MET @ CMS

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Introduction

Measurements of missing energy are important to detect

- Neutrinos
- Weakly interacting Dark Matter candidates
- BSM physics e.g. SUSY
- escaping gravitons in scenarios with large X'tra dimensions

The Transverse direction

- No detector can be completely hermetic
- For CMS $|\eta| < 5$
  $\Rightarrow$ Cannot use total energy balance as a signature for missing energy
- Transverse momentum (P_T) of a particle with $|\eta| > 5$ is

$$P_T \leq (\frac{7TeV}{\cosh 5} \approx 94.33GeV)$$

  $\Rightarrow$ Any significant imbalance in the transverse momentum is indicative of processes of interest
- Also in hard scattering events, the boost of “quark center of mass frame” is a priori unknown, hence we have a handle over the transverse direction only

Notations

Note that when we talk about MET we actually mean the missing transverse momentum. Thus the notations followed in this presentation are

- $\mathbb{E}_T$ represents the magnitude of the missing transverse momentum vector, while $\vec{\mathbb{E}}_T$ is the 2D-vector itself.
- $\mathbb{E}_x, \mathbb{E}_y$ are the x,y components of the $\mathbb{E}_T$ vector
- Also define E_T as the total visible energy in the transverse direction

MET determination

- MET is determined from the transverse vector sum over energy deposits in the calorimeter towers

$$\not{E}_T = -\sum_n \left(\frac{E_n}{\cosh \eta_n} \cos \phi_n + \frac{E_n}{\cosh \eta_n} \sin \phi_n\right)$$

- Does not use reconstructed particle momentum or corrected jet energies. Such a calculation therefore gives us the "raw" $\not{E}_T$ of the event. Thus a no. of careful corrections need to applied to the raw measurements in order to do any reliable analysis.
- The total visible transverse energy is obtained from

$$E_T = \sum_n \frac{E_n}{\cosh \eta_n}$$

MET profiles in the absence of missing energy

Note that in the absence of $\mathbb{E}_T$ producing events, $\mathbb{E}_x \& \mathbb{E}_y$ are expected to show a Gaussian profile with a standard deviation σ and centered at zero, while $\mathbb{E}_T$ will be described by the Rayleigh distribution

$$\mathbb{E}_T = \theta(\mathbb{E}_T) * \frac{\mathbb{E}_T}{\sigma^2} * exp(-\frac{{\mathbb{E}_T}^2}{2\sigma^2})$$

MET profiles in the absence of missing energy

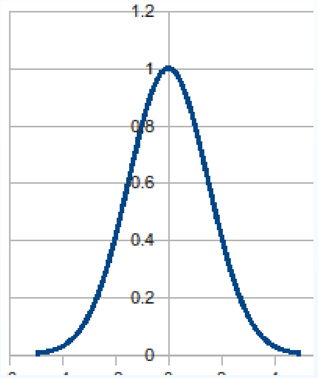


Figure 1: E_x and E_y will have a Gaussian profile

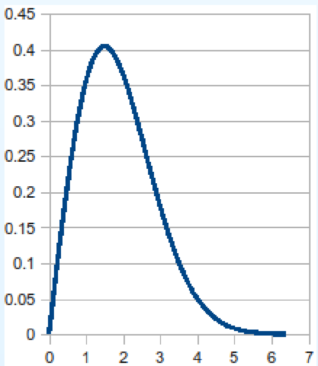


Figure 2: $\mathbb{E}_T$ will be a Rayleigh distribution

Experimental Challenges

- Energy Resolution : Need excellent energy resolution in all calos. (Usually limited by non-linearities of calorimeter response)
- Multi-jet events: Resolution is limited due to the statistical fluctuations in showering
- Non-compensating HCAL
- Electronic noise, Pile-ups and Underlying Events
- MET tails: These are large and non-Gaussian. Hence very hard to simulate; will have to wait for real data to see how large the effect is.

Experimental Challenges

- High Magnetic Field:
  - Assigned direction of charged particle $\vec{P}_T$ is different from the “true” $\vec{P}_T$ which gets bent
  - low P_T parts of the jets might be lost, giving a false MET signal
- Energy loss due to punch throughs
- Faulty calorimeter cells

