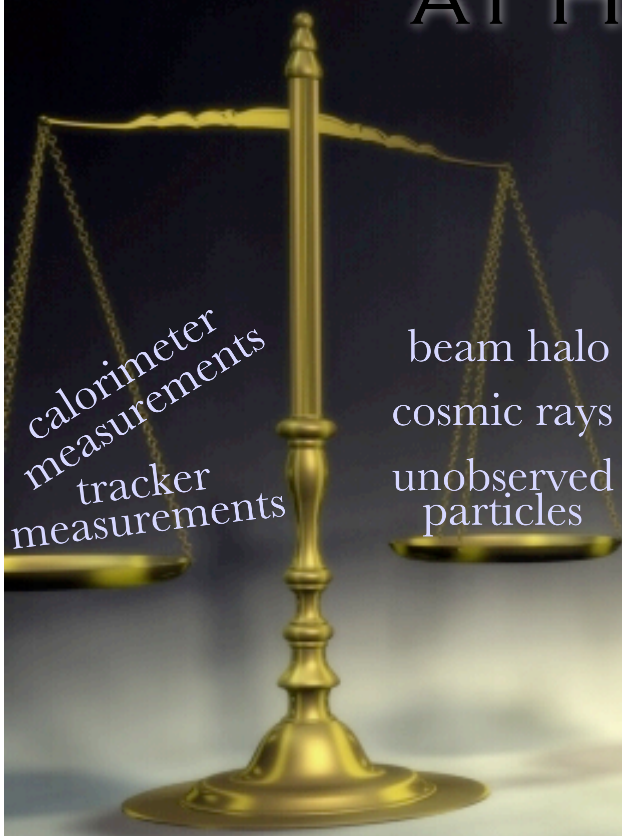
"Missing" Momentum Measurement at Hadron Colliders



Motivation

Measurement

Mismeasurement

Modelling

(Event selection)

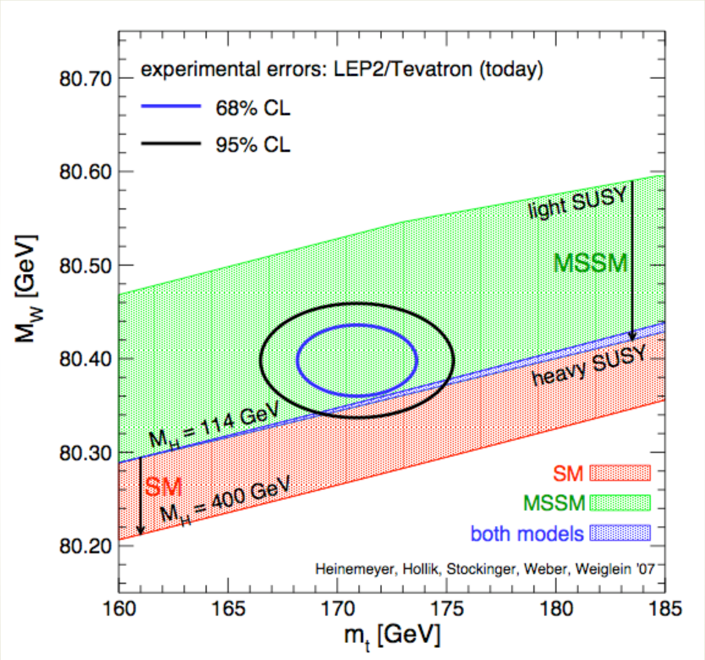
Chris Hays,

Oxford University

YETI 2008, Durham

Motivation

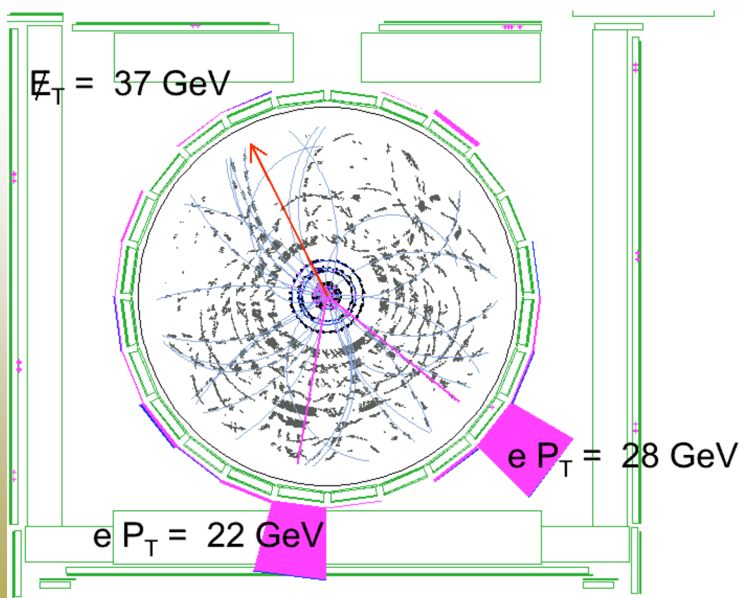
- *Unobserved particles crucial to standard model measurements and future discoveries*

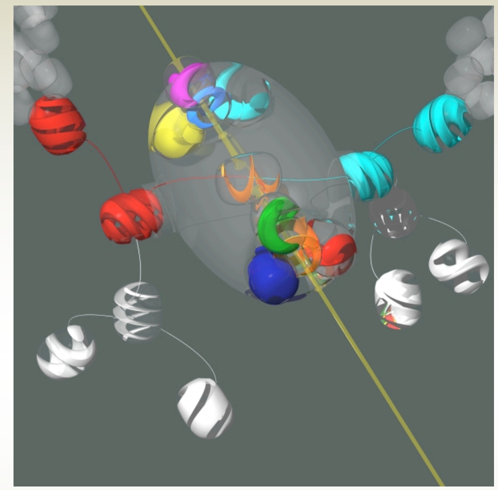


  - **Neutrinos:**
    - *W* and top mass measurements
      - *constrain the Higgs mass and the existence of supersymmetric particles*
    - Higgs decay to *WW*
      - *discovery channel if Higgs mass is ~160 GeV*
  - **Dark matter:**
    - Heavy neutral particles such as the lightest supersymmetric particle
      - *Inferred by excess of events with large momentum imbalance of observed particles*

Measurement

- *Initial state z-momentum not known, can only infer momentum imbalance in the direction transverse to the beam line*
- *Momentum imbalance measured primarily using calorimeter energy and a vertex*
  - Hence the jargon "missing transverse energy" or $\not{E}_T$





Jan Henrik-Andersen

WW decay to a pair of electrons and neutrinos (CDF)

Measurement

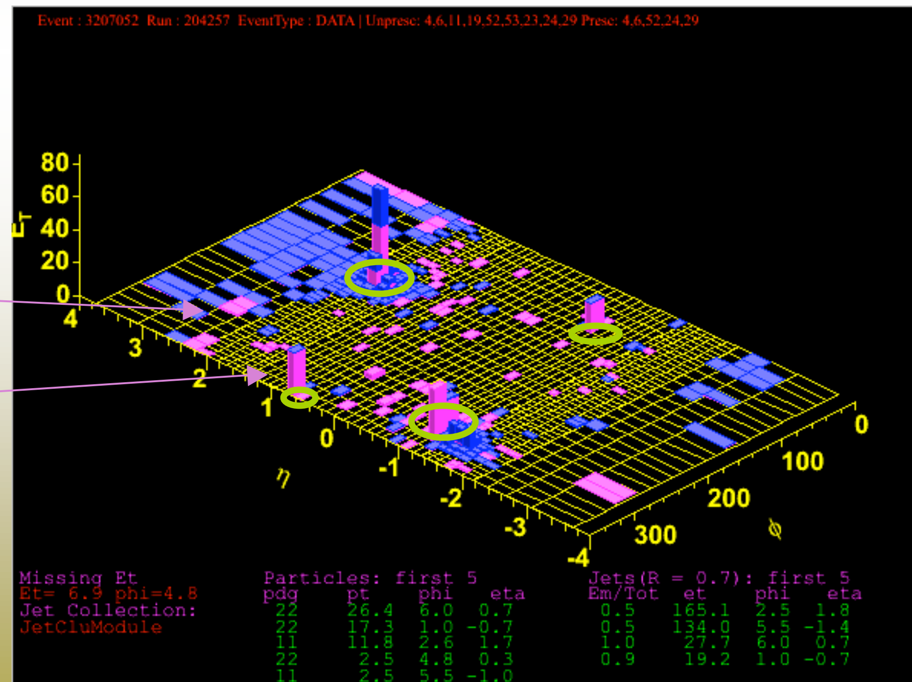
- *Correct for particles not measured well by calorimeter*
  - **Muons:** use track momentum, subtract energy in calorimeter
  - **Jets:** apply calibrations to correct for lost particles and calorimeter response

- *The end result is an accurate measurement of momentum imbalance*

$$\sum_i \vec{p}_i + \overrightarrow{\text{uncl}} + \vec{\not{p}} = \vec{0}$$

Unclustered energy

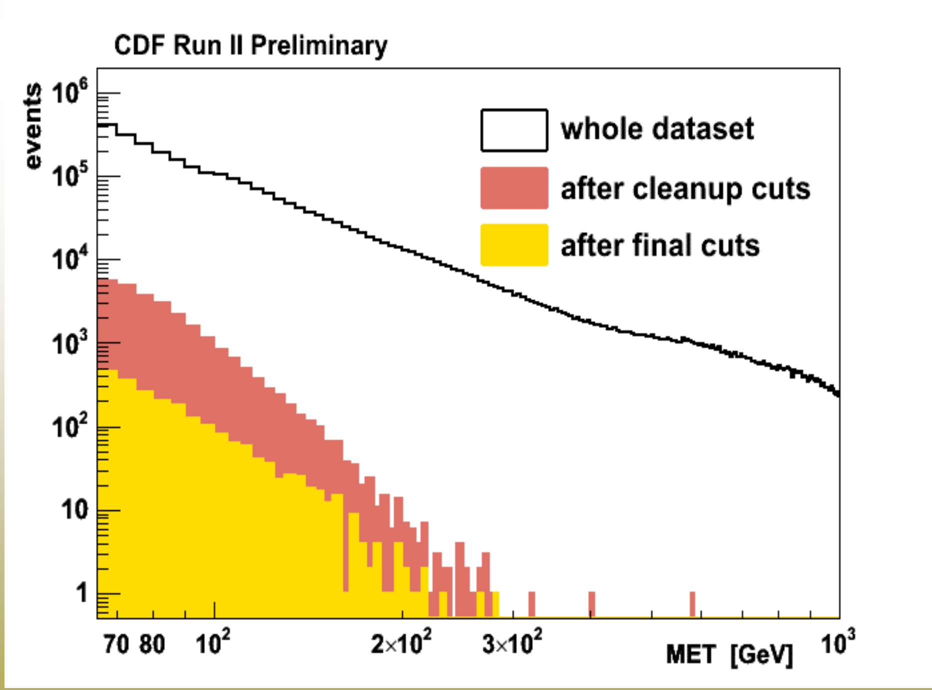
Object



Diphoton plus dijet event
(CDF)

