MET Performance at sqrt(s) = 8 TeV at CMS

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on behalf of the CMS Collaboration

JetMET Workshop at Vienna – August 25th, 2014

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A) Introduction

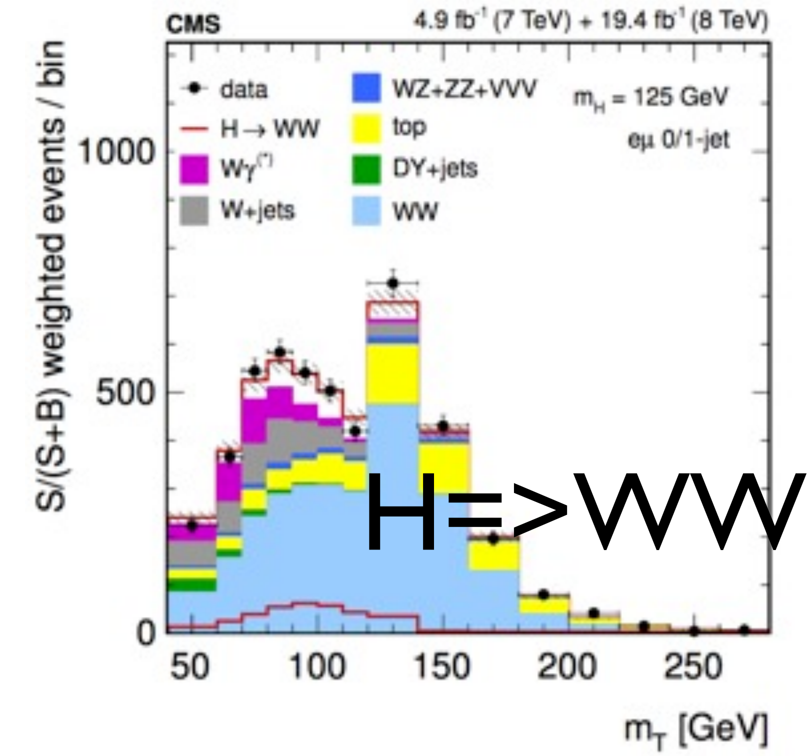
Missing Transverse Energy (MET) is used to estimate the missing energy and momentum carried away by undetected particles

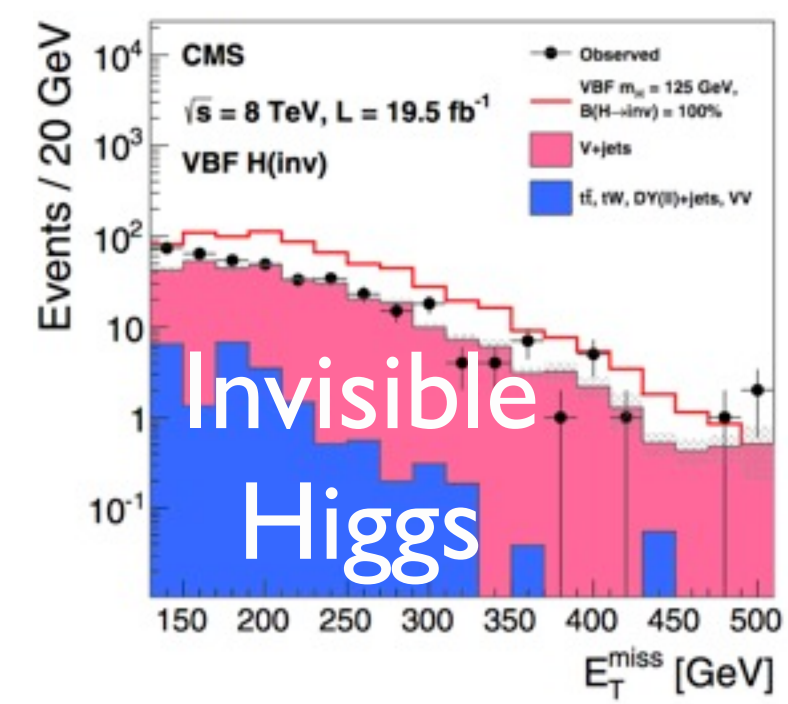
– neutrinos

– invisible particles predicted by BSM models

Even in events with no intrinsic MET, imperfect detector resolutions introduce spurious MET

Both SM and BSM analyses require an accurate characterization of MET





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A) Introduction

The CMS Collaboration has performed a comprehensive study of the reconstruction and performance of MET at the CMS detector for our full 2012 8 TeV pp dataset.

A publication focused on the following points will be released soon

1. The commissioning of MET filters to remove spurious MET events coming from detector noise
2. The evaluation of MET performance at CMS via Vector Boson + Hadronic Recoil events
3. The commissioning of two pileup mitigating MET algorithms
4. The commissioning of MET significance, a algorithm/variable that tests the compatibility of the observed MET with a nominal 0 MET value

B) MET Reco./Corrections

Basic mode of MET reconstruction at CMS:

1) Calculate basic MET variable

Calo MET

$$\vec{\not{E}}_T = -\sum_{\text{calo-towers}} \vec{E}_T$$

PF MET

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

PU Reducing MET

More details later

2) Correct the "raw" MET to account for detector nonlinearities, mismodeling of object scales/resolutions, etc.

2a) Propagate the jet energy corrections (JEC) into the MET computation (**Type 1** – **PF** and **Calo**)

$$\vec{\not{E}}_{\mathrm{T}}^{\mathrm{corr}} = \vec{\not{E}}_{\mathrm{T}} - \vec{\Delta}_{\mathrm{jets}} = \vec{\not{E}}_{\mathrm{T}} - \sum_{\mathrm{jets}} (\vec{p}_{\mathrm{T,jet}}^{\mathrm{corr}} - \vec{p}_{\mathrm{T,jet}})$$

2b) Reduce the biases induced by neutral hadrons coming from pileup interactions (**Type 0** – Just **PF**)

$$\vec{\not{E}}_{\mathrm{T}}^{\mathrm{corr}} = \vec{\not{E}}_{\mathrm{T}} - \vec{\Delta}_{\mathrm{PU}} = \vec{\not{E}}_{\mathrm{T}} - \sum_{\mathrm{PU}} f(v)\hat{v}$$

2c) Correct for an observed MET Phi asymmetry (All **MET** types)

$$\not{E}_{\mathrm{x}}^{\mathrm{corr}} = \not{E}_{\mathrm{x}} - \langle \not{E}_{\mathrm{x}} \rangle = \not{E}_{\mathrm{x}} - (c_{x_0} + c_{x_s} \cdot N_{\mathrm{vtx}}),$$
$$\not{E}_{\mathrm{y}}^{\mathrm{corr}} = \not{E}_{\mathrm{y}} - \langle \not{E}_{\mathrm{y}} \rangle = \not{E}_{\mathrm{y}} - (c_{y_0} + c_{y_s} \cdot N_{\mathrm{vtx}}).$$

2d) Compensate for observed jet energy resolution (JER) differences in data and simulation by smearing the individual JERs in simulation (approx. 10% smearing – **PF** and **PU Reducing**)

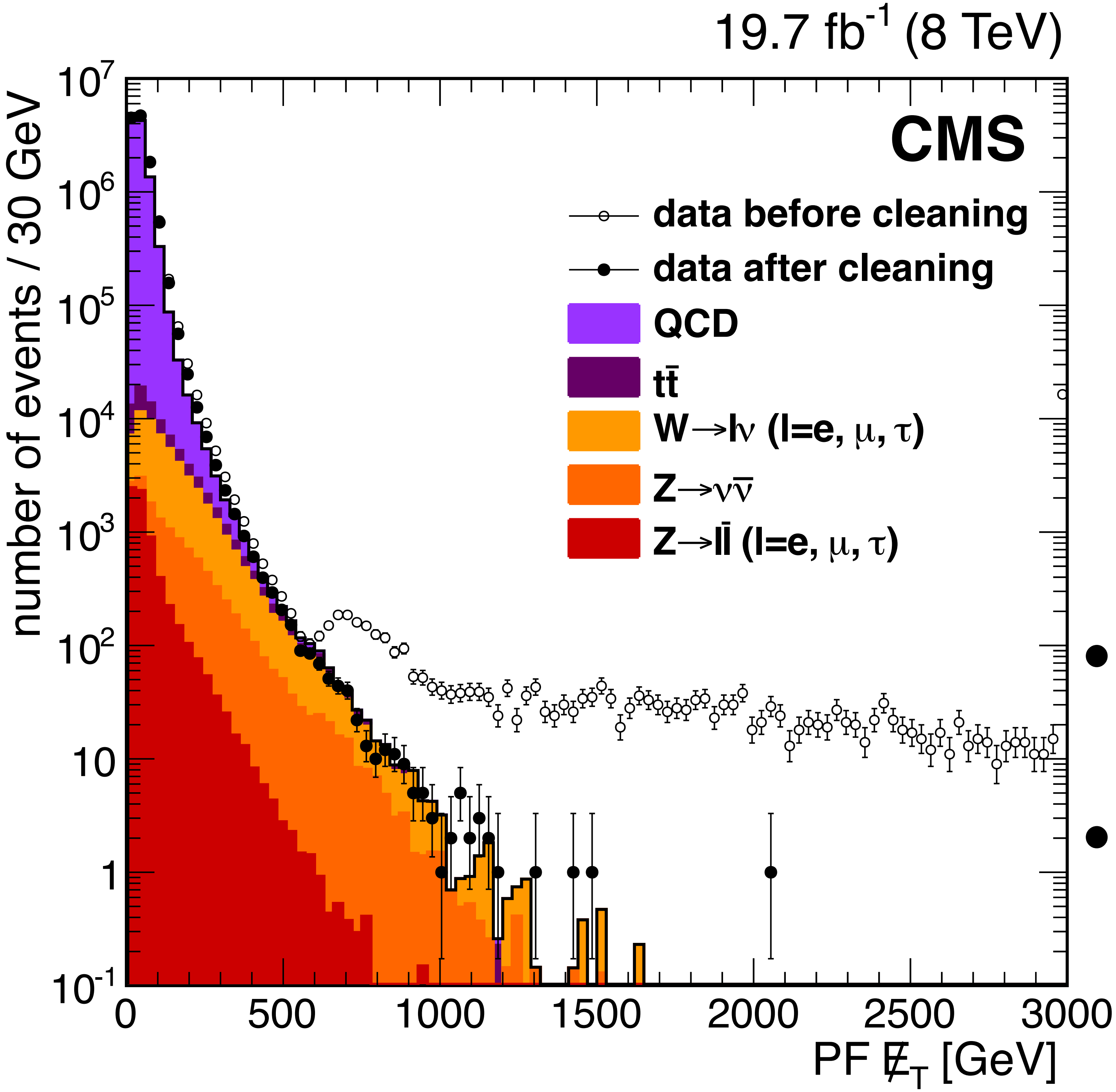
$$\vec{\not{E}}_{\mathrm{T}}^{\mathrm{corr}} = \vec{\not{E}}_{\mathrm{T}} - \vec{\Delta}_{\mathrm{jets}}^{\mathrm{Smear}} = \vec{\not{E}}_{\mathrm{T}} - \sum_{\mathrm{jets}} (\vec{p}_{\mathrm{T,jet}}^{\mathrm{Smear}} - \vec{p}_{\mathrm{T,jet}})$$

C) MET Filters

There are many possible sources of spurious noise signals that can induce large MET values including:

- Beam halo particles
- Laser calibration system misfires
- Nonfunctioning detector elements
- Extreme track misreconstructions

C) MET Filters



Plot on left shows performance of MET filters in the context of Dijet events

Good Data/MC agreement after applying filters

Notable features in the pre-cleaning MET spectrum:

- HCAL laser calibration misfires (bump around 600 GeV)
- Electronics noise in HB and HE (tail starting at 1.5 TeV)

D) MET Scale and Resolution

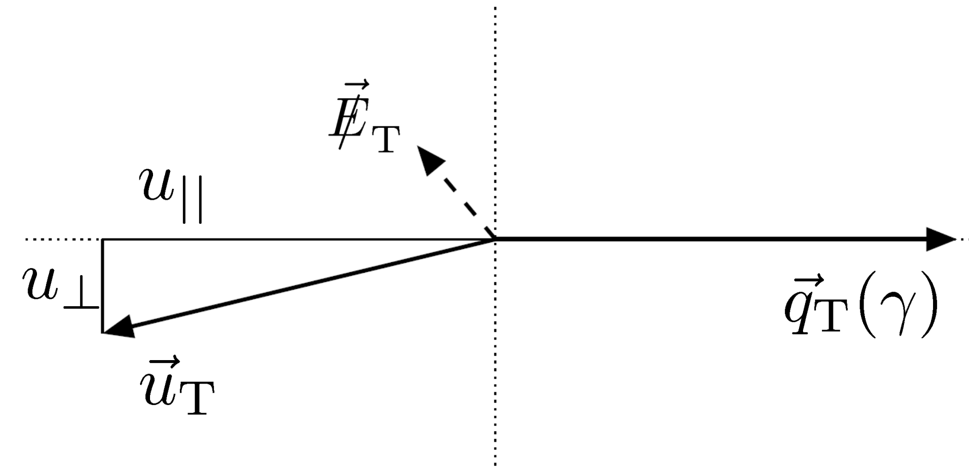
To quantify MET resolution and scale, we study V + jets events (where V = Z or Photon)

Define hadronic recoil vector, $\mathbf{u_T}$,

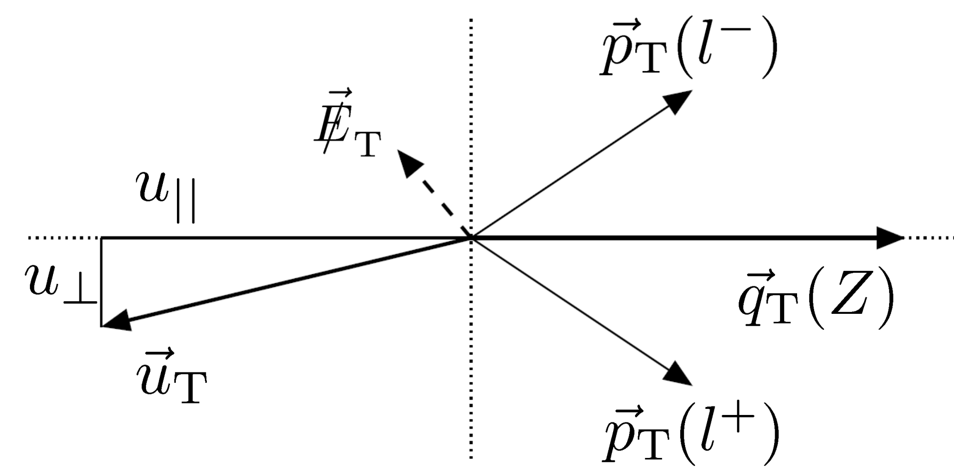
based off of balance in the transverse plane,

$$\vec{q}_T + \vec{u}_T + \vec{\not{E}}_T = 0.$$

Project the hadronic recoil onto the axis defined by the probe particle (Z or Photon)



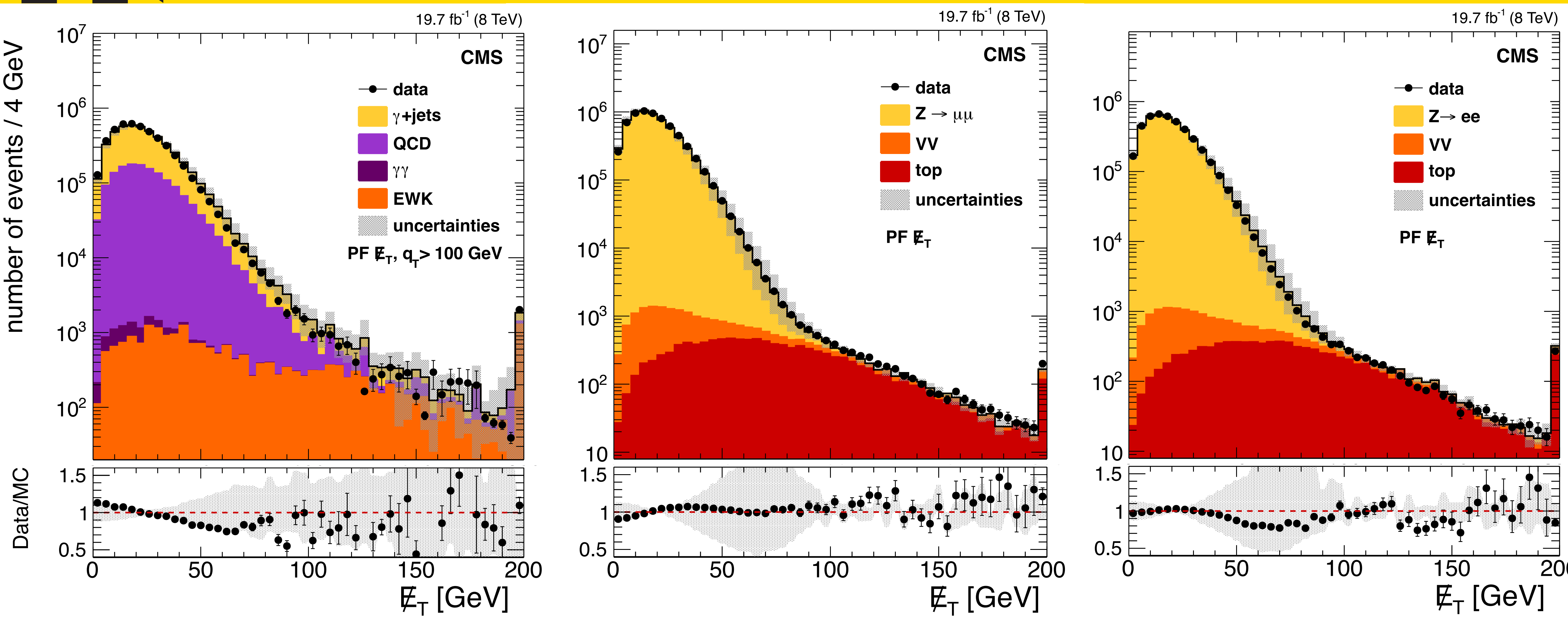
The parallel, U_{par}, and perpendicular, U_{perp}, components of the hadronic recoil can subsequently be used to quantify MET resolution and scale



$-\langle U_{par}\rangle/q_T$ defines MET energy scale/response

The spread of $U_{par} + q_T$ and U_{perp} characterize MET resolution – use a Voigtian fit to extract the width parameter

D) PF MET spectra

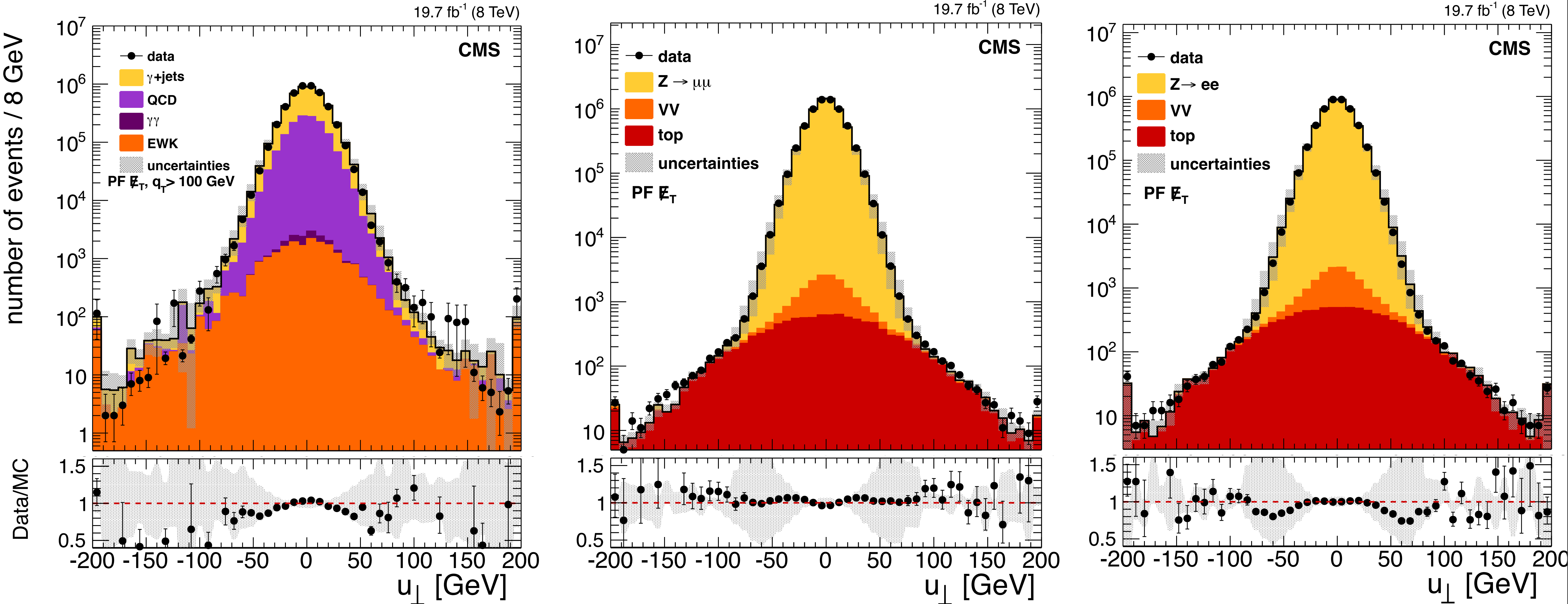


$\gamma + \text{jet(s)}$ $\quad Z \rightarrow \mu\mu$ $\quad Z \rightarrow ee$

Good Data/MC agreement in Core

Agreement within systematics for tails

D) PF U_{Perp} spectra

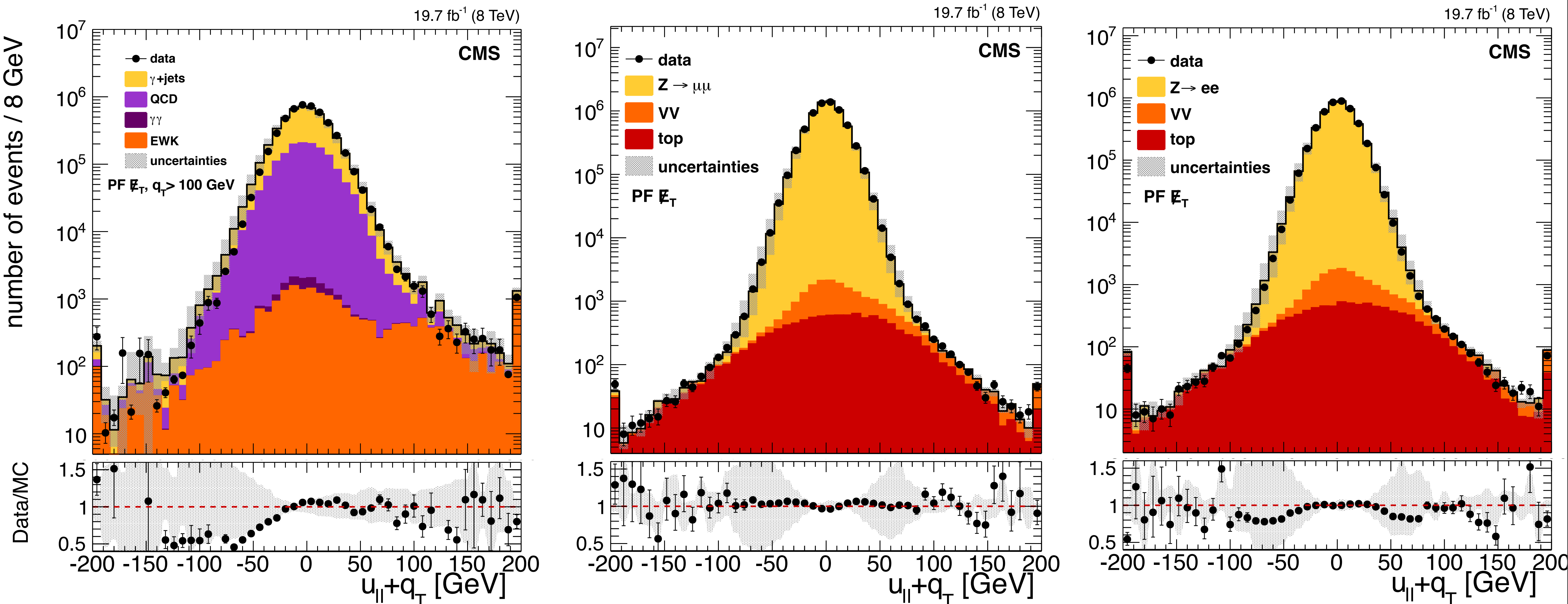


$\gamma + \mathrm{jet(s)}$ $\qquad Z \rightarrow \mu\mu$ $\qquad Z \rightarrow ee$

