DØ Results on W Boson Properties

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Hadron Collider Physics 97

Stony Brook

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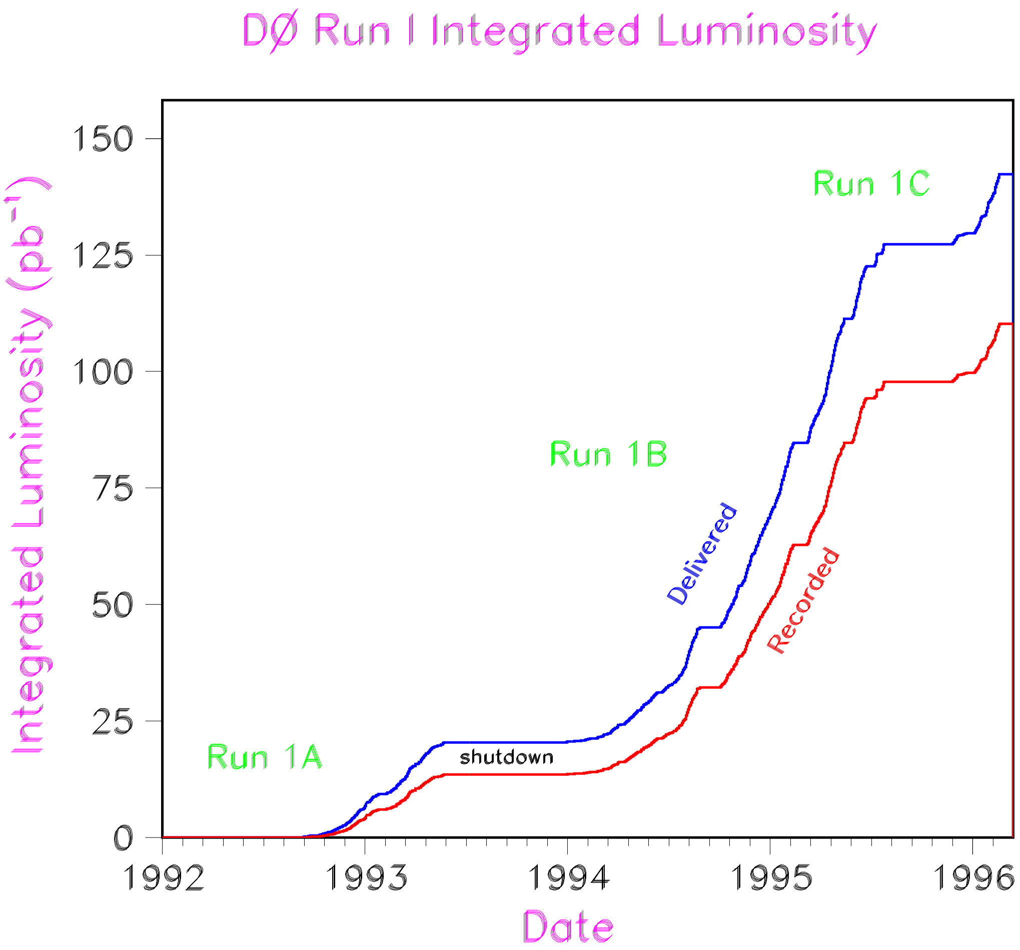
- W and Z Production
- W Mass



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

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

Inclusive W and Z Production

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

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

$\star$ **cleaner signature & lower background**

- $W \to e\nu, \mu\nu, \tau\nu$
- $Z \to ee, \mu\mu$

For the e and μ channels, trigger on events with:

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

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

Analyses:

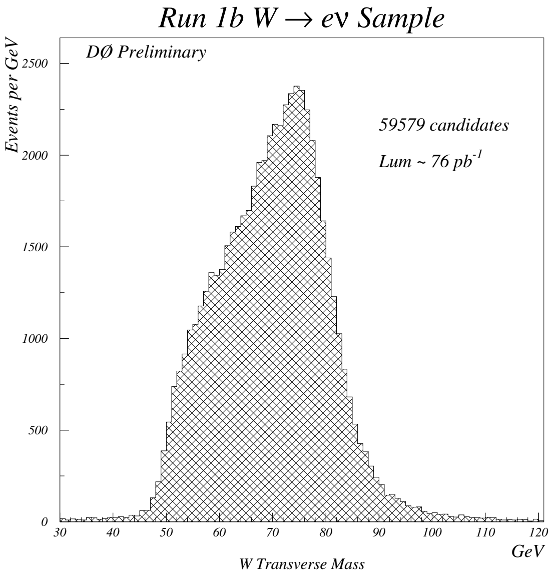
$\star$ $\sigma\cdot$ **BR** $\to$ **provides fundamental test of SM**

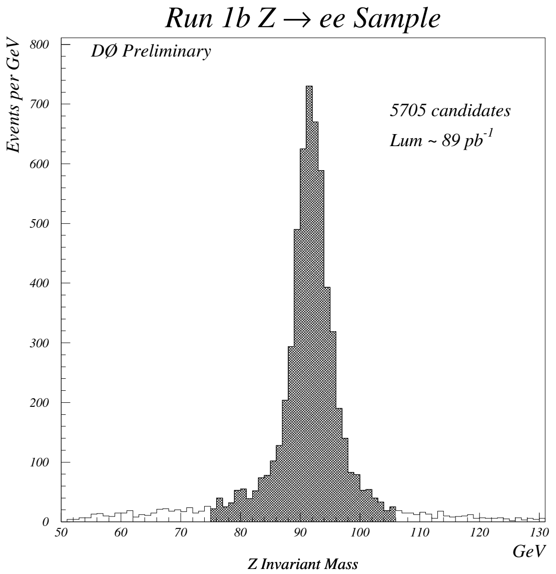
$\star$ $\Gamma_W \to$ **limit on unknown decays of W**

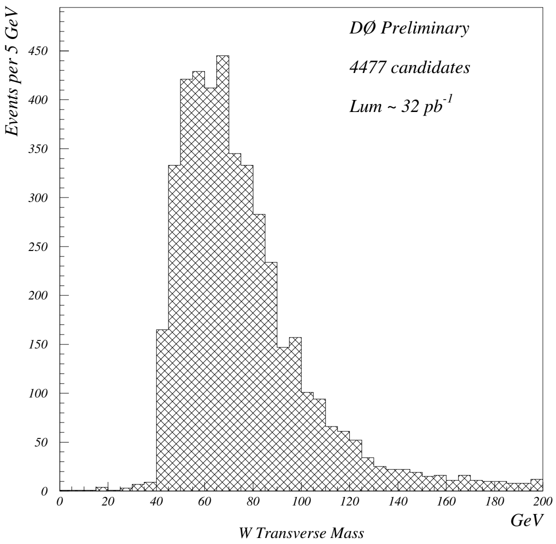
$\star$ $g_\tau^W / g_e^W \to$ **measure of lepton universality**

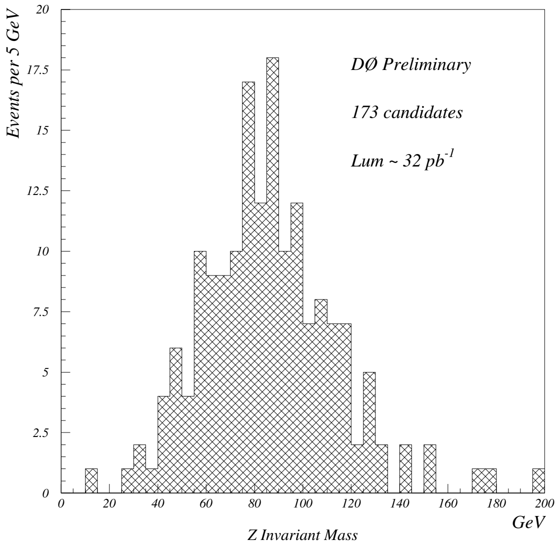
W and Z Production Cross Sections

Run 1B, preliminary





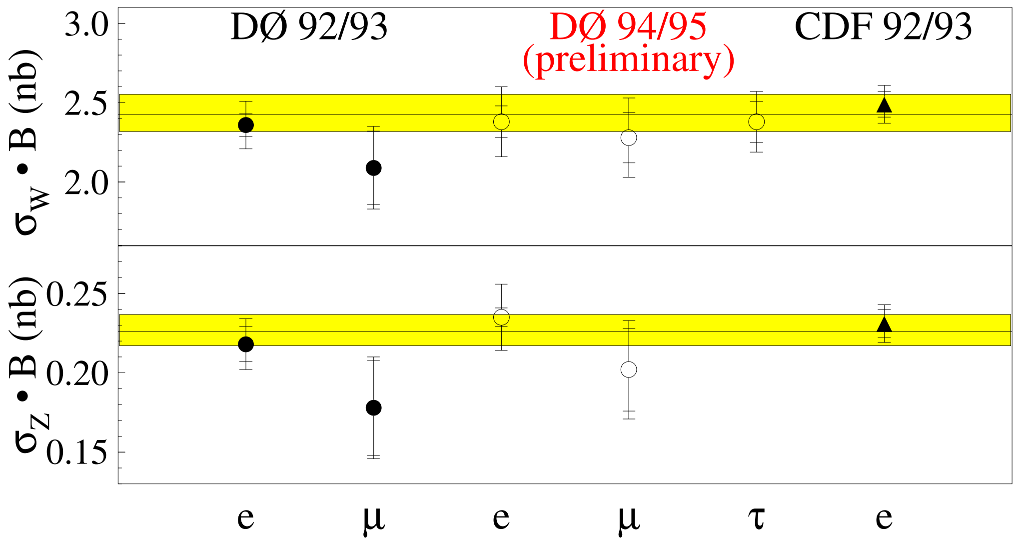




Final Event Selection:

- $p_T(e) > 25$ GeV, $p_T(\mu, \mu_2) > 20(15)$ GeV
- $\not\!\!E_T > 25, 20$ **for** $W \to e, \mu$ **events**
- $75 < M(ee) < 105$ GeV/c^2

W and Z Production Cross Sections



Theoretical Prediction at $\mathcal{O}(\alpha_s^2) \Rightarrow$

- **Hamberg, van Neerven & Matsuura, NP B359, 313; van Neerven & Zijlstra, NP B 382, 11**
- **uses CTEQ2M pdf**
- **error dominated by pdf uncertainties**

$\sigma_W \cdot B(W \to e\nu)$	$=$	**2.38**	$\pm$ **0.01**	$\pm$ **0.09**	$\pm$ **0.20 nb**
$\sigma_W \cdot B(W \to \mu\nu)$	$=$	**2.28**	$\pm$ **0.04**	$\pm$ **0.16**	$\pm$ **0.19 nb**
$\sigma_Z \cdot B(Z \to ee)$	$=$	**0.235**	$\pm$ **0.003**	$\pm$ **0.005**	$\pm$ **0.020 nb**
$\sigma_Z \cdot B(Z \to \mu\mu)$	$=$	**0.202**	$\pm$ **0.016**	$\pm$ **0.020**	$\pm$ **0.017 nb**
			($\pm$stat)	($\pm$syst)	($\pm$lum)

$\star$ **Final Results Soon!**

Cross Section Ratio $\Rightarrow \Gamma_W$

$\rightarrow$ **Take ratio - many errors cancel**

$$R = \frac{\sigma_W \cdot B(W \rightarrow l\nu)}{\sigma_Z \cdot B(Z \rightarrow ll)} = 10.32 \pm 0.43$$

$\rightarrow$ **Use theoretical calculation of σ_W/σ_Z and LEP measurement of $B(Z \rightarrow ll)$ to obtain $B(W \rightarrow l\nu)$**

$$B(W \rightarrow l\nu) = B(Z \rightarrow ll)\frac{\sigma_Z}{\sigma_W}R = (10.43 \pm 0.44)\%$$

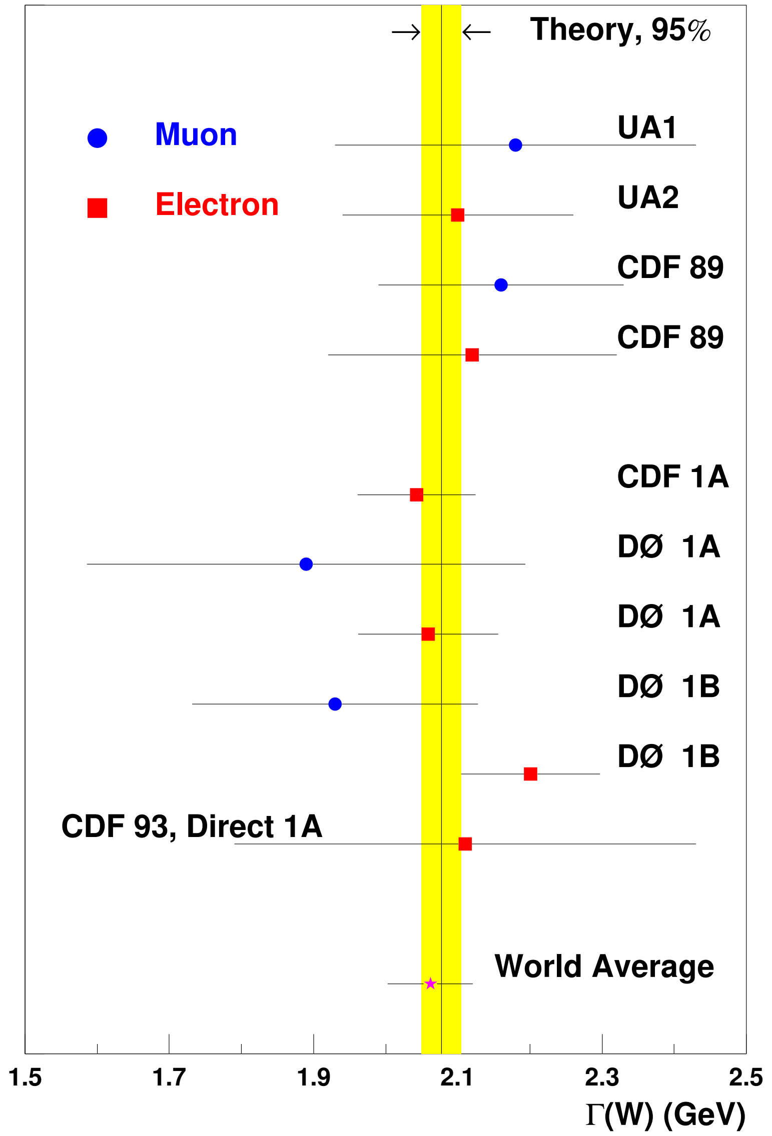
$\rightarrow$ **Use theoretical calculation of $\Gamma(W \rightarrow l\nu)$ to obtain Γ_W (Run 1B, preliminary)**

$$\Gamma_W = \frac{\Gamma(W \rightarrow l\nu)}{B(W \rightarrow l\nu)} = 2.159 \pm 0.092 \text{ GeV}$$

$\Rightarrow$ **Comparison of**
published world average ($\Gamma_W = 2.062$ GeV)
with SM prediction ($\Gamma_W = 2.077 \pm 0.014$ GeV)
gives limit on unknown decay modes of W $\Rightarrow$

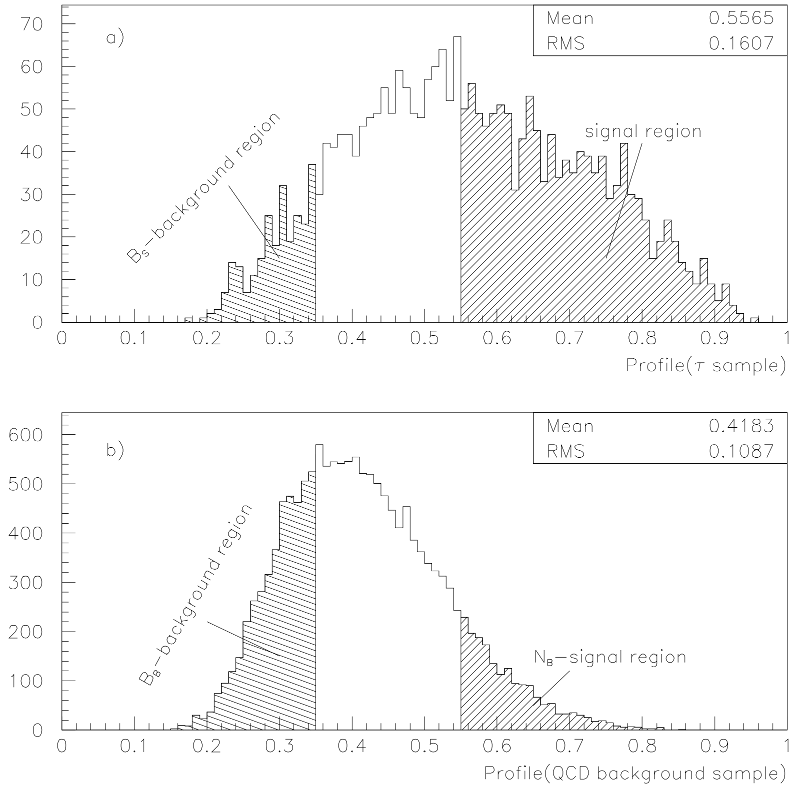
95% CL upper limit of $\Delta\Gamma < 109$ MeV on unexpected decays of the W

Γ_W



Theory, 95%
Muon
Electron
UA1
UA2
CDF 89
CDF 89
CDF 1A
DØ 1A
DØ 1A
DØ 1B
DØ 1B
CDF 93, Direct 1A
World Average
1.5
1.7
1.9
2.1
2.3
2.5
Γ(W) (GeV)

