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

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Will Cover...

- **Elementary Particle Physics**
- **The ElectroWeak 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**

molecules → atoms → p, n, e^- **→ quarks, leptons → ?**

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

$\Rightarrow$ **ElectroWeak:**

$\star$ **unified theory describing the electromagentic and weak forces**

$\star$ **discovery of W, Z in 1983 (UA1,UA2 experiments at CERN)**

$\Rightarrow$ **Quantum ChromoDynamics (QCD):**

$\star$ **theory describing strong force between colored objects (quarks and gluons)**

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

$\rightarrow$ **break the electroweak symmetry by introducing Higgs boson**

$\rightarrow$ **Higgs mechanism gives mass to $W^{\pm}, Z$ and fermions**

Experiments in High Energy Physics

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

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

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

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

DØ detector at Fermilab

⋆ **designed in early-1980's**
→ **large multi-purpose detector designed to study top, electroweak, QCD, new physics, etc.**

At that time:

⇒ **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**

⋆ **mid 1984, experiment approved**

⋆ **Feb 1992, detector completed**

⋆ **May 1992, first collisions**

⋆ **Aug 1992, commissioning completed, start taking data**

⋆ **1992-1993 Data Run 1A**

⋆ **1994-1995 Data Run 1B - (5 times the data as 1A)**

⋆ **1995** *top* **quark discovered !**

⋆ **1999 Data Run 2 - (20 times the data as run 1)**

$\Rightarrow$ Use the Fermilab Tevatron collider

Need high energies to study high-mass particles

$\star$ **remember!** $E = mc^2$

$\star$ **We measure properties of final-state particles from collisions**

$$p + \bar{p} \rightarrow X$$

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

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

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

- **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**

DØ Physics Menu

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

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

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

  - **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**

⇒ calorimeter - energy measurement of charged and neutral particles

⇒ muon system - momentum measurement of muons

⇒ tracking system (drift chambers) - charged particle tracking

electrons

photons

muons

quarks,gluons ⟶ "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 (minimum bias) 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

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:

$\rightarrow$ **Data is sufficiently precise**
- must include radiative corrections

$\Rightarrow$ **lump radiative corrections into** Δr

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

$\Rightarrow$ **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**

$\Longrightarrow$ **can write as**

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

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

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

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

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

Motivation

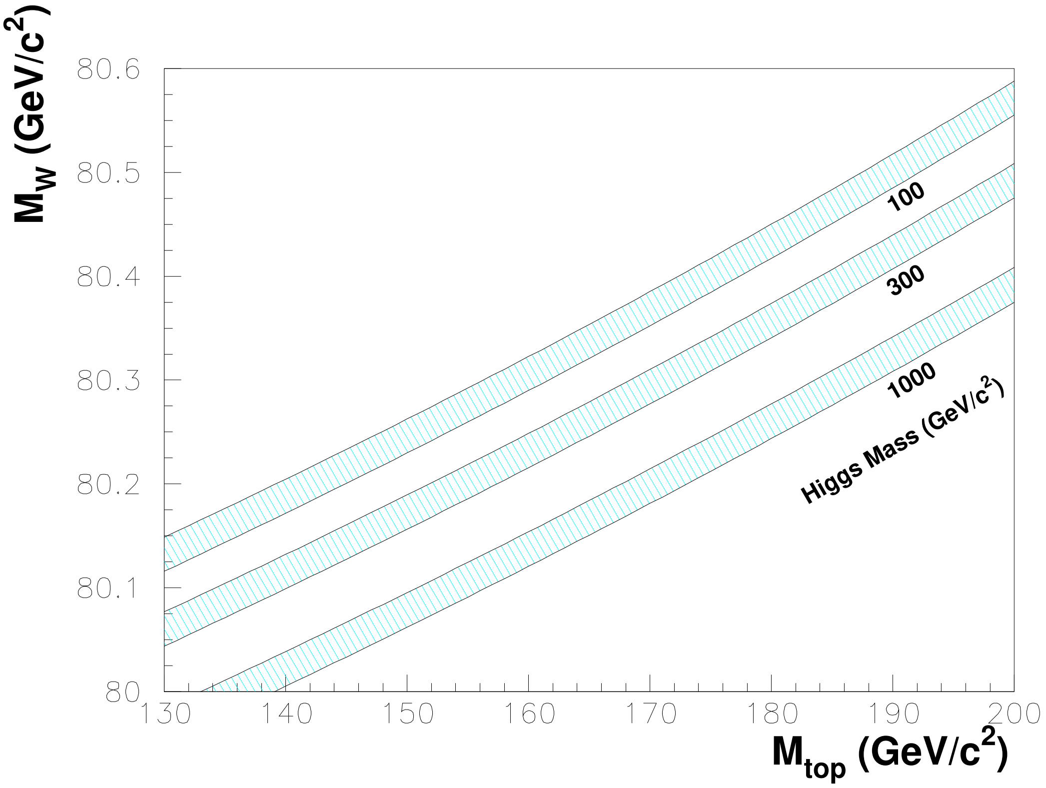
⇒ **Precision Measure of M_W provides**

- ⋆ **test of SM at level of radiative corrections**
  → **sensitive to M_{top} and M_{Higgs}**
  → **with M_{top} can constrain M_{Higgs}**

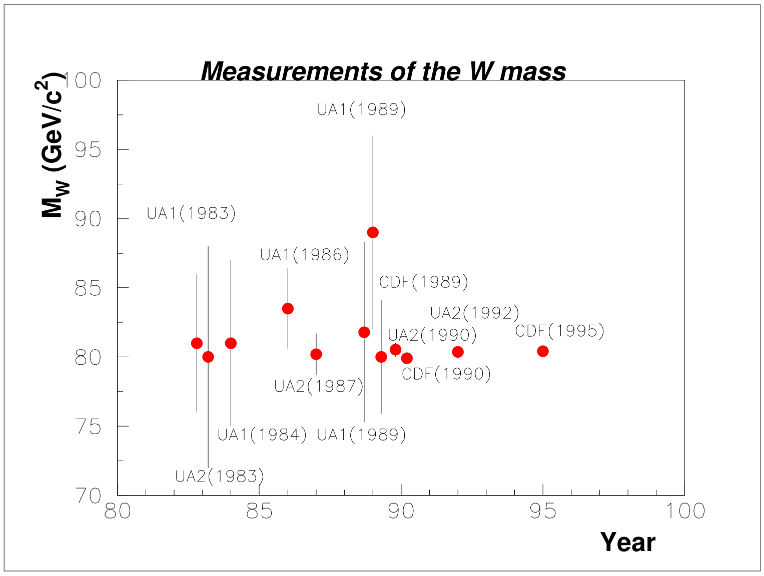
- ⋆ **Improvement in precision can further constrain allowed values of M_{Higgs} in SM or parameter space of other models**

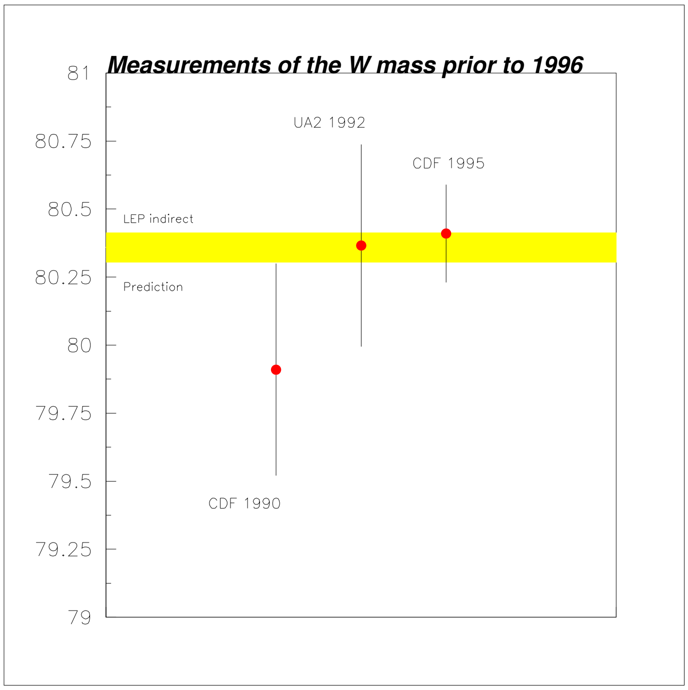
- ⋆ **A precise value of M_W from direct measurement could contradict the value determined indirectly, indicating breakdown of SM**

