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)

Electron Identification - DØ

Offline Selection - Electron Quality Cuts:

- fraction of energy in EM calorimeter $> 90\%$
- longitudinal and transverse shower shape requirements:
  H-matrix $\chi^2 < 100$
- isolation requirement:

$$\frac{E_{tot}(R = 0.4) - E_{EM}(R = 0.2)}{E_{EM}(R = 0.2)} < 0.15$$

- fiducial requirement: $\phi > 10\%$ from module edge
- match between track in central detector and calorimeter

$$\sigma_{trk} < 10$$

  where

$$\sigma_{trk} = \sqrt{\left(\frac{R\Delta\phi}{\sigma(R\Delta\phi)}\right)^2 + \left(\frac{\Delta z}{\sigma(z)}\right)^2}$$

- event requirement: no jets with fraction of energy in CH > 0.4

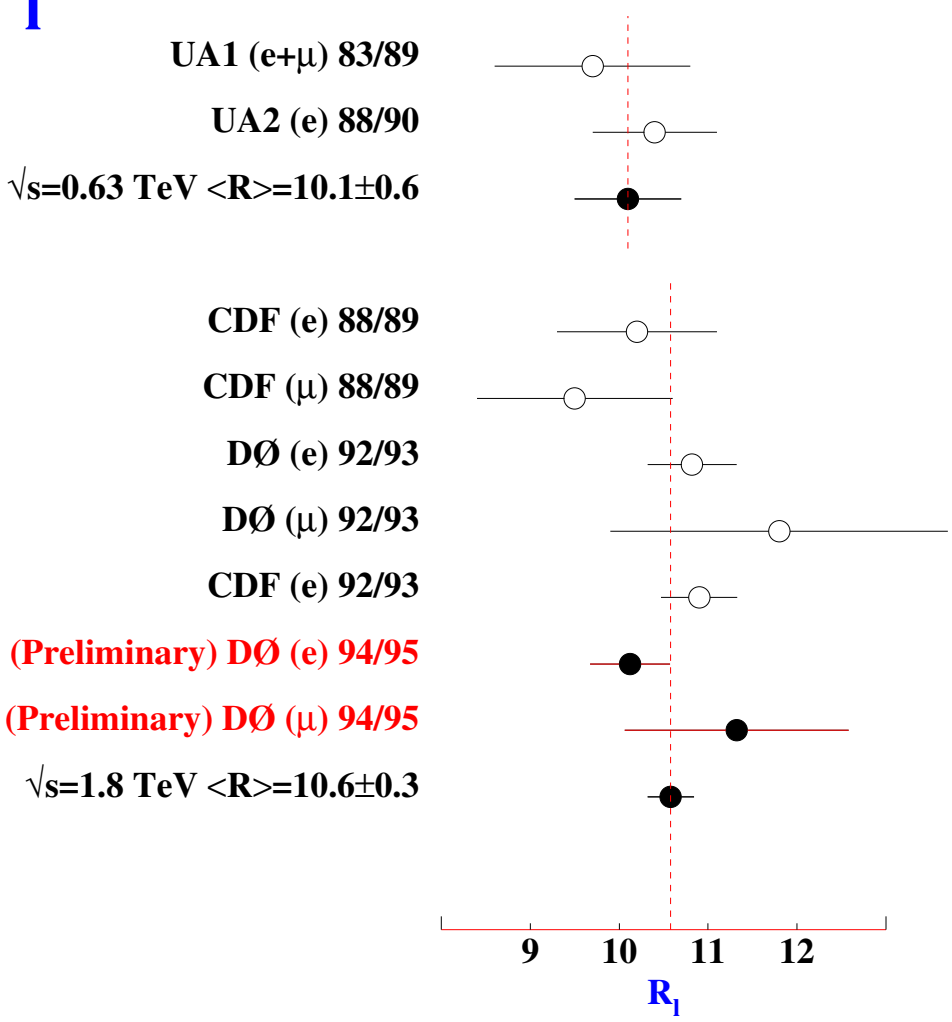
W and Z Production Cross Sections

Run 1B, preliminary

	Electron	Muon
W candidates	59579	4472
$A_W(\%)$	43.4 ± 1.5	20.1 ± 0.7
$\epsilon_W(\%)$	70.0 ± 1.2	24.7 ± 1.5
Bkg.(%)	8.1 ± 0.9	18.6 ± 2.0
Lum. (pb^{-1})	75.9 ± 6.4	32.0 ± 2.7
Z candidates	5702	173
$A_Z(\%)$	34.2 ± 0.5	5.7 ± 0.5
$\epsilon_Z(\%)$	75.9 ± 1.2	43.2 ± 3.0
Bkg.(%)	4.8 ± 0.5	8.0 ± 2.1
Lum. (pb^{-1})	89.1 ± 7.5	32.0 ± 2.7

W, Z Cross Section Ratio

R_l



Direct Measurement of Γ_W

- Measured from shape of $M_T(W)$ distribution
- expect statistical error of 170 MeV
- systematic studies currently in progress (shown at APS 97)

ElectroWeak Standard Model

Specified by 3 parameters:

fine structure constant:

- $\alpha = (137.0359895 \pm .0000061)^{-1} \quad (\delta\alpha/\alpha = 0.045\ ppm)$

Fermi constant:

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

Mass of the Z Boson:

- $M_Z = 91.1884 \pm .0022\ \mathrm{GeV/c^2} \quad (\delta M_Z/M_Z = 24\ ppm)$

At lowest order : $M_W = \dfrac{A}{\sin\theta_W}$ and $\sin^2\theta_W = 1 - \dfrac{M_W^2}{M_Z^2}$

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

$\Rightarrow$ **lump radiative corrections into** Δr **(on-shell scheme, Sirlin)**

$$M_W = \frac{A}{\sin\theta_W(1-\Delta r)^{1/2}} \text{ with } \Delta r \sim \Delta r_o - \rho_t/\tan\theta_W$$

ElectroWeak Standard Model

- $\Delta r_o \approx 0.06$ **- due to running of** $\alpha \rightarrow \alpha(M_Z^2)$
  - vacuum polarization diagrams

- $\rho_t \approx 0.01(M_{top}/180\ \text{GeV})^2$
  due to 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}
$\rightarrow$ **test the SM beyond the tree level**

ElectroWeak Standard Model

Specified by 3 parameters:

fine structure constant:

- $\alpha = (137.0359895 \pm .0000061)^{-1} \quad (\delta\alpha/\alpha = 0.045\ ppm)$

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:

- $M_Z = 91.1884 \pm .0022\ \mathrm{GeV/c^2} \quad (\delta M_Z/M_Z = 24\ ppm)$

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** $\alpha \to \alpha(M_Z^2)$
  - 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