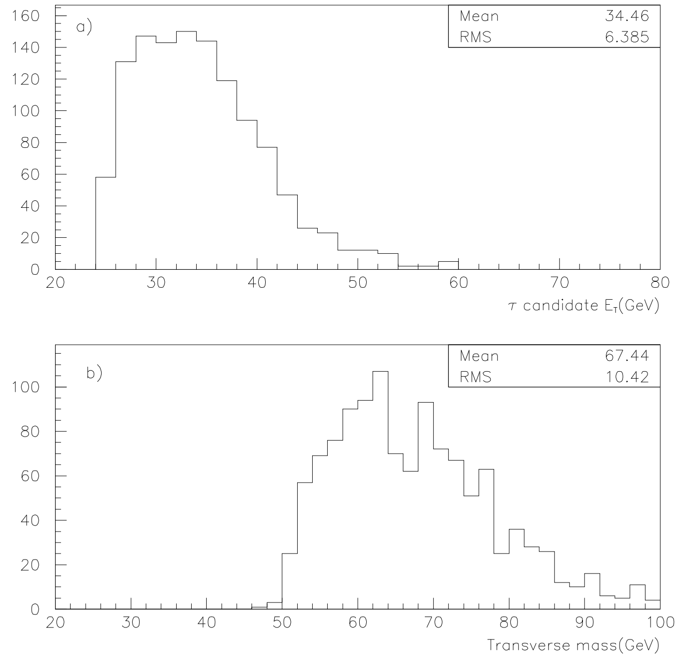
$W \rightarrow \tau\nu$ Data Sample

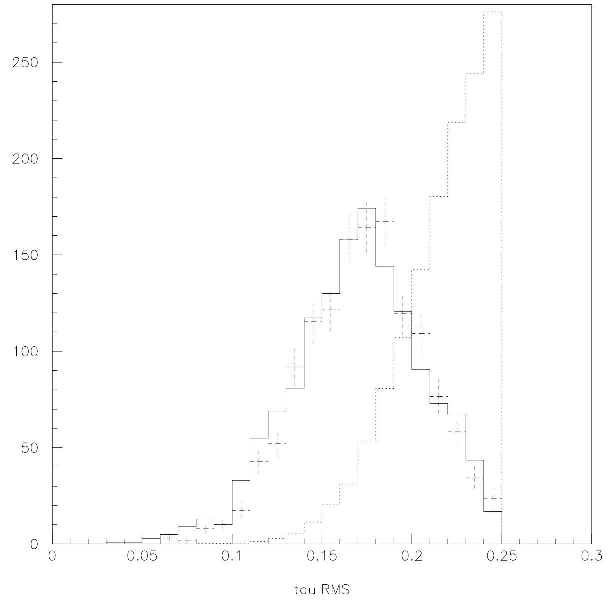


τ Candidate Selection

- **Use hadronic decay of the tau: isolated, narrow jet**
- E_T**(jet)**> 25 **GeV** ($|\eta| < 0.9$), $\not\!\!E_T > 25$ **GeV**
- **no opposite jet**
- **Isolation: Jet cone** $R = 0.7$, **Jet width:** $rms_{jet} < 0.25$
- **Estimate signal and bkgnd. from profile distribution**
  Profile=(sum of highest two tower E_T**)/(cluster** E_T**)**
  Require Profile > 0.55

$W \to \tau\nu$





$W \to \tau\nu$ results (Run 1B, preliminary)

	Number of Events
Final Data Sample	**1202**
QCD Background	$106 \pm 7 \pm 5$
Noise Events	81 ± 14
$Z \to \tau\tau$	32 ± 5
$W \to e\nu$	3 ± 1

Luminosity: 16.8 ± 0.9 pb^{-1}

(luminosity error not included below)

$$\sigma \cdot B(W \to \tau\nu) = 2.38 \pm 0.09(stat) \pm 0.10(syst) \text{ nb}$$

$$\boxed{g_\tau^W / g_e^W = 1.004 \pm 0.019(stat) \pm 0.026(syst)}$$

ElectroWeak Standard Model

Specified by 3 parameters:

- $\alpha = (137.0359895 \pm .0000061)^{-1}$
- $G_F = (1.16639 \pm .00002) \times 10^{-5}\mathrm{GeV}^{-2}$
- $M_Z = 91.1884 \pm .0022\ \mathrm{GeV/c^2}$

$$\textbf{At lowest order} : M_W = \frac{A}{\sin\theta_W} \quad \text{and} \quad \sin^2\theta_W = 1 - \frac{M_W^2}{M_Z^2}$$

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

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

Contributions to Δr:

- $\Delta r_o \approx 0.06 \rightarrow$ **due to running of** $\alpha \rightarrow \alpha(M_Z^2)$
- $\rho_t \approx 0.01(M_{top}/180\ \mathrm{GeV})^2 \rightarrow W, Z$ **self-energy diagrams**
- **also contributions from bosonic loops which** $\propto (\ln M_{Higgs})$

Therefore $\Delta r(M_{top}^2, \ln M_{Higgs})$

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

$\rightarrow$ **defines size of radiative corrections in SM**
$\rightarrow$ **with** M_{top} **can constrain** M_{Higgs}
$\rightarrow$ **tests the consistency of the SM**

M_W - Measurement by DØ

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

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

! This is a calorimetric measurement !

⟶ **calibrate calorimeter response to Z**

⟶ **measure ratio of W/Z mass**

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

M_W - Quantities Measured

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

- **"recoil" to W or Z, when $P_T(W) \neq 0$**
- **underlying event**

Measure in Calorimeter:

$\rightarrow$ **electron energy $\vec{E}(e)$ $(|E| \equiv |\vec{p}|!)$**

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

$$\vec{\not{E}}_T = -\vec{E}_T(R) - \vec{E}_T(e) = \vec{E}_T(W) - \vec{E}_T(e)$$

$$\textbf{Set } \vec{\not{E}}_T \equiv \vec{E}_T(\nu)$$

We measure:

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

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

M_W - Event Sample

		# events
$W \rightarrow e\nu$		**28323**
$\star$ e **in central region:**	$\lvert\eta\rvert < 1.0$	
$\star$ **electron:**	$E_T^e > 25$ **GeV**	
$\star$ **neutrino:**	$\not{E}_T > 25$ **GeV**	
$\star$ W **transverse mom.**	$P_T^W < 15$ **GeV**	
$Z \rightarrow ee$		**2179**
$\star$ e**'s in central region:**	$\lvert\eta\rvert < 1.0$	
$\star$ **2 isolated electrons:**	$E_T(e) > 25$ **GeV**	
$\star$ **invariant mass**	$70 < M_Z < 110$ **GeV**	

M_W - Measurement Technique

M_W determined from likelihood fit of $M_T(W)$ spectrum to Monte Carlo simulation

$\rightarrow$ MC simulates quantities as measured in data:

- **W production and decay**
- **electron and hadronic (recoil) energy scale**
- **energy & angular resolution**
- **additional energy due to underlying event**
- **selection biases & efficiencies**
- **kinematic cuts**
- **backgrounds included in fitting procedure**

$\Rightarrow$ Points to Note!!

$\longrightarrow$ use $Z \rightarrow ee$ and other data to set 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 NLO calculation with MRSA parton distribution function (pdf)**

  → **Ladinsky & Yuan, PRD 50, 4239 (1994)**

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

- W **resonance generated with relativistic Breit-Wigner, incorporating mass dependence of parton momentum distribution:**

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

- **angular decay of** W **at O**(α_s) **with** $(p_T(W) > 0)$

  → **E. Mirkes, Nucl. Phys. B 387, 3 (1992)**

$$\frac{d\sigma}{d\cos\theta} \sim (1 + \alpha_1 \cos\theta + \alpha_2 \cos^2\theta) \quad \text{where } \alpha = \alpha(P_T^W)$$

- **generate radiative decays:** $W \to e\nu\gamma$

  → **Berends & Kleiss, Z. Phys. C 27, 365(1985)**

- τ **decays:** $W \to \tau\nu \to e\nu\nu\nu$

  generated in MC since indistinguishable from $W \to e\nu$ **in data**

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

→ **EM energy response:**

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

then

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

Measure Ratio:

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

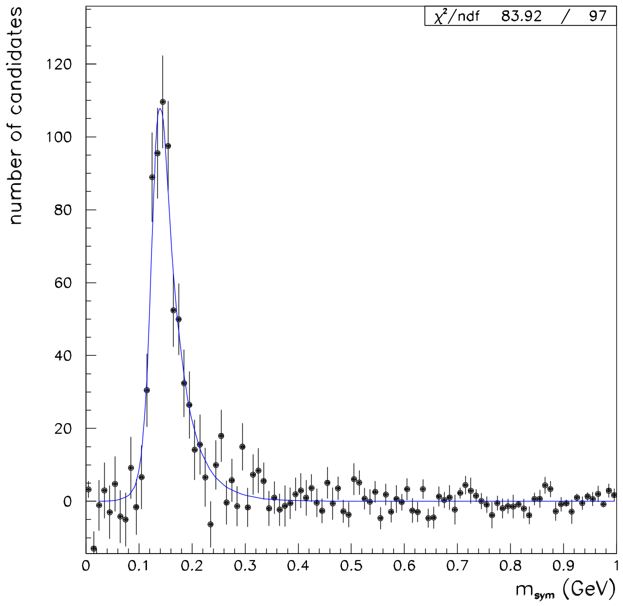
→ **Ratio insensitive to scale (first order)**

