Missing Energy and New Physics

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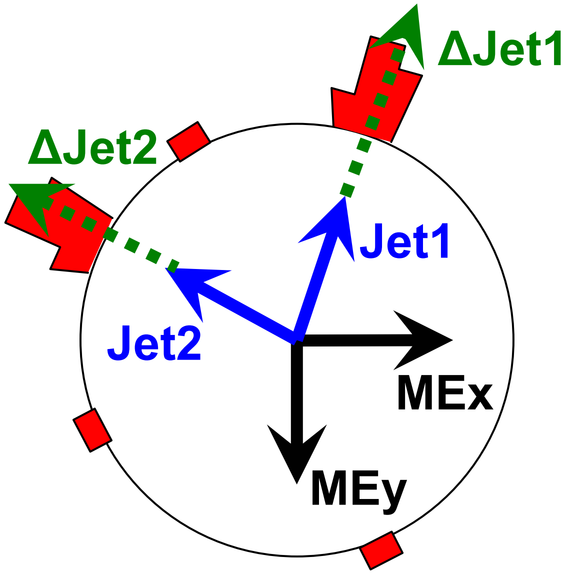
What is MET?

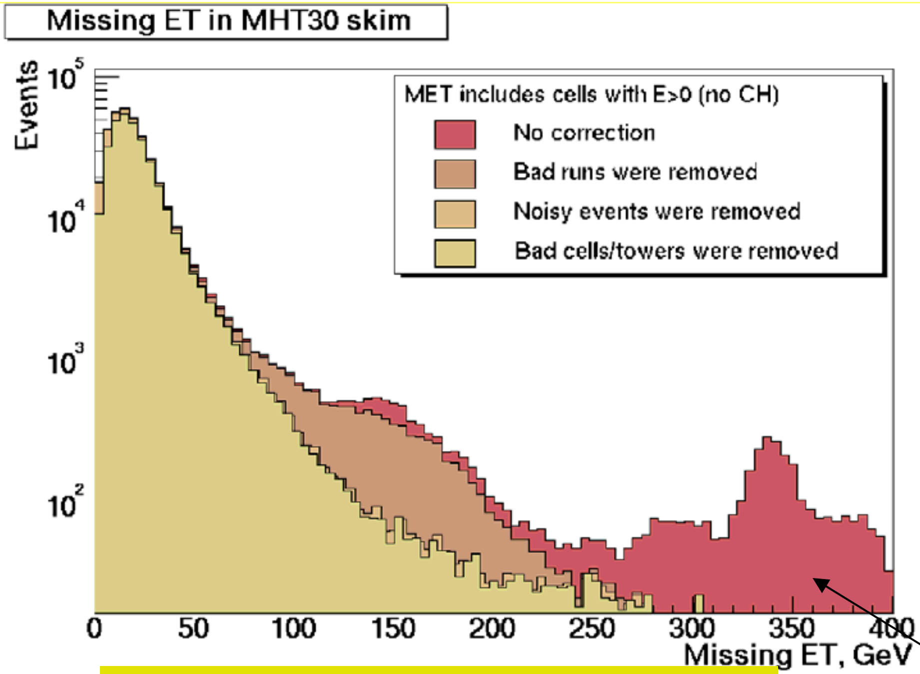
$$\mathbf{E}_{\mathrm{T}}^{\mathrm{miss}} = -\Sigma(E_n \sin\theta_n \cos\phi_n \hat{\mathbf{i}} + E_n \sin\theta_n \sin\phi_n \hat{\mathbf{j}})$$
$$= E_x^{\mathrm{miss}}\hat{\mathbf{i}} + E_y^{\mathrm{miss}}\hat{\mathbf{j}}$$



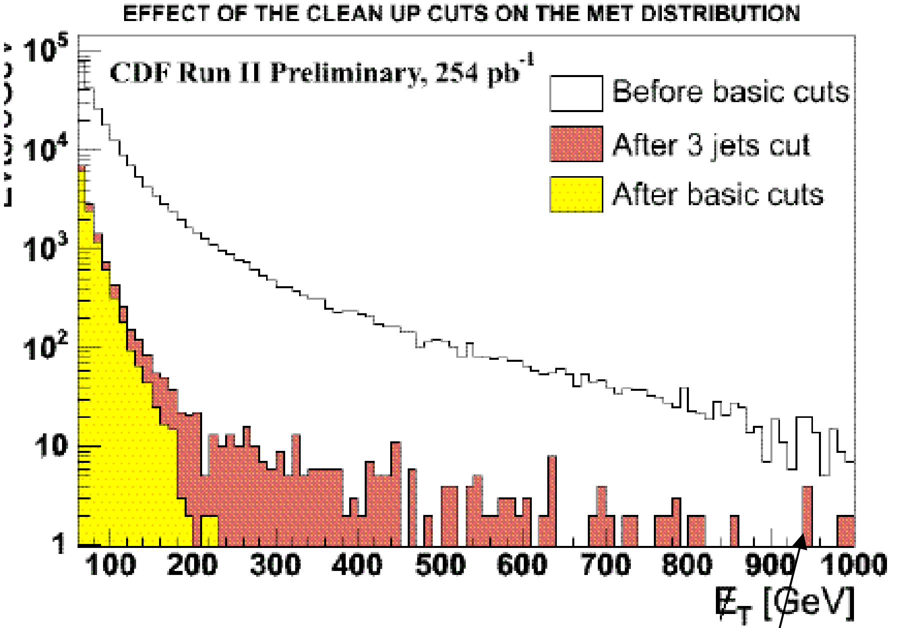
Different stages of MET

- L1 MET for triggering
- Corrected MET for analysis:
  - μ/e/τ correction
  - vertex corrections
  - hot/dead channels
  - jet energy corrections
  - ...and many more.

MET at Tevatron



MET, before corrections (D0)



MET, after corrections (CDF)

This is where new physics would sit

What physics with MET?

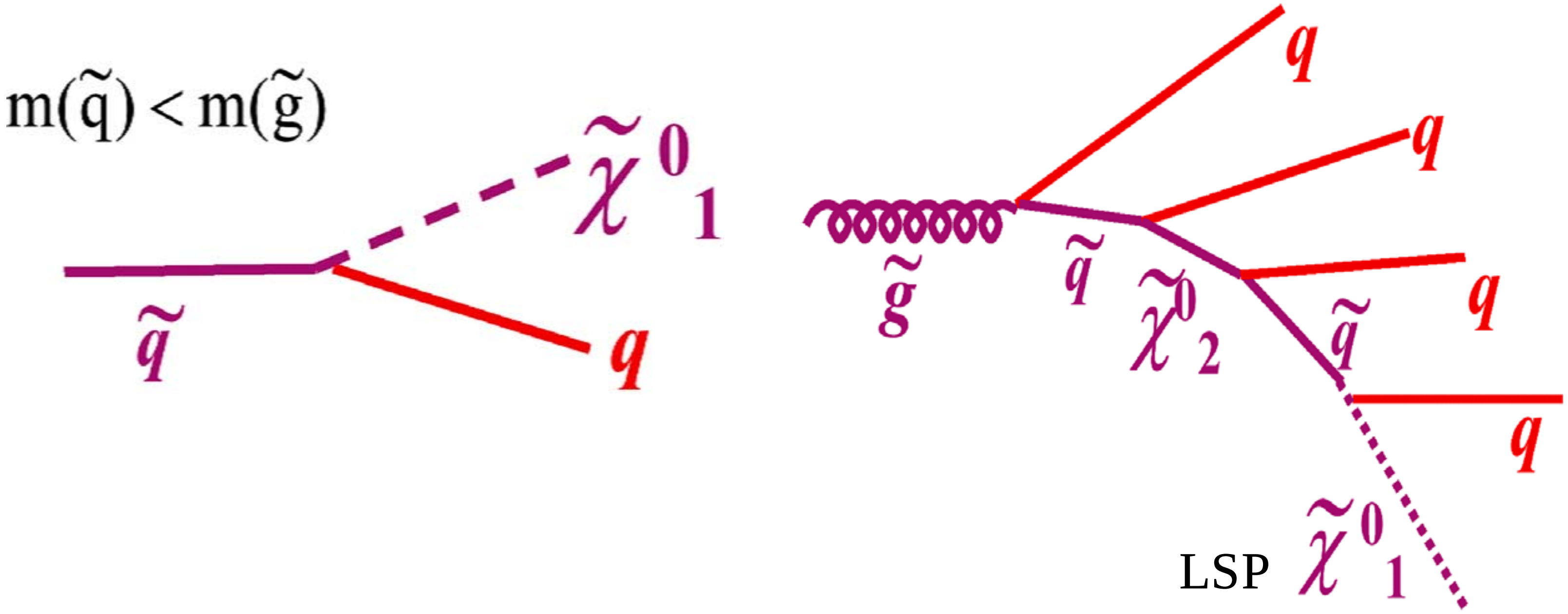
- Large MET (> 200 GeV)
  - Extra Dimension searches (monojet)
  - SUSY (gluino searches: jets+MET)
- Medium/Low MET (~ 50 - 100 GeV)
  - Top quark
  - Ditau
  - H→WW*
- Very Low MET (~ 20 GeV)
  - $W \rightarrow \ell \nu$

Physics with LARGE MET

Squark+gluinos with MET

If R-parity is conserved, LSP should give LARGE MET.

CMS Study: >= 3 jets with large MET (>200 GeV)
squark = 550 GeV, gluino = 600 GeV.



Squark + gluinos (CMS)

