The Precision Measurement of the W Mass using the DØ Detector at Fermilab

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14 May 1997

Will Cover...

- **The Standard Model**
- **The DØ Experiment at Fermilab**
- **Motivation for Measuring the W Boson Mass**
- **Measurement of the W mass**
- **Comparisons to other Measurements**
- **Future Prospects**

Elementary Particle Physics

(High Energy Physics)

⇒ **Study of fundamental particles in universe and the forces between them**

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?)

⋆ **Also have Higgs Boson which gives mass to the fundamental particles**

The Standard Model

⇒ **ElectroWeak:**

- ⋆ **unified theory describing the electromagentic and weak forces**
- ⋆ **discovery of W, Z in 1983 (UA1,UA2 experiments at CERN)**

⇒ **Quantum ChromoDynamics (QCD):**

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

Experiments in High Energy Physics

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

⋆ **measurements of parameters in Standard Model**
⋆ **test how well predictions match data**
⋆ **search for results that are not predicted by Standard Model**

$\longrightarrow$ **Is the Standard Model the final answer?**

$\Longrightarrow$ **Standard Model has survived all experimental tests so far!** $\Longleftarrow$

⋆ **TOP quark recently (1995) discovered at Fermilab**

DØ and CDF current results (May 1997)

DØ $\rightarrow M_T = 172.0 \pm 7.5$ **GeV**
CDF $\rightarrow M_T = 176.8 \pm 6.5$ **GeV**

⋆ **Higgs (H) is only undiscovered SM particle**

FUTURE

$\longrightarrow$ **search for Higgs boson**
$\longrightarrow$ **why are masses and strengths of forces these particular values? - otherwise would have totally different universe!**

Fermilab $p\bar{p}$ Tevatron Collider

$\Rightarrow$ **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,** $\mathcal{L} \approx 2000\ pb^{-1}$

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

DØ Detector at Fermilab:

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

$\star$ **mid 1984, experiment approved**
$\rightarrow$ **still searching for** *top* **quark and** *Higgs* **boson**
$\rightarrow$ **study properties of newly-discovered** $W^{\pm}$ **and** Z°

$\star$ **Feb 1992, detector completed**

$\star$ **May 1992, first collisions**

$\star$ **Aug 1992, commissioning completed, run 1 starts**

ElectroWeak Standard Model

- **Glashow, Weinberg, Salam (1967-1968)**
  - SU(2) $\times$ U(1) model of electroweak interactions

- **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** $W^\pm$

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

- **gauge symmetry of electroweak model implies:**
  W, Z **and fermions have** $mass = \mathbf{0}$

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

ElectroWeak Standard Model

Specified by 3 parameters:

fine structure constant:

- $\alpha = (137.03599 \pm .09)^{-1} \quad (\delta\alpha/\alpha = 0.045\ ppm)$

Fermi constant:

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

Mass of the Z Boson:

- $M_Z = 91.1863 \pm .0020\ \mathrm{GeV/c^2} \quad (\delta M_Z/M_Z = 22\ ppm)$

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

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

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

where θ_W is the weak mixing angle and

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

Radiative Corrections:

→ **Data is sufficiently precise**
- must include radiative corrections

⇒ **lump radiative corrections into** Δr

$$M_W = \frac{A}{\sin\theta_W(1-\Delta r)^{1/2}}$$

⇒ **Dominate contributions to** Δr **due to**

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

⟹ **can write as**

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

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

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

$+$ **contributions from bosonic loops which** $\propto (\ln M_{Higgs})$

Therefore $\Delta r(M_{top}, M_{Higgs})$

Motivation

$\Rightarrow$ **Precision Measure of M_W provides**

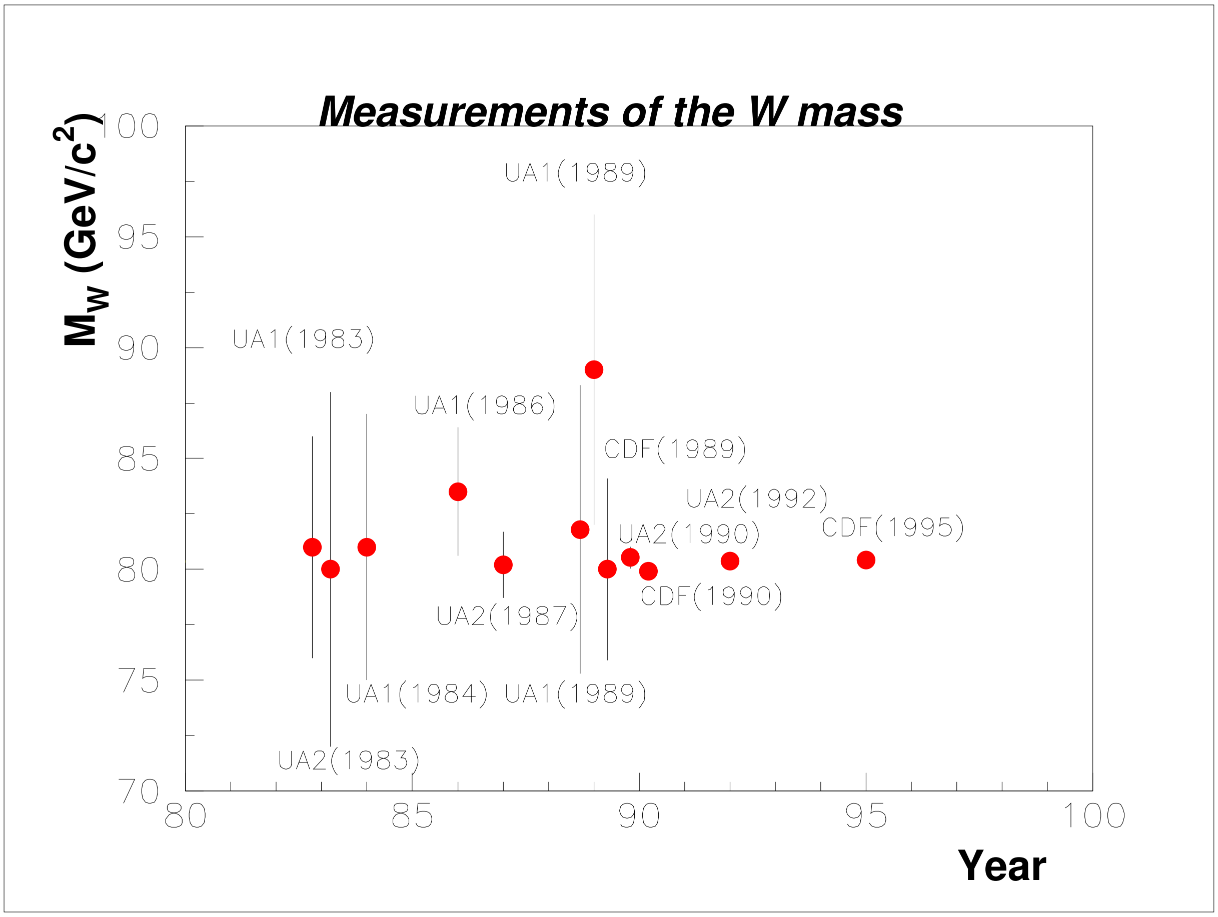
- $\star$ **test of SM at level of radiative corrections**
  $\rightarrow$ **sensitive to M_{top} and M_{Higgs}**
  $\rightarrow$ **with M_{top} can constrain M_{Higgs}**

- $\star$ **Improvement in precision can further constrain allowed values of M_{Higgs} in Standard Model or parameter space of other models**

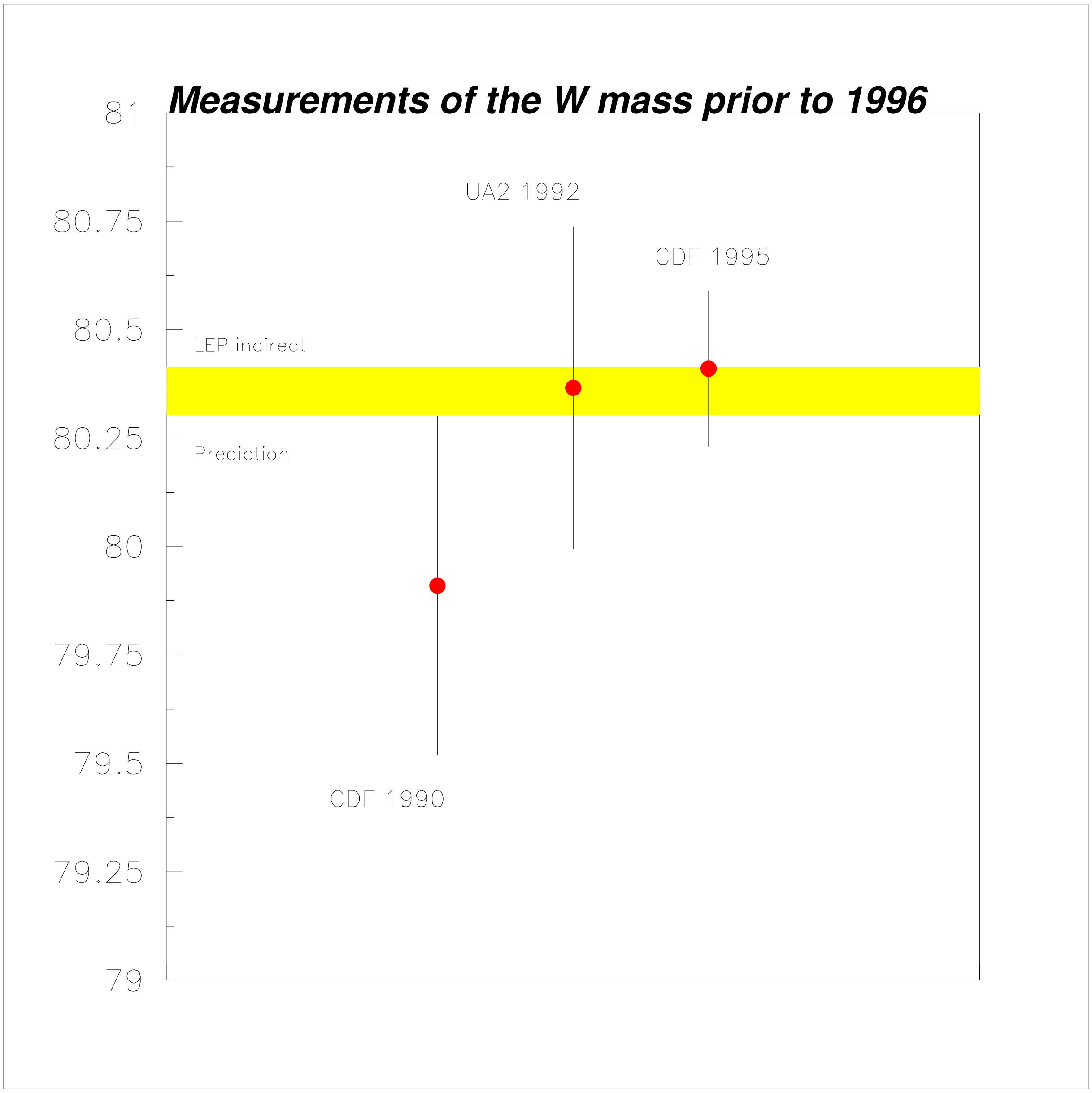
- $\star$ **A precise value of M_W from direct measurement could contradict the value determined indirectly, indicating breakdown of Standard Model**

