W Mass Measurements at the Tevatron and Lessons for ATLAS

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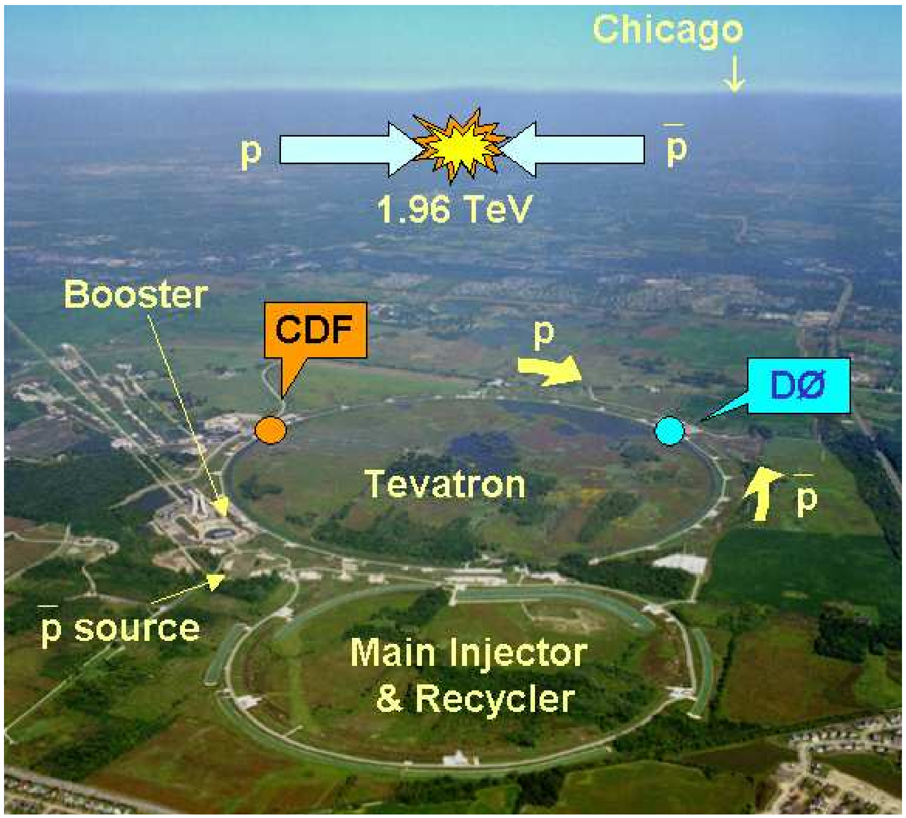
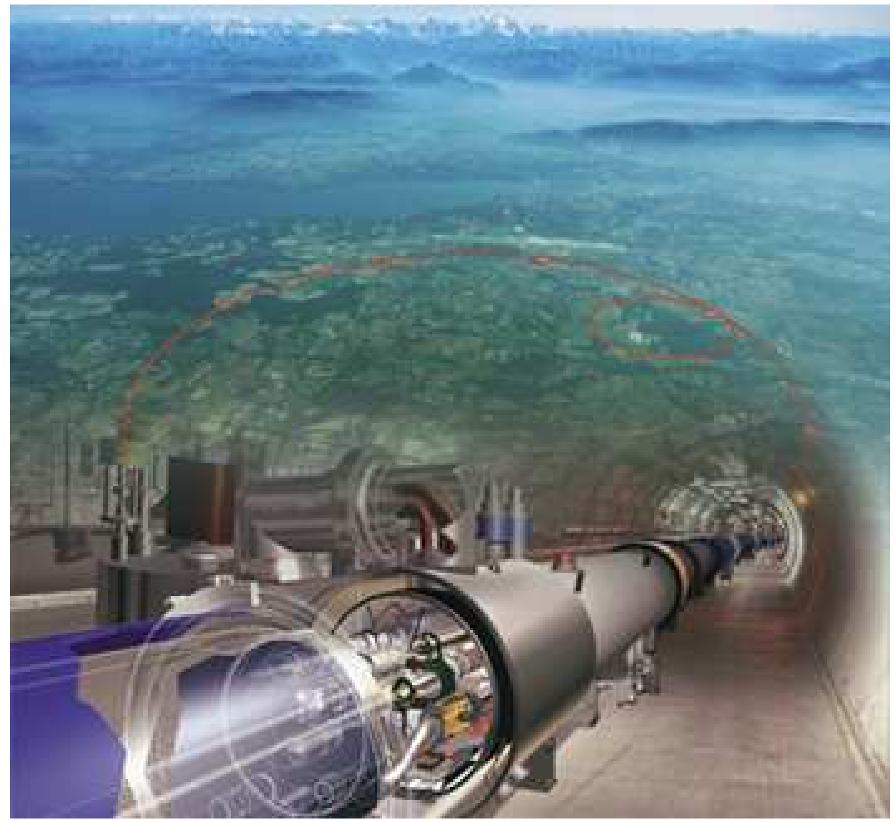
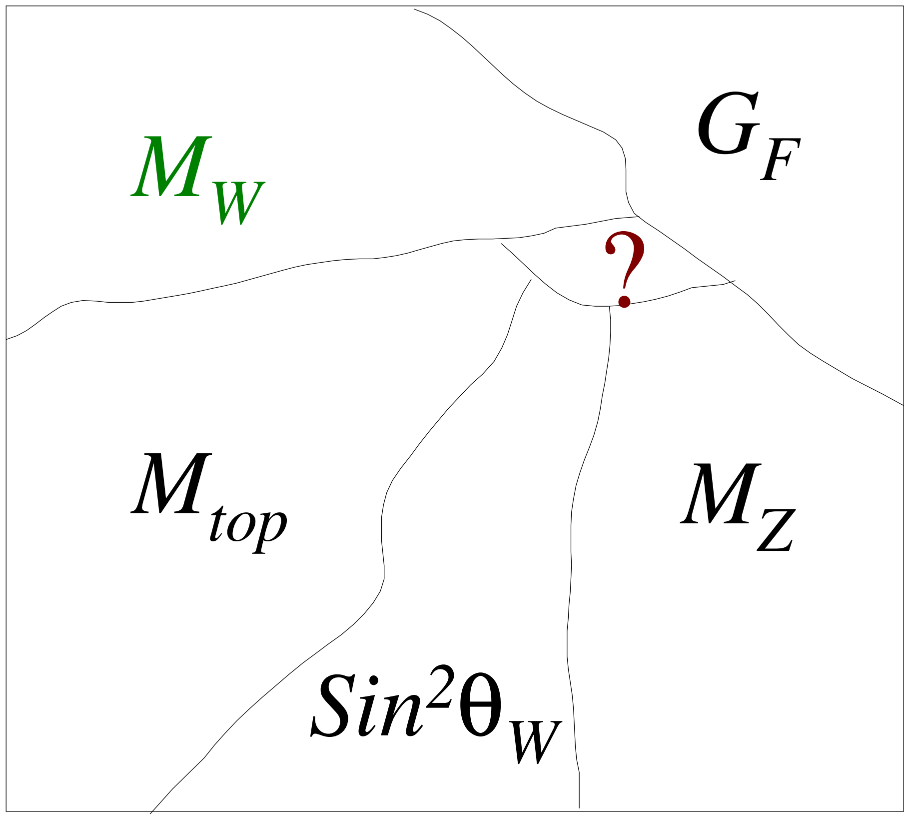