Mismeasurement

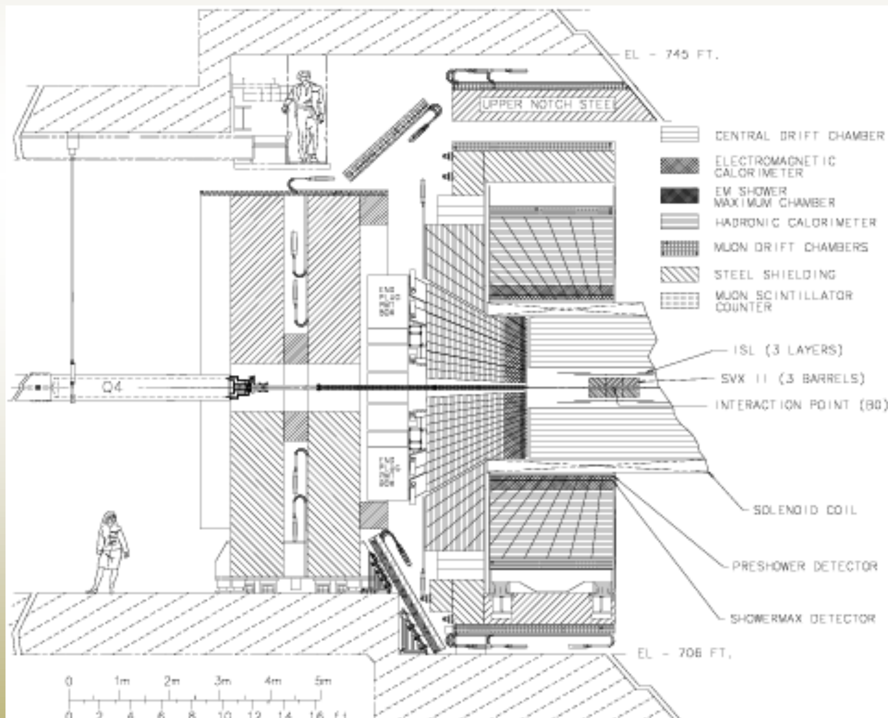
- *Background to events with large $\not{E}_T$ results predominantly from pathological mismeasurements*
  - **Beam-induced background**
  - **Cosmic-ray muons**
  - **Jet energy lost in detector cracks**



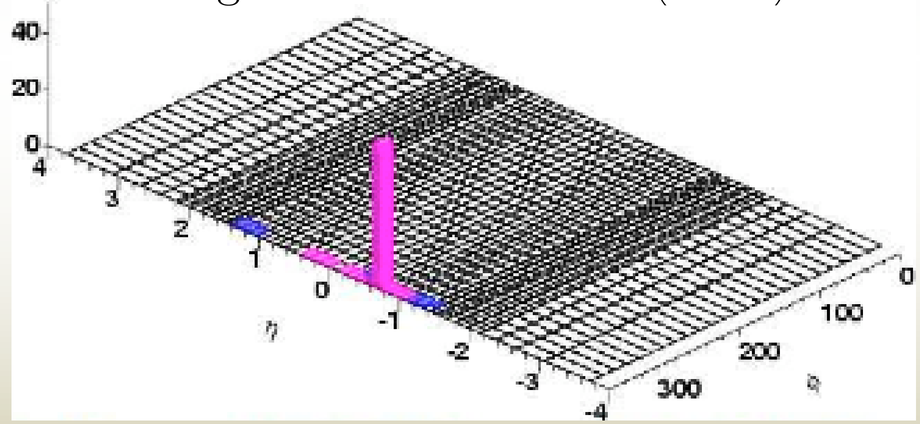
Jets plus $\not{E}_T$ search for squarks and gluinos (CDF)

Beam Halo

- *Beam interactions with pipe produce showers upstream of detector*
  - **CDF: shielding significantly attenuates shower**
  - **Muons can penetrate shielding and deposit energy in calorimeter**



Photon plus $\not\!\!E_T$ search for large extra dimensions (CDF)

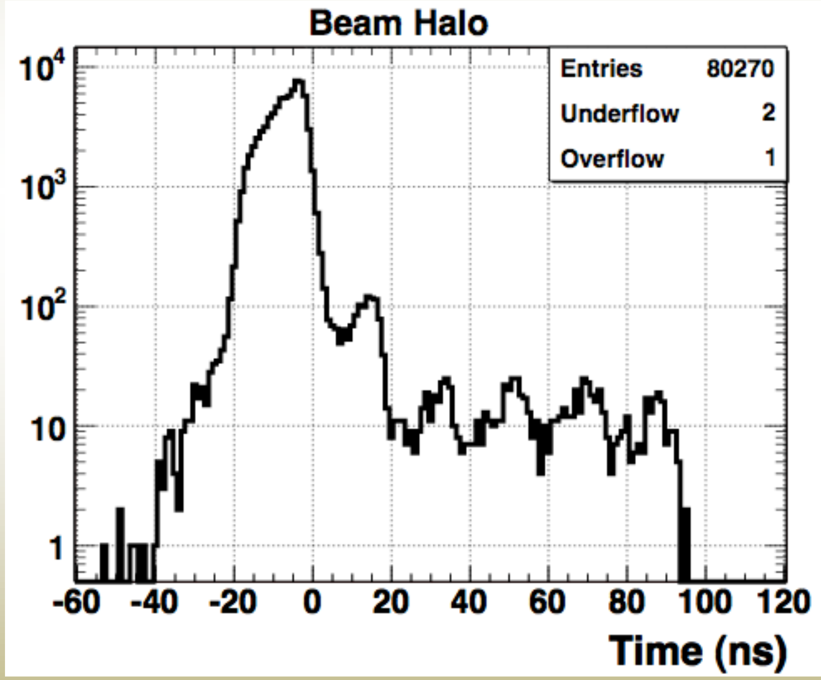


Line of minimum-ionizing energy deposition

Bremsstrahlung results in single high-momentum photon

Beam Halo

- *Halo observable in timing distribution of photon candidates*
  - **18 ns beam bunch structure**
  - **Width due to size of central calorimeter**



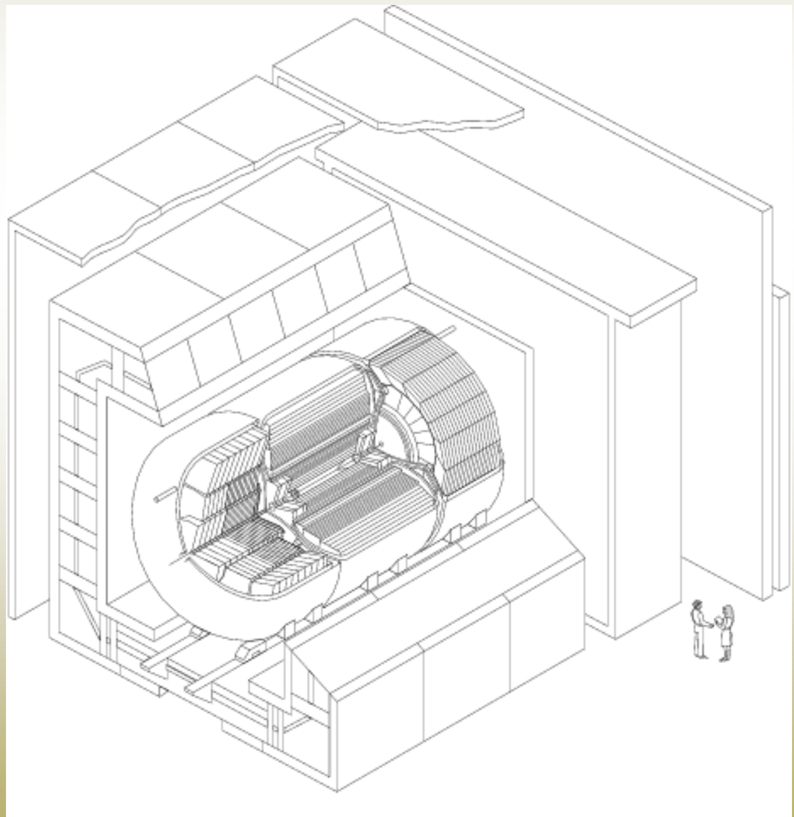
Timing cut reduces background

Residual background removed with calorimeter requirements:

No more than 8 central EM and 2 forward hadronic towers with energy along the line of the candidate photon

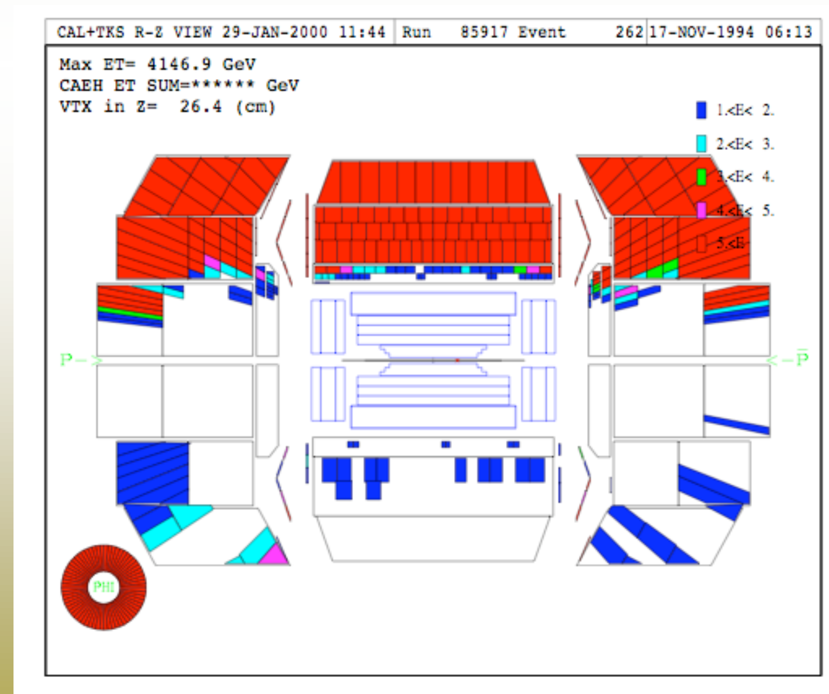
Beam Splash

- *Tevatron Run 1: Two accelerator rings, one went through top of DØ calorimeter*
  - Beam interactions with pipe produced showers inside detector
    - **Vetoed events collected while beam passed through top ring**



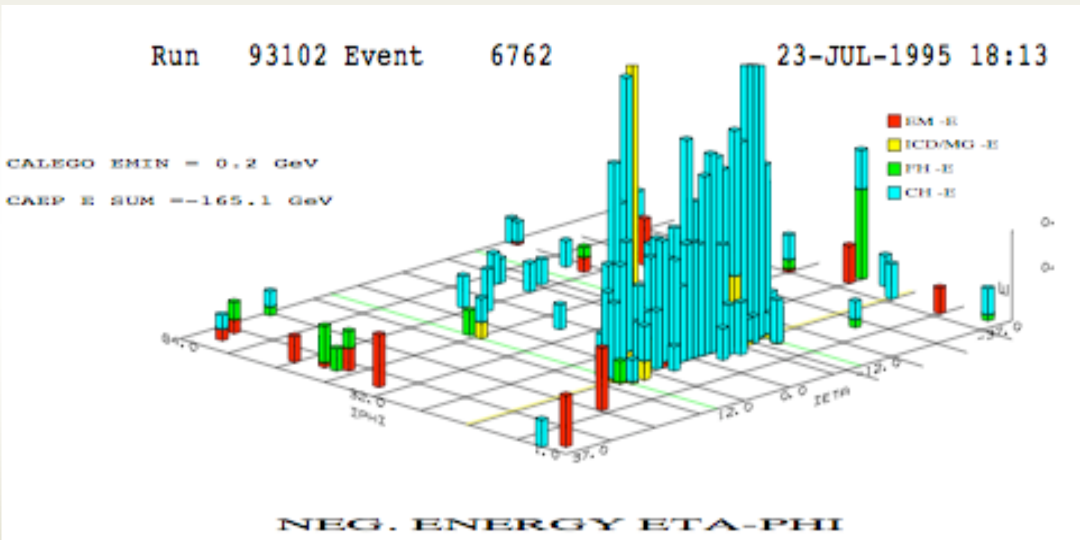
DØ Detector

Two jets plus $\not\!\!E_T$ search for leptoquarks (DØ)

