Aspects of Missing Energy at the LHC

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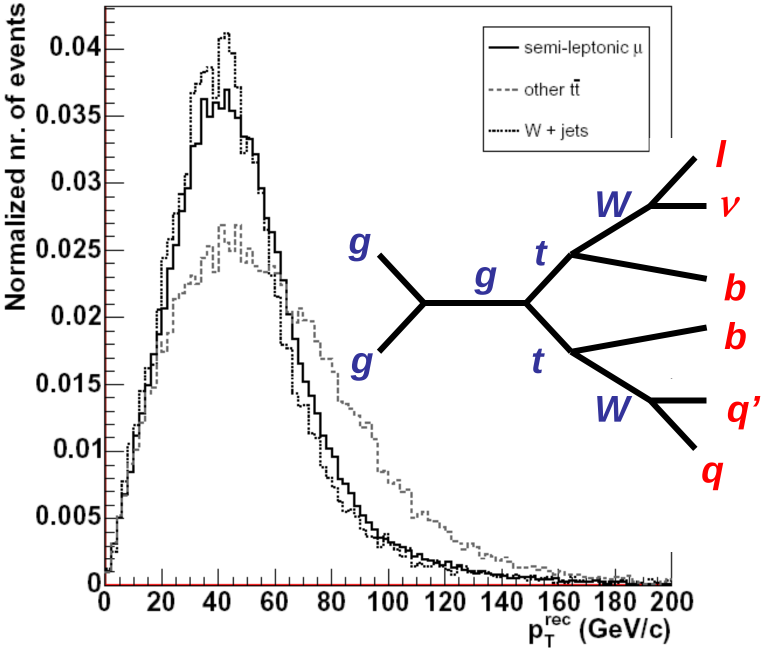
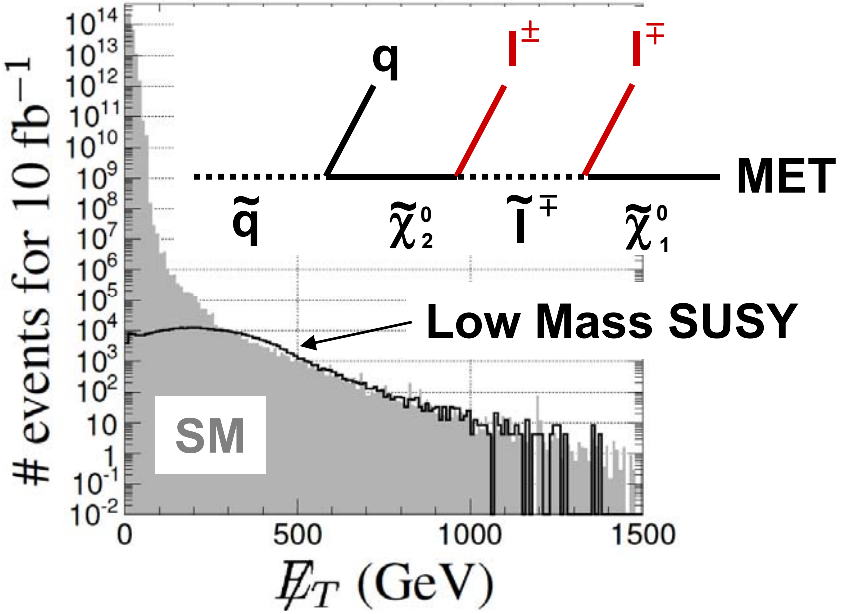
- Physics Motivation
- Traditional Calorimetric Methods
- Environmental Challenges at the LHC
- Outlook: Energy Flow Methods

LHC Early Phase for the ILC, Fermilab, 13 April 2007

Physics Motivation

- **“Small” Missing Energy**
  - **Standard Model Physics**
- **Experimental Challenge**
  - **Understanding QCD and other environmental bkgs.**
  - **good low-energy resolution**





- **“Large” Missing Energy**
  - **New Physics**
- **Experimental Challenge**
  - **Understanding Tails!**

Physics Motivation

- **H→ττ Mass Reconstruction**

Slide from B.Mellado

Assume tau decay products are collinear to tau direction

Fraction of τ momentum carried by visible τ decay

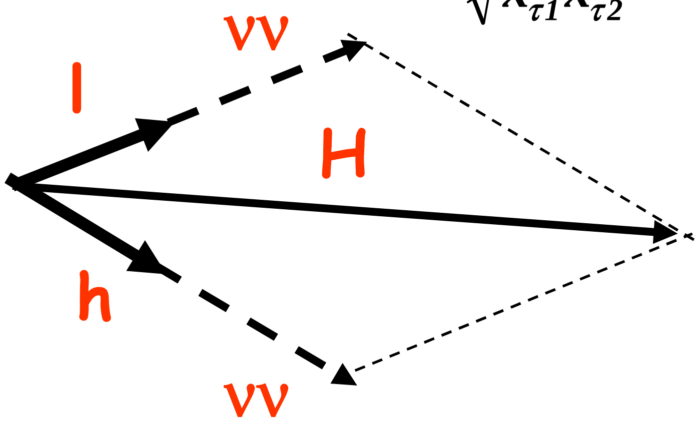
$$\vec{P}_\tau = \frac{\vec{P}_l}{x_\tau}$$

$$M_{\tau\tau} \approx \frac{M_{ll}}{\sqrt{x_{\tau 1} x_{\tau 2}}}$$

$$\vec{P}_{T\tau 1} + \vec{P}_{T\tau 2} = \vec{P}_{Tl1} + \vec{P}_{Tl2} + \vec{P}_{Tmiss}$$

$$x_{\tau_1} = \frac{p_{T_{lep1},x} \cdot p_{T_{lep2},y} - p_{T_{lep1},y} \cdot p_{T_{lep2},x}}{p_{T_{Higgs},x} \cdot p_{T_{lep2},y} - p_{T_{Higgs},y} \cdot p_{T_{lep2},x}}$$

$$x_{\tau_2} = \frac{p_{T_{lep1},x} \cdot p_{T_{lep2},y} - p_{T_{lep1},y} \cdot p_{T_{lep2},x}}{p_{T_{Higgs},y} \cdot p_{T_{lep1},x} - p_{T_{Higgs},x} \cdot p_{T_{lep1},y}}$$

