Missing Transverse Momentum

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Many materials taken from previous CMS DAS

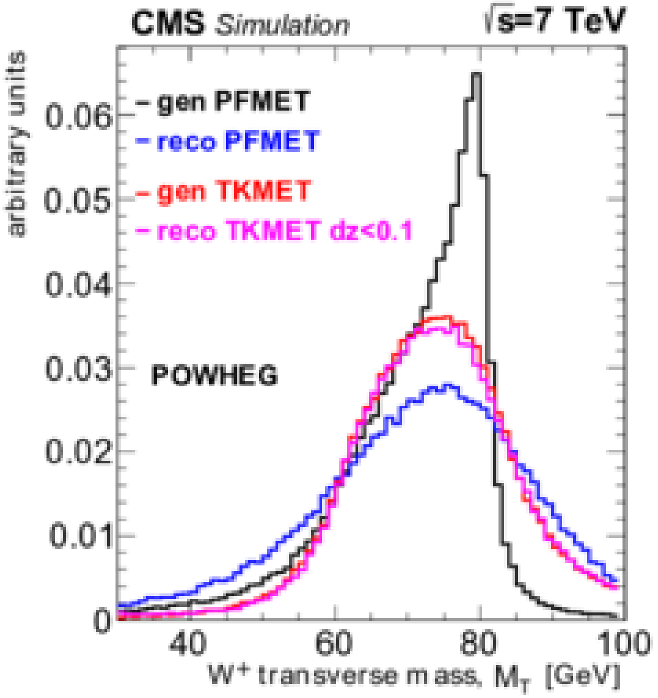
Introduction

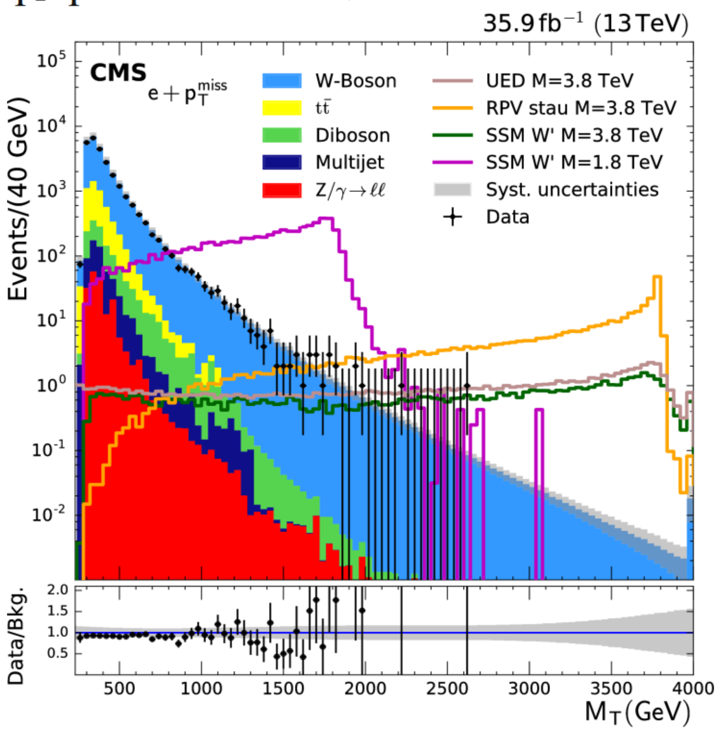
- Missing transverse momentum (丢失横动量or横动量失衡: MET, E_T^{miss}, p_T^{miss})
  - Momentum imbalance evaluated by vectorially adding all the particle flow (PF) candidates (electrons, photons, muons, neutral hadrons, charged hadrons & other particles in the forward region).
  - We can only evaluate the transverse direction (x,y), since the momenta do not balance in the z direction in hadron colliders.
- Indirect probe for weakly interacting neutral particles (neutrinos, dark matter candidates, long-lived particles) that leave no signal in CMS.

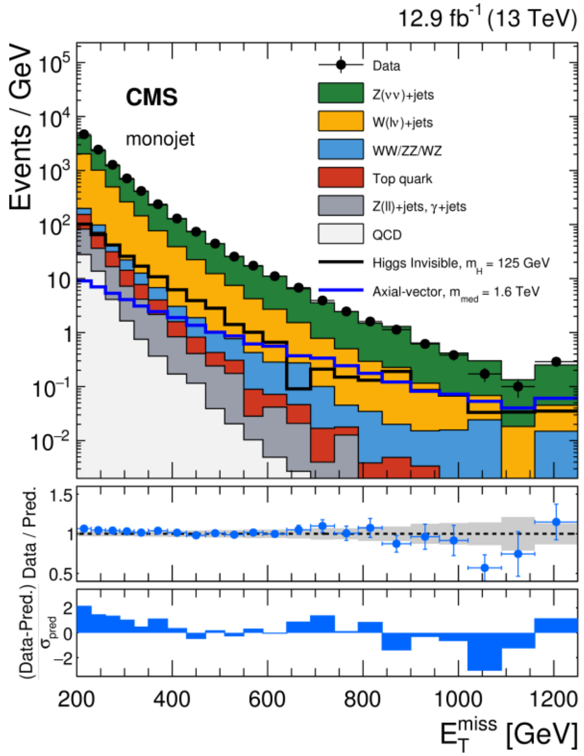
Why MET Important?