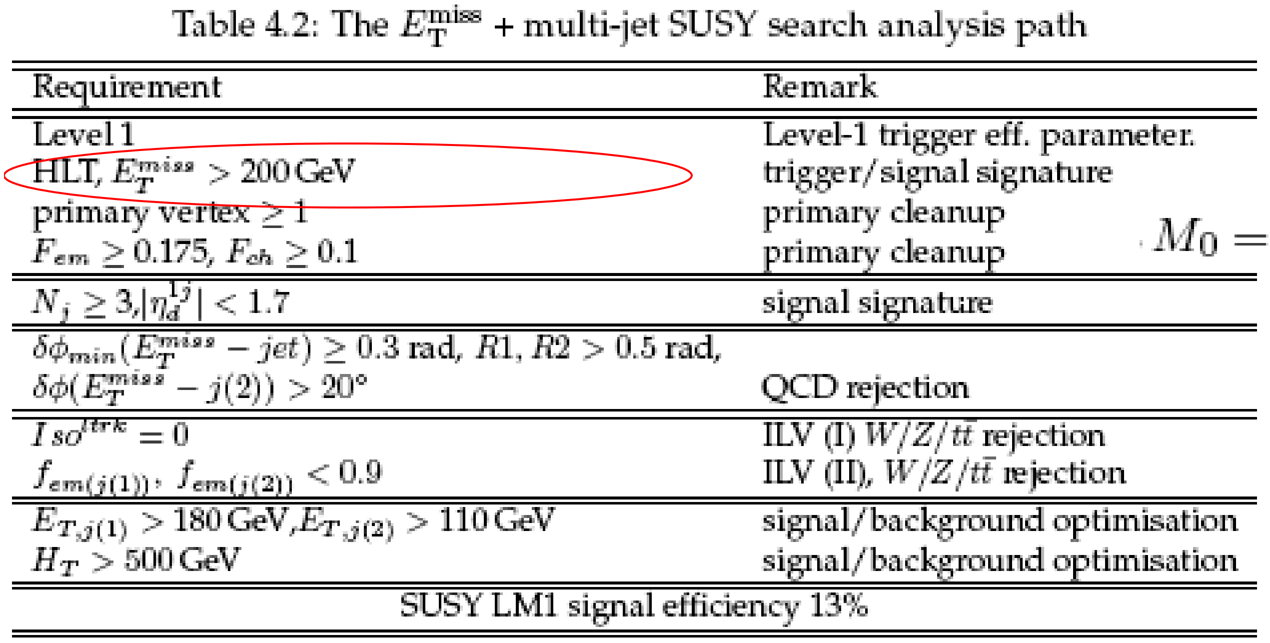


Table 4.2: The $E_T^{\rm miss}$ + multi-jet SUSY search analysis path

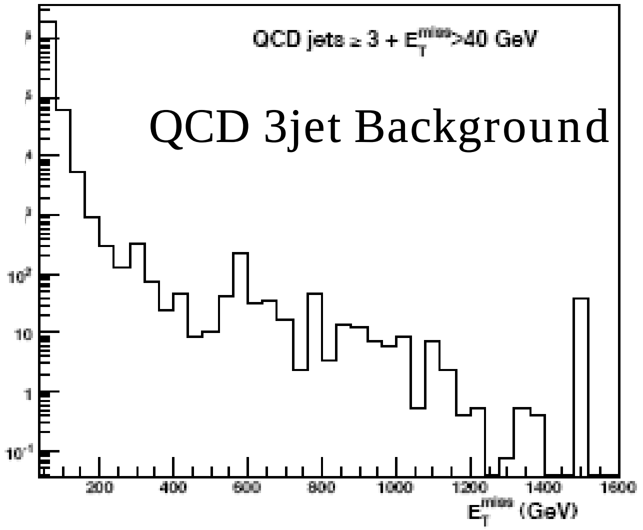
Requirement	Remark
Level 1	Level-1 trigger eff. parameter.
HLT, $E_T^{miss} > 200\,\mathrm{GeV}$	trigger/signal signature
primary vertex ≥ 1	primary cleanup
$F_{em} \geq 0.175$, $F_{ch} \geq 0.1$	primary cleanup
$N_j \geq 3, \lvert\eta_d^{1j}\rvert < 1.7$	signal signature
$\delta\phi_{min}(E_T^{miss} - jet) \geq 0.3$ rad, $R1, R2 > 0.5$ rad,	
$\delta\phi(E_T^{miss} - j(2)) > 20°$	QCD rejection
$Iso^{ltrk} = 0$	ILV (I) $W/Z/t\bar{t}$ rejection
$f_{em(j(1))}, f_{em(j(2))} < 0.9$	ILV (II), $W/Z/t\bar{t}$ rejection
$E_{T,j(1)} > 180\,\mathrm{GeV}, E_{T,j(2)} > 110\,\mathrm{GeV}$	signal/background optimisation
$H_T > 500\,\mathrm{GeV}$	signal/background optimisation
SUSY LM1 signal efficiency 13%	

LM1 Test Point
m(gluino)=600 GeV
m(squark)=550 GeV

$\tilde{g}\tilde{q}$ is 53%, $\tilde{q}\tilde{q}$ 28% and $\tilde{g}\tilde{g}$ 12%.

$$M_0 = 60\,\mathrm{GeV/c^2},\ M_{1/2} = 250\,\mathrm{GeV/c^2}$$

$$A_0 = 0,\ \mu > 0 \text{ and } \tan\beta = 10$$



QCD 3jet Background

Squark gluino reach.

ϕ (jet2) – ϕ (MET)

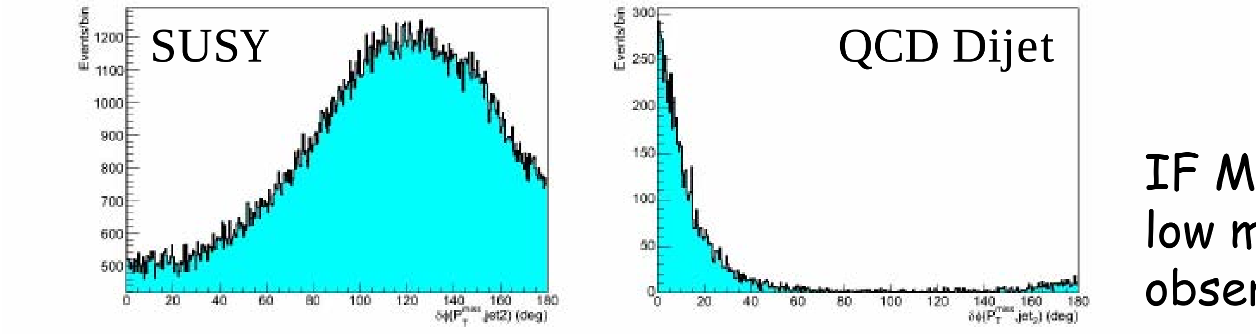
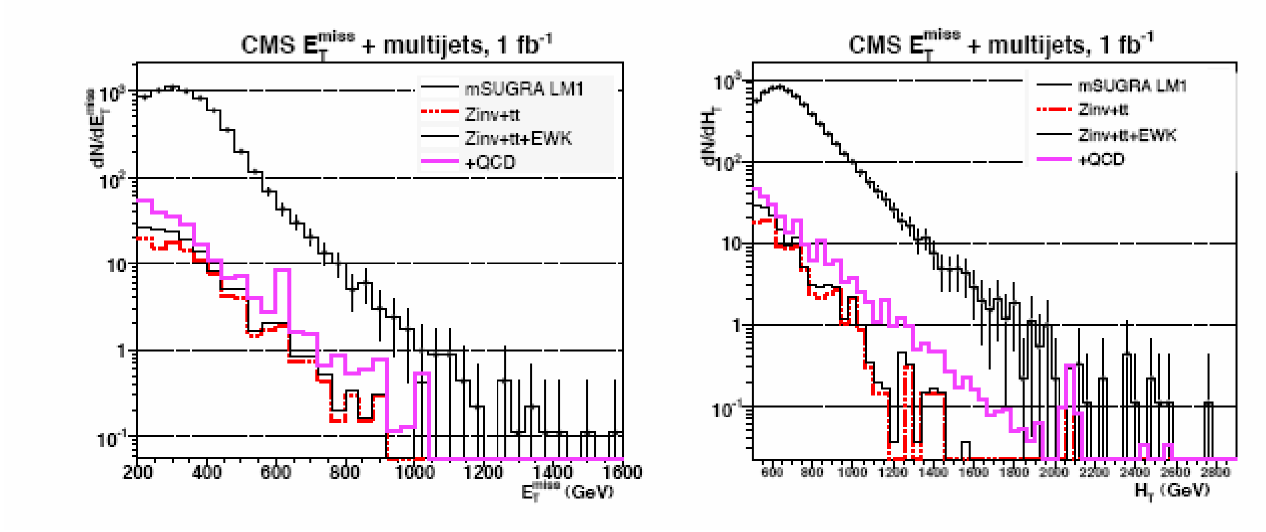


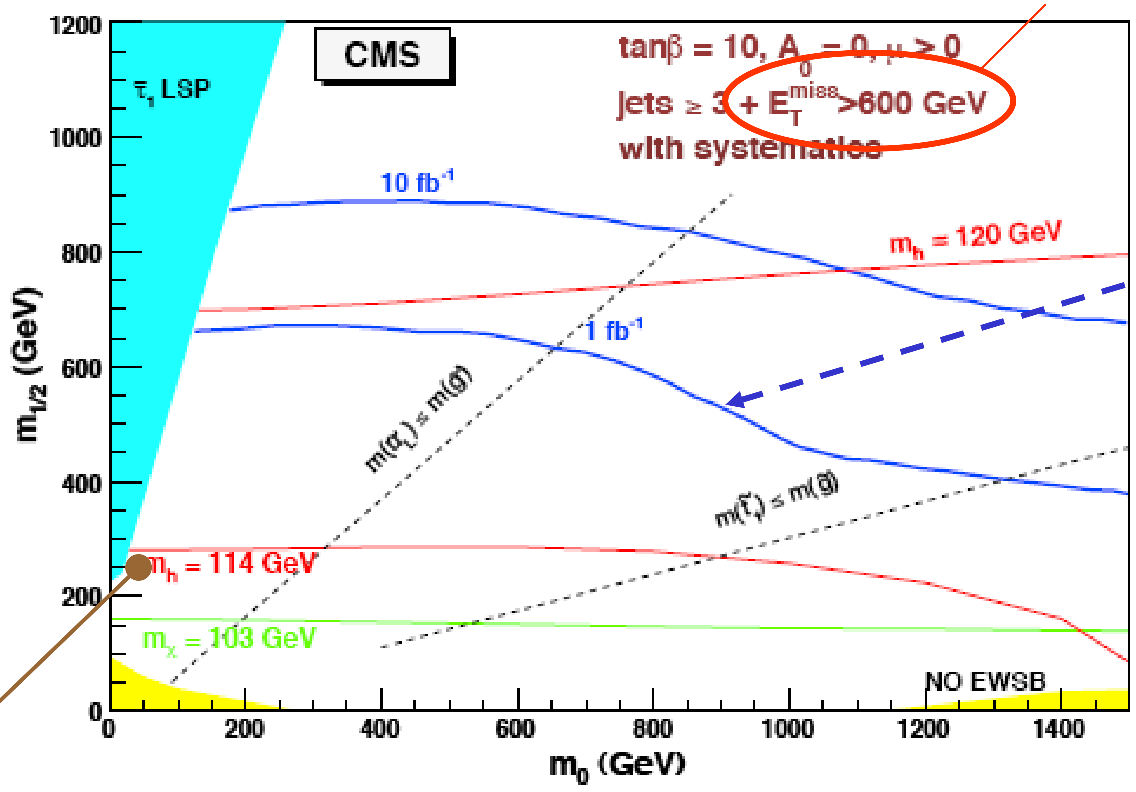
Figure 4.11: $\delta\phi_2 = |\phi_{j(2)} - \phi(E_T^{miss})|$ for (left) SUSY signal and (right) QCD dijet events

IF MET behaves, 5σ obs of low mass SUSY (Test point LM1) observable with 6pb-1.



SUSY reach

Different cut, higher MET



Effective coverage of most low-mass SUSY space.

IF R-parity is conserved…

LM1 Test Point

Extra Dimensions (ADD)

Large Extra Dimensions (ADD) Model

("ADD" => N. Arkani-Hamed, S. Dimopoulos, and G.Dvali)

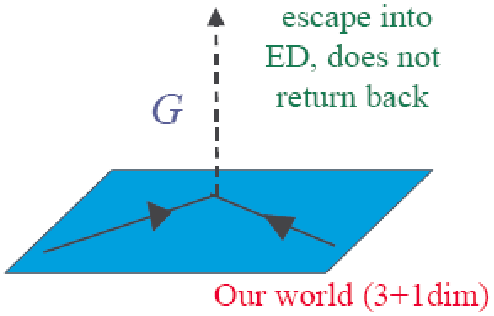
- $M_{Pl}^{2} \sim R_c^n M_D^{2+n}$
  - M_{Pl}: Planck scale
  - R_c : radius of ED
  - M_D: new effective fundamental scale
  - n : # extra dimensions

- Large extra dimension : R~1mm for n=2, $M_D \sim$ 1TeV
- Kaluza-Klein states of Graviton is dense and evenly spaced
  - Mass spectrum appear continuous
  - Interfere with SM scattering amplitude

- **Direct G emission :**

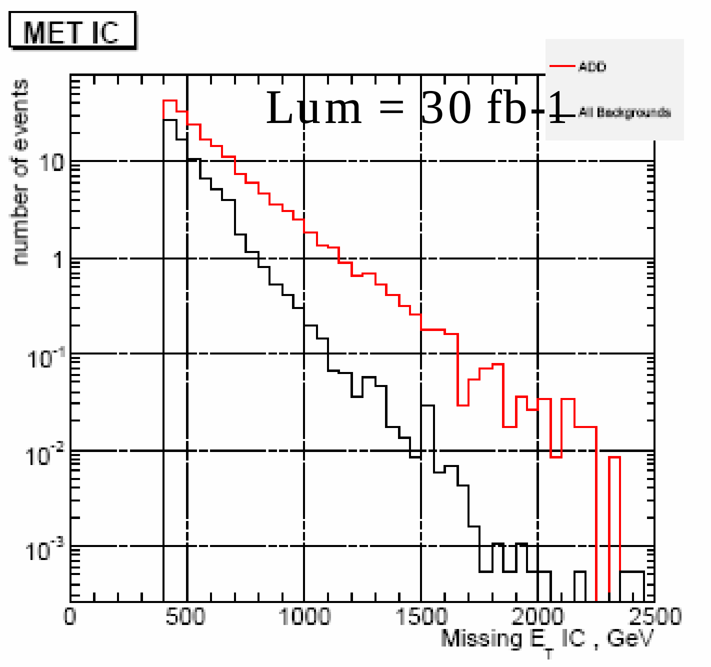
$$\left.\begin{array}{lcl} q\,\bar{q} & \rightarrow & \gamma G \end{array}\right\} \text{Photon +MET}$$

$$\left.\begin{array}{lcl} q\,\bar{q} & \rightarrow & Gg \\ qg & \rightarrow & Gq \\ gg & \rightarrow & Gg \end{array}\right\} \text{jet+ MET}$$



