The Precision Measurement of the W Mass using the DØ Detector

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- Particle Physics
- The ElectroWeak Standard Model (SM)
- Motivation
- The DØ Experiment at Fermilab
- Measurement of the W mass
- Comparisons to other Measurements and SM
- Future Prospects

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Particle (High Energy) Physics

$\Rightarrow$ **Study of fundamental particles in universe and the forces and interactions between them**

molecules $\rightarrow$ **atoms** $\rightarrow p, n, e^- \rightarrow$ **quarks, leptons** $\rightarrow$ **?**

Fundamental Particles

leptons	quarks
e	u
ν_e	d
μ	c
ν_μ	s
τ	t
ν_τ	b

Interactions

Force	Mediator Particles
weak	$W^\pm, Z$
electromagnetic	γ
strong	g
gravity	(graviton?)

$\star$ **Also have Higgs particle which gives mass to the fundamental particles**

The Standard Model

⇒ **ElectroWeak:**

- ⋆ **unified theory describing the electromagentic and weak interactions**
- ⋆ **mediated by $\gamma, W^{\pm}, Z^{\circ}$**

⇒ **Quantum ChromoDynamics (QCD):**

- ⋆ **theory describing strong interaction between colored objects (quarks and gluons)**

Experiments in High Energy Physics

$\longrightarrow$ Aim for higher energy interactions
+ better precision measurements

⋆ test Standard Model predictions

⋆ Search for results not predicted by Standard Model $\longrightarrow$ Is the SM the final answer?

ElectroWeak Standard Model

- Glashow, Weinberg, Salam (1967-1968)
  - SU(2)× U(1) model of electroweak interactions
  - electromagnetic and weak forces unified

- massless interacting vector particles: W^1, W^2, W°, B
  (Yang-Mills)
  W°, B mix to produce γ, Z° with mixing angle θ_W
  W^1, W^2 mix to produce $W^\pm$

- gauge symmetry of electroweak model implies:
  W, Z and fermions have $mass = 0$

→ break the electroweak symmetry by introducing Higgs boson:
  Higgs' mechanism gives mass to $W^\pm, Z$ and fermions

  - interactions mediated by $\gamma, W^\pm, Z$

- charged currents (interactions mediated by $W^\pm$)
- neutral currents (mediated by γ, Z°)

Verification of ElectroWeak theory

⋆ existence of neutral weak currents (1973 - CERN)

⋆ ratio of neutral-current to charged-current events (1973 - CERN)

⋆ interference between electromagentic and neutral weak currents (1978 - SLAC) - parity violation in what seemed to be purely QED interaction

⋆ discovery and properties of W, Z (1983 - UA1,UA2 at CERN)

Current Status of Standard Model

$\Longrightarrow$ SM has survived all experimental tests so far!

⋆ TOP quark recently (1995) discovered at Fermilab

DØ and CDF current results
(from DPF in August 96):

$$\text{DØ} \rightarrow M_T = 169 \pm 11 \text{ GeV}$$
$$\text{CDF} \rightarrow M_T = 176.8 \pm 6.5 \text{ GeV}$$
$$\text{Combined} \rightarrow M_T = 175 \pm 6 \text{ GeV}$$

! announced last week - (Feb. 21):

$$\text{DØ} \rightarrow M_T = 173.3 \pm 8.4 \text{ GeV}$$

⋆ Higgs (H) is only undiscovered SM particle

$\rightarrow$ Future: look for Higgs & physics outside SM

ElectroWeak Standard Model

Specified by 3 parameters:

- $\alpha = (137.03599 \pm .09)^{-1}$ $(\delta\alpha/\alpha = 0.045\ ppm)$
  but $\alpha(M_Z^2) \approx 1/128$ known to $(\delta\alpha/\alpha \approx 700\ ppm)$

- $G_F = (1.16639 \pm .00002) \times 10^{-5}\mathrm{GeV}^{-2}$
  $(\delta G_F/G_F = 17\ ppm)$

- $M_Z = 91.1863 \pm .0020\mathrm{GeV}$ $(\delta M_Z/M_Z = 22\ ppm)$

Then obtain M_W and $\sin\theta_W$ at tree level from:

$$M_W = A/\sin\theta_W$$

$$M_Z = A/\sin\theta_W\cos\theta_W$$

where

$$A = (\pi\alpha/\sqrt{2}G_F)^{1/2}$$

EW Radiative Corrections:

$\longrightarrow$ Data is sufficiently precise - must include radiative corrections

define: (on-shell scheme, Sirlin)

$$sin^2\theta_W = 1 - \frac{M_W^2}{M_Z^2}$$

then lump radiative corrections into Δr

$$M_W = \frac{A_o}{\sin\theta_W(1-\Delta r)^{1/2}} \quad \text{with} \quad A_o = (\frac{\pi\alpha}{\sqrt{2}G_F})^{1/2}$$

$\Rightarrow$ Dominate contributions to Δr due to

- running of $\alpha \longrightarrow \alpha(M_Z^2)$ - vacuum polarization diagrams
- W, Z self-energy diagrams
- bosonic loop diagrams

$\Longrightarrow$ can write as

$$\Delta r \sim \Delta r_o - \rho_t/\tan\theta_W \quad \text{with}$$

$$\Delta r_o \approx 1 - \frac{\alpha}{\alpha(M_Z)} \approx 0.06 \quad \text{and}$$

$$\rho_t \approx 0.01(M_T/180\ \text{GeV})^2$$

$+$ contributions from bosonic loops which $\propto (\ln M_H)$

Motivation

⇒ **Precision Measure of M_W**

- ⋆ **test of SM at level of radiative corrections**
  → sensitive to m_t and M_H

- ⋆ **Improvement in precision can further constrain allowed values of M_H in SM or parameter space of other models**

- ⋆ **A precise value of M_W from direct measurement could contradict the value determined indirectly, indicating breakdown of SM**

DØ experiment designed in mid-1980's

⇒ **still searching for *top* quark and *Higgs* boson**

⇒ **want to study properties of $W^{\pm}, Z^{\circ}$**

⇒ **want to study properties of Strong and Electroweak interactions**

⇒ **Need to produce these particles and interactions so we can measure them!**

Use the Fermilab Tevatron collider

Need high energies to study high-mass particles

⋆ **remember!** $E = mc^2$

$\Rightarrow$ **use** $p + \bar{p}$ **collisions**

900 GeV protons **900 GeV anti-protons**

relativistic particles: $E^2 = m^2c^4 + p^2c^2$

set speed of light $c \equiv 1$

therefore E, m, p **expressed in GeV**

⋆ **We measure properties of final-state particles from the** $p + \bar{p}$ **collisions**

Fermilab $p\bar{p}$ Tevatron Collider

- **Each quark carries only fraction of p or $\bar{p}$ momentum**

- **different processes can take place depending on momentum and types of partons (quarks,gluons) that interact**

Looking at low cross section processes...
$\rightarrow$ To get better precision, need high luminosity

Luminosity $\mathcal{L}$ is function of machine parameters

$$N = \sigma \mathcal{L}$$

N = number of events/sec observed

σ = cross section (cm^2) for the beam-beam interaction

$\mathcal{L}$ = luminosity in ($cm^{-2}s^{-1}$)

