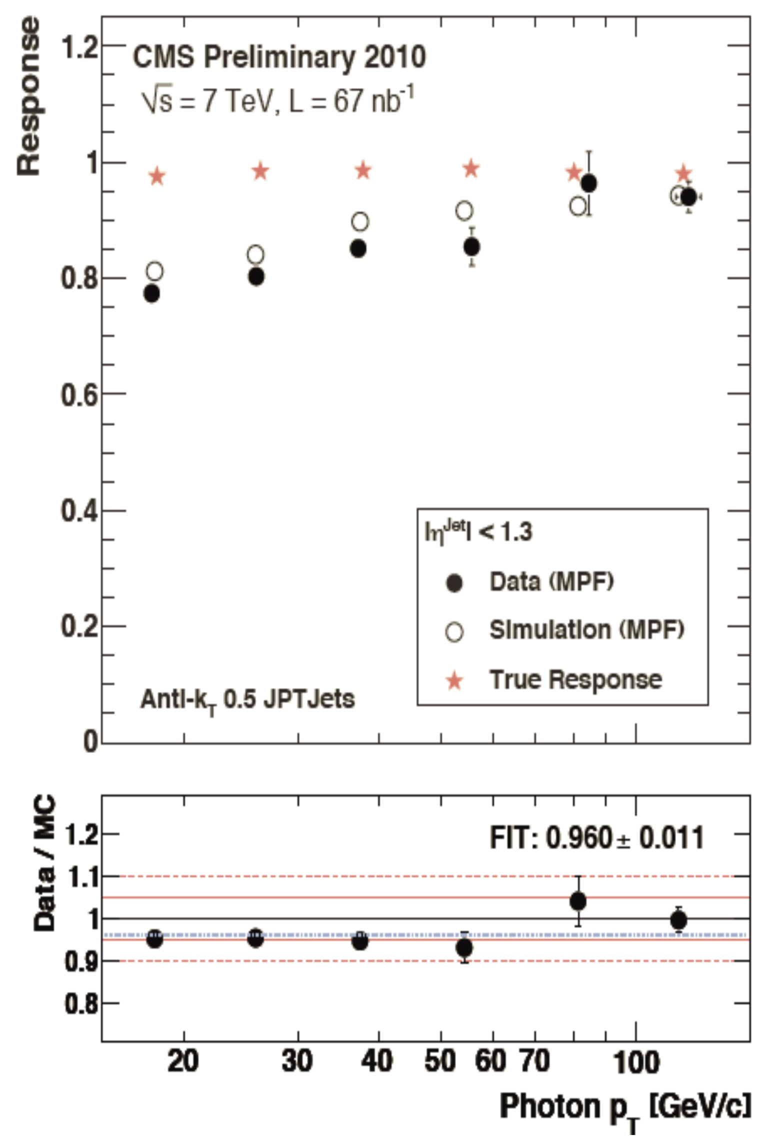
Backup: Absolute MPF

MPF “Response” versus p_T^{γ}

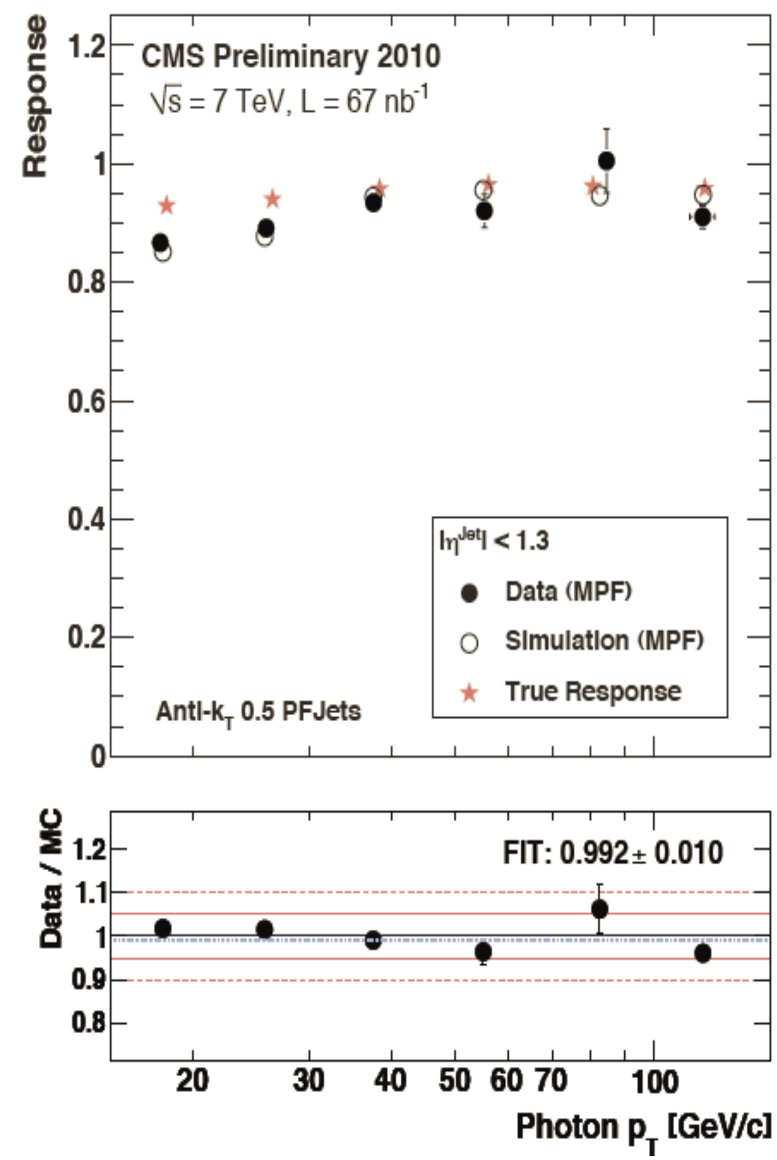
Calo Jet



JPT Jet



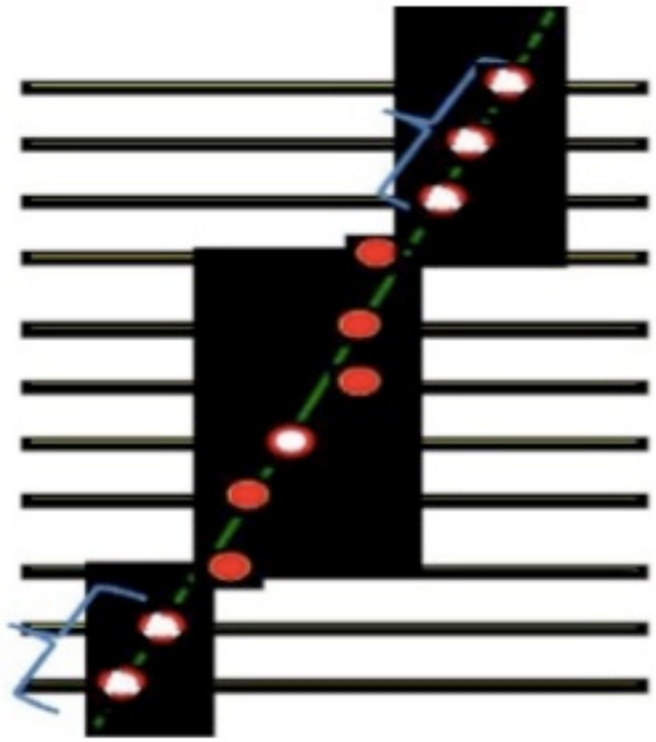
PF Jet



- Measured “response” is closer to MC-truth response than for p_T balance
- Good data/MC agreement when the same MPF method is applied to data and simulation.

