Performance of Jet and Missing E_T in CMS

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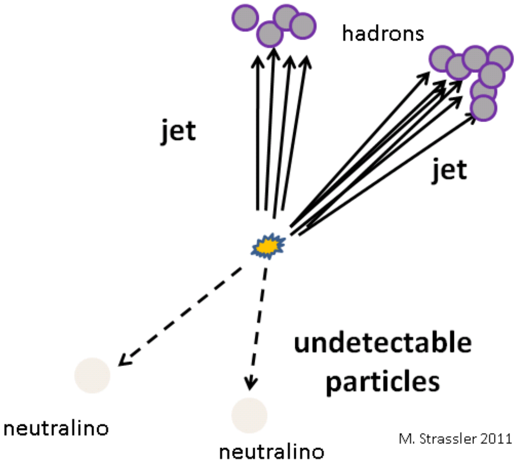
CHEF2013 22-25 April 2013, Paris (France)

Introduction

★ Jet

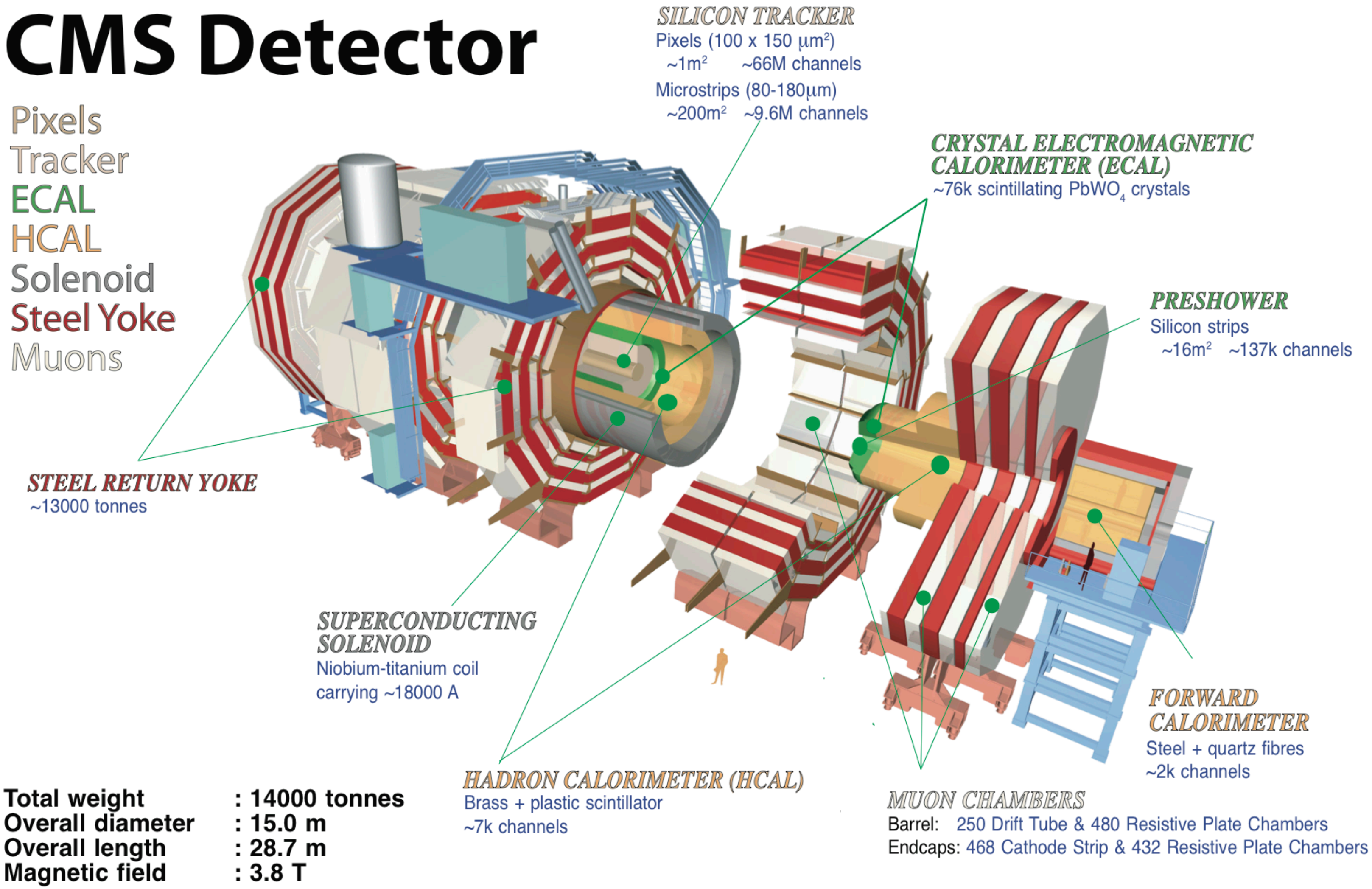
- unavoidable at hadron colliders, e.g. quarks and gluons produced in hard scattering of partons
- well-defined by clustering algorithm, e.g. Anti-k_T algorithm
- crucially important for many physics analyses



★ Missing Transverse Energy (Missing E_T, MET)

- momentum imbalance in the transverse plane of all reconstructed particles in an event
- used to estimate the momentum carried away by undetected particles, e.g. neutrinos (SM) and invisible particles (BSM)
- also plays a vital role in many physics analyses
- important to understand the behavior of MET in both data and simulations

Compact Muon Solenoid (CMS)



CMS Detector

Pixels
Tracker
ECAL
HCAL
Solenoid
Steel Yoke
Muons

SILICON TRACKER
Pixels (100 x 150 μm^2)
~1m^2 ~66M channels
Microstrips (80-180μm)
~200m^2 ~9.6M channels

CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76k scintillating $PbWO_4$ crystals

PRESHOWER
Silicon strips
~16m^2 ~137k channels

STEEL RETURN YOKE
~13000 tonnes

SUPERCONDUCTING SOLENOID
Niobium-titanium coil
carrying ~18000 A

FORWARD CALORIMETER
Steel + quartz fibres
~2k channels

HADRON CALORIMETER (HCAL)
Brass + plastic scintillator
~7k channels

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

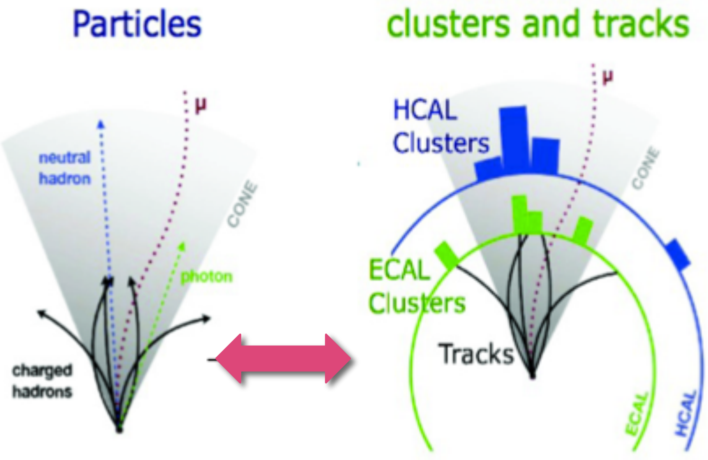
Total weight	**: 14000 tonnes**
Overall diameter	**: 15.0 m**
Overall length	**: 28.7 m**
Magnetic field	**: 3.8 T**

Jet reconstruction & energy correction

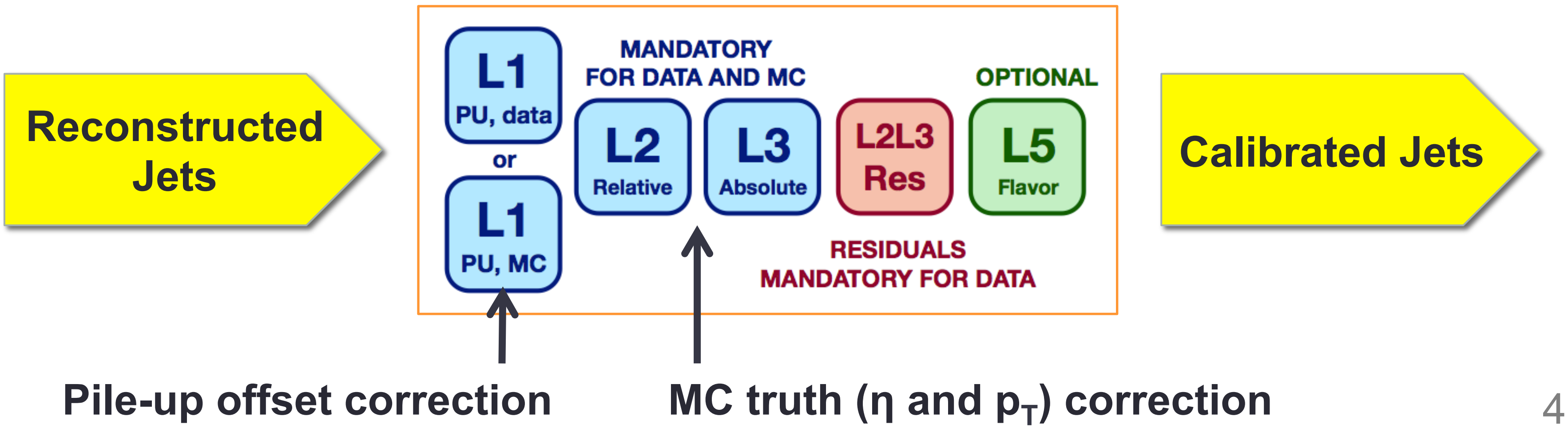
Jets are reconstructed using Anti-k_T clustering algorithm (R = 0.5, 0.7)

★ Particle-Flow (PF) jets

- include all sub-detectors' information
- jets built by clustering of PF-candidates
- widely used in current CMS analyses