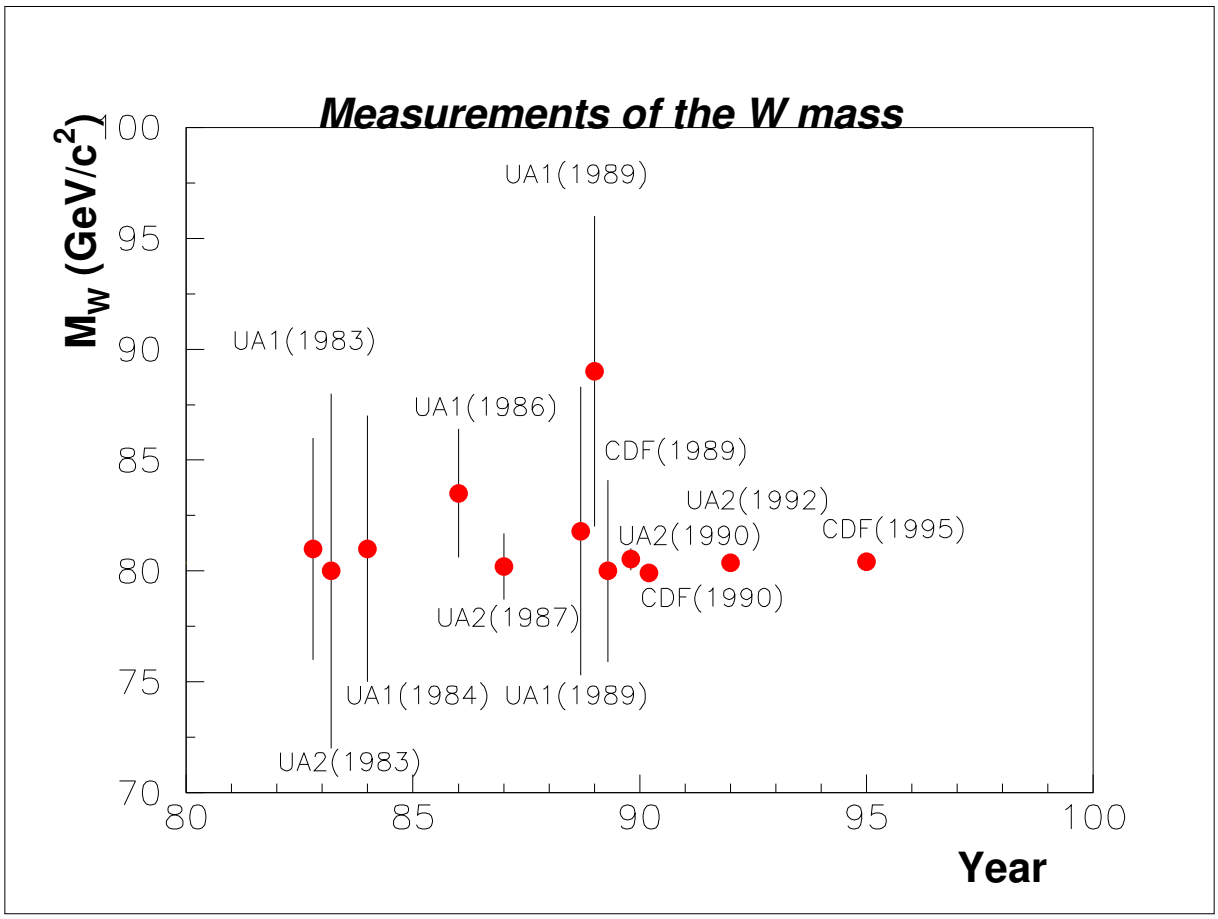
$\Rightarrow$ **Precision Measure of M_W provides**

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

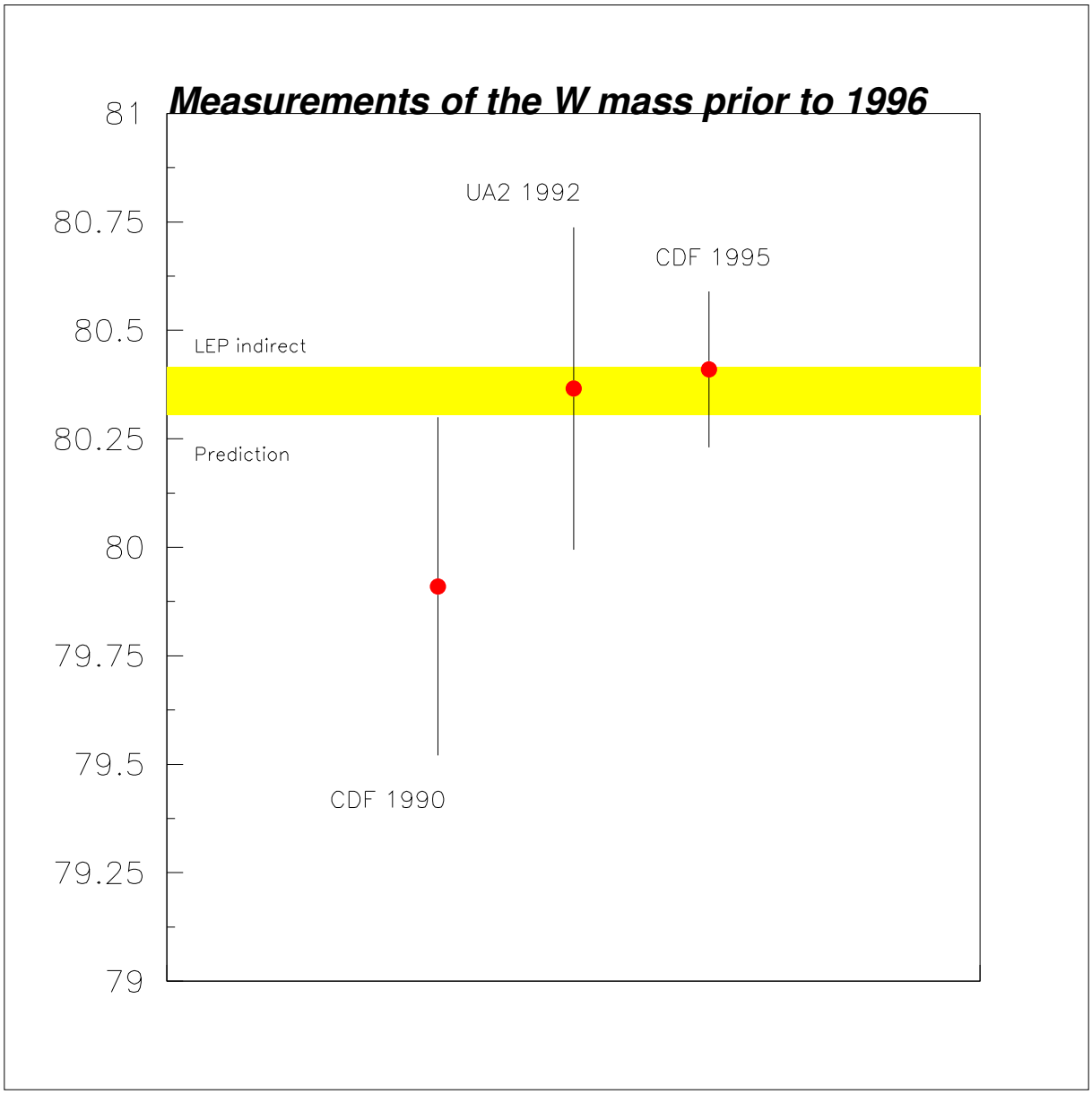
- $\star$ **Improvement in precision can further constrain allowed values of M_{Higgs} in Standard Model or parameter space of other models**

