# Missing* Energy and Searches in CMS

* Transverse

- Motivation / Introduction
- Reconstruction methods
- Challenges in applications
- Outlook


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# Motivation

- Three quarters with missing transverse energy (MET)

## Signatures

[edit]

### Final State Configuration

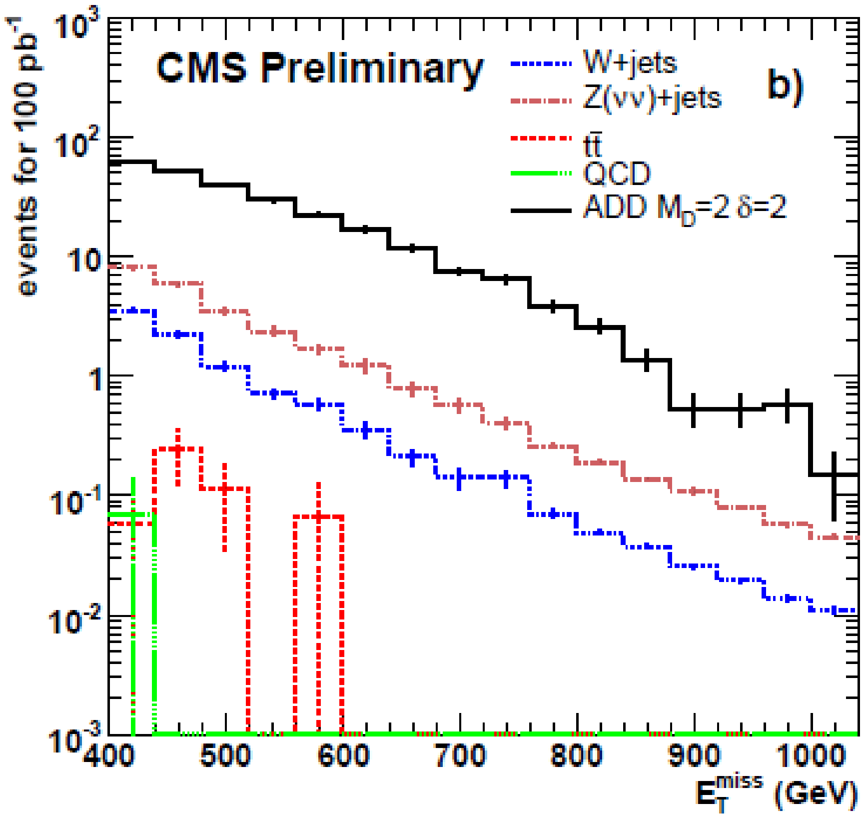
The following signatures refer to specific final state configurations that can, in principle, be observed at the LHC. If you are adding a signature, please choose a meaningful page name, and clearly indicates the signature (e.g. m jets / n leptons / MET). The database software does not like '+' symbols in the page-names, so avoid names like (m jets + n leptons), etc. Additionally, you may provide a short description of the signature.

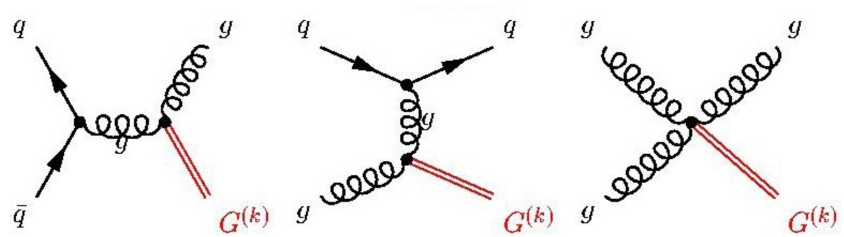
1. Displaced Vertices
2. Stable Charged Tracks
3. multi b-jets / 2 tau leptons / 2 charged tracks
4. multi b-jets / 1 tau lepton / MET
5. multi-jets / 2 b-jets / 2 SS leptons / MET
6. 2 jets / 2 OS tau leptons / MET
7. 0 hard jets / 2 OSDF leptons / MET
8. 0 hard jets / 3 leptons / MET (jet pT < 30 GeV)
9. 0 hard jets / 4 leptons / MET
10. 4 jets / multi-resonance
11. 4 tau leptons
12. 4 e/mu leptons
13. 2 OSSF leptons / MET
14. 2 OSSF lepton pairs
15. 2 OSDF leptons / MET
16. multi-jets / 0 leptons / MET
17. multi-jets / 1 leptons / MET
18. multi-jets / 2 SS leptons / MET
19. multi-jets / 2 OS leptons / MET
20. multi-jets / 3 leptons / MET
21. 2 jets / 2 OS leptons / MET
22. 2 jets / 2 b-jets / 1 lepton / MET
23. 2 jets / 3 leptons / MET
24. 2 jets / 4 leptons
25. 2 jets / MET
26. 1 photon / MET
27. 2 photons / MET
28. 2 photons / 2 leptons / MET
29. 2 photons / 1 jet / 2 leptons / MET
30. 2 photons / 4 jets / MET
31. 4 photons
32. 2 top-jets / 2 charm-jets / MET
33. 2 top-jets / 2 b-jets / 2 SS leptons / MET
34. 4 b-jets / 2 SS leptons / MET
35. 4 b-jets / 4 leptons / MET
36. 4 b-jets / 1 lepton / MET
37. 3 b-jets / 1 lepton / MET
38. 2 b-jets / 1 lepton / MET
39. 2 b-jets / 3 leptons / MET
40. 1 b-jet / OSSF leptons

http://lhcsigs.physics.lsa.umich.edu

# Introduction

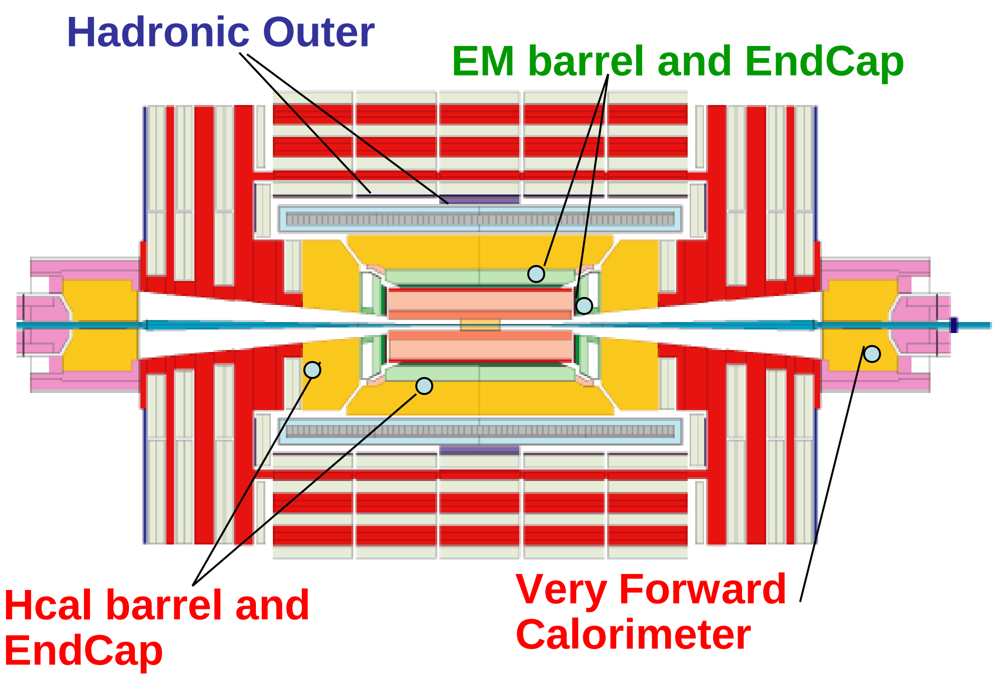
- Many models of new physics introduce particles that escape undetected, leading to apparent energy-momentum non-conservation → missing transverse energy (MET)
- Standard Model missing energy "small" in comparison
- Experimental challenges
  - Understand instrumental backgrounds (mismeasurements, "QCD")
  - For desired resolution, need entire detector (jets, unclustered energy, electrons, muons, taus, ...)
  - Control energy resolution over wide range, including low energy
  - Understand tails




ADD Large Extra Dimensions

# CMS Calorimeters




## EM calorimeter $|\eta| < 3$ :

$PbW0_4$ crystals

1 longitudinal section + PS 1.1 $\lambda$

$\Delta\eta\times\Delta\varphi = 0.0174 \times 0.0174$

## Central Hadronic $|\eta| < 1.7$ :

Brass/scintillator

2 + 1 (Hadron Outer) long. sections

5.9 + 3.9 $\lambda$ ($|\eta| =0$)

$\Delta\eta\times\Delta\varphi = 0.087 \times 0.087$

## Forward calorimeter $2.9 < |\eta| < 5$:

Fe/quartz fibers

$\Delta\eta\times\Delta\varphi = \sim 0.175\times 0.17$

## Endcap Hadronic $1.3< |\eta| < 3$ :

Brass/scintillator + WLS

2/3 longitudinal sections 10$\lambda$

$\Delta\eta\times\Delta\varphi = \sim 0.15 \times 0.17$

# Missing Transverse Energy

- Definition $$\vec{\not{E}}_T = -\sum_n (E_n \sin\theta_n \cos\phi_n \hat{\mathbf{i}} + E_n \sin\theta_n \sin\phi_n \hat{\mathbf{j}}) = \not{E}_x \hat{\mathbf{i}} + \not{E}_y \hat{\mathbf{j}}$$
- Sum over calibrated energy deposits in semi-projective calorimeter towers
- Apply corrections *a posteriori*
- MET resolution $$\sigma(\not{E}_T) = A \oplus B\sqrt{\Sigma E_T - D} \oplus C\,(\Sigma E_T - D)$$