- Standard model measurements: W mass (from $W \rightarrow e\nu_e, \mu\nu_\mu$), top-quark mass ($tt \rightarrow bWbW$), Higgs decays to W+W-, τ+τ-
- Physics beyond the Standard Model: heavy bosons, supersymmetry, dark matter, etc.

$$m_T = \sqrt{2 p_T^{\ell} p_T^{miss} (1 - \cos \Delta\phi)},$$

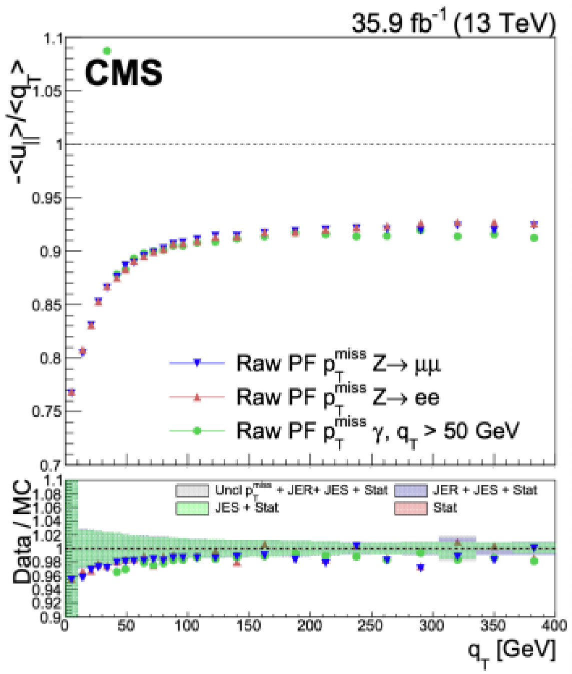


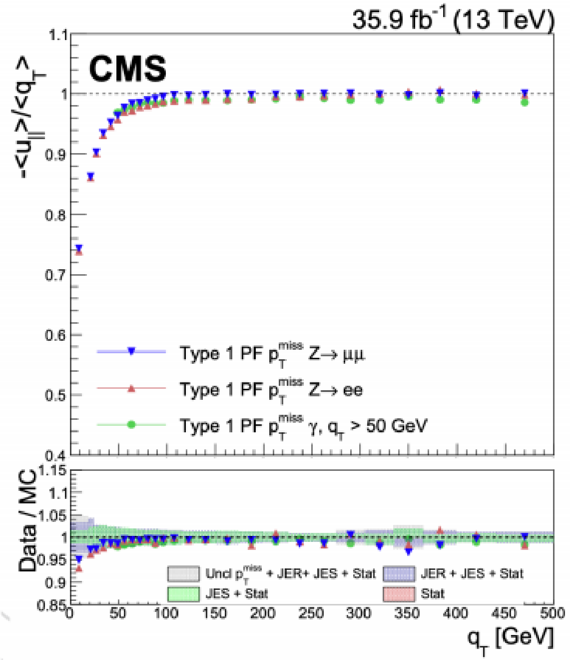




Types of MET

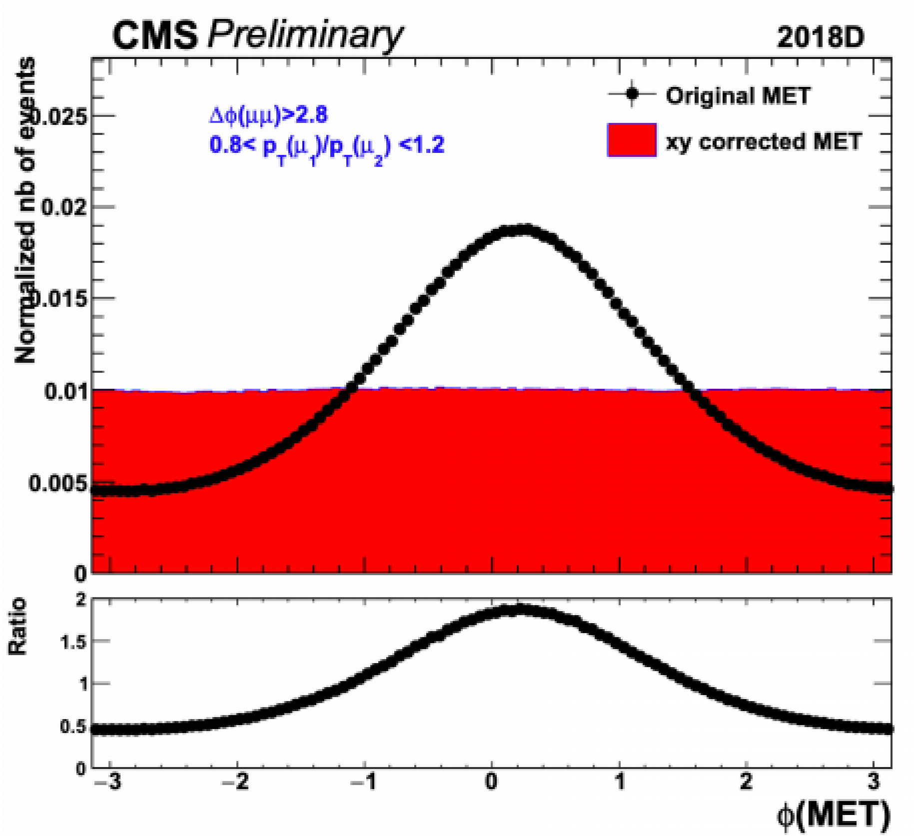
- In reality, we cannot avoid inaccuracy in MET due to:
  - Minimum p_T threshold to suppress calorimeter noise, etc.
  - Non-linearity in the calorimeter response
  - Inefficiency in track reconstruction
  - Pileup & etc.
- Raw PF MET: a simple vector sum of all the PF candidates.
- Type-1 PF MET: propagate jet energy corrections to corresponding PF. → default in most of LHC Run 2
- PUPPI MET: Pileup contributions are removed from PF. → will be default in Run 3