★ Jet Energy Corrections in CMS



Reconstructed Jets

L1 PU, data

or

L1 PU, MC

MANDATORY FOR DATA AND MC

L2 Relative

L3 Absolute

L2L3 Res

OPTIONAL

L5 Flavor

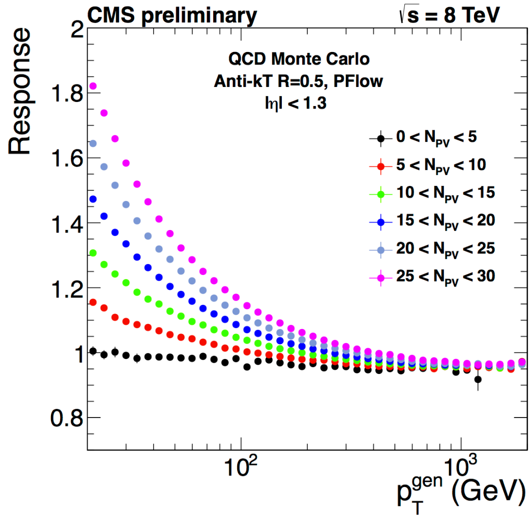
RESIDUALS MANDATORY FOR DATA

Calibrated Jets

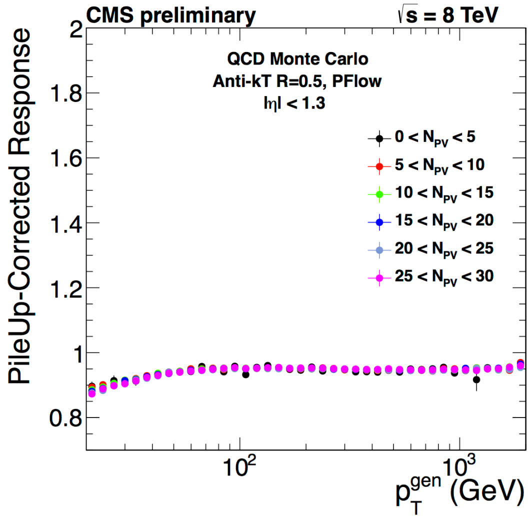
Pile-up offset correction

MC truth (η and p_T) correction

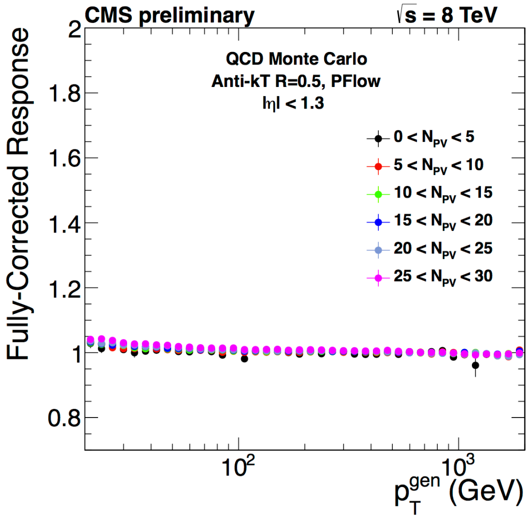
Jet energy corrections and uncertainty



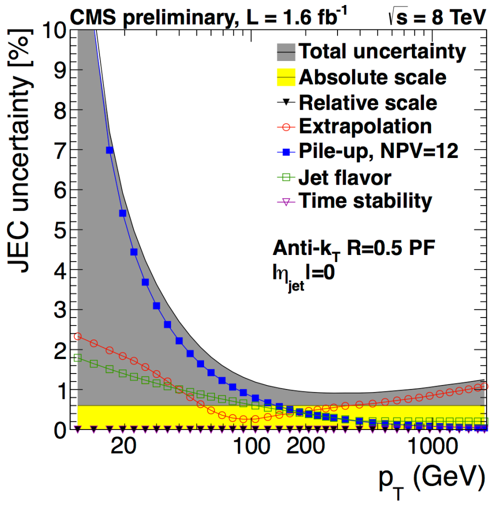
Before corrections

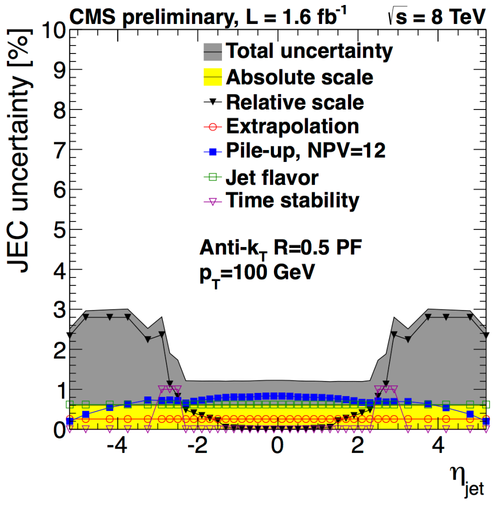


After Pile-up corrections



After PU+MC truth corrections





★ Jet energy correction uncertainty in function of jet p_T (left) and rapidity (η) at p_T = 100 GeV (right), dominated by:

- pile-up at low p_T
- extrapolation at high p_T
- relative scale at high η

MET reconstruction algorithms

Particle-Flow (PF) MET

$$\vec{\not{E}}_T = -\sum_{\text{pf-candidates}} \vec{p}_T$$

- ★ negative of the vector sum over all transverse momentum of PF-candidates
- ★ used in most current CMS analyses

New

No-PU PF MET

- ★ divide PF particles into: particles from hard scattering and particles from pile-up
- ★ contribution from "pile-up" particles is scaled down
- ★ re-calculate MET from two particles categories above

MVA PF MET

- ★ multivariate regression (BDT) that produces a correction for the hadronic recoil
- ★ 5 MET variables calculated from PF particles
- ★ Trainings have been done to optimize the MET resolution

MET corrections

★ Type 1 MET correction

- propagation of jet energy corrections into MET calculation
- applied to PF MET algorithm

★ Type 0 MET correction

- reduce effects of pile-up by subtracting charged hadrons and compensating for remaining imbalance from neutral hadrons
- applied to PF MET algorithm

★ MET Φ-asymmetry correction

- in both data and simulation, there is a shift of MET x and y components which leads to a Φ-asymmetry in MET
- applied to each MET algorithm

★ Jet energy resolution smearing (MC simulations)

- approximately 10% additional smearing on jets in MC in order to better match data
- applied to each MET algorithm

MET corrections and uncertainty

★ Recoil correction (MC simulation)

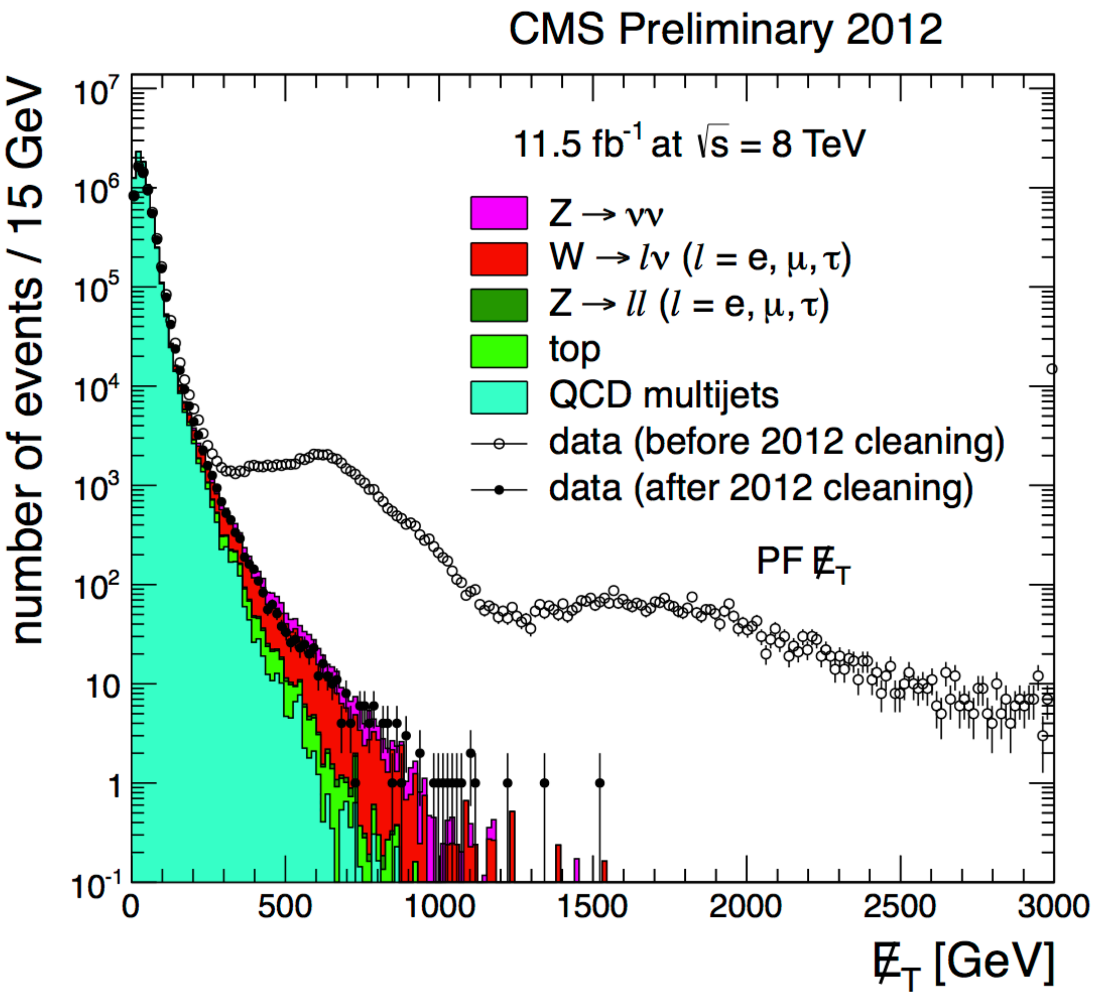
- only applied to No-PU PF MET and MVA PF MET
- compensates for differences between data/simulation in both scale and resolution

★ Systematic uncertainty sources

- The propagation of energy scale and energy resolution uncertainties of all reconstructed objects into MET computation

- ❖ Jets : energy scale 5 - 15%, energy resolution 6 - 15%
- ❖ Leptons :
  - electron energy scale : 0.6 - 1.5%
  - muon energy scale : 0.2%
- ❖ Photon : energy scale : 0.6 - 1.5%
- ❖ Unclustered energy : particles not clustered into jets, leptons or photons
  - energy scale 10%

Performance of MET filters



★ Performance of MET filters has been studied in di-jets events

★ Anomalous high MET events in data before 2012 cleaning mainly come from:

- misfires of the HCAL laser calibration system
- electronics noise in HCAL
- fake MET from track reconstruction

★ Few remaining anomalous events are removed by applying jet identification cuts

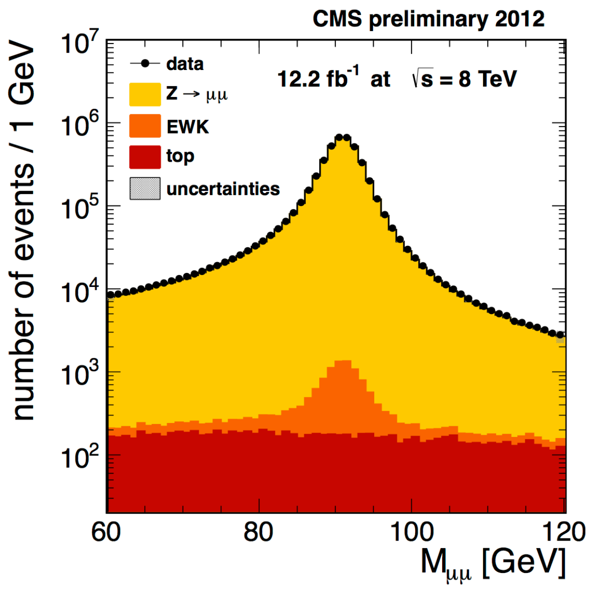
Performance of MET

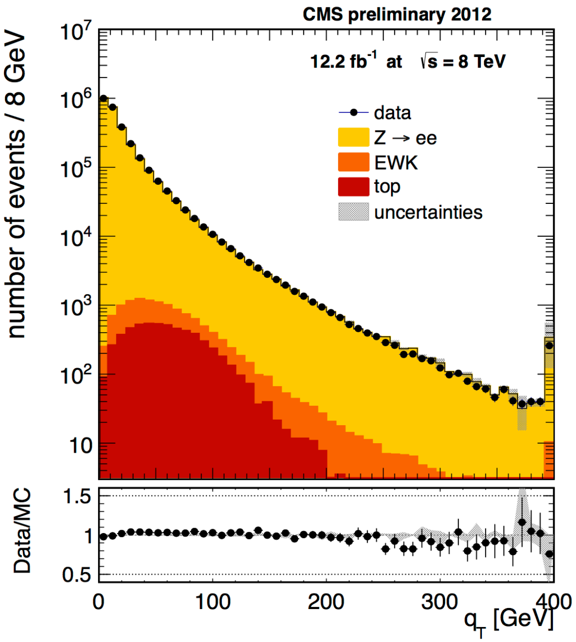
★ MET performance studies in three different channels using 2012 data

