Missing Transverse Energy (MET) at CMS

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Introduction

- MET measures the energy imbalance in the plane transverse to the colliding proton beams
  - Proton PDFs make the longitudinal momentum unknown
- The imbalance is caused by
  - particles escaping detection by CMS
  - detector effects: noise, dead/hot cells
  - unaccounted physics processes: beam halo, cosmics, pile-up, underlying event
- The typical escaping particles are:
  - Neutrinos
  - Potential weakly interacting non-SM particles (e.g. SUSY LSP)
  - Very forward particles with |eta| > 5 (outside calorimeter acceptance)
    - Their expected transverse energy is less than 15 GeV
- Due to its impact on new physics discovery, MET needs to be scrutinized and well understood

MET definition and types

- MET is the magnitude of the 2D vector ($-\sum E_x^i, -\sum E_y^i$)
  - E_x^i is the energy of the i[th] input object projected along x-axis

$$MET = \sqrt{\left(\sum_n E_x\right)^2 + \left(\sum_n E_y\right)^2}$$

- At CMS exist several types of MET quantities depending on the input objects
- CaloMET collection
  - using calorimeter towers
- GenMET collection
  - from generator level stable particles
- PFMET collection -> *pfMet*
  - from Particle Flow candidates
- MET collection
  - using reconstructed jets
    - *htMetSC5*, *htMetSC7* (SisCone)
    - *htMetKT4*, *htMetKT6* (Fast KT)
    - *htMetIC5* (Iterative Cone5)
  - *tcMet* -> e,μ,track corrections

Optimized towers	Scheme B towers	Features
metOpt	*met*	No HO
metOptNoHF	*metNoHF*	No HO or HF
metOptHO	*metHO*	Uses HO
metOptNoHFHO	*metNoHFHO*	Uses HO,no HF

genMet	No ν,μ,BSM
genMetNoNuBSM	No prompt ν,μ,BSM
genMetCalo	genMet (30x)
genMetCaloAndNonPrompt	genMetNoNuBSM (30x)
genMetTrue	No ν,BSM (30x)
genMetFromIC5GenJets	Uses IC5 genJets

Access MET objects in CMSSW

• Your EDAnalyzer should contain lines like these to run over RECO samples:

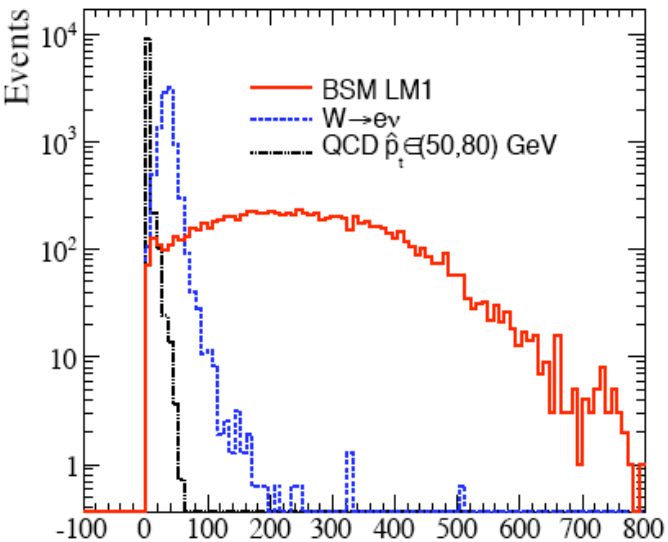
```
#include "DataFormats/METReco/interface/CaloMETCollection.h"
#include "DataFormats/METReco/interface/CaloMET.h"
#include "DataFormats/METReco/interface/GenMETCollection.h"
#include "DataFormats/METReco/interface/GenMET.h"
---------
edm::Handle<CaloMETCollection> Met;
edm::Handle<CaloMETCollection> CorrMet;
edm::Handle<GenMETCollection> genMet;

-----------
void YourAnalyzer::analyze(const edm::Event& evt, const edm::EventSetup& iSetup)
{
  evt.getByLabel ("genMet",genMet);
  evt.getByLabel ("met",Met);
  evt.getByLabel ("corMetType1Icone5",CorrMet);

  for (GenMETCollection::const_iterator gmt=genMet.begin(); gmt!=genMet.end();gmt++){
      double genmet = gmt->pt();
      double genmetphi = gmt->phi();
    }

  for (CaloMETCollection::const_iterator mt=Met.begin(); mt!=Met.end();mt++){
      double met = mt->pt();
      double metphi = mt->phi();
    }

  for (CaloMETCollection::const_iterator cmt=CorrMet.begin(); cmt!=CorrMet.end();cmt++){
      double corrmet = cmt->pt();
      double corrmetphi = cmt->phi();
    }
}
```

• Similar code for PAT samples

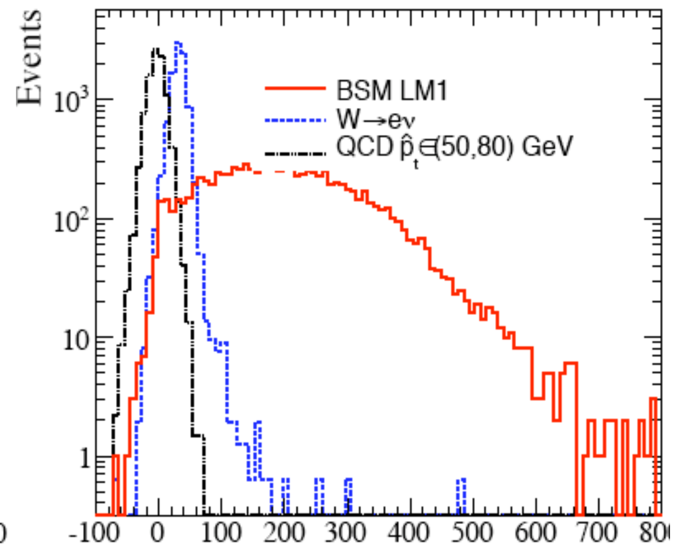
• Put this in your python file:

```
process.load("JetMETCorrections.Configuration.L2L3Corrections_Summer08_cff")
process.prefer("L2L3JetCorrectorIC5Calo")
process.load("JetMETCorrections.Type1MET.MetType1Corrections_cff")
process.corMetType1Icone5.corrector = cms.string('L2L3JetCorrectorIC5Calo')
```

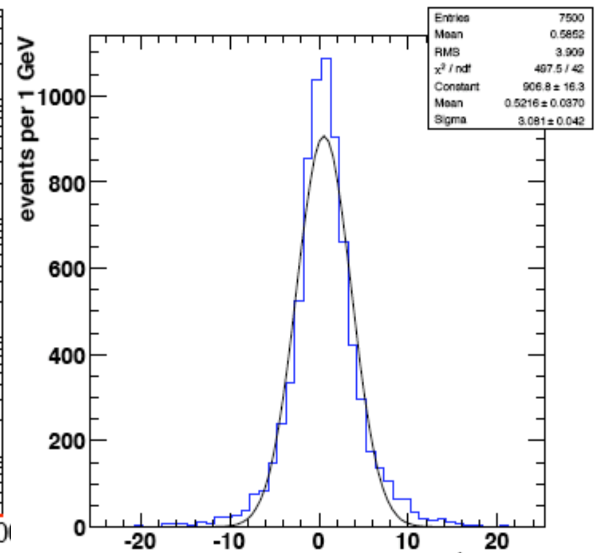
MET distributions



Gen MET



Reco MET



Reco MET_x

- Different physics processes have different MET distributions
  - One can use MET in the event selection to enhance desired signal
- True MET (left) distribution is reasonably well reproduced by the reconstructed MET (middle)
  - Example here is clean of MET from non-essential physics backgrounds (e.g. PU, cosmics) or detector malfunctions
- MET distribution has a non-gaussian shape: $(\sqrt{(2\pi)}/\sigma)\theta(MET)MET \times G(MET,0,\sigma)$
  - Note that MET_x (right) is a gaussian centered at 0 for QCD