Backup:Single Particle Response

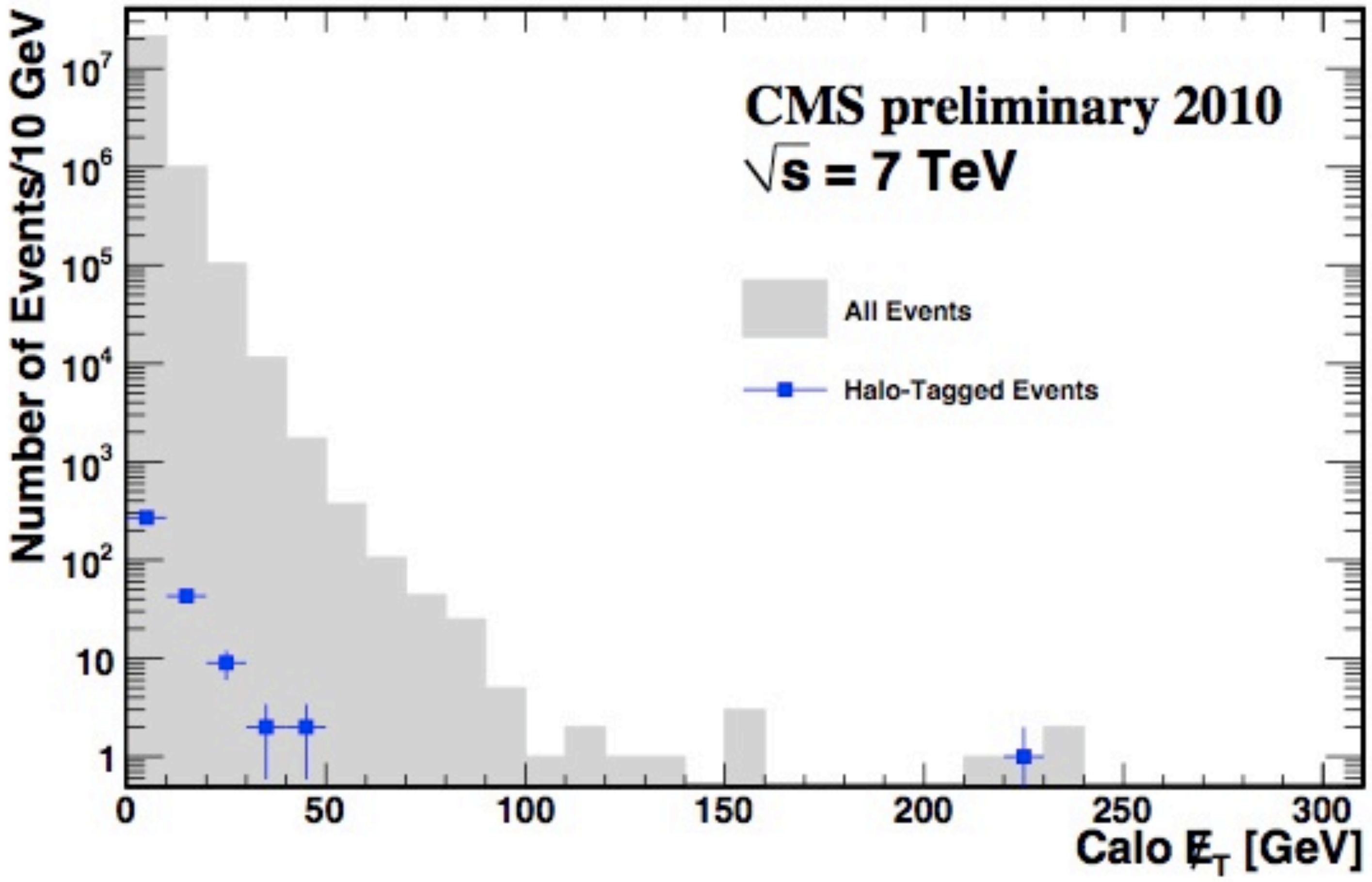
- Well measured tracks which do not interact in tracker material are used for measuring response of calorimeter
- Tracks reconstructed with High Purity quality
- Track Pt > 1.0 GeV/c
- Atleast 8 tracker layers crossed
- No missing hits in the innermost or outermost track layers
- Track (dxy) < 0.2 mm |Track dz| < 0.2 mm
  Track X^2/ndof < 5.0

