The First W Mass Measurement from Run II of the Tevatron

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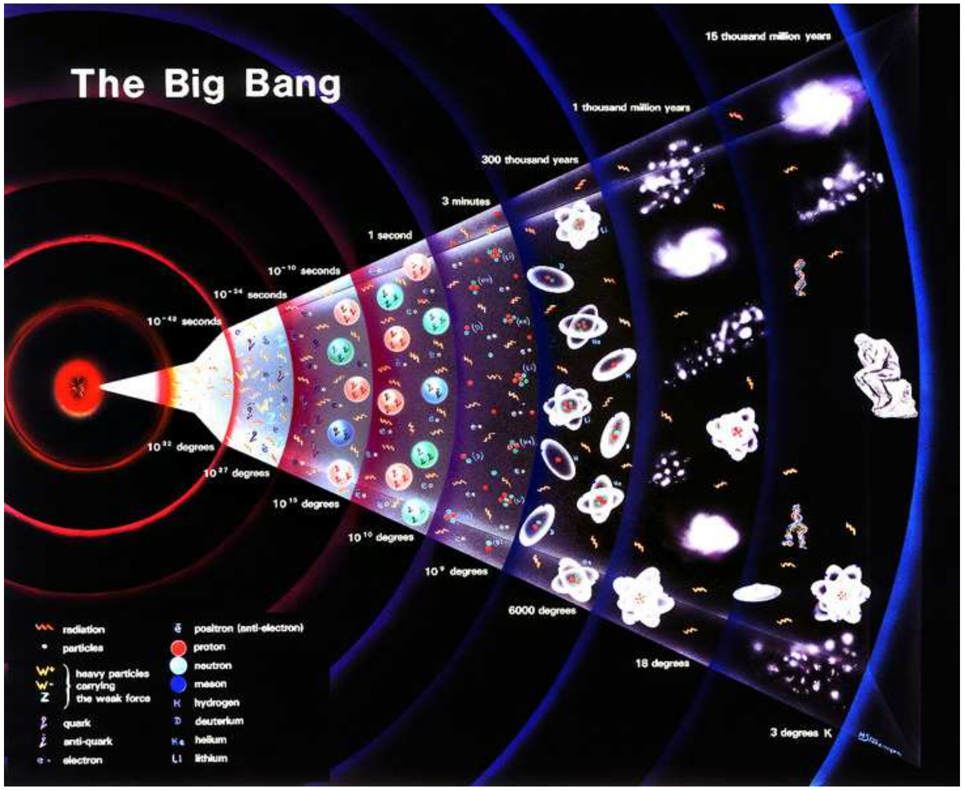
For the CDF Collaboration



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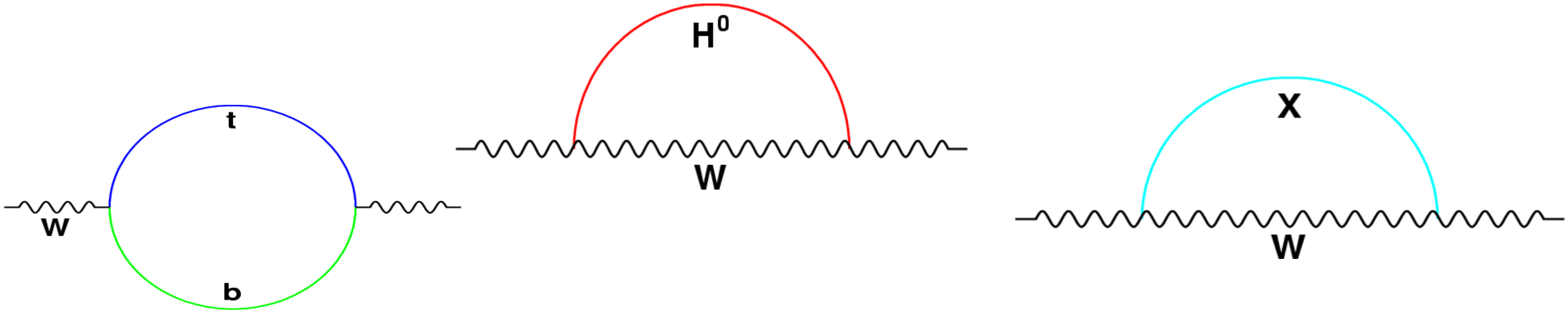
Motivation

- The electroweak sector of the standard model is constrained by three precisely known parameters
  - $\alpha_{EM}(M_Z) = 1 / 127.918(18)$
  - $G_F = 1.16637\ (1) \times 10^{-5}\ \text{GeV}^{-2}$

    $M_Z = 91.1876\ (21)\ \text{GeV}$
- At tree-level, these parameters are related by
  - $M_W^2 = \pi\alpha / \sqrt{2} G_F \sin^2\theta_W$
  - $M_Z^2 = \pi\alpha / \sqrt{2} G_F \sin^2\theta_W \cos^2\theta_W$
  - $M_W = M_Z \cos\theta_W$
    - Where θ_W is the weak mixing angle

Motivation

- Radiative corrections due to heavy quark and Higgs loops and exotica

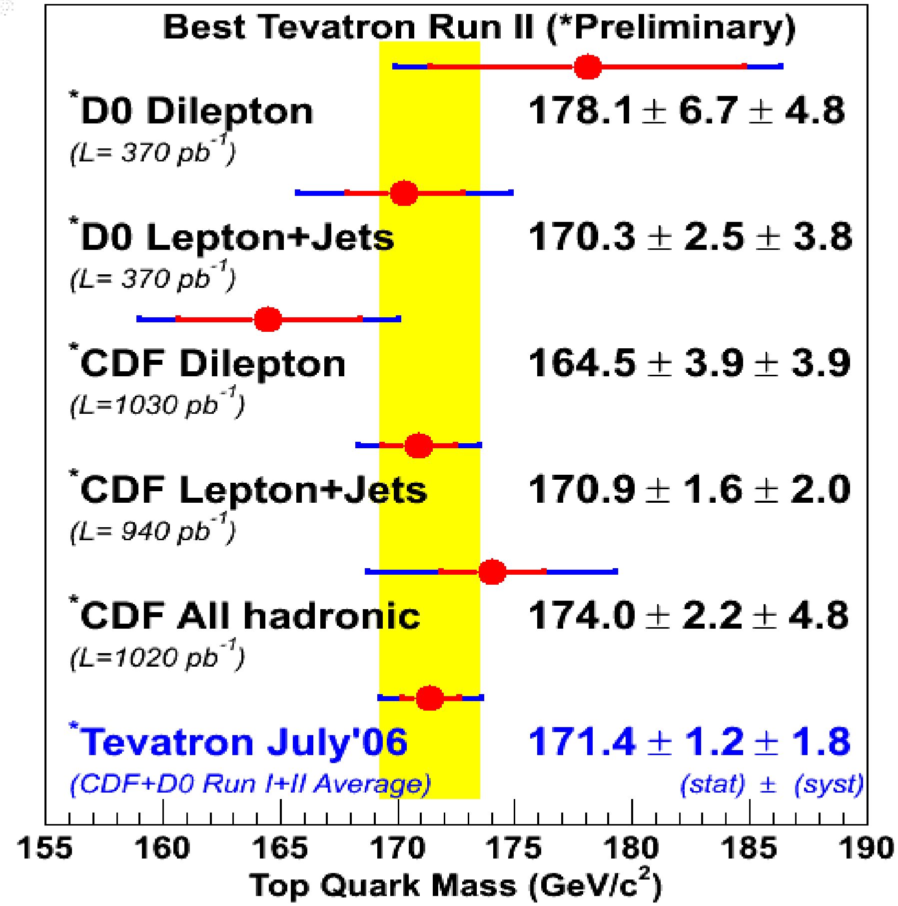


Motivate the introduction of the ρ parameter: $M_W^2 = \rho\, M_Z^2 \cos^2\theta_W$

with the predictions $(\rho-1) \sim M_{top}^2$ and $(\rho-1) \sim \ln M_H$

- In conjunction with M_{top}, the W boson mass constrains the mass of the Higgs boson, and possibly new particles beyond the standard model

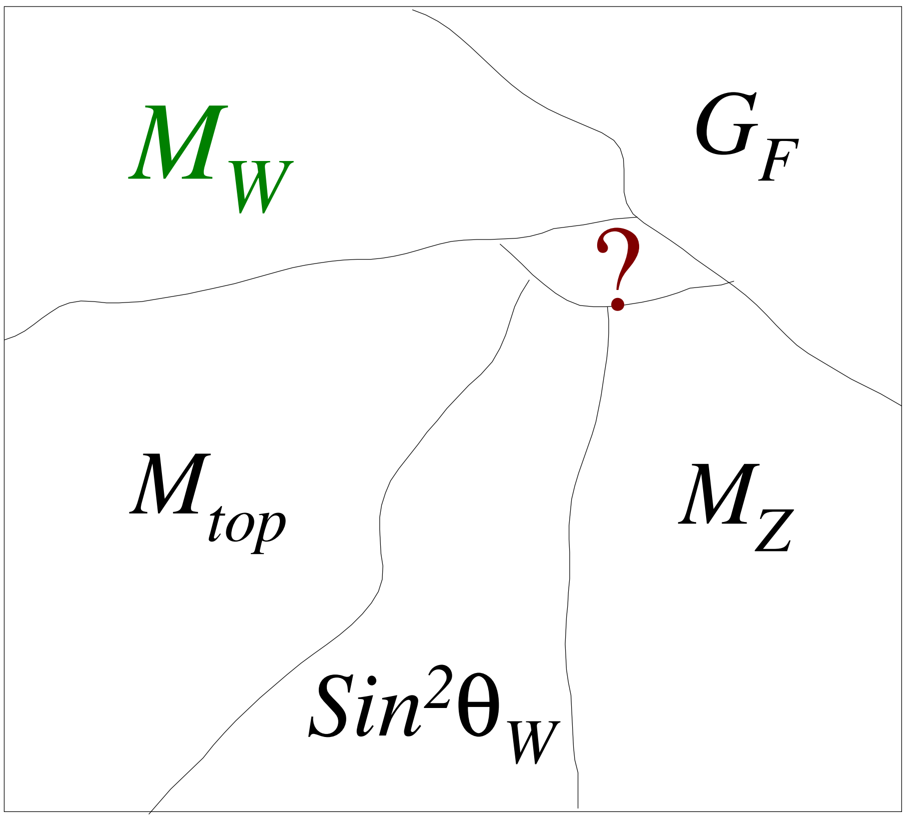
Progress on M_{top} at the Tevatron



- From the Tevatron, $\delta M_{top} = 2.1$ GeV => $\delta M_H / M_H = 18\%$
- equivalent $\delta M_W = 12$ MeV for the same Higgs mass constraint
- Current world average $\delta M_W = 29$ MeV
  - progress on δM_W now has the biggest impact on Higgs constraint!

Motivation

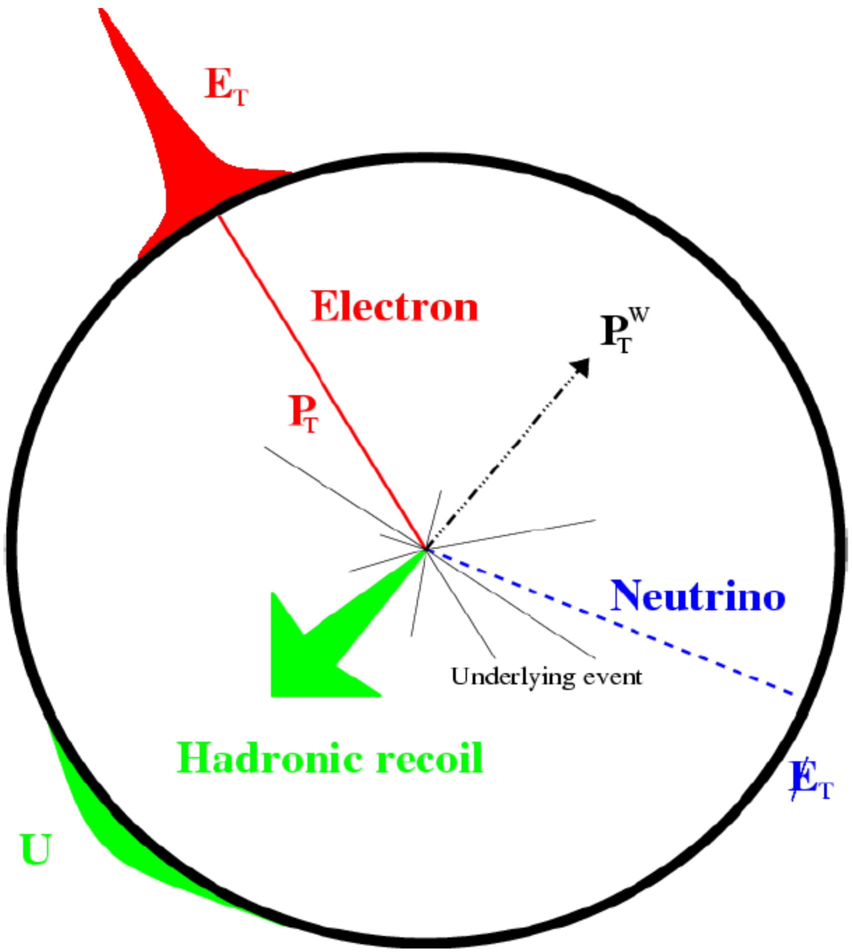
- Current SM Higgs fit: $M_H = 85^{+39}_{-28}$ GeV (LEP Collaborations and LEPEWWG, hep-ex/0612034)
- LEPII direct searches exclude $M_H < 114.4$ GeV @ 95% CL (PLB 565, 61)



In addition to the Higgs,
is there another missing piece
in this puzzle?

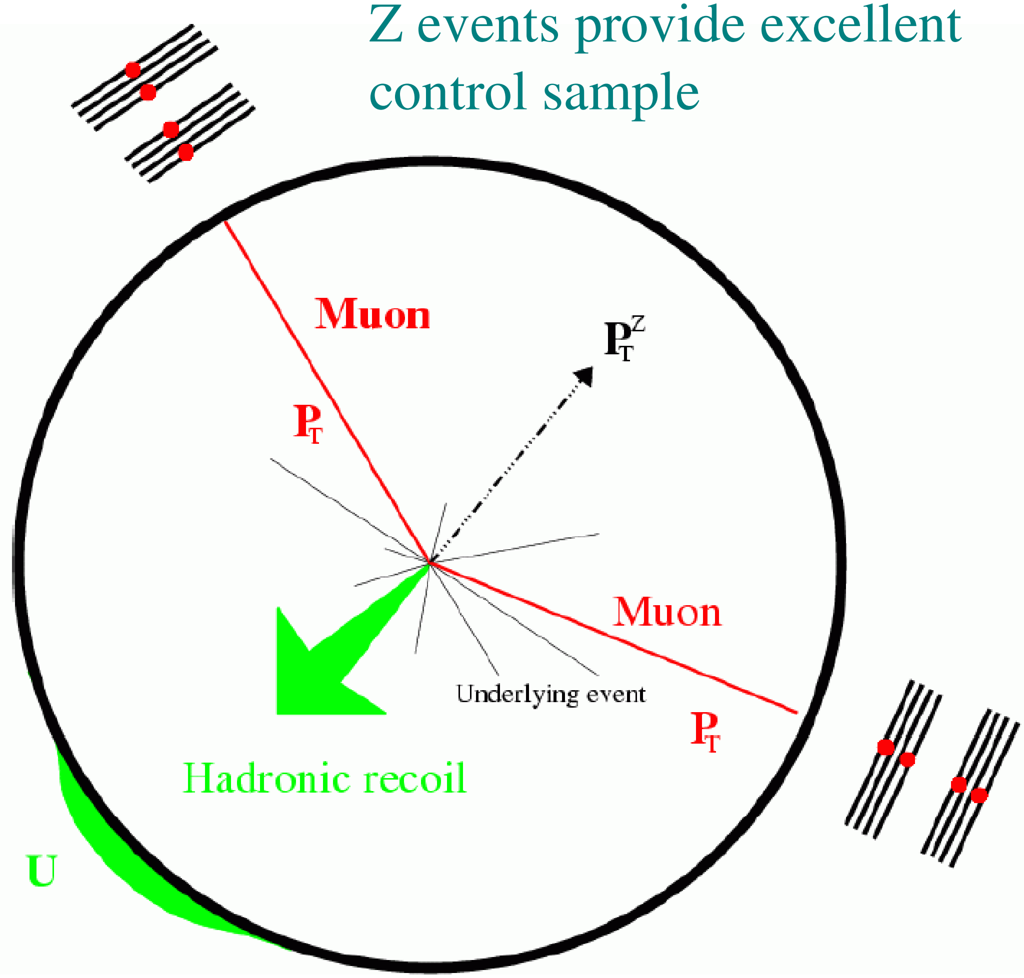
Analysis Strategy

W and Z production at the Tevatron



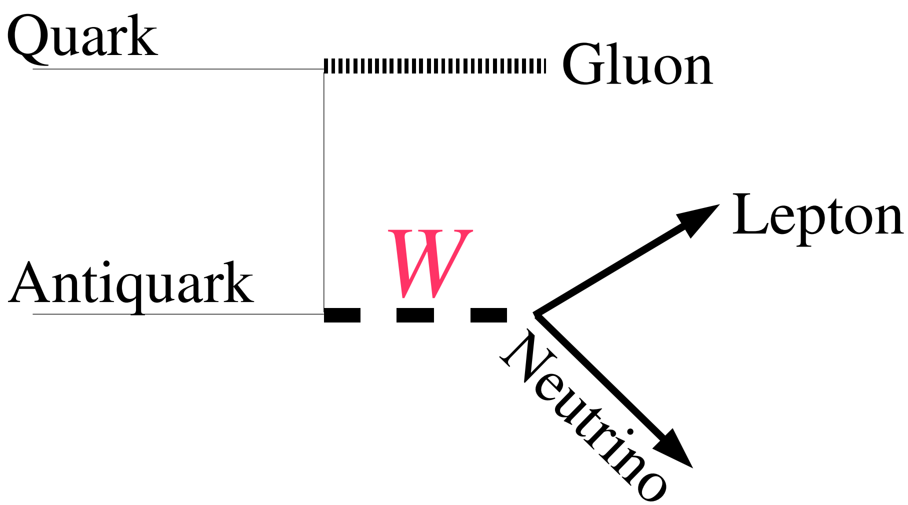
Isolated, high p_T leptons,
missing transverse momentum in W's

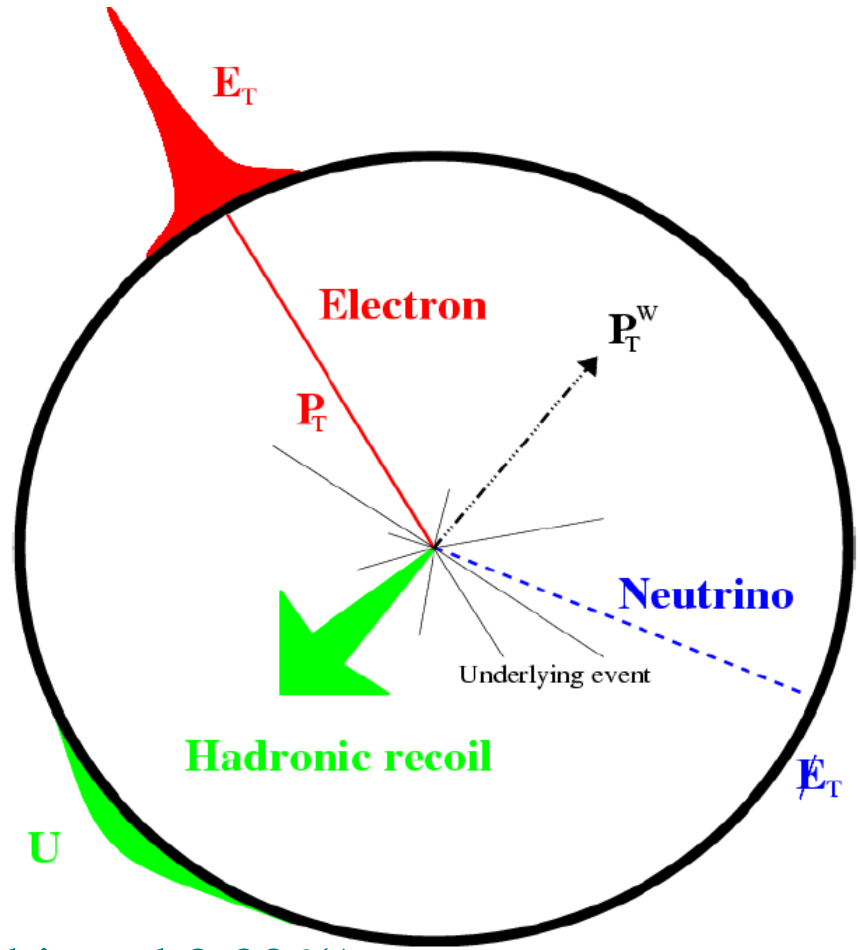
Z events provide excellent
control sample



Typically small hadronic (jet) activity

W Boson Production at the Tevatron





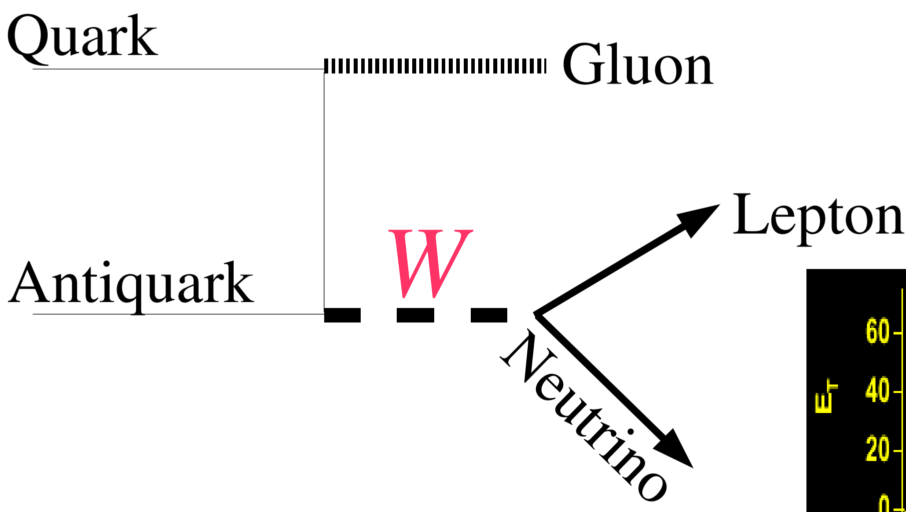
Quark-antiquark annihilation dominates (80%)

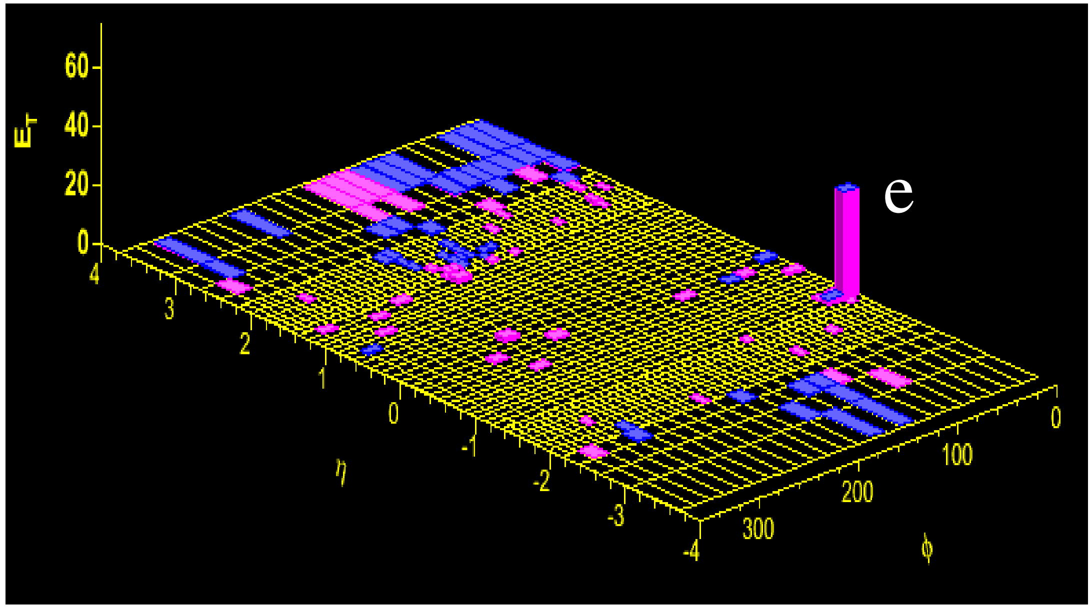
Lepton p_T carries most of W mass information, can be measured precisely (achieved 0.03%)

Initial state QCD radiation is O(10 GeV), measure as soft 'hadronic recoil' in calorimeter (calibrated to ~1%)

