Missing Transverse Energy at the LHC

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TeV4LHC Workshop, Brookhaven (Feb. 3-5, 2005)

Pauli Revisited

- Nearly 75 years later, the "missing energy" measurement is still a powerful technique of searching for weakly interacting particles

Computed with Calorimeter Cells (and muons):

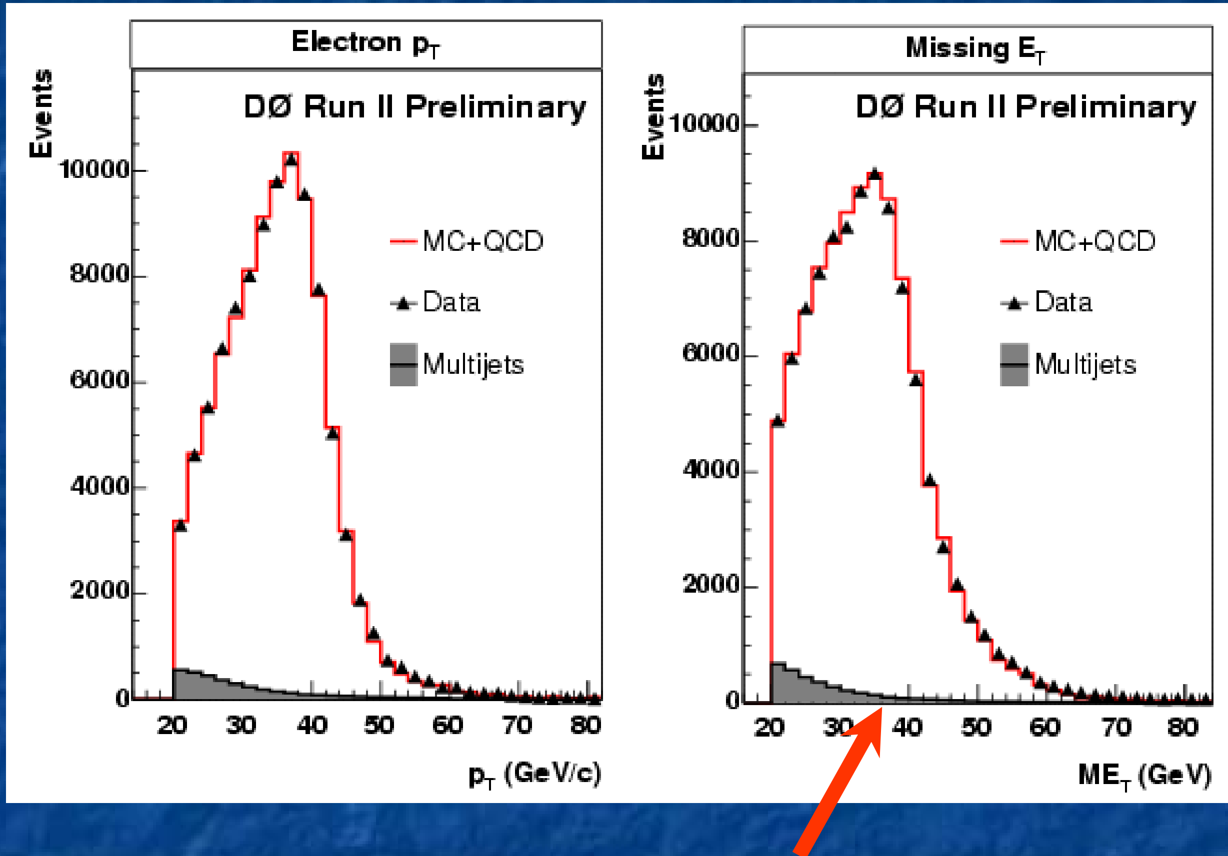
$$E_{T,x} = -\sum_i E_i \sin\theta \cos\varphi = -\sum_i E_{x,i} / \cosh\eta$$

$$E_{T,y} = -\sum_i E_i \sin\theta \sin\varphi$$

$$E_T = E_x \hat{i} + E_y \hat{j} \qquad \text{("MET")}$$

TeV: W→eν Selection: Electron & MET

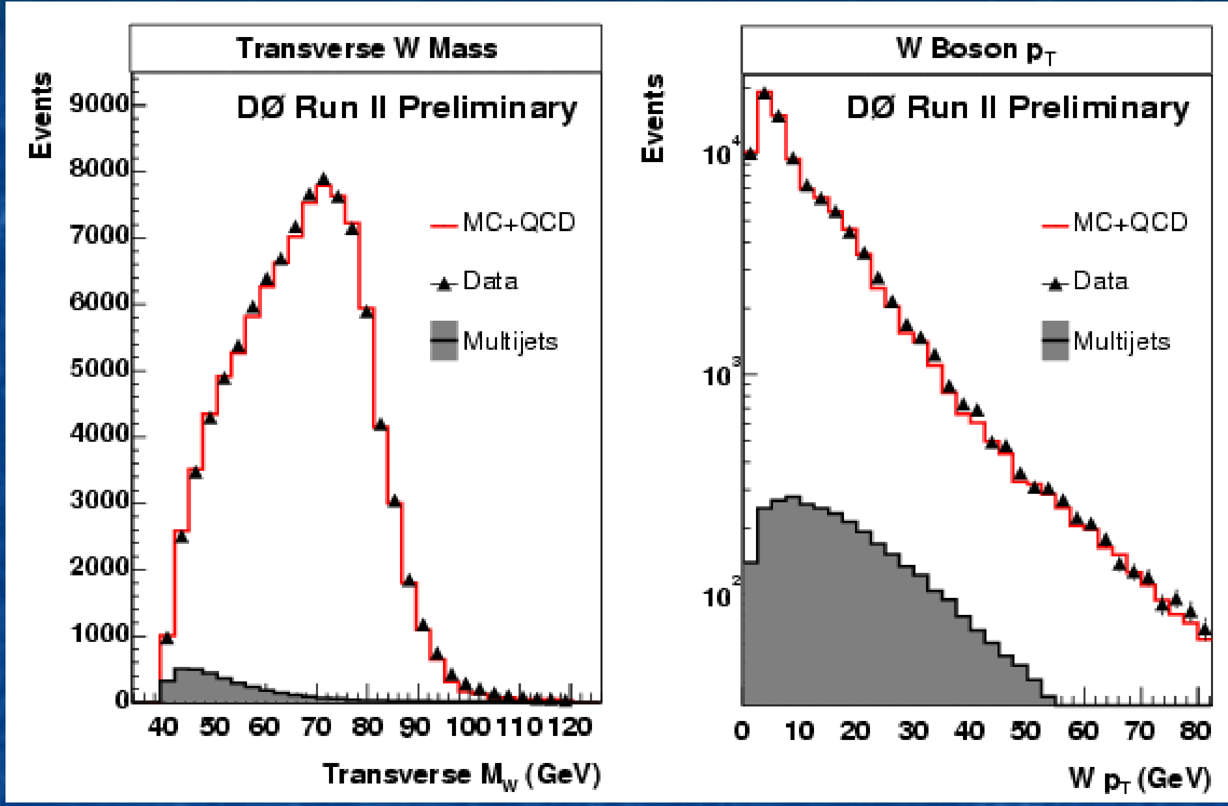
- Require one isolated electron with a matching track
  - $p_T > 20$ GeV/c
  - $|\eta| < 1.1$
- Require the MET to be at least 20 GeV



- MET allows us to "measure" the neutrino

TeV: W→eν Selection: W Boson

- Reconstruct transverse W mass
- Produces Jacobian peak with low pT tail

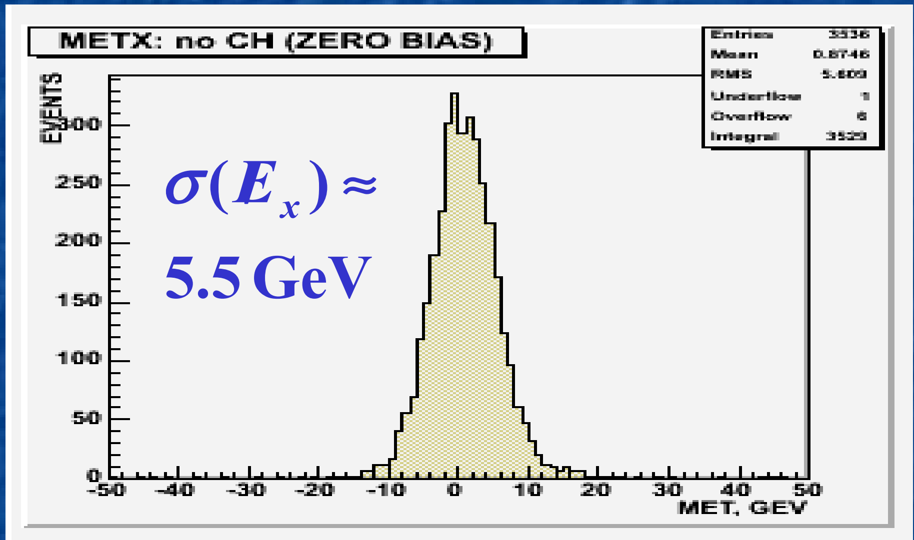


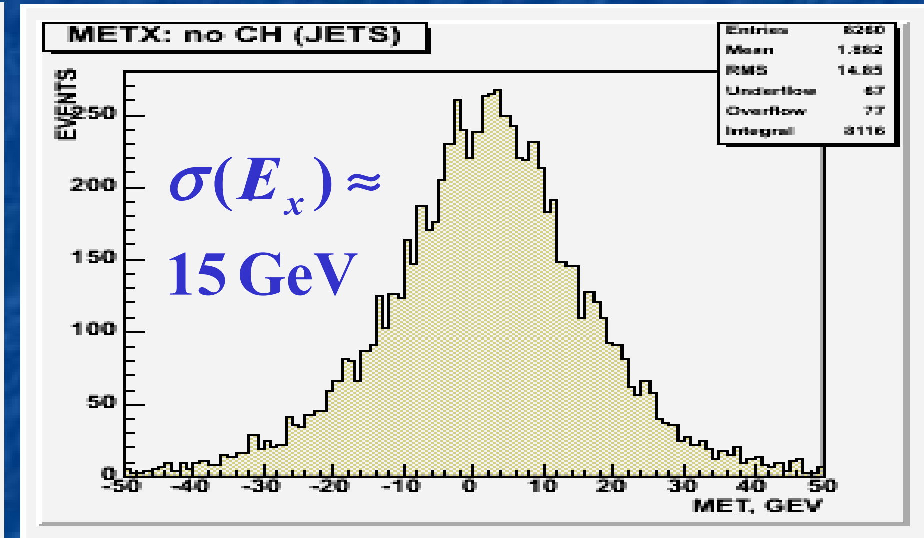
- Transverse W mass reconstruction requirements:
  - $\Delta\varphi$(electron,MET) > $\pi/8$
  - 40 GeV/c^2 < M_{WT} < 120 GeV/c^2