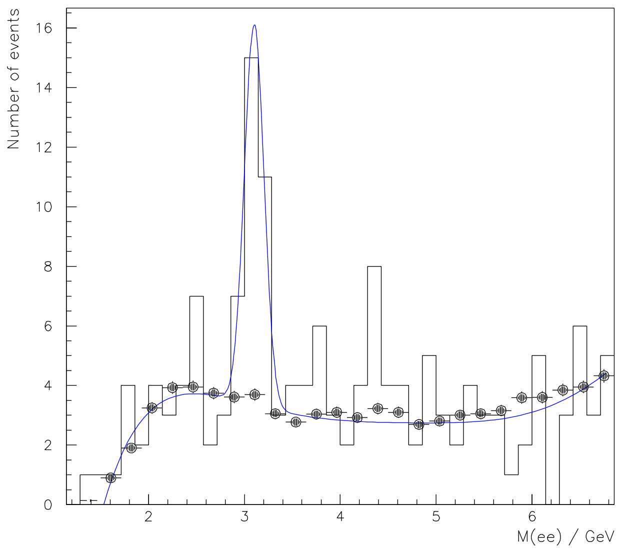
$$\frac{\partial M_W}{\partial \alpha} \approx 0 \quad \text{if} \quad \delta = 0$$

- 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 ⇒





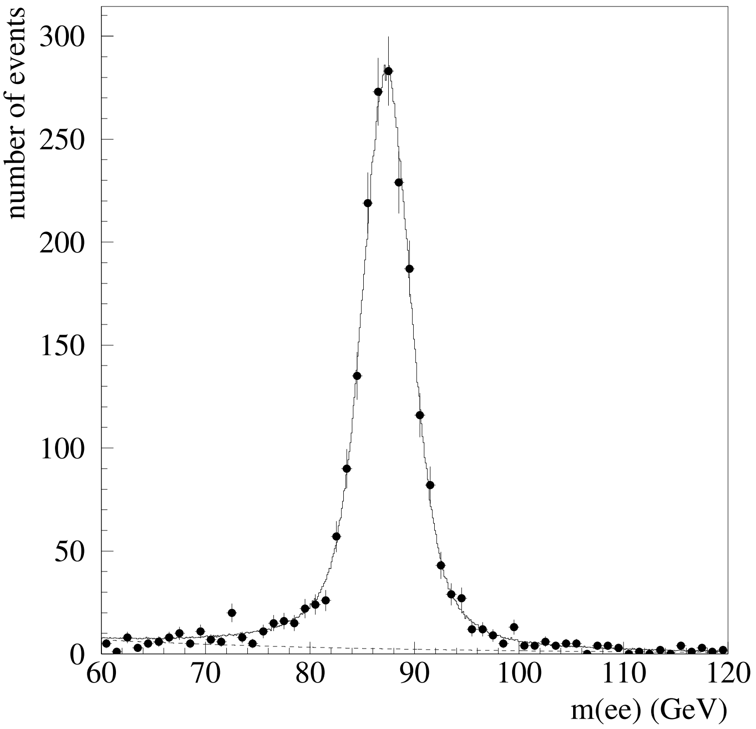


Fig1: $\pi^0 \rightarrow \gamma\gamma \rightarrow e^+e^-e^+e^-$

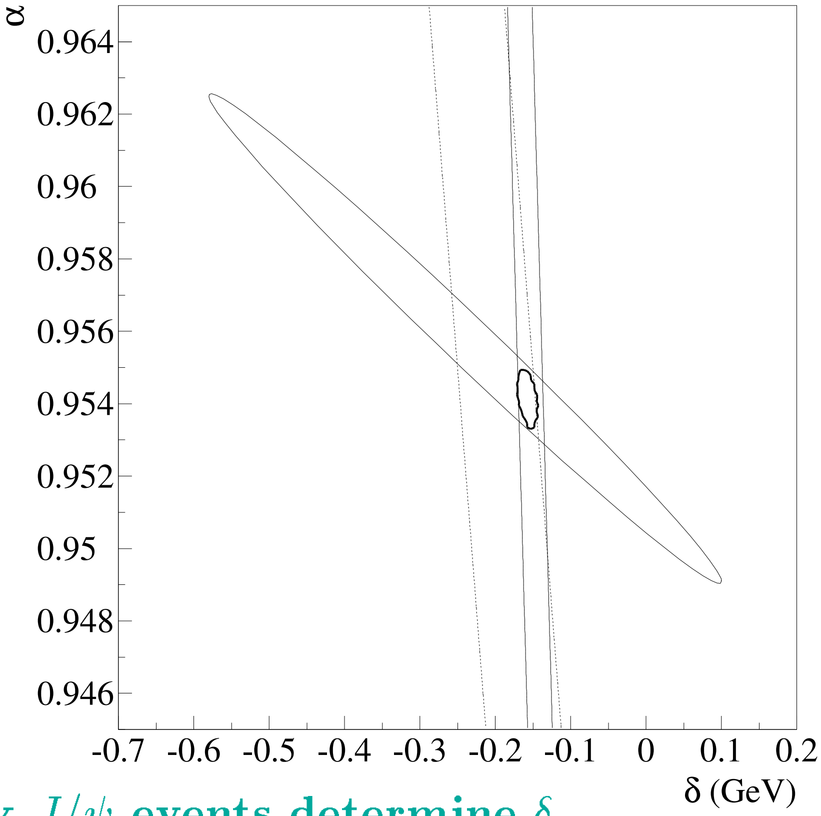
$M(\pi^0) = 135.4 \pm 10$ **MeV**

Fig2: $J/\psi \rightarrow e^+e^-$

$M(J/\psi) = 3.032 \pm .035 \pm .190$ **GeV**

Fig3: $Z^0 \rightarrow e^+e^-$

M_W - electron energy scale



⋆ π^0 & J/ψ events determine δ

⋆ Z data determines α

$$\alpha = 0.95329 \pm 0.00077$$

$$\delta = -0.160 \pm .016(stat)\ ^{+.060}_{-.210}(syst)\ \text{GeV}$$

Error due to electron energy scale: $\sigma(M_W) = 65$ MeV

⋆ error dominated by limited Z statistics

$J/\psi, \pi^0, Z$ data samples: dotted bands, solid bands, contour

$\Rightarrow$ overlap region is 1σ contour from all data samples

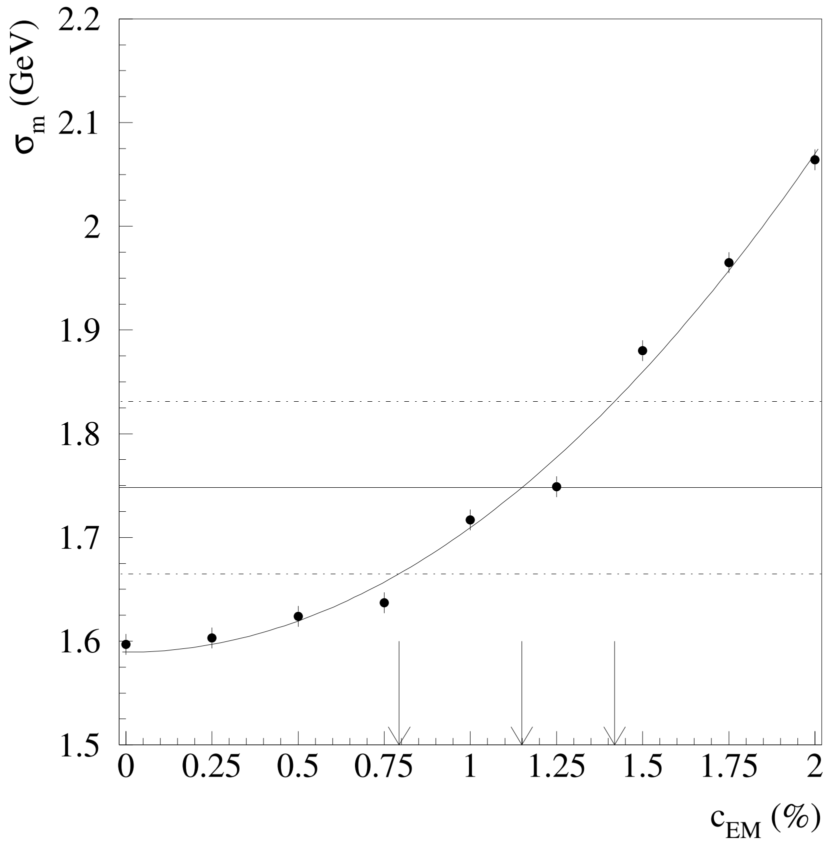
Systematic Error in δ: underlying event ($\pm$ 30 MeV),

γ response ($\pm$ 50 MeV), low energy response ($-$ 200 MeV)