Non linear HCAL response Vs E_T

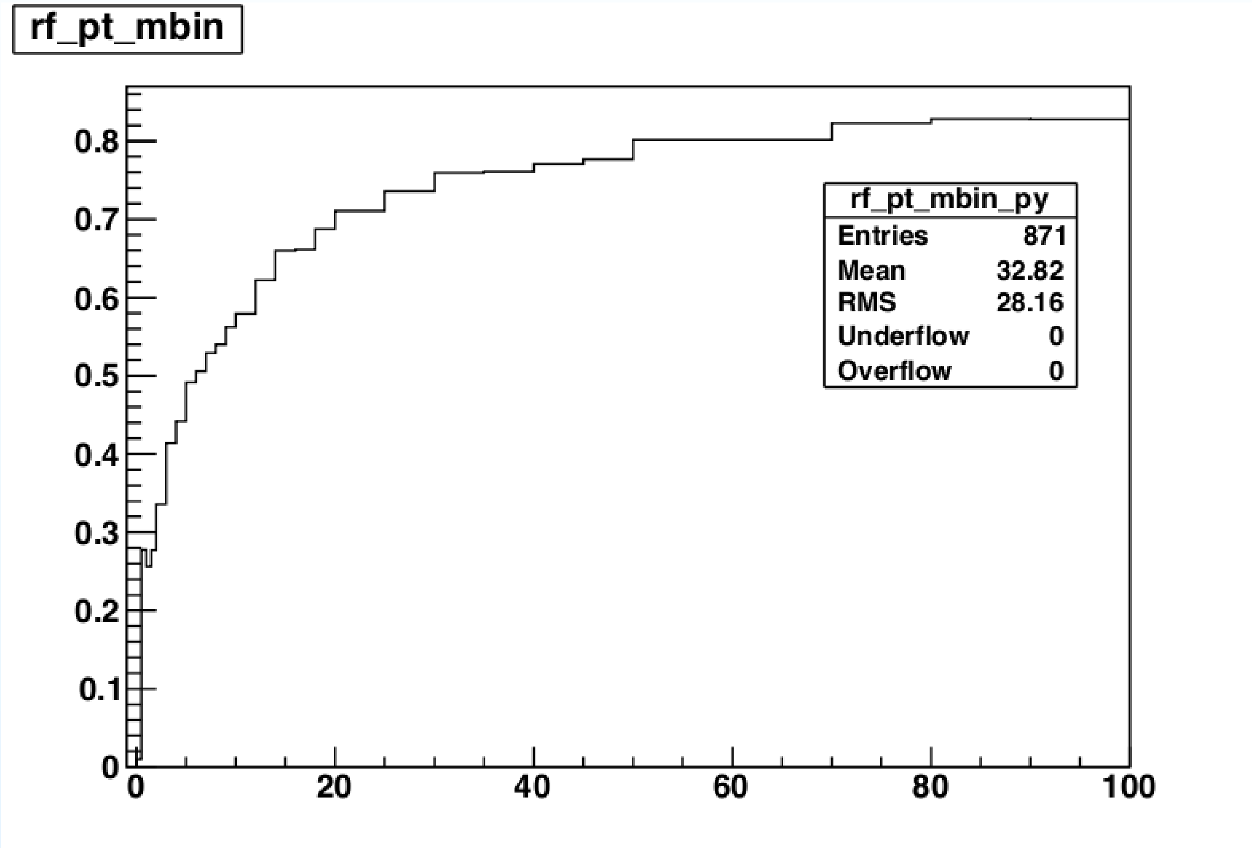


Figure 3: This is a single pion response as measured in Monte Carlo simulations

MET resolution

Most generally, the resolution of MET can be characterized in terms of the following parameters

- A $\longrightarrow$ noise, pile-ups (PU) and underlying events (UE)
- B $\longrightarrow$ statistical sampling nature of energy deposits in the calos.
- C $\longrightarrow$ non-linear calorimeter response, dead material and cracks
- D $\longrightarrow$ the shift in E_T due to noise, PU and UE

$$\sigma^2(\not{E}_T) = A^2 + B^2(E_T - D) + C^2(E_T - D)^2$$

- A, B and C are a priory uncorrelated while A and D are strongly correlated. However separating A and D is helpful.