Luminosity = 164 pb^{-1}

MET(x) from Online Monitor

- Dzero Data from Zero Bias (left) and Jets (right)





# of channels

Electronic Noise per channel

LHC: Dynamic range

Broadening from √(∑ Et)

LHC: Larger average ∑ Et

Higher stochastic term

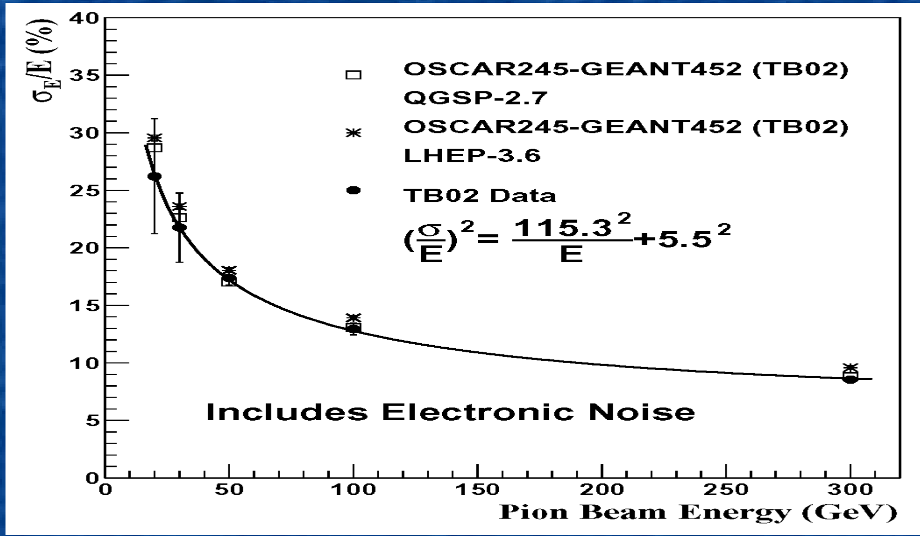
Constant term for ∑ Et~2 TeV

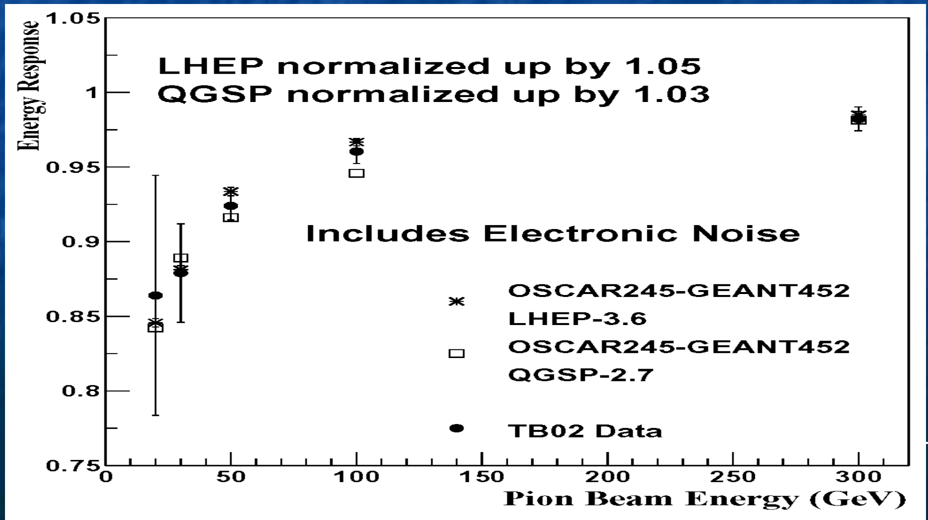
CMS Hadron Calorimeter |η|<5

ATLAS Barrel EM+Tile (in pit!)

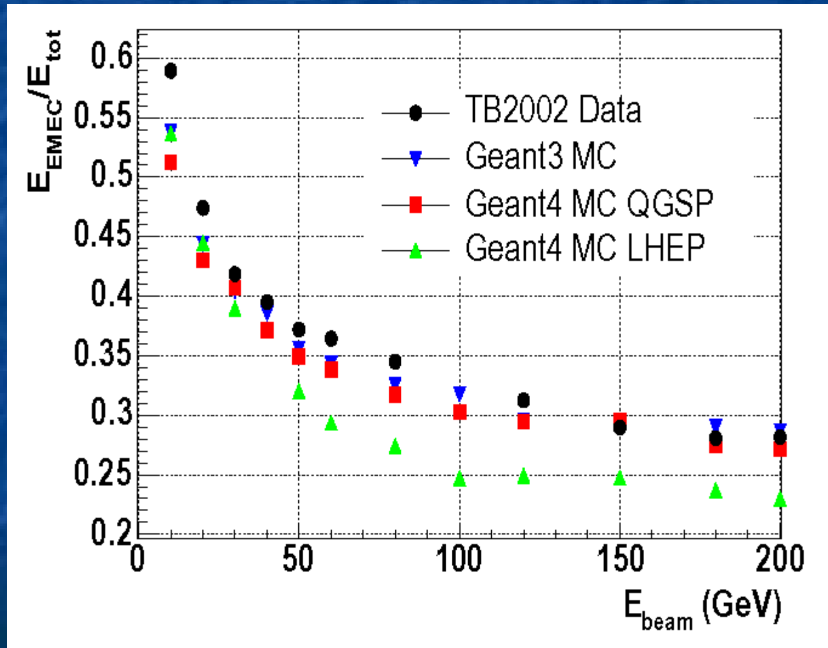
Test Beam/Full Simulation

- CMS HCAL Test Beam data





- Atlas EMEC longitudinal fraction



GEANT4 Tuning

- Both Atlas and CMS made significant contributions to the development of GEANT4

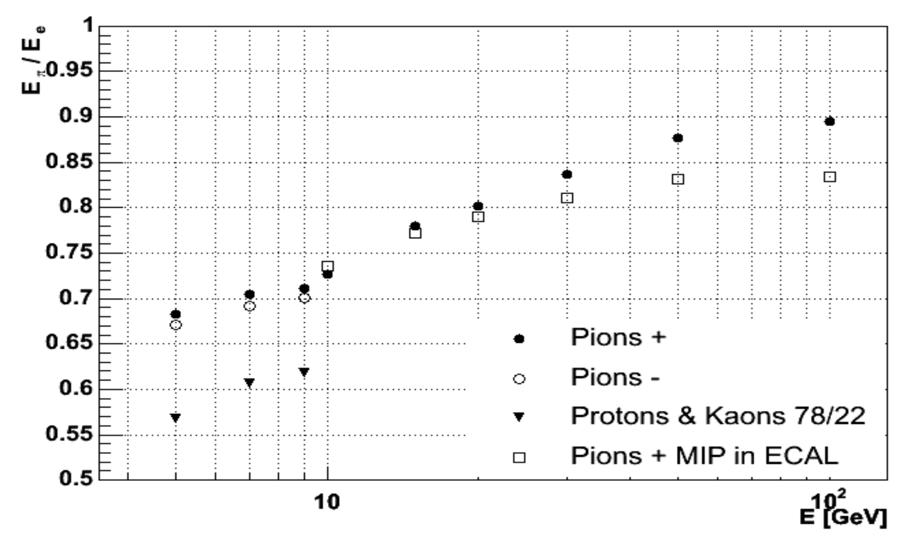
  - ATLAS Tile test-beam *
  - CMS Tile test-beam *
  - LHCb tile test-beam
  - ATLAS HEC test-beam *
  - ATLAS FCAL test-beam
  - BTEV crystal test-beam *
  - CMS combined test-beam
  - CsI test-beam benchmark
  - GLAST (starting) test-beam
  - H1 forward barrel *
  - ATLAS combined endcap

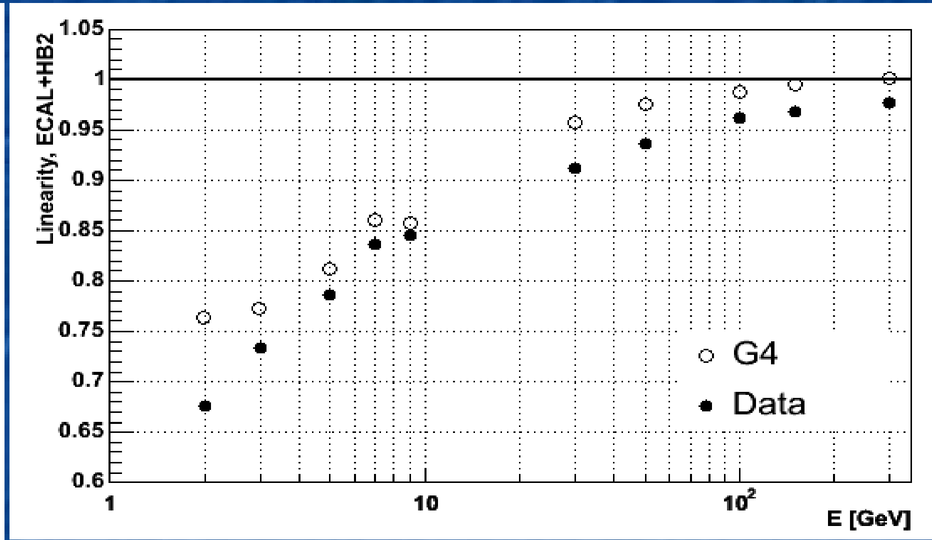
EMEC + HEC combined run 2002:

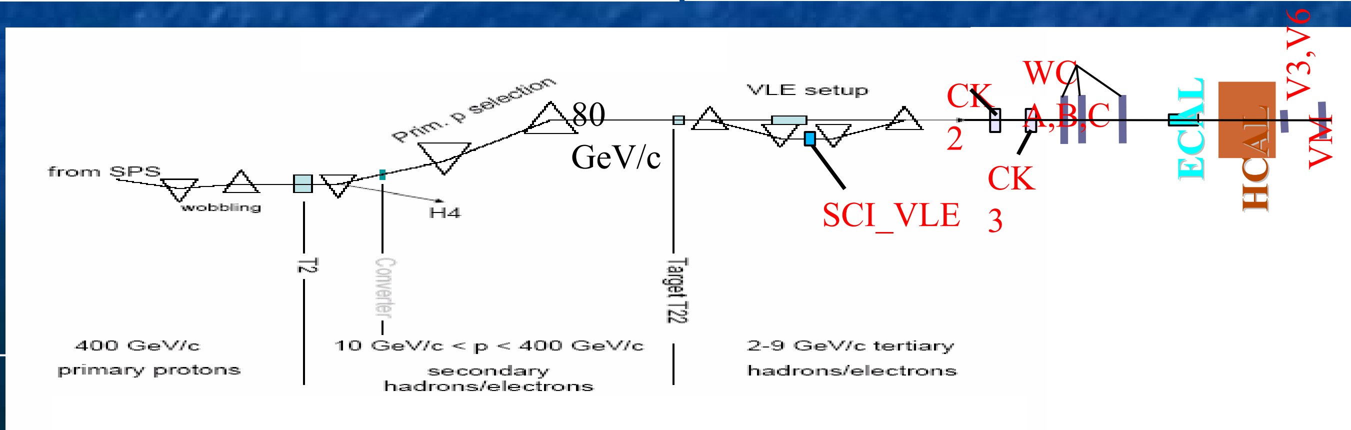
- Atlas first with relevant test beam data
- CMS extensive large-scale MC production (20M)