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

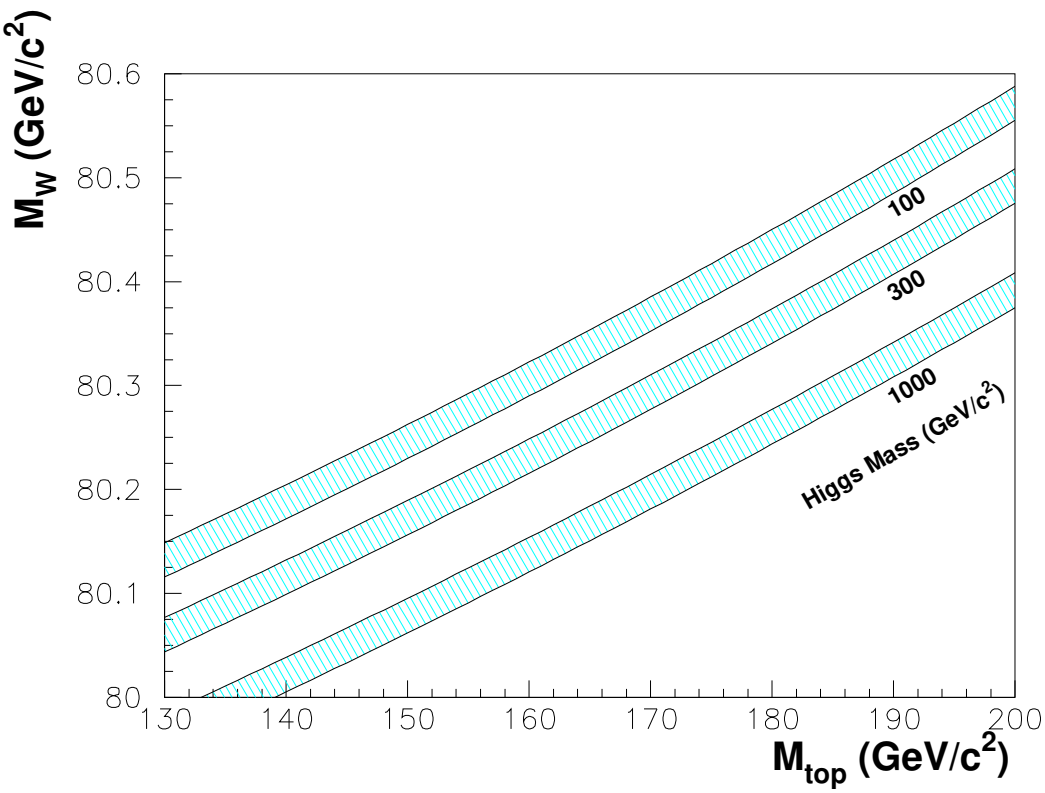
Previous Measurements of M_W



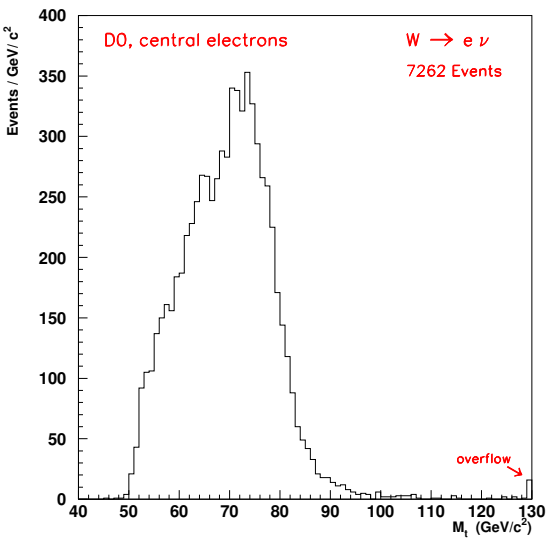
Previous Measurements of M_W

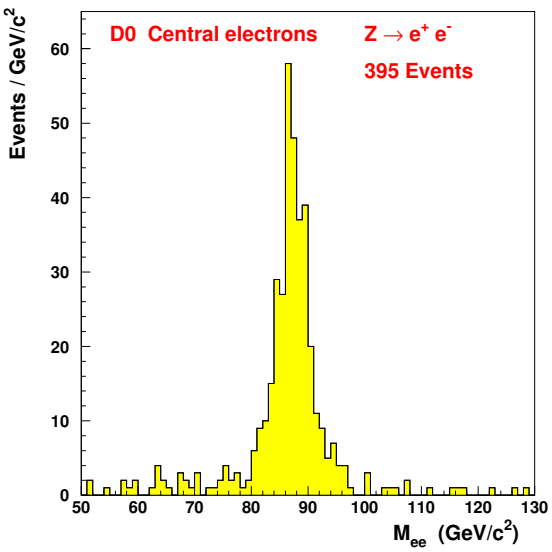


M_W vs. M_{top} - Higgs Mass Dependence



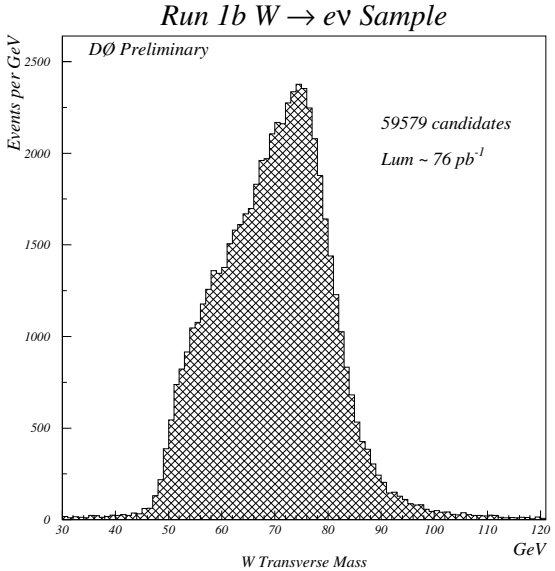
Run 1A - spectra:



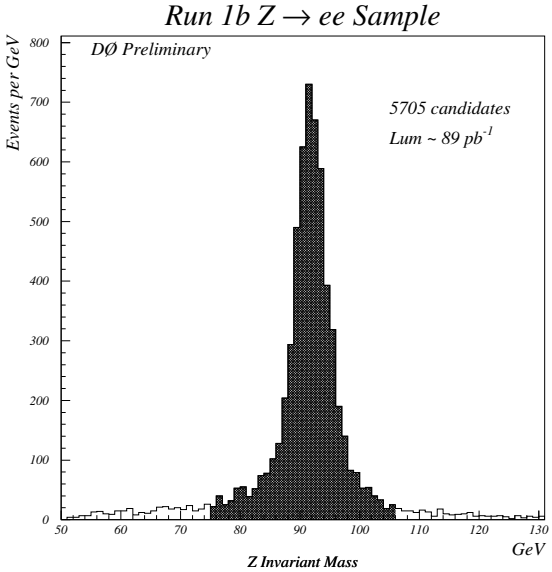


Run 1B - spectra:

Run 1b W → eν Sample



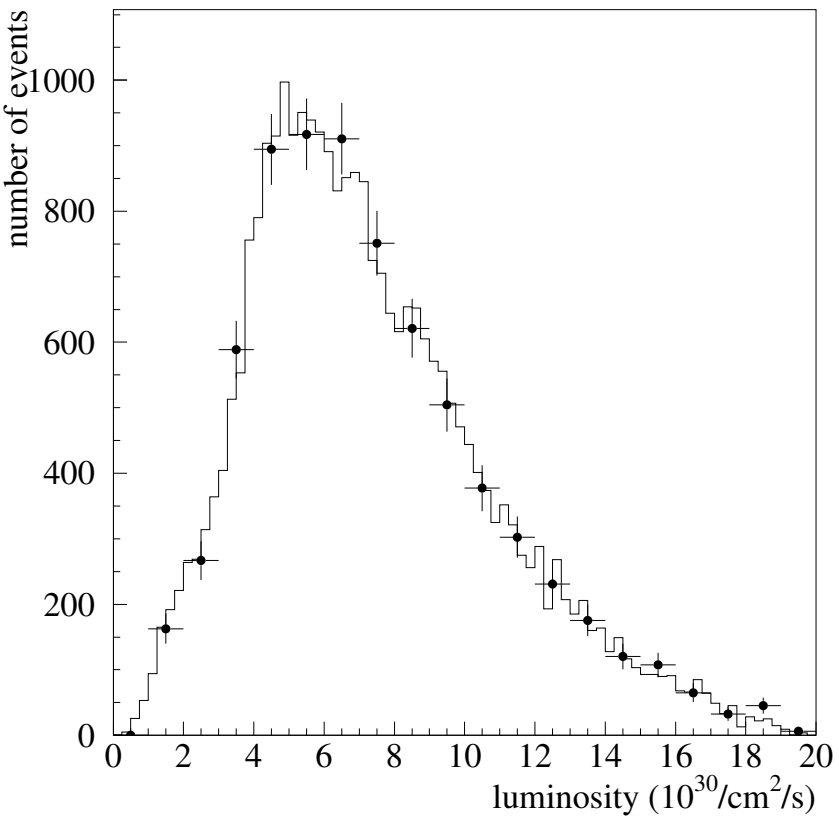
Run 1b Z → ee Sample



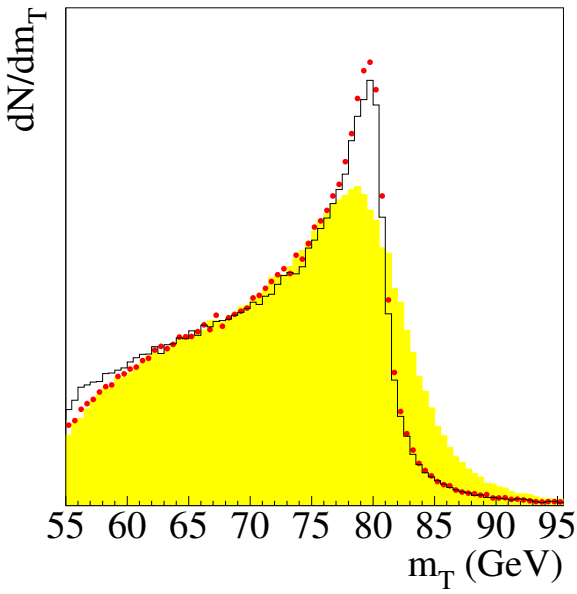
M_W - Event Sample

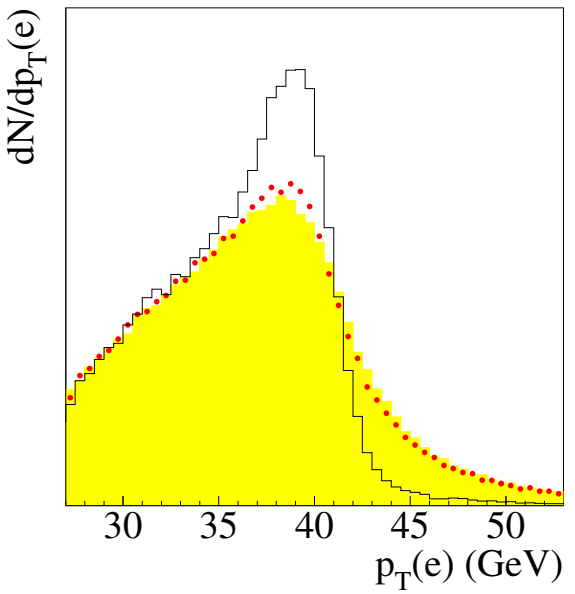
		# events: 1A	1B
$W \to e\nu$		**7234**	**28323**
⋆ e **in central region:**	$\lvert\eta\rvert < 1.2(1.0)$		
⋆ **electron:**	$E_T^e > 25$ **GeV**		
⋆ **neutrino:**	$\not\!\!E_T > 25$ **GeV**		
⋆ W **transverse mom.**	$E_T^W < 30(15)$ **GeV**		
⋆ **transverse mass (1A)**	$50 < M_T^W < 110$ **GeV**		
$Z \to ee$		**366**	**2179**
⋆ e**'s in central region:**	$\lvert\eta\rvert < 1.2(1.0)$		
⋆ **2 isolated electrons:**	$E_T(e) > 25$ **GeV**		
⋆ **invariant mass (1A)**	$70 < M_Z < 110$ **GeV**		