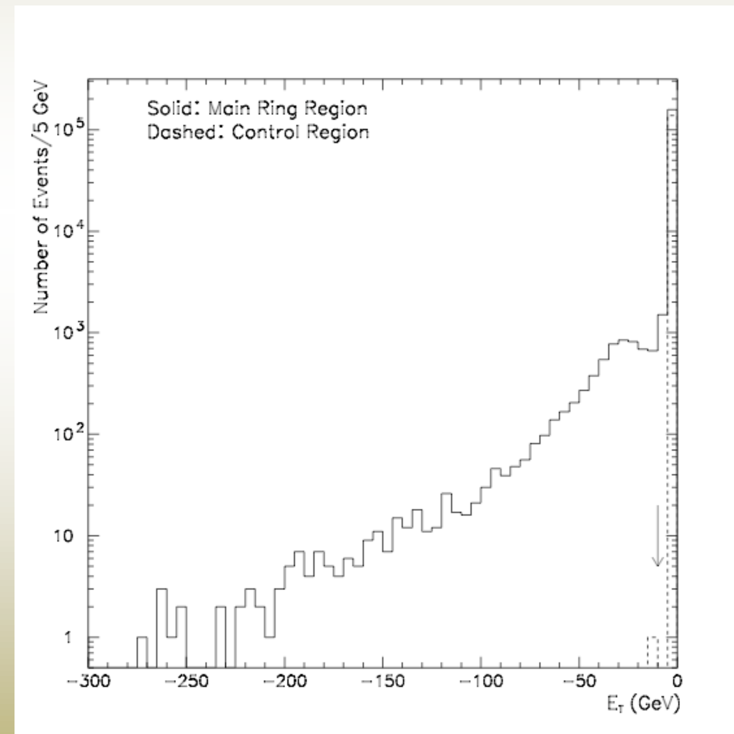


Beam Splash

- *Events collected in crossings after beam splash also had large $\not\!\!E_T$*
  - Charge dissipation from readout resulted in negative observed energies
    - **Charge at end of bunch lower than at start of bunch**



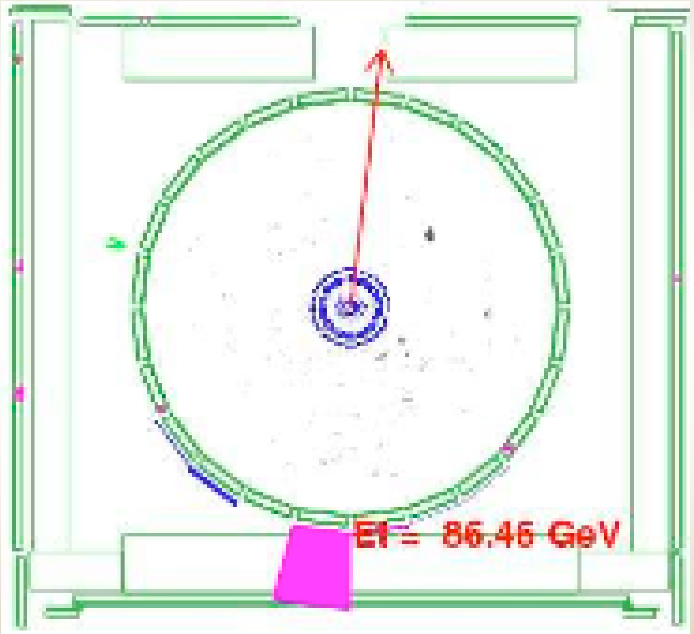
Remove events with either positive or negative energy resulting from beam splash ($|E_T| > 10$ GeV)

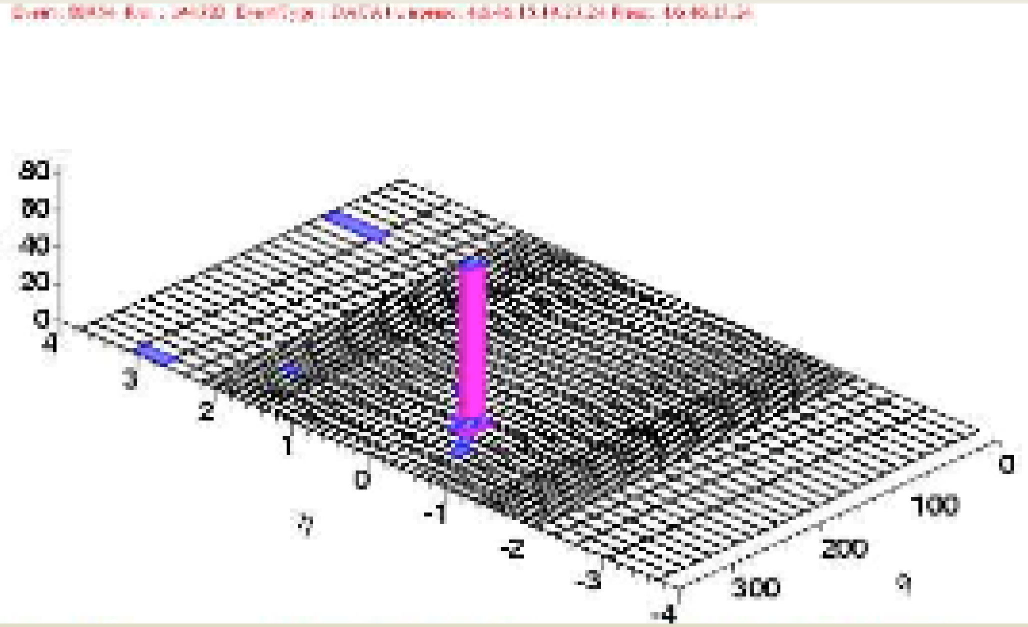


Two jets plus $\not\!\!E_T$ search for leptoquarks (DØ)

Cosmic-Ray Muons

- *Cosmic-ray muon bremsstrahlung contributes to $\not\!\!E_T$*
  - Predominantly single-photon and single-jet events



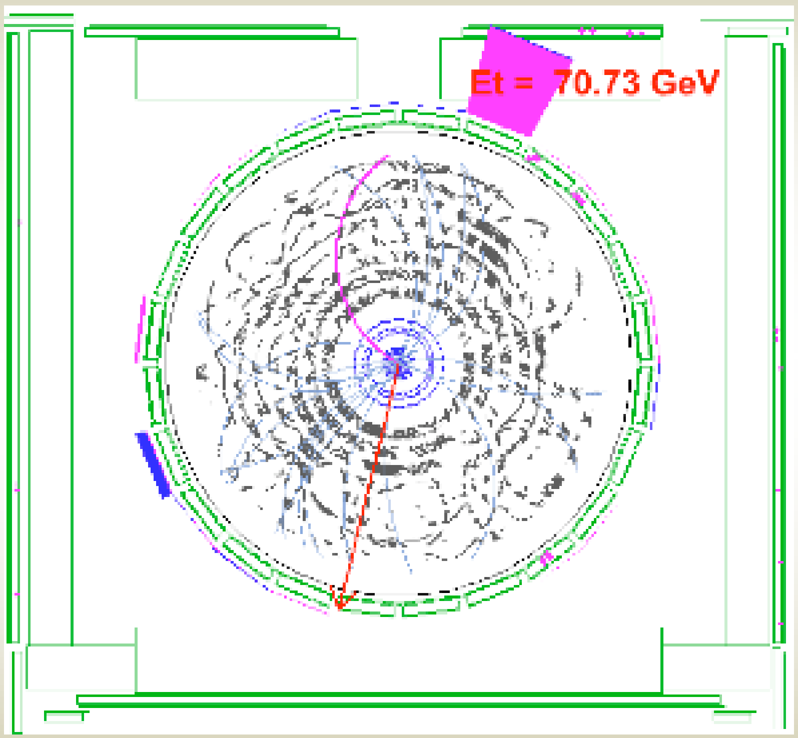


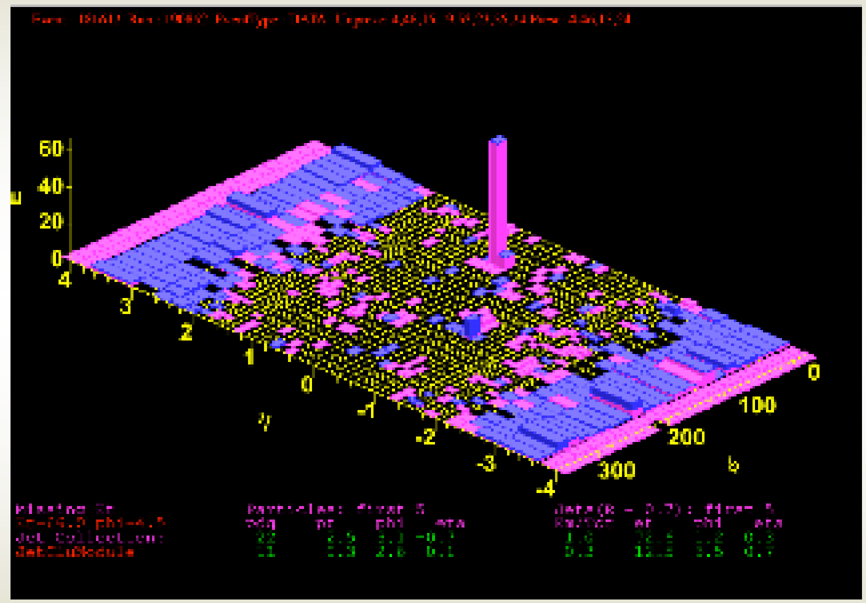
Remove events with fewer than 3 central tracks

Photon plus $\not\!\!E_T$ search for large extra dimensions (CDF)

Cosmic-Ray Muons

- *Cosmic-ray muons can overlap collision events*



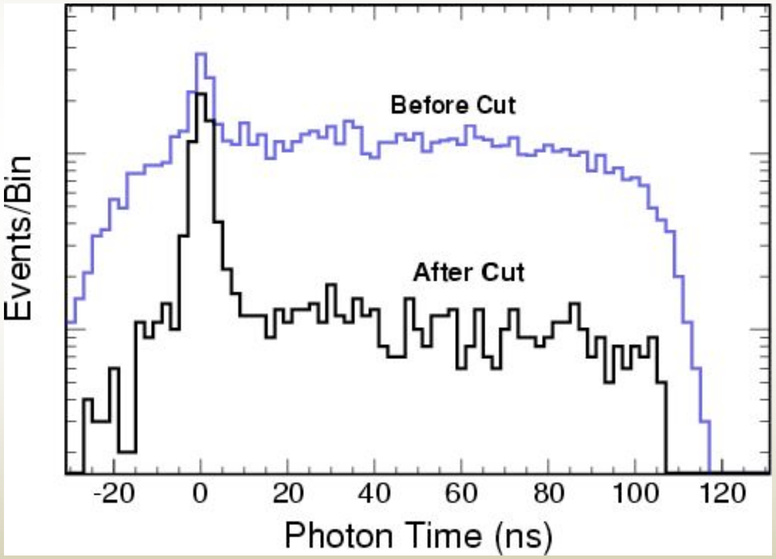


Use EM timing system to remove cosmic overlaps with collisions

Photon plus $\not{E}_T$ search for large extra dimensions (CDF)

Cosmic-Ray Muons

- *Large residual background of cosmic-ray muons overlapping collision events*
  - Create discriminant using:
    - Track stubs in muon chamber in the same direction as photon candidate
    - Energy in hadronic calorimeter and in strip chamber at nominal shower maximum