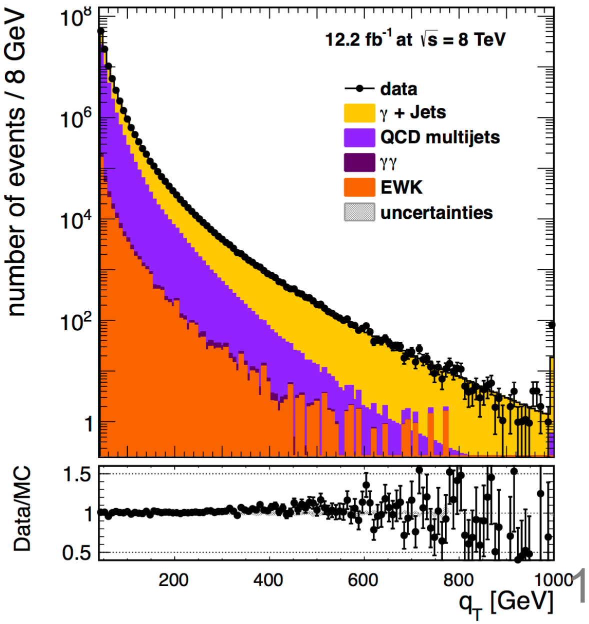
- $Z \rightarrow \mu\mu$ channel
- $Z \rightarrow ee$ channel
- γ + jets channel

★ Good agreement between data/simulation in all three channels.

★ Z/γ transverse momentum is denoted by $\mathbf{q_T}$

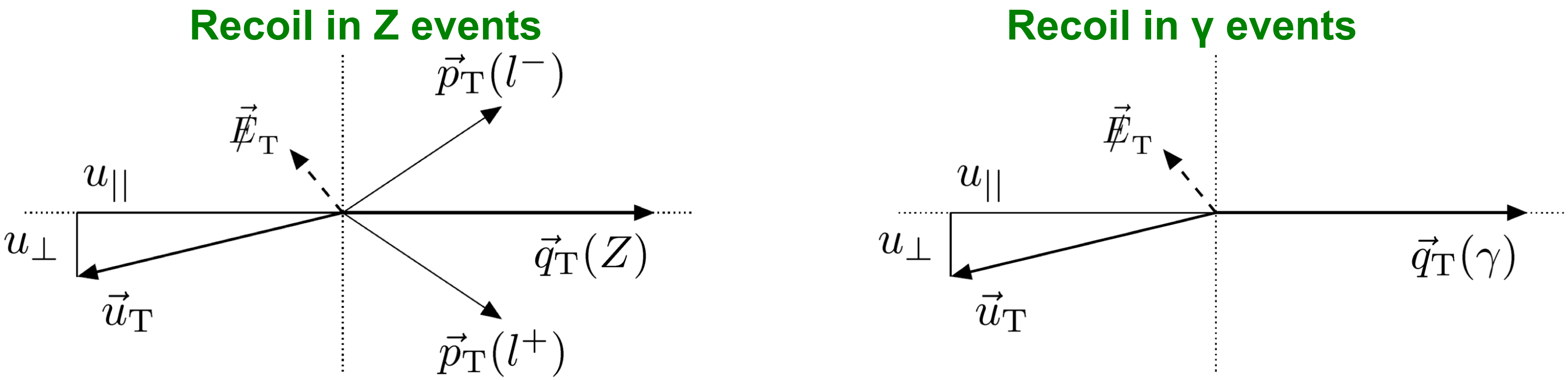






MET scale and resolution

★ Hadronic recoil vector $\mathbf{u_T}$ is defined by : $\vec{q}_{\mathrm{T}} + \vec{u}_{\mathrm{T}} + \vec{\not{E}}_{\mathrm{T}} = 0$



★ Recoil components :

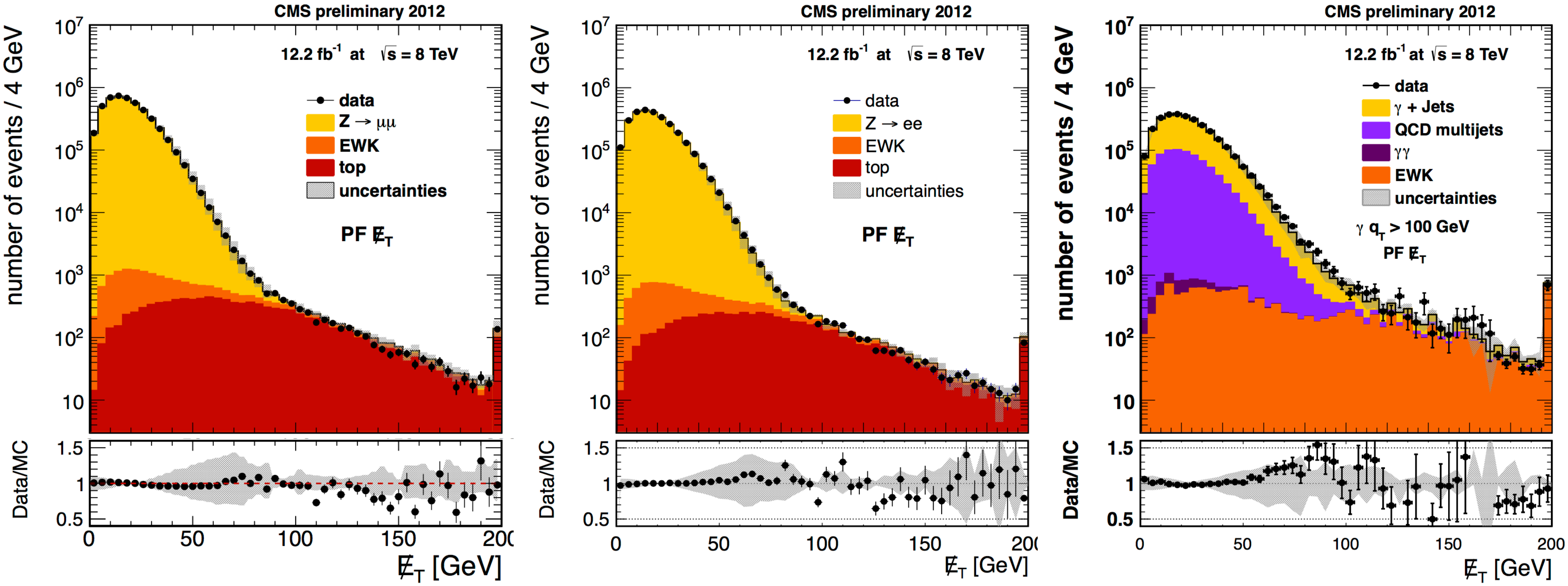
$u_{||}$ parallel to the q_T axis and $u_{\perp}$ perpendicular to the q_T axis

★ MET scale is characterized by $-\langle u_{||}\rangle/q_T$

★ MET resolution

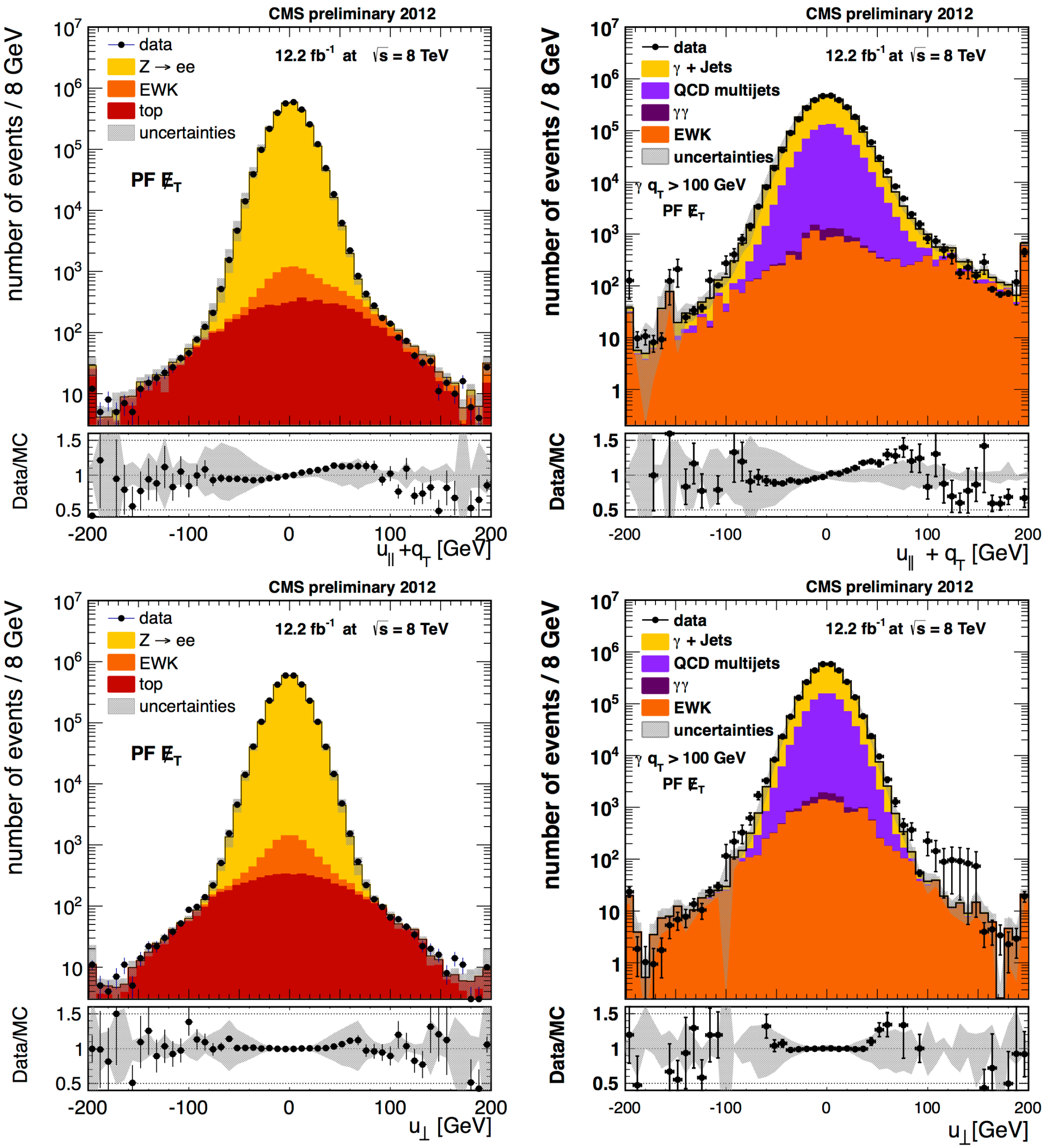
the width of $u_{||}+q_T$ or $u_{\perp}$ distributions is used to estimate the MET resolution

PF MET distributions



- ★ After all corrections applied : type0, type1, phi correction, jet smearing
  - Good agreement between data and simulation for the three channels
  - Good agreement between Z → μμ and Z → ee channels as expected

