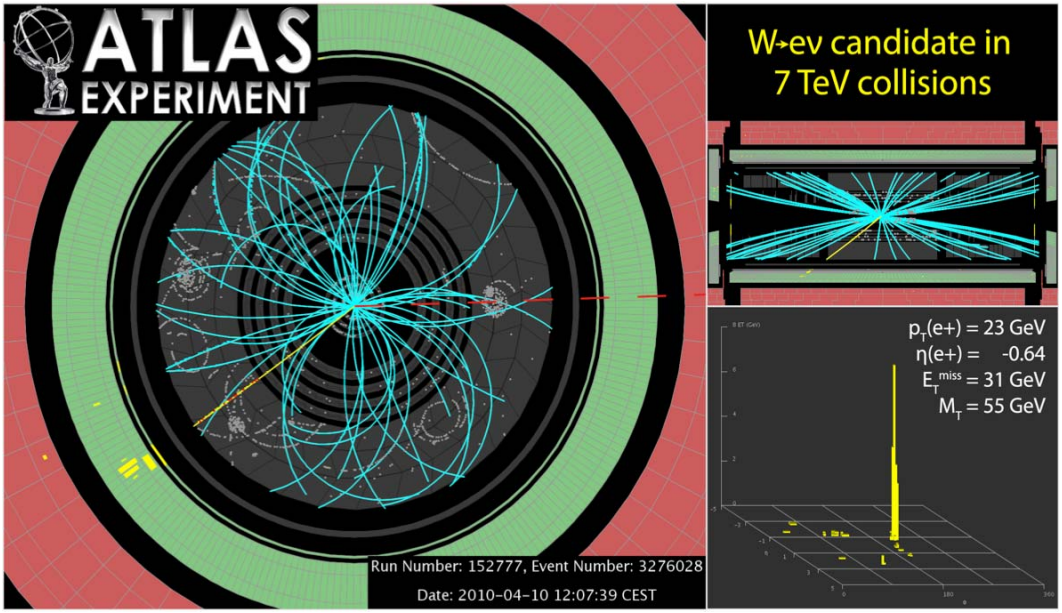
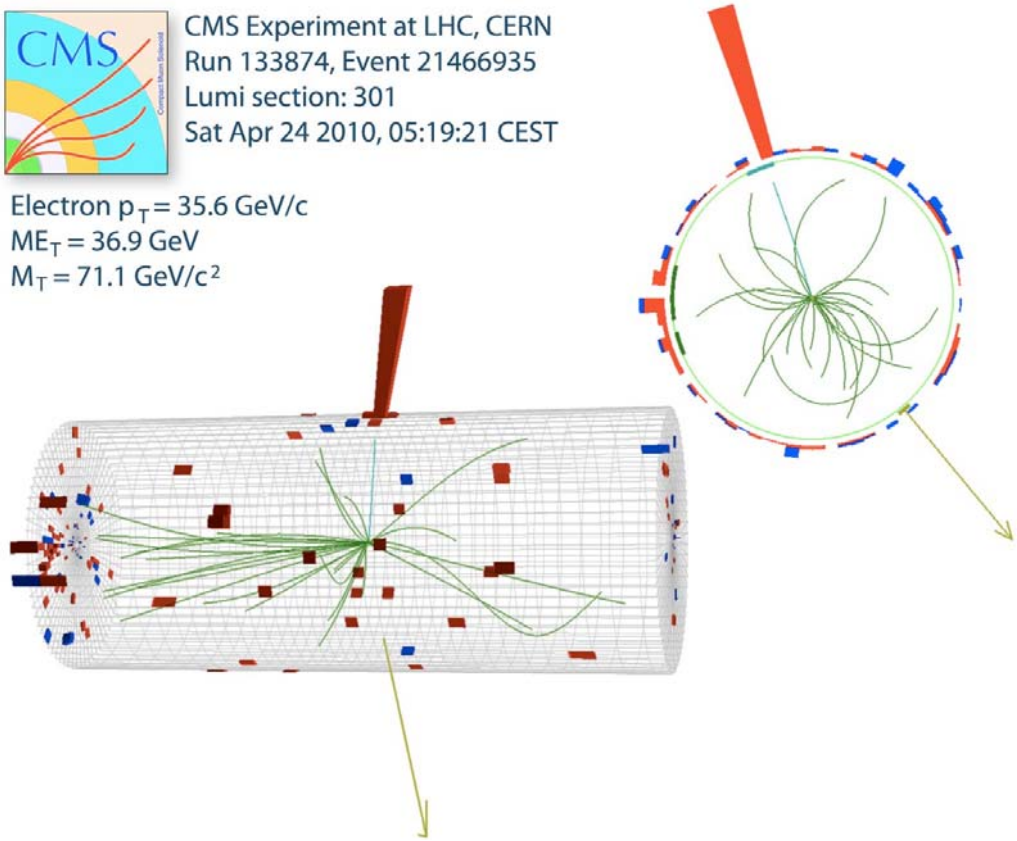
Missing Transverse Energy Reconstruction at the LHC





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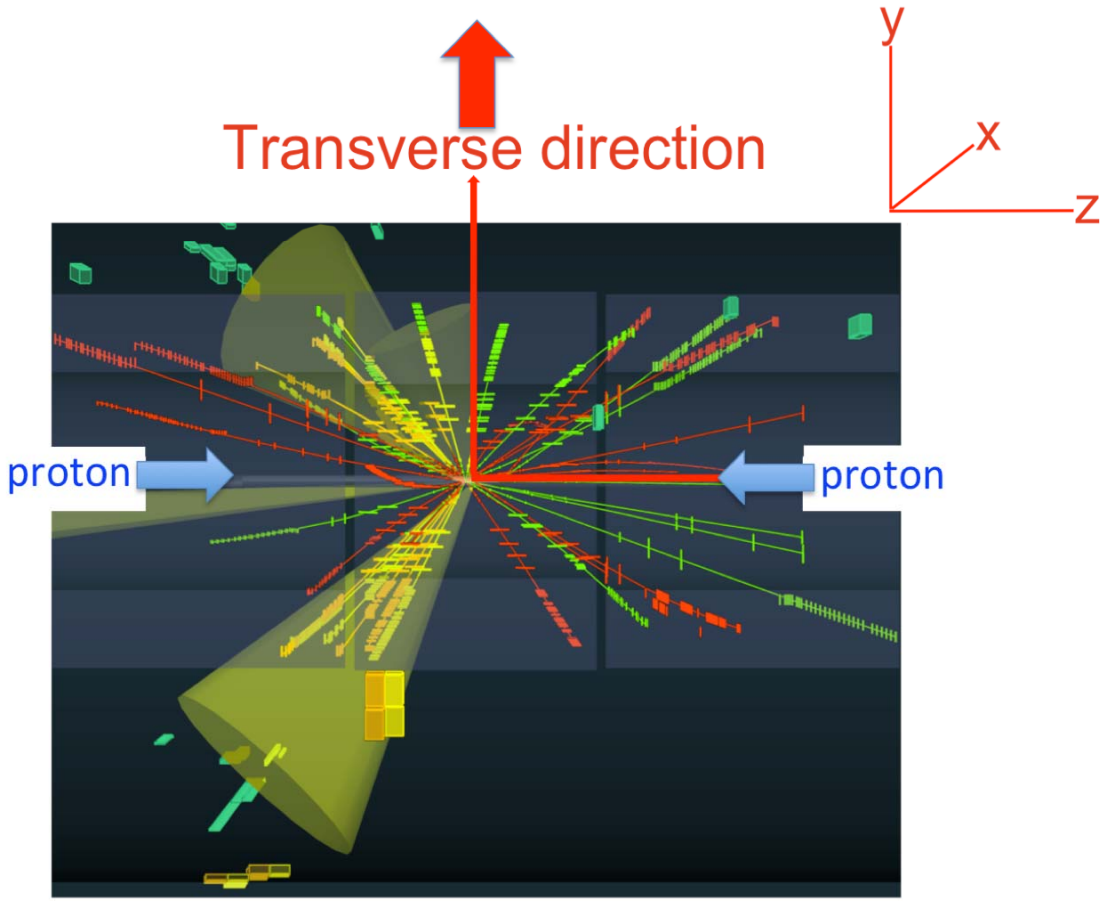
Missing Transverse Energy (E_T^{miss})

- In pp collisions at the LHC, a significant, unmeasured amount of energy escapes in z direction
- Total initial and final momentum is zero in transverse direction
- Imbalance of energy in transverse direction signals presence of weakly or non-interacting particles such as neutrinos



$$E_T^{miss} = \sqrt{(E_x^{miss})^2 + (E_y^{miss})^2}$$

$$E_{x(y)}^{miss} = -\sum_{particles} E_{x(y)}$$

$$\sum E_T = \sum_{particles} E_T$$

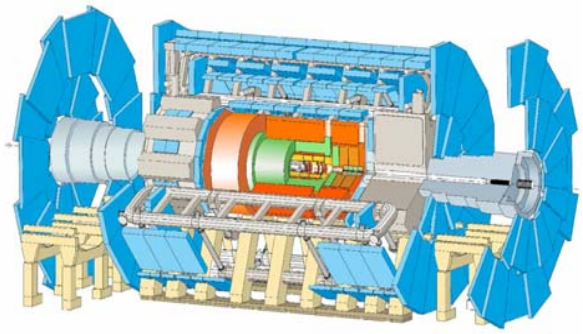
Inputs to Missing ET

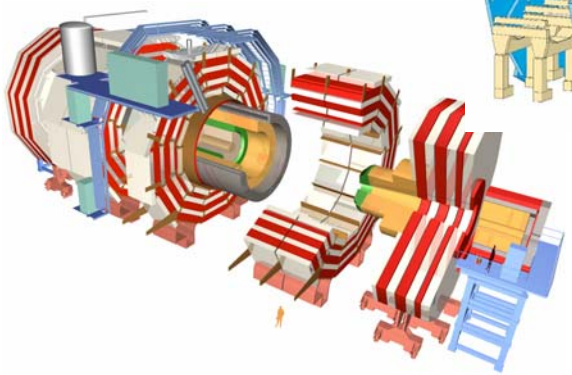
Electrons / Photons / Jets / Taus

- Overlap resolution needed for calorimeter-based signals
- Object quality cuts change MET
- Use best calibration for each

Muons

- Use good reconstructed muons
- Possible source of fake MET
- Avoid double-counting signal in calorimeters