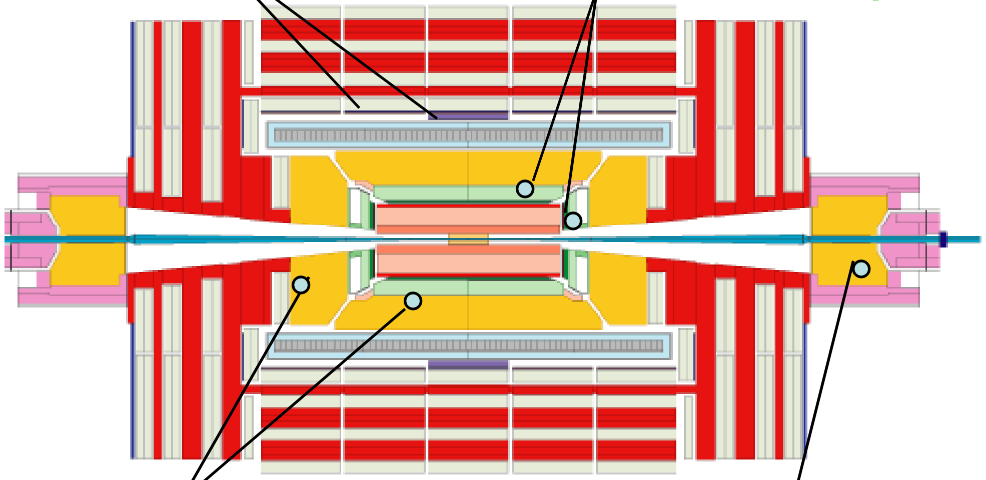


- $x_{\tau 1}$ and $x_{\tau 2}$ can be calculated if the Missing E_T is known
- Good Missing E_T reconstruction (response & resolution) essential

Missing Transverse Energy

- **Definition**
  - $\mathbf{E}_{\mathrm{T}}^{\mathrm{miss}} = \Sigma(E_n \sin\theta_n \cos\phi_n \hat{\mathbf{i}} + E_n \sin\theta_n \sin\phi_n \hat{\mathbf{j}}) = E_x^{\mathrm{miss}} \hat{\mathbf{i}} + E_y^{\mathrm{miss}} \hat{\mathbf{j}}$
- **Traditional Approach**
  - **Sum over Calibrated Calorimeter Objects**
  - **Apply Corrections *a posteriori***
- **MET Resolution** $\frac{\sigma}{\mathrm{E}} = \frac{A}{\sqrt{E}} \oplus \frac{B}{E} \oplus C$ (E = “Scalar Sum ET”)
  - **A = “Stochastic” Term; B = “Noise” Term; C = “Constant” Term**
- **Important considerations**
  - **A: Good Hermitic coverage, Energy Resolution**
  - **A: Compensating Calorimeter Response**
  - **B: Electronic Noise**
  - **B: Pile-up and Underlying event**
  - **B: High Magnetic Field (sweeps out low pt particles)**
  - **C: Energy loss due to inactive material and punch through**
  - **C: Other residual non-linearities**

The CMS Calorimeters



EM calorimeter $|\eta| < 3$:

PbW0$_4$ crystals

(forward)

1 longitudinal section/preshower 1.1 λ

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

Central Hadronic $|\eta| < 1.7$:

Brass/scintillator

2 + 1 Hadronic Outer – long. sections

5.9 + 3.9 λ ($|\eta| = 0$)

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

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

Brass/scintillator +WLS

2/3 longitudinal sections 10λ

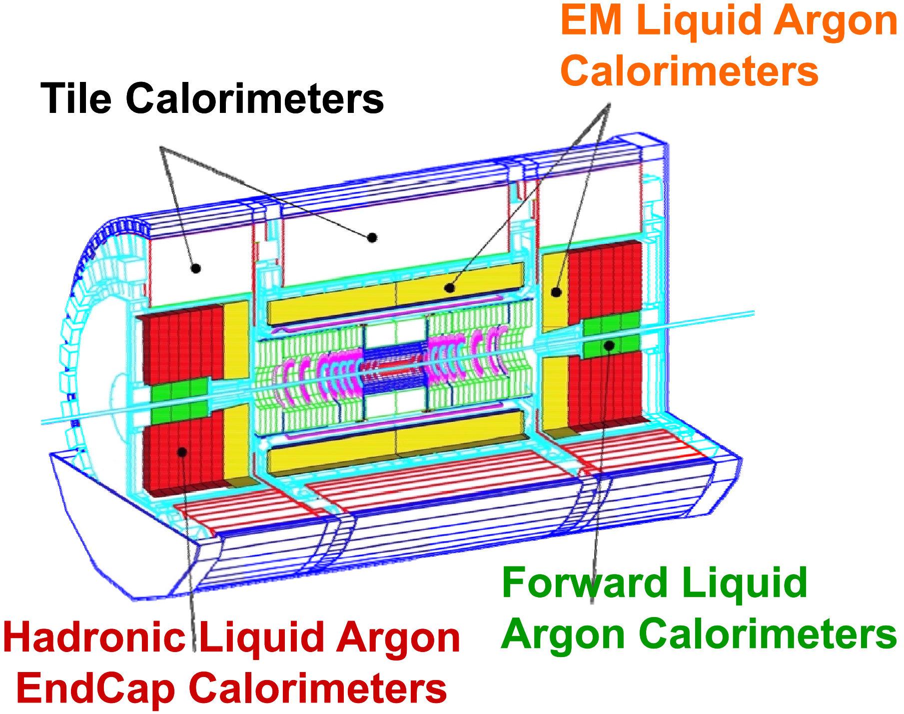
$\Delta\eta\times\Delta\varphi = \sim 0.15 \times 0.17$

Forward calorimeter $2.9 < \eta < 5$:

Fe/quartz fibers $\Delta\eta\times\Delta\varphi = \sim 0.175 \times 0.17$

Long fibers collect light from the entire length of the calorimeter,
sensitive to both EM & hadronic components
Short fibers begin further inside calorimeter,
sensitive to hadronic component

The ATLAS calorimeters



EM accordion $|\eta| < 3.2$:

Pb/LAr 3 longitudinal sections 1.2 λ
+ preshower

$\Delta\eta\times\Delta\varphi = 0.025 \times 0.025$ and higher

Central Hadronic $|\eta| < 1.7$:

Fe / scintillator

3 longitudinal sections 7.2 λ

$\Delta\eta\times\Delta\varphi = 0.1 \times 0.1$ and higher

Forward calorimeter $3.1 < \eta < 4.9$:

EM Cu/LAr – HAD W/Lar

3 longitudinal sections – 9 λ

$\Delta\eta\times\Delta\varphi = 0.2 \times 0.2$

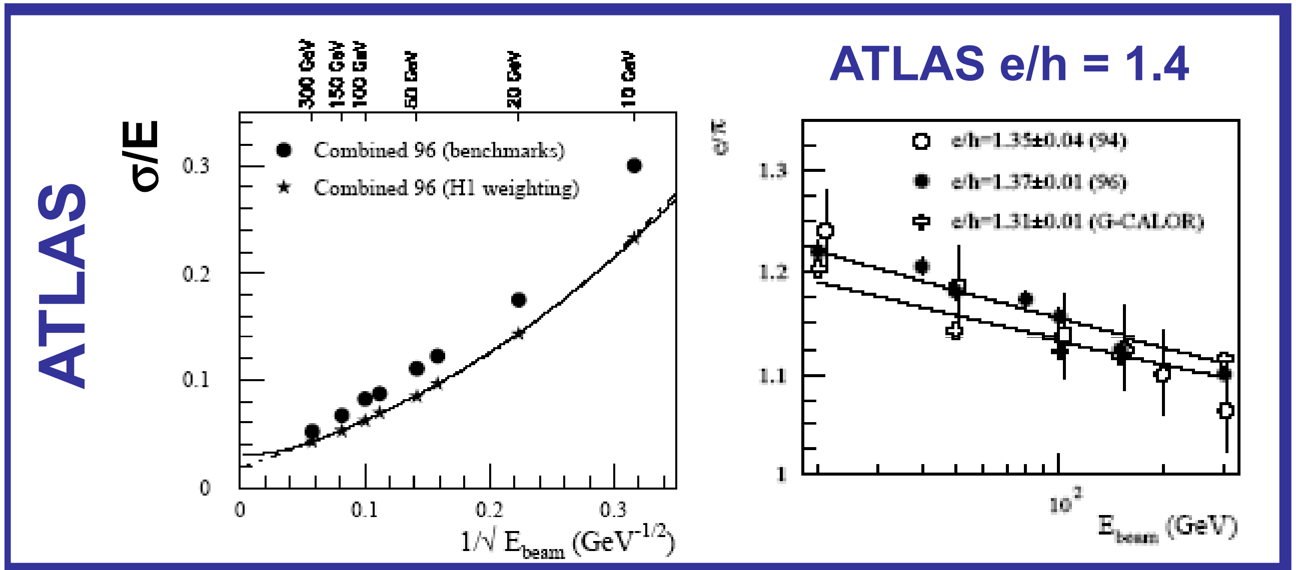
End Cap Hadronic $1.5 < \eta < 3.2$
Cu/LAr – 12 λ

4 longitudinal sections

$\Delta\eta\times\Delta\varphi < 0.2 \times 0.2$

Calorimeter Calibration & Performance

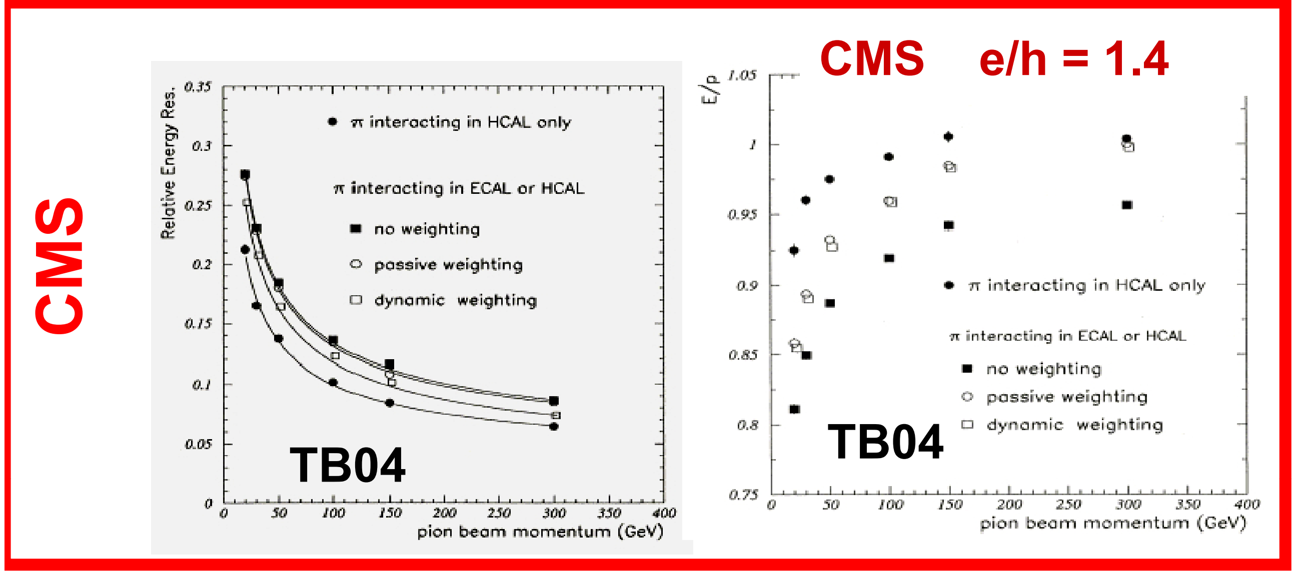
ATLAS



ATLAS e/h = 1.4

$$\frac{\sigma}{\mathrm{E}} \approx \frac{42\%}{\sqrt{E}} \oplus 2\%$$

CMS



CMS e/h = 1.4

TB04

TB04

Both calorimeter systems reach the design performances after calibrating for non-compensation (e/h)

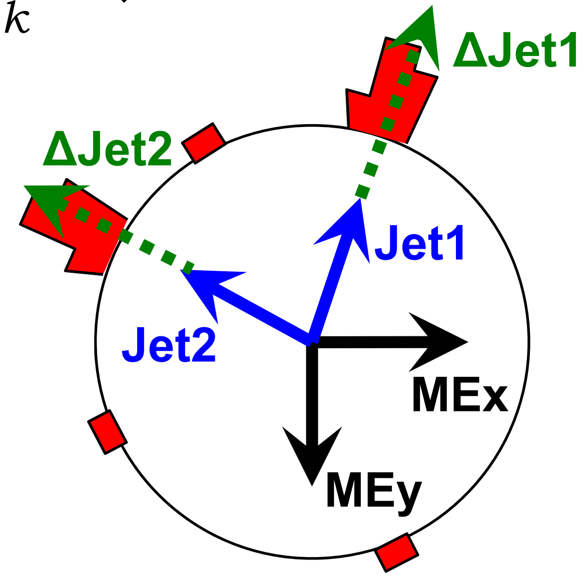
$$\frac{\sigma}{\mathrm{E}} \approx \frac{90\%}{\sqrt{E}} \oplus 7\%$$

Latest from **TB06**
(additonal improvements being studied)