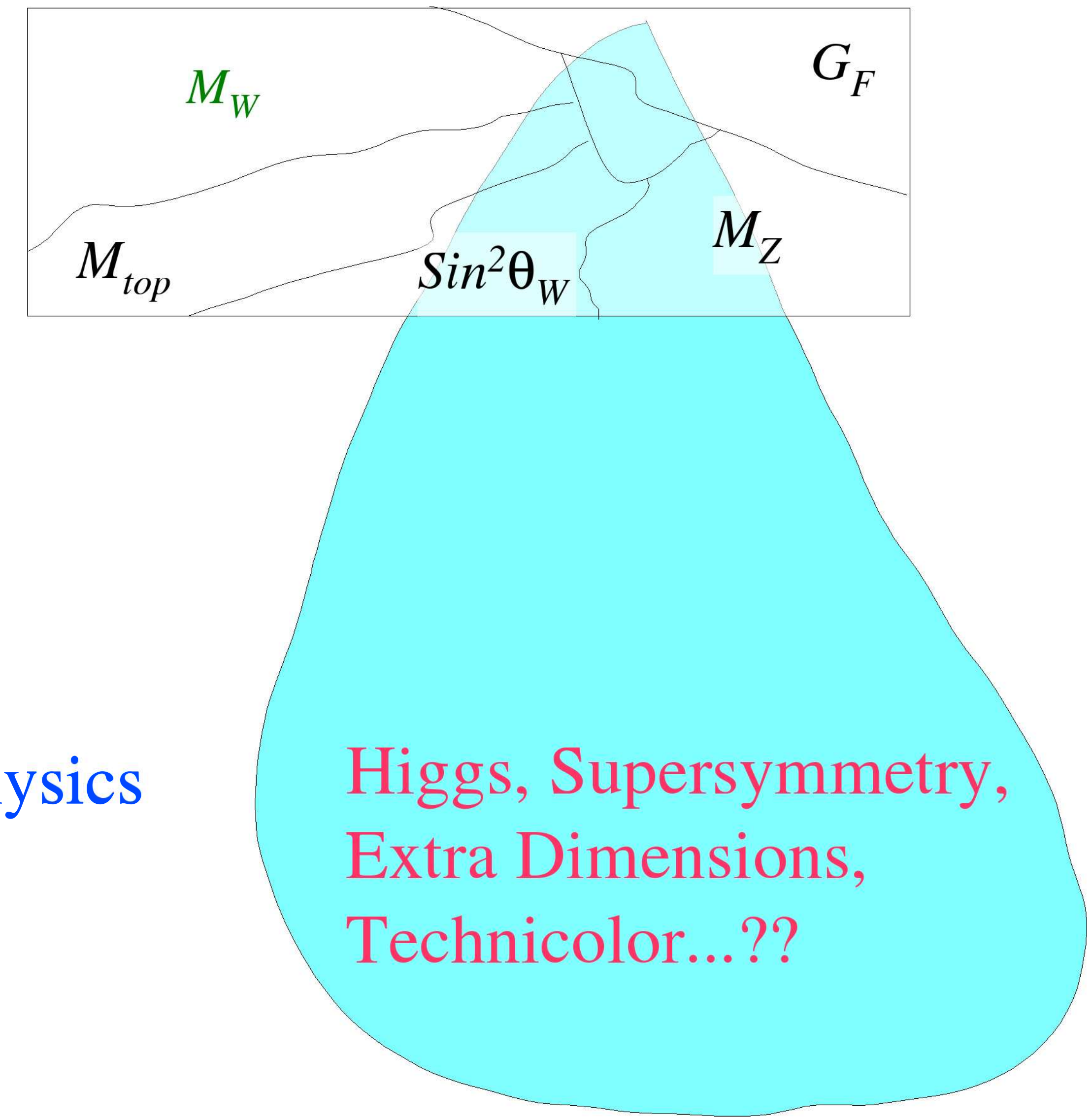
ATLAS Tutorial on Electroweak Physics
February 14, 2005

Role of Precision Electroweak Measurements



Need precision to tell that there is a missing piece !

Role of Precision Electroweak Measurements



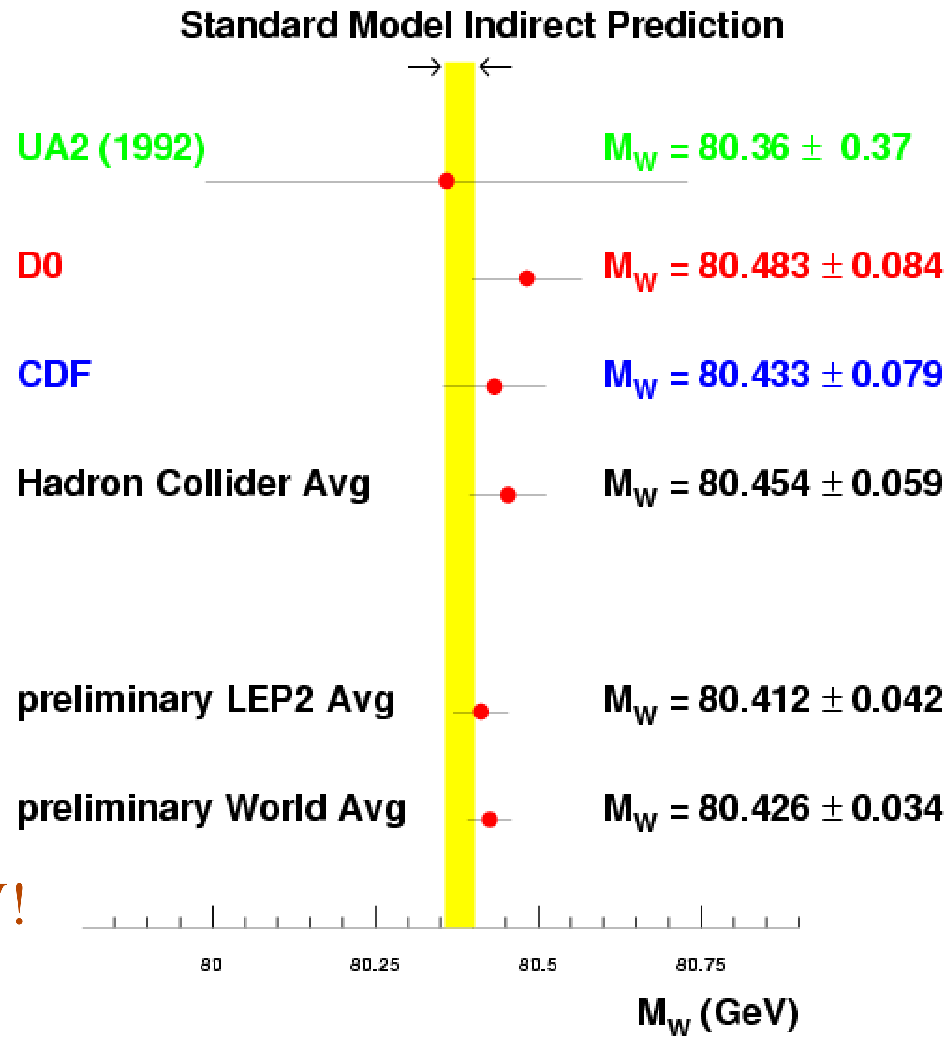
Reveal the "tip of the iceberg"

Big iceberg of new physics lurking just below the surface!

Status and Future of W Mass Measurements

Using data ~110 pb^{-1} / experiment collected upto 1995

CDF & D0 Collaborations, PRD70, 092008 (2004)



Extrapolating on the basis of statistics alone:

Tevatron (say 4 fb^{-1}): $\Delta M_W \sim 10$ MeV!

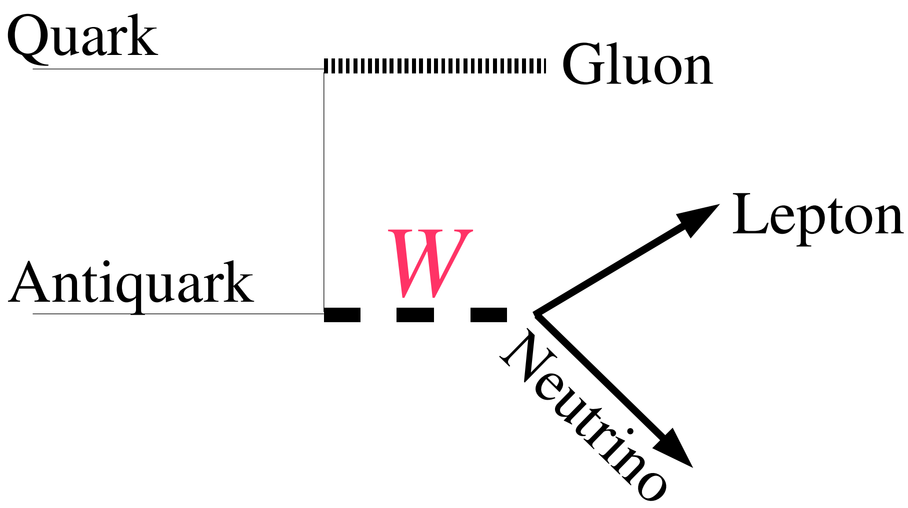
LHC: $\Delta M_W < 5$ MeV !!

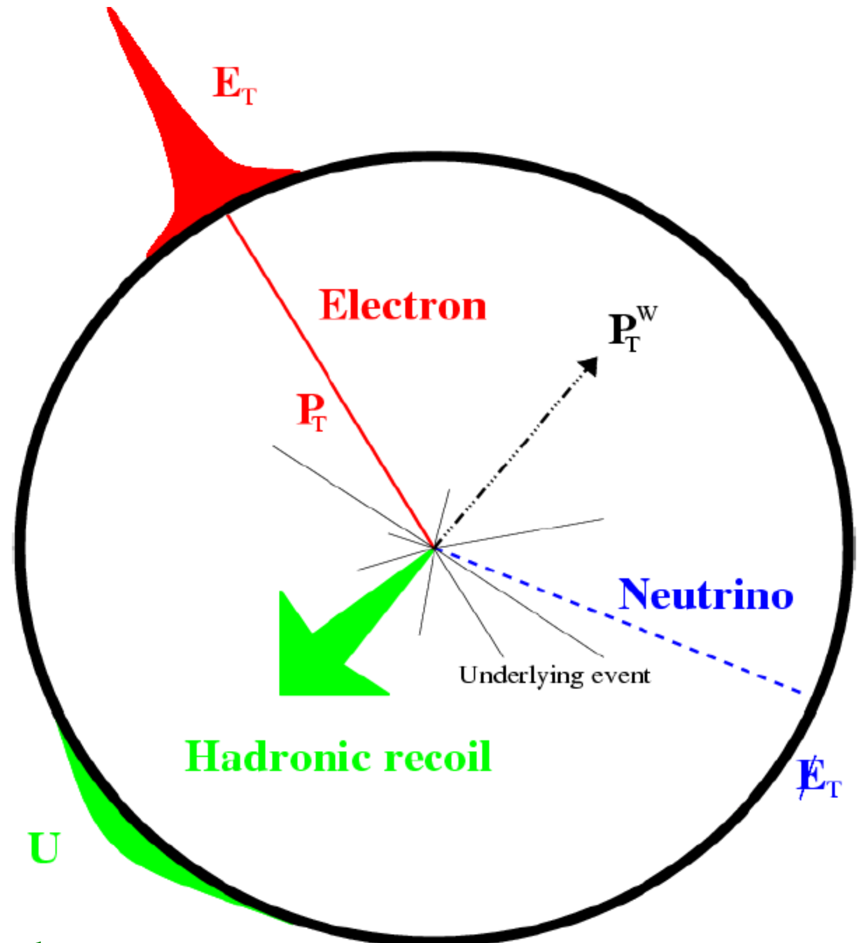
Q: how can we use all these data to control systematics at the same level?