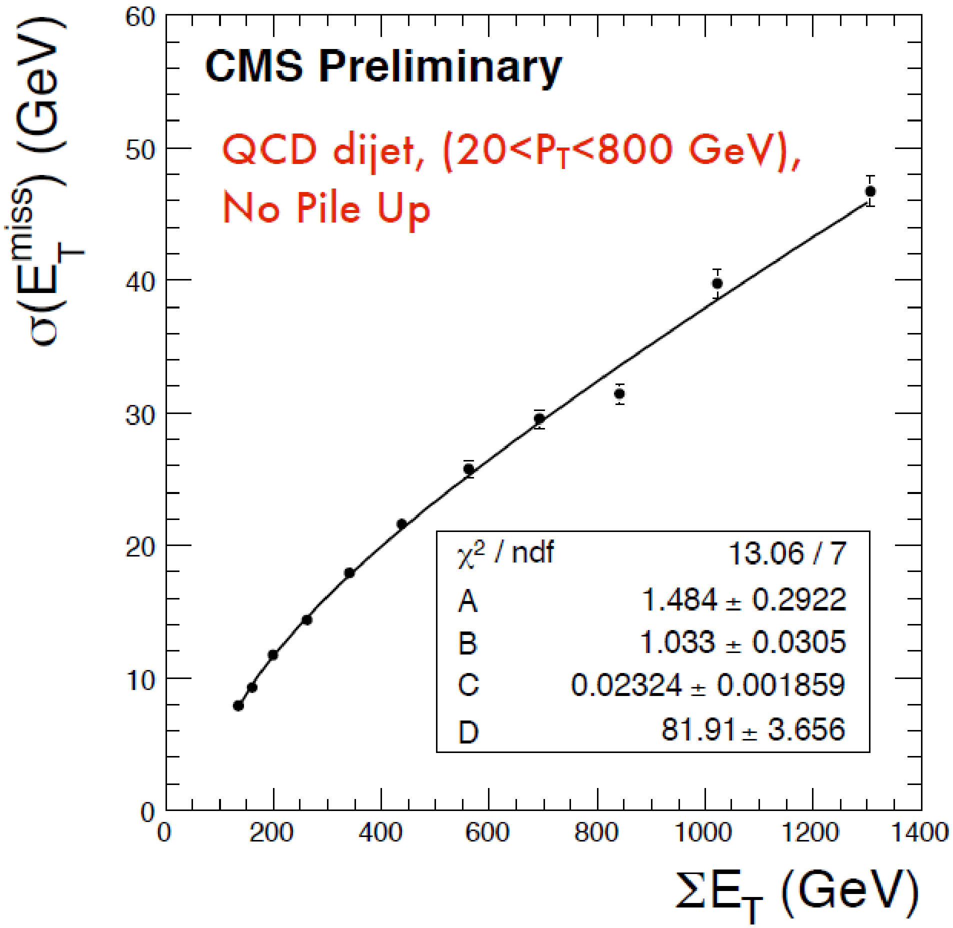
A = "Noise" B = "Stochastic" C = "Constant" Term D = "Offset"

- Important considerations
  - A: Electronic noise
  - A: Pile-up and underlying event
  - A: High magnetic field (sweeps out low pt particles)
  - B: Good hermetic coverage, energy resolution
  - B: (Non-)compensating calorimeter response
  - C: Energy loss due to inactive material and punch through
  - C: Other residual non-linearities
  - D: Effects of noise and pile-up on scalar $E_T$

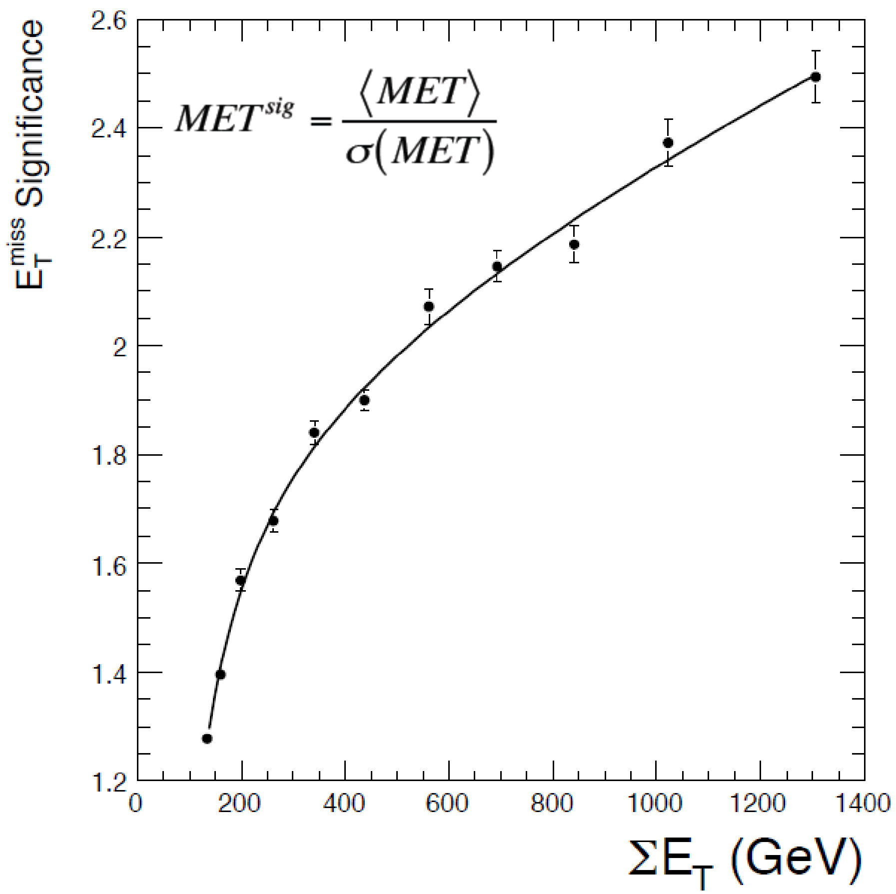
# Performance

- MET resolution $$\sigma(\not{E}_T) = A \oplus B\sqrt{\Sigma E_T - D} \oplus C\,(\Sigma E_T - D)$$

A = "Noise" B = "Stochastic" C = "Constant" Term D = "Offset"

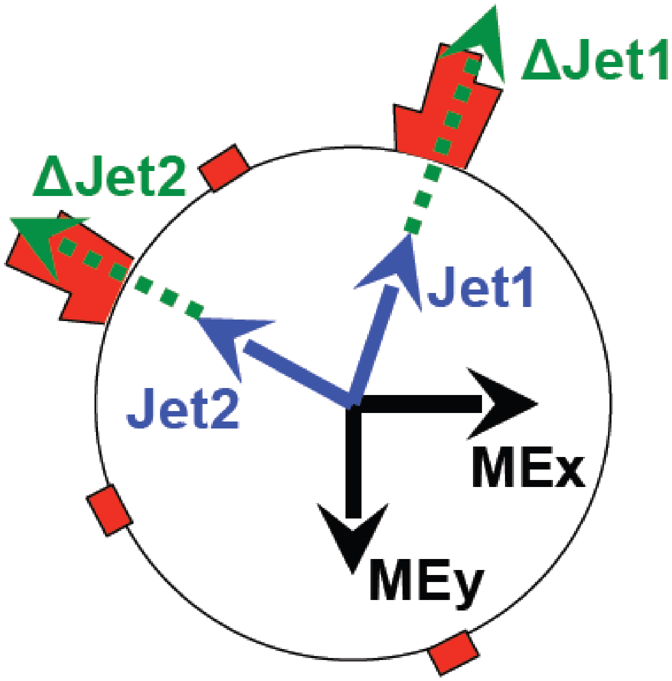



| $\chi^2$ / ndf | 13.06 / 7 |
|---|---|
| A | 1.484 ± 0.2922 |
| B | 1.033 ± 0.0305 |
| C | 0.02324 ± 0.001859 |
| D | 81.91 ± 3.656 |



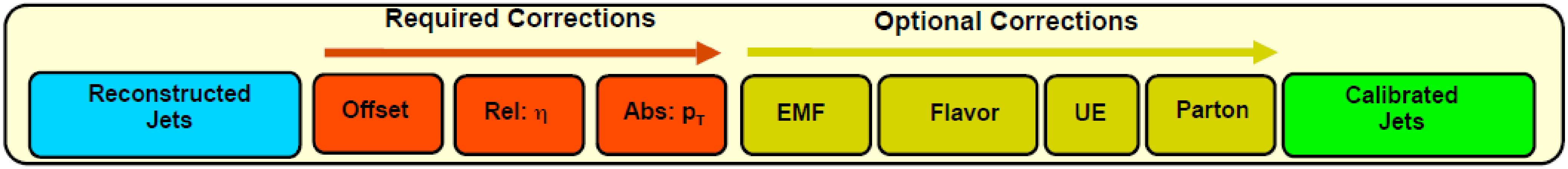
# Corrections

- Orders of magnitude in MET
  - "Nothing"
    - Drell-Yan, …
  - Small / medium (20-100 GeV)
    - top, W, H, …
  - Large (several 100 GeV)
    - supersymmetry, large extra dimensions, …
- Corrections to achieve good performance in many topologies
  - Jet energy scale
  - e, μ, τ
  - Hot, dead, warm, … channels
  - Vertex corrections



