Missing Transverse Energy at the Tevatron

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Outline:

- Introduction
- Missing E_T and the W mass
- Higgs searches relying on missing E_T
- Searches for new physics with missing E_T

Thanks to Viacheslav Shary, Patrice Verdier, Song Ming Wang

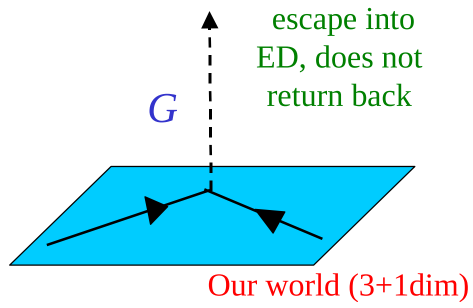
Physics sources of $\not\!\!E_T$

Particle detection in collider detectors based on

- electromagnetic or strong interaction
- instrumentation above a certain minimum angle wrt the beam

Collider detectors will miss:

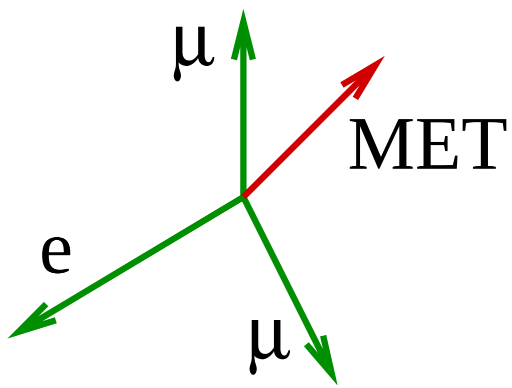
- proton remnants (momentum along the beam direction)
- neutrinos
- gravitons
- neutralinos, gravitinos etc.



Can use conservation of transverse momentum to infer p_T of particles escaping:

$\longrightarrow$ theorist's definition of Missing E_T

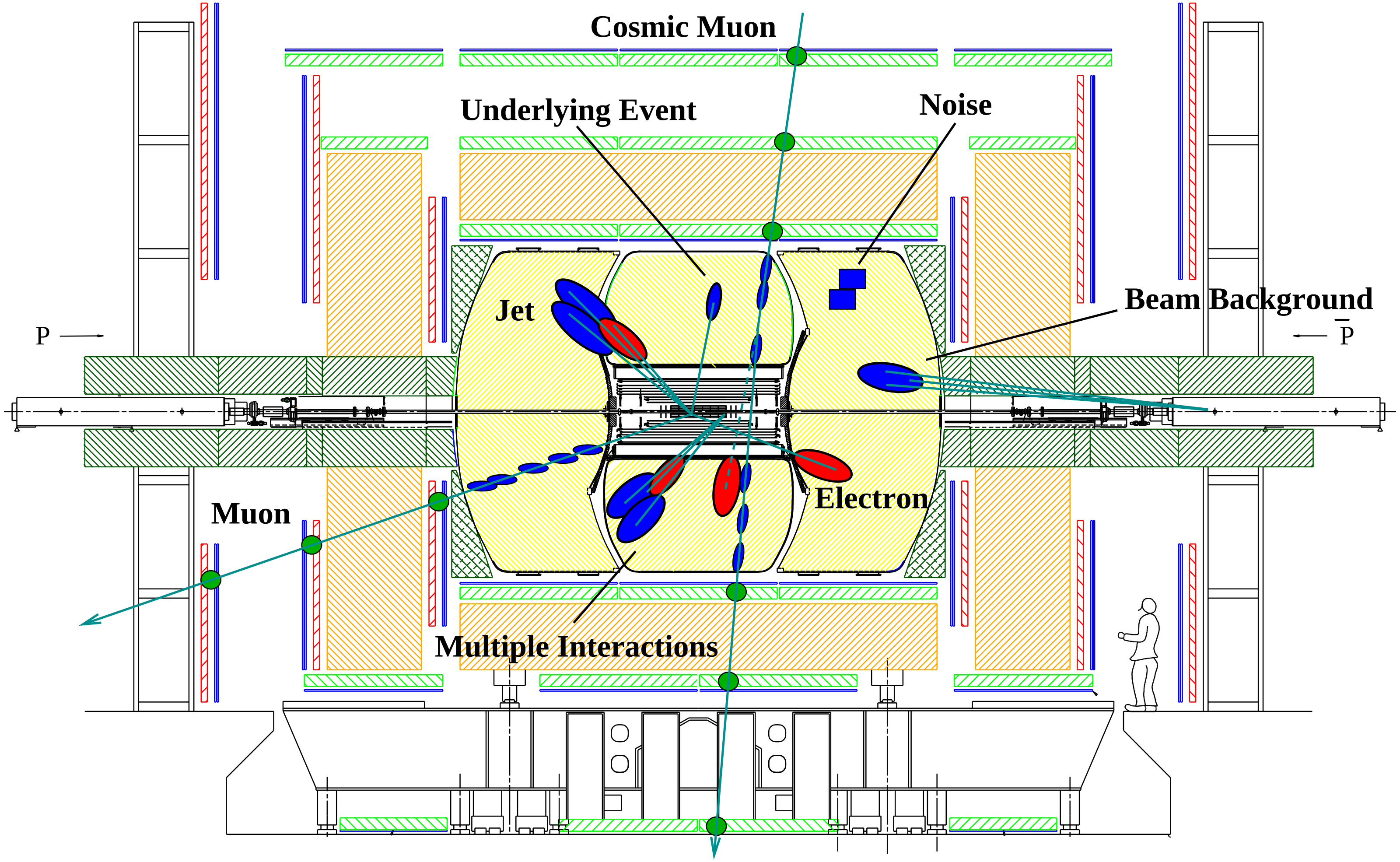
$$\not\!\!E_T = -\sum_{vis} p_T$$



Experimentalist's View

The challenge: precise measurement of $\Sigma\, p_T^{vis}$

- requires hermetic detector $\longrightarrow$ calorimeter: $\Sigma_{cell}\, E_T^{cal}$



Several problems:

- need to relate calorimeter energy deposition to particle momentum (calibration etc.)
- need to separate energy from event under study from all other depositions
- need to combine with tracking to measure direction of energy flow

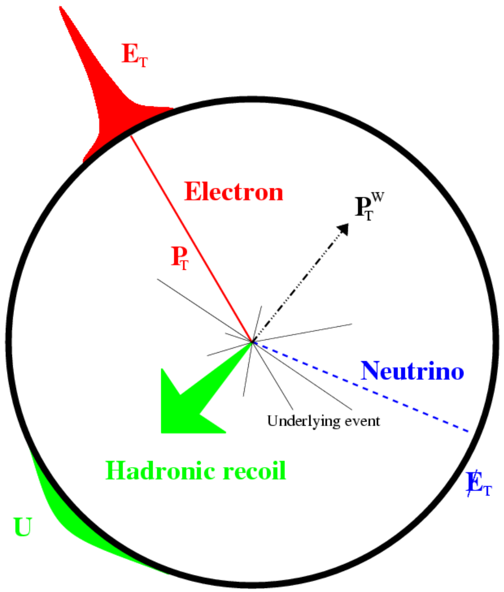
Measurement of W mass and width

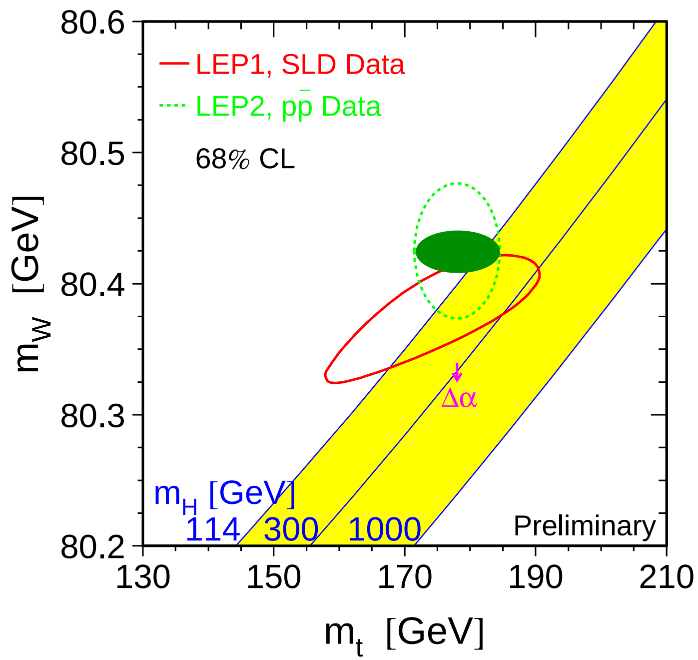
Tevatron collider provides massive samples of W events

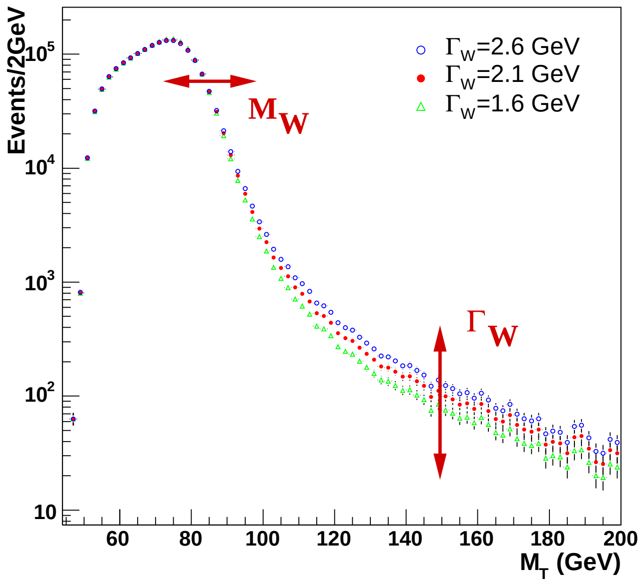
→ **precision measurements of W mass and width**