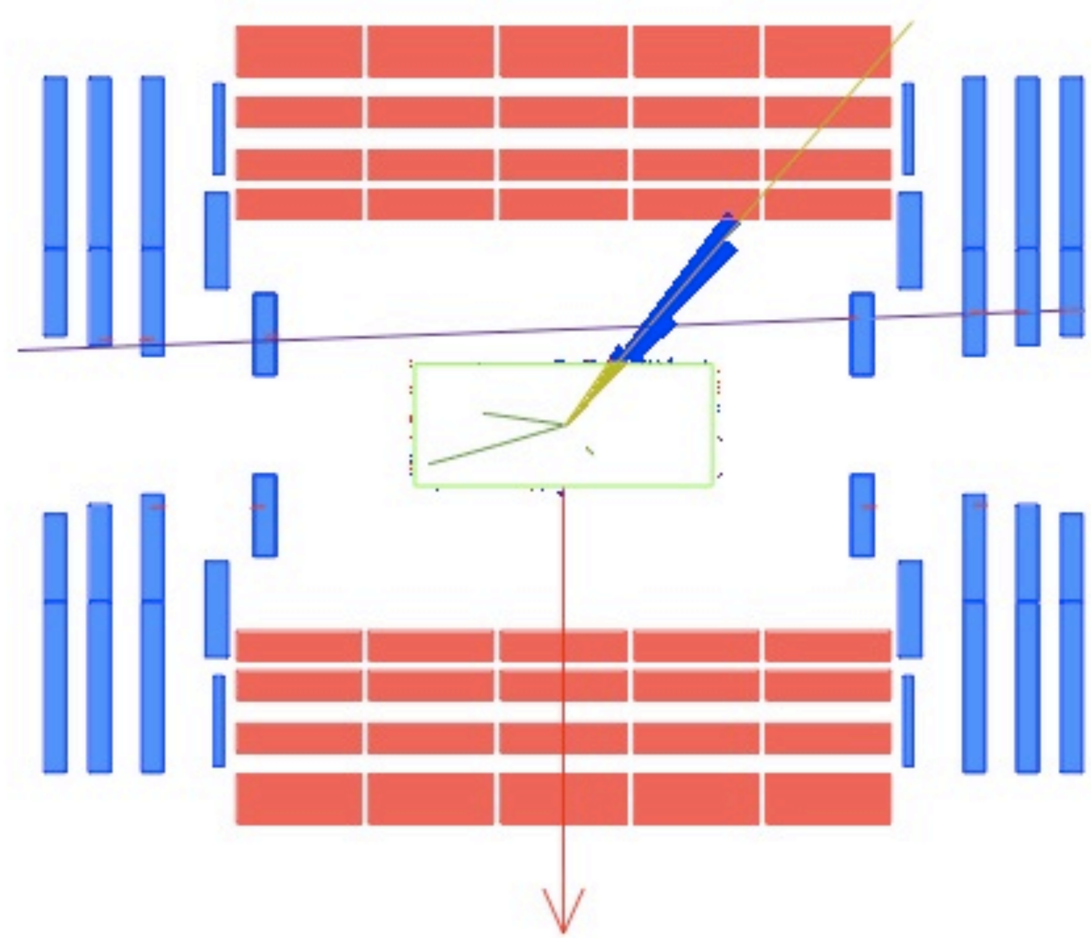


Backup: Anomalous Signal Cleaning

- ECAL spikes
  - Remove rechits with ET>5 GeV and “1-E4/E1<0.95“
  - Remove out-of-time rechits (kOutOfTime and E>2GeV)
- HF anomalous signals
  - Cut on (L-S)/(L+S) for short fibers (PET algorithm)
  - Topological isolation cut for long fibers based on S9/S1 isolation
  - Remove rechits with “faulty” pulse shape
- HBHE noise in RBX/HPD
  - Rejects events with high energy/high hit multiplicity anomalous noise

Backup: Beam Halo





CaloMET for events before the beam-halo fitler is applied and for beam-halo tagged events in minimum-bias or jet 15 trigger events

