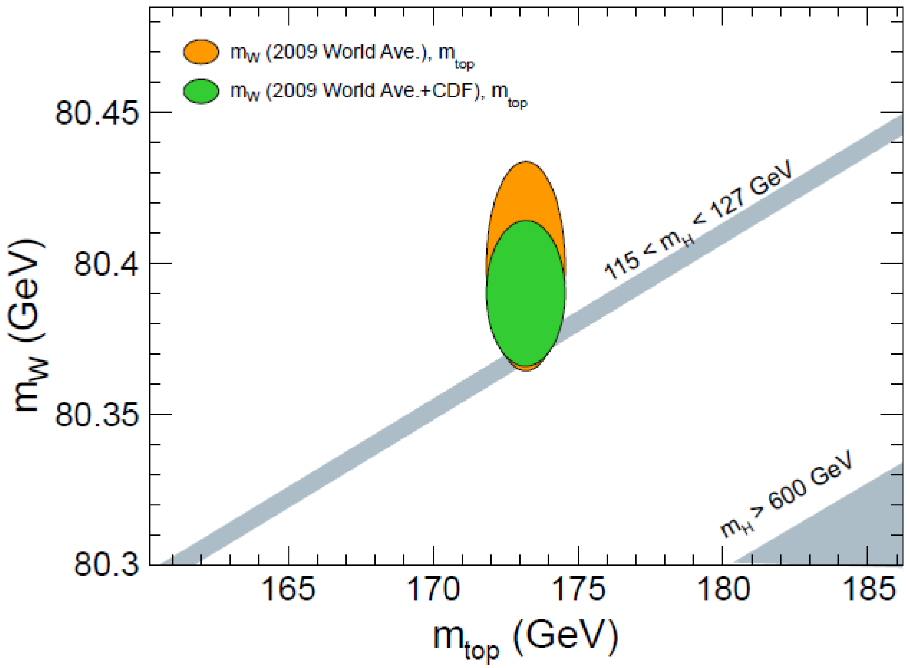
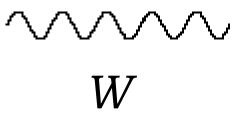
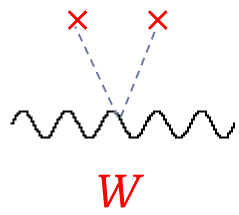


A Precise Measurement of the W Boson Mass with CDF

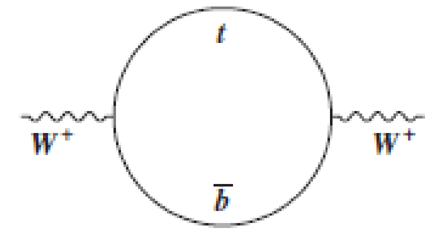
Chris Hays, Oxford University

Evolution of a propagator





(Tree level)



$\mathcal{L} = \mathcal{L}_{\text{gauge}}$

$\mathcal{L} = \mathcal{L}_{\text{gauge}} + \mathcal{L}_{\text{scalar}}$

$\mathcal{L} = \mathcal{L}_{\text{gauge}} + \mathcal{L}_{\text{scalar}} + \mathcal{L}_{\text{fermion}}$

$$\frac{1}{q^2} \Rightarrow \frac{1}{q^2 - m_W^2} \Rightarrow \frac{1}{q^2 - (m_W + \delta m_W)^2}$$

$m_W^2 = 0$

$m_W^2 = g^2 v^2/2$

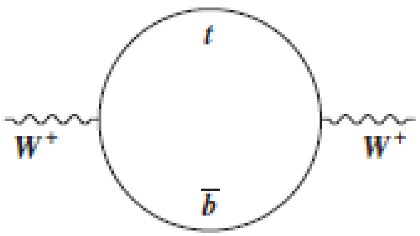
$= (79.916 \text{ GeV})^2$

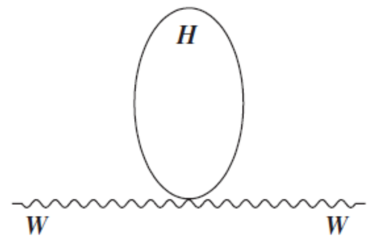
$(m_W + \delta m_W)^2$

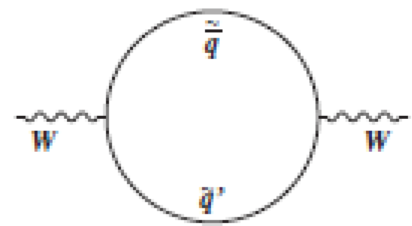
$= (80.360 \text{ GeV})^2$

Probing new particles

$$M_W^2\left(1-\frac{M_W^2}{M_Z^2}\right)=\frac{\pi\alpha_{em}}{\sqrt{2}G_F}\,\frac{1}{1-\Delta r}$$



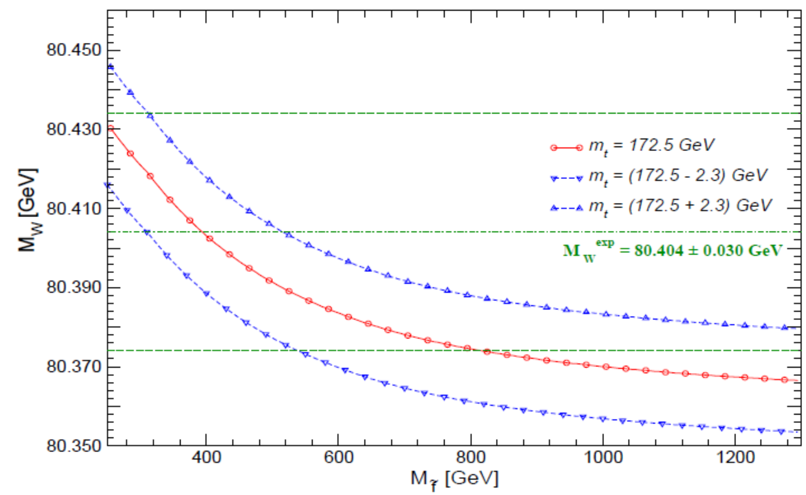




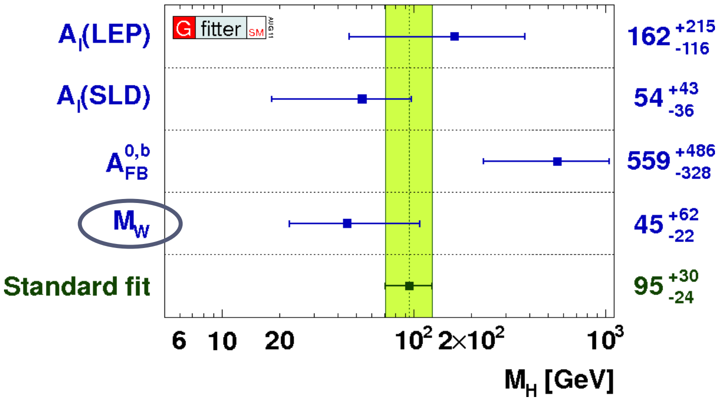
$\Delta r \sim m_t^2$

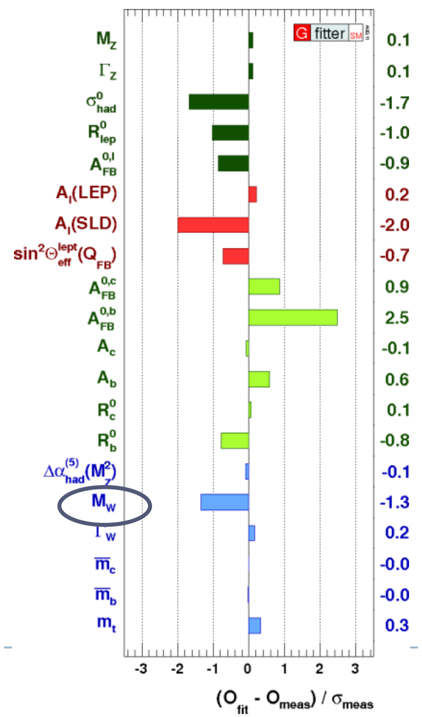
$\Delta r \sim \ln m_H$

Parameter shift	m_W shift (MeV)
$\Delta(\ln m_H) = +0.693$	-41.3
$\Delta m_t = +0.9$ GeV	5.5
$\Delta\alpha_{em} = +0.00033$	-5.8
$\Delta m_Z = +2.1$ MeV	2.6



Electroweak measurements



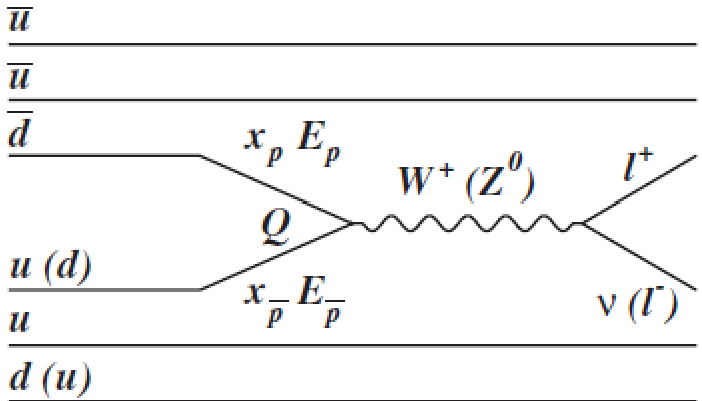


Status in 2011 (Gfitter)

Parameter	Input value	Free in fit	Results from global EW fits: *Standard fit*	*Complete fit*	*Complete fit w/o exp. input in line*
M_Z [GeV]	91.1875 ± 0.0021	yes	91.1874 ± 0.0021	91.1877 ± 0.0021	$91.1983^{+0.0133}_{-0.0155}$
Γ_Z [GeV]	2.4952 ± 0.0023	–	2.4959 ± 0.0015	2.4955 ± 0.0014	$2.4951^{+0.0017}_{-0.0016}$
σ^0_{had} [nb]	41.540 ± 0.037	–	41.478 ± 0.014	41.478 ± 0.014	41.469 ± 0.015
R^0_ℓ	20.767 ± 0.025	–	20.743 ± 0.018	20.741 ± 0.018	$20.718^{+0.027}_{-0.026}$
$A^{0,\ell}_{FB}$	0.0171 ± 0.0010	–	0.01641 ± 0.0002	$0.01620^{+0.0002}_{-0.0001}$	0.01606 ± 0.0001
A_ℓ $^{(\star)}$	0.1499 ± 0.0018	–	0.1479 ± 0.0010	$0.1472^{+0.0009}_{-0.0006}$	–
A_c	0.670 ± 0.027	–	$0.6683^{+0.00044}_{-0.00043}$	$0.6680^{+0.00040}_{-0.00028}$	$0.6679^{+0.00042}_{-0.00025}$
A_b	0.923 ± 0.020	–	$0.93470^{+0.00009}_{-0.00008}$	$0.93463^{+0.00008}_{-0.00005}$	$0.93463^{+0.00007}_{-0.00005}$
$A^{0,c}_{FB}$	0.0707 ± 0.0035	–	0.0741 ± 0.0005	$0.0737^{+0.0005}_{-0.0004}$	0.0738 ± 0.0004
$A^{0,b}_{FB}$	0.0992 ± 0.0016	–	0.1037 ± 0.0007	$0.1035^{+0.0003}_{-0.0004}$	$0.1038^{+0.0003}_{-0.0005}$
R^0_c	0.1721 ± 0.0030	–	0.17226 ± 0.00006	0.17226 ± 0.00006	0.17226 ± 0.00006
R^0_b	0.21629 ± 0.00066	–	$0.21578^{+0.00005}_{-0.00008}$	$0.21577^{+0.00005}_{-0.00008}$	$0.21577^{+0.00005}_{-0.00007}$
$\sin^2\theta^\ell_{eff}(Q_{FB})$	0.2324 ± 0.0012	–	0.23141 ± 0.00012	$0.23150^{+0.00008}_{-0.00011}$	$0.23152^{+0.00006}_{-0.00013}$
M_H [GeV] $^{(\circ)}$	Likelihood ratios	yes	$95^{+30[+74]}_{-24[-43]}$	$125^{+8[+21]}_{-10[-11]}$	$95^{+30[+74]}_{-24[-43]}$
M_W [GeV]	80.399 ± 0.023	–	$80.382^{+0.014}_{-0.015}$	$80.368^{+0.007}_{-0.010}$	$80.360^{+0.012}_{-0.011}$
Γ_W [GeV]	2.085 ± 0.042	–	2.093 ± 0.001	2.092 ± 0.001	$2.091^{+0.002}_{-0.001}$
$\overline{m}_c$ [GeV]	$1.27^{+0.07}_{-0.11}$	yes	$1.27^{+0.07}_{-0.11}$	$1.27^{+0.07}_{-0.11}$	–
$\overline{m}_b$ [GeV]	$4.20^{+0.17}_{-0.07}$	yes	$4.20^{+0.16}_{-0.07}$	$4.20^{+0.16}_{-0.07}$	–
m_t [GeV]	173.2 ± 0.9	yes	173.3 ± 0.9	173.5 ± 0.9	$177.2^{+2.9}_{-3.1}$ $^{(\nabla)}$
$\Delta\alpha^{(5)}_{had}(M_Z^2)$ $^{(\dagger\triangle)}$	2749 ± 10	yes	2750 ± 10	2748 ± 10	2716^{+60}_{-45}
$\alpha_s(M_Z^2)$	–	yes	0.1192 ± 0.0028	0.1193 ± 0.0028	0.1193 ± 0.0028
$\delta_{th} M_W$ [MeV]	$[-4, 4]_{theo}$	yes	4	4	–
$\delta_{th} \sin^2\theta^\ell_{eff}$ $^{(\dagger)}$	$[-4.7, 4.7]_{theo}$	yes	4.7	4.7	–

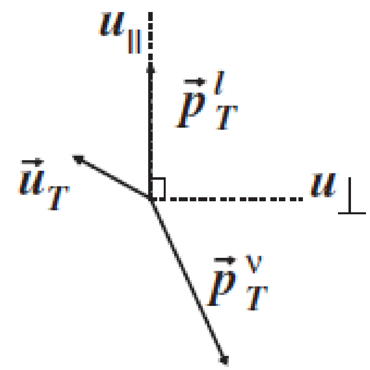
W mass measurement at the Tevatron

High statistics from resonant single W production



Momentum of charged lepton (e, μ) dominates mass information

Neutrino p_T calculated from lepton and recoil measurements



In situ calibration lepton and recoil measurements

Mass determined from a combined fit to charged-lepton p_T, neutrino p_T, and m_T

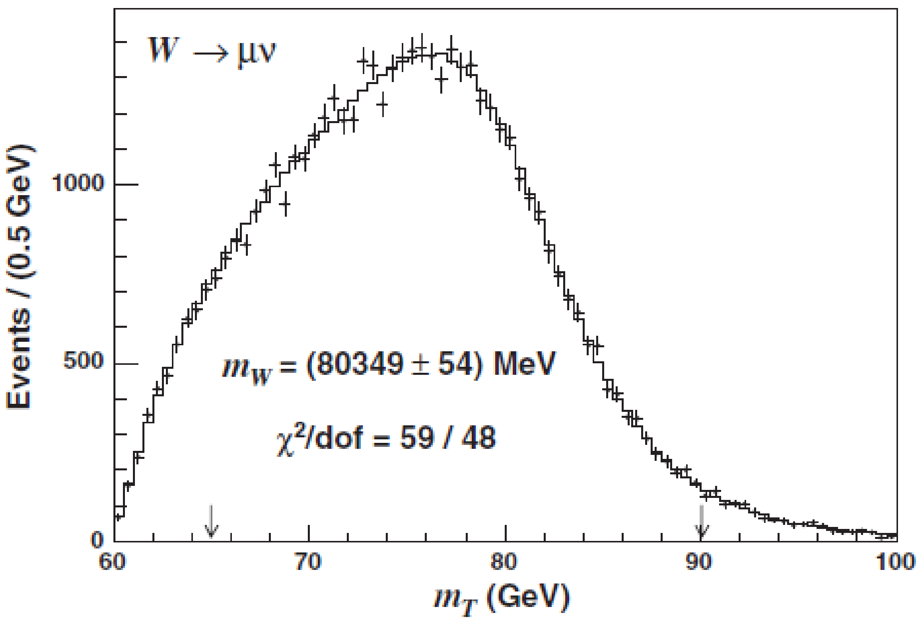
$$m_T = \sqrt{2p_T(l)p_T(\nu)[1 - \cos(\phi_l - \phi_\nu)]}$$