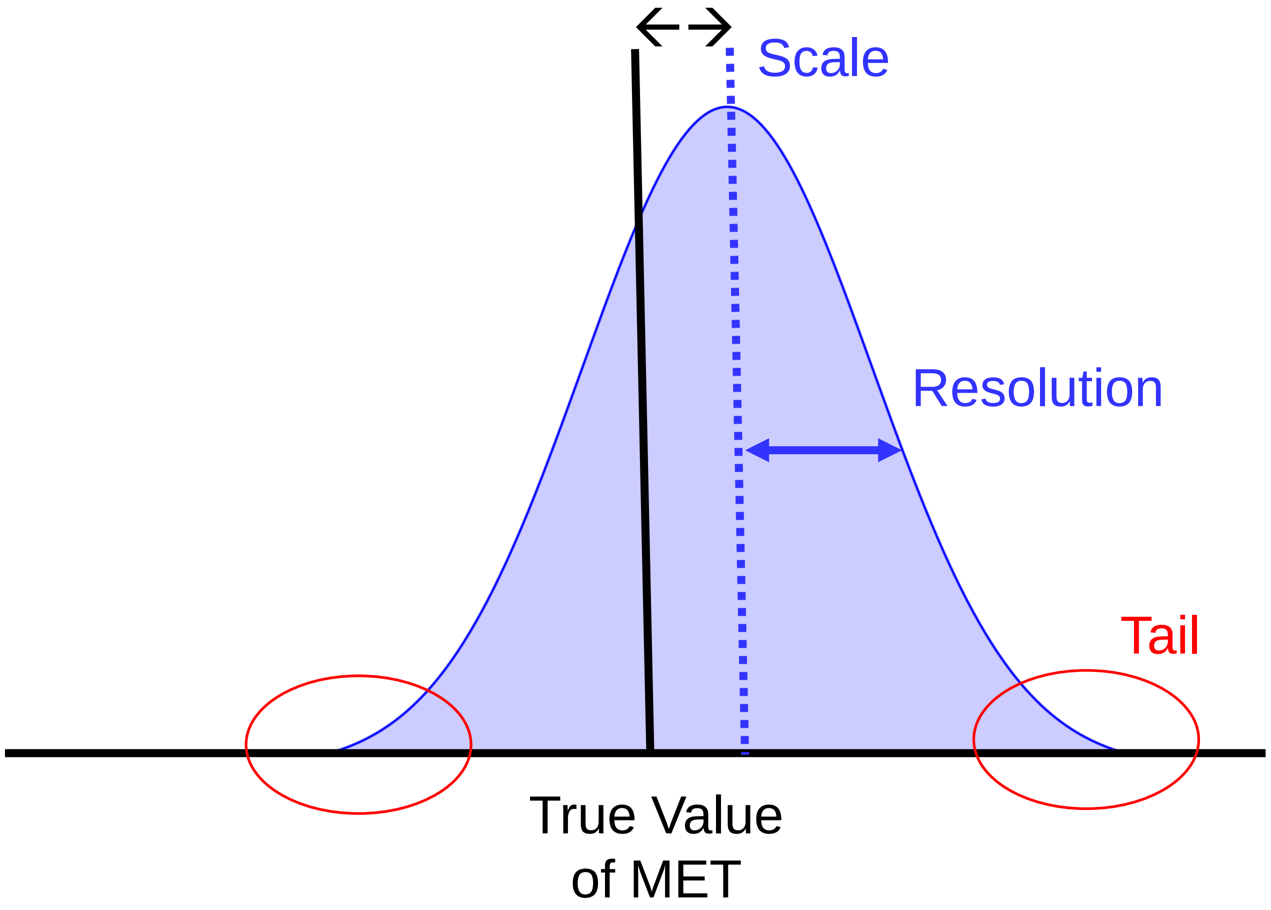
Optional Corrections

- Smeared MET
  - Corrects for the differences in data and simulation regarding the jet energy resolution.
- XY corrections
  - Ideally, MET should have a uniform ϕ distribution.
  - In reality, there is a sinusoidal modulation due to detector issues (non-uniform response, dead calorimeter cells, inefficient tracker regions, detector misalignment) & displacement of the beam spot.