$\longrightarrow$ **want to measure W mass to 0.1%!**

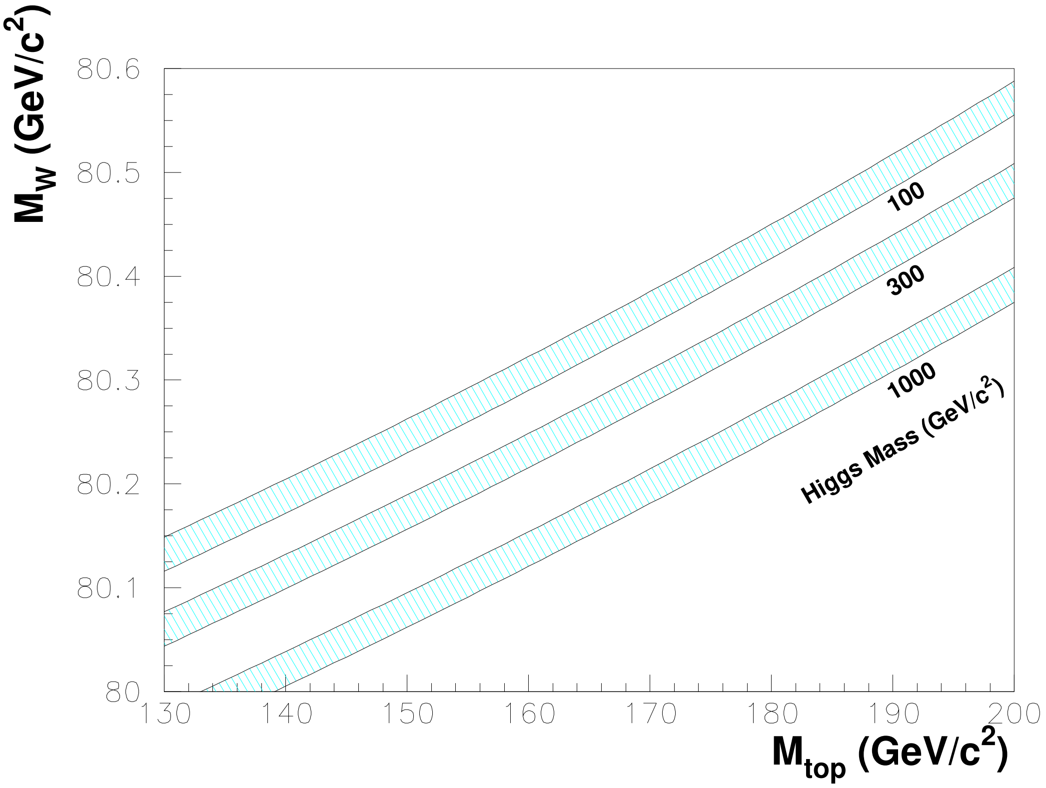
Previous Measurements of M_W



Previous Measurements of M_W



M_W vs. M_{top} - Higgs Mass Dependence



M_W - Measurement by DØ

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

⇒ **Preliminary results based on Run 1B data**
- **announced end of March 1997 at Fermilab**
- **PRL in progress**

Inclusive W and Z Production

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

$\Longrightarrow$ **detect W and Z via their leptonic decays**

- $W \rightarrow e\nu, Z \rightarrow ee$

trigger on events with:

$\Rightarrow$ **high p_T electron + large $\not\!\!E_T$ (W)**

$\Rightarrow$ **2 high p_T electrons (Z)**

- **cleaner signature**
- **lower background**

In addition to W or Z decay products have hadronic energy X in event due to $\rightarrow$

- **"recoil" to W or Z**
  - **if $p_T(W, Z) \neq 0$ then recoil quark(gluon) is also produced**
- **underlying event due to**
  - **multiple interactions in the event**
  - **spectator parton interactions**
  - **detector effects**

M_W - Quantities Measured

We measure quantities in calorimeter (set $|E| \equiv |\vec{p}|$!) (includes underlying event):

$\rightarrow$ **electron energy** $\vec{E}(e)$

$\rightarrow$ **missing transverse energy (** $\vec{\not{E}}_T$ **) in calorimeter cells**

$$\vec{\not{E}}_T = -\Sigma_i E_i \sin\theta_i = -\Sigma_i \vec{E}_T^i$$

$\star$ **missing longitudinal energy not known because particles escape down beamline**

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

Then can determine recoil and boson transverse energy $\vec{E}_T(R) \equiv -\vec{E}_T(W)$

From Measured Quantities:

$$\vec{E}(e), \vec{E}_T(\nu), \vec{E}_T(R), \vec{E}_T(W)$$

Cannot reconstruct W invariant mass

$$M_W^2 = (E^e + E^\nu)^2 - (\vec{E}^e + \vec{E}^\nu)^2$$

$\rightarrow$ **Instead measure M_T^W where $M_T^2 = M^2 + E_x^2 + E_y^2$**

$\star$ **transverse mass of W**

$$M_T^W = \sqrt{2E_T^e E_T^\nu (1 - \cos\varphi)}$$

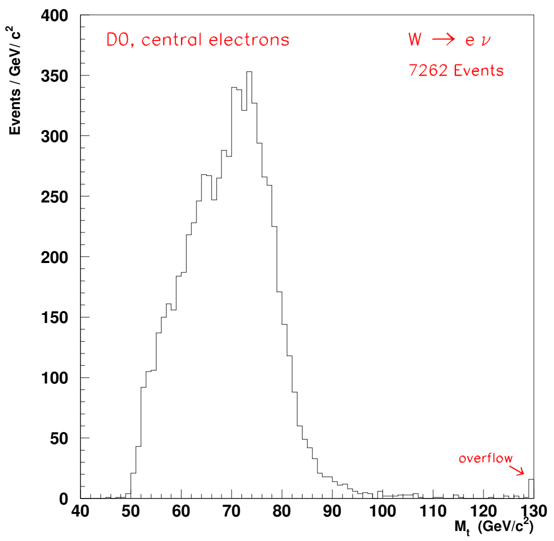
$\star$ **invariant mass of Z**

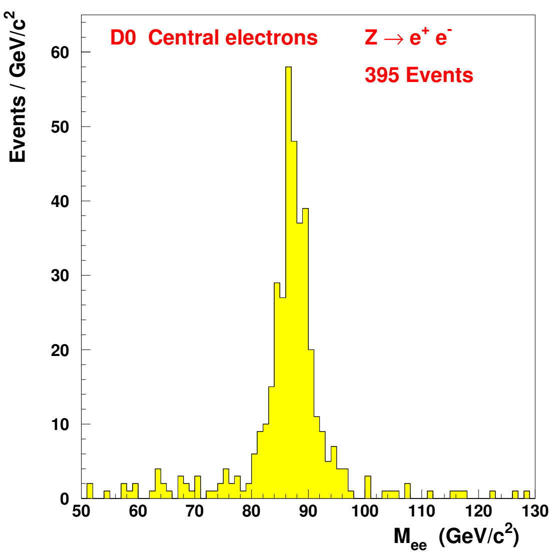
$$M_Z = \sqrt{2E^{e1} E^{e2} (1 - \cos\varphi)}$$

M_W - Event Sample

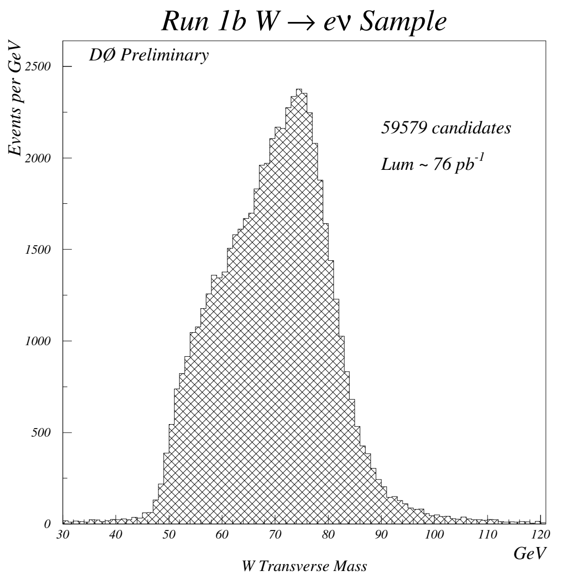
		# events: 1A	1B
$W \rightarrow e\nu$		**7234**	**32856**
⋆ e **in central region:**	$\lvert\eta\rvert < 1.2$		
⋆ **electron:**	$E_T^e > 25$ **GeV**		
⋆ **neutrino:**	$\not{E}_T > 25$ **GeV**		
⋆ W **transverse mom.**	$E_T^W < 30$ **GeV**		
⋆ **transverse mass (1A)**	$50 < M_T^W < 110$ **GeV**		
$Z \rightarrow ee$		**366**	**1562**
⋆ e**'s in central region:**	$\lvert\eta\rvert < 1.2$		
⋆ **2 isolated electrons:**	$E_T(e) > 25$ **GeV**		
⋆ **invariant mass (1A)**	$70 < M_Z < 110$ **GeV**		

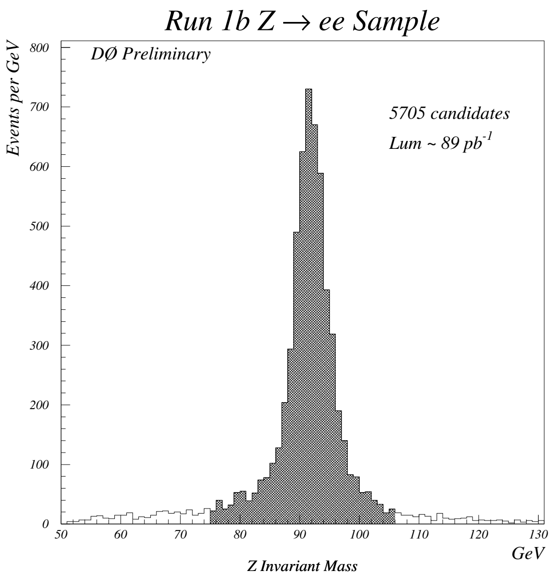
Run 1A - spectra:





Run 1B - spectra:





M_W - Measurement Technique

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

- **model data with fast Monte Carlo (MC) simulation**
  - model kinematic variables and detector effects

- **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 maximum-likelihood fit of data to MC simulation**

$\longrightarrow$ **largest error is due to calibration of electron energy scale, therefore**

$\longrightarrow$ **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
which is very precise combined value from the 4 experiments at LEP collider at CERN in Geneva, Switzerland

M_W - Monte Carlo Simulates:

- W **production and decay** $\longrightarrow$ **to get** $\vec{P}_T(e)$ **&** $\vec{P}_T(W)$ **(and therefore can calculate** $\vec{P}_T(\nu)$**)**
- **electron and hadronic (recoil) 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!!**

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

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

M_W - Monte Carlo W Production

- **Events generated using calculation by Ladinsky-Yuan (NLO) with MRSA parton distribution function (pdf)**

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

- **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 calculation by Berends & Kleiss**

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

- **boost decay products to lab frame**

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

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

M_W - electron energy scale

→ **Absolute calibration of calorimeter not known**

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

→ **EM energy response:**

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

$$M_{meas} = \alpha M_{true} + \delta f \qquad f = \frac{2(E_1 + E_2)}{M} \sin^2 \frac{\gamma}{2}$$

Measure Ratio:

$$\left(\frac{M_W}{M_Z}\right)^{meas} = \left(\frac{M_W}{M_Z}\right)^{true} \left[1 + \frac{\delta}{\alpha} \cdot \frac{(f_W \cdot M_Z - f_Z \cdot M_W)}{M_W M_Z}\right]$$

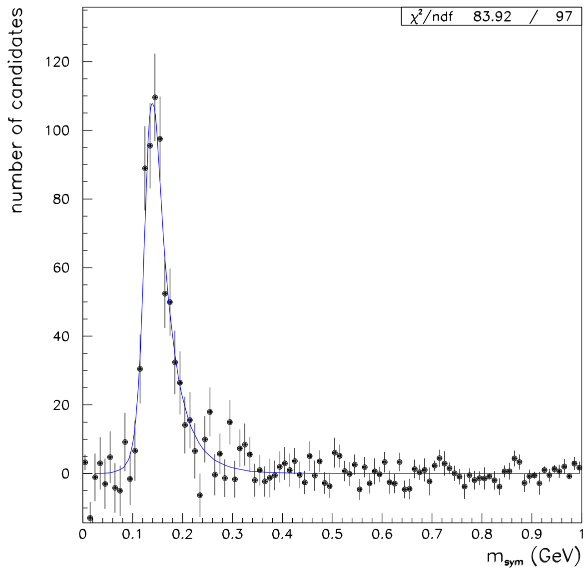
→ **Ratio insensitive to scale (first order)**

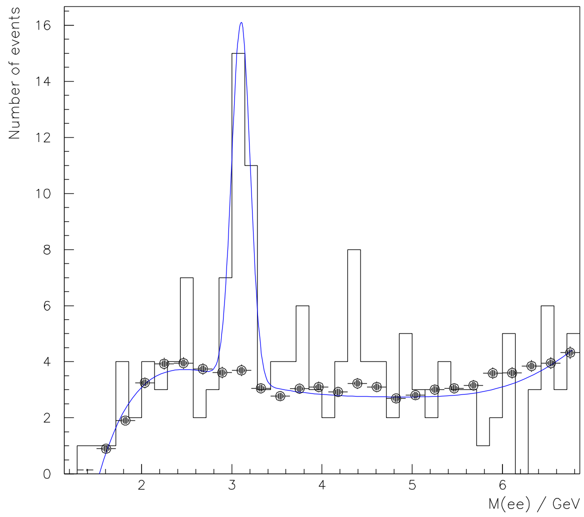
$\frac{\partial M_W}{\partial \alpha} \approx 0$ **if** $\delta = 0$