CDF m_W measurement

First Tevatron Run 2 measurement: 200 pb^{-1} of 2 TeV $p\bar{p}$ data

63 964 W → eν candidates
51 128 W → μν candidates

$$m_W = [80.413 \pm 0.034(\text{stat}) \pm 0.034(\text{sys}) = 80.413 \pm 0.048]\ \text{GeV}$$



Systematic uncertainties

Source	Uncertainty (MeV)
Lepton scale	23.1
Lepton resolution	4.4
Lepton efficiency	1.7
Lepton tower removal	6.3
Recoil energy scale	8.3
Recoil energy resolution	9.6
Backgrounds	6.4
PDFs	12.6
W boson p_T	3.9
Photon radiation	11.6

New CDF m_W measurement (2.2 fb^{-1})

Charged lepton model and calibration

Recoil model and calibration

W boson sample and mass fits

Charged lepton model and calibration

QED radiation in production process

Ionization energy loss and bremsstrahlung in the tracker

Tracker alignment with cosmic-ray muons and W electrons

Track momentum calibration with J/ψ & Υ mesons, Z bosons

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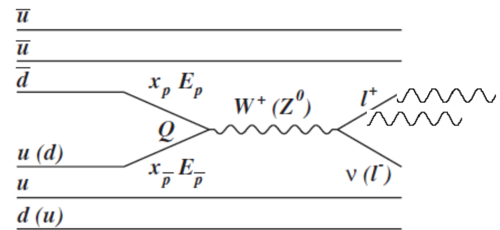
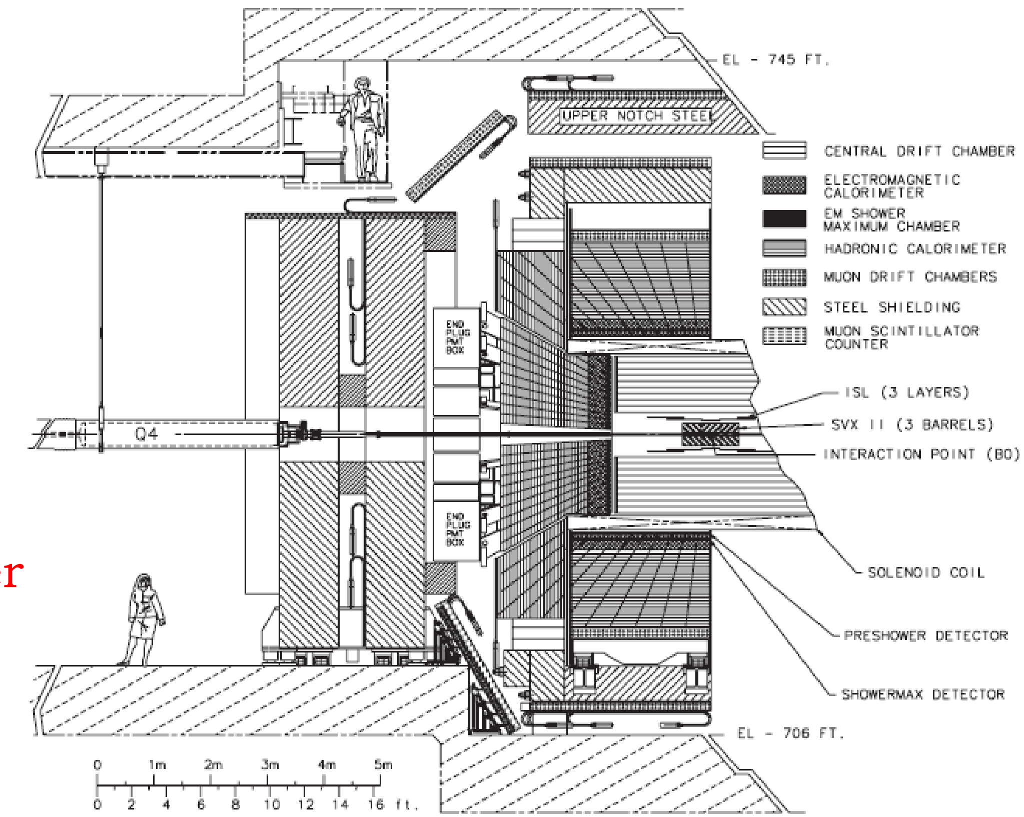




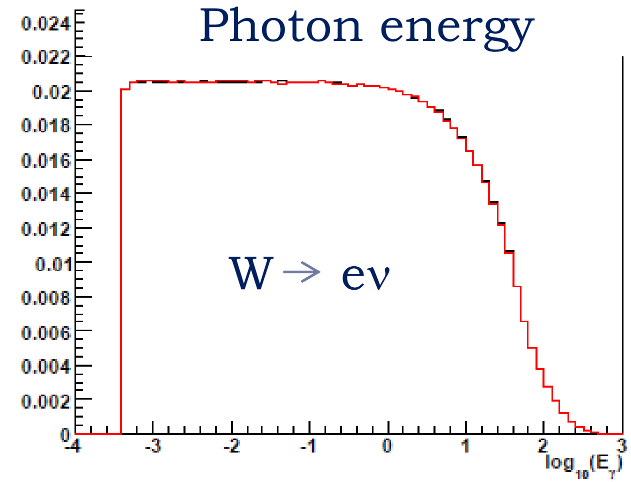
QED radiation model

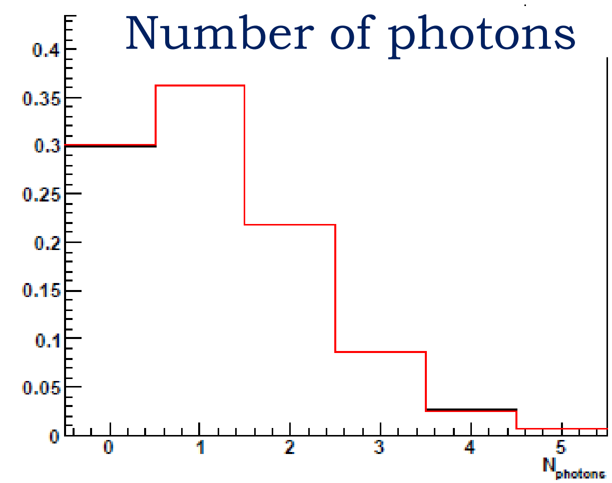
Based on PHOTOS & HORACE

PHOTOS: Leading log FSR, with weight to correct to matrix-element calculation

HORACE: Leading log ISR/FSR, with weight to match O(α) calculation; equivalent weight applied to all emitted photons

Uncertainties derived from comparisons of PHOTOS to HORACE, leading log to corrected leading log, and variation of the photon cutoff energy





$\delta m_W^{QED} = 4$ MeV

Energy loss model

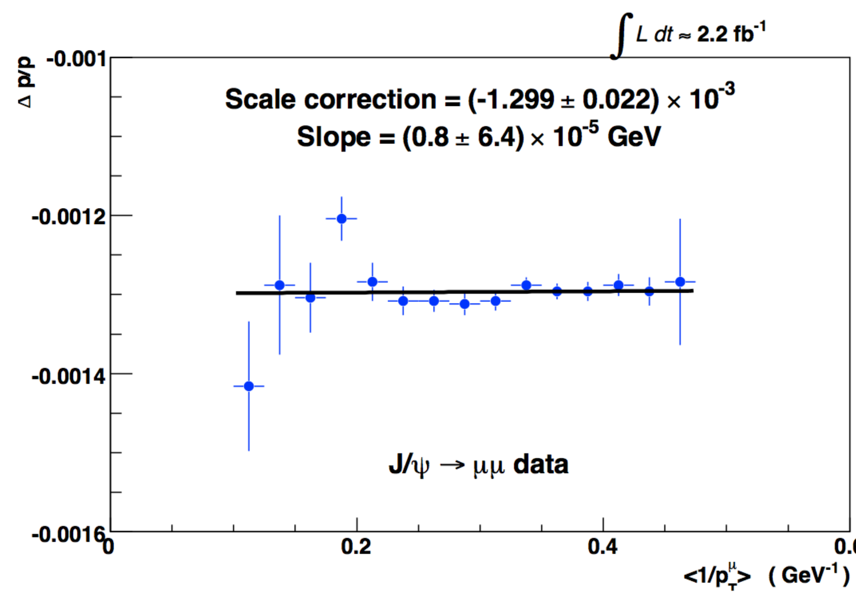
Custom fast simulation & reconstruction based on parameterizations of standard CDF simulation and full GEANT simulation

Ionization energy loss model uses fine-grained lookup table of tracker for Bethe-Bloch parameters

Correct a priori energy loss by 4.3% using data fits to J/ψ mass

Mass as a function of the mean inverse p_T of the muons is linearly dependent on energy loss

$$\frac{\Delta m}{m} = \frac{E_I^{\mu^+}}{2p_T^{\mu^+}} + \frac{E_I^{\mu^-}}{2p_T^{\mu^-}} \approx E_I \langle p_T^{-1} \rangle$$



Bremsstrahlung and conversions

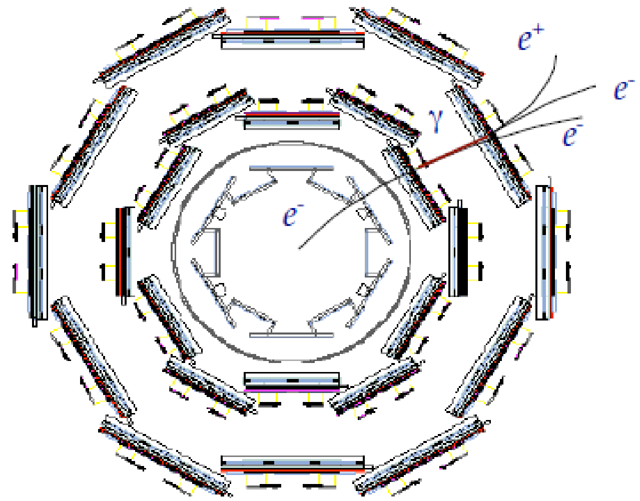
Fine-grained lookup table provides radiation length information in tracker

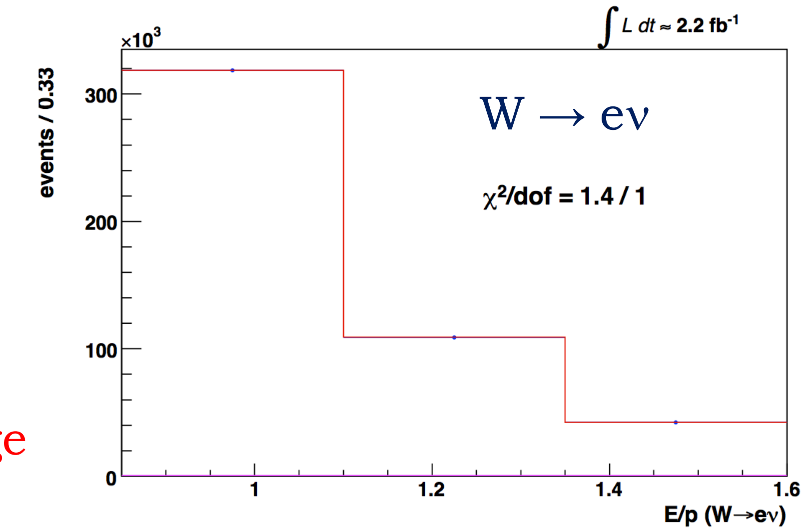
Bremsstrahlung reduces track momentum relative to cluster energy (high E/p)

Correct a priori radiation lengths by 2.6% using fits to electrons from W & Z decays

Low-energy radiation (E_γ < 20 MeV) Migdal-suppressed through coherent interference effects

Suppression model incorporates knowledge of heavy and light elements in tracker





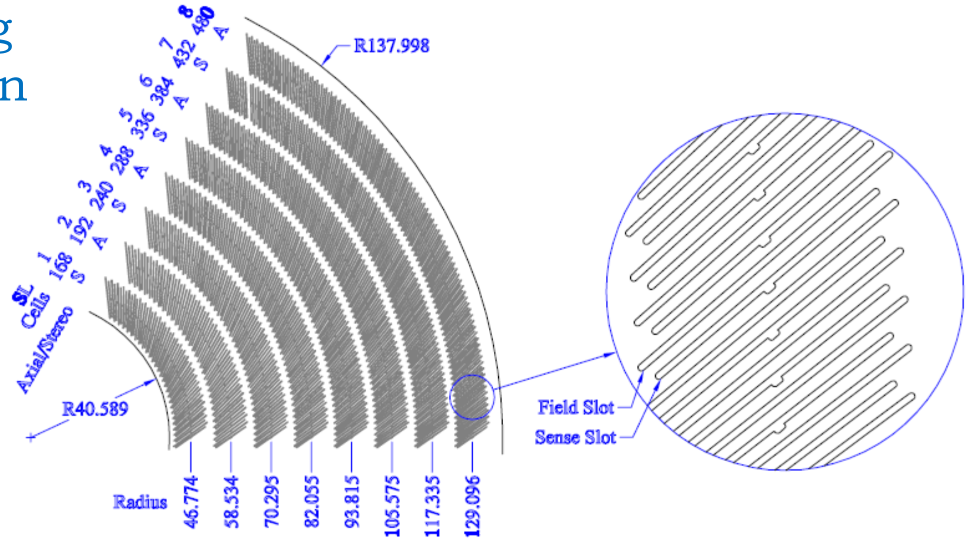
Tracker alignment

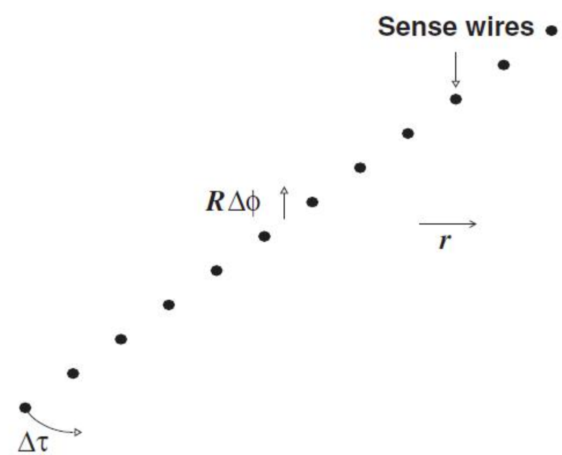
Track momentum determined using central outer tracker + beam position

Tracker wire positions measured under load during contruction

Relative positions at end plates determined to ~3 microns using *in situ* alignment with cosmic-ray muons

Positions between endplates adjusted using parameter differences between incoming and outgoing cosmic-ray tracks as a function of z





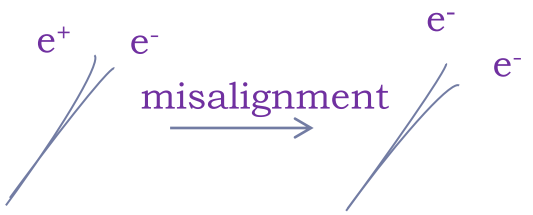
Track curvature corrections

Class of biases unconstrained by cosmic-ray alignment

Study remaining charge-dependent biases using difference in mean E/p between electrons and positrons from W decays