Low-Energy e/h Studies

- Most particles in the event will be in a difficult energy range with respect to e/h energy variation and linearity

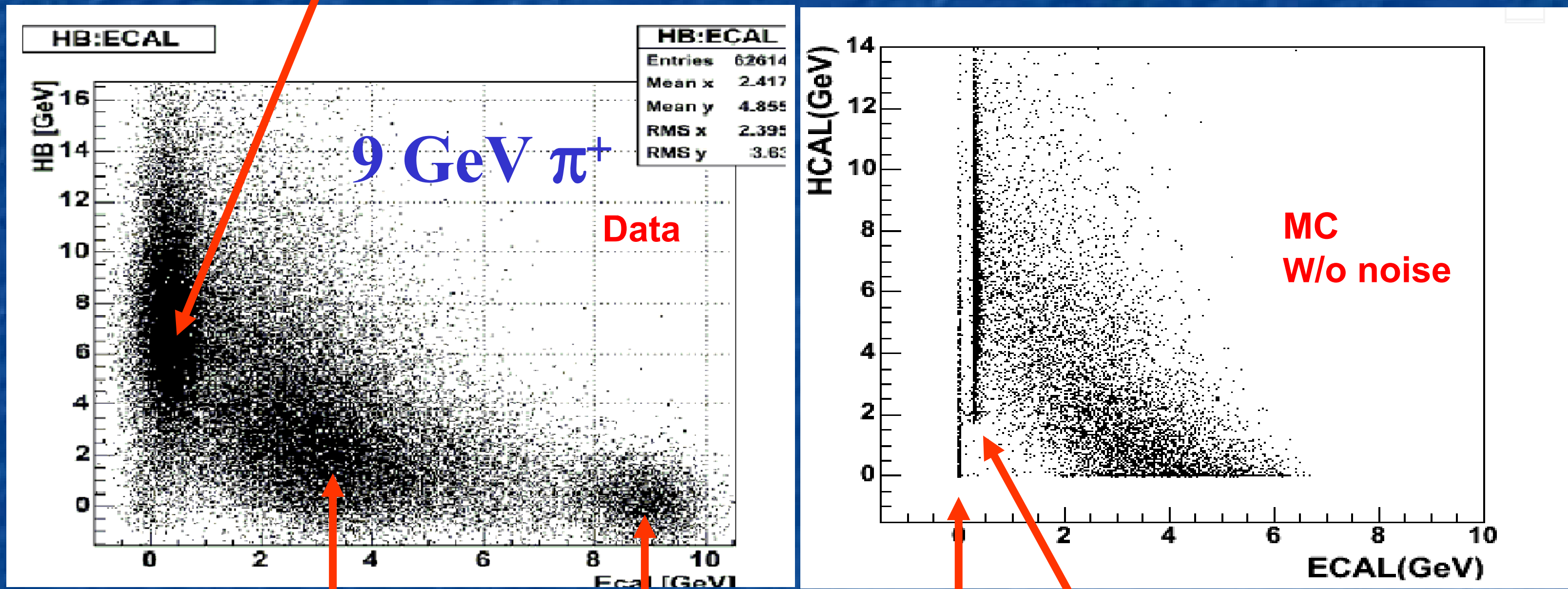






Low-Energy Test beam Analysis

mip in ECAL, i.e. no-interaction in ECAL



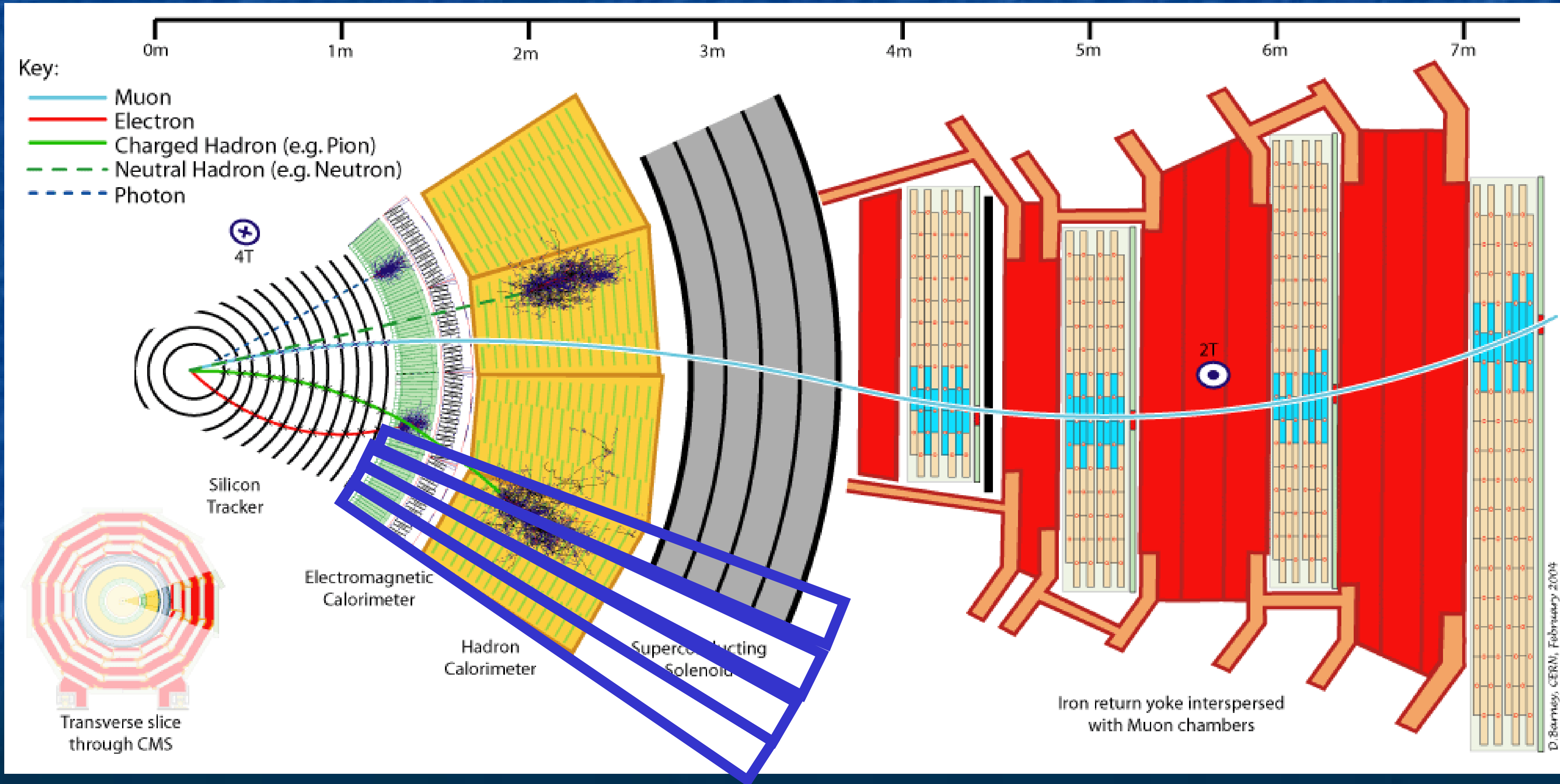
Interactions in ECAL

e^+

$\pi \rightarrow \mu\nu$ decays in beam line

Interactions in beam line

EM+HAD Calorimeter Projective Towers



O(1) Physics Goals using MET

- SUSY
  - Large MET:
    - Unambiguous detection of MET~200-300 GeV essential for first discoveries – commissioning of calorimeters will be intense. **Assign one grad student per 10 channels?**
- Higgs
  - Small (~20-100 GeV) MET:
    - qqH($\rightarrow\tau\tau$) mass reconstruction against Z($\rightarrow\tau\tau$)jj background
- Standard-Candle Model Measurements
  - Z/W+Jets – MET calibration, Luminosity measurement
  - ttbar – JES calibration, 3rd generation mass measurement
  - QCD dijet – Minimize resolution on balanced events – Important for triggers

What changes at the LHC?

- Centrally a question of MET resolution and reliability
  - Non-compensating calorimeters
  - Underlying event, pile-up
    - Typical pile-up jet pT spectrum higher than at Tevatron
  - Strong magnetic fields in tracker region (looping)
  - Calibration algorithm biases
  - Electronic noise (performance related to large dynamic range)
  - Hot/dead cells
    - Inaccessibility + eventual radiation damage
  - Event synchronization (event mixing)
    - 40 MHz operation and near deadtime-less operation

Atlas ETmiss Reconstruction and Calibration

- ETmiss Reconstruction from all calorimeter cells in |η|<5 and from muons
- ETmiss Calibration H1-style: weights depend on cell ET and Calorimeter region (talk by P.Loch)

⇒ Use cell energy density instead of ET (cell E/V)

- apply cryostat correction W*sqrt(Em3*TILE1)

Minimize Resolution-Linearity Functional:

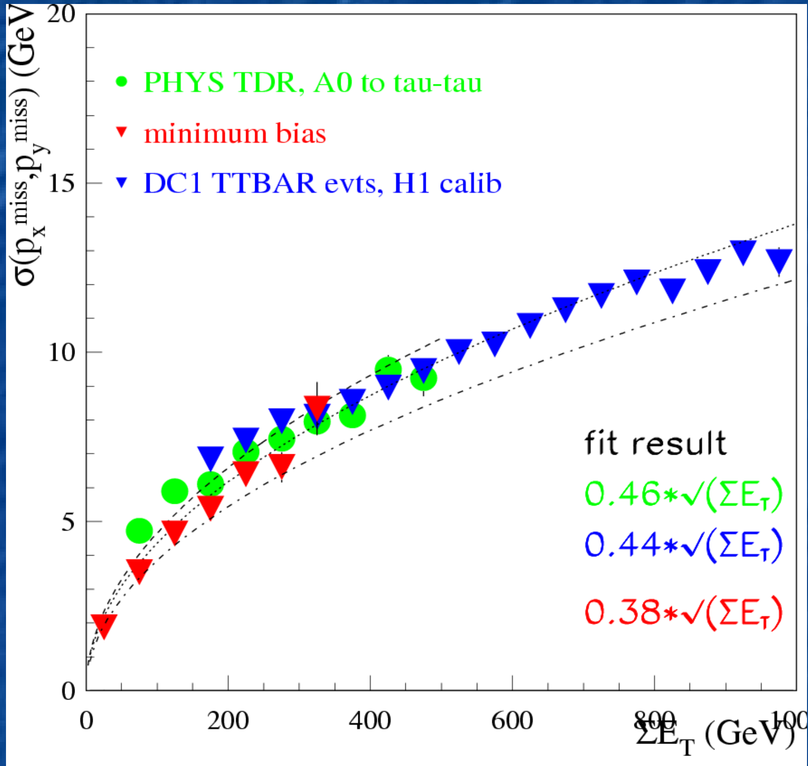
$$\sum_{k=1}^{n}\left(E_{rec}^{k}(\bar{a})-E_{kin}^{k}\right)^{2}+\alpha\sum_{k=1}^{n}\left(E_{rec}^{k}(\bar{a})-E_{kin}^{k}\right)$$