M_W vs. M_{top} - Higgs Mass Dependence



Previous Measurements of M_W





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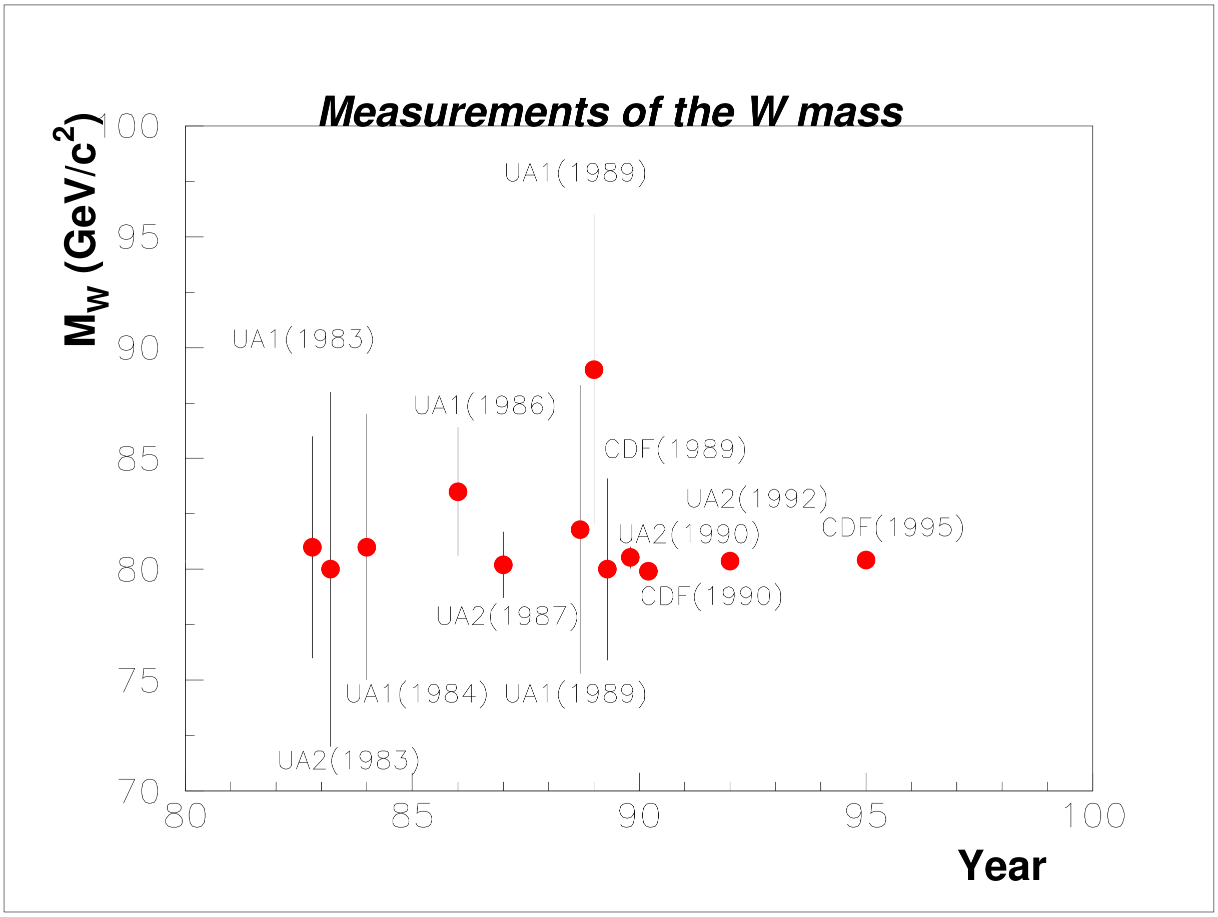

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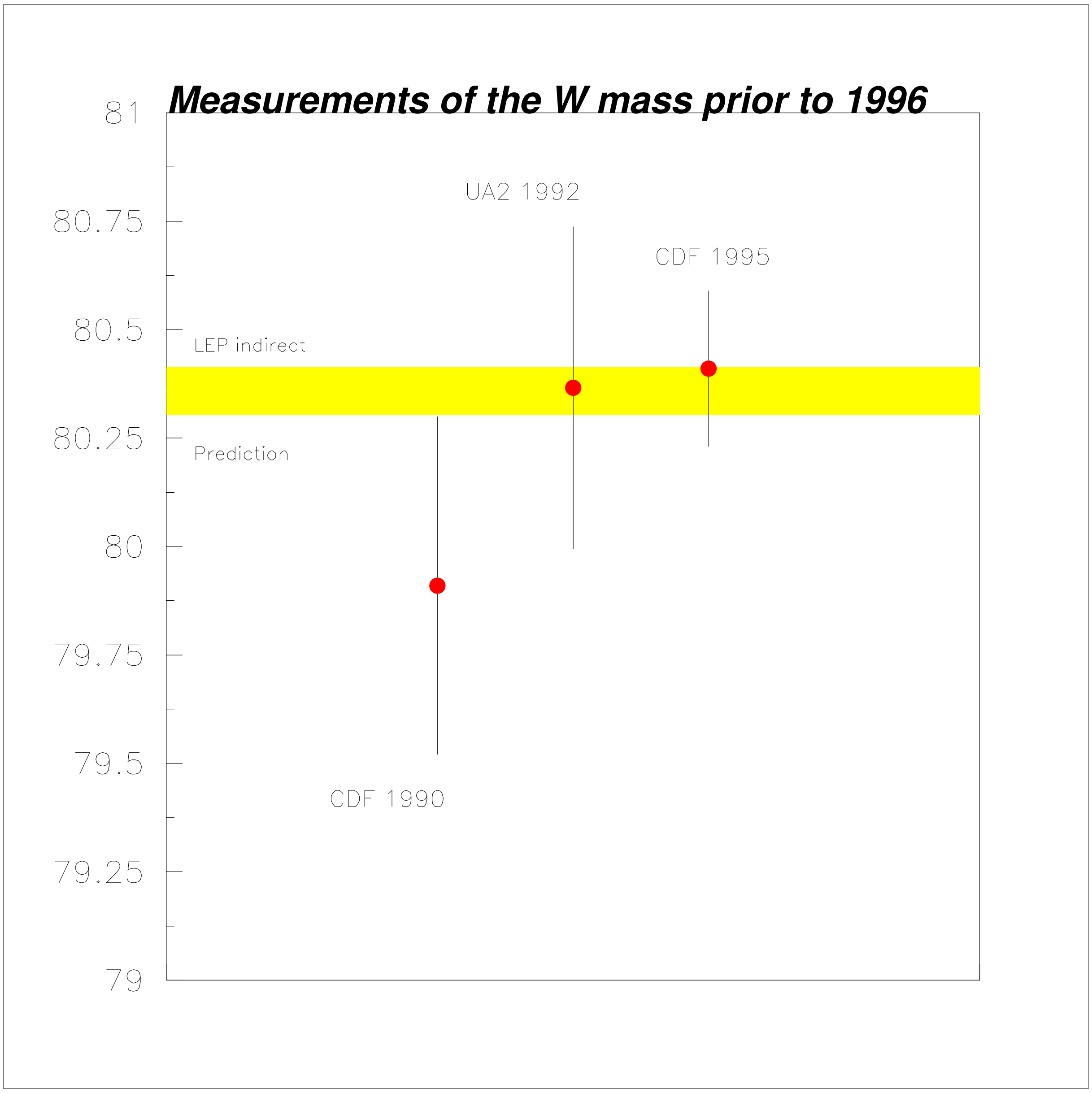


Inclusive W and Z Production

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

$\Longrightarrow$ **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 - Measurement by DØ

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

$\Rightarrow$ **Preliminary results based on Run 1B data**
- **presented for first time 28 March 1997 at Fermilab**

M_W - Quantities Measured

We measure 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 $\vec{E}_T(R) \equiv -\vec{E}_T(W)$

Measured Quantities:

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

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**

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

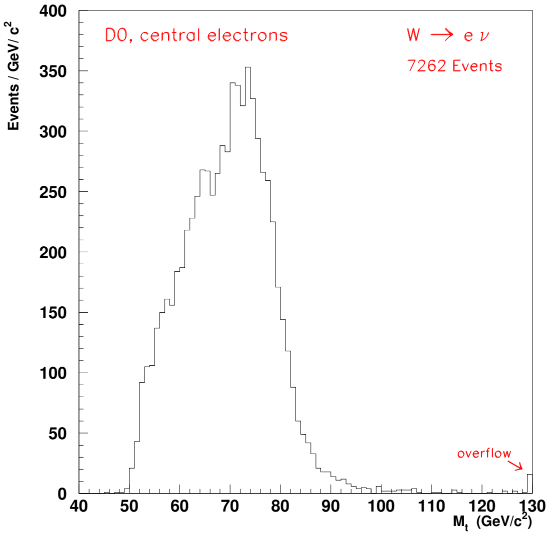
$\star$ **invariant mass of Z**

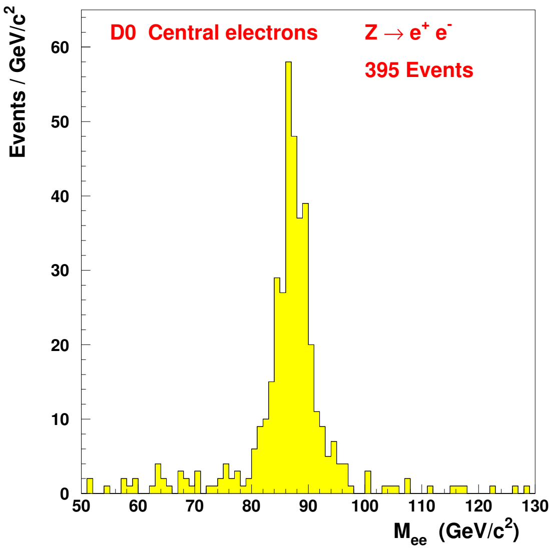
$$M_Z = \sqrt{2E^{e1} E^{e2} (1 - \cos\varphi)}$$