Good Data/MC agreement in Core

Agreement within systematics for tails

D) PF U_{Par} + q_T spectra

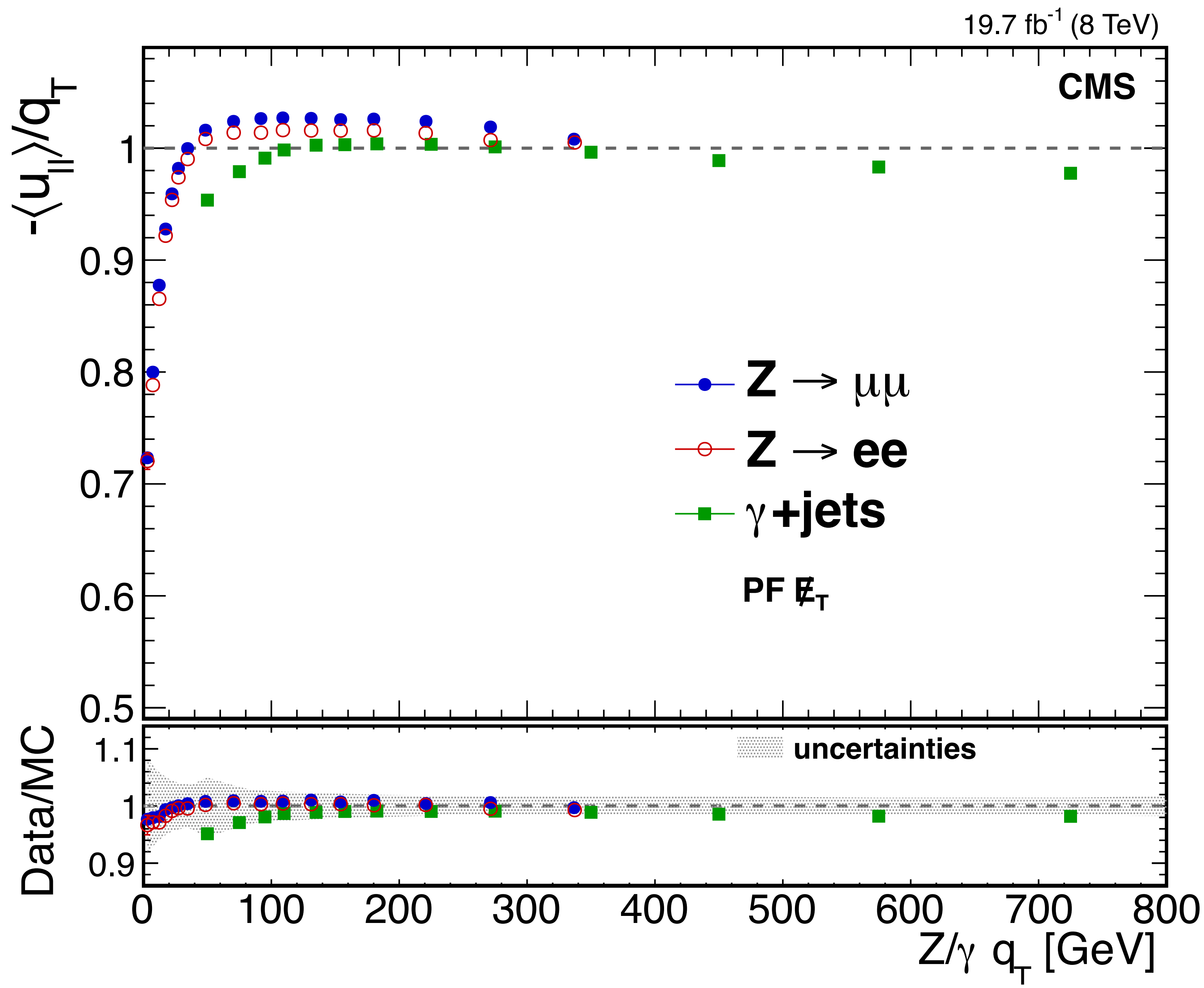


$$\gamma + \mathrm{jet(s)} \qquad Z \to \mu\mu \qquad Z \to ee$$

Good Data/MC agreement in Core

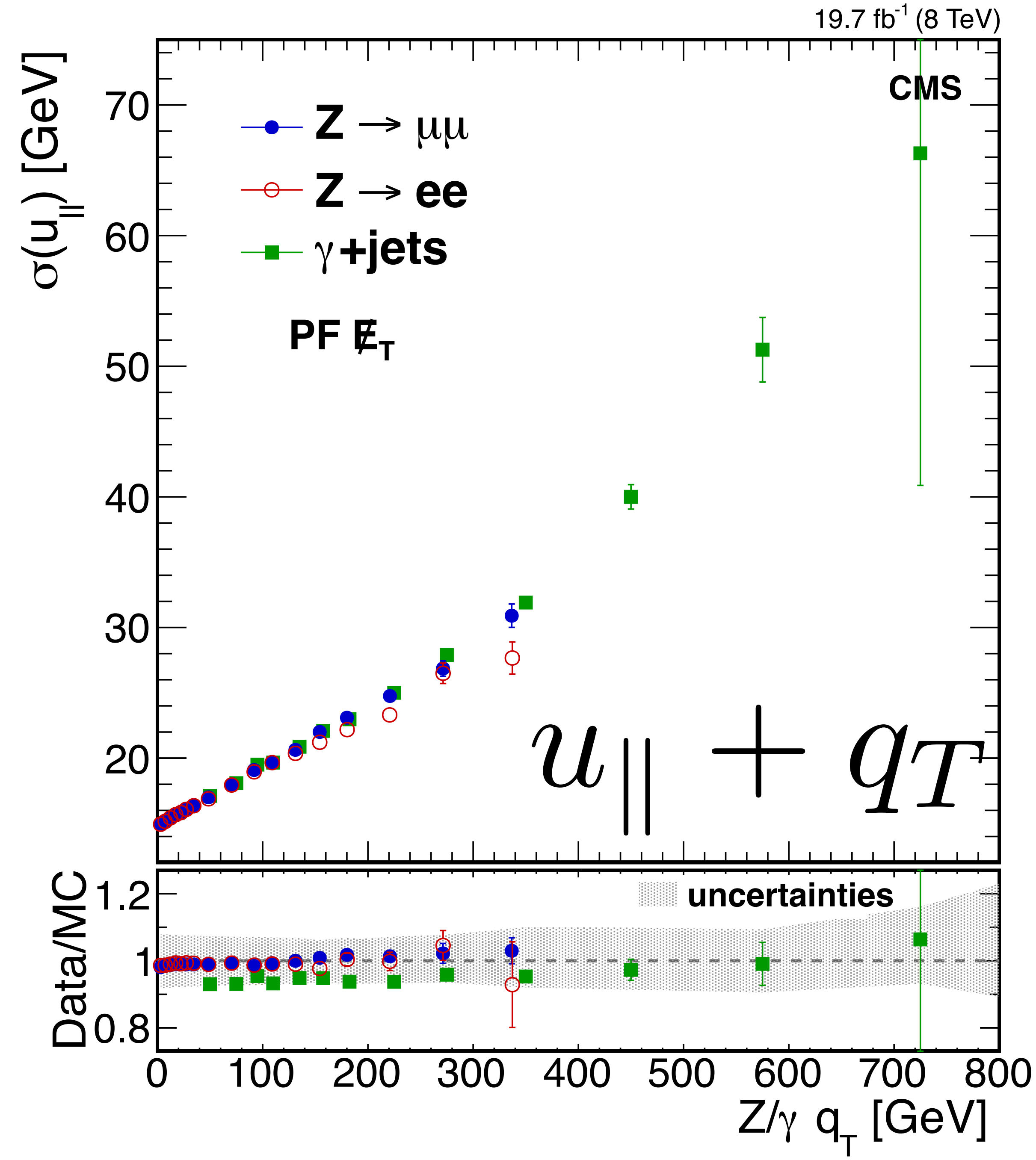
Agreement within systematics for tails

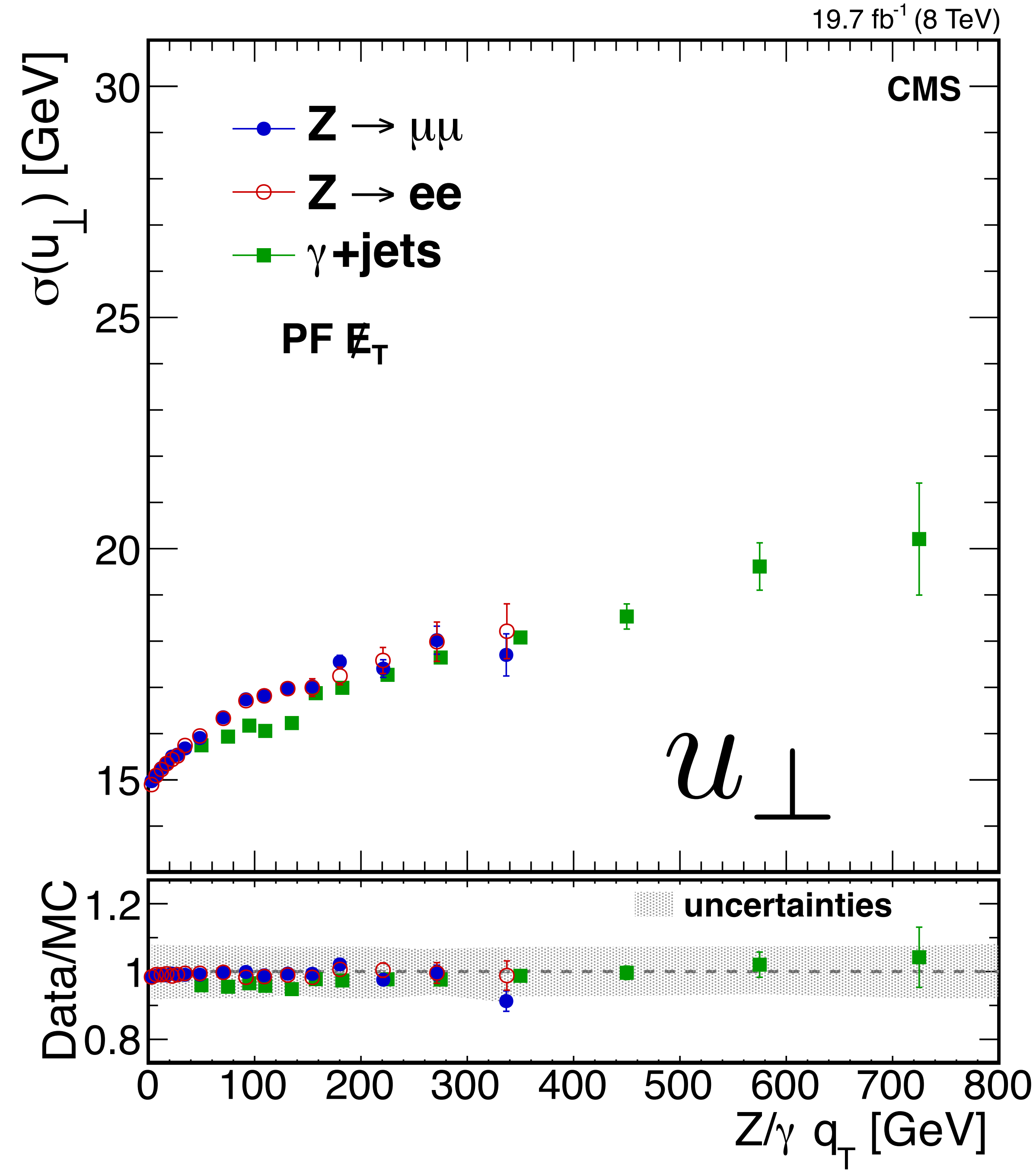
D) PF MET Scale



All three channels show close to unity response after MET corrections;

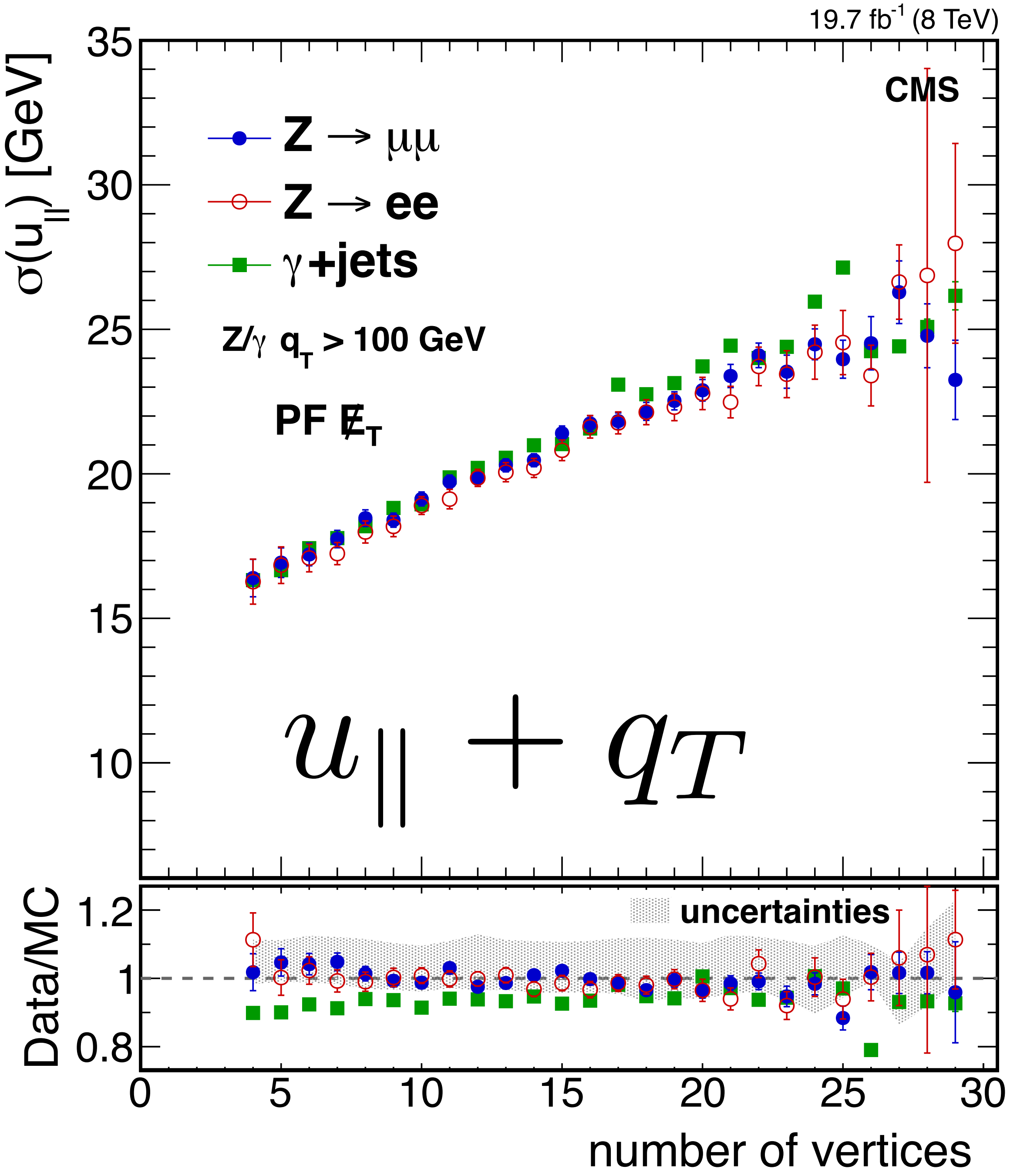
D) PF MET Res. vs. q_T

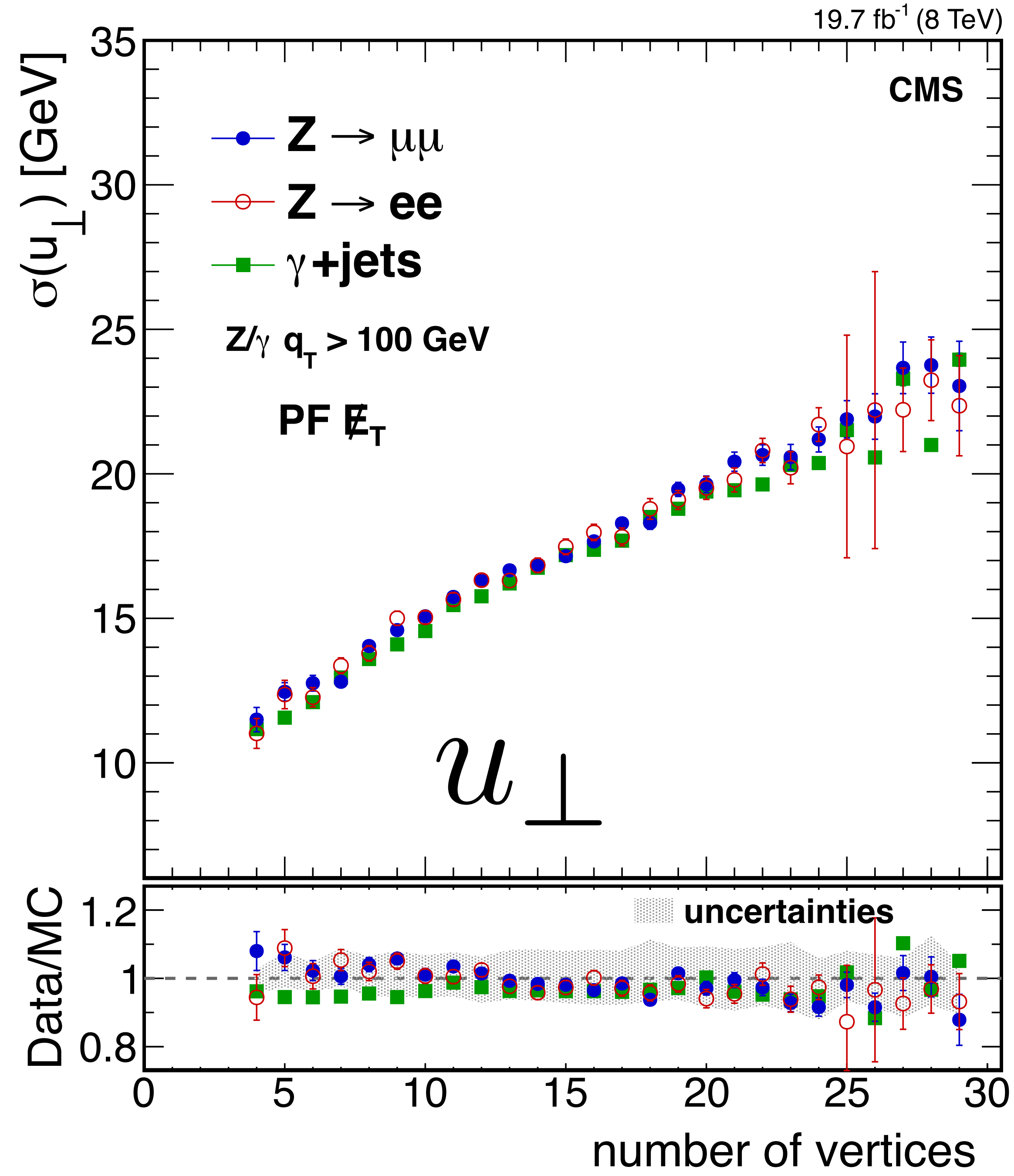




MET resolution dependence on energy scale of event

D) PF MET Res. vs. N_{vtx}





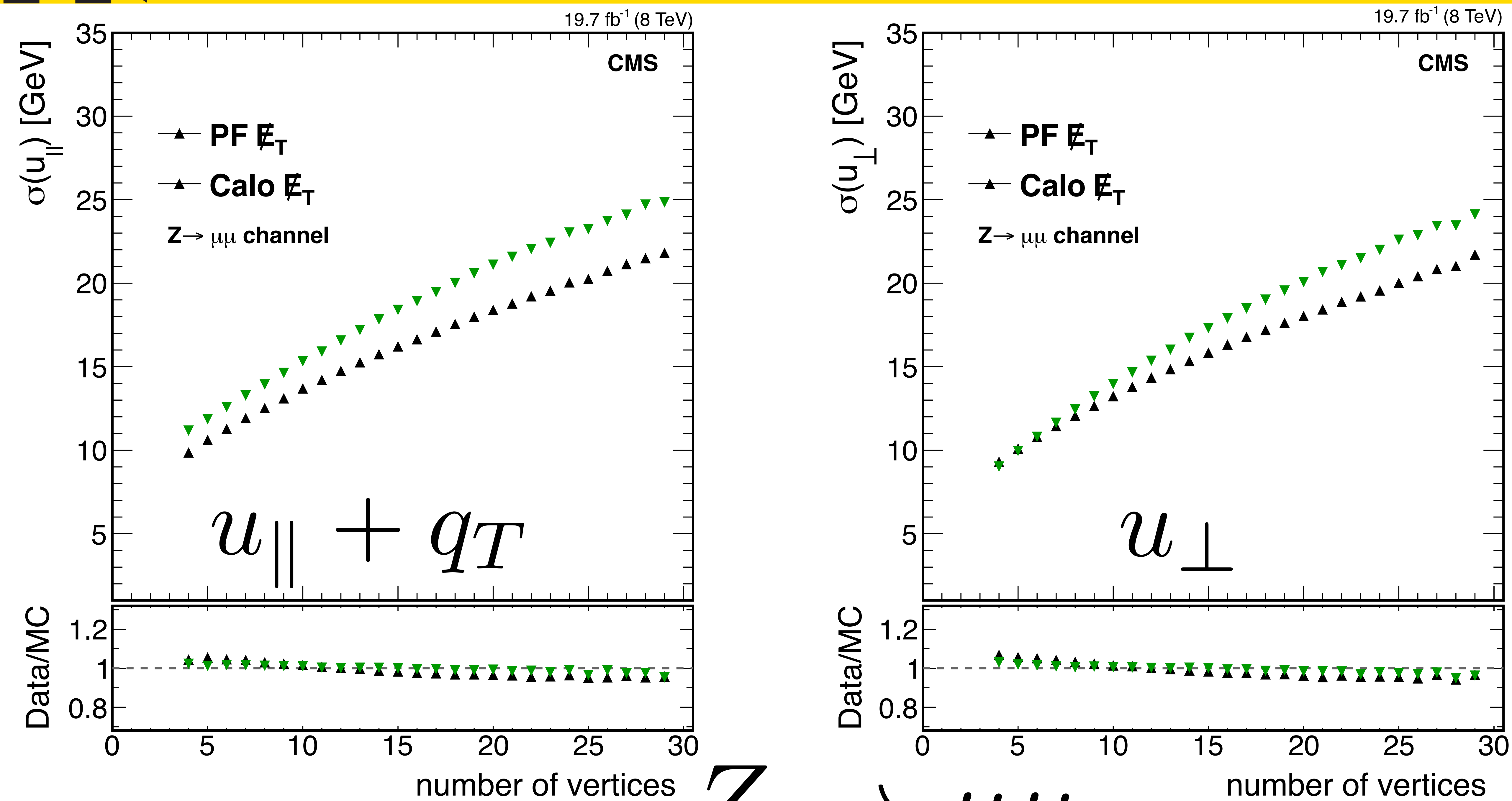
MET resolution dependence on event pileup

D) PF MET Res. vs. N_{vtx}

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

Channel	$u_{\parallel}$ component			
	σ_c (GeV)	$R = \sigma_c(\text{data})/\sigma_c(\text{MC})$	σ_{PU} (GeV)	$R = \sigma_{PU}(\text{data})/\sigma_{PU}(\text{MC})$
$\gamma + \text{jets}$	13.70 ± 0.05	$1.13 \pm 0.03 \pm 0.01$	3.57 ± 0.01	$1.02 \pm 0.04 \pm 0.10$
$Z \to e^+e^-$	13.89 ± 0.36	$0.94 \pm 0.05 \pm 0.03$	3.36 ± 0.08	$1.06 \pm 0.05 \pm 0.09$
$Z \to \mu^+\mu^-$	14.25 ± 0.26	$0.95 \pm 0.03 \pm 0.06$	3.37 ± 0.06	$1.07 \pm 0.04 \pm 0.11$
	$u_{\perp}$ component			
	σ_c (GeV)	$R = \sigma_c(\text{data})/\sigma_c(\text{MC})$	σ_{PU} (GeV)	$R = \sigma_{PU}(\text{data})/\sigma_{PU}(\text{MC})$
$\gamma + \text{jets}$	7.79 ± 0.04	$1.15 \pm 0.05 \pm 0.03$	3.28 ± 0.01	$1.00 \pm 0.03 \pm 0.08$
$Z \to e^+e^-$	8.24 ± 0.34	$0.72 \pm 0.09 \pm 0.05$	3.32 ± 0.05	$1.10 \pm 0.03 \pm 0.10$
$Z \to \mu^+\mu^-$	8.21 ± 0.26	$0.79 \pm 0.07 \pm 0.05$	3.33 ± 0.03	$1.08 \pm 0.03 \pm 0.11$

D) Calo MET Res. vs. N_{vtx}



$$Z \to \mu\mu$$

CaloMET has worse performance vs. pileup

E) PU mitigating MET algorithms

Increasing instantaneous luminosity → increasing pileup

→PF MET resolution degrades by 3.3 - 3.6 GeV for each additional PU interaction

The CMS Collaboration has commissioned two **pileup mitigating** MET algorithms:

1) No PileUp PF MET – a weighted sum of PF particles

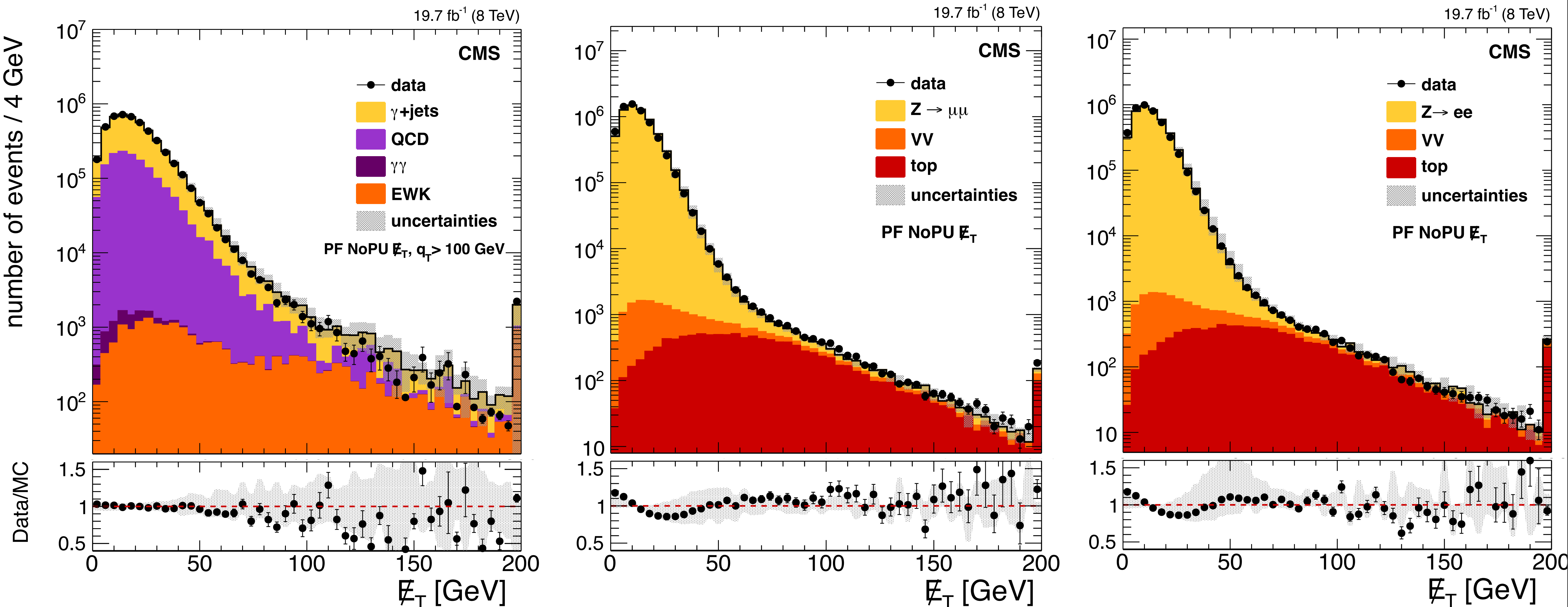
2) MVA PF MET – MET calculation using a BDT regression

(two versions of MVA training – **unity** and **non-unity** response)

Basic idea: combine **standard PF object ID** with **pileup ID algorithms** → mitigate MET resolution degradation from PU

As a tradeoff, sacrifices some MET response (**unity** MVA training helps this somewhat)

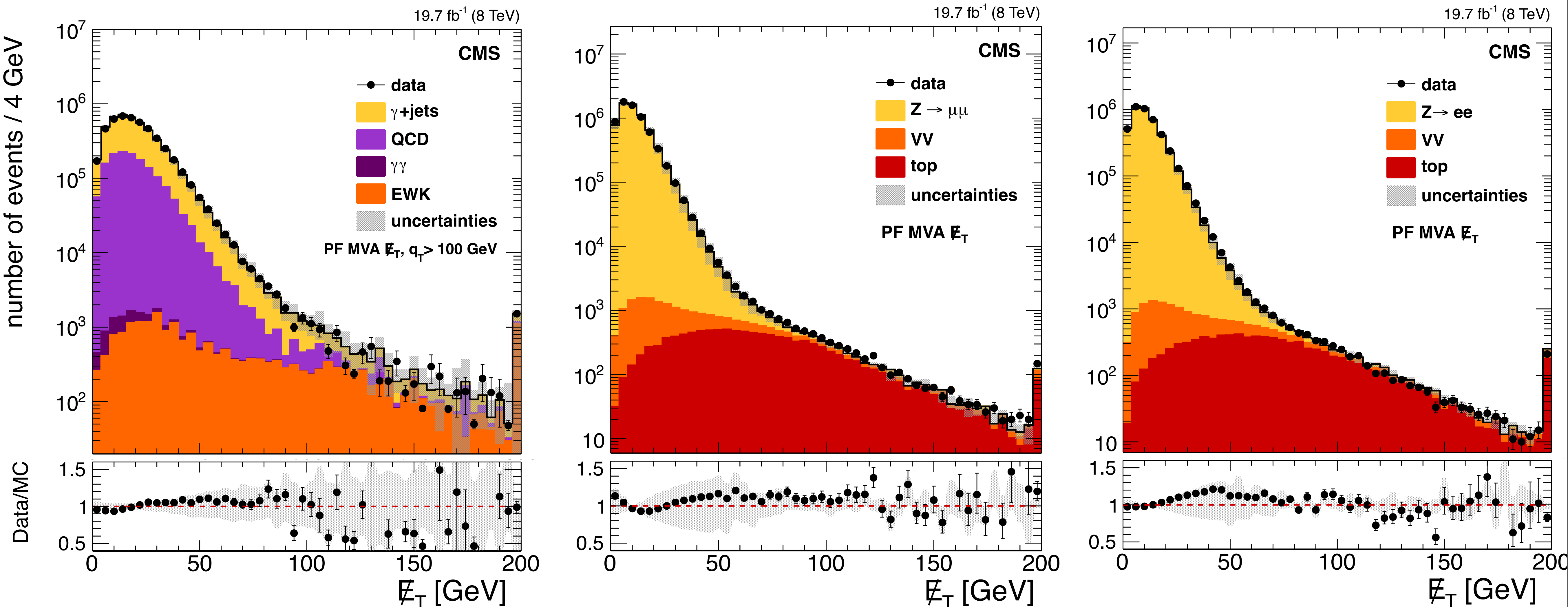
E) NoPU PF MET spectra



$\gamma + \mathrm{jet(s)}$ $Z \to \mu\mu$ $Z \to ee$

Systematics cover observed data/MC discrepancies

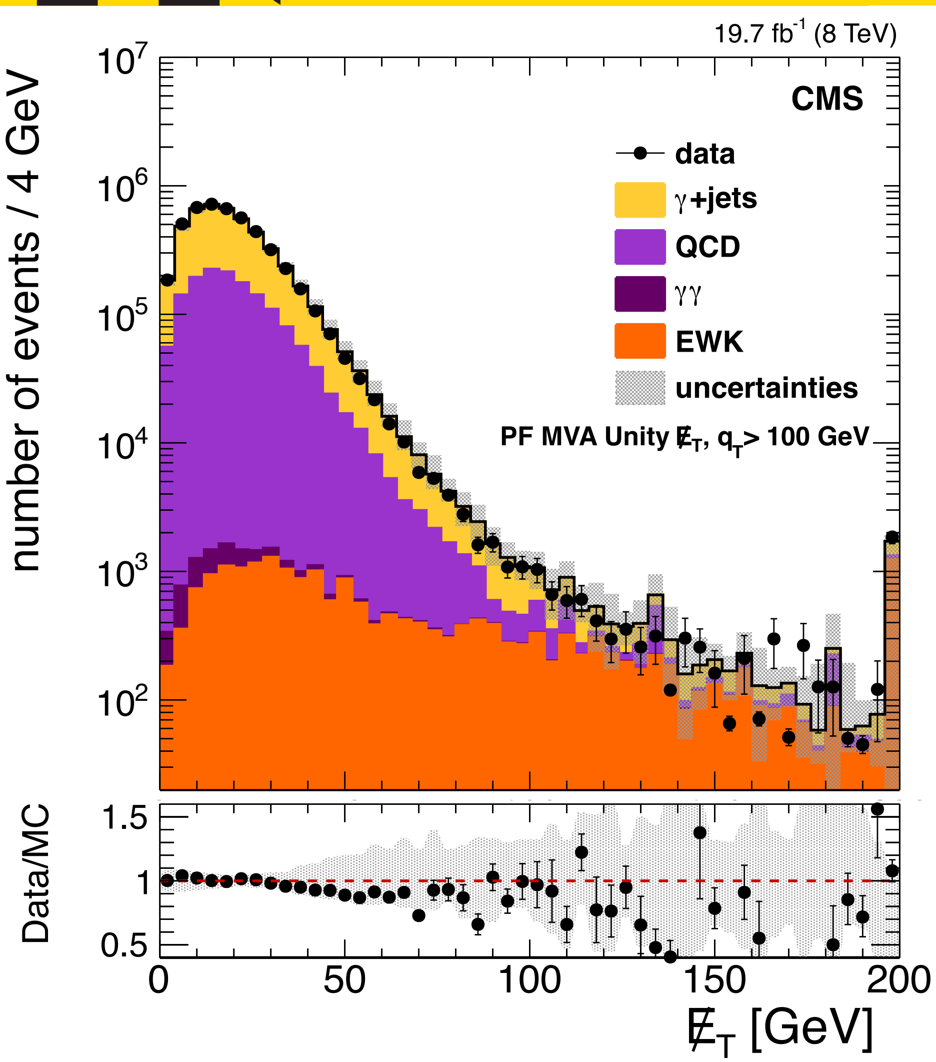
E) MVA PF MET spectra



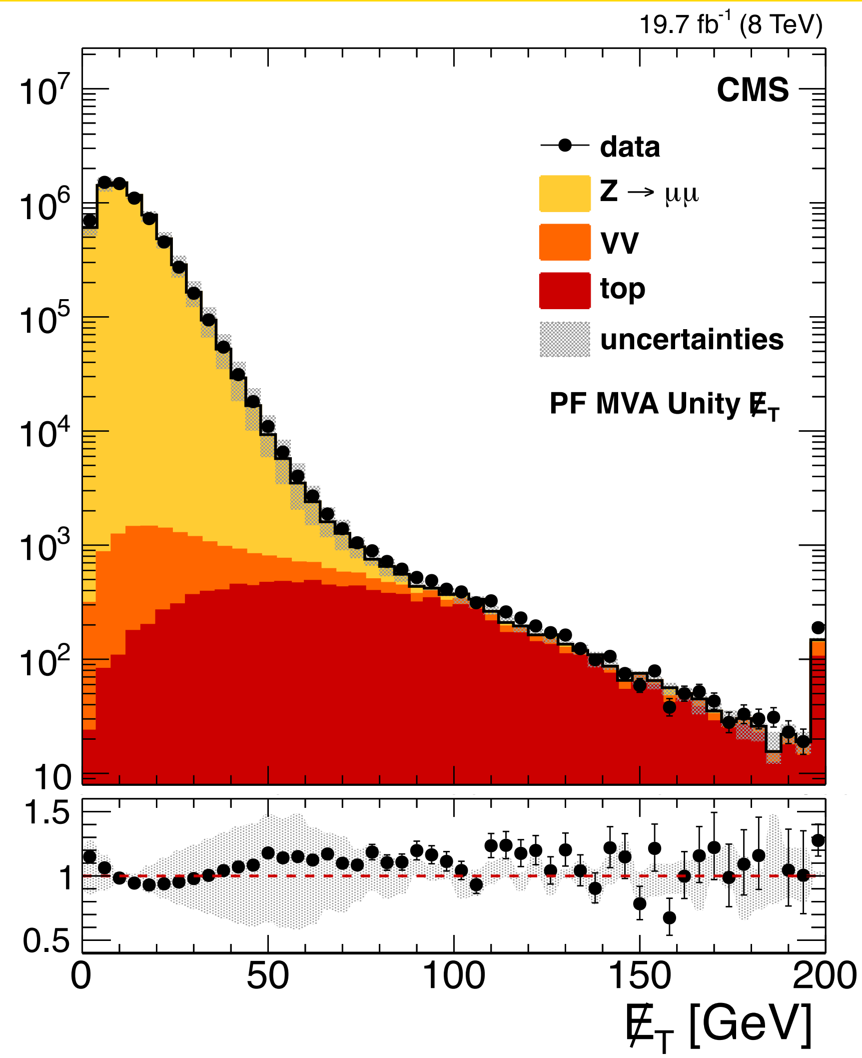
$\gamma + \mathrm{jet(s)}$ $\quad$ $Z \to \mu\mu$ $\quad$ $Z \to ee$

Systematics cover observed data/MC discrepancies

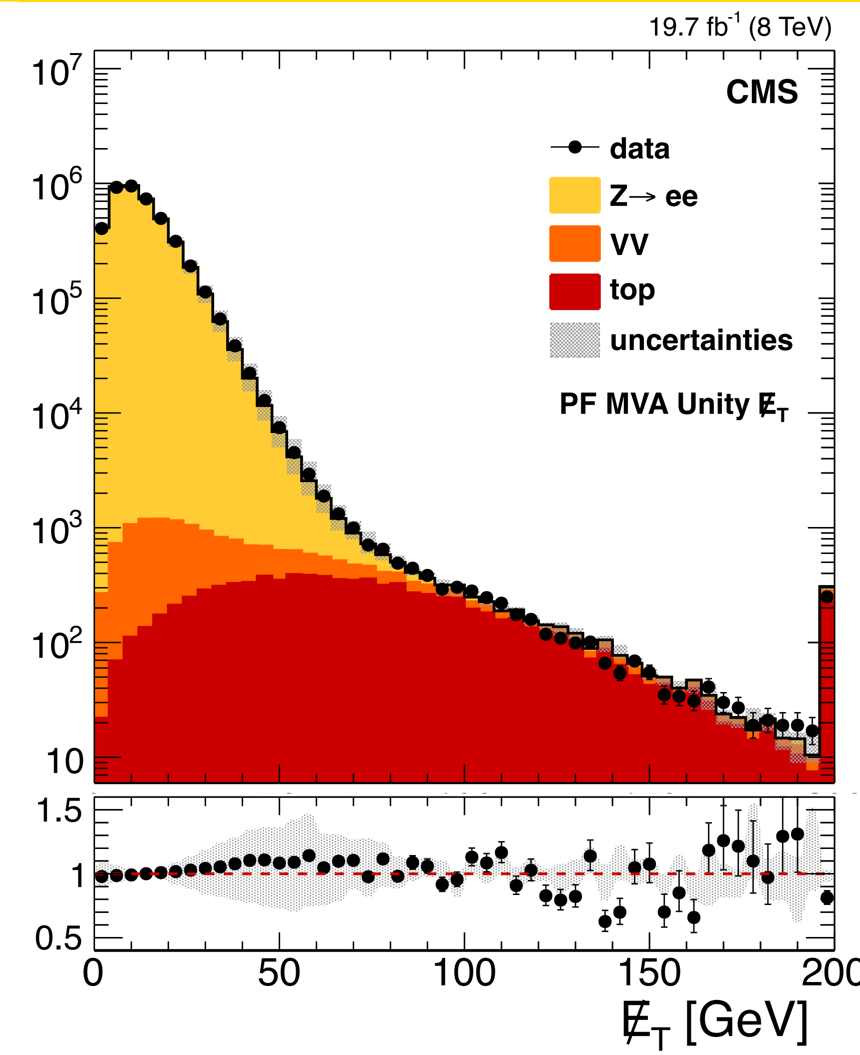
E) MVA Unity PF MET spectra



$\gamma + \text{jet(s)}$



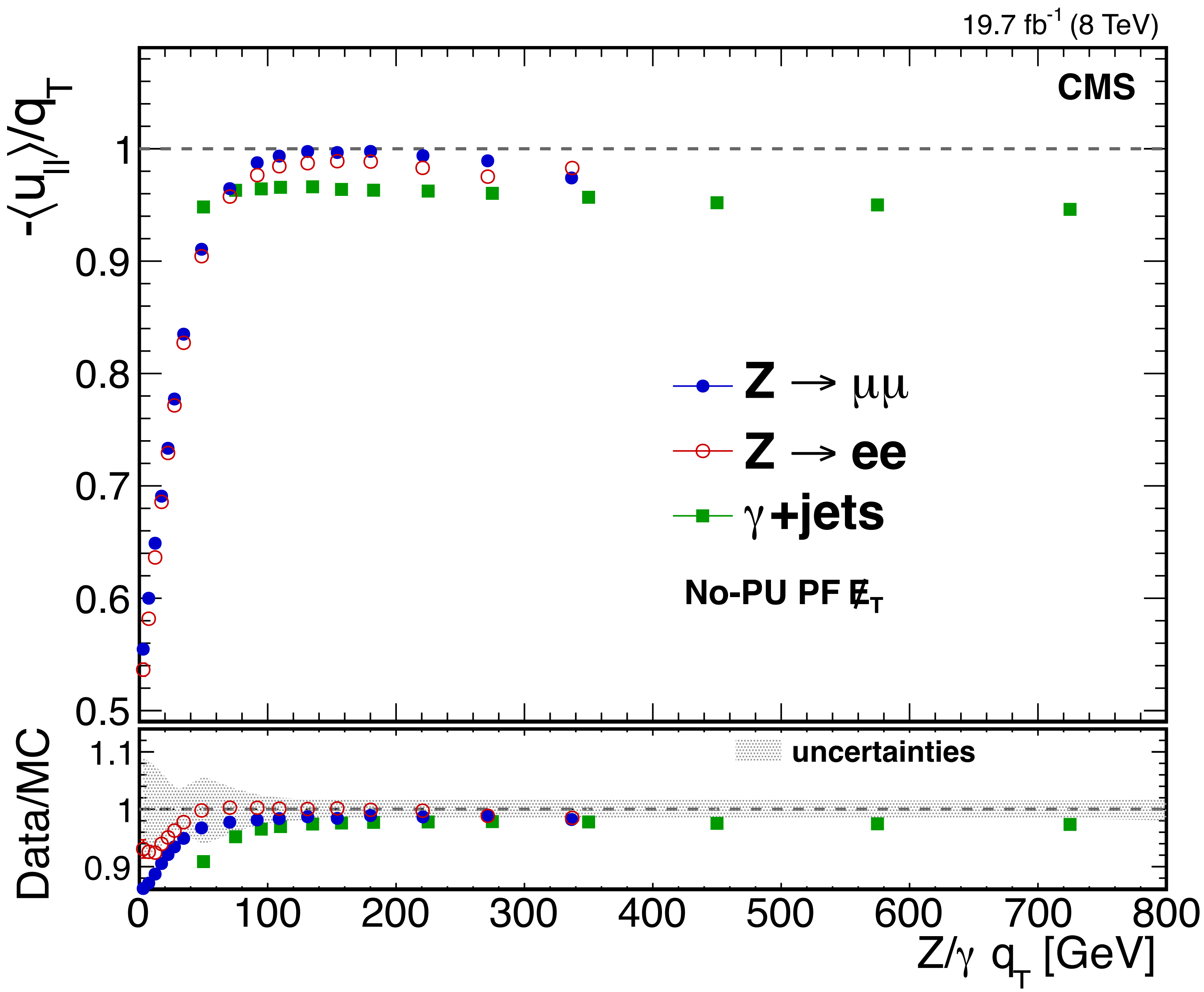
$Z \rightarrow \mu\mu$



$Z \rightarrow ee$

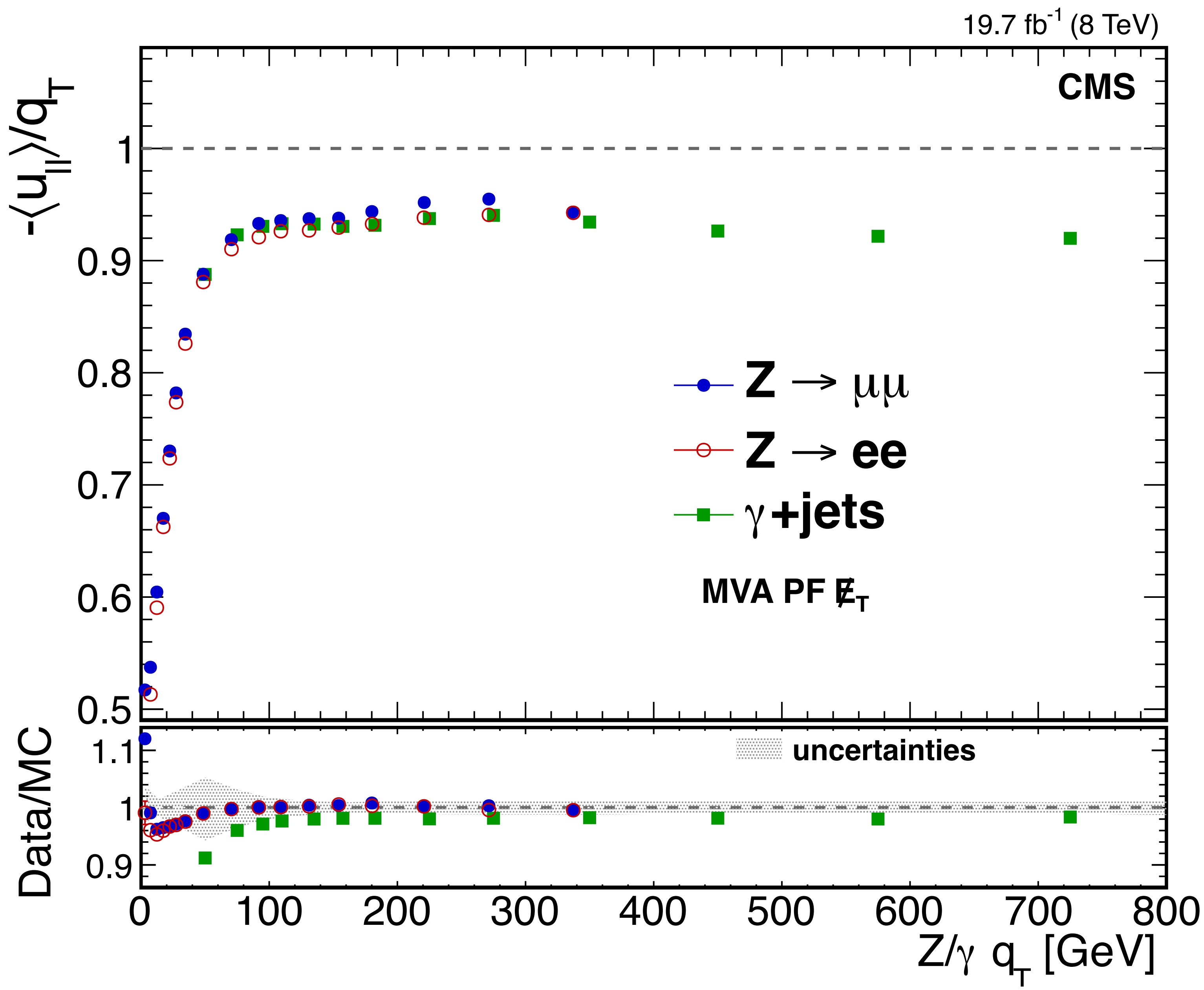
Systematics cover observed data/MC discrepancies

E) NoPU PF MET Scale



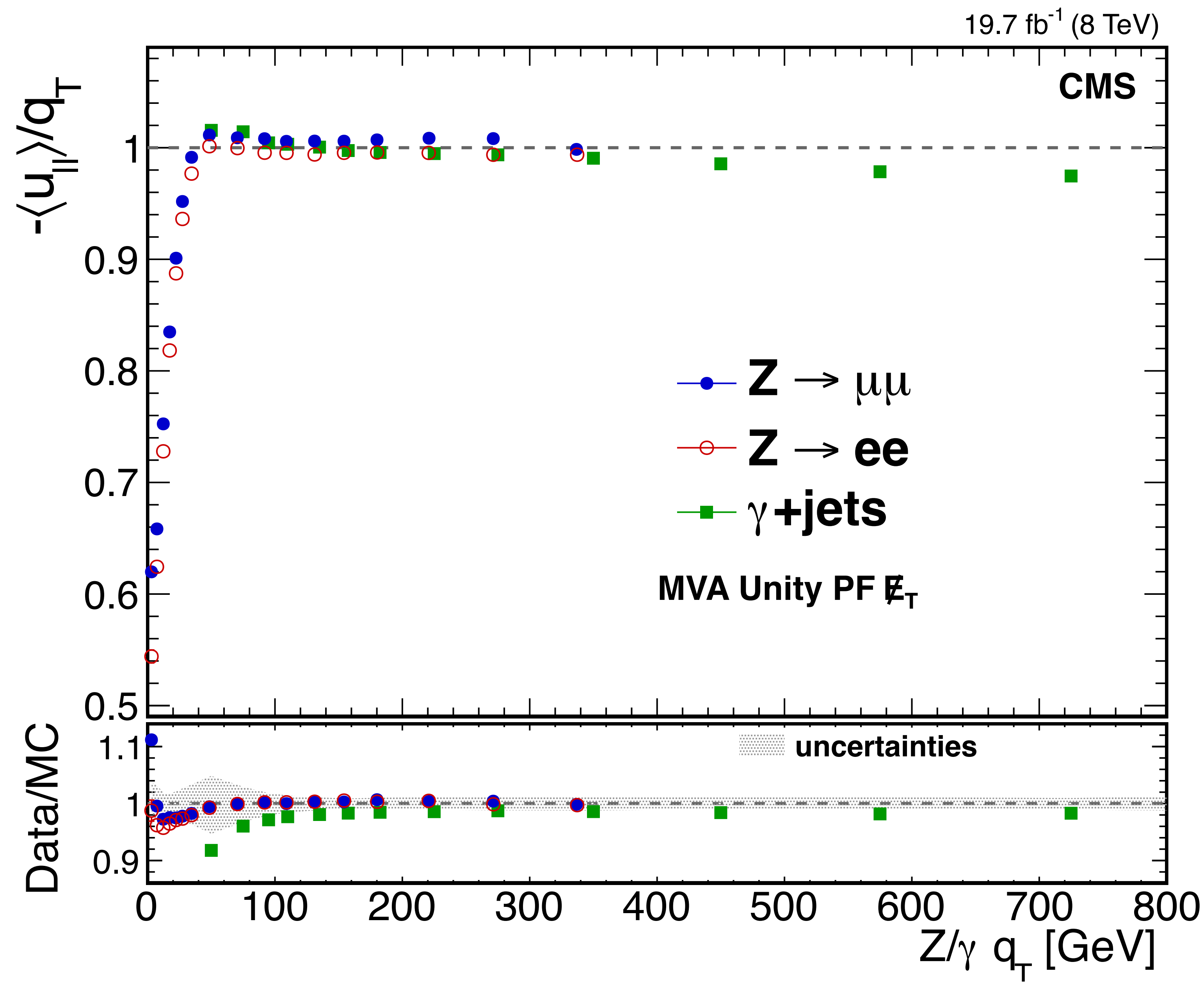
As noted before, NoPU MET algorithm sacrifices some of the MET response in exchange for improved resolution.