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

W Boson Production at the Tevatron





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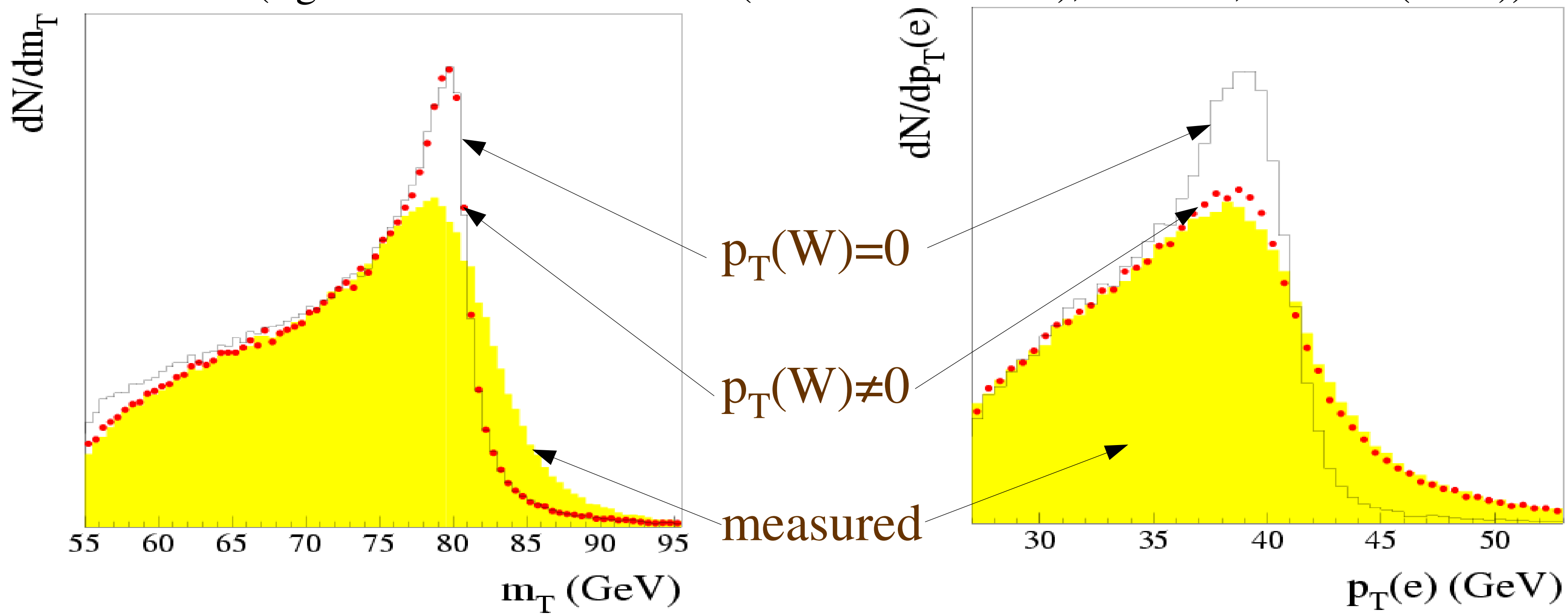
W Mass Measurement at the Tevatron

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



W mass information contained in location of transverse Jacobian edge

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

Insensitive to $p_T(W)$ to first order

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

$p_T(l)$ fit: provides cross-check of production model:

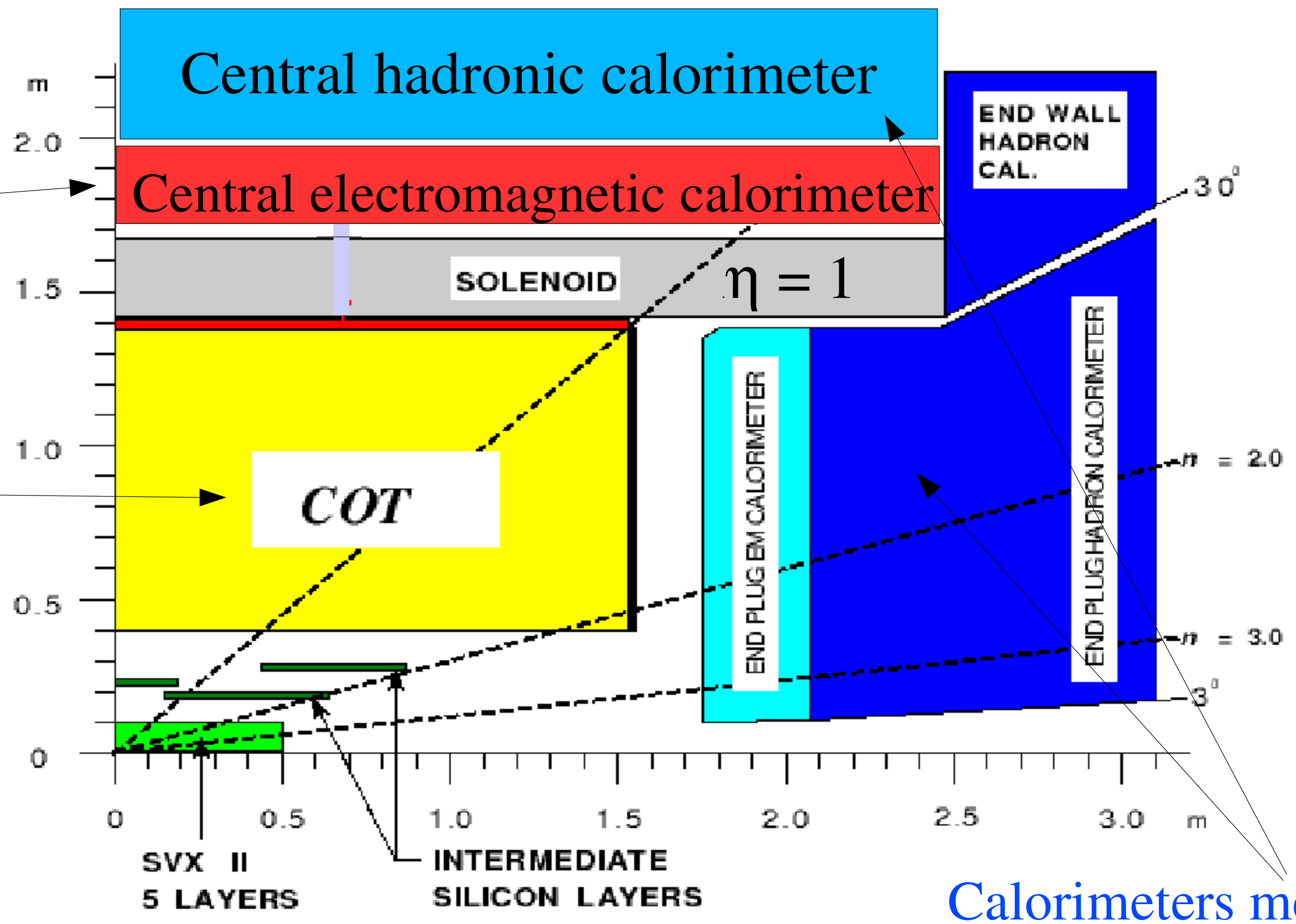
Needs theoretical model of $p_T(W)$

$P_T(\nu)$ fit provides cross-check of hadronic modelling

Quadrant of Collider Detector at Fermilab (CDF)

EM calorimeter provides precise electron energy measurement

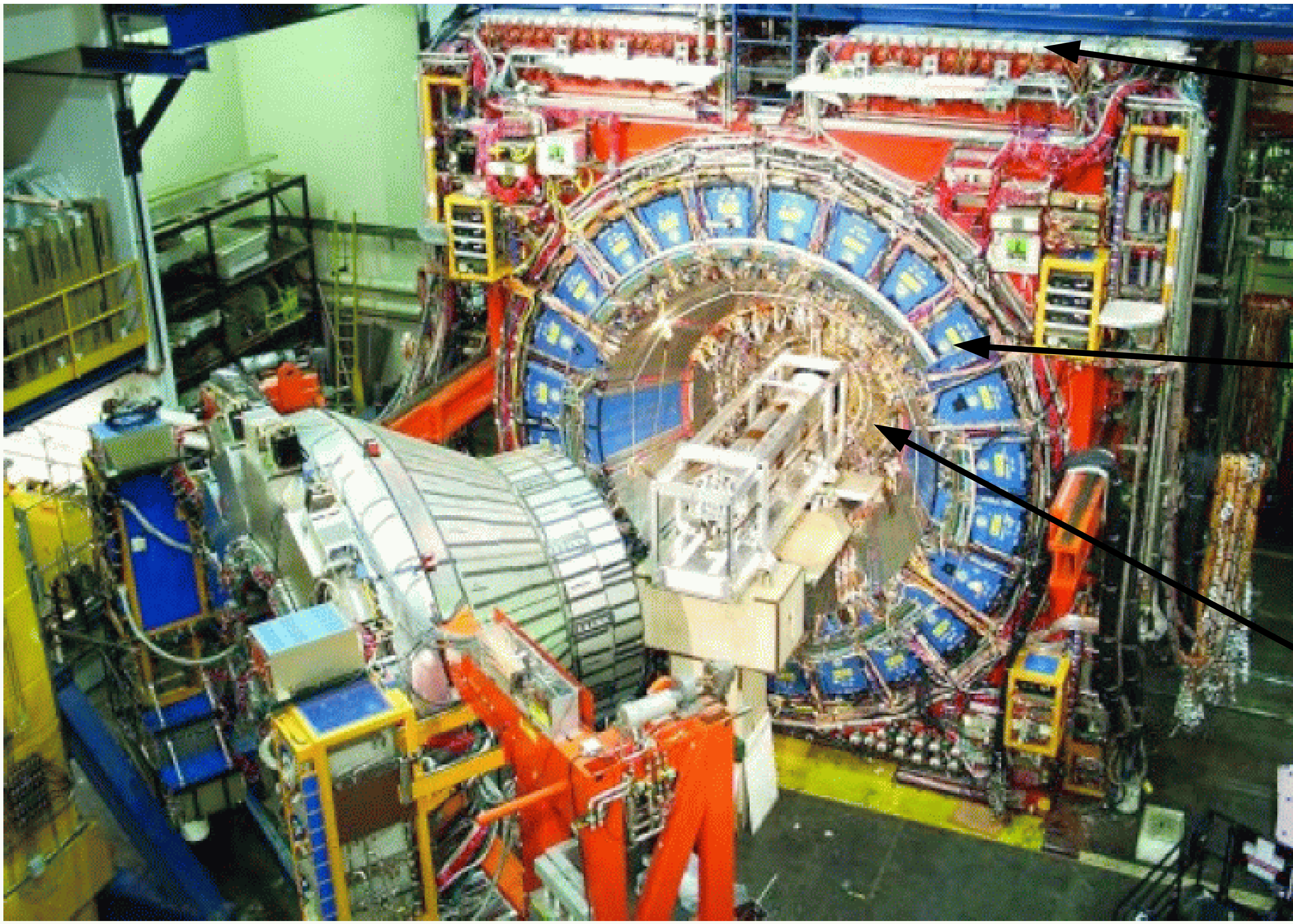
COT provides precise lepton track momentum measurement



Calorimeters measure hadronic recoil particles

Select W and Z bosons with central (| η | < 1) leptons

Collider Detector at Fermilab (CDF)



W & Z Data Samples

- Event selection: high p_T leptons ($p_T > 30$ GeV) and small hadronic recoil activity
  - to maximize W mass information content and minimize backgrounds

Sample	Candidates
$W \to e\nu$	63964
$W \to \mu\nu$	51128
$Z \to e^+e^-$	2919
$Z \to \mu^+\mu^-$	4960

- Integrated Luminosity (collected between February 2002 – September 2003):
  - Electron channel: $\mathcal{L} = 218$ pb^{-1}
  - Muon channel: $\mathcal{L} = 191$ pb^{-1}
- Event selection gives fairly clean samples
  - Mis-identification backgrounds ~ 0.5%

Outline of Analysis

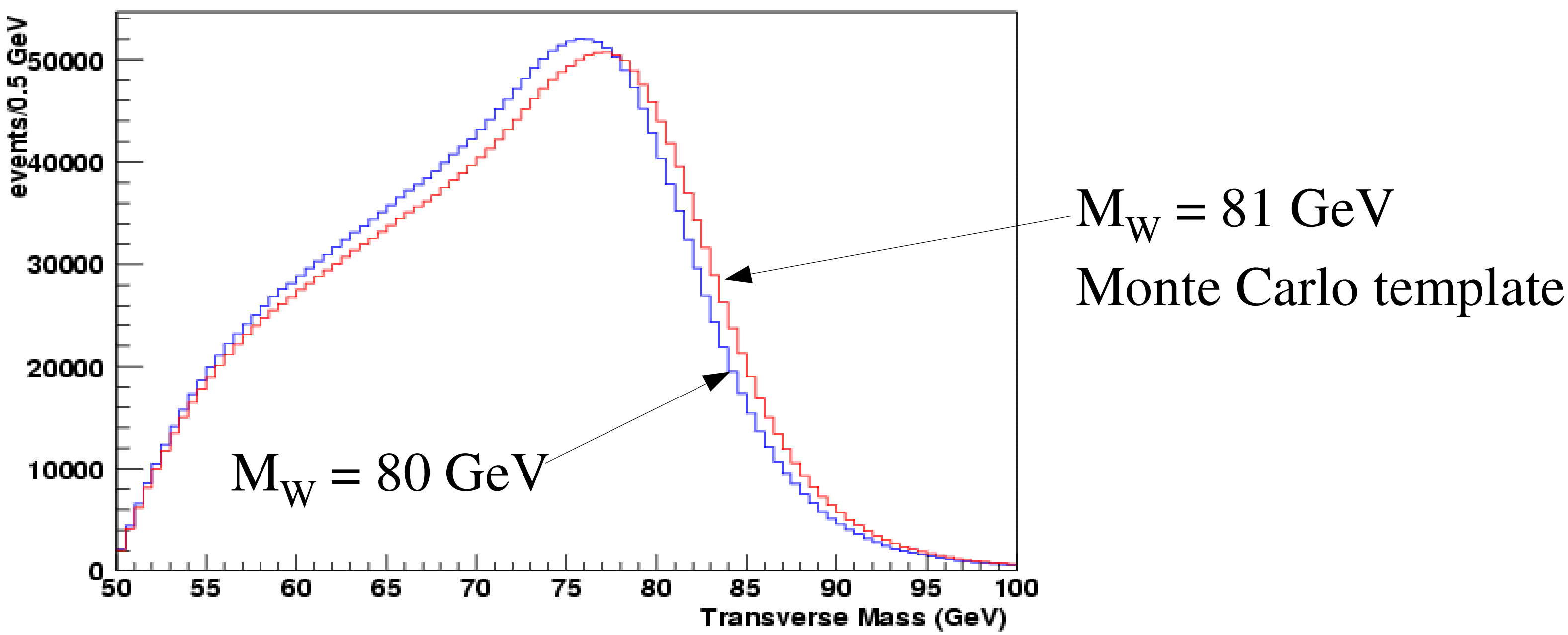
Energy scale measurements drive the W mass measurement

- Tracker Calibration
  - alignment of the COT (~2400 cells) using cosmic rays
  - COT momentum scale and tracker non-linearity constrained using $J/\psi \rightarrow \mu\mu$ and $\Upsilon \rightarrow \mu\mu$ mass fits
    - Confirmed using $Z \rightarrow \mu\mu$ mass fit
- EM Calorimeter Calibration
  - COT momentum scale transferred to EM calorimeter using a fit to the peak of the E_{cal}/p_{track} spectrum, around $E/p \sim 1$
  - Calorimeter energy scale confirmed using $Z \rightarrow ee$ mass fit
- Tracker and EM Calorimeter resolutions
- Hadronic recoil modelling
  - Characterized using p_T-balance in $Z \rightarrow ll$ events

Signal Simulation and Fitting

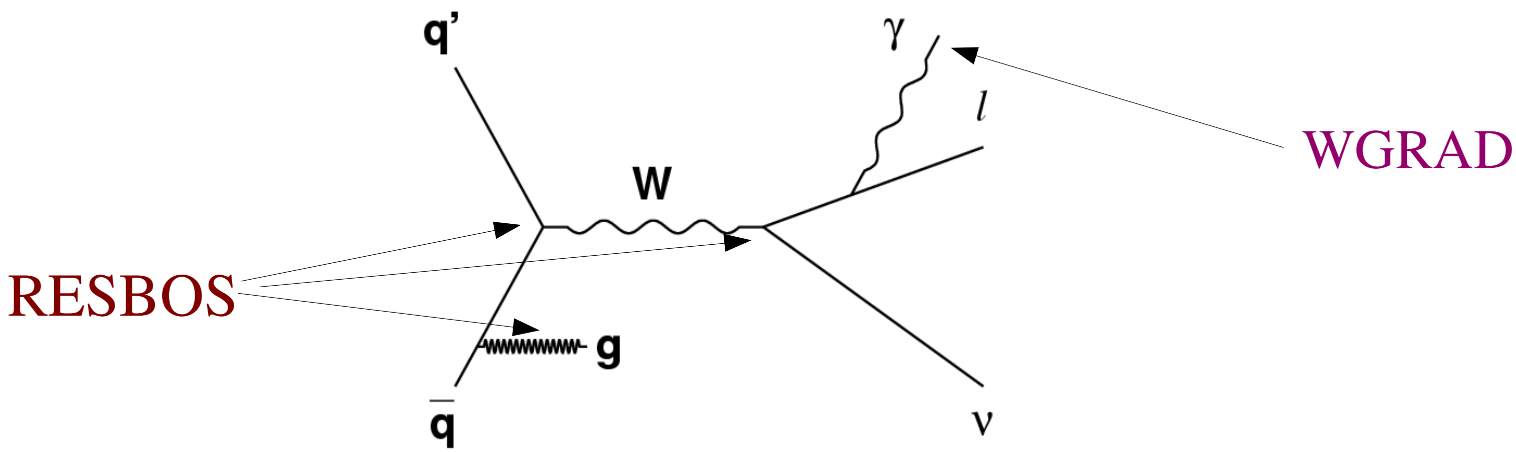
Signal Simulation and Template Fitting

- All signals simulated using a fast Monte Carlo
  - Generate finely-spaced templates as a function of the fit variable
  - perform binned maximum-likelihood fits to the data
- Custom fast Monte Carlo makes smooth, high statistics templates
  - And provides analysis control over key components of the simulation



- We will extract the W mass from six kinematic distributions: Transverse mass, charged lepton p_T and missing E_T using both electron and muon channels

Generator-level Signal Simulation



- Generator-level input for W & Z simulation provided by RESBOS (C. Balazs & C.-P. Yuan, PRD56, 5558 (1997) and references therein), which
  - Calculates triple-differential production cross section, and p_T-dependent double-differential decay angular distribution
  - calculates boson p_T spectrum reliably over the relevant p_T range: includes tunable parameters in the non-perturbative regime at low p_T
- Radiative photons generated according to energy *vs* angle lookup table from WGRAD (U. Baur, S. Keller & D. Wackeroth, PRD59, 013002 (1998))

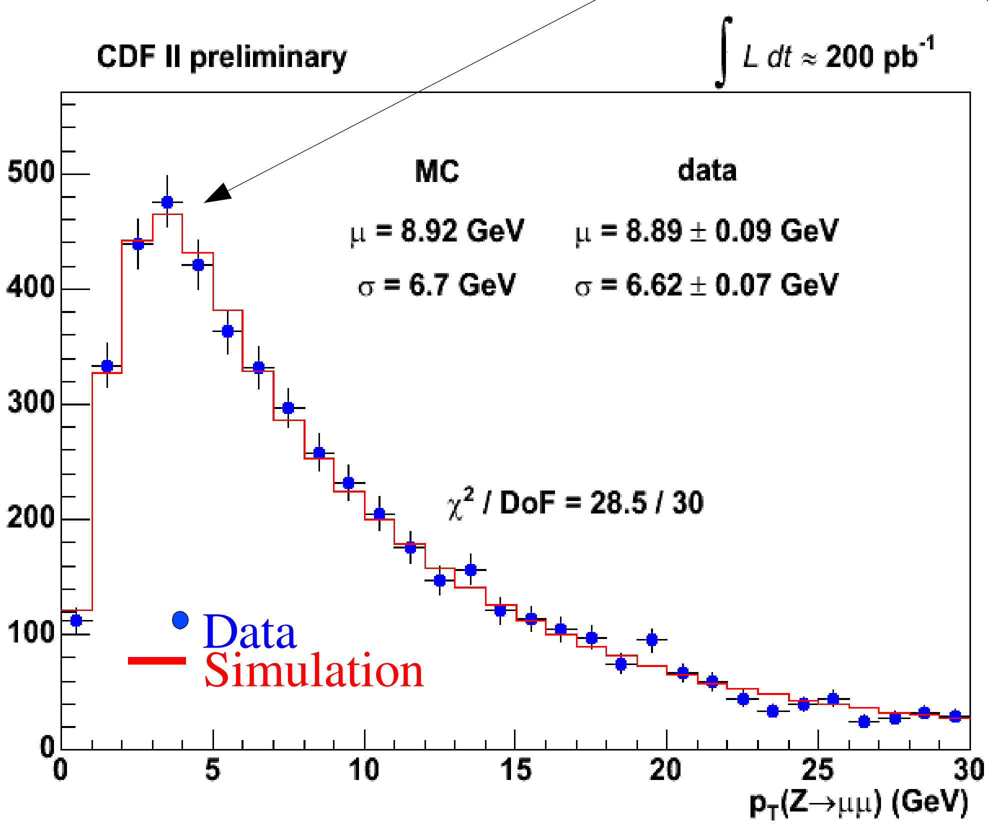
Constraining Boson p_T Spectrum

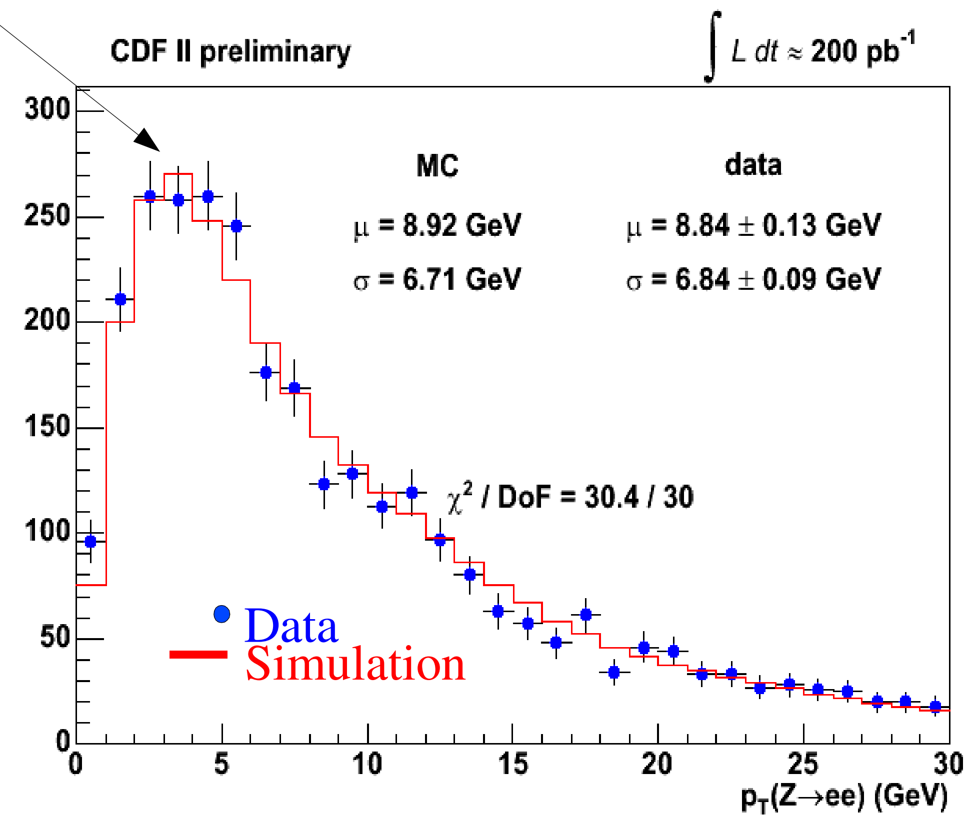
- Fit the non-perturbative parameter g_2 in RESBOS to $p_T(ll)$ spectra: find $g_2 = 0.685 \pm 0.048$

$\Delta M_W = 3$ MeV

  - Consistent with global fits (Landry *et al,* PRD67, 073016 (2003))
- Negligible effect of second non-perturbative parameter g_3

Position of peak in boson p_T spectrum depends on g_2





Fast Monte Carlo Detector Simulation

- A complete detector simulation of all quantities measured in the data
- First-principles simulation of tracking
  - Tracks and photons propagated through a high-resolution 3-D lookup table of material properties for silicon detector and COT
  - At each material interaction, calculate
    - Ionization energy loss according to complete Bethe-Bloch formula
    - Generate bremsstrahlung photons down to 4 MeV, using detailed cross section and spectrum calculations
    - Simulate photon conversion and compton scattering
    - Propagate bremsstrahlung photons and conversion electrons
    - Simulate multiple Coulomb scattering, including non-Gaussian tail
  - Deposit and smear hits on COT wires, perform full helix fit including optional beam-constraint

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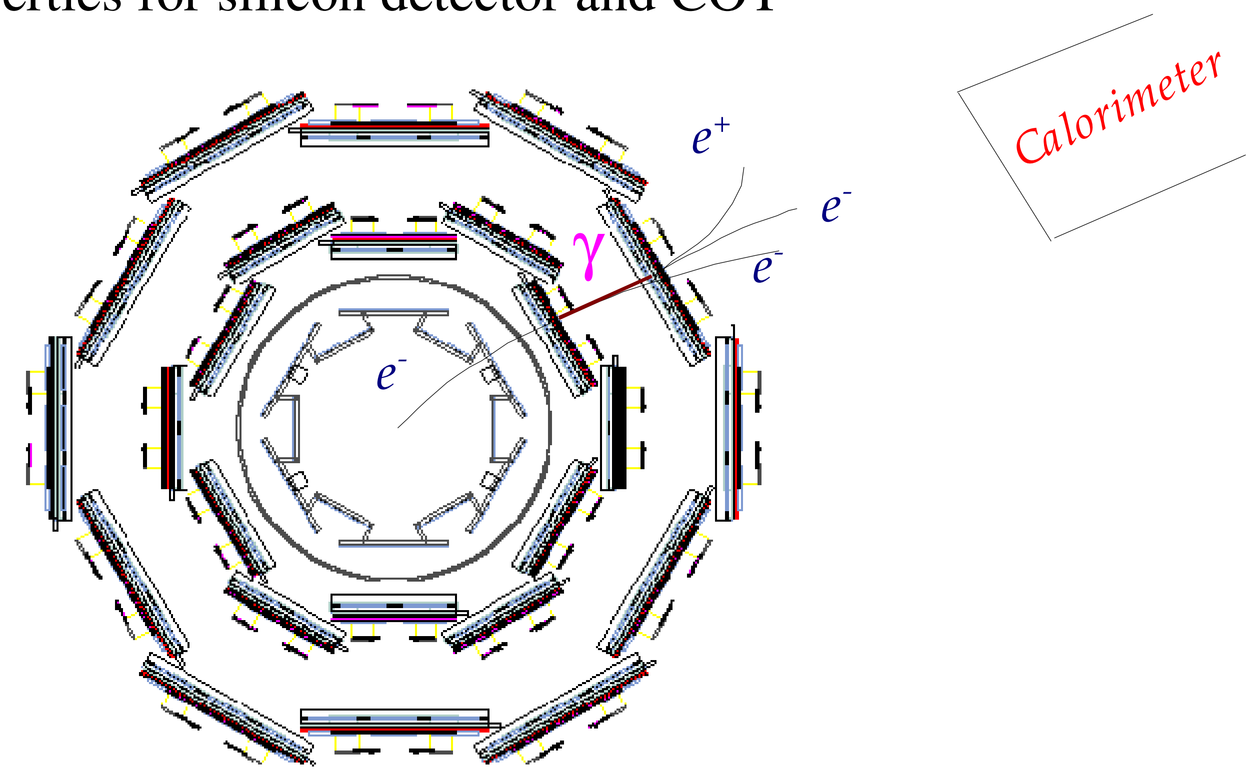