$\Rightarrow$ **Oct. 1985 - test run**

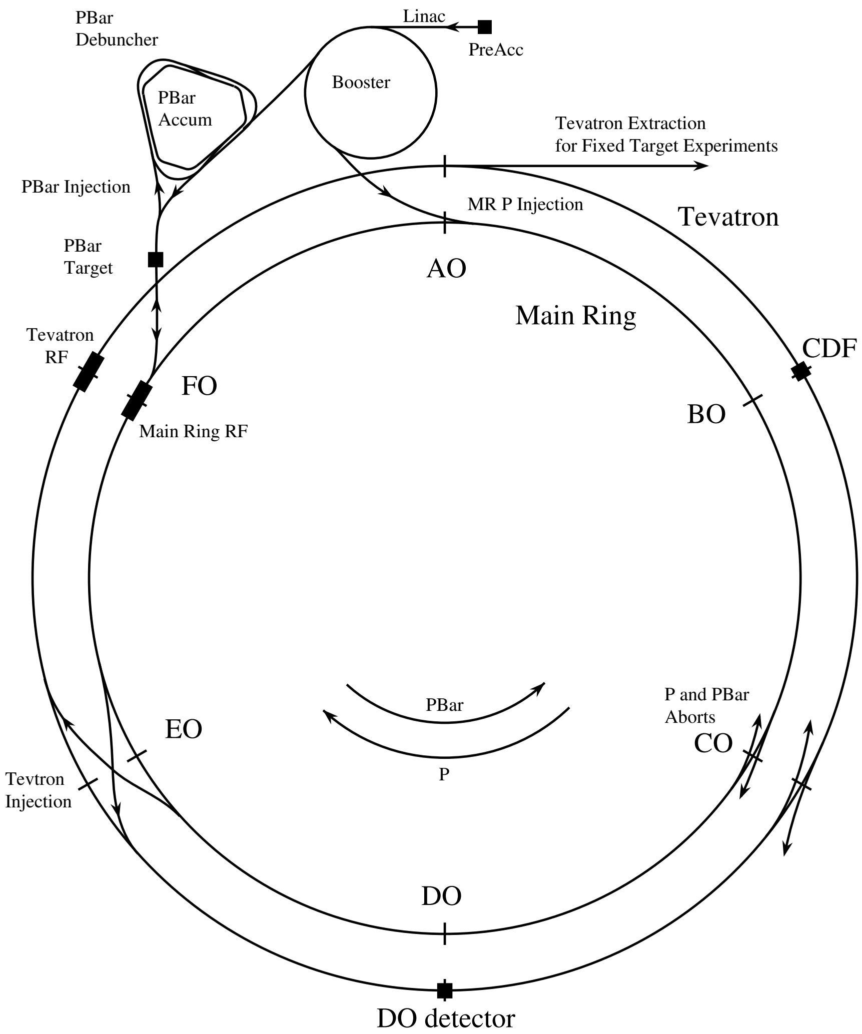
$\Rightarrow$ **1987 - first operating run (CDF only), $\mathcal{L} \approx 4.3\ pb^{-1}$**

$\Rightarrow$ **1992-1993: Run 1A, $\mathcal{L} \approx 15\ pb^{-1}$**

$\Rightarrow$ **1994-1995: Run 1B, $\mathcal{L} \approx 89\ pb^{-1}$**

$\Rightarrow$ **1999? start Run 2, $\mathcal{L} \approx 2000\ pb^{-1}$**

Fermilab Collider



DØ Detector at Fermilab:

$\rightarrow$ **large multi-purpose detector designed to study top, electroweak, QCD, new physics, etc.**

⋆ **mid 1984, experiment approved**

⋆ **Feb 1992, detector completed**

⋆ **May 1992, first collisions**

⋆ **Aug 1992, commissioning completed, run 1 starts**

DØ Physics Menu

- **final states we look for** $\Rightarrow$

  - **discovery of** *top* **quark and measure properties** $\rightarrow$

  - **measure properties of** $W^{\pm}, Z^{\circ}$ **bosons** $\rightarrow$

  - **study strong interactions (QCD)** $\rightarrow$

  - **plus many other measurements of properties!!!**

Particle Detection

Use detector to measure final products of collision

- **then can reconstruct event**

$\Rightarrow$ **calorimeter - energy measurement of charged and neutral particles**
$\Rightarrow$ **muon system - momentum measurement of muons**
$\Rightarrow$ **tracking system (drift chambers) - charged particle tracking**

electrons

photons

muons

quarks,gluons $\longrightarrow$ "jets" of hadrons

neutrinos

Data Collection

$p + \bar{p}$ **interaction rate** $\approx 10^5$ Hz

have $\approx 100,000$ **signals from detector electronics**

- **most interactions not interesting**
- **"trigger" to select and keep only interesting events**
- **use analog sums of calorimeter cell information (digitized in 350 ns) to make decision**

3 Stages of Triggering:

L0 - signals an inelastic collision

L1 - hardware trigger using calorimeter E_T
output rate to L2 ≈ 200 Hz

L2 - software trigger using 50 node μ**processor farm**
allow 200 msec for decision
output rate to tape ≈ 2 Hz

Inclusive W and Z Production

$\Longrightarrow$ $p\bar{p} \rightarrow W + X$ $\qquad$ $p\bar{p} \rightarrow Z + X$

$X \rightarrow$ have extra hadronic activity in event due to recoil to the W or Z **plus**

$\rightarrow$ have underlying event energy:
- multiple interactions per event
- interactions among spectator partons
- detector noise

$\Longrightarrow$ detect W and Z via their leptonic decays
- cleaner signature
- lower background

$W \rightarrow l\nu$ signature: high p_T lepton + large $\not{E}_T$
$Z \rightarrow ll$ signature: 2 high p_T leptons

M_W - Measurement by DØ

$\Rightarrow$ **Analysis based on Run 1A data sample (published)**
- **PRL 77 (1996) 3309**
- **PRD in progress**

$\star$ **will concentrate on this measurement**

$\Rightarrow$ **Preliminary results based on Run 1B data**
- **larger statistics - larger average luminosity**

$\star$ **for M_W measurement use data samples:**

$W \rightarrow e\nu$ **(BR $\approx$ 10%) and** $Z \rightarrow ee$ **(BR $\approx$ 3%)**

$\rightarrow$ **require electrons in central region**

This is a calorimetric measurement!

M_W - Quantities Measured

Measured in calorimeter (includes underlying event and detector noise):

$\longrightarrow$ electron energy $\vec{E}(e)$

$\longrightarrow$ missing transverse energy ($\vec{\not{E}}_T$) in event

$\star$ missing longitudinal energy not known

because particles escape down beamline

$\longrightarrow$ have $\vec{\not{E}}_T \equiv \vec{E}_T(\nu) = -\vec{E}_T(e) - \vec{E}_T(R)$

therefore can determine recoil transverse energy $\vec{E}_T(R) \equiv -E_T(W)$

$\longrightarrow$ **Cannot reconstruct W invariant mass**

Instead study E_T^e and M_T^W distributions:

At current luminosities, best to use M_T^W

Measure:

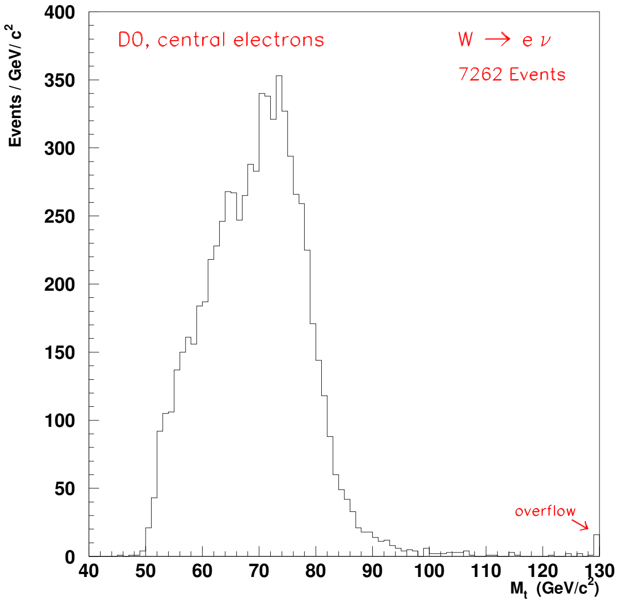
transverse mass of W and invariant mass of Z