E) MVA PF MET Scale



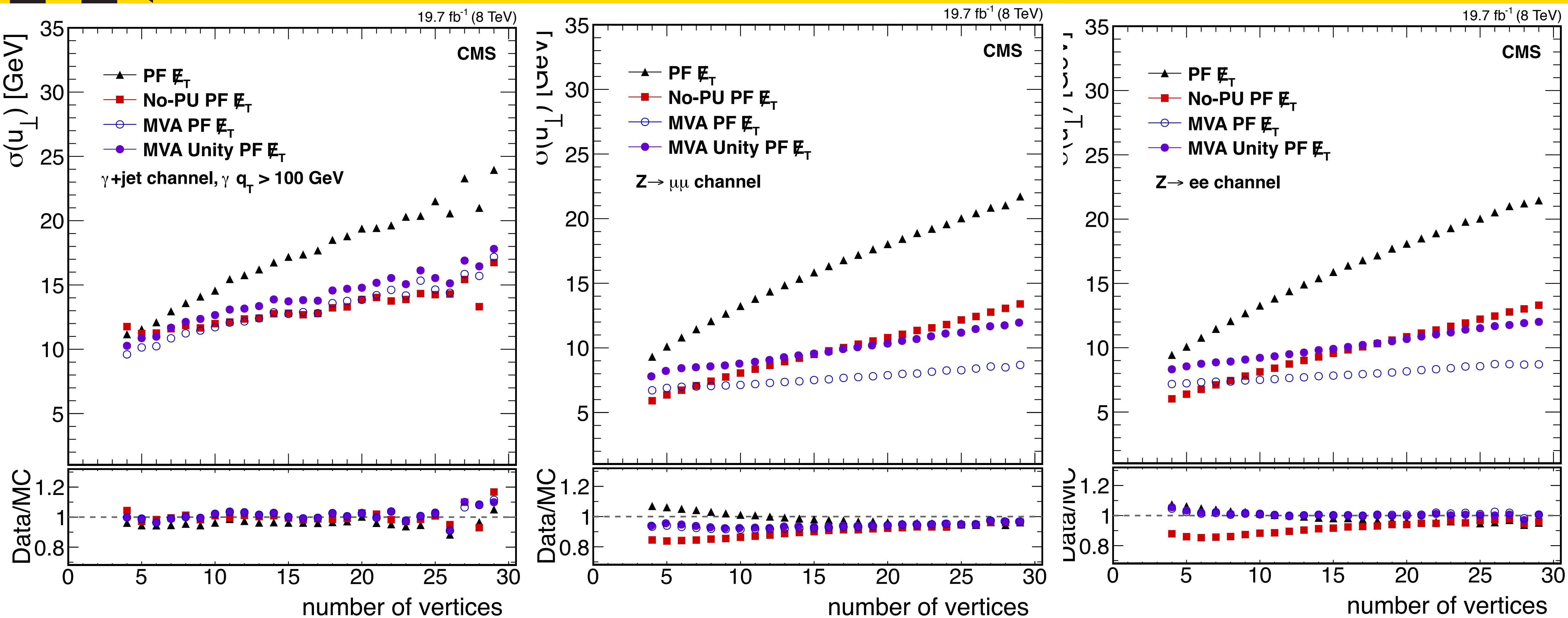
As noted before, MVA MET algorithm with **non-Unity** training sacrifices some of the MET response in exchange for improved resolution

E) MVA Unity PF MET Scale



As shown on last slide, **without** **Unity** response, MVA MET algorithm loses MET response

E) U_{perp} Res. vs. N_{vtx}



$$\gamma + \mathrm{jet(s)} \qquad Z \to \mu\mu \qquad Z \to ee$$

PU Mitigation algorithms greatly help with MET resolution degradation from Pileup

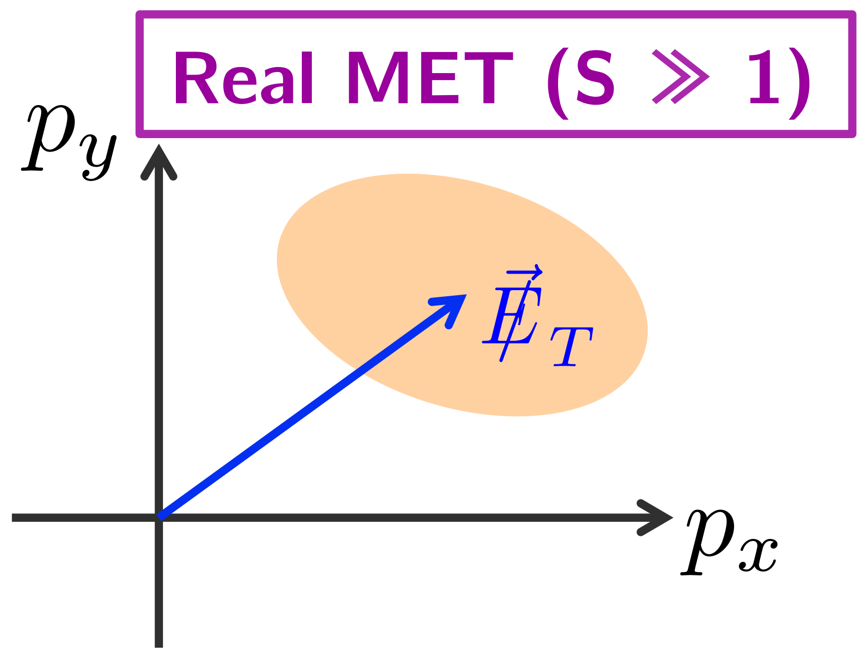
F) MET Significance

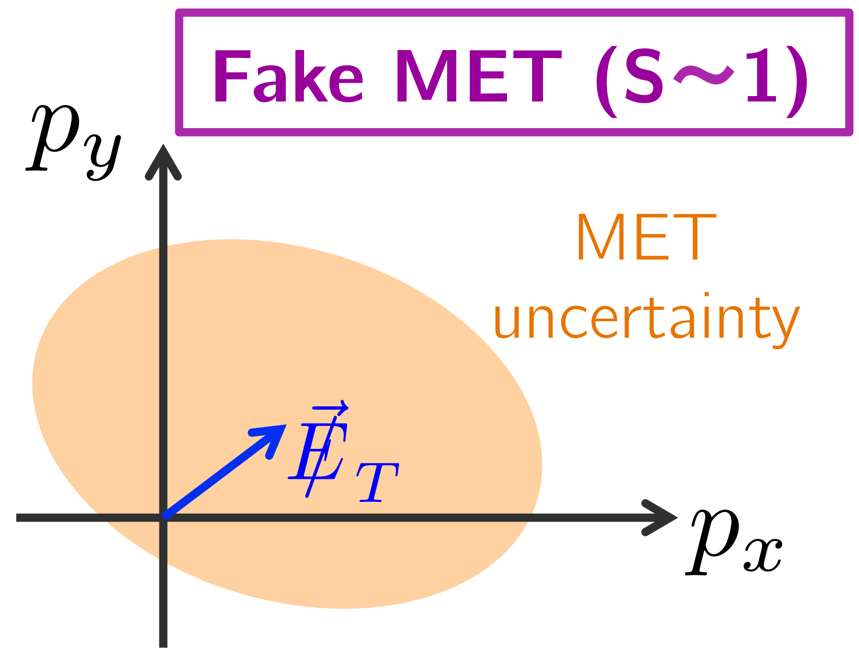
Many BSM searches benefit from the ability to distinguish genuine MET sources (SUSY, DM, etc.) and spurious MET sources (e.g. Multijet, DY + jets)

The CMS Collaboration has developed the MET significance variable ($\mathcal{S}$) to achieve this goal

$\mathcal{S}$ evaluates the likelihood that the observed MET in an event is compatible with just object mismeasurements – that is, no "true MET" needed

$$\mathcal{S} \sim \frac{\not{E}_T^2}{\sigma^2_{\not{E}_T}}$$





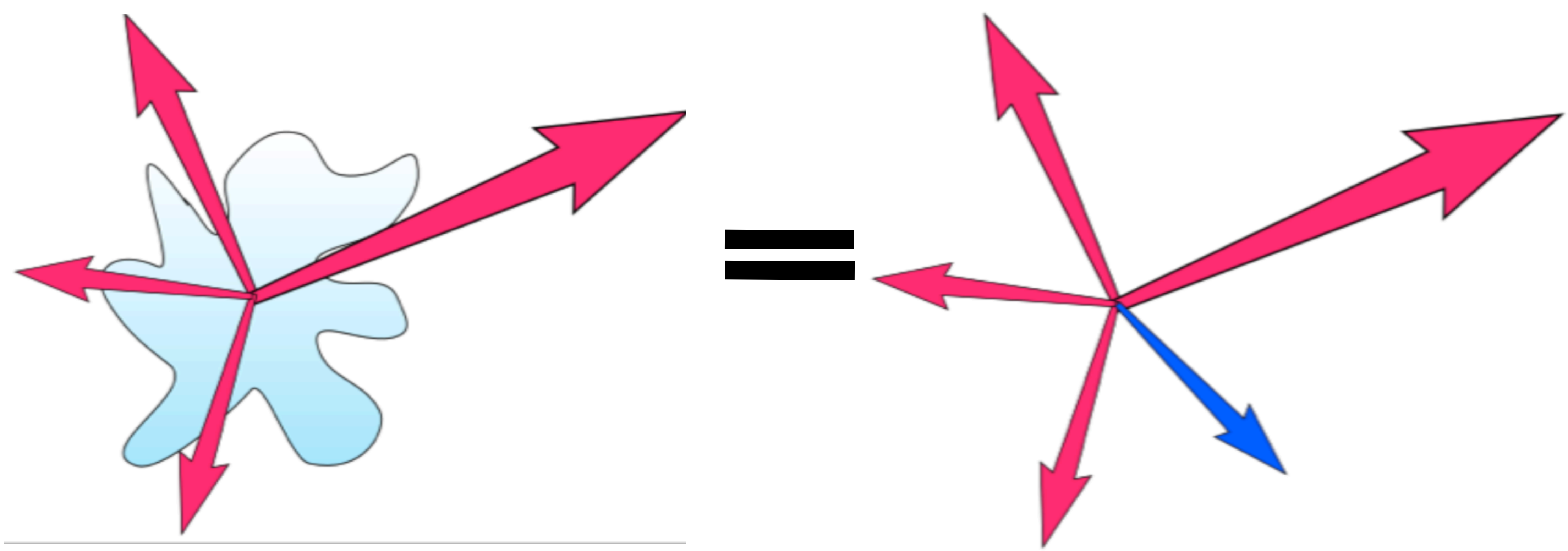
Monday, August 25, 14

F) MET Significance

Events are broken down into two components:

1. **Individual Jets from hard scatter** (p_T > 20 GeV)
2. **The underlying soft hadronic component** composed of PU jets, underlying event activity, etc. (i.e. all PF jets with p_T < 20 GeV)

– particles in 2. get grouped into a single "pseudo-jet"



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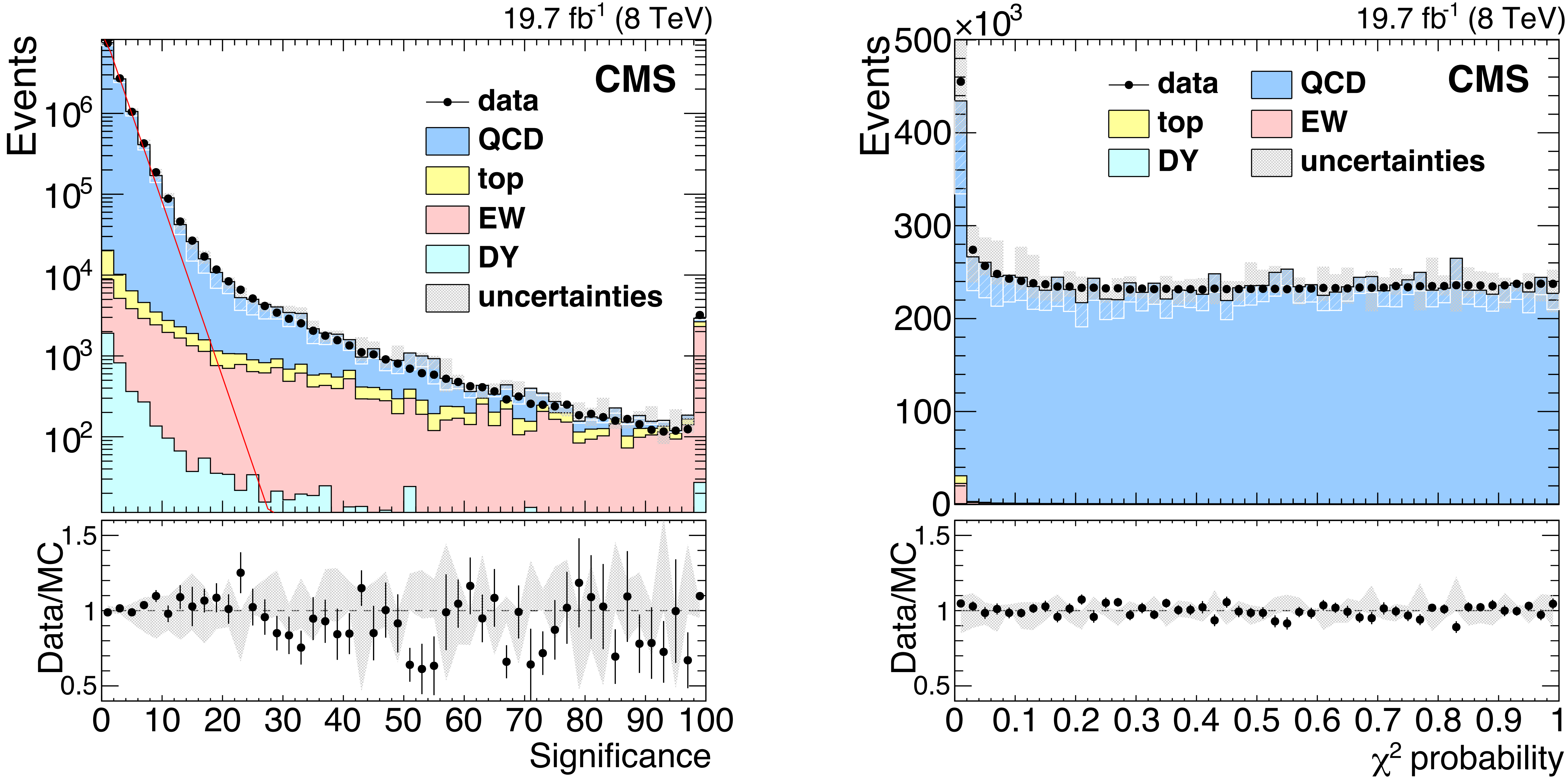
F) MET Significance

We evaluated the performance of $\mathcal{S}$ in two overall classes of events

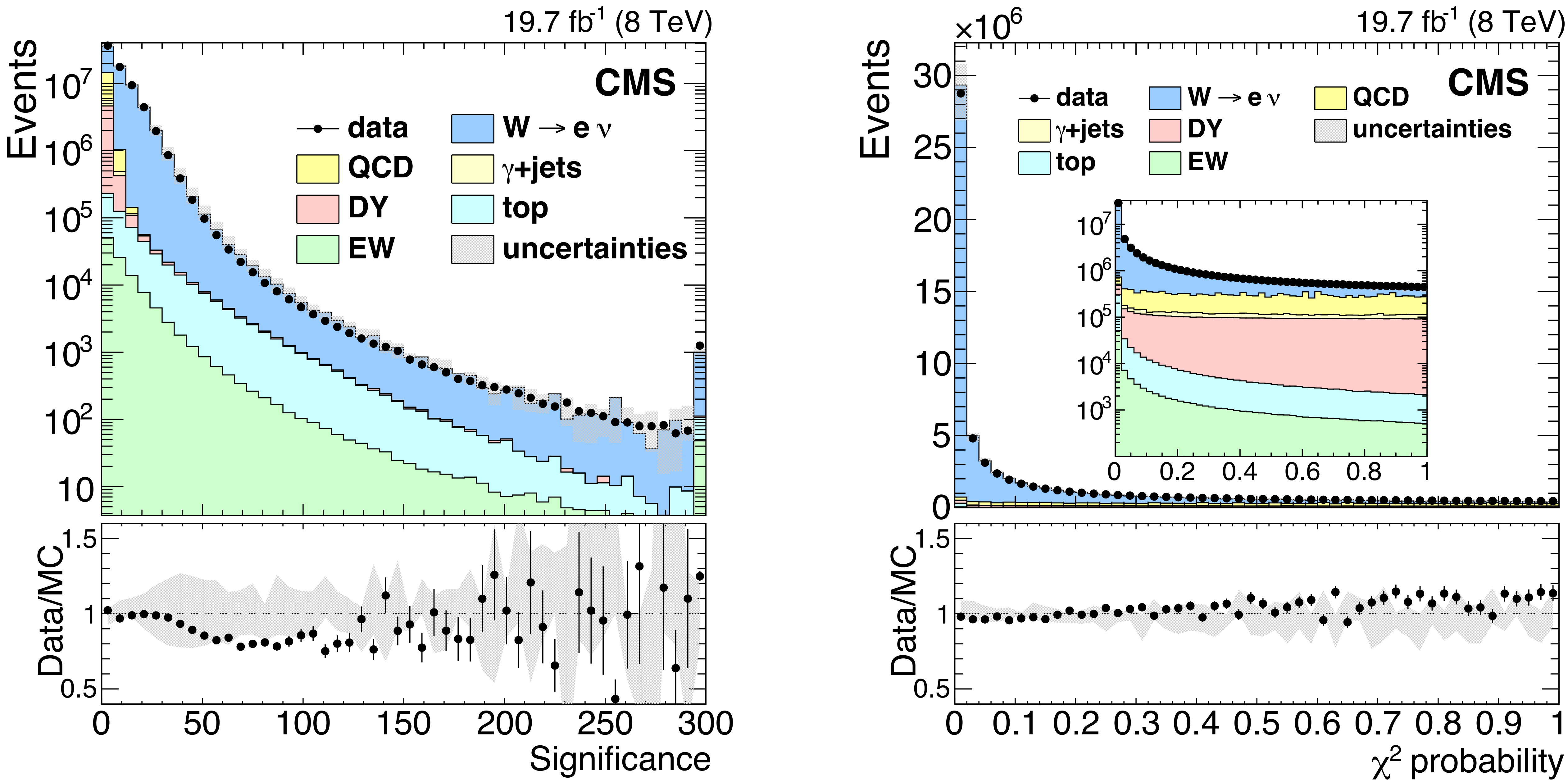
1. **MET_{true} = 0** → jet resolution tuning, general performance, and testing in zero-MET scenarios
   1.1. Z⇒μμ
   1.2. Dijets
2. **MET_{true} > 0** → validate signal/bkgd. discriminating performance
   2.1. W⇒eν
   2.2. Semi-leptonic ttbar

F) MET Significance (MET = 0)



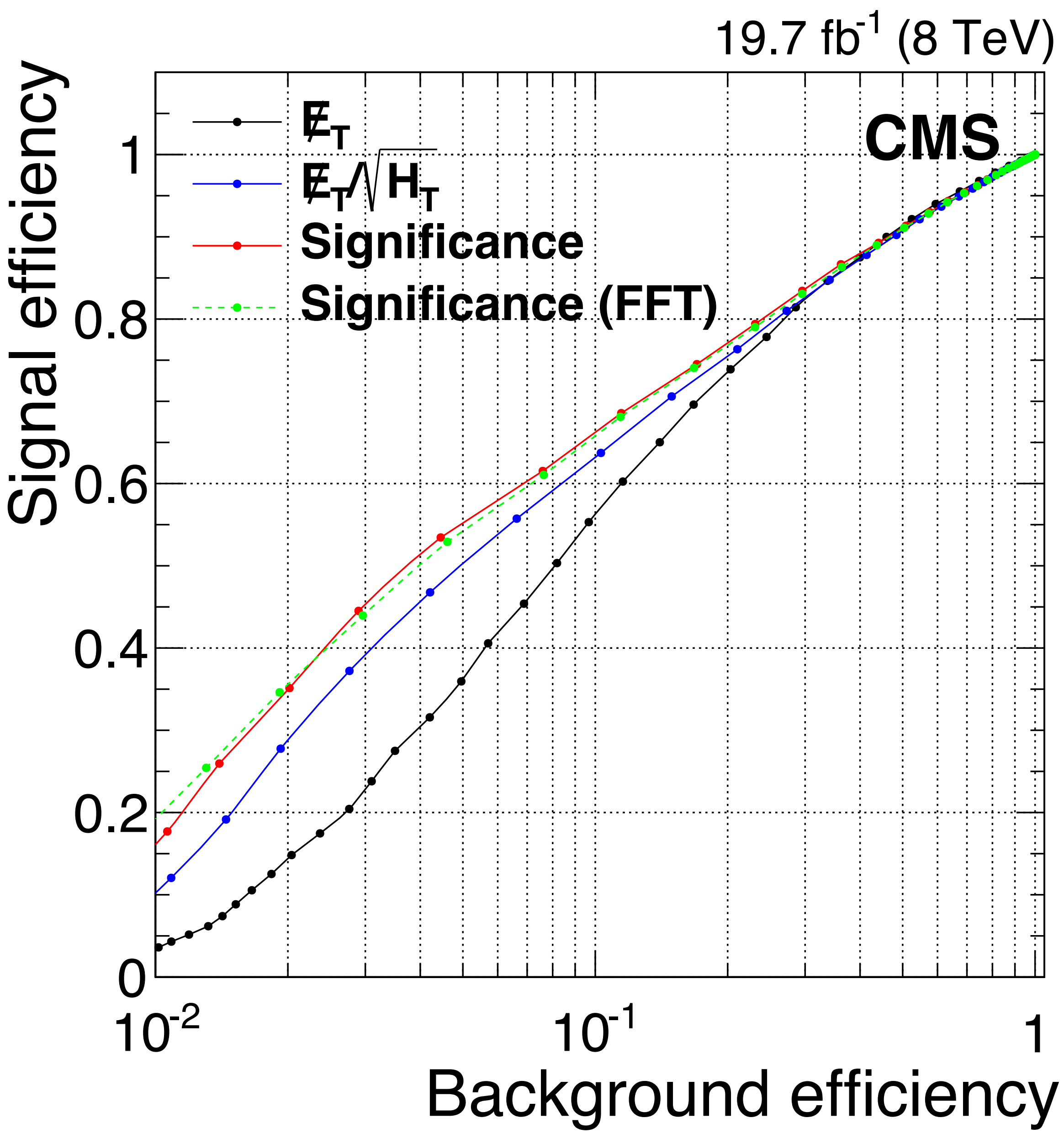
Dijets

F) MET Significance (MET > 0)



W⇒eν

F) MET Significance (MET > 0)