Both measurements rely on transverse mass distribution

$$M_T = \sqrt{2p_T^\ell \not{E}_T(1 - \cos\Delta\Phi(\ell, \not{E}_T)}$$



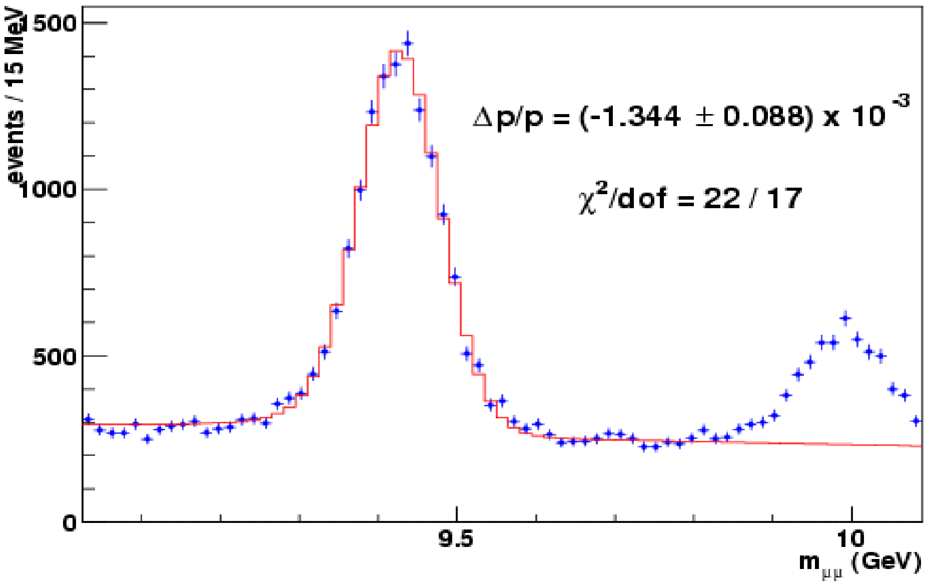


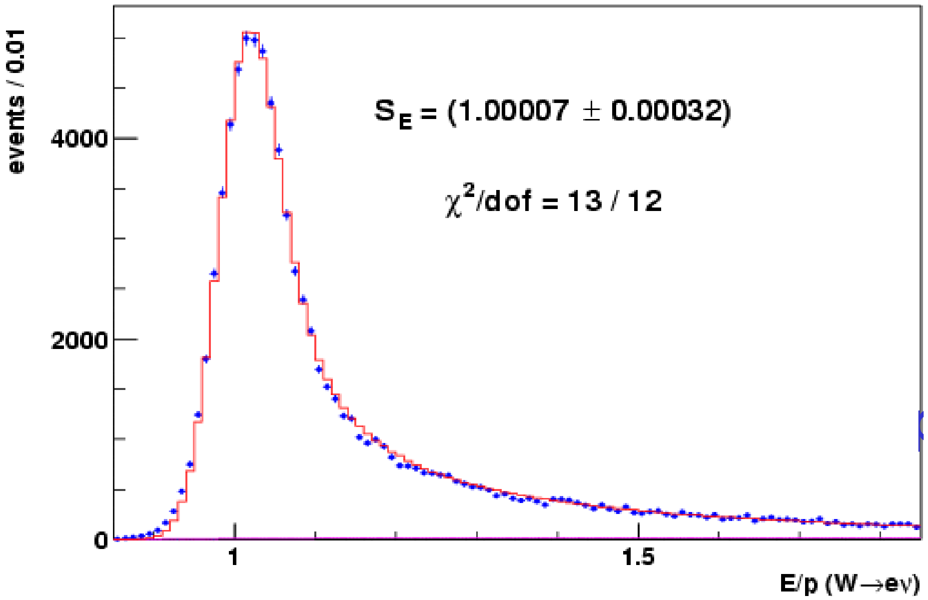


CDF/DØ currrently aiming at 50 MeV error on M_W

→ **need very precise calibration of electrons, muons and recoil**

W mass and width – Lepton Calibration



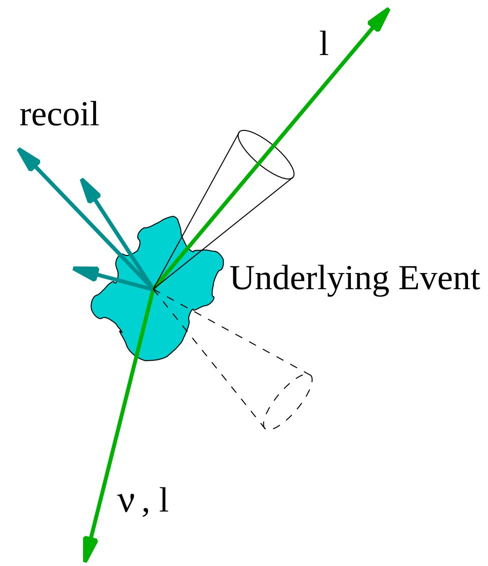


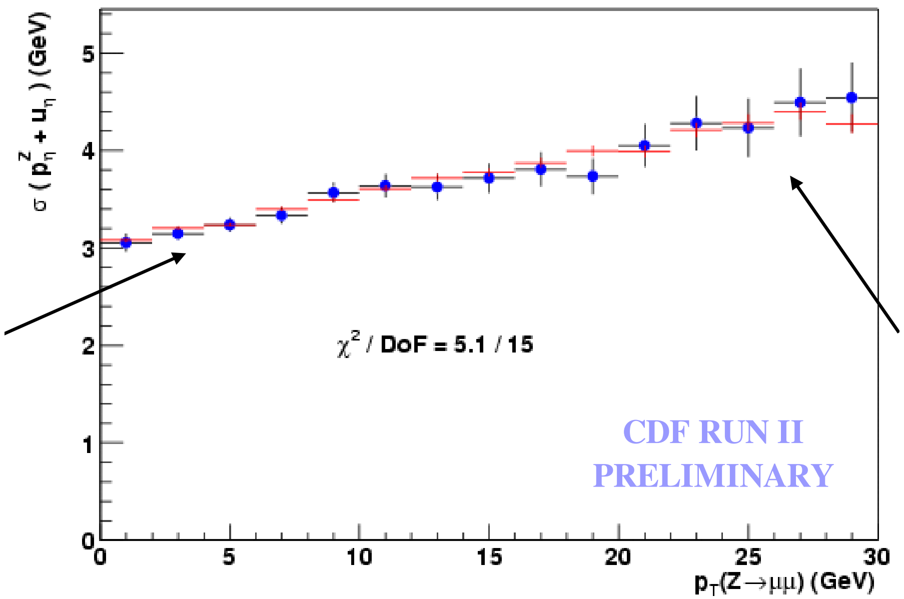
- Muon momentum scale measured in J/Ψ and Upsilon decays
  - CDF: calibrated to 0.03% (→ $\Delta M_W = \pm 25$ MeV)
- Electron energy scale measured using E/p
  - CDF: energy scale contributes with $\Delta M_W = \pm 35$ MeV
- use tail of E/p to tune modelling of upstream material distribution (Bremsstrahlung!)
  - CDF: material distribution: $\Delta M_W = \pm 55$ MeV

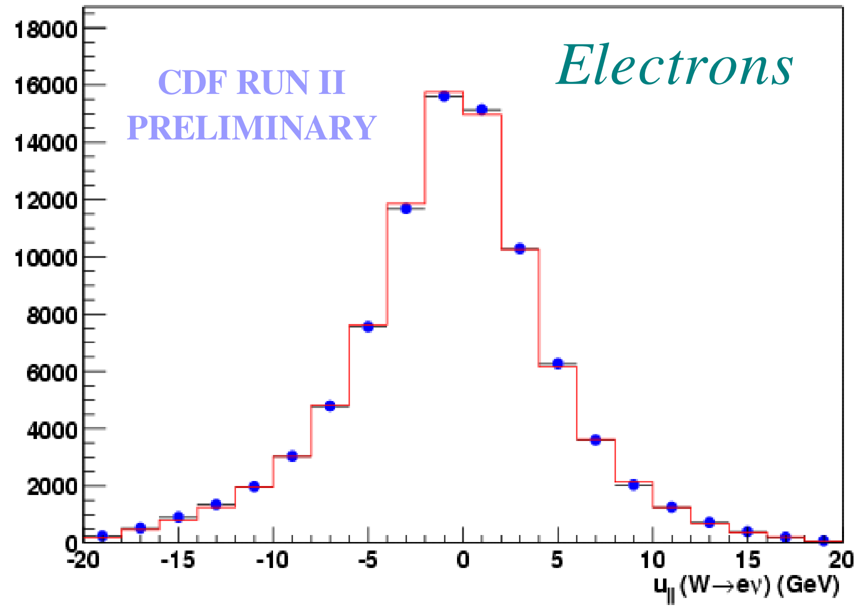
W mass and width – Recoil Calibration

Recoil modelling:

- calorimeter response to hadrons (measured and modelled using $Z \to ll$)
- noise/pileup modelled using minimum-bias data
- measurement of energy flow from underlying event is biased by lepton reconstruction and isolation ($u_{||}$)
  - modelled in W events