MET correction Strategies

- Calorimeter based MET correction
- Track-corrected MET
- PF-MET

Calorimeter based MET corrections

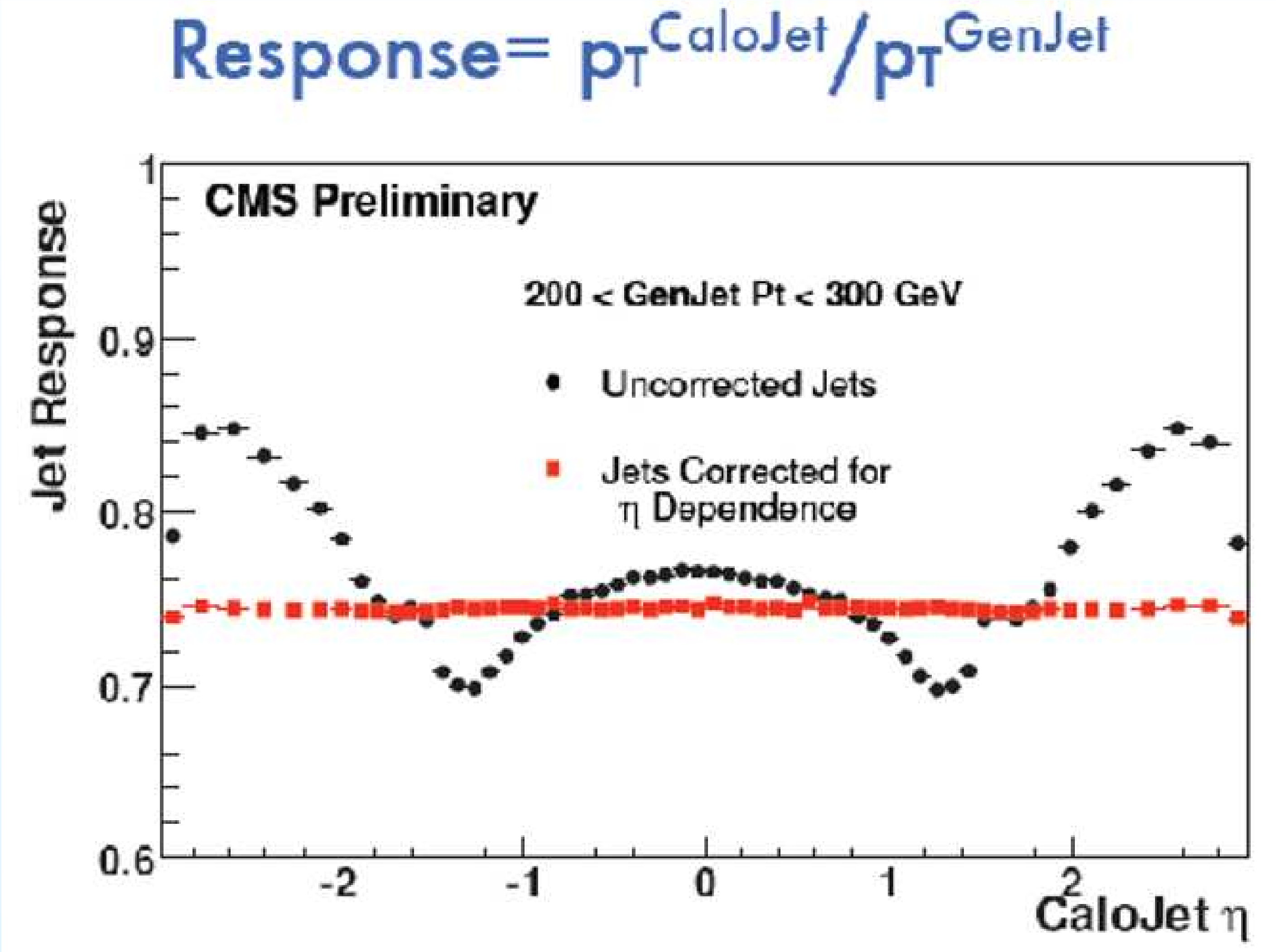
Some of the major corrections applied to “colorimeter tower based” $\mathbb{E}_T$ are

- Jet Energy Scale (JES) corrections
- Muon corrections
- Corrections due to hadronically decaying Taus
- Electron corrections

JES corrections : MCJet

- Adjust for the difference between the the raw jet energy (as seen in the calo.) and true jet energy, as defined by the Jet Energy Scale group.
- Remove biases due to non-linear calorimeter response to jet energy at different values of E_T and rapidity
- Derived by fitting relative response of the calorimeter i.e. $E_T^j(Rec)/E_T^j(MC)$ with a Gaussian in each E_T^j, $|\eta_j|$ bin
- The final result is a uniform response in η and E_T

Jet Response before and after corrections



EMF dependent JES corrections

- More advanced in nature
- Applied on top of MCJet
- Take into account non-compensation in the calorimeter by utilizing the fraction of jet energy deposited in ECAL
- Fit $E_T^j(Rec) - E_T^j(MC)$ with a Gaussian in each E_T^j, $|\eta_j|$ bin
- Can improve resolution of jet energy by as much as 10%

Quality cuts on JES corrections

- Average MCJEt corrections are not applicable to true jets with high EM fraction.
  $\Rightarrow$ exclude jets with EMF above a certain threshold, from the corrections
- Jet corrections are poorly known for jets at low P_T^j
  $\Rightarrow$ exclude jets with P_T^j below a certain threshold, from the corrections