M_W - Event Sample

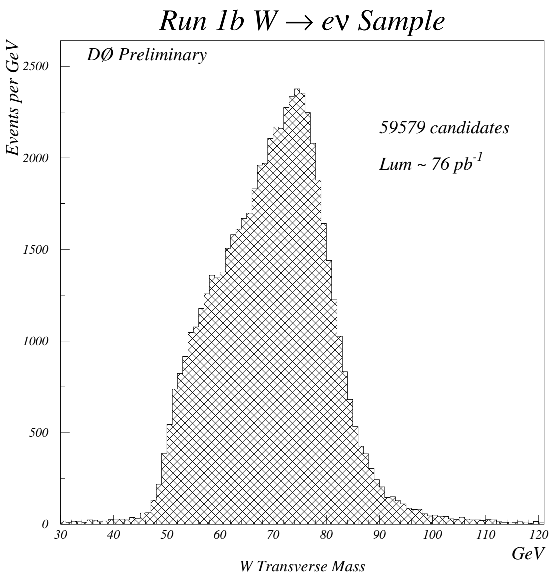
		# events:	1A	1B
$W \to e\nu$			**7234**	**32856**
⋆ e **in central calorimeter:**	$\lvert\eta\rvert < 1.2$			
⋆ **electron:**	$p_T^e > 25$ **GeV**			
⋆ **neutrino:**	$\not\!\!E_T > 25$ **GeV**			
⋆ W **transverse momentum:**	$P_T^W < 30$ **GeV**			
⋆ **transverse mass (1A)**	$50 < M_T^W < 110$ **GeV**			
$Z \to ee$			**366**	**1562**
⋆ e**'s in central calorimeter:**	$\lvert\eta\rvert < 1.2$			
⋆ **2 isolated electrons:**	$p_T(e) > 25$ **GeV**			
⋆ **invariant mass (1A)**	$70 < M_Z < 110$ **GeV**			

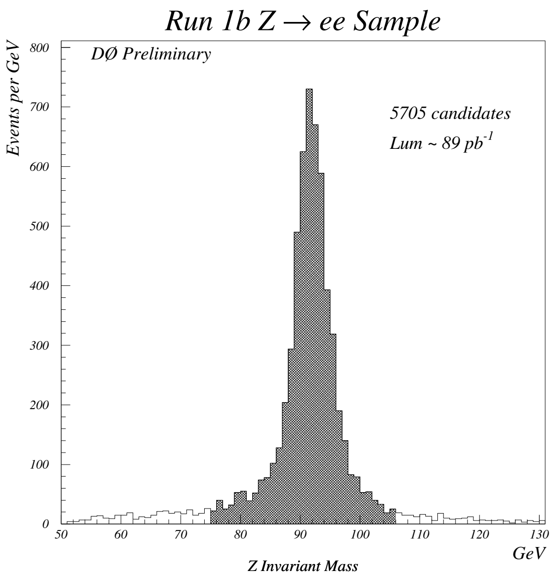
Run 1A - spectra:





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**

M_W - Measurement Strategy

$\longrightarrow$ **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 $Z \to ee$ 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: $W \rightarrow e\nu\gamma$ generated according to calculation by Berends & Kleiss**

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

- **boost decay products to lab frame**

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

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

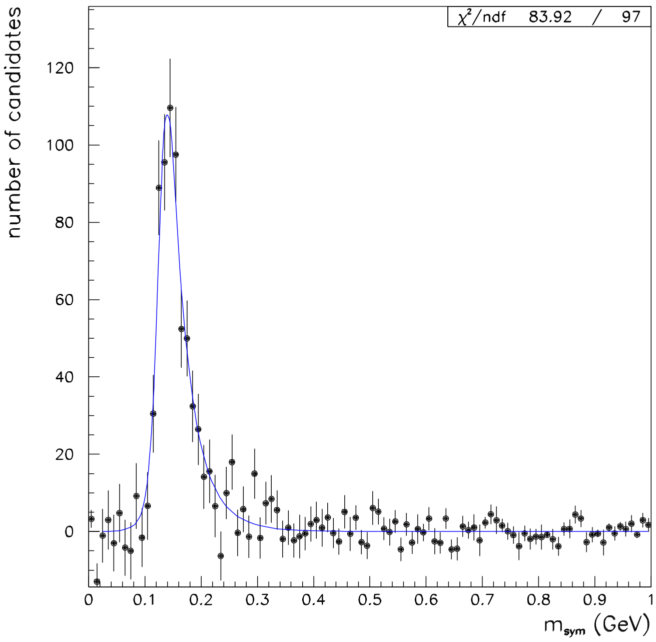
M_W - electron energy scale

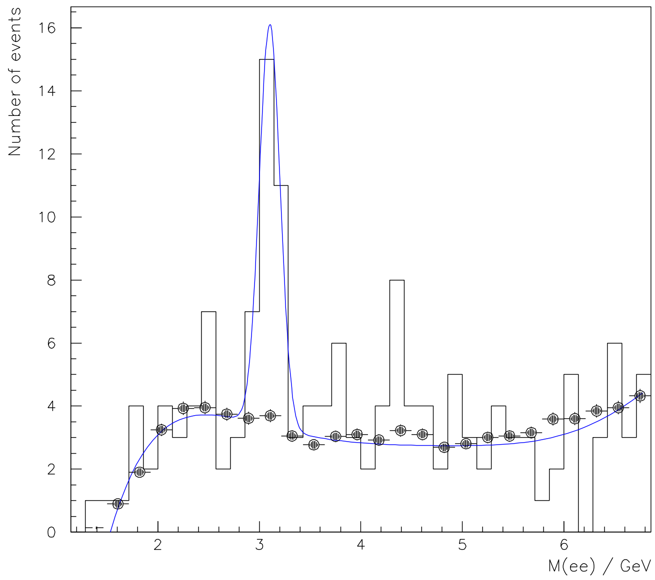
→ **Determine electron energy scale using J/ψ, π^0, and Z event samples**

→ **electron energy response:**

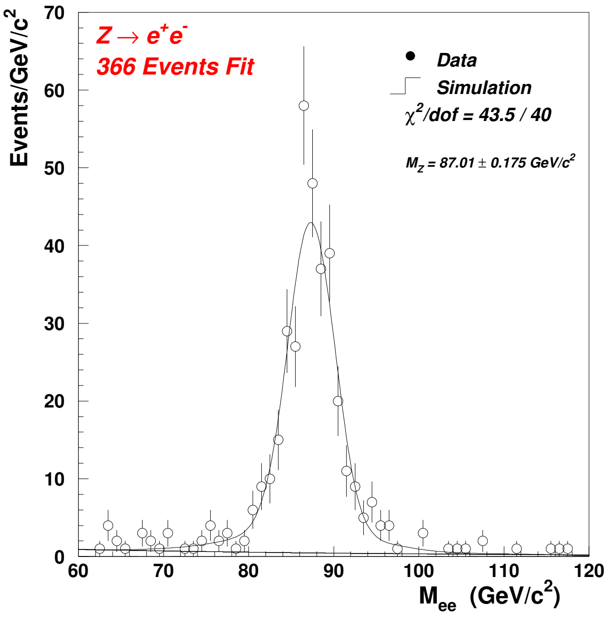
$$E^{meas} = \alpha E^{true} + \delta$$

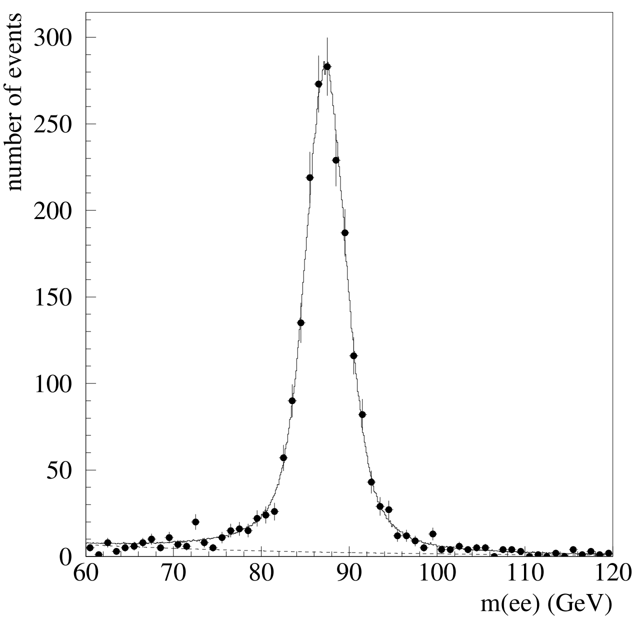
⋆ **compare mass values measured to known values to determine α, δ**