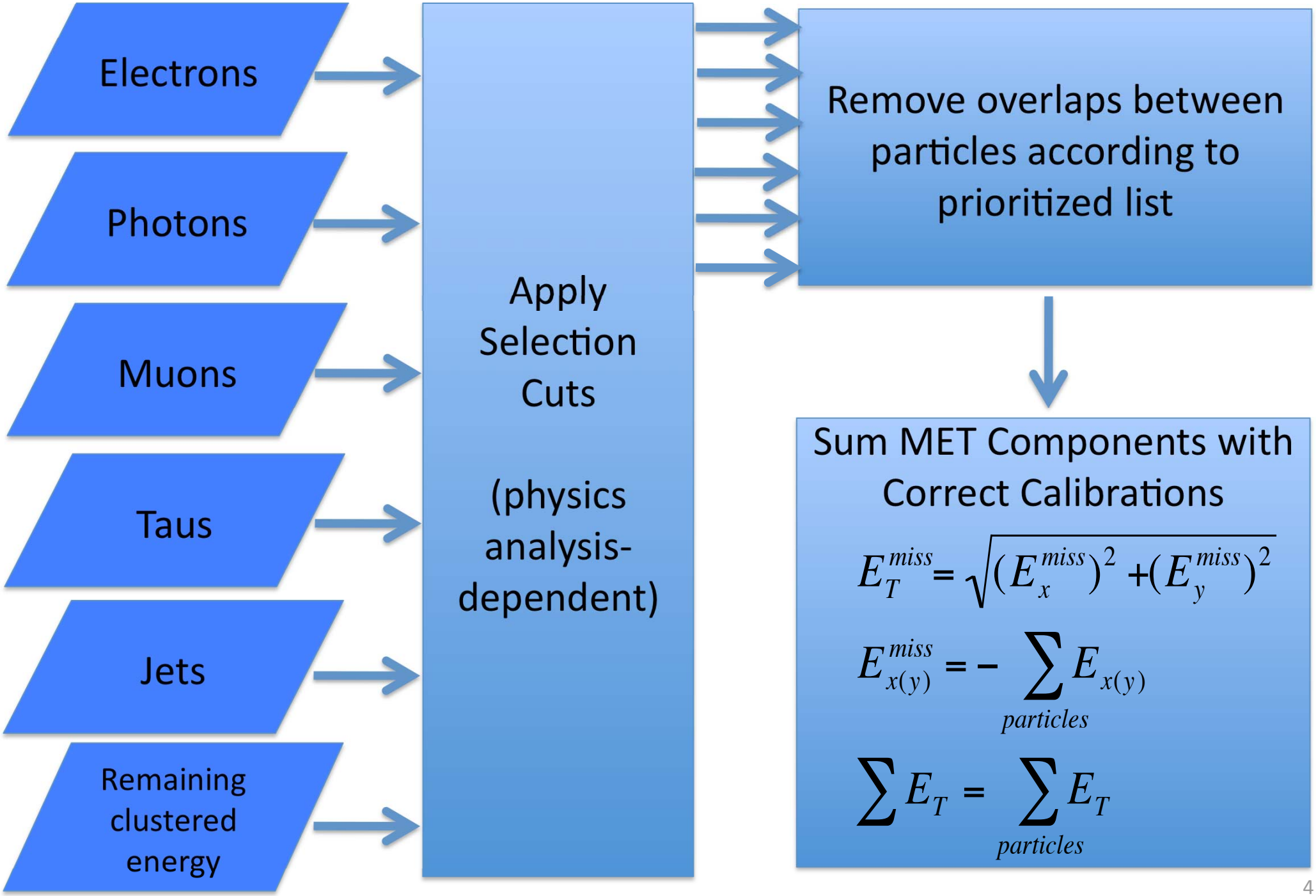
Remaining Clustered Energy

- Important to use all real signals in calorimeters, but ignore noise
- Need to derive calibration for soft signals

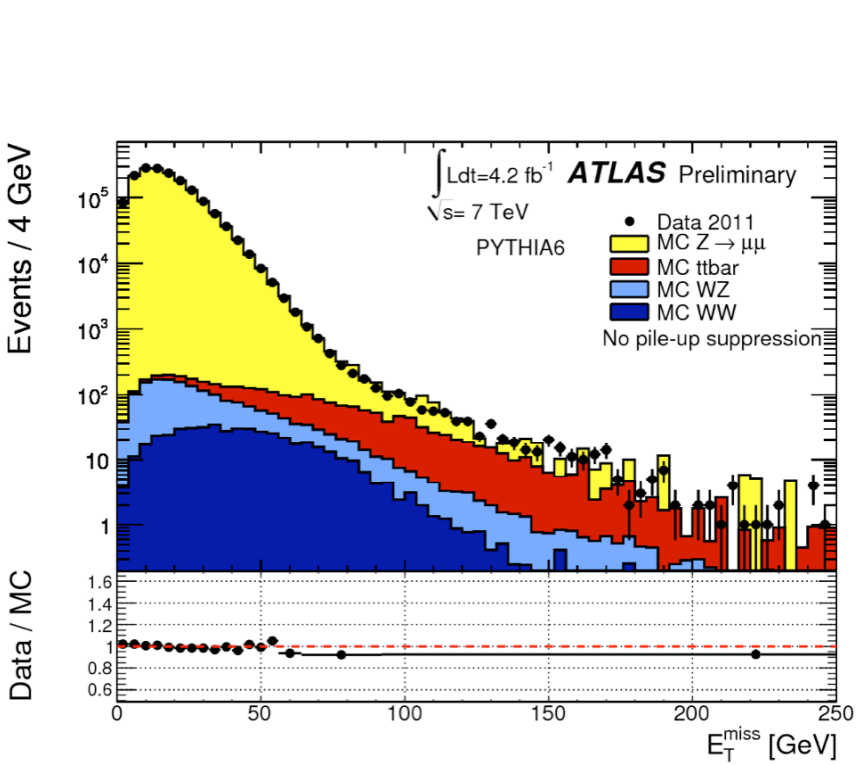
Data Quality/ Monitoring

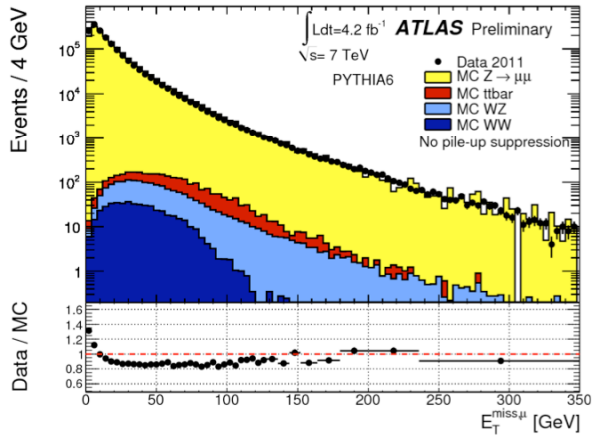
- Physics analyses must exclude/ understand data with detector problems

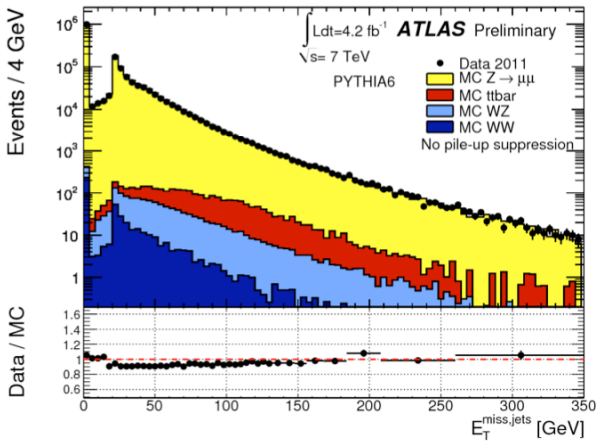
Missing ET Reconstruction at ATLAS

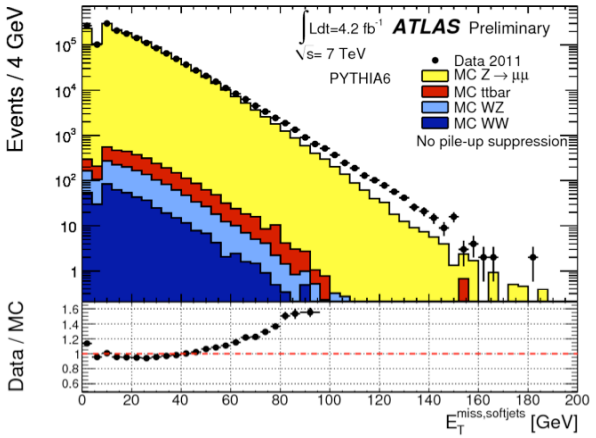


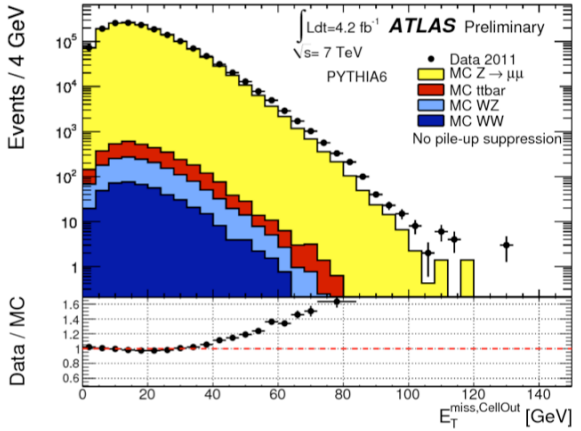
Contributions to MET (Z->mumu)





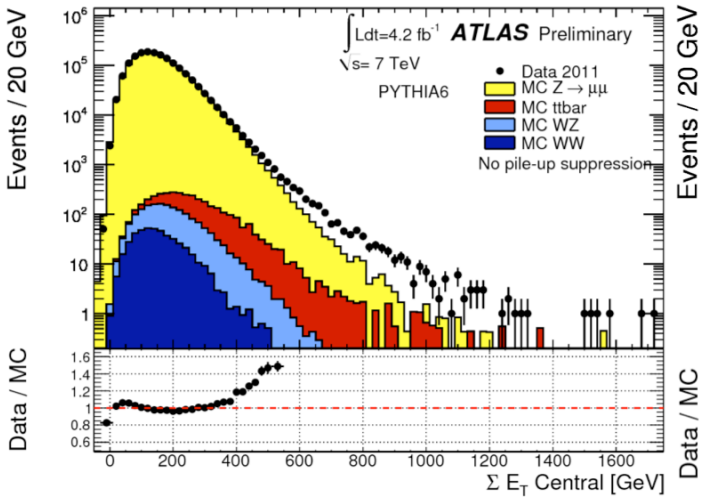


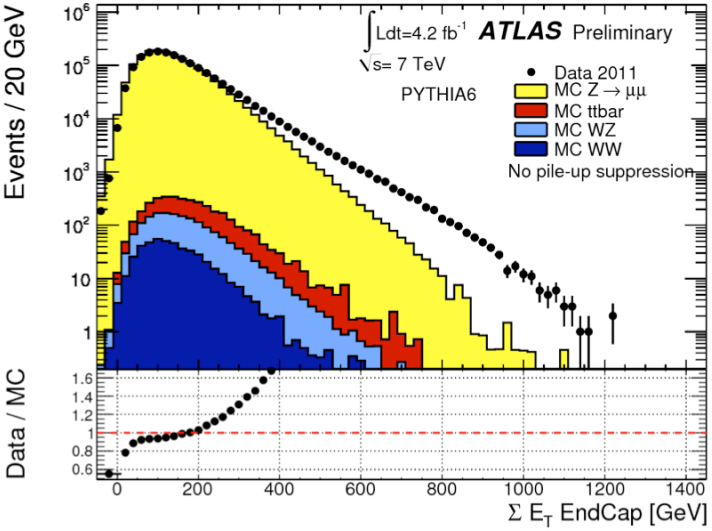


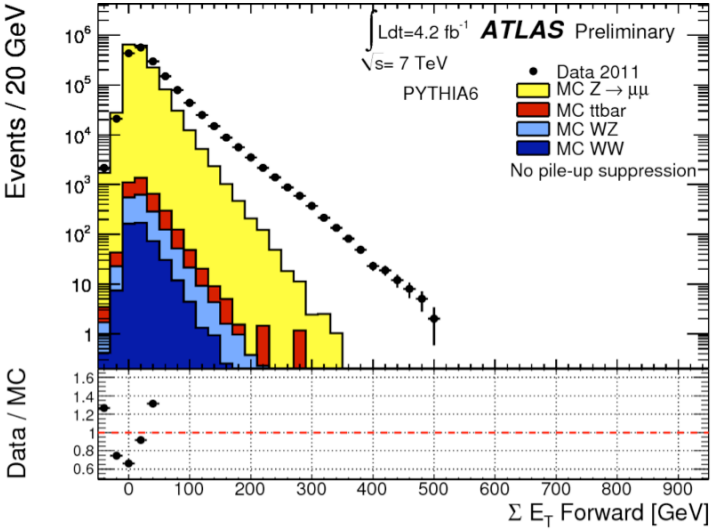


- By building the missing ET from physics objects, can
  - study the performance of terms built from each kind of object separately
  - improve calibration of each term separately
  - estimate systematics using uncertainties from physics objects