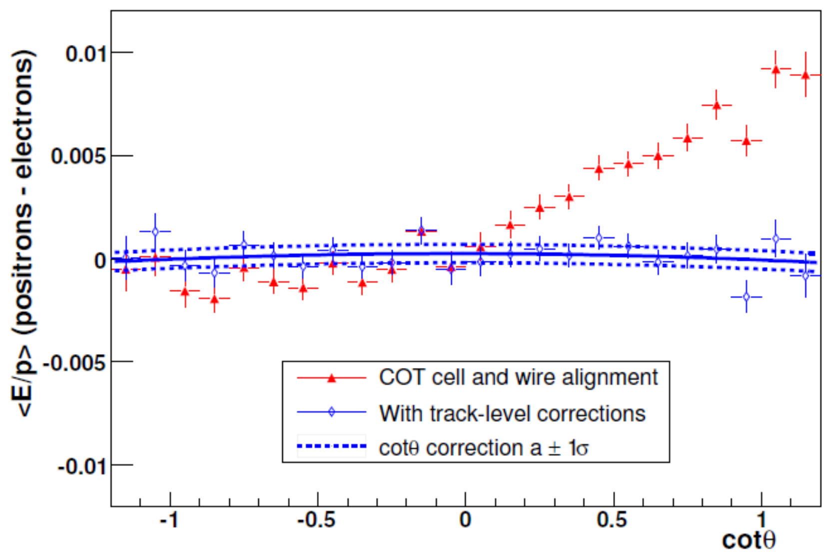
Small non-zero value of inclusive E/p difference: consistent with alignment to O(micron) precision

Remove differences (including azimuthal & polar dependences) with correction to track curvature



e^- has reduced p_T, e^+ has increased p_T

Calorimeter energy is independent

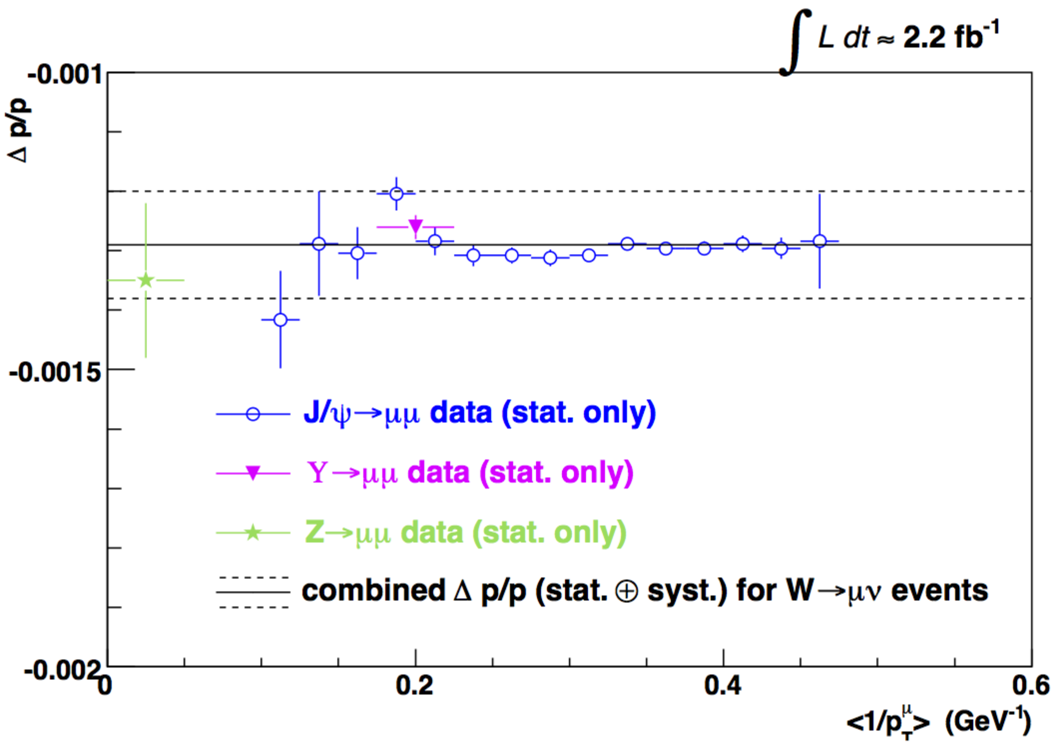


$\delta m_W^{align} = 1$ MeV

Momentum calibration

Combines high-statistics measurements of three resonance decays to muons

Wide range of momenta to test linearity, alignment, resolution



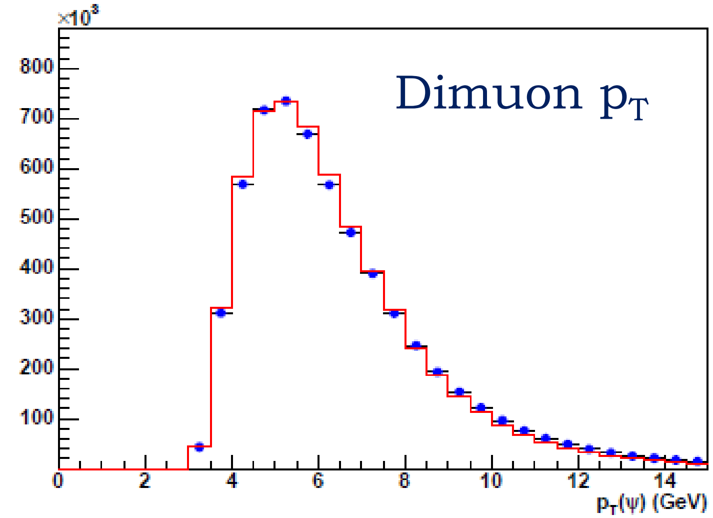
J/ψ meson measurement

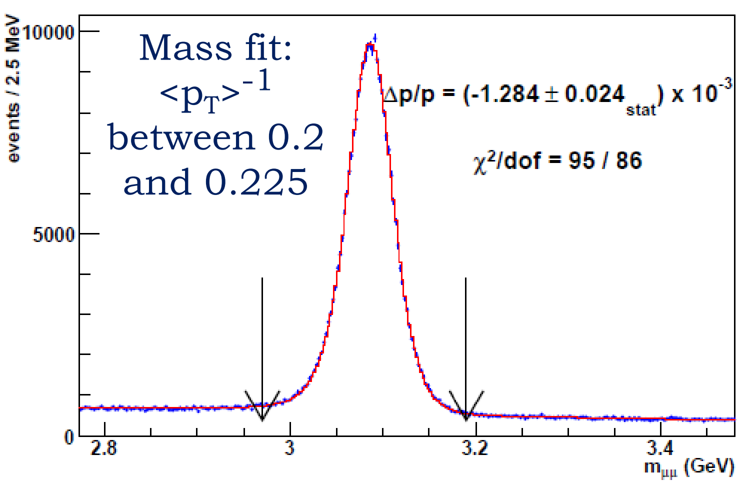
>5 million candidate J/ψ decays to muon pairs for calibration

Two muons with $p_T > 2.2$ GeV

Requires calibration of hit resolution, energy loss distribution, meson p_T, decay angle

Fits in bins of cotθ and Δcotθ provide corrections for alignment, tracker length scale, magnetic field nonuniformities



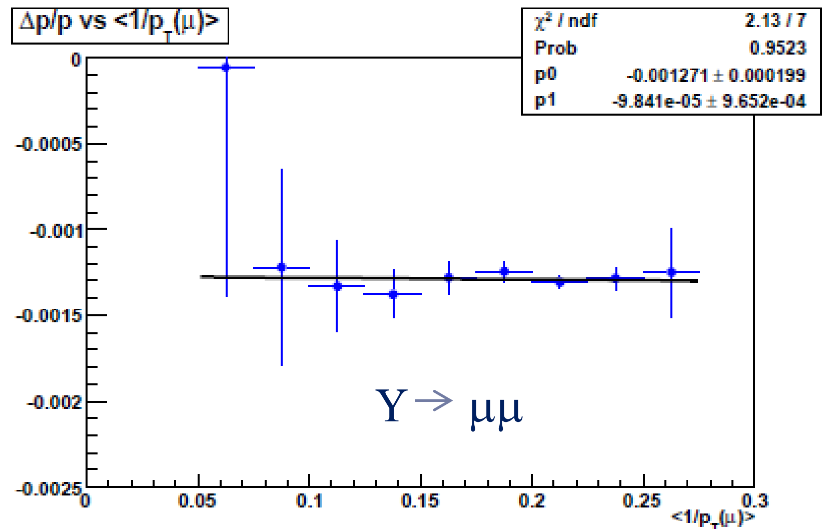


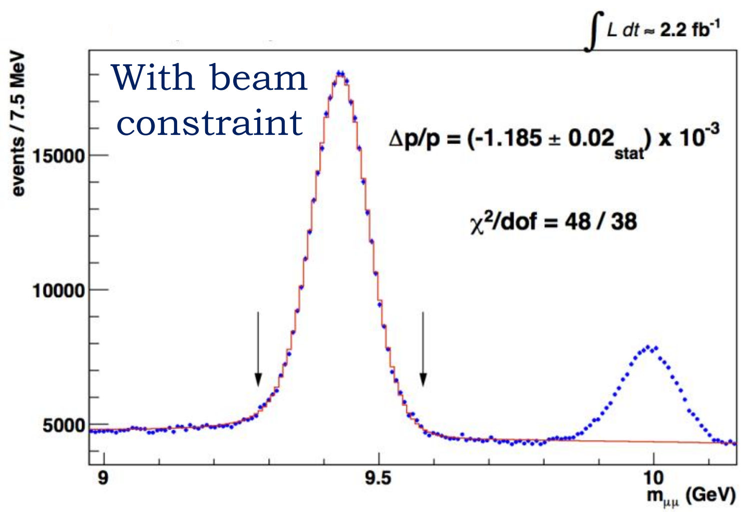
Υ meson measurement

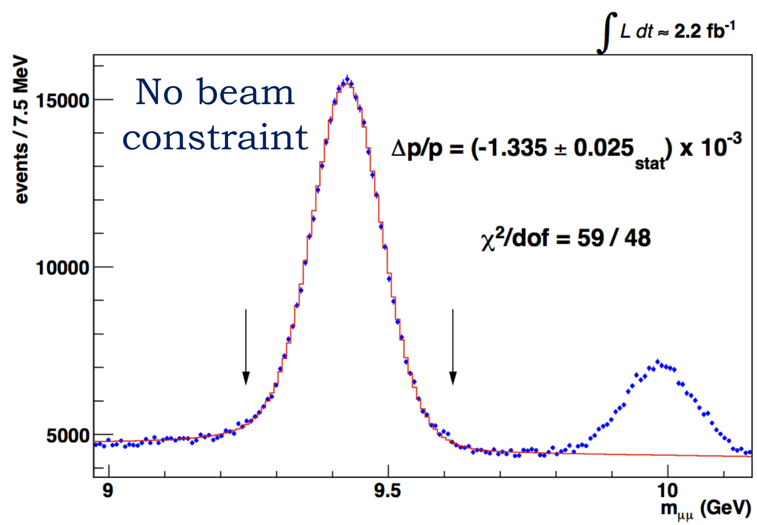
~200k candidate Υ decays to muon pairs with p_T > 3.2 GeV

Check J/ψ calibrations

Calibrate beam position resolution, compare fits with and without including beam information







Combined calibration (J/ψ and Υ)

Combination of fits without beam constraint:

$$\left(\frac{\Delta p}{p}\right)_{J/\psi + NBC\,\Upsilon} = (-1.329 \pm 0.004_{\text{stat}} \pm 0.068_{\text{syst}}) \cdot 10^{-3}$$

Source	J/ψ $(\cdot 10^{-3})$	NBC-Υ $(\cdot 10^{-3})$	common $(\cdot 10^{-3})$
QED	0.080	0.045	0.045
B field non-uniformity	0.032	0.034	0.032
Ionizing material	0.022	0.014	0.014
Resolution	0.010	0.005	0.005
Backgrounds	0.011	0.005	0.005
Misalignment	0.009	0.018	0.009
Trigger efficiency	0.004	0.005	0.004
Fitting window	0.004	0.005	0.004
$\Delta p/p$ step size	0.002	0.003	0
World-average	0.004	0.027	0
Total systematic	0.092	0.068	0.058
Statistical	0.004	0.025	0
Total	0.092	0.072	0.058

Including fit with beam constraint:

$$\left(\frac{\Delta p}{p}\right)_{final} = (-1.257 \pm 0.004_{\text{stat}} \pm 0.101_{\text{syst(total)}}) \cdot 10^{-3}$$

$\delta m_Z^{scale} = 9$ MeV

Z boson measurement

59738 $Z \rightarrow \mu\mu$ events

Test momentum calibration with a blinded fit for m_Z
Blinding offset a random number between -75 & 75 MeV

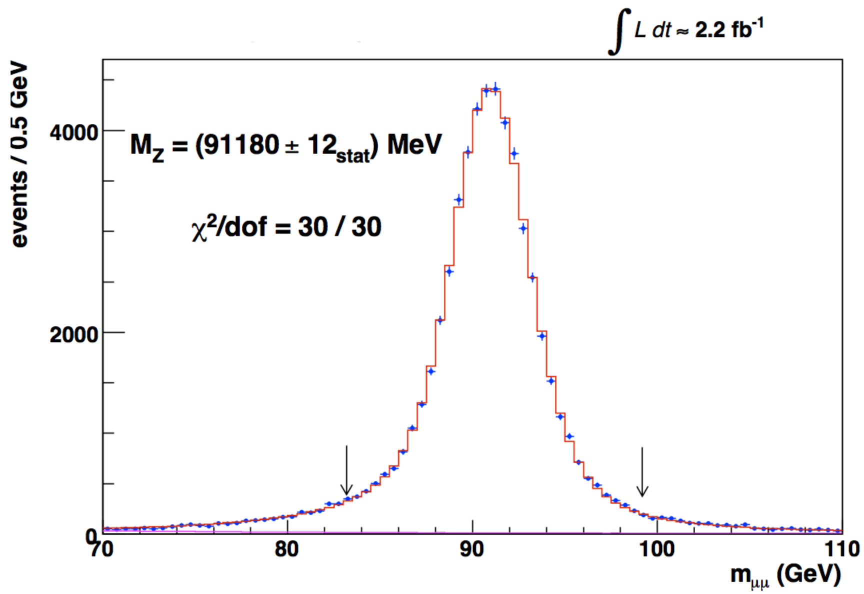
Systematic uncertainties on fit:
momentum scale (9 MeV), QED (5 MeV), alignment (2 MeV)

Z boson measurement

59738 $Z \longrightarrow \mu\mu$ events

Test momentum calibration with a blinded fit for m_Z
Blinding offset a random number between -75 & 75 MeV

Systematic uncertainties on fit:
momentum scale (9 MeV), QED (5 MeV), alignment (2 MeV)