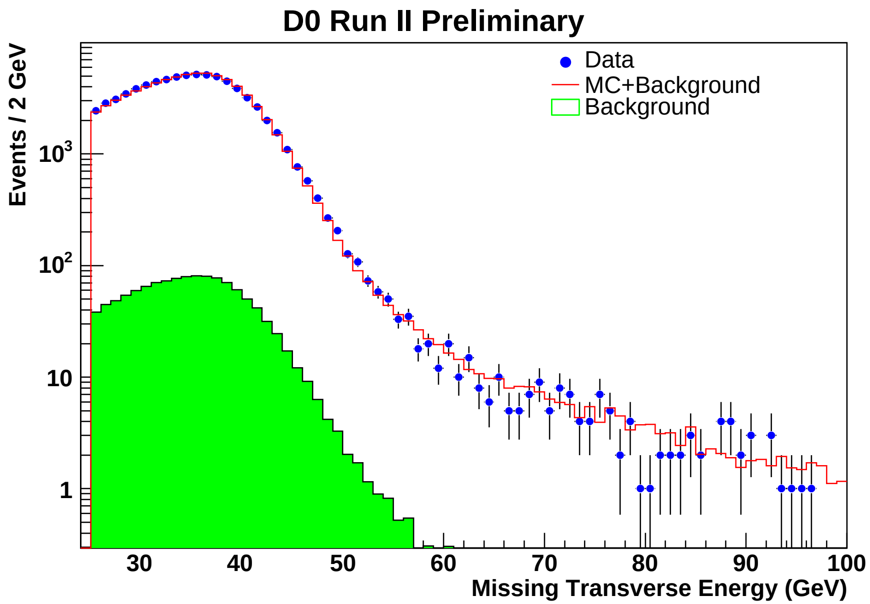


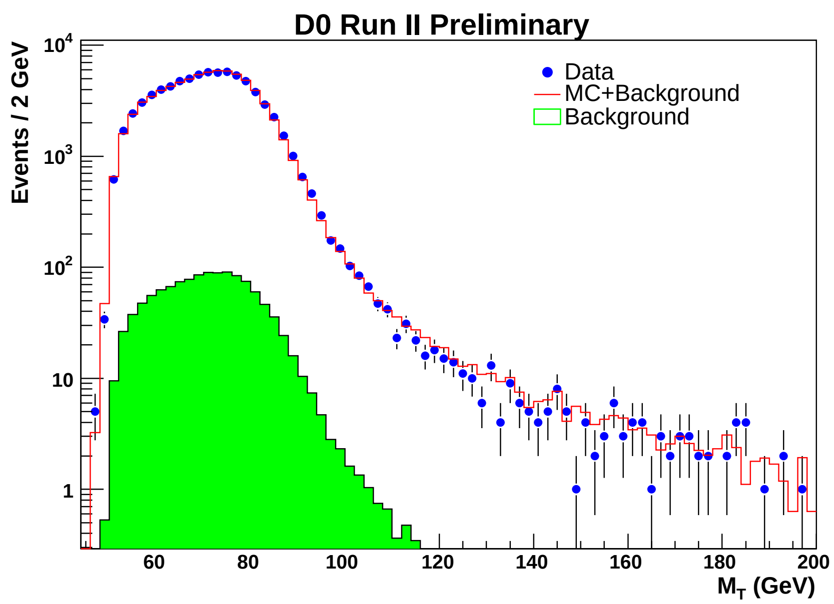




- CDF: Recoil resolution modelling contributes with $\Delta M_W = \pm 42$ MeV
- CDF: Simulation of bias $u_{||}$ matches data within 30 MeV

W width – Results



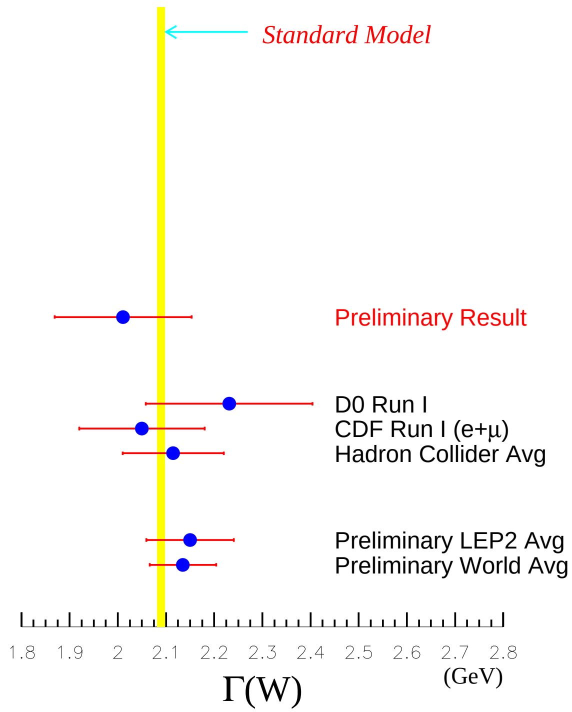


DØ Run II measurement (preliminary, 177 pb^{-1}):

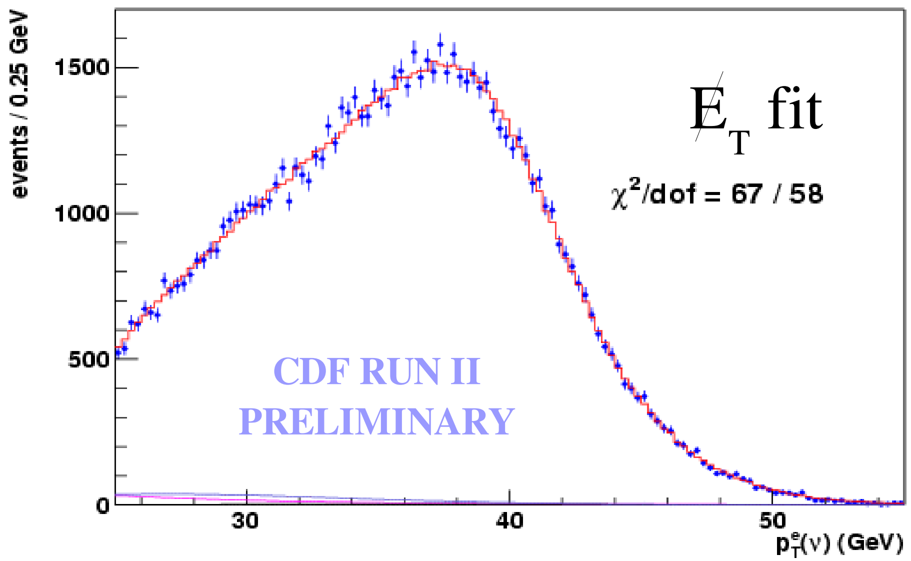
$$\Gamma_W = 2.011 \pm 0.093(\text{stat}) \pm 0.107(\text{syst})\ \text{GeV}$$

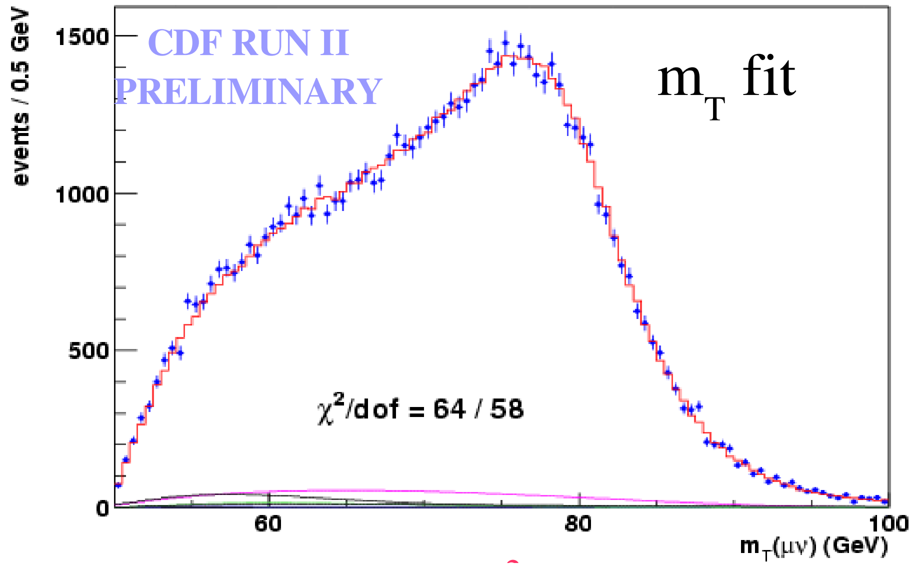
Dominant systematic errors:

Electron energy resolution:	51 MeV
Hadronic recoil calibration:	40 MeV
Hadronic recoil resolution:	50 MeV
Underlying event Modelling:	47 MeV



W mass – Results





CDF (200 pb^{-1}): (blind) analysis is in place, no result quoted yet

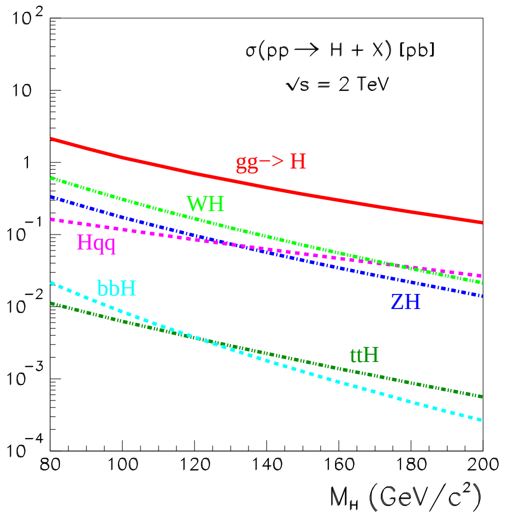
Errors already improve on Run I:

Uncertainty	Electron Channel Run II	Electron Channel Run I	Muon Channel Run II	Muon Channel Run I
Lepton Energy Scale and Resolution	70	80	30	87
Recoil Scale and Resolution	50	37	50	35
Backgrounds	20	5	20	25
Statistics	45	65	50	100
Production and Decay Model	30	30	30	30
Total	105	110	85	140

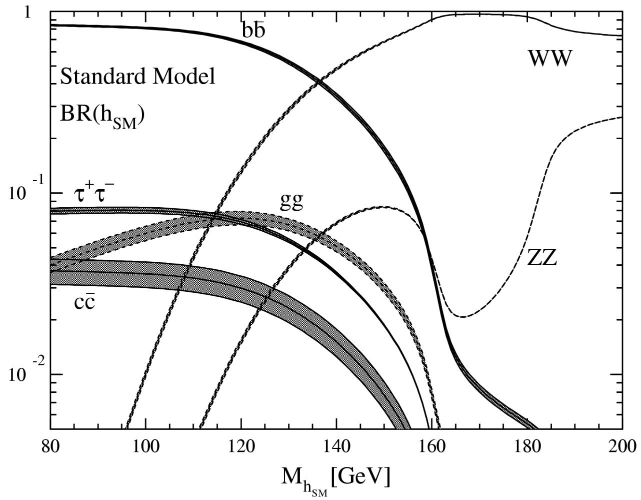
Hoping to achieve 50 MeV combined uncertainty this year (now: 76 MeV, Run I: 79 MeV)

Search for Higgs bosons at the Tevatron

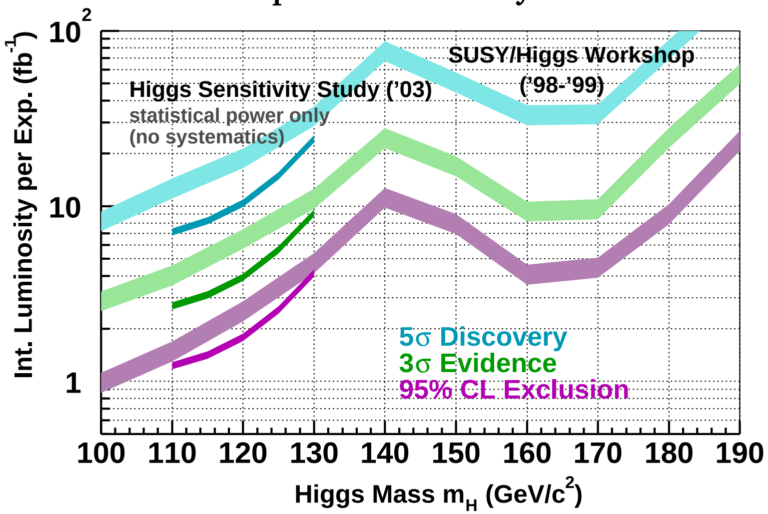
Production Cross-Sections



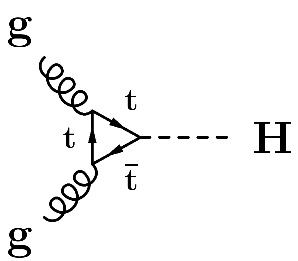
Branching Ratios



Expected Sensitivity



Heavy Higgs bosons ($m_H > 130$ GeV):



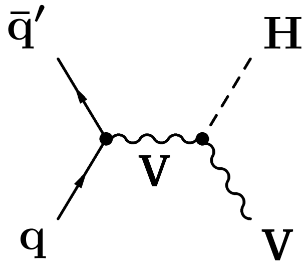
Dominant decay mode: H⟶WW

Production: Gluon-Gluon Fusion

⟶ relatively high cross-section

⟶ clean 2-lepton+$\not{E}_T$ signature via H⟶WW⟶$l\nu l\nu$

Light Higgs bosons ($m_H < 130$ GeV):



Dominant decay mode: H⟶$b\bar{b}$

Production: in association with W,Z

⟶ leptonic W,Z-decays provide best signature

⟶ b-tagging to suppress background from W/Z+jets

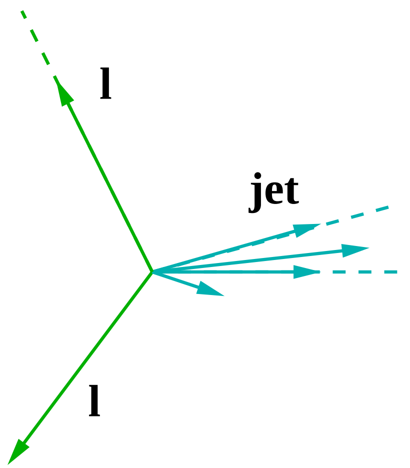
Search for $H \to WW$ – Backgrounds

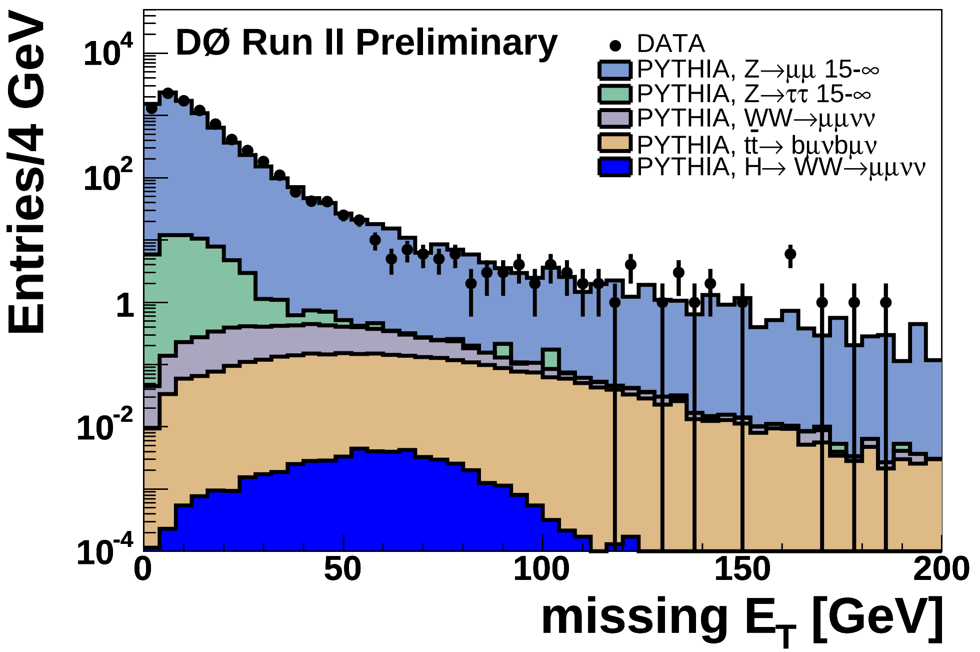
Search for heavy Higgs bosons is in progress (CDF 184 pb^{-1}, DØ 175 pb^{-1})

- Selections for $ee + \not{E}_T$, $e\mu + \not{E}_T$, $\mu\mu + \not{E}_T$
- Backgrounds:
  - WW$\to l\nu l\nu$ (irreducible)
  - W+γ/jet (in particular with converted photons)
  - Z/$\gamma^* \to ll$