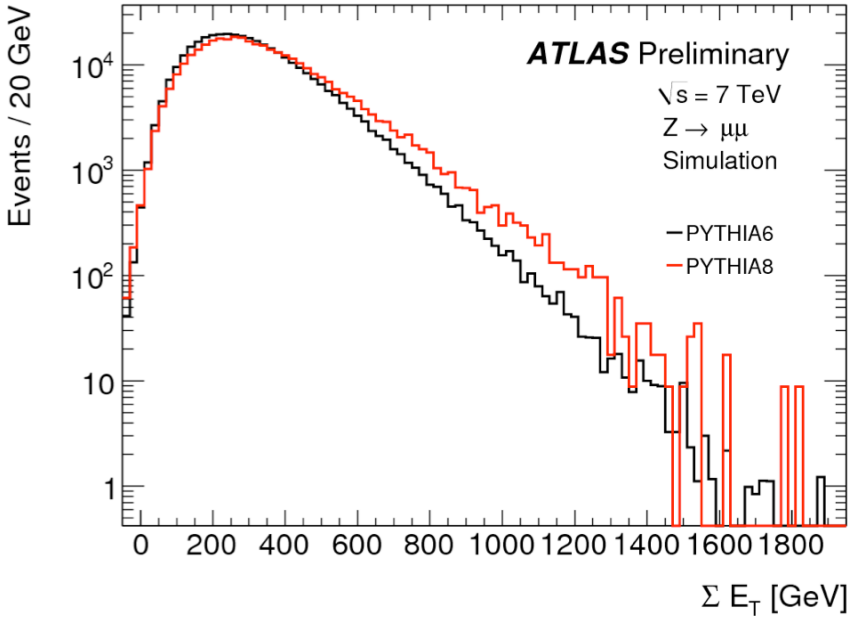
Contributions to Sum ET (Z->mumu)





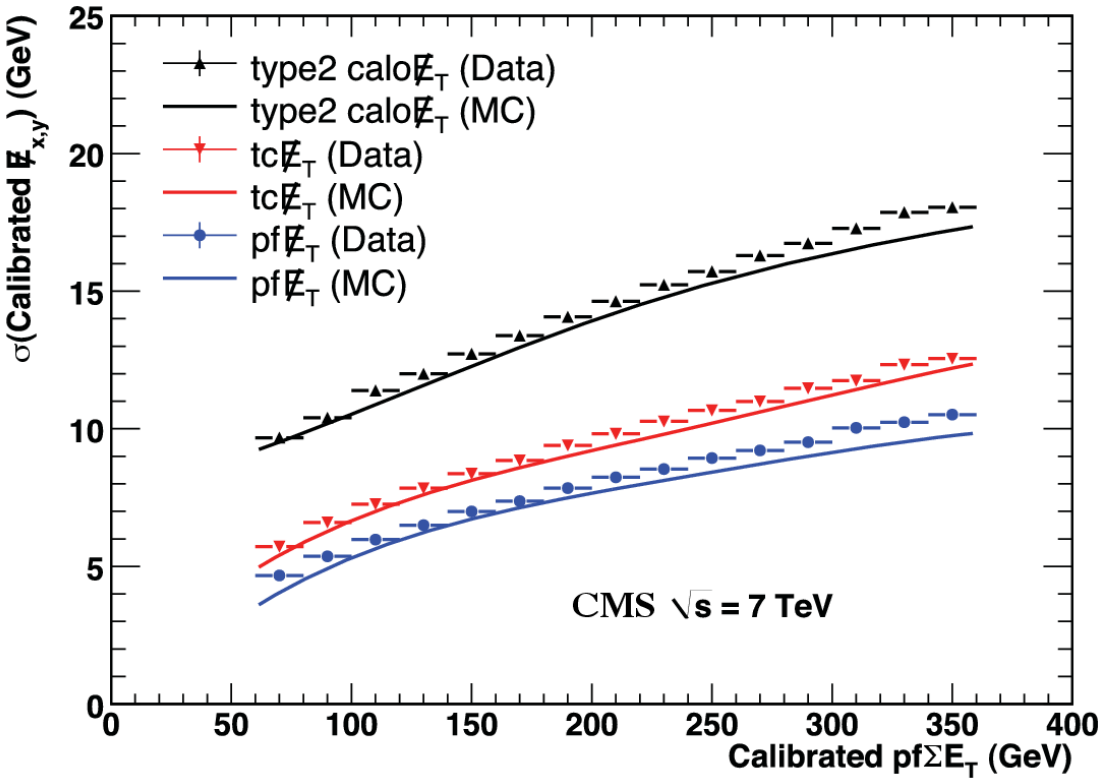


- Data-MC disagreement worse at higher eta
- PYTHIA8 agrees better with data than PYTHIA6

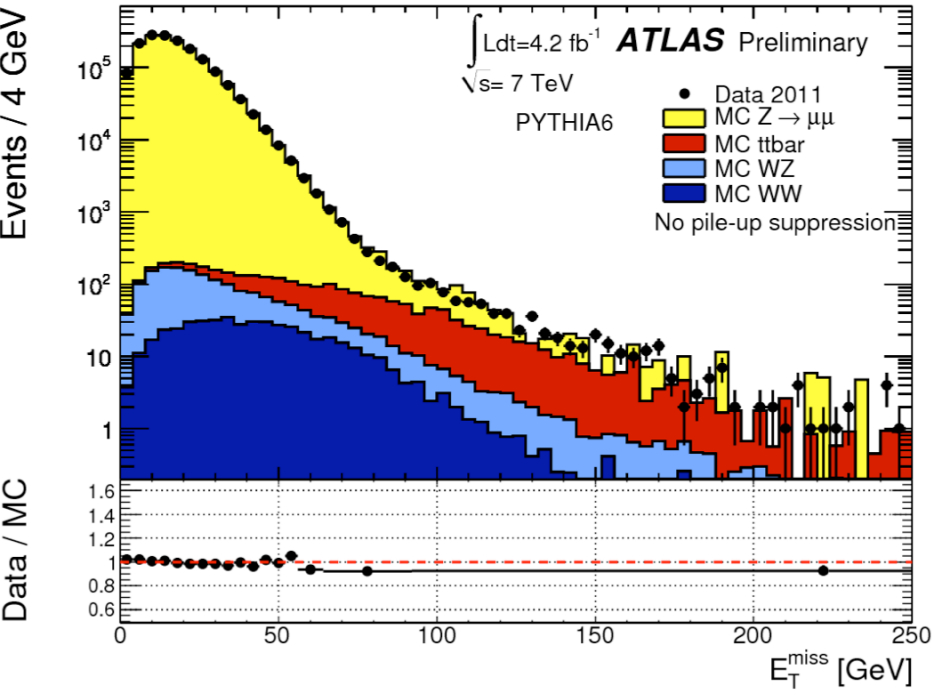


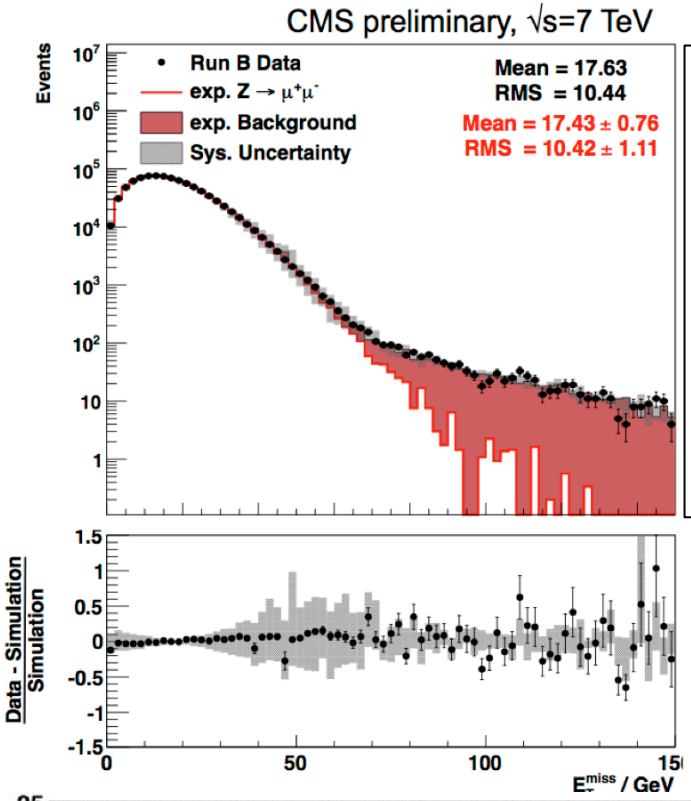
Missing ET Reconstruction at CMS

- Three missing ET algorithms available
  - Calo MET – based on energy in calorimeter towers
  - TC MET – based on Calo MET, but also uses tracks
  - Particle Flow MET (pfMET) uses all stable objects
- Mainly results from pfMET presented today
- In pfMET, can apply particle-level corrections/calibrations
  - JES corrections applied to jets
  - Muon energy loss corrections applied
  - Some residual corrections derived from balancing in W/Z events