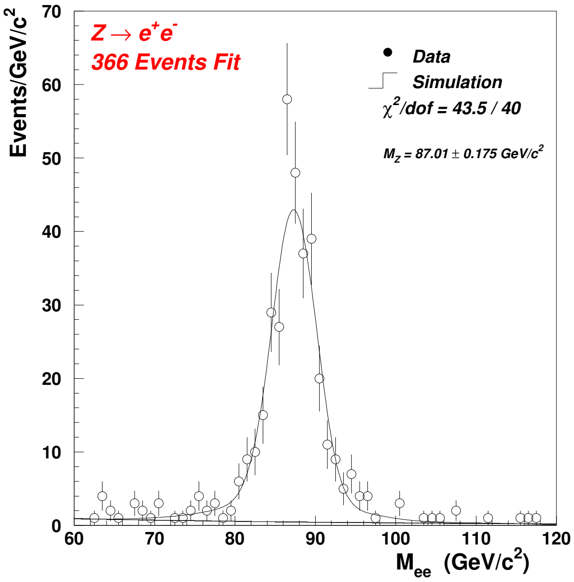
- **error from offset suppressed**

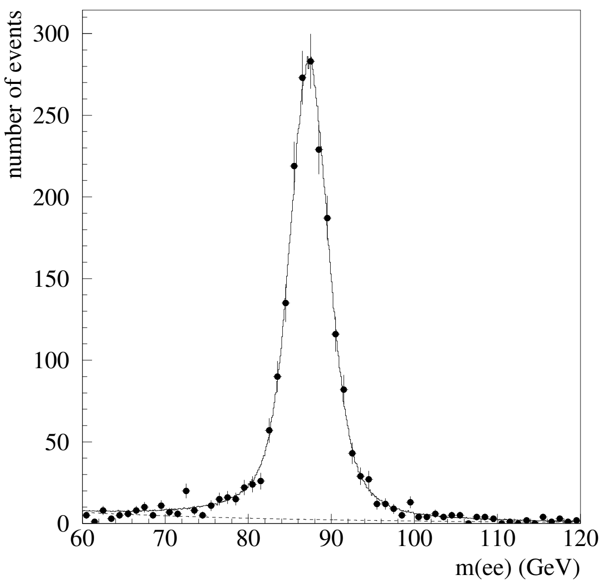
$\frac{\partial M_W}{\partial \delta} \approx \frac{f}{\alpha} \cdot \frac{(M_Z - M_W)}{M_Z}$

M_W - electron energy scale

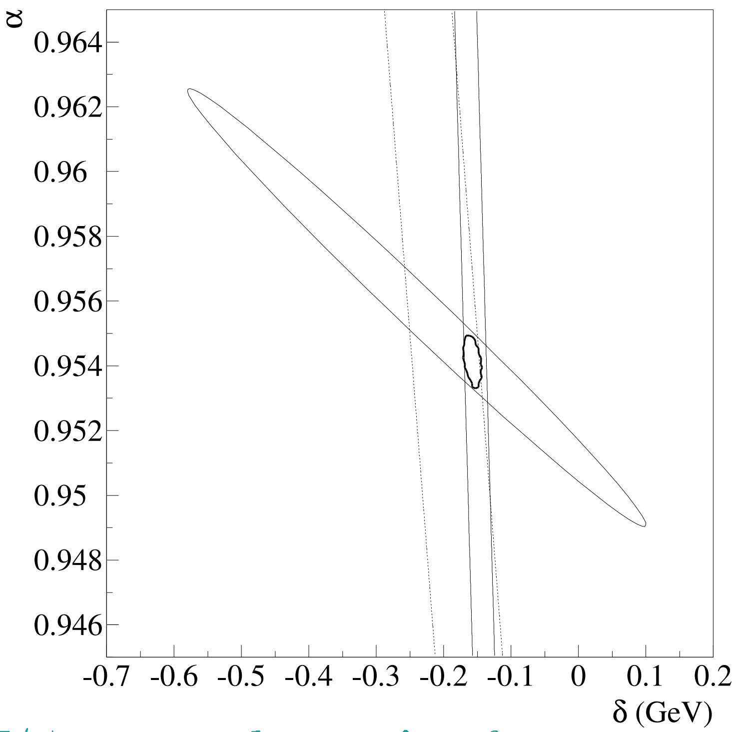








M_W - electron energy scale



⋆ π^0 **& J/ψ events determine δ**

⋆ Z **data determines α**

$$\alpha_{(1A)} = 0.9514 \pm 0.0018 \qquad \alpha_{(1B)} = 0.95329 \pm 0.00077$$

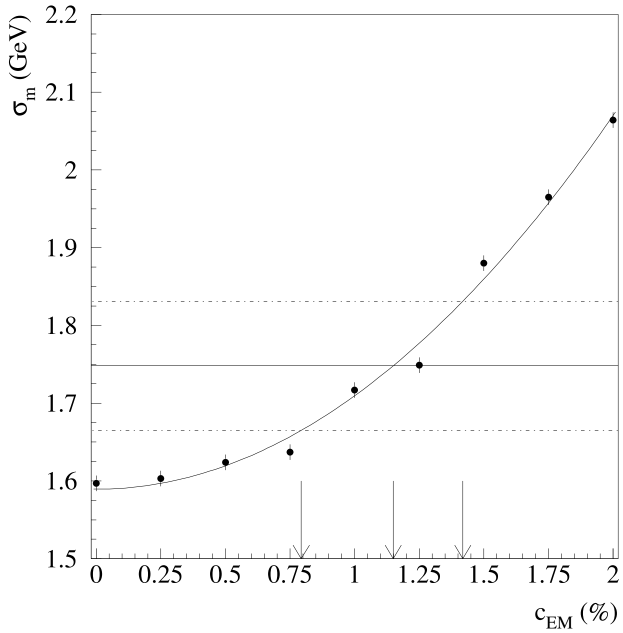
$$\delta = -0.158 \pm 0.015 \; ^{+.030}_{-.210} \text{ GeV}$$

Error on M_W due to electron energy scale:

run 1A: $\sigma(M_W) = 160$ MeV **run 1B:** $\sigma(M_W) = 65$ MeV

⋆ **error dominated by limited Z statistics**

M_W - Electron Energy Resolution



Use $Z \to ee$ events:

- **width of M_Z constrains EM energy resolution:**

EM Energy resolution:

$$\frac{\Delta E}{E} = \sqrt{C^2 + (\frac{S}{\sqrt{E_T}})^2 + (\frac{N}{E})^2}$$

from test beam have: $S = 0.13$ **and** $N = 0.4$
from Z data have

$\longrightarrow$ **Run 1B:** $C = (1.15\ ^{+0.27}_{-0.36})\%$

Error on M_W due to electron energy resolution:

run 1A: $\sigma(M_W) = 70\ \text{MeV}$ **run 1B:** $\sigma(M_W) = 23\ \text{MeV}$

Underlying Event Correction to $P_T(e)$

Electron energy measured in
$\Rightarrow$ **cone of** 5×5 **towers of size** $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$

- **energy is in cluster that is *not* due to electron from:**
  - **spectator interactions**
  - **recoil energy leaking into cluster**
  - **positive tails from zero-suppression of asymmetric pedestal distribution**
- **energy is lost from cluster that *is* due to electron from:**
  - **electron energy below zero-suppression cut-off**

Corrections obtained from

- $\star$ **comparing suppressed and non-suppressed minimum bias data**
- $\star$ **rotating away from electron in** W **events**

corrections in electron direction (Run 1A):

$$\vec{P}_T(e)^{meas} = \vec{P}_T(e) + \vec{U}(e) - \vec{U}_{zs} = \vec{P}_T(e) + 212 \text{ MeV}$$

In Run 1B, correction is made as a function of luminosity, η **and size recoil in electron direction**

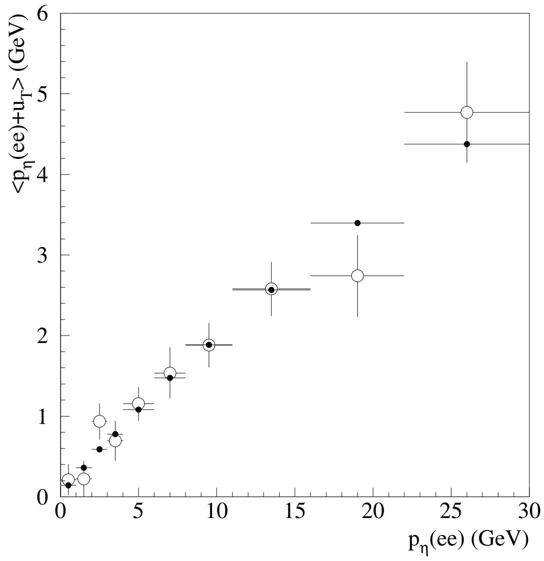
Error due to underlying event modelling:
run 1A: $\sigma(M_W) = 35$ MeV **run 1B:** $\sigma(M_W) = 16$ MeV

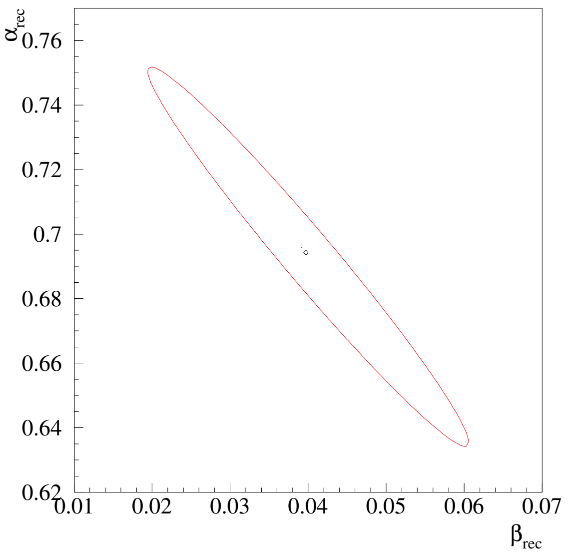
M_W - Recoil Energy Scale

$\Longrightarrow$ **determine hadronic relative to electron energy scale**
- due to differences in electron and hadron showering processes in calorimeter

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

$$E_T\text{−balance} \equiv [\vec{E}_T(ee) + \vec{E}_T(R)] \text{ vs } \vec{E}_T(ee)$$





have $E_T(R) = \mathcal{R}_R E_T(ee)$

with $\mathcal{R}_R = \alpha_R + \beta_R \log\, p_T(W)/(\mathrm{GeV})$

obtain $\alpha_R = 0.69 \pm 0.06$ **and** $\beta_R = 0.04 \pm 0.02$

Error on M_W due to hadronic energy scale:

Run 1A: $\sigma(M_W) = 50$ MeV **Run 1B:** $\sigma(M_W) = 23$ MeV

Recoil (Hadronic) Energy Resolution and Underlying Event

Recoil is composed of two parts ⇒

1. A symmetric part due to the spectator partons

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

- $\vec{U}_{mb}$ **is total** $\vec{E}_T$ **of minimum bias event**
- **luminosity distribution of data is modelled**
- $\alpha_{mb} = \#$ **minbias events needed to model** W **underlying event**

2. A part due to the initial P_T **of the boson**

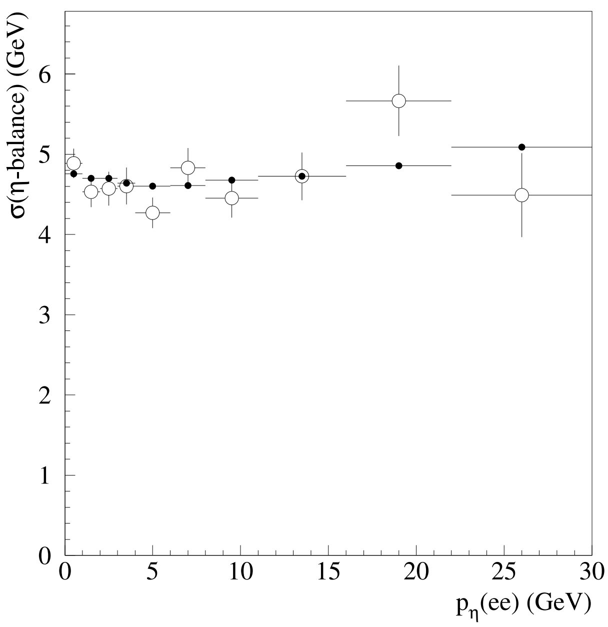
- **smear** $P_T(R)$ **by** $\sigma_{rec} = s_{rec}\sqrt{P_T(R)}$

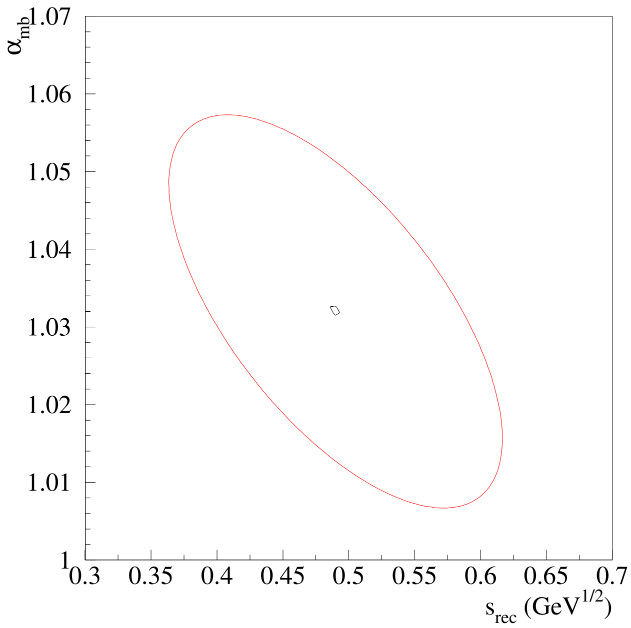
Recoil Resolution cont.