# Corrections: Jet Energy Scale

- Factorized multi-level jet corrections



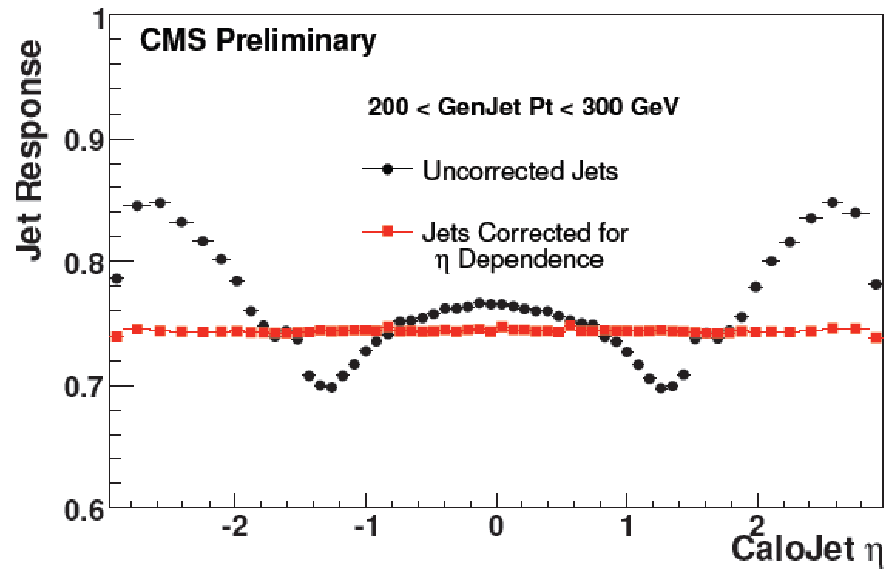

- Offset: correct for pile-up and electronic noise (measure in zero-bias)
- Relative (η): variations in jet response with eta
- Absolute ($p_T$): correct to particle level jets
- EMF: variations in jet response with electromagnetic energy fraction
- Flavor: variations in jet response according to flavor (uds, c, b, gluon)
- Underlying event
- Parton: correct measured jet $p_T$ to parton level

Derive from MC simulation tuned on testbeam data for now, use real data as soon as available

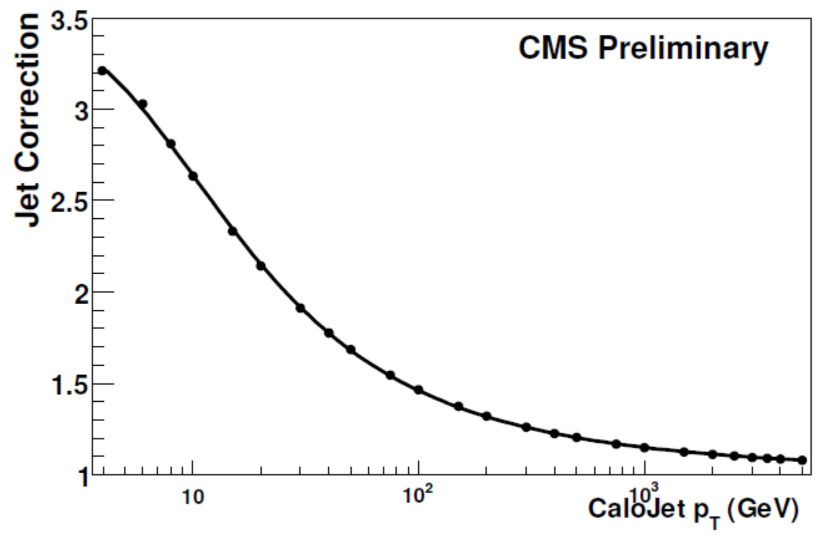
# Corrections: Jet Energy Scale

- Flatten jet response vs. eta
- Now MC-based, later data-driven (di-jet balance)

Response= $p_T^{CaloJet} / p_T^{GenJet}$



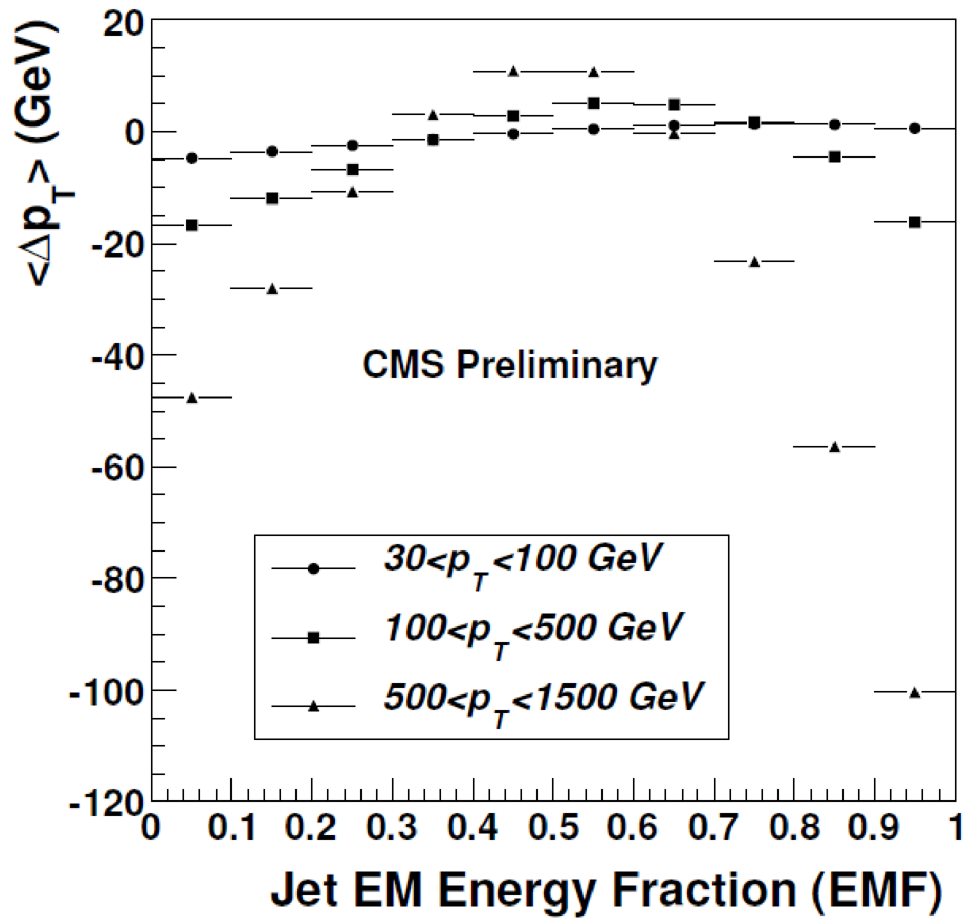

Absolute Jet Correction vs. $p_T$(CaloJet)




- Correct jet energy to particle level
- Now MC-based, later data-driven ($p_T$ balance in γ+jet, Z+jet)

# Corrections: Jet Energy Scale

- Correct for variations in jet response as a function of electromagnetic energy fraction (non-compensating calorimeter, e/h ≠ 1)



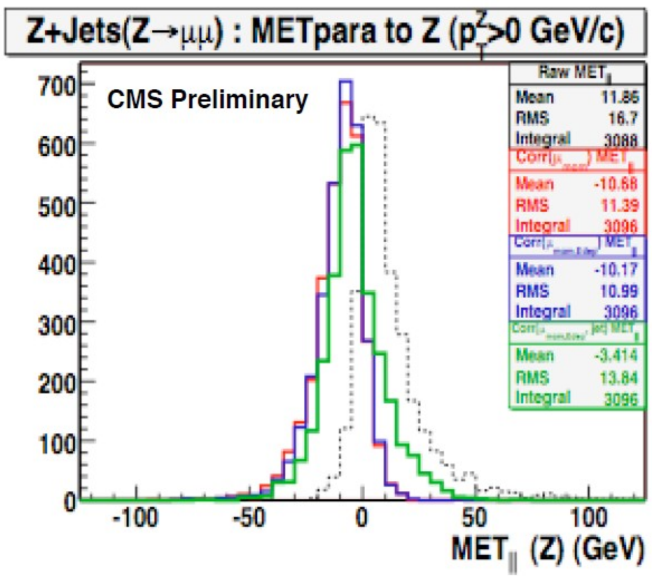

$$\vec{\not{E}}_T^{\,\mathrm{corr}} = \vec{\not{E}}_T - \sum_{i=1}^{\mathrm{N_{jets}}} \left[\vec{p}_{T_i}^{\,\mathrm{corr}} - \vec{p}_{T_i}^{\,\mathrm{raw}}\right]$$