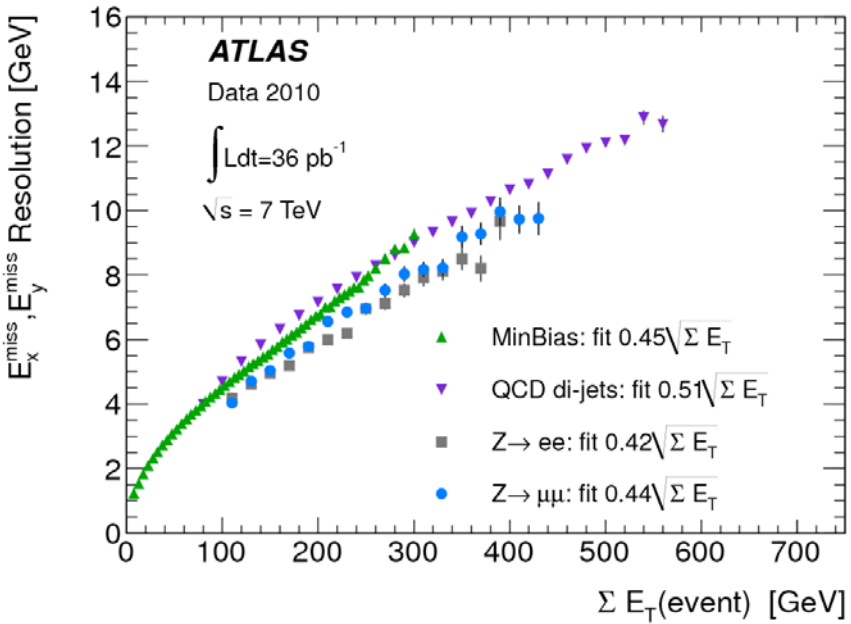
Missing ET Performance in Z->mumu

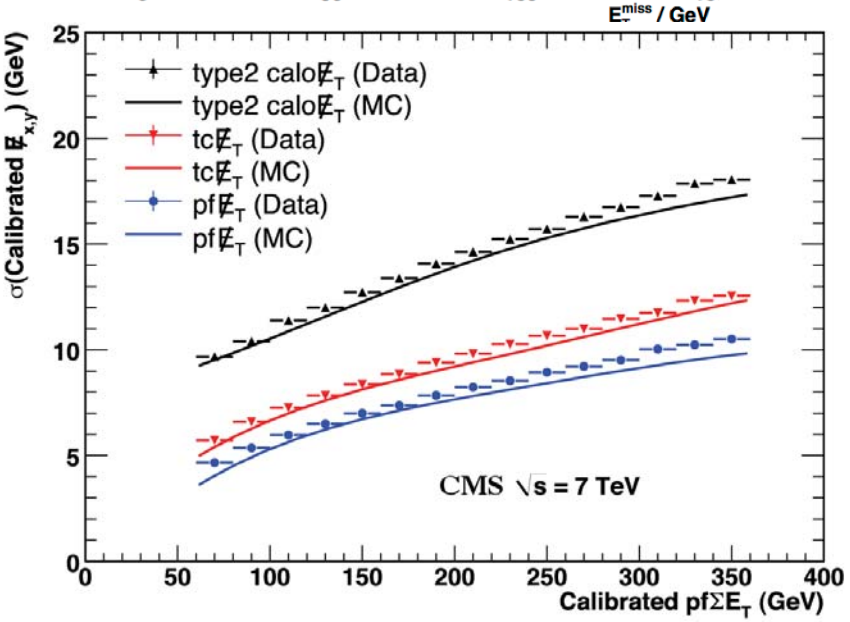




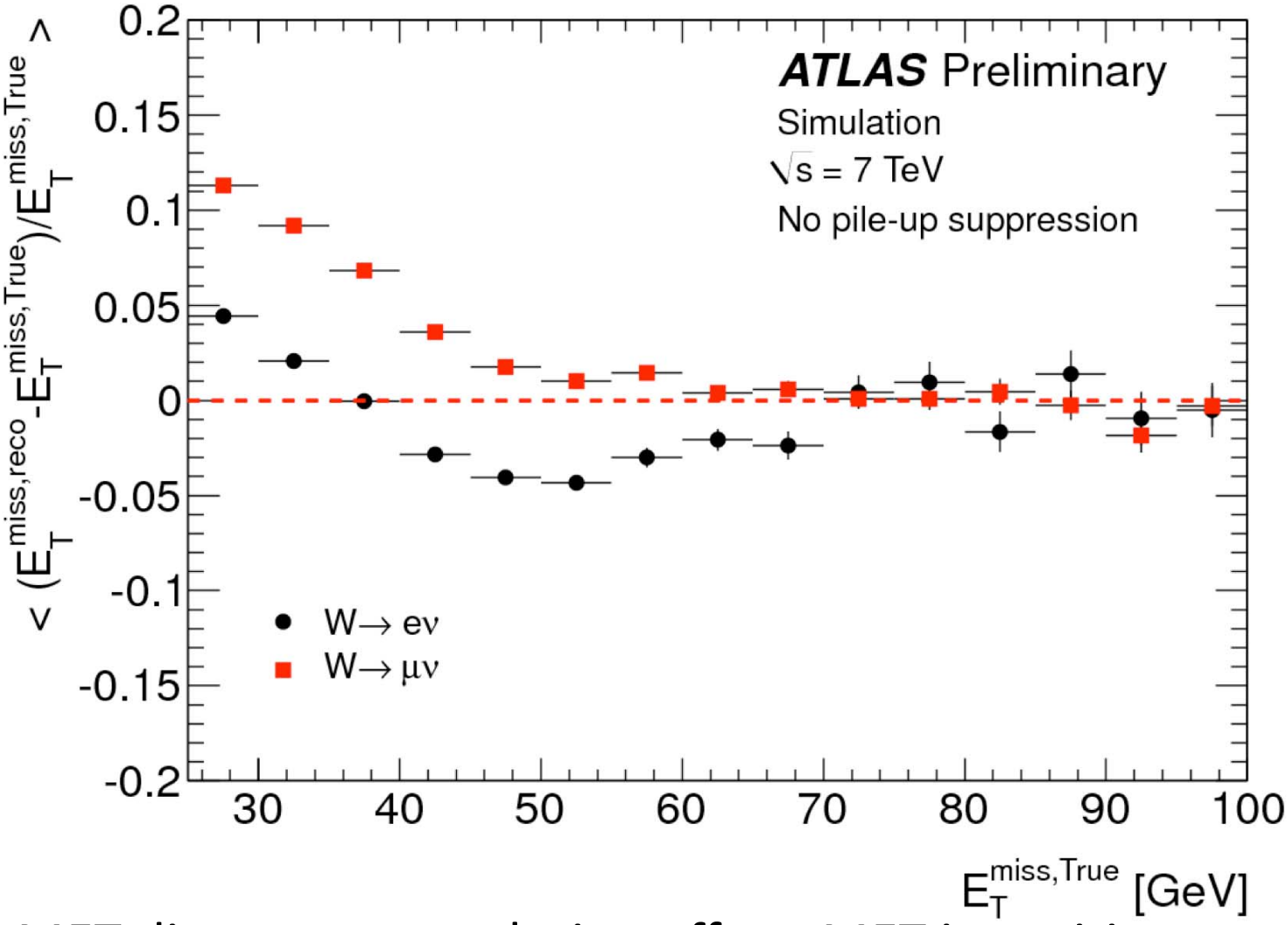
CMS 2011 Run A:
2.0 fb^{-1}
<vertices>= 5.5

CMS 2011 Run B:
2.6 fb^{-1}
<vertices> = 9.2





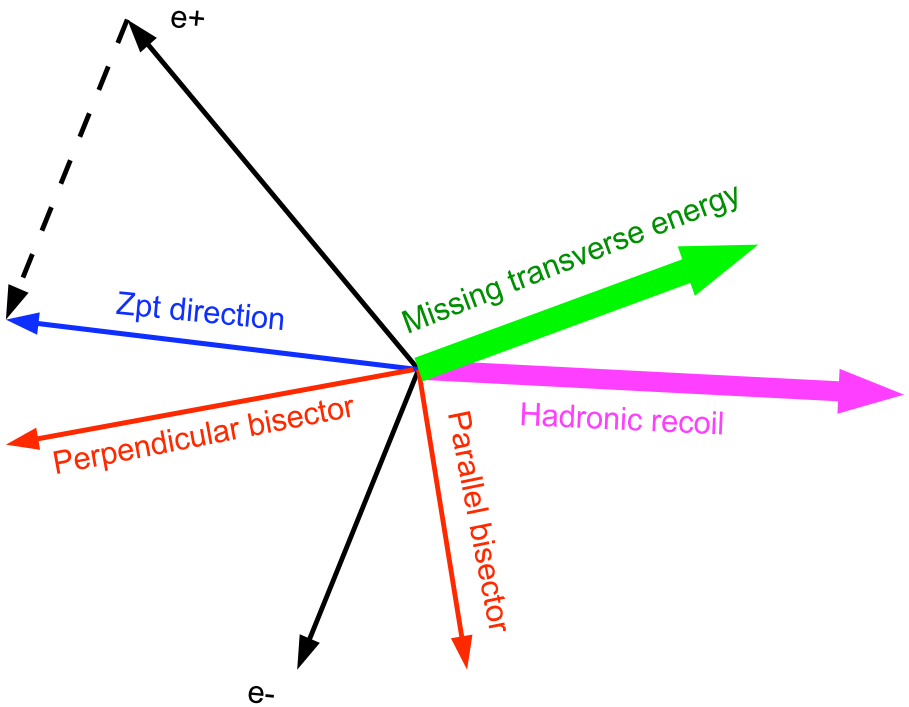
Linearity in Z->mumu MC

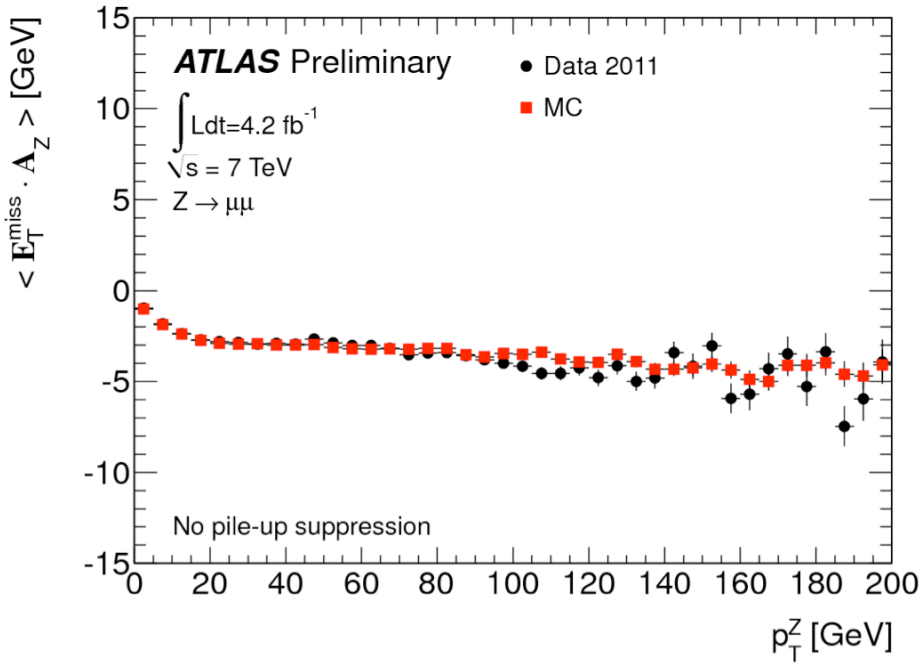


- Low MET divergence resolution effect, MET is positive quantity
- <~3% from linearity after 40 GeV, becoming better at very high MET due to more jets in events
- Some disagreement at low MET probably due to underestimate of muon energy deposited in calorimeters in presence of pileup