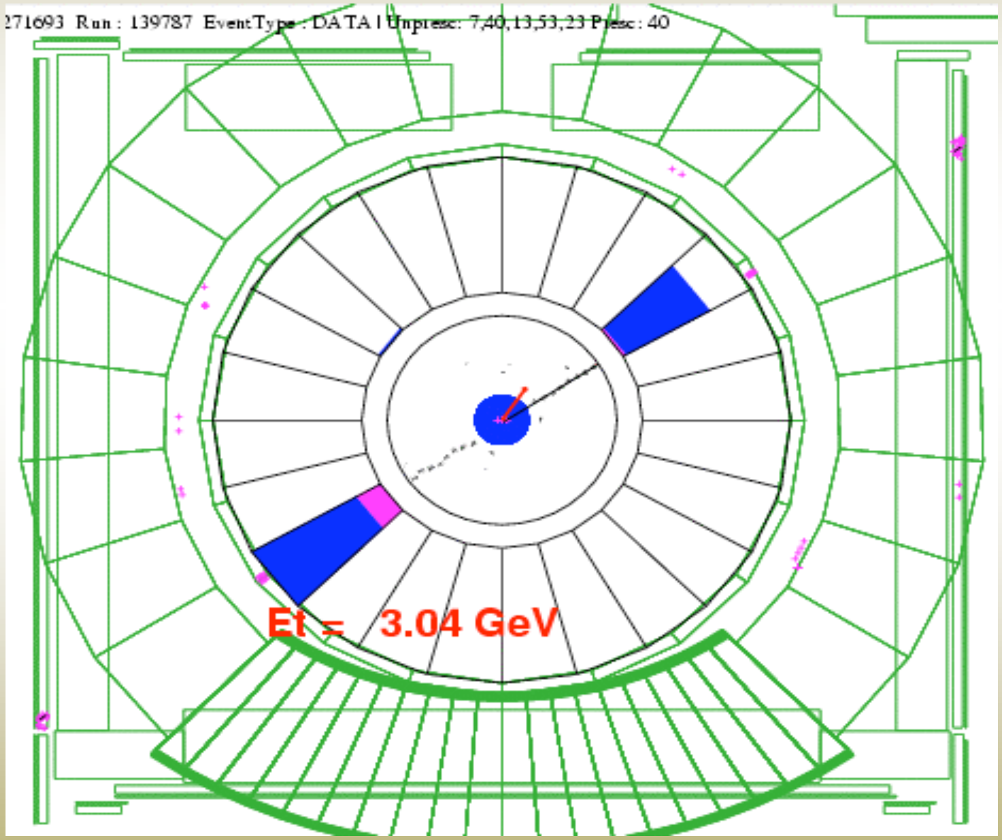
Photon plus $\not{E}_T$ search for large extra dimensions (CDF)

- *Cosmics can also produce jets if bremsstrahlung is in hadronic calorimeter*
  - Remove by requiring jets to have EM fraction between 0.1 and 0.95

Two jets plus $\not{E}_T$ search for leptoquarks (DØ)

Cosmic-Ray Muons

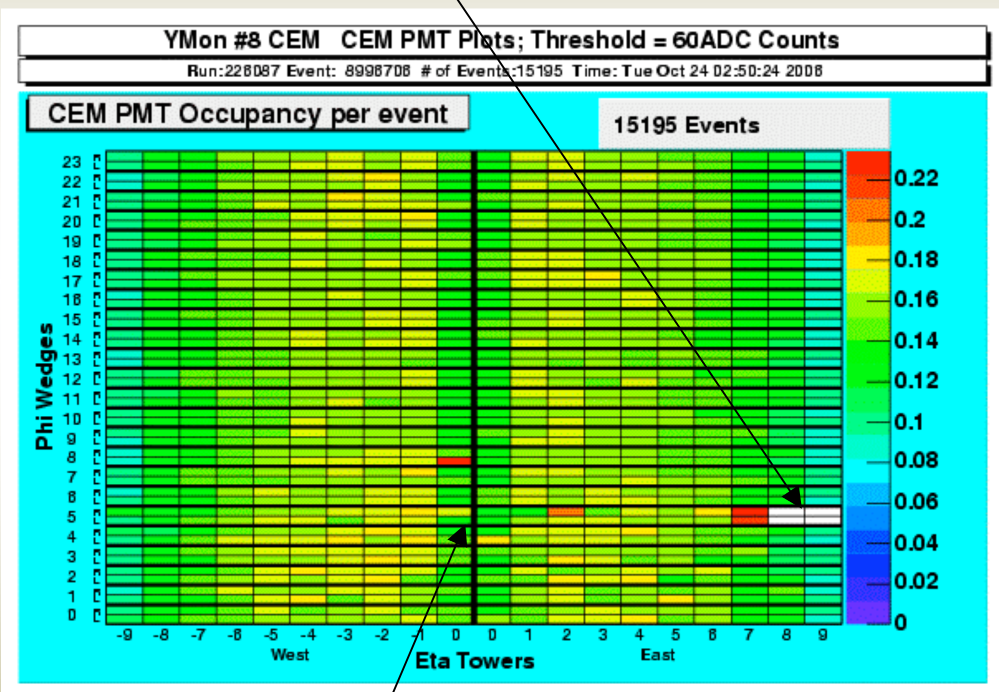
- *A cosmic-ray muon reconstructed on only one side of detector results in* $\not{E}_T$
  - Search for muon track opposite to reconstructed muon

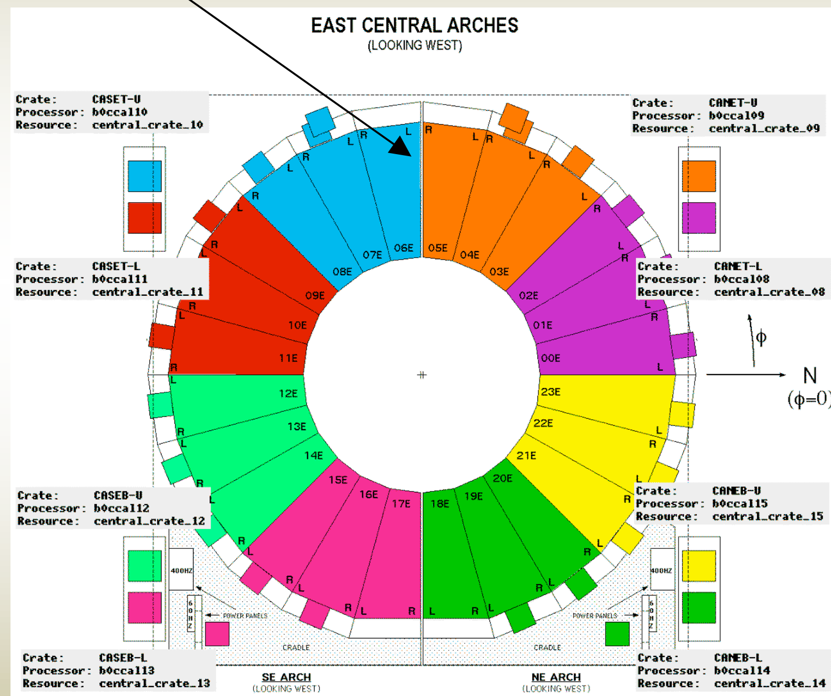


All final states with muons (CDF)

Lost Particles in Jets

- *Detector cracks a significant source of $\not\!\!E_T$*
  - CDF: "Chimney" for cables at top of calorimeter

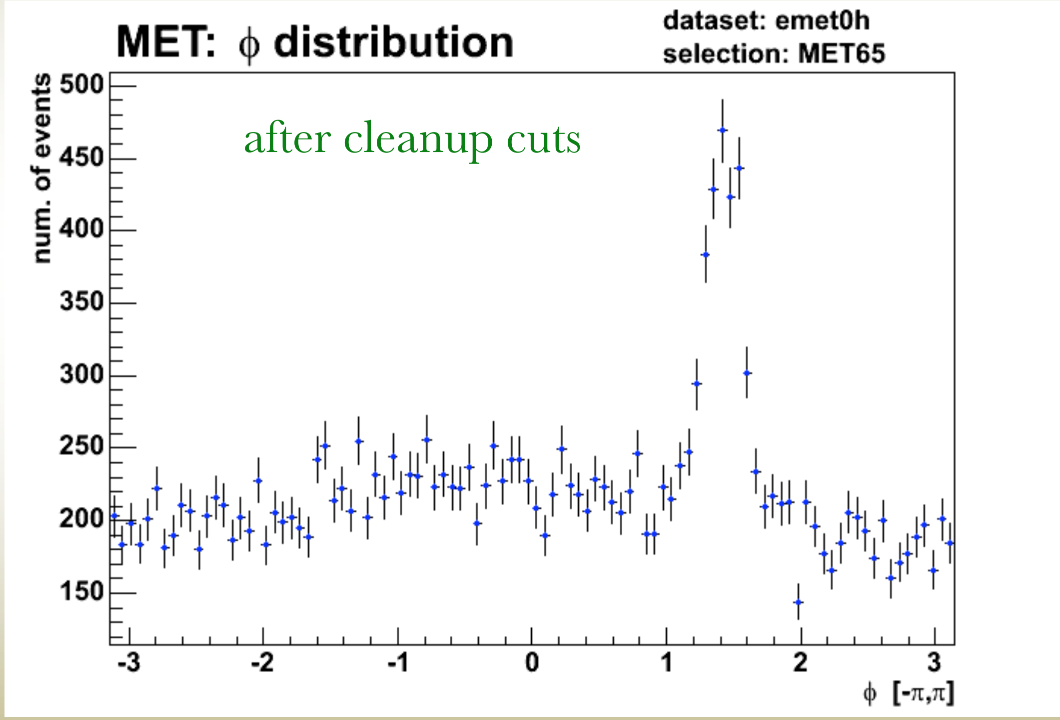


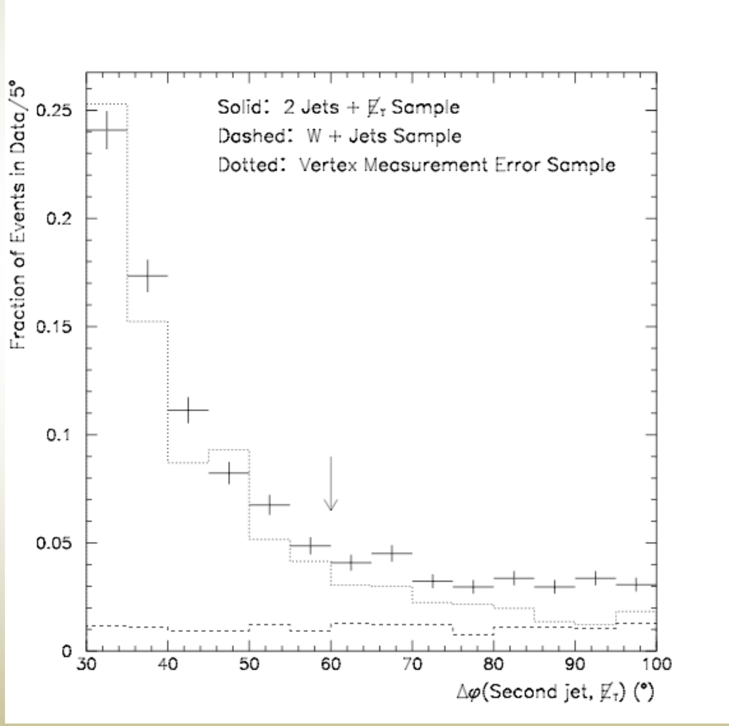


  - CDF: Central crack between calorimeters

Lost Particles in Jets

- *Chimney observable in ϕ distribution of $\not{E}_T$*
  - Reduce background by requiring separation between $\not{E}_T$ and jet directions