A posteriori Corrections to MET

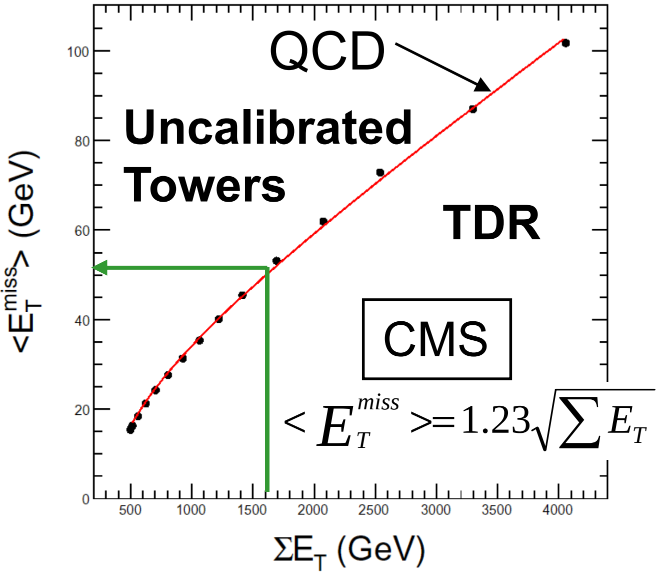
- Correct for Jet Energy Scale and (optionally) muons:

$$\mathbf{E}_{\mathbf{T}}^{\mathbf{miss}} = -\sum_i \mathbf{E}_{\mathbf{T},i}^{\mathbf{tower}} - \sum_j \left(\mathbf{p}_{\mathbf{T},j}^{\mathbf{corr},jet} - \mathbf{p}_{\mathbf{T},j}^{\mathbf{raw},jet}\right) - \sum_k \mathbf{p}_{\mathbf{T},k}^{\mu}$$

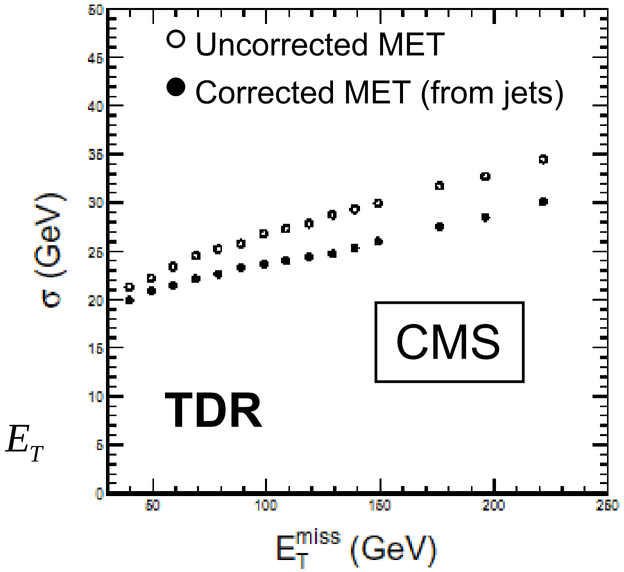


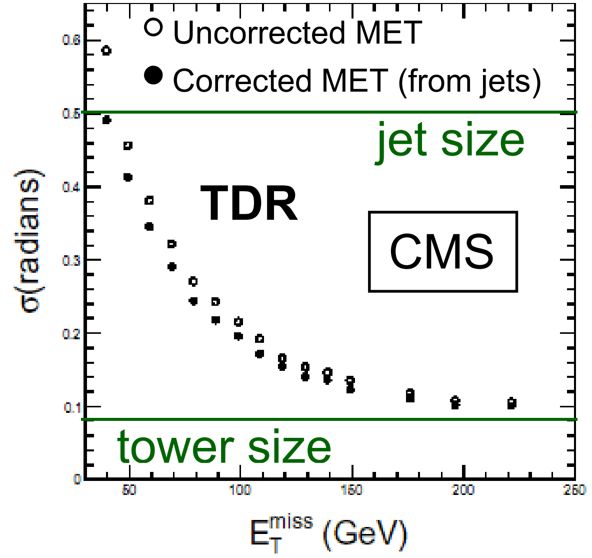
- Raw MET calculation based on sum over calibrated cells or towers
- Clustered (Jets) and Unclustered Energy Calibrations
  - Type-1 (most commonly used)
    - Calibrated Jets + Unclustered Towers
    - Jet Energy Scale
  - Type-2
    - Calibrated Jets + Calibrated Unclustered Towers
    - Include Pile-up and Underlying Event

CMS MET Resolution from QCD



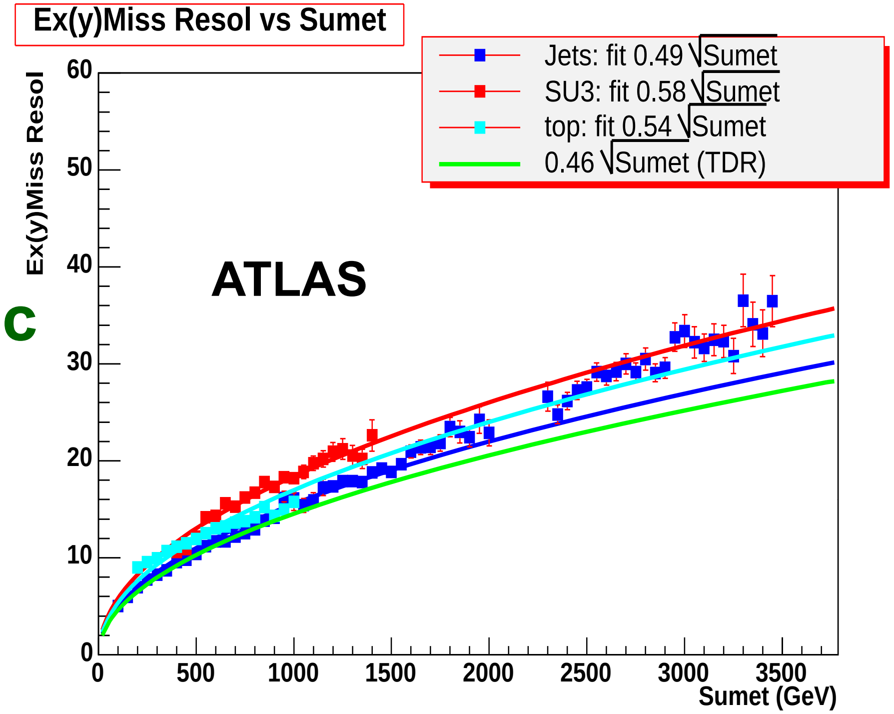
$$< E_T^{miss} > = 1.23\sqrt{\sum E_T} + 5.4 + 0.019\sum E_T$$