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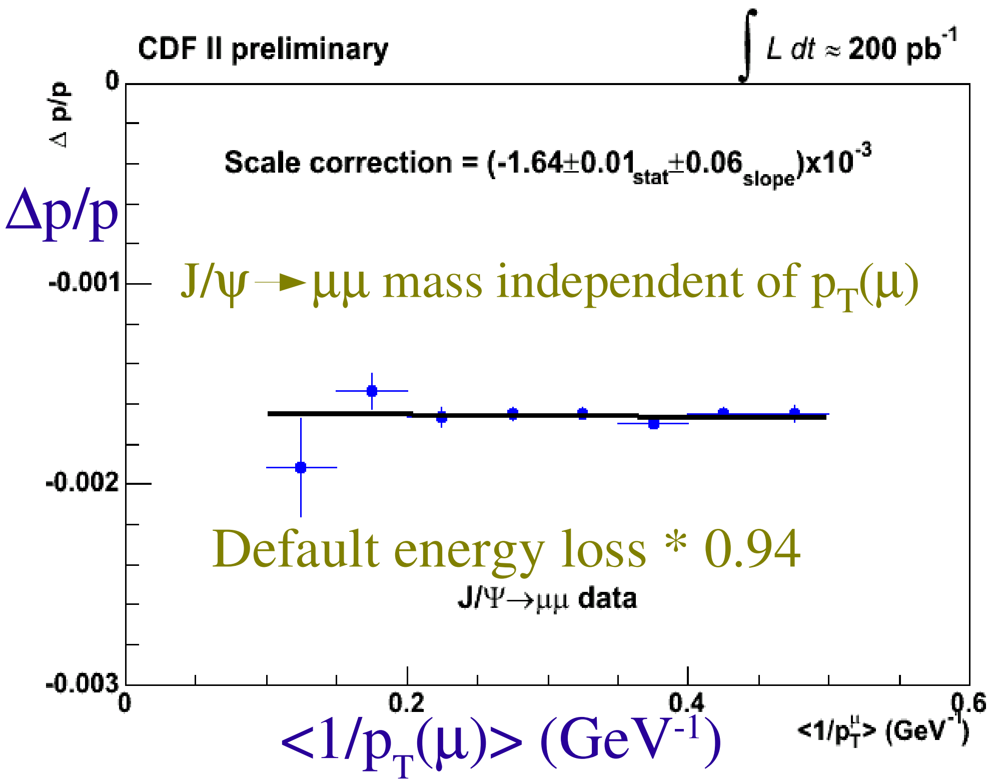
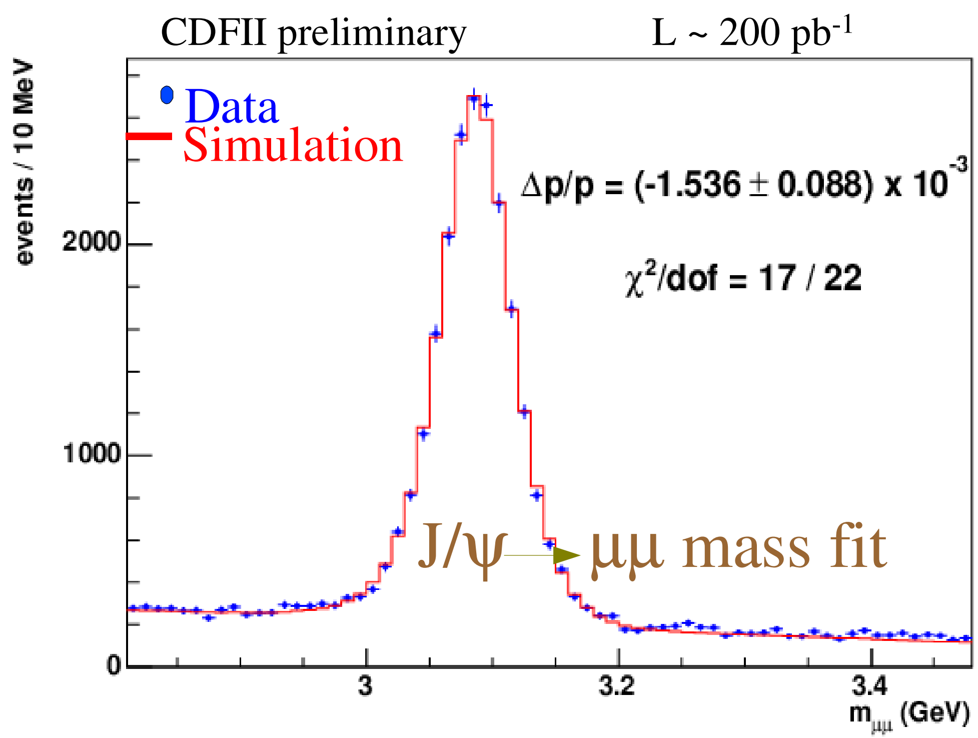
Lepton Momentum & Energy Scales

Tracking Momentum Scale

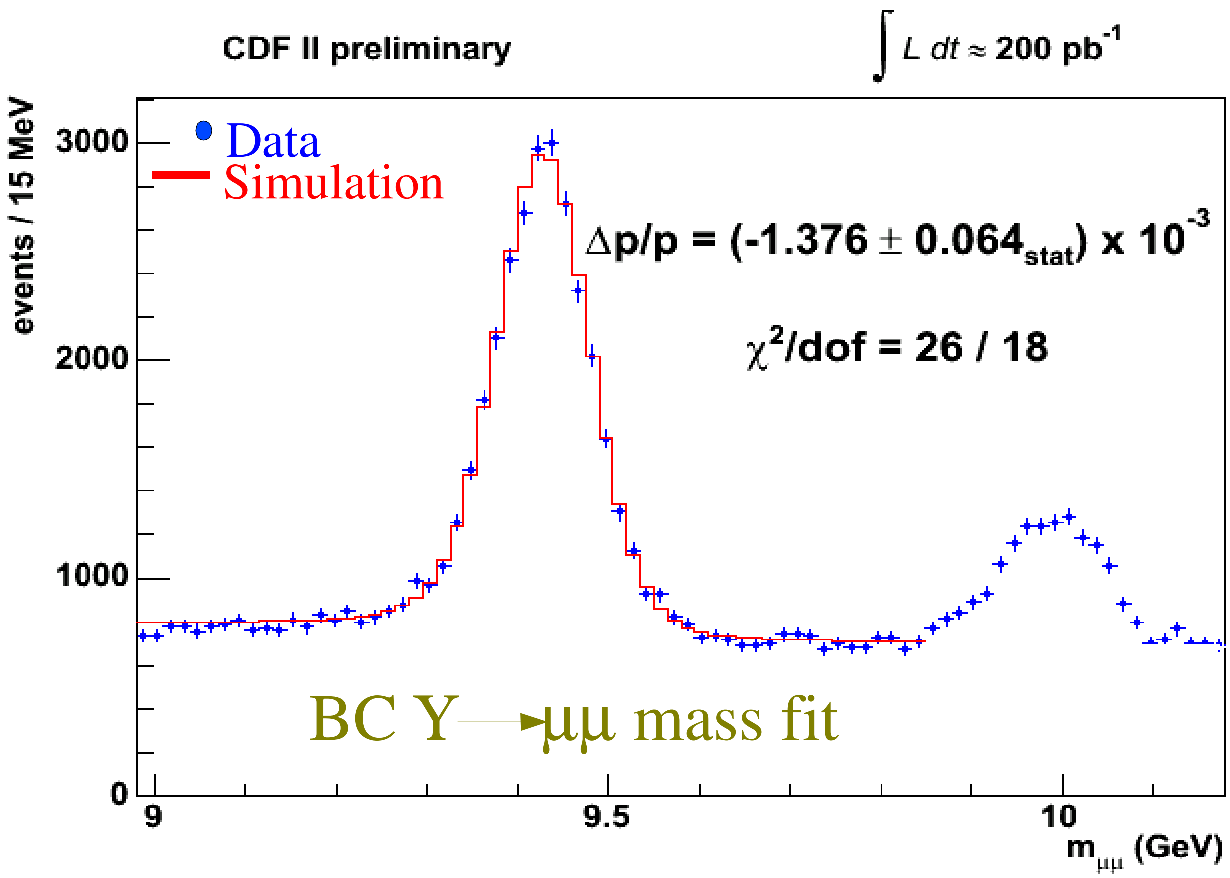
- Set using J/ψ → μμ and Υ → μμ resonance and Z → μμ masses
- J/ψ: $\Delta p/p = (-1.64 \pm 0.06_{stat} \pm 0.24_{sys}) \times 10^{-3}$
  - Extracted by fitting J/ψ mass in bins of $<1/p_T(\mu)>$, and extrapolating momentum scale to zero curvature
- Uncertainty dominated by QED radiative corrections and magnetic field non-uniformity





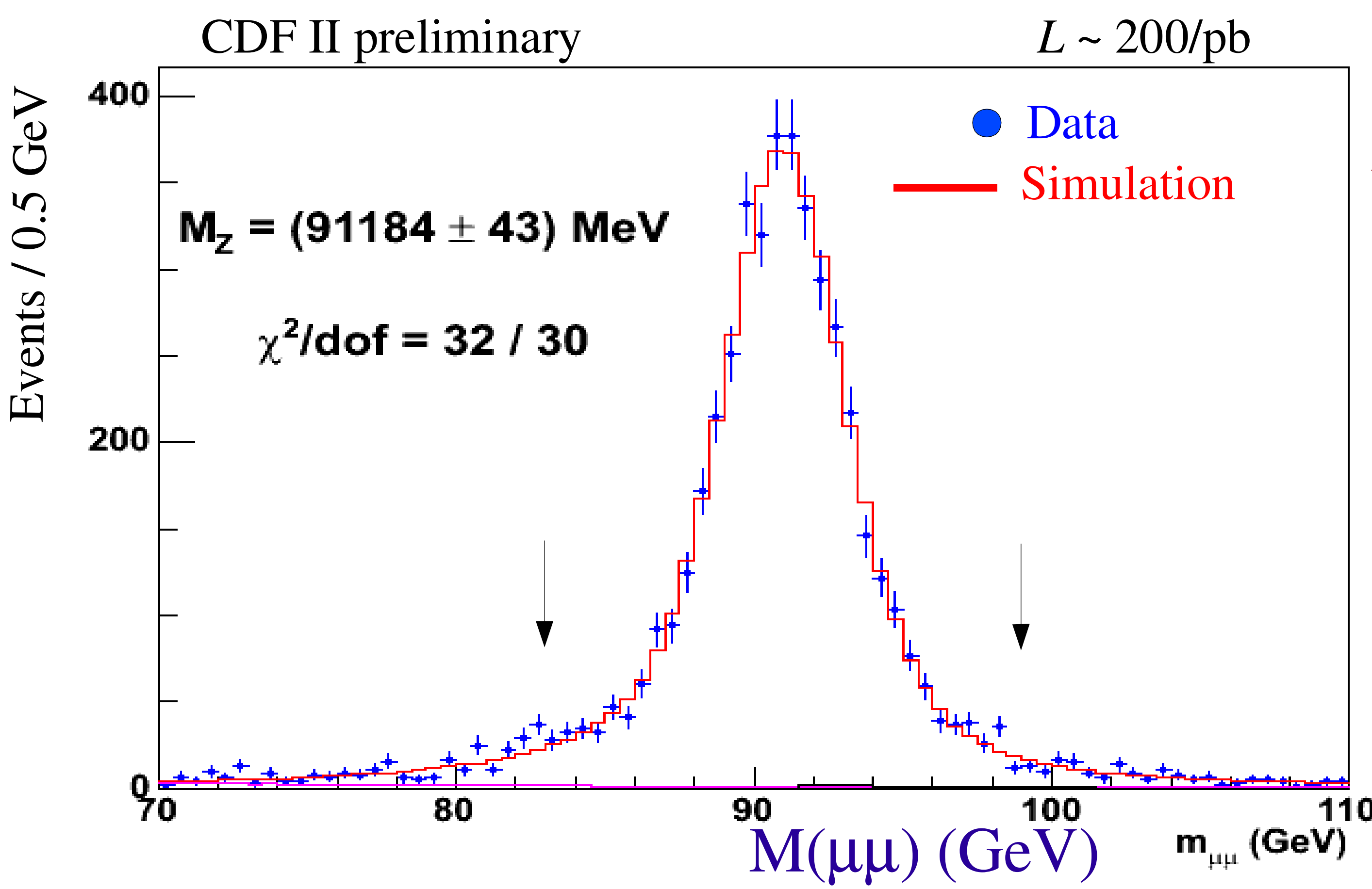
Tracking Momentum Scale

- $\Upsilon \rightarrow \mu\mu$ resonance provides
  - Momentum scale measurement at higher p_T
  - Validation of beam-constaining procedure (upsilons are promptly produced)
  - Non-beam-constrained and beam-constrained (BC) fits statistically consistent



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

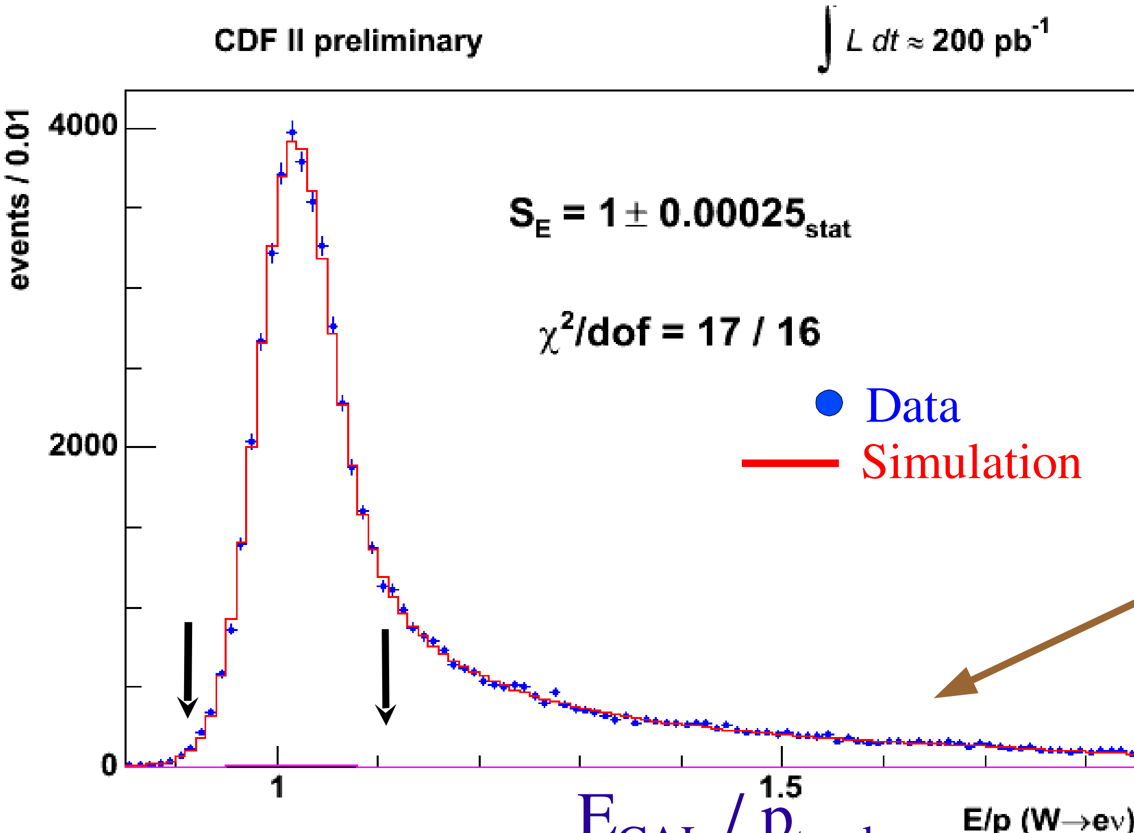
- Using the J/ψ and Υ momentum scale, measured Z mass is consistent with PDG value
- Final combined: $\Delta p/p = (-1.50 \pm 0.15_{independent} \pm 0.13_{QED} \pm 0.07_{align}) \times 10^{-3}$



$\Delta M_W = 17$ MeV

EM Calorimeter Energy Scale for Electrons

- E/p peak from $W \longrightarrow e\nu$ decays provides measurements of EM calorimeter scale and its (E_T-dependent) non-linearity
  - $S_E = 1 \pm 0.00025_{stat} \pm 0.00011_{X0} \pm 0.00021_{Tracker}$
- Setting S_E to 1 using E/p calibration



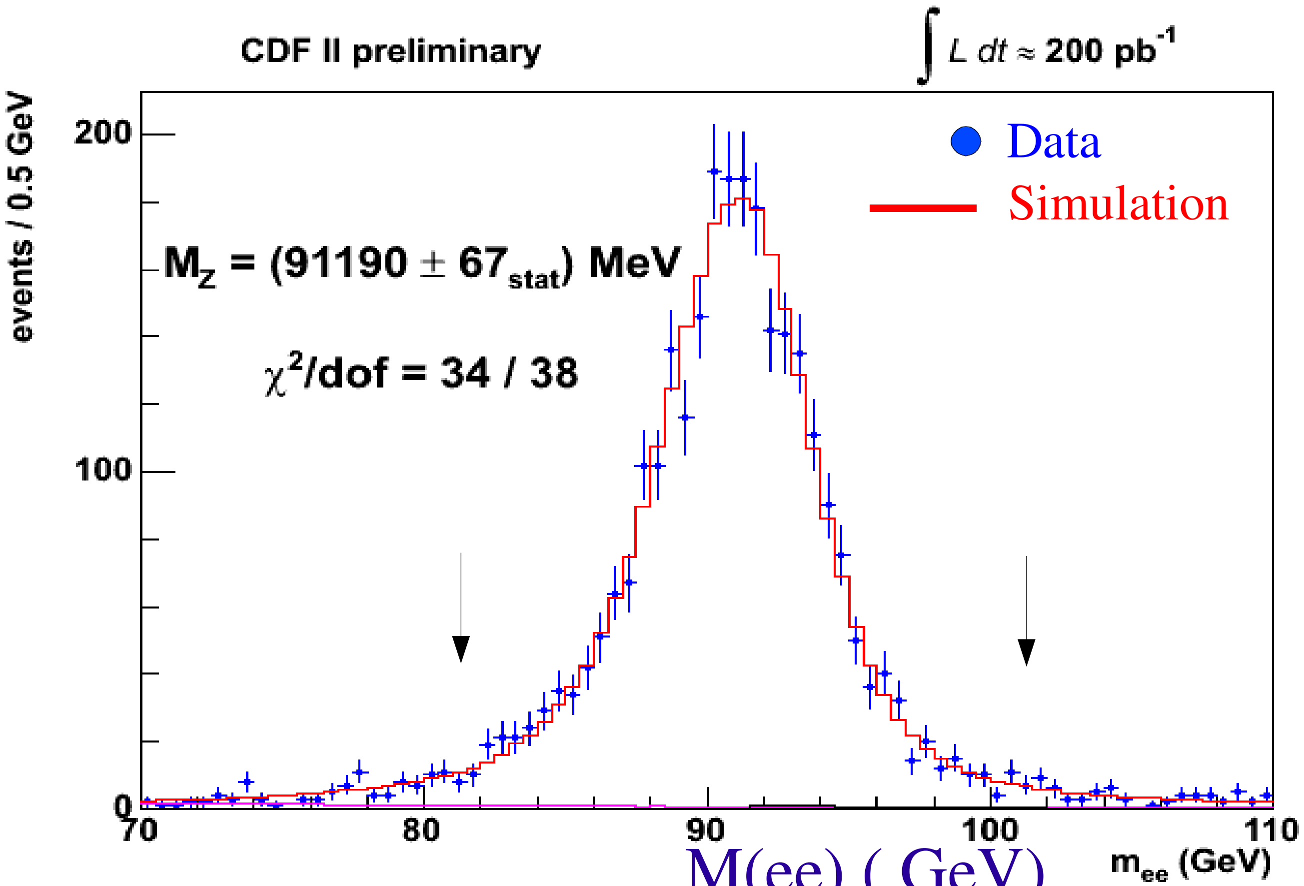
E_{CAL} / p_{track}

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

$Z \rightarrow$ ee Mass Cross-check and Combination

- Z mass consistent with E/p-based measurements
- Combining E/p-derived scale & non-linearity measurement with $Z \rightarrow ee$ mass yields the most precise calorimeter energy scale:
  - $S_E = 1.00001 \pm 0.00037$

$\Delta M_W = 30$ MeV



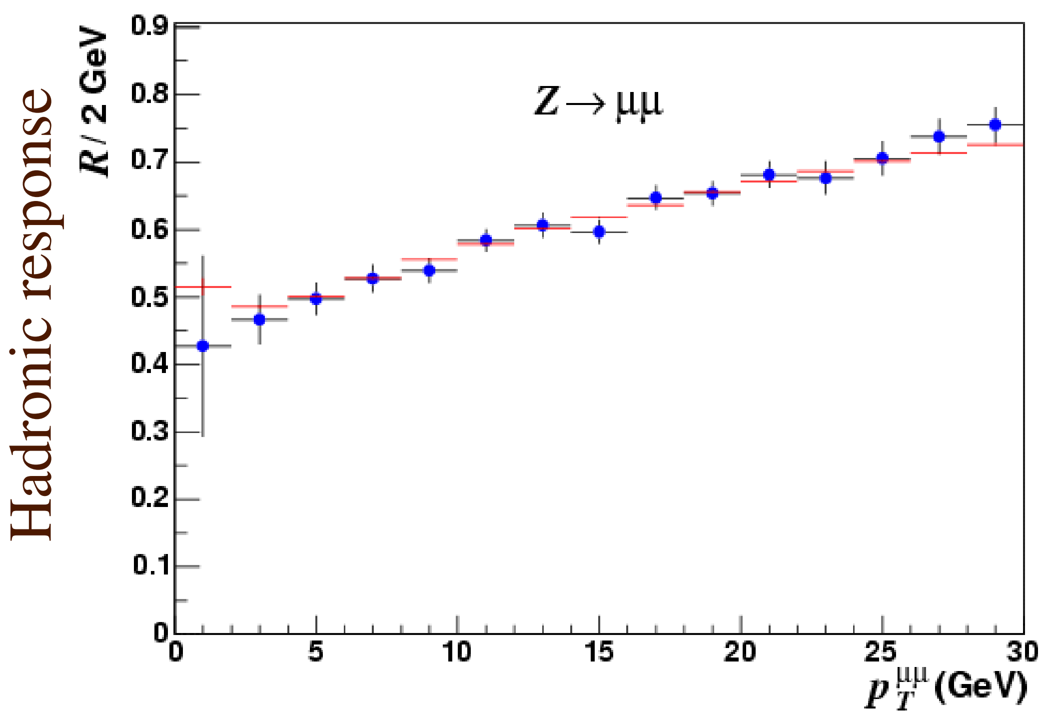
M(ee) (GeV)