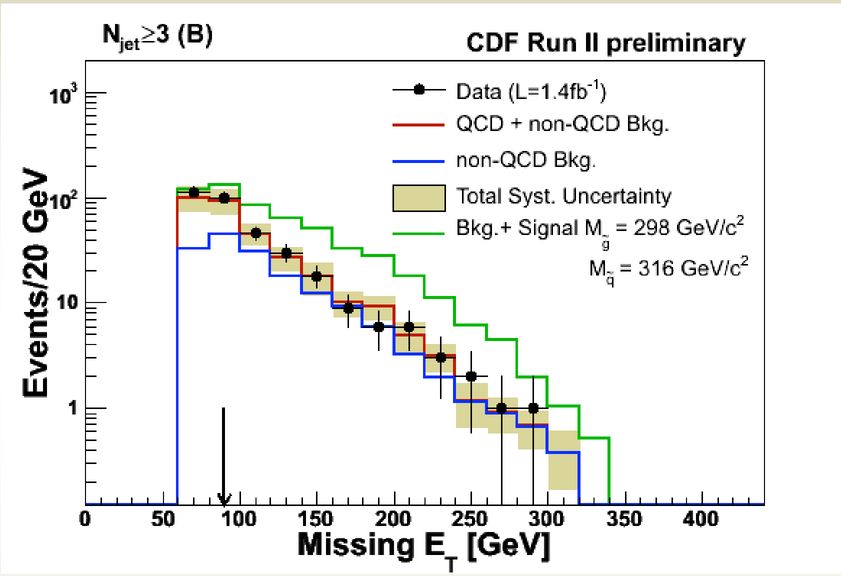




Jets plus $\not{E}_T$ final states (CDF and DØ)

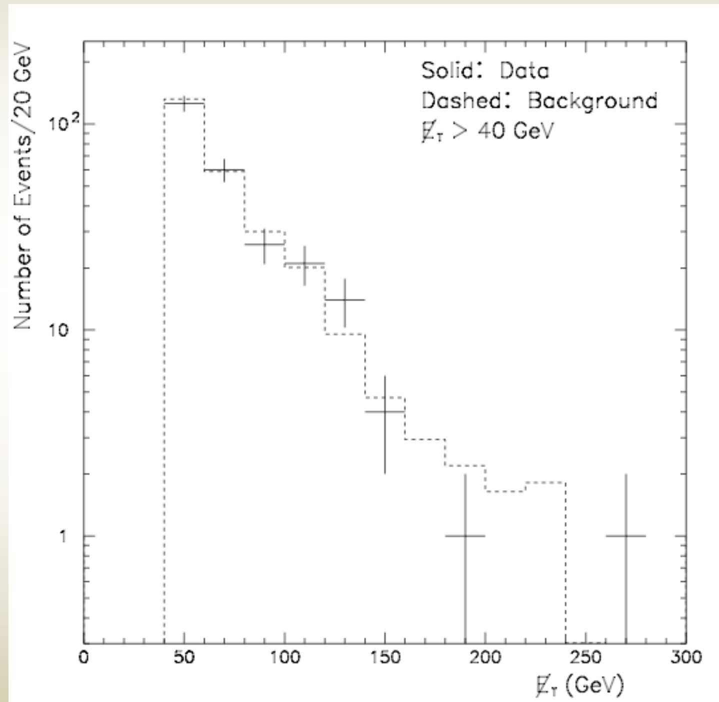
Physics Results

- *After removing pathological events a good description of $\not{E}_T$ is achieved*



Events in 1.4 fb^{-1}	Observed	Total + statistics + systematics
4-jets	29	27 ± 2 ± 9
3-jets(A)	616	607± 16 ± 146
3-jets(B)	166	154± 7 ± 44
3-jets(C)	22	25 ± 2 ± 8
2-jets	13	11 ± 2 ± 3

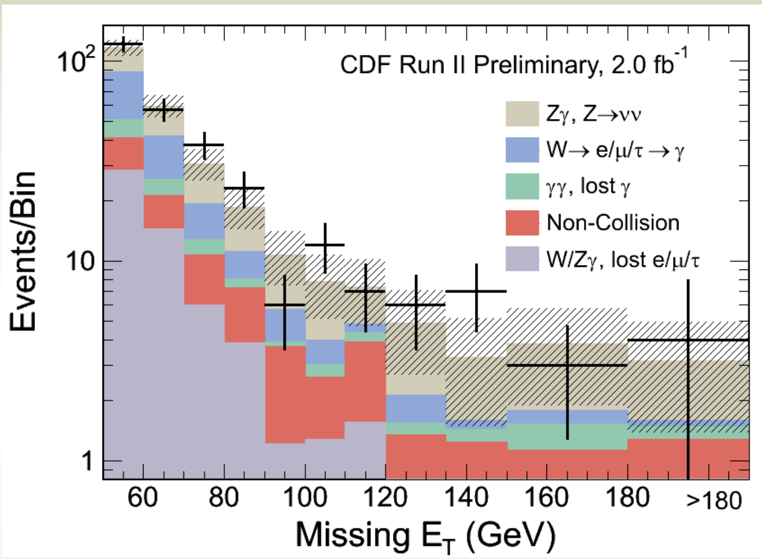
Jets plus $\not{E}_T$ squark/gluino search (CDF)



Two jets plus $\not{E}_T$
leptoquark search (DØ)

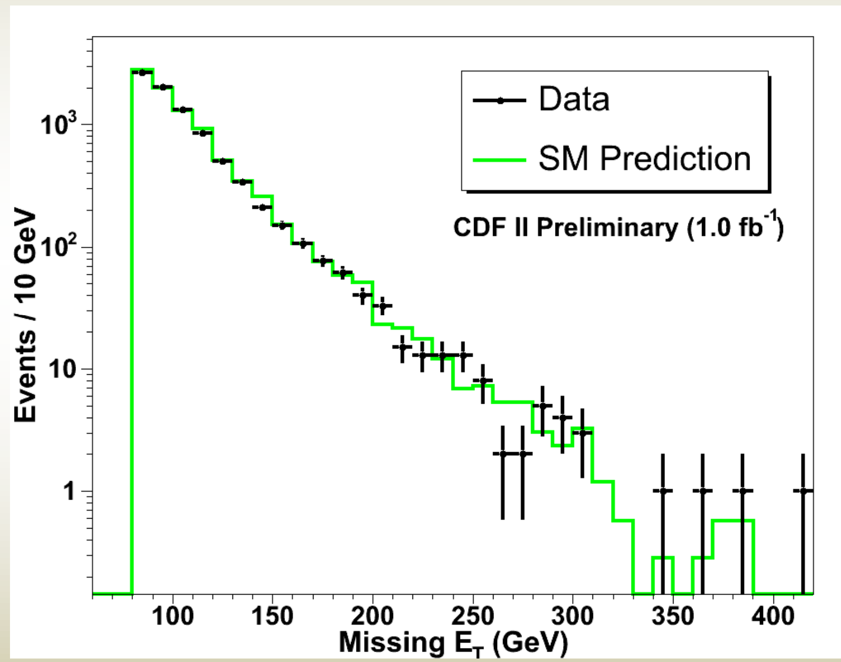
Physics Results

- *After removing pathological events a good description of $\not{E}_T$ is achieved*



CDF RunII Preliminary, 2.0 fb^{-1}		
Channel	$\gamma E_T > 50$ GeV	$\gamma E_T > 90$ GeV
$W \to e \to \gamma$	47.3 ± 5.1	2.6 ± 0.4
$W \to \mu/\tau \to \gamma$	19.1 ± 4.2	1.0 ± 0.2
$W\gamma \to \mu\gamma \to \gamma$	33.1 ± 10.2	1.7 ± 1.2
$W\gamma \to e\gamma \to \gamma$	8.0 ± 3.0	0.8 ± 0.7
$W\gamma \to \tau\gamma \to \gamma$	17.6 ± 1.6	2.5 ± 0.2
$\gamma\gamma \to \gamma$	18.9 ± 2.3	2.3 ± 0.6
cosmics	36.4 ± 2.5	9.8 ± 1.3
$Z\gamma \to \nu\nu\gamma$	84.4 ± 8.0	20.9 ± 2.0
Total	264.8 ± 14.8	42.4 ± 2.9
Data	280	40

One photon plus $\not{E}_T$ large extra dimensions search (CDF)



One jet plus $\not{E}_T$ large extra dimensions search (CDF)

Modelling Momentum Imbalance

- *Given understanding of pathologies, $\not\!\!E_T$ can be modelled by understanding scale and resolution of collision products*

$$\sum_i \vec{p}_i + \overrightarrow{\mathrm{uncl}} + \vec{\not{p}} = \vec{0}$$

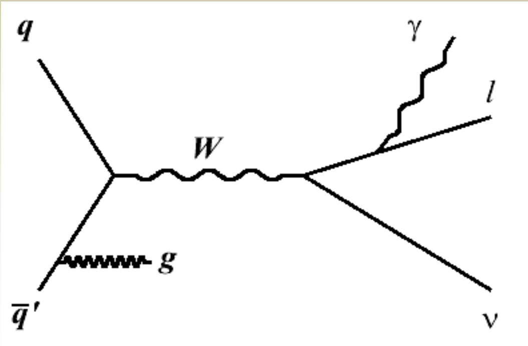
muons
electrons & photons
taus
jets

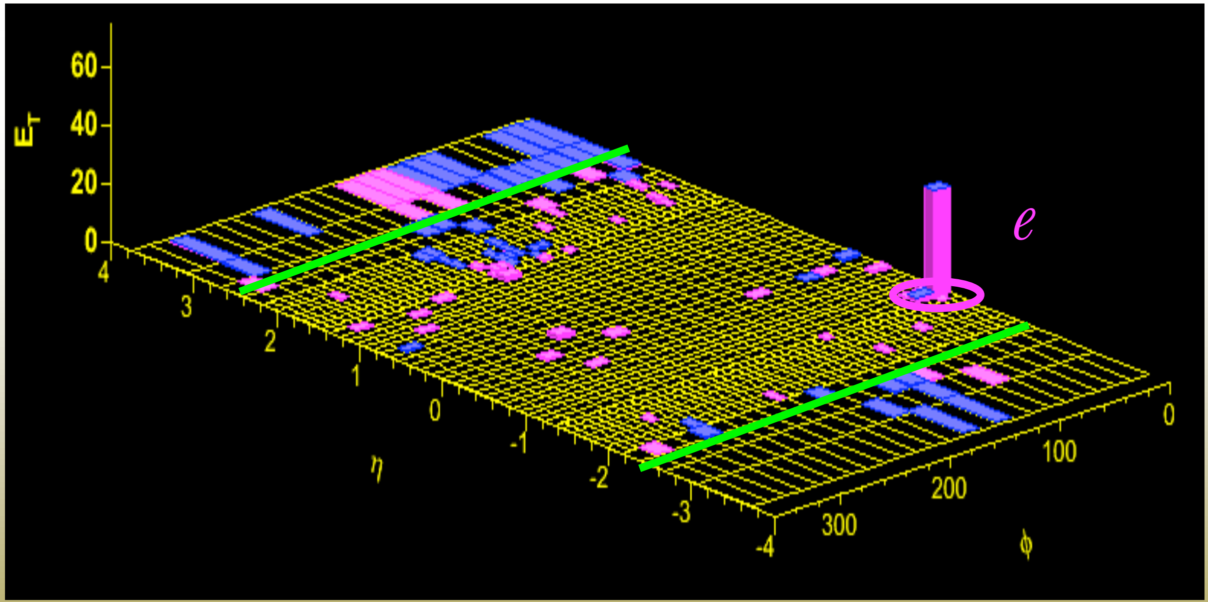
underlying event
extra interactions

- *Approaches to modelling $\not\!\!E_T$*
  - Data-based — 2 jets + $\not\!\!E_T$ search (DØ), 2 photons + $\not\!\!E_T$ search (CDF)
  - Fast simulation tuned to data — W mass measurement (CDF & DØ)
  - Full GEANT simulation tuned to data — Jets + $\not\!\!E_T$ search (CDF)