- **Missing Transverse Energy**
  - **Low luminosity Pileup included**
  - **<MET> from QCD**
    - **Stochastic term ≈ 123%$\sqrt{\Sigma E_T}$**
    - **≈1700 GeV ΣE_T →**
      ≈700 GeV P_T dijets →
      ≈50 GeV observed MET
  - **MET φ Resolution**
    - **Low MET : approaches Jet size**
    - **High MET : approaches calo cell size**

ATLAS MET Resolution



- **Resolution**
  - **Low SumET**
    - **Noise & Stochastic Terms dominate**
  - **High SumET**
    - **Constant Term dominates**
- **Performance depends on event content**
  - **Different resolution for different objects**
    - **e/γ, charged hadrons, neutral hadrons**
  - **non-linearity, non-uniformity, etc**

Use of Tracks in Reconstruction

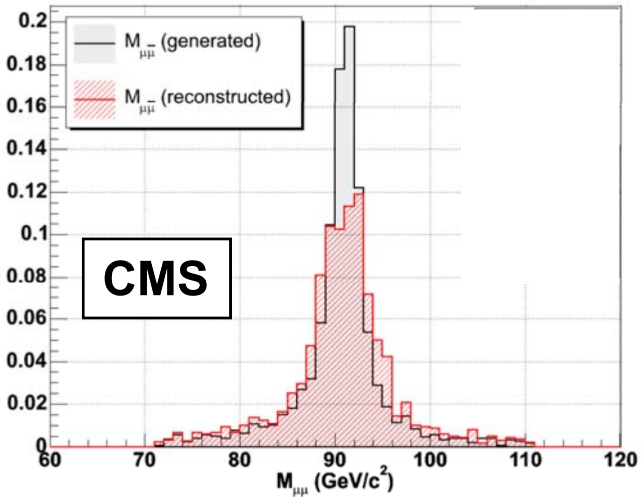
Slide adapted from C. Roda

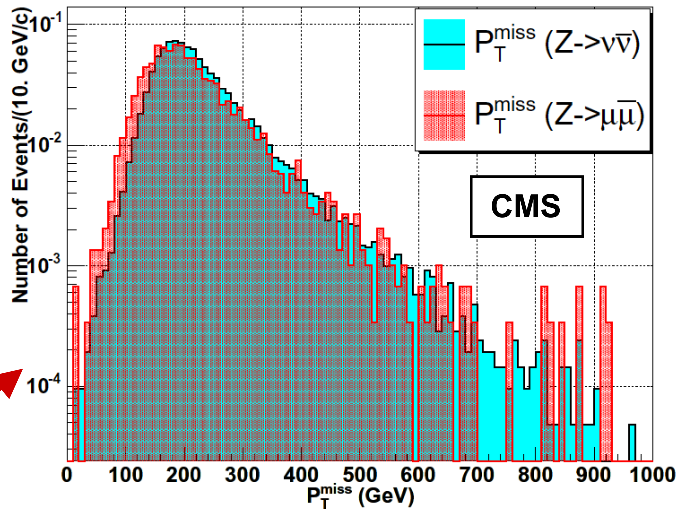
	ATLAS	**CMS**
Ecal+Hcal pion resolution	$\frac{\sigma}{E} = \left(\frac{41.9\%}{\sqrt{E}} + 1.8\%\right) \oplus \frac{1.8}{E}$	$\frac{\sigma}{E} = \frac{90\%}{\sqrt{E}} \oplus 7\%$ *e/h calibrated*
MET resolution (TDR)	$\sigma(\not{E}_T)/\Sigma E_T \approx 53\%/\sqrt{\Sigma E_T}$ *e/h calibrated*	$\sigma(\not{E}_T)/\Sigma E_T \approx 120\%/\sqrt{\Sigma E_T} + 2\%$ *e/h* ***un****calibrated*
Inner tracker resolution (TDR)	$\sigma(p_T)/p_T = 1.8\% + 60\%\ p_T$ (p_T in TeV)	$\sigma(p_T)/p_T = 0.5\% + 15\%\ p_T$ (p_T in TeV)
B field inner region	2 Tesla : p_T swept < 350 MeV	4 Tesla : p_T swept < 700 MeV

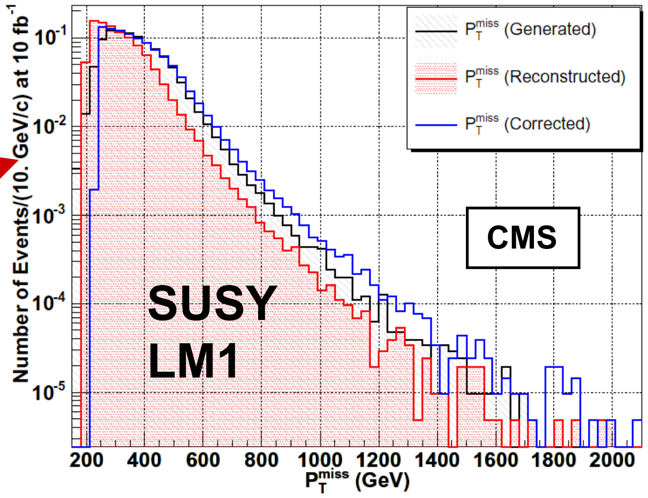
Significant improvement in CMS MET resolution expected by using calibrated calorimeter towers (e/h) and inner detector (tracks)...

...work in progress!

Use Track and Muon System to Calibrate Calorimeter (MET)