⇒ **determine s_{rec} and α_{mb} from width of E_T−balance (sensitive to hadronic resolution)**

⇒ **minimize χ^2 and obtain**

$s_{rec} = 0.49 \pm 0.14$ **and** $\alpha_{mb} = 1.03 \pm 0.03$





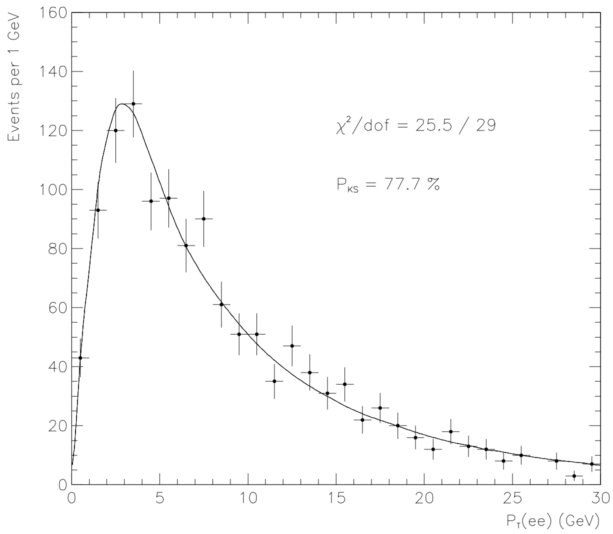
Error on M_W due to $C = \#$ min. bias events and hadronic energy resolution

Run 1A: $\sigma(M_W) = 88$ MeV **Run 1B:** $\sigma(M_W) = 33$ MeV

Errors from theoretical model

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

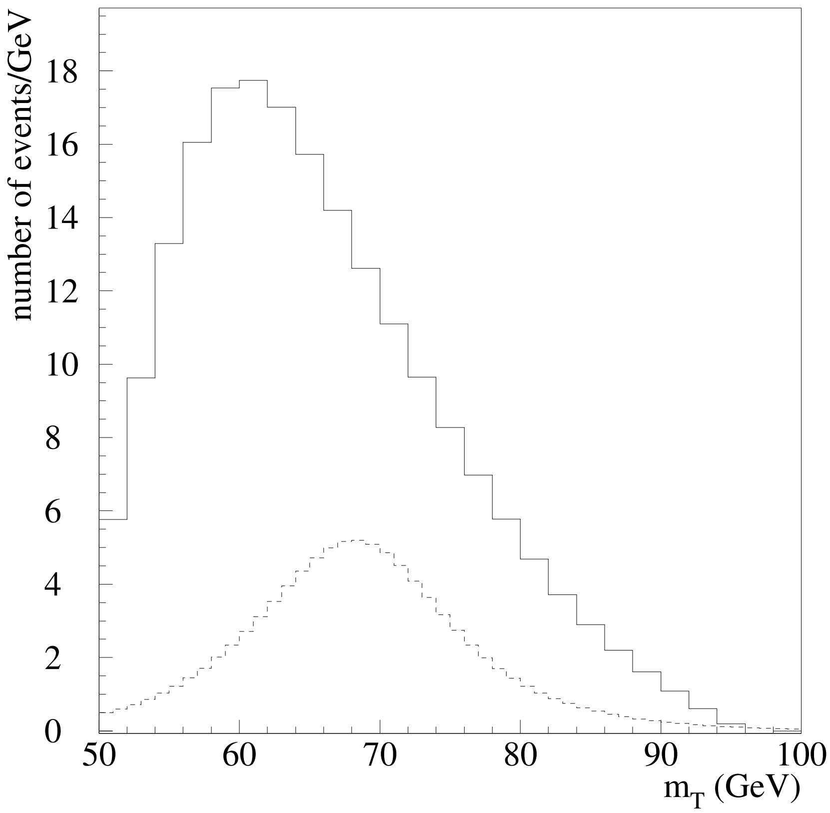
- **range of phenomenological parameters in calculation constrained by $E_T(Z)$ spectrum from data**
- **different models of pdf's are constrained using latest available world data**
- **vary these two contributions simultaneously**



Error on M_W due to theoretical model

Run 1A: $\sigma(M_W) = 65$ MeV **Run 1B:** $\sigma(M_W) = 24$ MeV

M_W - Backgrounds



⇒ **included in likelihood fitting procedure**

multi – jet ⇒ **QCD event with $\not\!\!E_T$ and where one jet fakes an electron**

$Z \rightarrow ee$ ⇒ Z **event in which one electron lost**

⇒ **Included in MC event generation:**

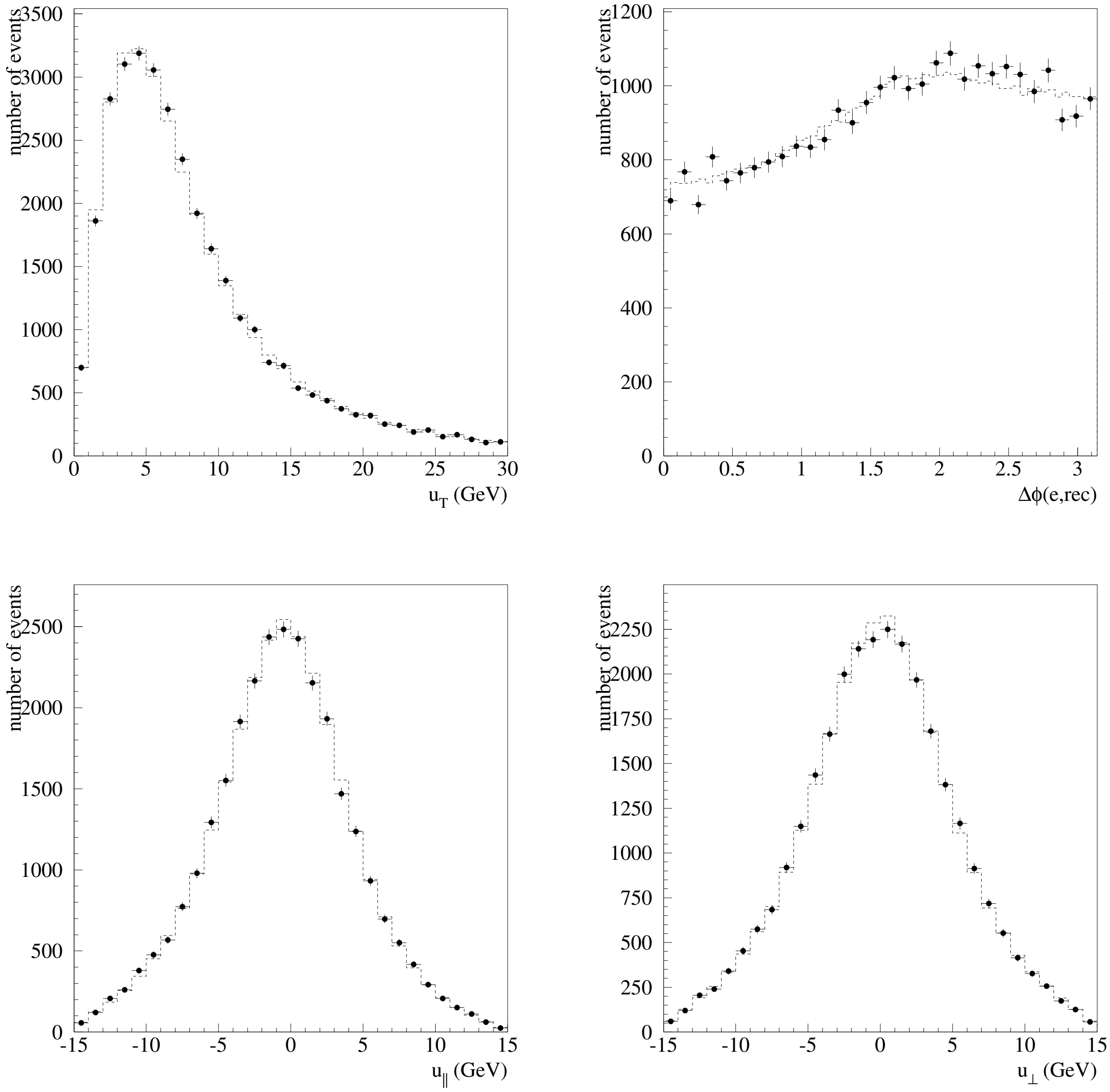
$W \rightarrow \tau\nu$ ⇒ **indistinguishable from** $W \rightarrow e\nu$ **events**

Error due to shape and size of backgrounds:

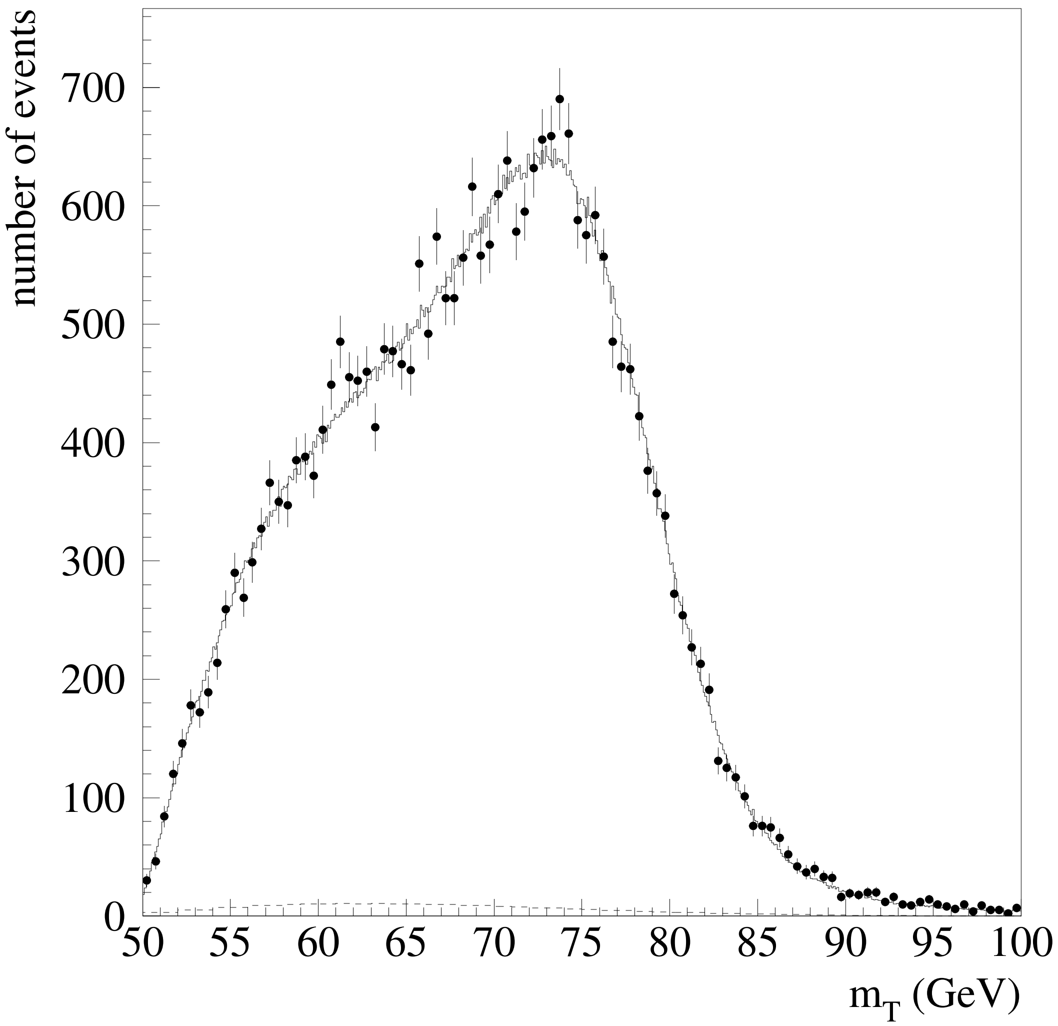
Run 1A: $\sigma(M_W) = 35$ MeV **Run 1B:** $\sigma(M_W) = 11$ MeV

Data and MC Comparison(Run 1B)