History of W Mass Uncertainty at the Tevatron

- Scaling of ΔM_W with integrated luminosity:
- During 1987-1995 running period, integrated luminosity per collider experiment increased from 4 pb^{-1} $\rightarrow$ 20 pb^{-1} $\rightarrow$ 110 pb^{-1}
  - ΔM_W reduced correspondingly: ~400 MeV $\rightarrow$ 150 MeV $\rightarrow$ 60 MeV, following $L^{-½}$ scaling
  - Systematics constrained with collider data
- Key features of experiments:
  - Triggering and reconstruction of signal and control samples with high efficiency, low bias and low backgrounds
  - Linearity of detectors measuring energy and/or momentum

W Boson Production at the Tevatron





Quark-antiquark annihilation dominates (80%)

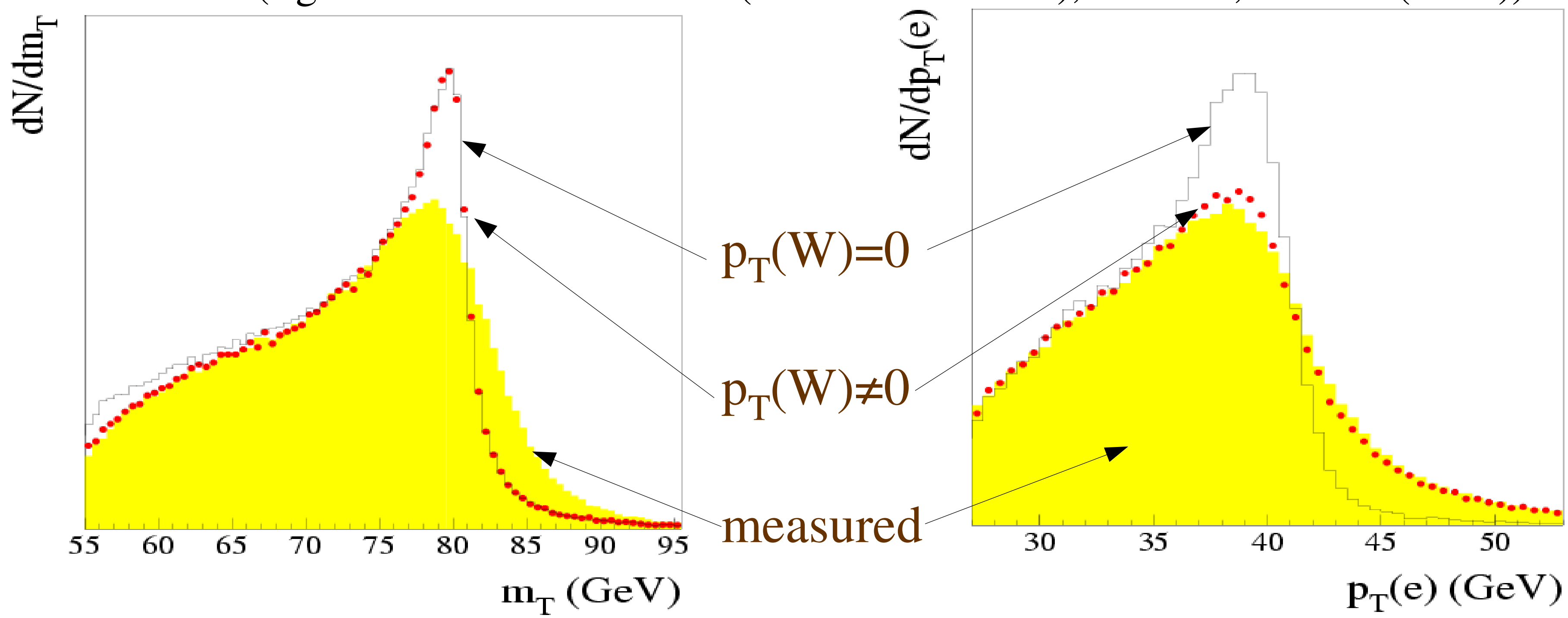
Lepton p_T carries most of *W* mass information, and can be measured precisely

Initial state QCD radiation is O(10 GeV), appears as soft 'hadronic recoil' in calorimeter

Pollutes *W* mass information, fortunately $p_T(W) << M_W$

W Mass Measurements at the Tevatron

(figures from Abbott *et. al.* (D0 Collaboration), PRD 58, 092003 (1998))



$M_T = \sqrt{(2\, p_T^{\,l}\, p_T^{\,\nu}\, (1 - \cos\phi_{l\nu})}$

Insensitive to $p_T(W)$ to first order

(if $p_T(W) << M_W$)

Reconstruction of $p_T^{\,\nu}$ sensitive to hadronic response and multiple interactions

Advantage of $p_T(l)$: less sensitive to hadronic response modelling

Need theoretical model of $p_T(W)$

$P_T(\nu)$ fit provides stringent cross-check

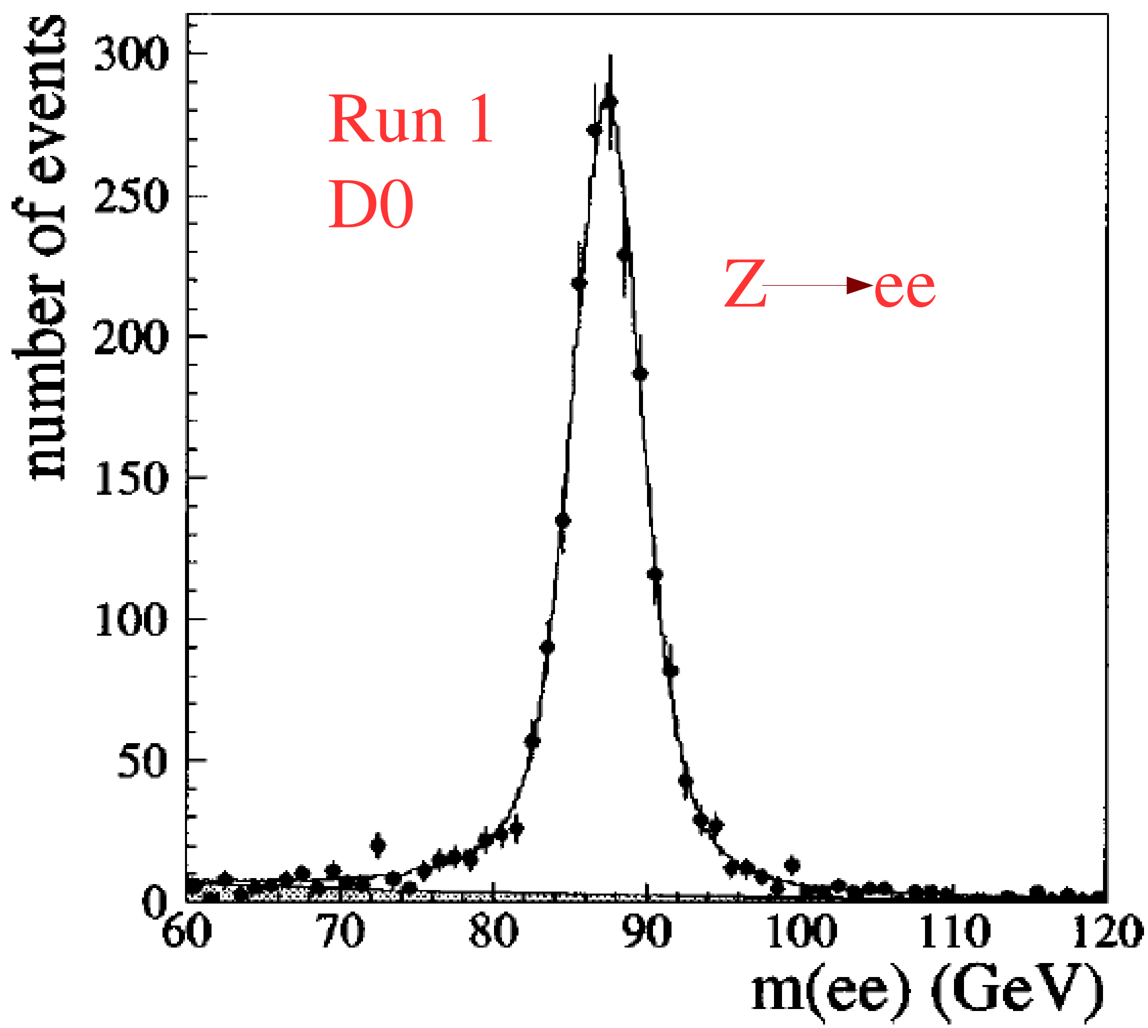
Lepton Energy/Momentum Measurement

In Run 1, D0 did not have magnetic tracker for momentum measurement, used electron channel only