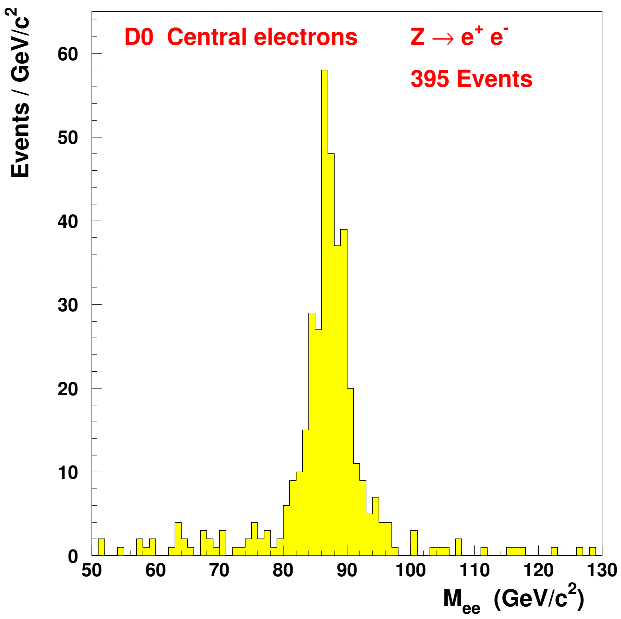
$M_T^W = \sqrt{2E_T^e E_T^\nu (1 - \cos\varphi)}$ $\qquad$ $M_Z = \sqrt{2E^{e1}E^{e2}(1 - \cos\varphi)}$

M_W - Event Sample

		# events: 1A	1B
$W \to e\nu$		7234	32856
⋆ e in CC:	$\|\eta\| < 1.2$		
⋆ electron:	$p_T^e > 25$ GeV		
⋆ neutrino:	$\not{E}_T > 25$ GeV		
⋆ W transverse momentum:	$P_T^W < 30$ GeV		
⋆ transverse mass (1A)	$50 < M_T^W < 110$ GeV		
$Z \to ee$		366	1562
⋆ e's in CC:	$\|\eta\| < 1.2$		
⋆ 2 isolated electrons:	$p_T(e) > 25$ GeV		
⋆ invariant mass (1A)	$70 < M_Z < 110$ GeV		

Run 1A - spectra:





⋆ Also have data sample of $Z \to ee$ in EC/EC and CC/EC

- to ensure equivalent event topologies for some studies

M_W - Measurement Technique

No analytic description of the $M_T(W)$ distribution... therefore

- **model data with fast Monte Carlo simulation**
  - **model detector effects and variables** *as measured in data*!
  - **most corrections made to MC instead of data**
- **generate $M_T(W)$ distributions as a function of M_W**
  - **do for 21 values of M_W, 100 MeV apart**
- **extract value of M_W by doing event-by-event max-likelihood fit of data to simulation**
- **backgrounds included during fitting**

M_W - Fast Monte Carlo

⋆ **main components of MC listed below**

- W **production and decay** $\longrightarrow$ **to get** $\vec{P}_T(e)$ **&** $\vec{P}_T(W)$
- **electron and hadronic energy scale**
- **energy & angular resolution**
- **additional energy due to underlying event**
- **selection biases & efficiencies**
- **kinematic cuts**

(Z events modelled in analagous way)

$\Rightarrow$ **Points to Note!!**

$\longrightarrow$ **calibrate EM response using** Z**'s,** π°**,** J/ψ

$\longrightarrow$ **measure ratio of** W/Z **mass (reduces systematic errors):**

$$M_W = \frac{M_W^{meas}}{M_Z^{meas}} \cdot M_Z^{LEP}$$

use $M_Z^{LEP} = 91.1884 \pm 0.0024$ GeV

$\longrightarrow$ **use** $Z \rightarrow ee$ **and other data to set most parameters**

$\longrightarrow$ **systematic errors set using large statistics samples of MC data - vary parameter within its errors**

M_W -Monte Carlo W Production

- Events generated using Ladinsky-Yuan (NLO) with MRSA pdf [PRD 50,4239(1994)]

$$\frac{d^2\sigma}{dp_T(W)dy(W)}$$

- W resonance generated with relativistic Breit-Wigner, skewed by mass dependence of parton luminosity:

$$\frac{d\sigma}{dm} \sim \frac{e^{-\beta\cdot m}}{m} \cdot \frac{m^2}{(m^2 - M^2)^2 + \frac{m^4\Gamma^2}{M^2}}$$

- angular decay of W, respecting polarization

$$\frac{d^2\sigma}{dyd\cos\theta} \sim (1-\cos\theta_{cm})^2\cdot(\frac{1}{2}\frac{d\sigma_s^{W+}}{dy} + \frac{d\sigma_v^{W+}}{dy}) + (1+\cos\theta_{cm})^2\cdot(\frac{1}{2}\frac{d\sigma_s^{W+}}{dy})$$

- radiative decays: $W \to e\nu\gamma$ generated according to Berends & Kleiss [Z. Phys. C 27, 365(1985)]

- τ decays: $W \to \tau\nu \to e\nu\nu\nu$
  generated in MC - cannot differentiate in data from $W \to e\nu$

- boost decay products to lab frame

  - have $\vec{p}(e), \vec{p}_T(W) = -\vec{p}_T(R)$ and then

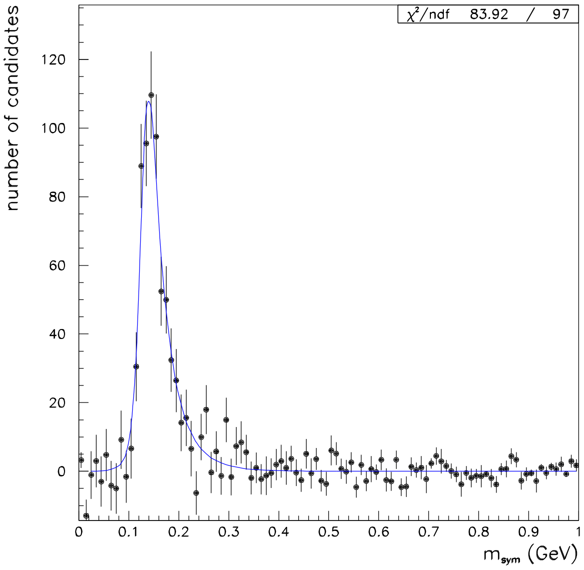
    infer: $\vec{p}_T(\nu) = -\vec{p}_T(R) - \vec{p}_T(e)$

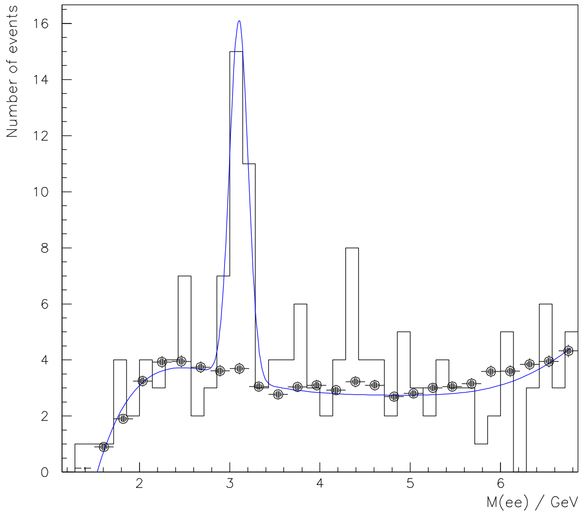
M_W - $P_T(e)$ energy scale

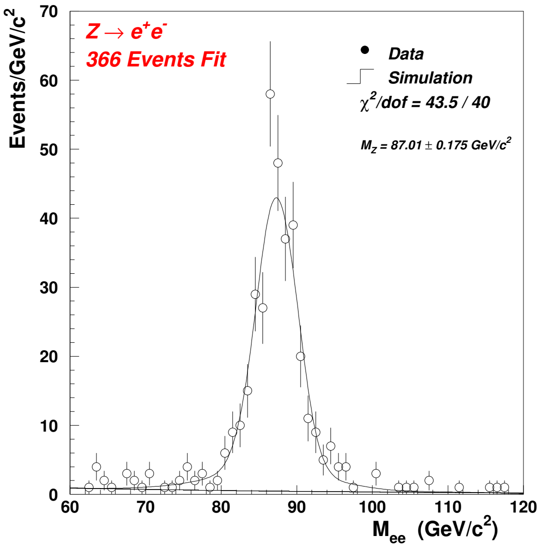
$\rightarrow$ **Determine EM energy scale using J/ψ, π^0, and Z event samples**