LED: Photon + MET

- Photon pt > 400 GeV
- MET > 400 GeV
- Δphi(photon, MET) > 2.5
- No tracks > 40 GeV

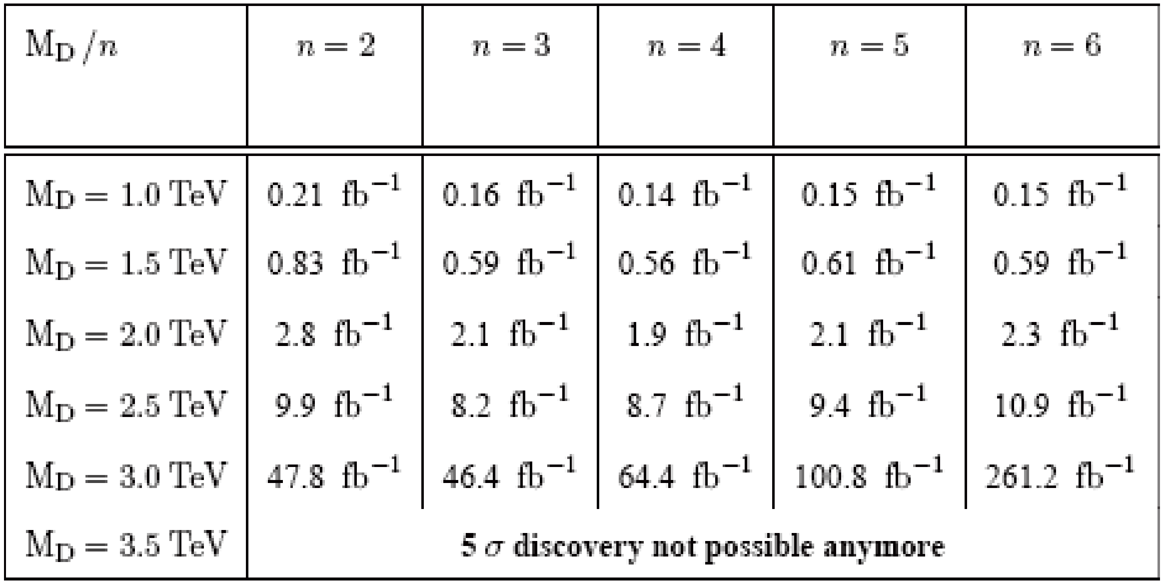


Lum = 30 fb-1

Md = 2.5 TeV
n=2

LED Reach Photon+MET

M_D: Fundamental Plank mass;   n = # ED.

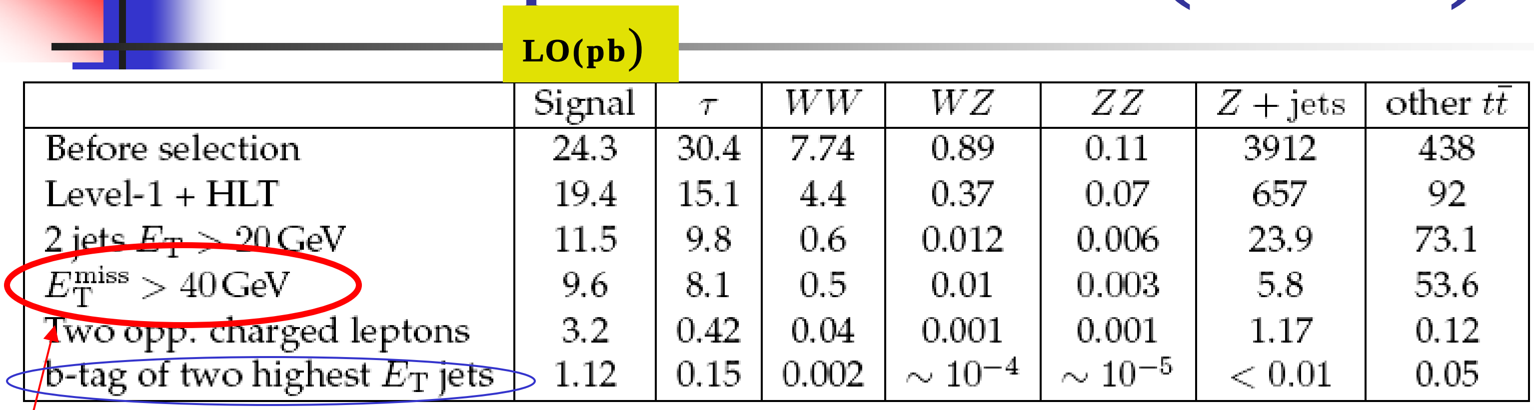


M_D/n	$n=2$	$n=3$	$n=4$	$n=5$	$n=6$
$M_D = 1.0$ TeV	0.21 fb^{-1}	0.16 fb^{-1}	0.14 fb^{-1}	0.15 fb^{-1}	0.15 fb^{-1}
$M_D = 1.5$ TeV	0.83 fb^{-1}	0.59 fb^{-1}	0.56 fb^{-1}	0.61 fb^{-1}	0.59 fb^{-1}
$M_D = 2.0$ TeV	2.8 fb^{-1}	2.1 fb^{-1}	1.9 fb^{-1}	2.1 fb^{-1}	2.3 fb^{-1}
$M_D = 2.5$ TeV	9.9 fb^{-1}	8.2 fb^{-1}	8.7 fb^{-1}	9.4 fb^{-1}	10.9 fb^{-1}
$M_D = 3.0$ TeV	47.8 fb^{-1}	46.4 fb^{-1}	64.4 fb^{-1}	100.8 fb^{-1}	261.2 fb^{-1}
$M_D = 3.5$ TeV	**5 σ discovery not possible anymore**				

TeV scale reached
well below 1 fb-1.

Medium /Low MET Analyses

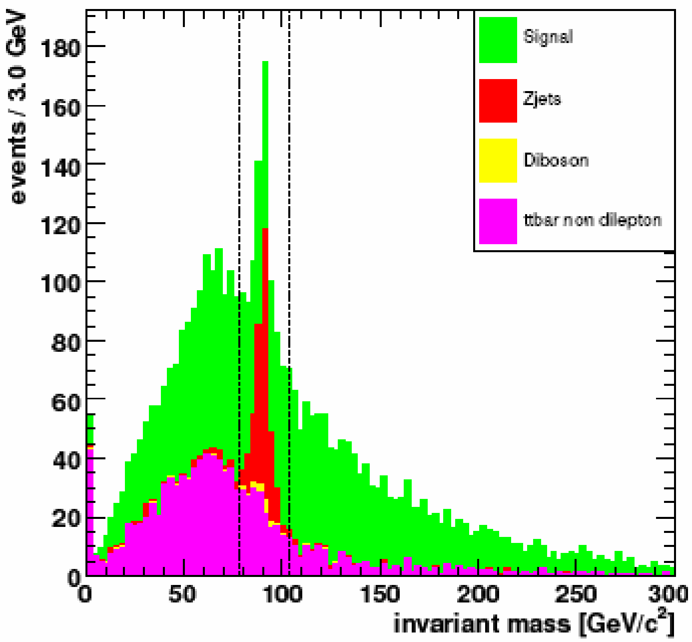
Di-Leptonic ttbar (CMS)

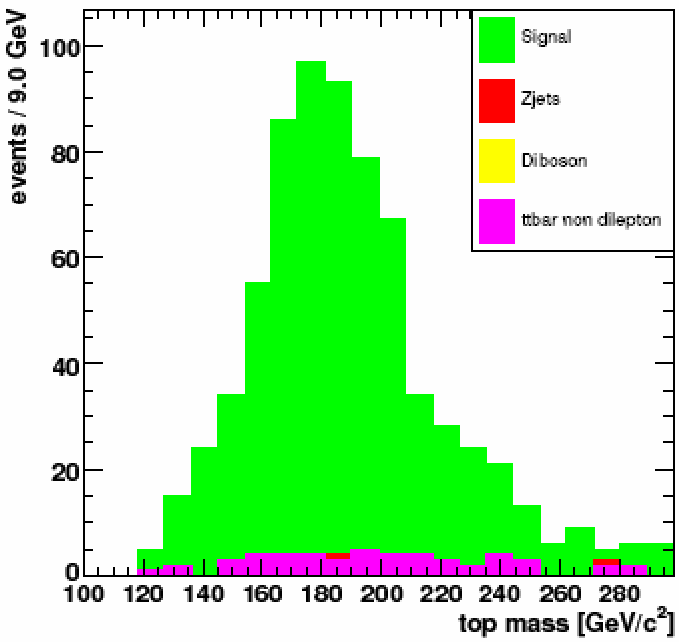


LO(pb)

	Signal	τ	WW	WZ	ZZ	Z + jets	other $t\bar{t}$
Before selection	24.3	30.4	7.74	0.89	0.11	3912	438
Level-1 + HLT	19.4	15.1	4.4	0.37	0.07	657	92
2 jets $E_T > 20\,\text{GeV}$	11.5	9.8	0.6	0.012	0.006	23.9	73.1
$E_T^{\text{miss}} > 40\,\text{GeV}$	9.6	8.1	0.5	0.01	0.003	5.8	53.6
Two opp. charged leptons	3.2	0.42	0.04	0.001	0.001	1.17	0.12
b-tag of two highest E_T jets	1.12	0.15	0.002	$\sim 10^{-4}$	$\sim 10^{-5}$	< 0.01	0.05

Only slight improvement in background rejection





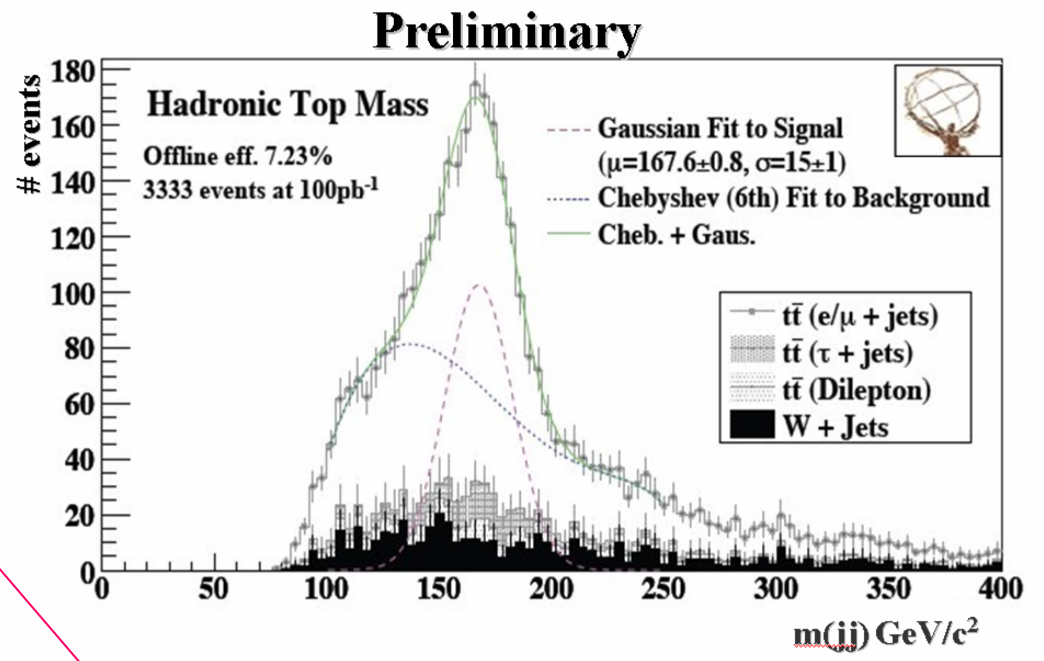
Semi Leptonic ttbar (ATLAS)

Selection A

- 1 high-pT lepton > 20 GeV/c
- at least 3 high-pT jets > 40 GeV/c
- 1 high-pT jets > 20 GeV/c
- ET miss>20 GeV
- |eta(lepton)|<2.4, |eta(jet)|<2.5
- top is reconstructed as the 3-jet combination with the highest PT sum