MET resolution

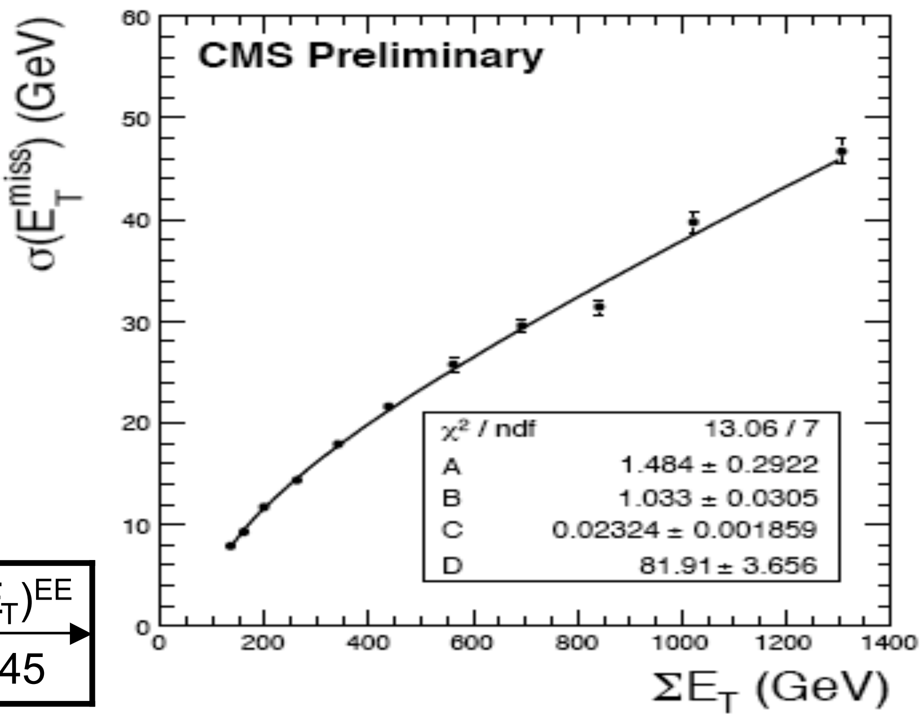
- Resolution = rms of MET built from calorimeter towers
- In the absence of MET from escaping particles, the resolution is affected by:
  - A: electronic noise, pile-up (PU), underlying event (UE)
  - B: stochastic effects
  - C: non-linearities, cracks, dead cells

$$\sigma(MET) = A \oplus B\sqrt{\sum E_T - D} \oplus C\left(\sum E_T - D\right)$$

- $\sum E_T$ is the scalar sum of transverse energies of the towers
- D is the offset due to noise & UE

- Plot shows MET resolution in QCD sample with $p_T \in (20,800)$ GeV
  - no pile-up, Scheme B tower energy thresholds

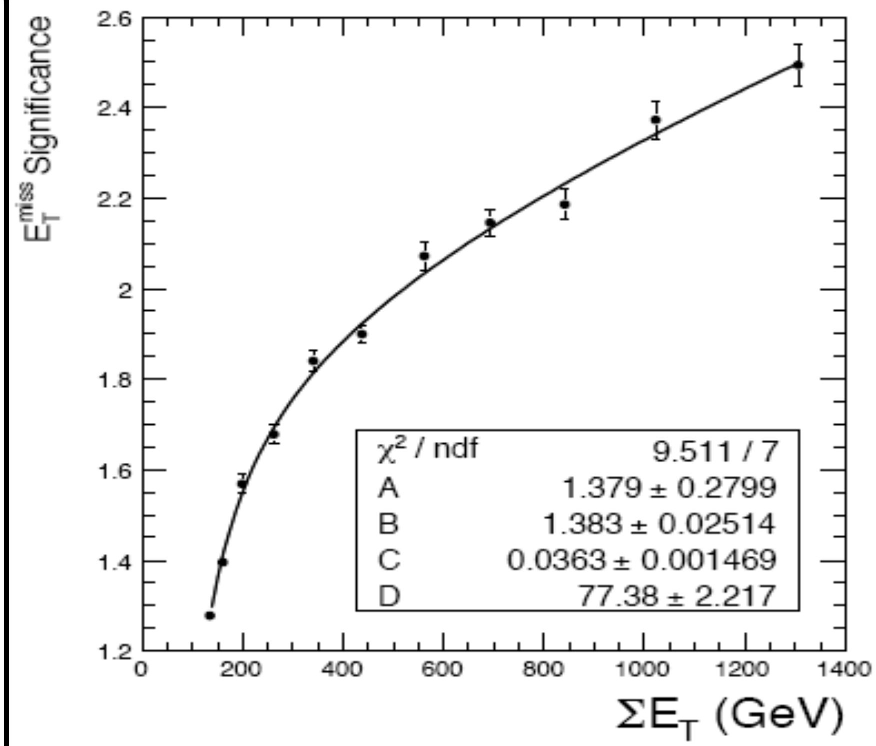
HB	HO	HE	HF(S)	HF(L)	$(\sum E_T)^{EB}$	$(\sum E_T)^{EE}$
0.9	1.1	1.4	1.8	1.2	0.2	0.45



MET significance

- Defined as ratio of avg MET over MET resolution
- If the stochastic effects dominate and no offset
  - Estimates the number of standard deviations of measured MET from 0
  - For QCD dijet events, MET_x and MET_y are Gaussians $G(0,\sigma)$
    - σ -> detector resolution
  - Then <MET>/ σ(MET) ~ 1.9
- The plot clearly shows dependence on $\sum E_T$ which indicates that non-stochastic effects are important
  - QCD sample with $p_T \in (20,800)$ GeV, no pile-up, Scheme B

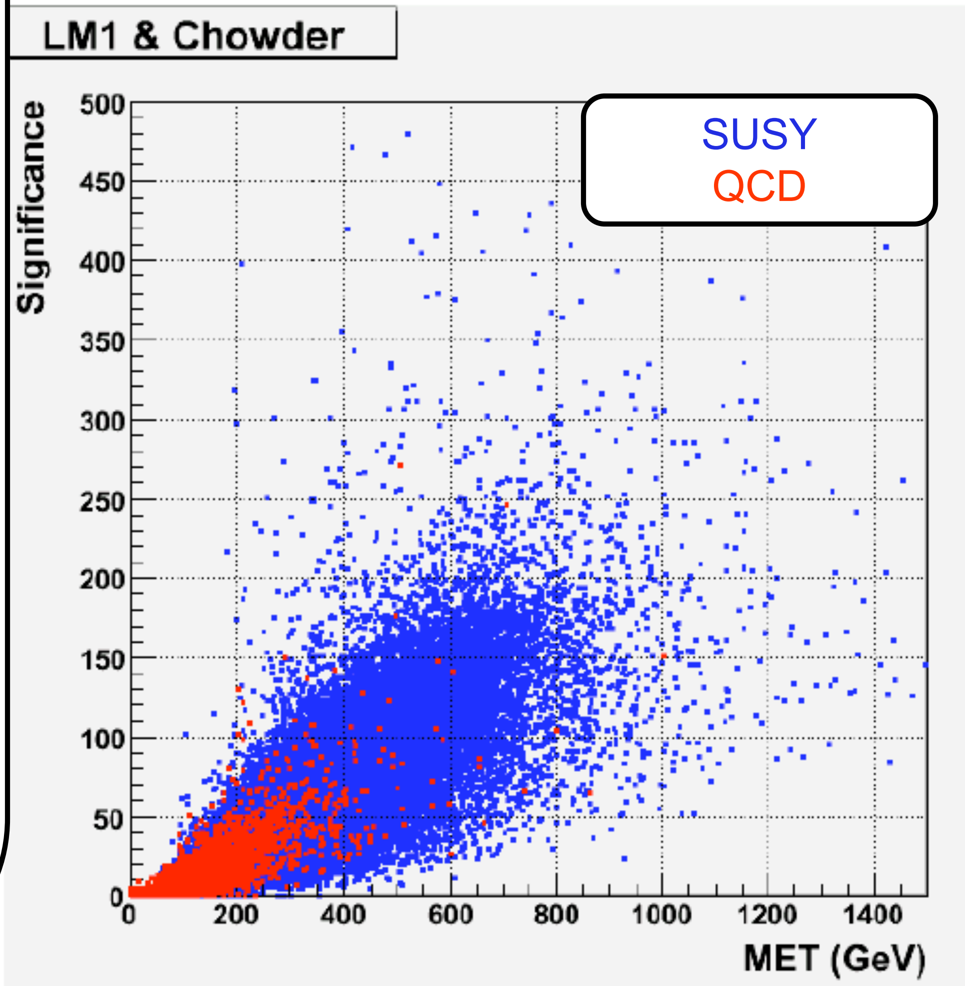
$$MET^{sig} = \frac{\langle MET \rangle}{\sigma(MET)}$$