Exploited linearity of EM calorimeter (Uranium-liquid Argon with unit gain) at high energy, demonstrated using test beam at $O(0.1\%)$

Non-linearity constrained using reconstructed π^0 and $J/\psi \rightarrow ee$

PRD 58, 092003 (1998)

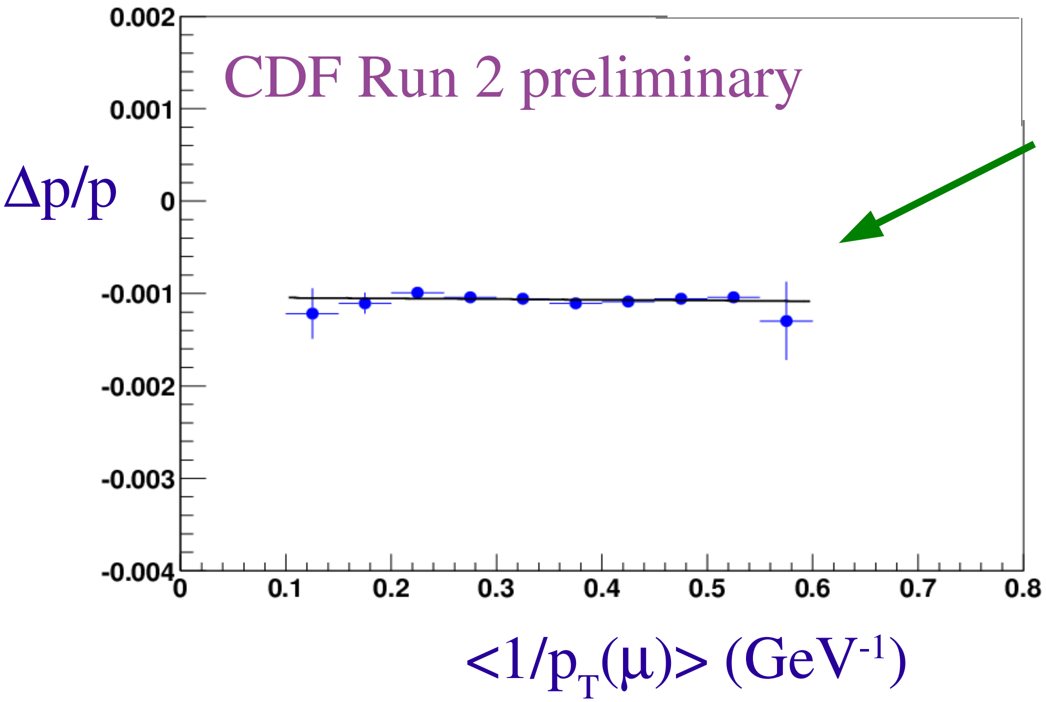


Lepton Energy/Momentum Measurement

- Magnetic tracker provides substantial additional information
  - Muon channel measurement possible
  - *In-situ* calibration of EM calorimeter with electron tracks
  - CDF (Run 1 & Run 2, starting 2000) and D0 (in Run 2) using magnetic tracker
- Tracker alignment and calibration are critical for ensuring tracker linearity
  - Mechanical alignment of $O(50\mu)$ provides good starting point
  - *In-situ* alignment of $O(5\mu)$ necessary
  - Track alignment using electron charge dependence of $E_{\mathrm{CAL}} / p_{\mathrm{track}}$ used by CDF in Run 1
  - Complements primary alignment method using cosmic rays (Kotwal, Gerberich and Hays, NIMA 506, 110 (2003)) used by CDF in Run 2

Momentum Scale

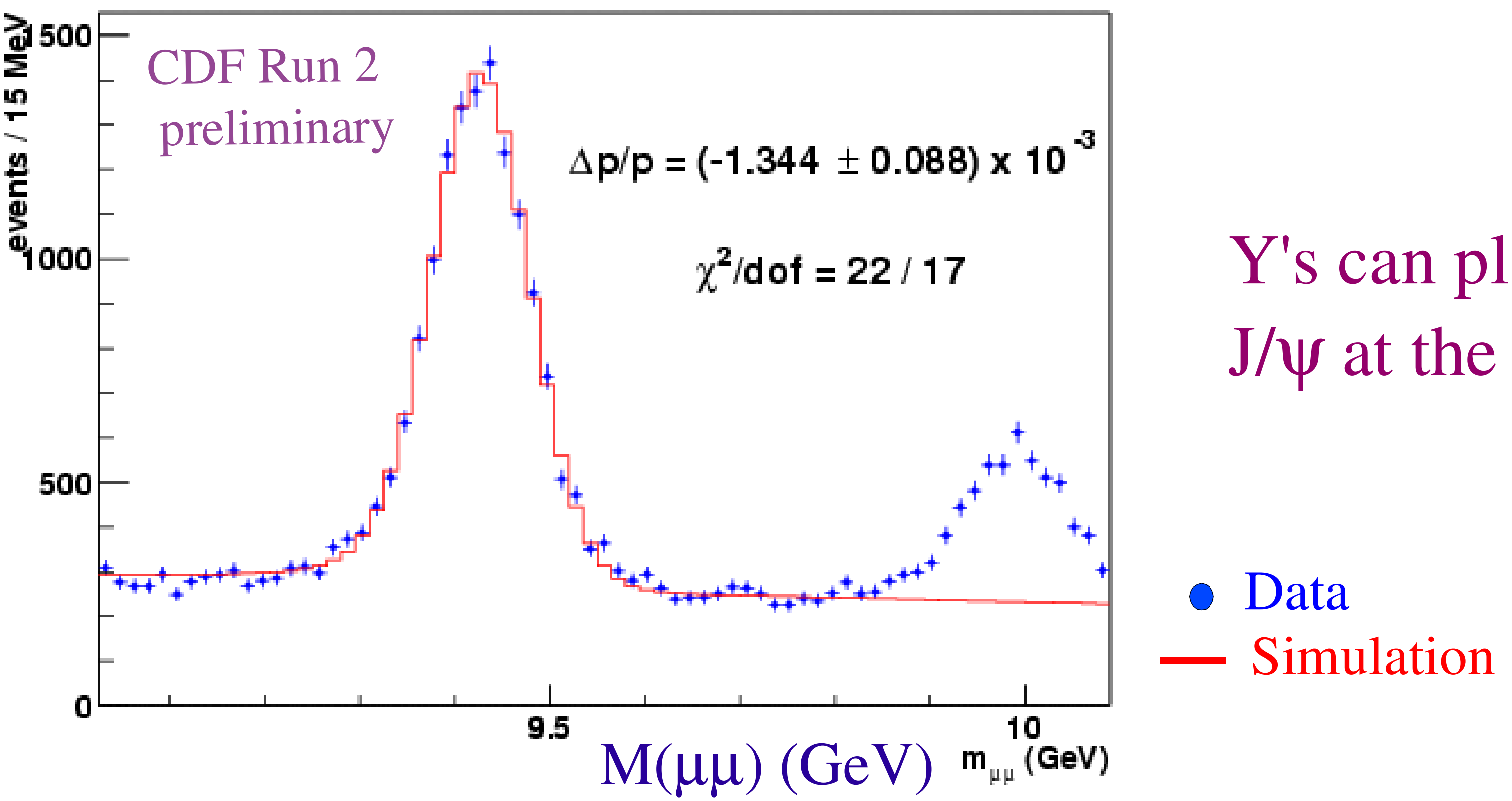
- Set using $J/\psi \rightarrow \mu\mu$ and $\Upsilon \rightarrow \mu\mu$ resonances
  - Need accurate calculation of ionization energy loss
  - Construction-based map of passive material implemented in GEANT provides important starting point
  - Validated using photon conversion data (*X*-ray) and momentum-dependence of J/ψ mass



Momentum (p) scale extracted from $J/\psi \rightarrow \mu\mu$ mass independent of muon momentum within 0.03%