M_W(Run 1B) - Luminosity of W Events

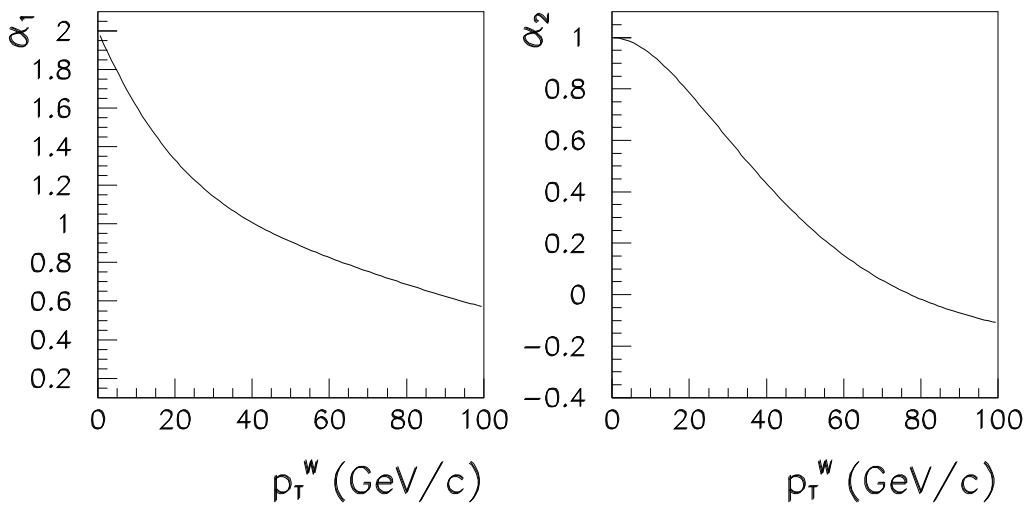


M_W - Measurement Method

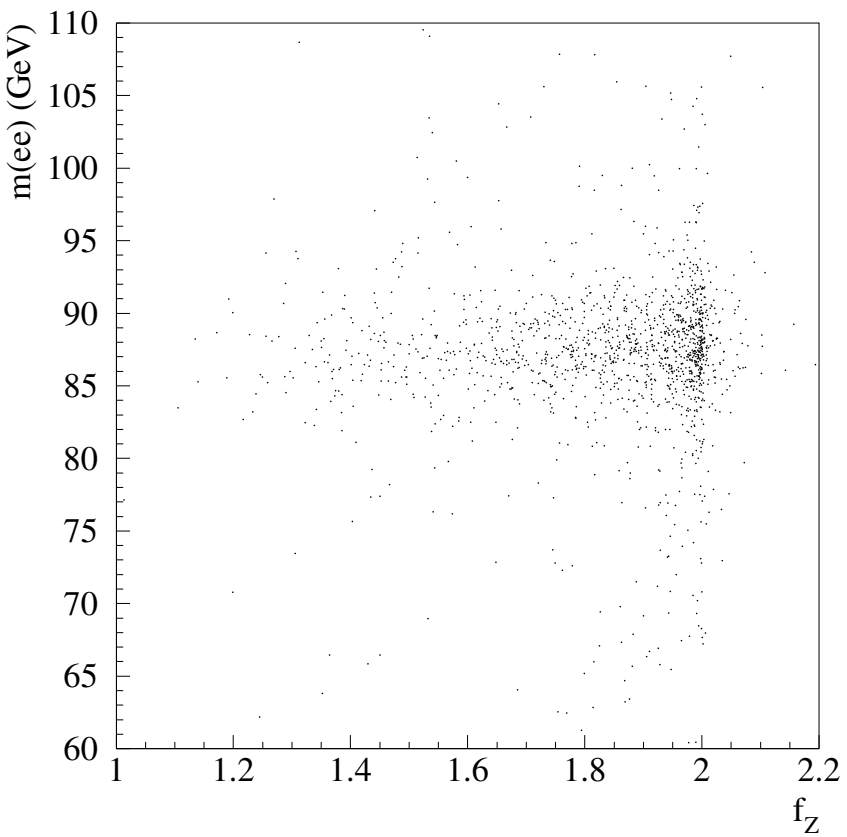




W Decay Model (Mirkes)



M_W - electron energy scale $\Rightarrow$



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 lost from cluster that *is* due to electron:**
  - **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:

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

$\star$ $\vec{U}(e)$ due to multiple interactions & spectator partons
$\rightarrow$ function of luminosity and $(u_{\parallel})$

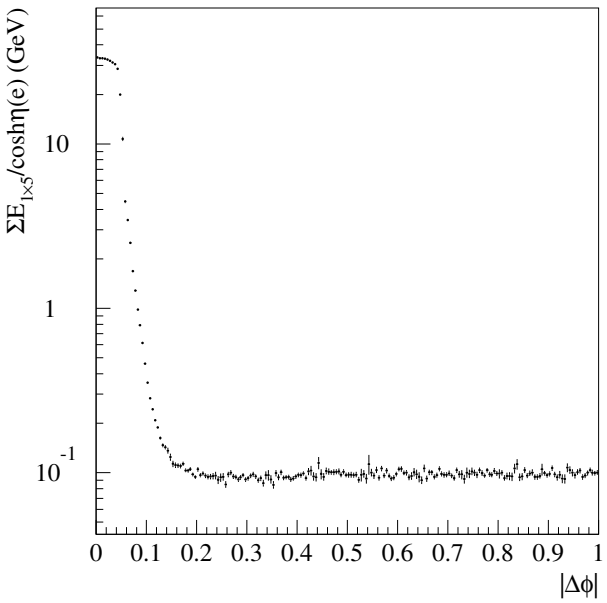
$\langle \vec{U}(e) \rangle = 479 \pm 2(stat) \pm 6(syst)$ **MeV**

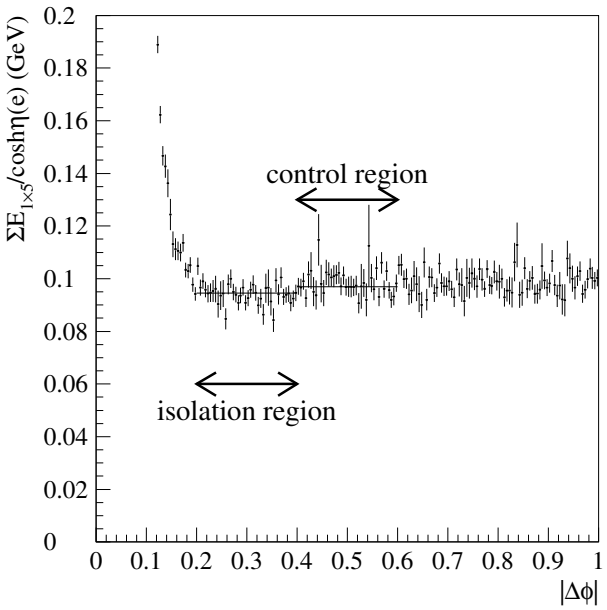
$\star$ $\vec{U}_{zs}$ due to the zero-suppression

$\vec{U}_{zs} = 212$ **MeV**

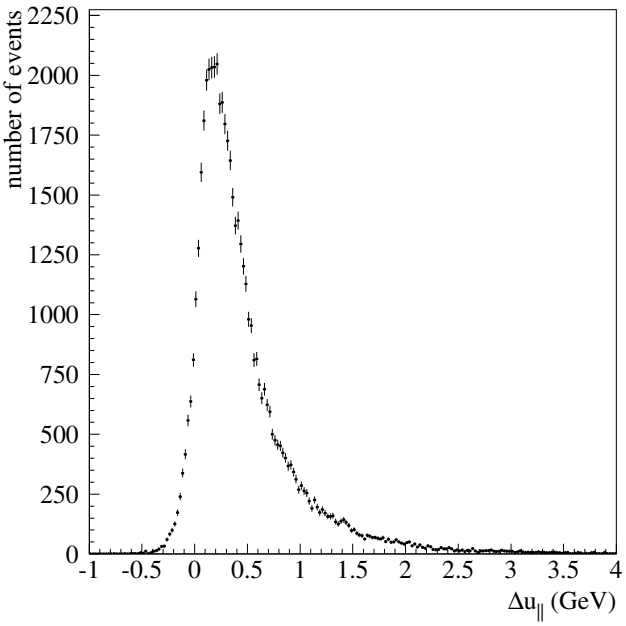
Error due to e underlying event modelling: $\sigma(M_W) = 16$ MeV