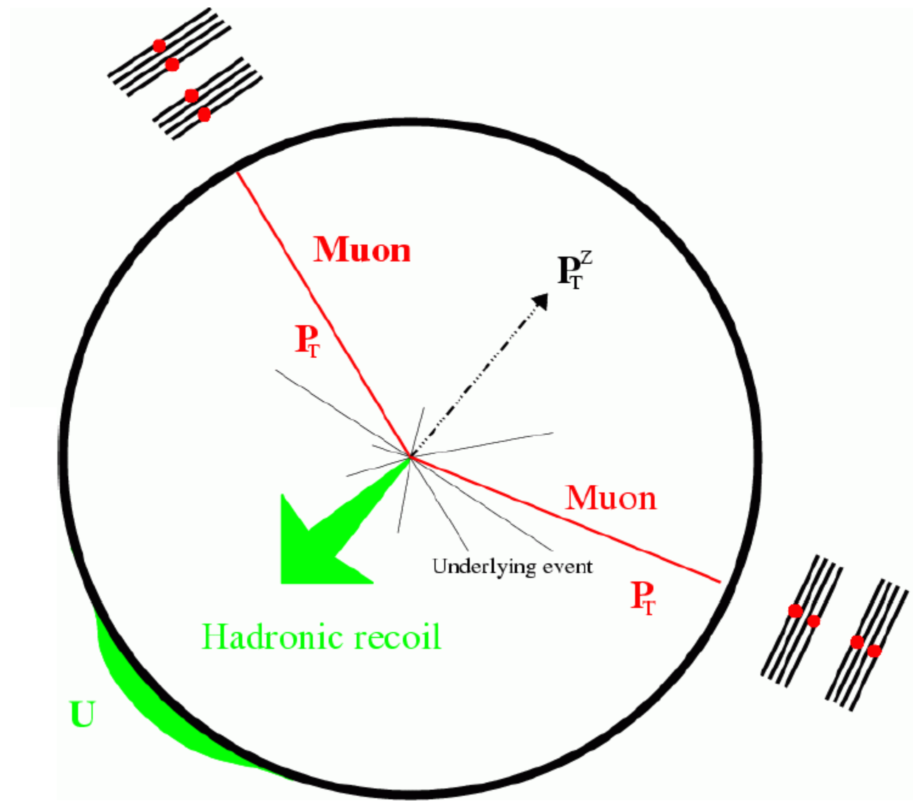
Hadronic Recoil Model

Constraining the Hadronic Recoil Model

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

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

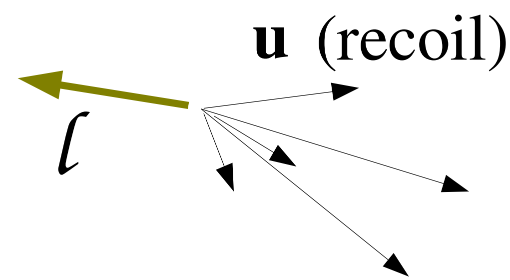


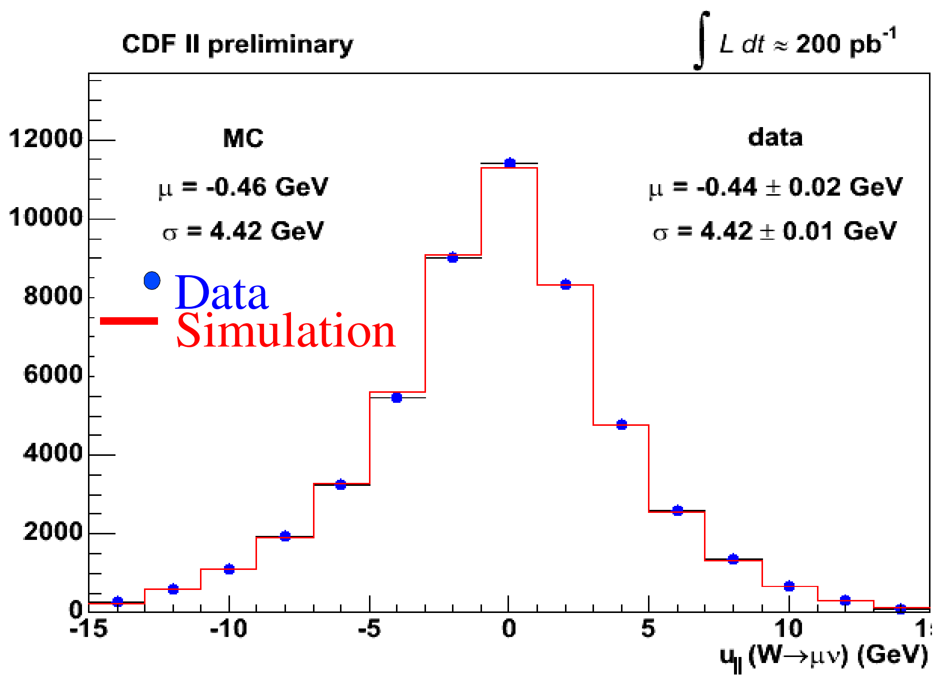


$\Delta M_W = 12$ MeV

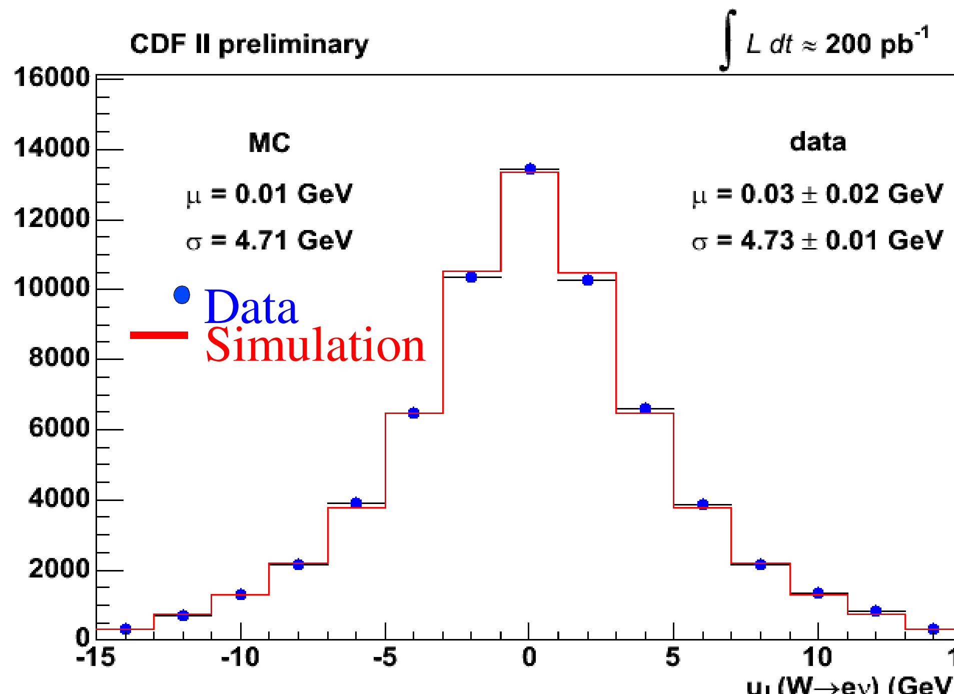
Testing Hadronic Recoil Model with *W* events

Compare recoil distributions between simulation and data





Recoil projection (GeV) on lepton direction



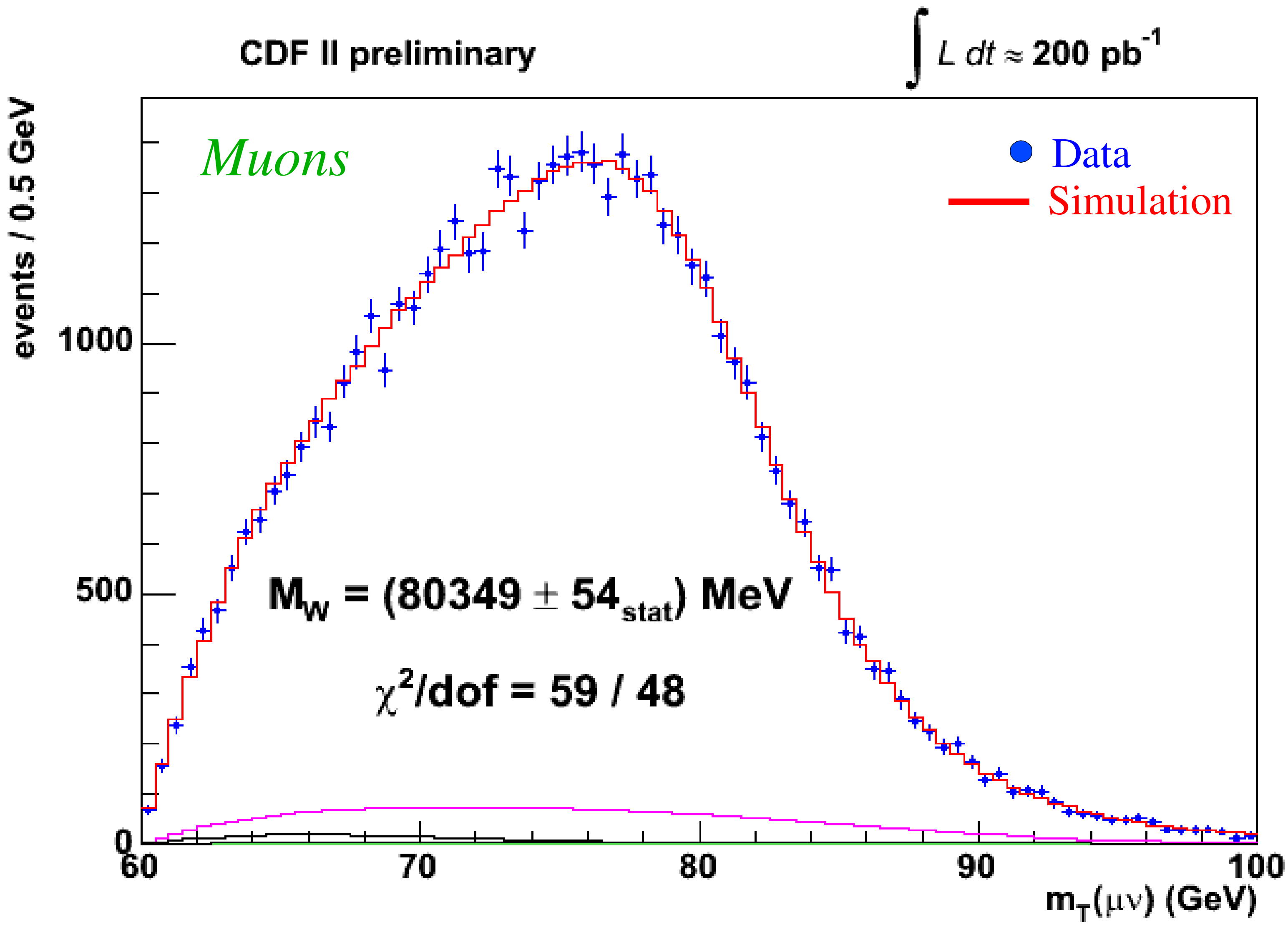
Recoil projection (GeV) perpendicular to lepton

W Mass Fits

Blind Analysis Technique

- All W mass fit results were blinded with a random [-100,100] MeV offset hidden in the likelihood fitter
- Blinding offset removed after the analysis was declared frozen
- Technique allows to study all aspects of data while keeping W mass result unknown within 100 MeV

W Transverse Mass Fits



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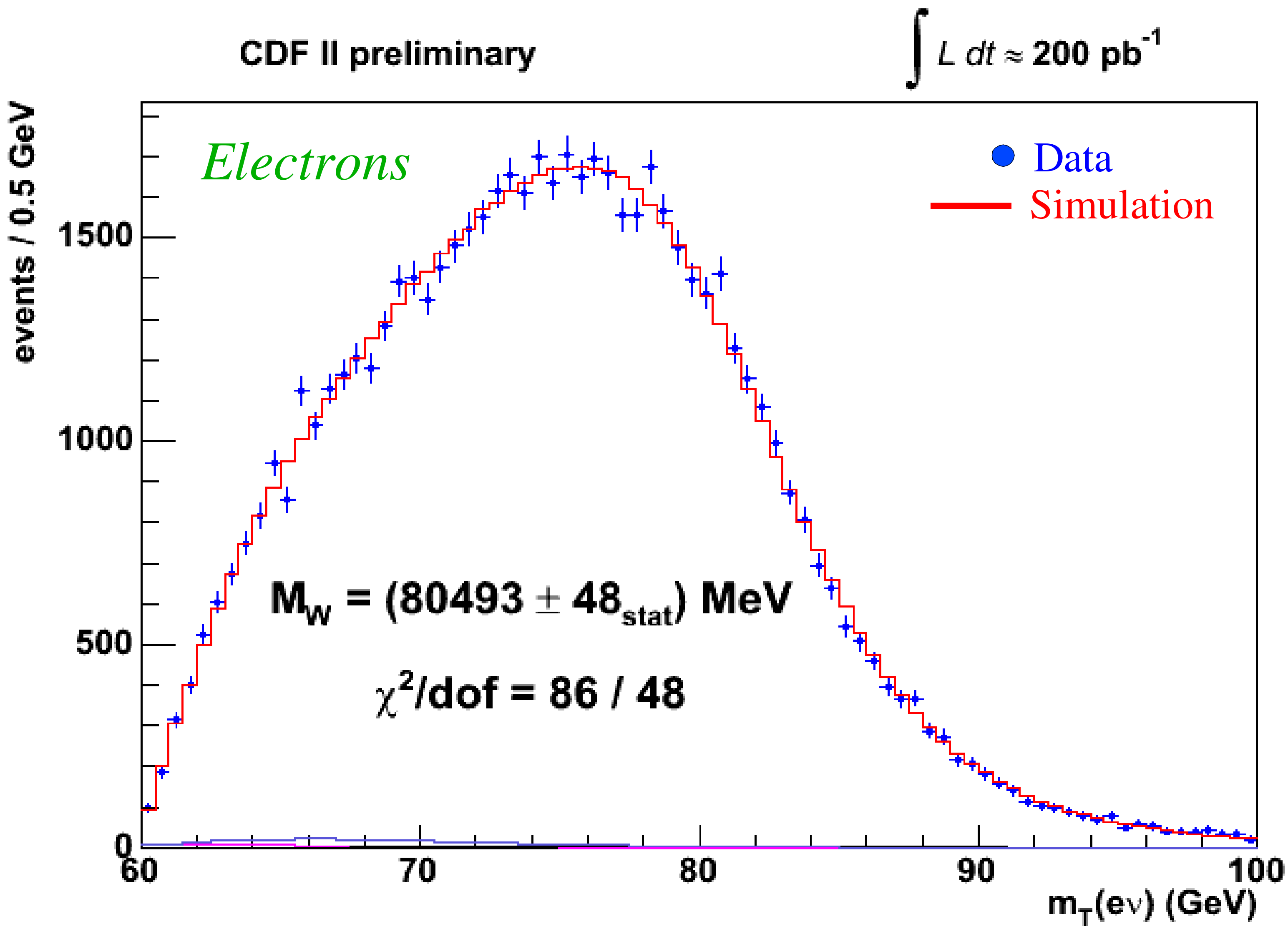
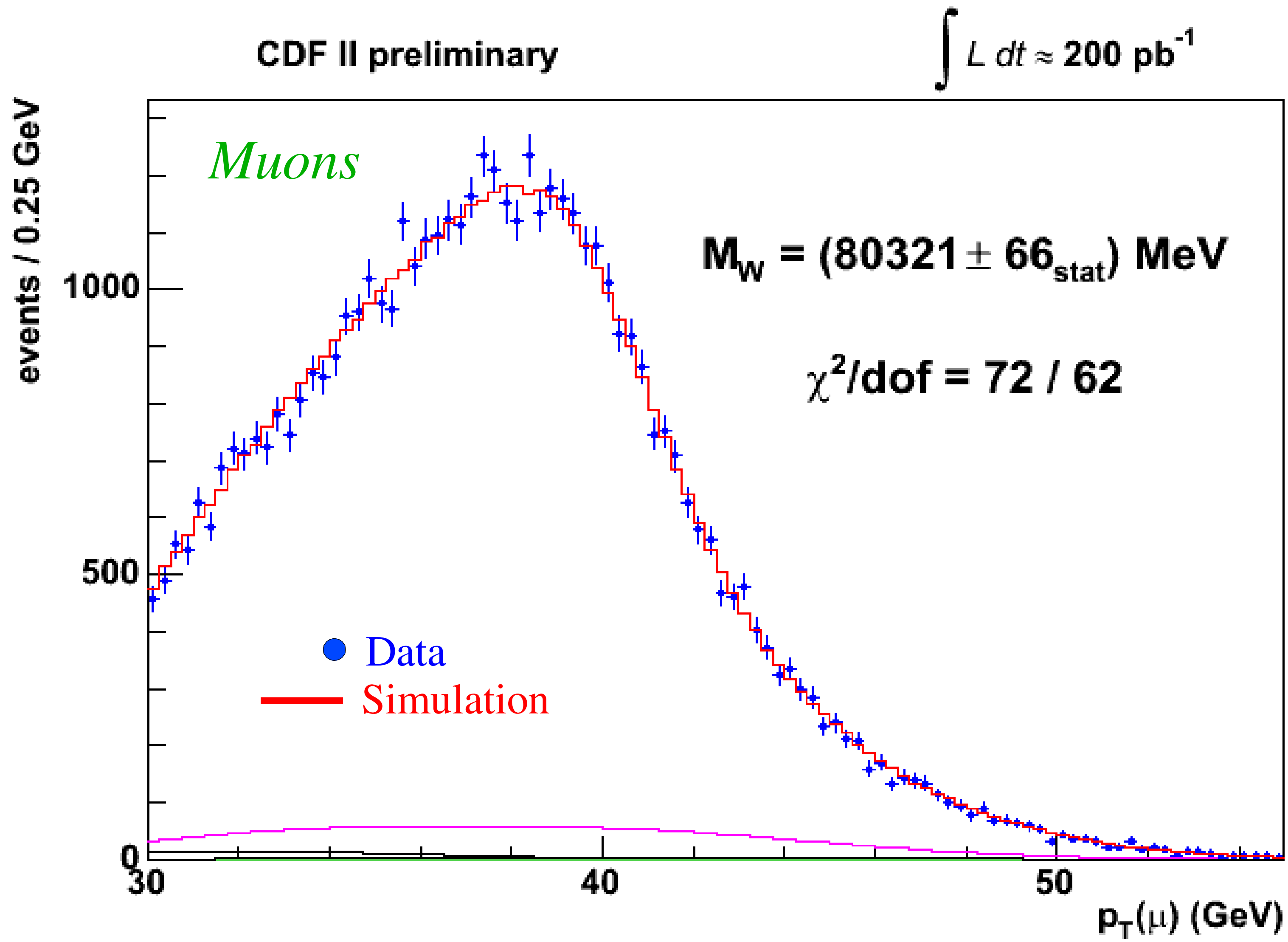


Muon & electron combined: $M_W = 80417 \pm 48$ MeV ($P(\chi^2) = 7\%$)

W Lepton p_T Fits



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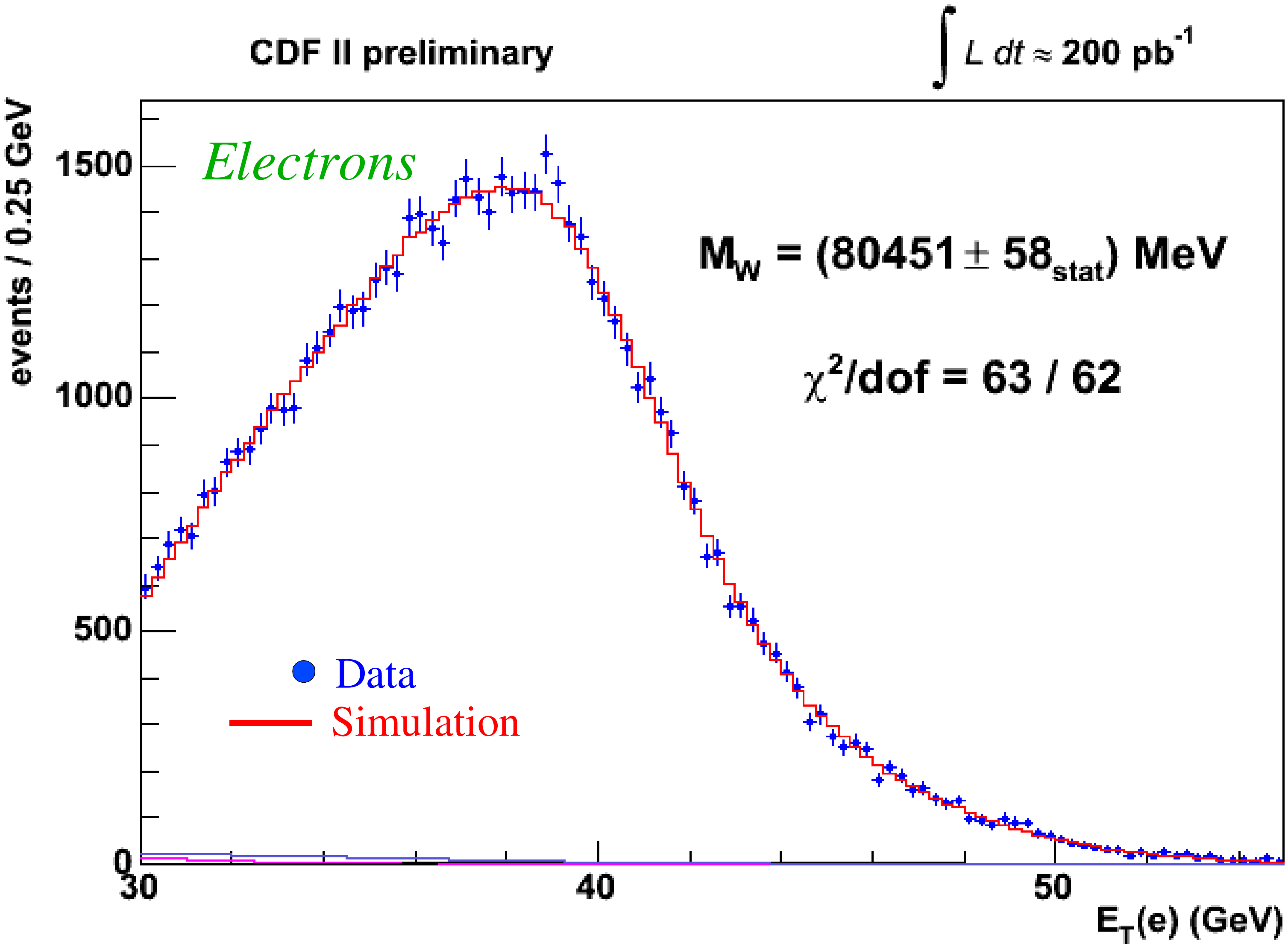
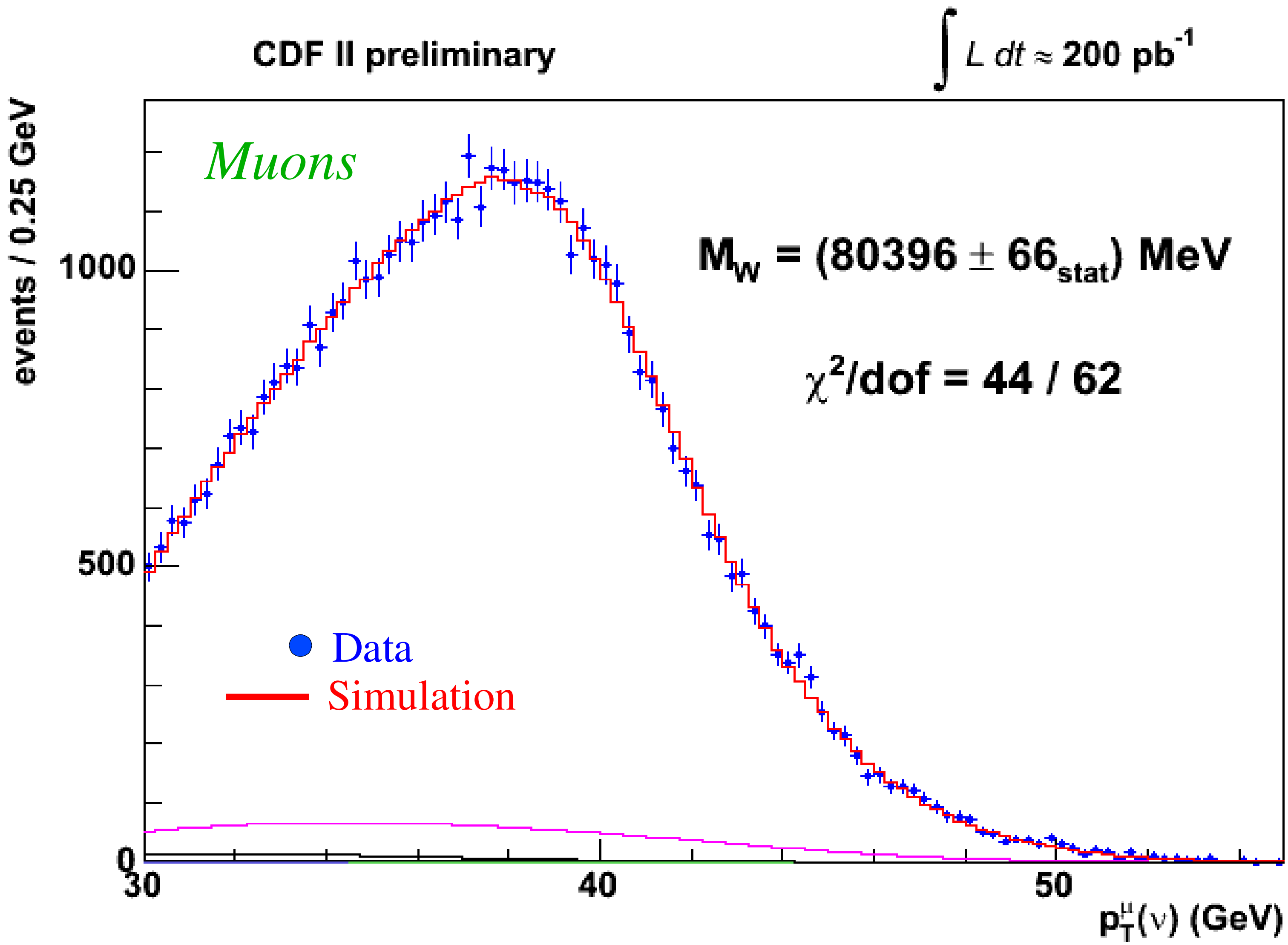
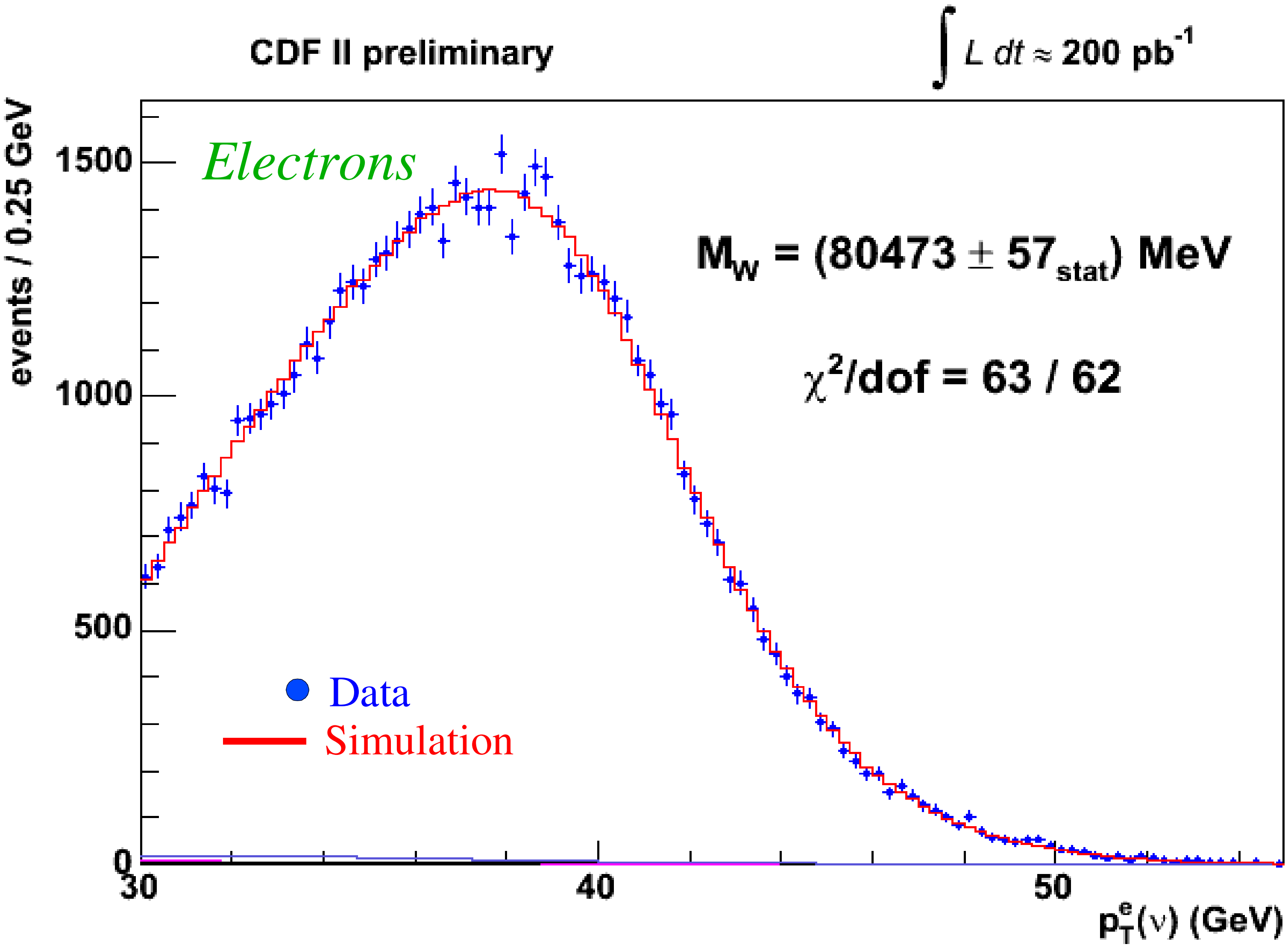