Momentum Scale

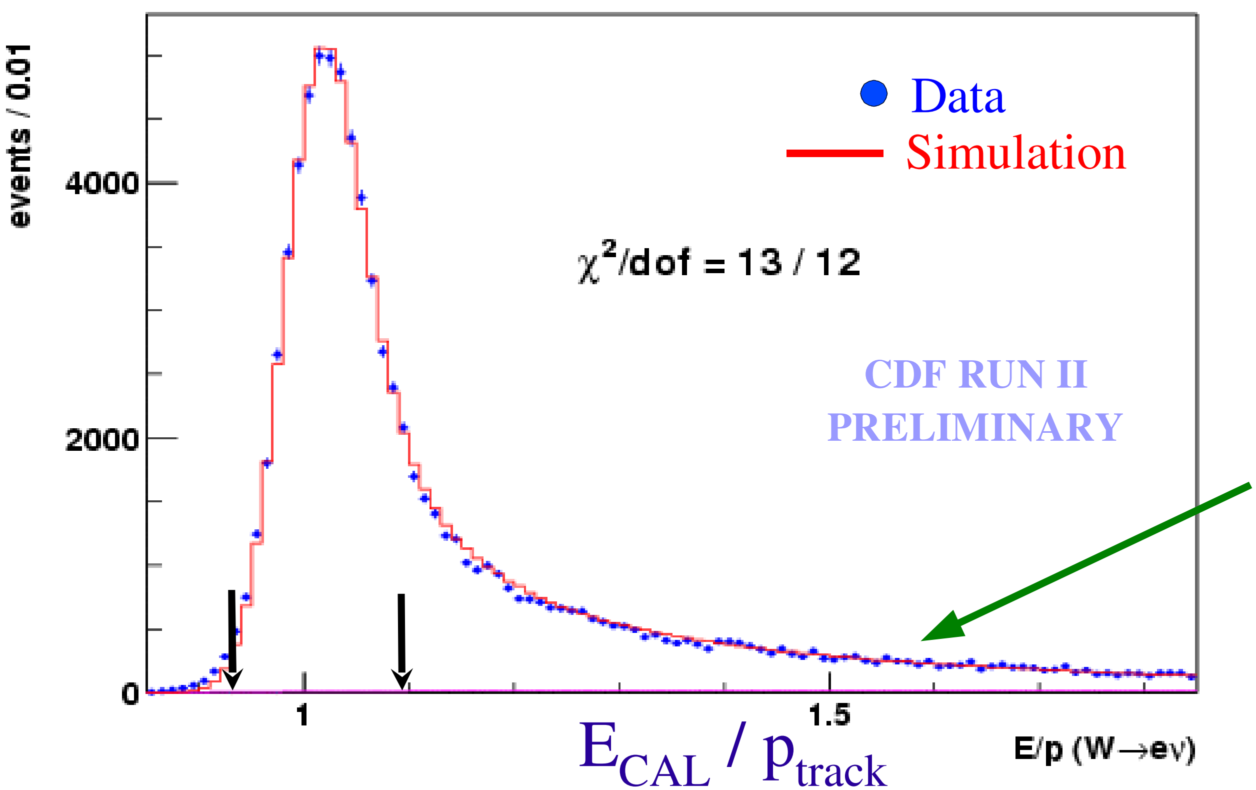
- $\Upsilon \rightarrow \mu\mu$ resonance provides complementary information
  - Track curvature is closer to *W*'s than J/ψ tracks
  - Υ are all primary, tracks can be beam-constrained like *W* tracks
    - Beam-constraining improves accuracy and precision of primary tracks
    - ...but biases tracks from secondary J/ψ decays (e.g. $B \rightarrow J/\psi\ X$)



Υ's can play the role of J/ψ at the LHC

EM Calorimeter Scale

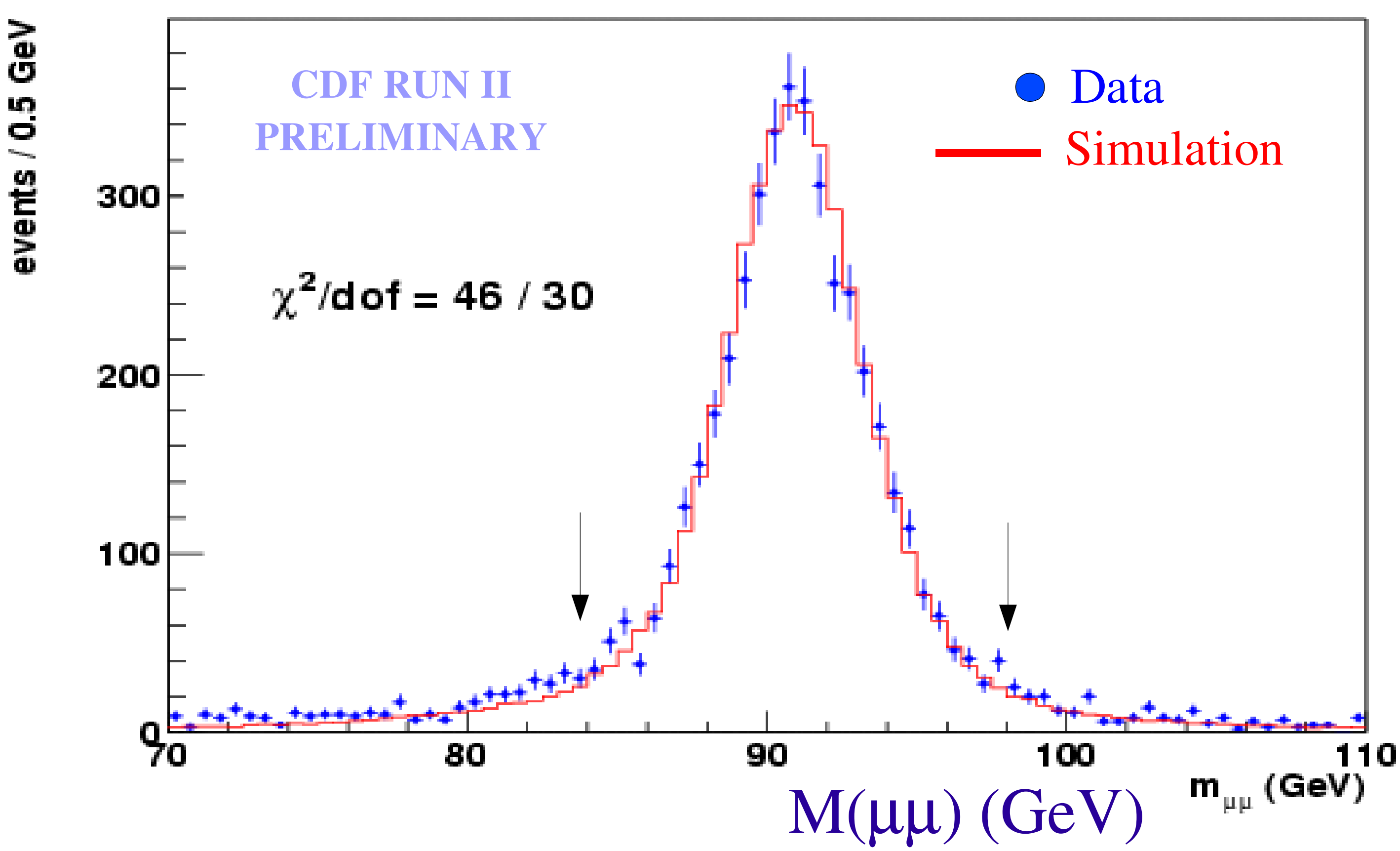
- Transfer calibration from tracker to calorimeter using electrons from $W \rightarrow e\nu$ decays
  - Fit peak region of E/p spectrum
  - Dominant systematic due to amount of passive material (causing bremsstrahlung and subsequent conversions)



Tail region of E/p spectrum used for tuning model of passive material

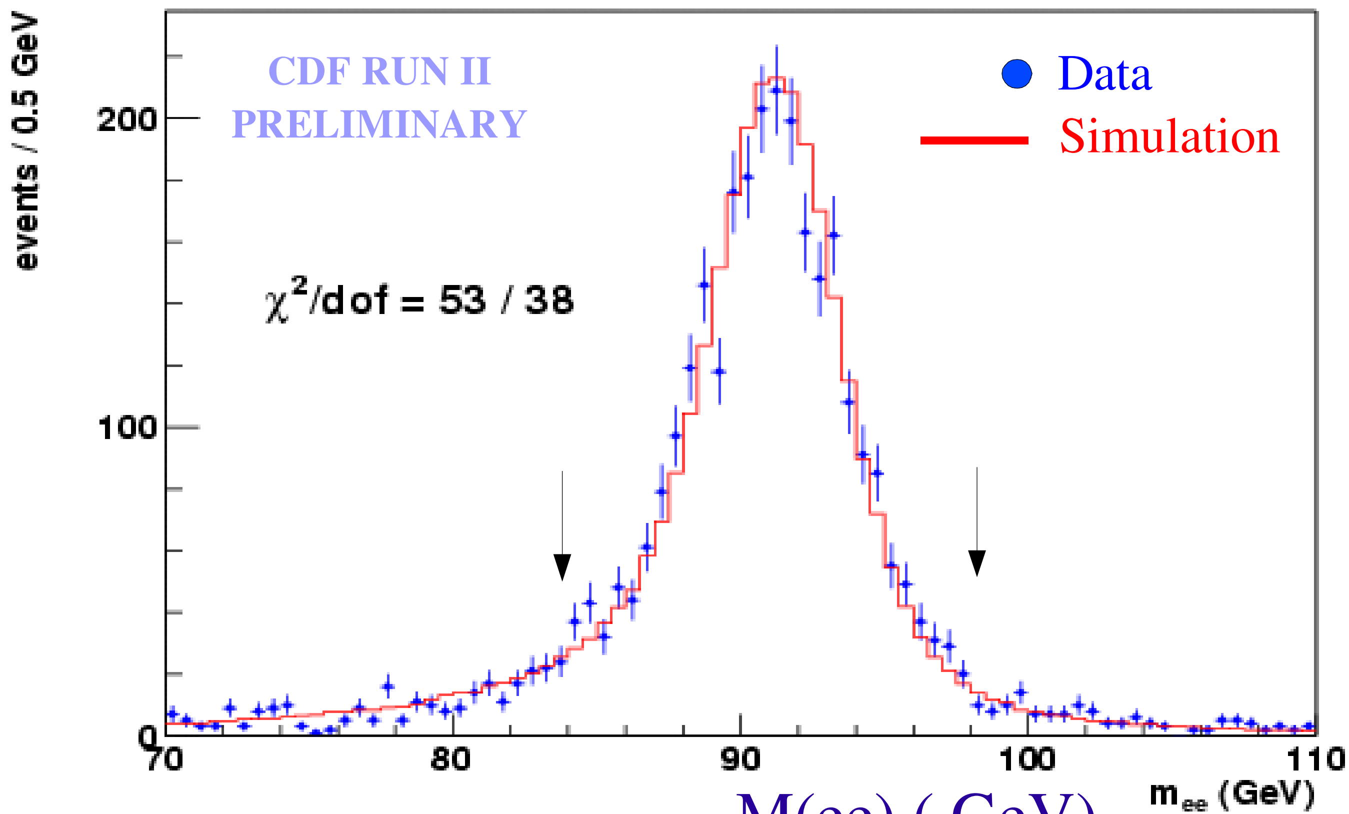
$Z \rightarrow \mu\mu$ Mass Cross-check

- Ultimate test of
  - Tracker momentum scale
  - QED radiative corrections (modelling of radiative photons)