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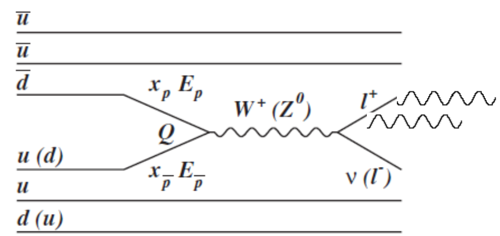
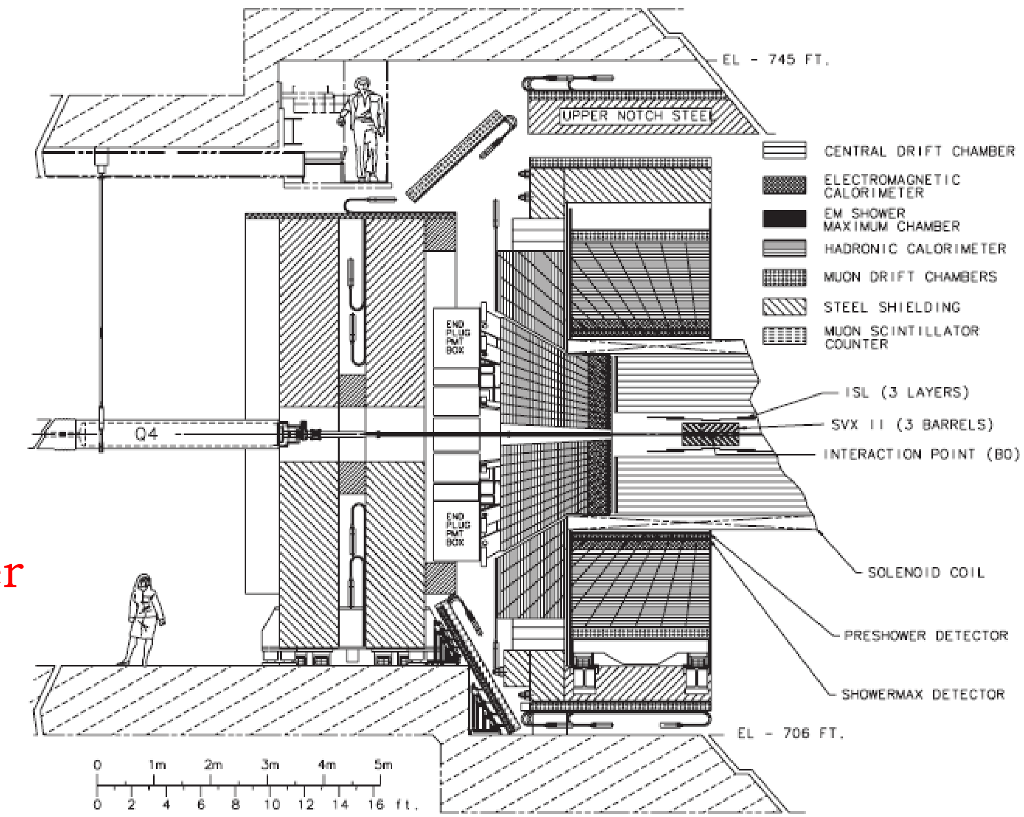


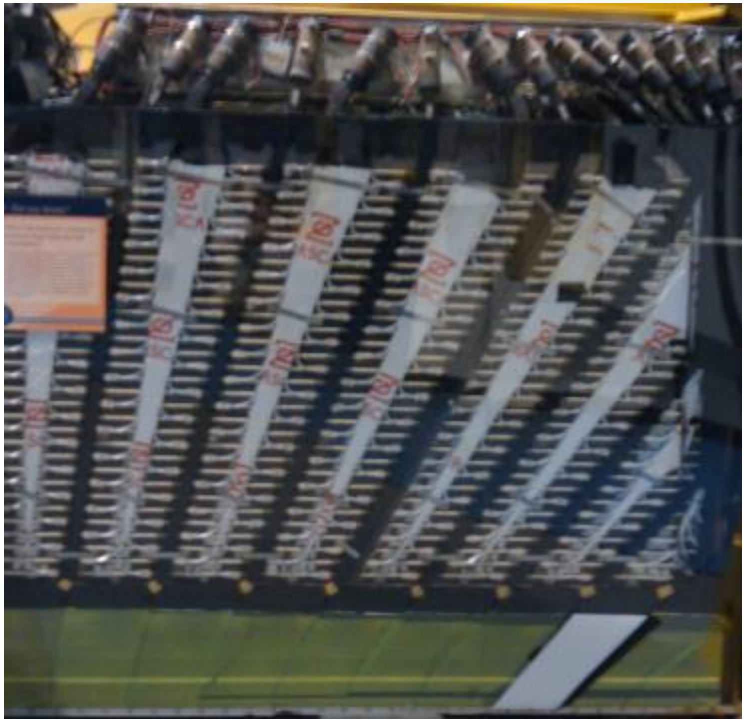


Calorimeter shower model

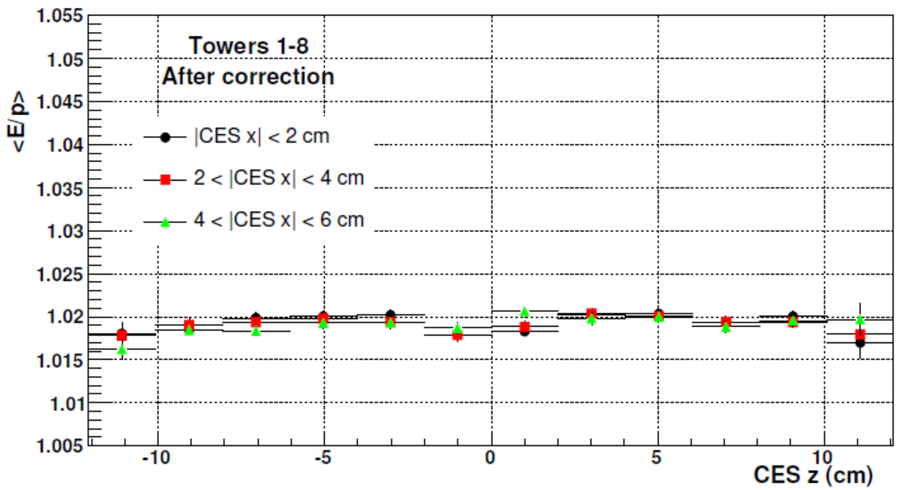
Custom GEANT simulation of calorimeter used to parameterize response and sampling resolution as functions of electron and photon energy

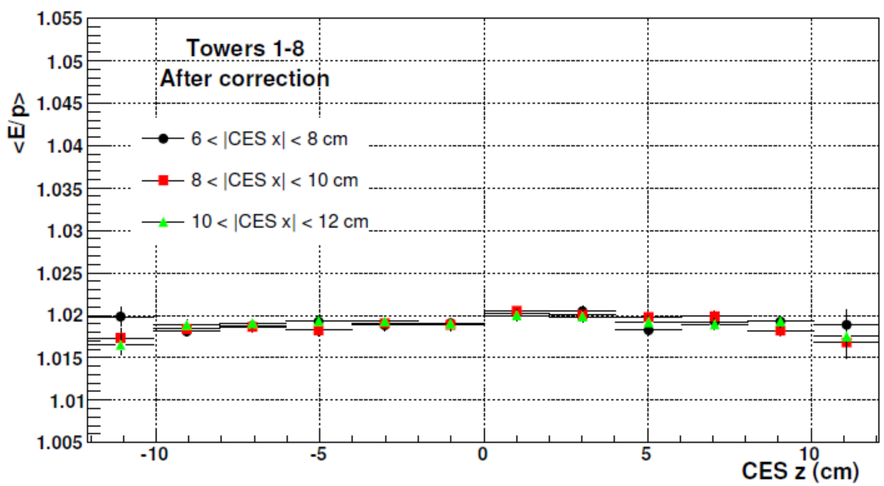
Test response model using electrons with $E/p < 1$ (region sensitive to shower leakage)

0-3% correction to calorimeter + solenoid material as a function of tower in $|\eta|$



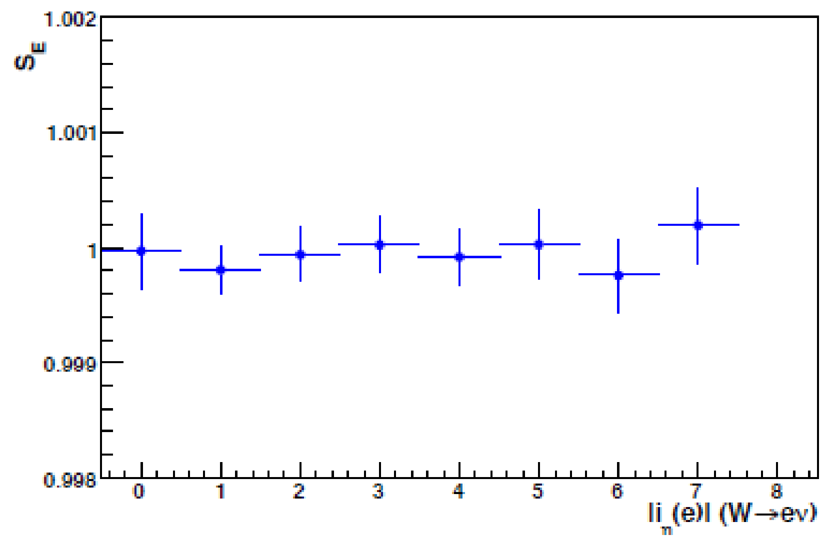
Calorimeter uniformity calibrations





Use <E/p> from W electrons to improve response uniformity

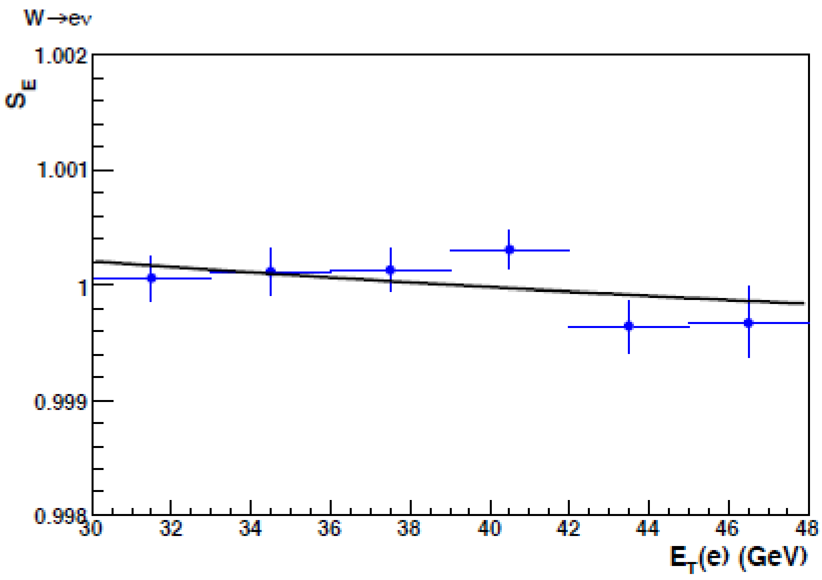
Check uniforimities in fast simulation response model

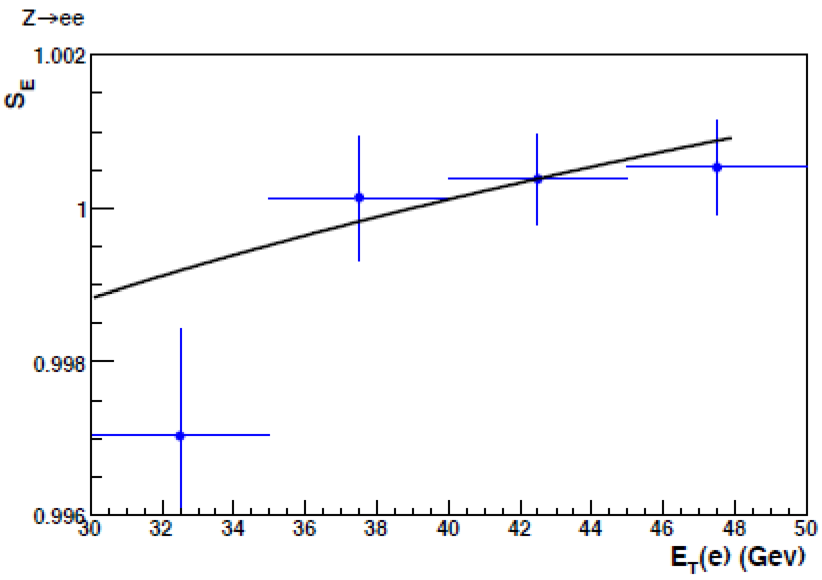


Calorimeter non-linearity

Fit E/p distribution in bins of E_T for W & Z electrons

Logarithmic response model for electrons and photons in simulation

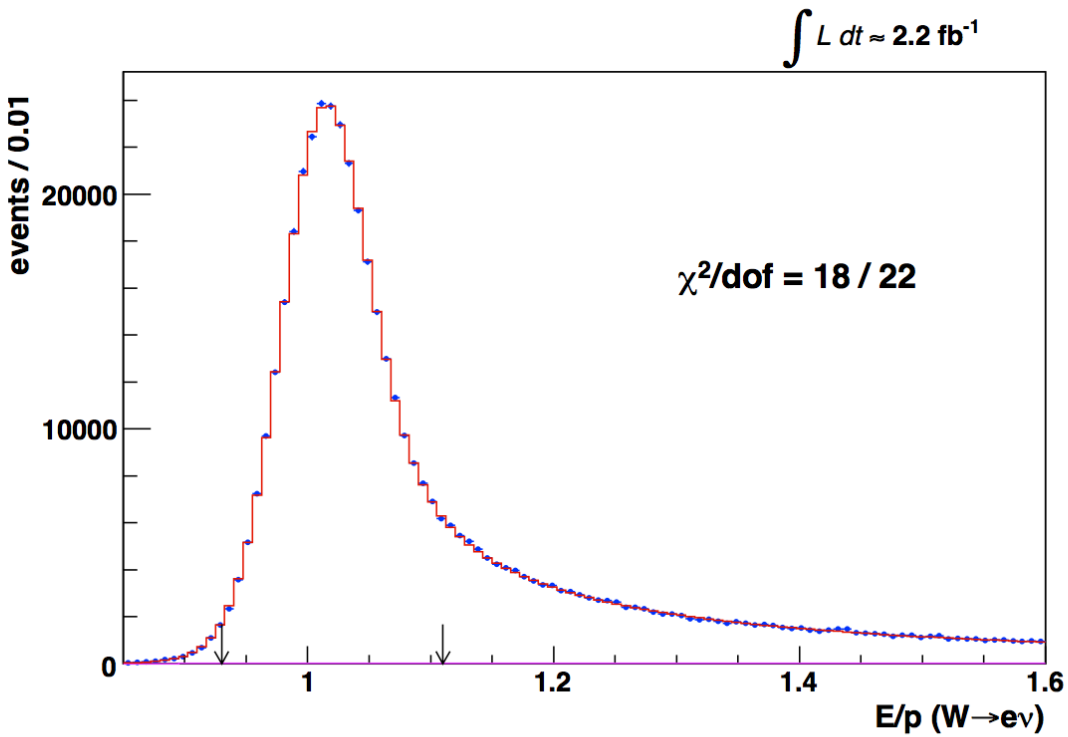




Calorimeter energy calibration

Fit to inclusive E/p distribution calibrates calorimeter energy scale

Width of peak sets constant resolution term



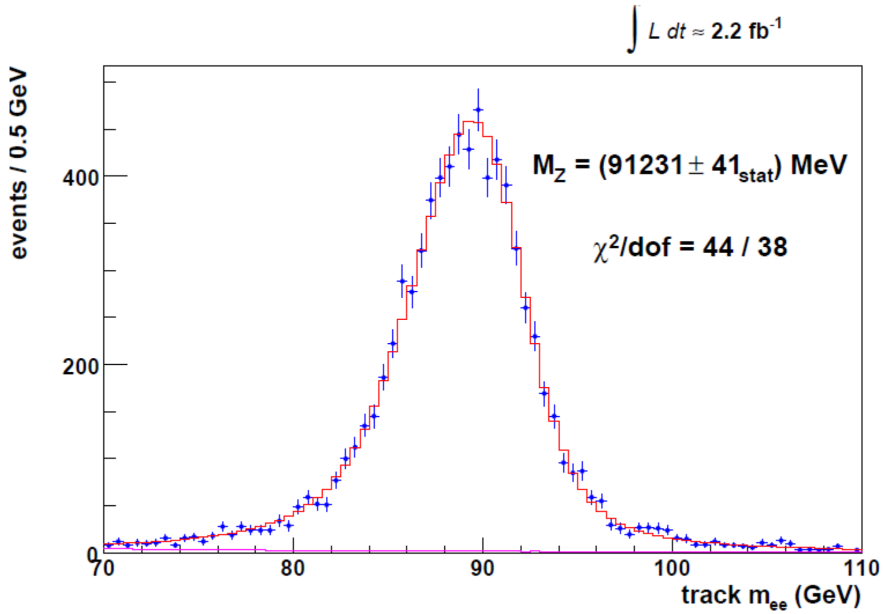
$\delta m_Z^{E/p}$ = 10 MeV

Z boson measurement

16134 $Z \rightarrow ee$ events

Verify tracker energy loss modelling with a track-only fit to the Z mass

Low E/p (<1.11) most statistically sensitive
Tests modelling of soft radiation in calibration peak