Topological MET significance

- Probability that in each event the observed MET fluctuates from 0 due to finite resolution
- Typically L is constructed assuming Gaussian resolutions
  - S -> chi squared
  - MET significance when calo towers are used
  - MHT significance when jets, muons and electrons
- Physics objects resolutions propagated into denominator
  - mainly jet resolutions
- Acts as a discriminant between signal (LM1) & background (QCD)
  - Provides more information than MET

$$S = \frac{L(MET^{obs})}{L(MET=0)} = \frac{1}{2}\frac{MET^2}{\sigma^2(MET)}$$



MET corrections

- MET corrections meant to bring the measured MET closer to the truth
- There are several types used at CMS:
  - Type I -> jet energy scale corrections
  - Muon -> correct for presence of the muons
  - Electron -> use electron scale
  - Tau -> based on particle flow
  - Type II -> due to soft underlying event, pile-up, double counting of unclustered energy

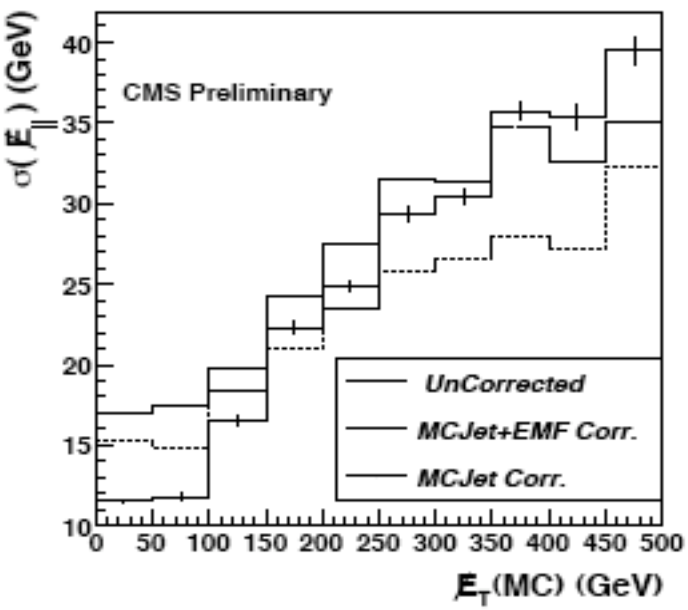
$$(\vec{MET})^{corr} = (\vec{MET})^{raw} + \vec{\Delta}$$

Corrected MET

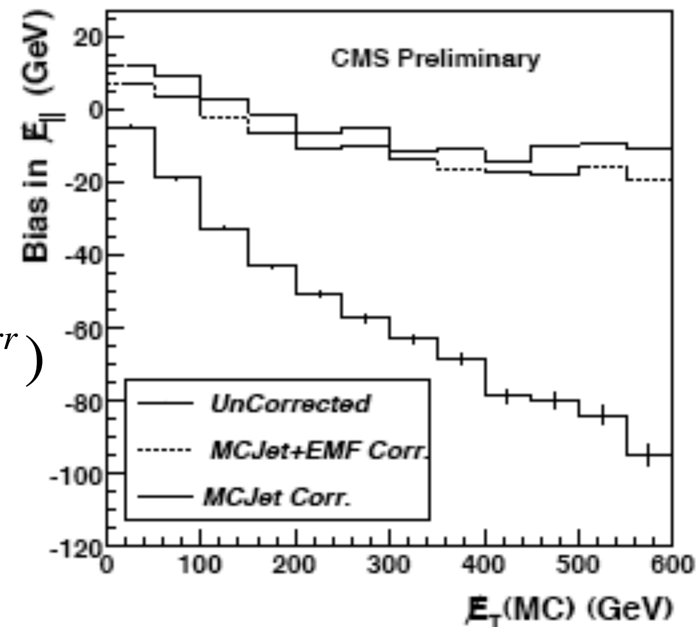
Uncorrected MET

Correction

Type I corrections



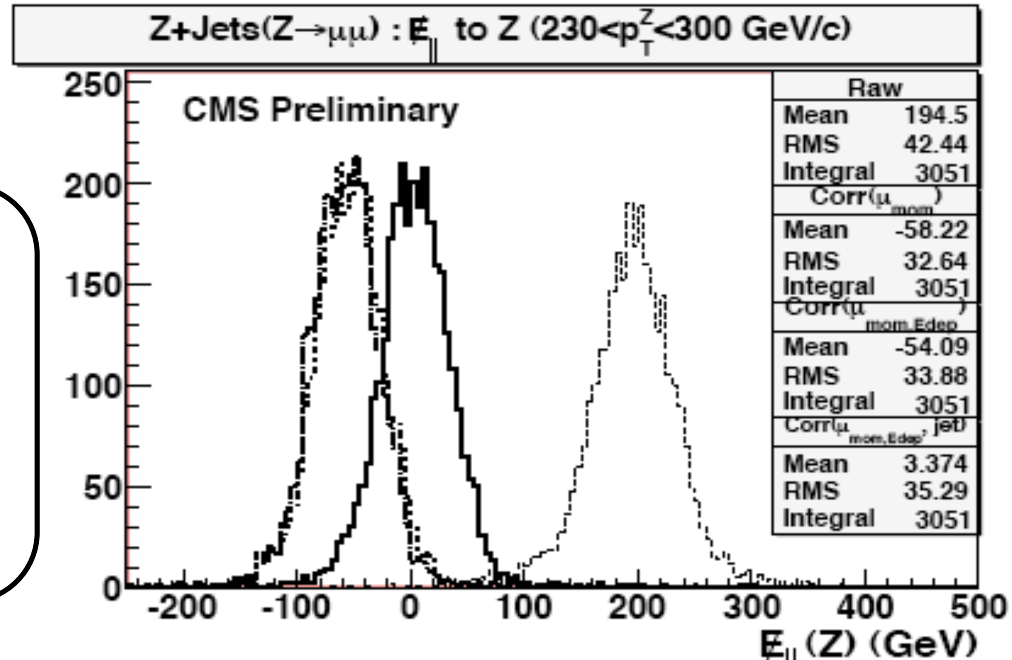
$$\vec{\Delta} = \sum_{jets} (\vec{p}_T^{\,raw} - \vec{p}_T^{\,corr})$$