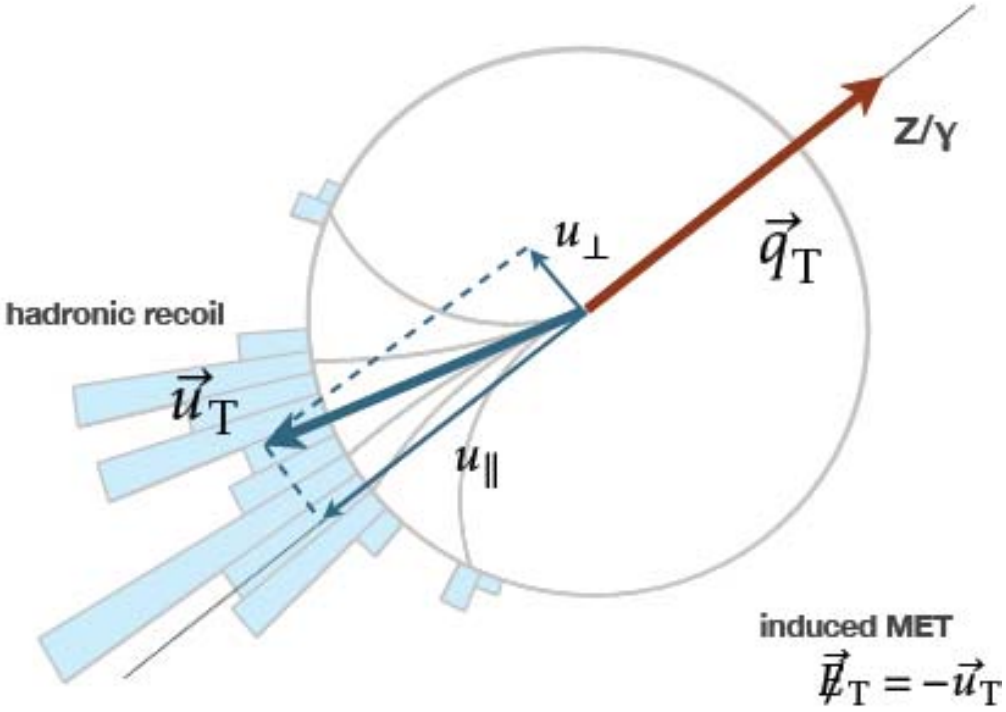
Measuring Performance using Z Boson Decays

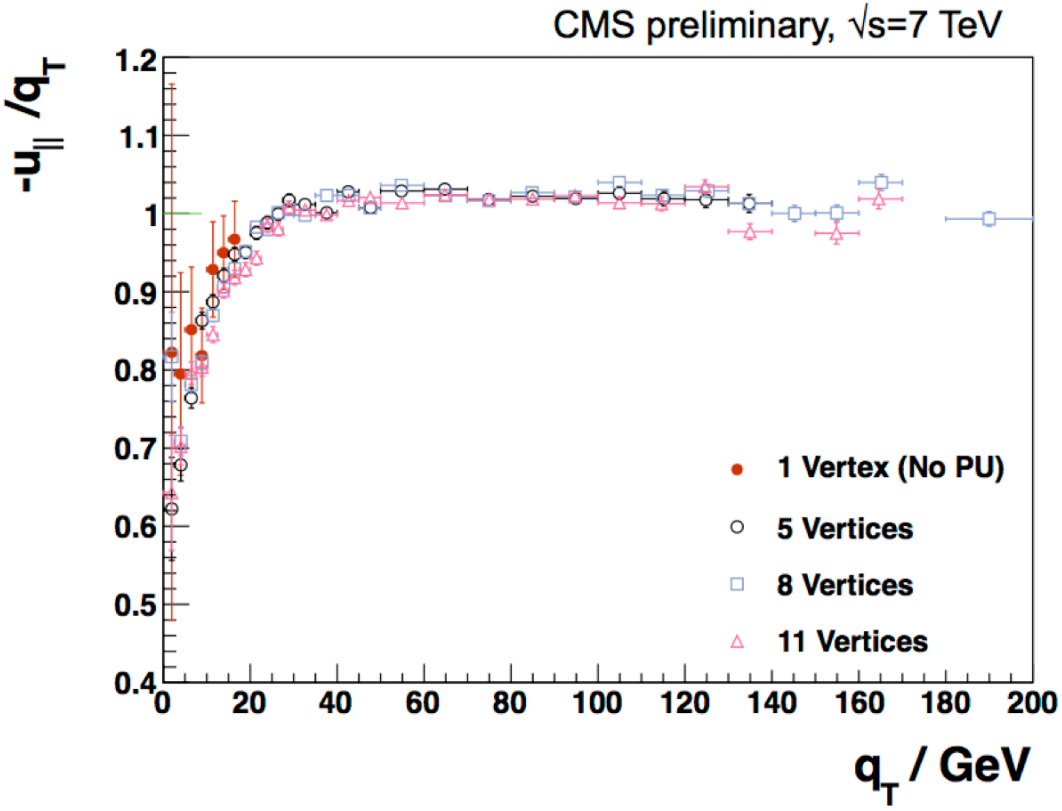
- Use Z boson decays to muon or electron pairs
- Define “perpendicular bisector” axis that bisects the directions defined by the two leptons
- Project MET along this direction and the direction perpendicular
- Bias seen shows recoil energy is undermeasured





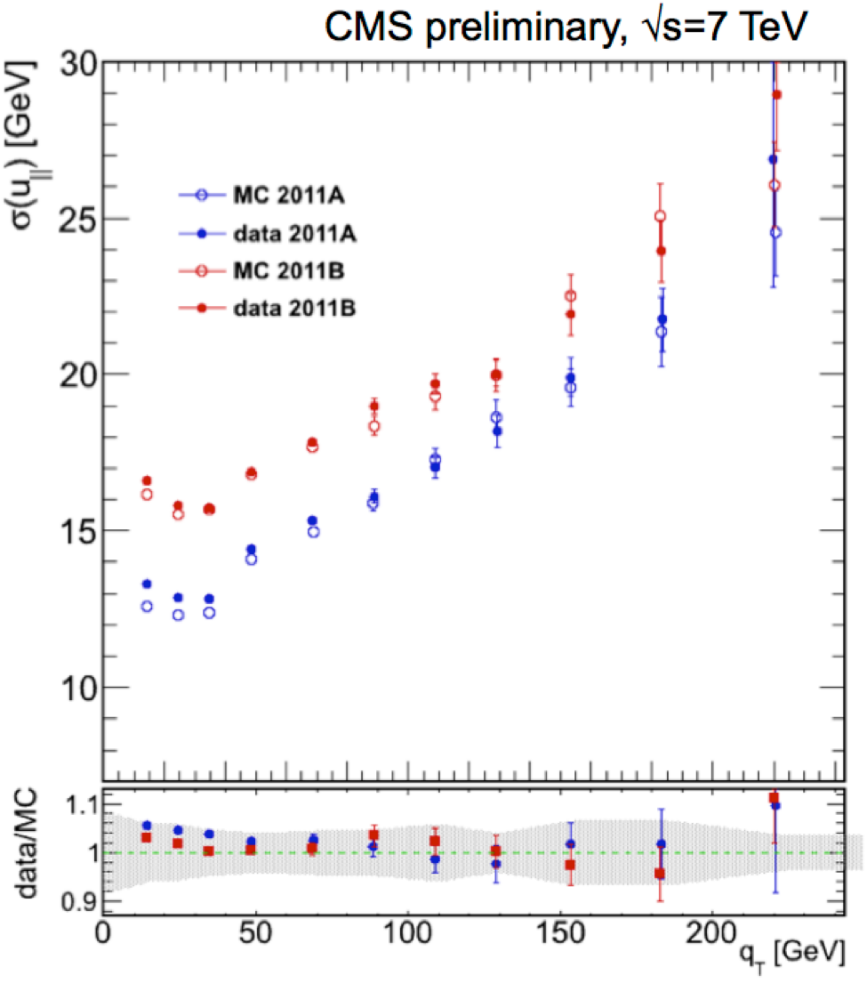
Using Z/gamma Decays to check Scale at CMS

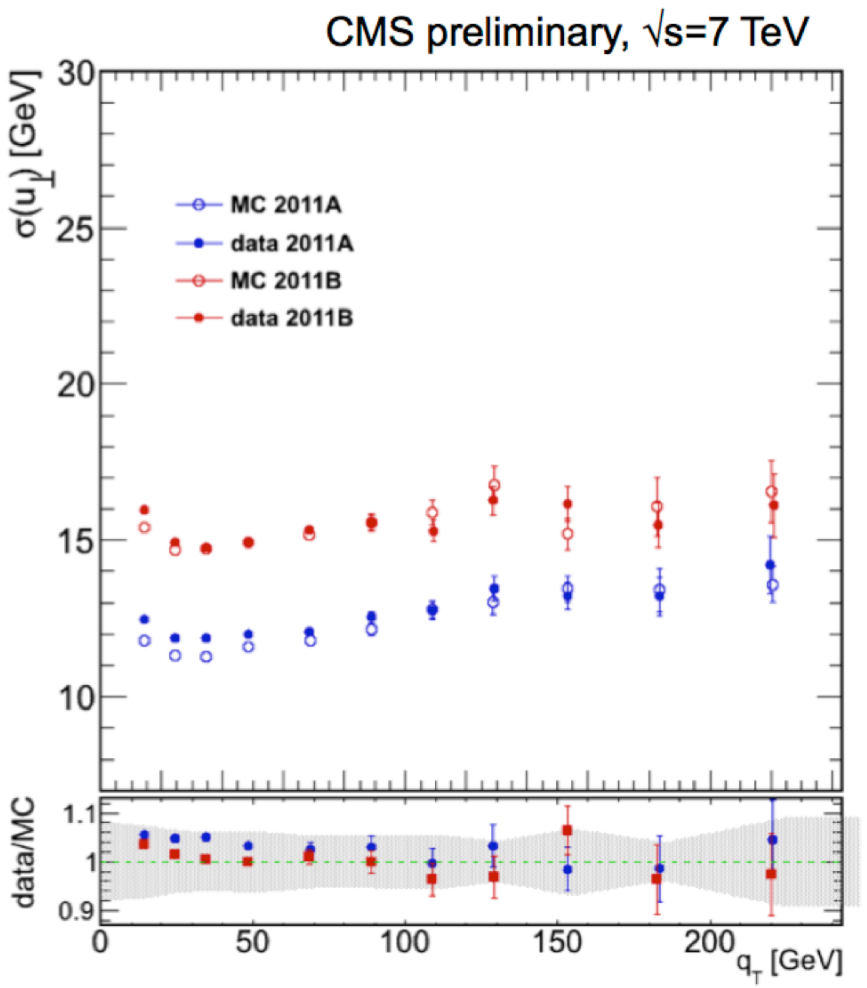




- At low q_T, deviation from 1 likely due to under-measurement of soft particles in hadronic recoil
- No pileup dependence seen in scale