W⇒eν

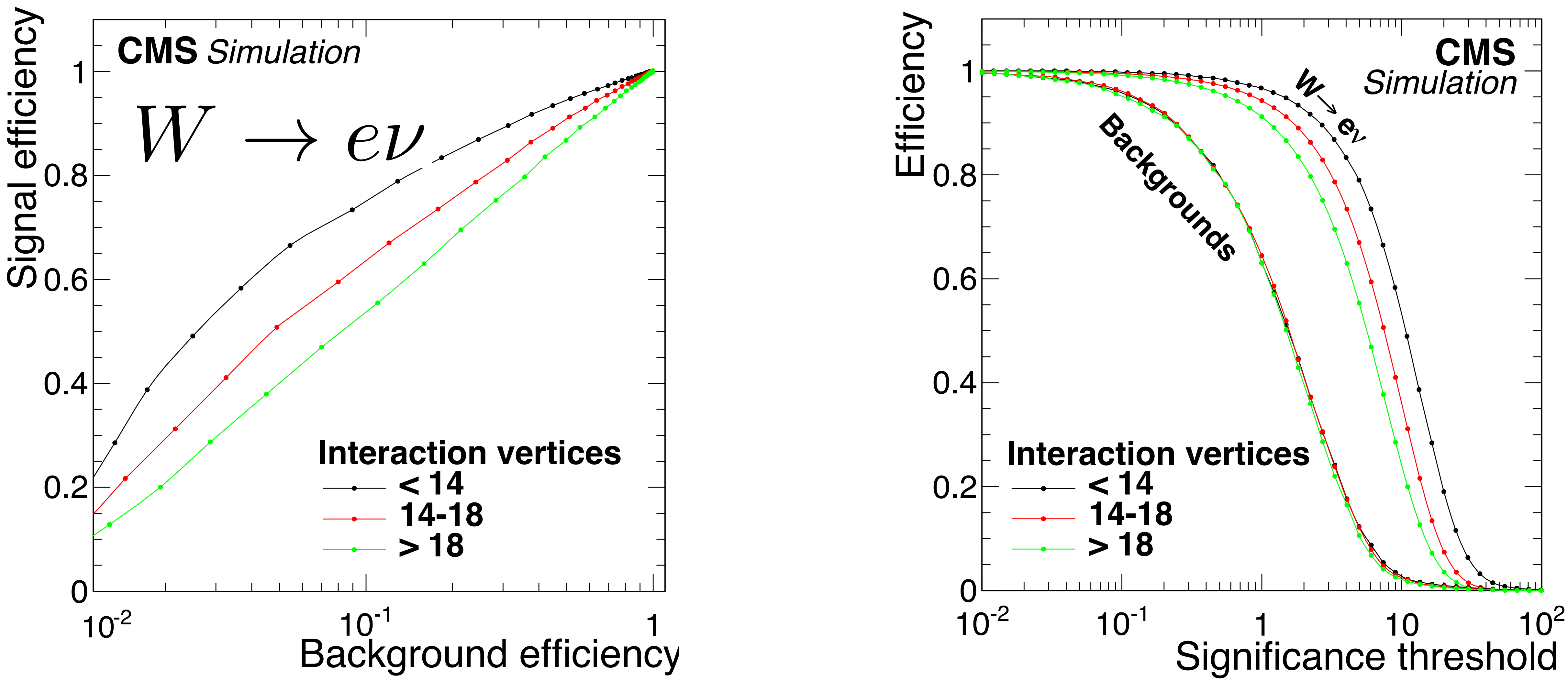
Major backgrounds in the leptonic W selection are "spurious MET" events (DY, QCD)

$\mathcal{S}$ demonstrates a performance boost relative to other standard discrimination variables

Background efficiencies at 50% signal efficiency

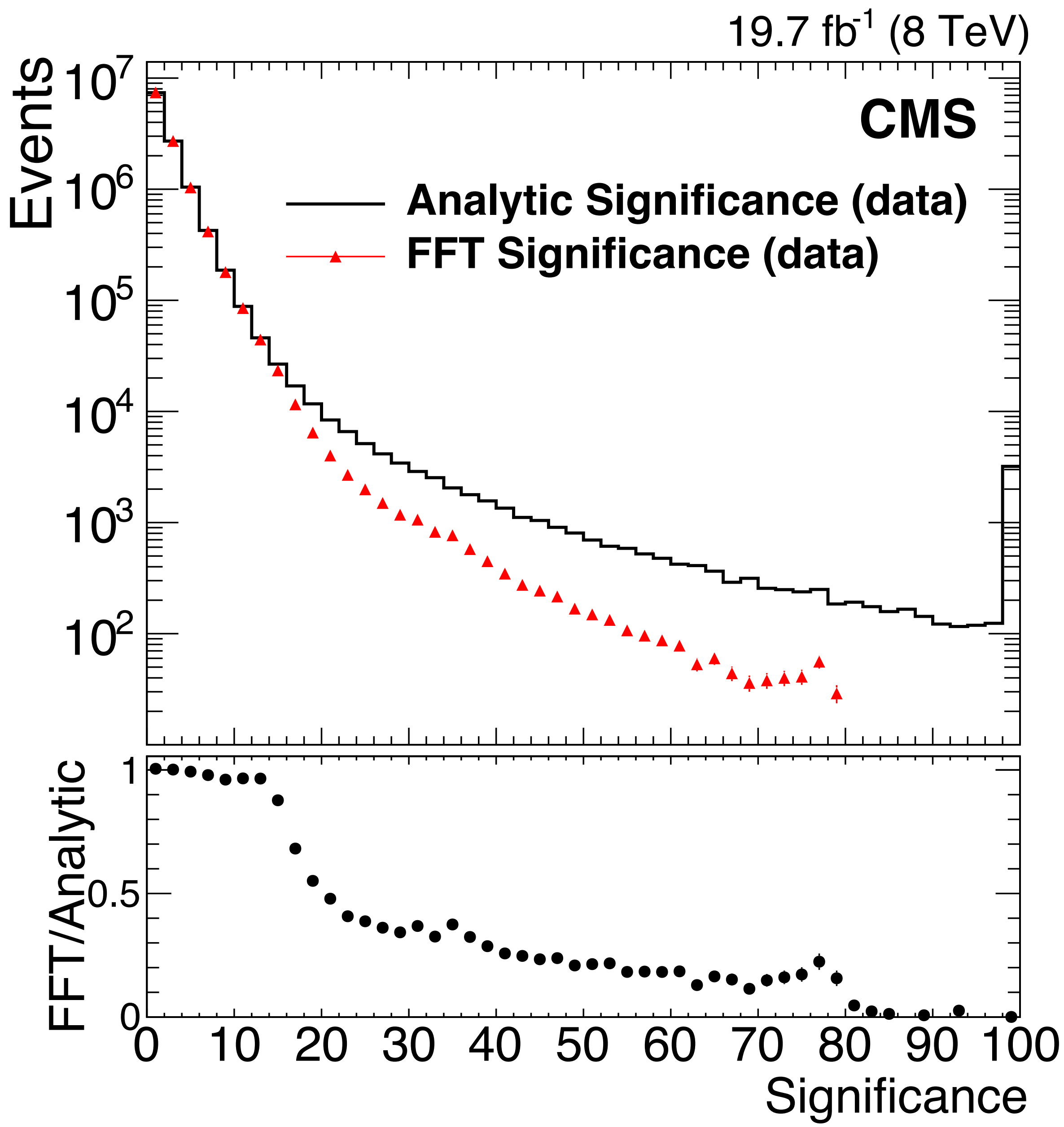
MET	8.2%
MET/$\sqrt{H_T}$	5.1%
Significance	4.0%

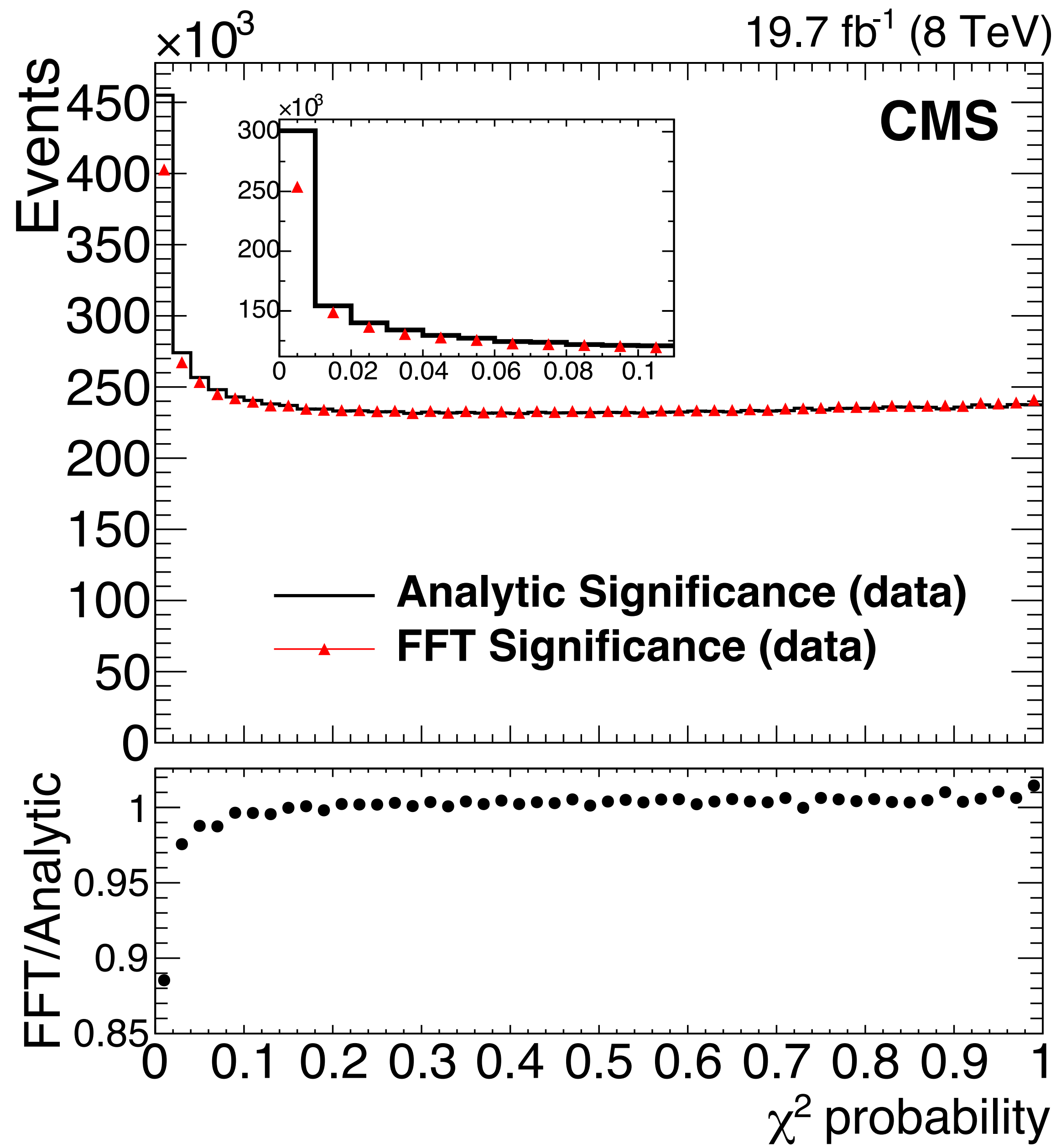
F) MET Significance (MET > 0)



Backgrounds for leptonic W selection are relatively stable against PU, while the leptonic W events are not

F) MET Sig (MET > 0) $W \Rightarrow e\nu$





Jet resolution functions have non-Gaussian tails

Convolve the individual objects' non-Gaussian resolutions using FFT

G) Conclusions/Summary

We have performed a comprehensive performance study of the MET variable with the full 2012 8 TeV pp dataset and corresponding simulation:

- MET filters have strong performance in removing fake MET events
- Standard PF MET is well modeled by the CMS simulation and shows consistent performance across different channels
- We have fully commissioned two PU Mitigating algorithms to combat the worsening of MET resolution from pileup (PF MET suffers a degradation of 3.3 – 3.6 GeV in quadrature for each additional PU interaction)
    - Both algorithms are acceptably modeled by the CMS simulation and both demonstrate notable improvements in the MET resolution dependence on pileup
- We have also commissioned the MET significance variable, which has stronger discrimination powers than standard MET related variables when it is used to demarcate between signals with “true MET” and backgrounds with “spurious MET”

TOC Backup slides

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MET Filters Selection Details

Events for MET filters dijet selection were collected using a **single jet trigger** requiring a PF jet with **p_T > 320 GeV**

To maximize trigger efficiency we require the **leading jet** have **p_T > 400 GeV**

To ensure that we are using dijet events we require a **second leading jet** with **p_T > 200 GeV**

Basic Selection criteria

$Z \rightarrow \mu\mu$ Kinematic cuts : $p_T > 20$ GeV, |eta|< 2.1
di-muon mass window: 60 to 120 GeV

$Z \rightarrow ee$ Kinematic cut: $p_T > 20$ GeV, |eta| < 1.444 or 1.57 < |eta| < 2.5
di-electron mass window: 60 to 120 GeV

$\gamma + \text{jet(s)}$ Kinematic cut: $p_T > 40$ GeV, |eta| < 1.444

MET Scale and Resolution

The main sources of events depend upon the channel

Z channels:

SM DY, **ttbar**, **single-top**, **VV** (V = Z/W)

Single Photon:

Gamma + Jet, **QCD**, **W+Jets**, **Diboson**, **VG**

All sources are modeled with simulation (**Madgraph**, **Pythia**, **Powheg**) except for **QCD**, which is modeled using a **data-driven method**

QCD Estimation for Photons

To mitigate the effects of large statistical weights on the QCD multijet simulation, the expected contribution of QCD events to the final photon selection is estimated using a data-driven method.

We define a **QCD enriched** region of events using a selection of photon events where the photon **failed** a specific **isolation cut** (**charged hadron** isolation)

For a given desired spectrum we want to plot, we take **data** from this **QCD enriched** region and **remove** the expected **non-QCD backgrounds** from this region **using** their estimation from **simulation**

This "**QCD Data**" spectrum is then **normalized** to the nominal **expected QCD contribution** in the **main selection** (using Data - nonQCD MC from main selection)

Shape corrections are **applied** to the "**QCD Data**" to account for **response differences** for events from the two selections (**main** and **QCD-enriched**) – see next slide

QCD Recoil Correction

We estimate the contribution of QCD multijet events to our final selection region by plugging in events from an isolation sideband of data.

We utilize QCD multijet simulation to estimate the systematic bias that comes from this extrapolation and subsequently correct for this bias

Correction = fit to the ratio of MET scale vs. q_T for QCD multijet MC events from the two photon candidate isolation regions

Systematic uncertainty intrinsic to the correction is based on fit parameter values and correlations

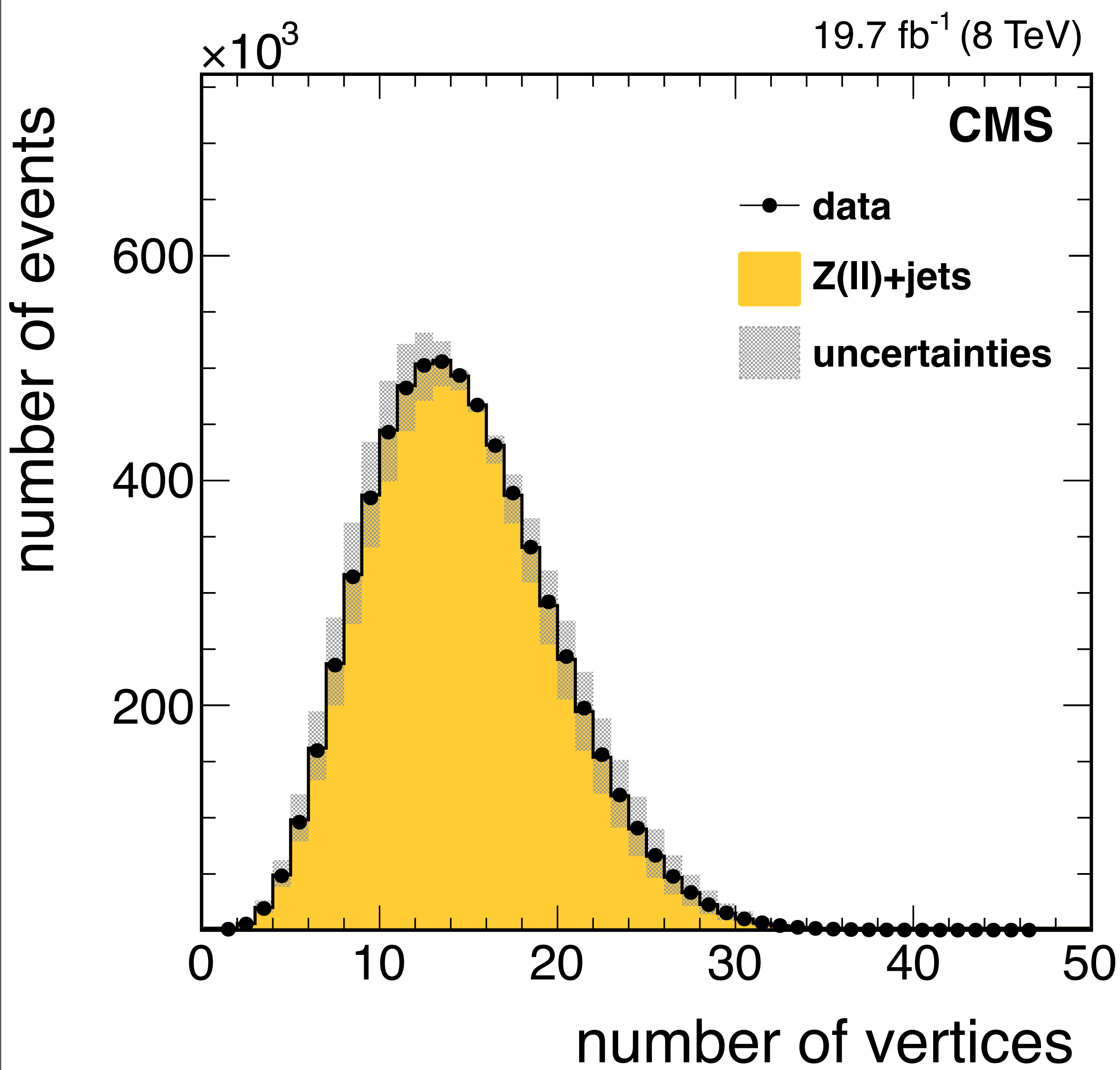
MET Systematics

As a composite object, MET is subject to energy scale (ES) and resolution (ER) uncertainties on all visible objects

- Leptons
  - Electron ES: 0.6% (barrel) / 1.5% (endcap)
  - Muon ES: 0.2%
- Photon ES: same as Electrons
- Unclustered ES: 10%
- Jet ES: 2-10%
- Jet ER: 6-15%
- QCD estimation uncertainty (photon events only): 5%

Backup TOC

Baseline Spectra: N_{vtx}



$$Z \to \mu\mu$$

Pileup has several adverse effects on event reconstruction

– Smears out MET resolution

– Deposits energy in isolation cones of probe particles (leptons/photons) interfering with proper ID/energy measurement

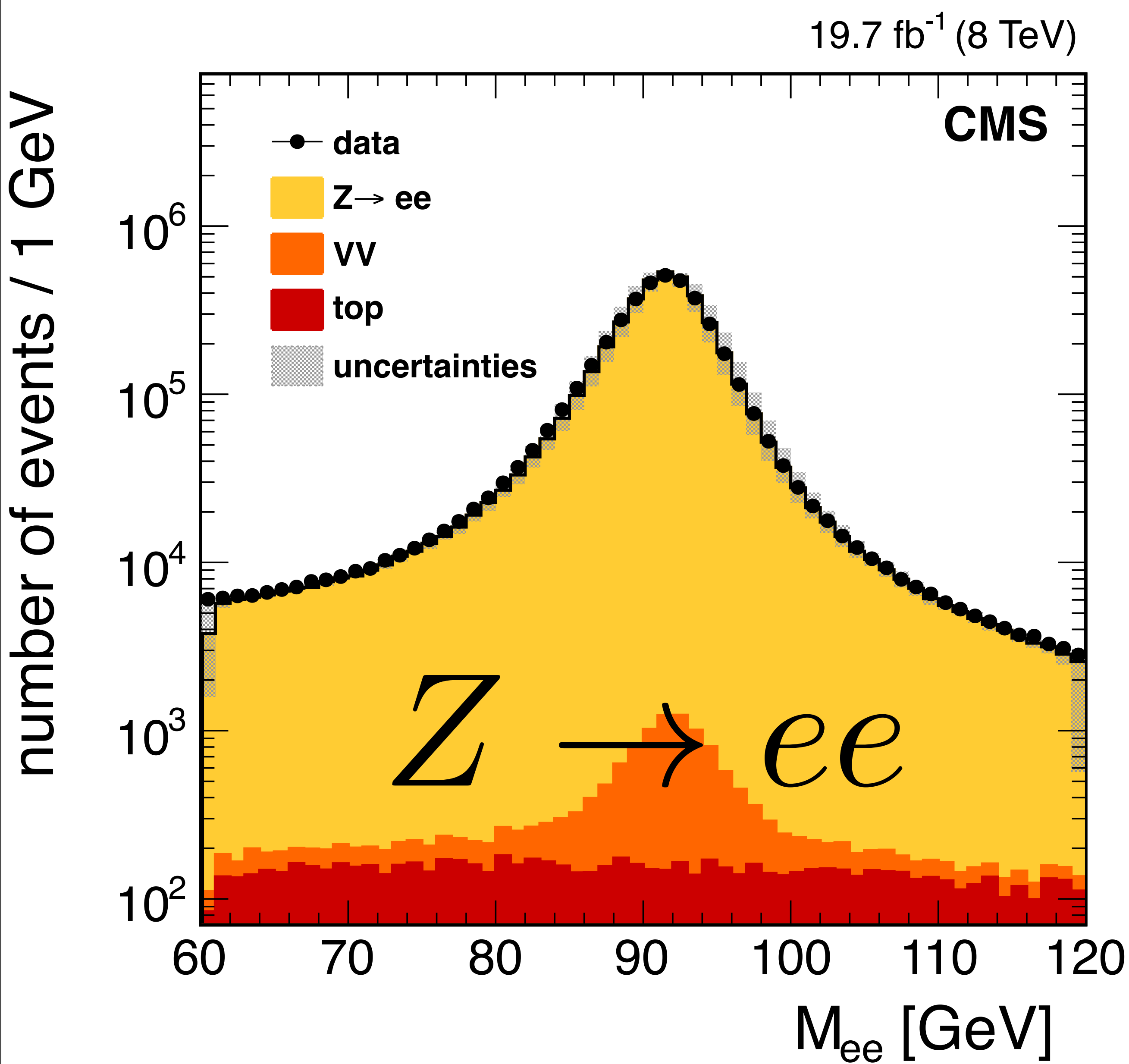
In order to have sensible data/MC comparisons, MC PU re-weighted to match observed distribution in data

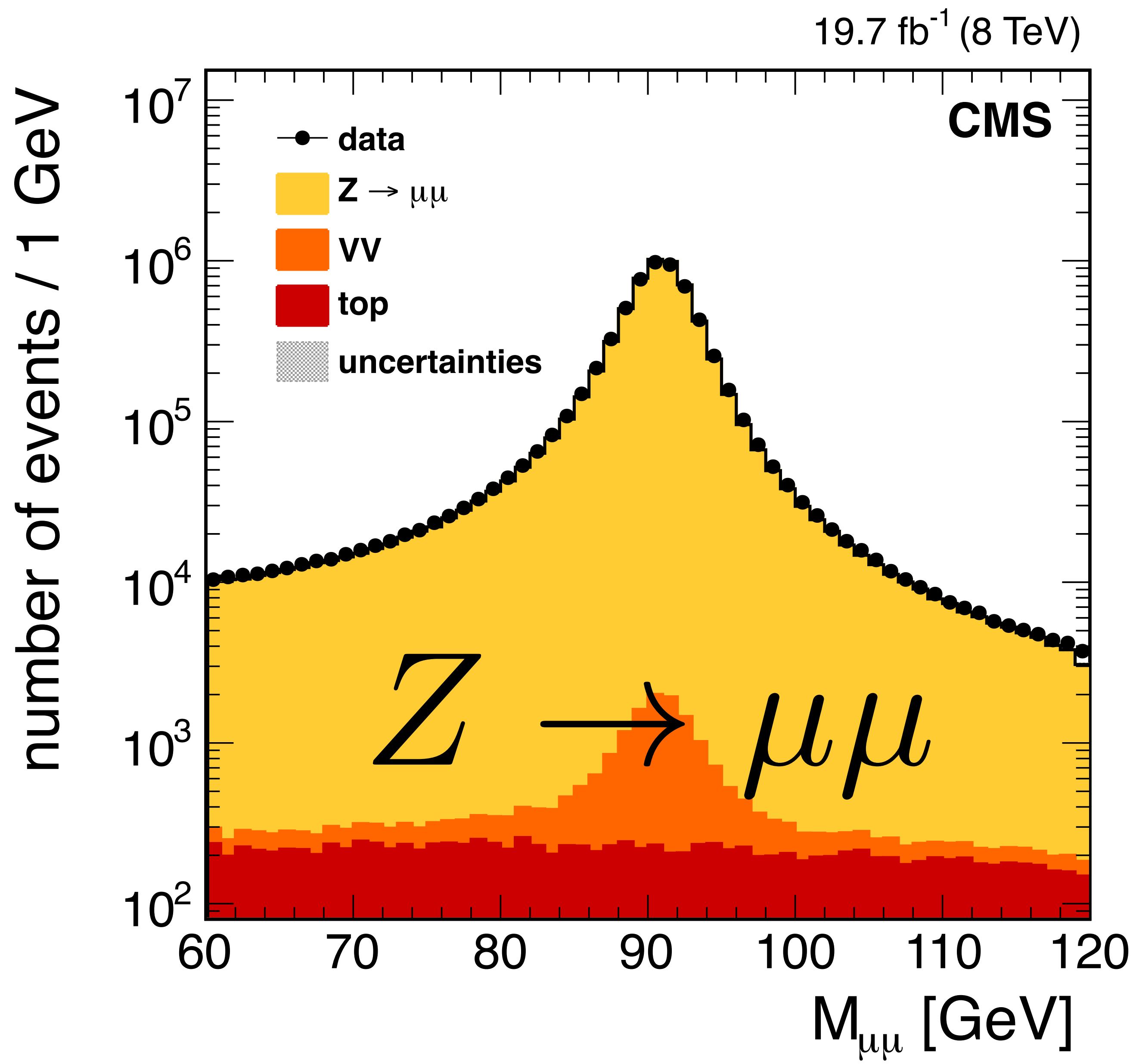
Systematic uncertainties are:

Inelastic scattering xsec (4.5%)

Instantaneous lumi measurement (2%)

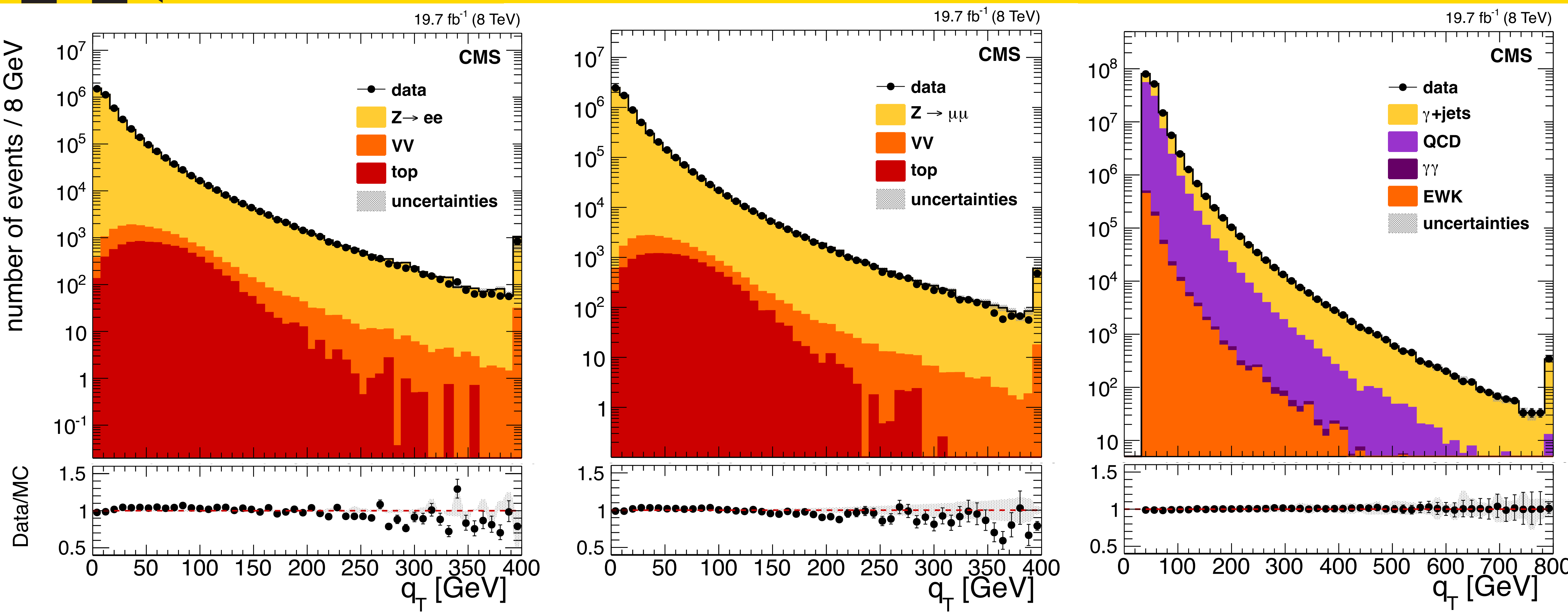
Baseline Spectra: ZMass





Well-modeled within systematics

Baseline Spectra: q_T

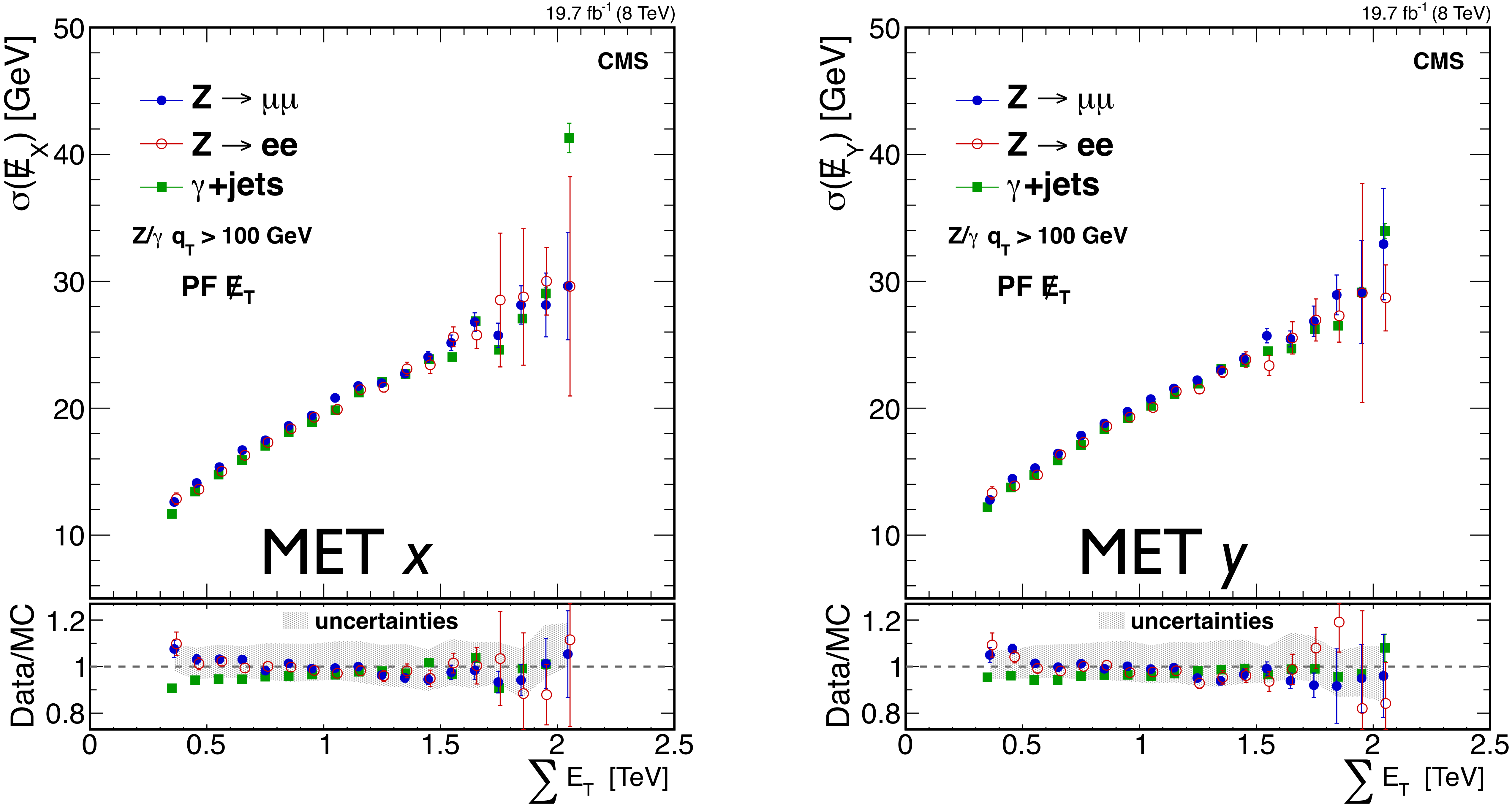


$Z \to ee$ $\quad$ $Z \to \mu\mu$ $\quad$ $\gamma + \mathrm{jet(s)}$

Z channels show good Data/MC agreement

Photon q_T reweighted for Data/MC agreement

Combo Plot: PF Res. vs. Sum E_T



Sum E_T = (Standard SumE_T - photon/leptons E_T)

MET resolution dependence on total hadronic activity in event

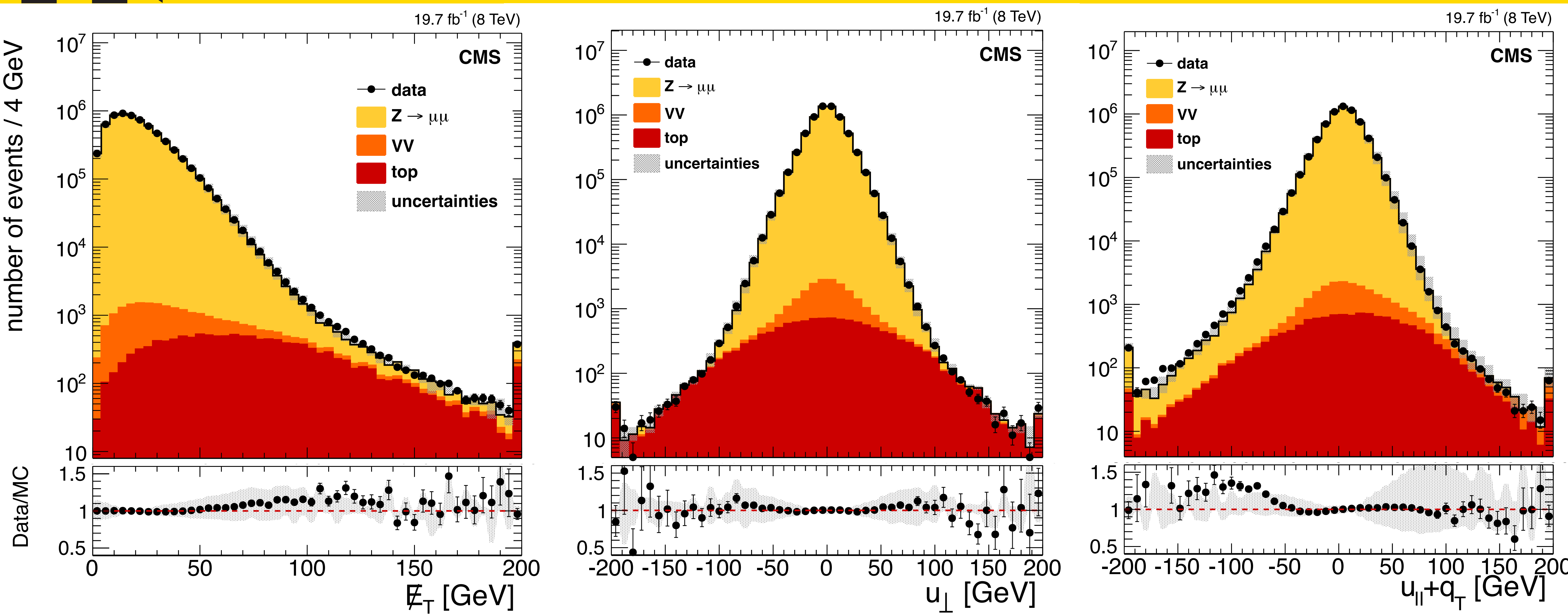
Parameter Fit: PF Res. vs. Sum E_T

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

Channel	$\not{E}_x$ component			
	σ_0 (GeV)	$R = \sigma_0(\text{data})/\sigma_0(\text{MC})$	σ_s ($\text{GeV}^{1/2}$)	$R = \sigma_s(\text{data})/\sigma_s(\text{MC})$
γ + jets	0.70 ± 0.01	$2.37 \pm 1.11 \pm 0.17$	0.60 ± 0.01	$0.99 \pm 0.05 \pm 0.06$
$Z \rightarrow e^+e^-$	0.84 ± 0.46	$0.83 \pm 0.16 \pm 0.00$	0.60 ± 0.02	$1.01 \pm 0.02 \pm 0.07$
$Z \rightarrow \mu^+\mu^-$	1.37 ± 0.34	$0.51 \pm 0.30 \pm 0.00$	0.59 ± 0.01	$1.05 \pm 0.02 \pm 0.08$
	$\not{E}_y$ component			
	σ_0 (GeV)	$R = \sigma_0(\text{data})/\sigma_0(\text{MC})$	σ_s ($\text{GeV}^{1/2}$)	$R = \sigma_s(\text{data})/\sigma_s(\text{MC})$
γ + jets	0.76 ± 0.05	$2.34 \pm 1.10 \pm 0.35$	0.60 ± 0.01	$0.99 \pm 0.05 \pm 0.04$
$Z \rightarrow e^+e^-$	1.30 ± 0.45	$0.70 \pm 0.76 \pm 0.09$	0.58 ± 0.02	$1.04 \pm 0.06 \pm 0.08$
$Z \rightarrow \mu^+\mu^-$	1.47 ± 0.33	$0.48 \pm 0.26 \pm 0.00$	0.59 ± 0.01	$1.07 \pm 0.02 \pm 0.09$

Table 2: Parametrization results of the resolution curves for the components of $\vec{\not{E}}_T$, as functions of $\sum E_T$. The parameter values σ_0 and σ_s are obtained from data. For each parameter, we also present R, the ratio of values obtained in data and simulation. For the ratios, the first uncertainty is from the fit, and the second uncertainty corresponds to the propagation of the following into the parameterization: systematics uncertainties in the jet energy scale, jet energy resolution, lepton/photon energy scale, and unclustered energy scale, as well as, for direct-photon events only, the systematic uncertainty assigned to the QCD multijet estimation response correction described in Section 3.

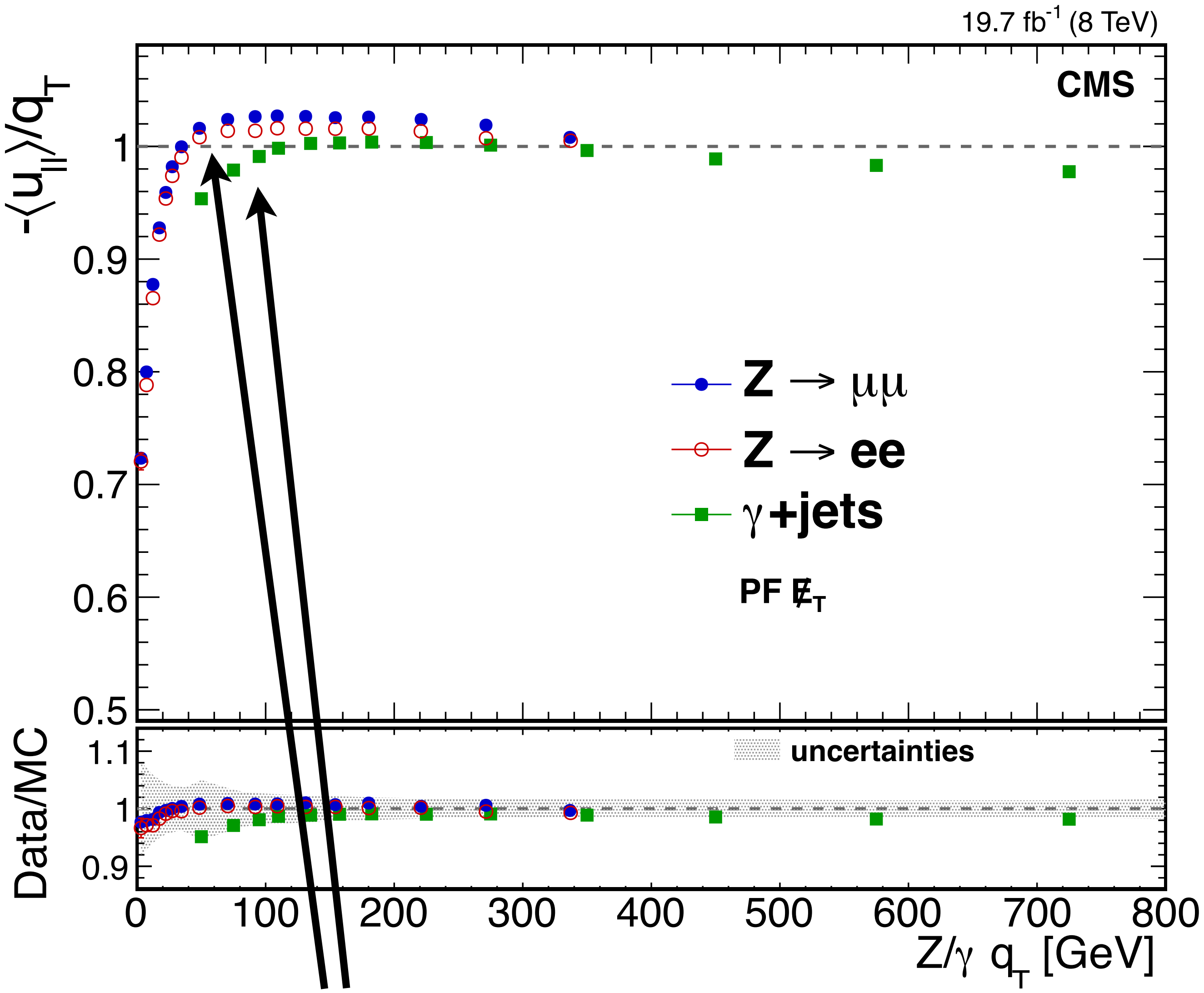
Calo MET spectra $Z \to \mu\mu$



$\not{E}_T$ $\qquad$ $u_\perp$ $\qquad$ $u_{||} + q_T$

Jet ES and Unclustered ES systematics shown

PF QCD scale comparison



Why the difference?

1) Gluon jets have lower response compared with quark jets

2) The sample of events used in the photon MET study has a non-trivial contribution from QCD multijets (jet enriched in pi$_0$s provides the photon candidate)

2a) These QCD multijet events have much larger gluon jet fractions in their hadronic recoil compared with normal photon + jet events (c.f. gluon vs. quark pdfs)

2b) For these pi$_0$ enriched jets, the reconstruction of the "photon" misses some of the energy from the jet. This biases the measurement of q_T for the QCD events

NoPU MET Guiding Principles

Separate visible objects in the event into

1. Hard scatter objects

- Leptons (electrons, high p_T photons, muons, hadronic taus)
- High p_T jets that pass a PU Jet ID
- Charged PF particles associated to the HS vertex

2. Particles that may or may not be coming from the pileup interactions

- High p_T jets that fail a PU Jet ID and all low p_T jets
- Neutral PF particles
- Charged PF particles not associated to the HS vertex

NoPU MET Formalism

$$\vec{E\!\!\!/}_{\mathrm{T}} = -\Bigg[\sum_{\text{leptons}} \vec{p}_{\mathrm{T}} + \sum_{\text{HS-jets}} \vec{p}_{\mathrm{T}} + \sum_{\text{HS-charged}} \vec{p}_{\mathrm{T}} + S_{\mathrm{F}} \cdot \left(\alpha \cdot \sum_{\text{PU-charged}} \vec{p}_{\mathrm{T}} + \beta \cdot \sum_{\text{neutrals}} \vec{p}_{\mathrm{T}} + \gamma \cdot \sum_{\text{PU-jets}} \vec{p}_{\mathrm{T}} + \delta \cdot \vec{\Delta}_{\mathrm{PU}}\right)\Bigg]$$

$$S_{\mathrm{F}} = \frac{\sum_{\text{HS-charged}} p_{\mathrm{T}}}{\sum_{\text{HS-charged}} p_{\mathrm{T}} + \sum_{\text{PU-charged}} p_{\mathrm{T}}}$$

Leptons: defined by user

HS-Jets: Jets with corrected p_T > 30 GeV that pass PU Jet ID

HS-charged: Charged PF Particles passing Δz < 2mm w.r.t. HS vertex

PU-Jets: Jets with corrected p_T > 30 GeV that fail PU Jet ID

PU-charged: Charged PF Particles failing Δz < 2mm w.r.t. HS vertex

PU-Jets: Neutral PF Particles

ΔPU: Pileup correction (Type 0 Correction from MET Corrections slide)

Parameters were determined by numerical optimization of the NoPU MET resolution and response

Jet p_T Thresh: 30 GeV

α: 1.0

β: 0.6

γ: 1.0

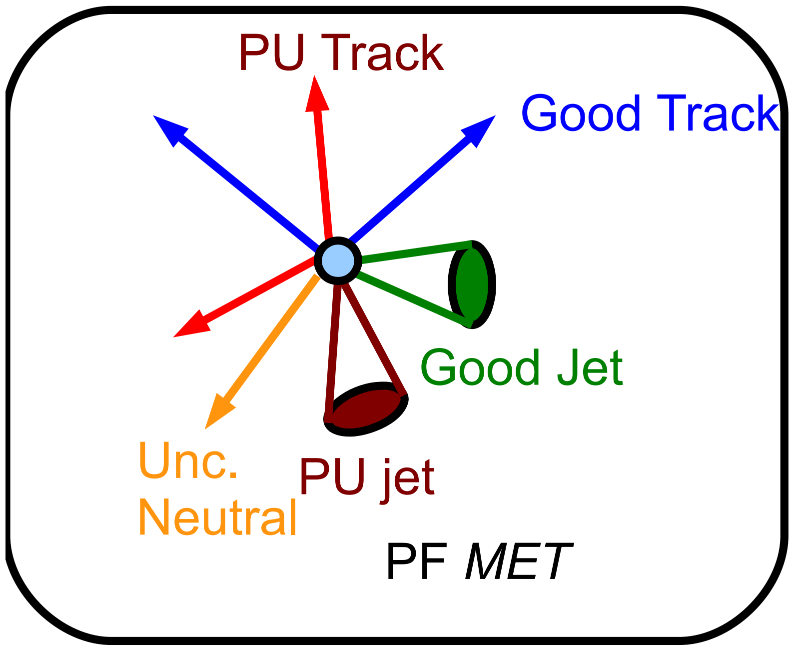
δ: 1.0

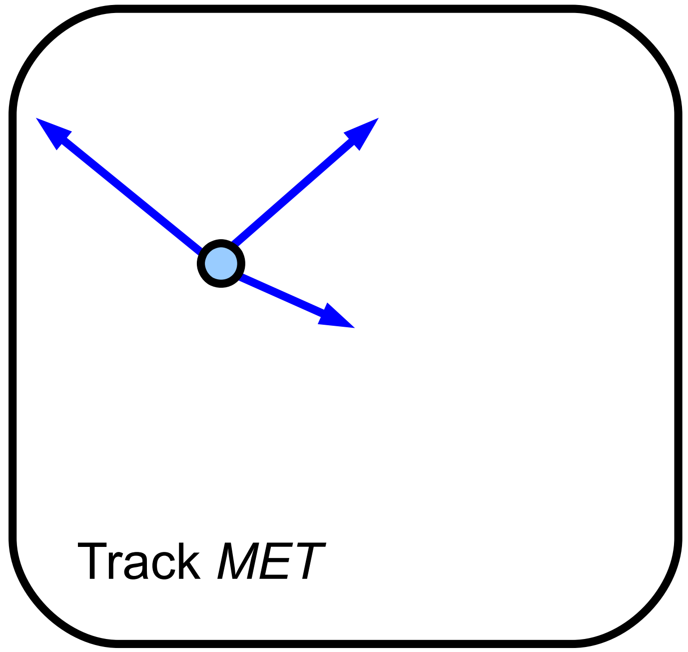
What is MVA *MET*?