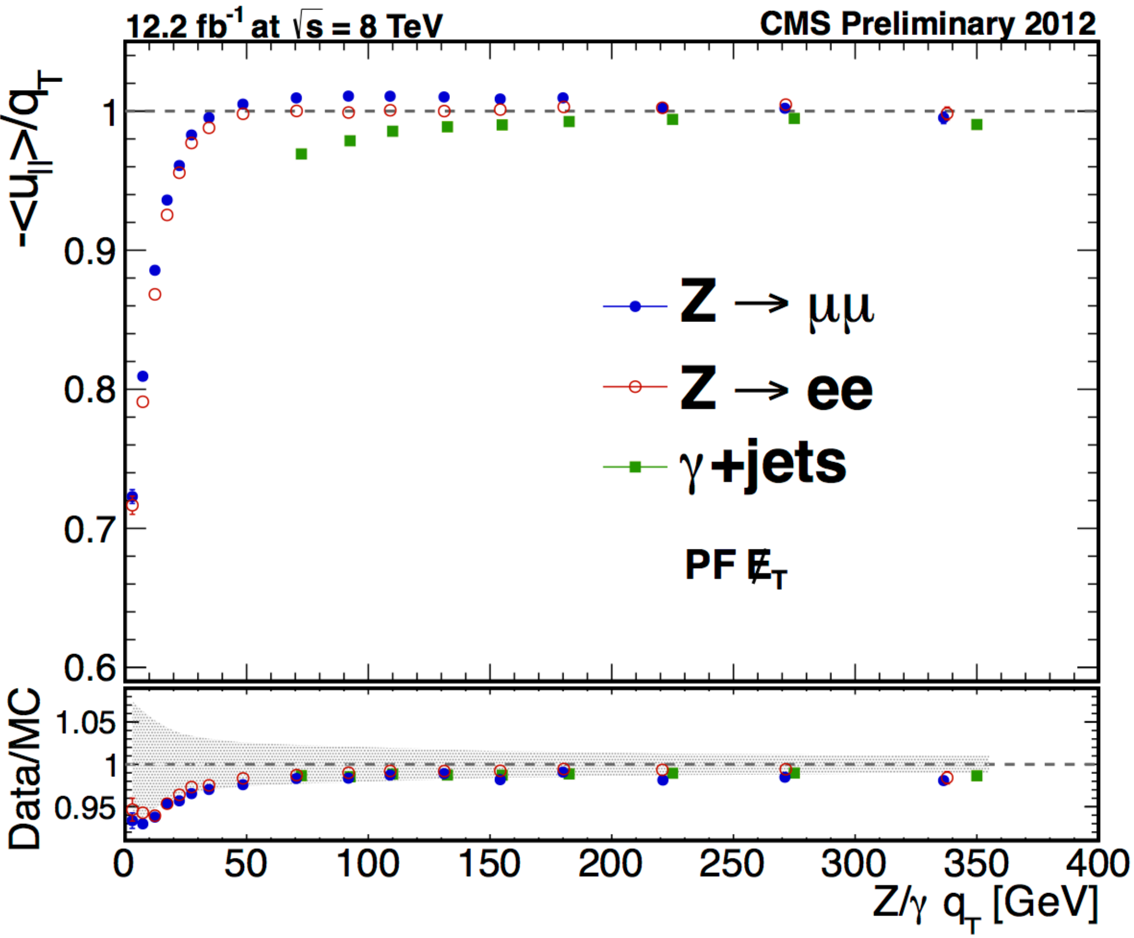
PF MET recoil components



- ★ Good data/simulation agreement for both recoil components in each channel

- ★ Disagreement in $u_{\perp}$ tail of γ + jets is due to using a LO generator (Pythia)

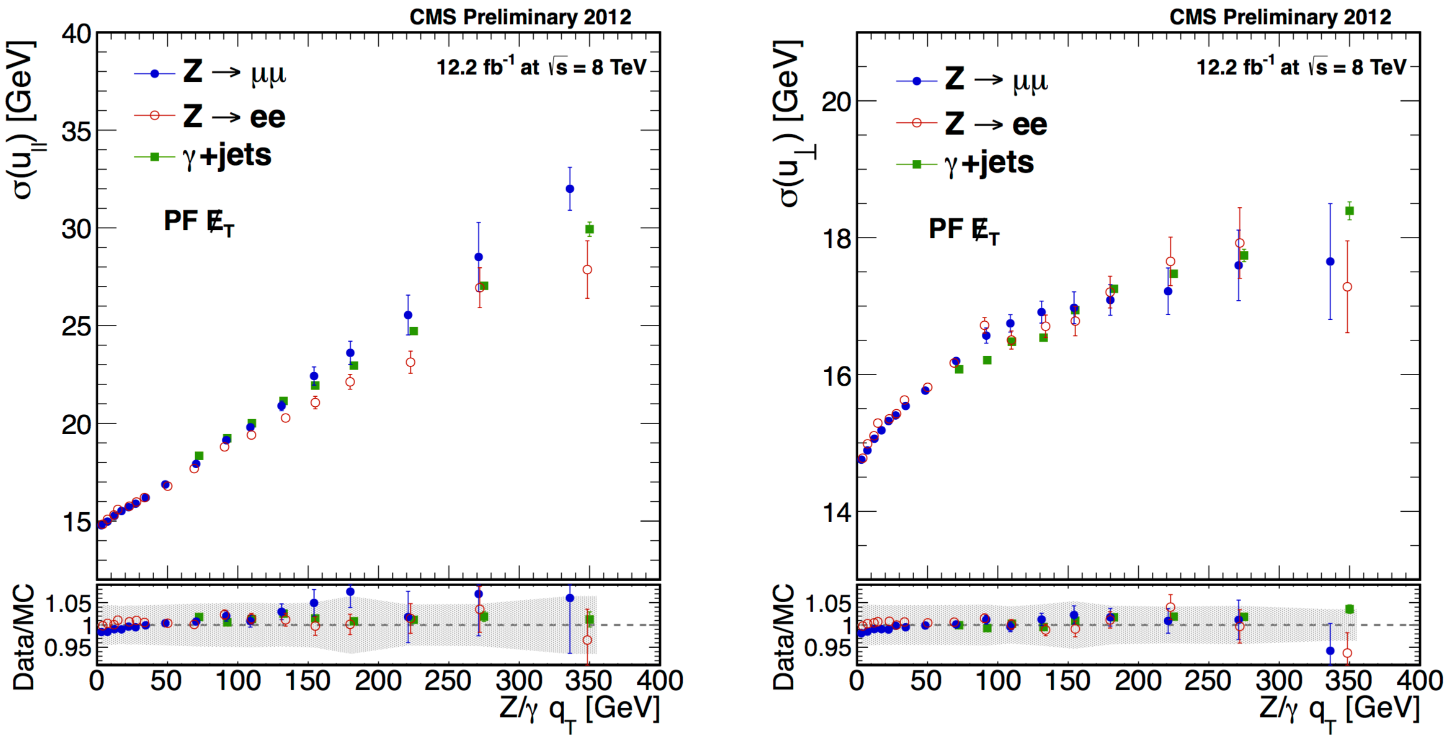
PF MET energy scale



- ★ Data/simulation agree well within systematic uncertainties
- ★ MET scale in both Z channels reaches unity for $q_T > 50$ GeV
- ★ MET scale drops for $q_T < 50$ GeV due to lack of energy scale correction on unclustered energy
- ★ MET scale in photon events is lower than Z events for $q_T <$ 100 GeV due to the difference of quark/gluon jets fraction in hadronic recoil

PF MET resolution : function of q_T

- ★ MET resolution depends on energy scale of event
- ★ PF MET resolution of $u_{||}$ increases approximately linearly due to jet energy resolution
- ★ PF MET resolution of $u_{\perp}$ is dominated by noise and pile-up

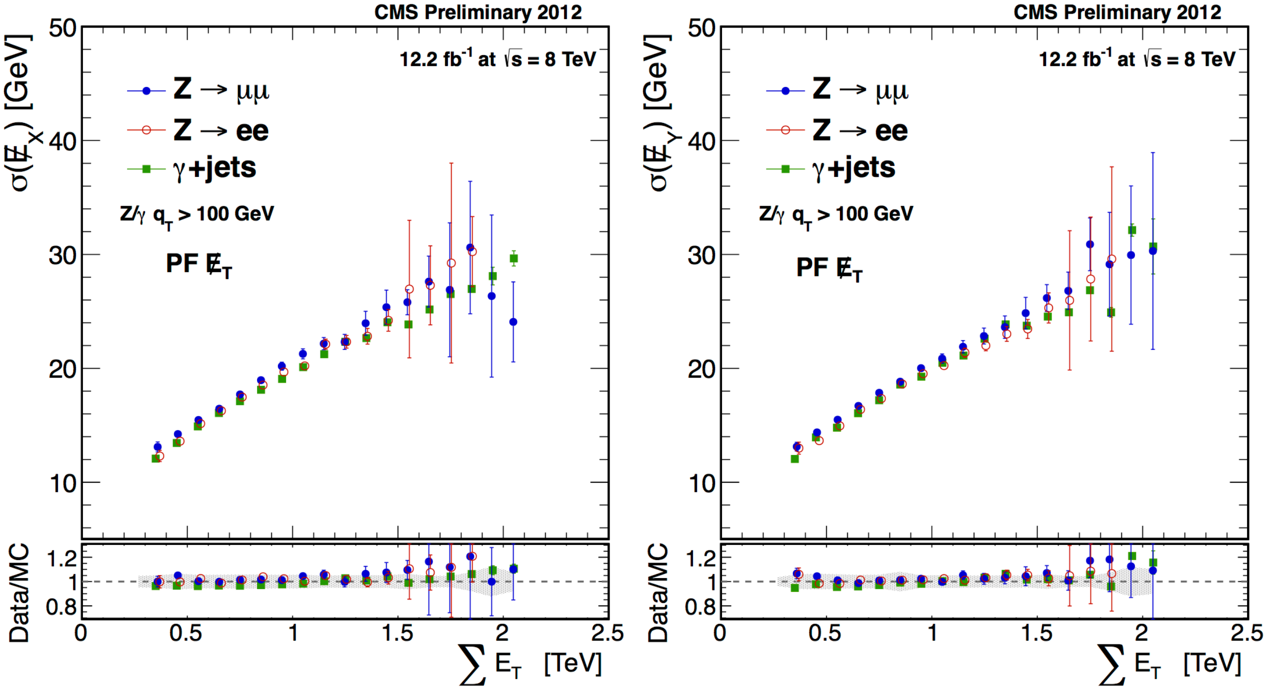


- ★ Good agreement between data/simulation and for the three channels

PF MET resolution : function of ΣE_T

- ★ MET resolution depends on total hadronic activity
- ★ ΣE_T : the scalar sum of E_T of all PF particles except dileptons from Z's or photons
- ★ Z events are reweighted to match photon q_T spectrum
- ★ The resolution curves are parametrized by :

$$\sigma(\not{E}_x, \not{E}_y) = \sigma_0 + \sigma_s \sqrt{\sum E_T}$$



- σ_0 : the intrinsic detector noise resolution
- σ_s : the MET resolution stochastic term; ~ 0.6 across all three channels