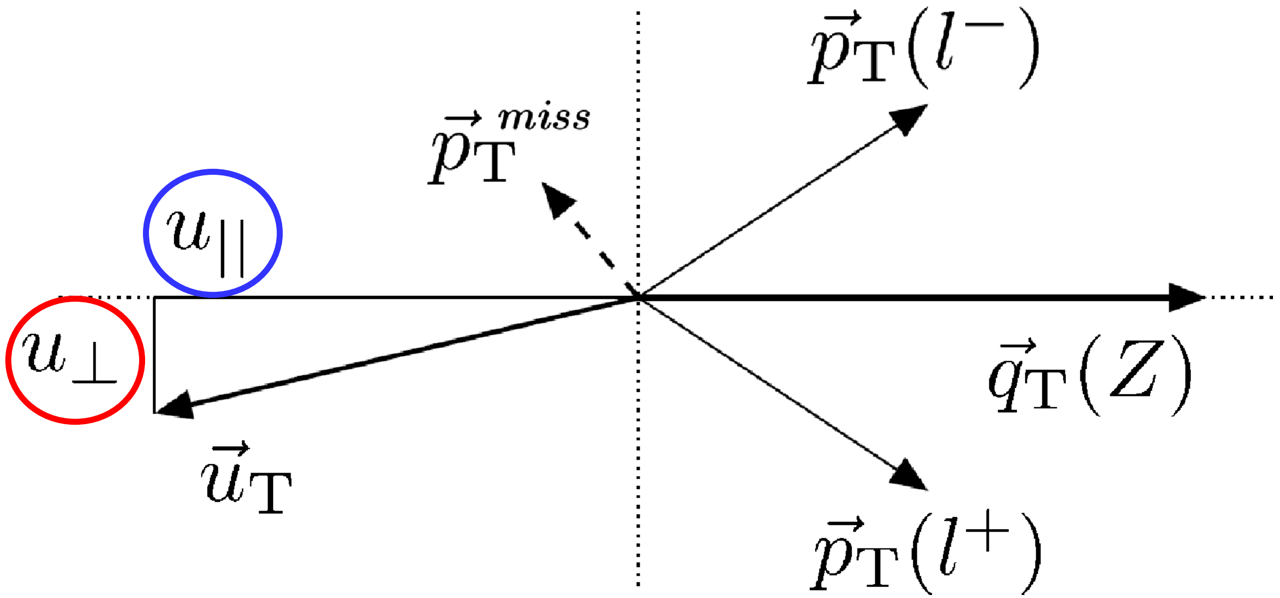
Key Components of MET Performance

- Scale
- Resolution
- Tail



Evaluation of MET Performance

- **Z(→ee,μμ)+jets, γ+jets** are standard "candles" to evaluate MET performance.
  - No genuine MET
  - Can define an axis to parametrize the hadronic recoil.



- $u_{||}$: parallel to Z boson axis. Sensitive to MET scale.
- $u_\perp$: perpendicular to Z boson axis. Sensitive to isotropic effects (e.g. detector noise, pileup, etc.)