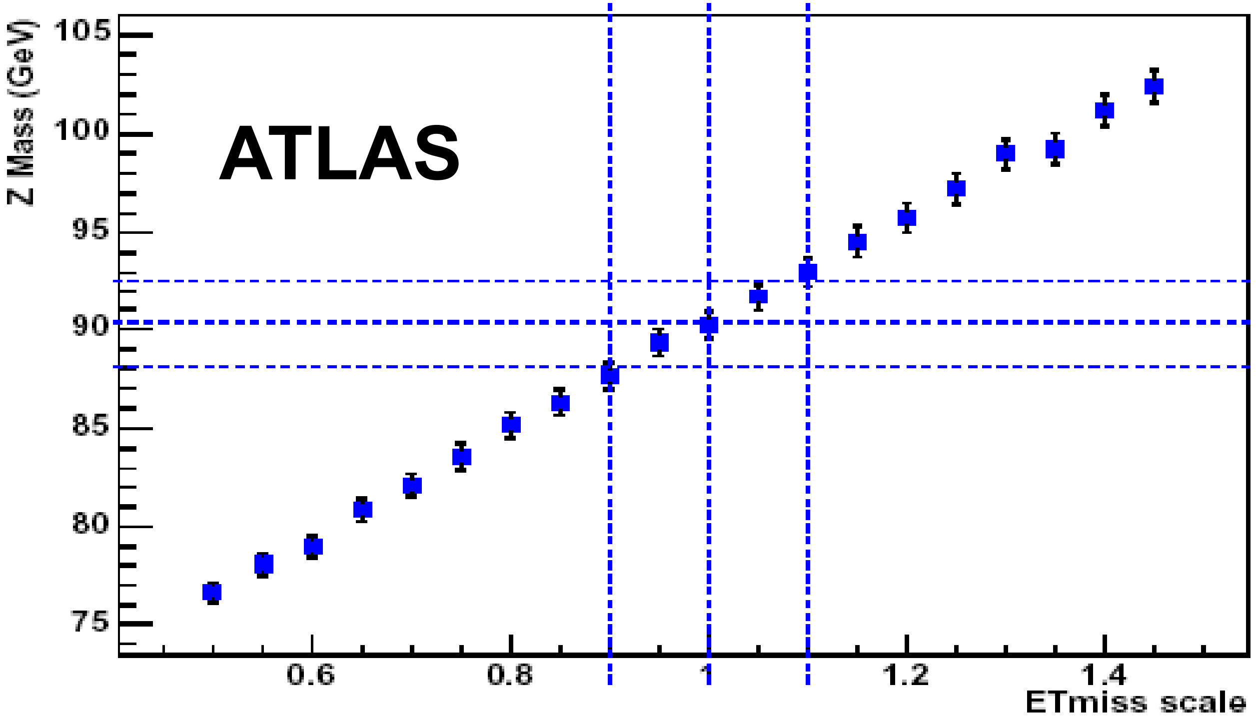




- Use $Z\rightarrow\mu\mu$ Candle
  - Derive calorimeter MET corrections from di-muon system
  - Apply to SUSY Sample (to test)
- Some fine tuning required
  - But basically works

Calibrate MET using Z → ττ

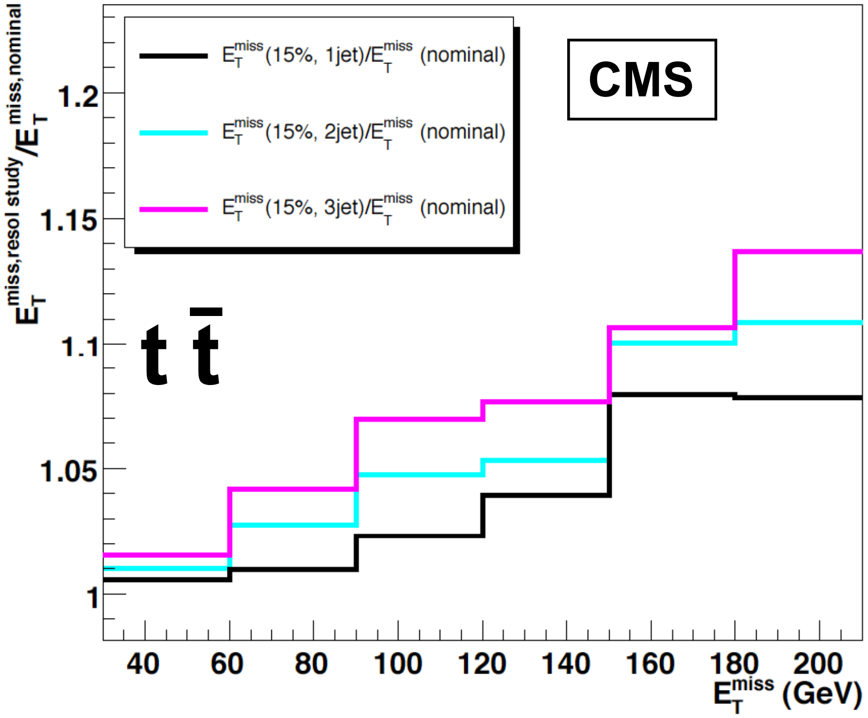
- Z mass from Z → ττ → *lept-had* events
- Z mass measured to 3% will result in an error of 10% on Missing ET



- ⇒ Plotted errors correspond to ~ 1000 evts
- ⇒ Signal only, background not added

MET Shape Systematics in CMS

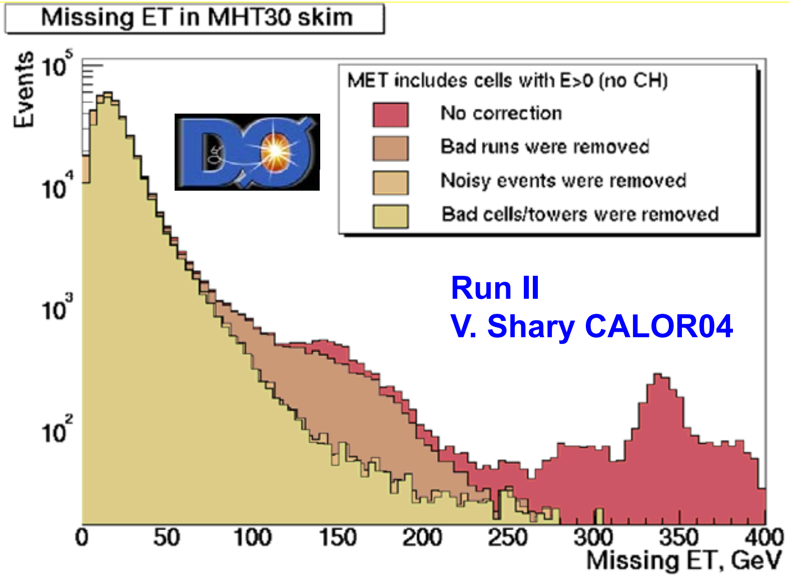
- Study effect of non-Gaussian tails in jet E_T resolution contributing to fake MET
  - ~ 15% of all jet are badly under measured
- Exaggerate non-Gaussian Tails
  - Weight each jet (up to 3) in the tails
- Three different scenarios
  - 3 jets under measured
  - 2 jets under measured
  - 1 jet under measured