Performance of Q-cuts on JES corrections

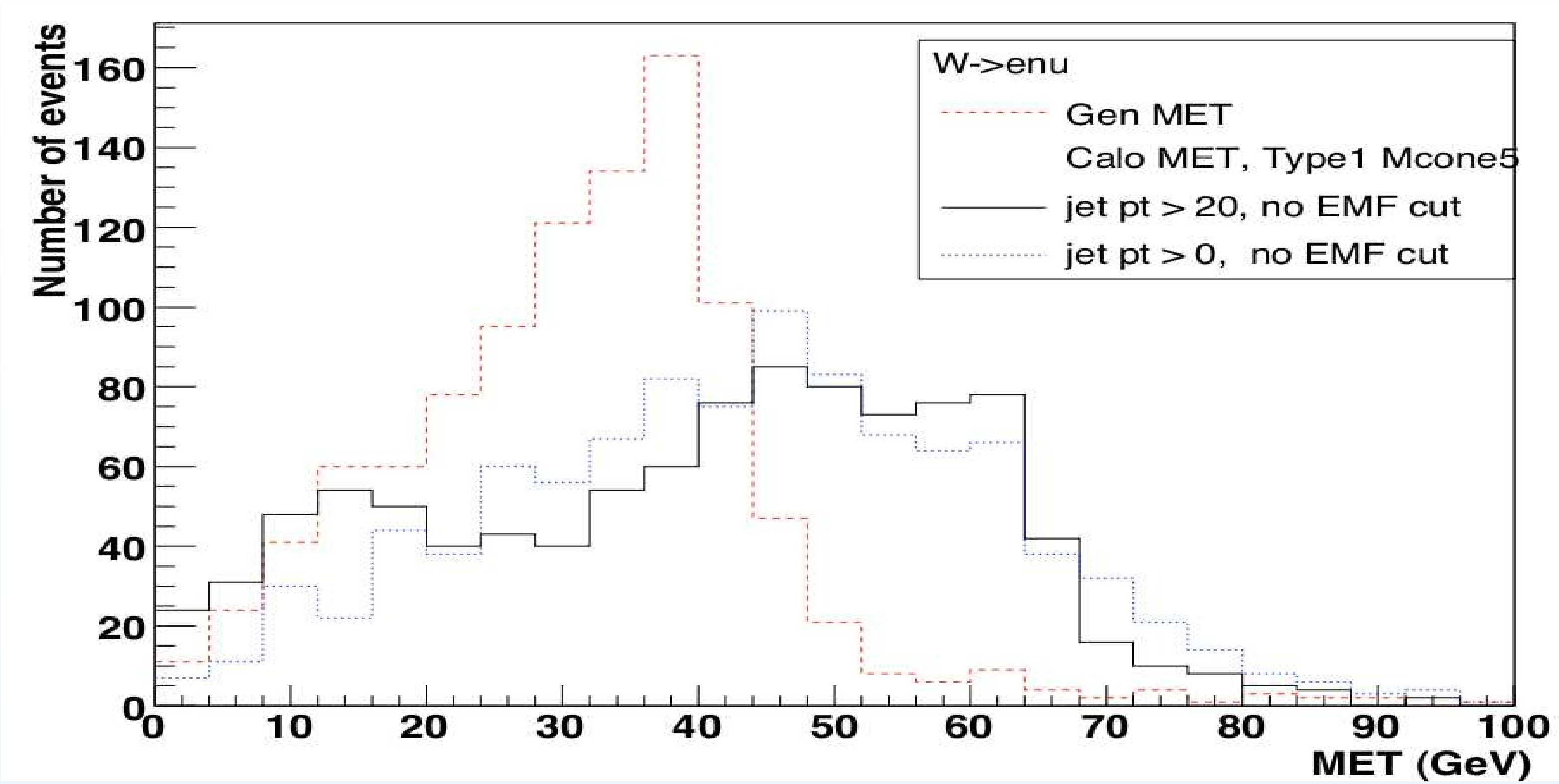


Figure 4: Calo-MET vs Gen-MET without any EMF cuts; Red $\rightarrow$ Gen-MET; Blue $\rightarrow$ Calo-MET with no P_T cut on jets; Black $\rightarrow$ Calo-MET using jets with $p_T > 20GeV$; Gen-MET was generated using MC for W$\rightarrow e\nu$