- Correction is based on the energy response of the reconstructed jets in the event
- Aimed at removing biases due to non-linear, rapidity dependent, non-compensating calorimeter
- Jets are used if P_T > 20 GeV and EM fraction <0.9
  - Jet corrections are poor for the other jets
- Resolution (left) and Bias (right) are clearly improved wrt to true MET
  - W->eν + jets sample, MC jet corrections

Muon corrections

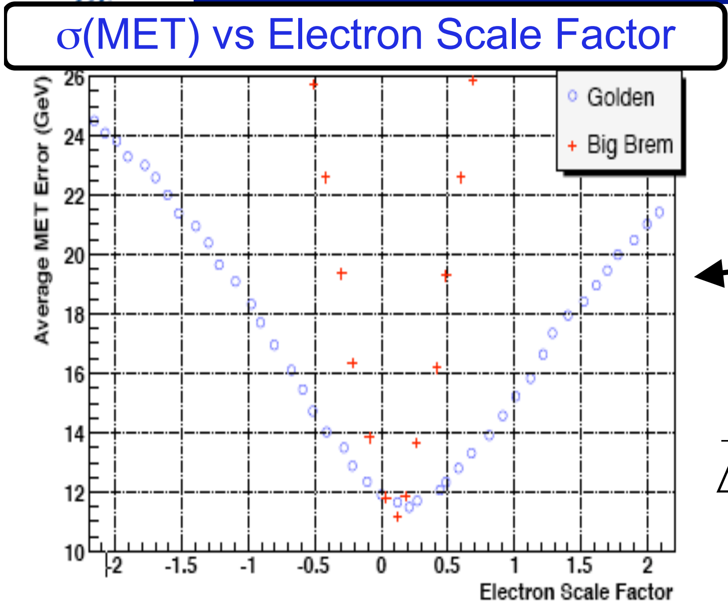
$$\vec{\Delta} = \sum_{\substack{muon\\deposits}} \vec{E}_T - \sum_{muons} \vec{p}_T$$



- Muons leave few GeV in the calorimeter creating energy imbalance
- Their momentum is very well determined in the tracking system

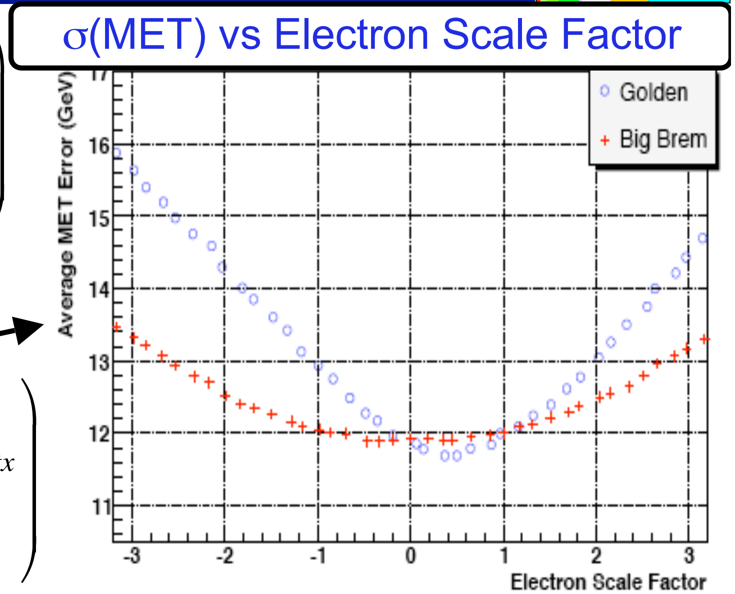
- Muons should satisfy
  - good quality criteria: $\Delta p_T/p_T<0.5$, $\chi^2<10$, $N_{hits}>13$
  - Isolation cuts: sum of p_T of tracks in 0.2 cone around muon < $0.2p_T^{muon}$
- Plot shows MET along Z-boson direction in a Z(->μμ) + jets sample
  - before corrections: <MET> ~ 200 GeV
  - After muon corrections: <MET> ~ - 54 GeV
  - After TypeI corrections: <MET> ~ 3 GeV

Electron corrections



$$\vec{\Delta} = c\left(\sum_{seed} \vec{E}_T - \sum_{\substack{electron\\track}} \vec{p}_T^{\,cal}\right)$$

$$\vec{\Delta} = c\left(\sum_{supercluster} \vec{E}_T - \sum_{\substack{electron\\track}} \vec{p}_T^{\,vtx}\right)$$

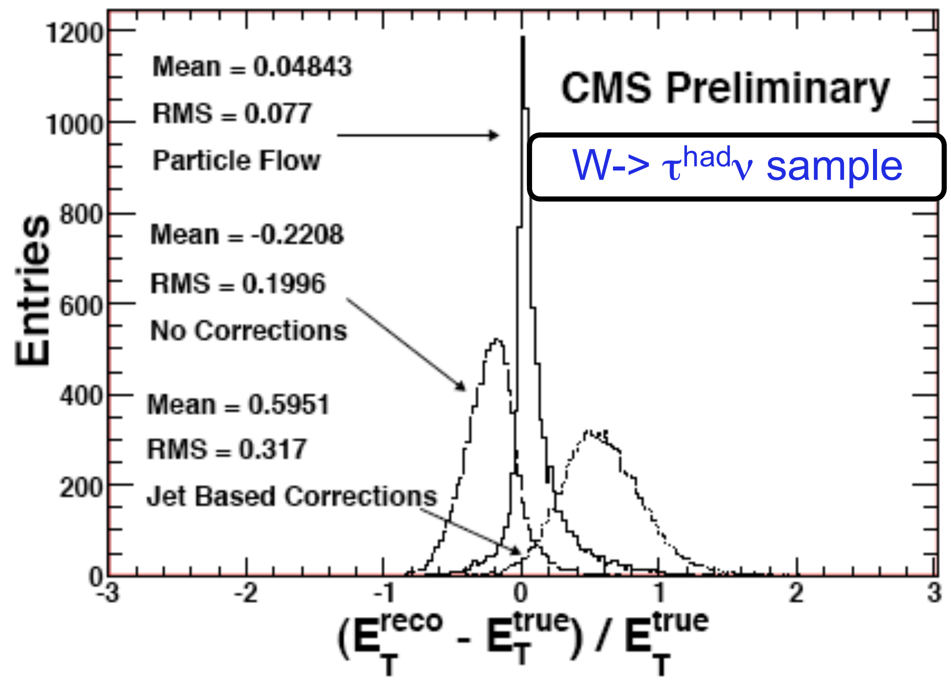


- This correction is expected to be small due to excellent energy resolution and coverage of ECAL
- The residual bias might arise from incorrect scale or measurements in uninstrumented regions
- Two types explored and optimized
  - (left) p_T of electron track at the face of ECAL corrects energy of seed
  - (right) p_T of electron track at the vertex corrects energy of supercluster
- Golden and Brem electrons studied in a Z->ee sample