- ⋆ $u_{\|} = \vec{P}_T^{Rec} \cdot \hat{e} = P_T^{Rec} \cos\phi$
  $\rightarrow$ **hadronic energy in electron direction**
- ⋆ **A bias in $u_{\|}$ directly affects the M_T spectrum**
- ⋆ **$u_{\|}$ is sensitive to the recoil resolution**



Run 1B, M_W - from Fit to $M_T(W)$



$$\boxed{M_W(\mathrm{Run1B}) = 80.45 \pm 0.07(stat)\ \mathrm{GeV/c^2}}$$

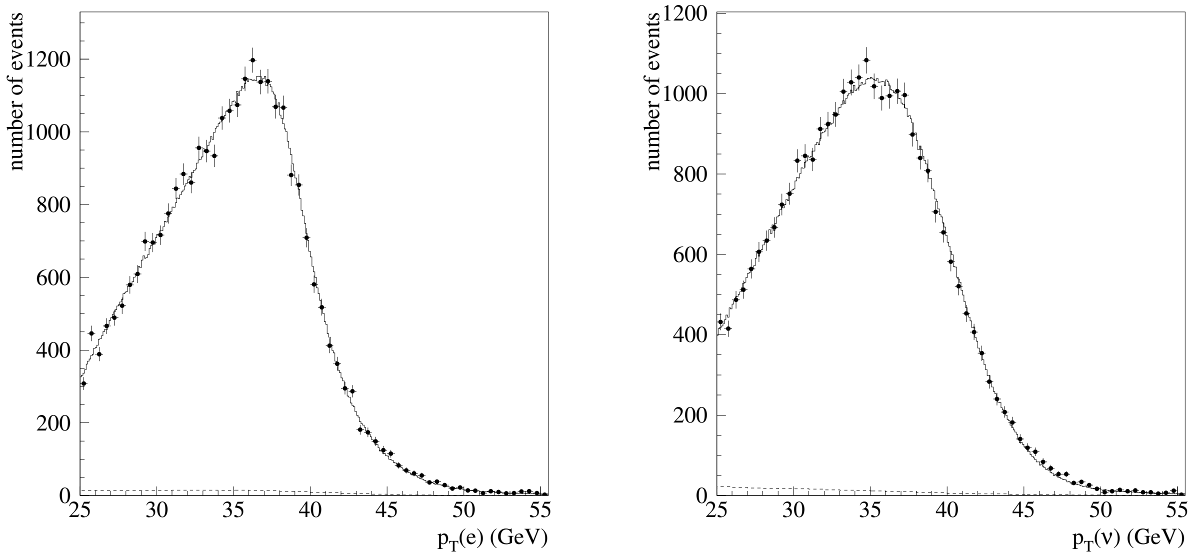
M_W - Summary of Errors

Source	$\sigma_{M(W)}$ **in** MeV/c^2 **Run 1B**	**Run 1A**
Statistical (W events)	**69**	**140**
Energy Scale (Z events)	**65**	**160**
Non-Uniform energy response (η)	**10**	**10**
Electron Angle Calibration	**28**	**50**
Electron Energy Resolution	**23**	**70**
Electron Energy Linearity	**20**	**-**
Electron Underlying Event	**16**	**35**
Efficiencies	**-**	**30**
Hadronic Energy Scale	**23**	**50**
Hadronic Energy Resolution	**-**	**65**
# of Min. Bias Events	**33**	**60**
P_T^W**, pdf, parton luminosity**	**24**	**65**
W **Width**	**9**	**20**
Radiative Decays	**20**	**20**
Backgrounds	**11**	**35**
Fit Error	**-**	**5**
Systematic Total	**70**	**165**
Total	**118**	**270**

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

$M_W(\text{Run1B}) = 80.450 \pm 0.070(stat.) \pm 0.065(scale) \pm 0.070(syst.)\ \text{GeV/c}^2$

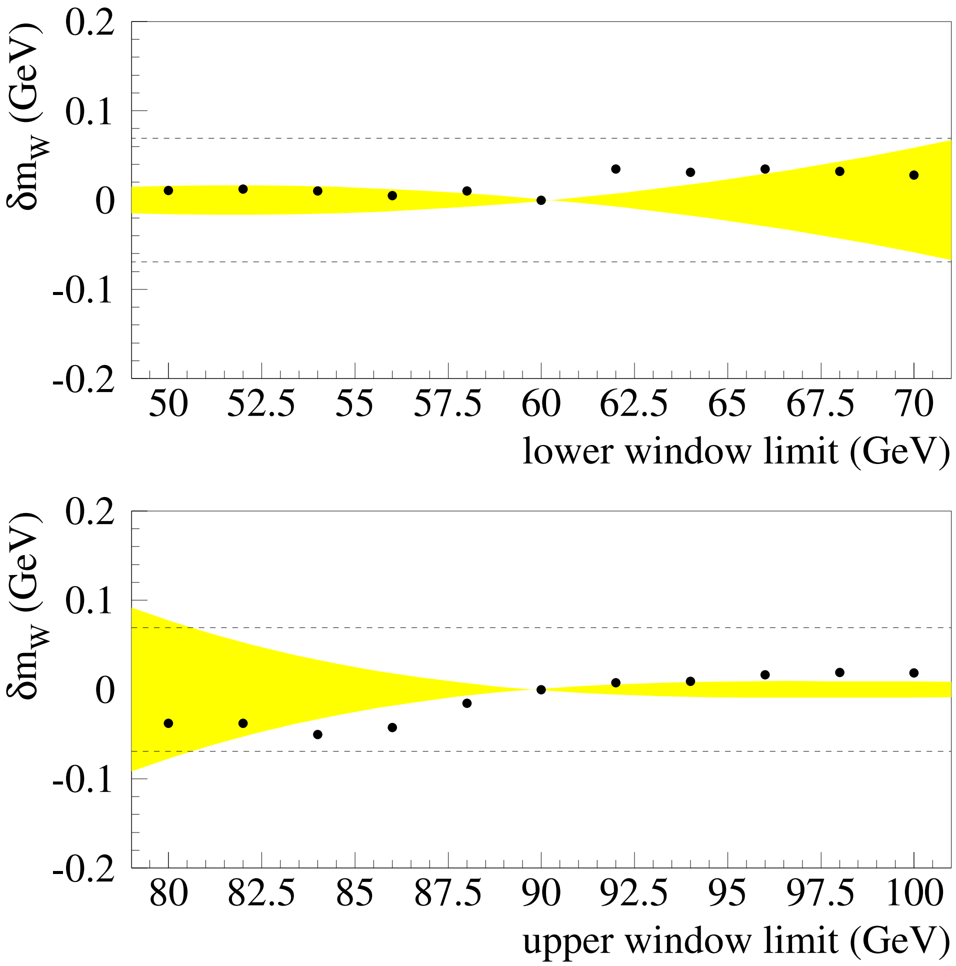
Run 1B: M_W - from P_T^e and P_T^ν fits
(Consistency Checks)



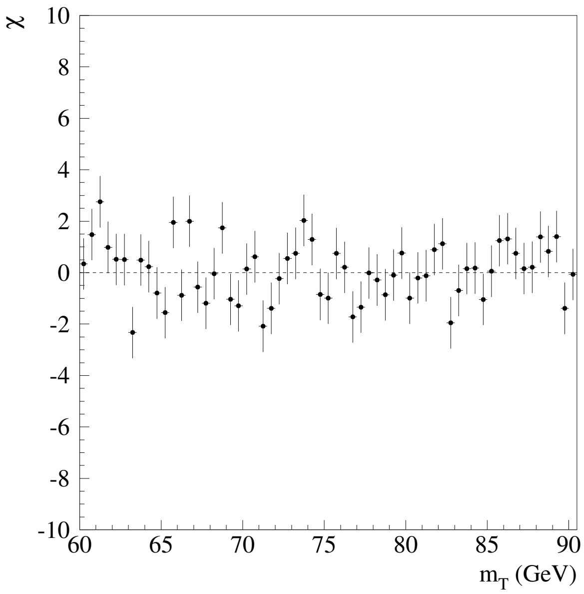
M_W **from** $P_T(e)$ **fit** $= 80.49 \pm 0.14$ GeV/c^2

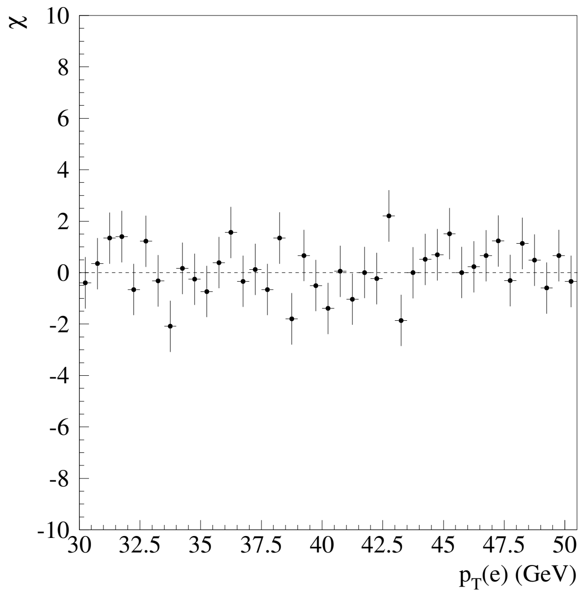
M_W **from** $P_T(\nu)$ **fit** $= 80.42 \pm 0.18$ GeV/c^2

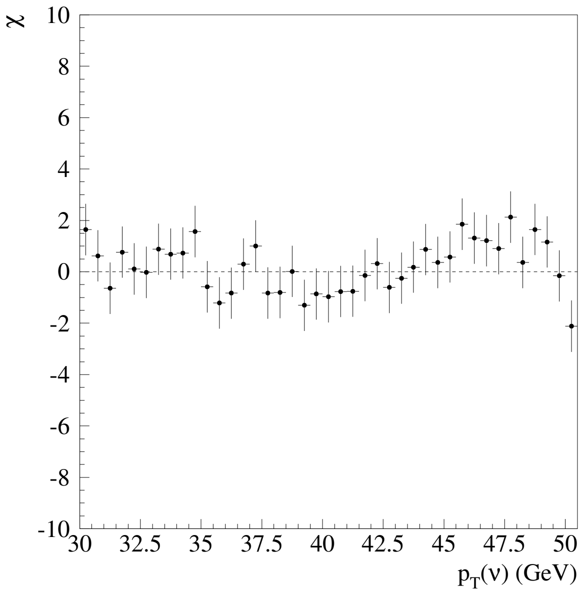
Run 1B, variation with fitting window, fit to $M_T(W)$



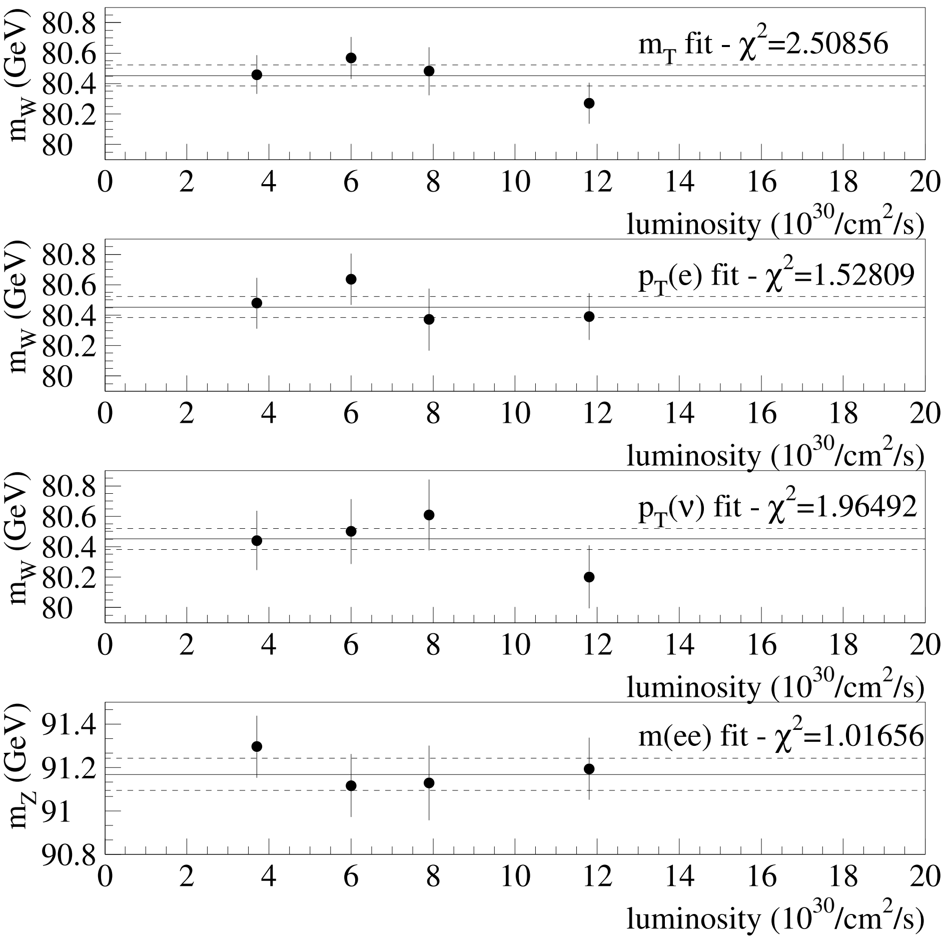
Run 1B, χ^2 of fits







Run 1B, Consistency Checks



Current Results of M_W from DØ experiment at Fermilab

- **DØ Run 1A data [PRL 77, 3309 (1996)]**

$$M_W = 80.35 \pm 0.27 \text{ GeV/c}^2$$

- **DØ Run 1B data [preliminary, 28 Mar 97]**

$$M_W = 80.45 \pm 0.12 \text{ GeV/c}^2$$

- **DØ Combined 1A + 1B [preliminary, 28 Mar 97]**

$$M_W = 80.44 \pm 0.11 \text{ GeV/c}^2$$

- **expect DØ error to decrease with addition of events with electrons in forward rapidity region ⇒**