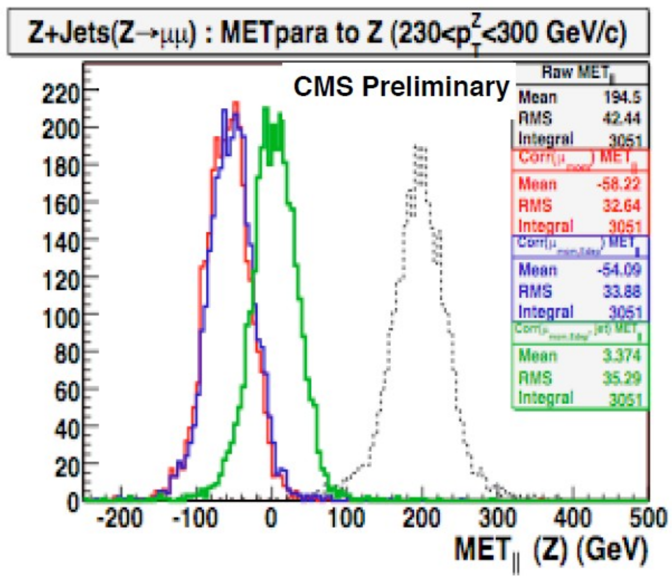
- Small (separate) correction for reconstructed electrons possible

# Corrections: Muons

- Muon leaves typically small deposit in calorimeters
- Correct using measurement in tracker and muon systems
- Also correct for muon energy deposition in calorimeters

$$\vec{\not{E}}_T = -\sum_{i=1}^{\text{towers}} \vec{E}_T^{\,i} - \sum^{\text{muons}} \vec{p}_T^{\,\mu} + \sum_{i=1}^{\substack{\text{deposit}\\ \text{towers}}} \vec{E}_T^{\,i}.$$




MET component Parallel to Z

+ muon correction

+ muon deposit

+ JES

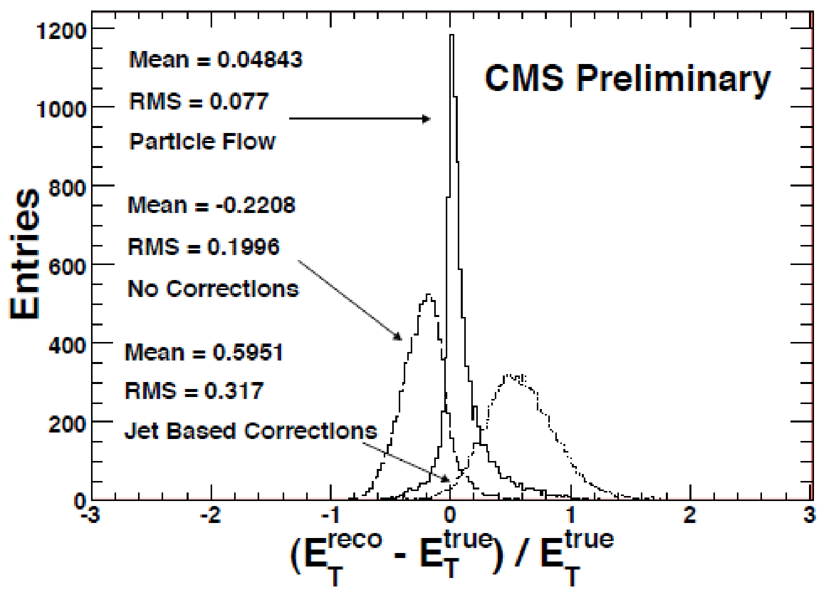
Note totally different pT dependent resolutions of muons and calorimeter objects – A handful “straight” muons reconstructed with O(TeV) can destroy new physics sensitivity (or fake a discovery)

# Corrections: Taus

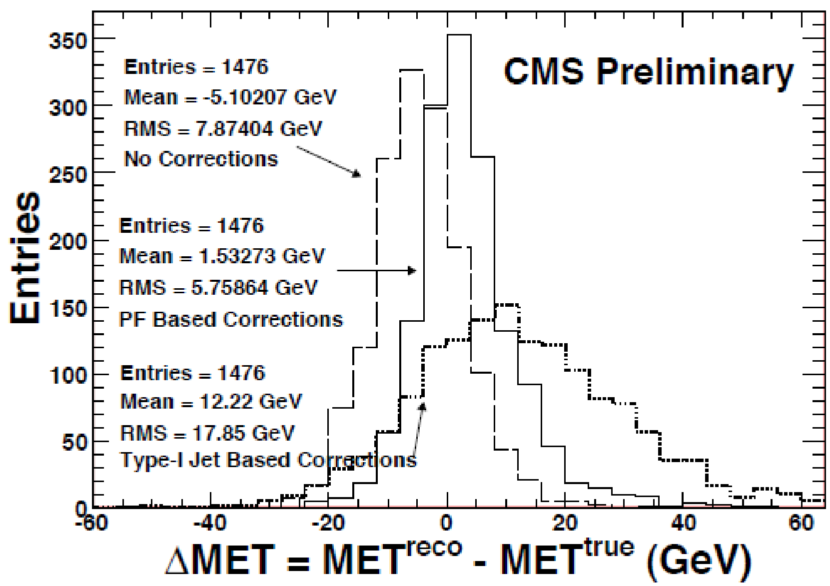
- Applying standard jet corrections to pencil-like hadronic τ jets would lead to over-corrected MET
- Use particle flow algorithm (tracking + calorimeter) to correct for τ's

$$\Delta \vec{\not{E}}_T = \sum \vec{E}_T^{\text{cal jet 0.5}} - \vec{E}_T^{\text{PF } \tau}$$