Missing $\not{E}_T$ requirement is critical to rejection of Z$\to$ll events

Problem: mismeasured leptons and jets cause tails in $\not{E}_T$ distribution

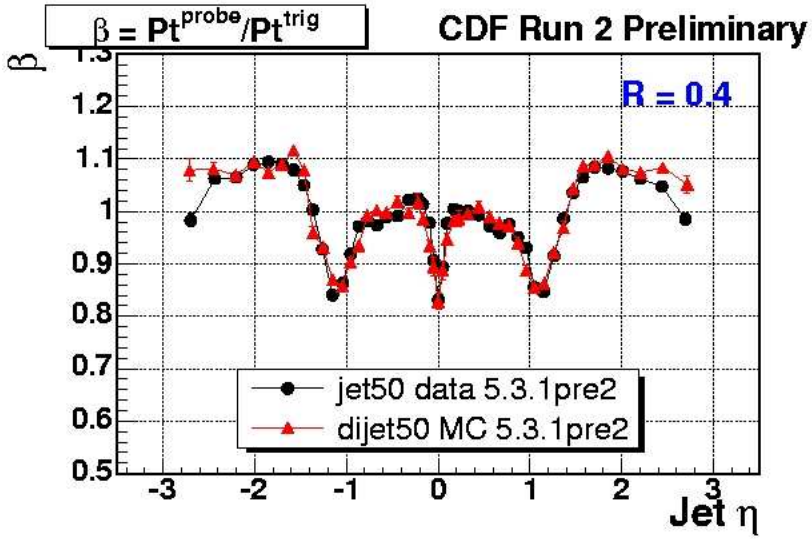




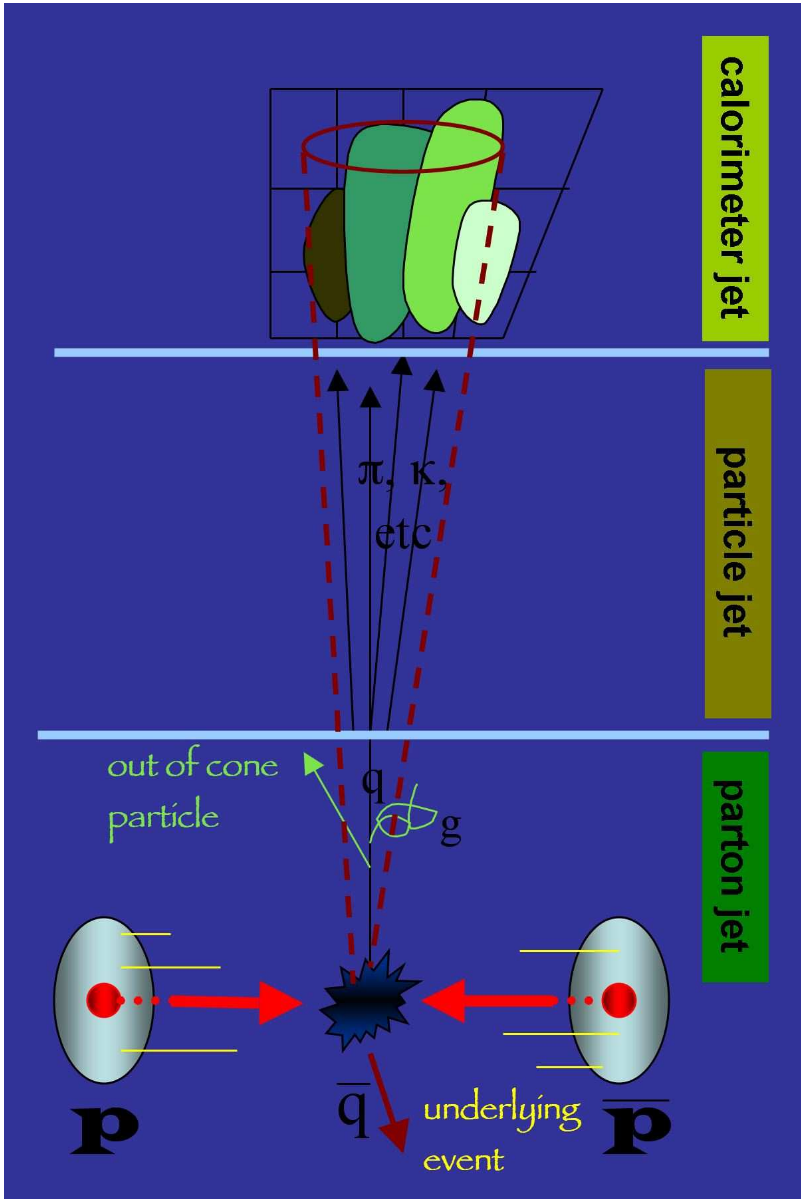
Search for $H \to WW$ – Jet Energy Scale

Calorimeter response correction

- determined from energy balance in γ+jet
- function of energy and position (cracks etc)



- Note: need high-statistics photon samples down to small photon E_T



Out-of-cone showering

- correct for leakage out of the jet cone

Offset correction (from minimum-bias data)

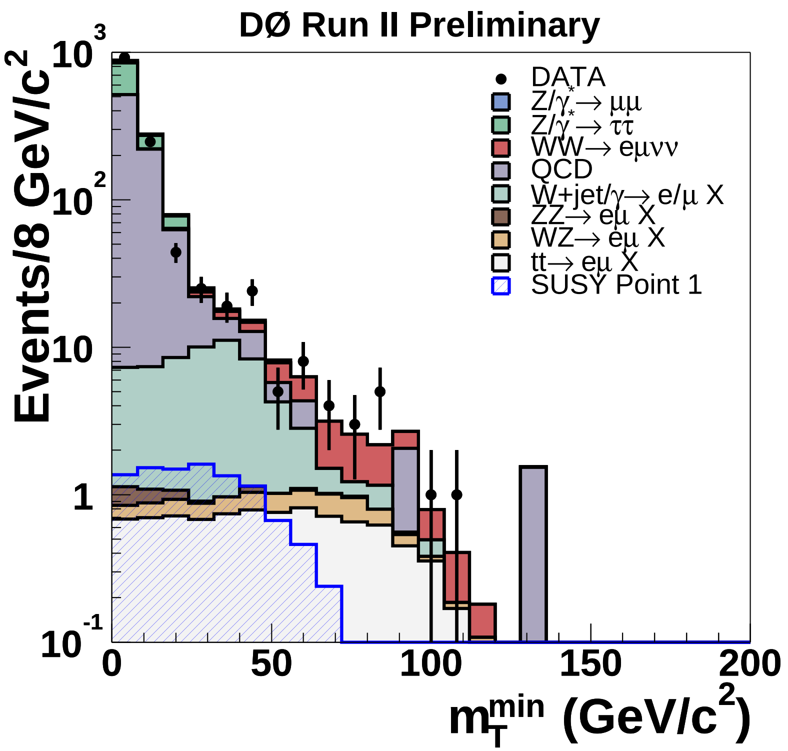
- subtract energy from underlying event
- subtract energy from multiple interactions (as a function of number of PV)

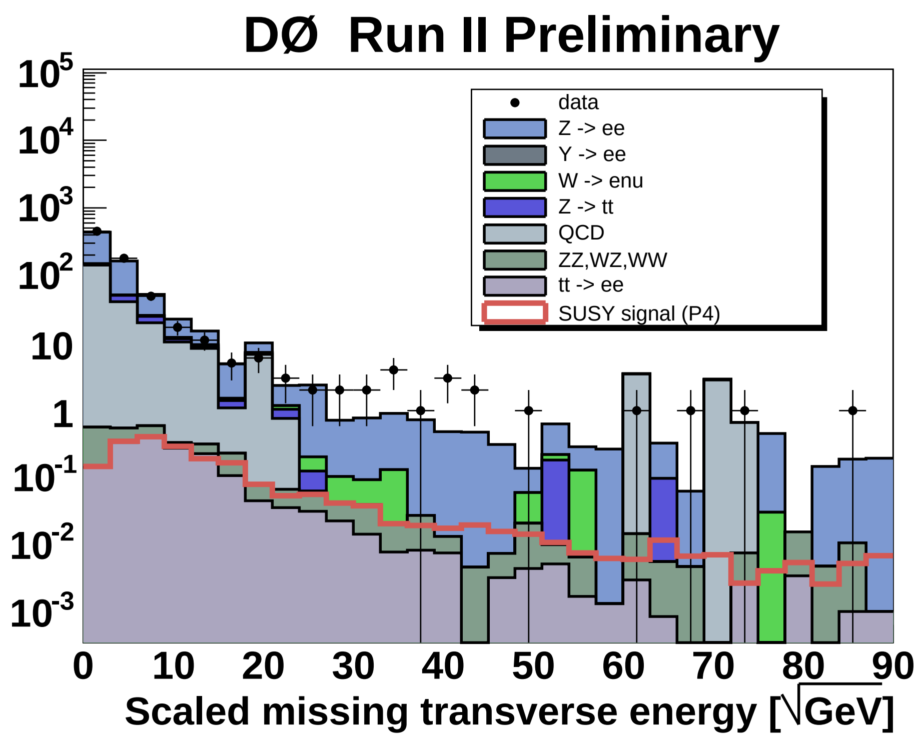
Search for $H \to WW$ – $\not\!\!E_T$ Significance

Several methods to deal with fake $\not\!\!E_T$ from mismeasured leptons or jets:

- remove events with $\not\!\!E_T$ pointing in direction of lepton/jet
- remove events with jets hitting poorly instrumented regions (cracks)
- cut on transverse mass of lepton and $\not\!\!E_T$
- calculate $\not\!\!E_T$ significance, i.e. normalize $\not\!\!E_T$ to expected resolution event-by-event:

$$\mathrm{Sig}(\not\!\!E_T) = \frac{\not\!\!E_T}{\sqrt{\sum_{\mathrm{jets}} \sigma^2_{E_T^j \parallel \not E_T}}}$$





Search for $H \to WW$ – Results

Results (for m_H=160 GeV):

	Background (# events)	Data (# events)	Efficiency (for $H \to WW$)
CDF (184 pb^{-1})	5.8±0.6	3	0.4%
DØ (175 pb^{-1})	11.1±0.8	9	0.7%

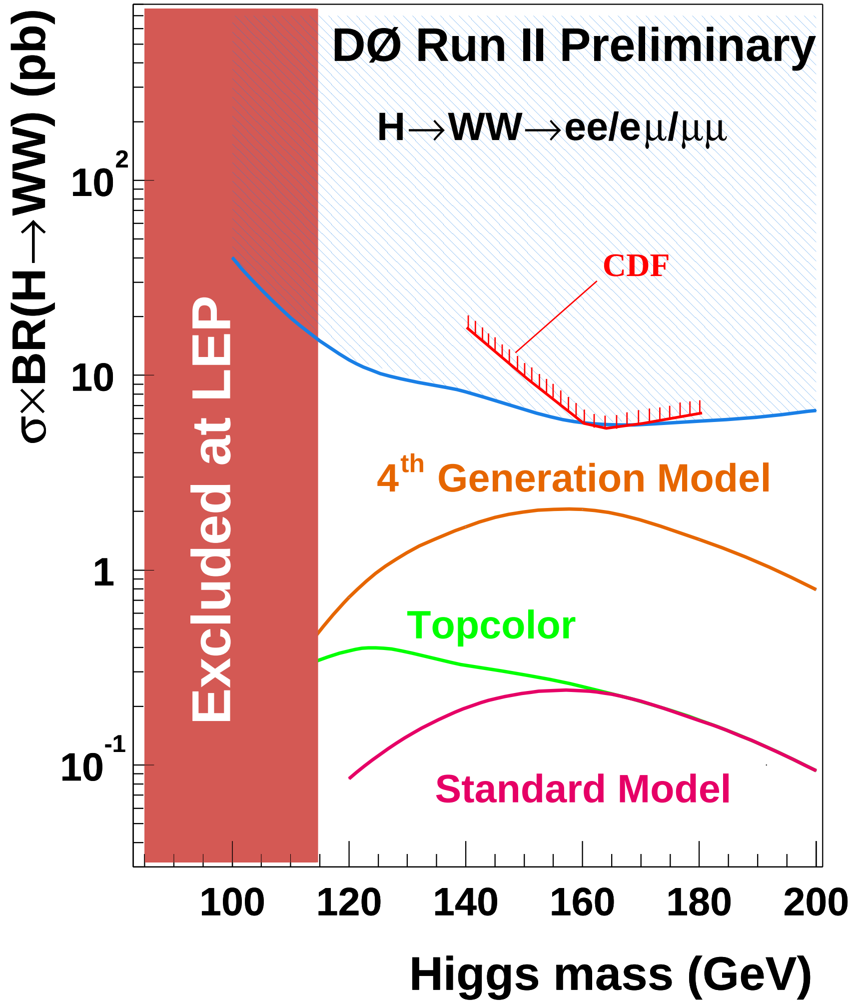
No excess of events observed

→ limits on σ x BR(H→WW)