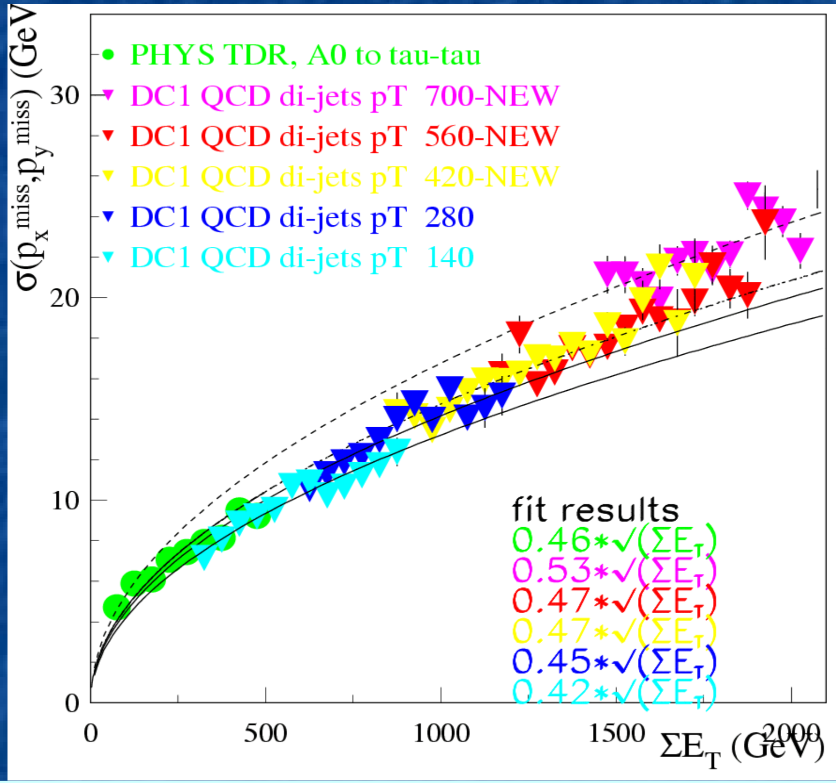
- avoid calibration bias: $\frac{\langle E_{kin}^{k}\rangle}{\langle E_{rec}^{k}\rangle}=1+\left(\frac{\sigma}{\langle E_{rec}^{k}\rangle}\right)^{2}$

- Min. bias events
- ttbar DC1 data

No Noise added !

QCD di-jets ($p_T >$ 140 → 560 GeV)





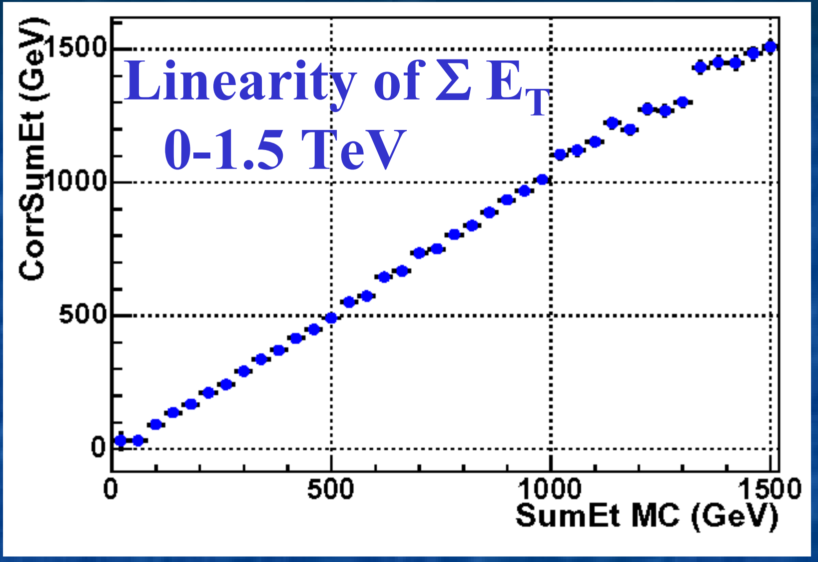
minimum bias:
check of calibration of
cells ouside clusters

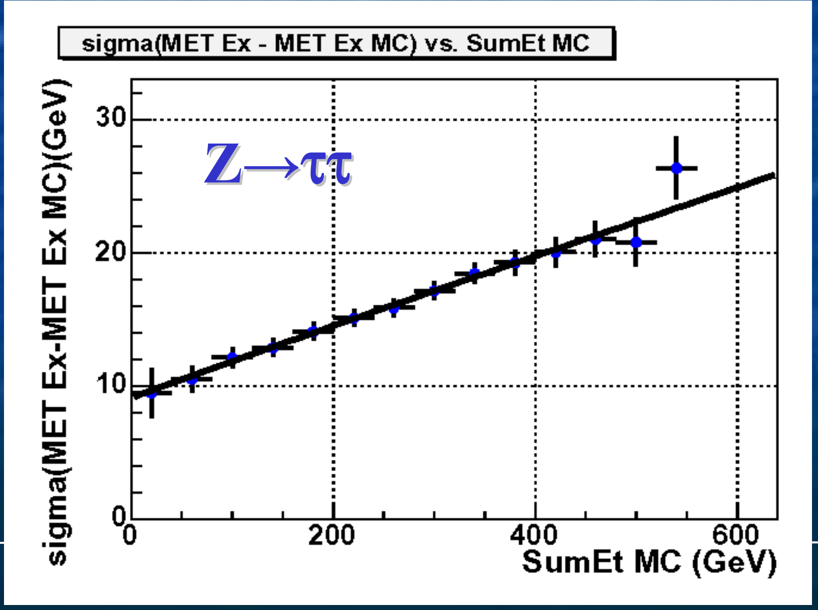
still some displacement from linearity
- Longitudinal leakage?

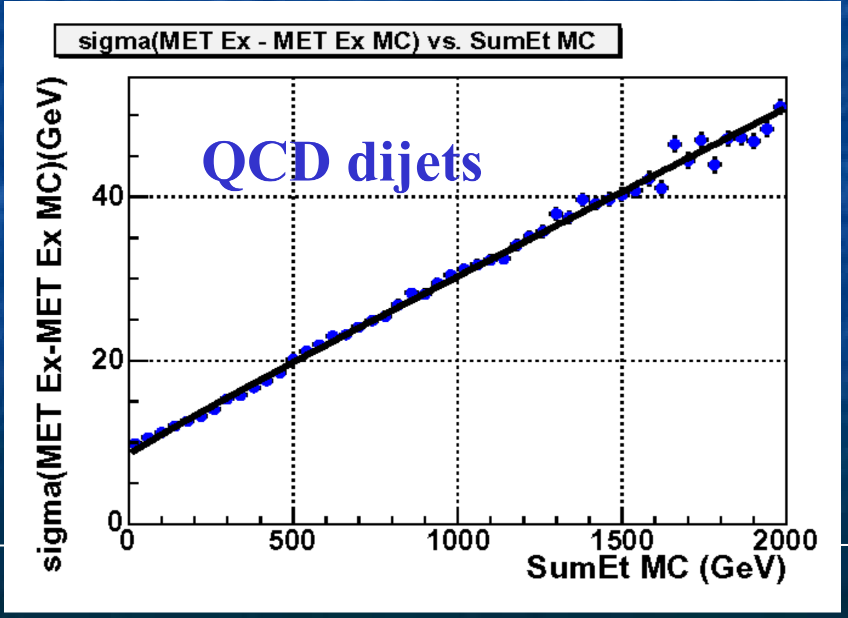
NEW H1 Calibration (16 ET bins)

Weights determined from MissingET

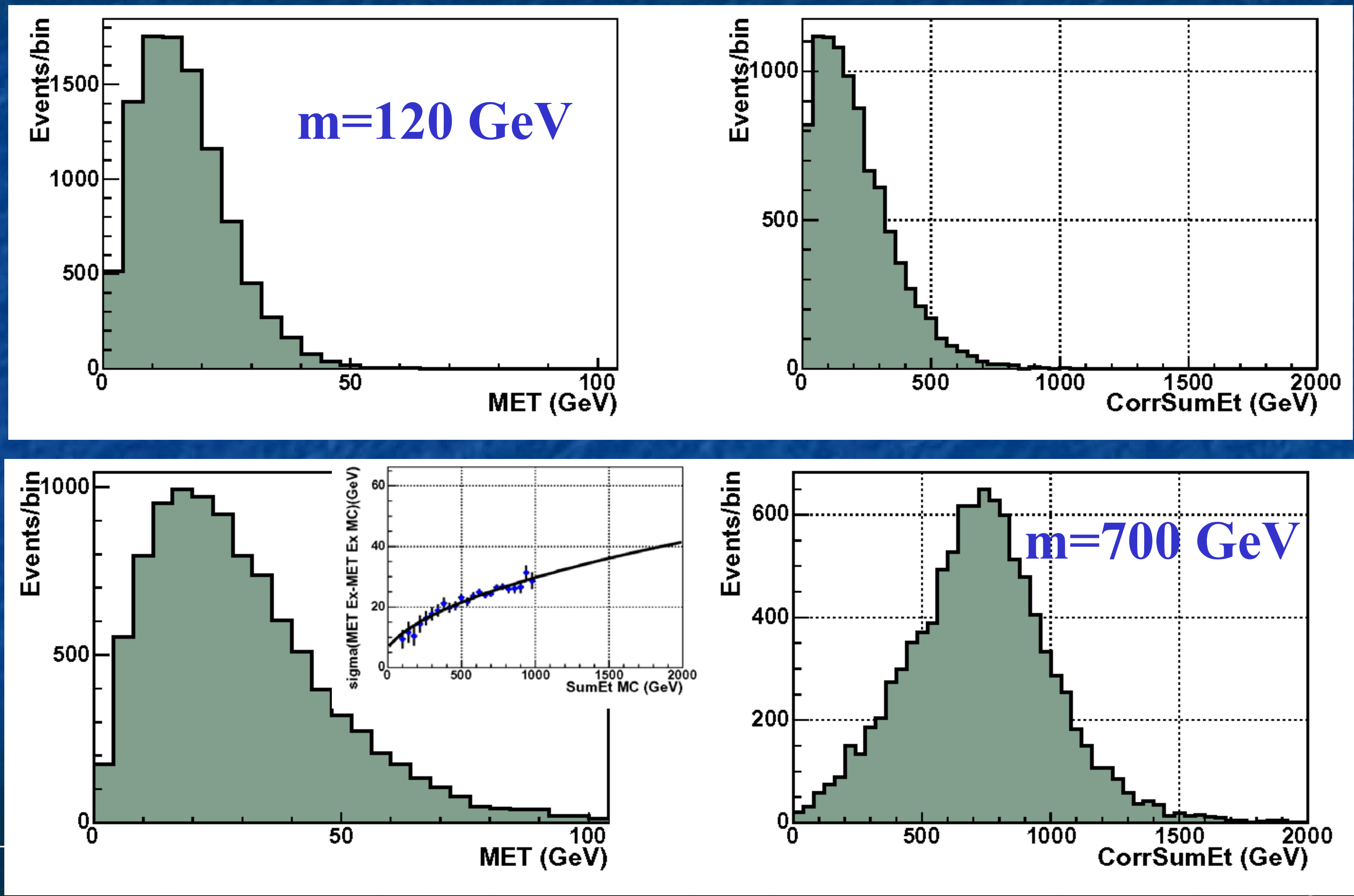
- MET resolutions including noise, full readout simulation and pile-up at $2x10^{33}/cm^2/s$
  - $Z \rightarrow ee$
  - $Z \rightarrow \tau\tau$
  - QCD dijets