Muon & electron combined: $M_W = 80388 \pm 59$ MeV ($P(\chi^2) = 18\%$)

W Missing E_T Fits



W Missing E_T Fits



Muon & electron combined: M_W = 80434 ± 65 MeV ($P(\chi^2)$ = 43%)

Transverse Mass Fit Uncertainties (MeV)

	electrons	*muons*	*common*
W statistics	48	54	0
Lepton energy scale	30	17	17
Lepton resolution	9	3	-3
Recoil energy scale	9	9	9
Recoil energy resolution	7	7	7
Selection bias	3	1	0
Lepton tower removal	8	5	5
Backgrounds	8	9	0
pT(W) model (g2,g3)	3	3	3
Parton dist. Functions	11	11	11
QED rad. Corrections	11	12	11
Total systematic	**39**	**27**	**26**
Total	**62**	**60**	

Systematic uncertainties shown in green: statistics-limited by control data samples

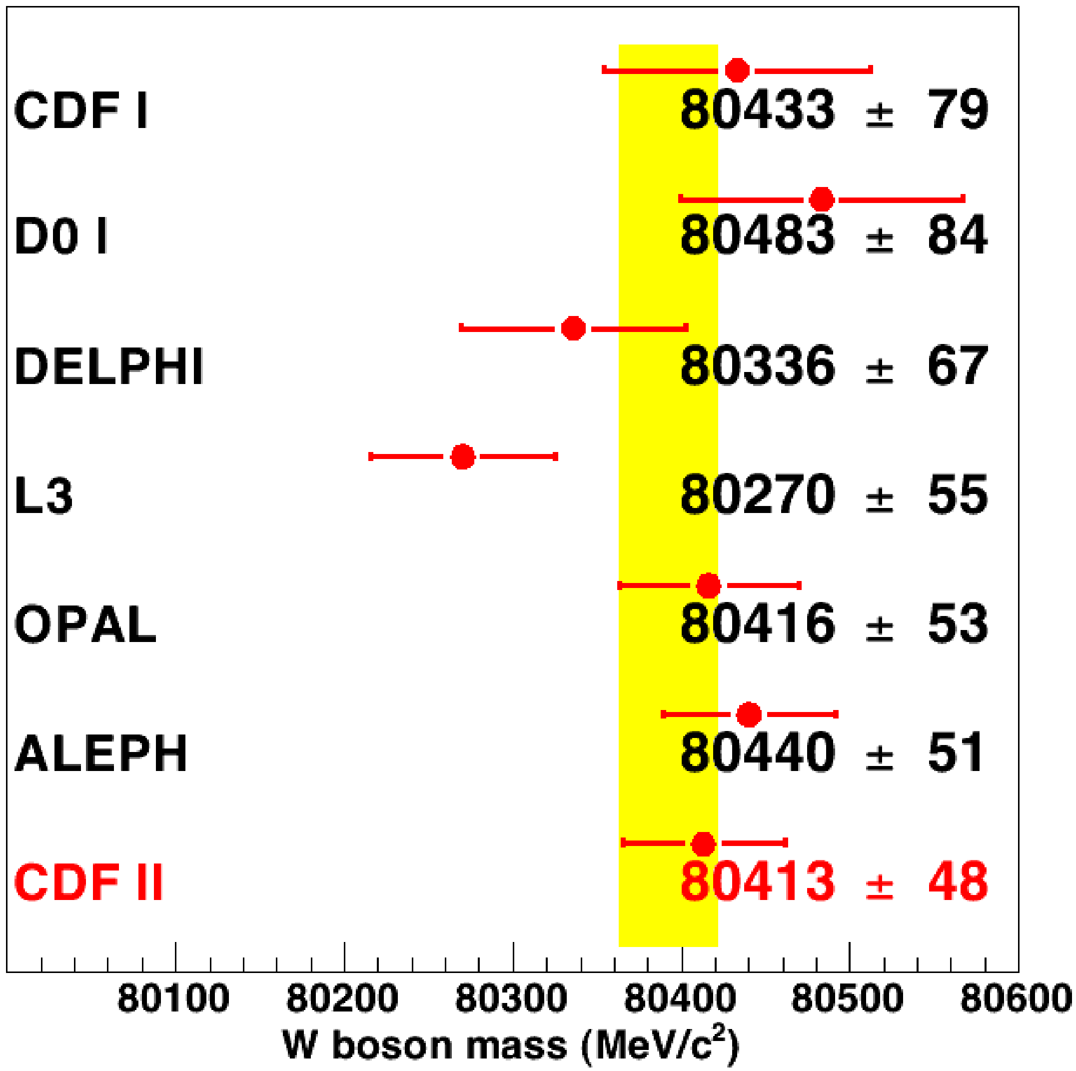
Combined Results

- Combined electrons (3 fits): $M_W = 80477 \pm 62$ MeV, $P(\chi^2) = 49\%$

- Combined muons (3 fits): $M_W = 80352 \pm 60$ MeV, $P(\chi^2) = 69\%$

- All combined (6 fits): $M_W = 80413 \pm 48$ MeV, $P(\chi^2) = 44\%$

Comparisons

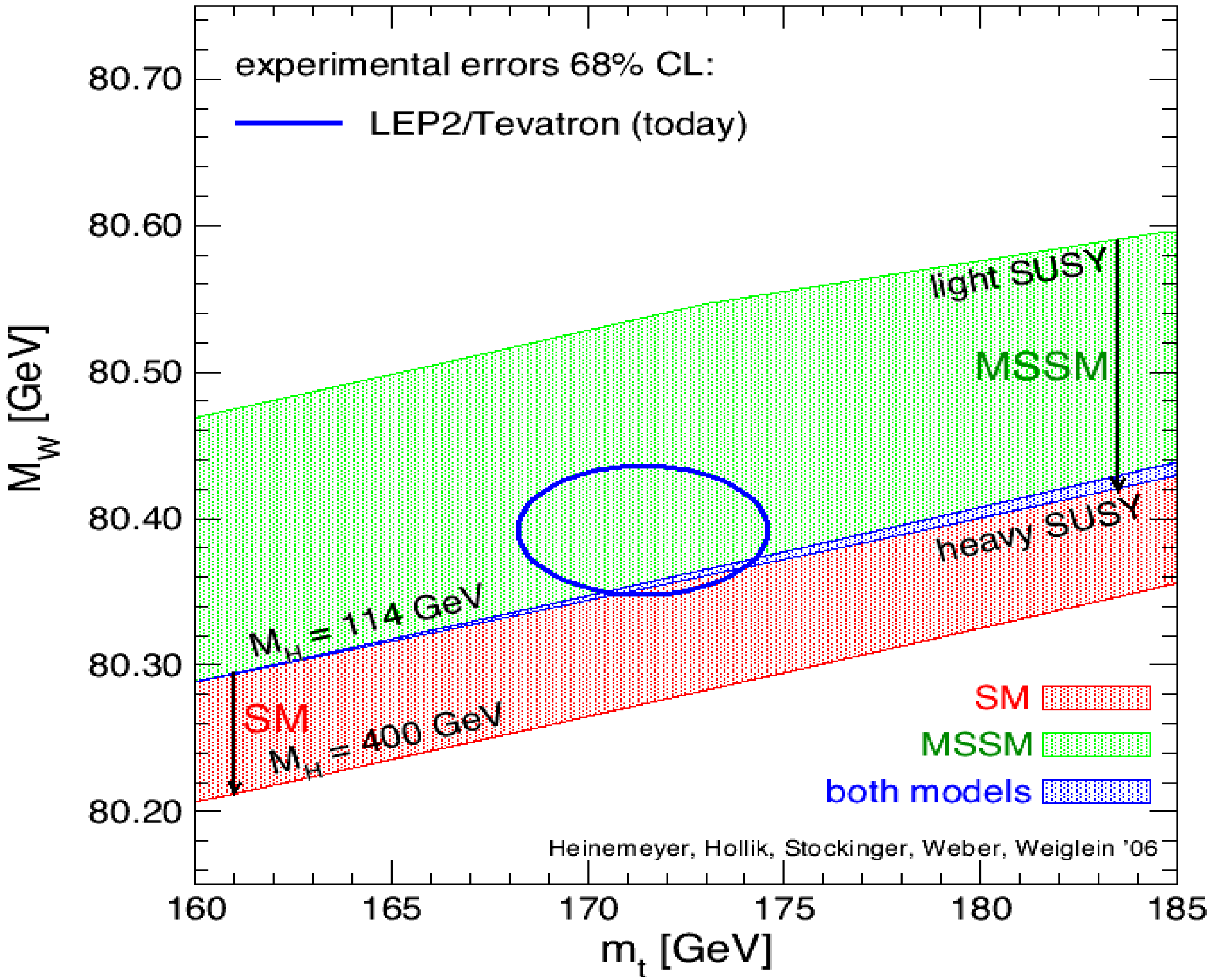


The CDF Run 2 result is the most precise single measurement of the W mass

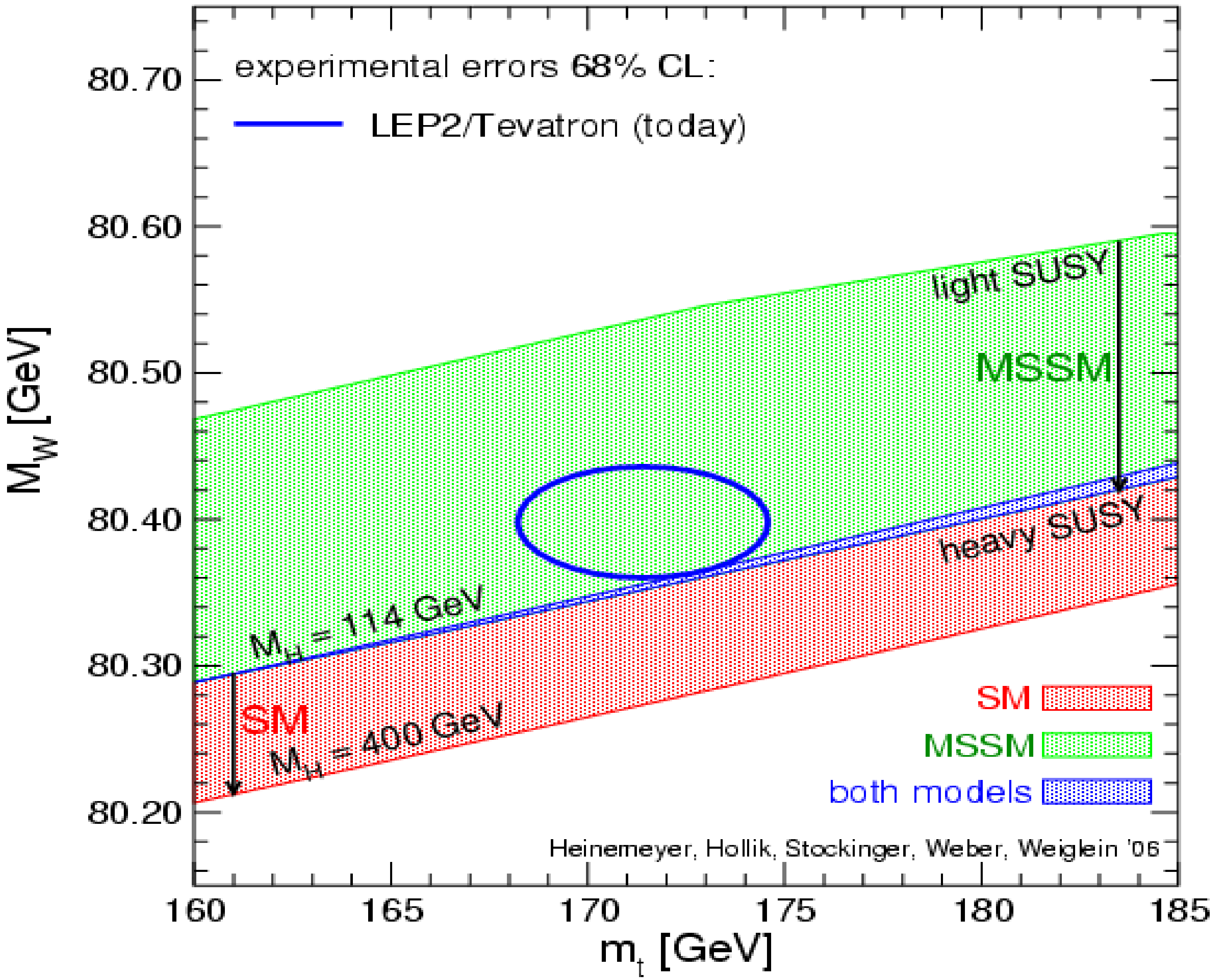
Comparisons

	W mass (MeV)
DELPHI	80336 ± 67
L3	80270 ± 55
OPAL	80416 ± 53
ALEPH	80440 ± 51
CDF-I	80433 ± 79
D0-I	80483 ± 84
LEP Average	80376 ± 33
Tevatron-I Average	80454 ± 59
Previous World Average	80392 ± 29
CDF-II (preliminary)	80413 ± 48
New Tevatron Average	80429 ± 39
New World Average	80398 ± 25

Previous M_W *vs* M_{top}



Updated M_W *vs* M_{top}



Standard Model Higgs Constraints

- previous SM Higgs fit: $M_H = 85^{+39}_{-28}$ GeV (LEPEWWG)
  - $M_H < 166$ GeV @ 95 C.L.
  - $M_H < 199$ GeV @ 95 C.L. Including LEPII direct exclusion
- Updated preliminary SM Higgs fit (M. Grunewald, private communication):
  - $M_H = 80^{+36}_{-26}$ GeV
  - $M_H < 153$ GeV @ 95 C.L.
  - $M_H < 189$ GeV @ 95 C.L. Including LEPII direct exclusion
  - SM fit results assume zero correlation between W mass and width, and follow LEPEWWG procedure

Summary

- The *W* boson mass is a very interesting parameter to measure with increasing precision
- CDF Run 2 W mass result is the most precise single measurement:
  - $M_W = 80413 \pm 34_{stat} \pm 34_{syst}$ MeV
    $= 80413 \pm 48$ MeV (preliminary)
- New preliminary $M_H = 80^{+36}_{-26}$ GeV (previous $M_H = 85^{+39}_{-28}$ GeV) further in the directly-excluded region

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- New preliminary $M_H = 80^{+36}_{-26}$ GeV (previous $M_H = 85^{+39}_{-28}$ GeV) further in the directly-excluded region
- M_W systematics are dominated by statistics of calibration data:
  - Looking forward to $\delta M_W < 25$ MeV from 1.5 fb^{-1} of CDF data

Backup

E/p Calibration *vs* $Z \rightarrow ee$ mass consistency

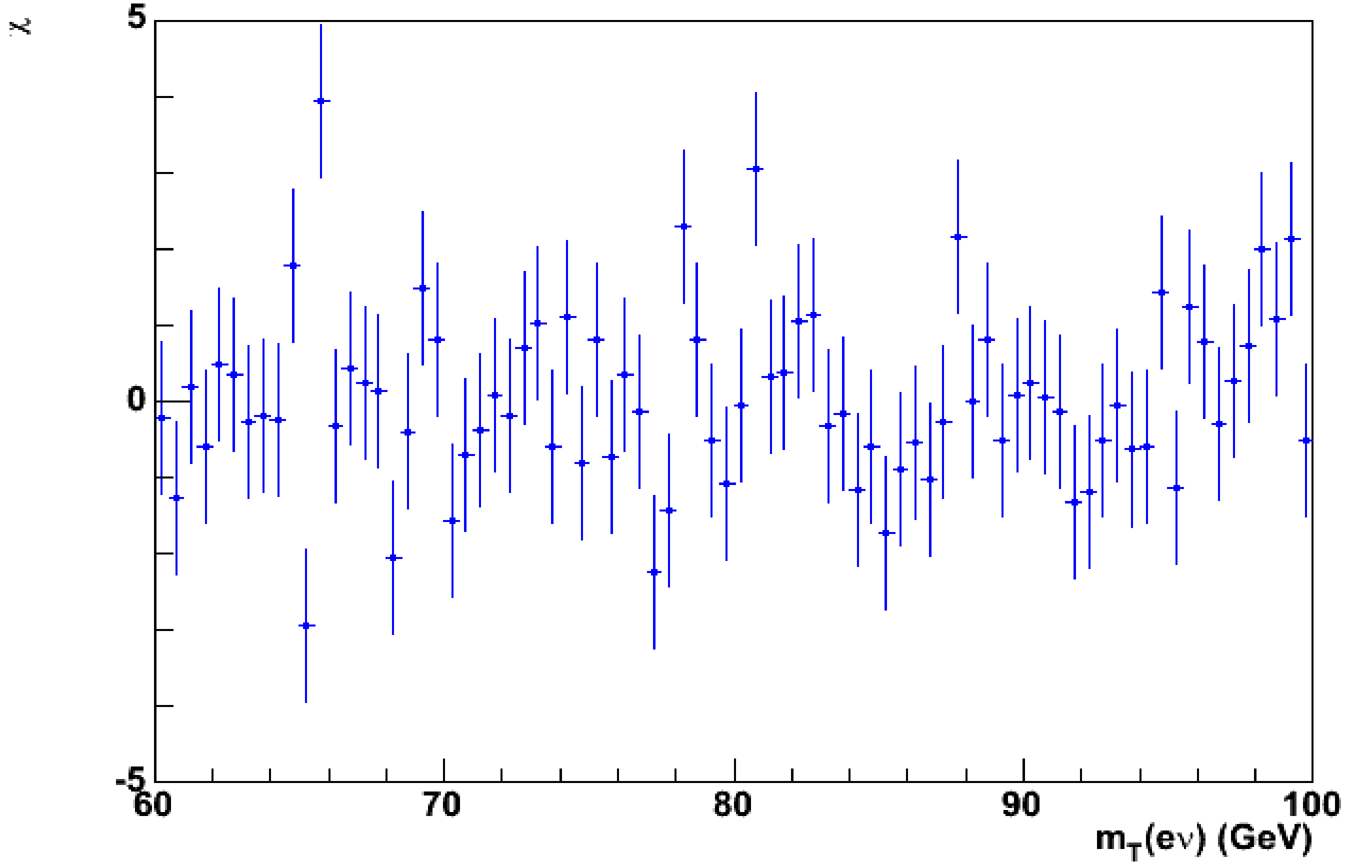
- Inclusion of hadronic calorimeter leakage distribution has a ~150 MeV effect on the fitted EM calorimeter scale from the E/p distribution

- Modelling the bremsstrahlung spectrum down to 4 MeV (from 40 MeV cutoff) has a ~60 MeV effect on the E/p calibration

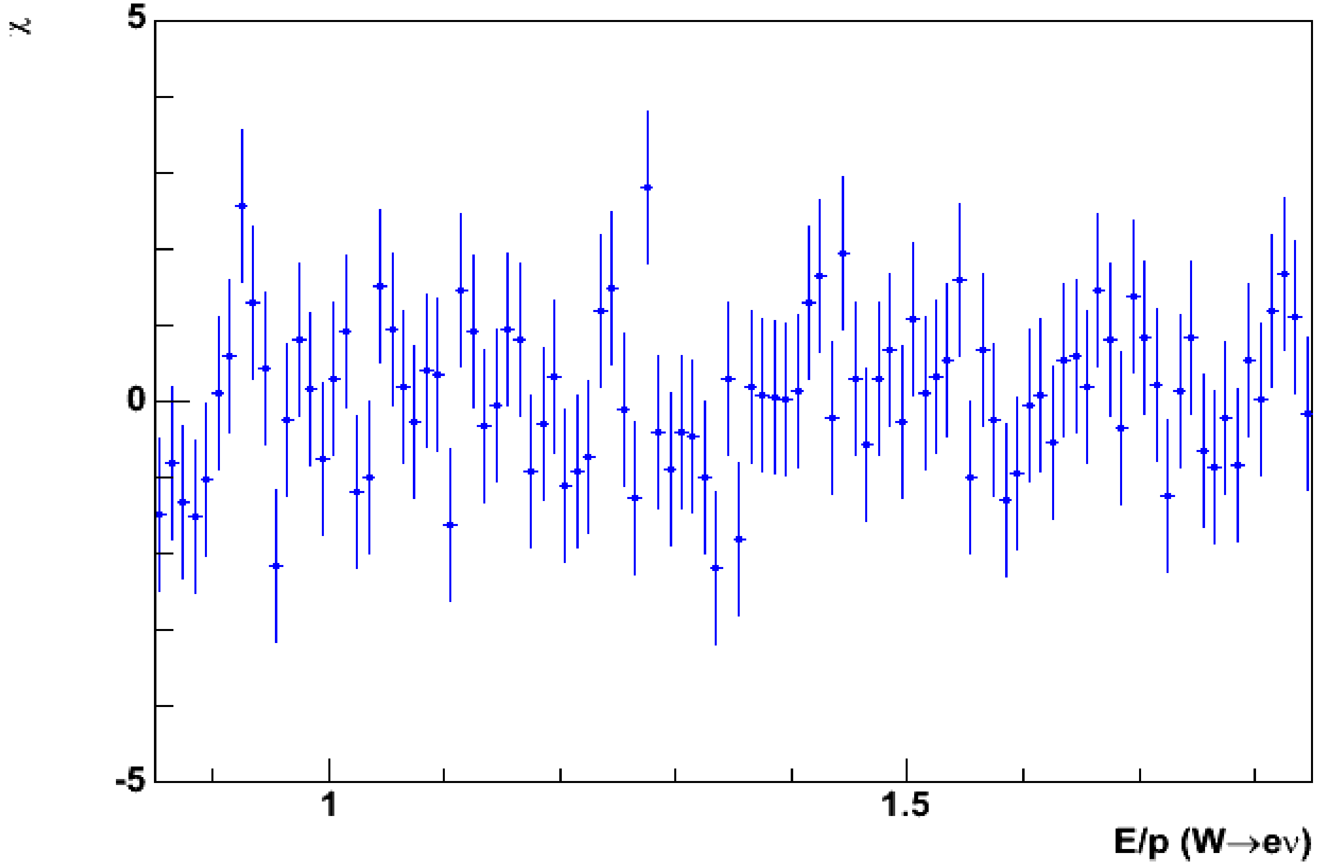
- Modelling the calorimeter non-linearity as a property of individual particles has a ~30 MeV effect

- Collectively, these simulated effects in the Run 2 analysis affect the consistency of the Z mass by ~240 MeV