- ★ Good agreement between data/simulation and for the three channels

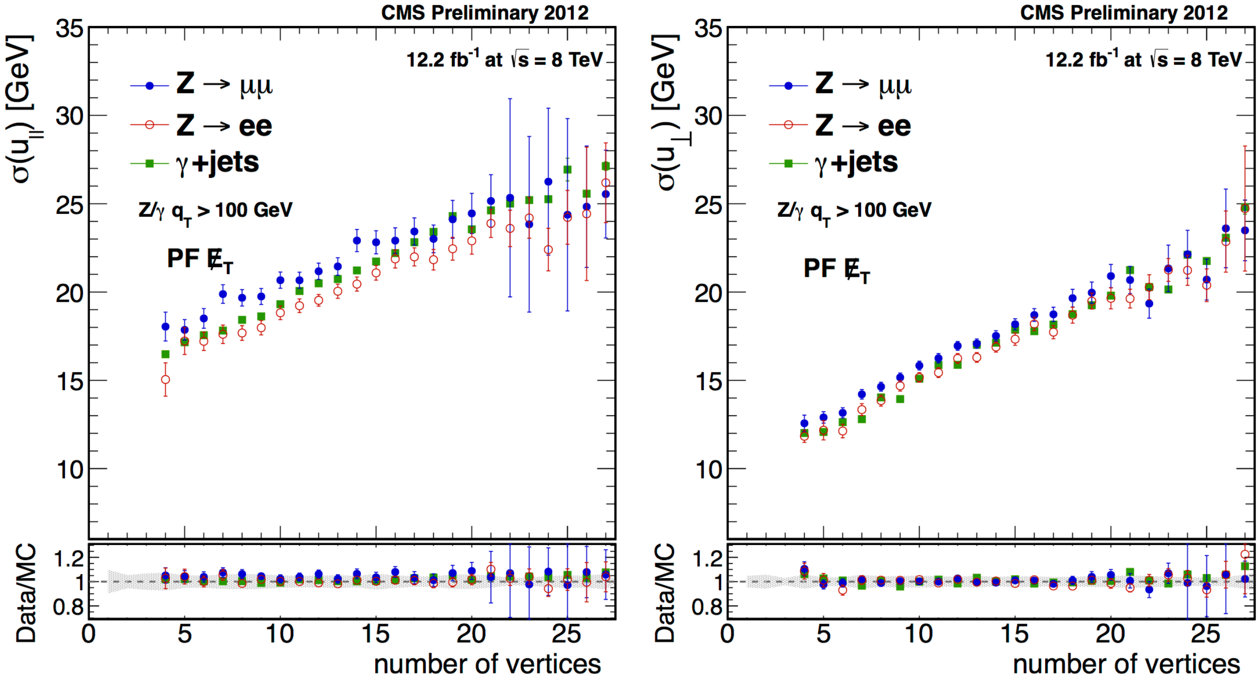
PF MET resolution : function of N_{vtx}

★ MET resolution depends on pile-up

★ Z events are reweighted to match photon q_T spectrum

★ The resolution curves are parametrized by :

$$f(N_{vtx}) = \sqrt{\sigma_c^2 + \frac{N_{vtx}}{0.7} \times \sigma_{PU}^2}$$

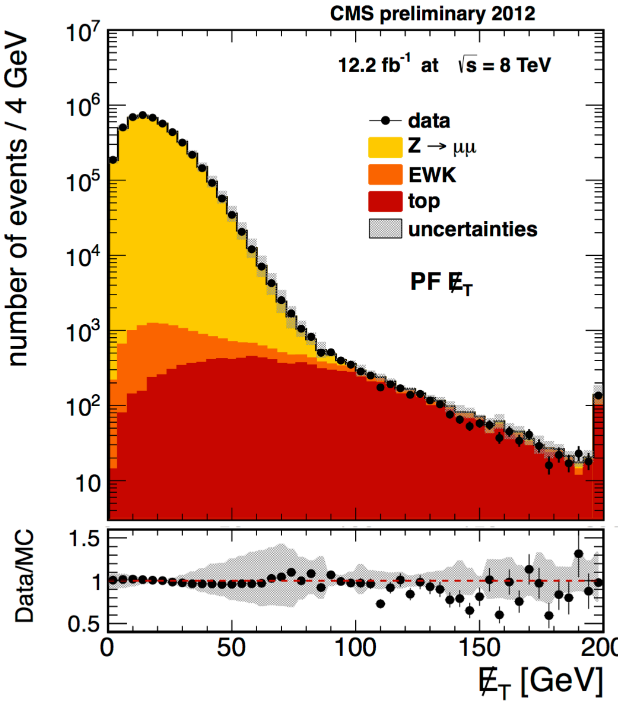


- σ_c : resolution coming from detector noise and the hard-scatter
- σ_{PU} : the resolution term induced on average by one additional pile-up collision
- factor 0.7 : accounts for the fact that only 70% of pp interactions produce a reconstructed vertex

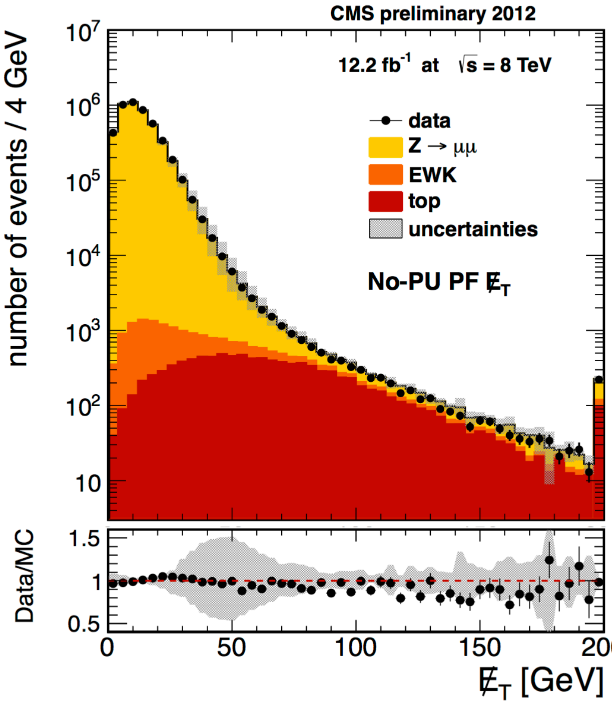
★ MET resolution is degraded by ~3.5 GeV in quadrature for each additional pile-up interaction

MET distributions : three algorithms

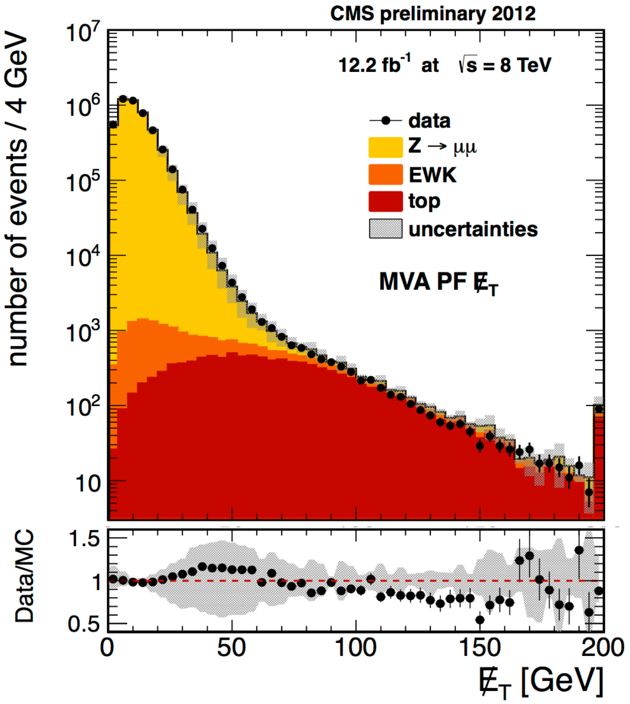
PF MET



No-PU PF MET



MVA PF MET

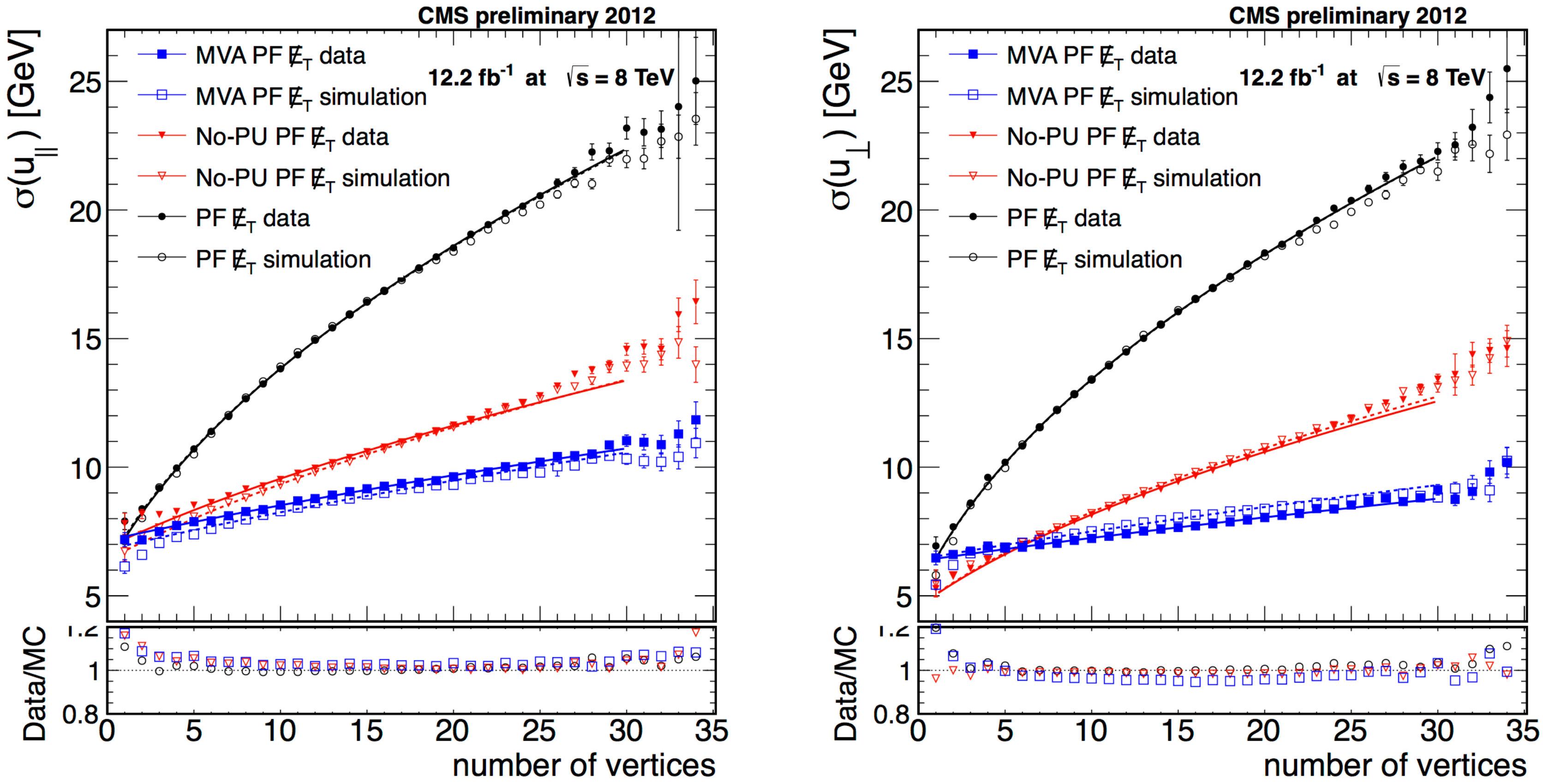


- ★ Good data/simulation agreement in all three algorithms
- ★ No-PU PF MET and MVA PF MET have lower MET tail w.r.t PF MET

MET resolutions : three algorithms

★ Two new pile-up mitigating algorithms show improve MET resolution versus pile-up w.r.t PF MET

★ σ_{PU} is reduced by a factor of 2 to 3



Summary

★ Jets and MET are important objects in many physics analyses for both SM and BSM

★ Jets are well understood and calibrated in CMS

★ MET filters have been developed to efficiently remove fake MET events

★ MET performance has been studied and presented in three different channels; a strong agreement is observed between data/simulation and across channels

★ Two new pile-up mitigating MET algorithms, No-PU PF MET and MVA PF MET, have been introduced; the improvement of MET resolution has been shown

References

★ Jet

CMS PAS-JME-10-011

- http://arxiv.org/pdf/1107.4277v1.pdf

Public Twiki :

- https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsJME2012JEC

★ MET

CMS PAS-JME-12-002

- “Performance of Missing Transverse Momentum Reconstruction Algorithms in Proton-Proton Collisions at $\sqrt{s} = 8$ TeV with the CMS Detector”

BACKUP

Performance of MET study

Performance studies have been performed in three different channels.