- Step 0 : Determine your final state
  - Could class of final states (*ie* leptons+photons)
- Step 1 : Apply PU Jet id to all jets
  - No pT requirement applied to jets (pT > 3 GeV)
- Step 2 : Apply type 1 corrections to pf *MET*
  - No L1 (Pileup) corrections for anything
- Step 3 : compute recoil for 5 different *METs*
  - Recoil defined as *MET* + final states (removing them)
  - Variables : φ+sum Et + magnitude + 2 leading jets
- Step 4 : apply regression to correct PF recoil φ/mag
  - $\varphi' = \varphi + corr_1$, $|u'_{PF}| = |u_{PF}| corr_2$

MVA PF MET

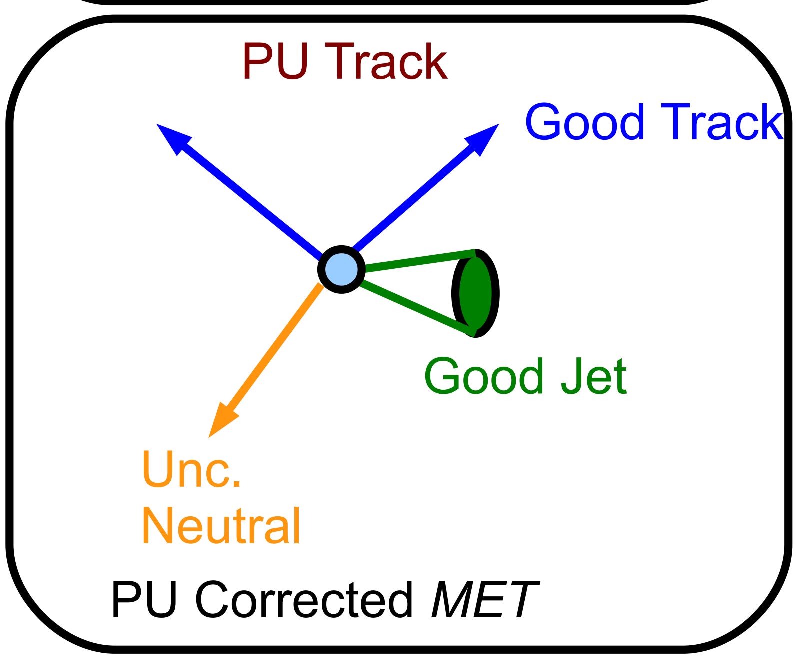
MVA *MET* Inputs

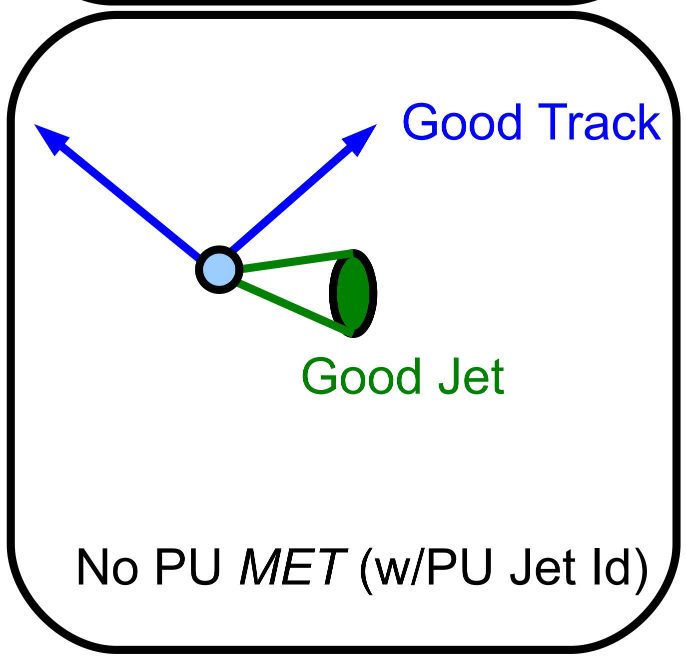


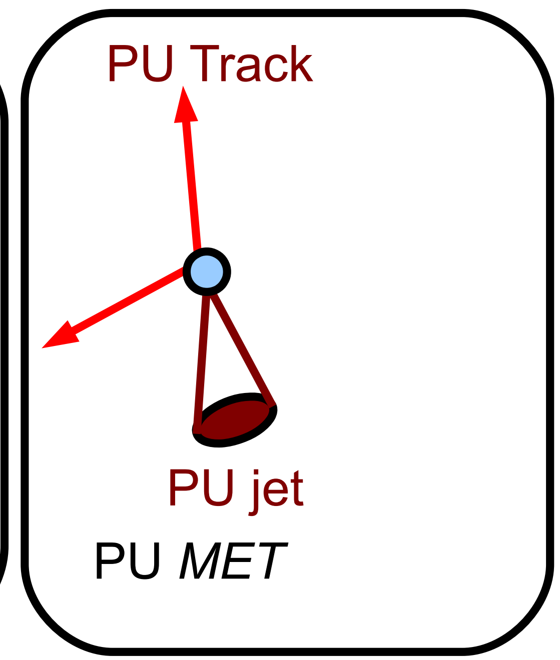


5 Different *METs*
Each targeted on a different aspect

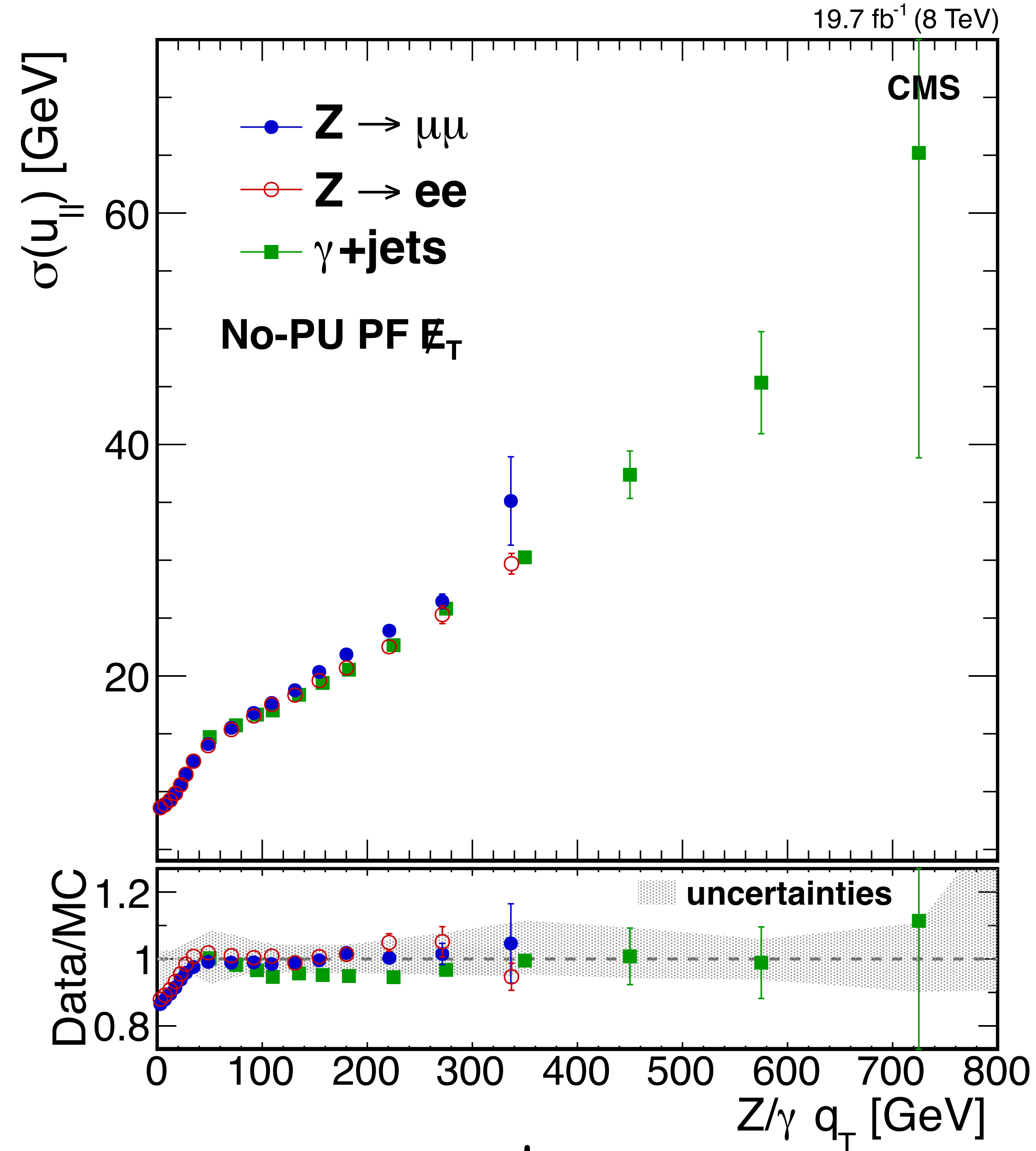
Take recoil
(except PU *MET*)