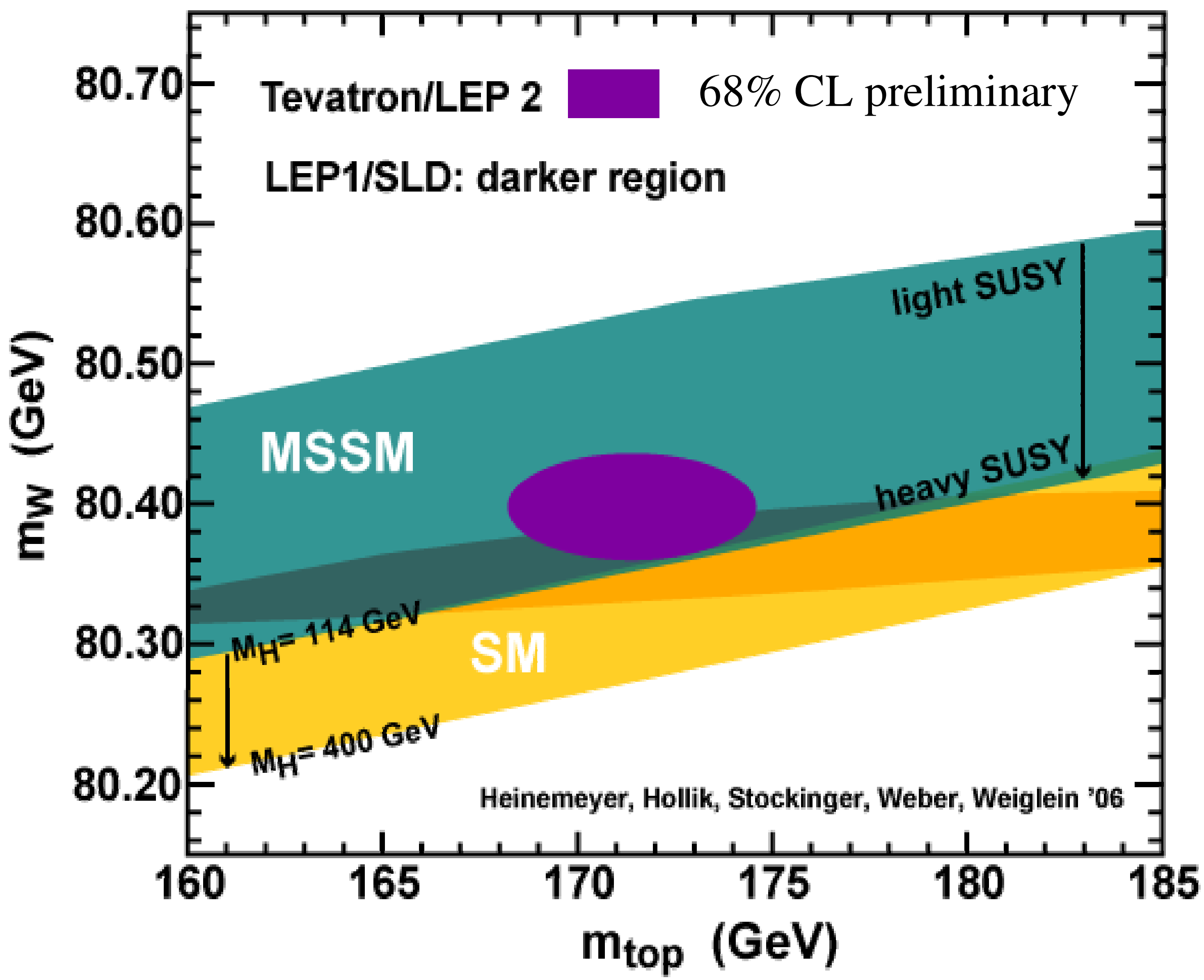
Electron Channel Transverse Mass Fit



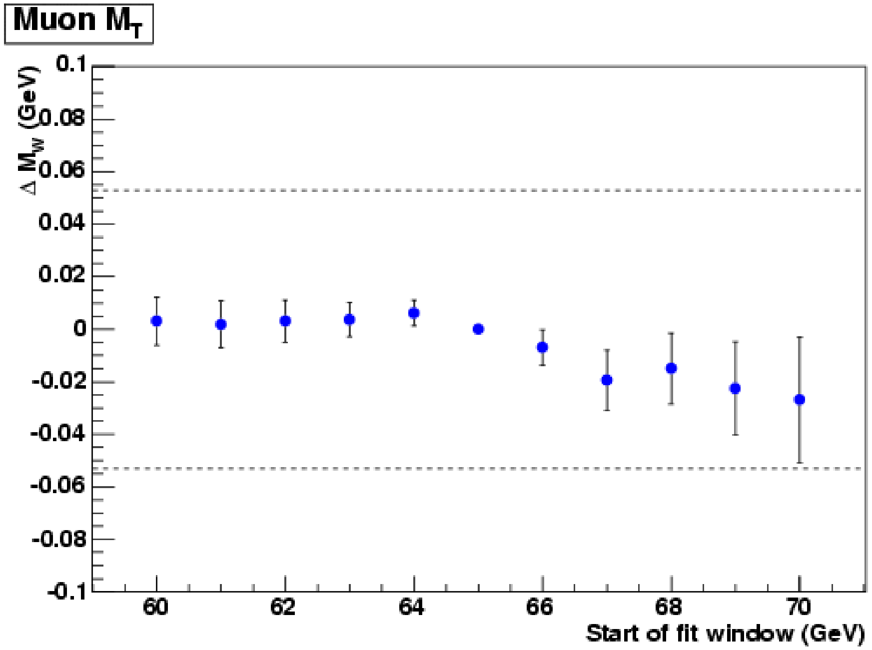
Electron Channel E/p Fit

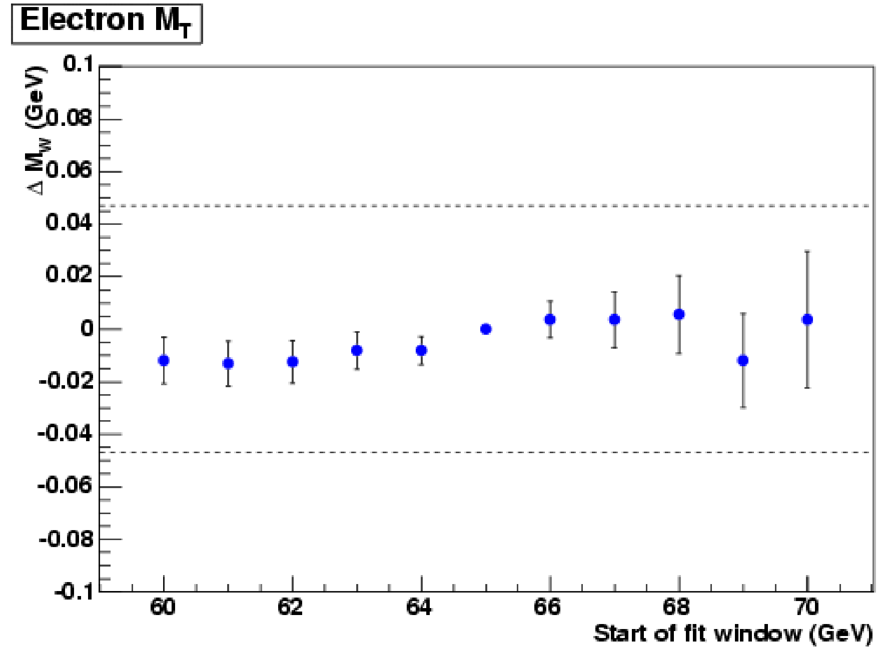


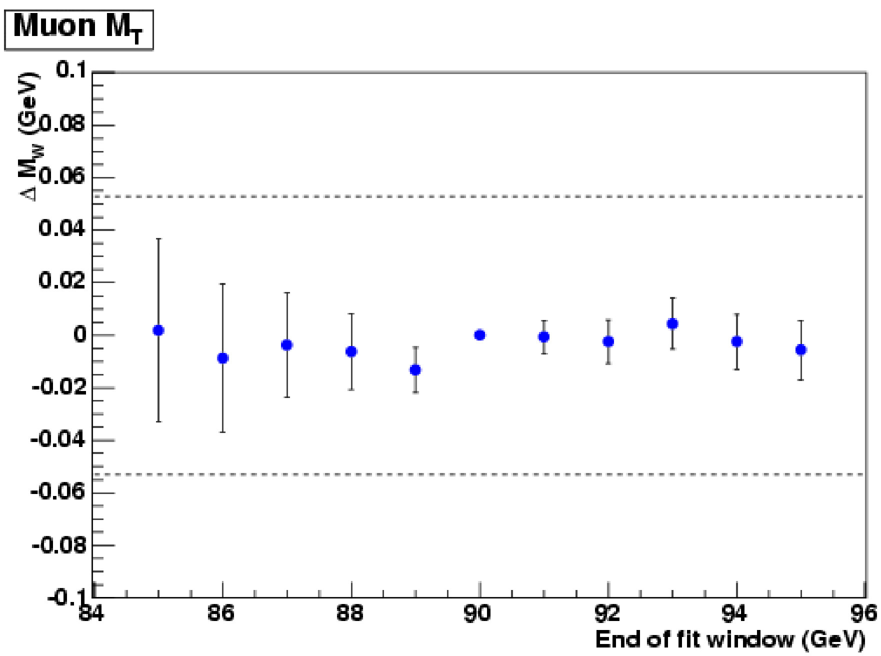
Updated M_W *vs* M_{top}

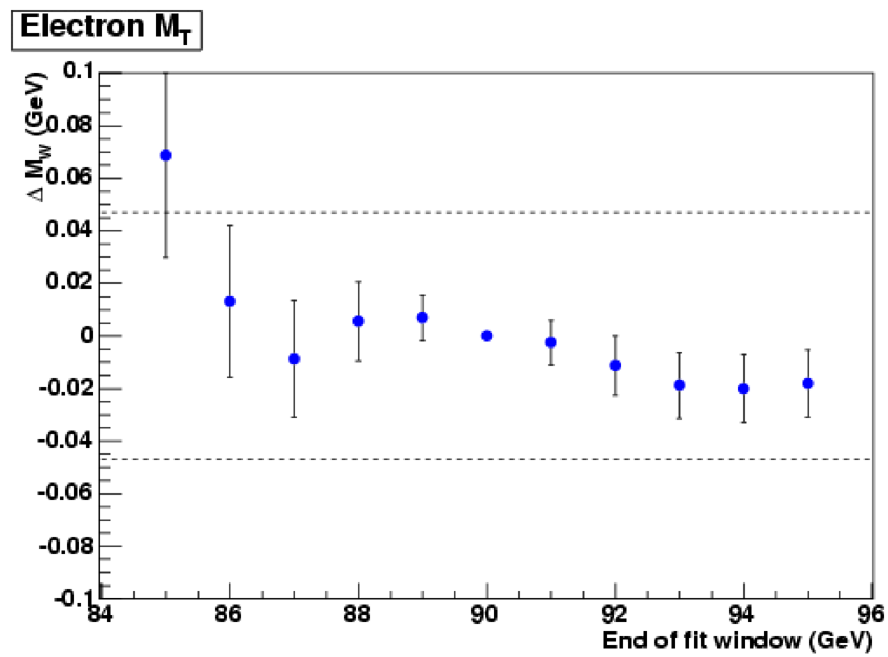


Transverse Mass Fits – Stability *vs* Fit Window

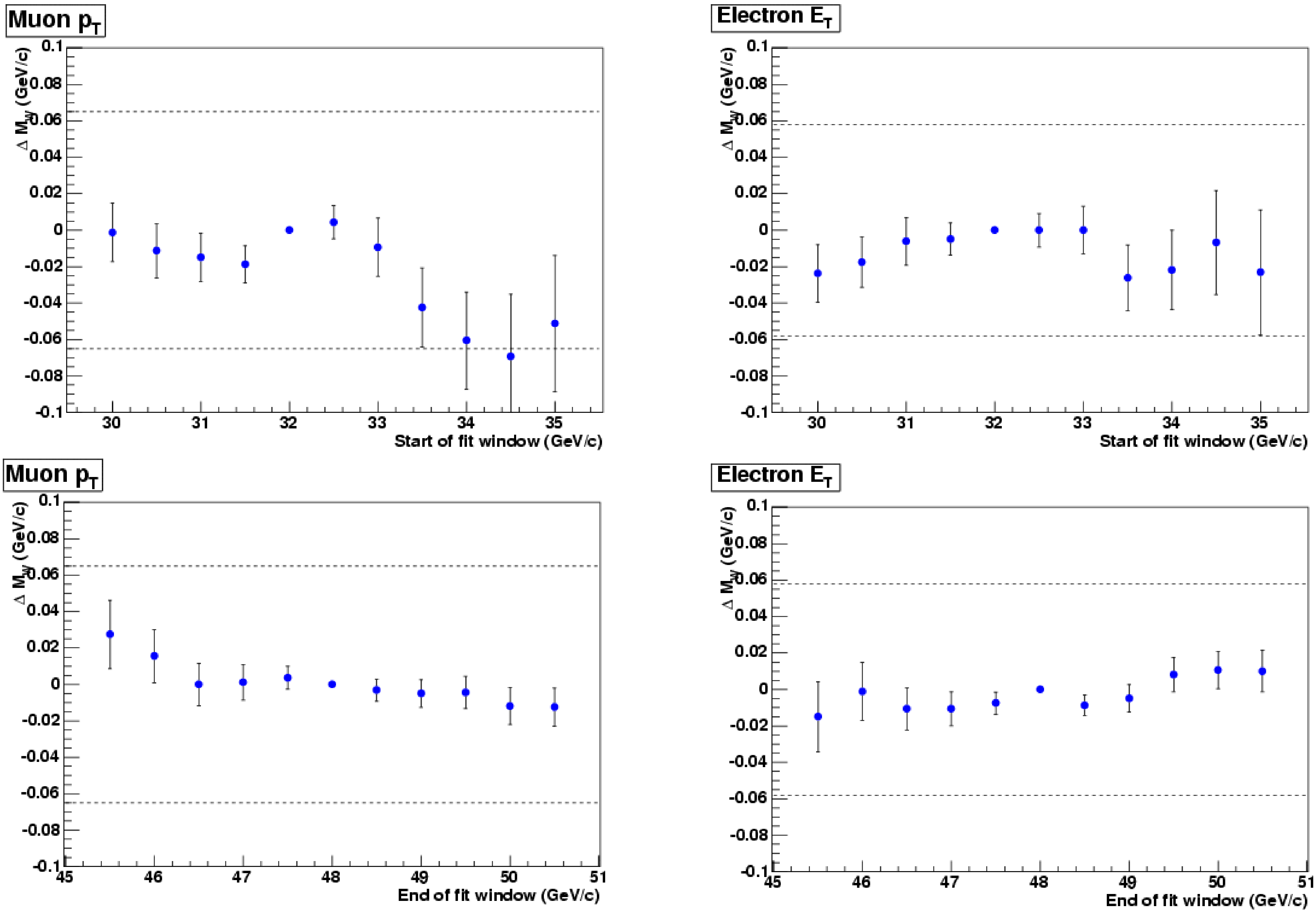




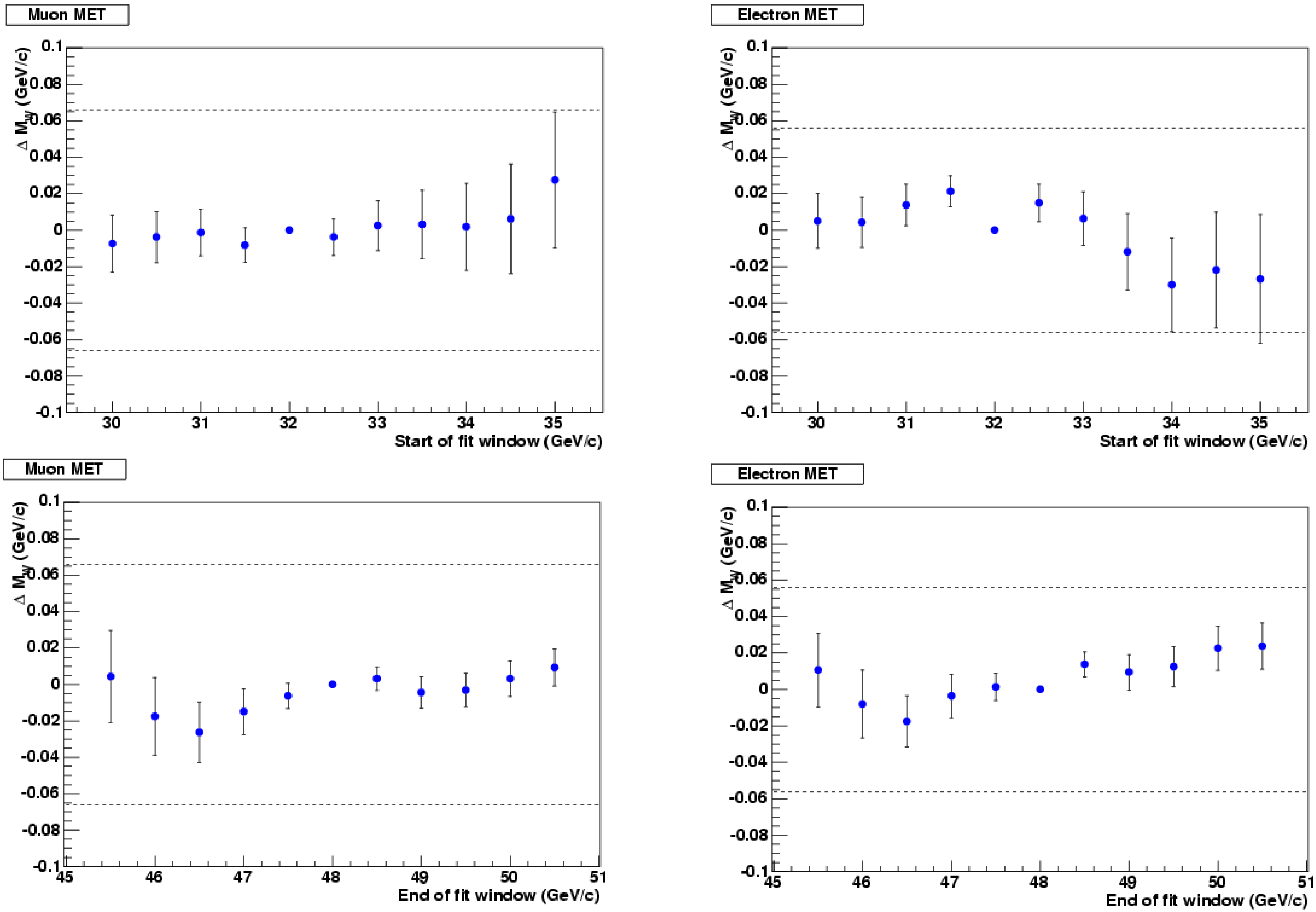




Lepton p_T Fits – Stability *vs* Fit Window



Missing E_T Fits – Stability *vs* Fit Window



Combined Results

- Combined electrons (3 fits): $M_W = 80477 \pm 62$ MeV, $P(\chi^2) = 49\%$
- Combined muons (3 fits): $M_W = 80352 \pm 60$ MeV, $P(\chi^2) = 69\%$
- All combined (6 fits): $M_W = 80413 \pm 48$ MeV, $P(\chi^2) = 44\%$

Lepton p_T and Missing E_T Fit Uncertainties

CDF II preliminary

Uncertainty (p_T)	Electrons	Muons	Common
Lepton Scale	30	17	17
Lepton Resolution	9	3	0
Recoil Scale	17	17	17
Recoil Resolution	3	3	3
Lepton Removal	0	0	0
$u_{\|\|}$ Efficiency	5	6	0
Backgrounds	9	19	0
$p_T(W)$	9	9	9
PDF	20	20	20
QED	13	13	13
Total Systematic	45	40	35
Statistical	58	66	0
Total	73	77	35

CDF II preliminary

Uncertainty (MET)	Electrons	Muons	Common
Lepton Scale	30	17	17
Lepton Resolution	9	5	0
Recoil Scale	15	15	15
Recoil Resolution	30	30	30
Lepton Removal	16	10	10
$u_{\|\|}$ Efficiency	16	13	0
Backgrounds	7	11	0
$p_T(W)$	5	5	5
PDF	13	13	13
QED	9	10	9
Total Systematic	54	46	42
Statistical	57	66	0
Total	79	80	42

Cross-checks: Consistency between W sub-samples

Lepton	Fit difference	Result (MeV/c^2)
Electron	$m_W(l^+) - m_W(l^-)$	257 ± 117
Electron	$m_W(\phi_l > 0) - m_W(\phi_l < 0)$	116 ± 117
Electron	$m_W(run > 161k) - m_W(run < 161k)$	-107 ± 117
Muon	$m_W(l^+) - m_W(l^-)$	$286 \pm 132_{\text{stat}} \pm 75_{COT}$
Muon	$m_W(\phi_l > 0) - m_W(\phi_l < 0)$	0 ± 133
Muon	$m_W(run > 161k) - m_W(run < 161k)$	75 ± 135

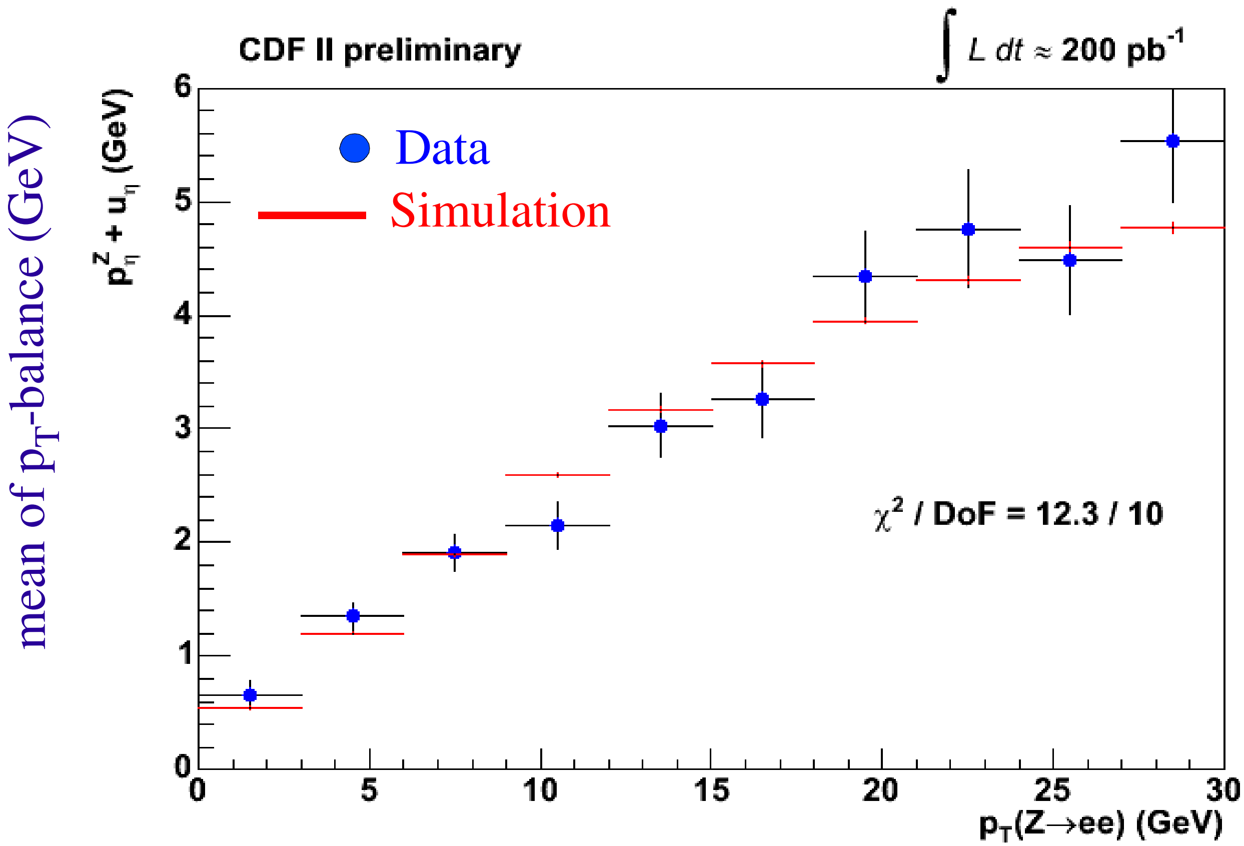
Hadronic Recoil Simulation

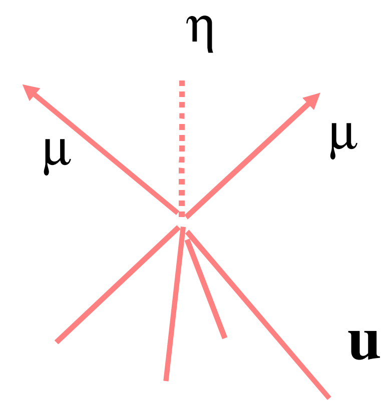
- Recoil momentum 2-vector $\boldsymbol{u}$ has
  - a soft 'spectator interaction' component, randomly oriented
    - Modelled using minimum-bias data with tunable magnitude
  - A hard 'jet' component, directed opposite the boson p_T
    - P_T-dependent response and resolution parameterizations
    - Response $R = \boldsymbol{u}_{reconstructed} / \boldsymbol{u}_{true} = \boldsymbol{a} \log (\boldsymbol{u}_{true}/\text{GeV} + \boldsymbol{b}) / \log (15 + \boldsymbol{b})$
      - Logarithmically increasing hadronic response motivated by Z boson data
      - $\boldsymbol{a}$ and $\boldsymbol{b}$ are fit to the Z data
    - Jet resolution parameterized as $\boldsymbol{s}_{had} (\boldsymbol{u}_{true})^{1/2}$
      - Spectator resolution and $\boldsymbol{s}_{had}$ are fit to the Z data

Tuning Recoil Response Model with *Z* events

Project the vector sum of $p_T(ll)$ and ***u*** on a set of orthogonal axes defined by lepton directions

Mean and rms of projections as a function of $p_T(ll)$ provide information hadronic model parameters





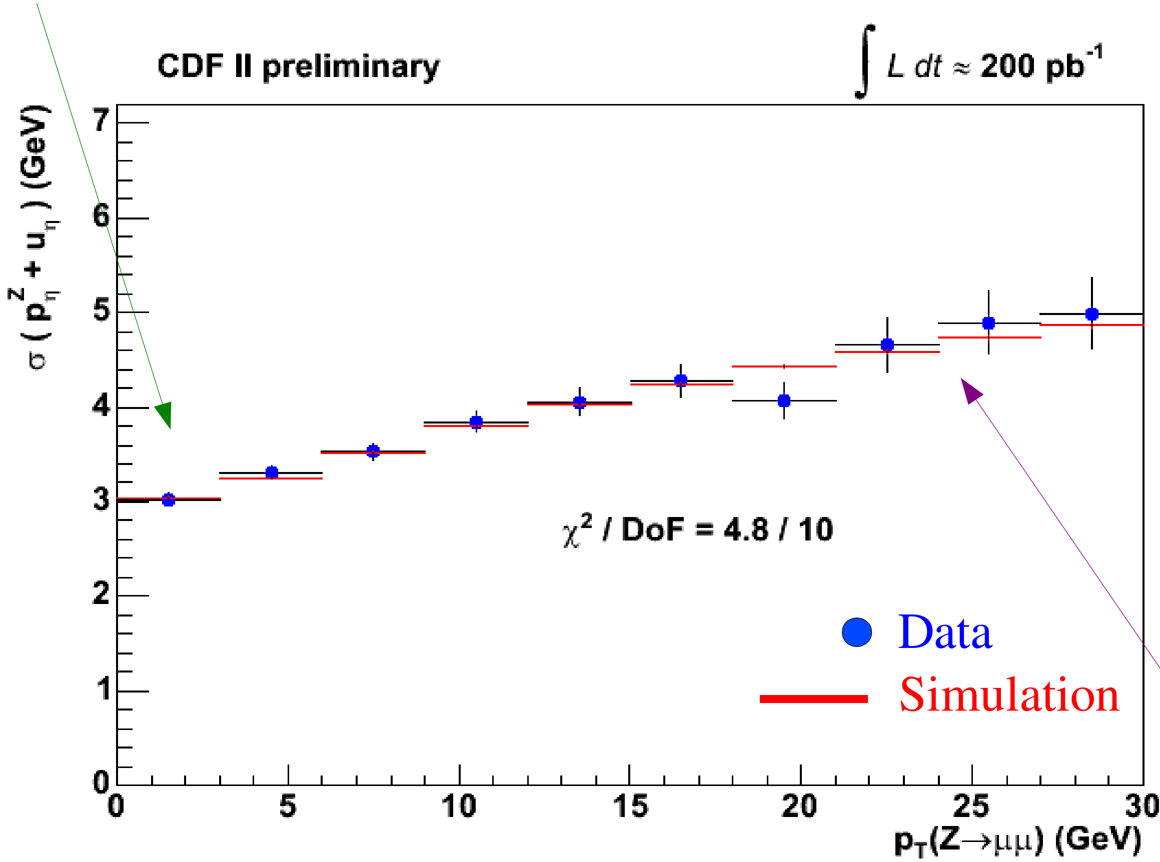
Hadronic model parameters tuned by minimizing χ^2 between data and simulation