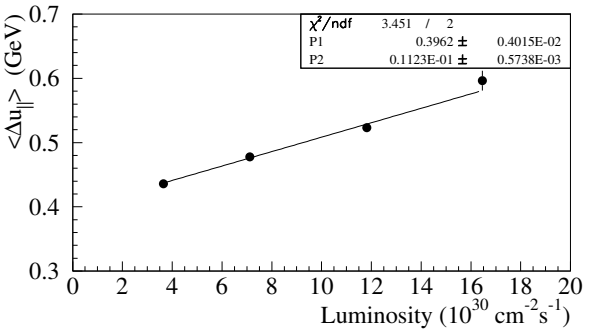
M_W(Run 1B) - Underlying Event

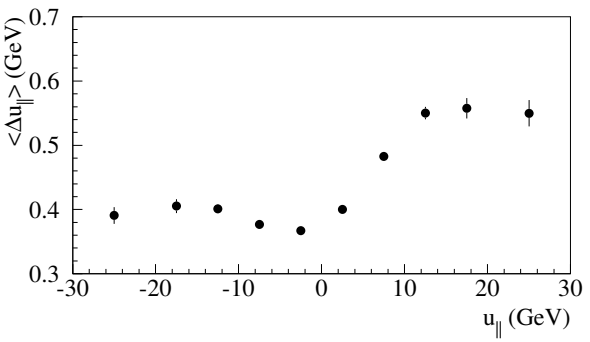




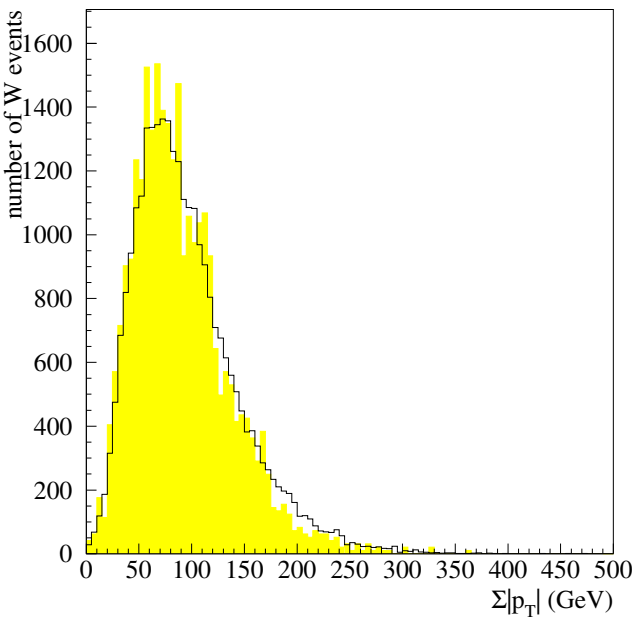
Underlying Event Contribution to $P_T(e)$

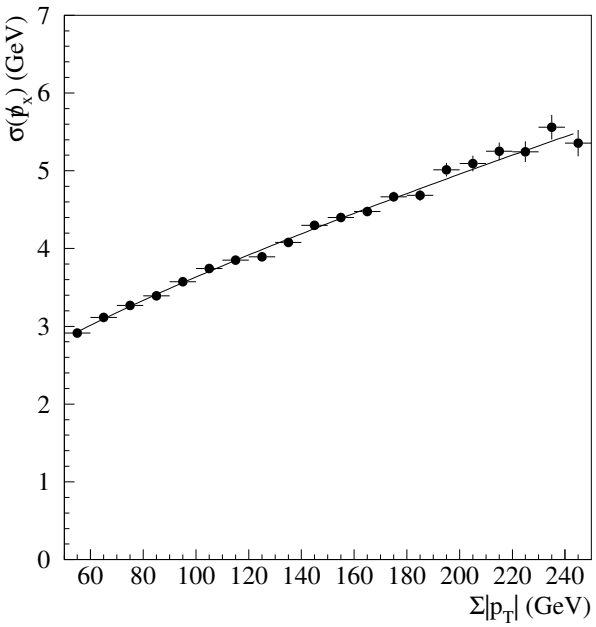






W, Z Underlying Event Difference



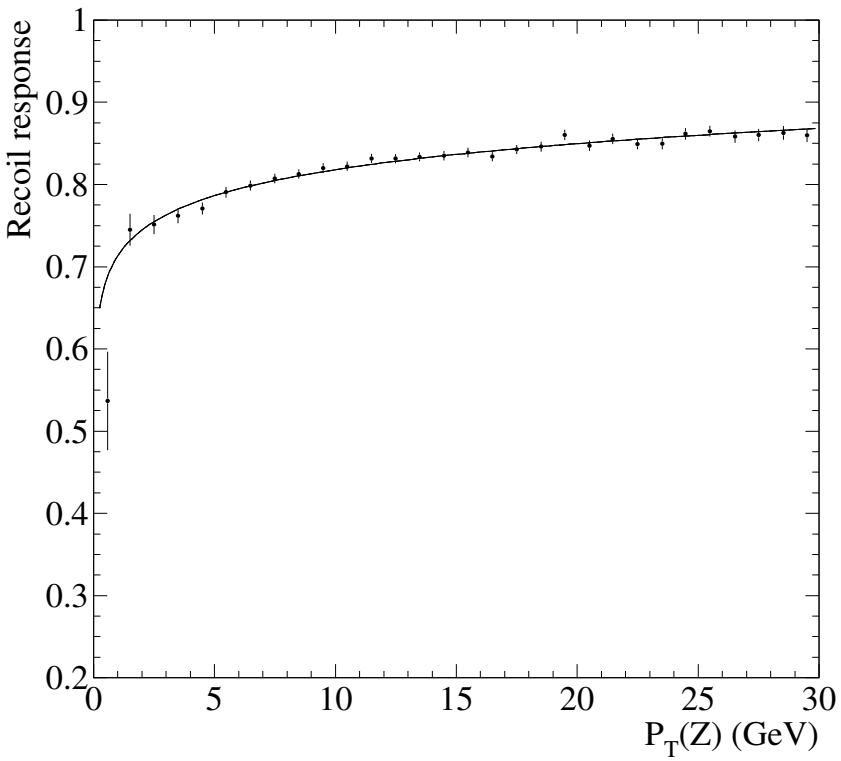


M_W - Hadronic (Recoil) Energy Scale

- **HERWIG + GEANT $Z \to ee$ Monte Carlo Sample**

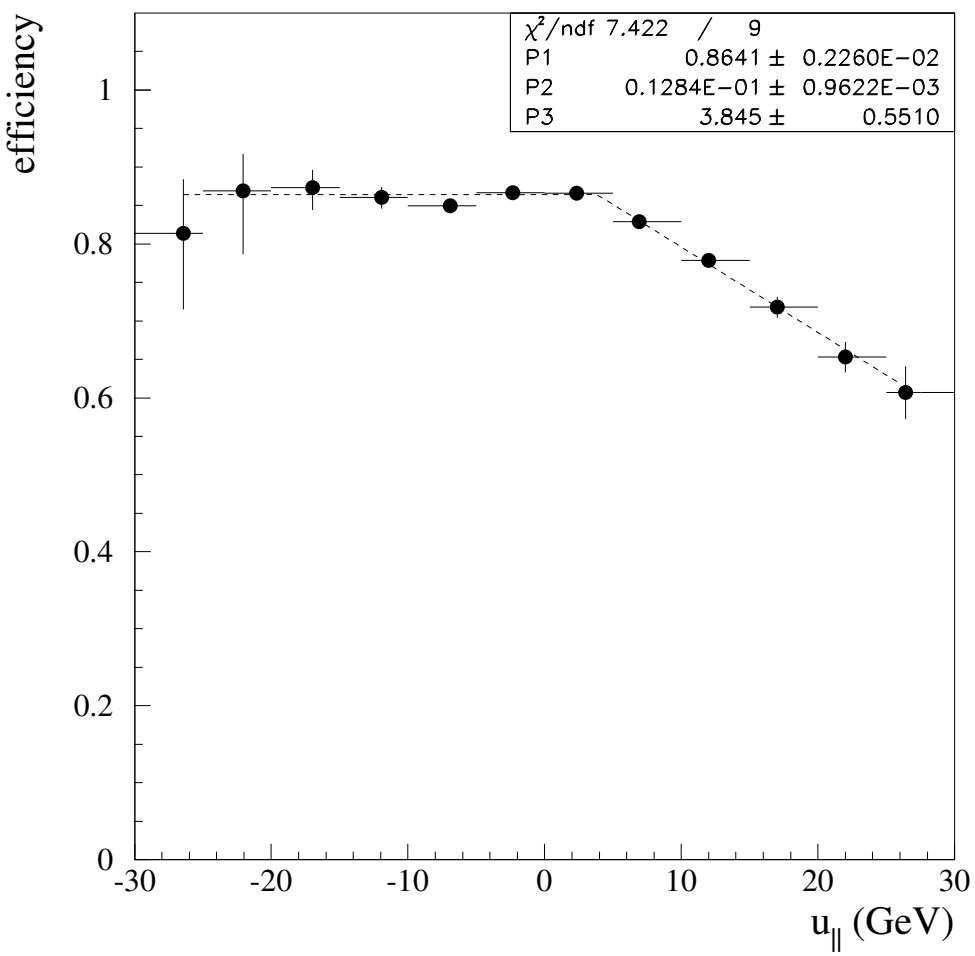
$\Rightarrow$ gives recoil response form