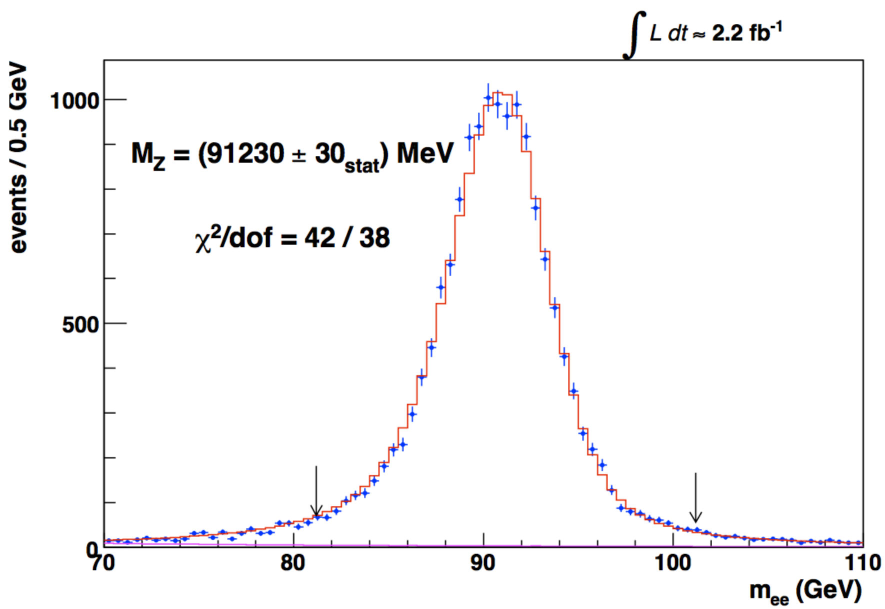


Z boson measurement

16134 $Z \longrightarrow ee$ events

Test energy calibration with a blinded fit for m_Z
Same blinding offset used in all m_Z fits

Systematic uncertainties on fit:
E/p (10 MeV), p scale (8 MeV), QED (5 MeV), alignment (2 MeV)



New CDF m_W measurement (2.2 fb^{-1})

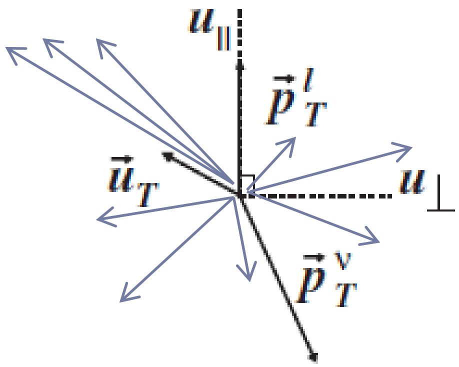
Charged lepton model and calibration

Recoil model and calibration

W boson sample and mass fits

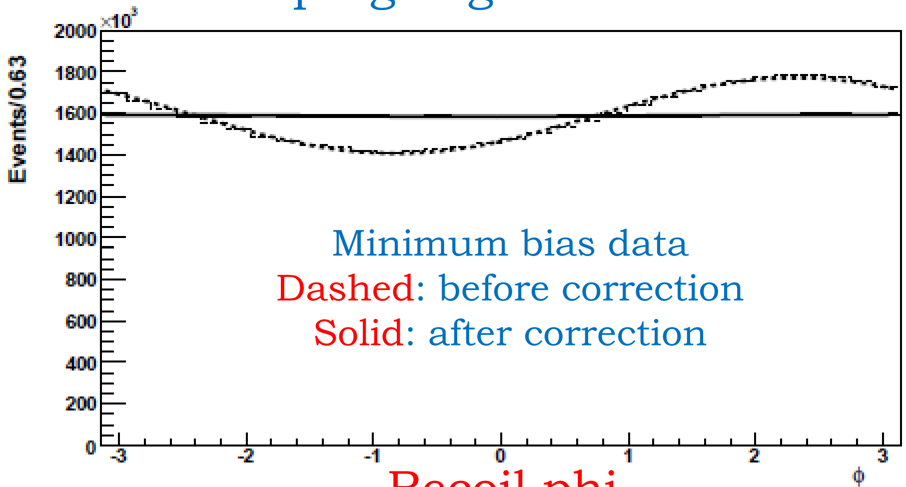
Recoil reconstruction

Sum over momentum calculated from each calorimeter tower and the primary vertex



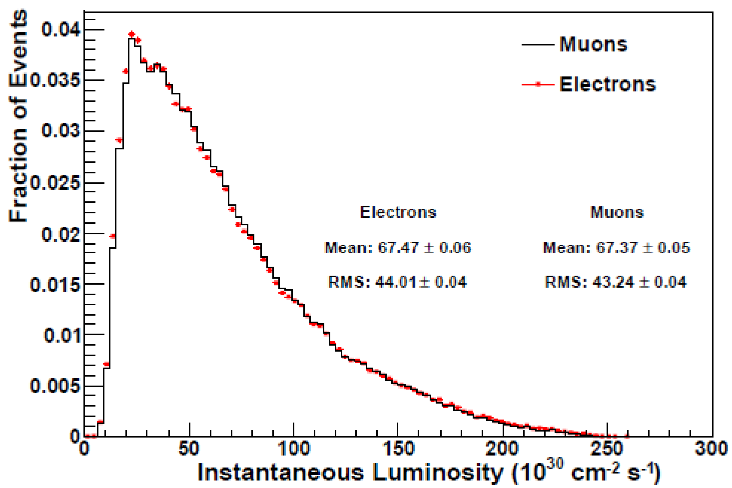
Steel-scintillator calorimeter: ~uniform hadronic response

Improve uniformity with relative central-plug alignment correction



Recoil phi

~2 additional interactions (396 ns bunch spacing)

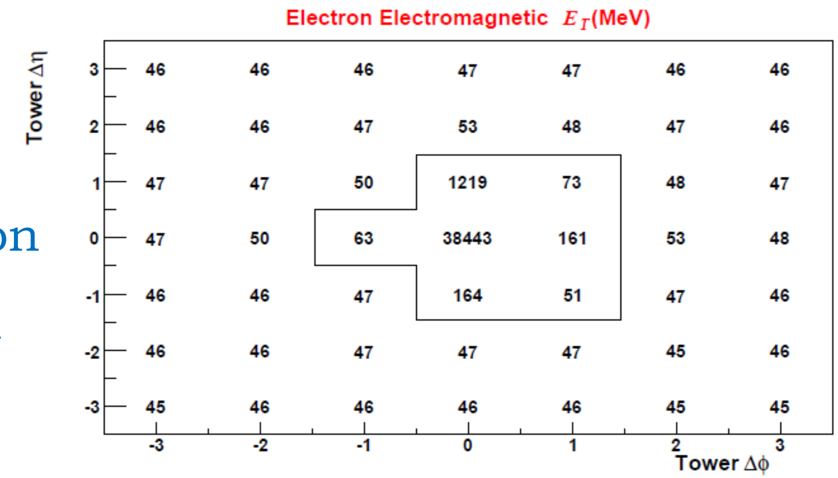


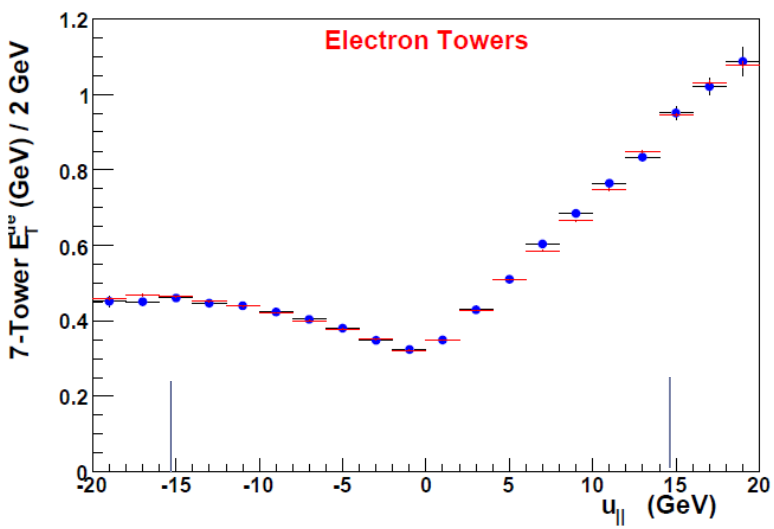
Recoil reconstruction

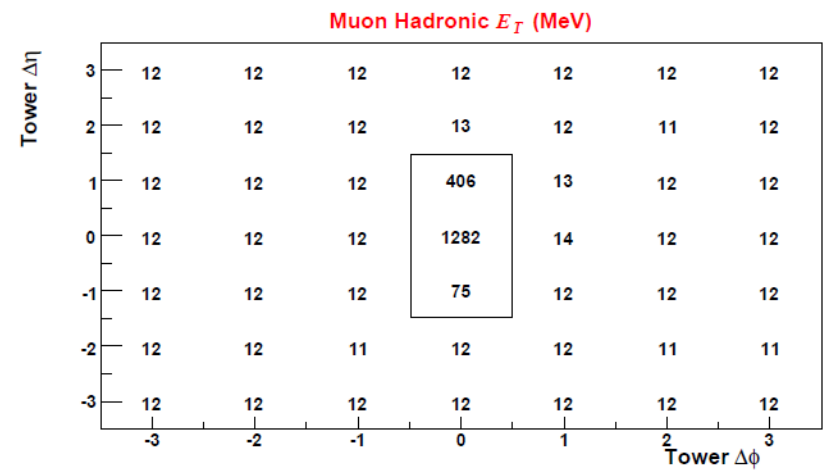
Remove calorimeter towers with energy depositions from W decay lepton

Model removed recoil energy in simulation

Measure energy in rotated window in W events & include η, $u_{||}$, $u_{\perp}$ dependence







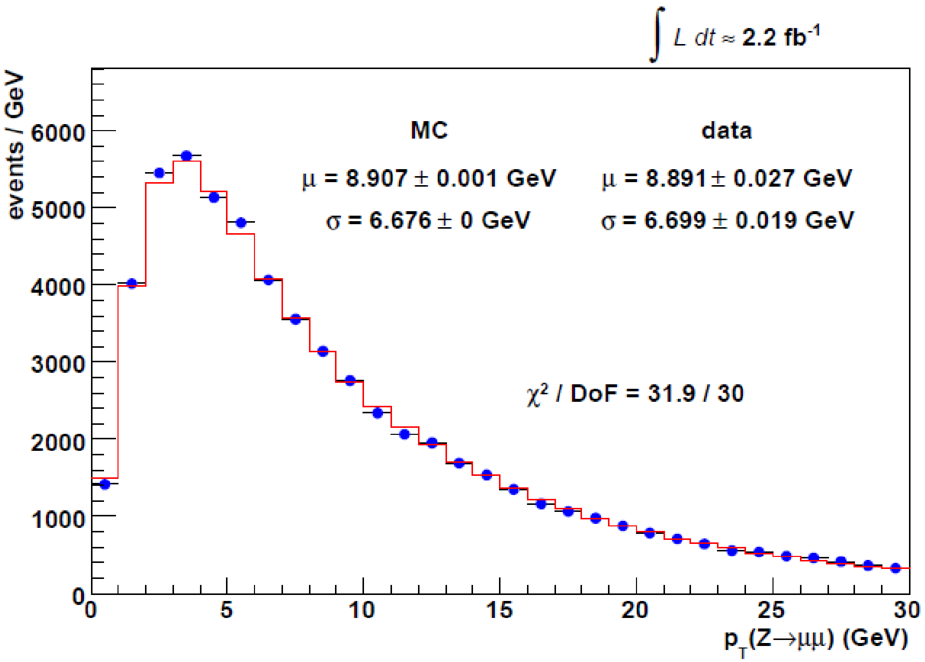
Recoil model

Fully parametrize detector response to boson p_T by tuning to Z boson data

Two main components:
response to the "jet" (-boson p_T)
response to the underlying event + additional interactions

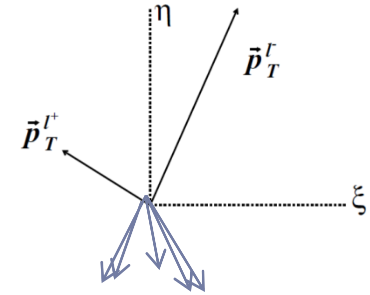
"jet" model includes energy response & resolution, angle resolution

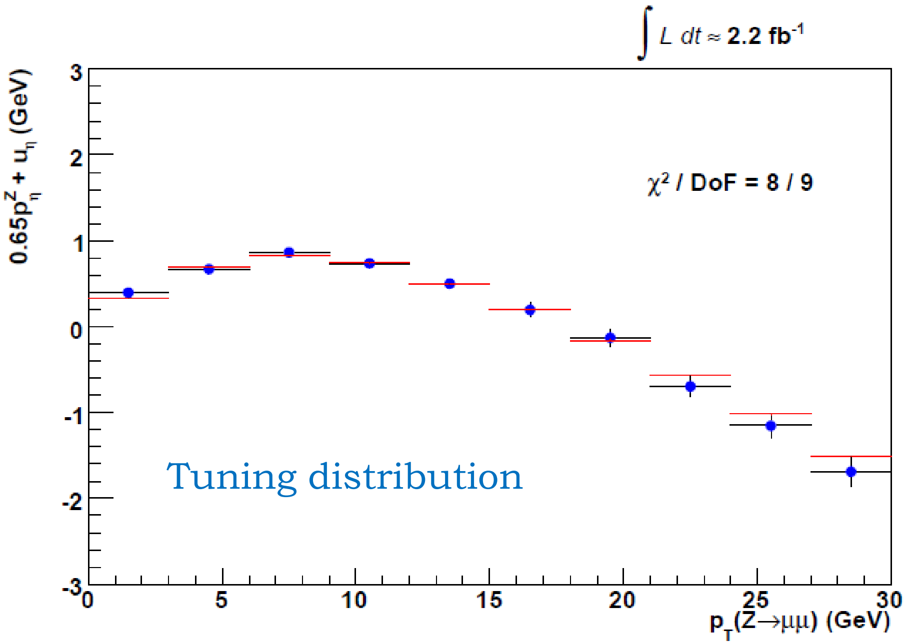
Boson p_T model:
RESBOS with one non-perturbative and one perturbative parameter tuned using the Z boson p_T