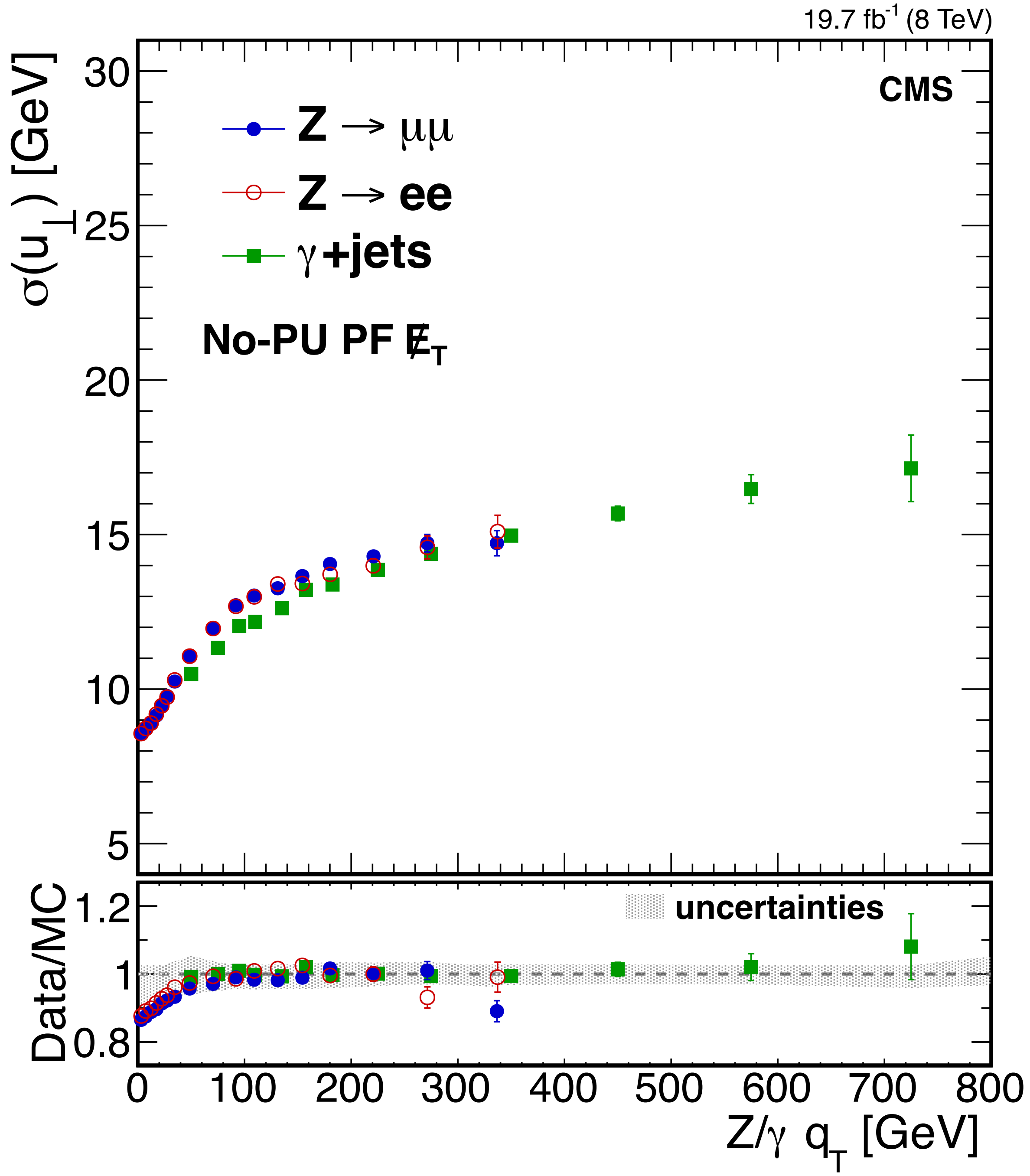




NoPU PF Res. vs. q_T

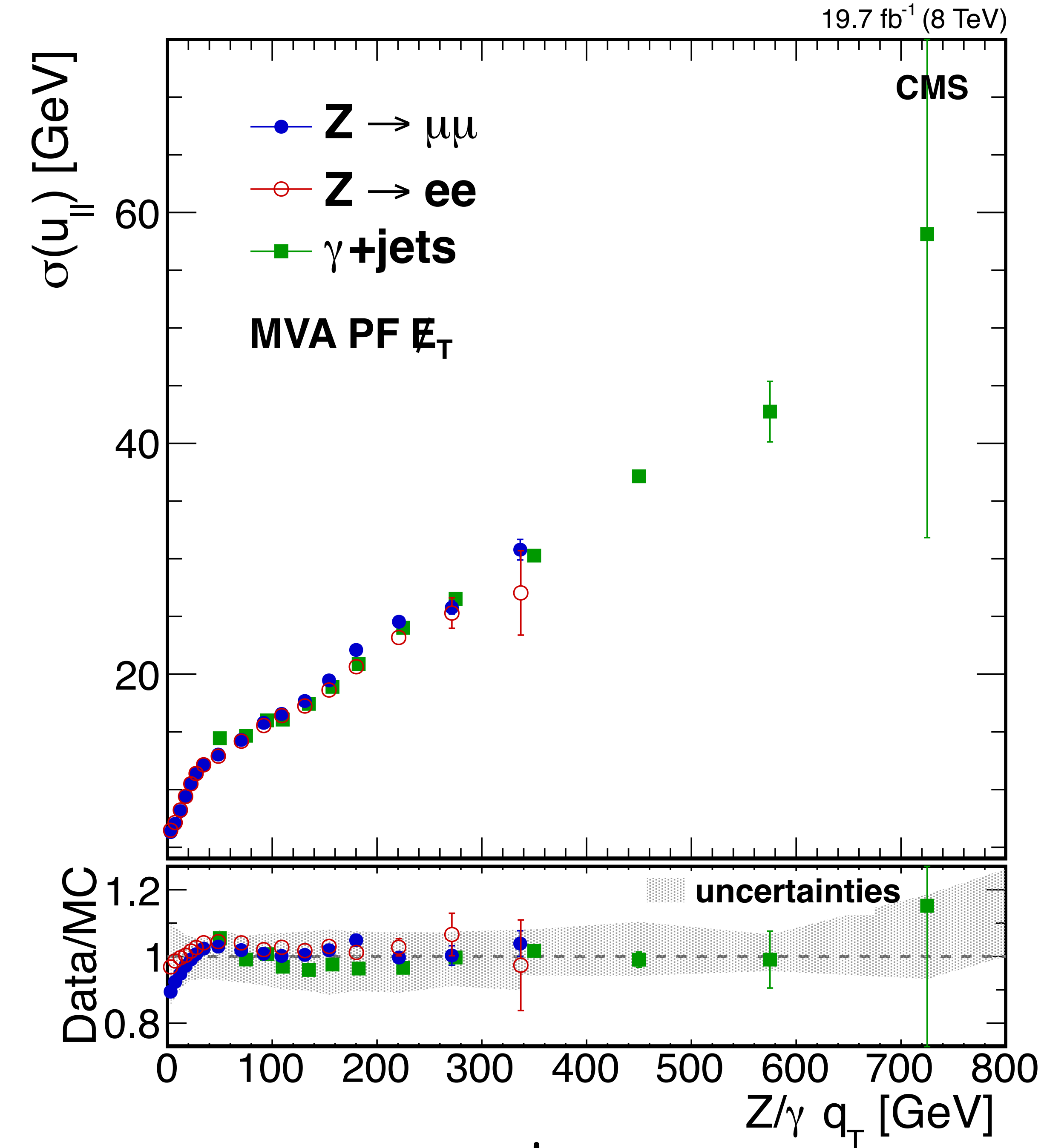


$$u_{||} + q_T$$

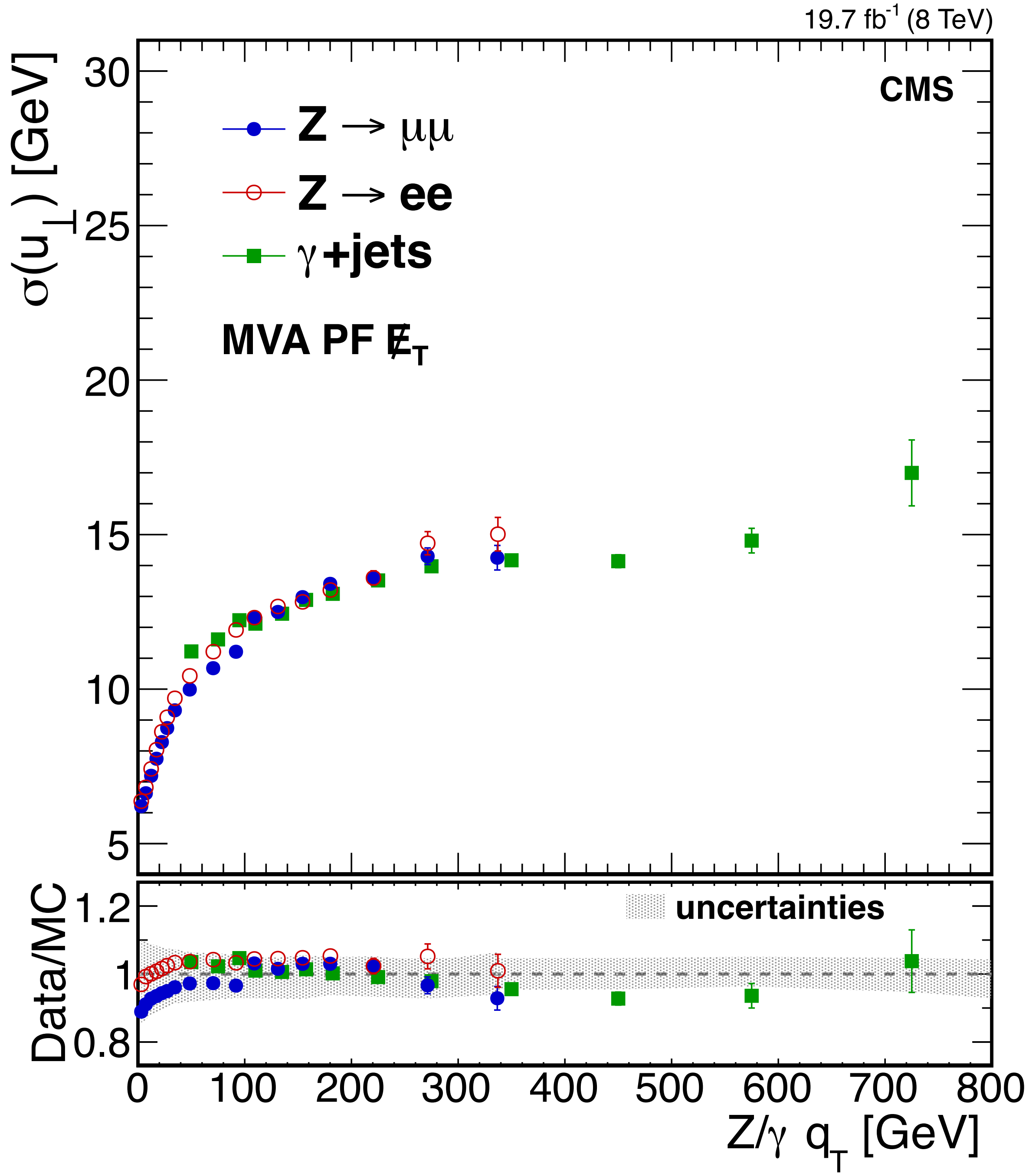


$$u_{\perp}$$

MVA PF Res. vs. q_T

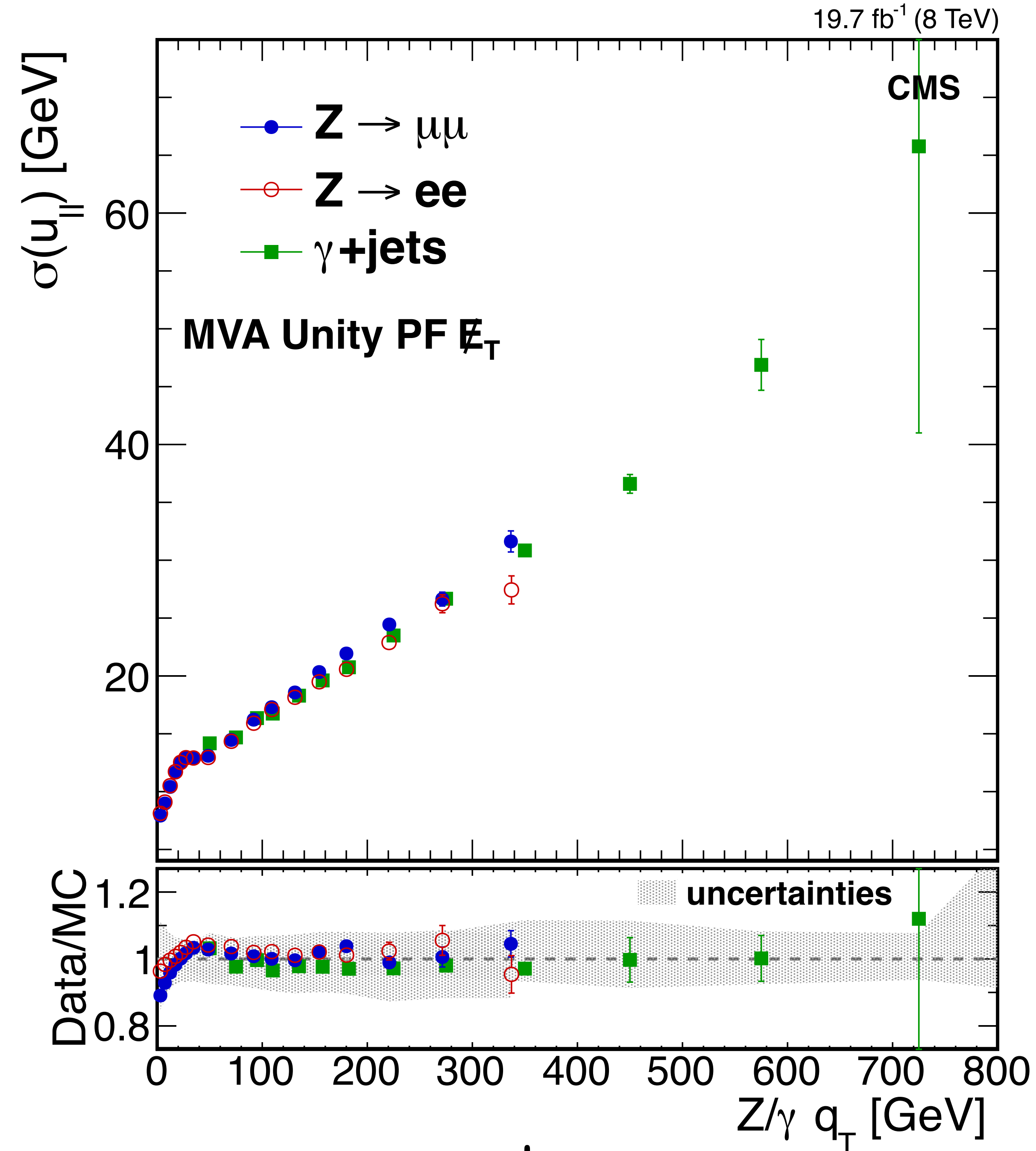


$$u_{||} + q_T$$

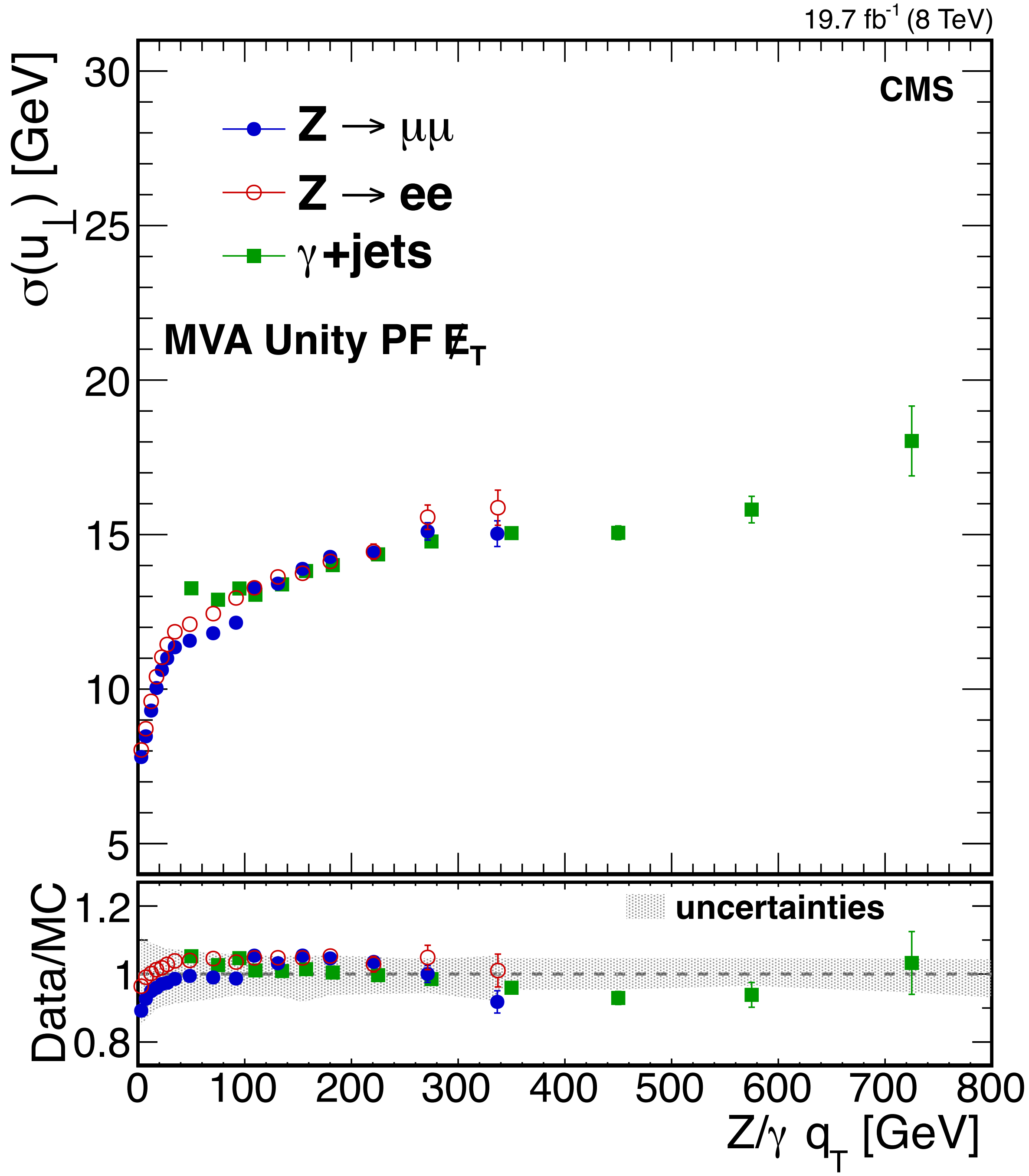


$$u_{\perp}$$

MVA Unity PF Res. vs. q_T

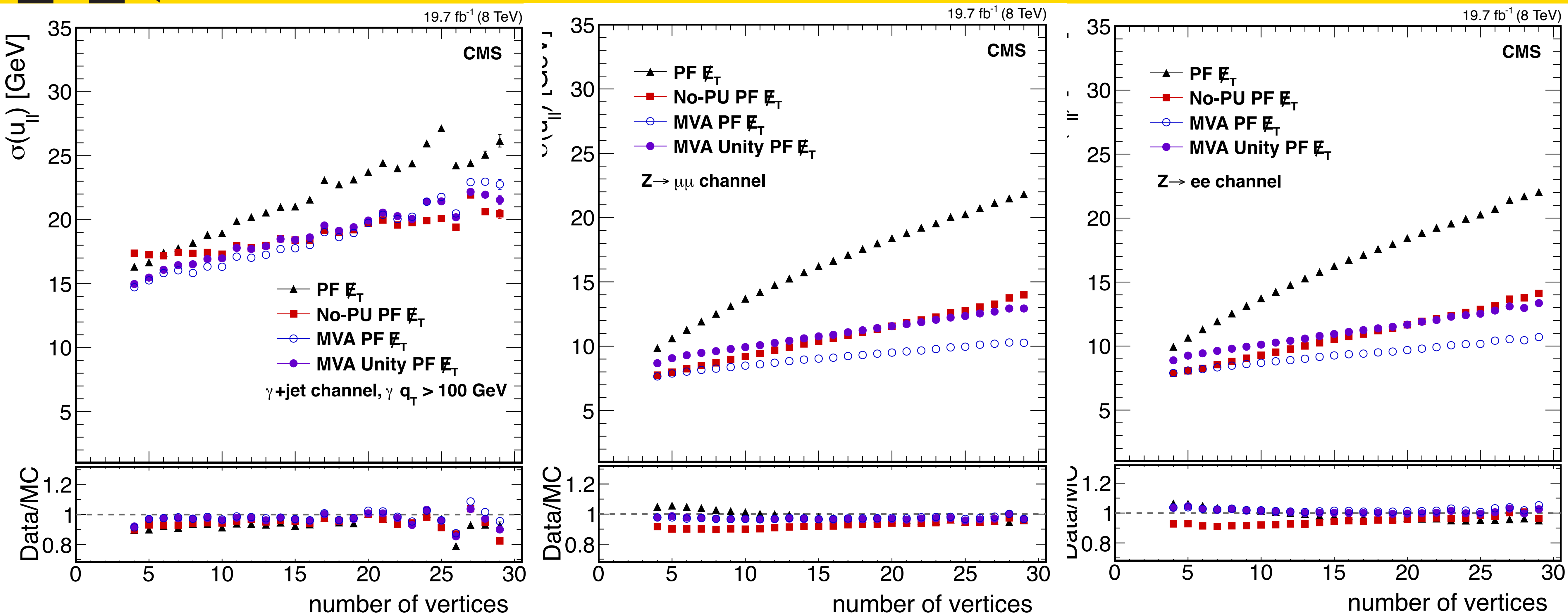


$$u_{||} + q_T$$



$$u_{\perp}$$

$U_{par}+q_T$ Res. vs. N_{vtx}

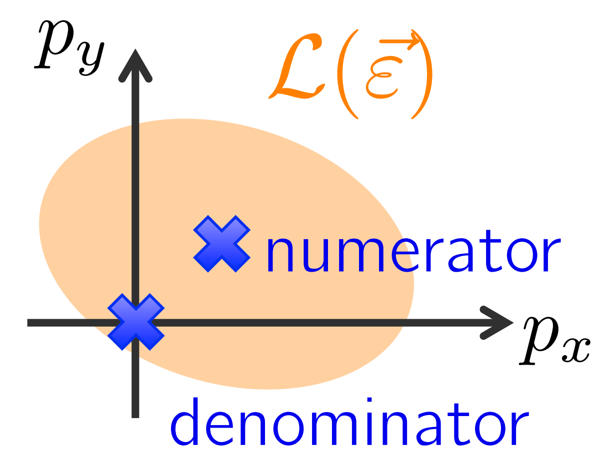


$\gamma + \text{jet(s)}$ $\quad Z \to \mu\mu$ $\quad Z \to ee$

PU Mitigation algorithms greatly help with MET resolution degradation from Pileup

MET Significance (Formalism)

$$\mathcal{S} \equiv 2\ln\left(\frac{\mathcal{L}(\vec{\varepsilon} = \sum \vec{\varepsilon}_i)}{\mathcal{L}(\vec{\varepsilon} = 0)}\right).$$



Consider the likelihood for an event to have a "true" MET given a measured MET value

In the Gaussian approximation, this simplifies

$$S = \left(\sum_i \vec{\varepsilon_i}\right)^{\dagger} \mathbf{V}^{-1} \sum_i \vec{\varepsilon_i}$$

where **V** is the event's **total covariance matrix**, constructed by summing over individual objects covariances, i.e.

$$\mathbf{U} = \begin{pmatrix} \sigma_{p_\mathrm{T}}^2 & 0 \\ 0 & p_\mathrm{T}^2\,\sigma_\phi^2 \end{pmatrix},$$

$$\sigma(p_\mathrm{T}, \eta) = a(\eta) \times \sigma^{\mathrm{MC}};$$

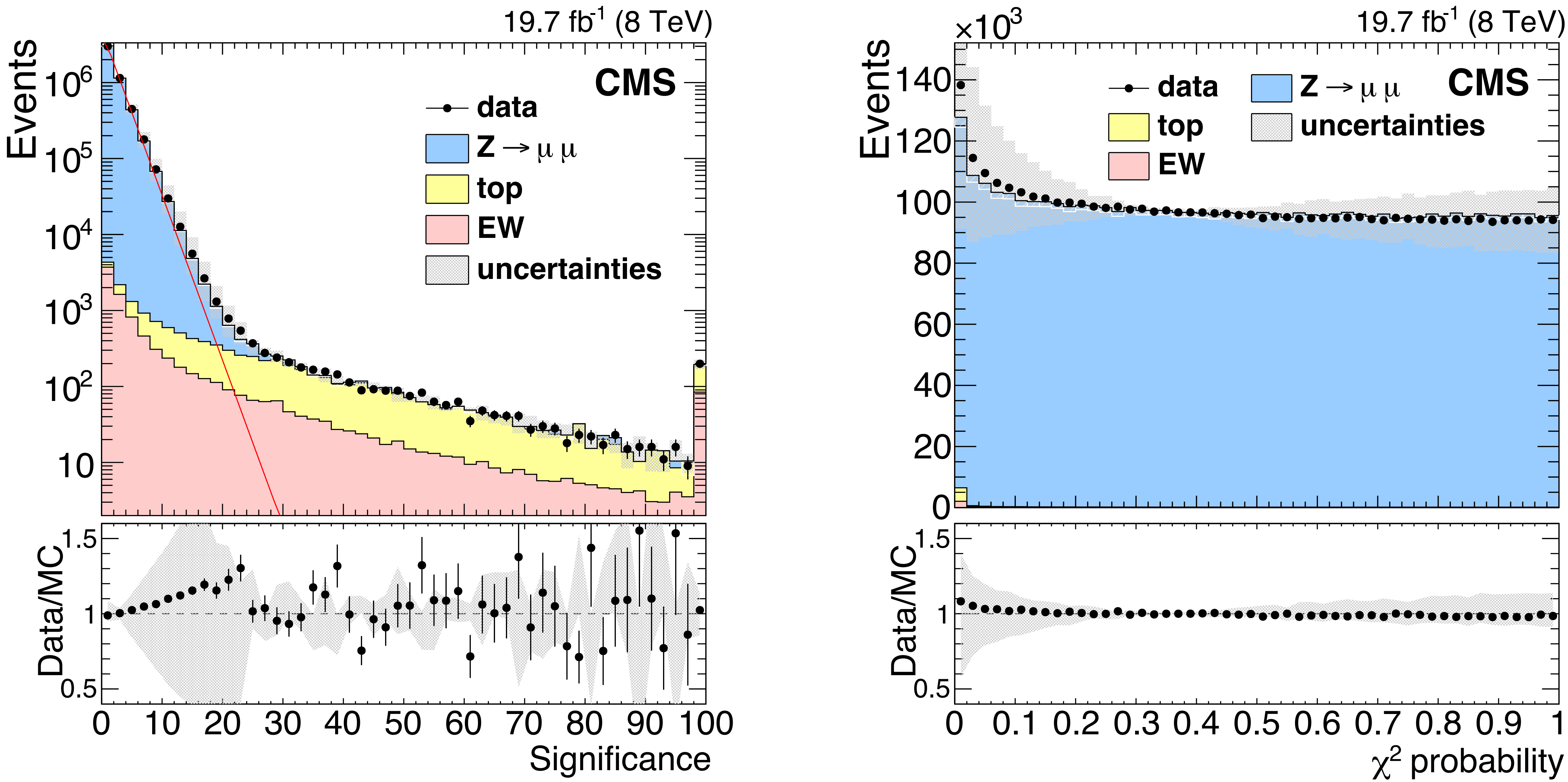
U – the covariance matrix(es) for the individual hard scatter PF jet(s)

V_{uc} – the covariance matrix for the unclustered energy "pseudo-jet"

$$\mathbf{V}_{uc} = \begin{pmatrix} \sigma_{uc}^2 & 0 \\ 0 & \sigma_{uc}^2 \end{pmatrix} = n\sigma_X^2\,\mathbf{I},$$

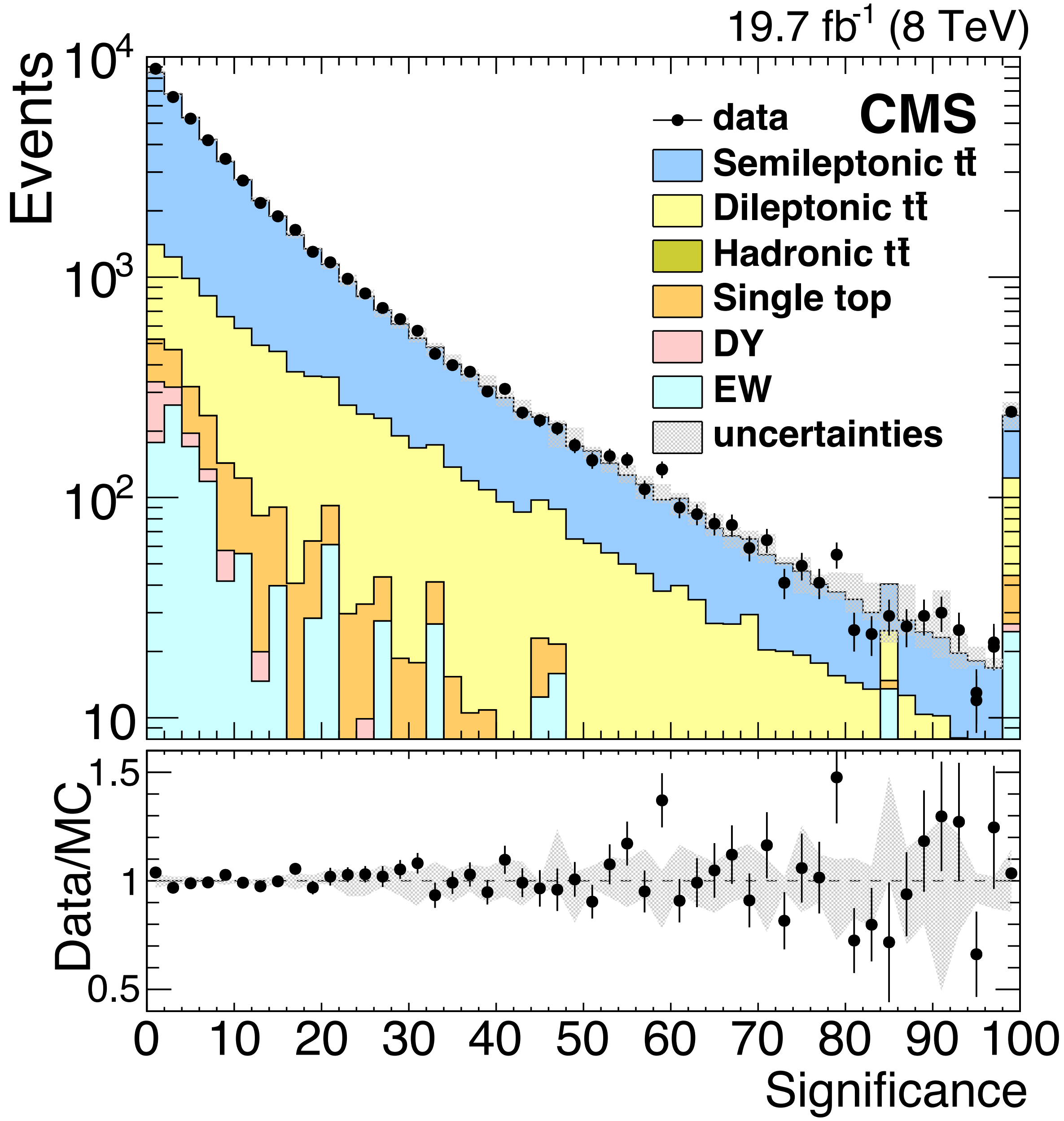
$$\sigma_{uc}^2 = \sigma_0^2 + \sigma_s^2 \sum_{i=1}^{n} |\vec{p}_{T_i}|,$$

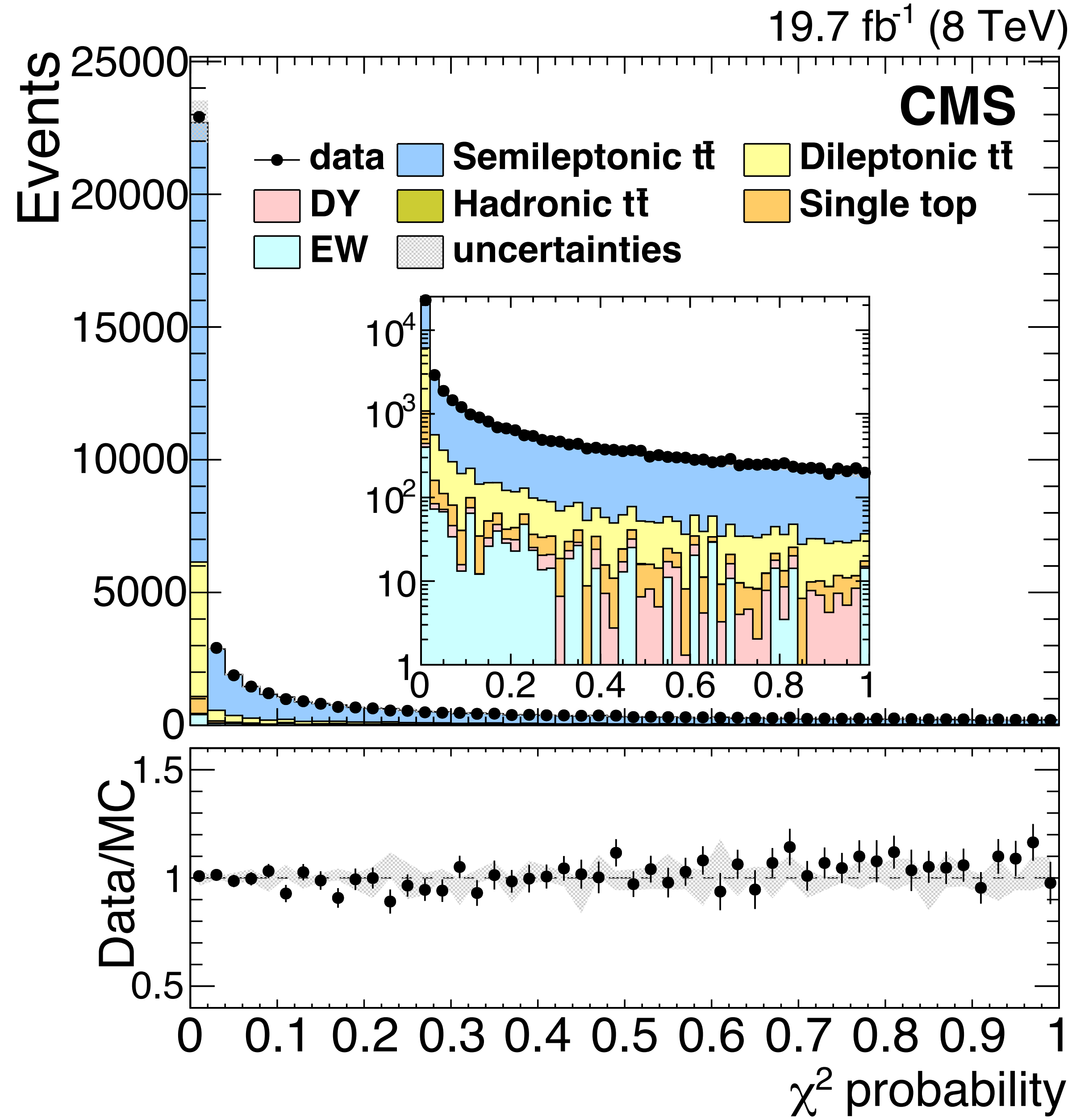
MET Significance (MET = 0)



$$Z \to \mu\mu$$

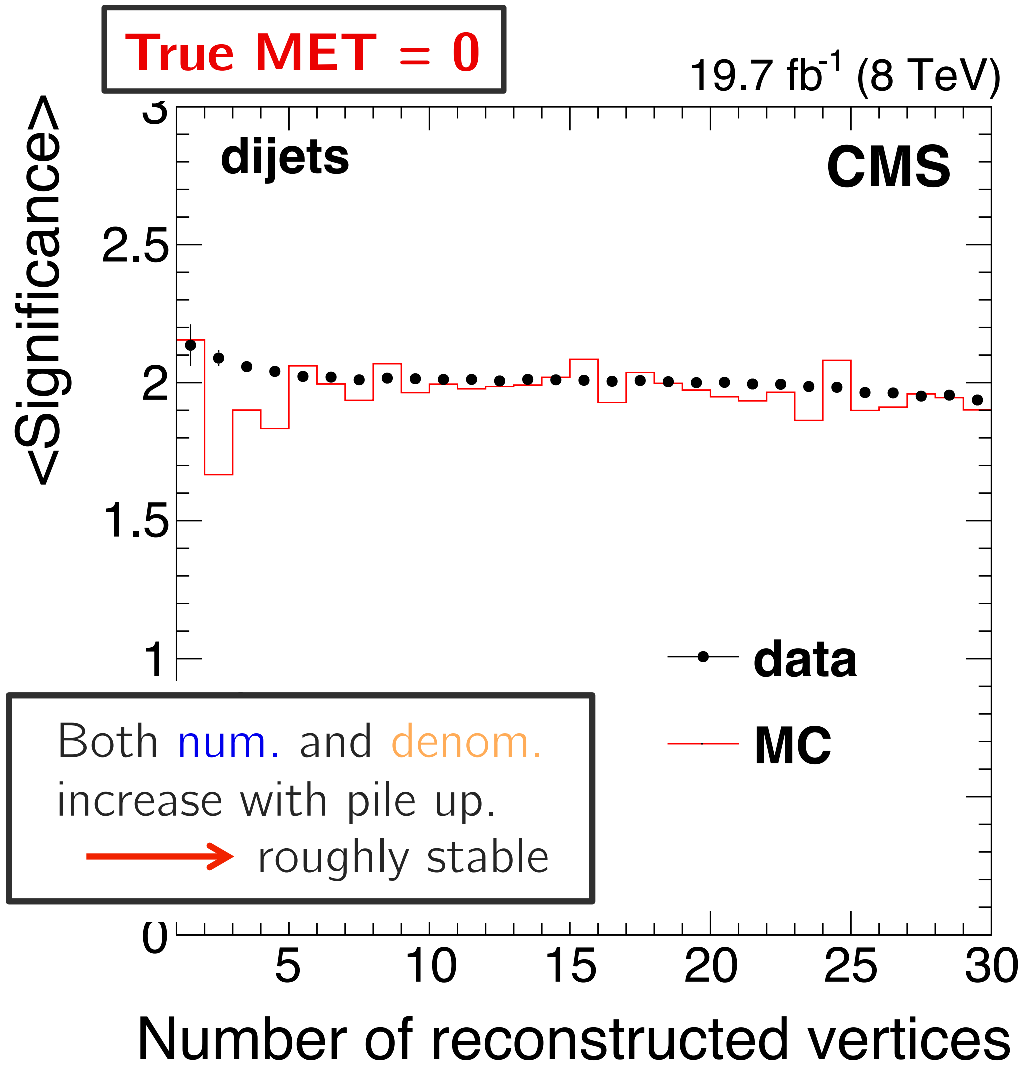
MET Significance (MET > 0)

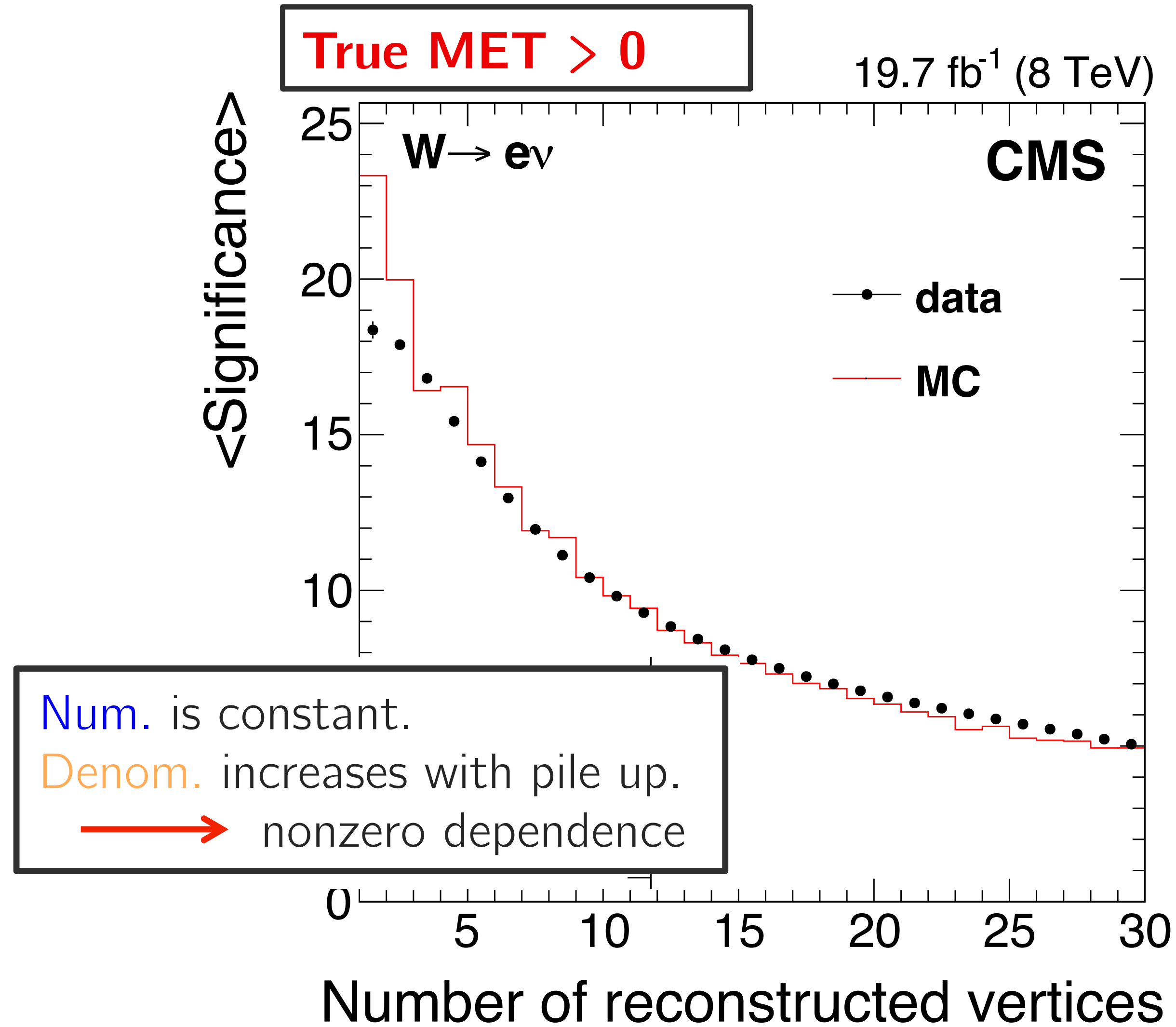




Semi-leptonic ttbar

MET Significance (MET > 0)





Pileup primarily contributes to soft hadronic activity

Behavior w.r.t. PU stems from the definition of MET Sig

$$\mathcal{S} \sim \frac{\not{E}_T^2}{\sigma^2_{\not{E}_T}}$$