M_W - electron energy scale





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

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

Error on M_W due to electron energy scale:

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

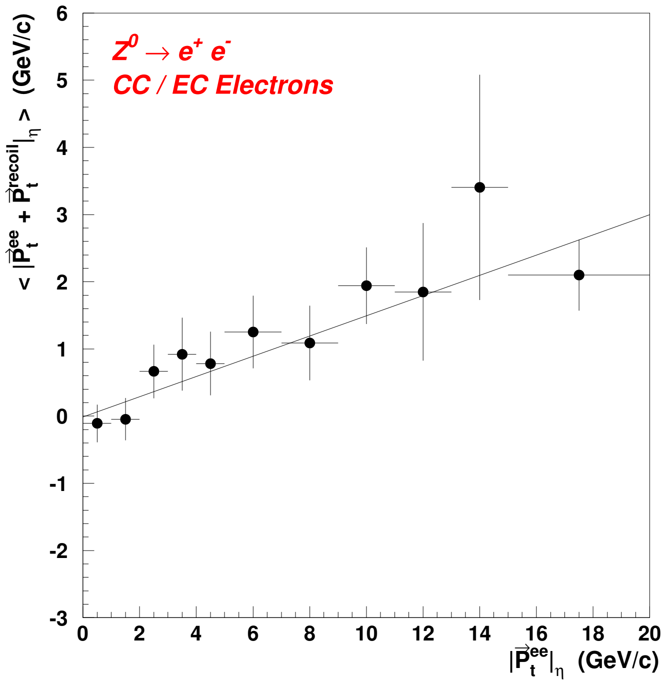
$\star$ **error dominated by limited Z statistics**

M_W - hadronic (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** $P_T(Z)$ **from** ee **or the recoil:**

$$P_T\text{–balance} \equiv [\vec{P}_T(ee) + \vec{P}_T(R)] \quad \text{vs} \quad \vec{P}_T(ee)$$



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

Error on M_W due to hadronic energy scale:

Run 1A: $\sigma(M_W) = 50\ \text{MeV}$ **Run 1B:** $\sigma(M_W) = 20\ \text{MeV}$

M_W - Model of Underlying Event

Add underlying event contributions to $\vec{P}_T(R)$ and $\vec{P}_T(e)$ $\rightarrow$ model in MC as measured in data:

$$\vec{P}_T(e)^{model} = \vec{P}_T(e) + U_T(\hat{e})$$

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

- $U_T(\hat{e})$ **is extra energy added to electron**
- $\vec{U}_T^{mb}$ **is total** $\vec{E}_T$ **of event from minimum bias data sample** $\rightarrow$ **requires only beam crossing to trigger**
- **resolution of** $P_T - \mathrm{balance}$ **constrains** $C \rightarrow 0.98 \pm 0.06$

Error on M_W due to C = # min. bias events:

Run 1A: $\sigma(M_W) = 60\ \mathrm{MeV}$ **Run 1B:** $\sigma(M_W) = 33\ \mathrm{MeV}$

M_W - Model of Underlying Event

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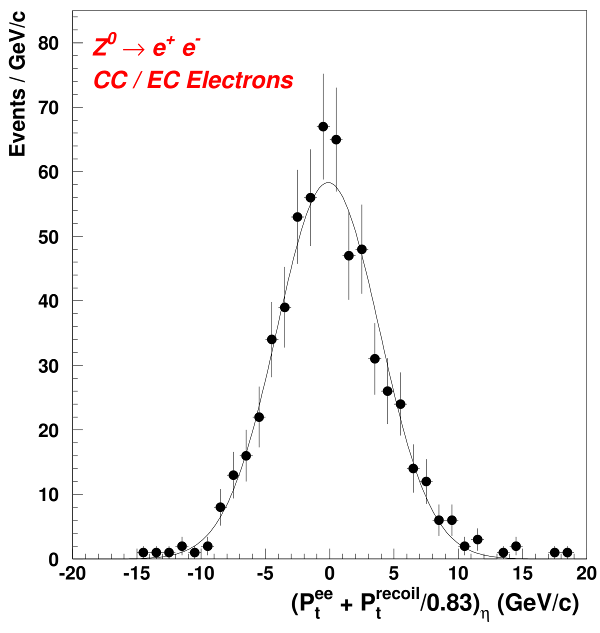
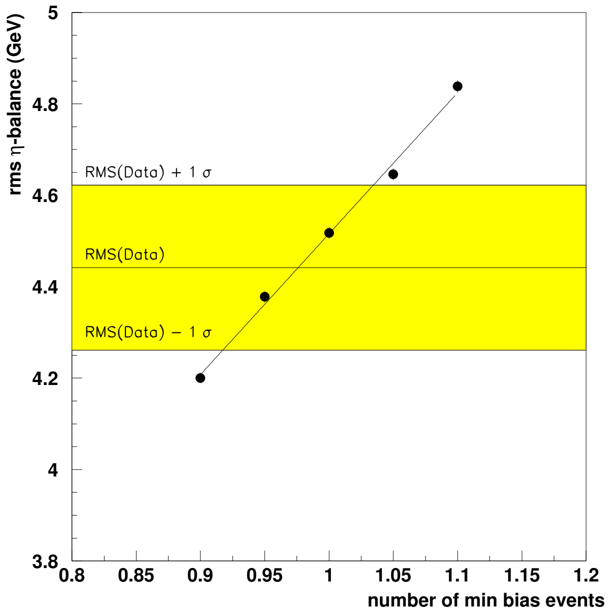




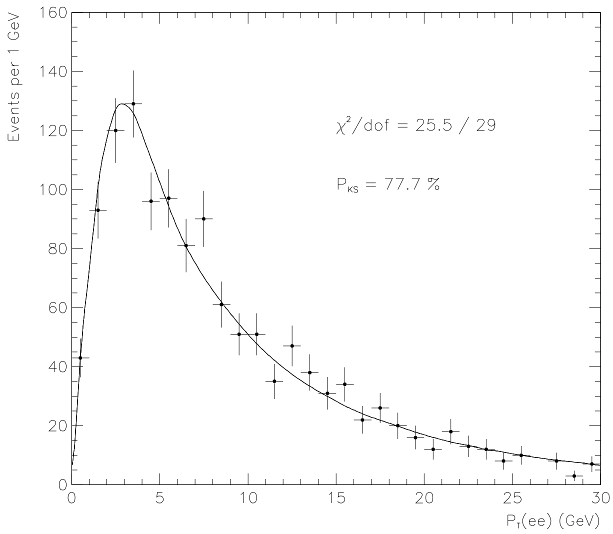
Error on M_W due to C = # min. bias events:

Run 1A: $\sigma(M_W) = 60$ 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

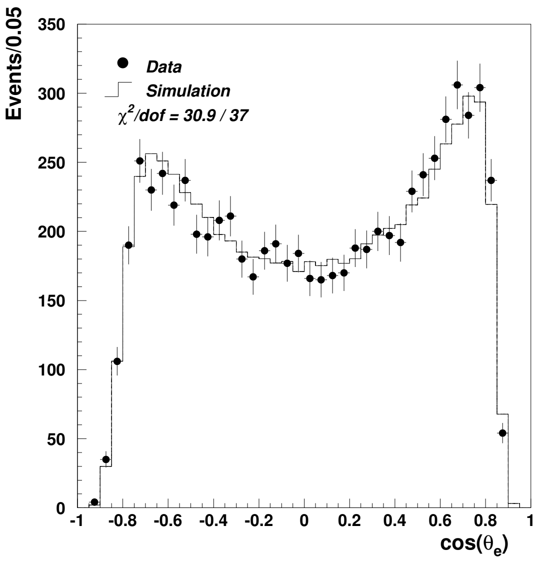
- **range of phenomenological parameters in calculation constrained by $P_T(Z)$ spectrum from data**
- **different models of pdf's are constrained using latest available world data**
- **vary these two contributions simultaneously**