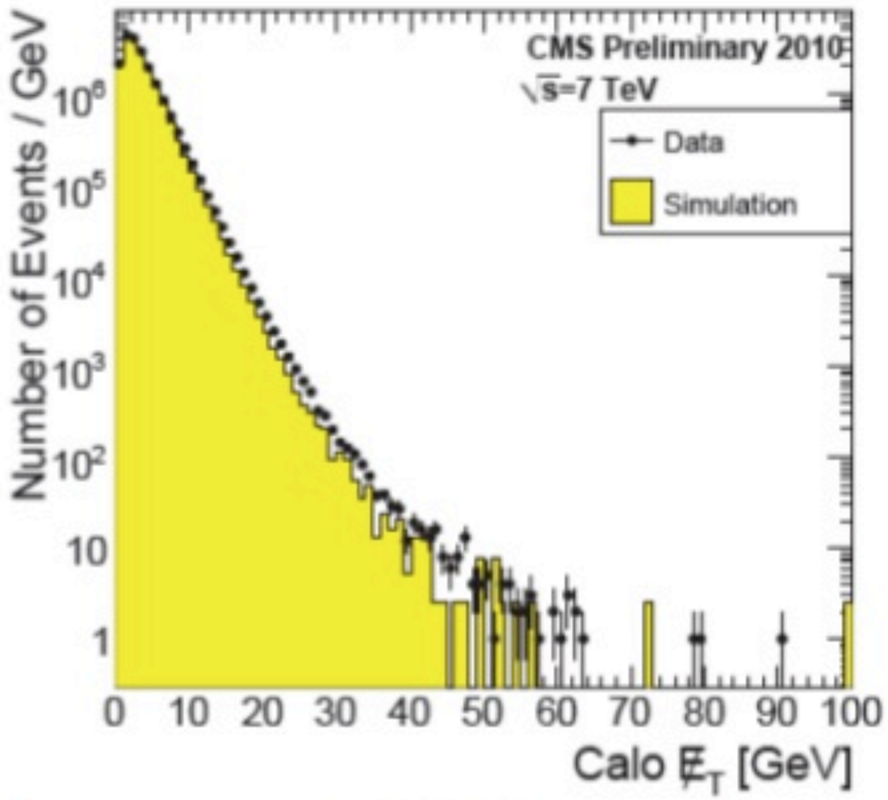
Beam-halo tagged events with highest CaloMET (224 GeV)

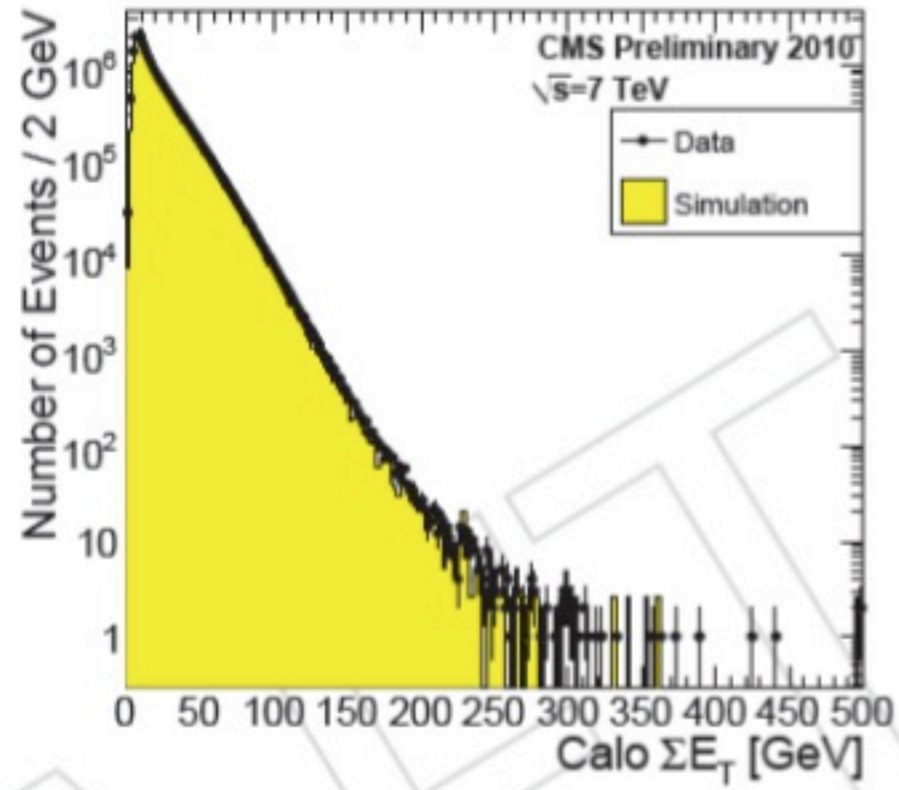
Beam halo does not significantly affect MET generally; however, it can cause high MET in an event.