$Z \rightarrow \mu\mu$

- Trigger line : p_T threshold of 17 and 8 GeV
- Kinematic cuts : $p_T > 20$ GeV, $|eta| < 2.1$
- di-muon mass window: 60 to 120 GeV

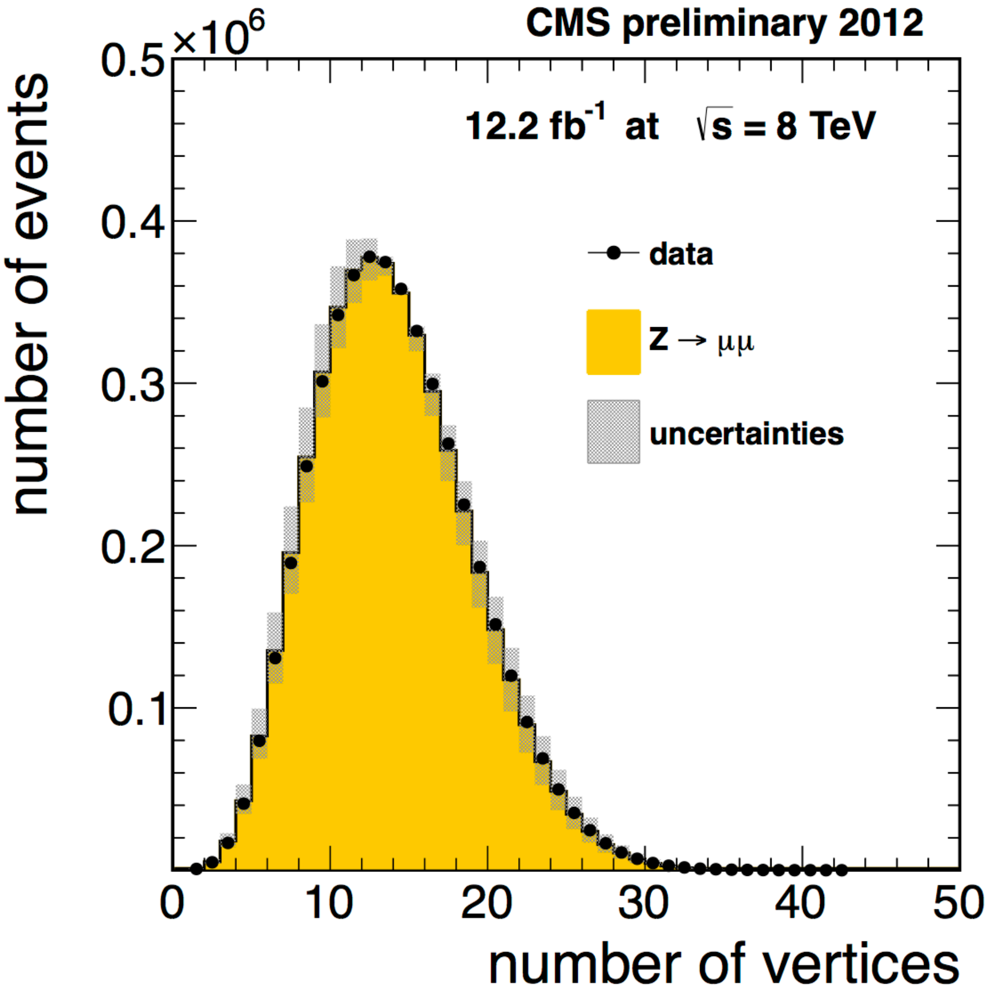
$Z \rightarrow ee$

- Trigger line: p_T threshold of 17 and 8 GeV
- Kinematic cut:
  $p_T > 20$ GeV, $|eta| < 1.444$ or $1.57 < |eta| < 2.5$
- di-electron mass window: 60 to 120 GeV

γ + jets

- Trigger line: for $p_T < 135$ GeV and $p_T > 135$ GeV
- Kinematic cut: $p_T > 40$ GeV, $|eta| < 1.444$

Pile-up reweighting



★ In order to match the number of pile-up interaction in simulations to the data.

★ Systematic uncertainty sources are from :

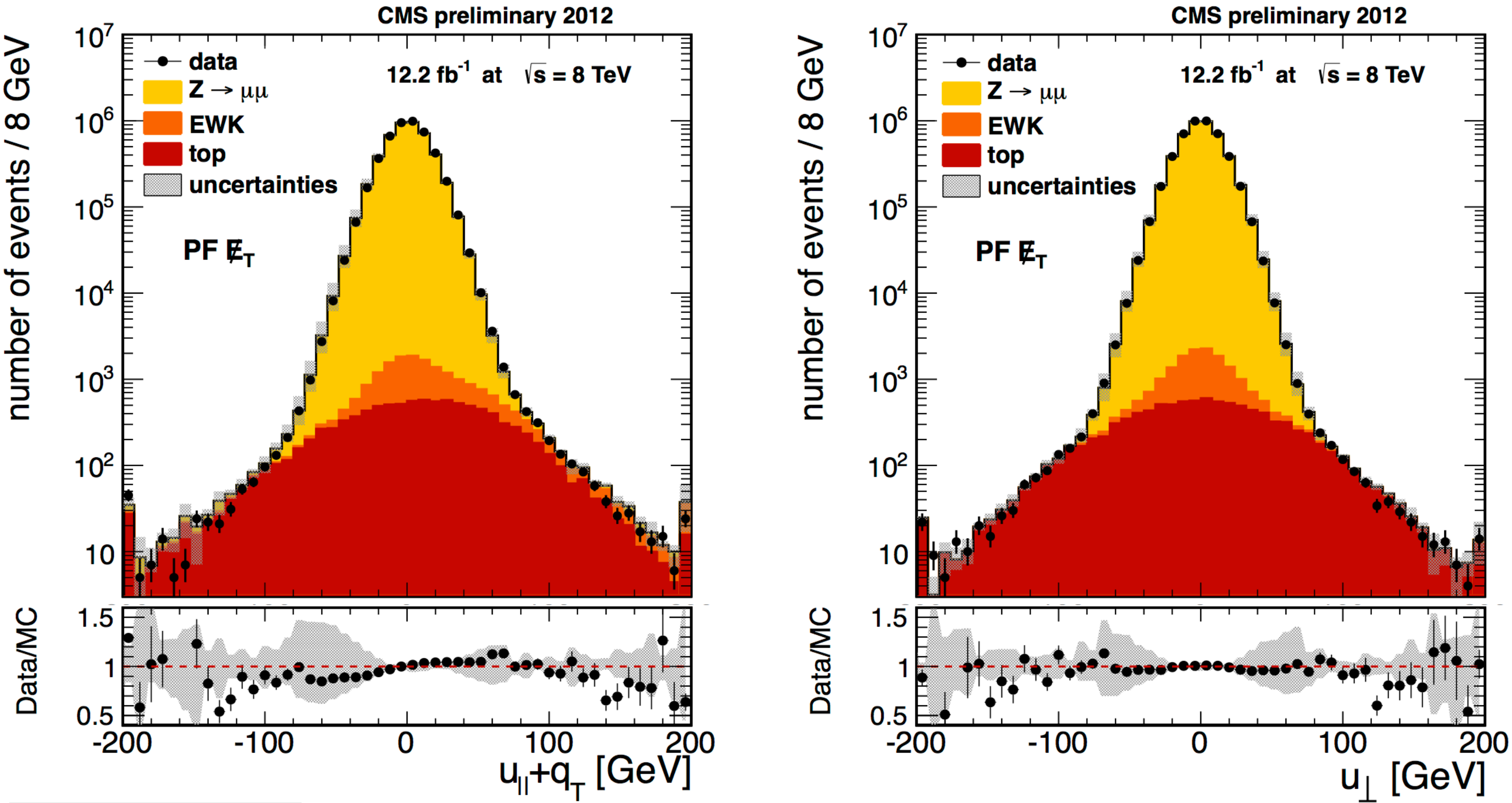
- Inelastic scattering cross-section (4.5%)
- Luminosity (2%)

References for the uncertainties :

CMS PAS-FWD-11-001

CMS PAS-LUM-12-001

PF MET recoil components



$Z \rightarrow \mu\mu$

MET resolution with Voigtian fit

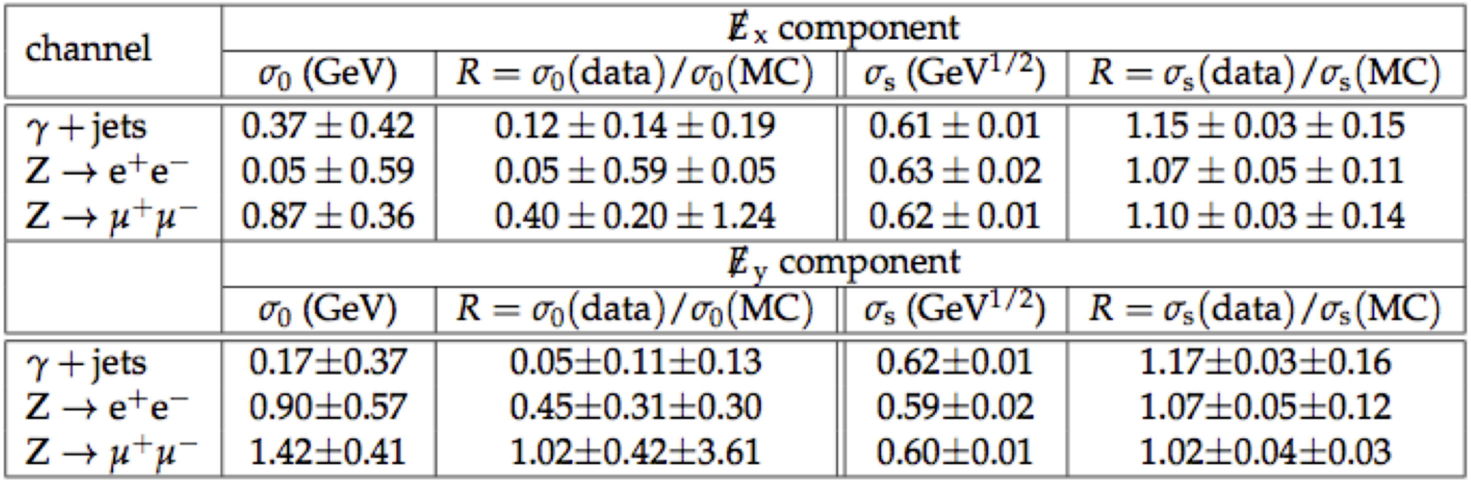
★ MET resolution is estimated by fitting a Voigtian function to the $u_{||}+q_T$ or $u_{\perp}$ distributions