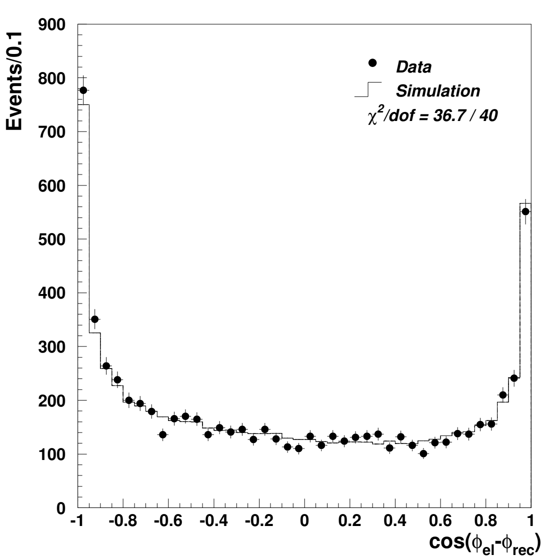


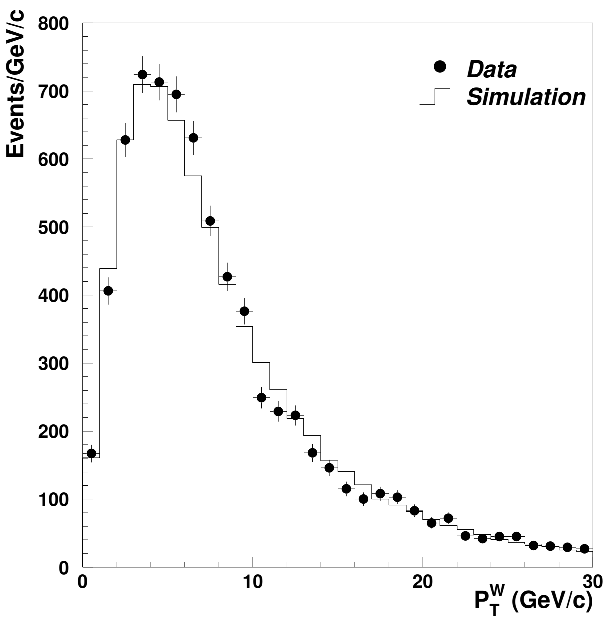
Error on M_W due to theoretical model

Run 1A: $\sigma(M_W) = 65$ MeV **Run 1B:** $\sigma(M_W) = 34$ MeV

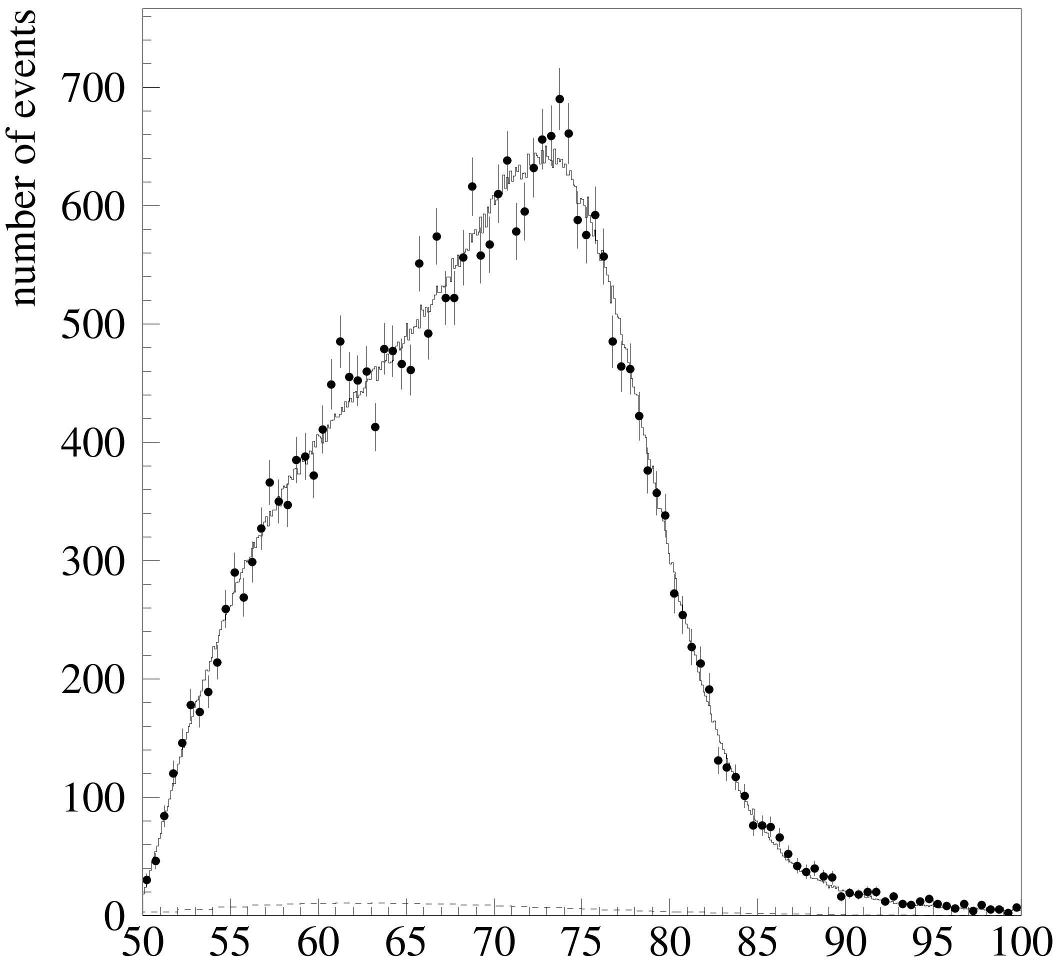
Comparison of Data and MC







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



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

M_W - Summary of Errors

Source	$\sigma_{M(W)}$ **in** MeV/c^2 **Run 1B**	**Run 1A**
Statistical (W events)	**70**	**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	**20**	**50**
Hadronic Energy Resolution	**-**	**65**
# of Min. Bias Events	**33**	**60**
P_T^W**, pdf**	**24**	**65**
W **Width**	**9**	**20**
Radiative Decays	**20**	**20**
Backgrounds	**12**	**35**
Fit Error	**-**	**5**
Systematic Total	**70**	**165**
Total	**118**	**270**

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

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

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]**

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

- **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]**

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

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

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

Results from experiments at LEP2 at CERN

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

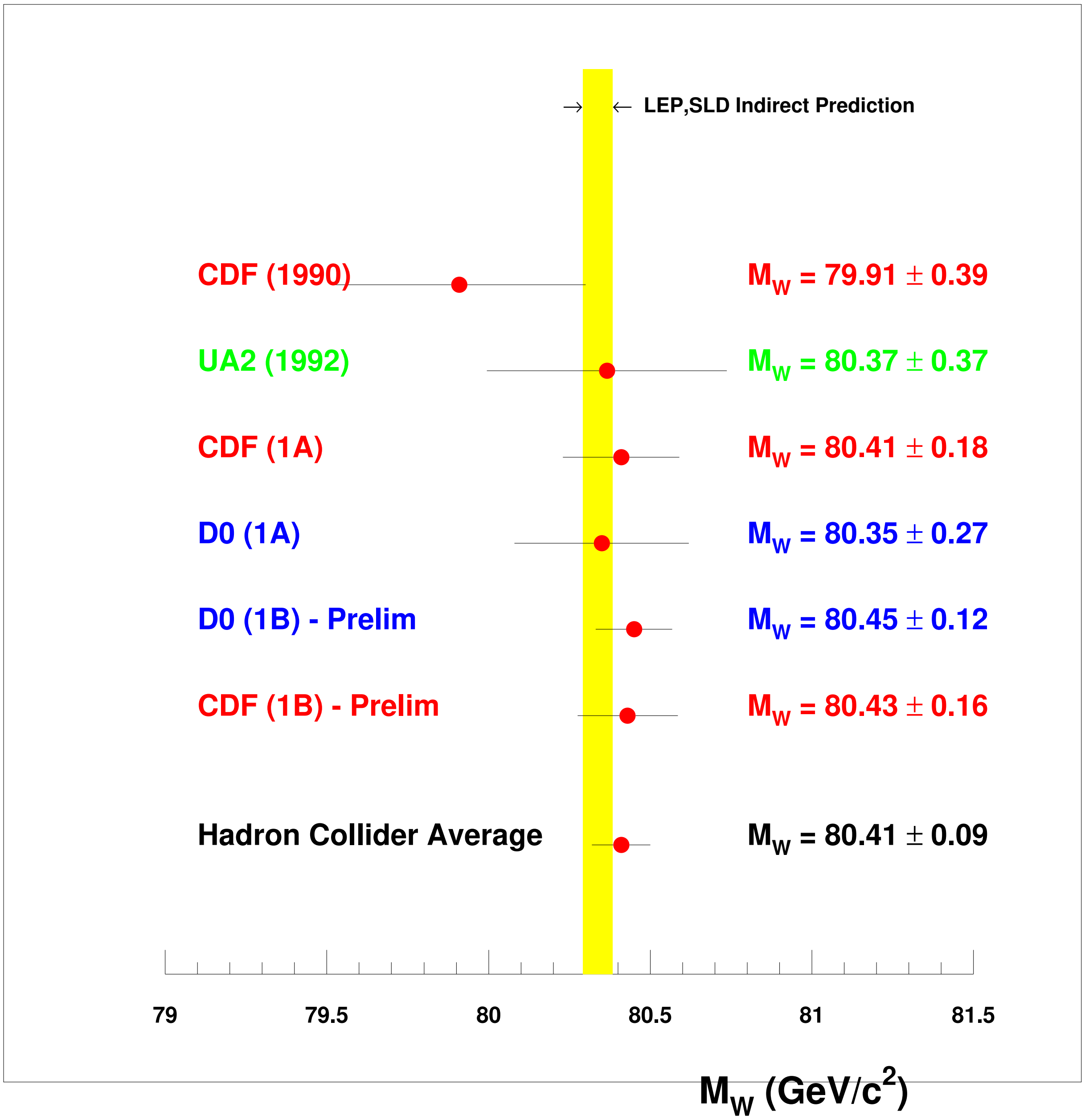
$\star$ M_W **for all 4 experiments as of Feb97:**
$\Rightarrow$ **Threshold Measurement:**