$$\Delta M_W \approx 100 \text{ MeV/c}^2$$

Current Results of M_W from CDF experiment at Fermilab

- **CDF Run 1A data ($W \to e\nu, \mu\nu$)**

$$M_W = 80.41 \pm 0.18 \text{ GeV/c}^2$$

- **CDF Run 1B data ($W \to \mu\nu$ only) [prelim., Feb 97]**

$$M_W = 80.43 \pm 0.16 \text{ GeV/c}^2$$

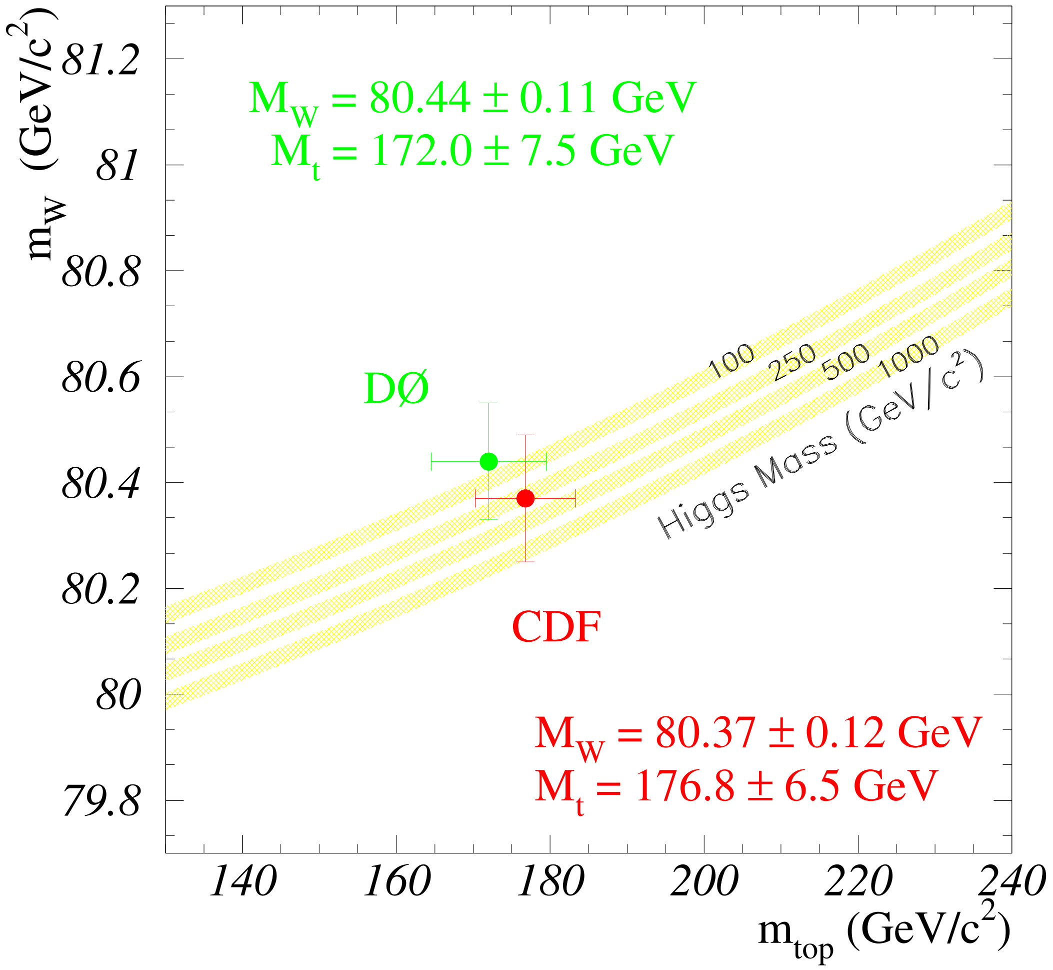
- **CDF Combined 1A + 1B data [preliminary, Feb 97]**

$$M_W = 80.375 \pm 0.120 \text{ GeV/c}^2$$

- **expect CDF error to decrease with addition of $W \to e\nu$ events $\Rightarrow$**

$$\Delta M_W \approx 100 \text{ MeV/c}^2$$

Constraints on Higgs Mass - May 1997



M_W - Using M_T^W/M_T^Z Ratio Method

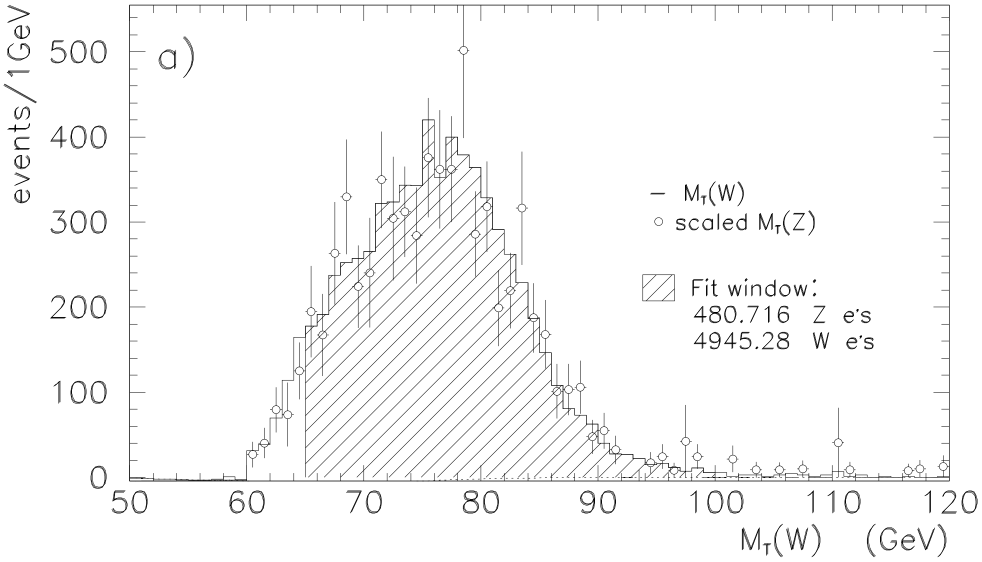
!! Preliminary Results - using run 1A data sample

- **assume W and Z production and decay are similar**
- **treat $Z \rightarrow ee$ events as $W \rightarrow e\nu$ events**
  - many systematic errors cancel
- **turn Z into W by treating 1 e's as a ν and computing M_T^Z**
- **scale down M_T^Z distribution and compare with M_T^W**
- **M_W determined from scale factor that gives best match of M_T distributions**

Dominate Corrections to Data $\Rightarrow$

- **scaled-down Z has better resolutions - must "oversmear" e and recoil in Z**
- **ν unrestricted(restricted) in $W(Z)$ events**
  - apply acceptance corrections
- **differences in W and Z production**
- **differences in W and Z radiative corrections**

M_W - Using M_T^W/M_T^Z Ratio Method



$$\Rightarrow M_W = 80.16 \pm 0.36(stat) \pm 0.075(syst) \text{ GeV}$$

Features of Ratio Method - compared to Standard Method

- **lower systematic errors (but higher errors due to Z statistics)**
- **may provide better measurement in higher luminosity, higher statistics running**
- **important cross-check on Standard Method**
  (can also compare p_T^e and p_T^ν)

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 !!

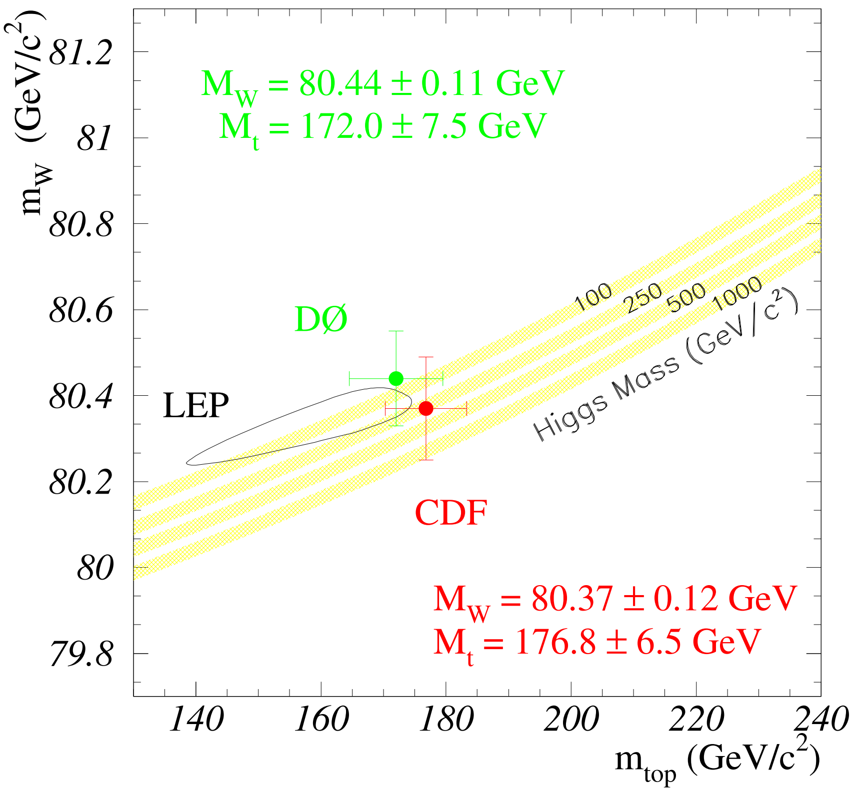
The determination of $sin^2\theta_W$ from νN scattering, when combined with M_Z gives (CCFR $\rightarrow$ Fnal-conf-96/227-E)

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

$\Rightarrow$ 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

Indirect measurement from LEP2 workshop (HEP-PH 9602352)



LEP EWWG

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

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

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

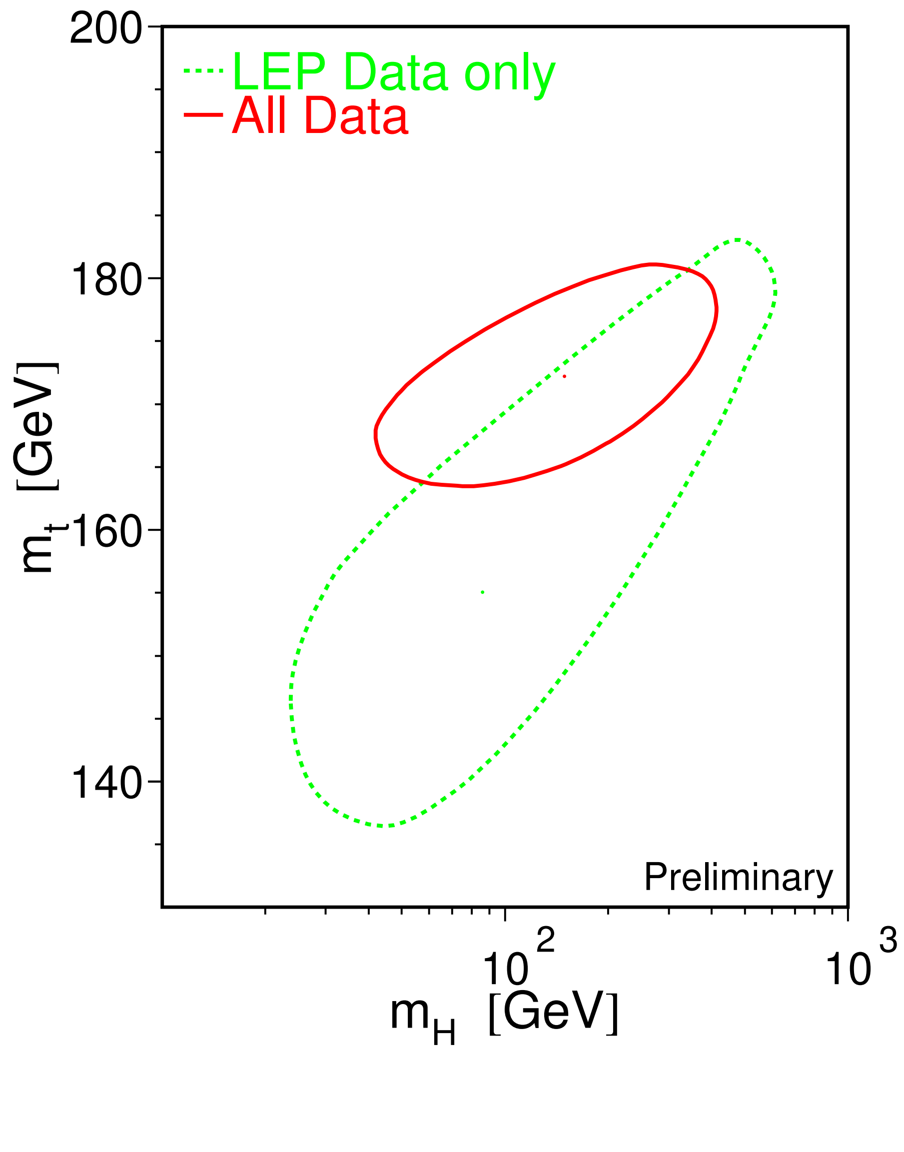
$$M_W = 80.359 \pm .051 \text{ GeV}$$

Electroweak results from LEP/SLD [CERN-PPE/96-183]
(LEP ElectroWeak Working Group, summer 1996)