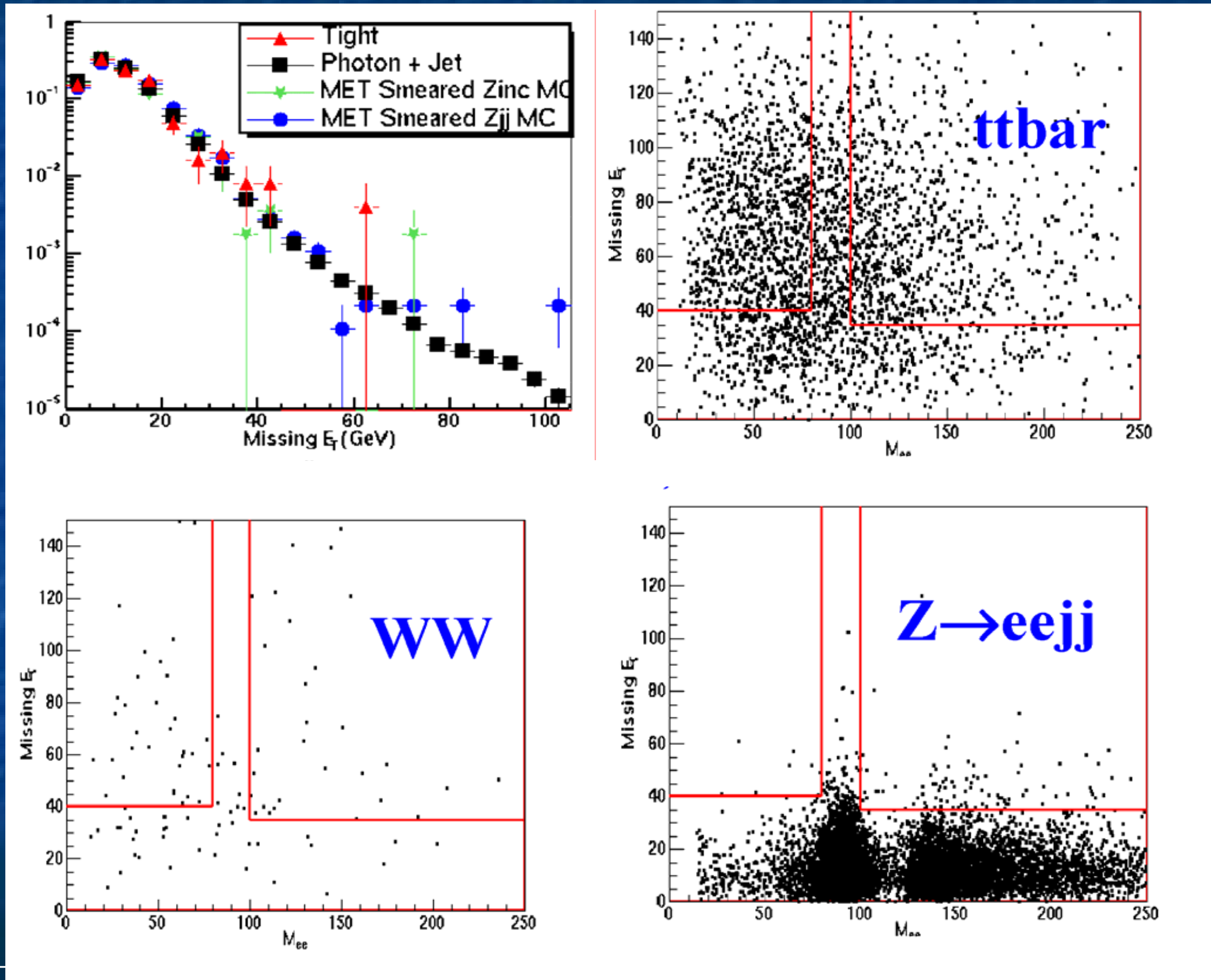




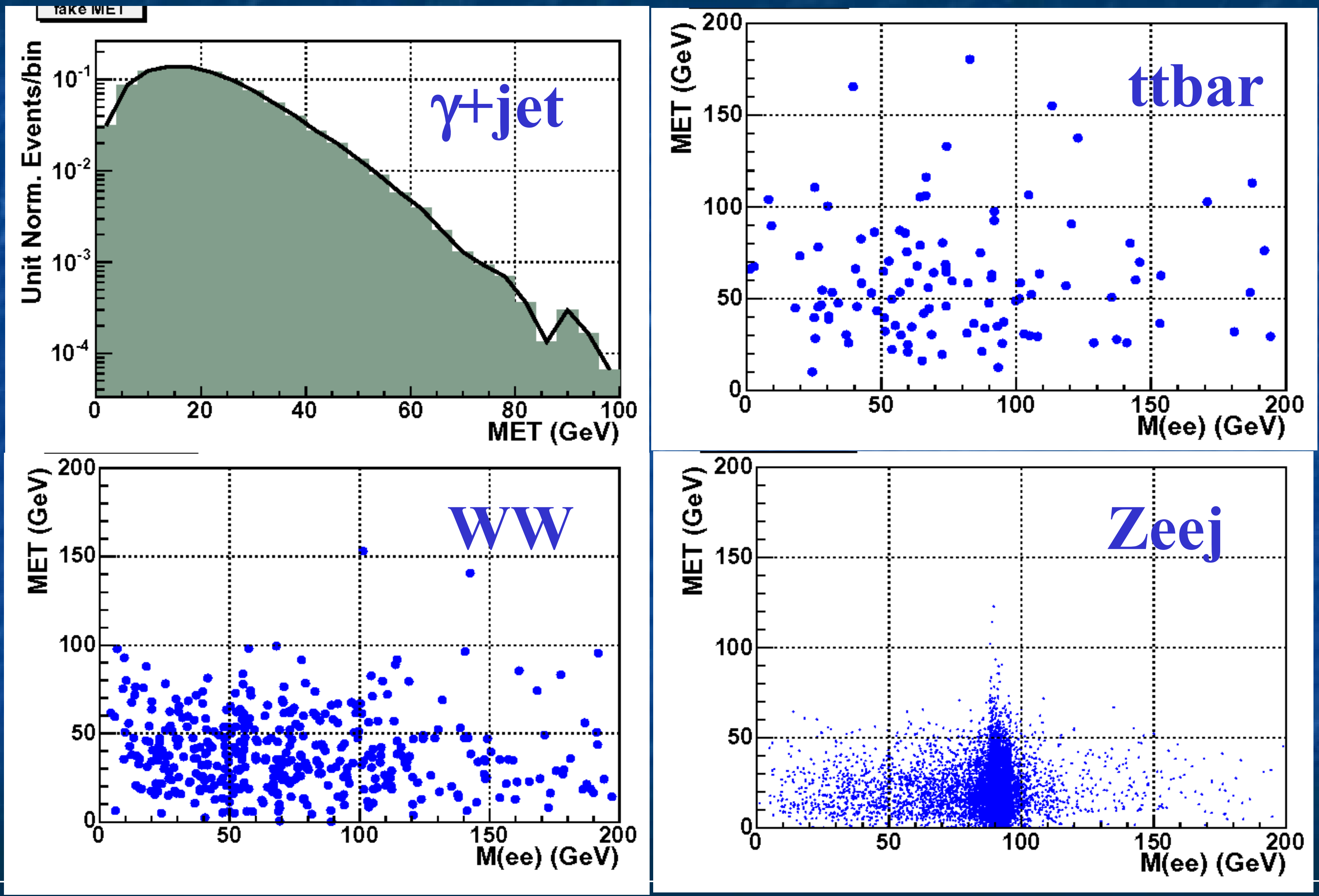
Z′→jj MET and Σ E_T



TeV: Top Dielectron Analysis



LHC: Dielectron mass vs. MET



Possible Improvements (for CMS)

$$E_T = \sum_j \left(\vec{E}_T\right)_j^{jet} \times C_j^{jet}(E_T,\eta) + \sum_i \left(\vec{E}_T\right)_i^{tower} \times C_i^{tower}(\eta)$$

- Raw MET calculation based on sum over towers
- Clustered + Unclustered Energy Calibrations
  - Type 1
    - Calibrated Jets + Uncalibrated Towers ($C^{towers}=1$)
  - Type 2
    - Calibrated Jets + Calibrated Towers
- Local Noise Suppression
  - Remove "Tail Catcher" (HO) from MET sum unless included in jet (similar to Coarse Hadronic use on D0)
  - T42-like noise suppession

Z/A → ττ Mass Reconstruction

$$m_{\tau\tau} \approx \sqrt{2(E_{\tau 1} + E_{\nu 1})(E_{\tau 2} + E_{\nu 2})(1 - \cos\theta)}$$