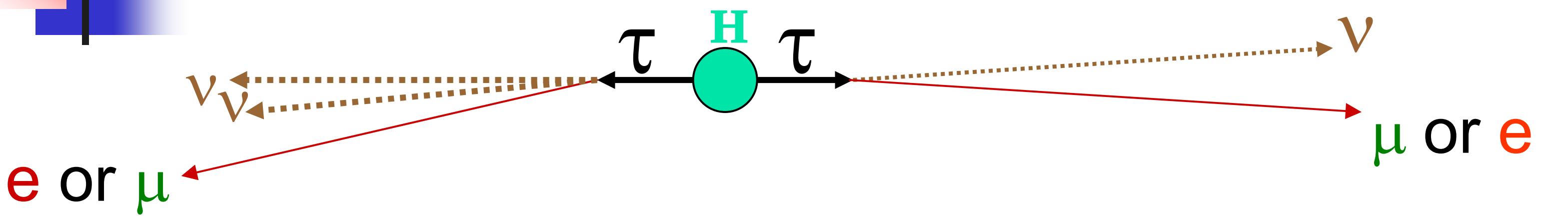
Selection B

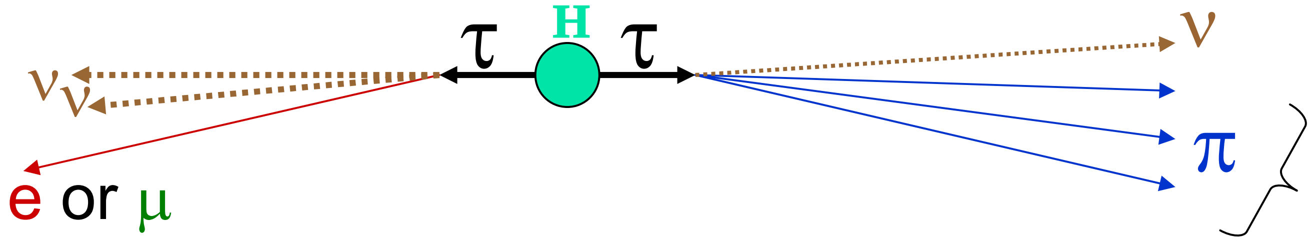
- Same as selection A
- additional cut |mjj-MW|<10 GeV



At (below?) resolving power of MET

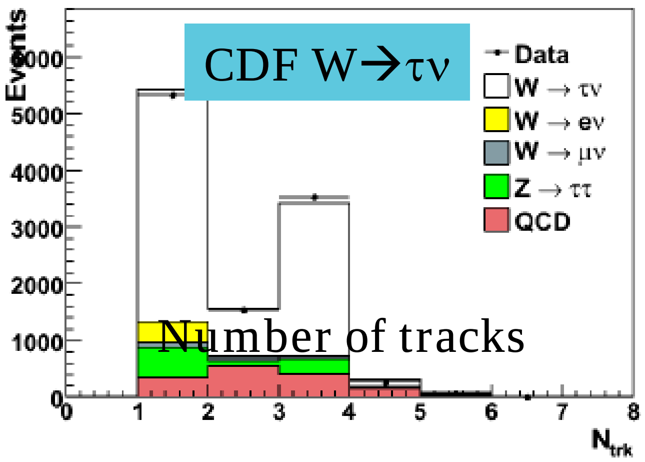
Ditau analyses





- Identifying hadronic tau is possible
  - Nested signal/isolation cones
- Need to separate from Z
  - Mvis (used in CDF, broad dist)
  - Invariant mass (no back-to-back taus)

Track multiplicity

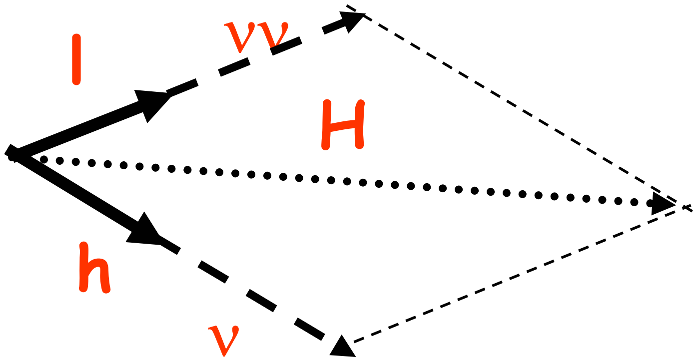


CDF W→τν

Number of tracks

Ditau invariant mass

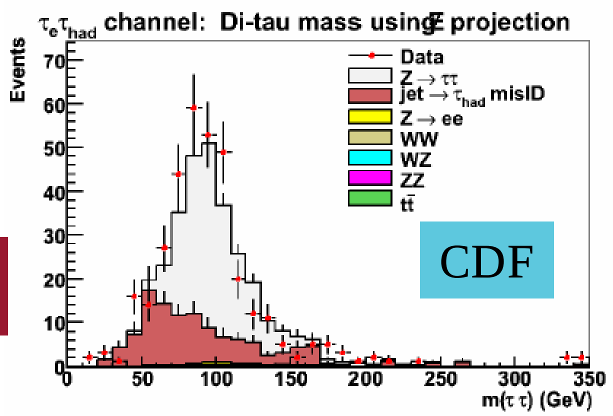
Assume tau decay products are collinear to tau directions - aka "projection method".



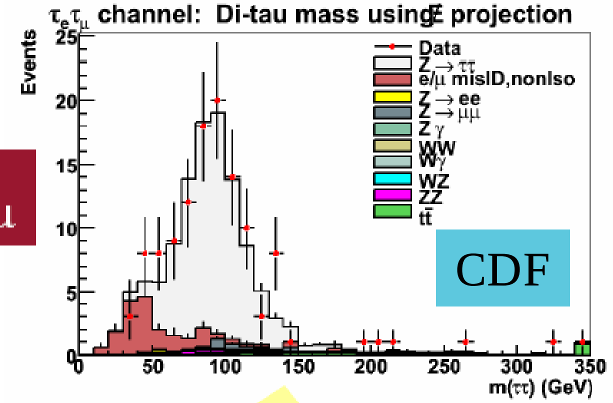
Requires good resolutions at **low MET**.

Does it work?
CDF 1.8 fb-1 results

$\tau_e\tau_{had}$



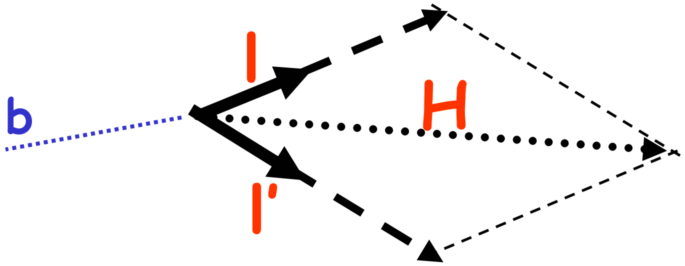
$\tau_e\tau_\mu$

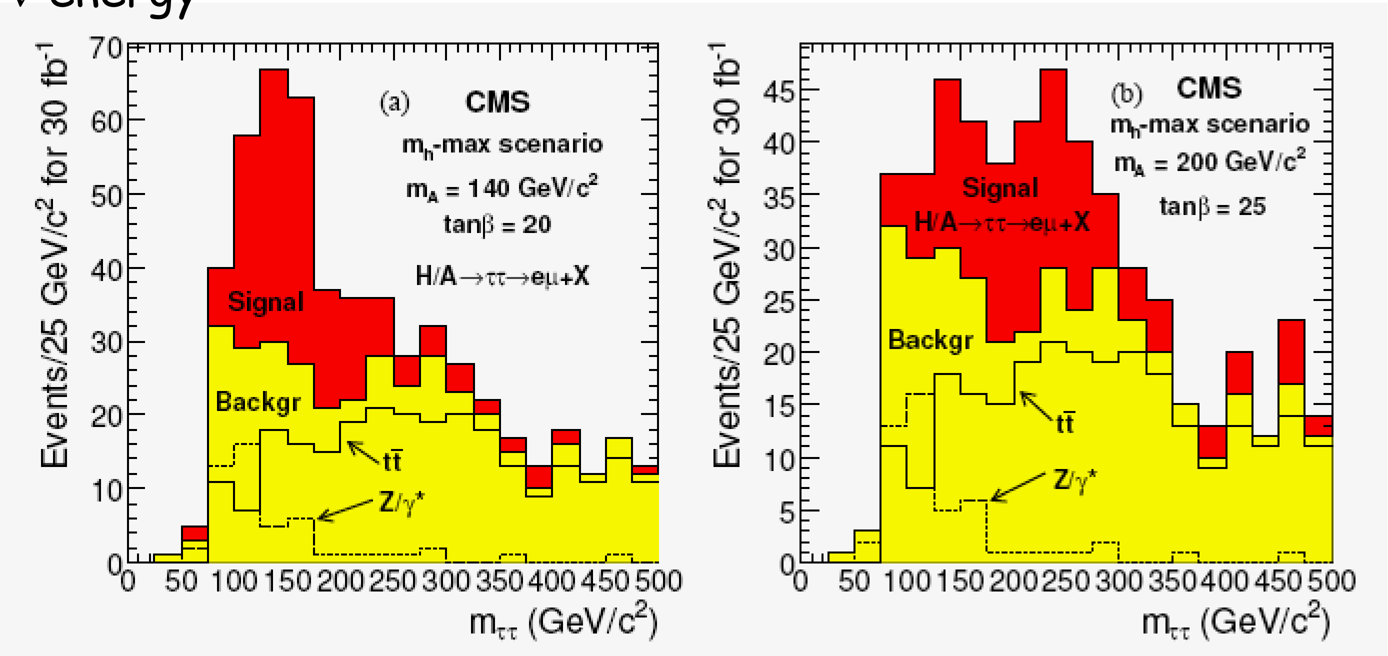


ττ invariant mass

Higgs → ditau (CMS)

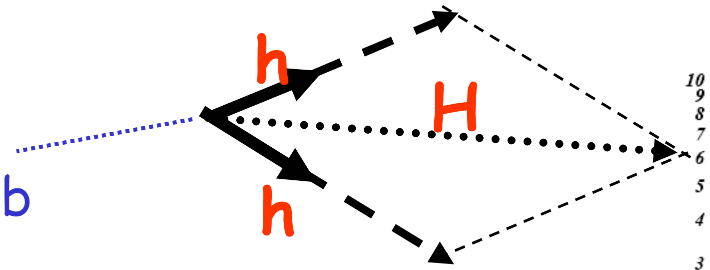
- 2 isolated leptons
- 1 b-tag (but associated b is soft)
- Only 1 extra central jet
- NO MET cut (but used in mass reco)
- Positive solution to ν energy