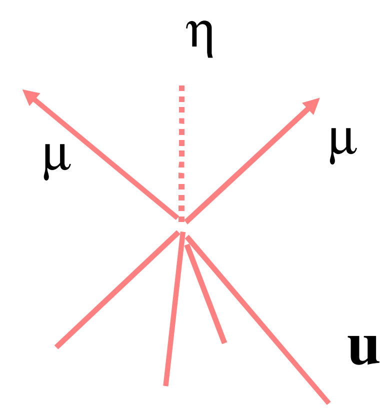
$\Delta M_W = 9$ MeV

Tuning Recoil Resolution Model with Z events

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

Resolution of p_T-balance (GeV)



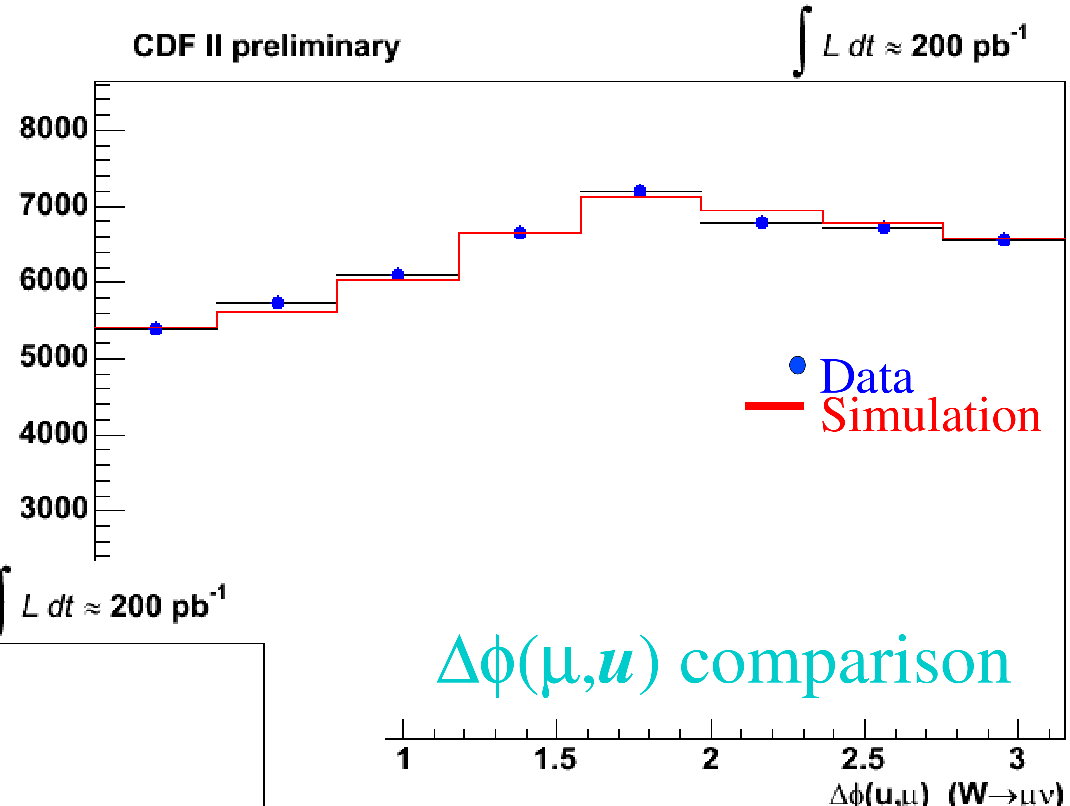


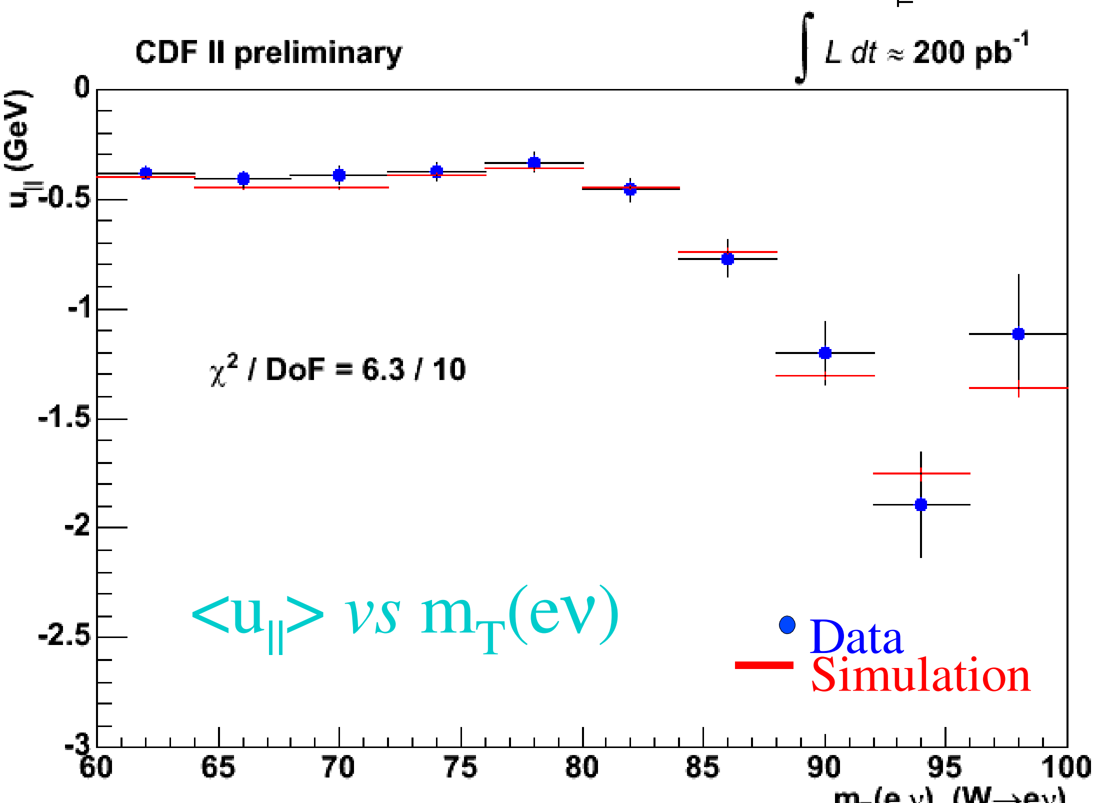
$\Delta M_W = 7$ MeV

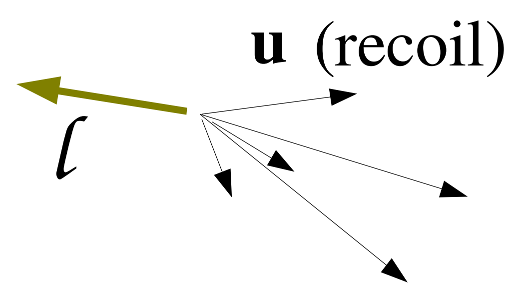
At high $p_T(Z)$, p_T-balance constrains jet resolution

Testing Hadronic Recoil Model with *W* events

Recoil model validation plots confirm the consistency of the model

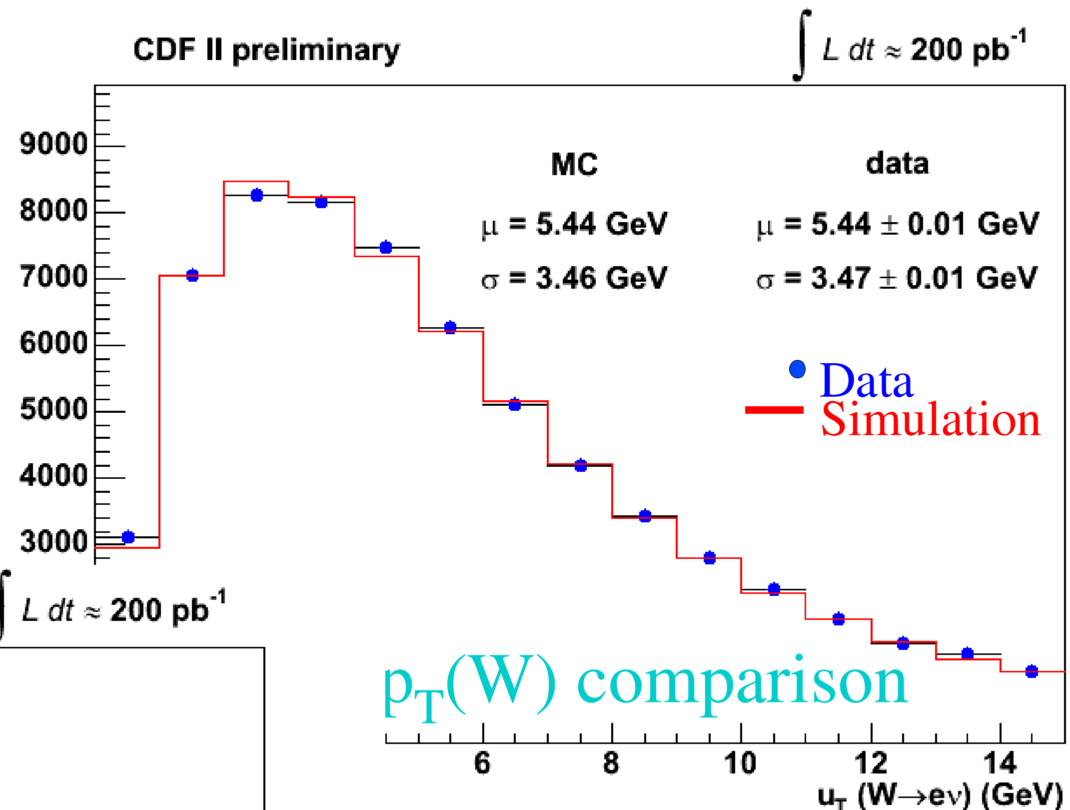


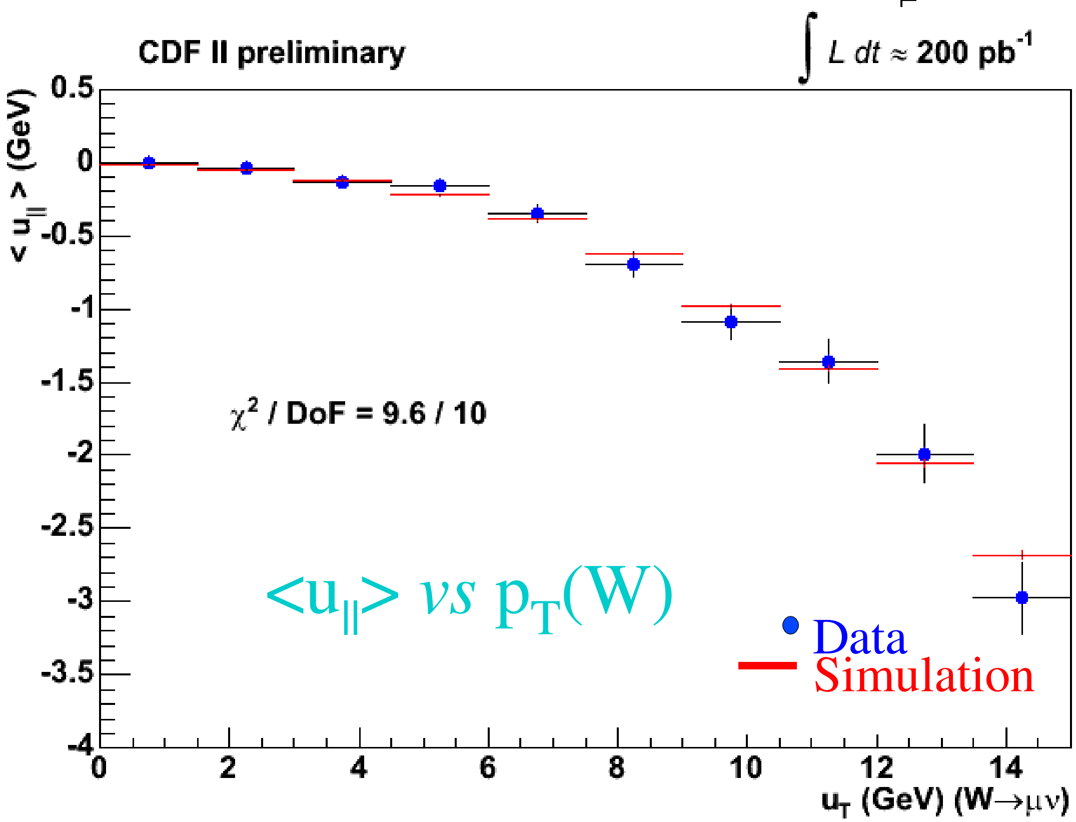


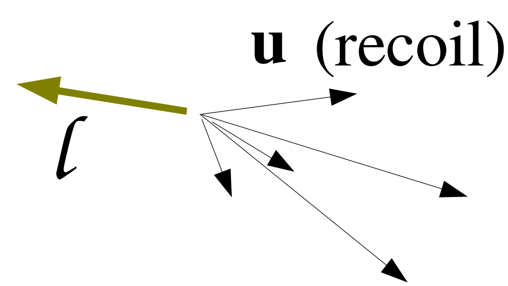


Testing Hadronic Recoil Model with *W* events

Recoil model validation plots confirm the consistency of the model

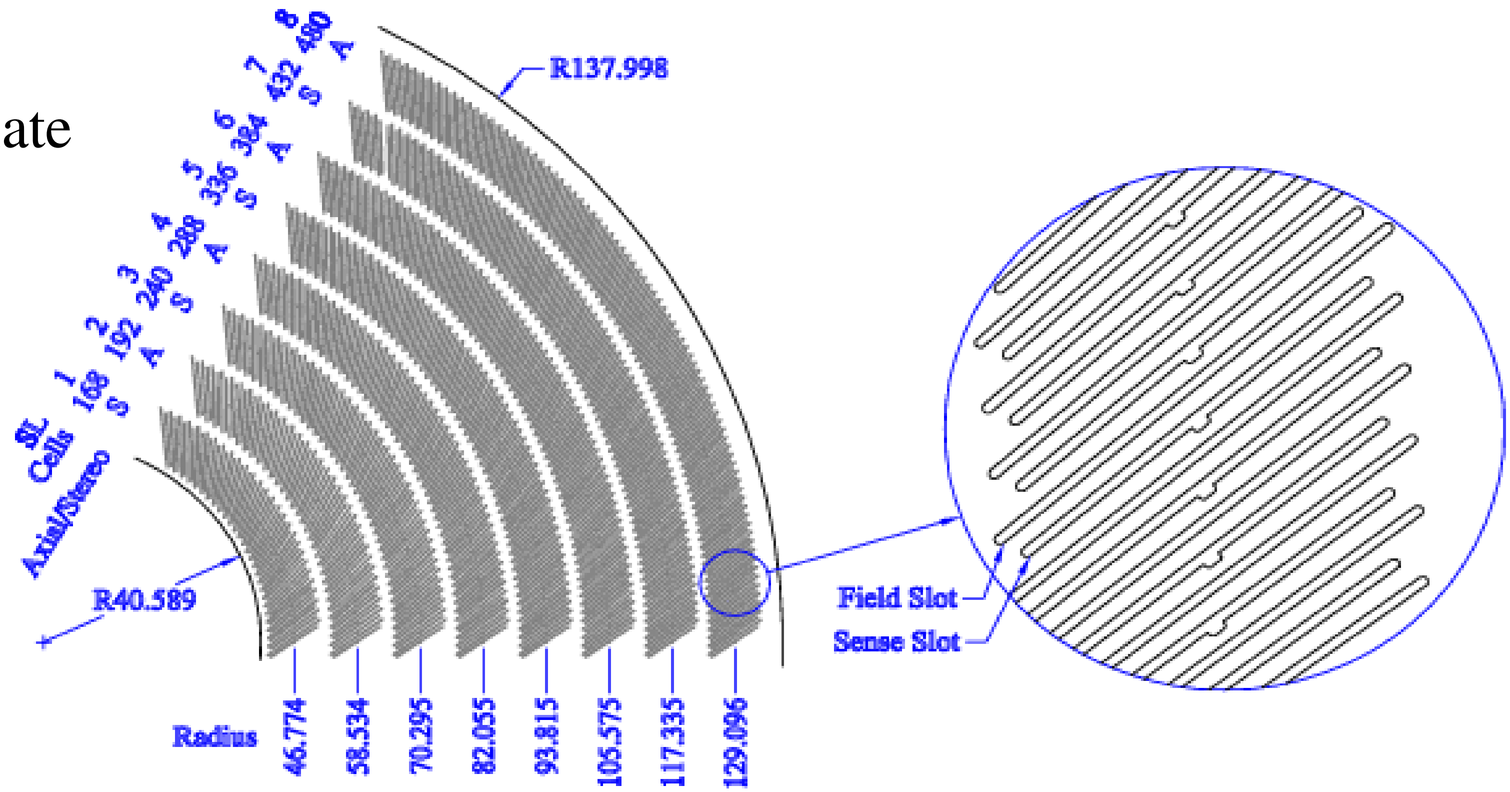






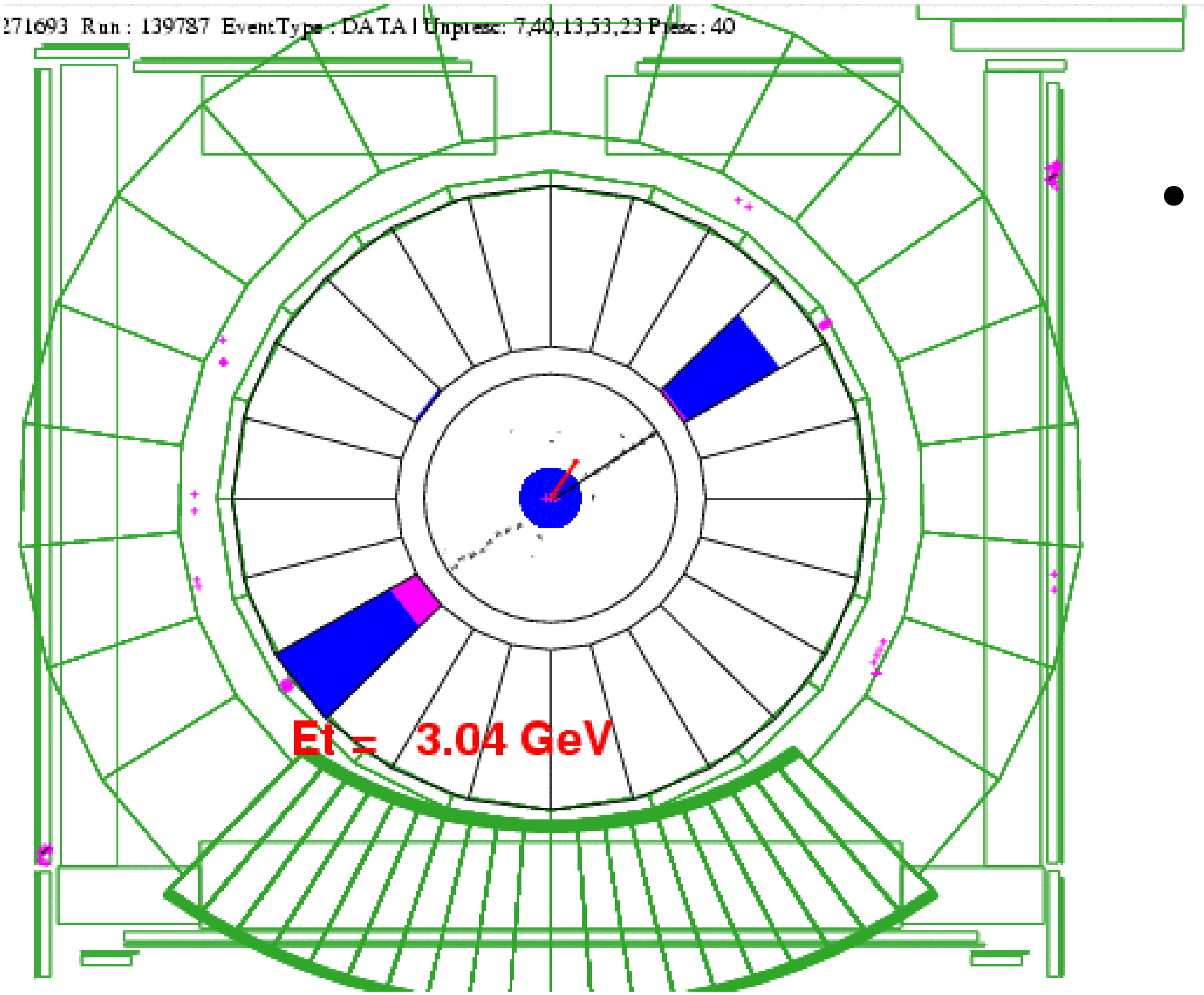
Drift Chamber (COT) Alignment

COT endplate geometry



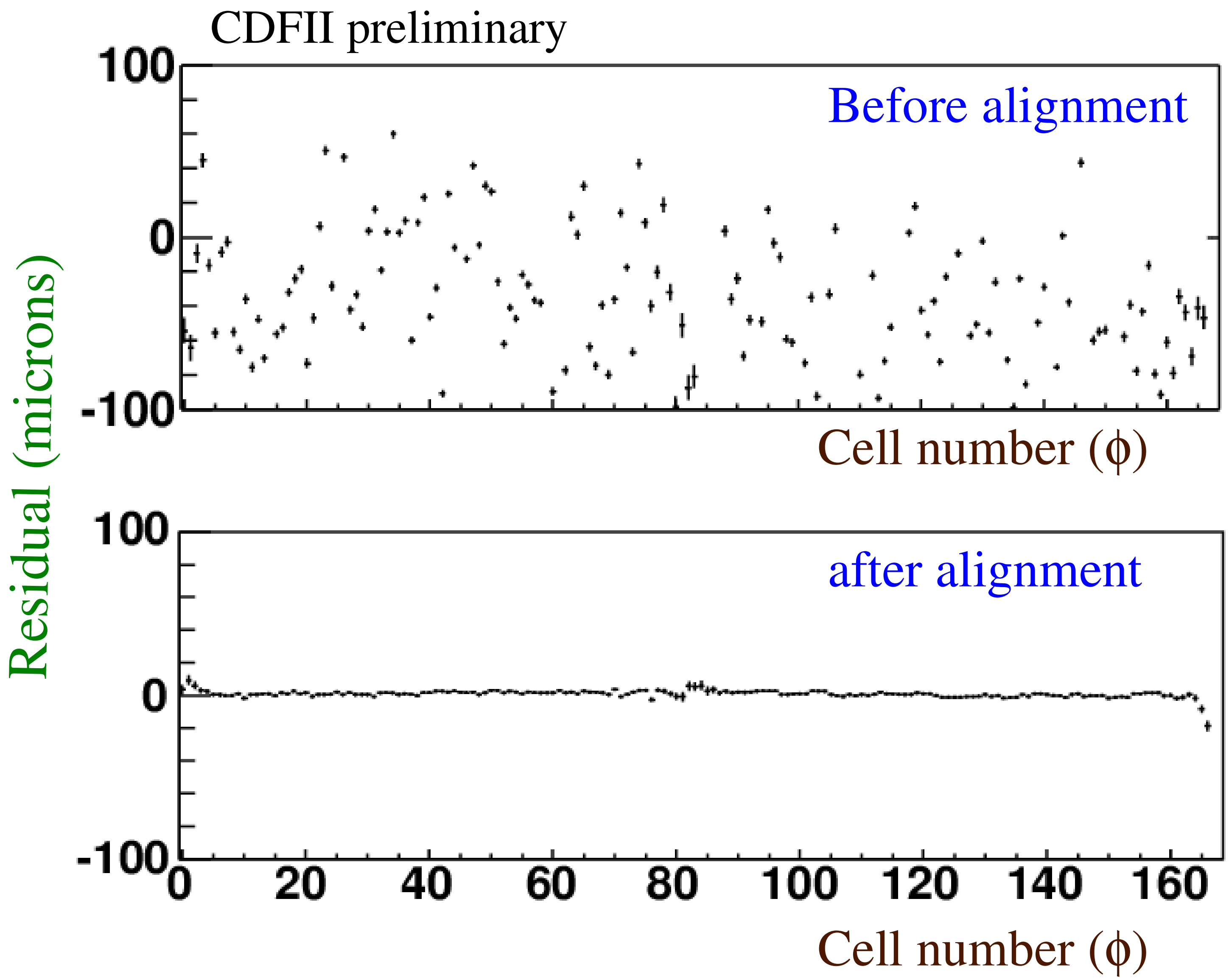
Internal Alignment of COT

- Use a clean sample of ~200*k* cosmic rays for cell-by-cell internal alignment



- Fit COT hits on both sides simultaneously to a single helix (AK, H. Gerberich and C. Hays, NIMA 506, 110 (2003))
  - Time of incidence is a floated parameter in this 'dicosmic fit'