Good tau energy reconstruction

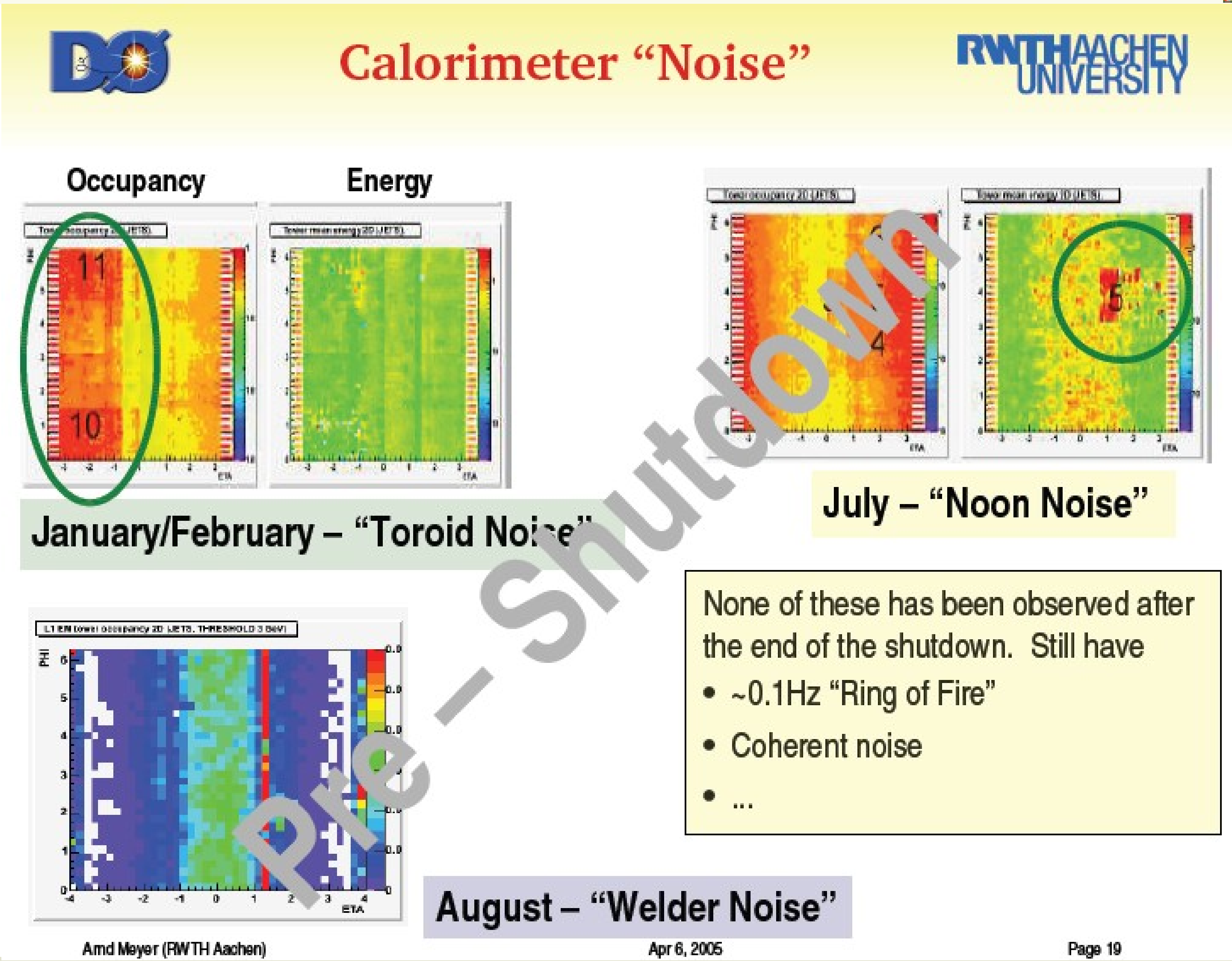



Best bias and resolution after correction

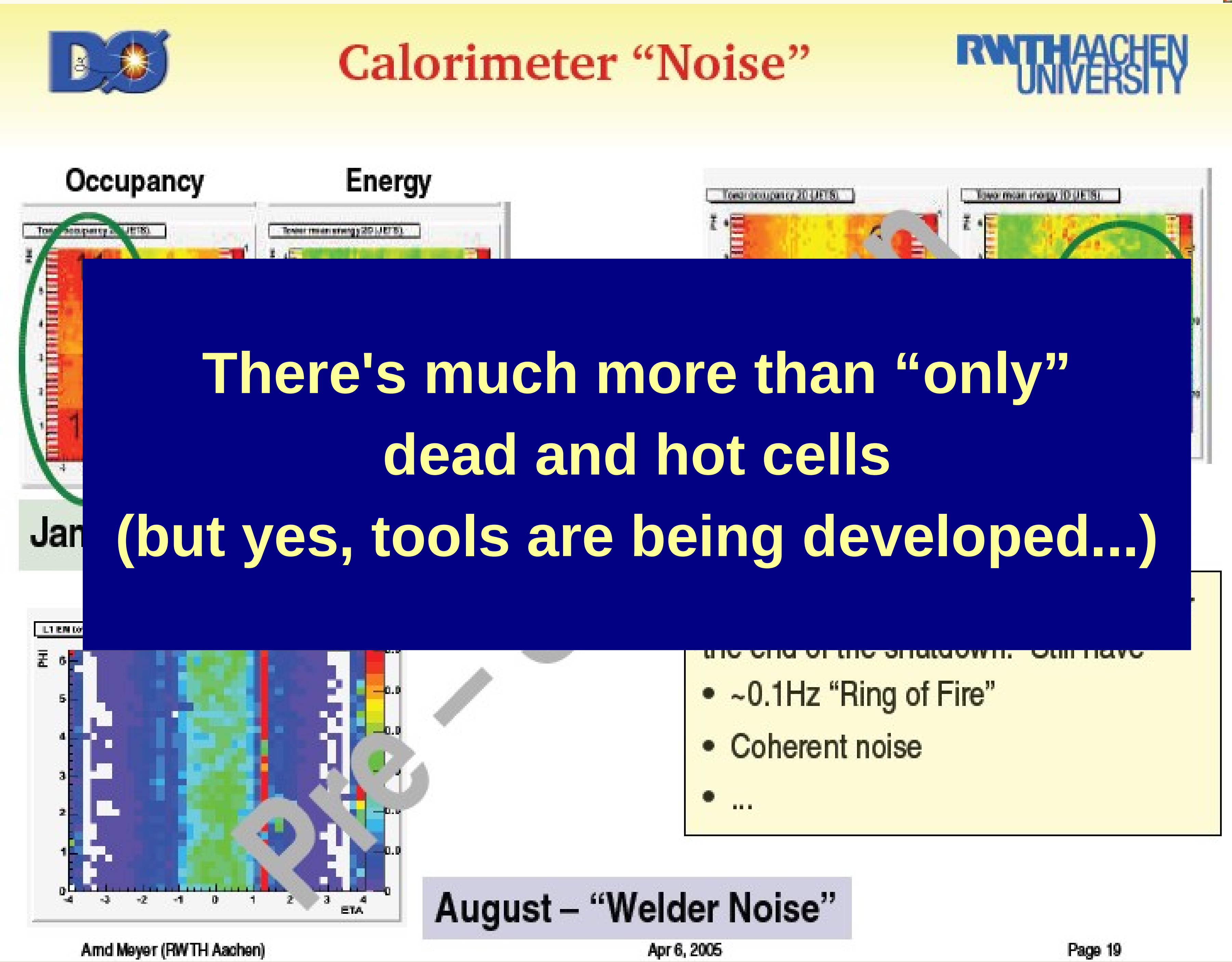



- Useful for analyses targeting τ's in the final state

# Data Quality



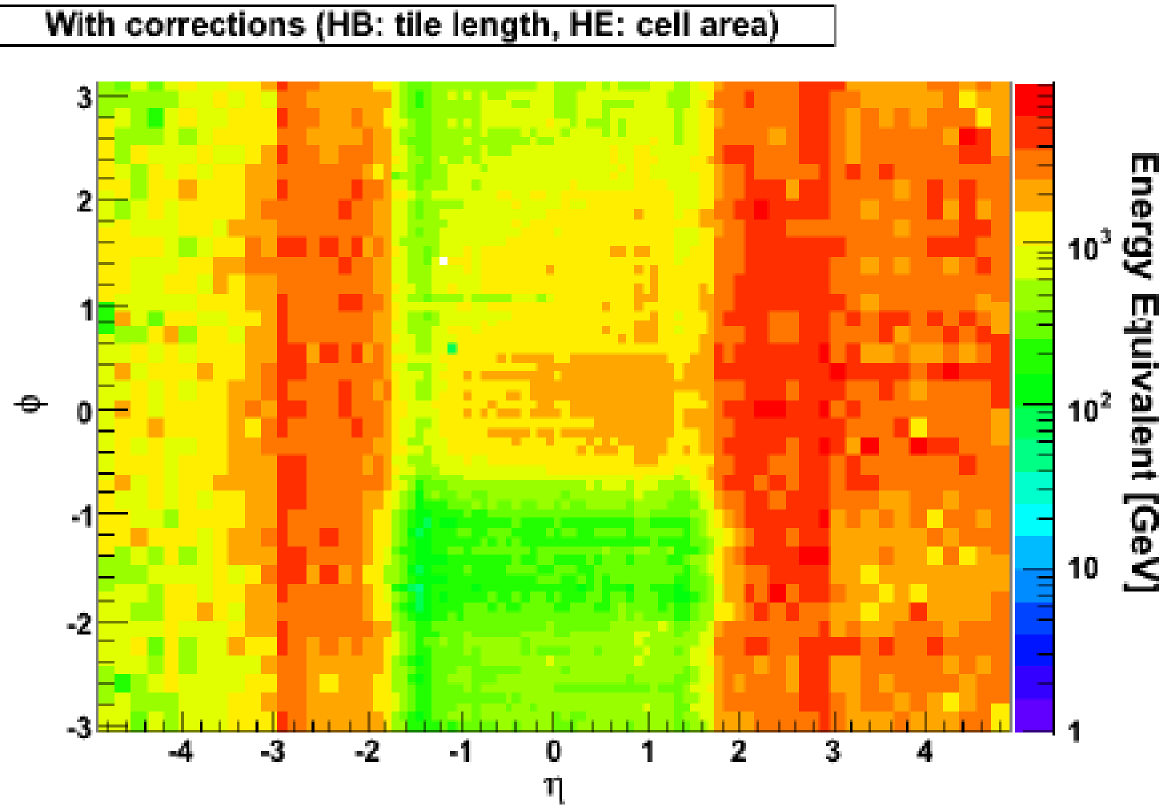
# Data Quality

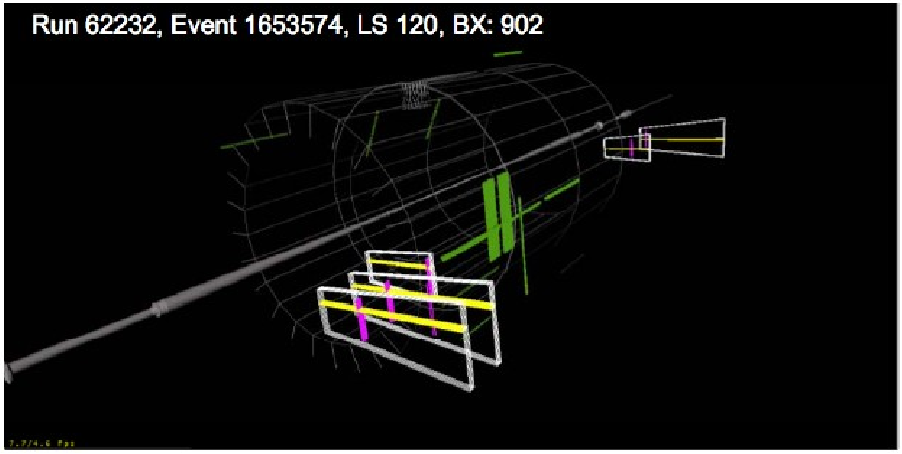



**There's much more than "only" dead and hot cells (but yes, tools are being developed...)**

# September 2008 – MET in CMS

**Beam on collimator**




**Halo muon**

**Performance depends on event content!**
**(jets, e, mu, tau, …)**

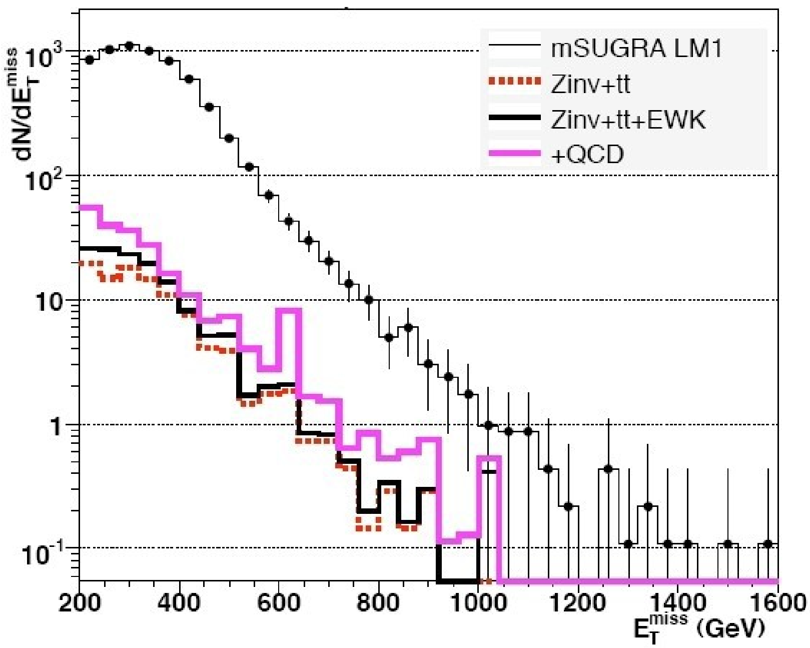
**Different resolution for different objects**