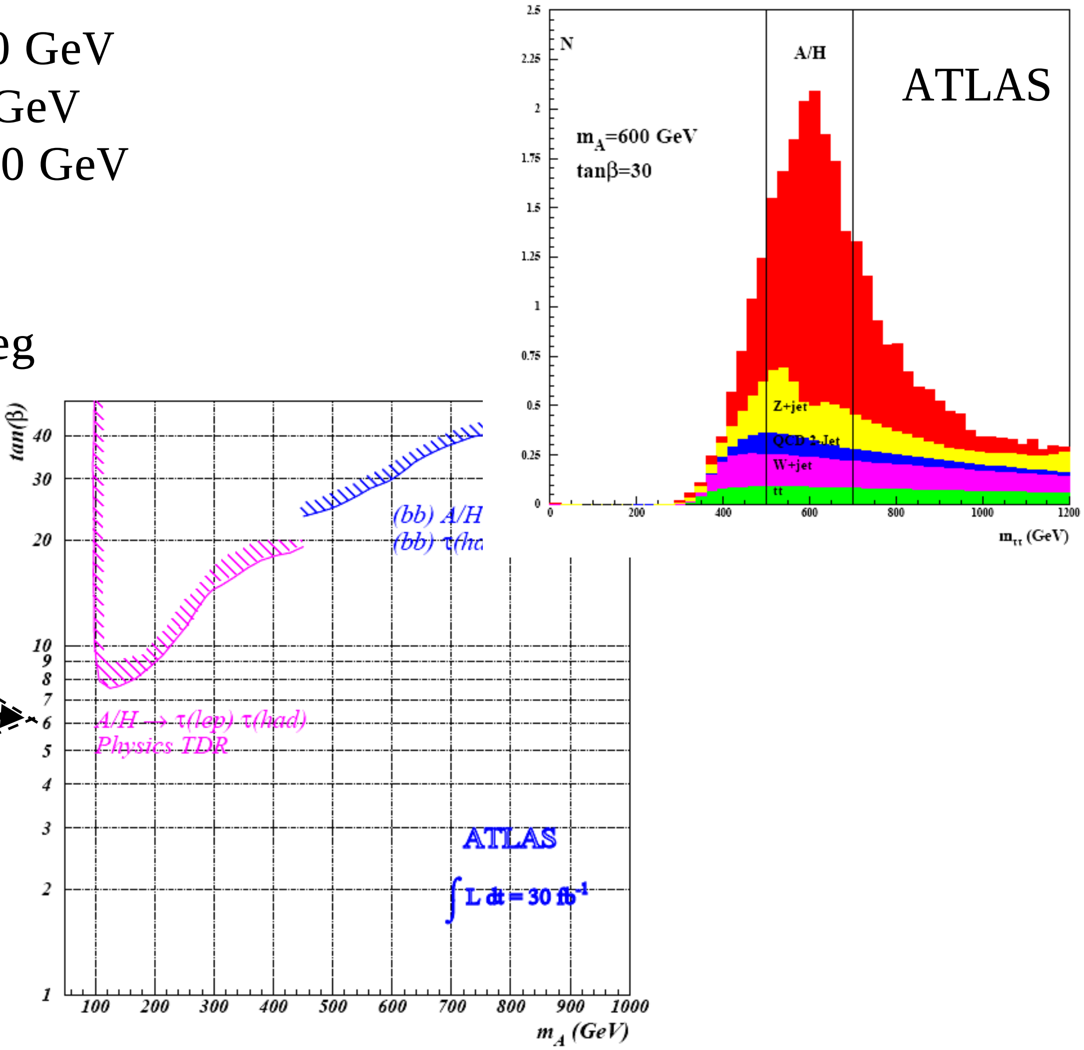




Higgs to ditau (ATLAS)

- 1. Two (had)τ 's *pT;* > 100 GeV
- 2. No lepton with *pT* > 10 GeV
- 3. <= 4 jets in with *pT* > 20 GeV
- 4. At least one b-jet tagged
- 5. **MET> 65 GeV**
- 6. *Dphi* b τ-τ: 145 – 175 deg
- 7. *mT* < 50 GeV
- 8. ττ mass recon possible





H→ WW*

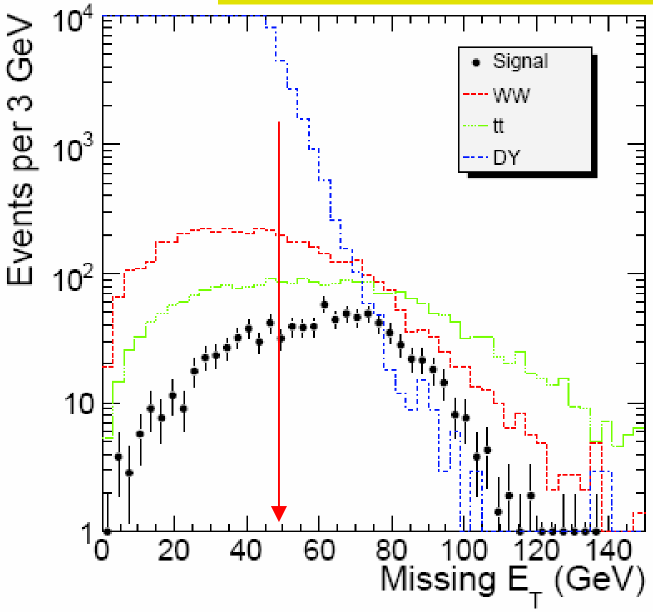
$$\boxed{q\,\bar{q} \rightarrow W^{+}W^{-} \rightarrow 2\mu 2\nu}$$

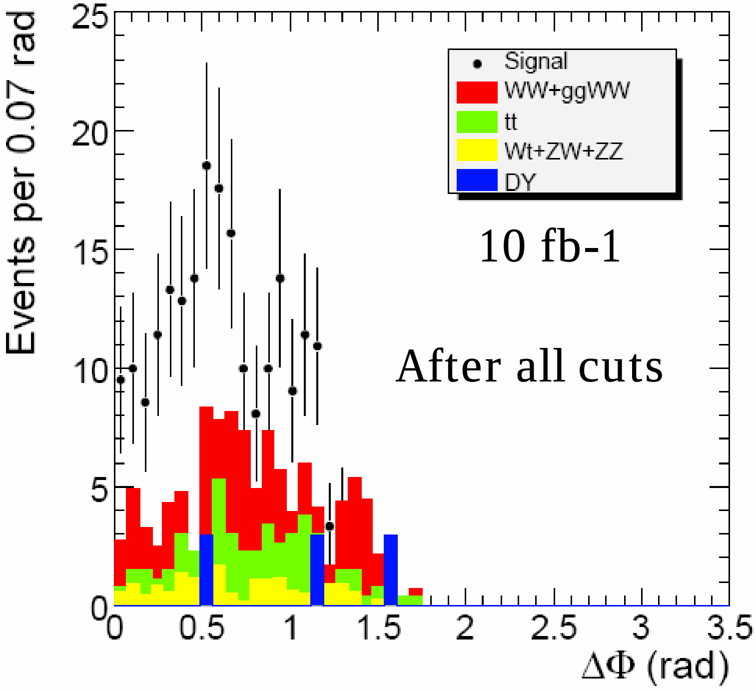
$$g\,g \rightarrow t\,\bar{t} \rightarrow 2\mu 2\nu$$

$$q\,\bar{q} \rightarrow \gamma^{*}, Z \rightarrow 2\mu$$

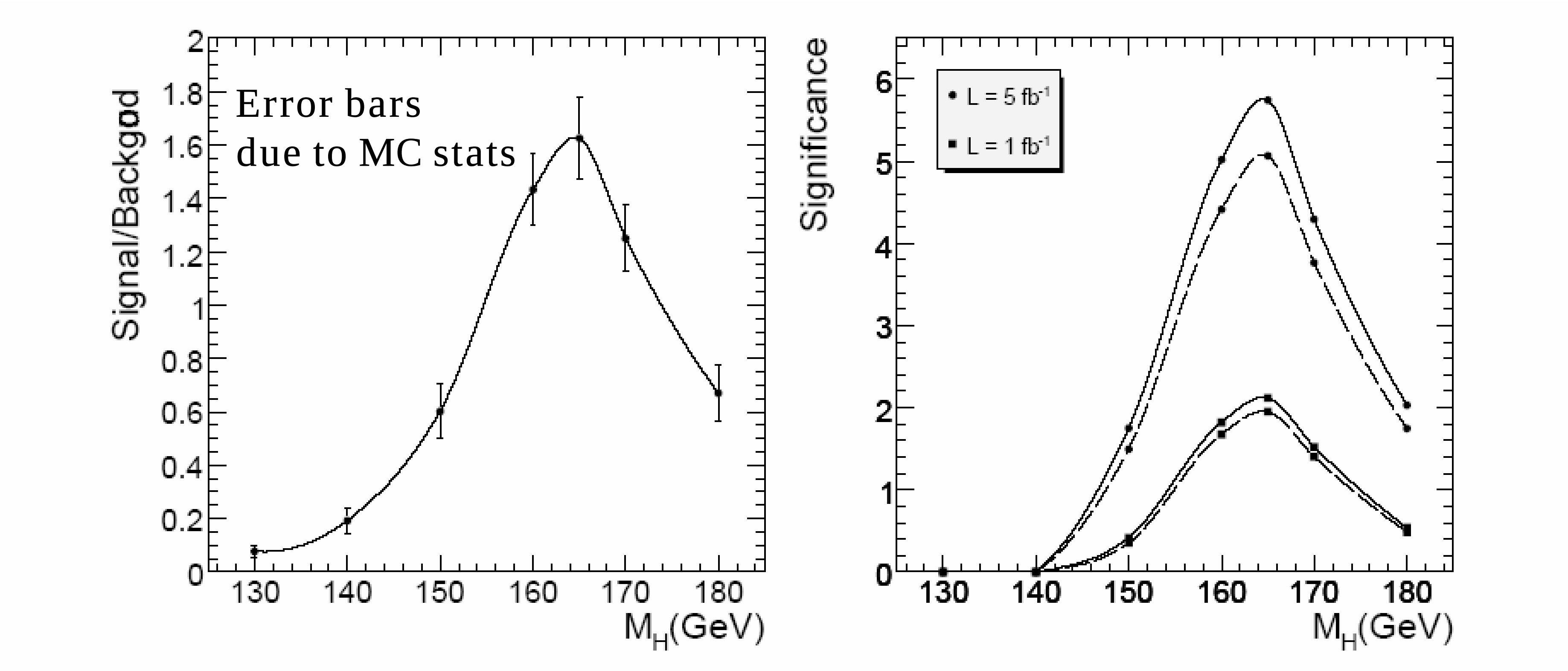
1	L1+HLT dimuon	6	MET> 50 GeV
2	2 μ opposite charge	7	$35\,\mathrm{GeV/c} < P_T(\mu_{max}) < 55\,\mathrm{GeV/c}$
3	Isolation	8	$25\,\mathrm{GeV/c} < P_T(\mu_{min})$
4	$\eta < 2.0 \quad IP < 3\sigma$	9	$m_{\mu_1\mu_2} < 50\,\mathrm{GeV/c^2}$
5	Jet Veto	10	$\Delta\phi_{\mu_1\mu_2} < 0.8$

Optimized for mh=165 GeV





H→WW* reach



Error bars
due to MC stats

MET Concerns

- Resolution
  - **Noise**: electronic underlying event
  - **Stochastic**:sampling effects, e/π.
  - **Constant**: non-linearities, cracks, hot/dead channels.
  - **Offset**: ΣEt shifts in empty detector (anticorrelated with Noise term).