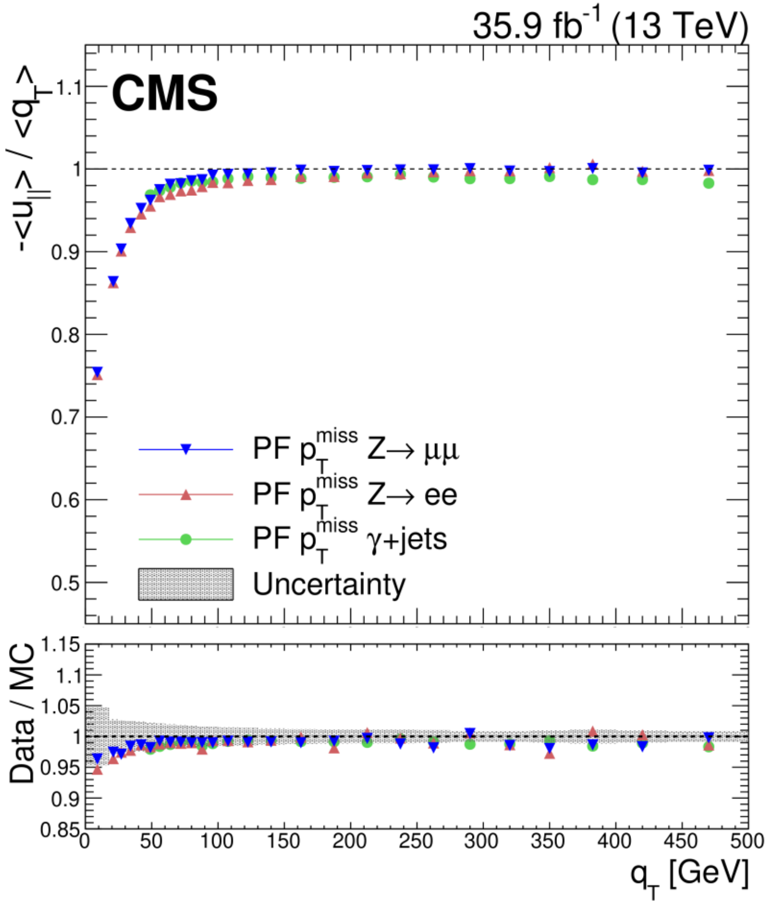
MET Performance

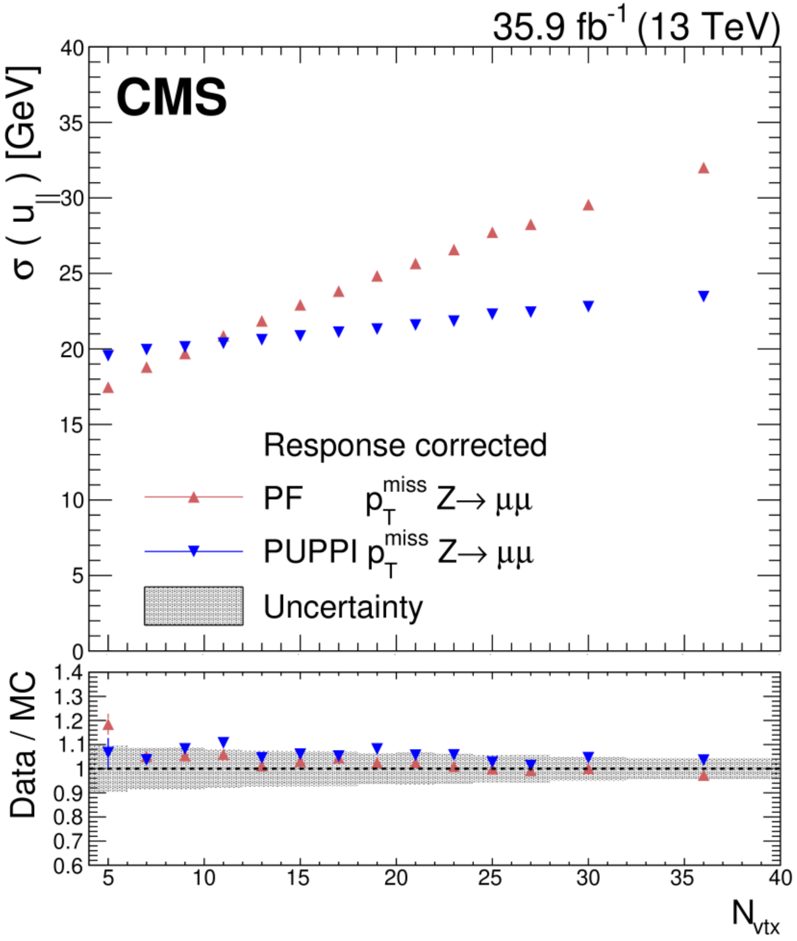
Response = - <u$_{||}$> / <q$_T$>

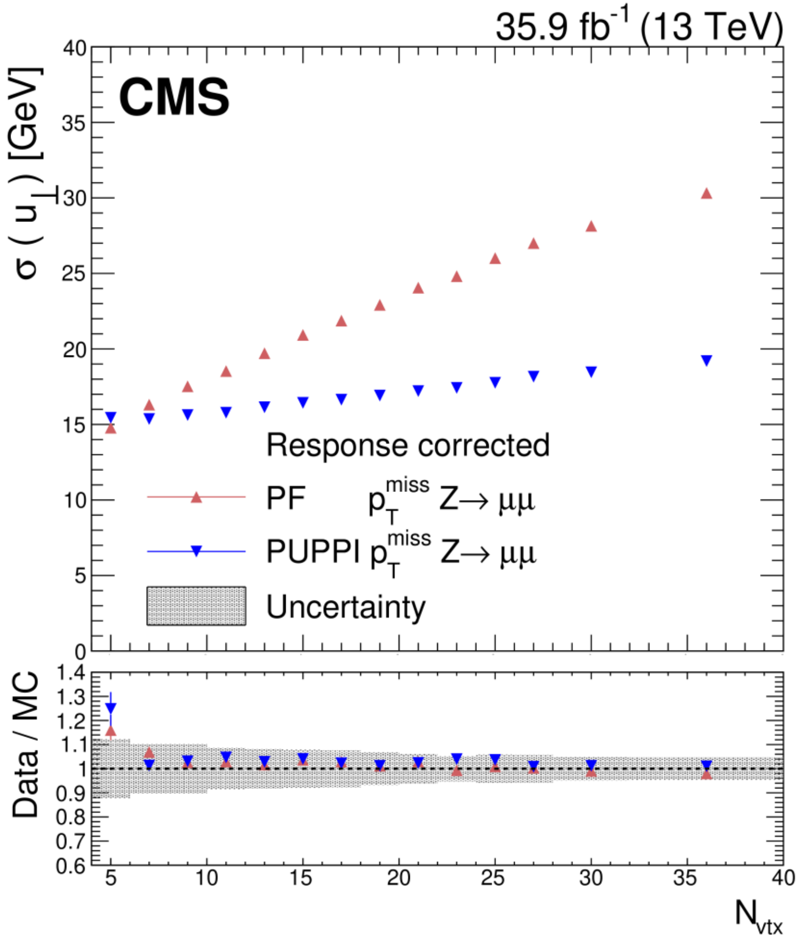
→ Should ideally be 1

Resolution in longitudinal and perpendicular directions

→ Better to be smaller. Ideally should be flat against pileup (N_{vtx})

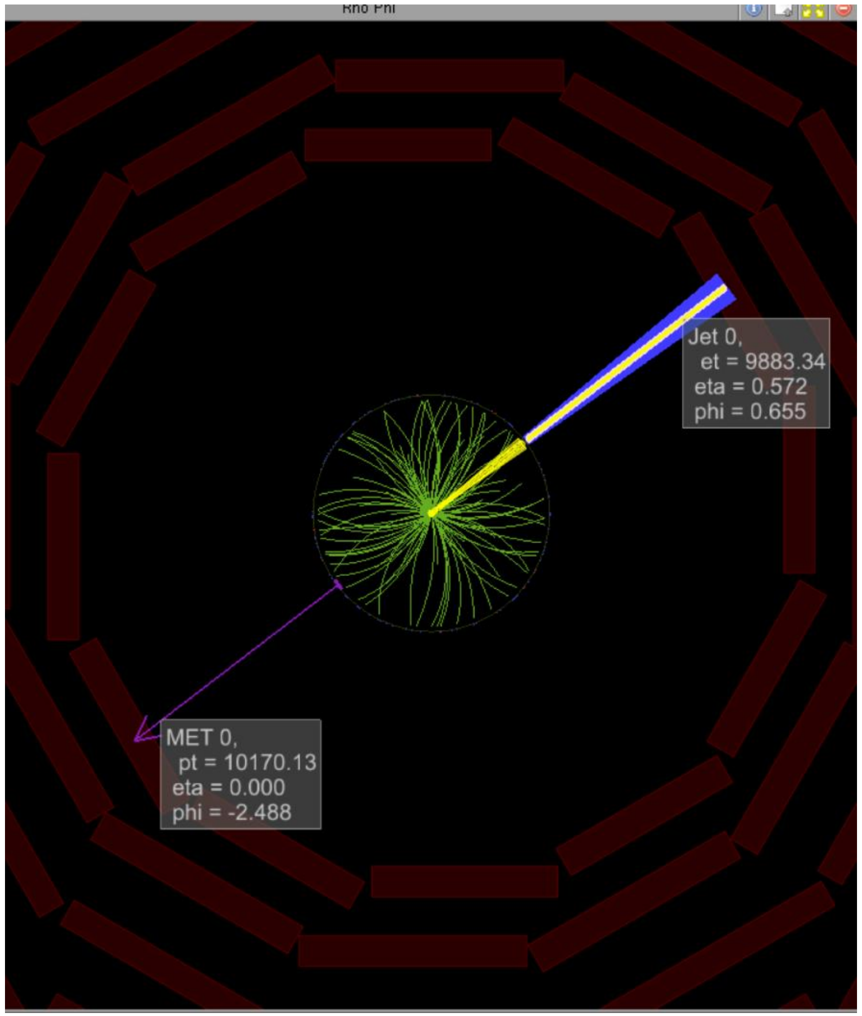






MET Filters = “Cleaning”, Tail Removal

- Anomalous high MET can show up in events without genuine MET (i.e. “zero” true MET) from:
  - Detector noise (e.g. from HCAL readout)
  - Detector inefficiencies (e.g. ECAL dead cells)
  - Non-collision background (e.g. beam halo, cosmic ray muons)
  - Mis-reconstruction of physics objects (e.g. fake particle flow muons)
- MET Filters are designed to reject such fake MET tail.