$\rightarrow$ **EM energy response:**

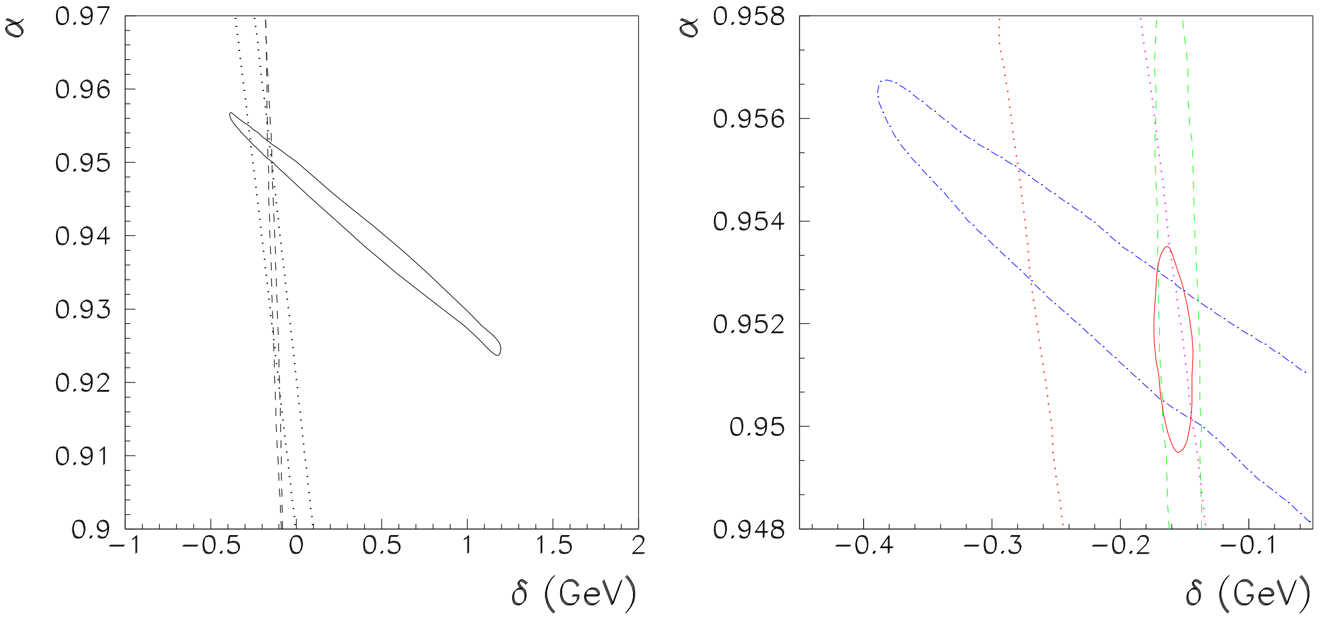
$$E^{meas} = \alpha E^{true} + \delta$$







M_W - $P_T(e)$ Scale



$\alpha = 0.9514 \pm 0.0018$ $\delta = -0.158 \pm 0.015 \ {}^{+.030}_{-.210}$ GeV

error on M_W due to EM scale: $\sigma(M_W) = 160$ MeV

run 1B: $\sigma(M_W) = 80$ MeV

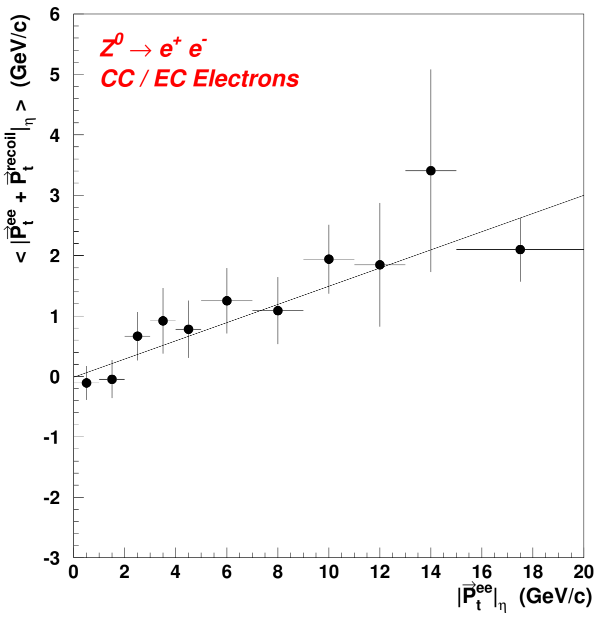
$\star$ **error dominated by Z statistics**

M_W - $\vec{P}_T(R)$ Scale

$\Longrightarrow$ hadronic energy scale relative to EM scale

$\Longrightarrow$ Z events - measure $P_T(Z)$ from ee or the recoil:

$$\eta\text{—balance} \equiv [\vec{P}_T(ee) + \vec{P}_T(R)] \cdot \hat{\eta} \quad \text{vs} \quad \vec{P}_T(ee)$$



$$\Rightarrow P_T(R) = (0.83 \pm 0.04) P_T(ee)$$

error due to hadronic energy scale: $\sigma(M_W) = 50\ \text{MeV}$

M_W - $\vec{P}_T(R)$ Resolution and Underlying Event

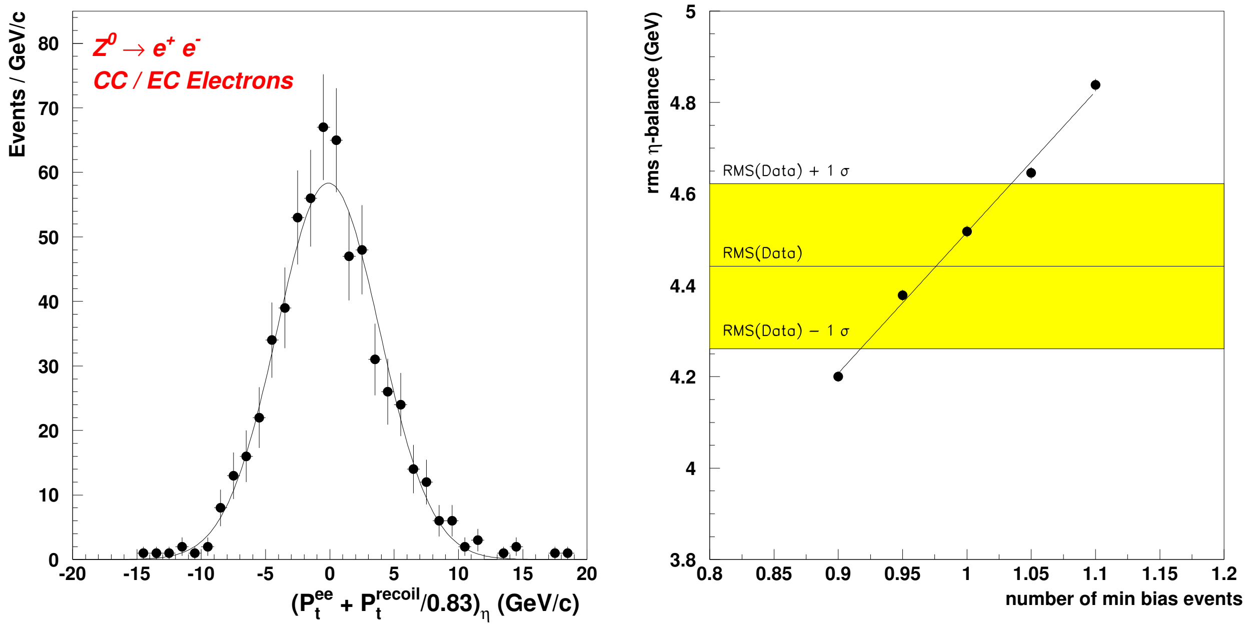
Underlying event affects magnitude and smears the $\vec{P}_T(R)$

$$\vec{P}_T(\nu) = \vec{P}_T(W) - \vec{P}_T(e) = -\vec{P}_T(R) - \vec{P}_T(e)$$

model in MC as measured in data:

$$\vec{P}_T(R)^{meas} = \vec{P}_T(R) + C \cdot \vec{U}_{mb}(tot) - U(\hat{e})$$

- $\vec{U}_{mb}$ is total $\vec{P}_T$ of minimum bias event - from library
- luminosity distribution of data is modelled
- $C = \#$ minbias events needed to model W underlying event
- resolution of $\eta-$balance of Z data constrains $C \rightarrow 0.98 \pm 0.06$