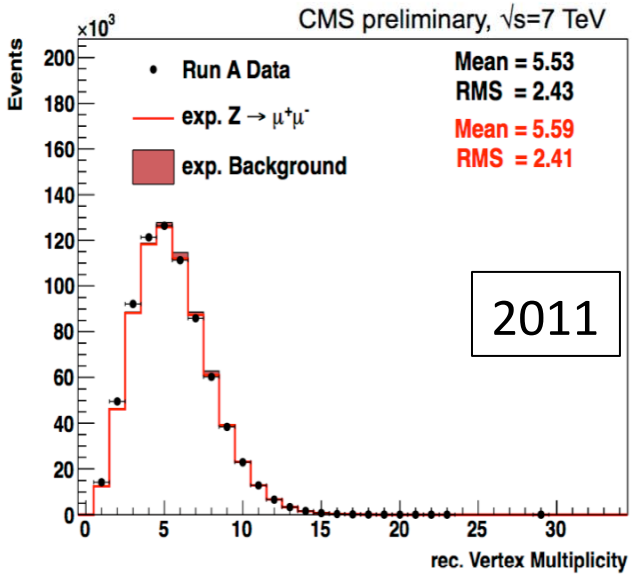
Using Z/gamma Decays to Study Resolution

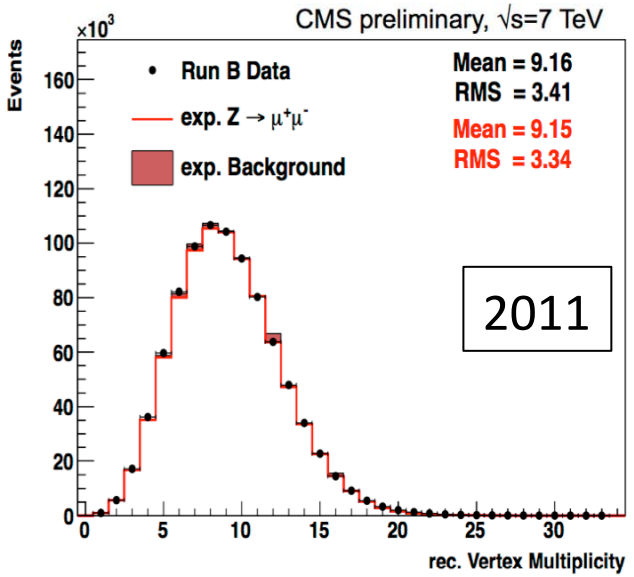


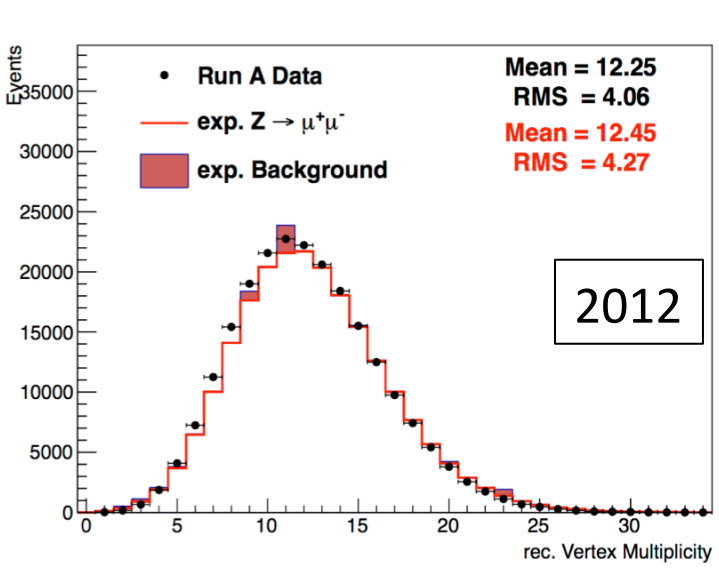


- Resolution worsens at higher Z/gamma momentum in direction parallel to Z/gamma, roughly constant perpendicular
- Pileup worsens MET resolution

Rising Pileup

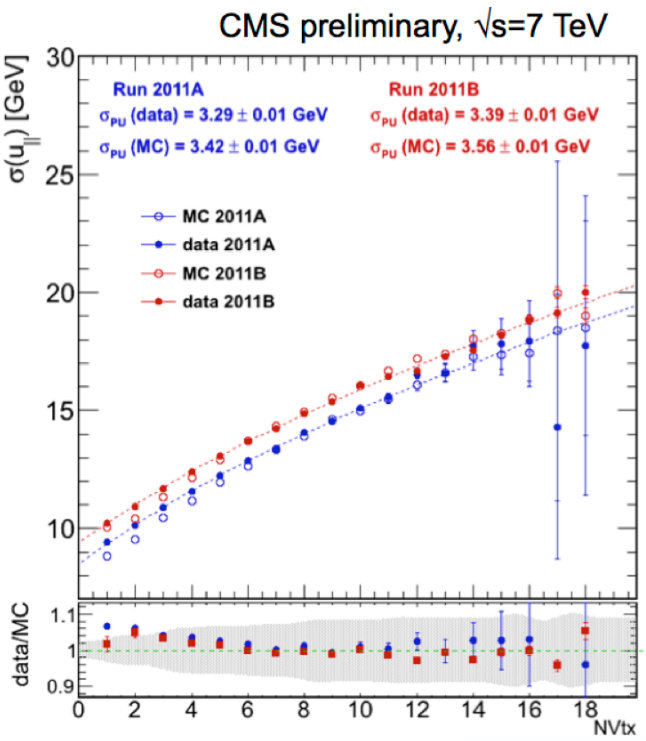


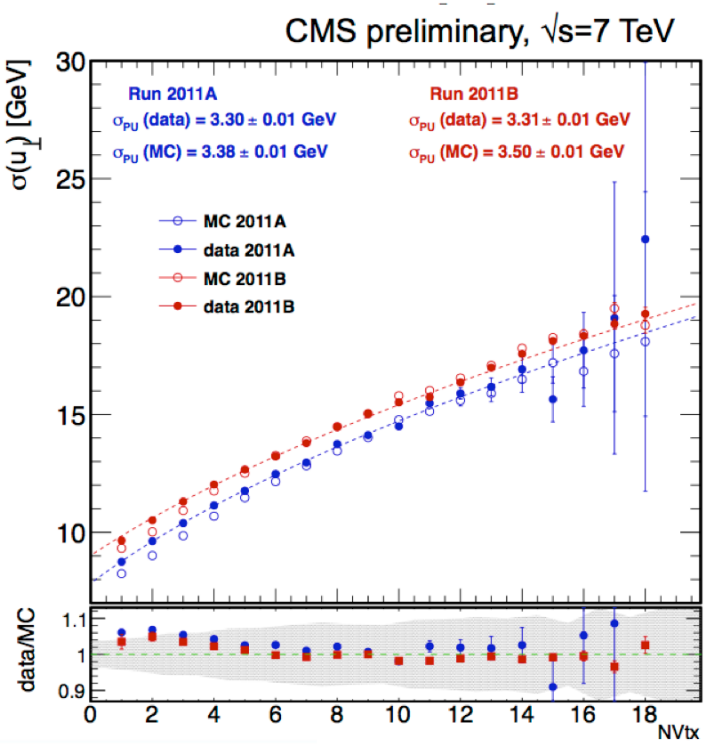




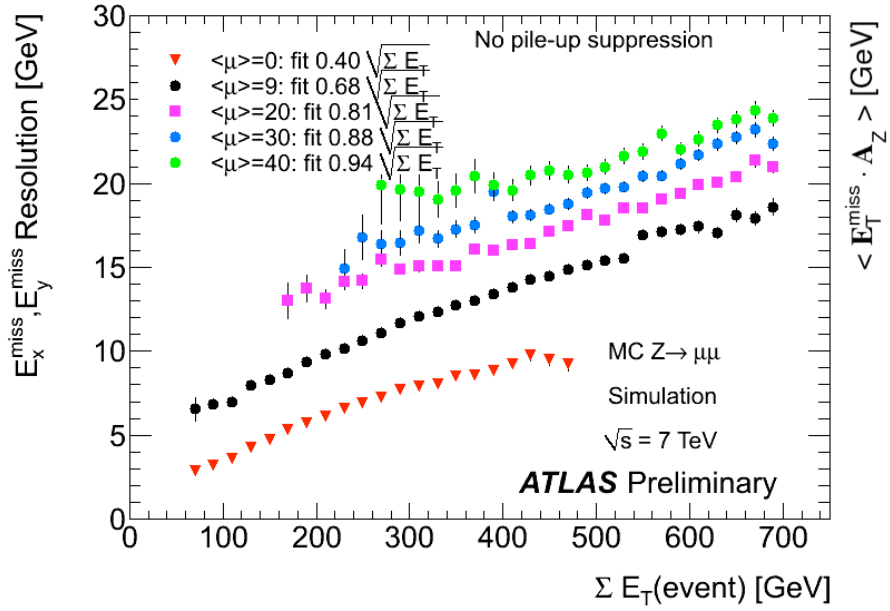
- Number of vertices (roughly number of p-p collisions) per event rising over time
- Particles from collisions other than the primary one add energy to the missing ET measurement and tend to degrade the missing ET resolution

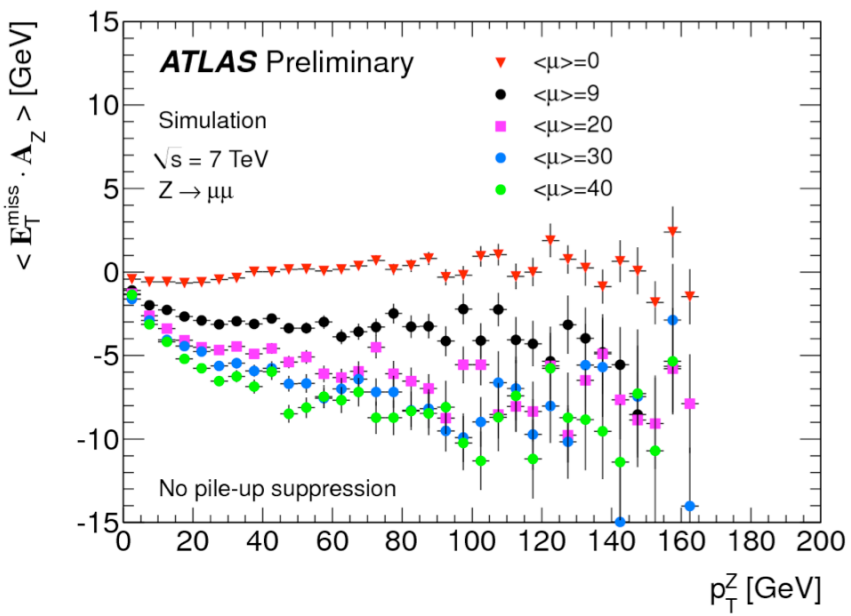
Pileup Performance in CMS/ATLAS





Main effect of additional pileup is worsening of MET resolution, but can also affect scale