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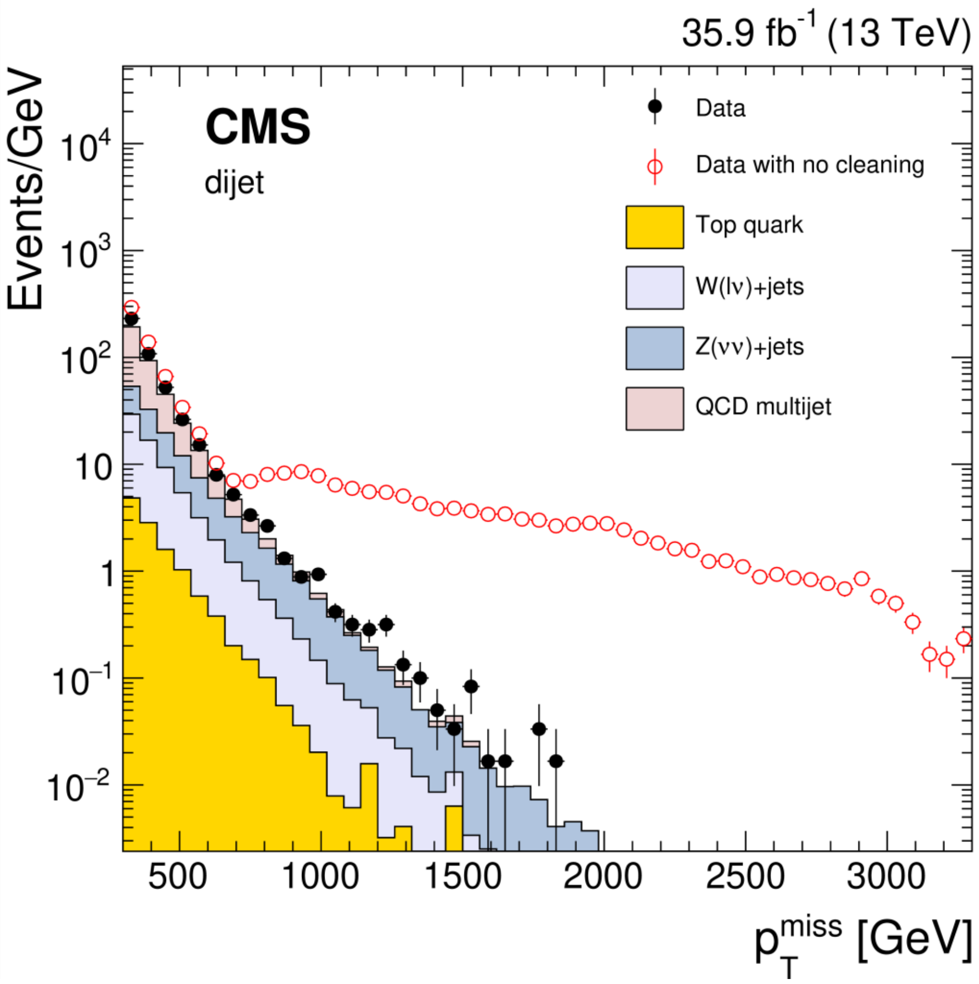
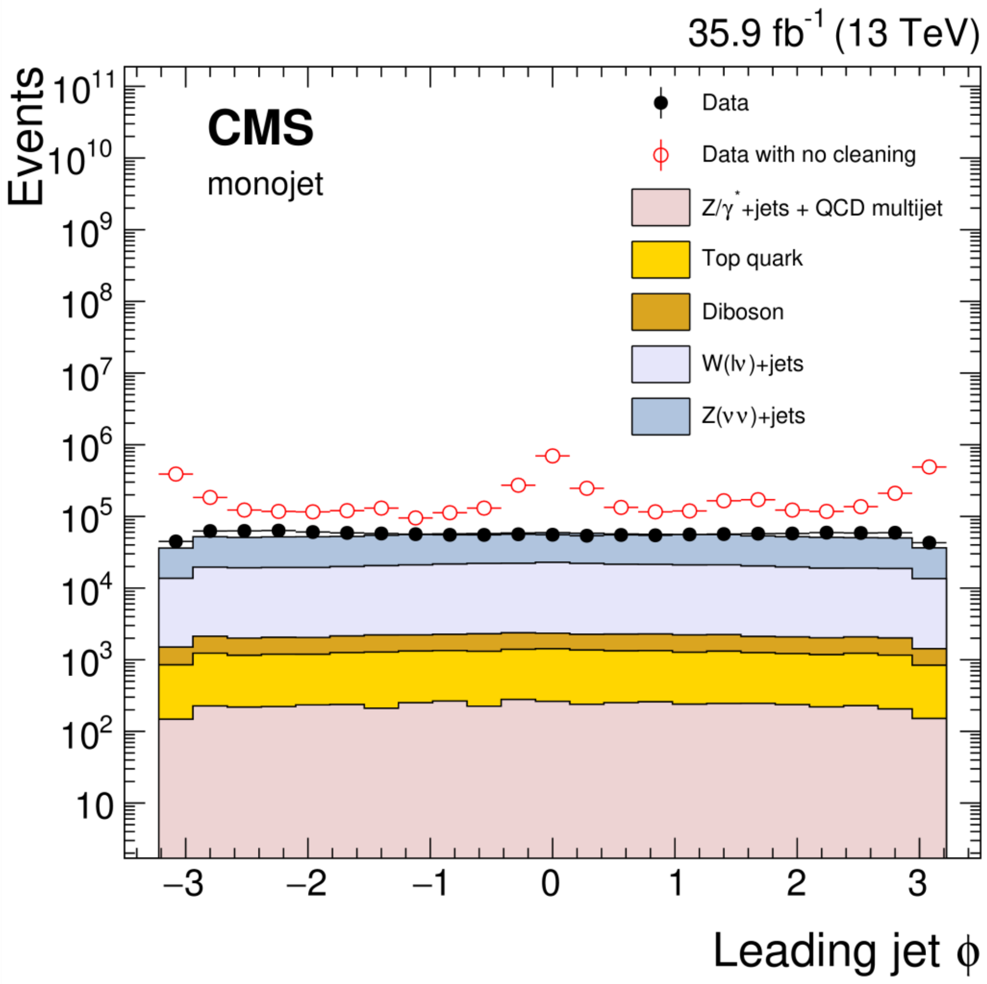
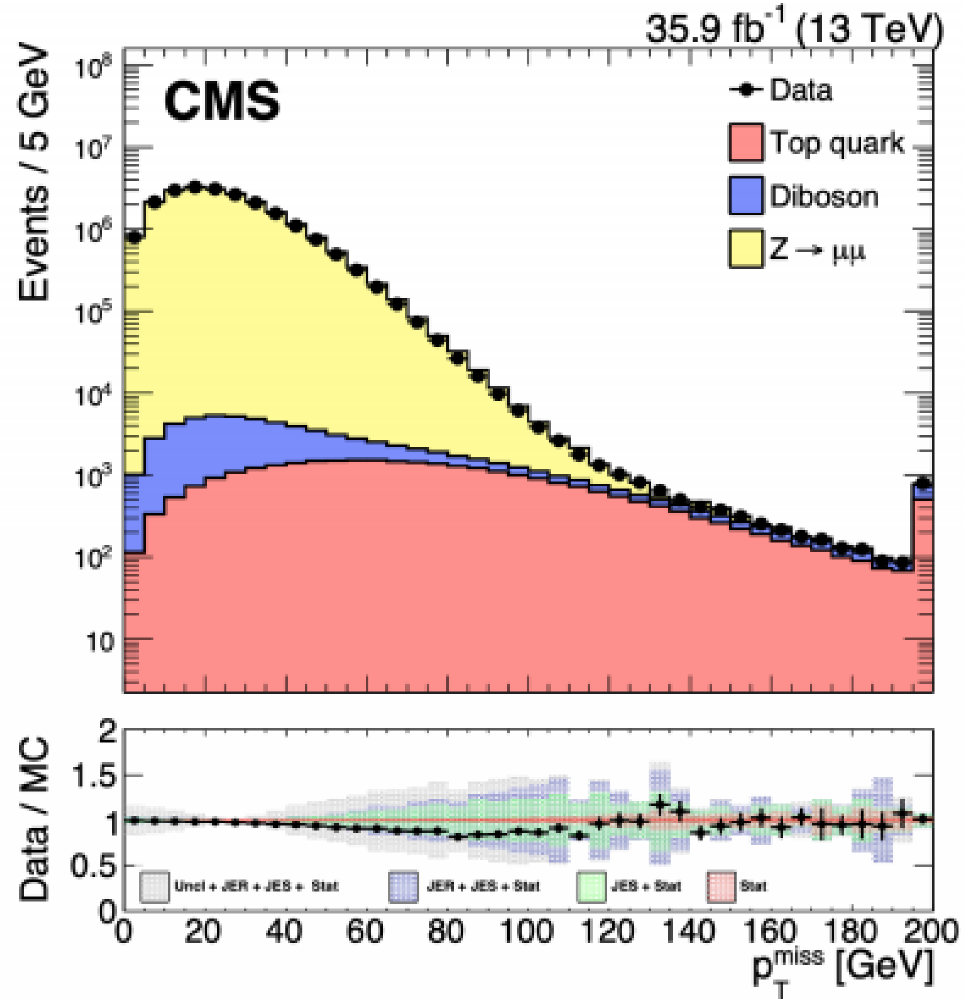




MET Uncertainties

- MET relies on accurate measurements of various physics objects.
- MET uncertainty is estimated by varying each reconstructed object momentum within its uncertainty & recompute MET. → The difference respect to the original value is the uncertainty.
- Important sources of uncertainties:
  - Jet energy scale, jet energy resolution
  - From un-clustered energy (particles not clustered into jets, leptons, photons) → usually low p_T particles



Hands-on Exercise

- Exercise 1: Contents in mini-AODs
- Exercise 2: Accessing MET information
- Exercise 3: MET calibration & performance
- Exercise 4 (auxiliary): PUPPI MET
- Exercise 5 (auxiliary): MET Filters
- Exercise 6 (auxiliary): MET Uncertainties

Summary

- MET is one of the key observables in Standard Model measurements as well as new physics searches.
- It is a complex observable that relies on the reconstruction of all the physics objects in the detector.
- Robustness against pileup is one of the most crucial items facing LHC Run 3 and there are many ongoing studies to improve the performance.

- I hope this short introduction will give you a brief idea about this exciting topic & help you to use it in your analyses in Run 3.