$E_{\tau 1,2}$ - energies of measured tau-decay products

$E_{\nu 1,2}$ - (unknown) energies of two neutrinos

θ - angle between measured tau-decay products

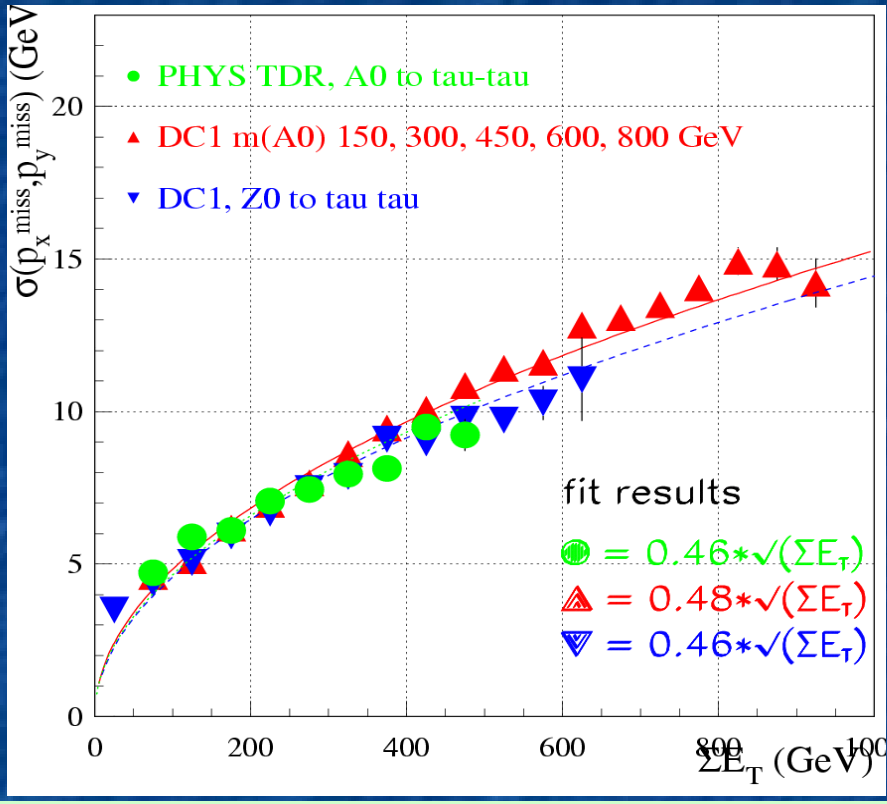
$$\vec{p}^{\,miss}_{x,y} = (\vec{p}_{\nu 1} \cdot \hat{u}_{\tau 1})_{x,y} + (\vec{p}_{\nu 2} \cdot \hat{u}_{\tau 2})_{x,y}$$

$\bar{u}_{\tau 1,\tau 2}$ - directions of the measured tau-decay products

$\vec{p}^{\,miss}_{x,y}$ - x,y-components of MET

Solve! (if physical)

$Z \rightarrow \tau\tau$ and $A \rightarrow \tau\tau$ DC1 simulation

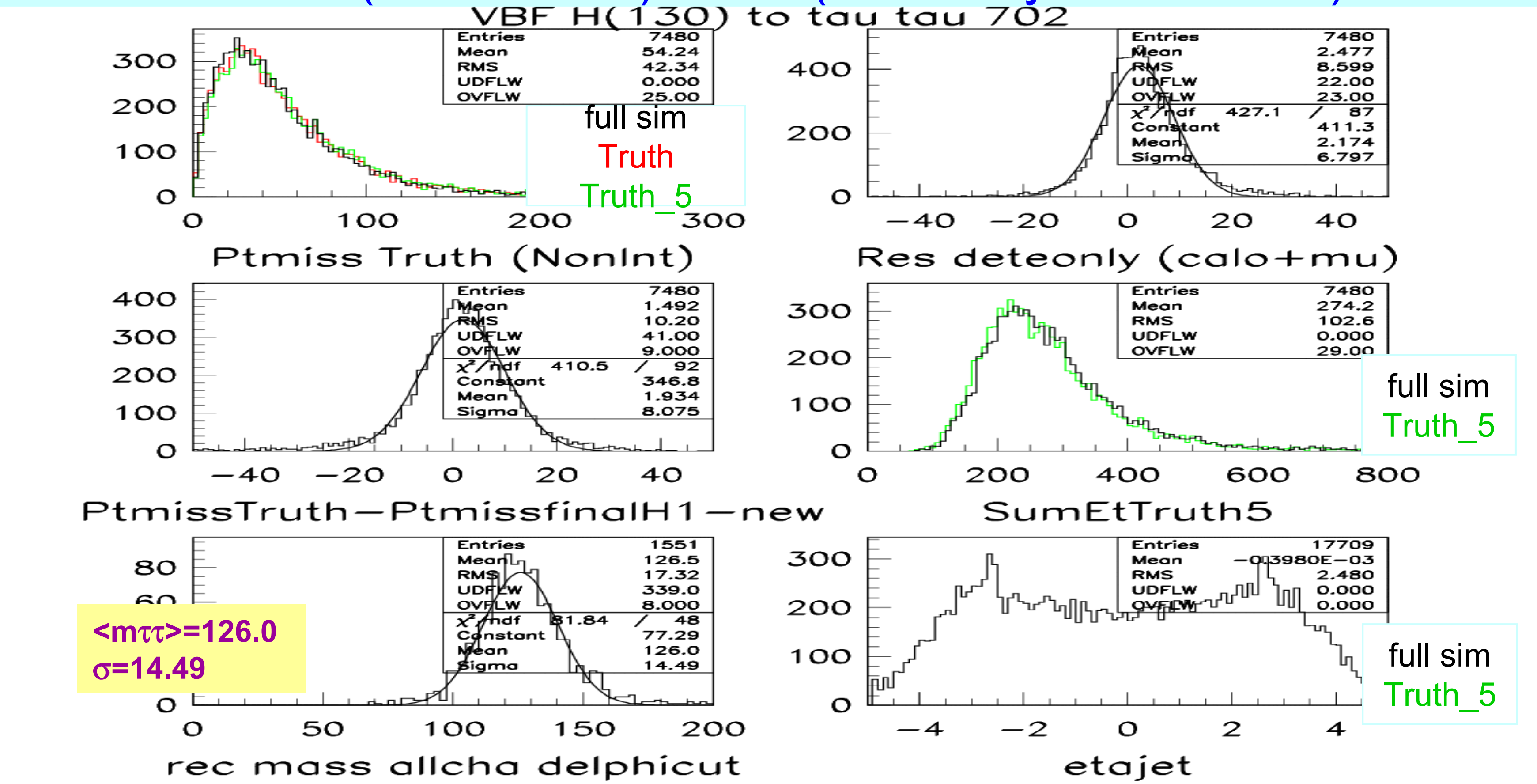


(Physics) ETmiss Resolution = σ (Ex(y)miss Truth - Ex(y)miss Rec $|\eta|< 5$)
includes detector effect and coverage

SumET = ΣE_T calo cells within $|\eta| < 5$ **No Noise added !**

ETmiss Resolution ÷ √ SumET

VBF H(m=130GeV) $\rightarrow \tau\tau$ (events by K. Cranmer)



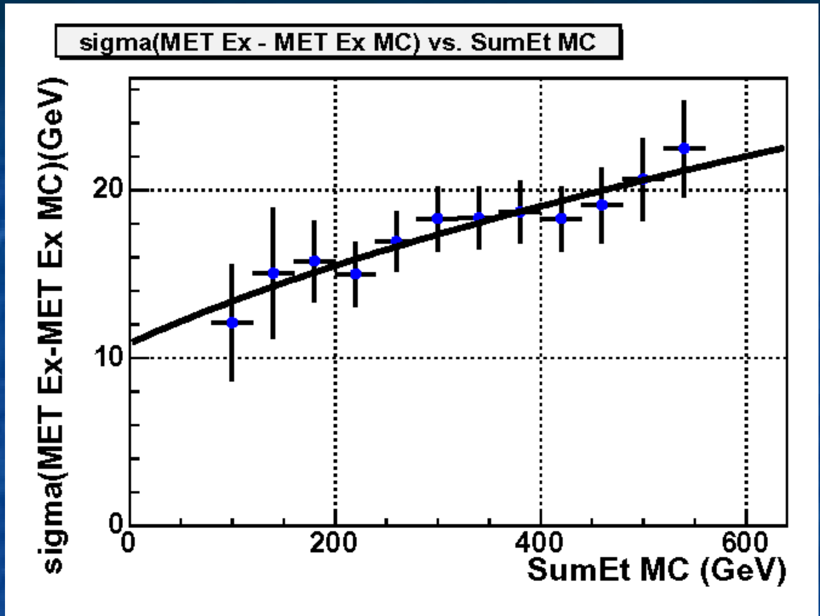
ETmiss_rec shifted of 4% and Resolution ~ 0.49 $\sqrt{\text{SumET}}$

- 2 forward jets
- High pT leptons

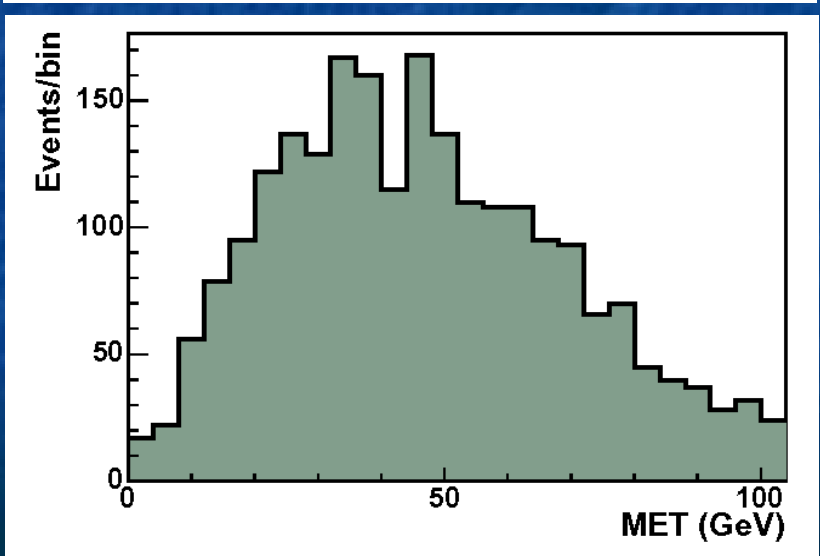
I.Rottlander studied in detail the correlation of the shift with η jets and pT(e)

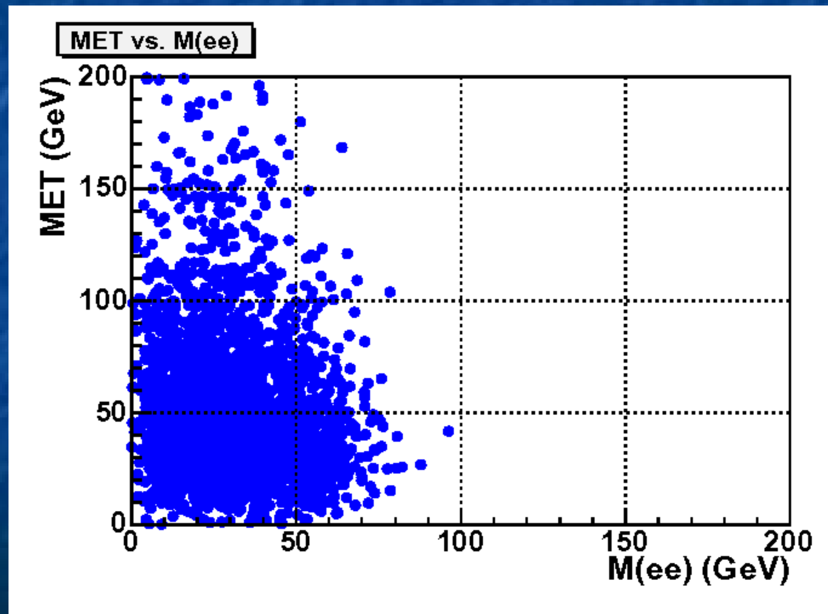
NEW H1 Calibration (16 ET bins)