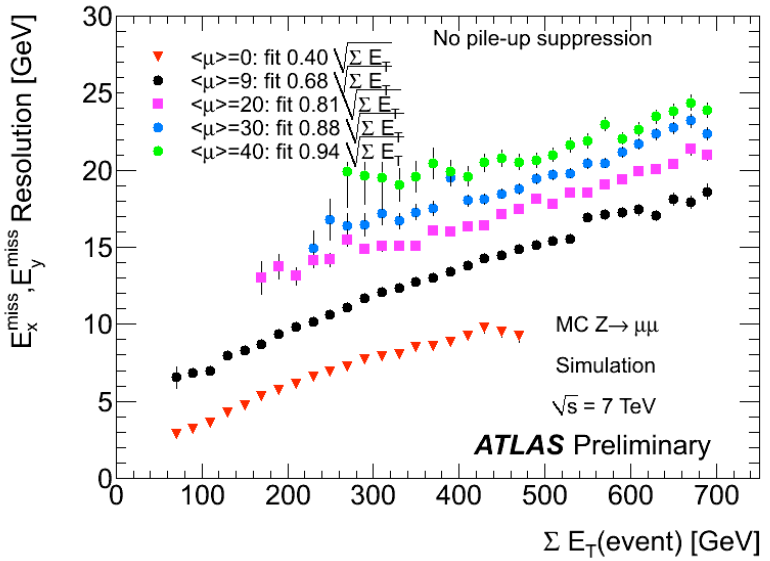


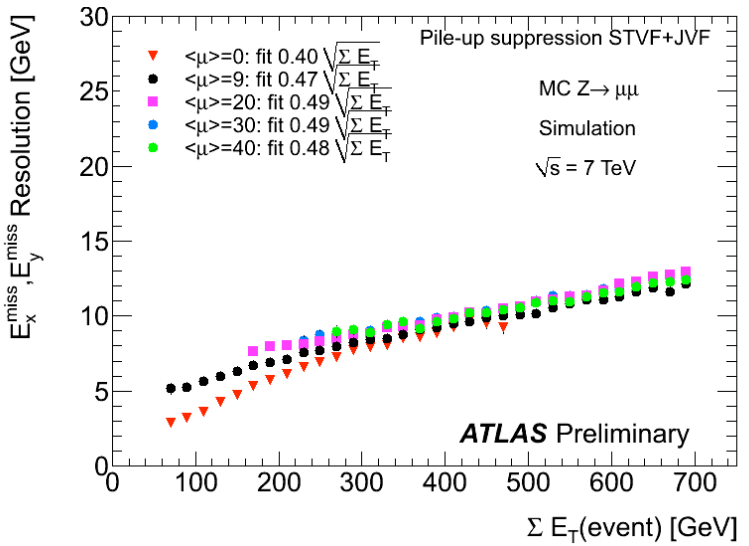
How to Mitigate Effects of Pileup? Method 1: SVTF and JVF

- Use Soft-term vertex fraction:

$$\mathrm{STVF} = \sum_{\mathrm{track,PV}} p_{\mathrm{T}} / \sum_{\mathrm{track}} p_{\mathrm{T}}$$

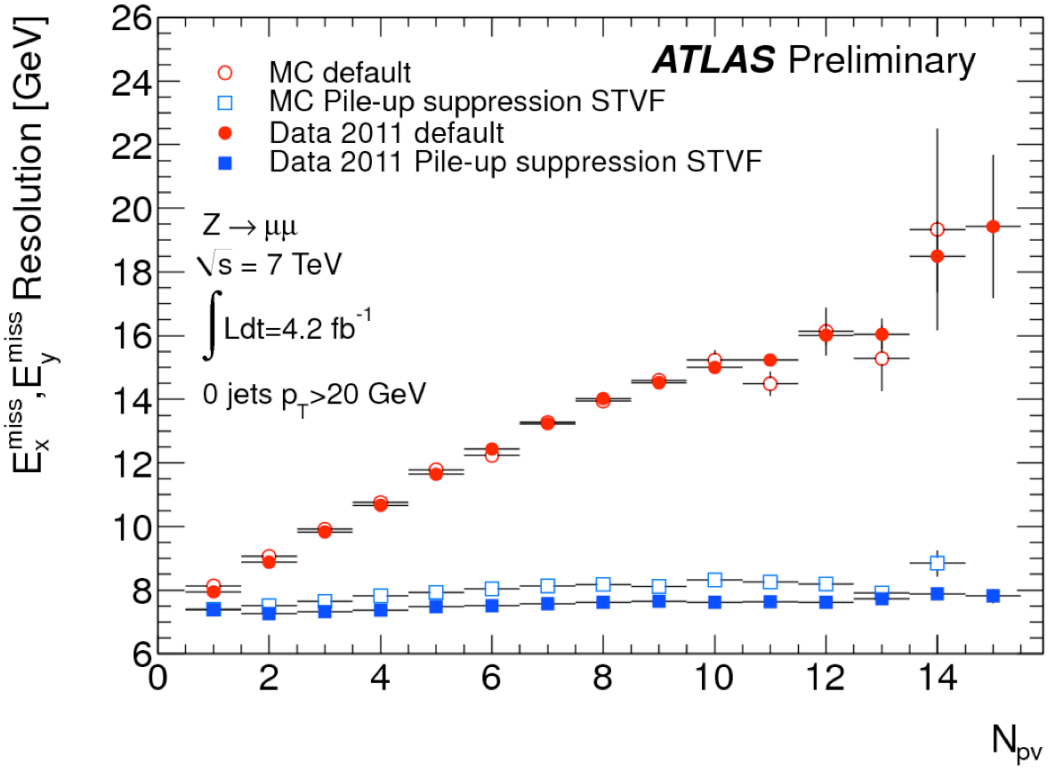
- Multiply soft term of MET by SVTF
  - Basically, weight soft term by fraction of charged energy coming from primary vertex
- Additionally, use jet vertex fraction (JVF) to weight high-pt jets in event
  - JVF is same as STVF but for tracks matched to a jet

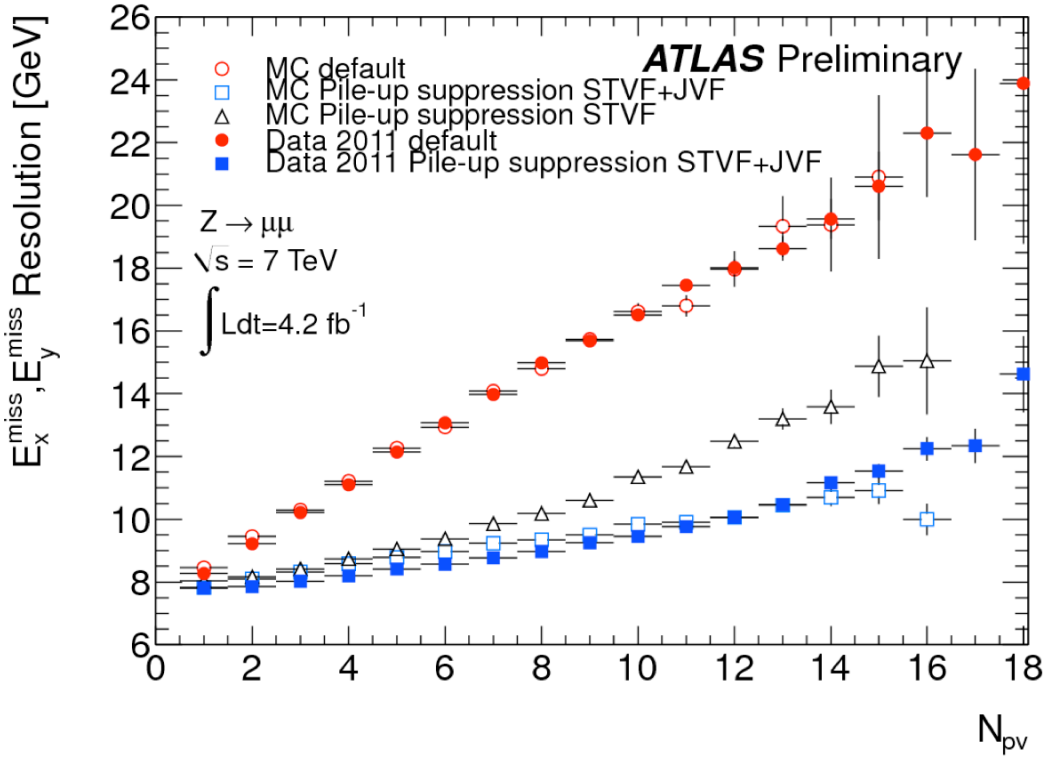




Mostly restores MET resolution for events with pileup

Improvement with STVF + JVF

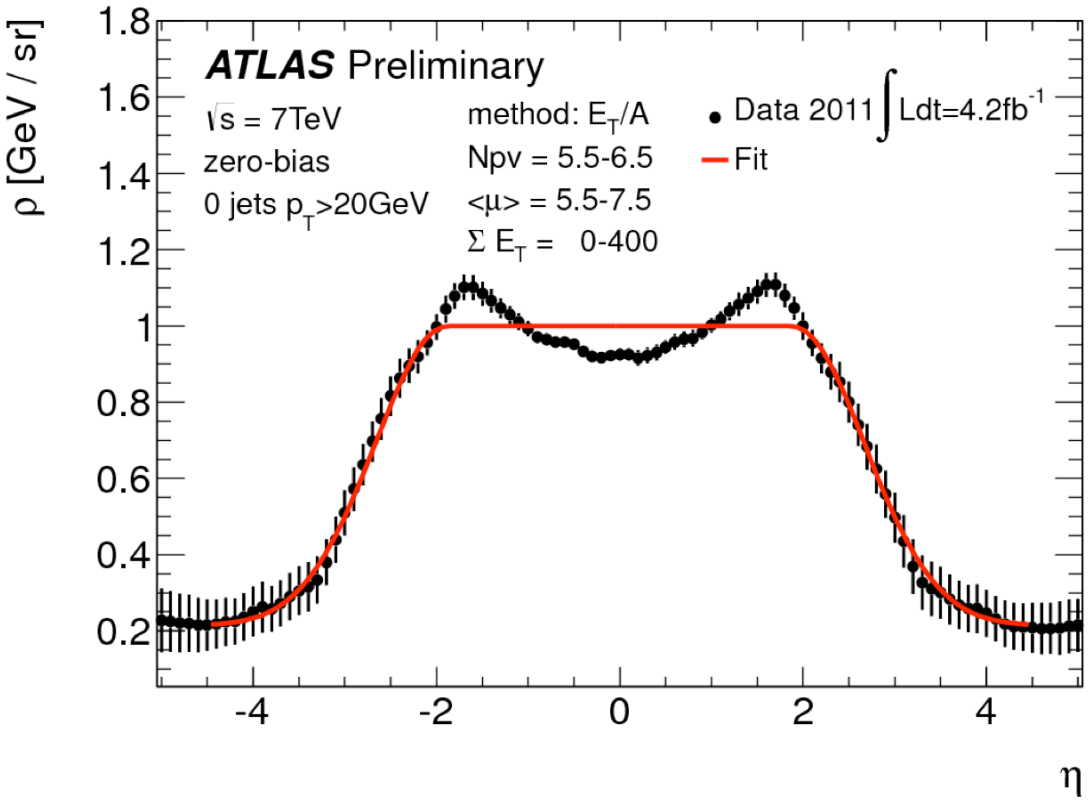




- Resolution in Z->mumu events mostly restored in events with zero jets
- Some residual dependence in events with jets, to be understood