$Z \rightarrow ee$ Mass Cross-check

- Ultimate test of
  - EM calorimeter energy scale
  - QED radiative corrections (modelling of radiative photons)
  - External bremsstrahlung and subsequent conversions



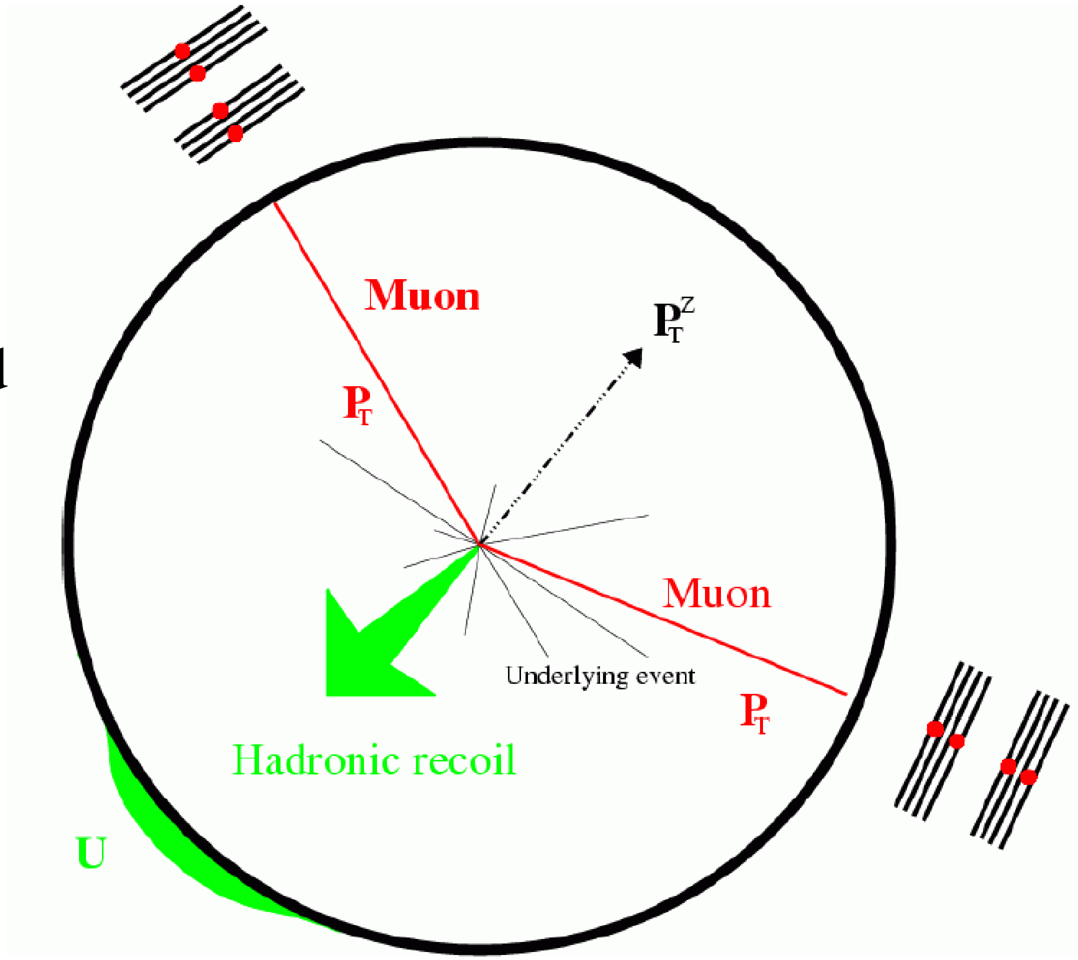
M(ee) (GeV)

Constraints on $p_T(W)$ and Hadronic Recoil Response

Exploit similarity in production and decay of *W* and *Z* bosons

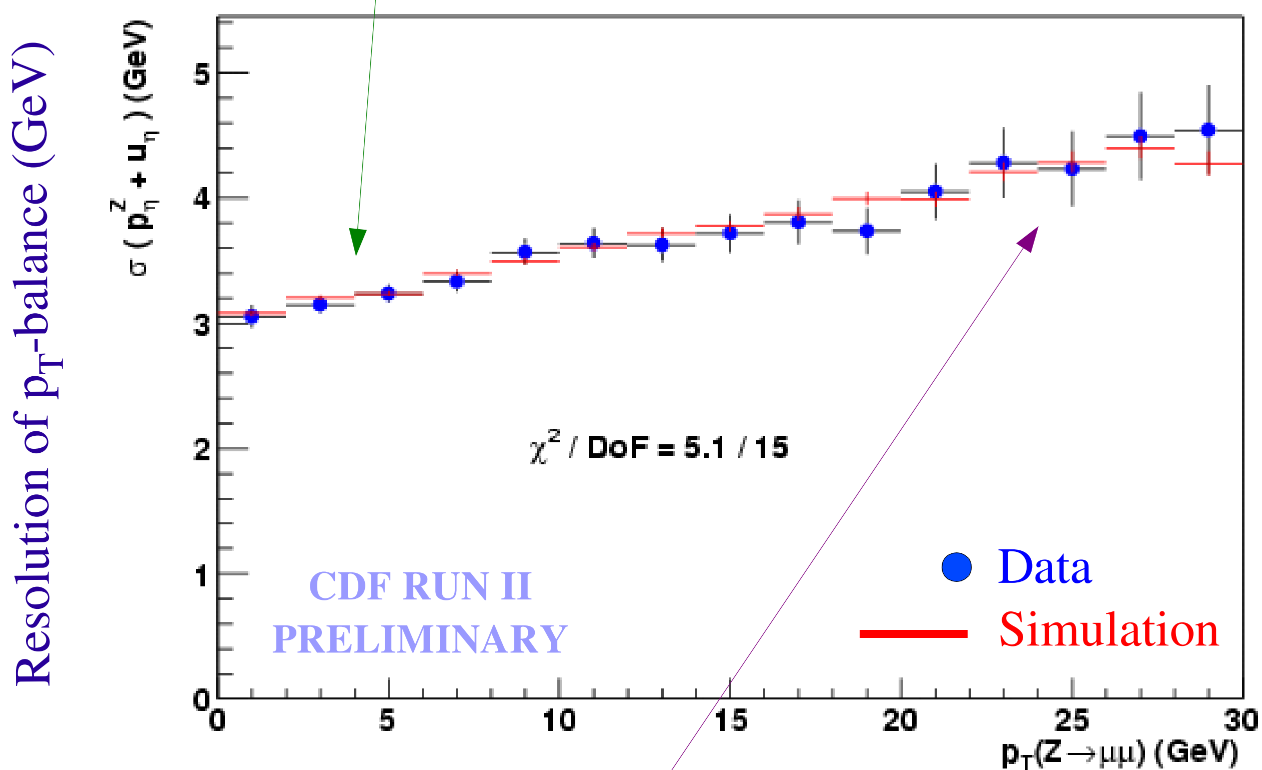
Theoretical model of $p_T(W)$ tuned on the $p_T(Z)$ measurement made with leptons

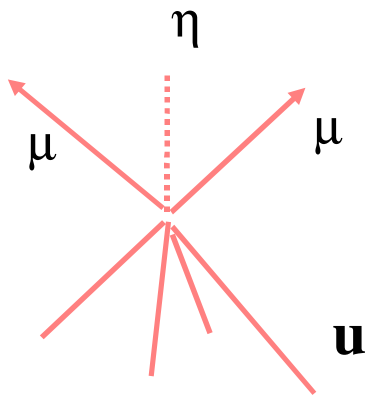
Detector response model for hadronic recoil tuned using p_T-balance in $Z \rightarrow ll$ events



Tuning Recoil Resolution Model with Z events

At low $p_T(Z)$, p_T-balance constrains hadronic resolution due to underlying event