Case Study: CDF Run II *W* Mass Measurement

- *$\not{E}_T$ calibrated to 0.1% accuracy*
  - Procedure:
    - **Calibrate electrons and muons**
    - **Define unclustered energy measurement**
    - **Calibrate unclustered energy**



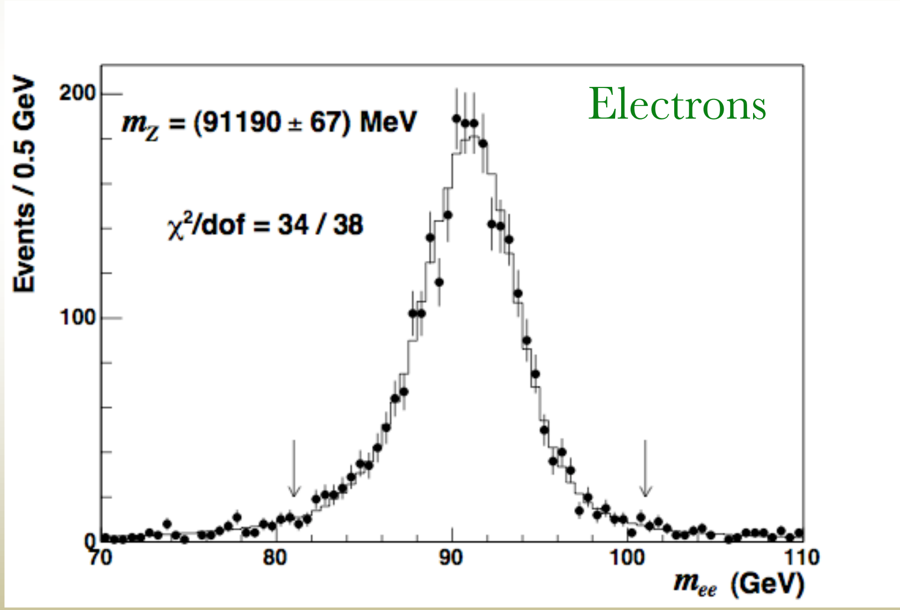


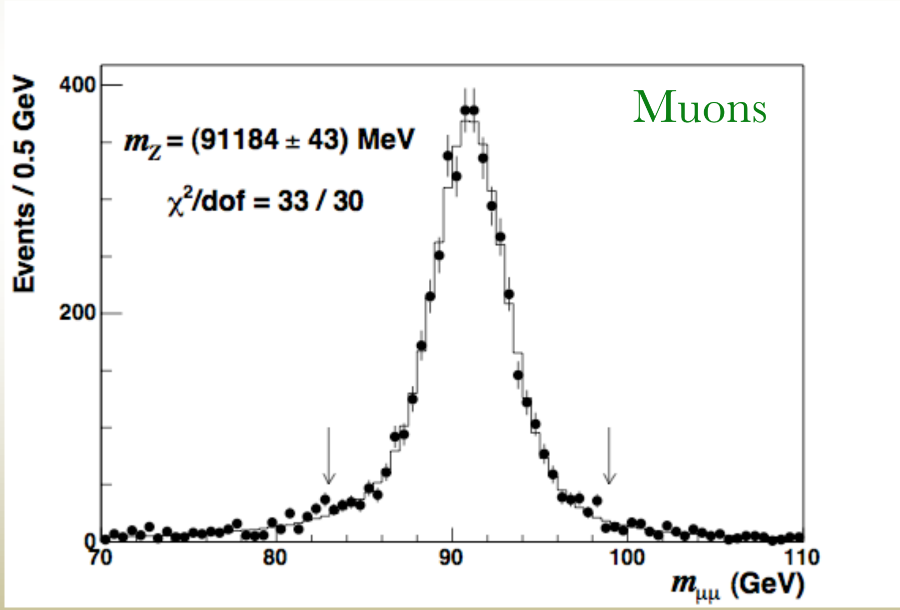
$$\vec{\not{p}}_T = -(\vec{p}_T^{\,l} + \vec{u}_T)$$

unclustered energy: "recoil"

Electron and Muon Calibration

- *Calibrate electron and muon momenta using masses of well-known resonances and ratio of calorimeter to tracker measurements*
- *Z mass measurement validates the calibration*

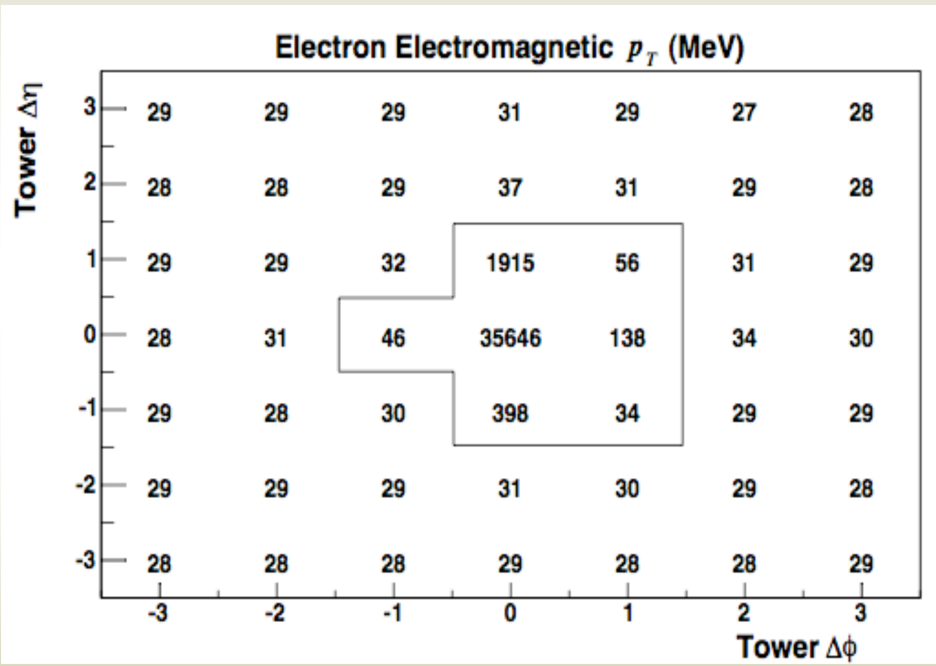


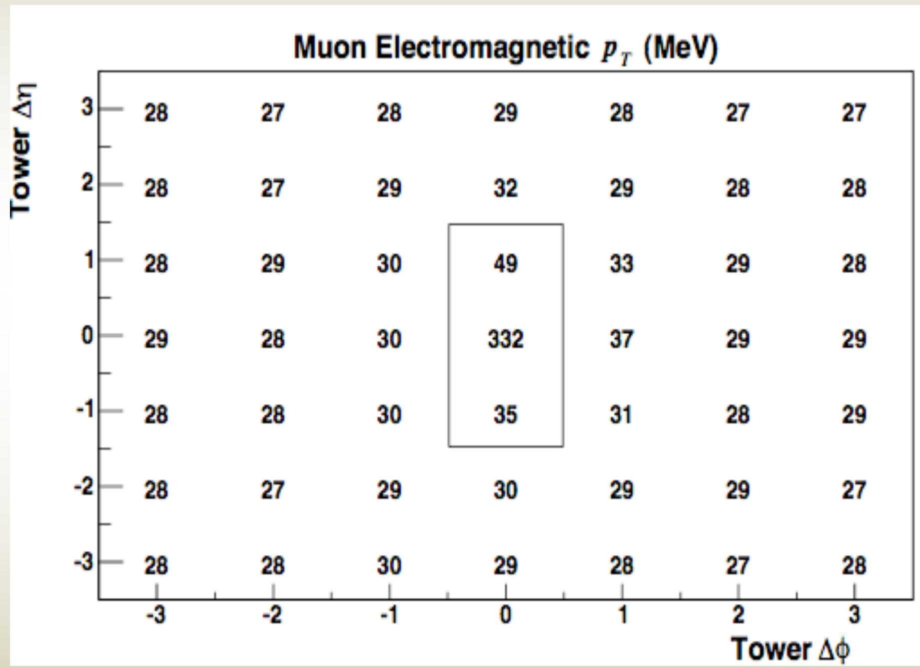


$m_Z^{PDG} = 91188$ MeV

Electron and Muon Removal

- *Remove calorimeter towers with energy from electron or muon*





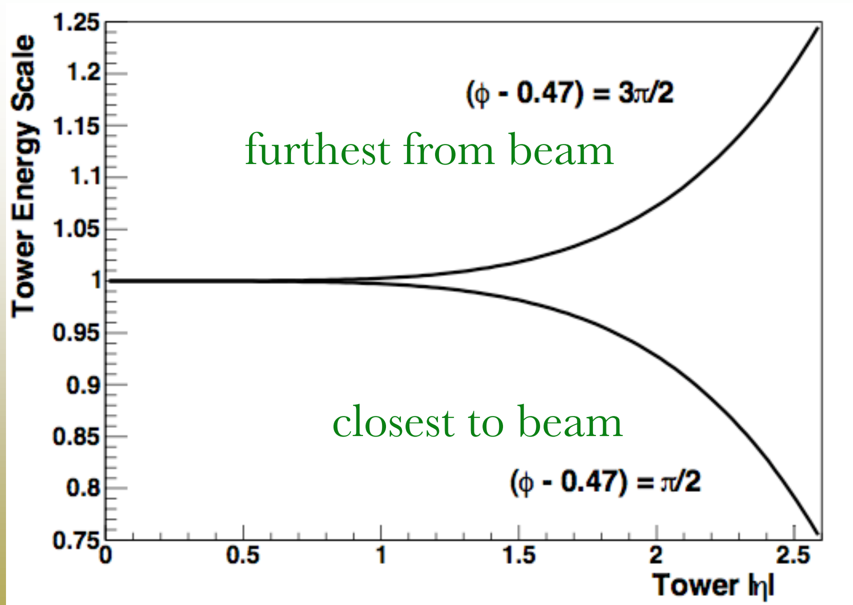
Need to simulate underlying event energy removed from towers

Unclustered Energy Measurement

- *Apply large (5 GeV) threshold to calorimeter towers closest to beam*
  - Reduces bias from beam splash and low-momentum central particles
  - Maintains measurement of high-energy jets

- *Apply 12% relative scale between central and forward calorimeter towers*
  - Determined by comparing calorimeter and tracker measurements for isolated charged pions
  - Improves resolution of unclustered energy measurement

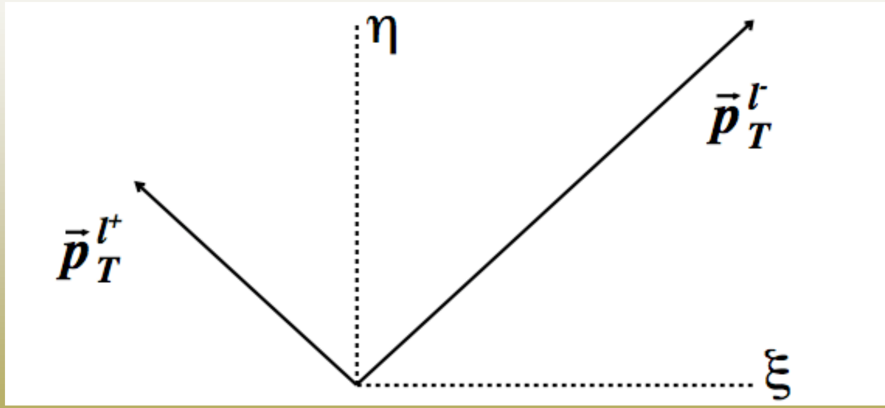
- *Correct measured energy for acceptance variations from beam radial offset*
  - Towers closest to beam have highest acceptance: scale down measured energy