$$\sigma(E_T) = A \oplus B\sqrt{\Sigma E_T - D} \oplus C\,(\Sigma E_T - D)$$

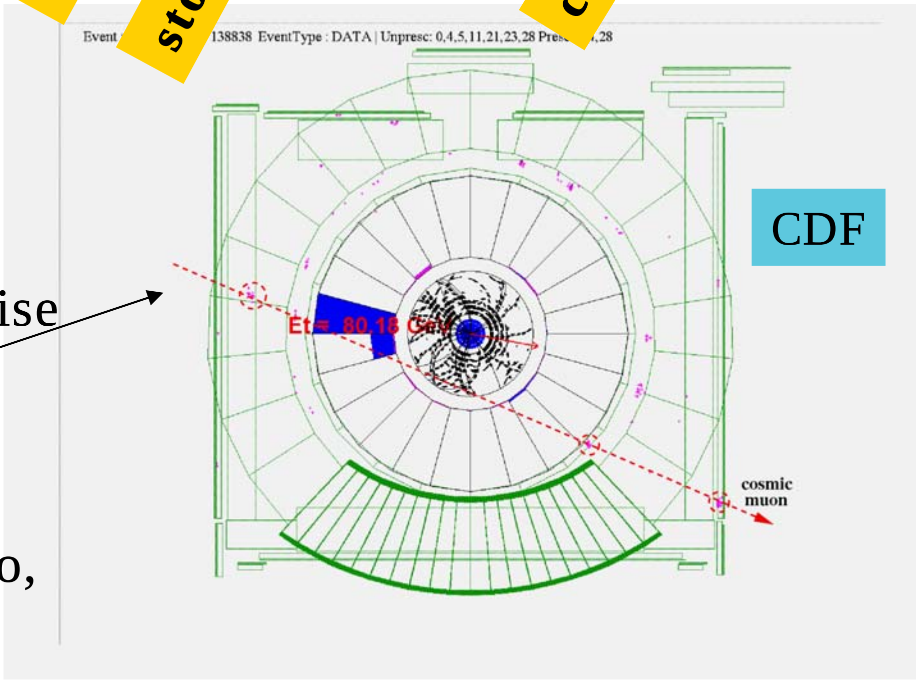
noise

stochastic

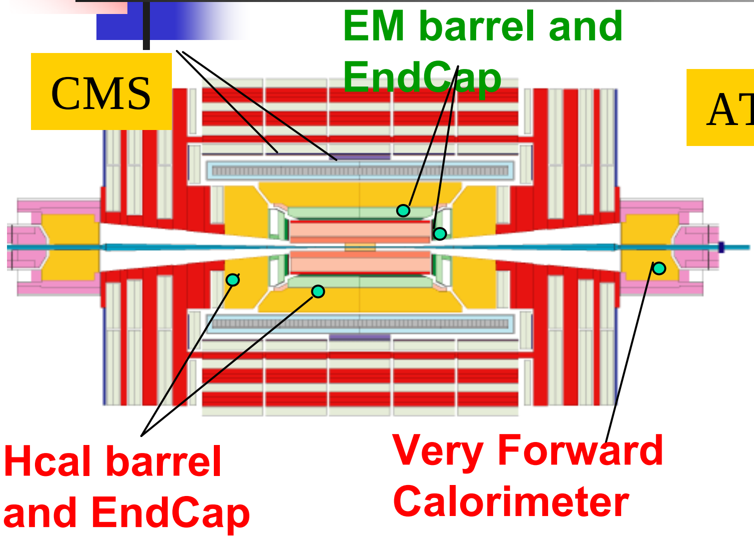
constant

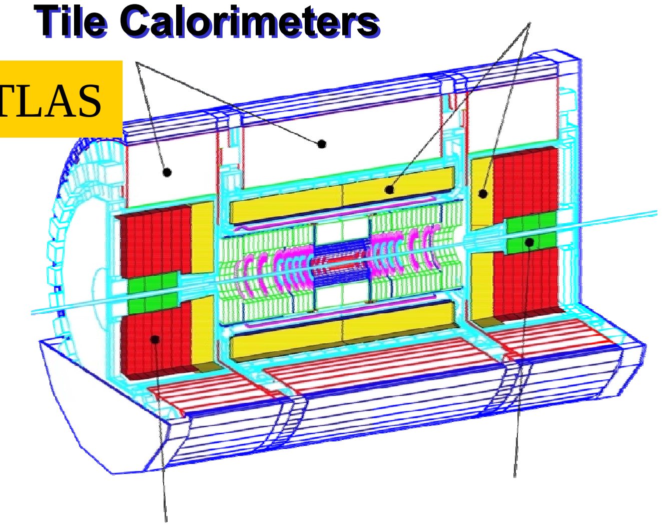
offset

- High MET Tails
  - Beam effects, muon halo, cosmics...



Calorimeter η coverage





EM calorimeter $|\eta| < 3$

Central Hadronic $|\eta| < 1.4$

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

Forward calorimeter $2.9 < \eta < 5$

EM accordion $|\eta| < 3.2$

Central Hadronic $|\eta| < 1.7$

End Cap Hadronic $1.5 < \eta < 3.2$

Forward cal $3.1 < \eta < 4.9$

Central $|\eta|<1.0$
Plug $1.3<|\eta|<3.6$

Better eta coverage → Better performance on MET const term.

better more

Segmentation, interaction lengths

CMS	ATLAS
EM calorimeter $\lvert\eta\rvert < 3$: PbW04 crystals $\Delta\eta\times\Delta\varphi = 0.0174 \times 0.0174$	**EM accordion** $\lvert\eta\rvert < 3.2$:Pb/LAr $\Delta\eta\times\Delta\varphi \sim 0.025 \times 0.025$
Central Hadronic $\lvert\eta\rvert < 1.7$ Brass/scintillator $\Delta\eta\times\Delta\varphi = 0.087 \times 0.087$	**Central Hadronic** $\lvert\eta\rvert < 1.7$:Fe / scint $\Delta\eta\times\Delta\varphi \sim 0.1 \times 0.1$
Endcap Hadronic $1.3<\lvert\eta\rvert<3$ Brass/scintillator +WLS $\Delta\eta\times\Delta\varphi = \sim 0.15 \times 0.17$	**End Cap Hadronic** $1.5 < \eta < 3.2$ Cu/LAr $\Delta\eta\times\Delta\varphi < 0.2 \times 0.2$
Forward calorimeter **$3<\eta<5$** Fe/quartz fibers $\Delta\eta\times\Delta\varphi = \sim 0.175\times 0.17$	**Forward calorimeter** **$3.1 < \eta < 4.9$:** **EM Cu/LAr – HAD W/Lar** $\Delta\eta\times\Delta\varphi = 0.2 \times 0.2$

CDF

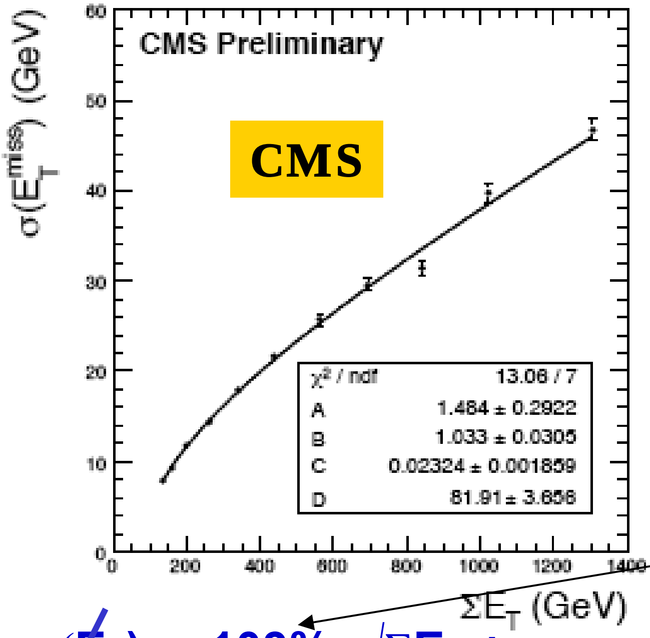
Central $\lvert\eta\rvert<1.0$
$\Delta\eta\times\Delta\varphi \sim 0.11\text{x}0.26$

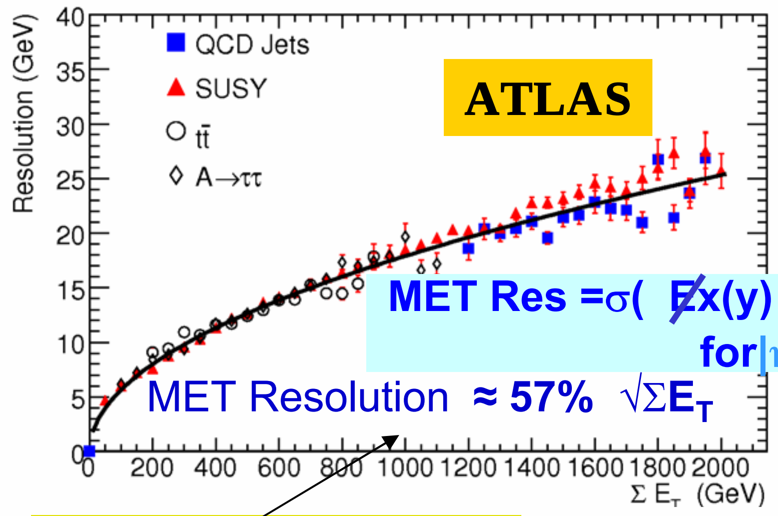
Plug $1.3<\lvert\eta\rvert<3.6$
$\Delta\eta\times\Delta\varphi$
from ~0.11x0.13
to ~0.36x0.26

CDF 5,5 - 7 λ

CMS cal has 7λ (w/out HO). ATLAS cal has >= 10 λ

MET Performance (stochastic term)





Not an apples-to-apples comparison…

MET Res $=\sigma(\not{E}x(y)\ \text{Rec} - \not{E}x(y)\text{Truth})$ **for** $|\eta|<3$

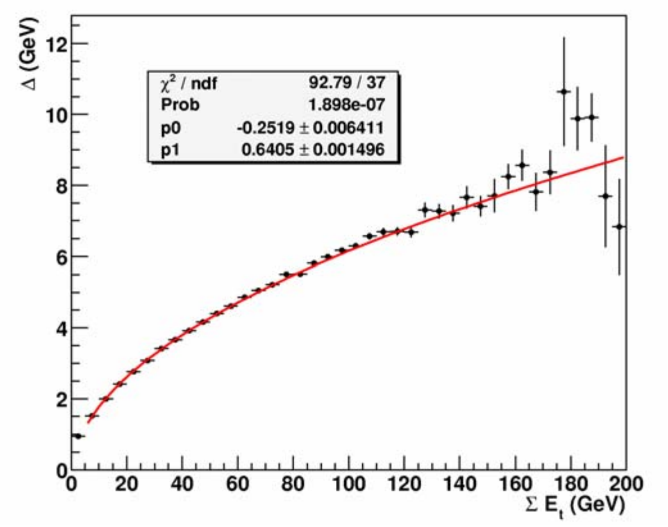
MET Resolution ≈ **57%** $\sqrt{\Sigma E_T}$

ATLAS cal has more longitudinal segmentation: (e/pi)

$\sigma(\not{E}_T) \approx 103\%\ \sqrt{\Sigma E_T} + \dots$

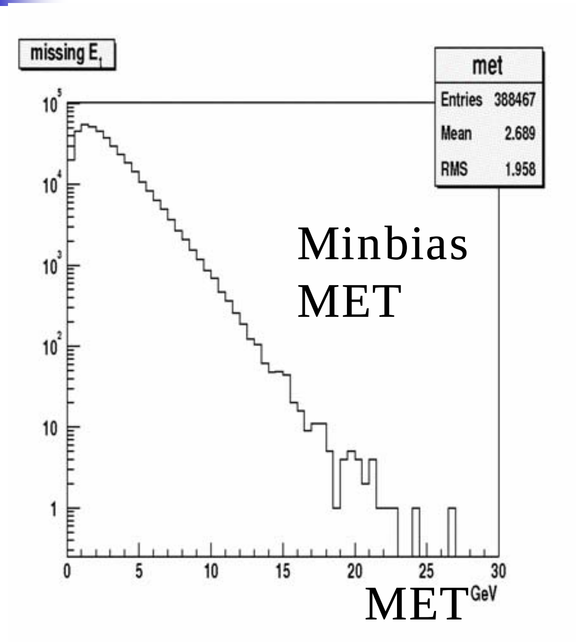
$$\sigma^2(\not{E}_T) = (1.48\ \text{GeV})^2 + (103\%\ \text{GeV}^{1/2})^2(\Sigma E_T - 82\ \text{GeV}) + (2.32\% \times (\Sigma E_T - 82\ \text{GeV}))^2.$$

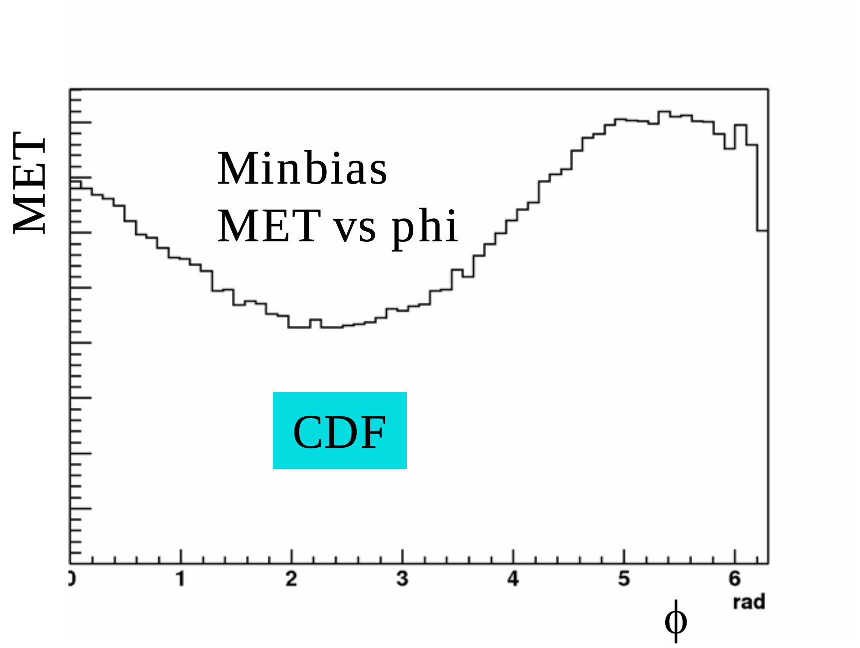
Minbias data, **underestimate** stochastic term.