Backup: MET in MinBias Events

- Calorimeter only MET and SumET distributions in minimum-bias events
- Minimum-bias events allow a study of MET tail in least-biased way
- Generator description of minbias events not as reliable as high Pt events

PAS

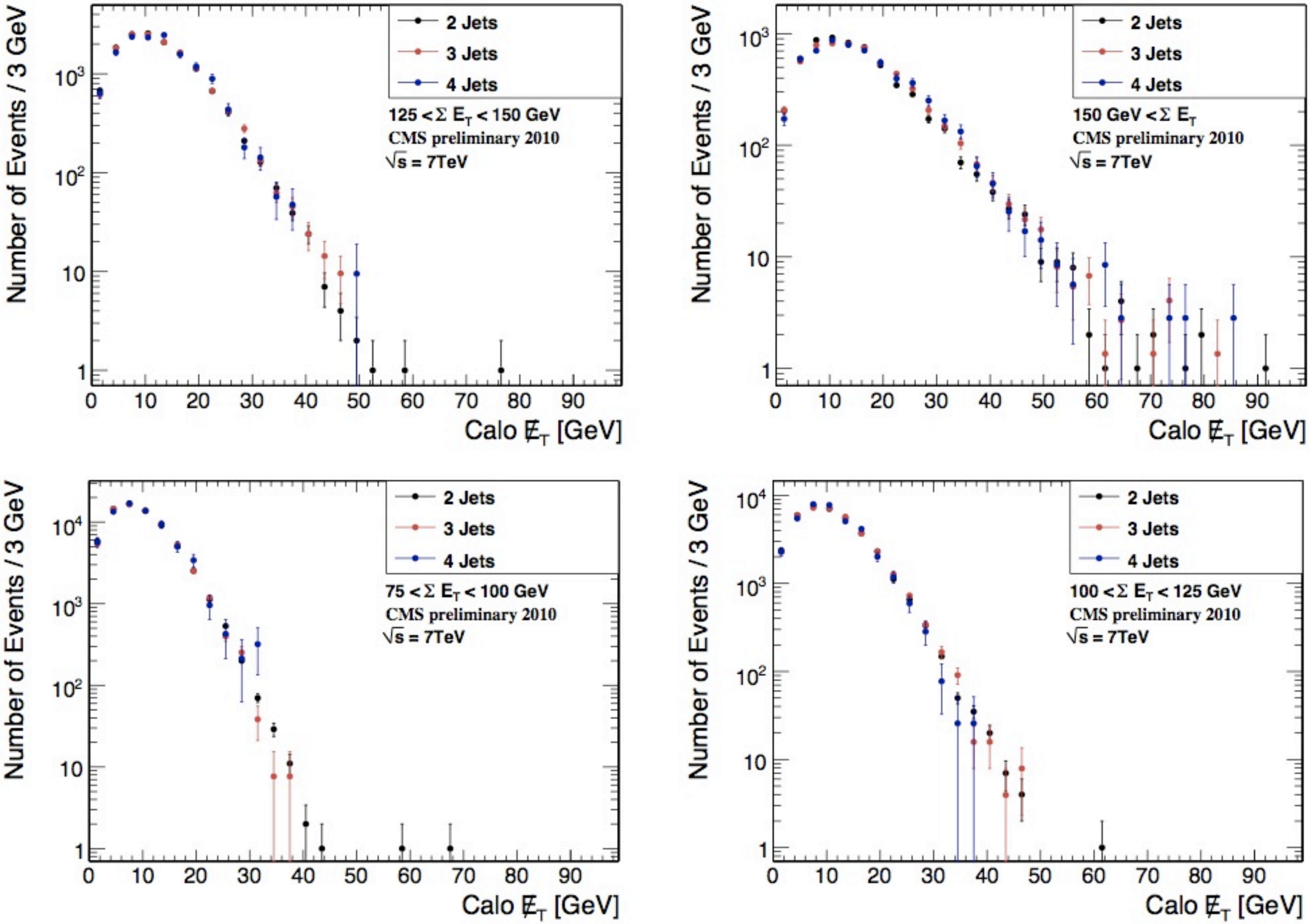




- General agreement between data and MC in both distributions
- MET tail under control after anomalous signal cleaning procedure
  - Slight excess in data attributed to residual noise in HF
- MET distribution slightly wider in data
  - Attributed mainly to imperfect modeling of the HB & HE response

Backup: MET in Multijets

Does MET depend on the jet multiplicity ?