Performance of Q-cuts on JES corrections

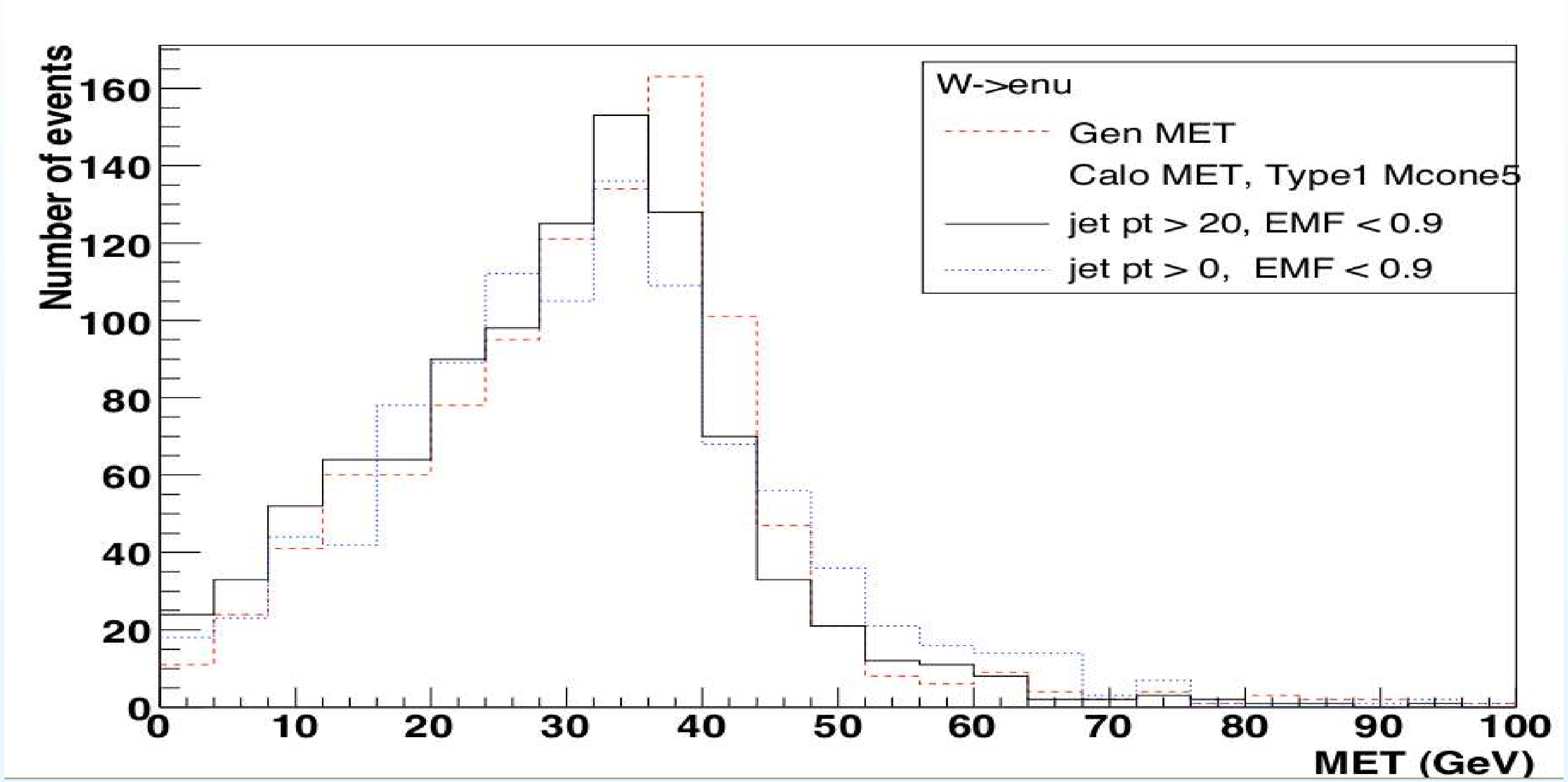


Figure 5: Calo-MET (with EMF < 0.9) vs Gen-MET; Red → Gen-MET; Blue → Calo-MET with no P_T cut on jets; Black → Calo-MET using jets with $p_T > 20GeV$; Gen-MET was generated using MC for W→ $e\nu$

Muon Corrections

- Muons deposit very little energy in the calos.
  $\Rightarrow$ since $\mathbb{E}_T$ is measured based on energy deposited in the calos. only, therefore muons will lead to a significant $\mathbb{E}_T$ signal
- Muon momentum can be measured very precisely in the muon chambers and the tracker
- Account for muons by adding their energy deposits in the calos. to $\mathbb{E}_T$ and then subtracting their transverse momentum

$$\mathbb{E}_{T\,corrected} = \mathbb{E}_T + \sum \vec{E}^{\mu}_{T,calo} - \sum \vec{P}^{\mu}_T$$

Quality cuts on Muon Corrections

In order to eliminate fake muons we also apply the following quality cuts on muons

- muon must be a Global Muon
- $P_T^{\mu} > 10.0 GeV/c$
- Number of valid hits in the silicon tracker > 5