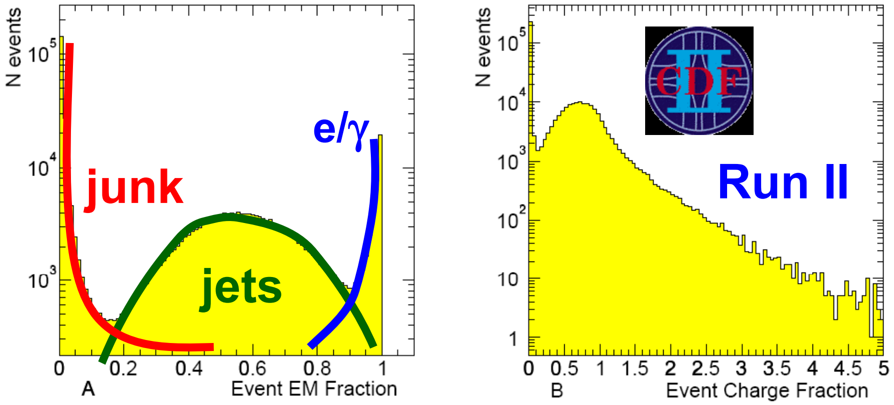
- Overall Effect :
  - ~ 7% increase in background acceptance for MET > 100 GeV

Environmental Challenges

- **MET is very powerful discriminator for New Physics**
  - **Difficult part is to convince yourself that there is a real excess!**
- **Tevatron teaches us**
  - **MET is not easily understood!**
- **Collisional backgrounds**
  - **Pile-up**
  - **Underlying Event**
- **Non-collisional backgrounds**
  - **Beam halo**
  - **Cosmic muons**
- **Detector Effects**
  - **Instrumental Noise**
  - **Hot/dead channels (DQM)**
  - **Inter-module calibration**


Missing ET in MHT30 skim

Run II
V. Shary CALOR04



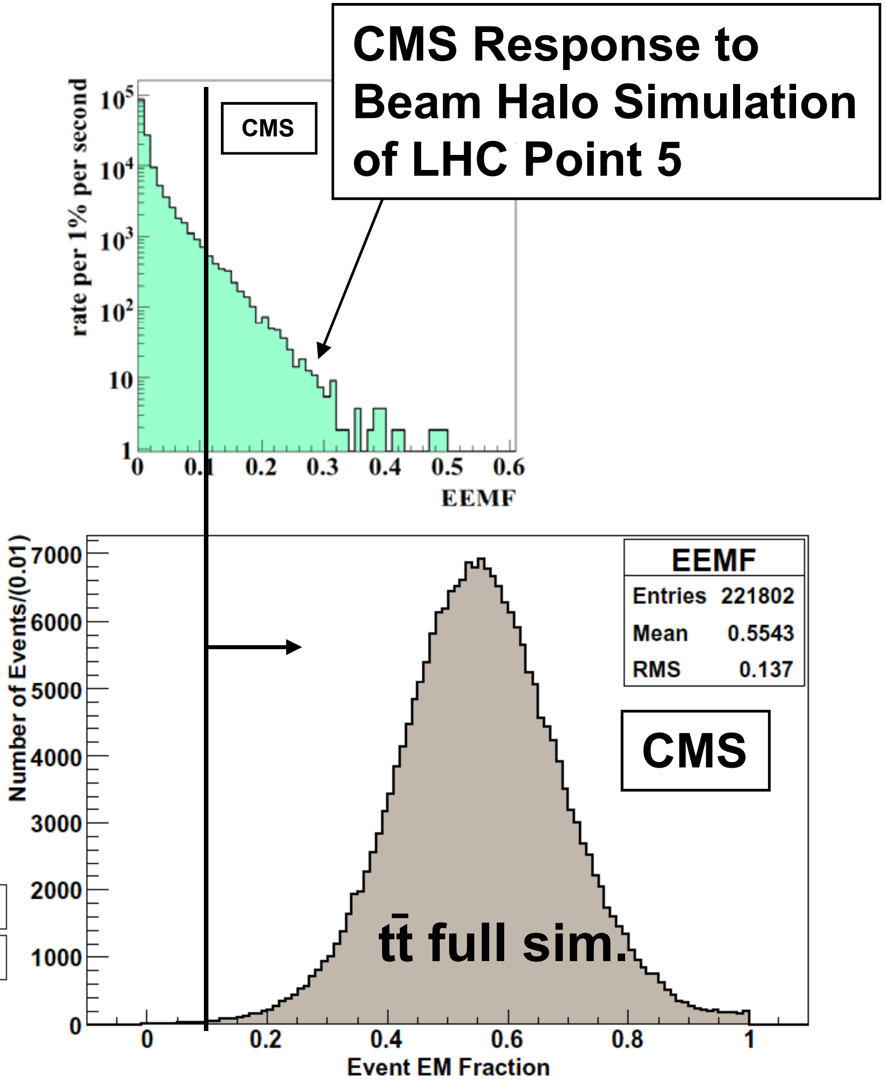
D. Tsybychev, Fermilab-thesis-2004-58

Early Study of MET Cleaning in CMS

(of course, Real Data will be different!)