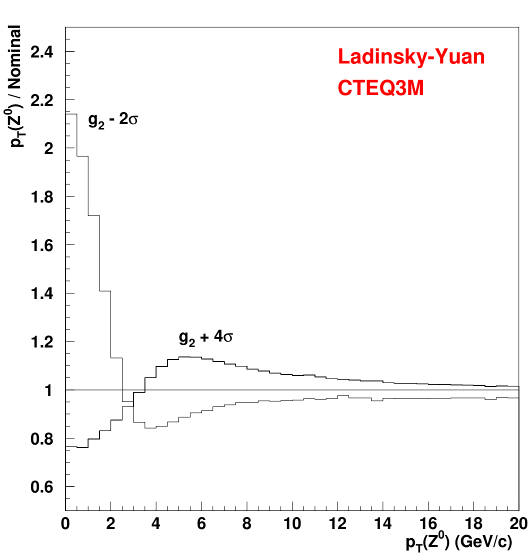
error due to # min bias events: $\sigma(M_W) = 60$ MeV

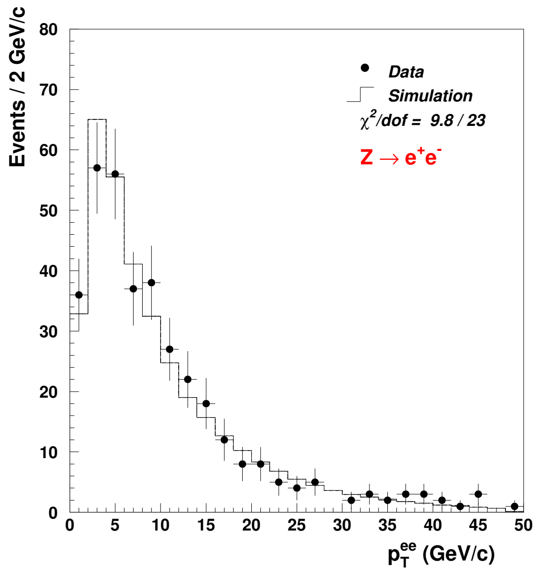
Errors from $P_T(W)$ spectrum and pdf's

Use Ladinsky-Yuan calculation of $\frac{d^2\sigma}{dy\,dP_T}$
- correlated with pdf choice

- new parametrization of non-perturbative (low P_T) region of the resummed cross section
- based on resummed calculation by Collins, Soper & Sterman
- modified to include perturbative high P_T part - Arnold & Reno

$\longrightarrow$ uses phenomenological parameters g_1, g_2, g_3 for non-perturbative region $\rightarrow$ P_T^Z most sensitive to g_2
$\longrightarrow$ constrain model using $P_T(Z)$ spectrum from data
$\star$ data allows $g_2 - 2\sigma$ to $g_2 + 4\sigma$

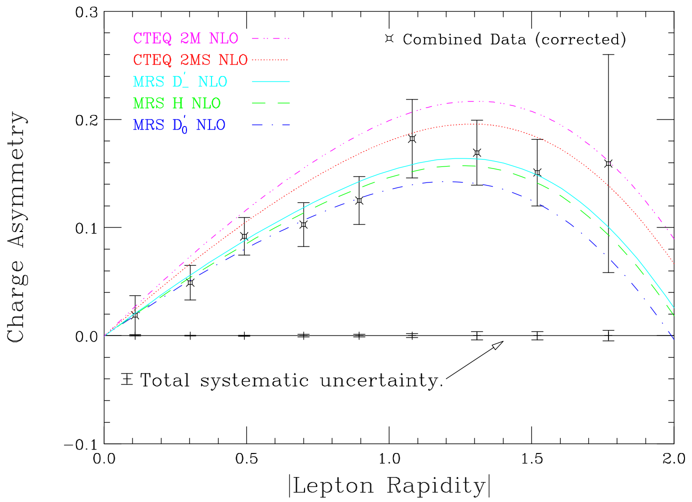




M_W - $P_T(W)$ spectrum and pdf's

⋆ CDF W-Asymmetry data constrains pdf's

$\longrightarrow$ Allow W-Asymmetry to vary by $\pm 1\sigma$



Obtain new parameterizations in which pdf & input spectrum - constrained by data - were varied simultaneously $\longrightarrow$

error due to theory
($P_T(W)$ spectrum and pdfs): $\sigma(M_W) = 65$ MeV

Comparison of Data and MC

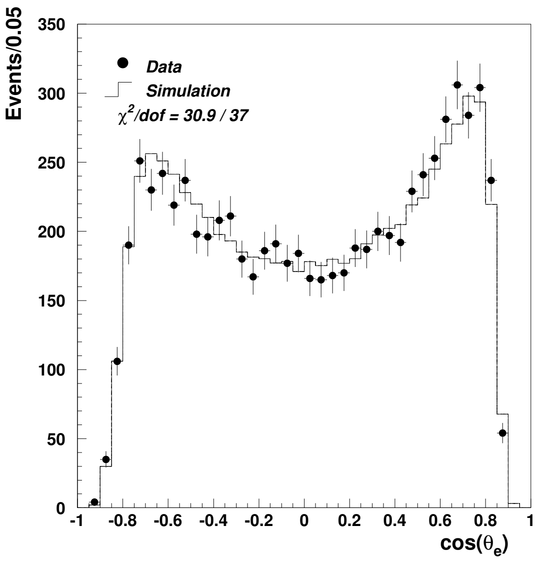
⋆ $U_{\parallel} = \vec{P}_T^{Rec} \cdot \hat{e} = P_T^{Rec} \cos\phi$

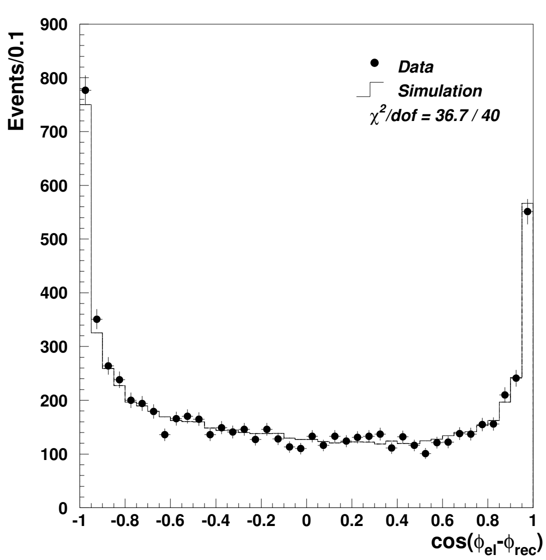
$\rightarrow$ hadronic energy in electron direction

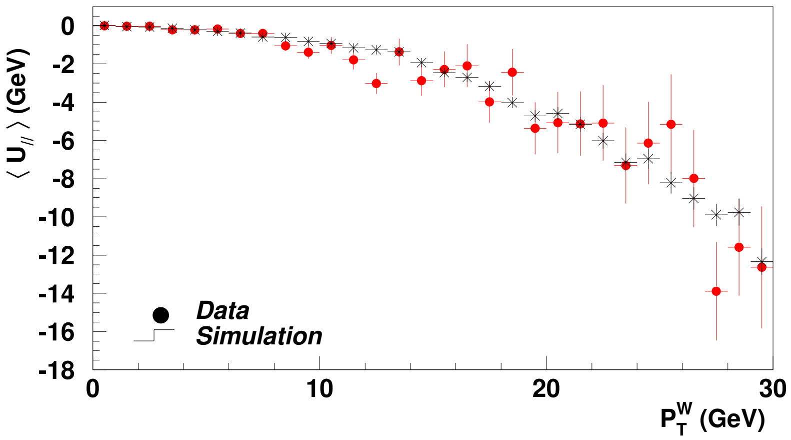
- ϕ is the angle between the electron and recoil vectors