**Different systematics for different objects**

**Not all objects at the same level of “understanding” at a given time, especially in early running**

# Early MET Applications

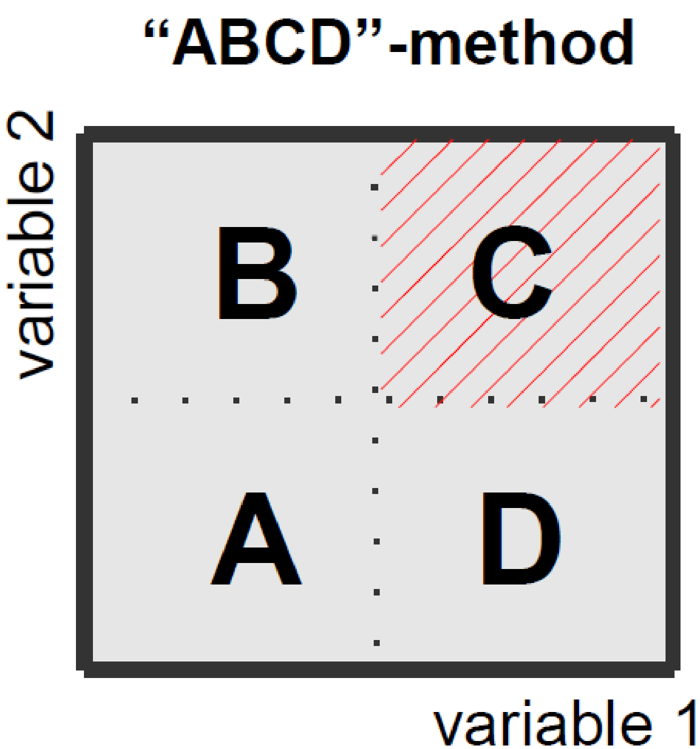
- Option (A): "We'll plan for success"
  - Assume entire detector is basically available
  - Assume systematic uncertainties can be controlled
  - Many "TDR-style" analyses in this category
  - Reflecting CMS capabilities correctly, but probably not what first results will look like
- Example: Typical cut-based search for supersymmetry in jets+MET
  - **MET > 200 GeV**
  - >=3 jets ($|\eta|<1.7/3/3$) with $E_T>180/110/30$ GeV
  - $H_T$ (jet1, jet2, jet3, MET) > 500 GeV
  - Indirect lepton veto
  - Cleanup and anti-QCD selection (topological cuts)
  - Can find low mass SUSY (mSUGRA, LM1) with 100 $pb^{-1}$



# Improvements

- Major backgrounds include QCD (mismeasured MET) and $Z \to \nu\nu$
- Several methods developed to constrain from data

**QCD example:**



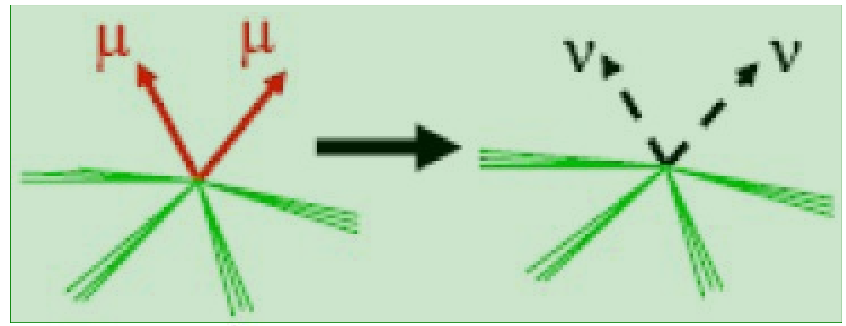

- **Two uncorrelated variables** (or account for correlations)
- **With separation power for signal and background**
- **In signal region C the background is**

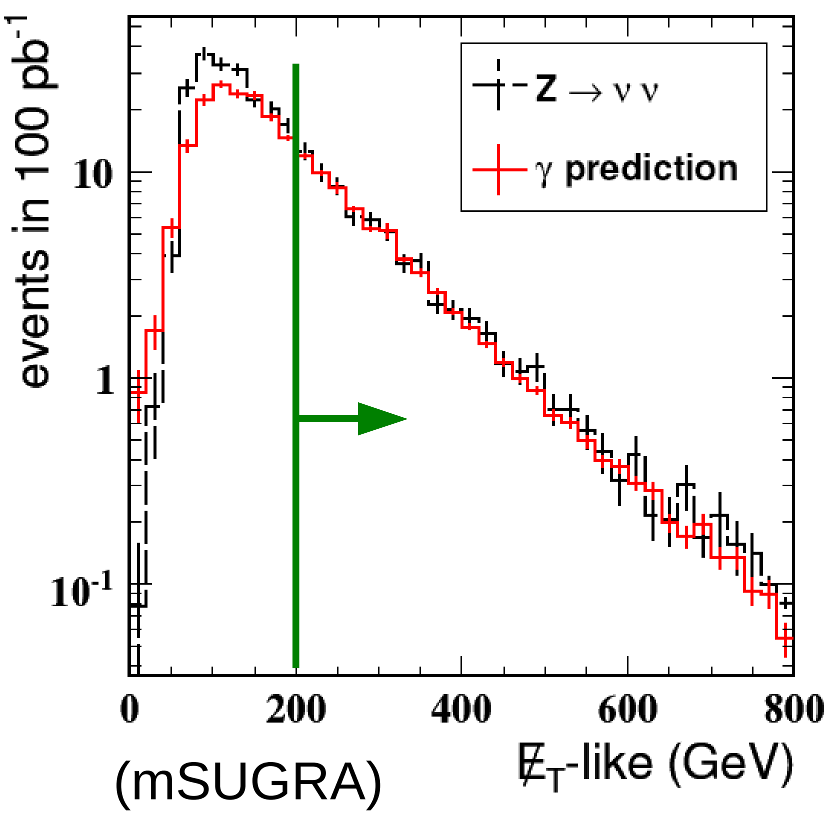
$$C = D \cdot \frac{B}{A}$$

- **Need to control signal contamination in A, B, D**

# Improvements: $Z \to \nu\nu$ (+ jets)

- Significant irreducible background to many searches: SUSY, monojets / monophotons (large extra dimensions etc.)
- Several methods to determine this background
  - Most direct: Z $p_T$ spectrum from $Z \to \mu\mu$ / ee decays, well established
  - But BF only 2 x 1/6 of $\nu\nu$




- Alternatively extrapolate from $W \to \mu\nu$ or $\gamma$ + jets (gain 10-30 x statistics)
- Need to control lepton efficiencies, backgrounds / $\gamma$ fake rates, trigger efficiencies, theoretical uncertainties

| $Z \to \nu\nu$ background estimate (100 $pb^{-1}$) | |
|---|---|
| MC-truth | 35 |
| From $\gamma$+jets | $29 \pm 3$ (stat) $\pm 5$ (sys) |
| From W+jets | $35 \pm 10$ (stat) $\pm 8$ (sys) $\pm 3$ (theory) |

# Improvements: $Z \rightarrow \nu\nu$ (+ jets)

- Significant irreducible background to many searches: SUSY, monojets / monophotons (large extra dimensions etc.)
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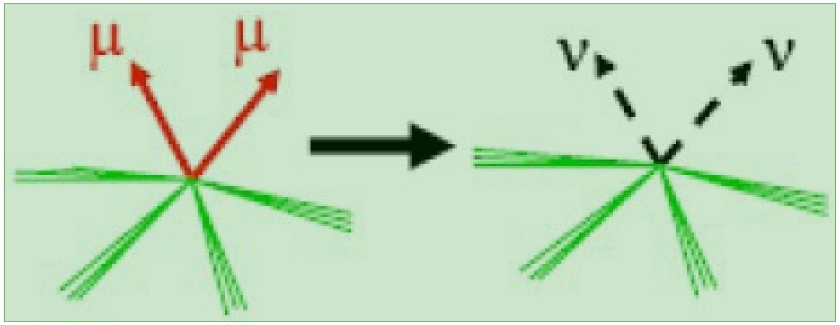
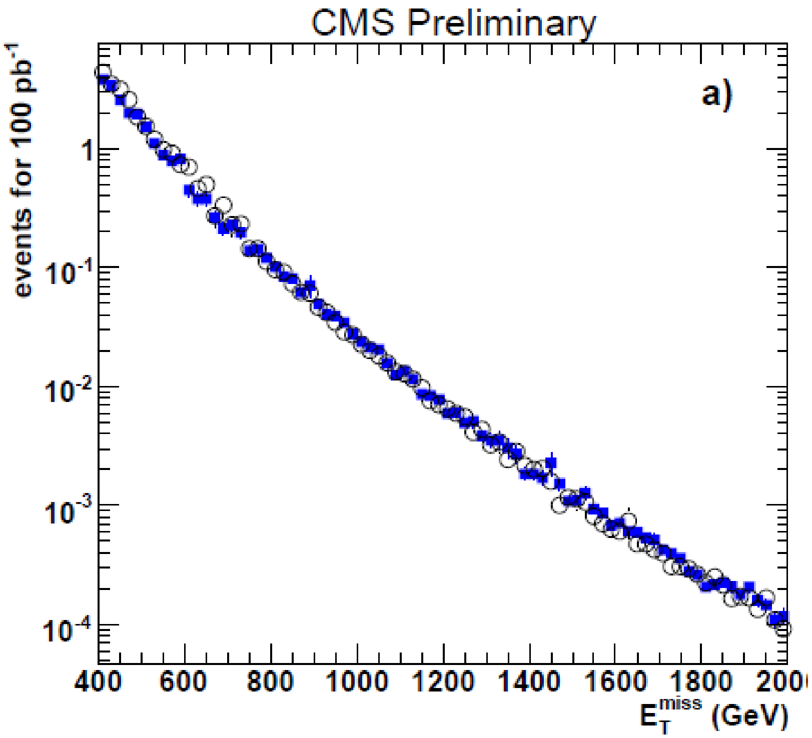