- Uncorrected Calo MET in jet events for different SumE$_T$ ranges
- Different jet multiplicity bins (jets w/p$_T$>20 GeV, $|\eta|<3$)

=> MET distribution "primarily" controlled by SumE$_T$, and not jet multiplicities

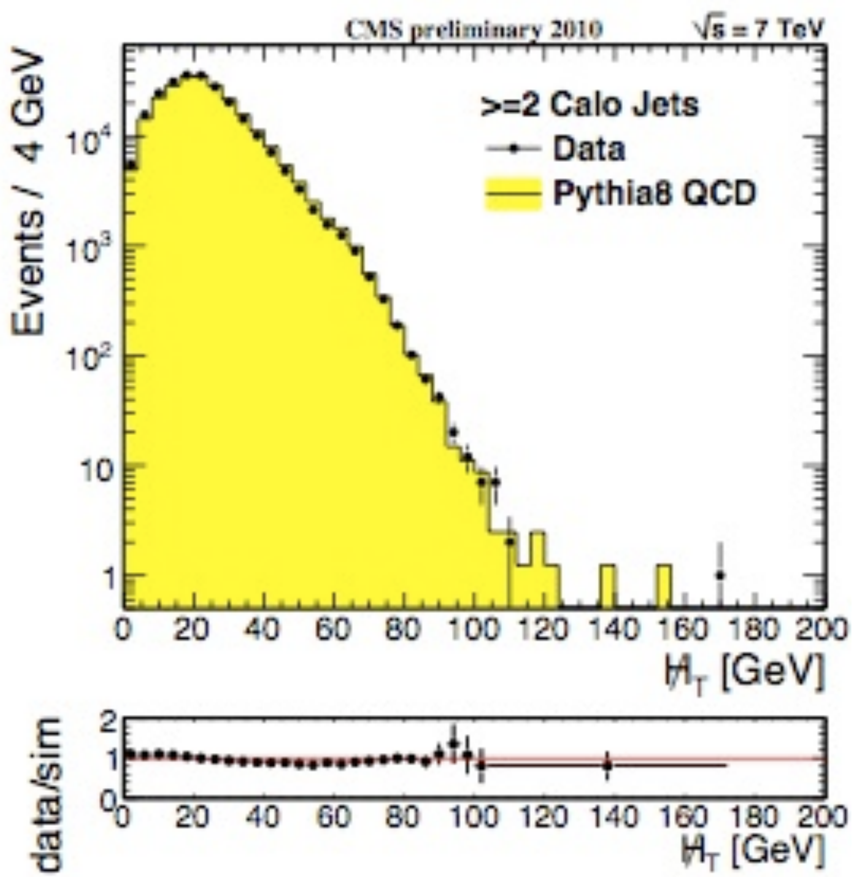
Backup: H_T and MH_T

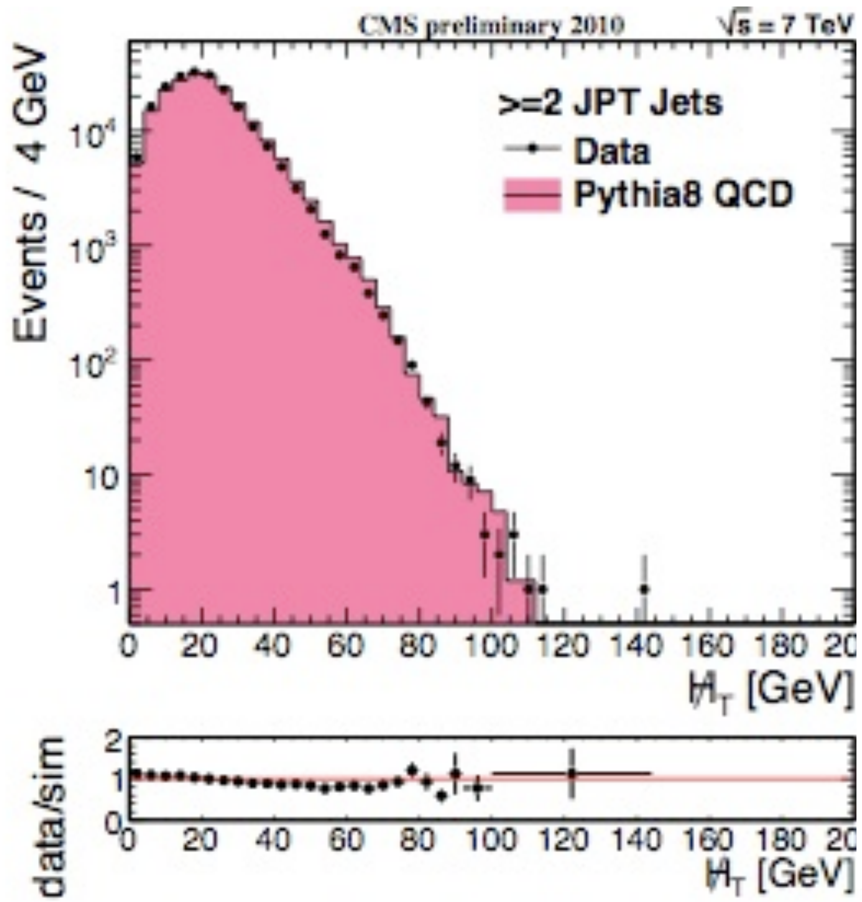
H_T & MH_T explored in various new physics searches