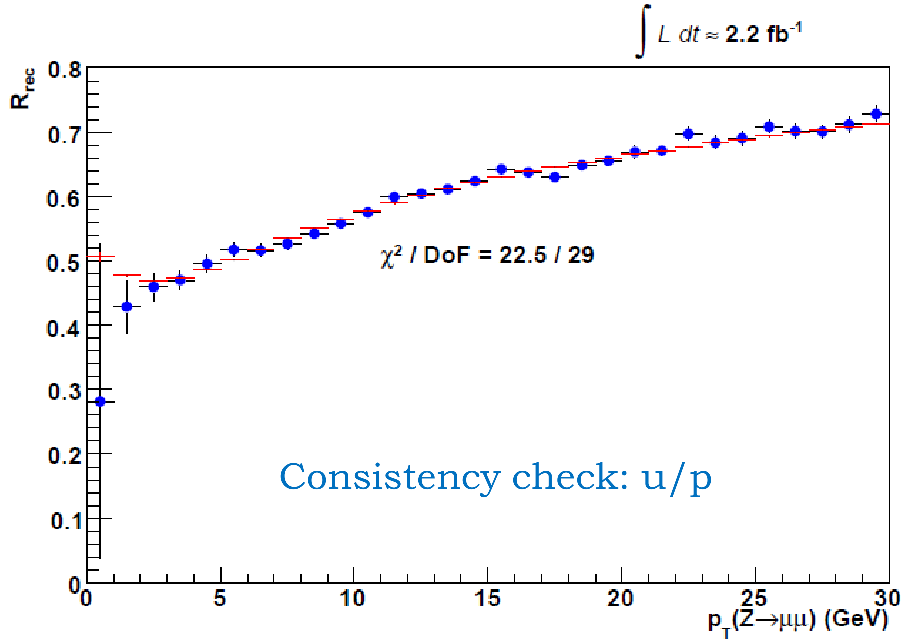
Recoil response

Tune jet response using the balance of boson p_T and recoil, projected along direction of boson p_T





Tuning distribution

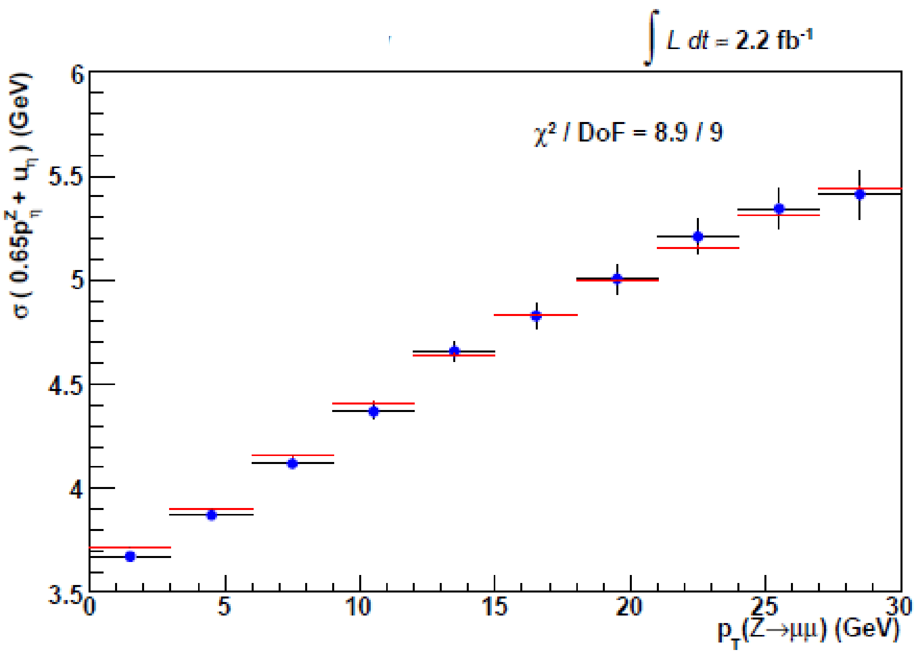


Consistency check: u/p

Recoil resolution

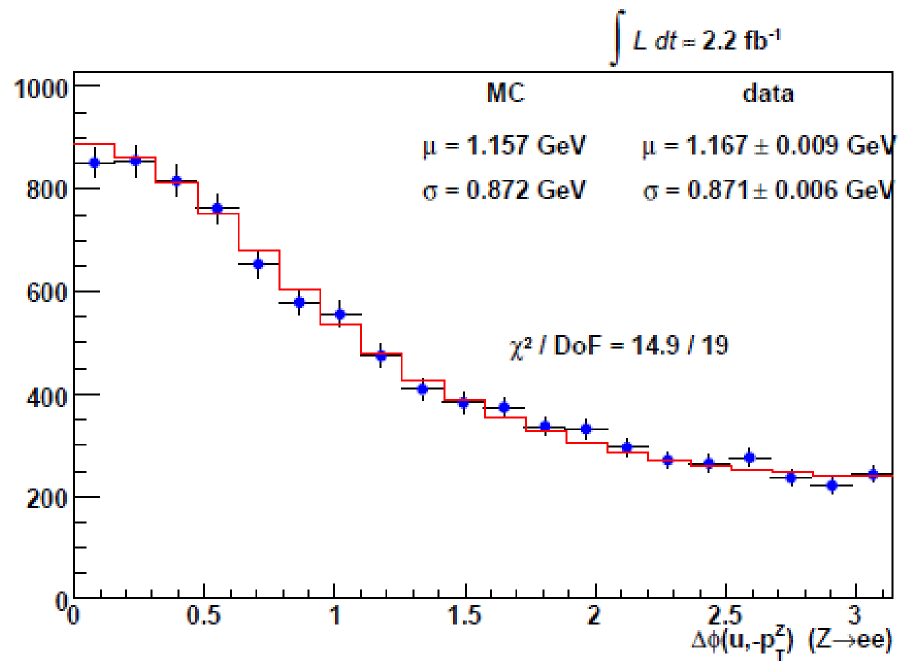
Energy resolution parameterized with a sampling term

Tuned using RMS of recoil-boson p_T balance



Angular resolution modelled as a function of boson p_T

Tuned using angle between recoil and boson p_T

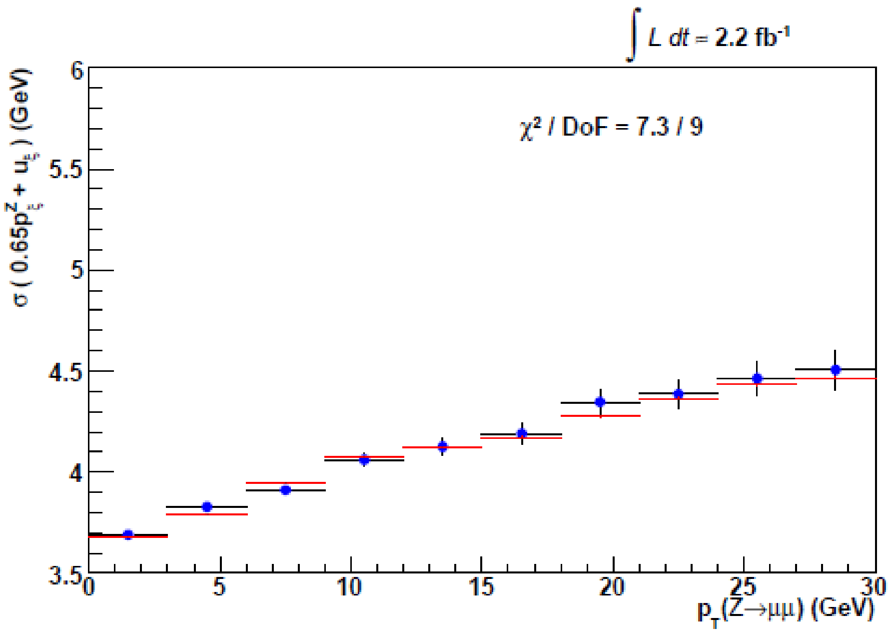


Underlying event & additional interactions

Parametrize sum of calorimeter E_T using zero- & minimum-bias data

Underlying event: Convolute a single interaction distribution to match the measured minimum bias ΣE_T

Additional interactions: Add energy drawn from zero bias ΣE_T

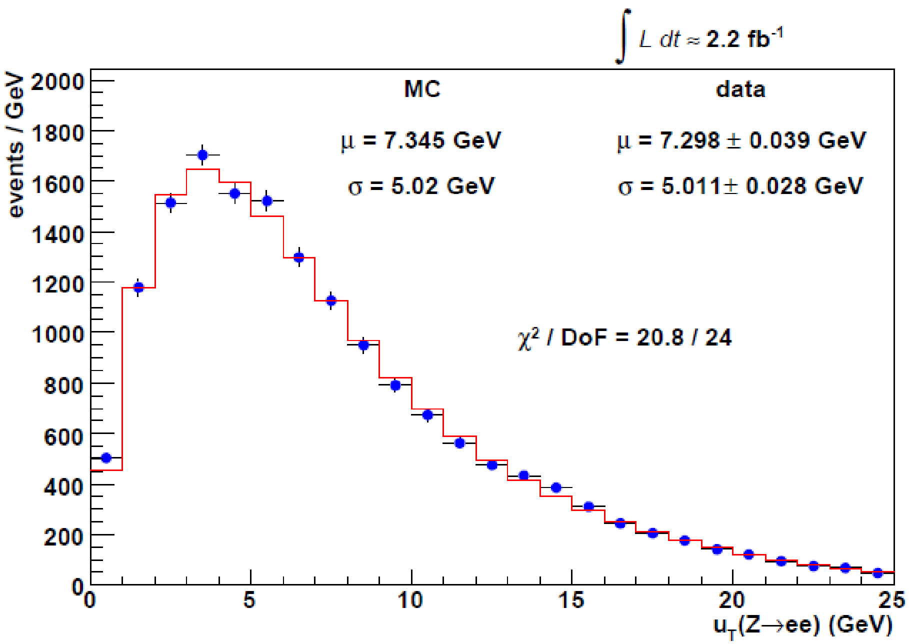


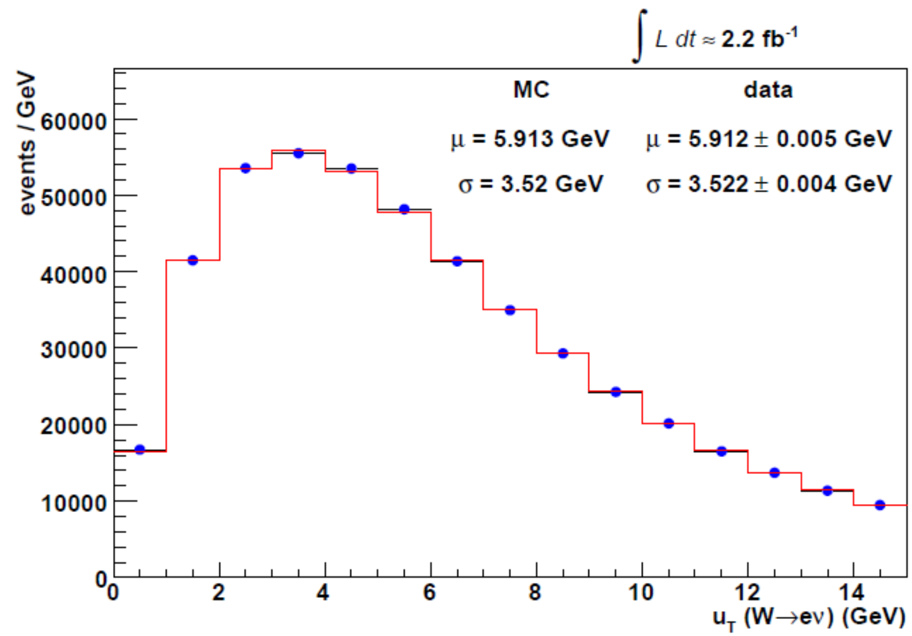
Resolution as a function of ΣE_T extracted from minimum bias data

One parameter (underlying event scale) tuned using recoil balance RMS

Recoil measurements

Distributions of recoil test model in W & Z events





Z p_T and recoil distributions used for tuning

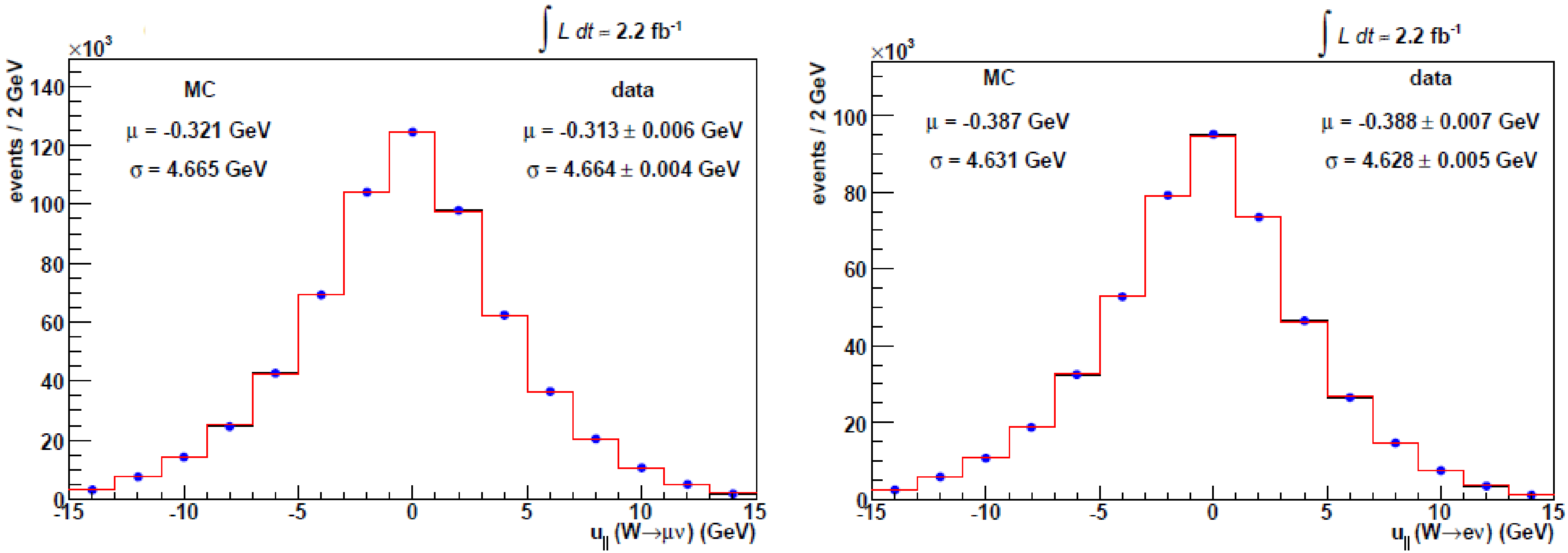
No W distributions used in tune

Recoil measurements

$u_{||}$ a key test of the model

Since u << lepton p_T, m_T can be approximated as

$$m_T \approx 2p_T\sqrt{1 + u_{||}/p_T} \approx 2p_T + u_{||}$$



New CDF m_W measurement (2.2 fb^{-1})

Charged lepton model and calibration

Recoil model and calibration

W boson sample and mass fits

W boson sample

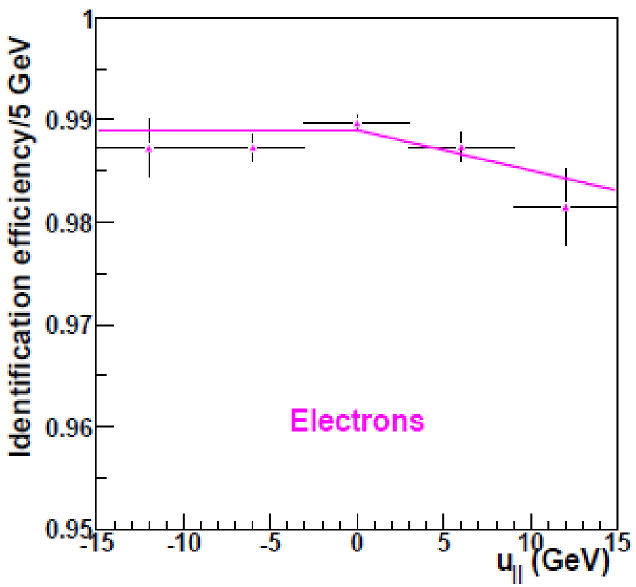
Kinematic selection aims to maximize mass information & minimize background