(ADD monojets)

- Alternatively extrapolate from $W \rightarrow \mu\nu$ or $\gamma$ + jets (gain 10-30 x statistics)
- Need to control lepton efficiencies, backgrounds / $\gamma$ fake rates, trigger efficiencies, theoretical uncertainties

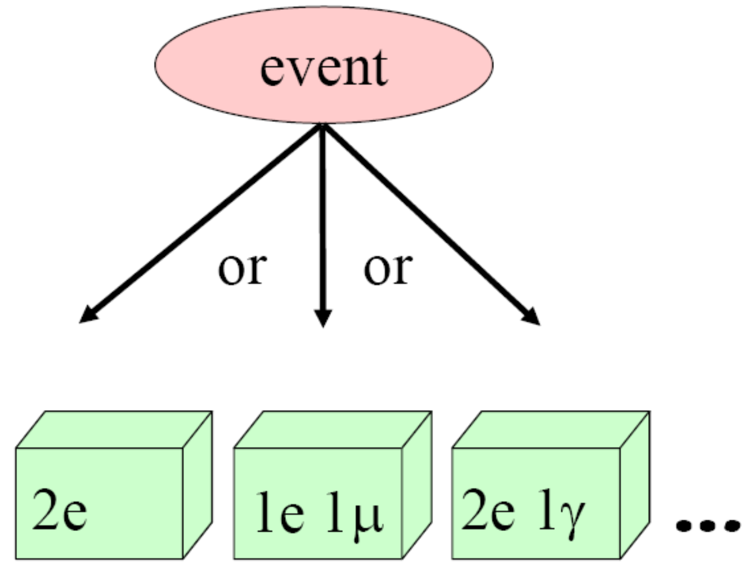
$Z \rightarrow \nu\nu$ + jets MC
Estimate from $W \rightarrow \mu\nu$

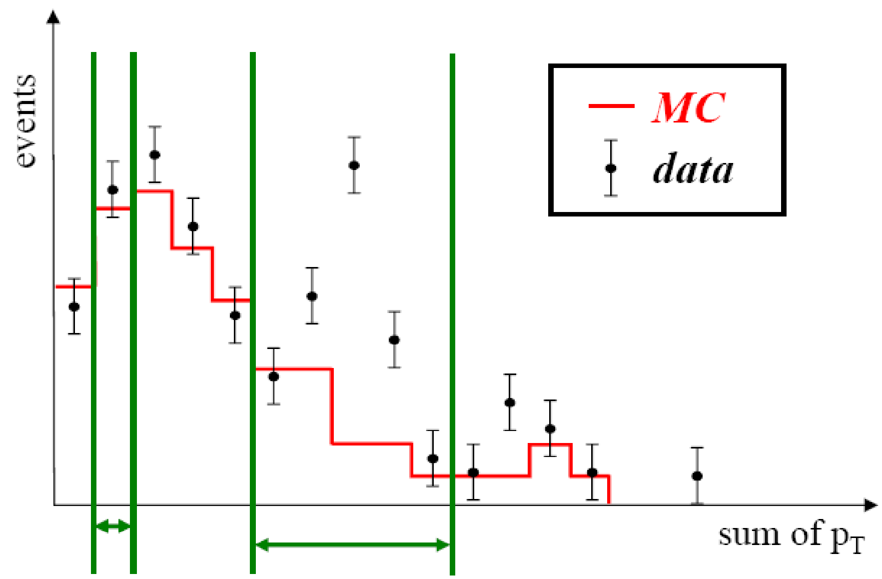
# Early MET Applications

- Option (B): "Be prepared for some failures"
  - Assume most of the detector is basically available for MET
  - Expect that certain systematic uncertainties cannot be controlled
- Reduce exposure using data-driven techniques
- Simpler / more robust MET varieties
- Example: Use MHT (missing $H_T$) instead of MET
  - Does mostly require JES
  - More robust, especially for trigger

# Model independent search MUSiC I

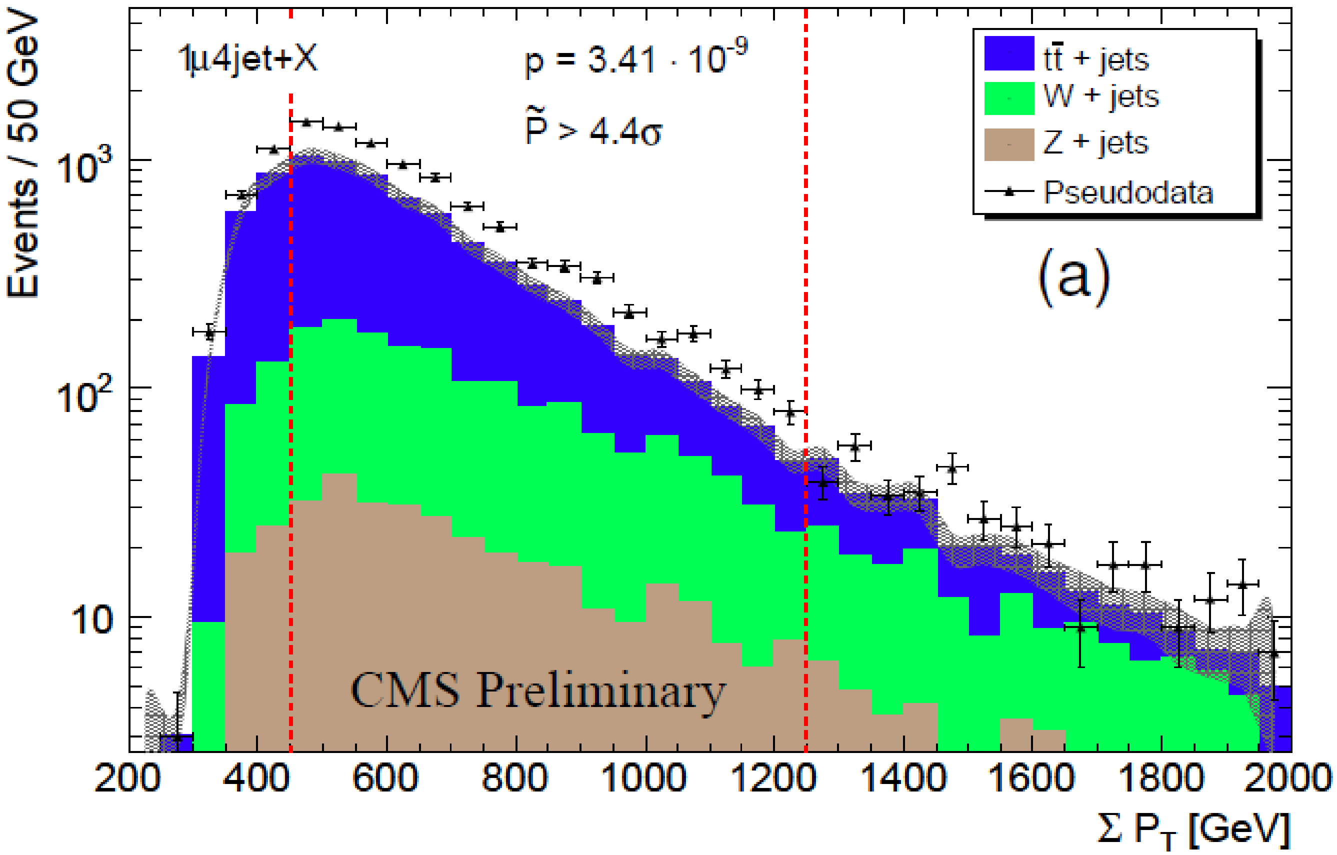
- MUSiC (Model Unspecific Search in CMS) performs a general scan of the data for deviations from the Standard Model expectation
- Classify events by particle content
  - Single isolated lepton always required
  - Exclusive vs. inclusive final states
- Scan distributions for statistically significant deviations
  - Presently $\Sigma p_T$, invariant (transverse) mass, MET
  - Find “Region of Interest” = one or more connected bins with the biggest discrepancy between data and SM
- Includes systematic uncertainties