M_W - Electron Energy Resolution

Data: range shown by horizontal bands

MC: solid dots with parameterization



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** $N = 0.4$
- **width of** M_Z **constrains EM energy resolution:**

$$\longrightarrow C = (1.15\ ^{+0.27}_{-0.36})\%$$

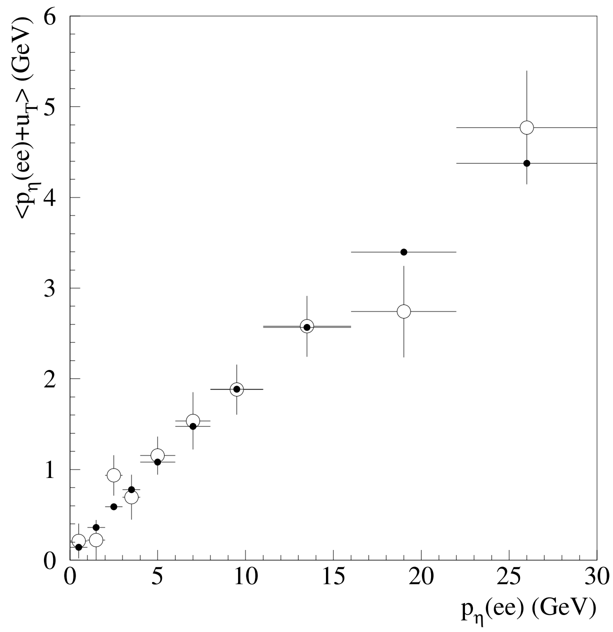
Error due to EM energy resolution: $\sigma(M_W) = 23\ \text{MeV}$

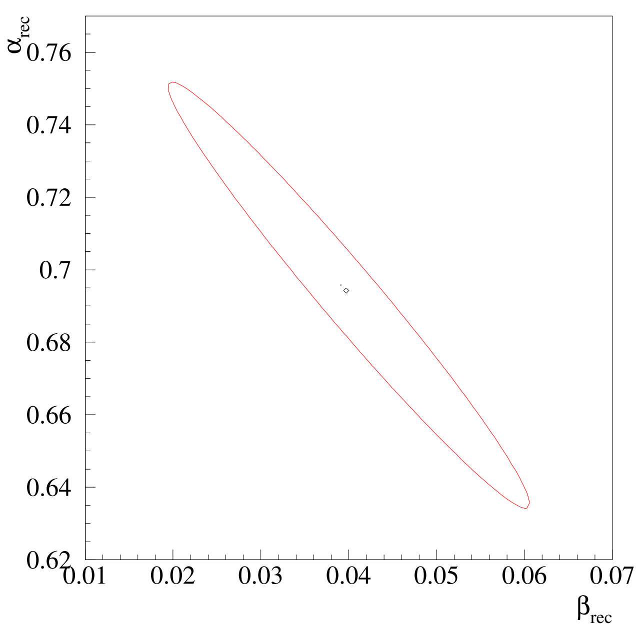
M_W - Hadronic (Recoil) Energy Scale

$\Longrightarrow$ **determine hadronic relative to electron energy scale**

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

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





have $P_T(rec) = \mathcal{R}_{rec} P_T(ee)$

with $\mathcal{R}_{rec} = \alpha_{rec} + \beta_{rec} \log\, p_T(W)$

Determine from fits of data to MC simulation:

$\Rightarrow$ $\alpha_{rec} = 0.69 \pm 0.06$ **and** $\beta_{rec} = 0.04 \pm 0.02$

Error due to hadronic energy scale: $\sigma(M_W) = 23\ \text{MeV}$

Recoil (Hadronic) Energy Resolution

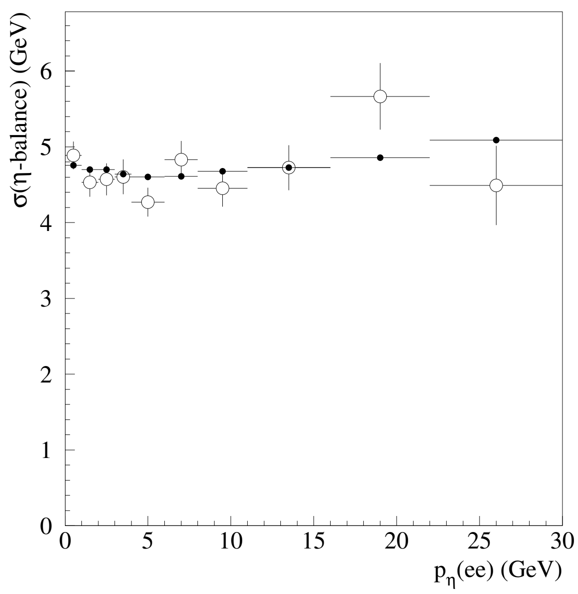
Recoil has two components $\Rightarrow$

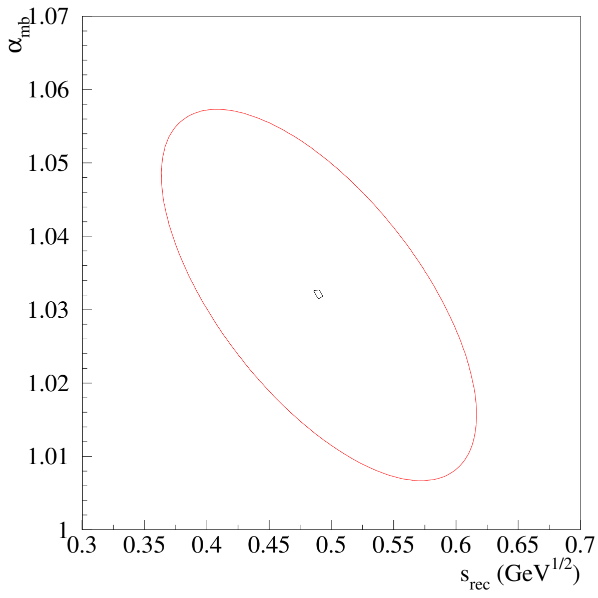
$$\vec{P}_T(R)^{meas} = \mathcal{R}\vec{P}_T(R) + \alpha_{mb} \cdot \vec{U}_{mb}(tot) - U(\hat{e})$$

1. **"soft" component due to underlying event**
   - **$\vec{U}_{mb}$ is total $\vec{E}_T$ of minimum bias event**
   - **luminosity distribution of data is modelled**
   - **$\alpha_{mb} = \#$ minbias events used**
2. **"hard" component due to the initial P_T of the boson**
   - **smear $P_T(R)$ by $\sigma_{rec} = s_{rec}\sqrt{P_T(R)}$**

$\Rightarrow$ **determine s_{rec} and α_{mb} from width of scaled P_T**—balance

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





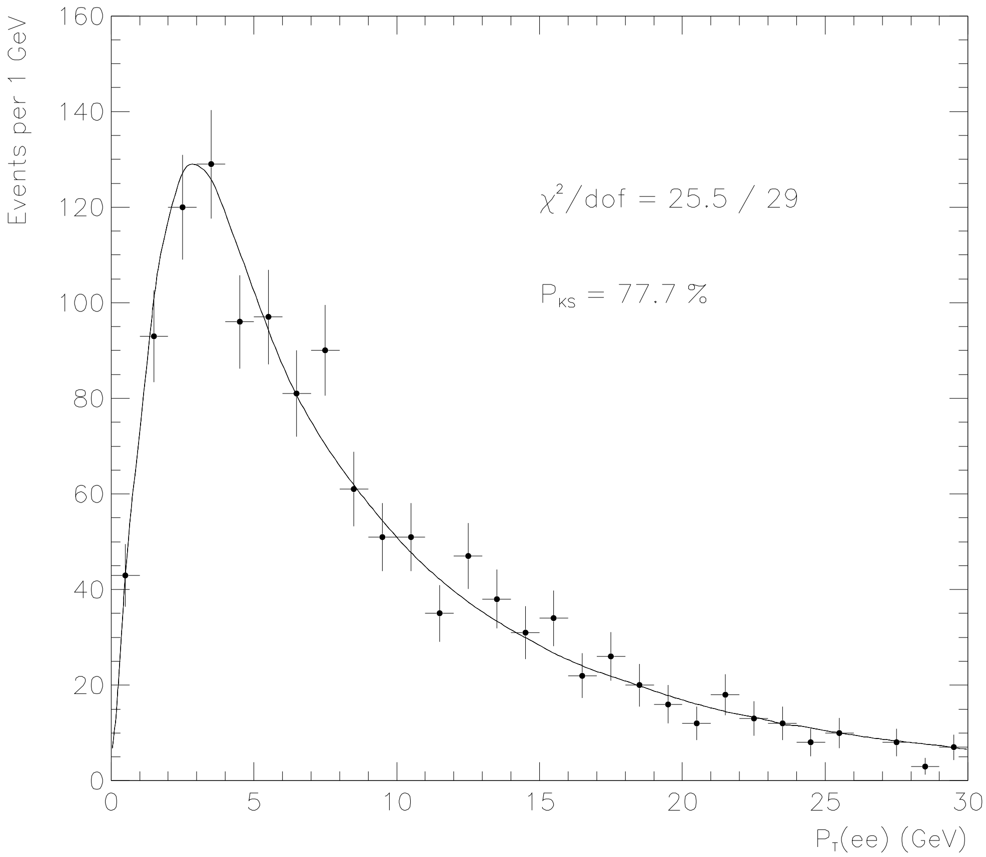
Error due to recoil resolution: $\sigma(M_W) = 33$ MeV

Errors due to W Production Model

⋆ **Use Ladinsky-Yuan calculation of** $\dfrac{d^2\sigma}{dy(W)dP_T(W)}$

- **phenomenological parameters in calculation :**
  $\rightarrow$ **largest sensitivity is to** g_2