Tau corrections

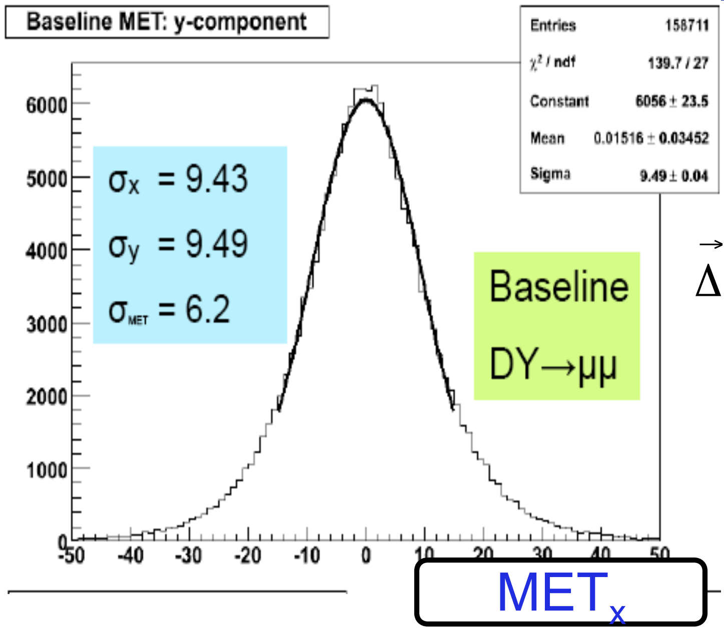
$$\vec{\Delta} = \sum_{taus} \left(\sum_{towers} \vec{E}_T^{cal0.5} - \vec{E}_T^{PF,tau} \right)$$

- Particle Flow algorithm used to ID the hadronic τ (see Rick's talk)
- Remove the energy of towers in a 0.5 cone around direction of τ
- Correction can be improved a bit using UE and PU estimates

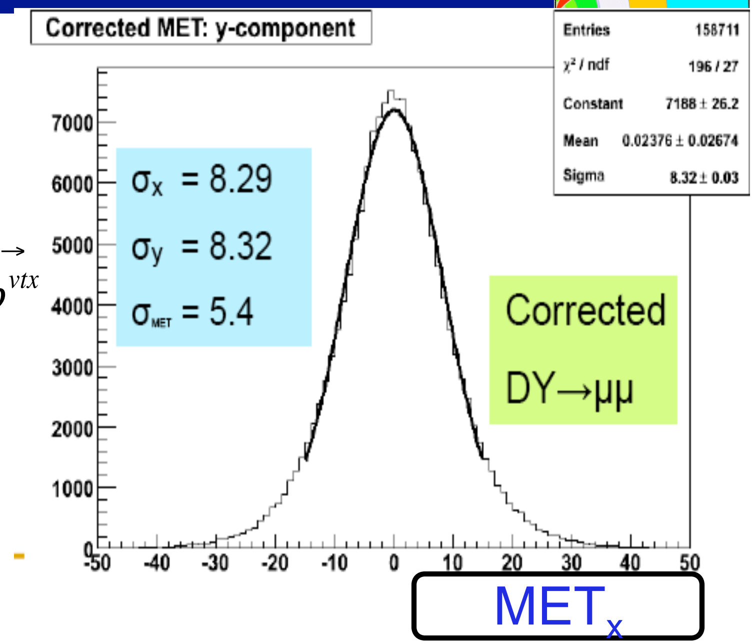


- Hadronic τ produce narrower jets which have less multiplicity than typical jet prompting for specific energy corrections
- The τ corrections based on calorimeter improves the MET scale, but not the resolution
- The τ corrections based on PF improve both
  - Solid line in the plot based on W-> $\tau^{had}\nu$ sample

MET+Tracks



$$\vec{\Delta} = \sum_{tracks} RF(p,\eta)\,\vec{p}^{\,cal} - \sum_{tracks} \vec{p}^{\,vtx}$$

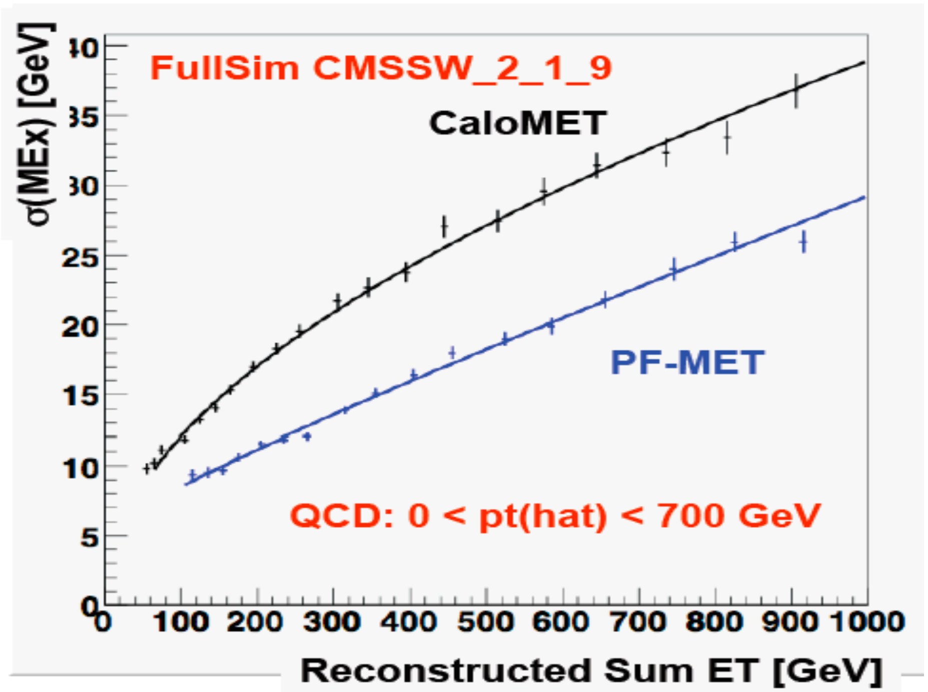


- Take advantage of the better resolution of the tracker versus that of the calorimeter
- Replace tower energies in a 0.5 cone around the track direction
  - Use tracks with p_T>2 GeV, N_{hits}>6, χ^2/N_{dof} <5, $|d_0|$<0.05
- Use a response function (RF) = E^{calo}/p^{trk} determined in single pion events
  - Parameterized as a function of track momentum and pseudorapidity
- Observe a 15% improvement in MET resolution for Drell-Yan muon events