# Model independent search MUSiC II

- Sensitive not only to new physics
- Can also uncover problems in simulation and detector




**JES 10% up for this exercise**

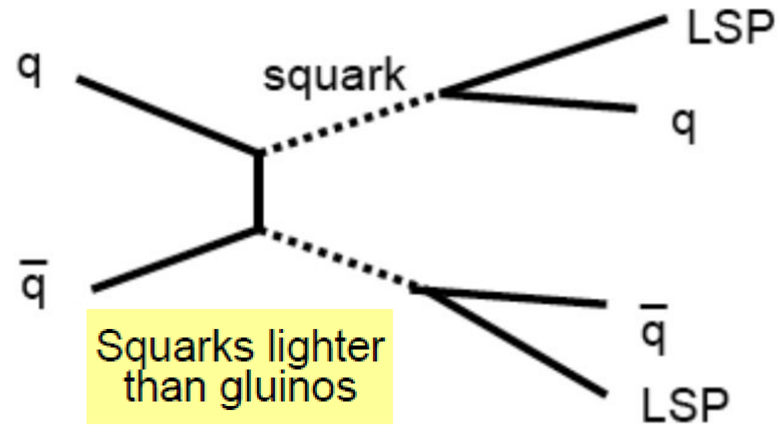
**(equivalent for MET)**

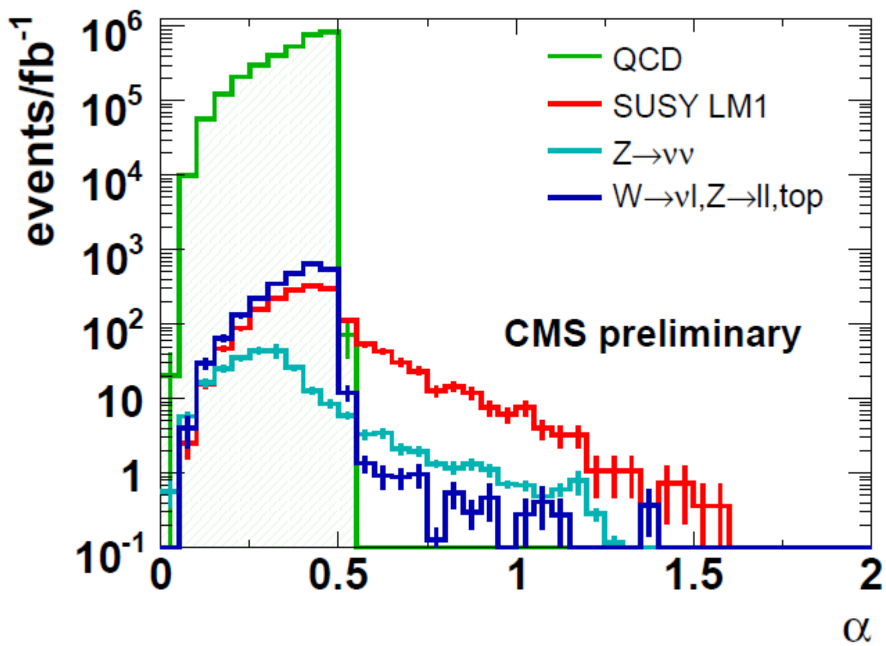
# Early MET Applications

- Option (C): "MET will not be usable for analysis"
  - Assume systematic uncertainties cannot be controlled early on
- Example: Search for clever alternatives to MET
- **SUSY in di-jet events**
  - = 2 jets with $p_T$ > 50 GeV, lepton veto
  - $H_T = p_{Tj1} + p_{Tj2}$ > 500 GeV
  - Angular/acceptance cuts for cleaning
  - New variable (Randall/Tucker-Smith):

$$\alpha = \frac{E_{T\ j2}}{M_{j1\,j2}} = \frac{E_{T\ j2}}{\sqrt{2E_1E_2(1-\cos\theta)}} > 0.55$$

- MET not (directly) used
- Nevertheless, low mass (mSUGRA LM1) SUSY discovery with 100 $pb^{-1}$ possible

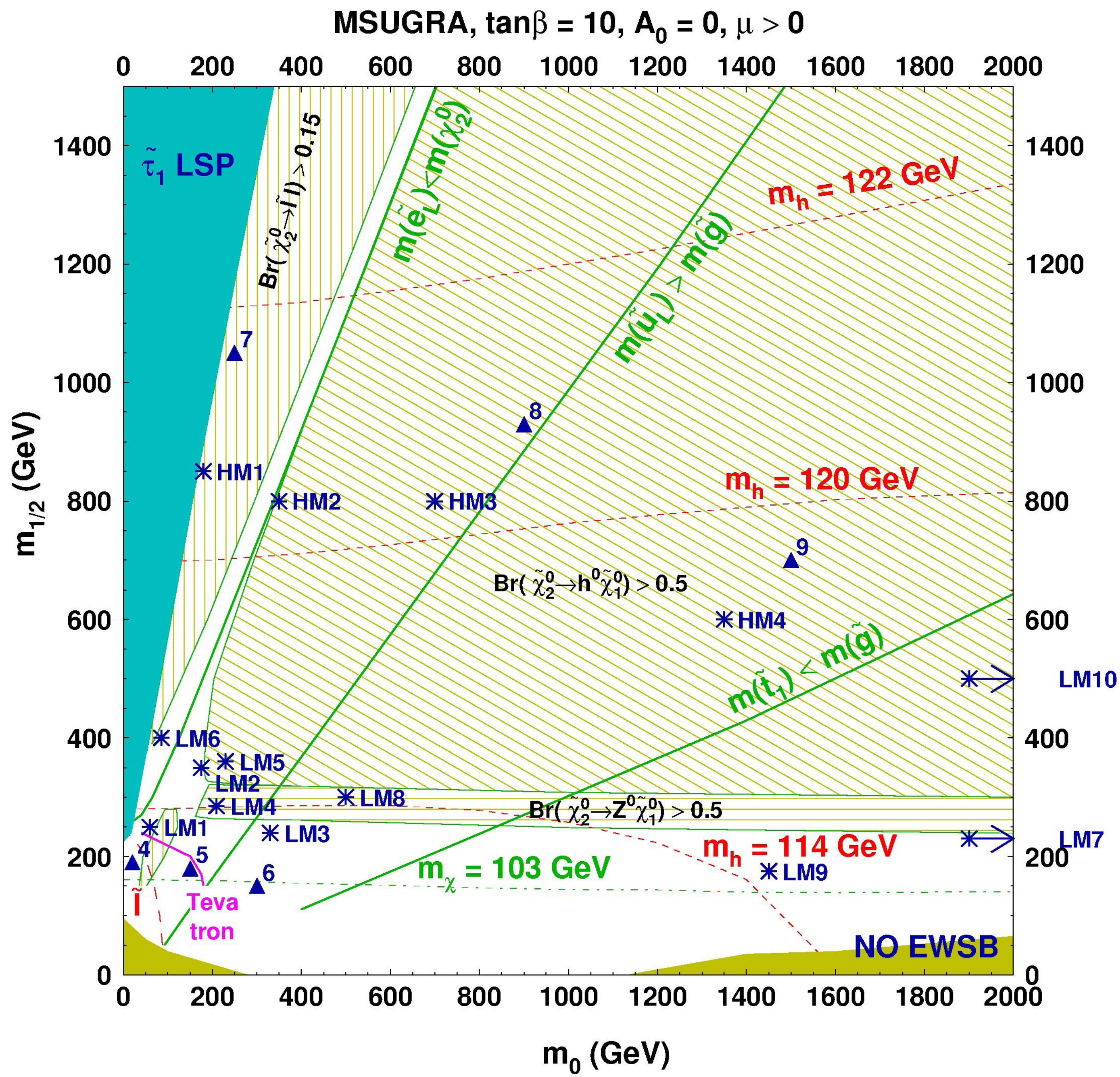


# Conclusions and Outlook

- Reconstructing MET is trivial, will be available on day one
- Workflows for most of the required or optional corrections at hand
- When will the entire chain be completed, and the ultimate resolution (?) be achieved? Probably 3 years after the LHC has been turned off
- When can MET be used for physics? Maybe sooner than one might imagine
  - First D0 Run II New Phenomena paper: GMSB (diphotons + MET)
  - Key: ability to measure all backgrounds from data
- Many refinements under development or in place, e.g.:
  - Track corrected MET (use tracks to replace charged particles)
  - Particle flow MET (optimally combine all CMS subdetectors for best resolution)
  - MET significance algorithm (optimally taking into account the uncertainties of all input objects)

# Backup



MSUGRA, tanβ = 10, A0 = 0, μ > 0
τ̃1 LSP
Br(χ̃02→l̃l) > 0.15
m(ẽL)<m(χ̃02)
m(ũL) > m(g̃)
mh = 122 GeV
mh = 120 GeV
mh = 114 GeV
Br( χ̃02→h0χ̃01) > 0.5
Br( χ̃02→Z0χ̃01) > 0.5
m(t̃1) < m(g̃)
mχ = 103 GeV
HM1
HM2
HM3
HM4
LM1
LM2
LM3
LM4
LM5
LM6
LM7
LM8
LM9
LM10
l̃
Teva tron
NO EWSB
m1/2 (GeV)
m0 (GeV)