Some MET Peculiarities from CDF

MET Peculiarities





MET has a phi dependence ~ few GeV.
→ collision not centered at 0,0,0.

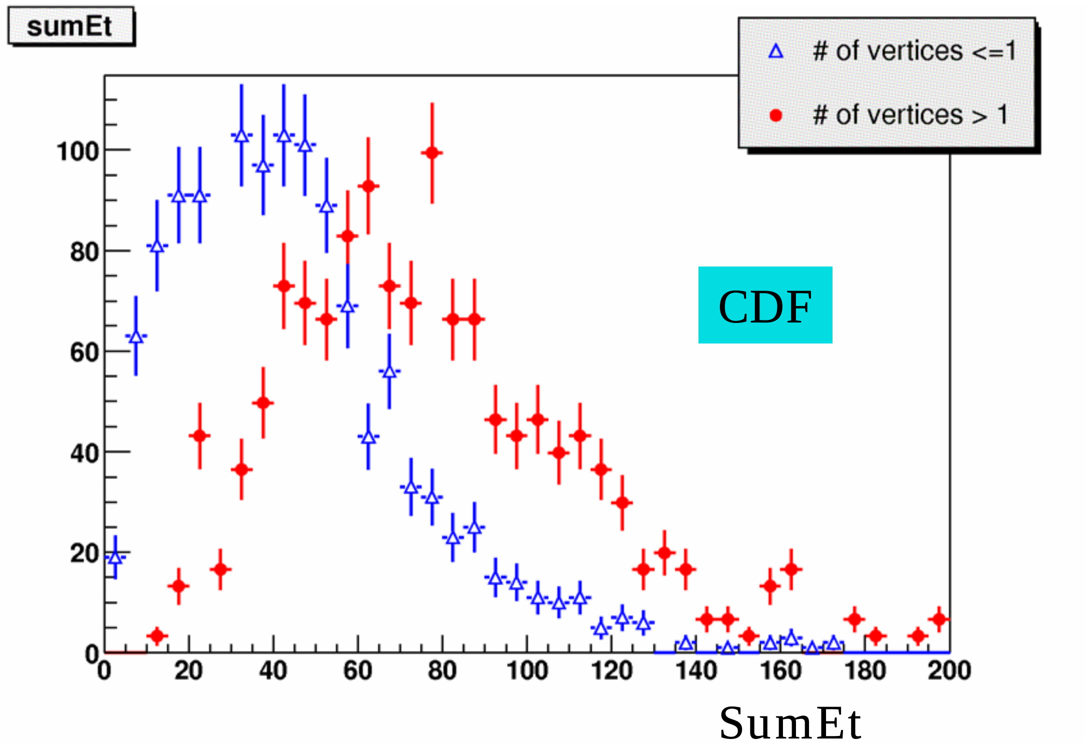
MET Peculiaritiess

SumEt from Z→ μμ events

Events with 2nd vertex have significantly higher SumEt.

Jets from 2nd vertex could affect MET calculation.

This will depend on lum, but non-trivial numbers at low luminosity.



Hopefully not as big a problem at LHC (smaller beam ellipse than Tevatron)

MET Peculiarities

Beam halo muons can deposit large amounts of IN-TIME energy.

EM/HAD ratio is fairly lopsided.

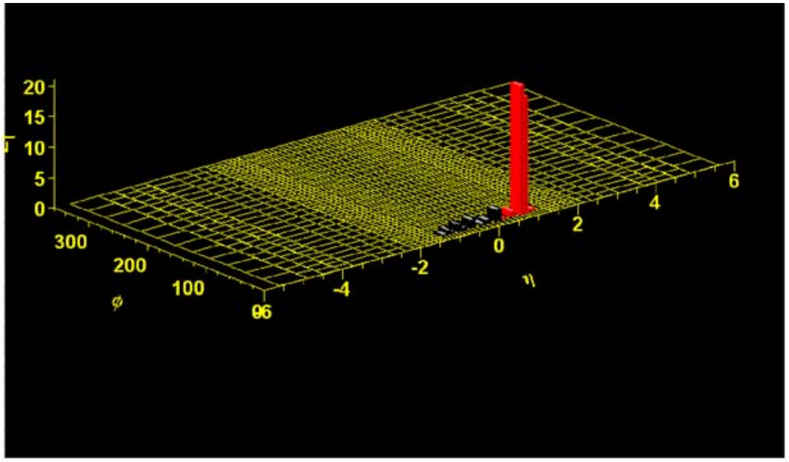
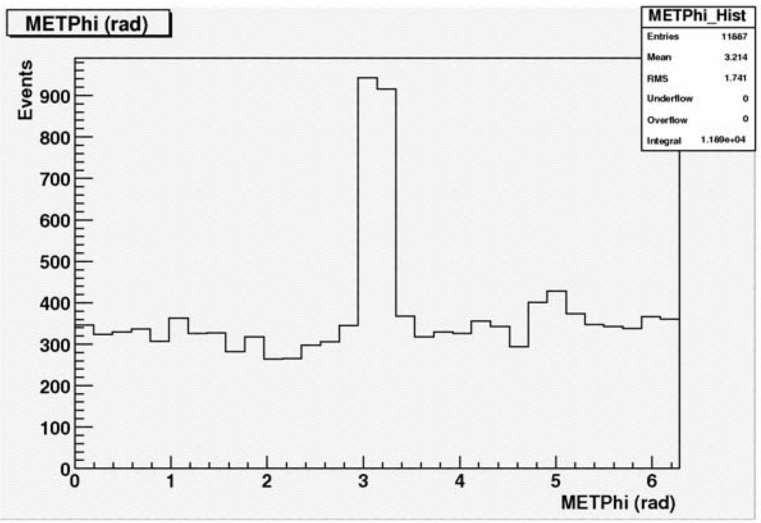
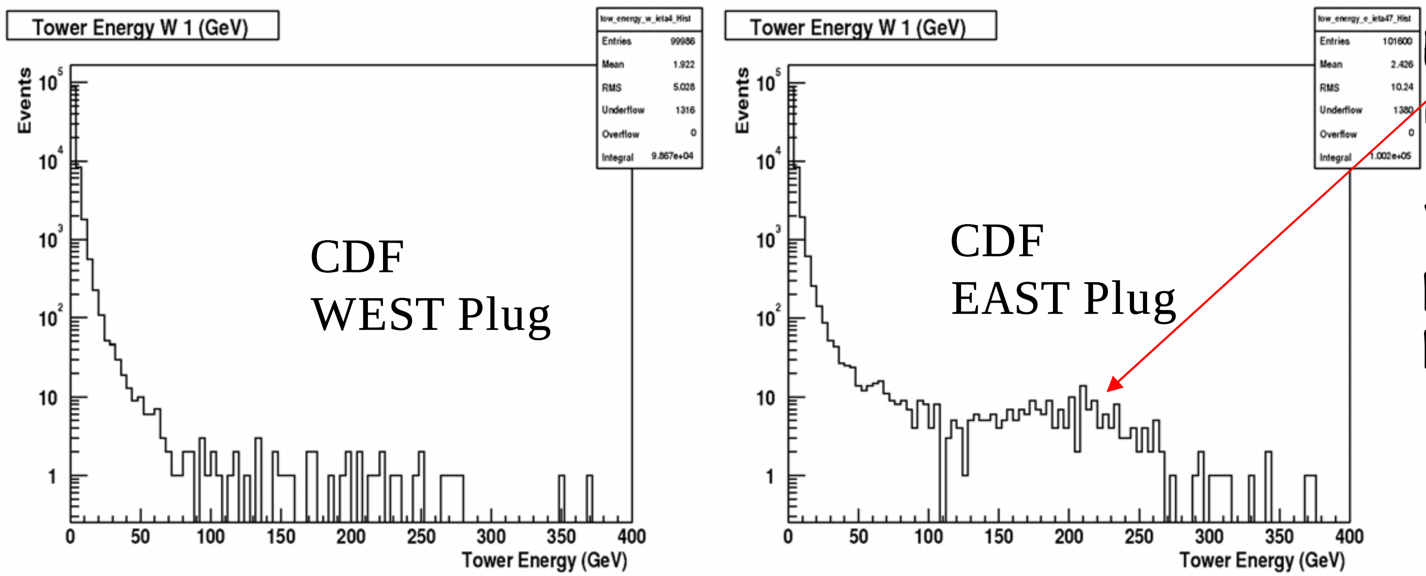


Figure 1: An $\eta - \phi$ plot of the energy in the calorimeter towers of a bunch crossing event that has a halo muon traversing through the central calorimeter in the direction parallel to the beam axis.



MET Peculiarities

Energy deposited in the Ring of Fire (highest eta towers)



CDF
WEST Plug

CDF
EAST Plug

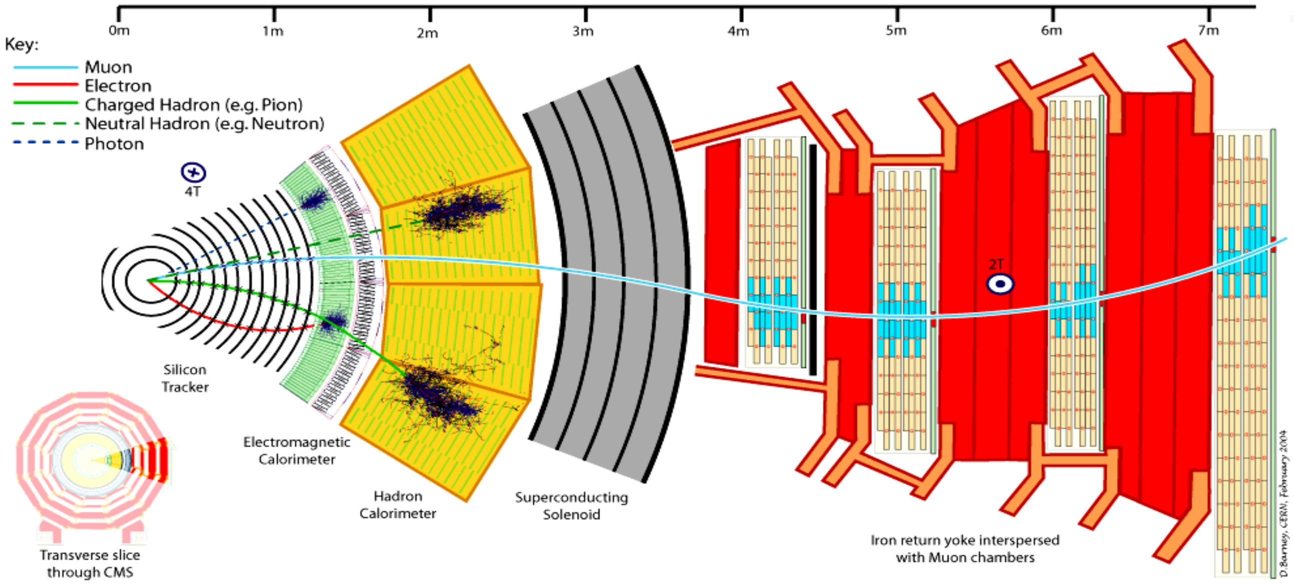
Figure 5: Plots on the energy of the towers in the highest η-ring for events taken with Pass2 MET25 trigger (with Level-2 and Level-3 pass through). (Left) Towers from the west Plug calorimeter. (Right) Towers from the east Plug calorimeter.

Tevatron protons travel W → E. So EAST Plug energy is in time.

W Plug should get pbars in time, but pbar flux is small.

Particle Flow: Improving MET

Particle Flow



Current MET: all calorimeter (+muon correction)

Particle Flow:

Biggest problem in MET: hadron energy.