Performance of Muon corrections

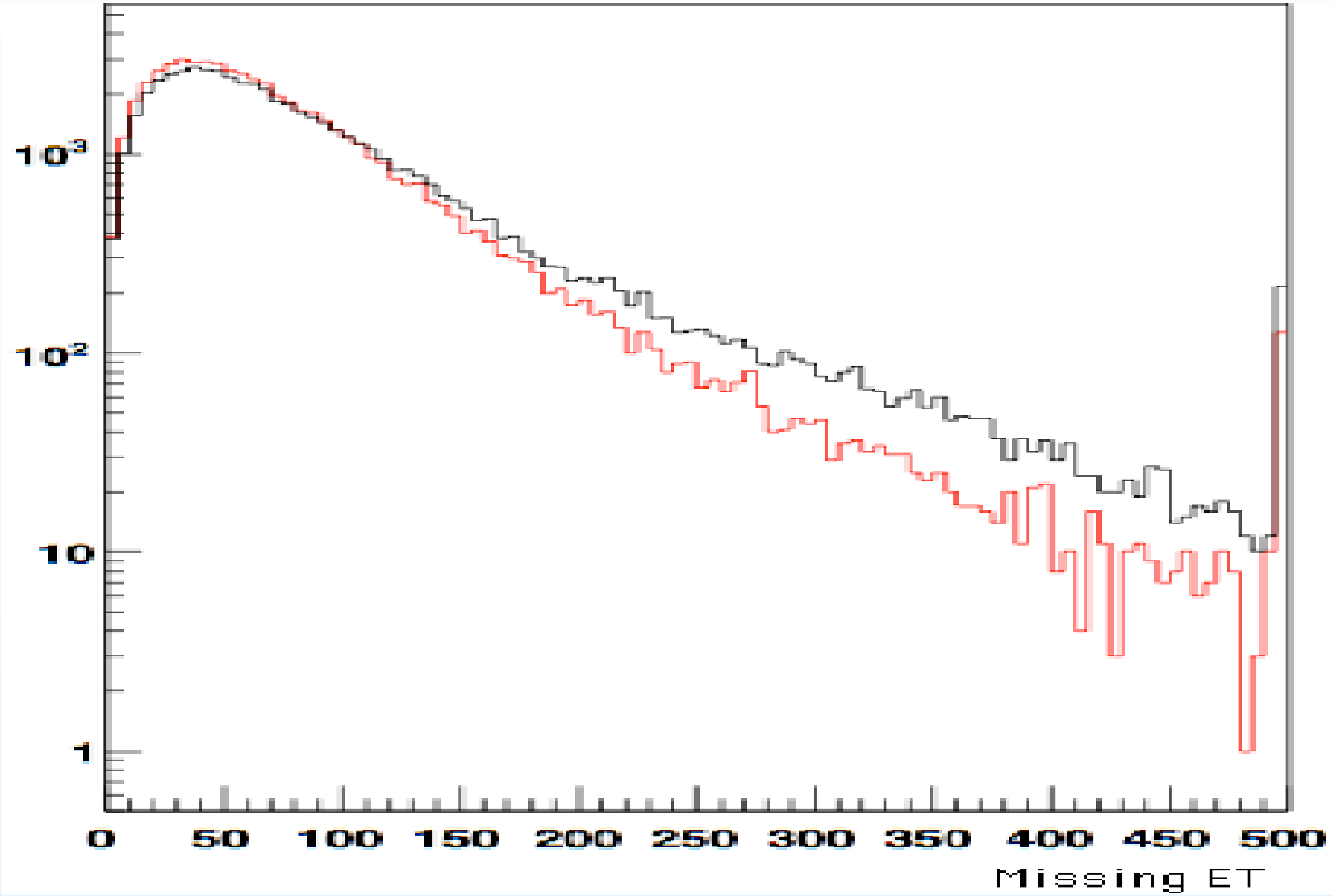


Figure 6: $\not{E}_T$ (in QCD Pythia MC events) including (red) and excluding (black) the muon corrections