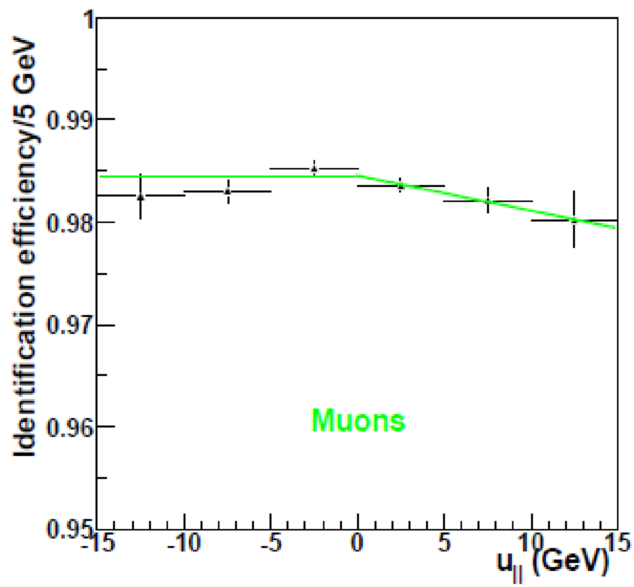
$30 < [p_T(l^{\pm})\ \&\ p_T(\nu)] < 55$ GeV

$60 < m_T < 100$ GeV

$u_T < 15$ GeV

470126 $W \rightarrow e\nu$ events
624708 $W \rightarrow \mu\nu$ events





Loose lepton identification to minimize bias

Inefficiency contributes negligible uncertainty on m_W

W boson sample background

Electroweak backgrounds ($W \to \tau\nu$ & $Z \to ll$):
Model with standard CDF simulation with tunes to improve recoil, muon & electron response

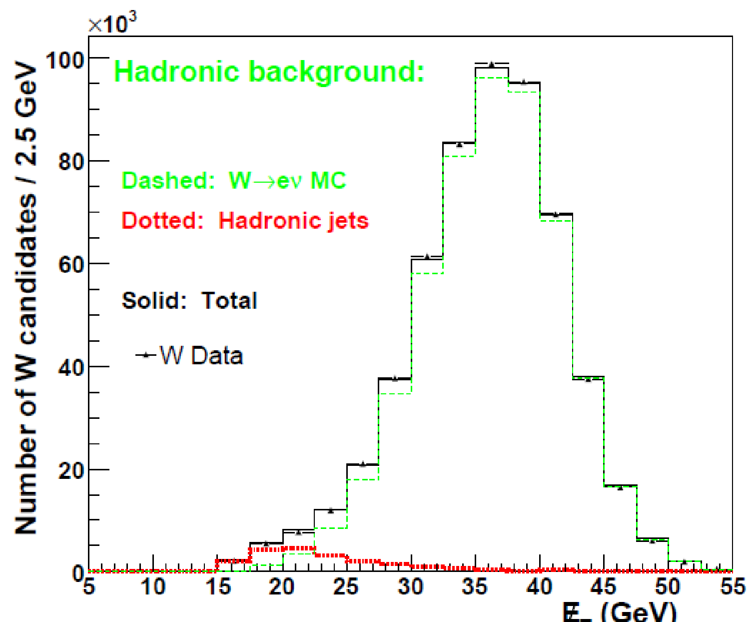
QCD backgrounds (jets and π/K meson DIF):
Measure using control regions in data

Background	% of $W \to \mu\nu$ data
$Z \to \mu\mu$	7.35 ± 0.09
$W \to \tau\nu$	0.880 ± 0.004
QCD	0.035 ± 0.025
DIF	0.24 ± 0.08
Cosmic rays	0.02 ± 0.02
Total	

Background	% of $W \to e\nu$ data
$Z \to ee$	0.139 ± 0.014
$W \to \tau\nu$	0.93 ± 0.01
QCD	0.39 ± 0.14
Total	

$\delta m_W^{Bd}(\mu) =$ 3 MeV

$\delta m_W^{Bd}(e) =$ 4 MeV

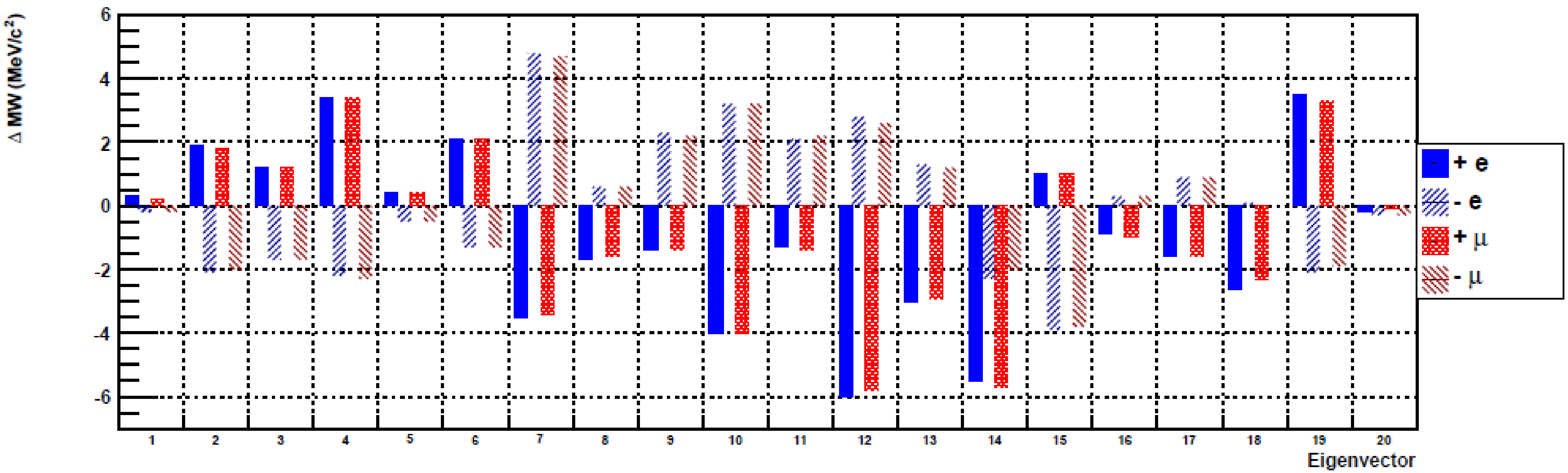


 Chris Hays, Oxford University 27 March 2012

Parton distribution functions

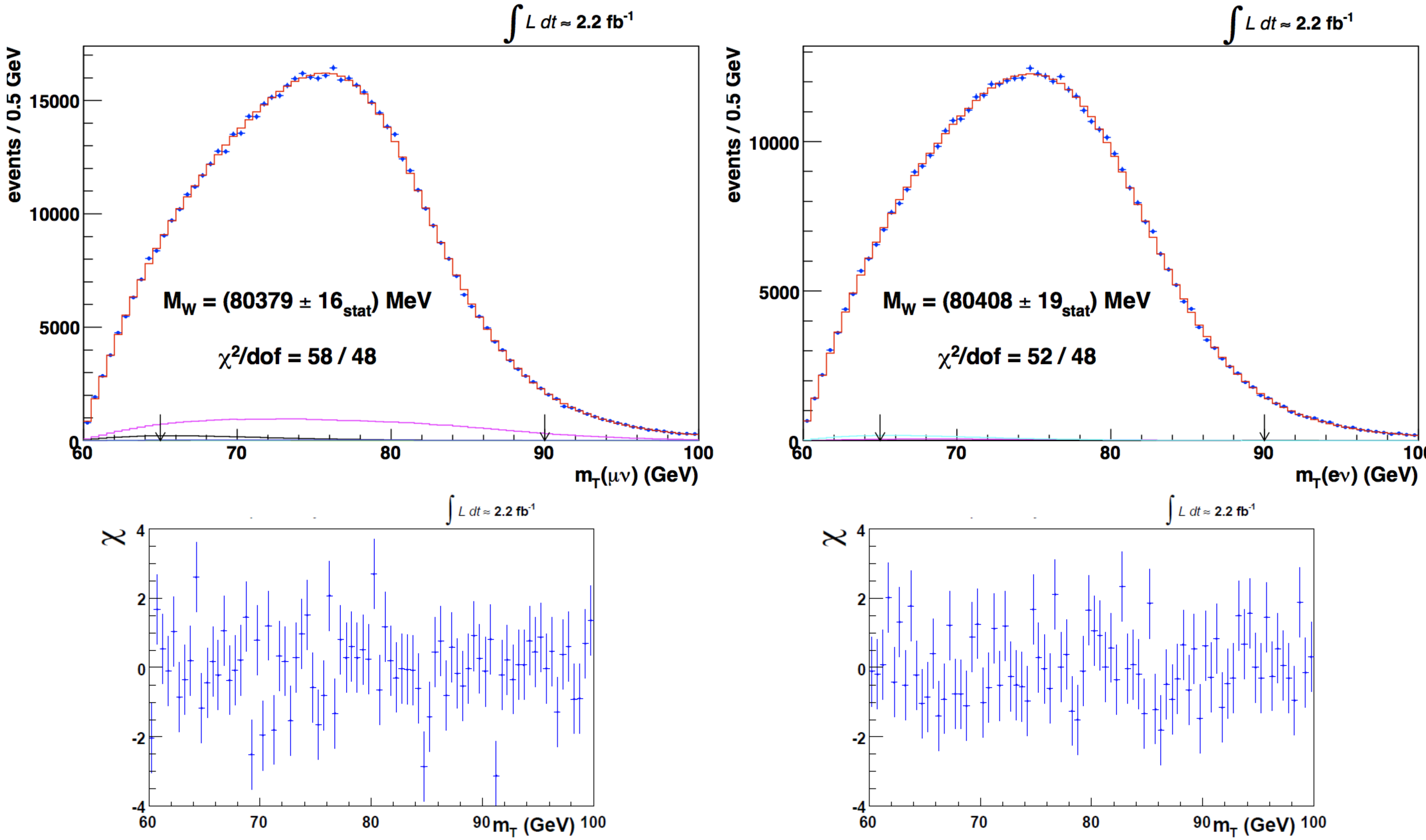
Transverse mass distribution sensitive to p_z^W modelling

Consistent results for central value and uncertainty using CTEQ6.6 and MSTW2008 (NLO & NNLO)