$$\sqrt{s} = 161, \;\; M_W = 80.40 \pm 0.22 \text{ GeV (final)}$$

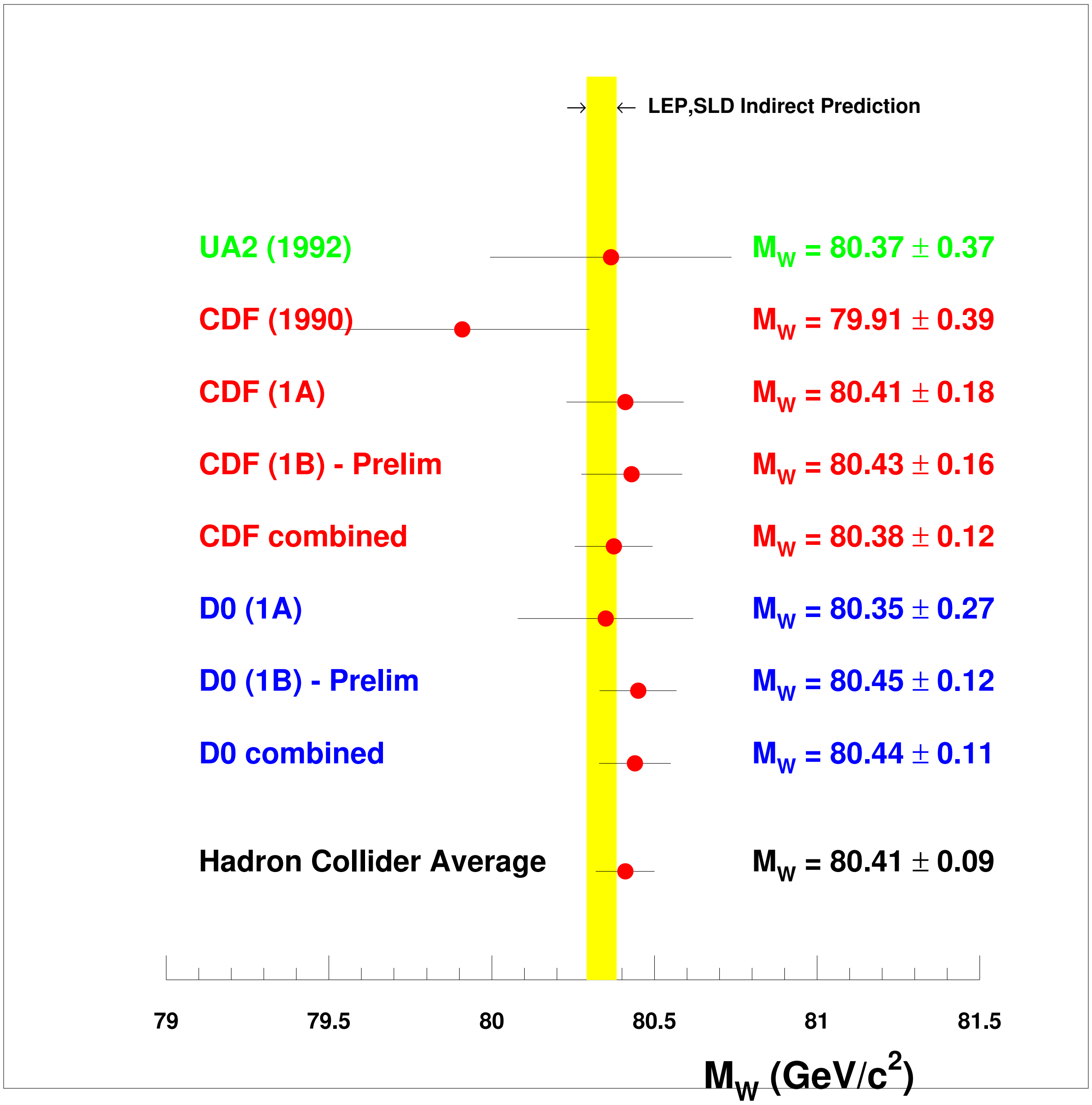
$\Rightarrow$ **Direct Reconstruction:**