	Measurement with Total Error	Standard Model	Pull
a) LEP			
line-shape and lepton asymmetries:			
M_Z **[GeV]**	91.1863 ± 0.0020	**91.1861**	0.1
Γ_Z **[GeV]**	2.4946 ± 0.0027	**2.4960**	-0.5
σ^0_{had} **[nb]**	41.508 ± 0.056	**41.465**	0.8
R_l	20.778 ± 0.029	**20.757**	0.7
$A^{0,l}_{FB}$	0.0174 ± 0.0010	**0.0159**	1.4
τ **polarization:**			
A_τ	0.1401 ± 0.0067	**0.1458**	-0.9
A_e	0.1382 ± 0.0076	**0.1458**	-1.0
b and c quark results:			
$R_b{}^{(a)}$	0.2179 ± 0.0012	**0.2158**	1.8
$R_c{}^{(a)}$	0.1715 ± 0.0056	**0.1723**	-0.1
$A^{0,b}_{FB}$	0.0979 ± 0.0023	**0.1022**	-1.8
$A^{0,c}_{FB}$	0.0733 ± 0.0049	**0.0730**	0.1
$q\bar{q}$ **charge asymmetry:**			
$sin^2\theta^{lept}_{eff}$	0.2320 ± 0.0010	**0.23167**	0.3
b) SLD			
$sin^2\theta^{lept}_{eff}$ (A_{LR})	0.23061 ± 0.00047	**0.23167**	-2.2
R_b	0.2149 ± 0.0038	**0.2158**	-0.2
A_b	$0.863 \pm 0.049z$	**0.935**	-1.4
A_c	$0.625 \pm 0.084z$	**0.667**	-0.5
c) p$\bar{\text{p}}$ and νN			
m_W [GeV] (p$\bar{\text{p}}$)	80.356 ± 0.125	**80.353**	**0.0**
$1 - m_W^2/m_Z^2$ (νN)	0.2244 ± 0.0042	**0.2235**	**0.2**
m_t **[GeV]** (p$\bar{\text{p}}$)	175 ± 6	**172**	**0.5**

m_t vs m_H - from LEP EWWG

SM fits of Data - Spring '96



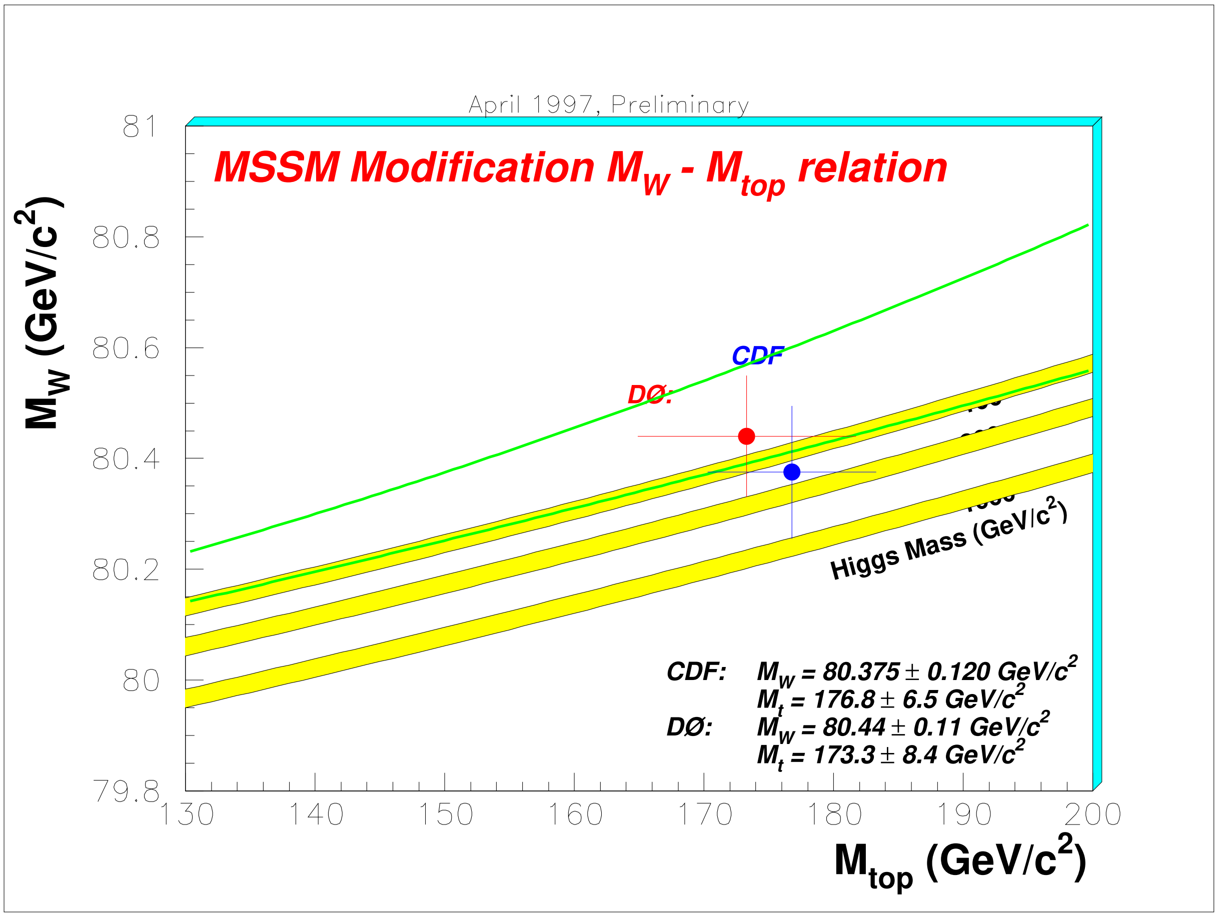
- **shows large correlation between m_t and m_H**
- **SM fit for m_t, α_s and m_H $\Rightarrow$**

	LEP data only	all data + m_t
m_t	155^{+18}_{-13}	$\mathbf{172 \pm 6}$
m_H	86^{+202}_{-51}	149^{+148}_{-82}

  - **LEP data prefer light top and Higgs**

M_W vs m_t - beyond SM

from LEP EWWG, Spring '96



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

LEP2 - New Direct M_W !

summer 1996 $\rightarrow e^+e^-$ **at** $\sqrt{s} = 161$ GeV
fall 1996 $\rightarrow e^+e^-$ **at** $\sqrt{s} = 172$ GeV

Next will go to $\sqrt{s} = 184, 192$ **until have** $500\ \mathrm{pb}^{-1}$ **for each of the 4 experiments (Aleph,Delphi,L3,Opal)**

Methods for Measuring $M_W \Rightarrow$

- **Threshold Method (used at** $\sqrt{s} = 161$**):**
  $\Rightarrow$ **determine** M_W **from turn-on of cross section**
  - compare measured event rate of W^+W^- **pairs to predictions as function of** M_W **for given** $\sqrt{s}$
- **Direct Reconstruction of Decay Products:**
  $W^+W^- \rightarrow q\bar{q}q\bar{q}$ **- interconnection effects**
  $W^+W^- \rightarrow qqe\nu$
- **Lepton End-Point Energy:**
  $W^+W^- \rightarrow q\bar{q}l\nu$

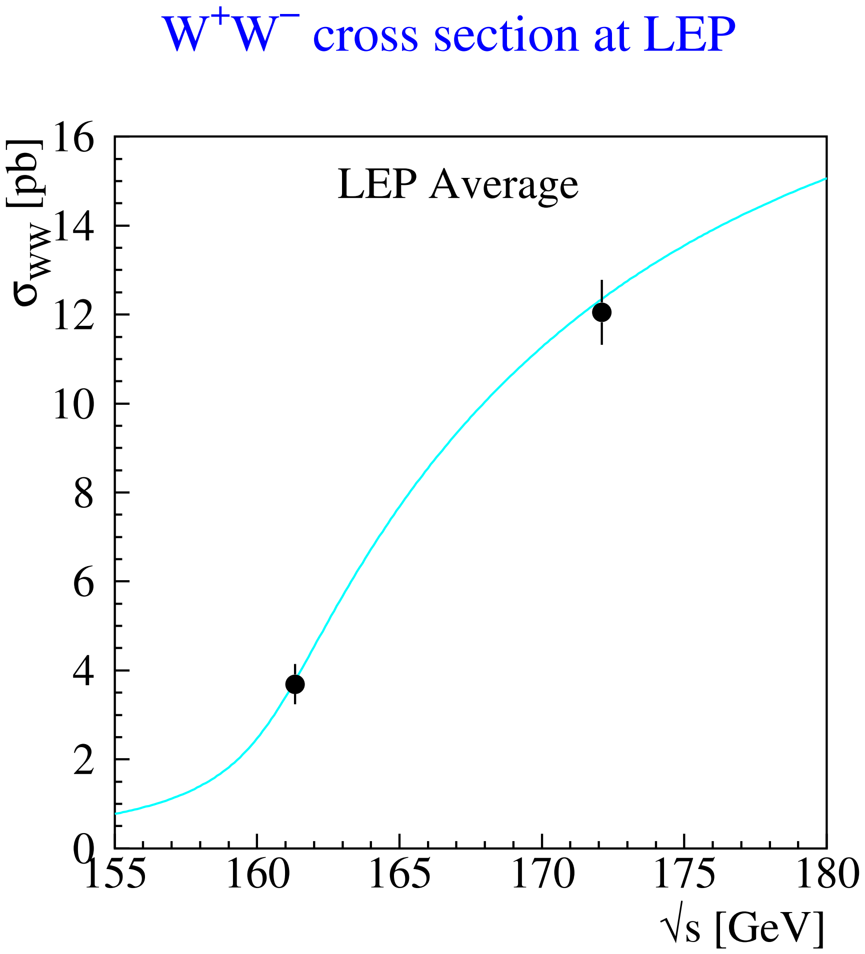
$\star$ M_W **for all 4 experiments as of LaThuile/Moriond in Feb97:**