Weights determined from MissingET

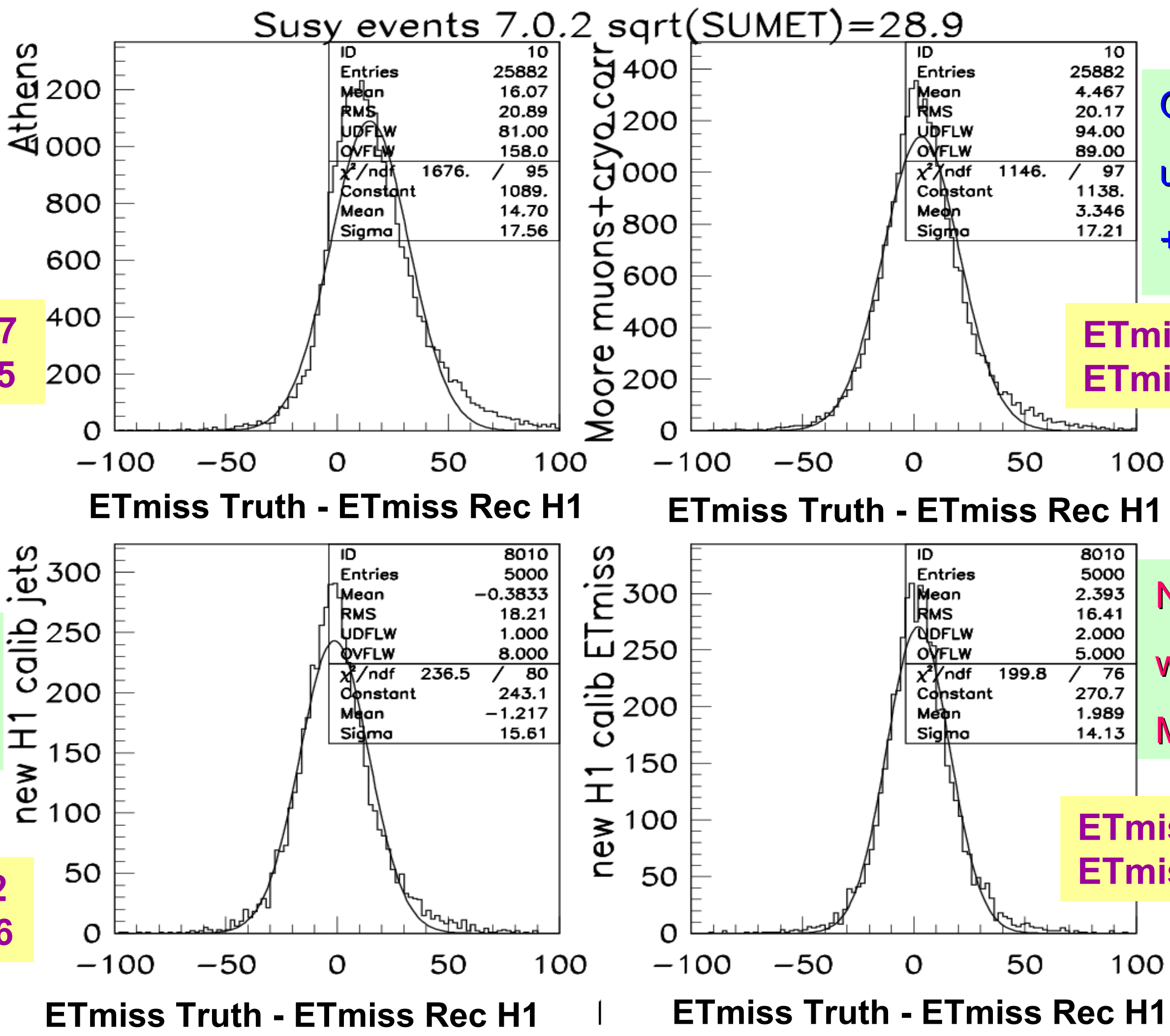


- MET resolution for
  - qqH→qqWW→qqee





Results on SUSY events from Atlas



OLD H1 Calib

(Athens results)

ETmiss Shift ~ 14.7
ETmiss Resol ~ 17.5

OLD H1 Calib

use Moore Muons

+ cryo correction

ETmiss Shift ~ 3.35
ETmiss Resol ~ 17.2

NEW H1 Calib

weights from jets

ETmiss Shift ~ -1.2
ETmiss Resol ~ 15.6

NEW H1 Calib

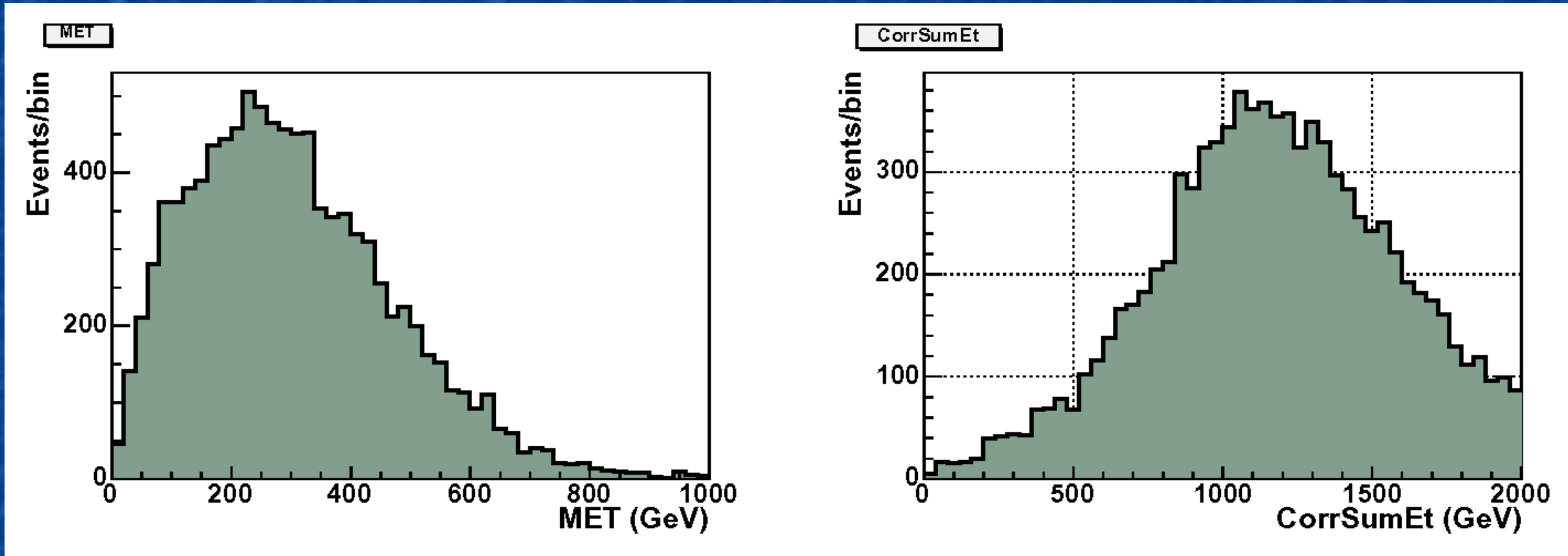
weights from

MissingET

ETmiss Shift ~ 1.9
ETmiss Resol ~ 14.1

SUSY MET

- Typically MET ~200-300 GeV w/ ΣE_T ~1-2 TeV



Well above expected resolutions:

Readiness tightly coupled to commissioning

Electronic Noise Studies

Contribution of noise w/ no cut to ETmiss resolution is about 13GeV

$\Rightarrow$ must be reduced

- Apply a threshold on cell energy
- Noise in LArg :

  Apply an Asymmetric Threshold $\Rightarrow$ E cell > 2 $*$ σ (el. noise)
  - Threshold chosen on the basis of the two channels

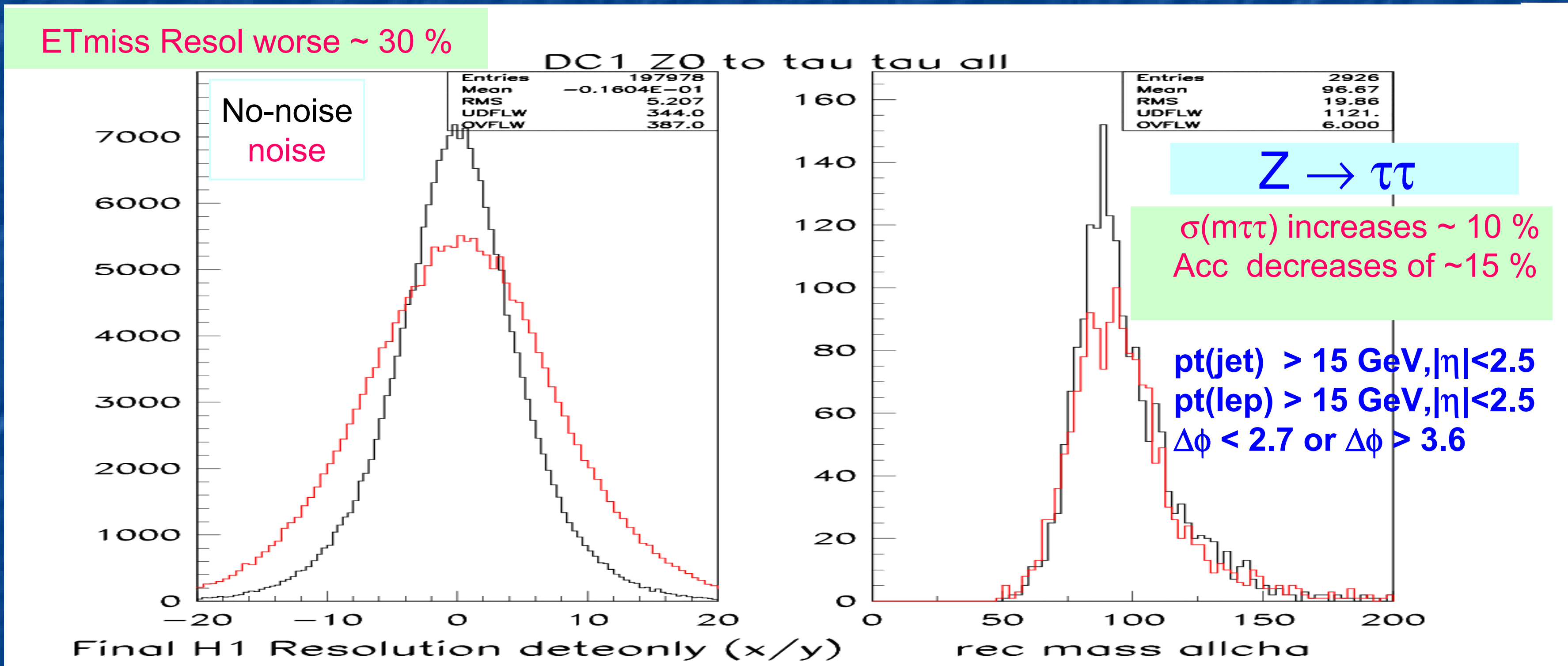
    $Z \to \tau\tau$, $bbA \to \tau\tau$:
    - optimise ETmiss resolution
    - Average values of significant quantities in event:

      ETmiss, SumET, Ncell... similar to no-noise case
- Noise in Tile is lower :

  Default Tile Zero Suppression applied: Ecell > 1.8σ(noise)
- Local noise cancellation on event-by-event basis (K. Cranmer)

  (for jets: noise-treatment combining towers with E<0 with nearby E>0)

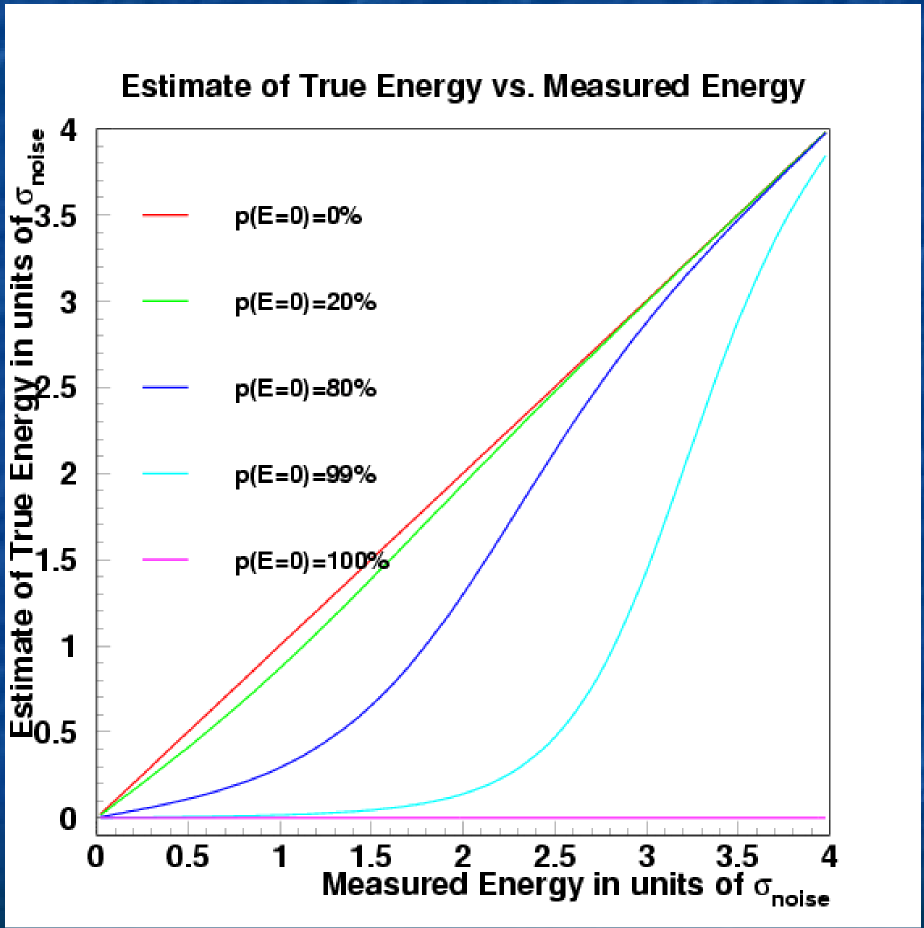
Effect of Electronic Noise



Contribution of noise no cut to ETmiss resolution is about 13 GeV
Effect of noise very large for Z events
ETmiss resolution ~6GeV without noise: noise cut necessary

K. Cranmer

Local Noise Suppression



- Use neighboring cells to estimate *a priori probability a cell is empty: p(E=0).*
- *The prior is cell-dependent, so the method automatically picks up topology of event.*
- *Use Bayes' Theorem to estimate true energy given prior and measured energy*
- *Acts like a local noise cut*

Effect from HV Dead Sectors(LAr EM)

Possible HV problems in increasing gravity:

- Some sectors operating at reduced voltage
- Some sectors with only one half gap biased
- Some sectors fully dead, because of shorts on both electrode sides

High Voltage system granularity:

Barrel: 448 sectors $\Delta\eta\times\Delta\varphi$=0.2x0.2

End-caps (outer wheel): 448 sectors $\Delta\eta\times\Delta\varphi$=0.1x0.2

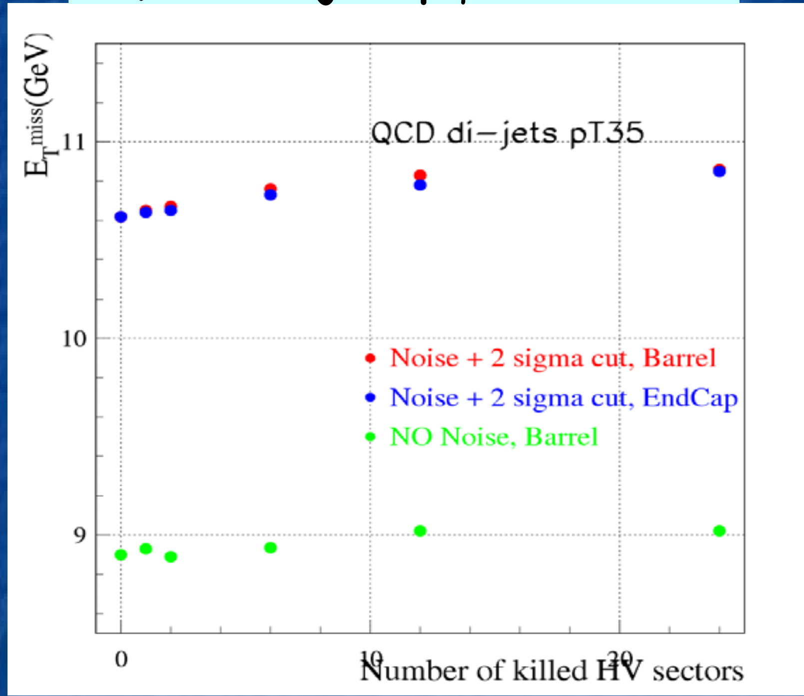
or =0.2x0.2 (η dep)

LArg Barrel already in the pit!

During HV barrel test at cold NO fully dead have been found.

HV Dead Sector Effects

QCD di-jet p_T> 35 GeV

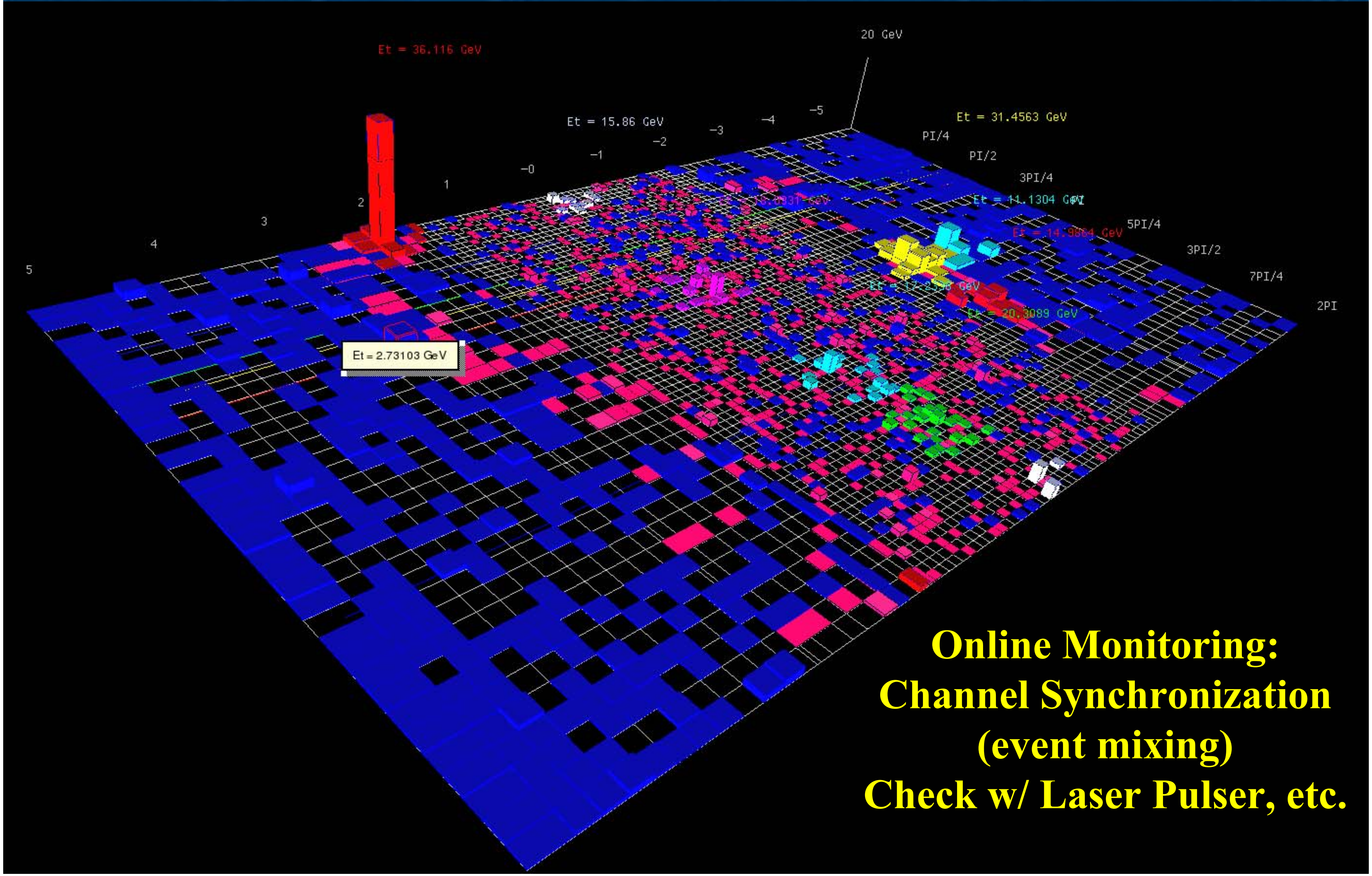


Barrel and EC studied separately

Dead sectors are chosen randomly
0, 1, 2, 6, 12, 24 sectors fully dead
Crack regions excluded from extraction

Maximum <E_T^{miss}> increase is < 3 %
With the current limited statistics is difficult to evaluate the effect on the E_T^{miss} tails in these distributions

LHC: Online Monitoring (?)



Online Monitoring:
Channel Synchronization
(event mixing)
Check w/ Laser Pulser, etc.

Summary

- MET is undoubtedly one of the most powerful experimental tools at the LHC
  - Commissioning is known to be a great challenge
  - Experience gained from Tevatron/HERA experiments on calibration is invaluable in coping with the hadronic environment
  - Many of the Atlas/CMS calorimeters are ready and currently operated in system tests and slice tests
  - What happens between now and Day 1 may determine which experiment sees first physics first