Standard Model with 4th generation:

– heavy quark loops enhance cross-section

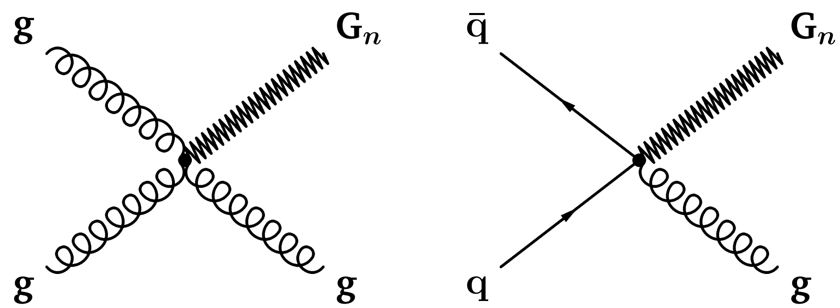
Standard Model: need $4fb^{-1}$ for sensitivity to exclude at 95% C.L.



Searches for SUSY and Extra Dimensions

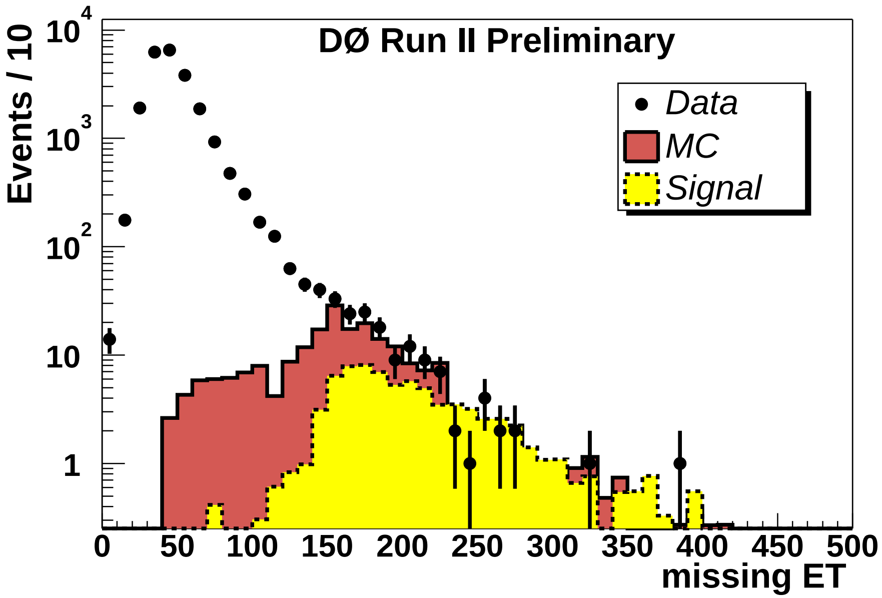
Search for large extra dimensions (ADD):

- Gravitons can be produced recoiling against quark/gluon
- Kaluza-Klein tower of many gravitons
  $\longrightarrow$ sizeable cross-sections
- Gravitons escape detection
  $\longrightarrow$ monojet signature



Search for Supersymmetry:

- $p\bar{p}$-Collider: strong production of Squarks/Gluinos ($\rightarrow$ large cross-sections)
- Signature: $\tilde{q}\tilde{q}\rightarrow q\tilde{\chi}^0_1 q\tilde{\chi}^0_1$ (Neutralino LSPs escape detection $\longrightarrow$ 2 jets + $\not{E}_T$)



Analyzed 85 pb^{-1} collected by Jets+$\not{E}_T$ trigger:

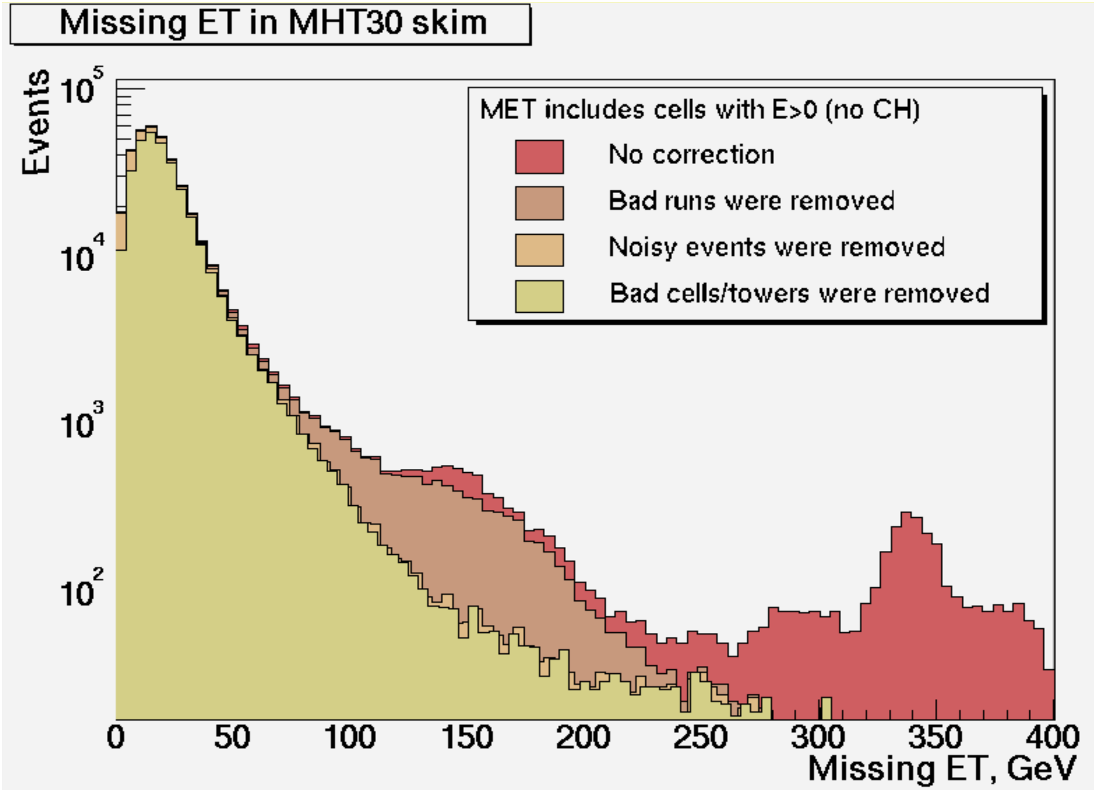
- requires missing HT$>$30
- jet acoplanarity$<$170

Typical offline analysis cuts:

- $\not{E}_T>$150 GeV, Jet $p_\perp>$150 GeV (monojets)
- $\not{E}_T>$175 GeV, $\sum_i pt^i_{jet}$ $>$275 GeV (squarks)

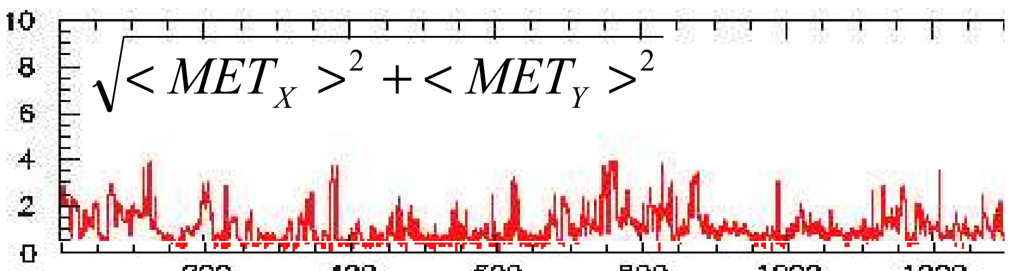
Searches for SUSY and ED – Calorimeter Noise

A trigger on $\not{E}_T$ provides an excellent test sample for data quality control:



Mean $\not{E}_T$ used as offline and online monitoring tool:

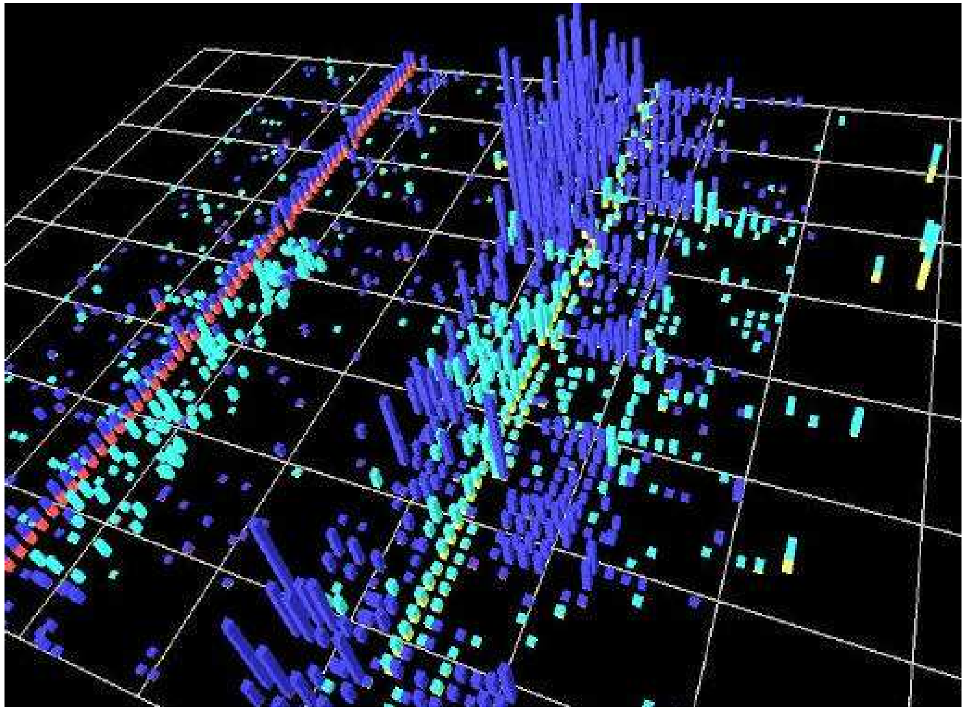
- online: monitoring mean and width of $\not{E}_T$ run-by-run
- offline: calculated for each 1-minute block of data to detect intermittent problems

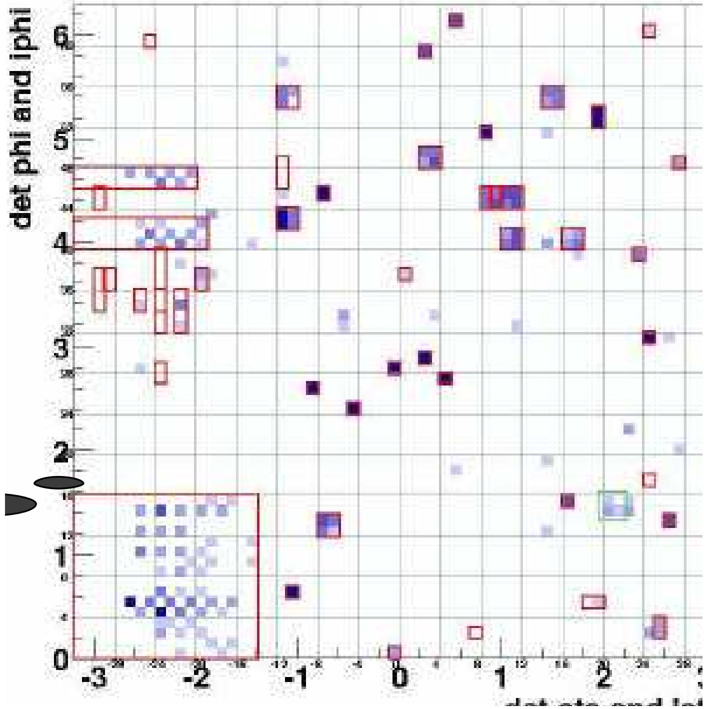


Searches for SUSY and ED – Calorimeter Noise

Large variety of (rare) problems detected by monitoring tools and physics analysis:

- Hot cells (hardware failures, pedestal shifts)
- External noise
- Gain variations (hardware failures)



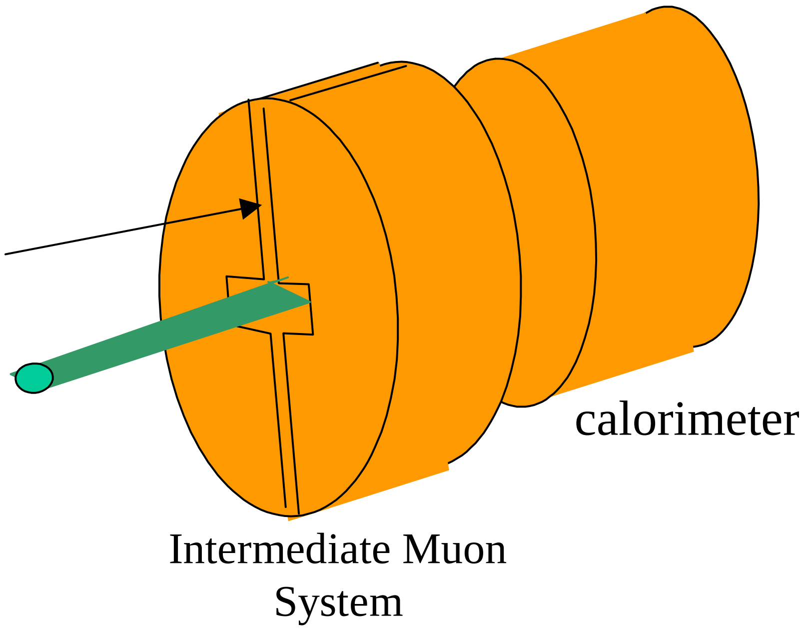


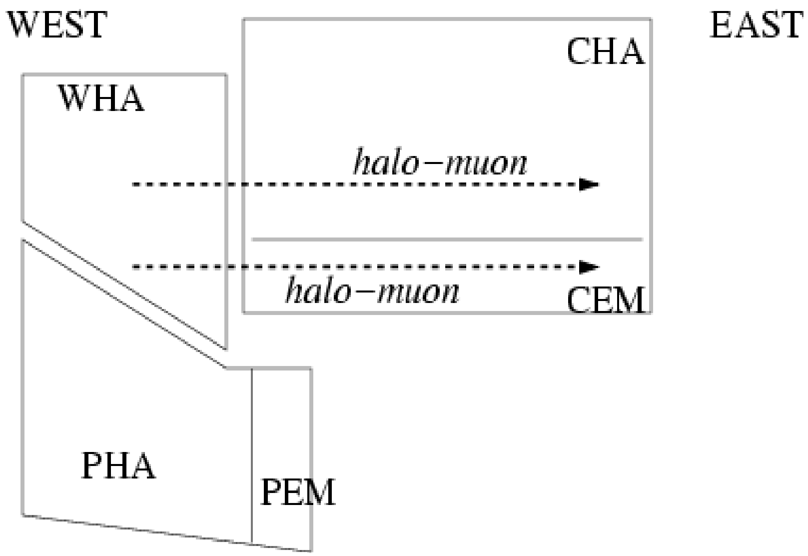
Fixing these problems involves:

- replacing/repairing hardware
- repairing data in software:
  - derived analysis samples contain cell-level information

  → can fix data and rerun calorimeter reconstruction with quick turnaround
- flagging data quality for each 1-minute block of data

Searches for SUSY and ED – Beam Background (CDF)





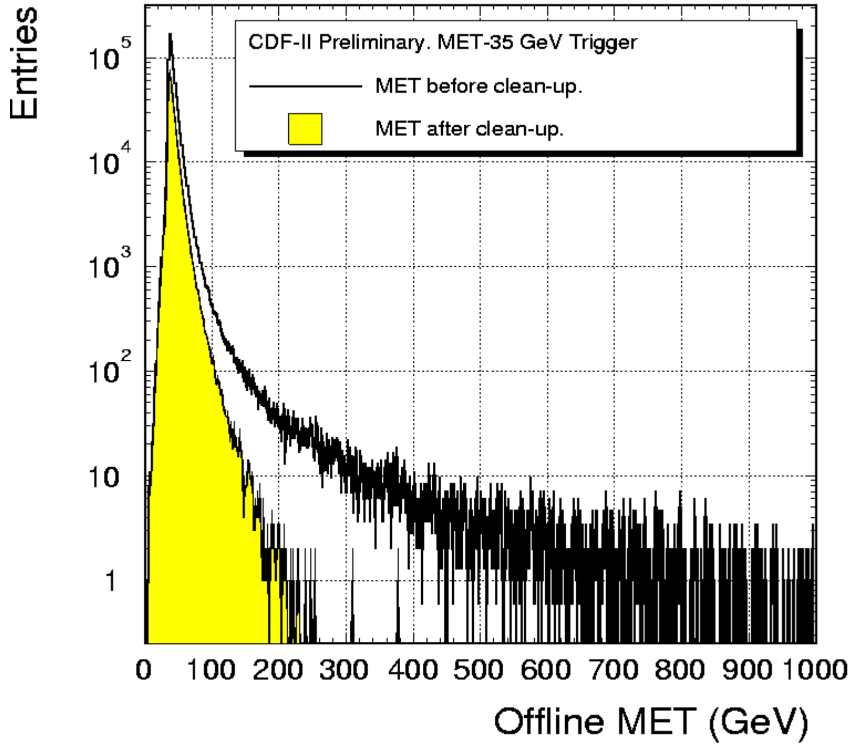
4 cm gap in shielding at $\phi = \pm 90°$

$\longrightarrow$ **fake $\not{E}_T$ due to energy depositions from beam losses**