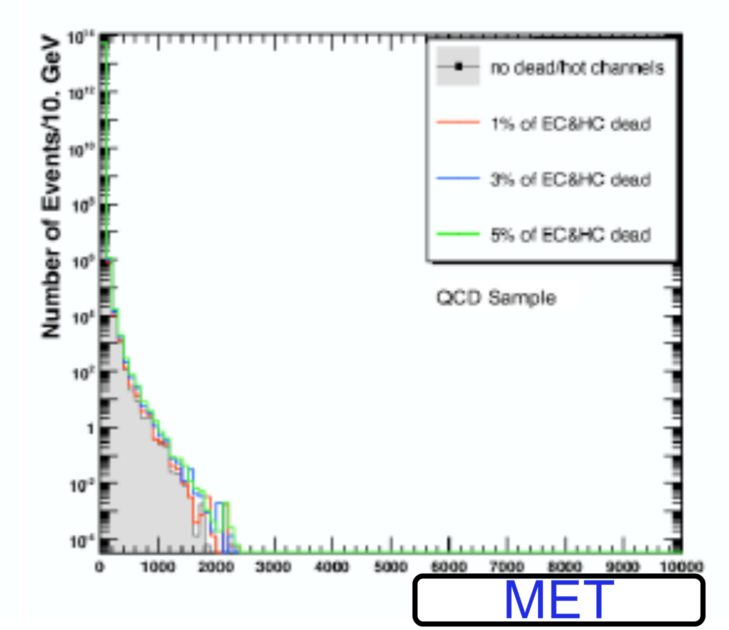
Particle Flow MET

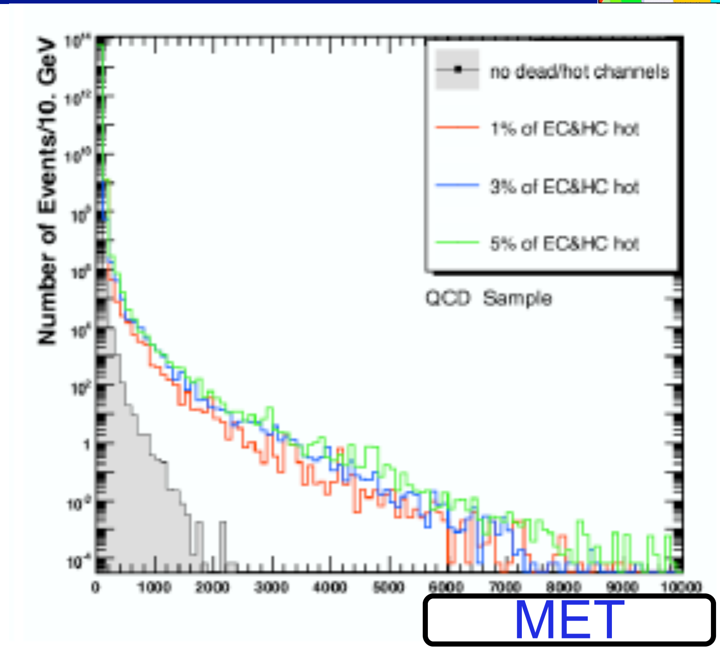
$$\overrightarrow{MET}^{PF} = -\sum p_T\left(e,\mu,\tau,\pi,\gamma,N^0,V^0,PU,NI\right)$$

- Determine MET from calibrated, reconstructed particles with PF algorithm
- PF employs tracking information thus improving the resolution
- Use all sub-detectors simultaneously
- Significant improvement observed wrt CaloMET
- More details about PF algorithm in Richard Cavanaugh's talk later



Detector effects



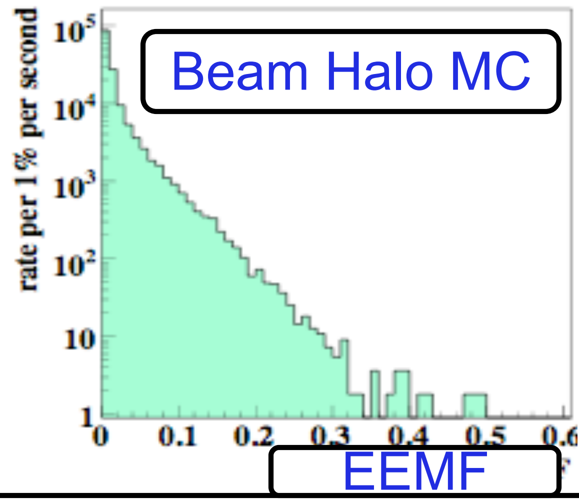


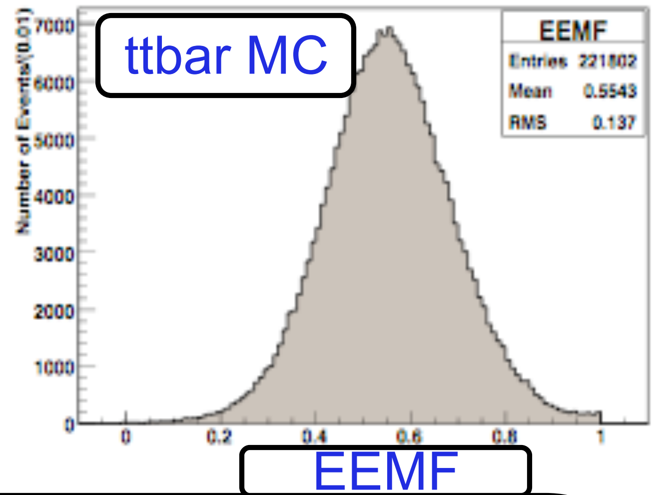
- Several detector failures have been studied
  - dead channels (left) -> small increase in tail of MET
  - hot (x5) channels (right) -> significant increase in tail
  - mix of dead and hot channels
  - dead/hot Readout Modules (18 HCAL towers each with 25 ECAL crystals)
- Channels are selected randomly except for the last case
  - 1% (20 HCAL), 3% (72 HCAL) and 5% (118 HCAL) are considered affected
- Readout Modules affected for ϕ = 3,4 or 5 segments

MET Clean-up

$$ECHF = < \frac{(\sum_i^{tracks} p_{T\,i})_j}{p_{T\,j}} > |_{N_{jet}}$$

$$EEMF = \frac{\sum_{j=1}^{N_{jet}} p_{T\,j} \times EMF_j}{\sum_{j=1}^{N_{jet}} p_{T\,j}}$$

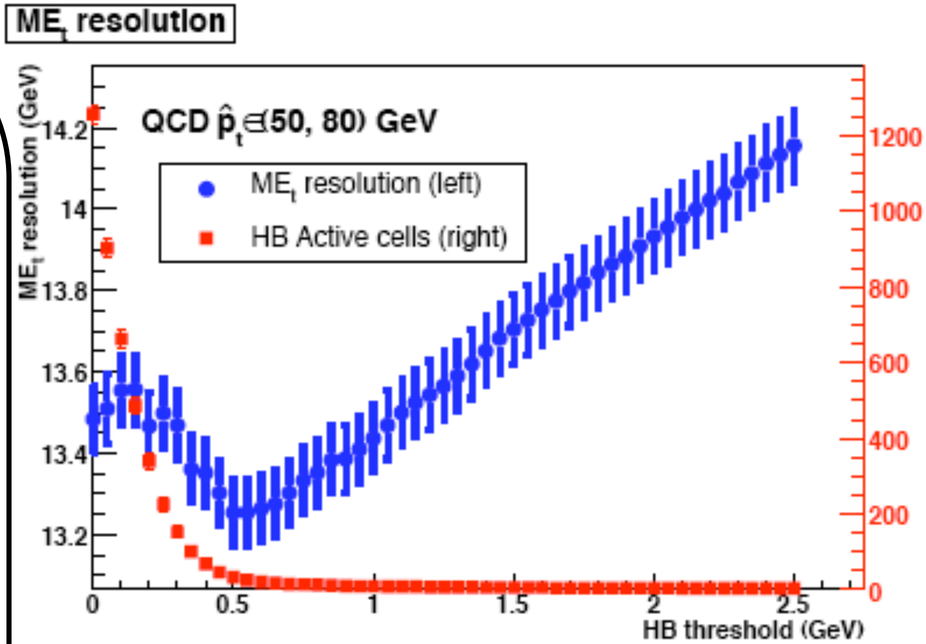




- MET is also affected by cosmic muons and proton beams halo
- Special clean-up event variables have been defined to minimize the presence of such backgrounds
- The event electromagnetic fraction (EEMF) defined above for jets with p_T>30 GeV, $|\eta|$<3
  - Clustered energy depositions from cosmics or beam halo are expected to be confined to either ECAL or HCAL
- The event charged fraction (ECHF) uses tracks matched to jet cones
  - Improbable tracks from these backgrounds are expected to be away from jets and not pointing to the primary vertex
- Events are rejected for EEMF < 0.175 and ECHF < 0.1