- **fix** g_1, g_3 **to nominal values**
- **use** $P_T(Z)$ **from data to constrain** g_2



Errors due to W Production Model

⋆ **Then find dependence of M_W when varying** *pdf*

pdf	constrained g_2	ΔM_W
MRSA	0.59	-
MRSD-	0.61	+20
CTEQ3M	0.54	+5
CTEQ2M	0.61	-21

systematic error due to $g_2 \rightarrow \pm 5$ MeV
systematic error due to *pdf* $\rightarrow \pm 21$ MeV

Also include errors due to $\Rightarrow$

- $\Gamma_W \rightarrow \pm$ **9 MeV**
- **parton luminosity parameter $\rightarrow \pm$ 10 MeV**
- **radiative decays $\rightarrow \pm$ 20 MeV**

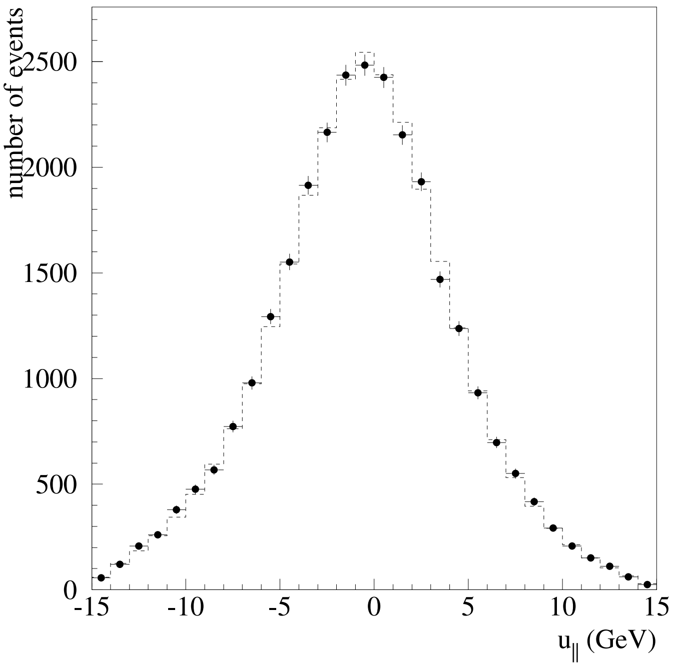
Error due to W production model: $\sigma(M_W) = 34$ MeV

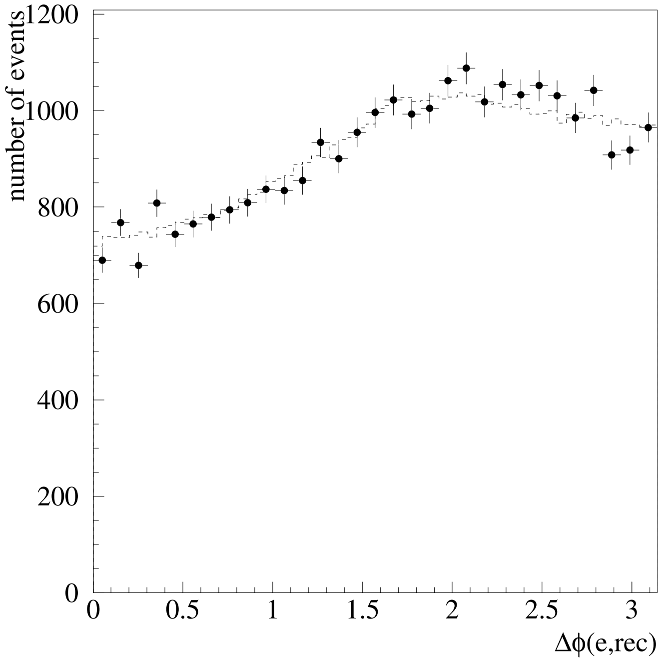
Data and MC Comparison

⋆ $u_{\parallel} = \vec{P}_T^R \cdot \hat{e} = P_T^R \cos\phi$
$\rightarrow$ **hadronic energy in electron direction**

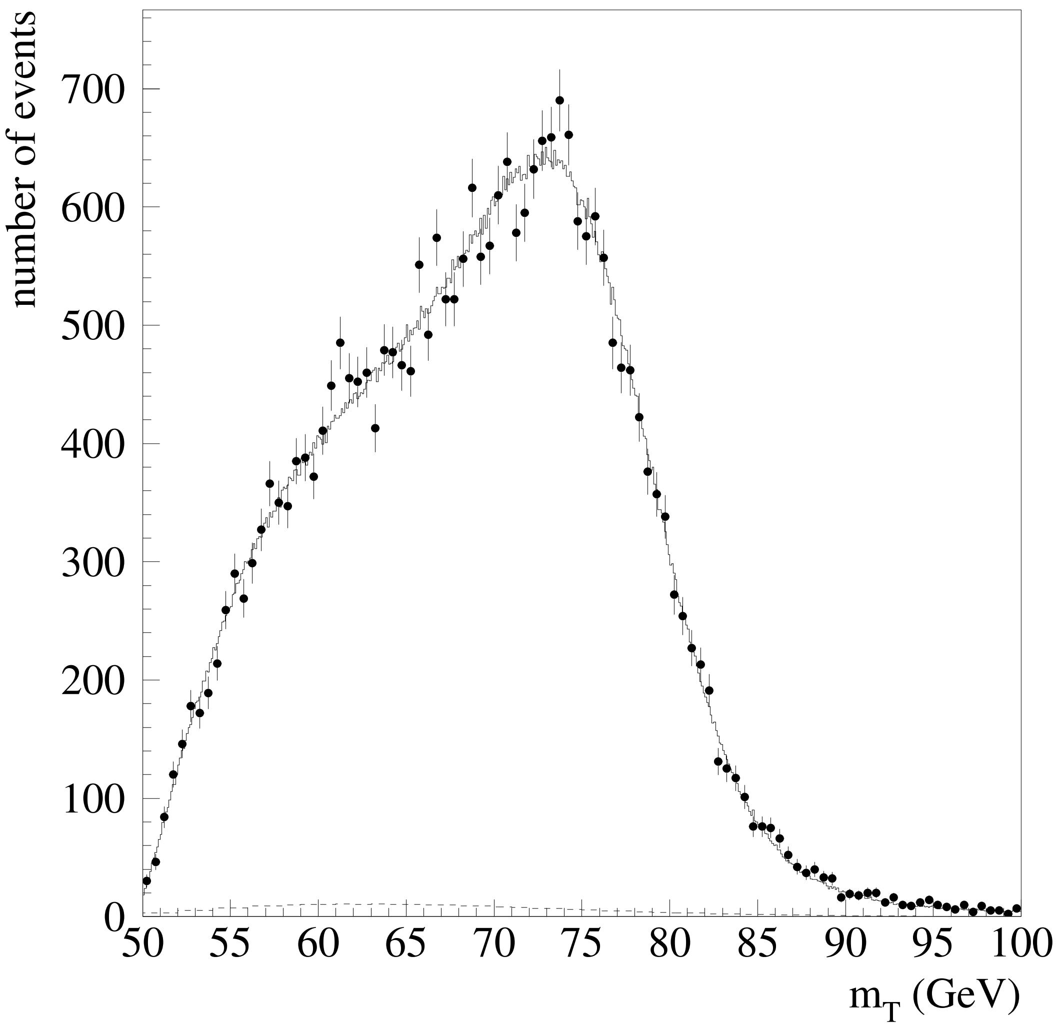
⋆ **A bias in $u_{\parallel}$ directly affects the M_T spectrum**