★ Voigtian function : $V(x;\sigma,\gamma)=\int G(y,\sigma)BW(x-y,\gamma)dy$

★ MET resolution is given by the width of the Voigtian function : $\sigma=\dfrac{FWHM(V)}{2\sqrt{\ln 2}}$

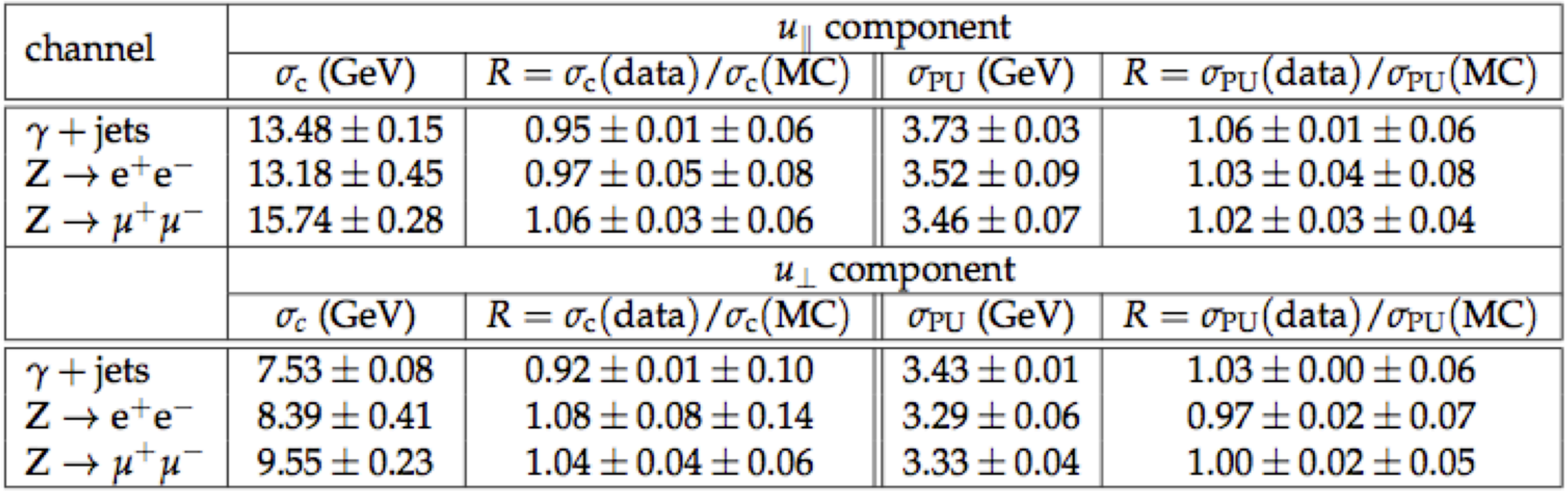
Parametrization results of MET resolution

★ PF MET resolution vs. ΣE_T



channel	$\not{E}_x$ component			
	σ_0 (GeV)	$R = \sigma_0(\text{data})/\sigma_0(\text{MC})$	σ_s (GeV$^{1/2}$)	$R = \sigma_s(\text{data})/\sigma_s(\text{MC})$
$\gamma + \text{jets}$	0.37 ± 0.42	$0.12 \pm 0.14 \pm 0.19$	0.61 ± 0.01	$1.15 \pm 0.03 \pm 0.15$
$Z \rightarrow e^+e^-$	0.05 ± 0.59	$0.05 \pm 0.59 \pm 0.05$	0.63 ± 0.02	$1.07 \pm 0.05 \pm 0.11$
$Z \rightarrow \mu^+\mu^-$	0.87 ± 0.36	$0.40 \pm 0.20 \pm 1.24$	0.62 ± 0.01	$1.10 \pm 0.03 \pm 0.14$
	$\not{E}_y$ component			
	σ_0 (GeV)	$R = \sigma_0(\text{data})/\sigma_0(\text{MC})$	σ_s (GeV$^{1/2}$)	$R = \sigma_s(\text{data})/\sigma_s(\text{MC})$
$\gamma + \text{jets}$	0.17 ± 0.37	$0.05 \pm 0.11 \pm 0.13$	0.62 ± 0.01	$1.17 \pm 0.03 \pm 0.16$
$Z \rightarrow e^+e^-$	0.90 ± 0.57	$0.45 \pm 0.31 \pm 0.30$	0.59 ± 0.02	$1.07 \pm 0.05 \pm 0.12$
$Z \rightarrow \mu^+\mu^-$	1.42 ± 0.41	$1.02 \pm 0.42 \pm 3.61$	0.60 ± 0.01	$1.02 \pm 0.04 \pm 0.03$

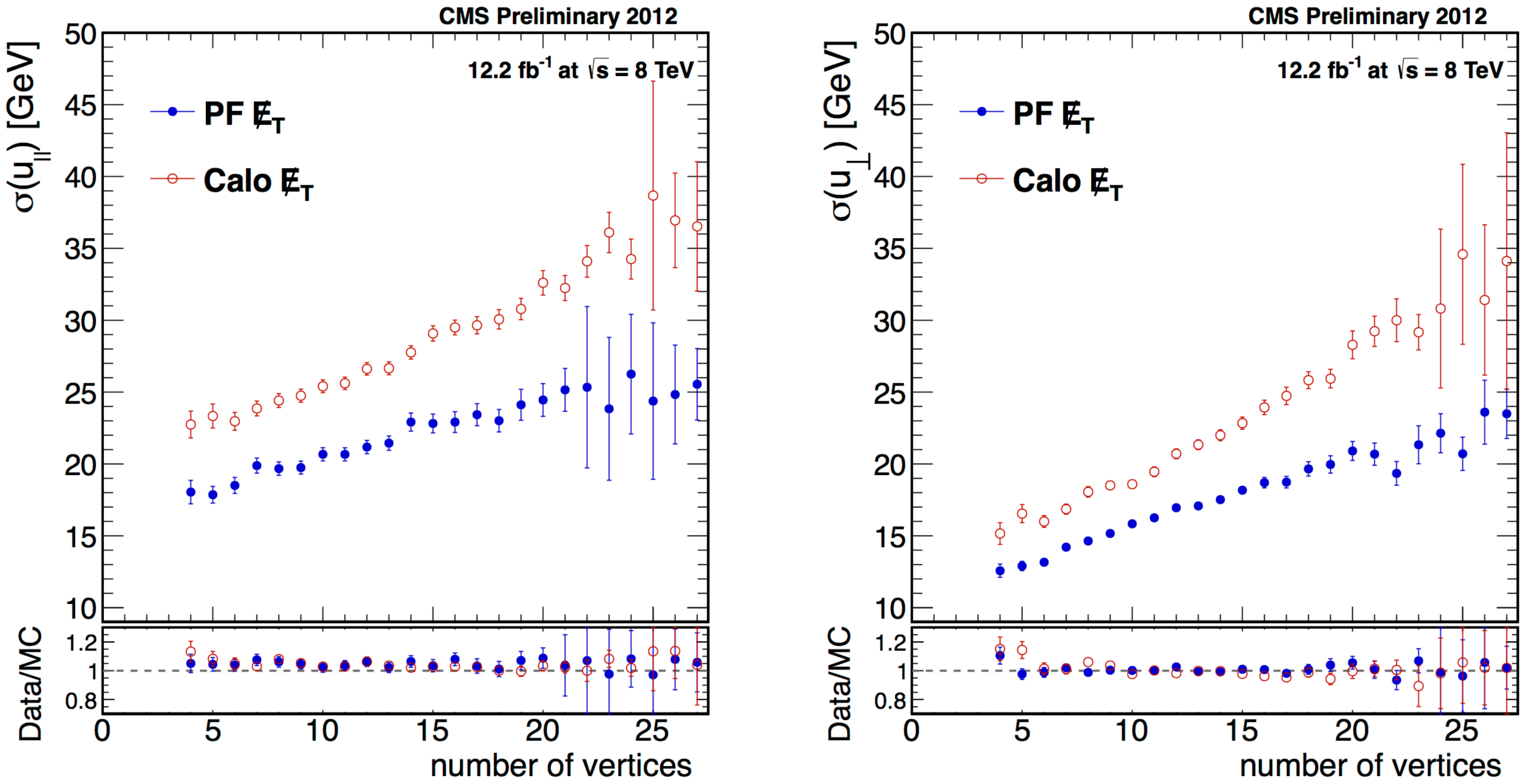
★ PF MET resolution vs. N_{vtx}



channel	$u_{\parallel}$ component			
	σ_c (GeV)	$R = \sigma_c(\text{data})/\sigma_c(\text{MC})$	σ_{PU} (GeV)	$R = \sigma_{PU}(\text{data})/\sigma_{PU}(\text{MC})$
$\gamma + \text{jets}$	13.48 ± 0.15	$0.95 \pm 0.01 \pm 0.06$	3.73 ± 0.03	$1.06 \pm 0.01 \pm 0.06$
$Z \rightarrow e^+e^-$	13.18 ± 0.45	$0.97 \pm 0.05 \pm 0.08$	3.52 ± 0.09	$1.03 \pm 0.04 \pm 0.08$
$Z \rightarrow \mu^+\mu^-$	15.74 ± 0.28	$1.06 \pm 0.03 \pm 0.06$	3.46 ± 0.07	$1.02 \pm 0.03 \pm 0.04$
	$u_{\perp}$ component			
	σ_c (GeV)	$R = \sigma_c(\text{data})/\sigma_c(\text{MC})$	σ_{PU} (GeV)	$R = \sigma_{PU}(\text{data})/\sigma_{PU}(\text{MC})$
$\gamma + \text{jets}$	7.53 ± 0.08	$0.92 \pm 0.01 \pm 0.10$	3.43 ± 0.01	$1.03 \pm 0.00 \pm 0.06$
$Z \rightarrow e^+e^-$	8.39 ± 0.41	$1.08 \pm 0.08 \pm 0.14$	3.29 ± 0.06	$0.97 \pm 0.02 \pm 0.07$
$Z \rightarrow \mu^+\mu^-$	9.55 ± 0.23	$1.04 \pm 0.04 \pm 0.06$	3.33 ± 0.04	$1.00 \pm 0.02 \pm 0.05$

PF MET vs. Calo MET resolution

- ★ Calo MET is computed from the energy deposits in HCAL and ECAL (calorimeter towers)
- ★ The resolution of PF MET improves with respect to Calo MET



The No-PU PF MET algorithm

★ **Principle:** divide PF particles into two categories

- **PF particles from hard scatter interaction (HS particles):** leptons/photons, PF particles within jets of $p_T > 30$ GeV and pass the MVA PU-jet ID, charged hadrons not clustered within jets of $p_T > 30$ GeV and associated to the HS vertex
- **PF particles from pile-up (PU particles):** charged hadrons that are neither within jets of $p_T > 30$ GeV nor associated to the HS vertex, neutral PF particles within jets of $p_T > 30$ GeV, PF particles within jets of $p_T > 30$ GeV and fail the MVA PU-jet ID