Optimization of MET resolution

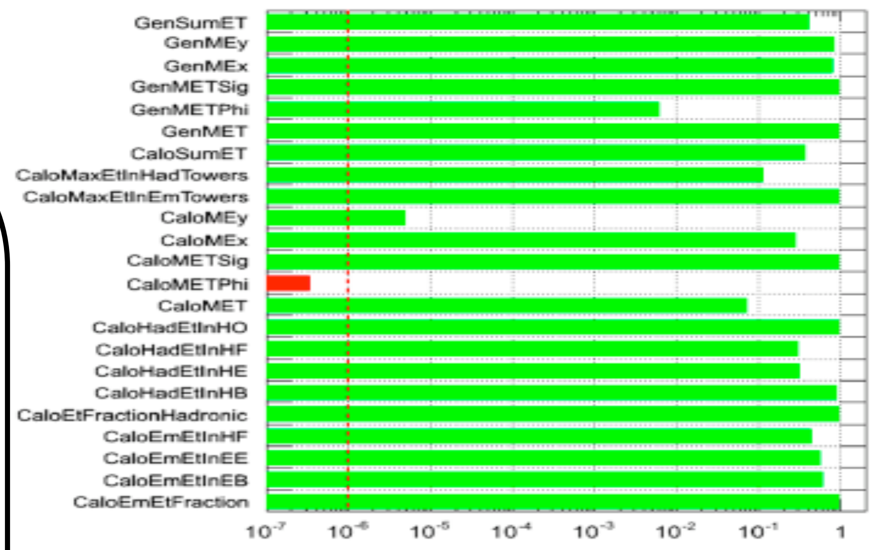
- Previous optimization studies of the tower thresholds were done in the context of jet reconstruction
- For MET resolution the optimum thresholds might differ than those for jets
- A new optimization study was done for HCAL using various samples
  - QCD, ttbar and SUSY LM1
- The values found are
  - 0.5 GeV for HB
  - 0.7 GeV for 5° HE cells(1..3<|η|<1.7)
  - Due to use of centrally produced events no optimum values for 10°HE and HF

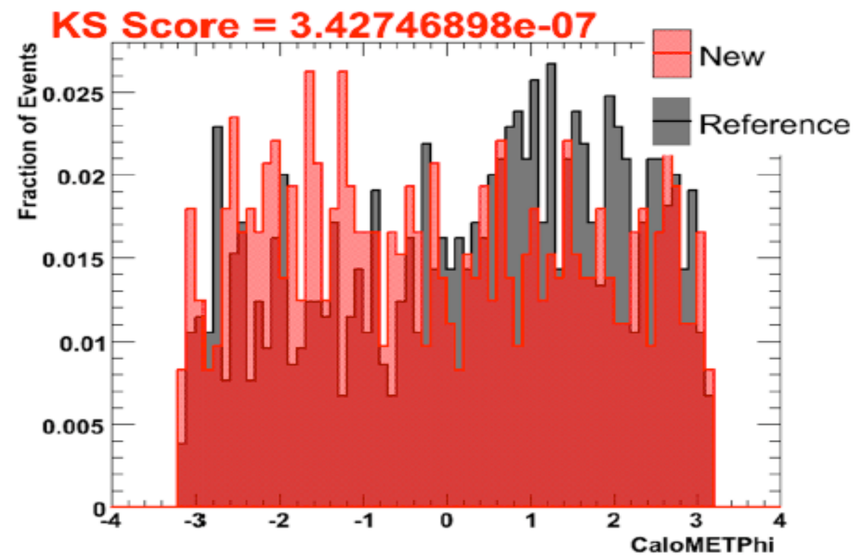


- Blue circles = MET resolution vs HCAL barrel tower threshold
- Red squares = number of towers above the threshold

MET validation

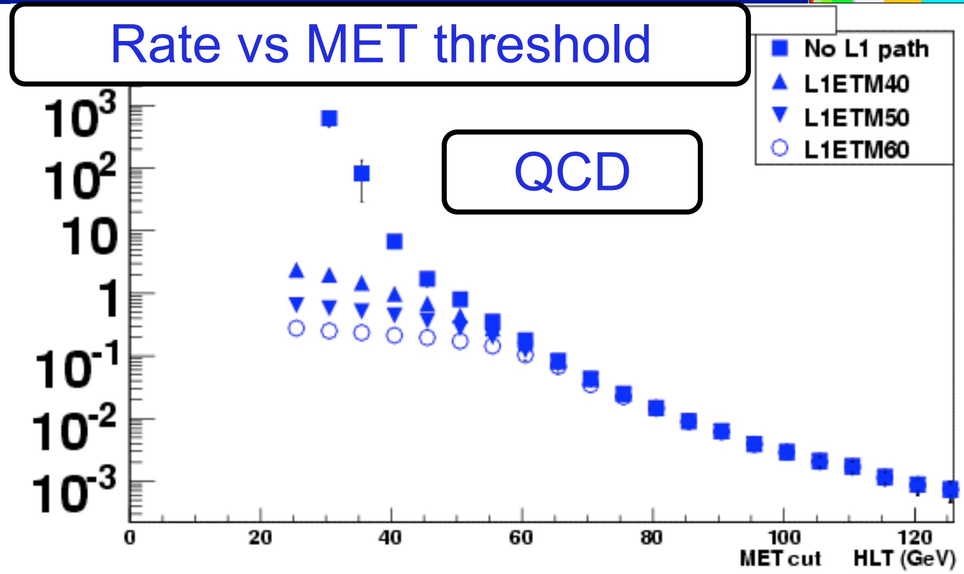
- Due to many alterations to CMSSW a validation package was developed
- Goal is to make sure MET variables return similar values across versions
- Composed of 4 modules: MET, CaloTower, HCALRecHit, ECALRecHit
- Every variable is histogrammed and compared to previous software releases
- A score quantifies the comparison
  - Highest of χ^2-test and KS-test
  - 1E-6 means failure
- Once a failure is detected further examination reveals the problem which is then fixed

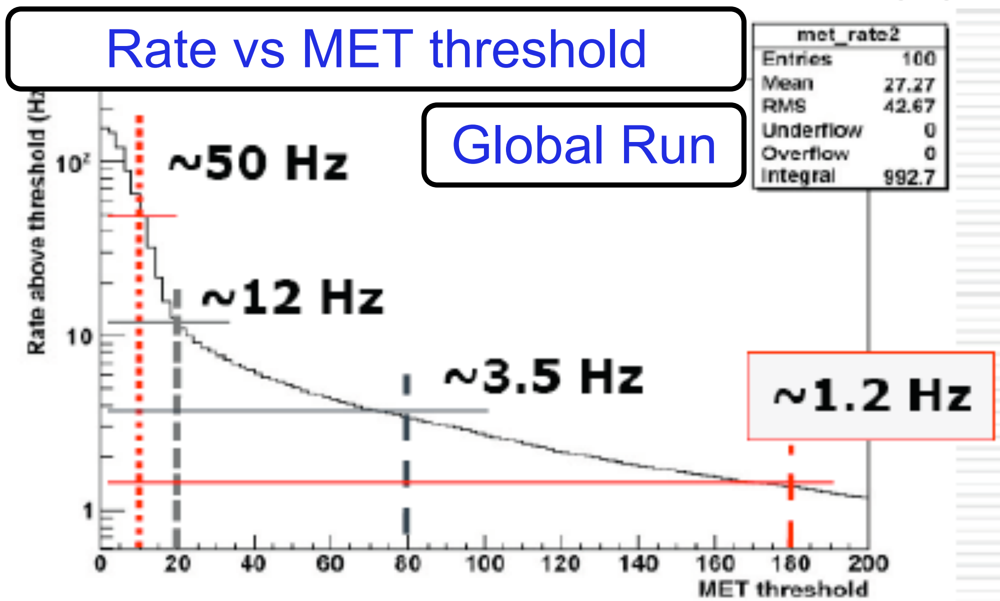




MET triggers

- MET calculated at the trigger level L1 and HLT
    - Similar to CaloMET
- There are significant efforts to add MHT (uses jets, not towers)
- MET triggers in start-up menus:
    - *For Lumi=8E29*
        - *L1ETM20*
        - *L1ETM30 & HLT_MET35*
    - *For Lumi=1E31*
        - *L1ETM20*
        - *L1ETM20 & HLT_MET25*
        - *L1ETM40 & HLT_MET50*
        - *L1ETM50 + HLT_MET65*
- Noise rate from GlobalRun data
    - for MET > 80 GeV ~ 3.5Hz
    - for MET > 180 GeV ~ 1.2Hz
- *To be added:*
    - *L1ETM80 & HLT_MET100*
    - *L1HT200 & HLT_HT300MHT100*