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





M_W - from Fit to $M_T(W)$



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

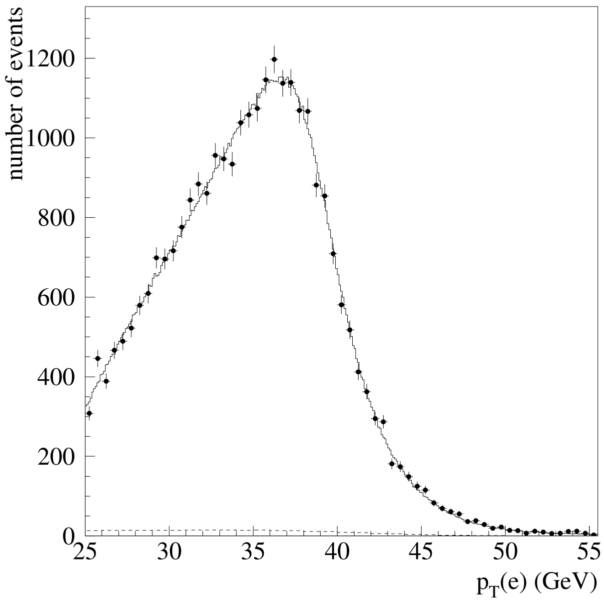
M_W - Summary of Errors

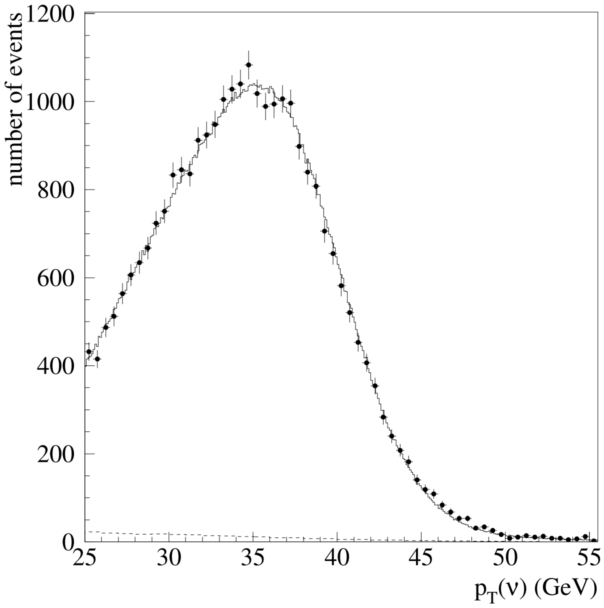
Source	$\sigma_{M(W)}$ **in** MeV/c^2
Statistical (W events)	**69**
Statistical (Z events)	**65**
Non-Uniform energy response (η)	**10**
Electron Angle Calibration	**28**
Electron Energy Resolution	**23**
Electron Energy Linearity	**20**
Electron Underlying Event	**16**
Hadronic Energy Scale	**20**
Hadronic Resolution	**33**
$P_T(W)$ **Spectrum**	**5**
pdf	**21**
parton luminosity	**10**
W **Width**	**9**
Radiative Decays	**20**
QCD background	**11**
Z background	**5**
Systematic Total	**70**
Total	**118**

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

M_W(Run 1B) - 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

(M_W **from** $M_T(W)$ **fit** $= 80.45 \pm 0.12$ GeV/c^2)

Current Results of M_W from DØ experiment at Fermilab

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

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

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

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

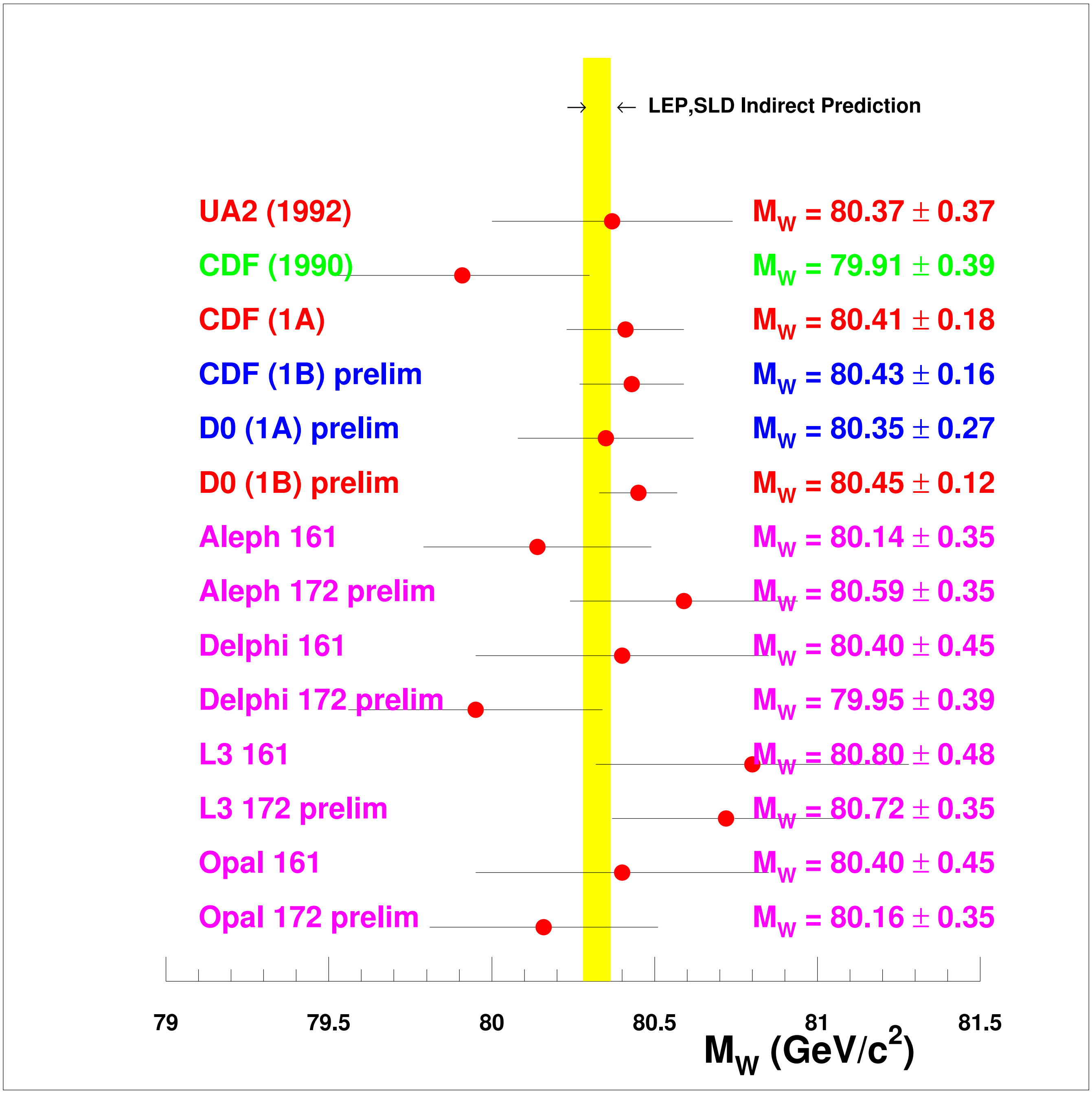
- **DØ Combined 1A + 1B [preliminary, March 97]**

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

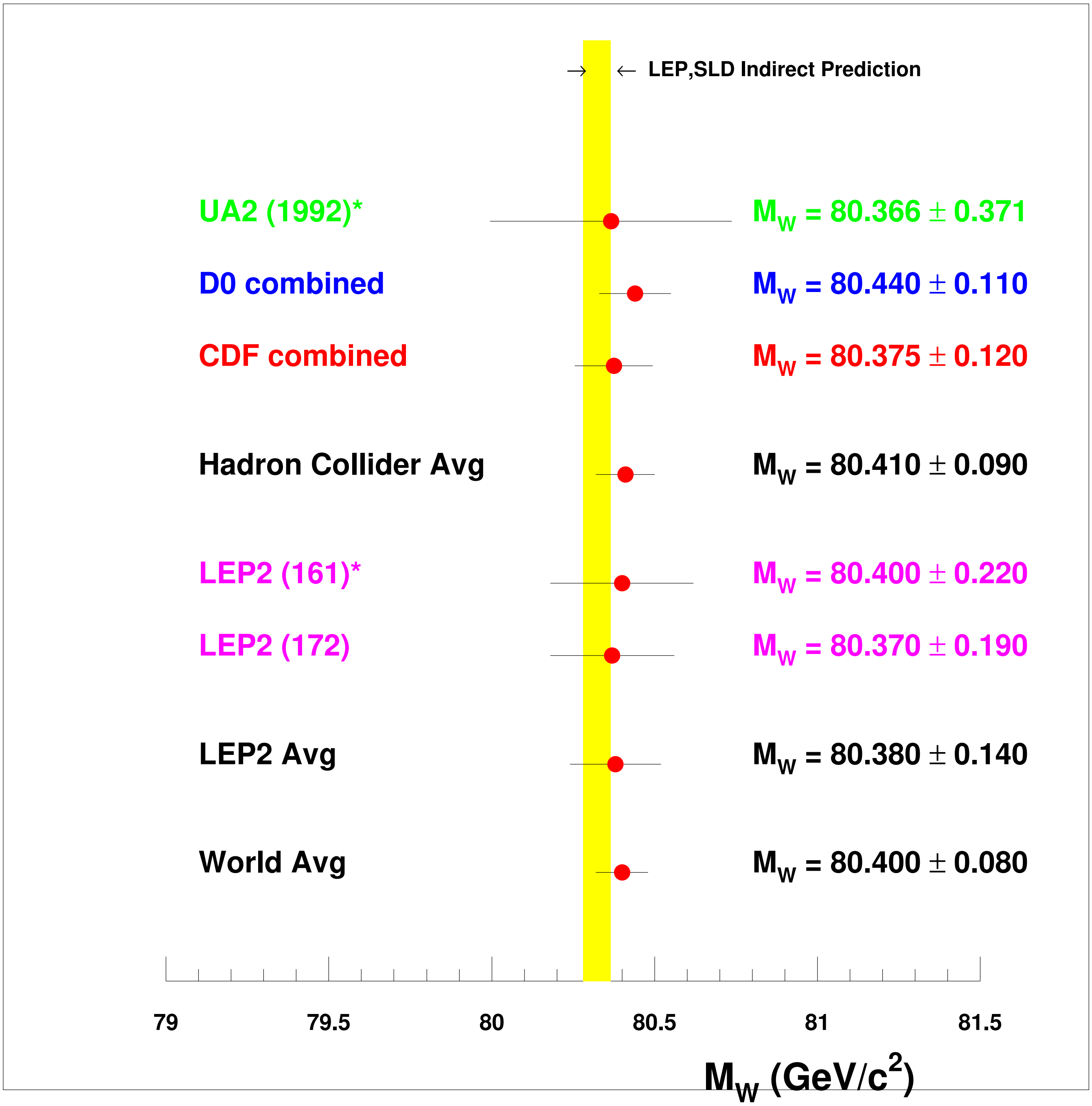
- **expect DØ error to decrease with addition of events with electrons in forward rapidity region ⇒**