performance of Muon + JES corrections

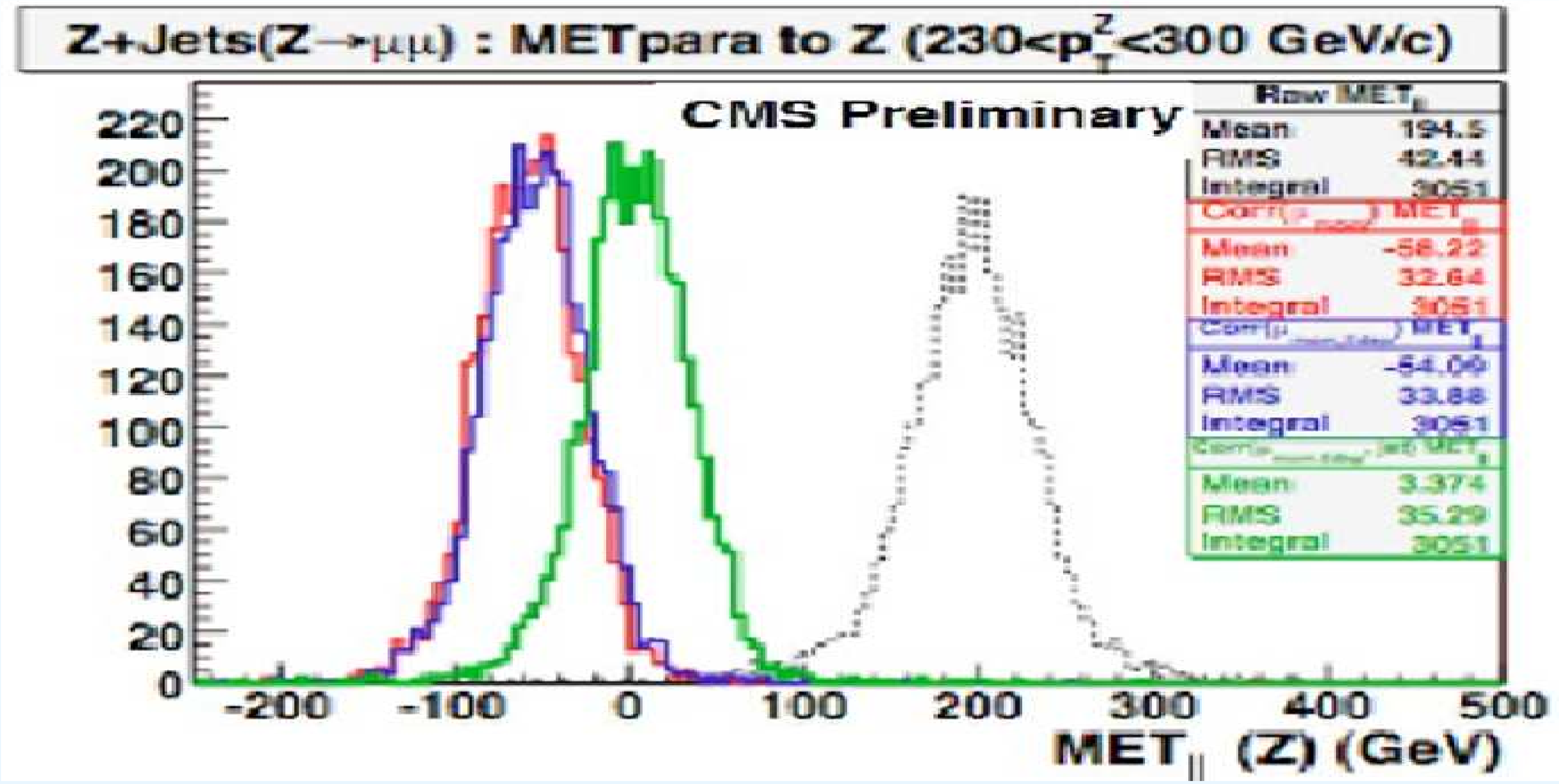


Figure 7: simulation of measured MET for $Z \to \mu\mu$;uncorrected calo-MET (Black) + Muon correction (Red) + Muon Deposit (Blue) + JES (Green)

Hadronically decaying Taus

- Reason for corrections due to Taus are same as those for QCD jets i.e. non-compensating nature of the calos. and magnetic field effects.
- QCD jet corrections can not be applied to Tau decays
  - Hadronic jets due to Taus have low particle multiplicity and fairly energetic products
  - Large EM fraction in Tau decays due to $\pi^0 \to \gamma\gamma$

Tau corrections

- The corrections can be established by defining a region in the calorimeter that is large enough to include energy deposits of all decay products of a Tau. The energy deposition is then replaced with the "true" tau transverse energy.
- The true "visible" Tau energy can be approximated by the measurements involving reconstruction of tau jets using particle flow techniques.
- The region of interest can be defined by the Tau isolation criteria, which is the main discriminator against QCD jets.
- The corrected $\mathbb{E}_T$ then is obtained as

$$\vec{\mathbb{E}}_{T\,corrected} = \vec{\mathbb{E}}_T - \left(\sum_{reg} \vec{E}^{\tau}_{T,cal} - \sum_{reg} \vec{E}^{PU}_{T,cal} - \sum_{reg} \vec{E}^{UE}_{T,cal}\right) + \sum_{reg} \vec{E}^{\tau}_{T}$$