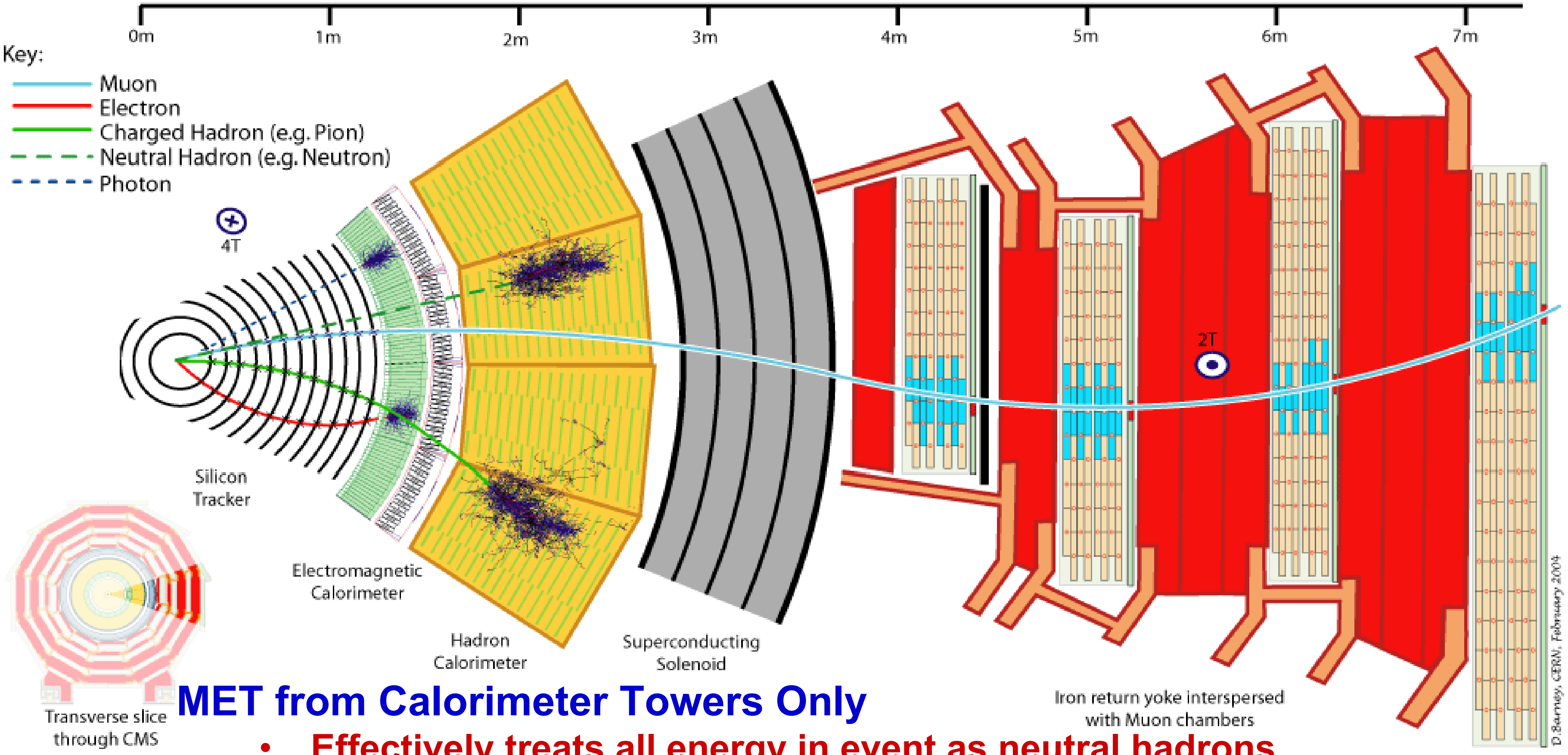
- **Apply clean up cuts to remove fake high MET events (inspired by CDF & D0)**
  - ≥ 1 central jet ($|\eta|<1.7$) with ≥ 4 tracks
  - ≥ 1 vertex
  - $F_{em} > 0.1$ (Event Electromagnetic Frac.)
  - $F_{ch} > 0.175$ (Event Charged Fraction)
- **Effect on SUSY Signal**

Sample/Requirement	$F_{em} > 0.1$	$F_{ch} > 0.175$	Both(%)
LM1	99.88%	91.32%	91.24%



CMS Response to Beam Halo Simulation of LHC Point 5

CMS Outlook: Energy Flow



MET from Calorimeter Towers Only

- **Effectively treats all energy in event as neutral hadrons**
- **Does not exploit richness of detector design, in particular tracker**

Reconstruct and identify all particles

- **γ, e, μ, charged hadrons, neutral hadrons, pileup particles, converted photons & nuclear interactions**
- **optimally estimate of E, angle, particle ID by combining all CMS detectors**

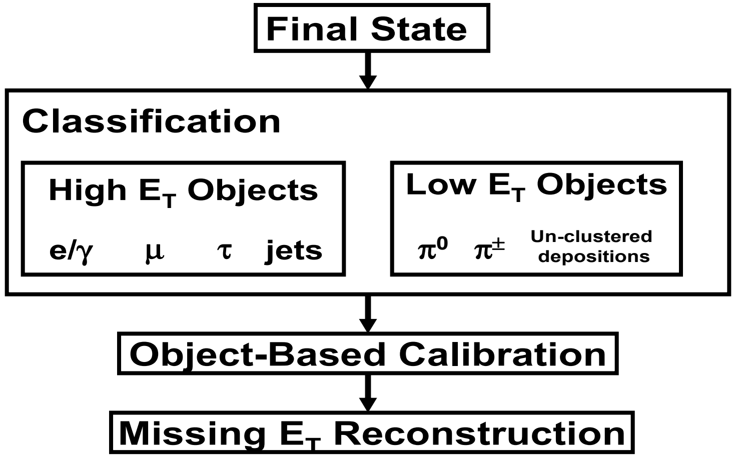
CMS Outlook: Energy Flow

- Motiviation: The energy of a typical jet consists roughly of
  - Charged particles : ~60%
    - Mostly charged pions, kaons and protons, but also some electrons and muons
  - Photons : ~25%
    - Mostly from π^0's, but also some genuine photons (brems,…)
  - Long-lived neutral hadrons : ~10%
    - K^0_L, neutrons
  - Short-lived neutral hadrons, "V^0's" : ~5%
    - $K^0_S \to \pi^+\pi^-$, $\Lambda \to \pi^- p$, …, but also γ conversions, and (more problematic) nuclear interactions in the detector material.
- Energy resolution determined (ideally) mostly by
  - the 10% neutral hadrons
  - inefficiencies in charged hadron reconstruction
- Attempt to use Full Detector/Event Information in MET reconstruction
  - Determine MET from calibrated, reconstructed particles

$$\mathbf{E}_{\mathbf{T}}^{\mathbf{miss}} = -\sum \mathbf{p}_{\mathbf{T}}(e^{\pm}, \mu^{\pm}, \pi^{\pm}, \gamma, N^{o}, V^{o}, etc)$$

Atlas Outlook: Object-based

- Similar in some ways to CMS Approach
  - but also uses higher level objects (τ, jets, etc)
- Use all reconstructed particles (calibrated)



Final State

Classification

High E_T Objects

e/γ μ τ jets

Low E_T Objects

π^0 $\pi^\pm$ Un-clustered depositions

Object-Based Calibration

Missing E_T Reconstruction

$$\mathbf{E}_{\mathbf{T}}^{\mathbf{miss}} = -\underbrace{\sum \mathbf{E}_{\mathbf{T}}(e, \gamma, \mu, \tau, \text{jet})}_{\text{High ET Objects}} - \underbrace{\sum \mathbf{E}_{\mathbf{T}}(\pi^+, \pi^o, \text{cells})}_{\text{Low ET Objects}}$$

MET at LHC Summary

- Important signature of new physics!
- Global Object – Very challenging to get “right”
  - Hadron Environment
  - New Detectors
  - New Energy Regime
  - Hard work to have MET ready for early LHC Physics!
- CMS and ATLAS
  - Well designed to exploit MET as an object for Physics
  - Simple, Robust Calorimeter Methods
  - Advanced Energy Flow Methods
- Special thanks to:
  - CMS: M. Spiropulu, T. Yetkin, B. Scurlock
  - ATLAS: N. Kanaya, D. Cavalli, C. Roda