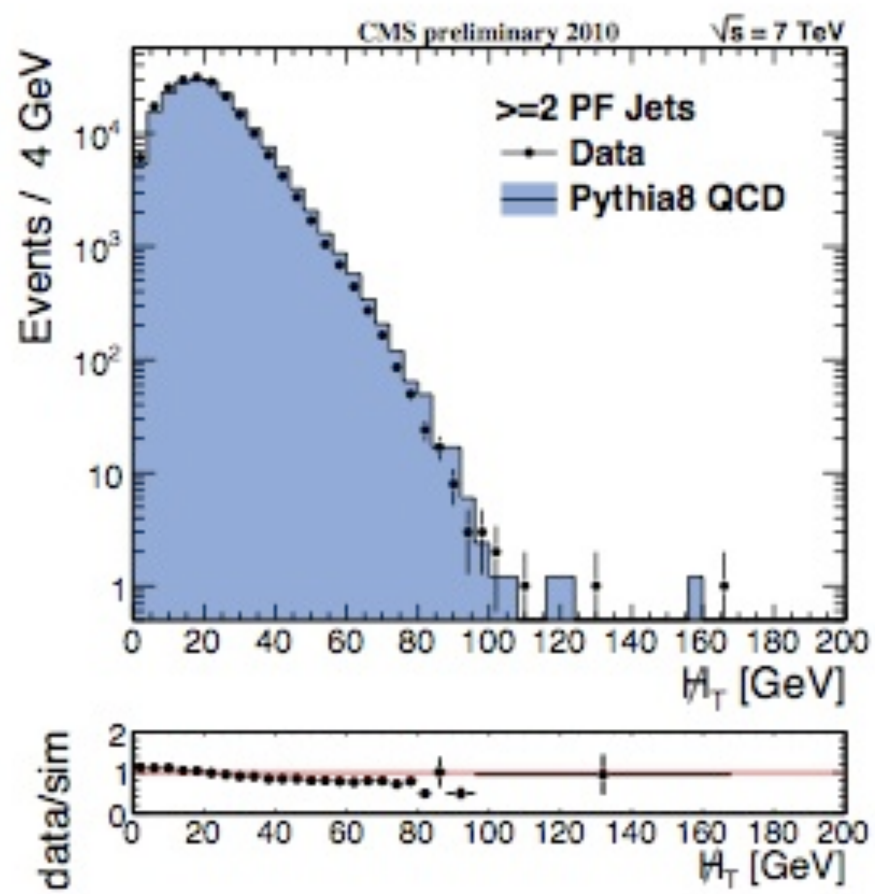
$$H_T = \sum p_{\mathrm{Tjets}} \text{ and } \not{H}_T = |\vec{\not{H}}_T| \; (\vec{\not{H}}_T = -\sum \vec{p}_{\mathrm{Tjets}}).$$

H_T and MH_T studies with Calo, JPT and PF jets
Calculation relies purely on clustered energy
-> more robust alternative, less sensitive to pile-up

(leading jet with $p_T > 40$ GeV, other ets w/p_T>20 GeV, $|\eta|$<5)







=> Good Agreement between data and MC