Performance of Tau corrections

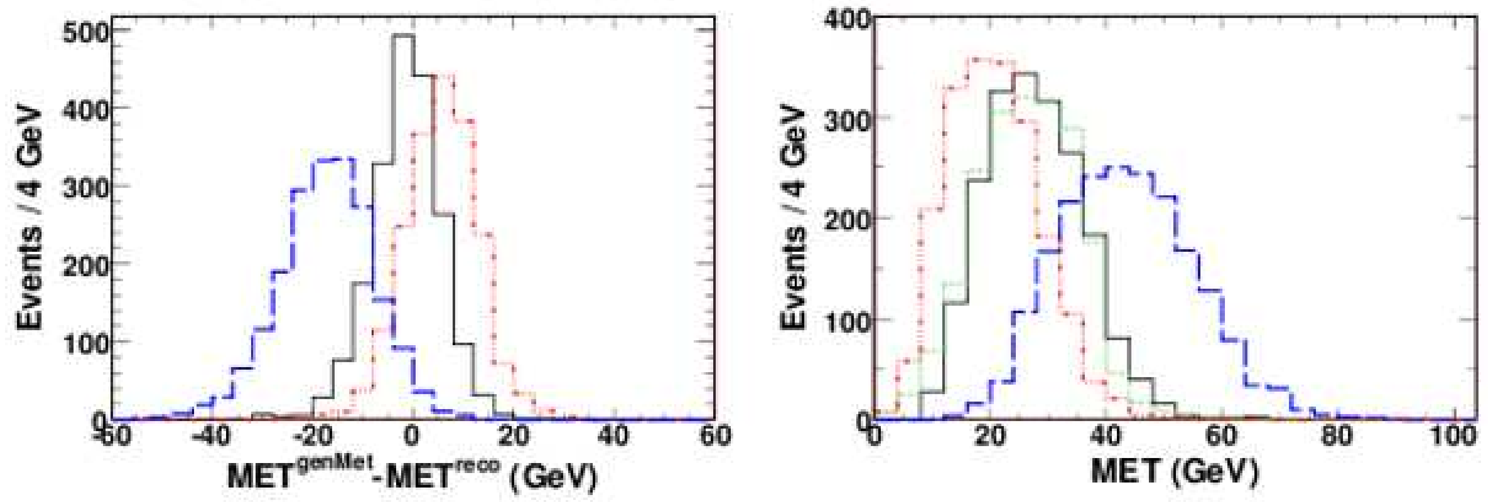


Figure 5: On the left:($\not{E}_T{}^{true} - \not{E}_T{}^{reco}$) distribution for the case of no correction (red, dashed-dotted), standard jet correction (blue, dashed) and tau correction (black, solid). On the right: $\not{E}_T$ distribution for "true" generator level $\not{E}_T$ (green, dotted), raw uncorrected $\not{E}_T$ (red, dashed-dotted), standard jet based correction (blue, long-dash), and tau based correction (black, solid).

Electron Corrections

Electrons have excellent energy resolution and coverage of ECAL. Thus corrections are small and won’t effect most of the analysis.

Other MET correction strategies

- Track-corrected MET: Compute MET by replacing the “expected” energy deposition of good tracks of charged hadron deposits with the corresponding momentum.
  - The “expected” energy deposition is computed based on response function derived from a single pion Monte-Carlo sample
  - Correcting Muons as pions results in under-corrections and generates fake MET; use standard muon corrections as described earlier
  - Electrons deposit most of their energy in ECAL-treating electrons as pions generates fake MET;remove tracks matched to electrons

Other MET correction strategies

- $\not{E}_T$ from Particle Flow:
  - PF reconstruction algorithms provide a global event description at the level of individually reconstructed particles
  - Include not only the charged particles but also photons, stable and unstable neutral hadrons (which may not necessarily be isolated)
  - PF-MET is reconstructed with certain efficiency, fake rate and possess a finite momentum resolution
    $\Rightarrow$ Need to calibrate and verify MET

The Significance variable

- Define a significance variable “S”

$$S = \frac{{\mathbb{E}_T}^2}{2\sigma^2_{\mathbb{E}_T}}$$

- S estimates the no. of standard deviations of the measured event $\mathbb{E}_T$ from the $\mathbb{E}_T = 0$ hypothesis. Thus in general S will be small when $\mathbb{E}_T$ can be attributed to measurement resolution and large otherwise.

Cosmic and Beam halo Cleaning

$\not{E}_T$ in an event can receive contributions from cosmic muons or detector related background such as beam halo. To eliminate such contributions

- require at least one primary vertex in the event
- event EMF < 0.1
- The event charge fraction $F_{ch} < 0.175$

Conclusion

- Measurement of $\mathbb{E}_T$ will give important information about many processes of interest
- A precise measurement of $\mathbb{E}_T$ is plagued with experimental challenges
- Improvement to calorimeter based $\mathbb{E}_T$ can be made by exploiting other CMS sub-detectors, particularly the tracker due to its far more superior resolution
- A more refined resolution can be obtained by employing particle flow tech.
- To ensure that detector malfunctions do not corrupt $\mathbb{E}_T$, a Data Quality Monitoring system has been set up
- $\mathbb{E}_T$ due to measurement resolution can be eliminated by using the $\mathbb{E}_T$ significance variable

Bibliography

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- R. Cavanaugh, “Reconstructing Jets and Missing Transverse Energy using the CMS Detector”, Nucl. Phys. B 172 129-131 (2007)