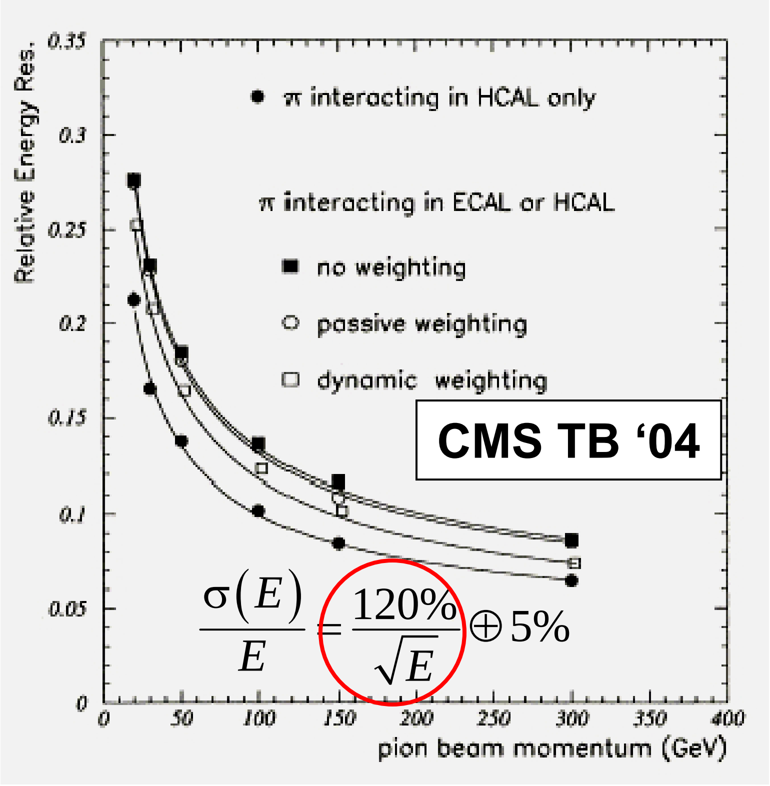
Identify **e**, γ, π, μ, **charged/neutral hadrons**, **pileup**, etc, and "correct".

Harder in jetty environment, but what isn't?

Benefits of Particle 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%
    - $K^0_S \rightarrow \pi^+\pi^-$, $\Lambda \rightarrow \pi^- p$, …, 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

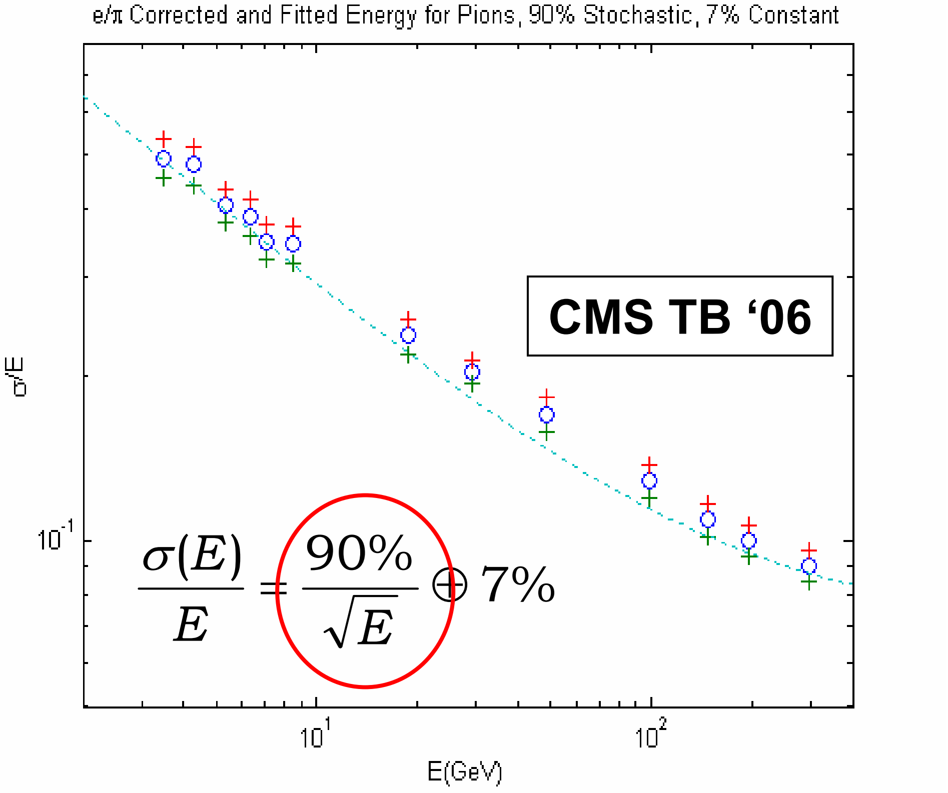
Improving e/π helps!



CMS TB '04

$$\frac{\sigma(E)}{E} = \frac{120\%}{\sqrt{E}} \oplus 5\%$$

e/π Corrected and Fitted Energy for Pions, 90% Stochastic, 7% Constant

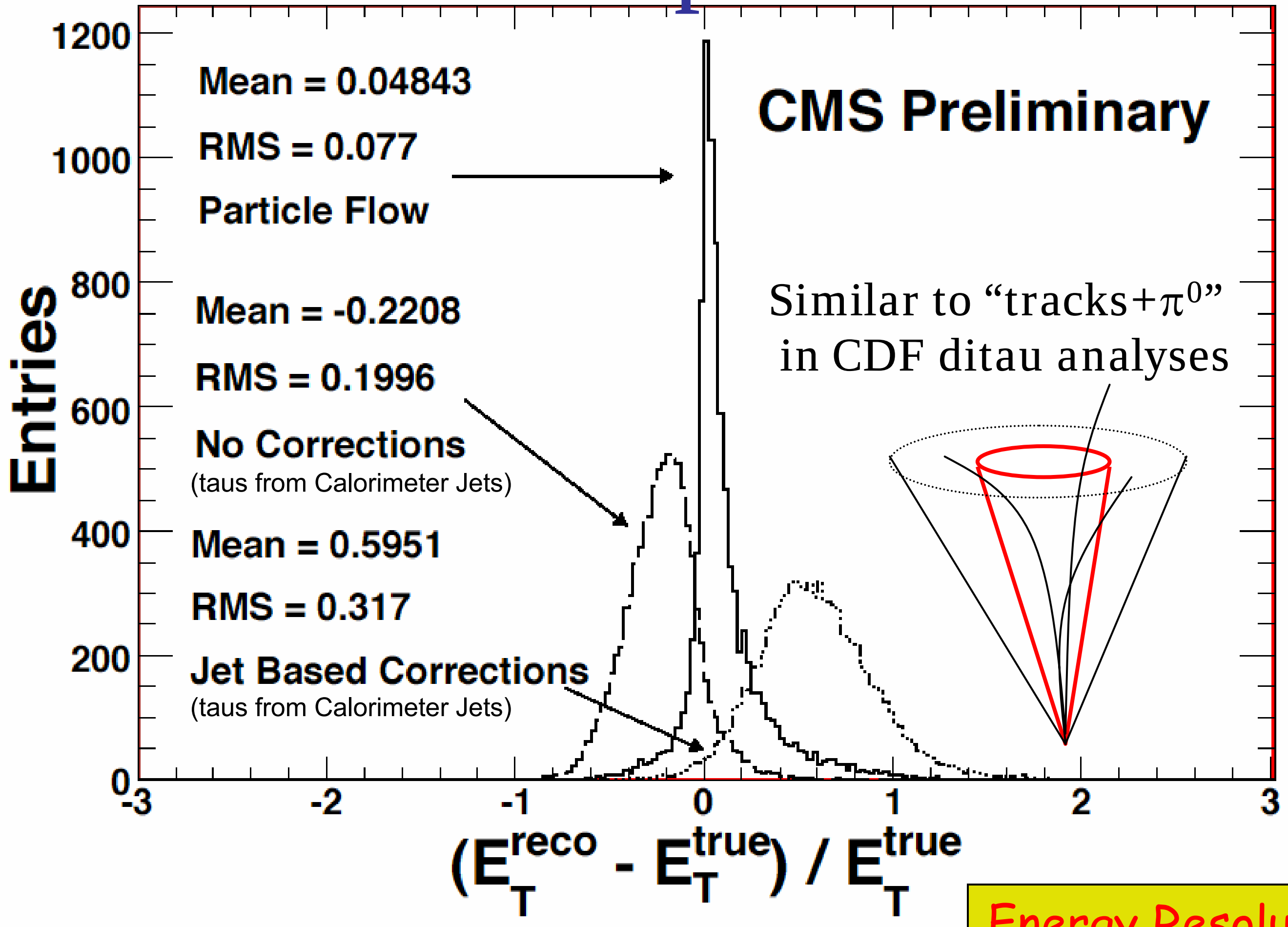


CMS TB '06

$$\frac{\sigma(E)}{E} = \frac{90\%}{\sqrt{E}} \oplus 7\%$$

Good beam conditions in 2006 combined with very clean Particle ID

PF Example: hadronic τ energy



Similar to “tracks+π^0” in CDF ditau analyses

- Calorimeter Jets strongly affected: low energy charged particles not
- PF Jets not affected much in the peak.
- Better energy resolution for objects using tracking info → better SumEt, MET resolution.
- Acid test: very jetty, noisy environments.

Energy Resolution Improves!

Summary

- MET is as difficult to reconstruct as it is important.
  - Current MET resolutions are only starting points.
  - Expect ATLAS vs CMS differences to get smaller
    - CMS learns to use tracking (PF).
    - Of course, ATLAS will also keep improving...
    - **Bottom line: ATLAS has better cal; CMS: better tracking.**
- Biggest problems in MET reconstruction will not be known until beams collide.
  - Look for beam effects, dead/hot channels, miscalib...
- Once MET is understood, lots of analyses benefit: low mass SUSY, LED, ditaus...

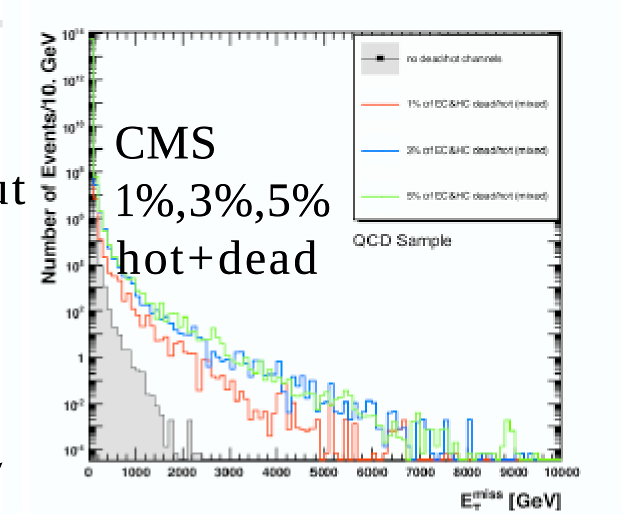
Backup stuff

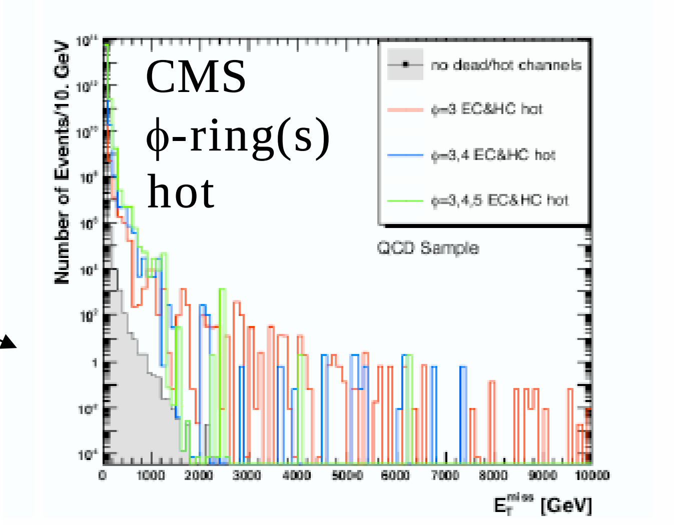
ATLAS vs. CMS MET

- ATLAS constant term ~ zero.
- CMS stochastic higher than ATLAS stochastic (but ATLAS quotes MET reco-truth…):

  ATLAS has
  - 6 radial cal segments
  - e/π ratio closer to 1
  - (slightly) more λ
  - Object based calib (em, had, other…)
  - CMS will need to use tracking info to compete (Particle Flow)

- Other effects (dead/hot channels)


CMS
1%,3%,5%
hot+dead


CMS
ϕ-ring(s)
hot