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

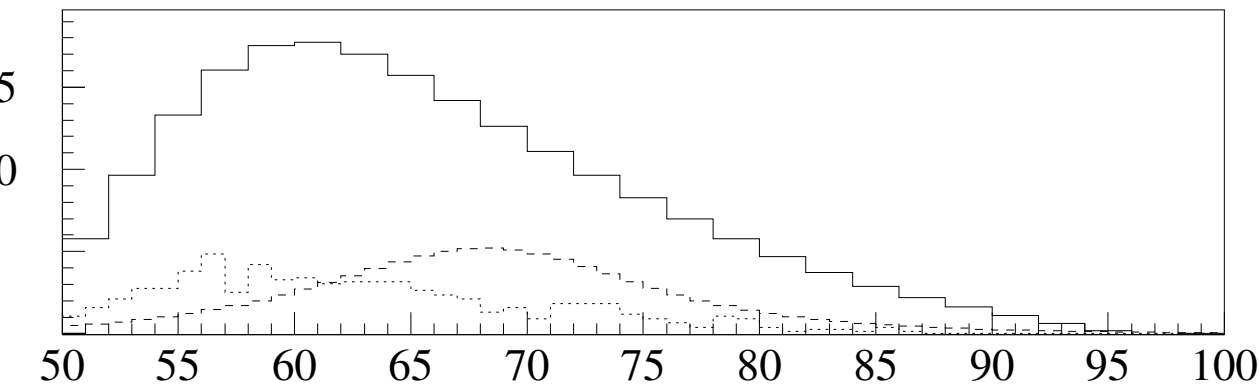


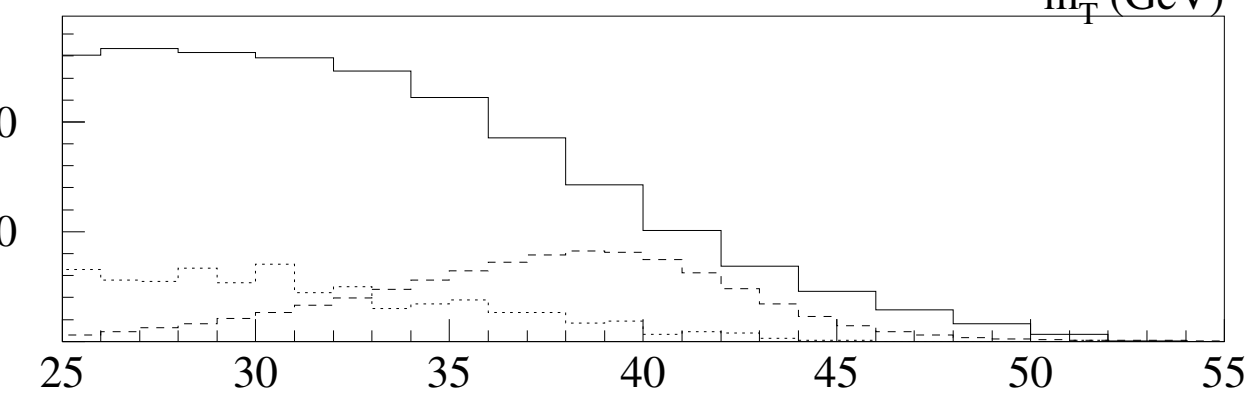
Event Selection Efficiency

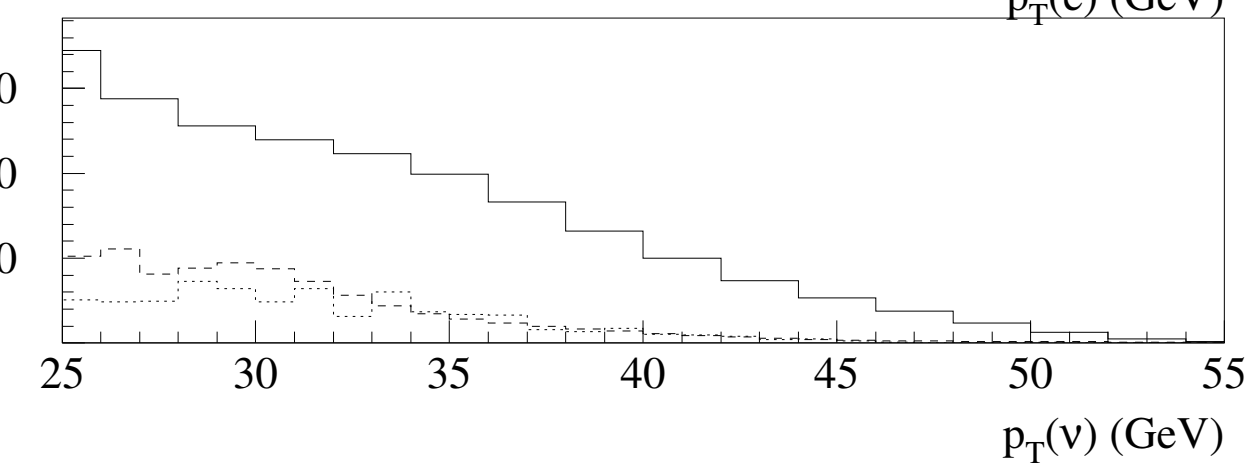
L2, iso/0.95, χ^2 (luminosity reweighted)