Method 2: Jet Area Method

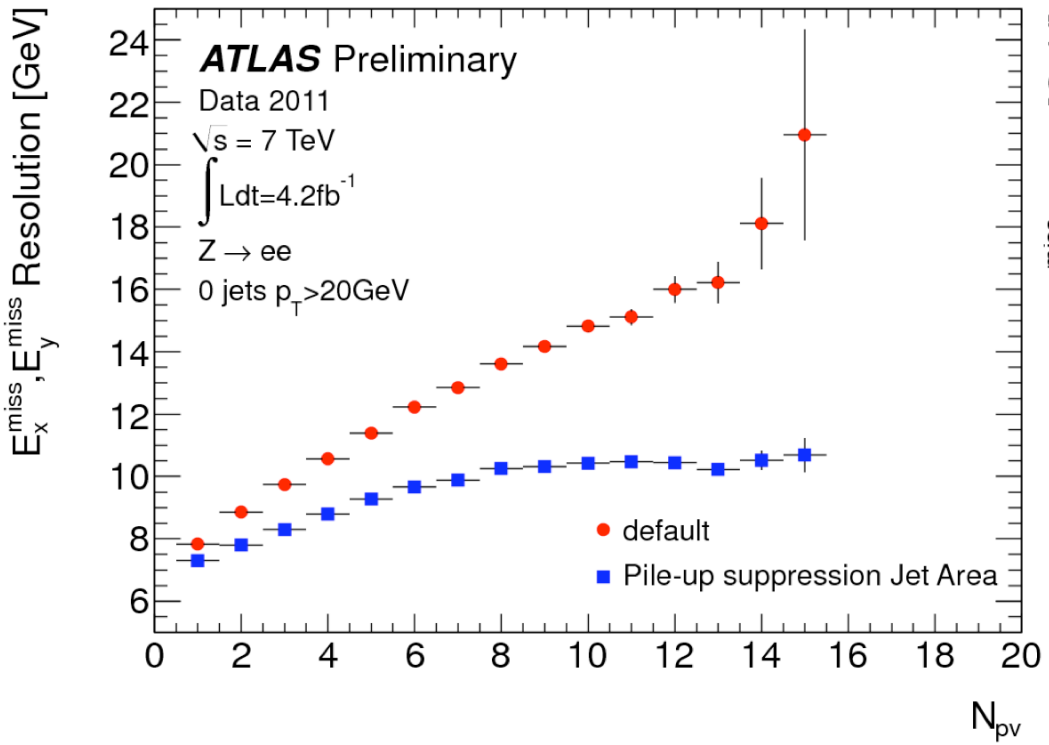
- Measure the average transverse energy density $\rho(\eta)$ in bins of sum et, average number of interactions per bunch crossing $<\mu>$, and number of vertices in zero-bias events
- Run jet clustering on all soft energy in the event (down to pT=0) and subtract estimated pileup energy

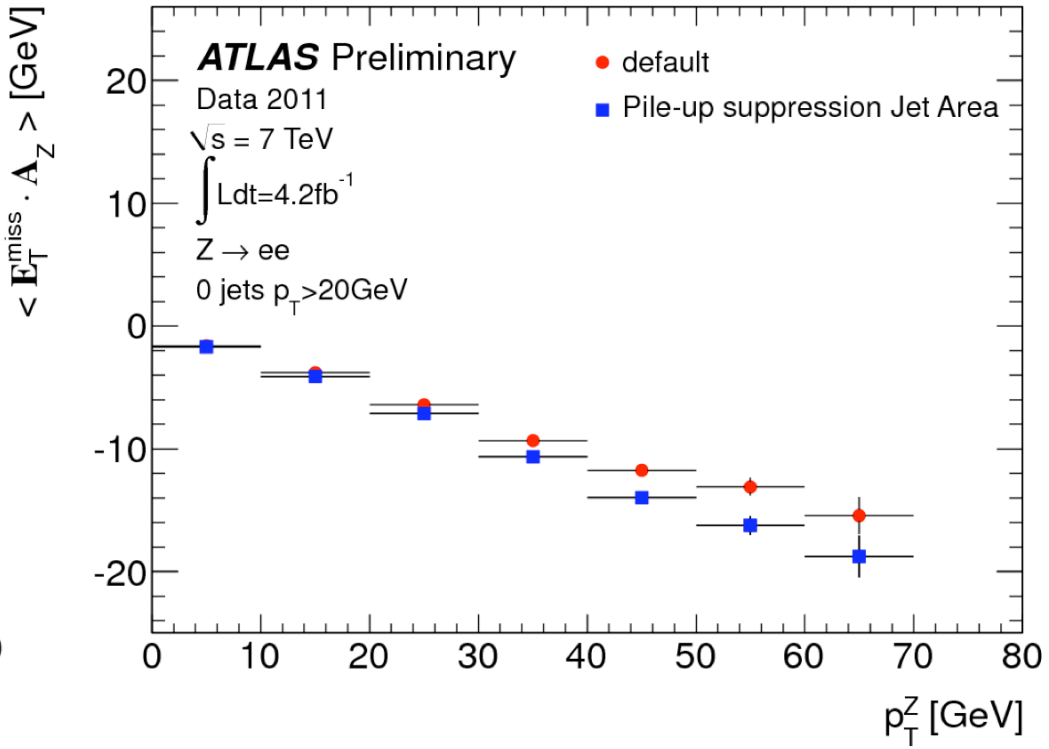


$$E_{\mathrm{T}}^{\mathrm{jet,PUcorr}} = \begin{cases} 0 & E_{\mathrm{T,jet}} \leq \rho_{\mathrm{reference}} A_{\mathrm{jet}} \\ E_{\mathrm{T,jet}} - \rho_{\mathrm{reference}} A_{\mathrm{jet}} & E_{\mathrm{T,jet}} > \rho_{\mathrm{reference}} A_{\mathrm{jet}} \end{cases}$$

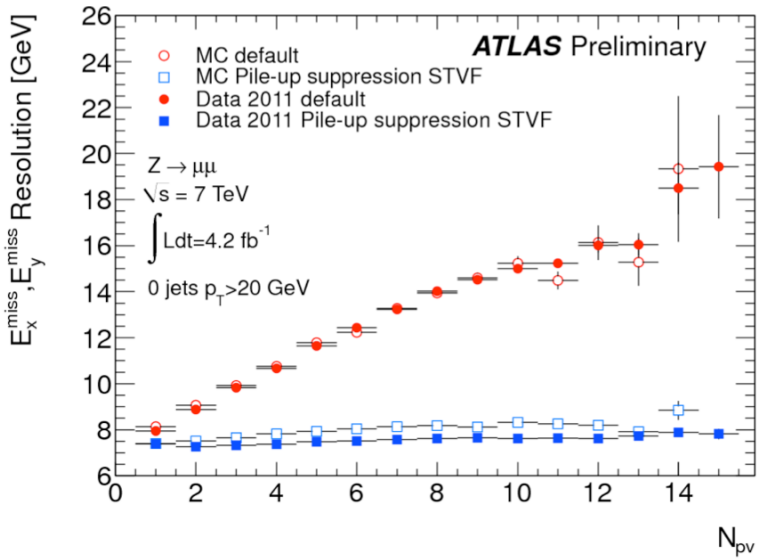
$$E_{x(y)}^{\mathrm{miss,SoftTerm,corr}} = -E_{x(y)}^{\mathrm{jet,PUcorr}}$$

Jet Area Method Results



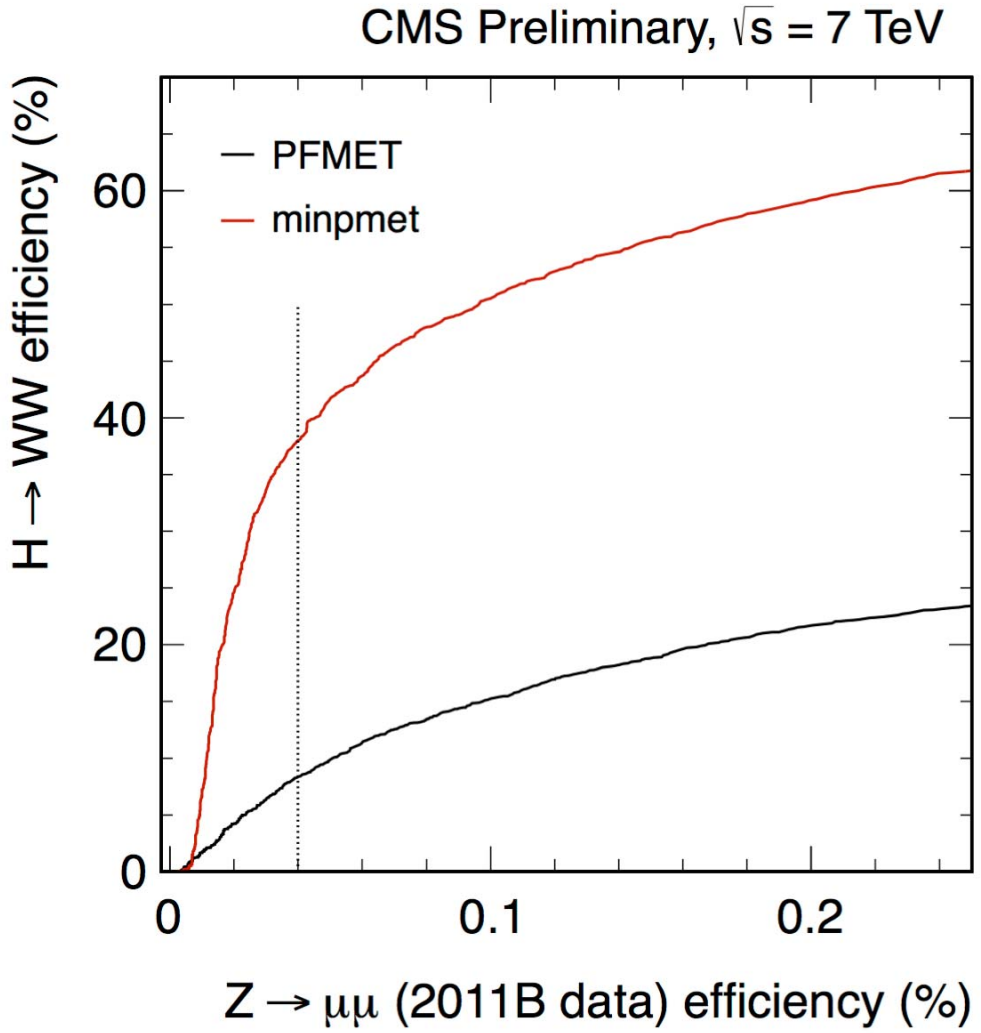


- Resolution in Z->mumu events mostly restored in events with zero jets using this method
- Comparing to SVTF+JVF method, SVTF+JVF is better so far
- Still work in progress though



Method 3: Track MET

- Reconstruct MET using charged tracks originating at primary vertex
  - Less sensitive to pileup than pfMET
- In CMS Higgs->WW analysis, use min(TrackMET, pfMET) and regain some signal efficiency / background efficiency lost due to pileup
- Using min() cut protects against cases with large TrackMET due to events with large missing neutral component



Conclusions

- E_T^{miss} reconstruction in ATLAS/CMS working very well
- Some challenges ahead due to increasing pileup, but several ideas look promising