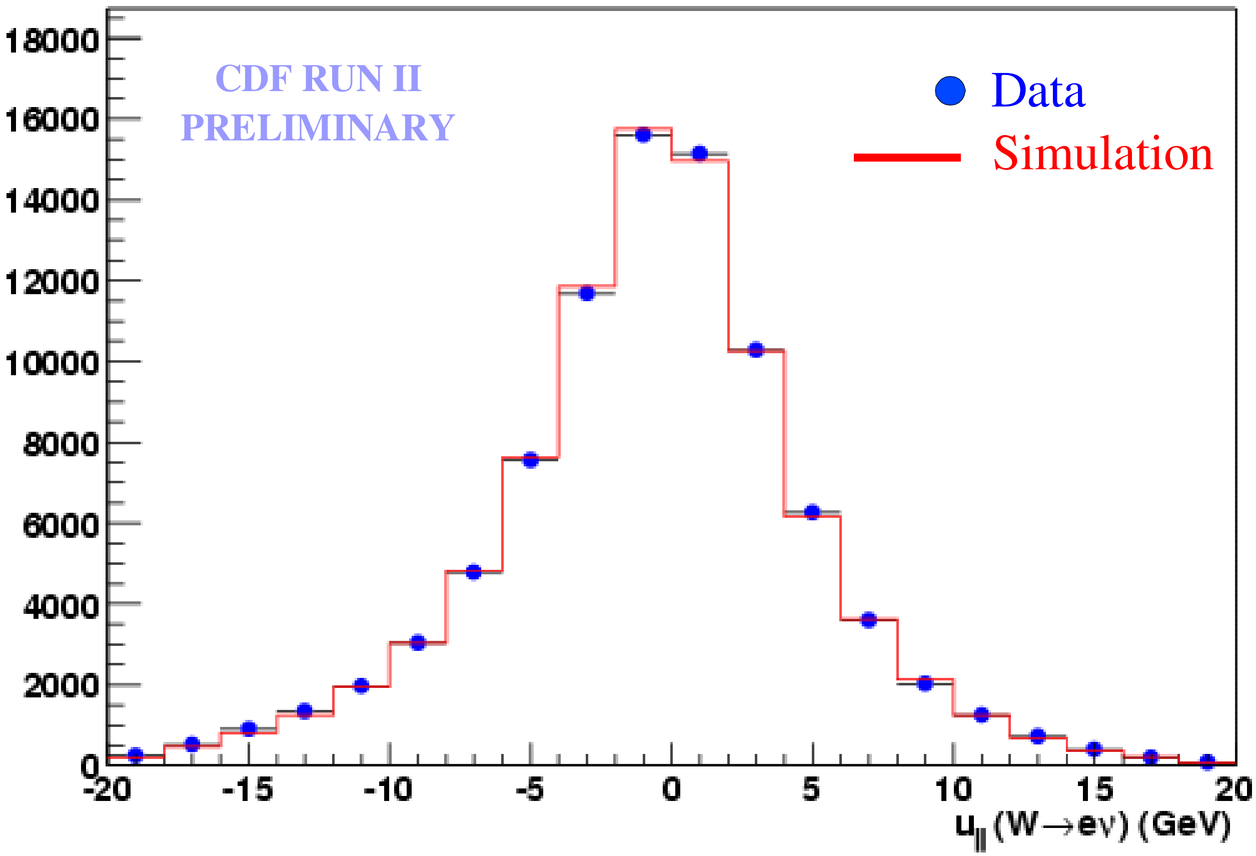




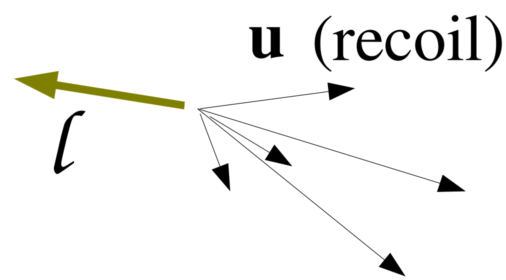
At high $p_T(Z)$, p_T-balance constrains jet resolution

Testing Hadronic Recoil Model with *W* events

Compare recoil distributions between simulation and data (magnitude, projections, angles)



Recoil projection (GeV) on lepton direction



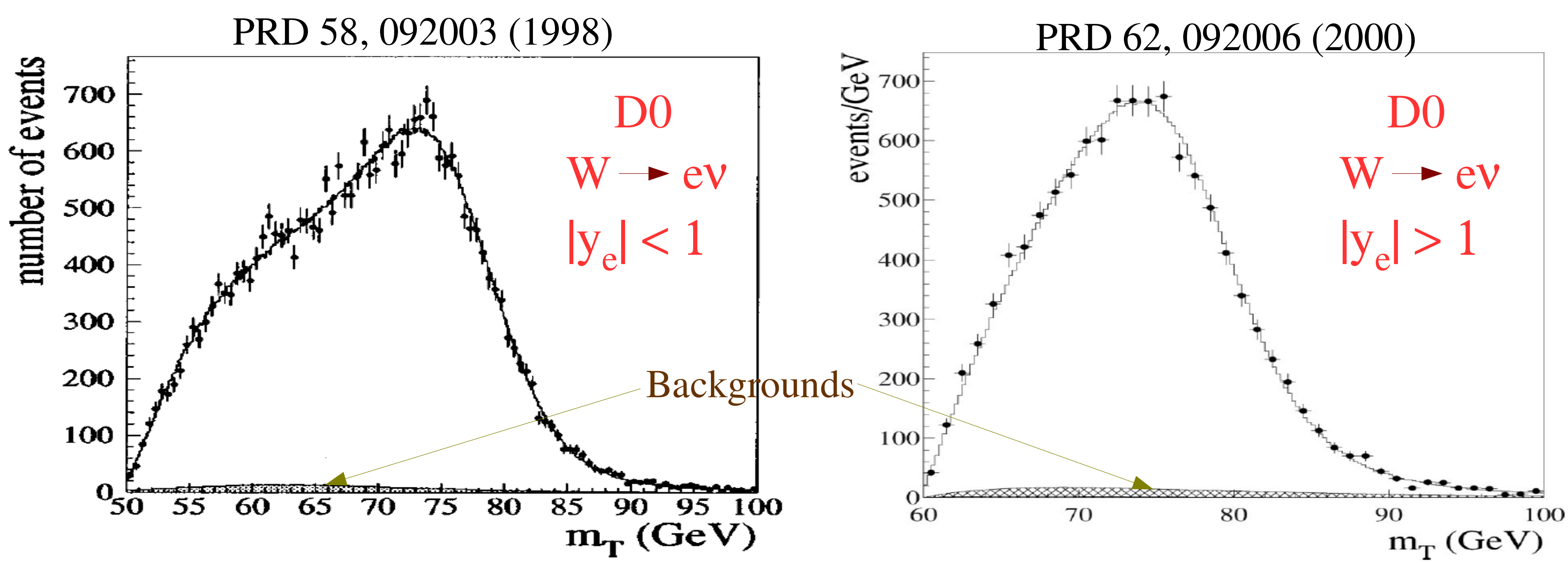
Stringent test of theoretical $p_T(W)$ model and detector recoil model: simulation should match model within quoted ΔM_W !

Other Theoretical Issues

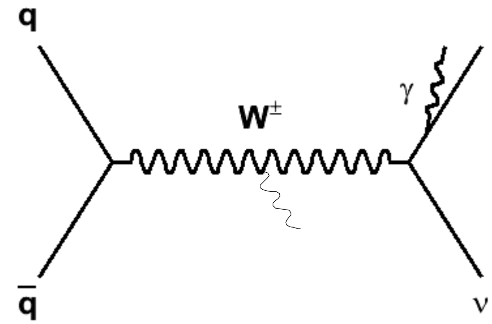
- Parton Distribution Functions
  - Control longitudinal boost of *W*'s
  - Affects transverse distributions ($p_T(l)$, m_T) through detector acceptance cuts in rapidity
  - PDF fitters (MRST, CTEQ...) now providing rigorous errors: boon to PDF uncertainty quantification!
  - consensus on "1σ" to emerge
- QED corrections through radiative photons
  - O(100 MeV) total shift induced in *W* mass at Tevatron

Parton Distribution Functions

- Forward rapidity coverage important to limit uncertainty from PDFs
  - *W* charge asymmetry measurement constrains *u/d* PDF ratio: statistics-limited so far (CDF) (different with *pp* at LHC!)
    - CDF and D0 can do this in Run 2
  - Use forward *W*'s in mass analysis
    - D0 did in Run 1, reduced PDF uncertainty (8 MeV vs 15 MeV)



QED Radiative Corrections



- Recent improvements:
  - Complete NLO QED calculations available (U. Baur *et. al.*) for single photon emission
  - 2-photon calculations performed (Carloni Calame *et. al.*, hep-ex/0303102; Placzek & Jadach, hep-ex/0302065), predict 2-8 MeV shift in *W* mass
  - Combined QCD+QED (FSR γ) generator for *W* and *Z* bosons available (Cao & Yuan)
- Uncertainty in QED corrections not a fundamental limitation
- Important to understand detector response to (soft) photons

Tevatron Run 1 (pre-1996) *W* Mass Systematic Uncertainties (MeV)