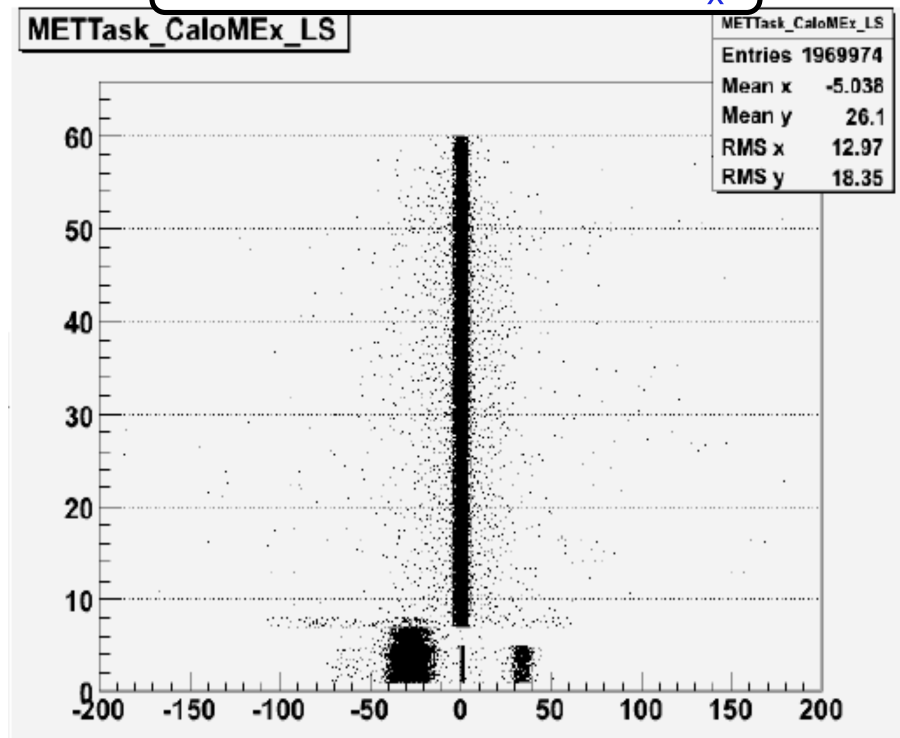


MET DQM

(data quality monitoring)

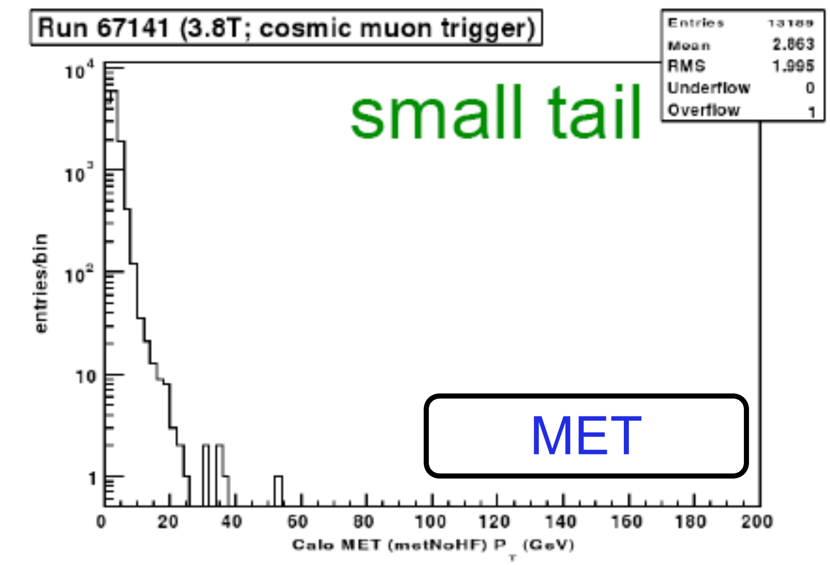
- This task is part of the greater JetMET DQM program
- Goals
  - identify luminosity sections & runs as good or bad using MET
    - e.g. plot of MET_x from CRAFT run 66594 (right)
  - Provide quality information for HCAL complementary to the detector performance monitoring
- Histograms containing MET variables are stored in ROOT files and posted on the DQM web too

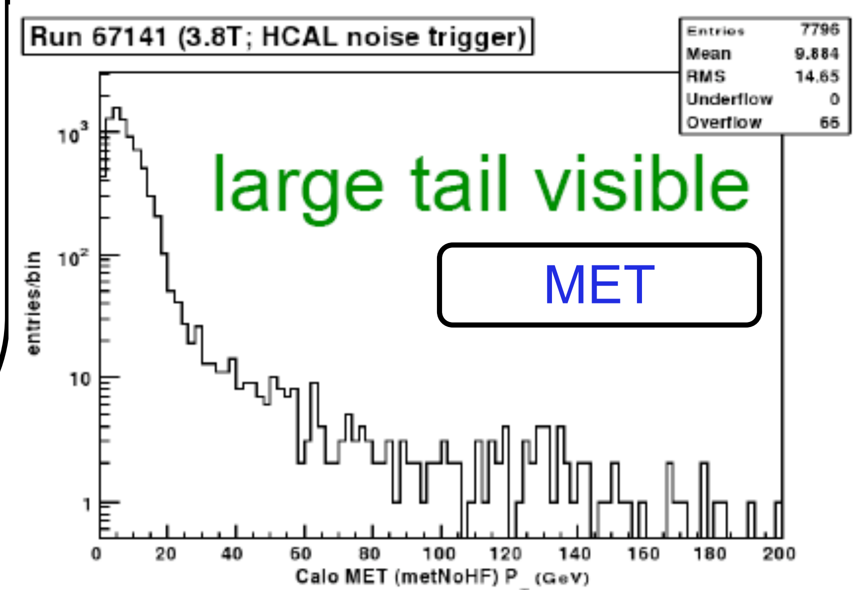
Lumi. Section vs MET_x



MET in CRAFT global runs

- Look at MET using cosmics data in order to understand our detector
- MET is produced by electronic noise
- Plots show METnoHF in Run 67141
  - Muon trigger (top)
  - HCAL noise trigger 10 GeV (bottom)
- Helps us understand various effects that might contribute to high MET tails
  - HPD discharges
  - RBX noise
  - Wrong detector conditions
- Event display is an essential tool to look for these pathologies





Conclusions

- MET as physics object at CMS benefits from a quite developed and sophisticated study
- These are where help is needed:
  - Understanding of pathological MET events in QCD MC
  - Optimization of type I corrections
  - Optimization of muon and tau ID cuts
  - Development of type II corrections
  - Understanding of the impact of pile-up effects on MET
  - Usage of more Particle Flow objects to improve MET resolution
  - Study of MET significance likelihood variable
  - Understanding of beam halo and cosmic backgrounds impact on MET
  - Study MET in cosmic runs during 2009 prior to beam collisions

MET group at LPC

- Conveners
  - F.Moortgat (at CERN)
  - G.Landsberg (outgoing)
  - T.Kamon (incoming)
- Activities
  - MET DQM - Rockefeller/FNAL
  - MET,MHT triggers - Brown/Rockefeller/UIC/Rochester
  - MET validation & software - Florida
  - Global Run - TAMU/FNAL/Princeton/Maryland/Iowa/Rockefeller
  - Type I,II corrections - Brown
  - Muon corrections - UCSB
  - Tau corrections - TAMU
  - MET significance algorithm - Cornell
  - PF MET - UIC/FNAL
  - MET tracks correction - UCSD
  - Threshold optimization - UCR
  - **Anything - YOU**