★ PF particles from pile-up are scaled down by a factor :

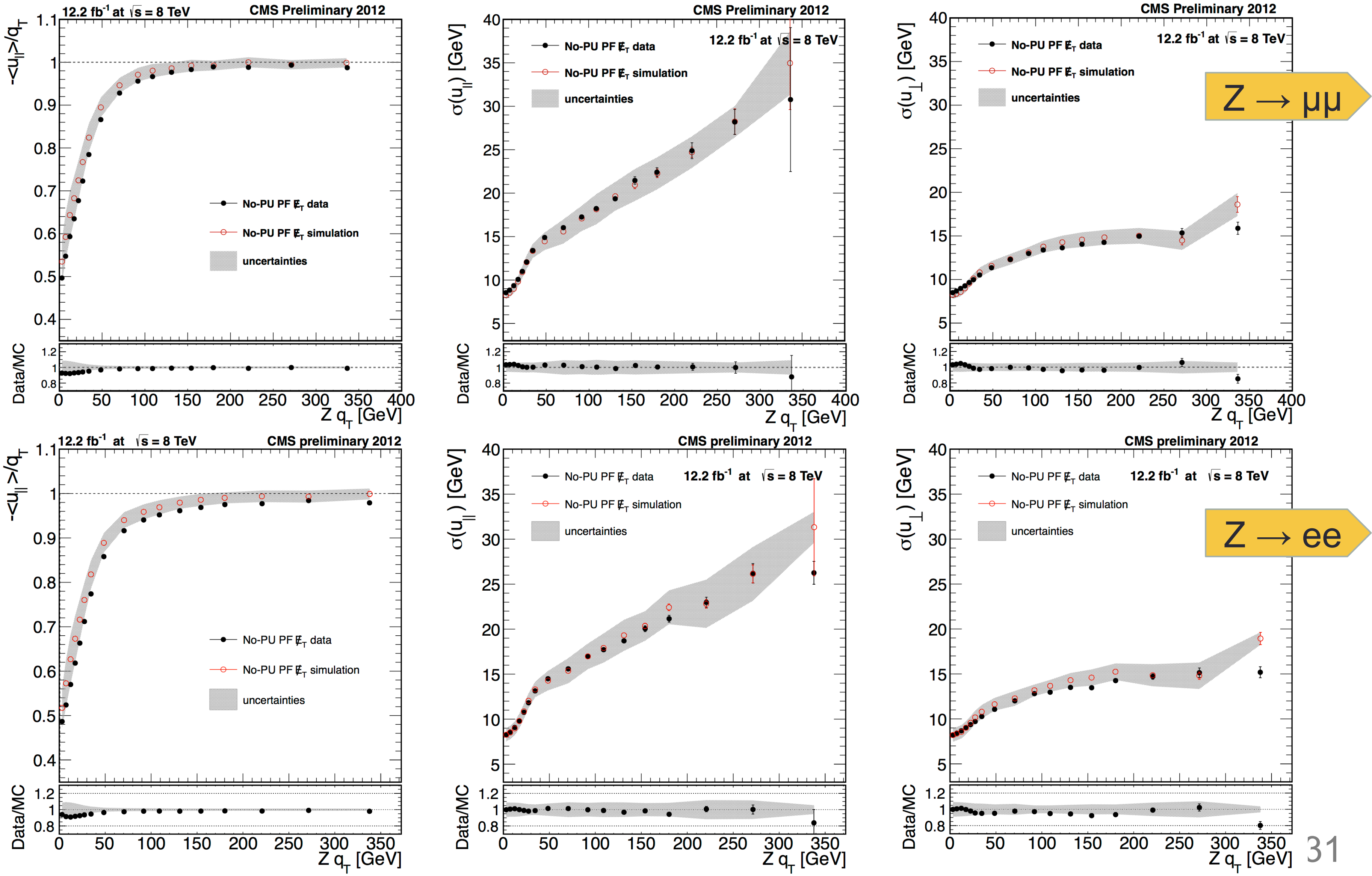
$$S_F = \frac{\sum_{\text{HS-charged}} p_T}{\sum_{\text{HS-charged}} p_T + \sum_{\text{PU-charged}} p_T}.$$

★ No-PU PF MET is computed from :

$$\begin{aligned} \vec{\not{E}}_T \;=\; -\Bigg[& \sum_{\text{leptons}} \vec{p}_T + \sum_{\text{HS-jets}} \vec{p}_T + \sum_{\text{HS-charged}} \vec{p}_T \\ & + S_F \cdot \left(\alpha \cdot \sum_{\text{PU-charged}} \vec{p}_T + \beta \cdot \sum_{\text{neutrals}} \vec{p}_T + \gamma \cdot \sum_{\text{PU-jets}} \vec{p}_T + \delta \cdot \vec{\Delta}_{\text{PU}} \right) \Bigg]. \end{aligned}$$

$\alpha,\beta,\gamma,\delta$ optimized on $Z \to \mu\mu$ to get the best MET resolution

No-PU PF MET scale and resolution



Z → μμ

Z → ee

The MVA PF MET algorithm

★ **Principle:** multivariate regression (BDT) which produces a correction of the hadronic recoil ($\mathbf{u}_T$). The corrected $\mathbf{u}_T$ is then added to $\mathbf{q}_T$ to obtain the negative MVA PF MET

★ Two steps of the BDT regression:

- a correction to the azimuthal angle of $\mathbf{u}_T$
- a correction of the magnitude of $\mathbf{u}_T$

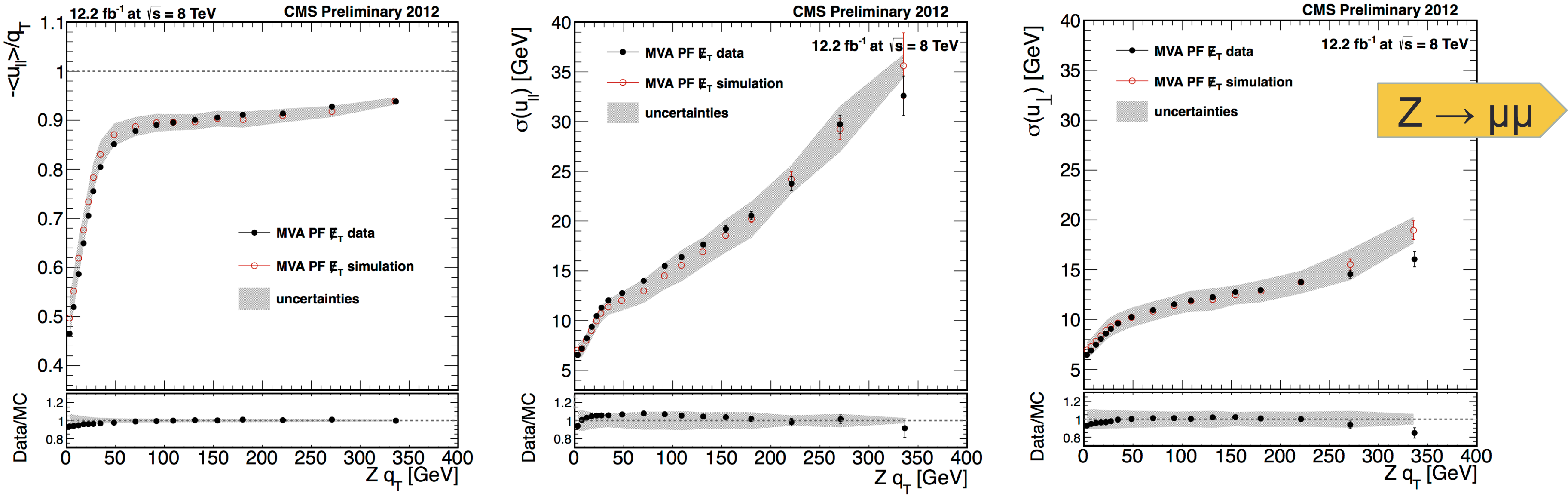
★ Input variables to the BDT regression:

- recoil magnitude and azimuthal angle associated to the following METs :

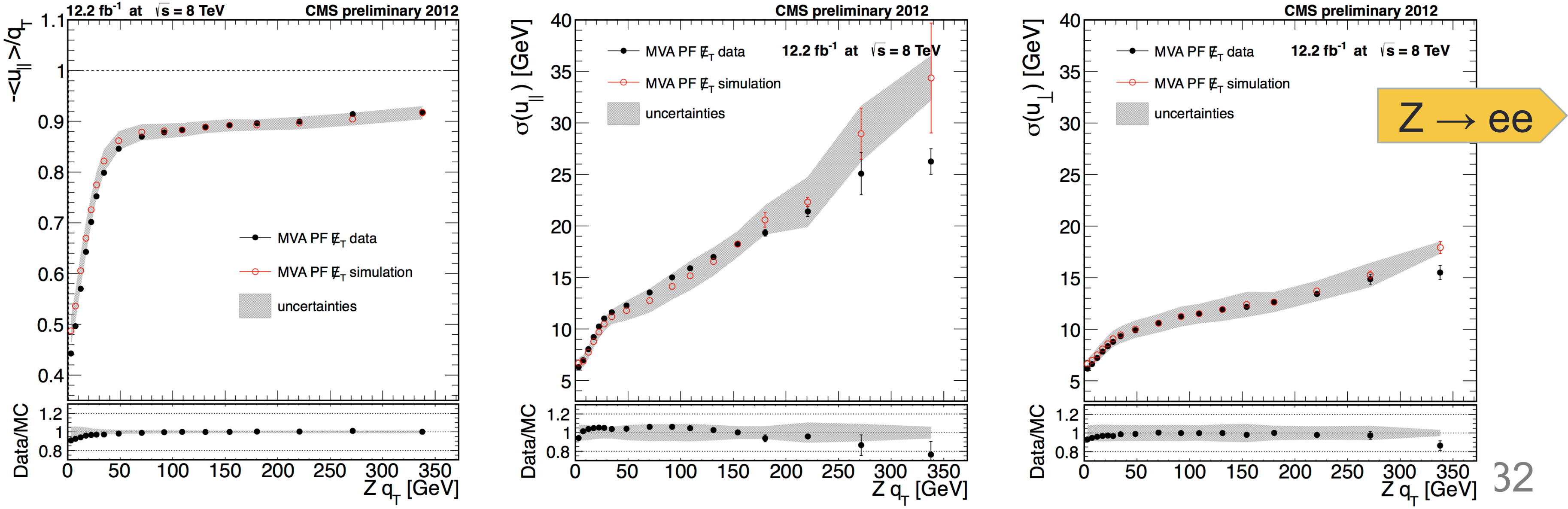
1) MET based on all PF particles (PF MET)
2) MET based on charged PF particles associated to the HS vertex
3) MET based on charged PF particles associated to the HS vertex + neutrals PF particles within jets and pass the MVA PU-jet ID
4) MET based on charged PF particles not associated to the HS vertex + neutrals PF particles within jets but fail the MVA PU-jet ID
5) MET based on charged PF particles associated to the HS vertex + all neutrals PF particles subtract neutrals PF particles within jets but fail the MVA PU-jet ID

- vector $\mathbf{p}_T$ of two leading jets
- number of primary vertices

MVA PF MET scale and resolution



Z → μμ



Z → ee