⋆ A bias in $U_{\parallel}$ directly affects the M_T spectrum

⋆ $U_{\parallel}$ is sensitive to the recoil resolution

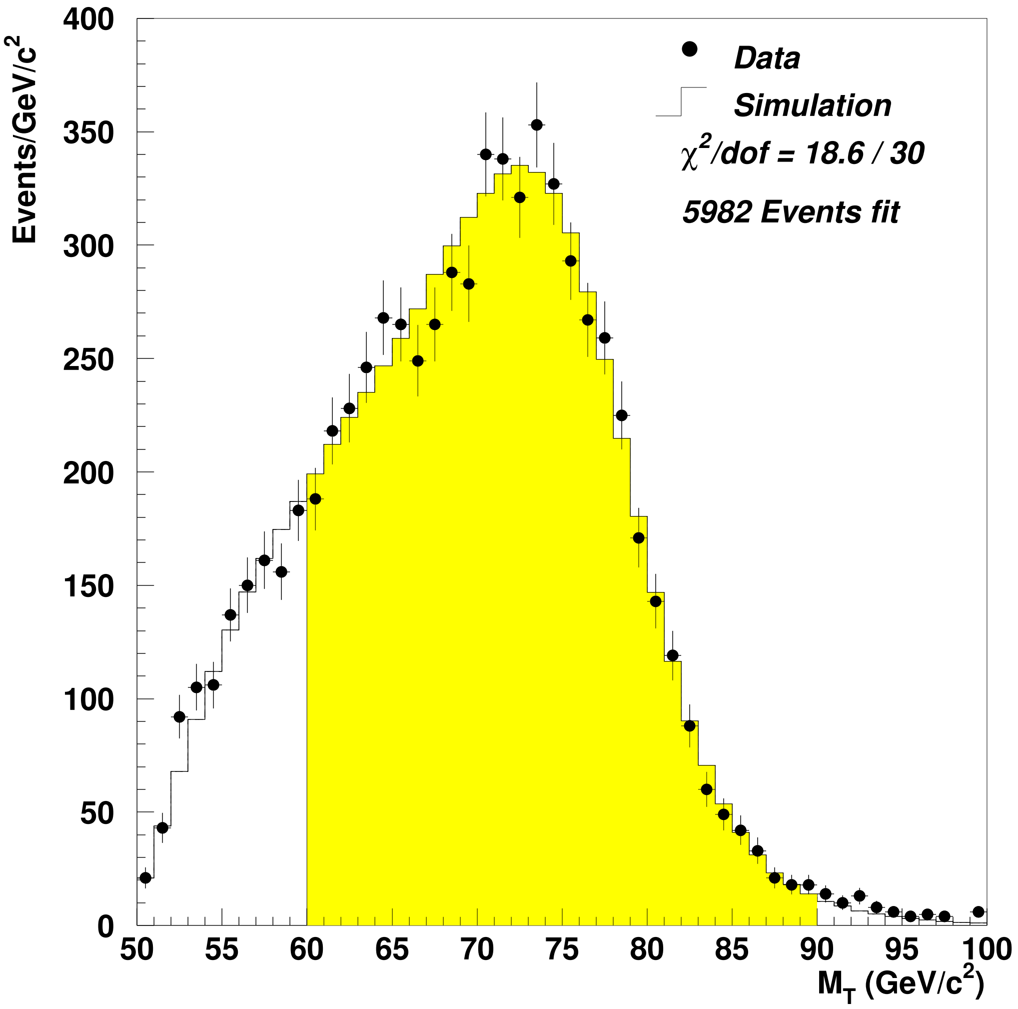






M_W - from Fit to Transverse Mass

perform unbinned maximum likelihood fit from 60 – 90 GeV



$$M_W(\text{Run1A}) = 80.350 \pm 0.140 \text{ GeV}/c^2$$

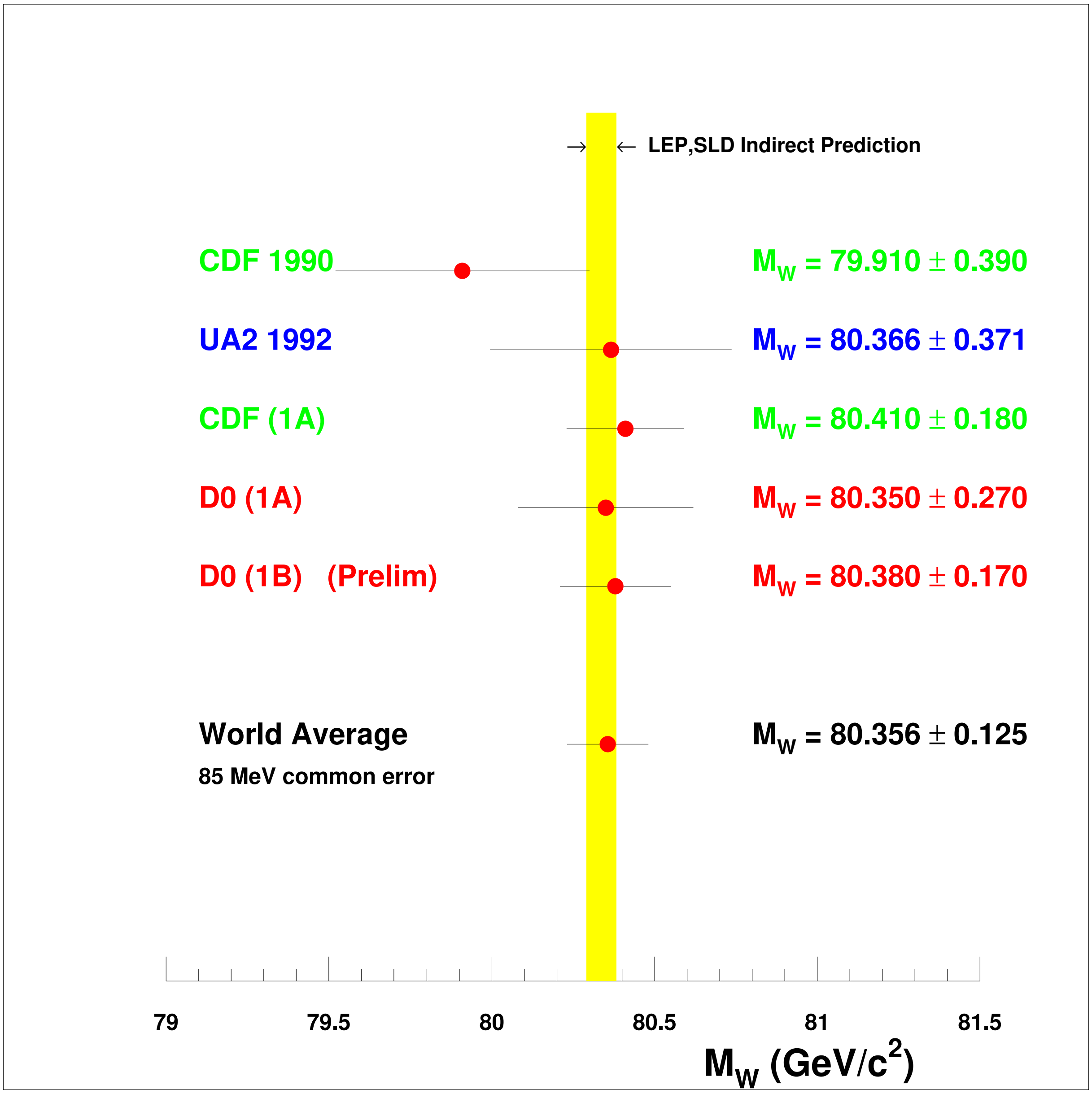
M_W - Summary of Errors on Fit to $M_T(W)$

Source	$\sigma M(W)$ (MeV)	
	Run 1B	Run 1A
Statistical	70	140
Energy Scale	80	160
Systematic	130	165
EM Energy Resolution	30	70
Hadronic Energy Resolution	20	65
P_T^W, pdf	65	65
# of Min. Bias Events	40	60
Hadronic Energy Scale	30	50
Electron Angle Calibration	40	50
Underlying Event	30	35
Backgrounds	15	35
Efficiencies	20	30
W Width	10	20
Radiative Decays	20	20
Non-Uniform energy response (η)	10	10
Fit Error	5	5
Luminosity Dependence*	70	
Total	170	270