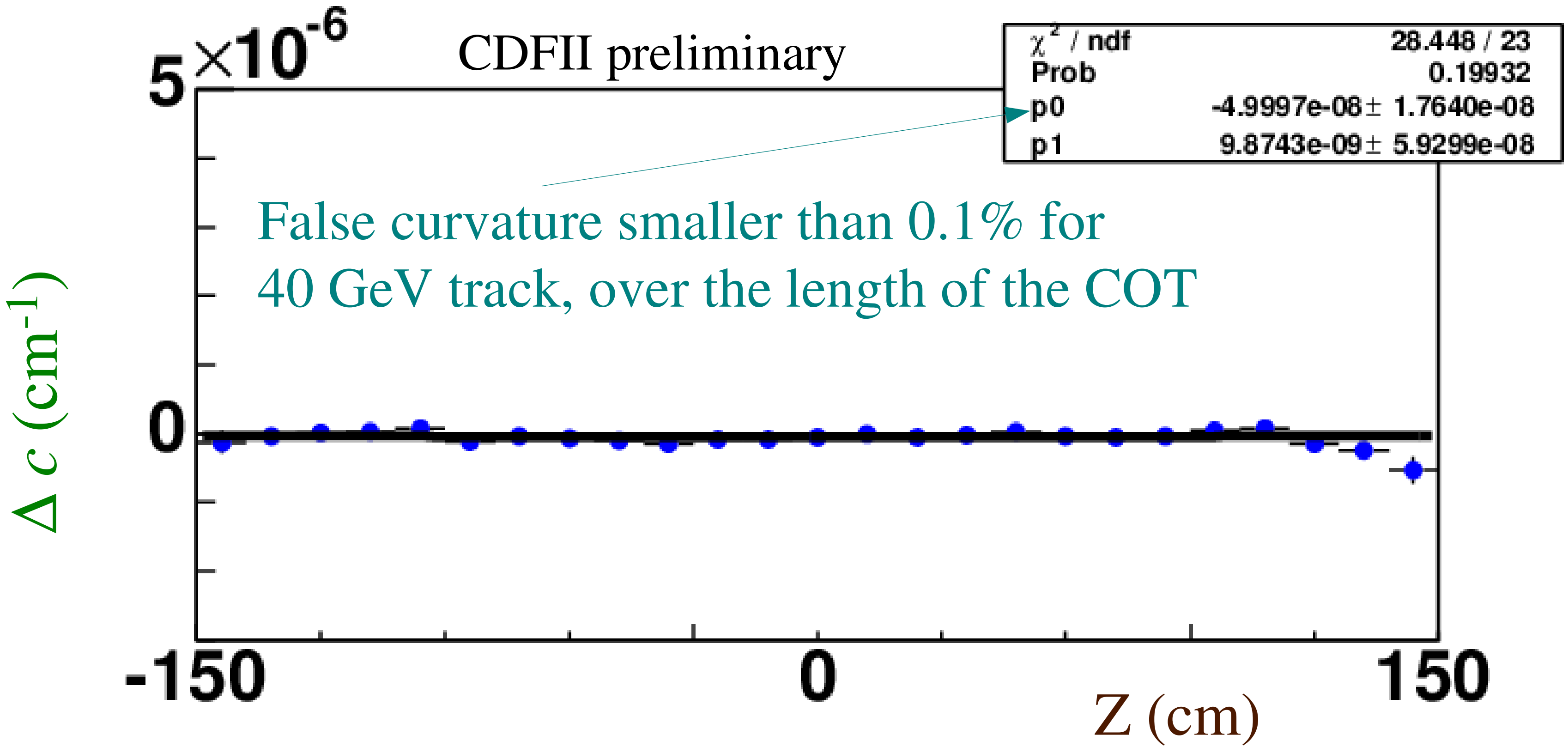
Residuals of COT cells after alignment



Final relative alignment of cells ~5 μm (initial alignment ~50 μm)

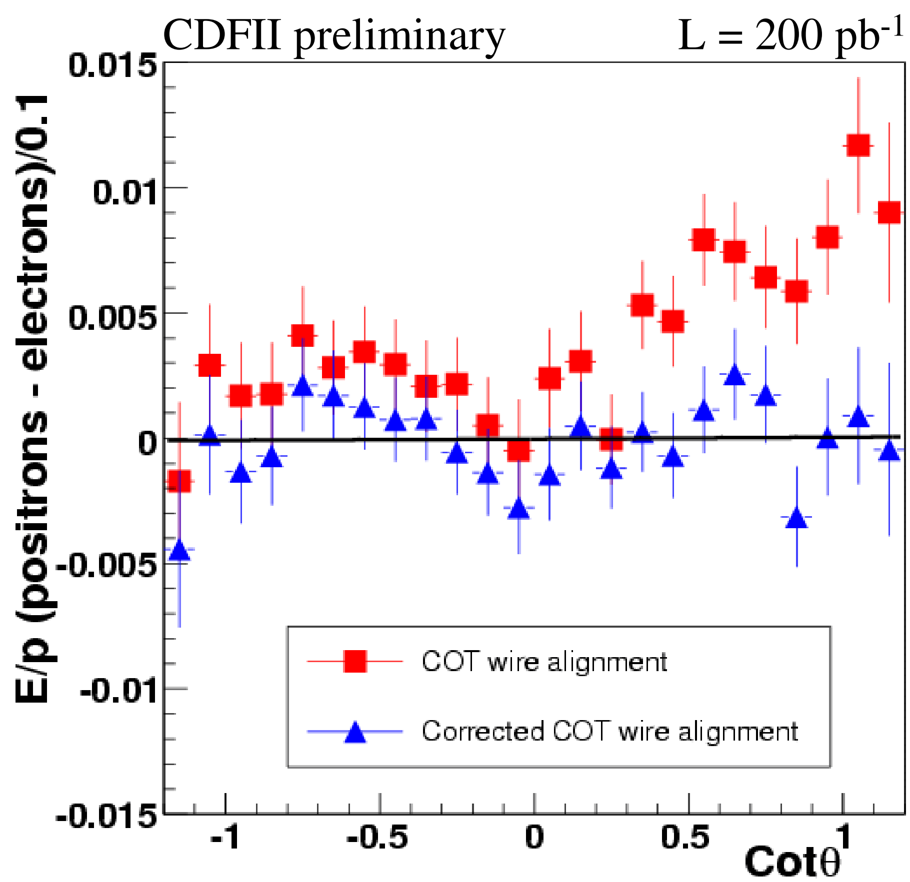
Consistency check of COT alignment procedure

- Fit separate helices to cosmic ray tracks on each side
- Compare track parameters (eg. Curvature, shown below) of the two tracks: a measure of track parameter bias



Cross-check of COT alignment

- Final cross-check and correction to beam-constrained track curvature based on difference of <E/p> for positrons *vs* electrons
- Smooth ad-hoc curvature corrections fitted and applied as a function of polar and azimuthal angle: statistical errors => $\delta M_W = 6$ MeV



Lepton Resolutions

- Tracking resolution parameterized in the fast Monte Carlo by
  - Drift chamber hit resolution $\sigma_h = 150 \pm 3_{stat}$ μm
  - Beamspot size $\sigma_b = 39 \pm 3_{stat}$ μm
  - Tuned on the widths of the $Z \rightarrow \mu\mu$ (beam constrained) and $\Upsilon \rightarrow \mu\mu$ (both beam constrained and non-beam constrained) mass peaks

  => $\Delta M_W = 3$ MeV (muons)

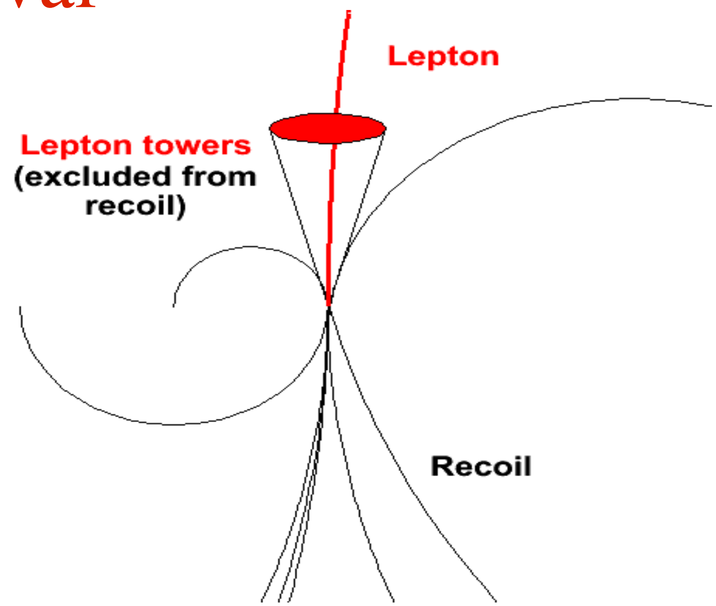
- Electron cluster resolution parameterized in the fast Monte Carlo by
  - $13.5\% / \sqrt{E_T}$ (sampling term)
  - Primary constant term $\kappa = 0.89 \pm 0.15_{stat}$ %
  - Secondary photon resolution $\kappa_\gamma = 8.3 \pm 2.2_{stat}$ %
  - Tuned on the widths of the E/p peak and the $Z \rightarrow ee$ peak (selecting radiative electrons)

  => $\Delta M_W = 9$ MeV (electrons)

Lepton Tower Removal

- We remove the calorimeter towers containing lepton energy from the hadronic recoil calculation
  - Lost underlying event energy is measured in ϕ-rotated windows

$$\Delta M_W = 8 \text{ MeV}$$



Electron channel W data

Electron Electromagnetic E_T (MeV)

Tower $\Delta\eta$ \ Tower $\Delta\phi$	-3	-2	-1	0	1	2	3
3	29	29	29	31	29	27	28
2	28	28	29	37	31	29	28
1	29	29	32	1915	56	31	29
0	28	31	46	35646	138	34	30
-1	29	28	30	398	34	29	29
-2	29	29	29	31	30	29	28
-3	28	28	28	29	28	28	29

η ϕ

Muon channel W data

Muon Hadronic E_T (MeV)

Tower $\Delta\eta$ \ Tower $\Delta\phi$	-3	-2	-1	0	1	2	3
3	8	7	8	8	8	8	8
2	7	7	8	9	8	8	8
1	8	8	8	432	9	8	8
0	9	8	9	1255	11	8	8
-1	8	9	9	83	9	8	8
-2	8	8	8	8	8	7	8
-3	8	8	8	7	8	9	8

η ϕ

Backgrounds in the W sample

Source	Fraction (*electrons*)	Fraction (*muons*)
Z -> *ll*	0.24 ± 0.04 %	6.6 ± 0.3 %
W -> $\tau\nu$	0.93 ± 0.03 %	0.89 ± 0.02 %
Mis-identified QCD jets	0.25 ± 0.15 %	0.1 ± 0.1 %
Decays-in-flight		0.3 ± 0.2 %
Cosmic rays		0.05 ± 0.05 %

Backgrounds are small (except $Z \rightarrow \mu\mu$ with a forward muon)

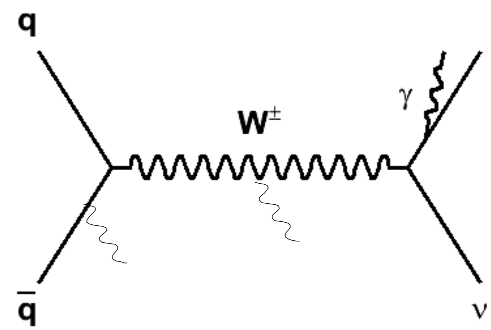
backgrounds contribute systematic uncertainty of 9 MeV on transverse mass fit

Tevatron Run 1 (100 pb^{-1}) *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
Total	144	113	84

Run 1 studies set the stage for the Run 2 analysis: reduce uncertainties using data-driven techniques

QED Radiative Corrections



- use complete NLO QED calculation (WGRAD) for single photon emission
  - We simulate final state radiation (FSR) photons
  - We estimate initial state radiation (ISR), ISR-FSR interference, and choice of infrared cutoff to contribute uncertainties of 5 MeV each
- 2-photon calculation (Carloni Calame *et. al.*, PRD69, 037301 (2004)) predict 2nd photon adds 10% shift in *W* mass compared to 1st photon
  - We apply 10% correction for 2nd photon, with 5% systematic uncertainty

$$\Delta M_W = 12 \text{ MeV}$$

Tracking Momentum Scale Systematics

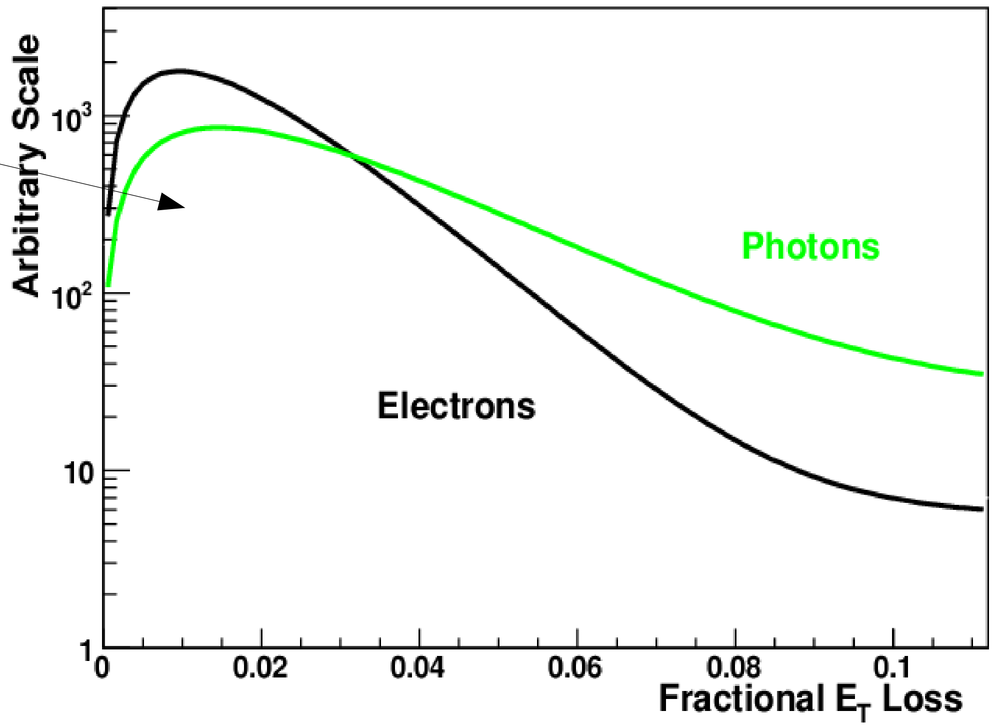
Systematic uncertainties on momentum scale

Source	J/ψ ($\times 10^{-3}$)	Υ ($\times 10^{-3}$)	Common ($\times 10^{-3}$)
QED and energy loss model	0.20	0.13	0.13
Magnetic field nonuniformities	0.10	0.12	0.10
Beam constraint bias	N/A	0.06	0
Ionizing material scale	0.06	0.03	0.03
COT alignment corrections	0.05	0.03	0.03
Fit range	0.05	0.02	0.02
p_T threshold	0.04	0.02	0.02
Resolution model	0.03	0.03	0.03
Background model	0.03	0.02	0.02
World-average mass value	0.01	0.03	0
Statistical	0.01	0.06	0
Total	0.25	0.21	0.17

Uncertainty dominated by QED radiative corrections and magnetic field non-uniformity

Calorimeter Simulation for Electrons and Photons

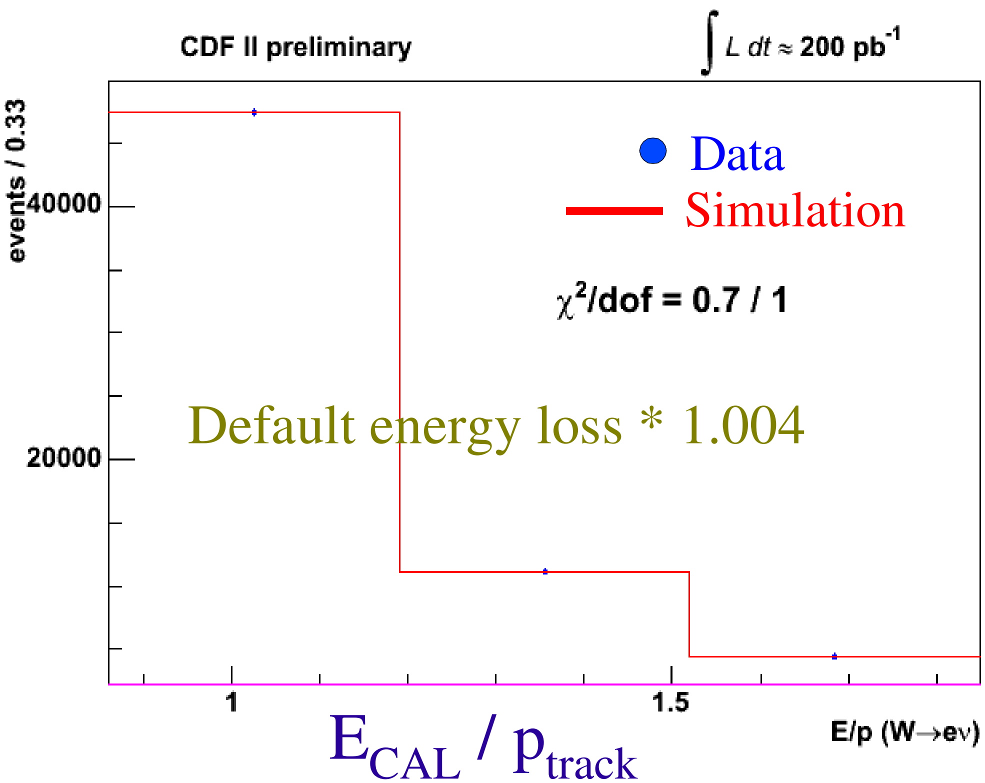
- Distributions of energy loss calculated based on expected shower profiles as a function of E_T
  - Leakage into hadronic calorimeter
  - Absorption in the coil
  - Relevant for E/p lineshape

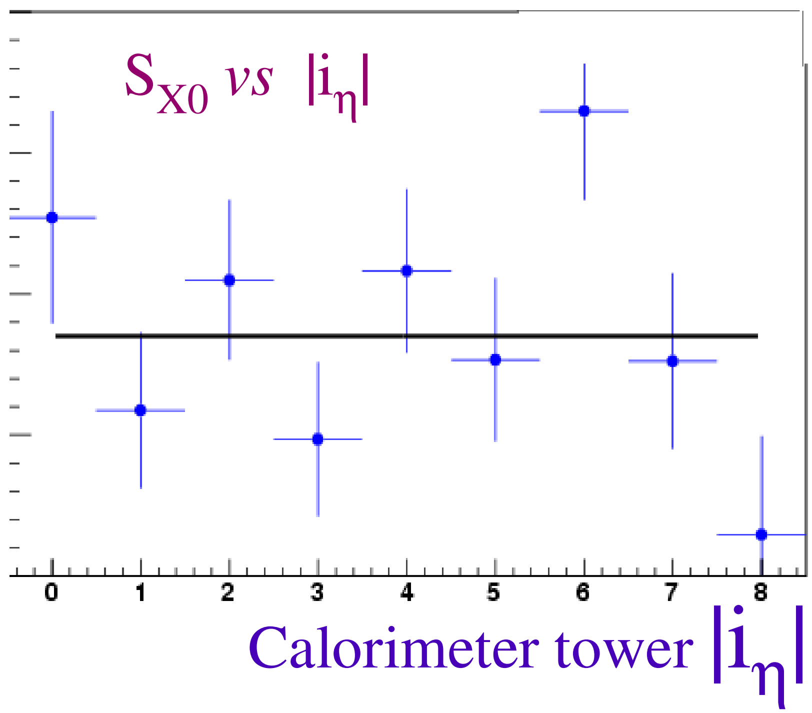


- Energy-dependent gain (non-linearity) parameterized and fit from data
- Energy resolution parameterized as fixed sampling term and two tunable constant terms
  - Constant terms are fit from the width of E/p peak and $Z \rightarrow ee$ mass peak

Consistency of Radiative Material Model

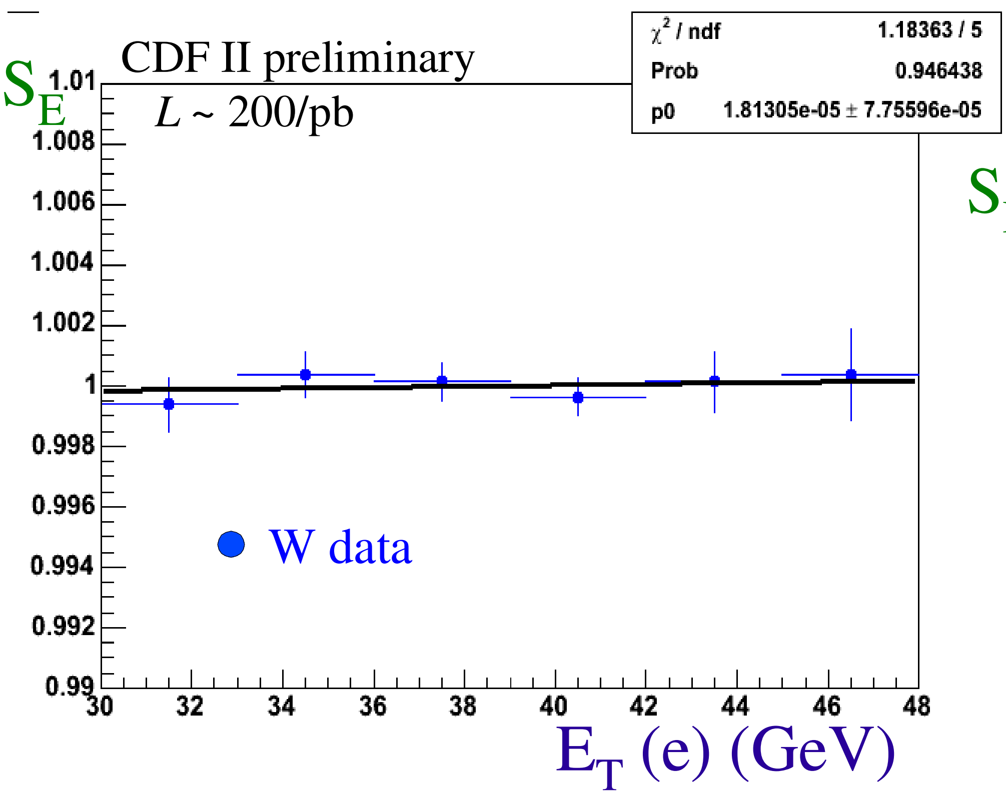
- Excellent description of E/p spectrum tail
- radiative material tune factor: $S_{X0} = 1.004 \pm 0.009_{stat} \pm 0.002_{background}$ achieves consistency with E/p spectrum tail
  - CDFSim geometry confirmed as a function of pseudorapidity: S_{MAT} independent of $|\eta|$

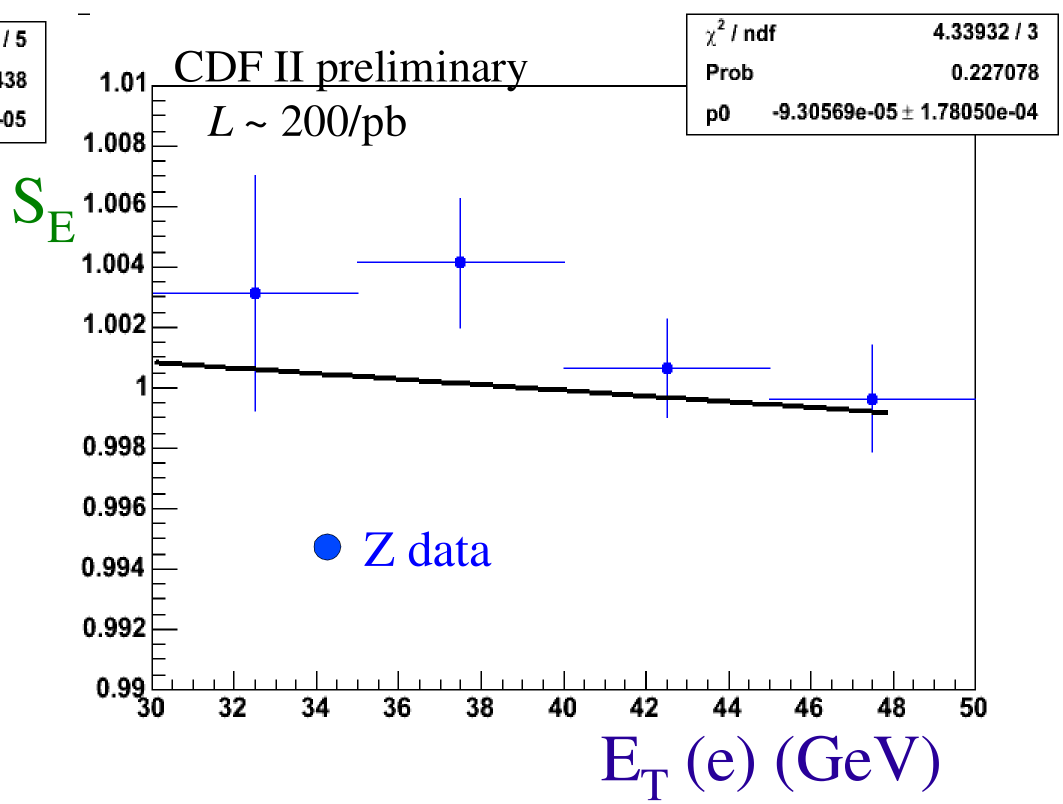




Measurement of EM Calorimeter Non-linearity

- Perform E/p fit-based calibration in bins of electron E_T
- Pameterize non-linear response as: $S_E = 1 + \xi\,(E_T/\mathrm{GeV} - 39)$
- Tune on W and Z data: $\xi = (6 \pm 7_{stat}) \times 10^{-5}$
  - => $\Delta M_W = 23$ MeV





Parton Distribution Functions

- Affect W kinematic lineshapes through acceptance cuts
- We use CTEQ6M as the default PDF
- Use CTEQ6 ensemble of 20 'uncertainty' PDFs
  - Represent variations of eigenvectors in the PDF parameter space
  - compute δM_W contribution from each error PDF
- Using CTEQ prescription and interpreting PDF ensemble as 90% CL, obtain total transverse mass systematic uncertainty of 11 MeV
  - Cross-check: fitting MC sample generated with MRST2003 with default CTEQ6M templates yields 8 MeV shift in W mass

PDF Uncertainty Contributions