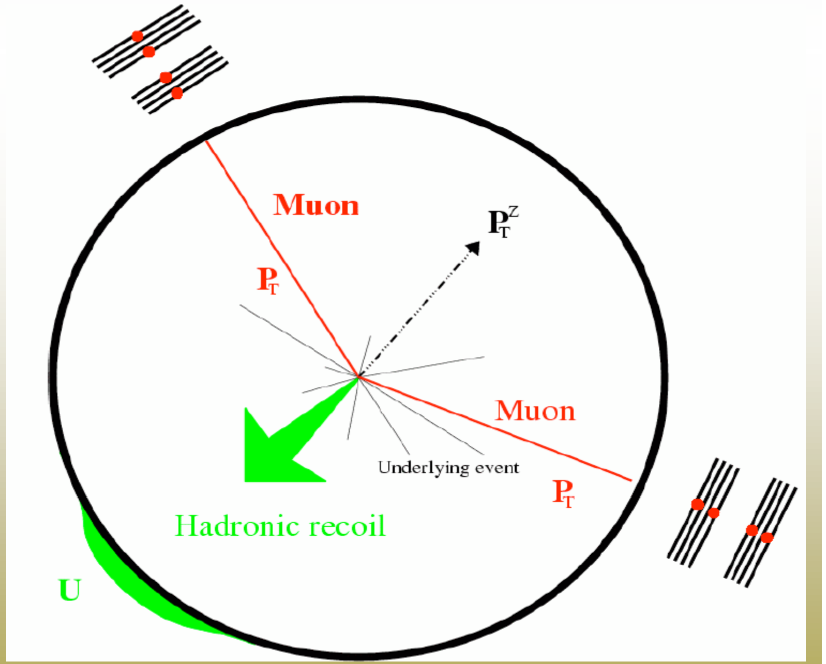


Unclustered Energy Calibration

- *Recoil model components*
  - Radiation in production of *W* boson
  - Radiation from "spectator" partons (underlying event) and additional $p\bar{p}$ collisions

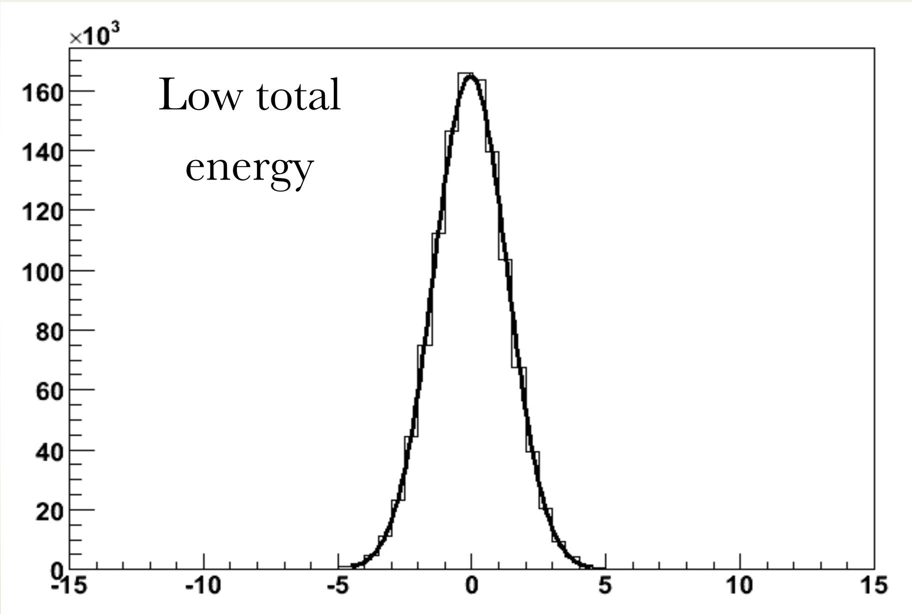
- *Calibrate radiation and measurement with events where all particles are observable*
  - Generic inelastic $\bar{p}p$ collisions
  - Z boson decays to charged leptons
    - Define coordinate system (η, ξ) such that net radiation lies along -η direction

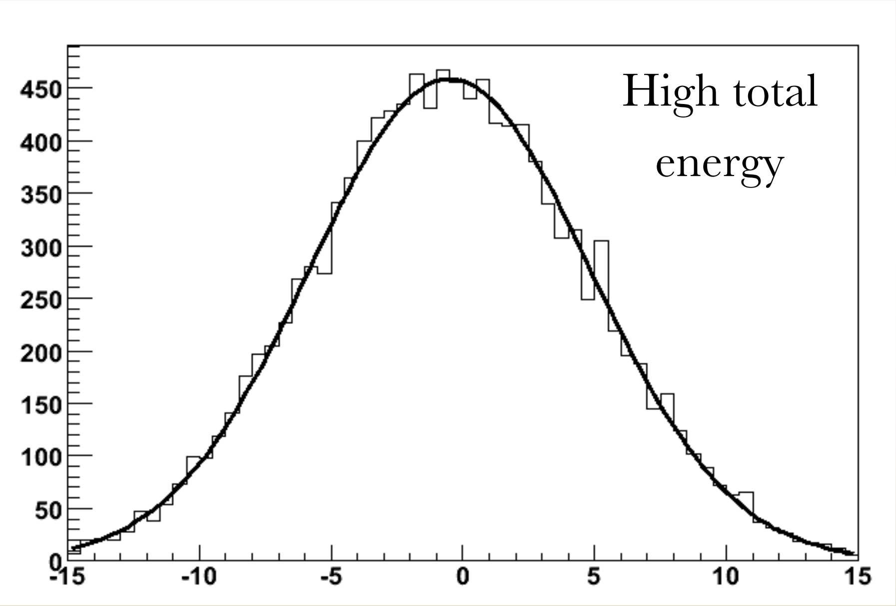




Underlying Event Energy Calibration

- *Underlying event and additional interactions*
  - Resolution depends on energy in calorimeter



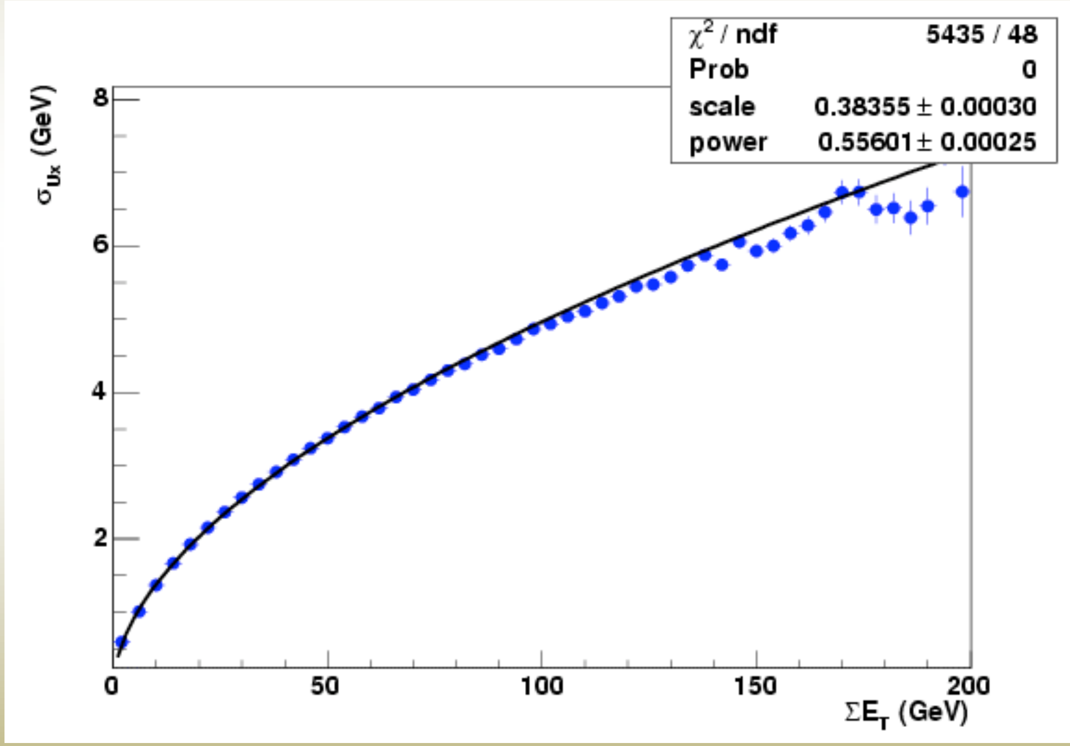


Net energy in *x*-direction (GeV)

Underlying event resolution gaussian for a given ΣE_T

Underlying Event Energy Calibration

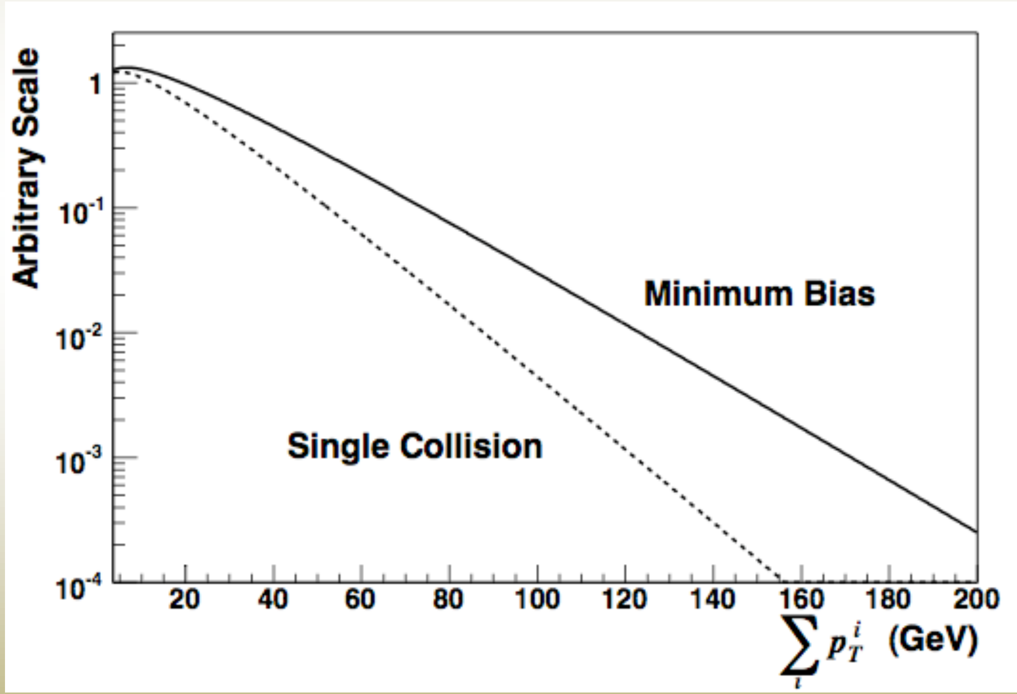
- *Calorimeter samples energy deposited by particle showers*
  - Statistical fluctuations on the number of sampled particles result in $\sqrt{\Sigma E_T}$ dependence to resolution