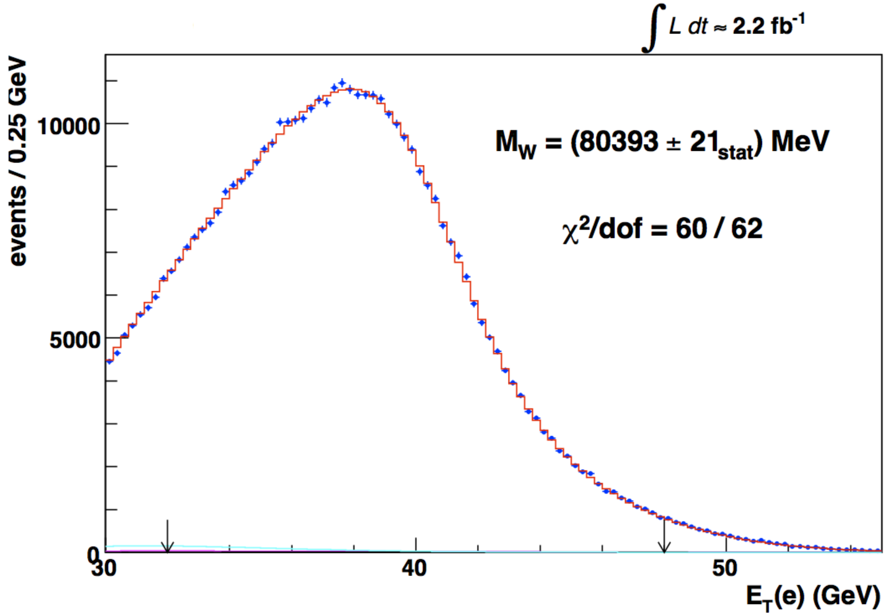


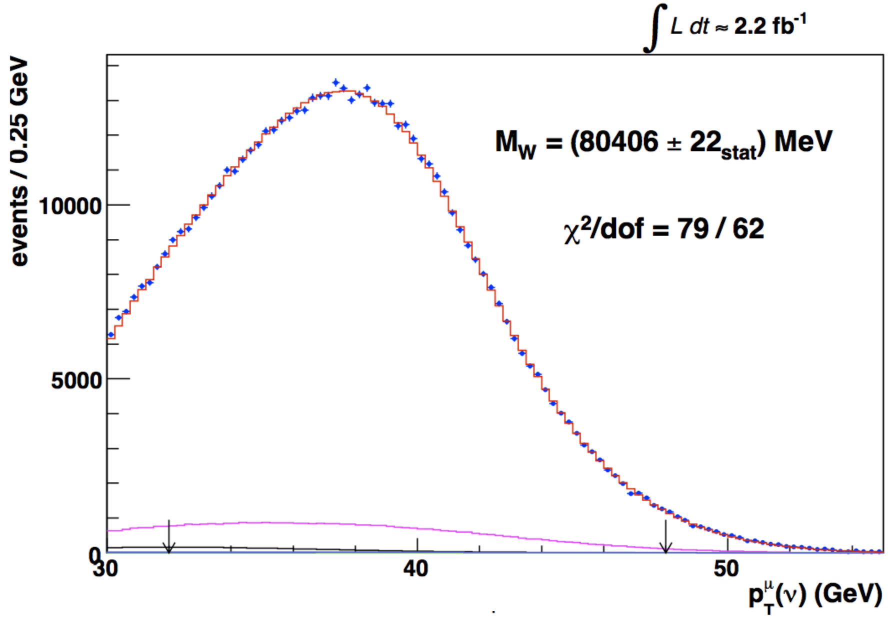
δm_W^{PDF} = 10 MeV

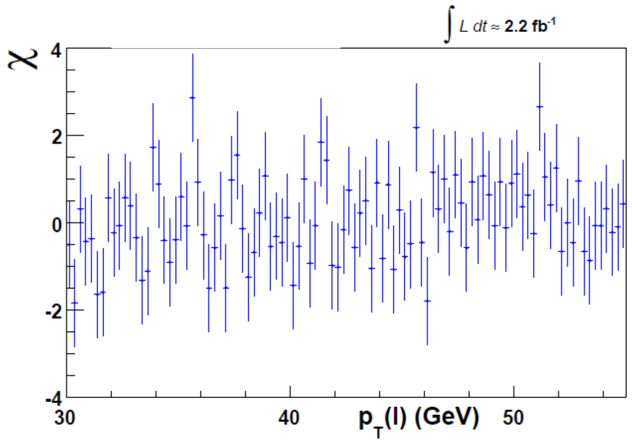
W boson mass fits

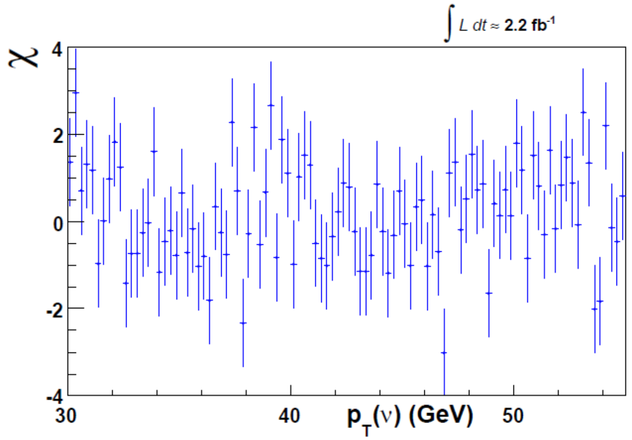


W boson mass fits







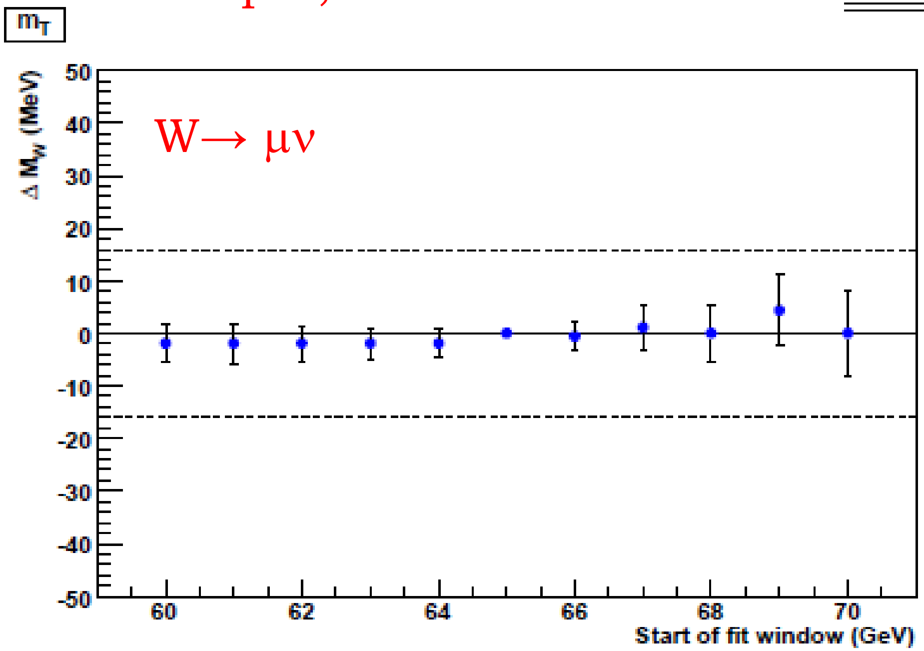


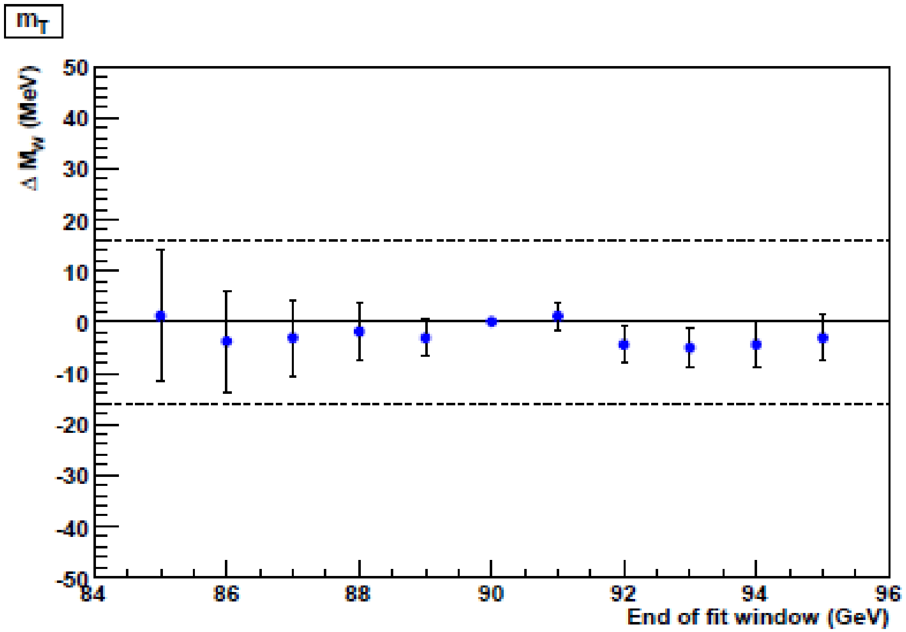
Stability

Good consistency between fits

No significant variation with charge, phi, or fit window

Distribution	W-boson mass (MeV)	χ^2/dof
$m_T(e,\nu)$	$80\ 408 \pm 19_{stat} \pm 18_{syst}$	52/48
$p_T^\ell(e)$	$80\ 393 \pm 21_{stat} \pm 19_{syst}$	60/62
$p_T^\nu(e)$	$80\ 431 \pm 25_{stat} \pm 22_{syst}$	71/62
$m_T(\mu,\nu)$	$80\ 379 \pm 16_{stat} \pm 16_{syst}$	58/48
$p_T^\ell(\mu)$	$80\ 348 \pm 18_{stat} \pm 18_{syst}$	54/62
$p_T^\nu(\mu)$	$80\ 406 \pm 22_{stat} \pm 20_{syst}$	79/62





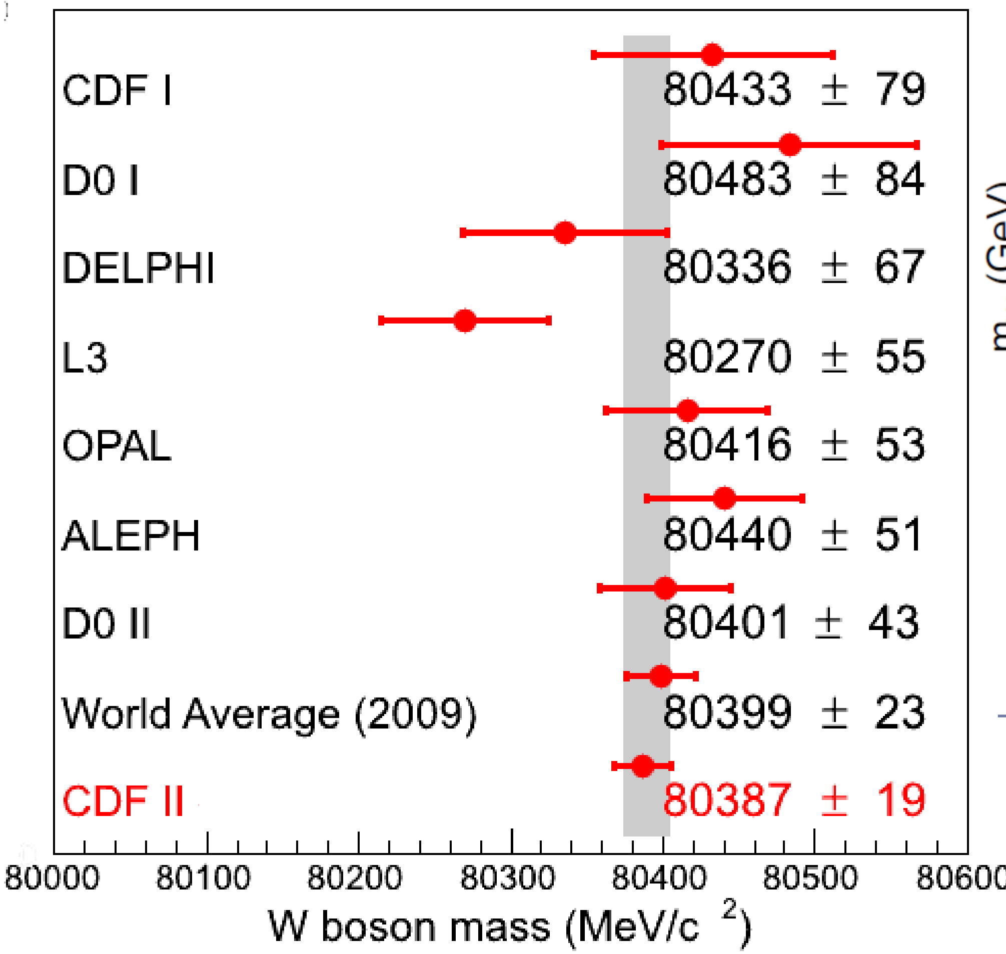
Combination

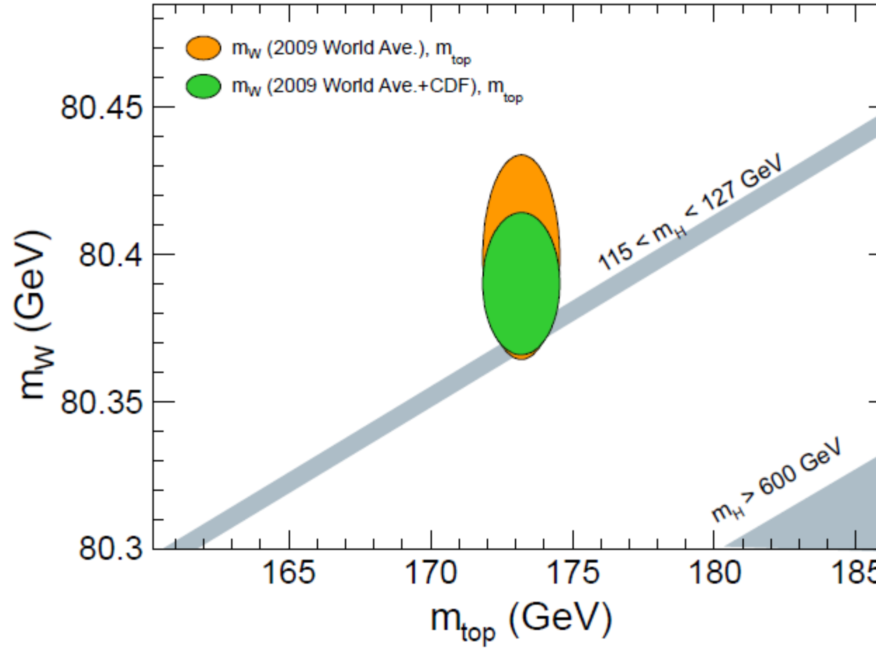
Combination of 6 fits
(χ^2 probability: 25%)

$$M_W = 80\ 387 \pm 12_{\rm stat} \pm 15_{\rm syst} = 80\ 387 \pm 19\ \text{MeV}$$

Source	Uncertainty (MeV)
Lepton energy scale and resolution	7
Recoil energy scale and resolution	6
Lepton removal	2
Backgrounds	3
$p_T(W)$ model	5
Parton distributions	10
QED radiation	4
W-boson statistics	12
Total	19

Comparison to previous results

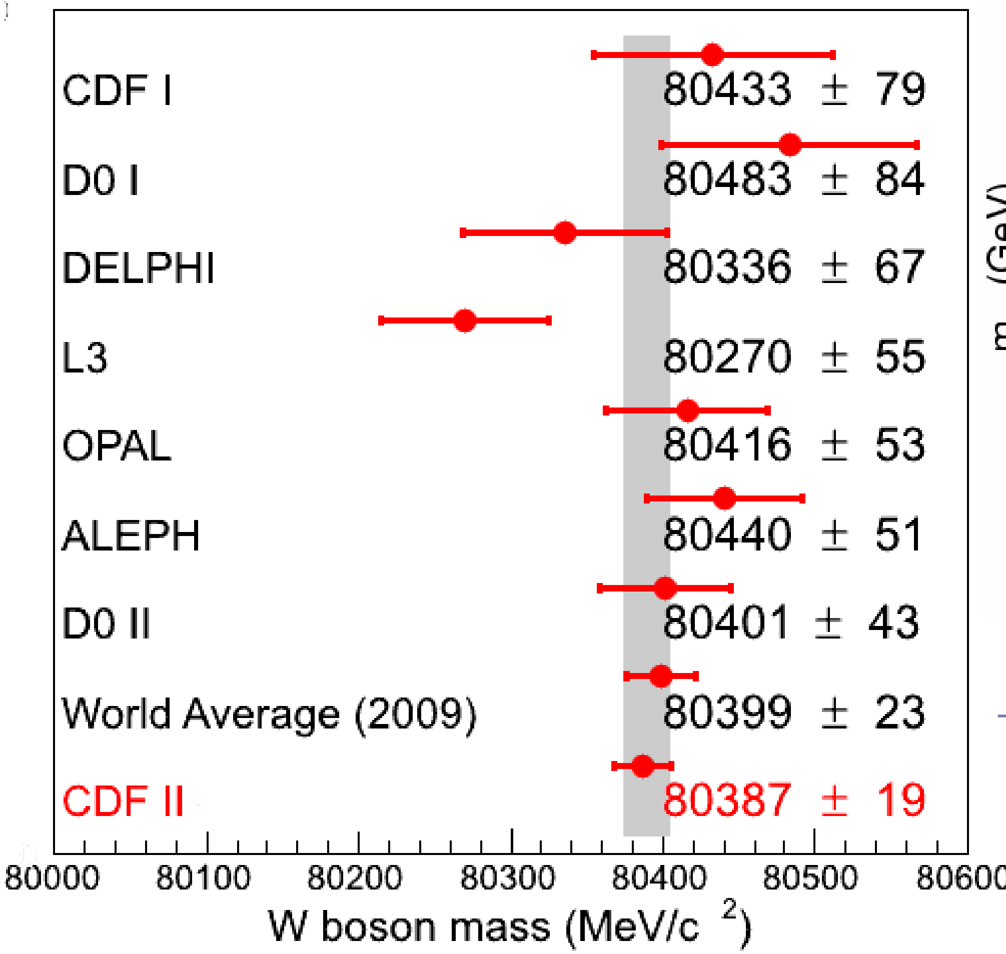


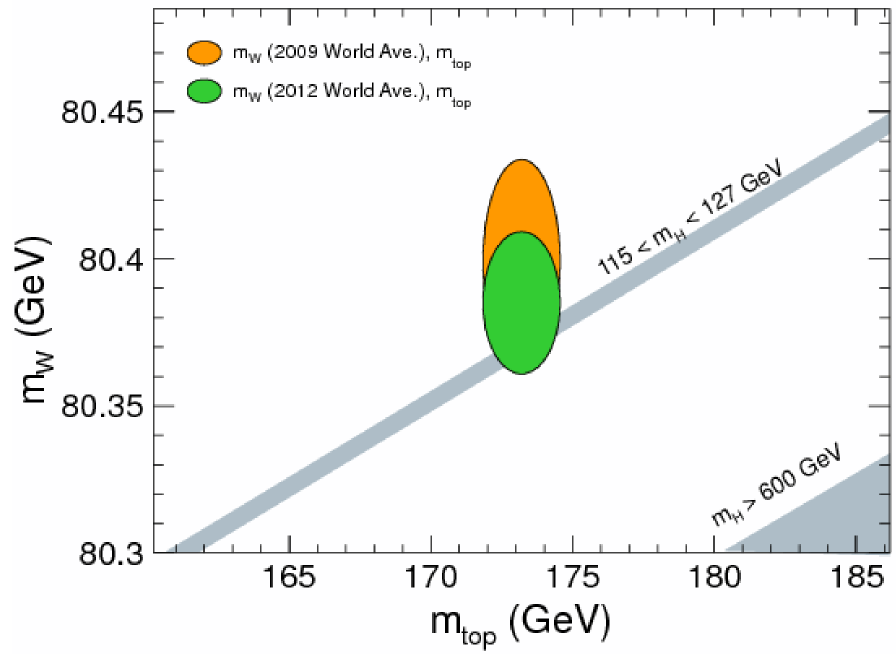


+ CDF →

$$M_W = 80\ 390 \pm 16\ \text{MeV}$$

Latest results





+ CDF →

$$M_W = 80\,390 \pm 16 \text{ MeV}$$

↓ + D0

$$M_W = 80\,387 \pm 15 \text{ MeV}$$

Summary

New CDF measurement of the W boson mass is more precise than the previous world average

Improves world precision on m_W from 23 to 16 MeV (now at 15 MeV)

Result accepted by PRL (arXiv:1203.0275)

Potential for further improvement with remaining data set