$$\sqrt{s} = 172, \;\; M_W = 80.37 \pm 0.19 \text{ GeV (preliminary)}$$

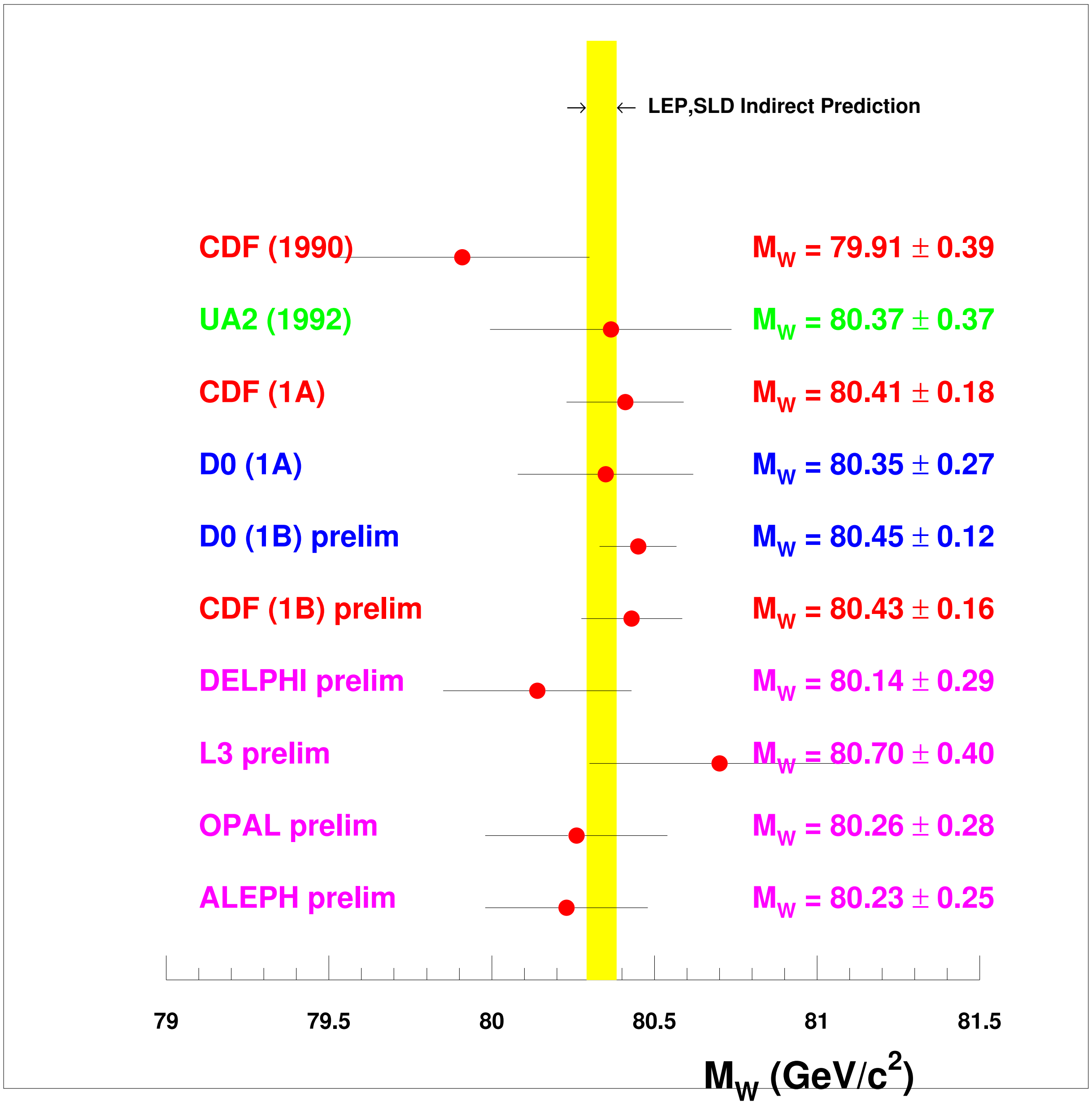
Current Results of M_W



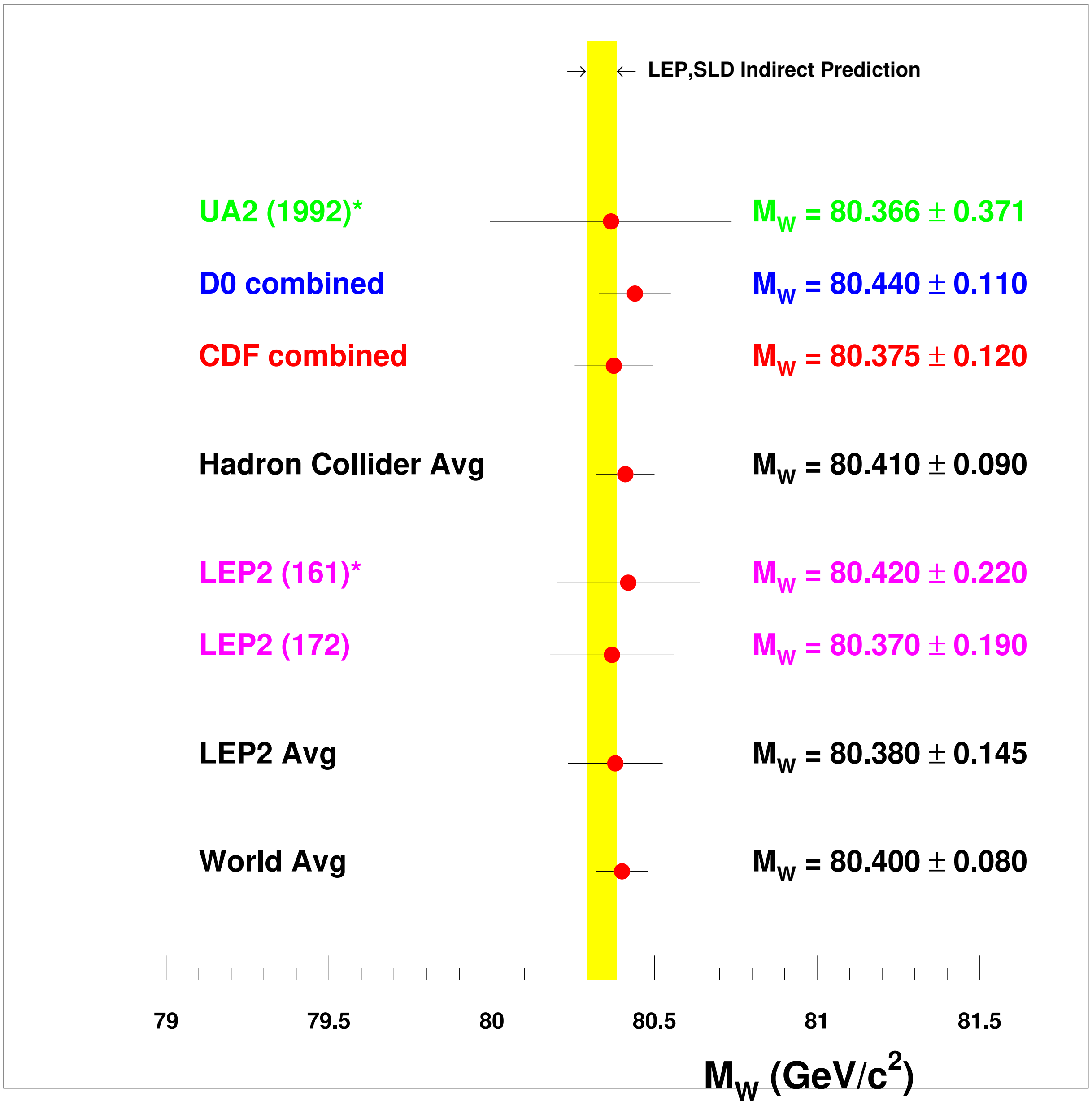
Current Results of M_W



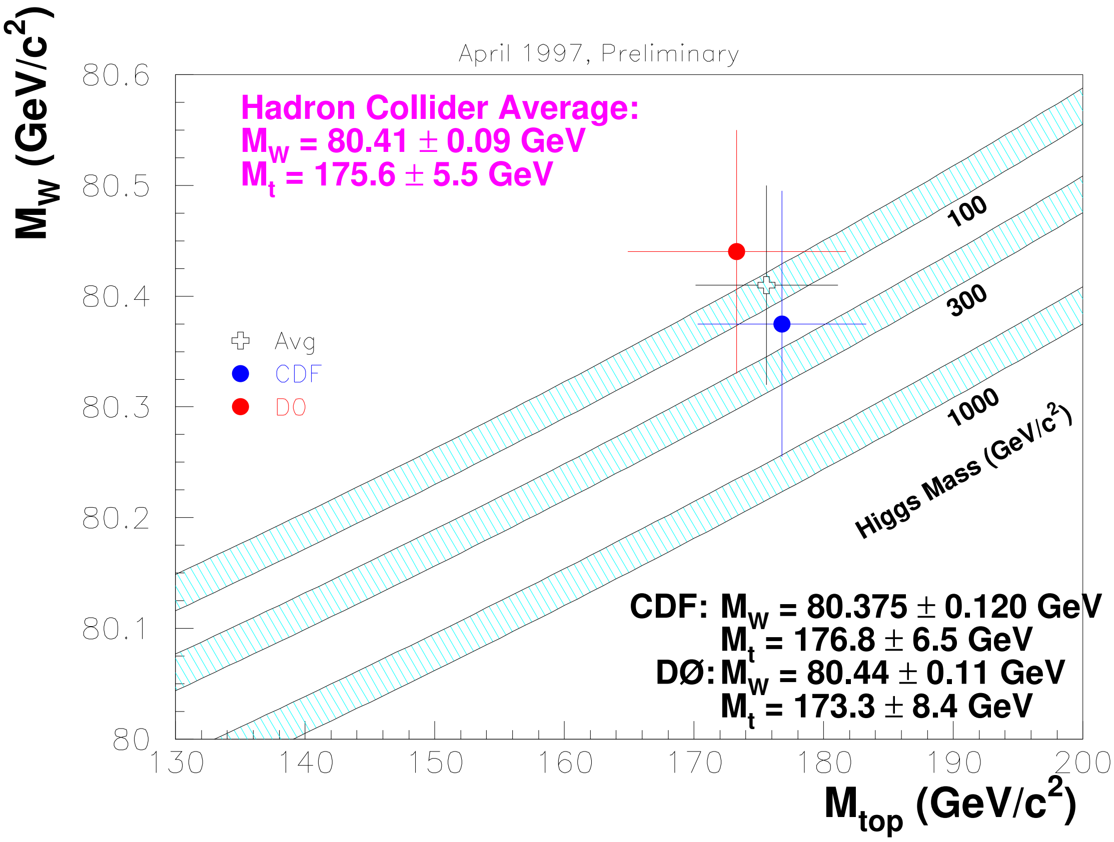
Current Results of M_W



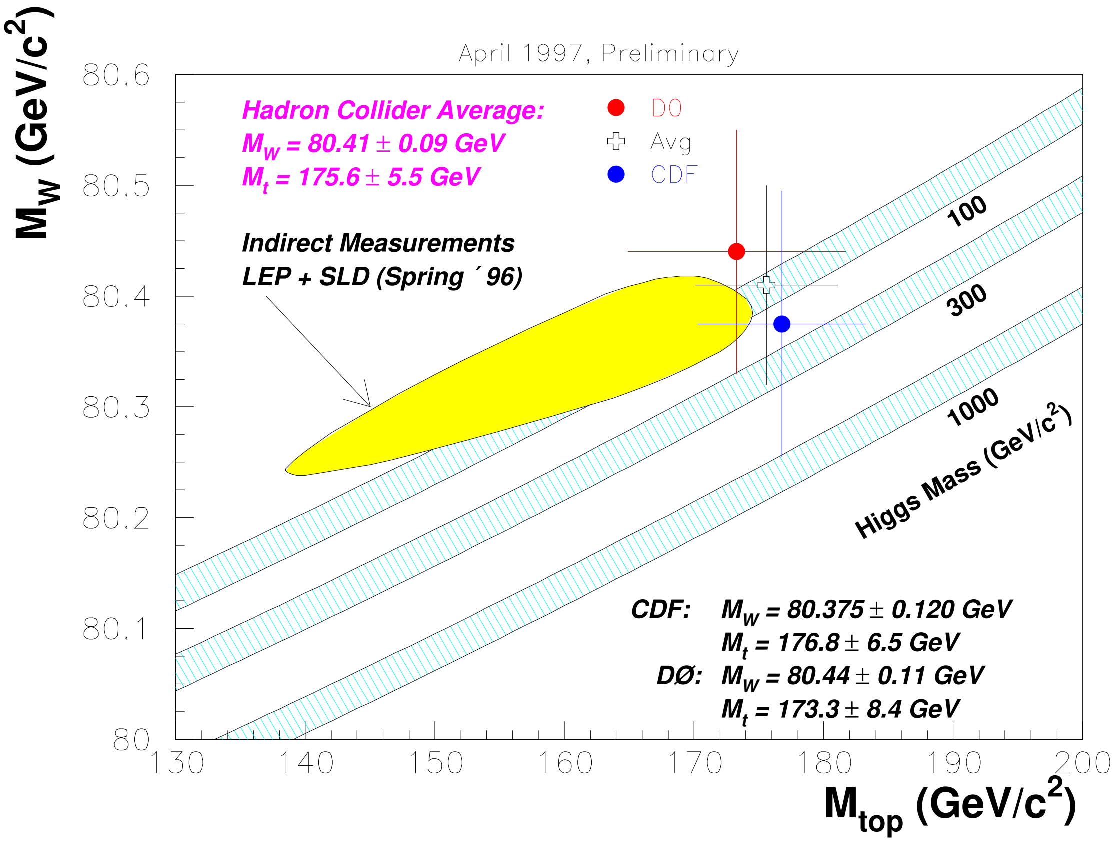
Current Results of M_W



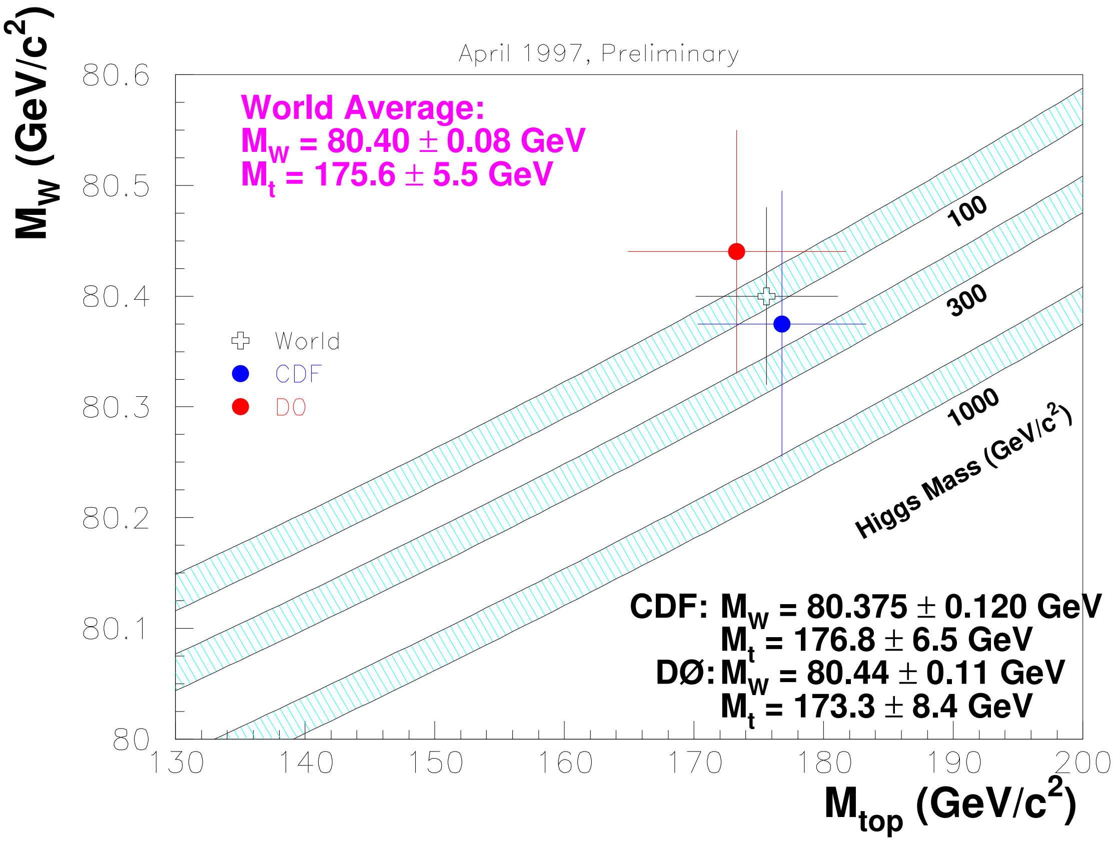
M_W vs m_t - Higgs constraint



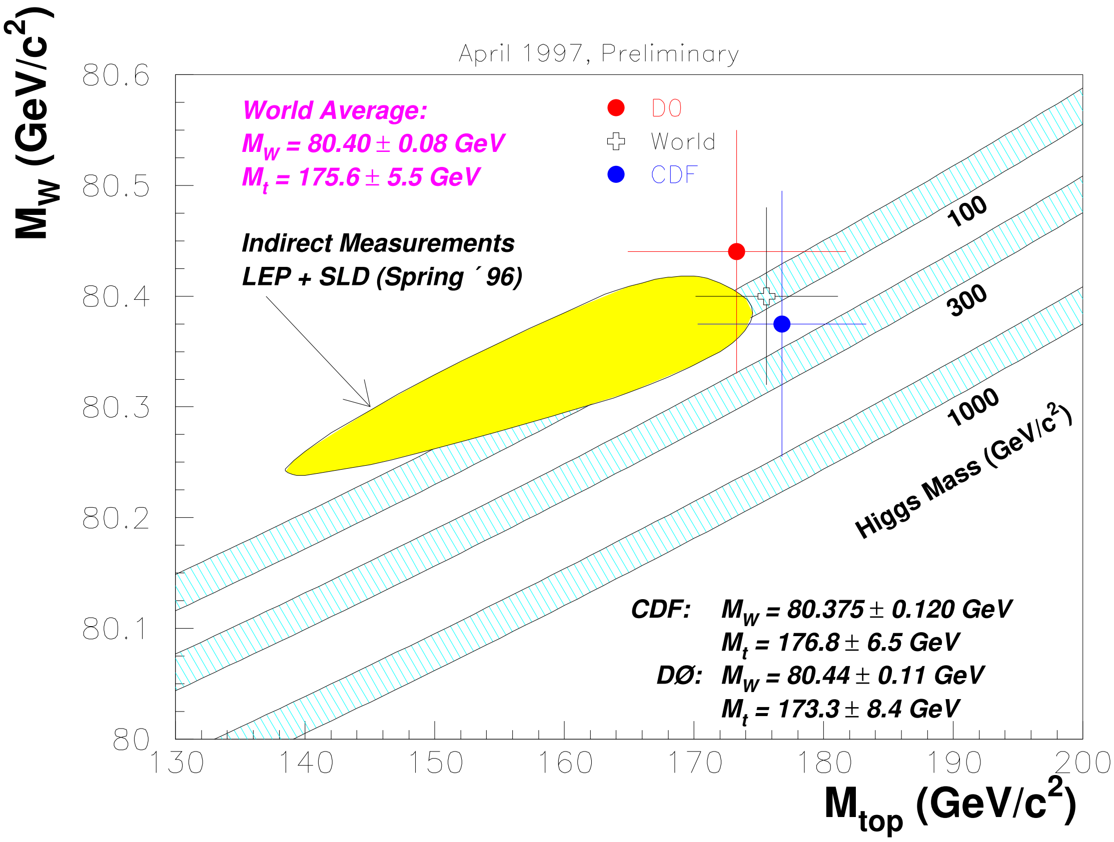
M_W vs m_t - Higgs constraint



M_W vs m_t - Higgs constraint



M_W vs m_t - Higgs constraint



Future M_W Measurements

- **Fermilab Tevatron Run 1 (1992-1995)** $\Rightarrow$
  DØ & CDF: $\Delta M_W \approx 80$ **MeV**
- **LEP2 (1996-1999?)** $\Rightarrow$
  $\Delta M_W \approx 35$ **MeV**
- **Tevatron Run 2 (starts 1999)** $\Rightarrow$
  DØ & CDF: $\Delta M_W \approx 40$ **MeV**
- **Large Hadron Collider (LHC) at CERN (starts 2005?)**
  $\Delta M_W \approx 20$ **MeV?**

As measurements of M_W and M_{top} become more precise
- **we will further constrain the M_H**
- **test reliability of the Standard Model**

Future Collider Experiments:

⋆ **search for Higgs Boson**

⋆ **find new physics results that aren't explained by Standard Model?!**