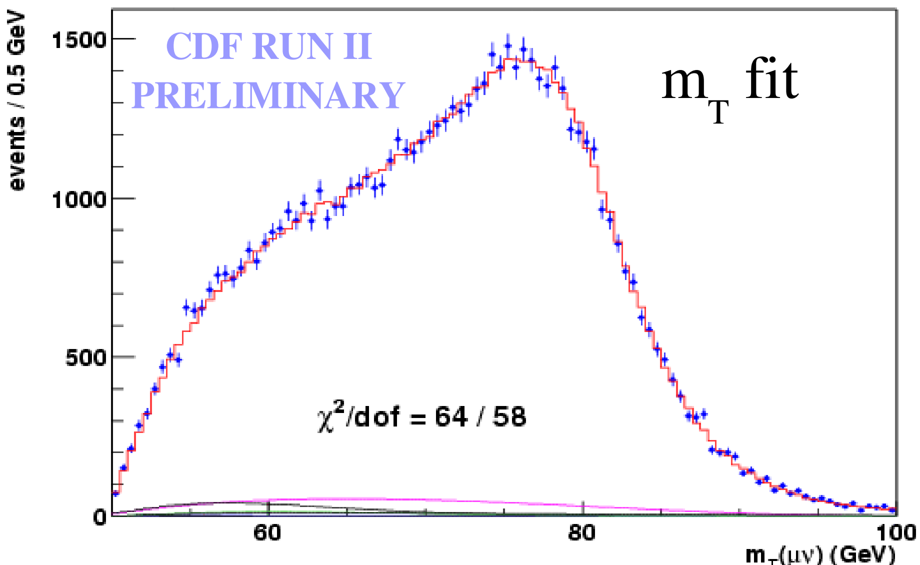
	CDF μ	CDF e	D0 e
W statistics	100	65	60
Lepton energy scale	85	75	56
Lepton resolution	20	25	19
Recoil model	35	37	35
pT(W)	20	15	15
Selection bias	18	-	12
Backgrounds	25	5	9
Parton dist. Functions	15	15	8
QED rad. Corrections	11	11	12
Γ(W)	10	10	10

(Correlated uncertainties between CDF and D0)

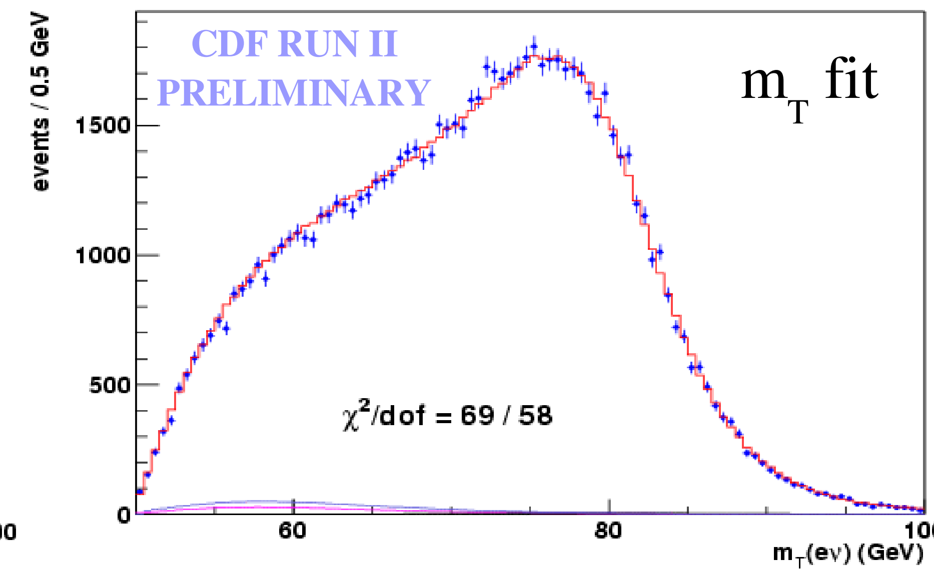
Systematic uncertainties limited by statistics of control samples

CDF Run 2 (post-2000) *W* Mass Fits

Muons

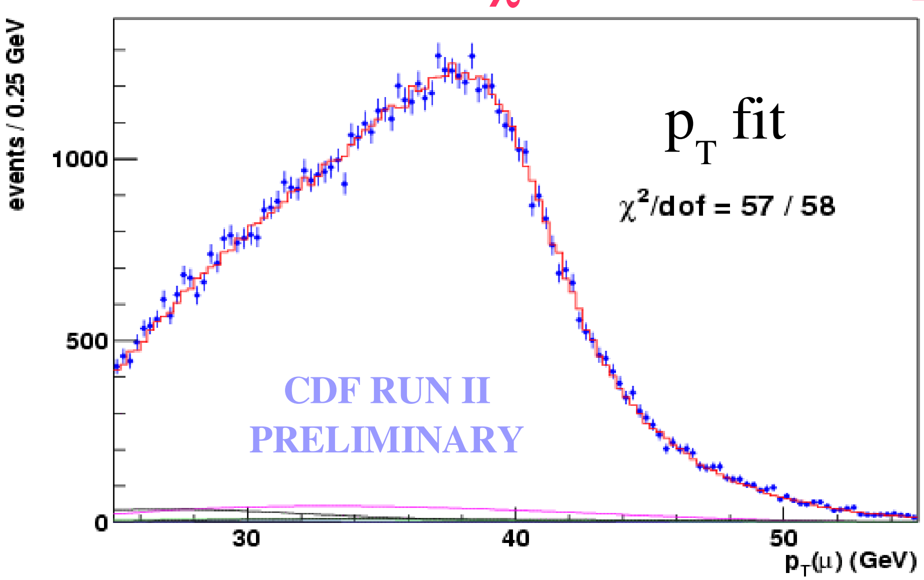


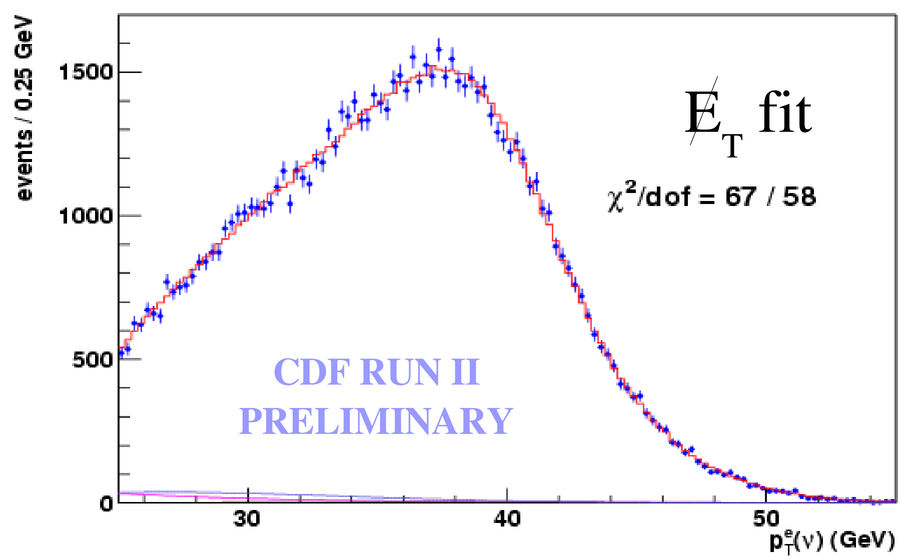
Electrons



Good χ^2 for fits

Fits blinded with [-100,100] MeV offset





CDF Run 2 *W* Mass Uncertainties (200 pb^{-1})

Systematic	Electrons (Run 1b)	Muons (Run 1b)
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)

CDF RUN II PRELIMINARY

Current estimated Run 2 uncertainty (*e* & μ combined): 76 MeV

Run 1 published: 79 MeV

Work in progress to reduce uncertainties due to recoil modelling, electron energy scale, theory model

Cross-checks and analysis validation in progress

Planning for *W* Mass Measurement at ATLAS

- Bias-free triggers for $W \rightarrow l\nu$, $Z \rightarrow ll$, $\Upsilon \rightarrow ll$ ($J/\psi \rightarrow ll$)
  - e.g. At the Tevatron, *W* and *Z* triggers are fully efficient for $p_T(l)$, $p_T(\nu) > 30$ GeV, J/ψ trigger efficient for $p_T(l) > 1.8$ GeV
  - Minimize *W*, *Z* trigger and reconstruction bias due to jet activity (kinematic and efficiency)
  - Minimize differences between *W* and *Z* trigger and reconstruction
    - Makes *Z*'s better control sample
- Forward rapidity coverage has great benefit
    - Triggering and precision tracking usually more difficult than central rapidity region

Planning for *W* Mass Measurement at ATLAS

- Good tracker alignment by construction and survey
  - Minimize number of degrees of freedom to be constrained by alignment from data analysis
- Careful accounting of passive material during detector construction, implement in GEANT map
  - Consider pre-measured detector elements or additional metal pieces for *in-situ* absolute calibration reference
- Calorimeter calibration using electronics pulsing, light pulsing
  - Test beam data for uniformity, linearity

Summary

- The *W* boson mass continues to be a very interesting parameter to measure with increasing precision
- Feasible to control systematic uncertainties at the same level as statistical error using control samples
- ΔM_W at the Tevatron
  - Run 1: 59 MeV
  - Run 2 Goal: 20 MeV
- Looking forward to $\Delta M_W \sim \Delta M_Z$ at the LHC!!