$$\sqrt{s} = 161, \ \ M_W = 80.40 \pm 0.22 \text{ GeV}$$

$$\sqrt{s} = 172, \ \ M_W = 80.37 \pm 0.19 \text{ GeV}$$

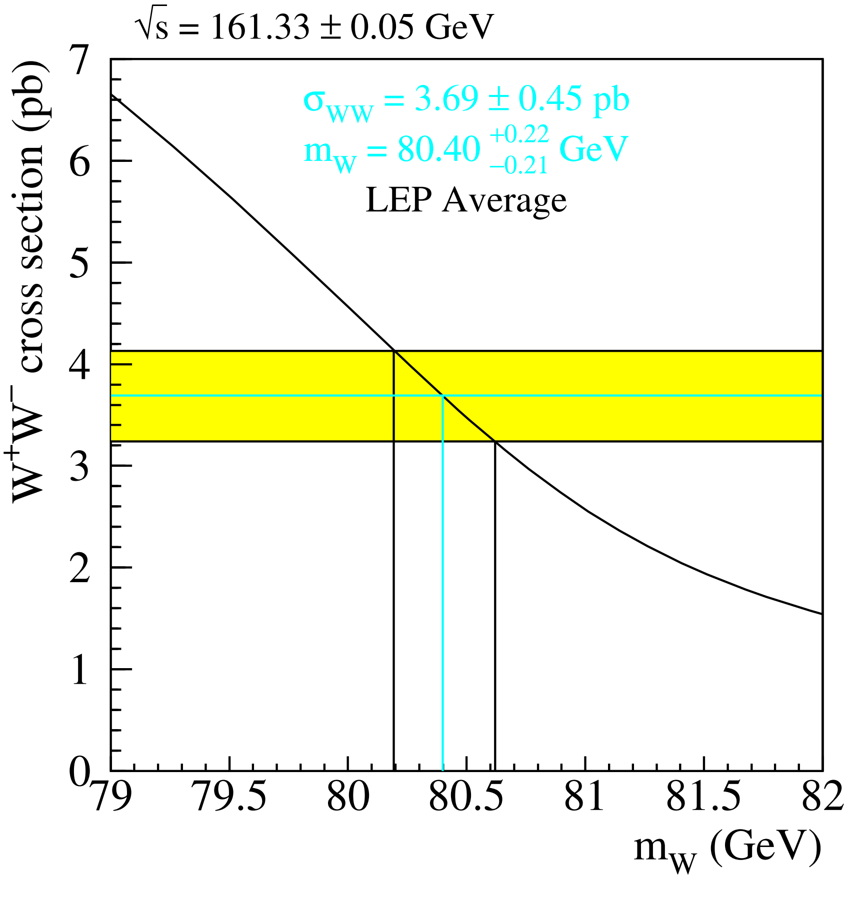
Combined Result:

$$M_W = 80.38 \pm 0.14 \text{ GeV}$$



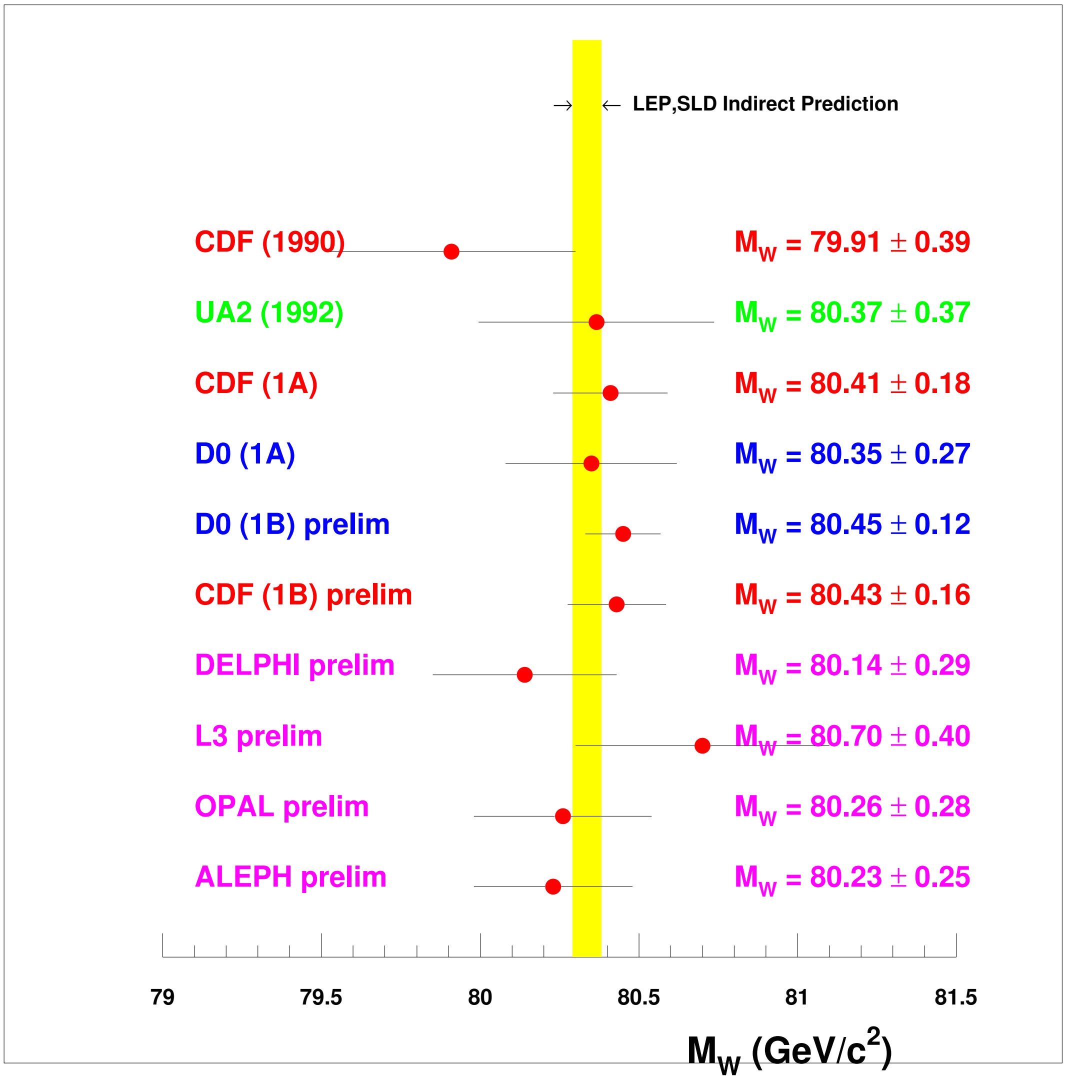
Feb 28, 1996
LEP EW Working Group

m_W from σ_{WW} at 161 GeV

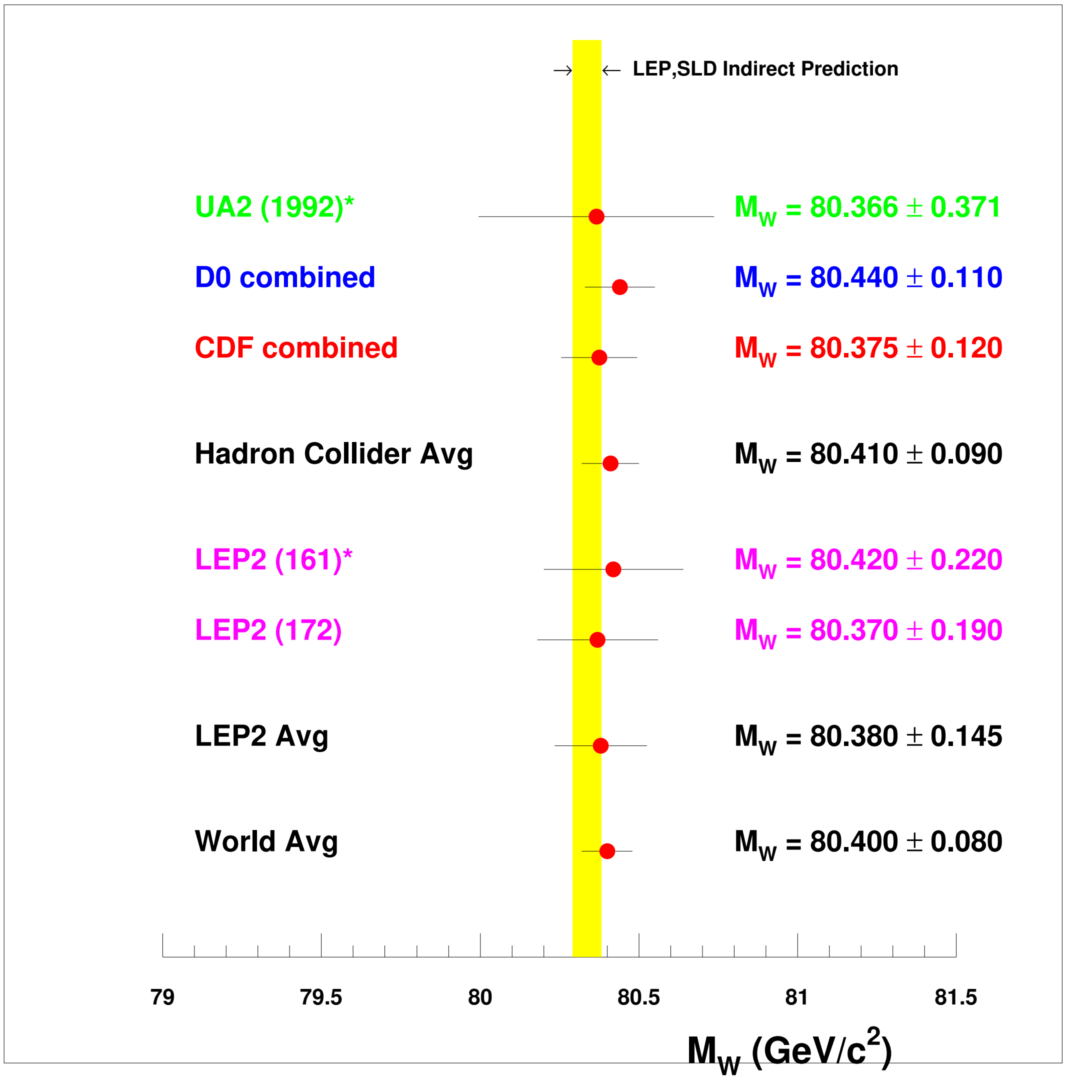


Final LEP 161 GeV W mass
LEP EW Working Group

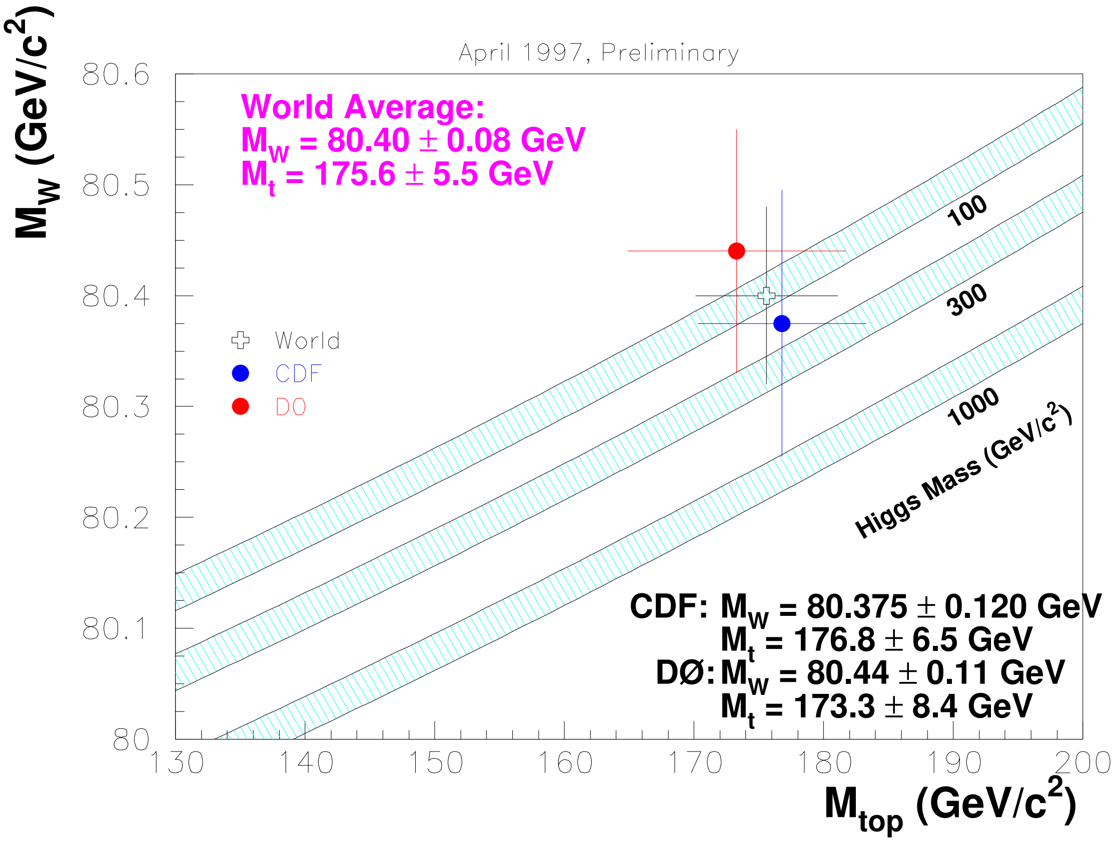
Current Results of M_W



Current Results of M_W



Current Constraints on Higgs Mass



Future M_W Measurements

- **Tevatron Run 1:**
  DØ & CDF $\rightarrow \Delta M_W \approx 80$ **MeV**
  $\rightarrow \Delta m_{top} \approx 5$ **GeV**

- **Tevatron Run 2:** $\Delta M_W \approx 40$ **MeV,** $\Delta m_t \approx 3$ **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