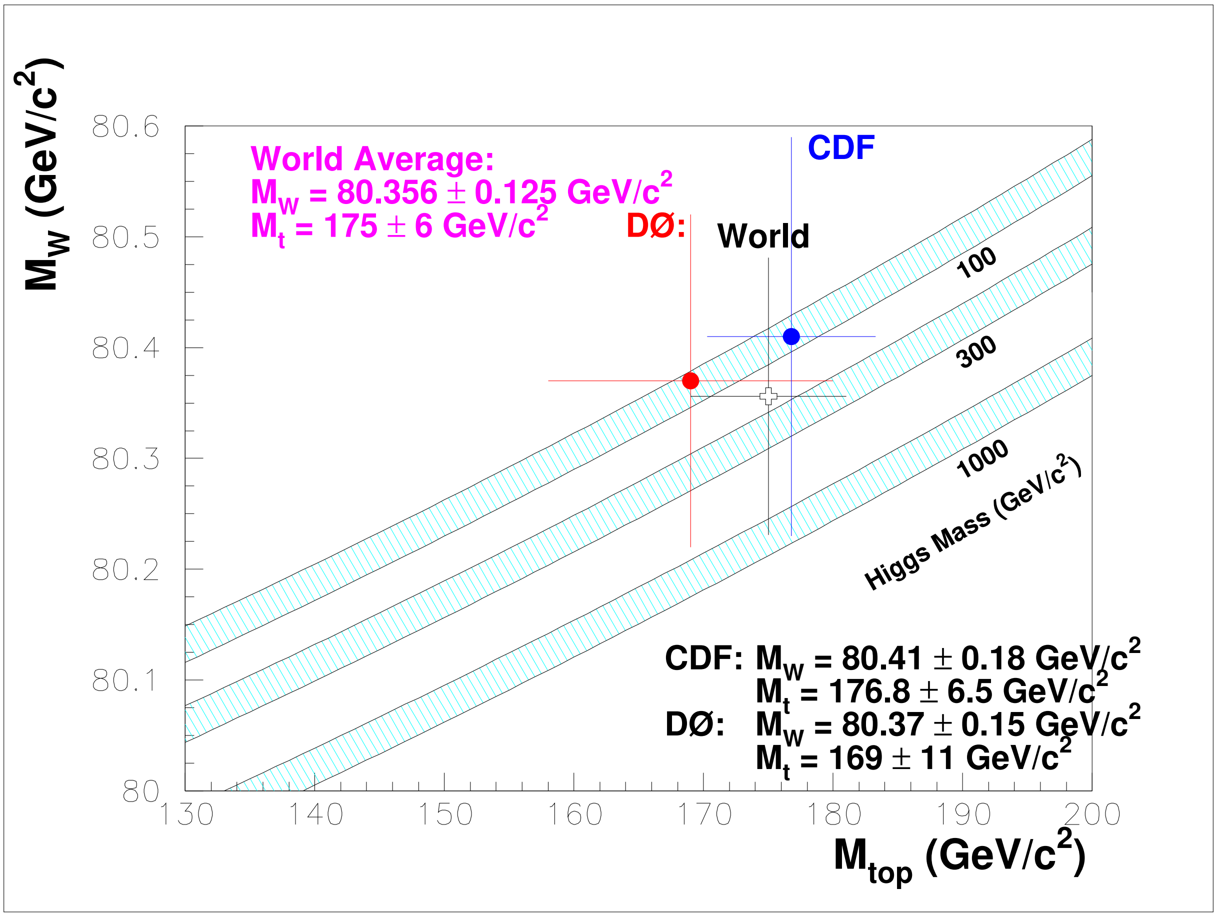
$$M_W(\text{Run1A}) = 80.350 \pm 0.140(stat.) \pm 0.160(scale) \pm 0.165(syst.)\ \text{GeV/c}^2$$

$$M_W(\text{Run1B}) = 80.380 \pm 0.070(stat.) \pm 0.080(scale) \pm 0.130(syst.)\ \text{GeV/c}^2$$

Current Results of M_W



Constraints on Higgs Mass



Indirect Measurements of M_W

from LEP ElectroWeak Working Group (EWWG),

shown at ICHEP(July) & DPF96(Aug)
(Fnal-conf-96/354 & CERN-PPE/96-183)

Do global fits of all LEP/SLD data to SM calculations to obtain
- optimum values
- estimate of free parameters

$\Rightarrow$

$$m_t = 177^{+7}_{-8}{}^{+17}_{-19}$$
$$M_W = 80.337 \pm 0.041^{+0.010}_{-0.021}$$

SM fits for m_t, α_s use all LEP & SLD data, derive M_W
central value assumes $M_H = 300$ GeV
2nd error: $60 < M_H < 1000$ GeV

!! direct $m_t = 175 \pm 6$ - more precise than indirect !!

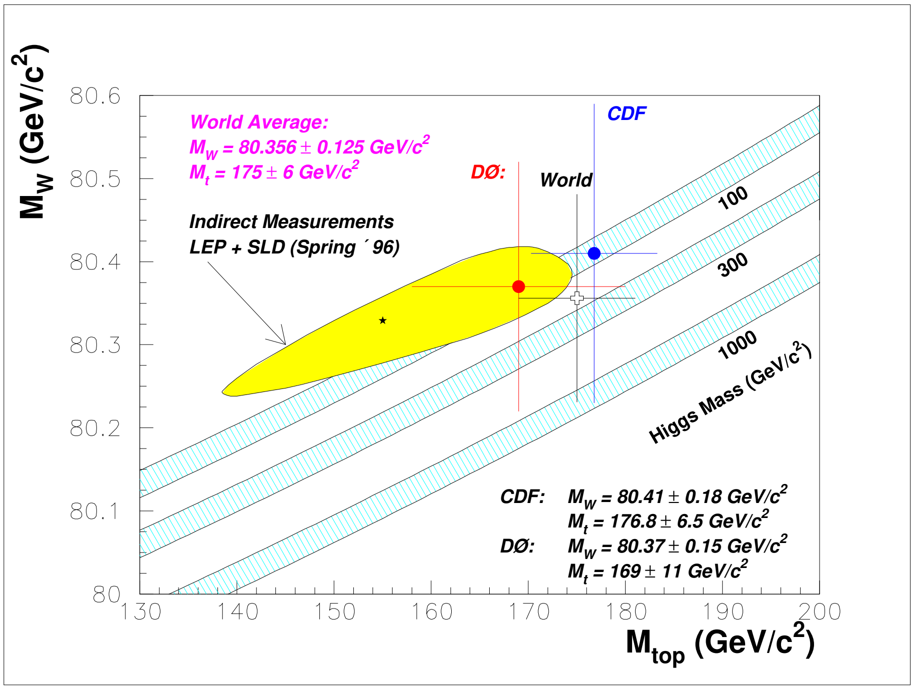
The determination of $sin^2\theta_W$ from νN scattering, when combined with M_Z gives (from CCFR $\rightarrow$ Fnal-conf-96/227-E)

$$M_W = 80.46 \pm 0.25 \text{ GeV}$$

$\Rightarrow$ **A precise value of M_W from a direct measurement could contradict the value determined indirectly from the global fit, thus indicating a breakdown of the SM**