$\longrightarrow$ **more shielding has been added**

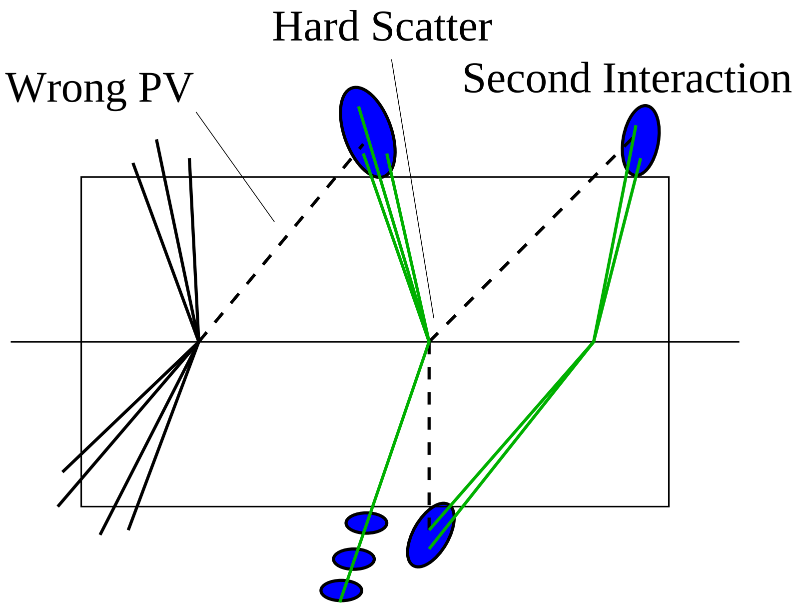
Halo muons from beam halo hitting roman pots

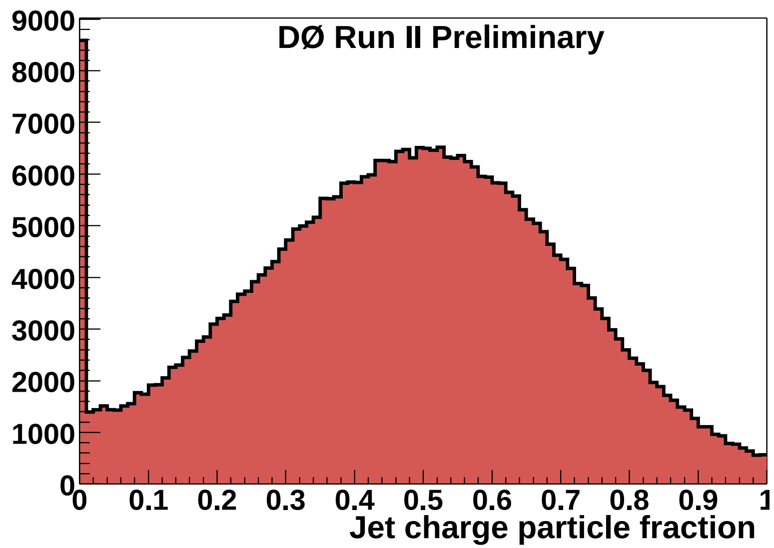
$\longrightarrow$ **fake $\not{E}_T$ from energy depositions parallel to beam at Φ=180°**



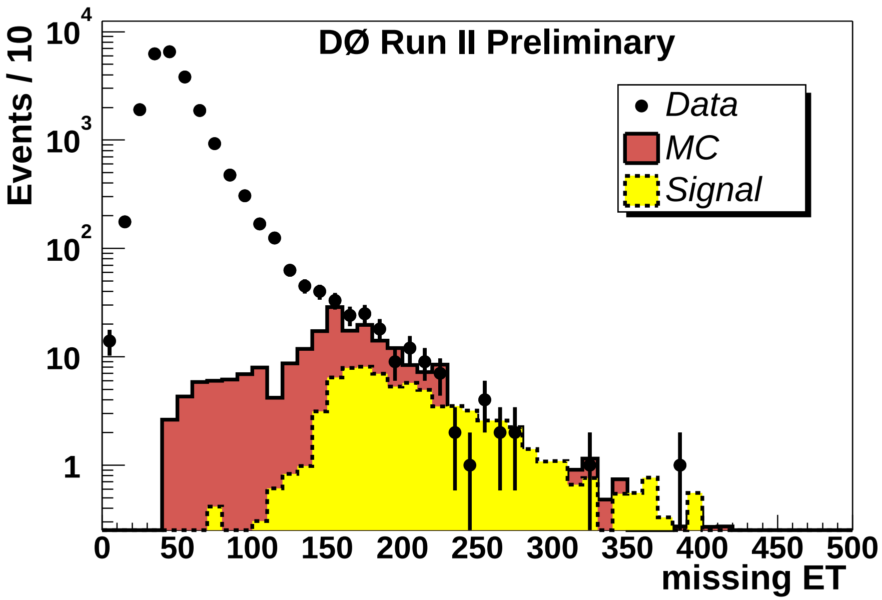
Searches for SUSY and ED – Vertexing

- Calculation of missing E_T needs direction of energy flow
- Fake $\not{E}_T$ can be caused by:
  - wrong primary vertex
  - energy from additional interactions
- important for “compact” detectors like DØ
- Solution:
  - sum transverse momenta of charged particles pointing from primary vertex to jet energy deposition in calorimeter
  - require a minimum charged particle fraction for each jet
- also rejects background from fake jets:
  - showers generated by cosmic muons
  - calorimeter noise
  - beam background





Searches for SUSY and Extra Dimensions – Results



Monojet search:

- 100^{+50}_{-30} events expected (mainly $Z \longrightarrow \nu\bar{\nu}$)
- 63 events observed

$\longrightarrow$ limit on M_D: >680 GeV

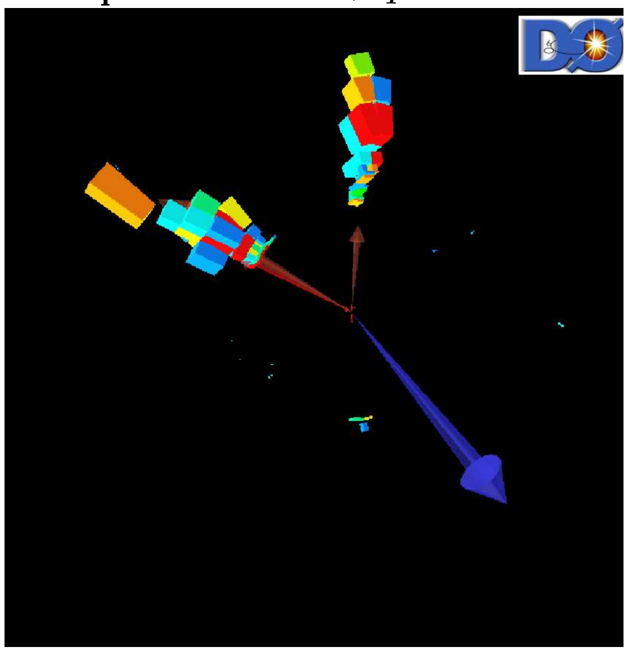
Search for squarks/gluinos:

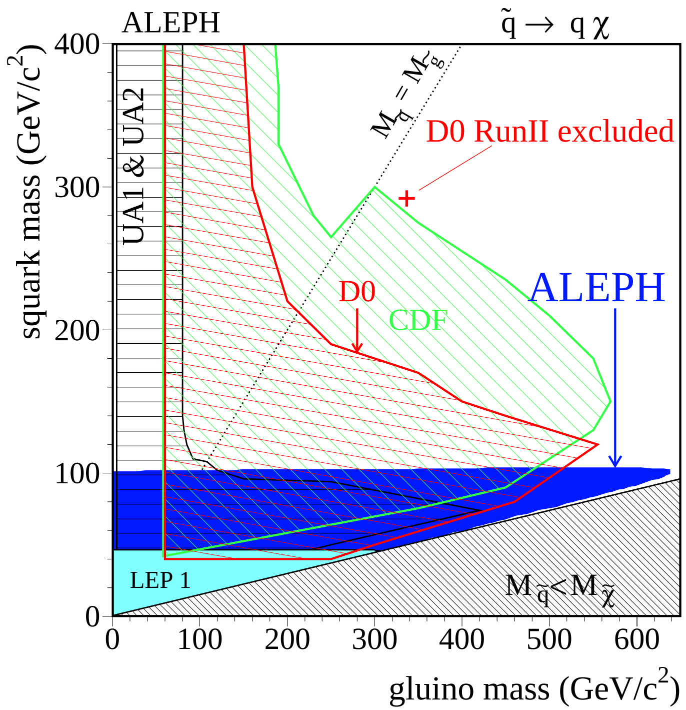
- 4 events observed (2.7±1.0 expected)

$\longrightarrow$ limits improved beyond Run I

Update (more data, improved JES) in progress

Squark Candidate: $\not{E}_T$=381 GeV





Conclusions

- Missing transverse energy is an important tool at hadron colliders
- Measurement of $\not{E}_T$ relies on calibration of leptons, jets, soft particles
- $\not{E}_T$ is a central ingredient in many high-profile Run II analyses:
  - W mass measurement
  - Search for Higgs bosons
  - Search for Supersymmetry and Extra Dimensions
- Searches with high $\not{E}_T$ require excellent understanding of fake $\not{E}_T$
  - Controlling and modelling of non-Gaussian tails
  - Calorimeter noise removal
  - Data quality control
- Still hoping to establish a Neutralino signal at the Tevatron to provide a standard candle for $\not{E}_T$ calibration at the LHC