Fit to function σ = $\boldsymbol{scale}$ $\Sigma E_T^{\,power}$

Underlying Event Energy Calibration

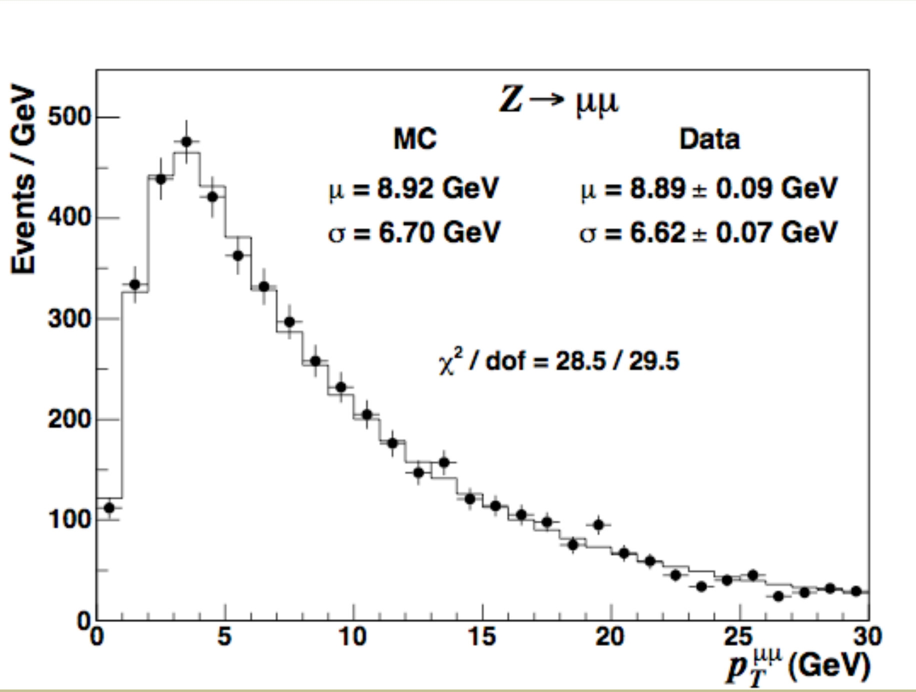
- *Model underlying event and additional interactions using a per-event ΣE_T distribution*
  - Take distribution from generic $\bar{p}p$ interactions ("minimum bias")
  - Use expected number of interactions per $\bar{p}p$ crossing to extract a single-interaction distribution

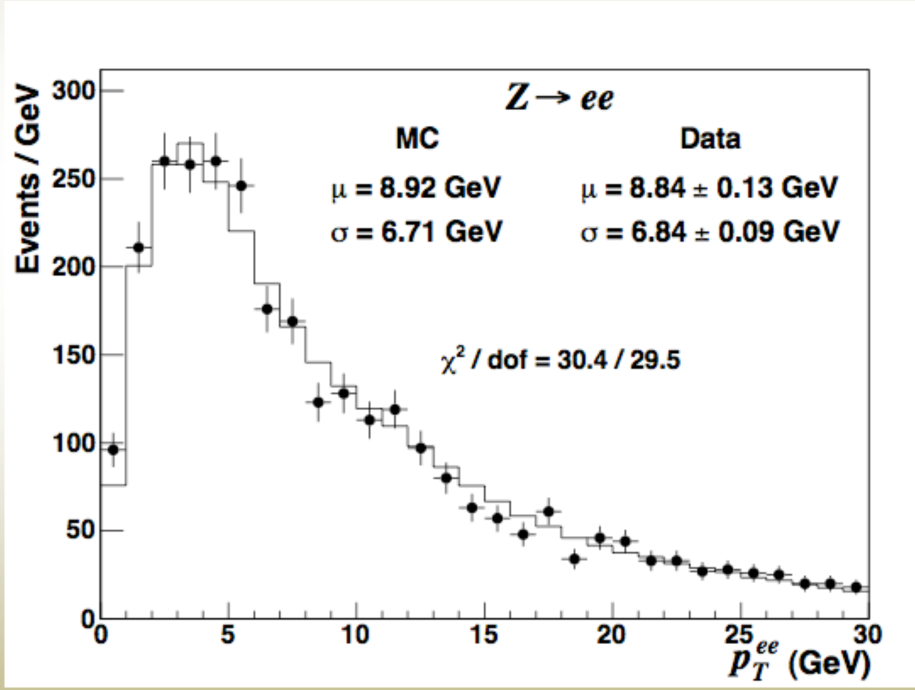


Scale single-collision energy according to *Z* data fit

Radiated Energy Calibration

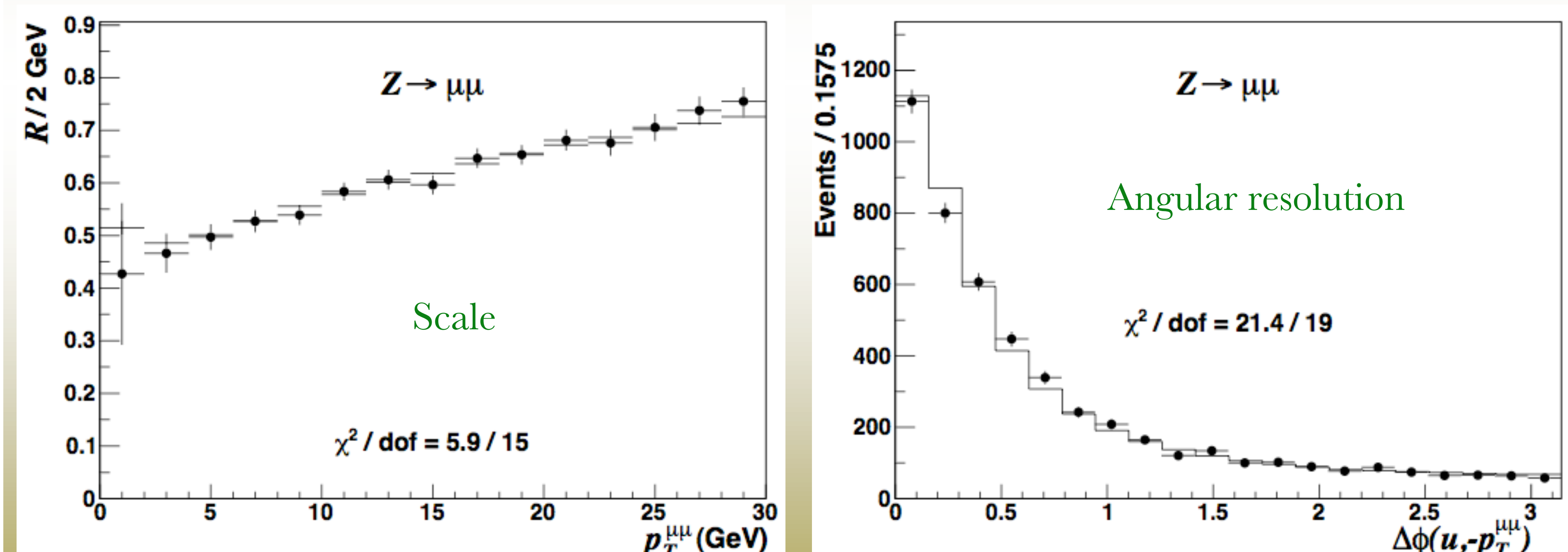
- *Net radiation in W production calibrated using Z production*
  - Small theoretical correction due to difference between *W* and *Z* masses





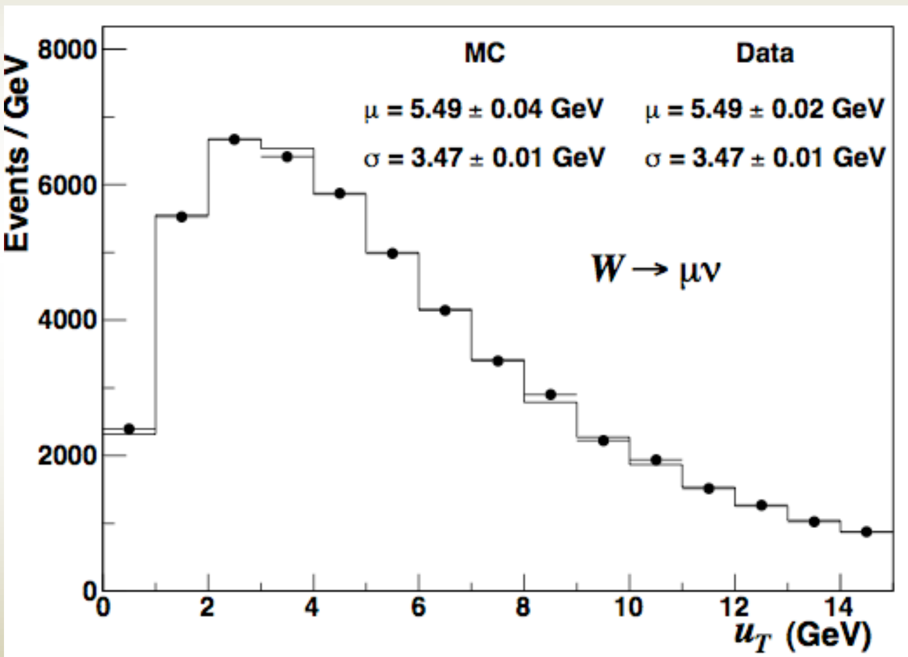
Radiated Energy Calibration

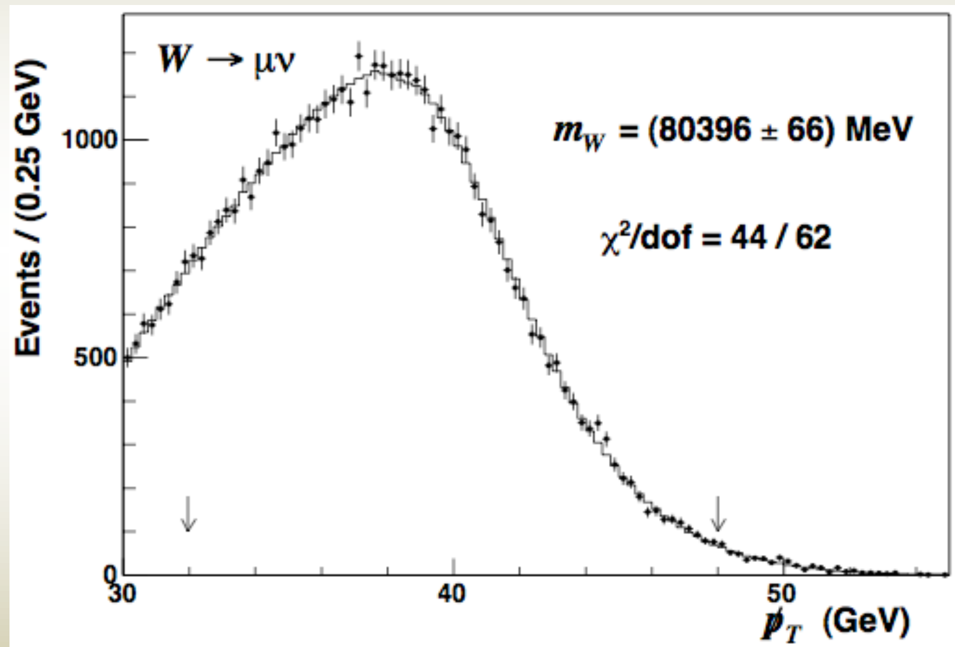
- *Fraction of measured radiation ("scale") and resolution calibrated using Z data*
  - Scale has logarithmic dependence on radiated energy
  - Resolution has quadratic dependence on radiated energy
  - Apply angular resolution to radiated momentum



Results

- *Net radiation in W events well modelled*
- *Missing momentum fit gives 0.1% accuracy on m_W*





Missing momentum fit in muon channel:
45 MeV systematic uncertainty
80 MeV total uncertainty

Summary

- *Missing transverse energy a part of many discovery and measurement signatures*

- *Two aspects to understanding missing momentum:*
  - Determine and reduce pathologies
    - Model residual pathological events with data using discriminating variables
  - Calibrate detector response to high-p_T particles and unclustered energy
    - Results can be used in tuned fast simulation or full GEANT simulation

- *Expect new challenges with the new collider and detectors at the LHC!*