M_W vs m_t - Higgs constraint

from LEP2 workshop, HEP-PH 9602352, Kunszt & Stirling



LEP EWWG

M_{top} and M_H allowed to float in global fit of LEP-only data

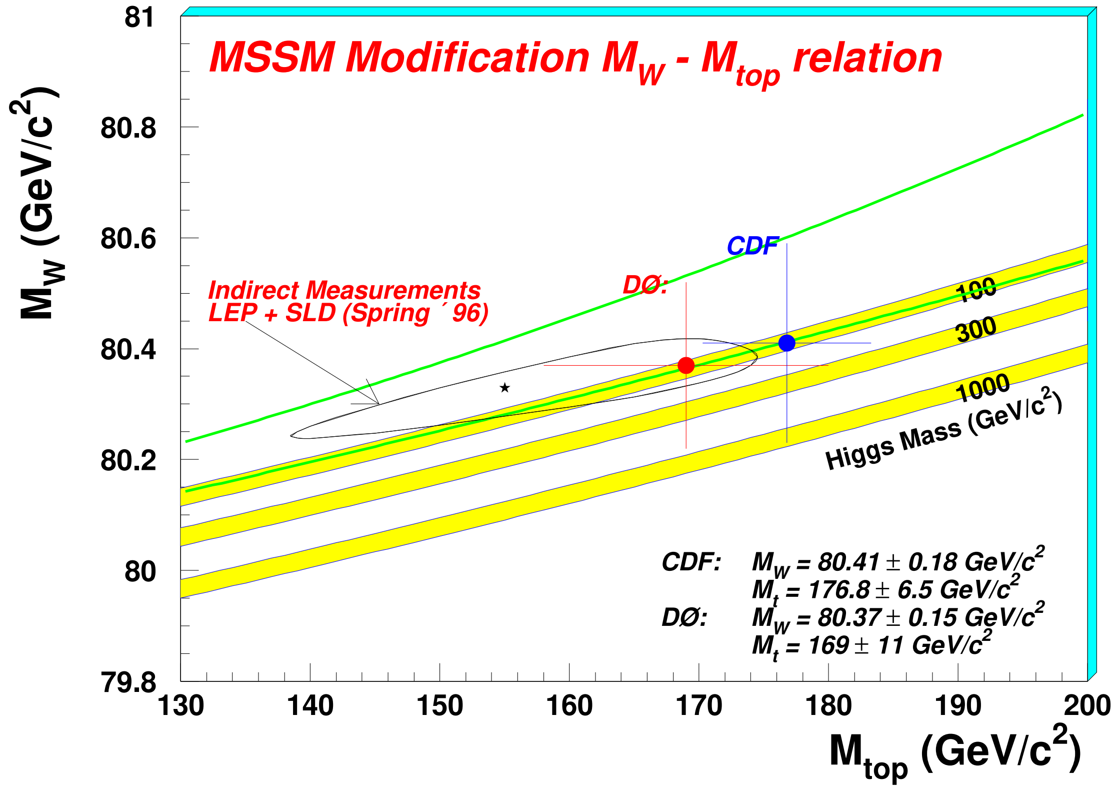
$$M_{top} = 155^{+18}_{-13}\ \text{GeV}$$

$$M_H = 86^{+202}_{-51}\ \text{GeV}$$

$$M_W = 80.359 \pm .051\ \text{GeV}$$

M_W vs m_t - beyond SM

from LEP EWWG, shown at DPF96



MSSM theory prediction assumes $90 < M_H < 1000$ GeV

LEP2 - new direct M_W !

summer 1996 $\rightarrow e^+e^-$ at $\sqrt{s} = 161.3$ GeV

$\Rightarrow$ determine M_W from turn-on of cross section:

- compare measured event rate of W^+W^- pairs to predictions made as a function of M_W for a given beam $\sqrt{s}$

updated value as of Aspen97 in January:

$$M_W(\text{LEP2}) = 80.42 \pm 0.22 \text{ GeV}$$

Conclusions - M_W at DØ

- have collected ≈ 100 pb^{-1} of data in Runs 1A & 1B

- from analysis of Run 1A data sample
  $\Rightarrow$ measured W mass (e channel)

$$M_W = 80.350 \pm .270 \text{ GeV}$$

- Run 1B preliminary result: $M_W = 80.380 \pm .170$ GeV

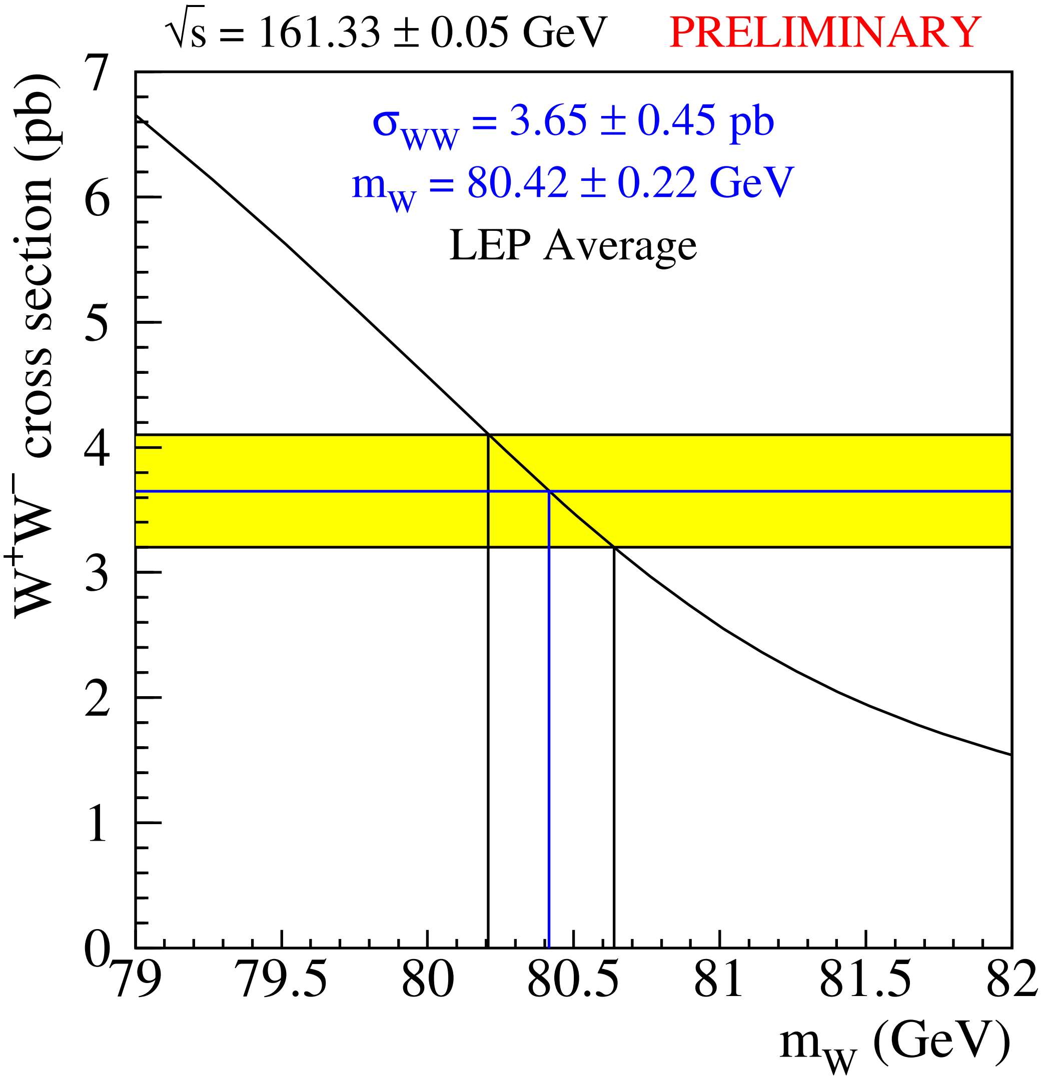
- Currently World's Best Measurement! (Run 1A + 1B)
  $M_W = 80.370 \pm .150$ GeV

- New World Average: $M_W = 80.356 \pm .125$ GeV

- for final Run 1B result expect
  - will further reduce errors to due to production model and luminosity dependence
  - adding $W \to e\nu$ events in forward region
    $\to$ DØ error ≈ 120 MeV

- DØ Tevatron Run 1 - expect to know W mass to ≈ 100 MeV!

Many exciting things happening in the world of ElectroWeak Precision Measurements!



Aspen 97
LEP EW Working Group

Future M_W Measurements

- Tevatron Run 1 - DØ & CDF: $\Delta M_W \approx 80$ MeV
- Tevatron Run 2: $\Delta M_W \approx 40$ MeV
- Tevatron Run 2: $\Delta m_t \approx 3$ GeV
- LEP2: $\Delta M_W \approx 45$ MeV

From LEP2 EWWG - Feb 1996
constraints on M_H:

	$M_T = 180 \pm 5$ **GeV**	
M_H**(GeV)**	$\Delta M_W = 25$ **MeV**	$\Delta M_W = 50$ **MeV**
100	**+86, -54**	**+140,-72**
300	**+196, -126**	**+323,-168**
800	**+ 538,-310**	**+958,-413**

As measurements of M_W and M_T become more precise, we will further constrain the M_H