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

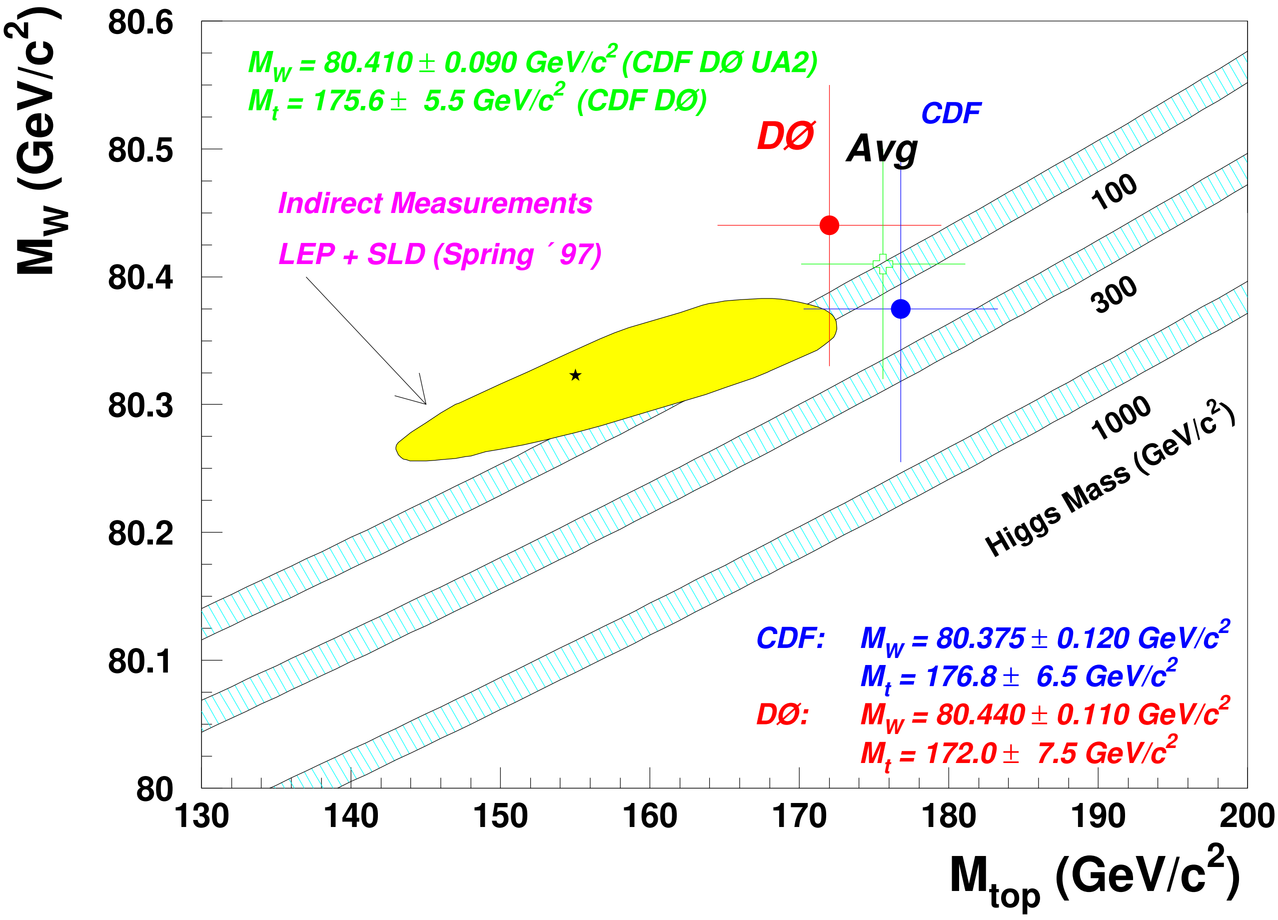
Current Results of M_W



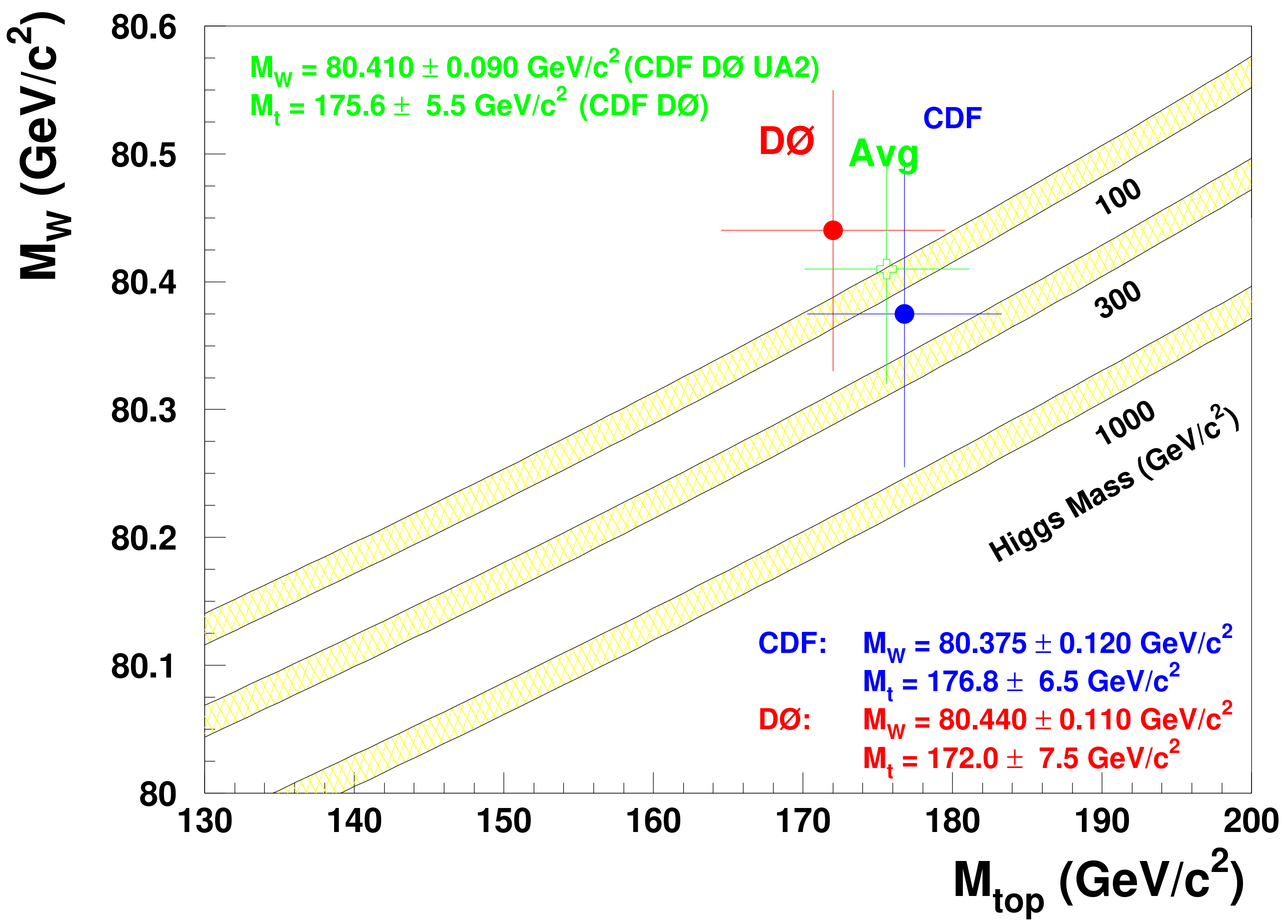
Current Results of M_W



Constraints on Higgs Mass



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**

- **LEP2:** $\Delta M_W \approx 45$ **MeV**

- **Tevatron Run 2** $(\mathcal{L} \approx 2000 pb^{-1})$**:**

  $\Delta M_W \approx 40$ **MeV,** $\Delta m_t \approx 3$ **GeV**

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

Conclusions

- **DØ has collected** $\approx 100\text{pb}^{-1}$ **of data from Run 1 of the Tevatron**
- W **and** Z **cross sections measured in** e, μ, τ **decay modes**
  $\Rightarrow$ **in agreement with SM**
- Γ_W **is measured and gives an upper limit of** $\Delta\Gamma < 109$ **MeV on unknown decays of** W
- **measure** $g_\tau^W / g_e^W = 1.004 \pm 0.032$
  $\Rightarrow$ **in agreement with SM**
- **measure** $M_W = 80.45 \pm 0.12$ **GeV**
  $\Rightarrow$ **in agreement with SM**