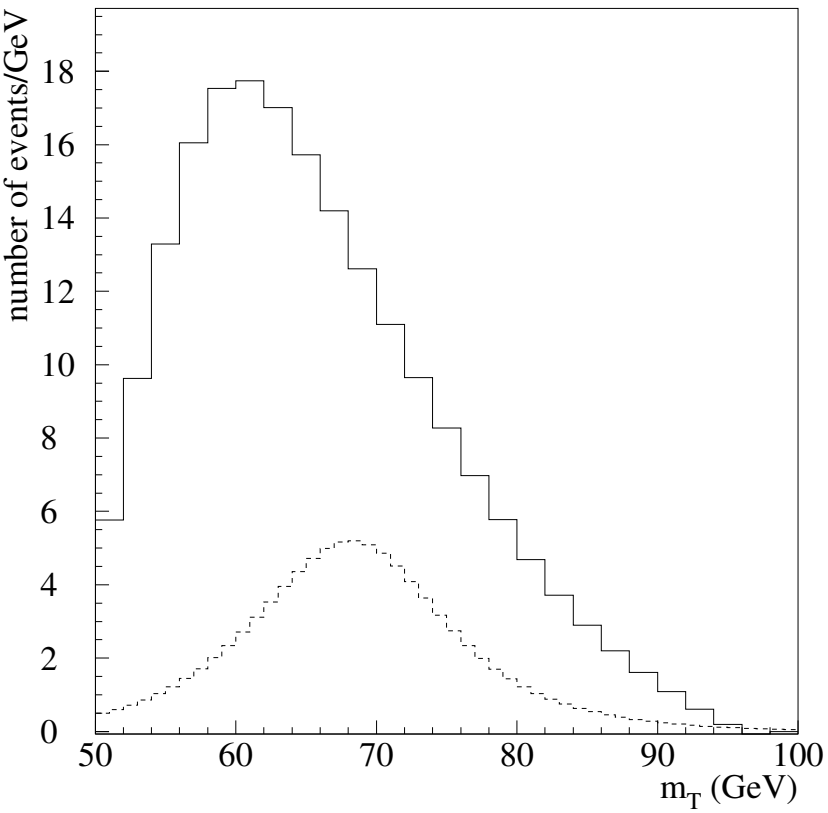
M_W(Run 1B) - Background Contributions







M_W - Backgrounds



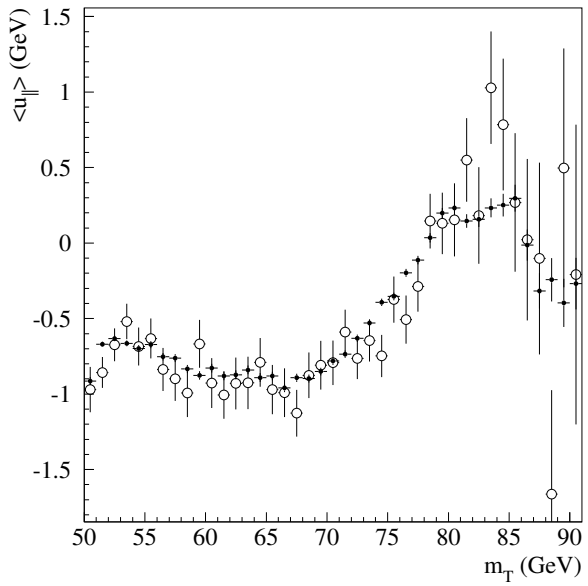
$\Rightarrow$ **included in likelihood fitting procedure**

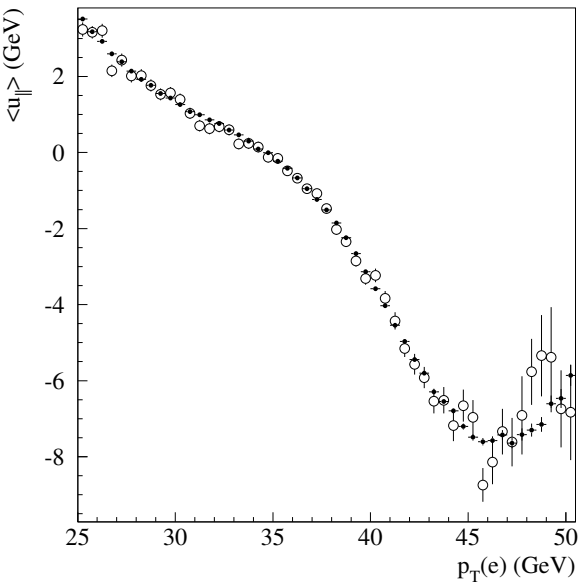
multi − jet $\Rightarrow$ **QCD event with** $\not\!\!E_T$ **and jet faking** e
$(1.4 \pm 0.2\%)$

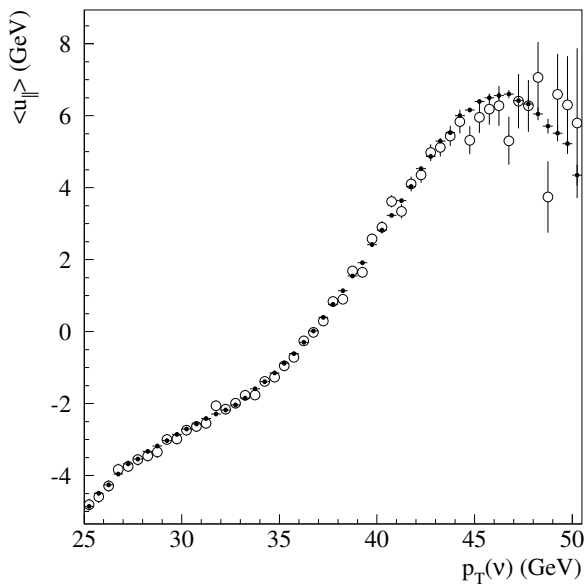
$Z \rightarrow ee$ $\Rightarrow$ Z **event in which one electron lost**
$(0.33 \pm 0.06\%)$

Error due to shape and size of backgrounds: $\sigma(M_W) = 12$ MeV

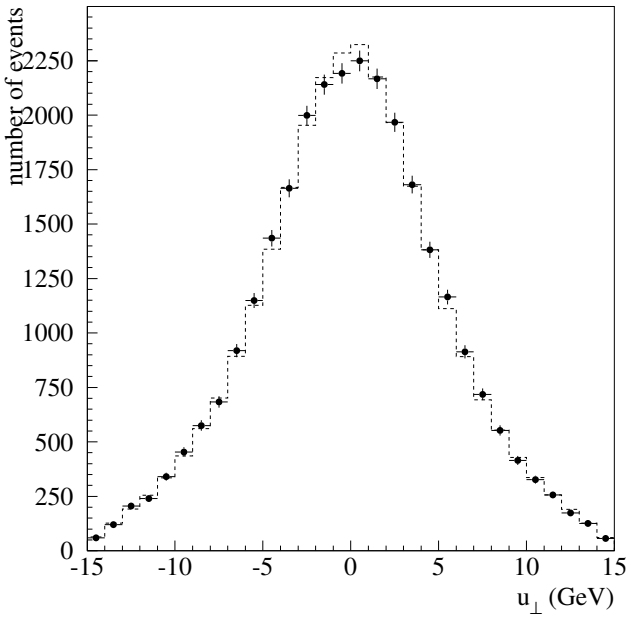
M_W(Run 1B) - Data vs. MC

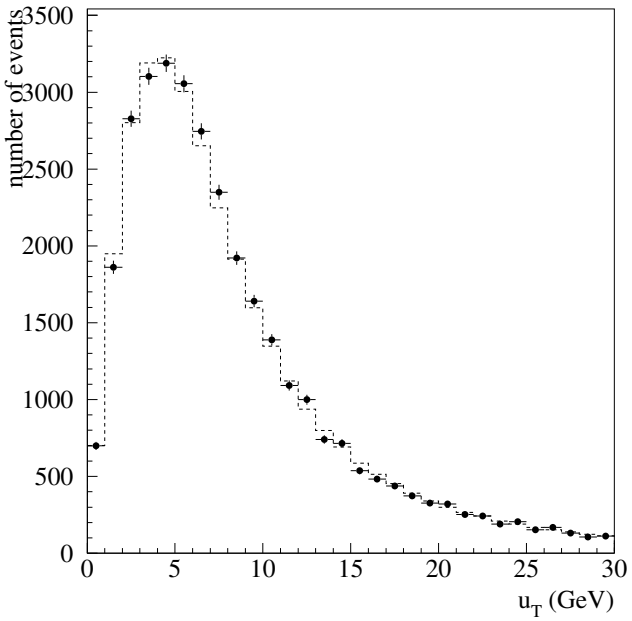






Data and MC Comparison





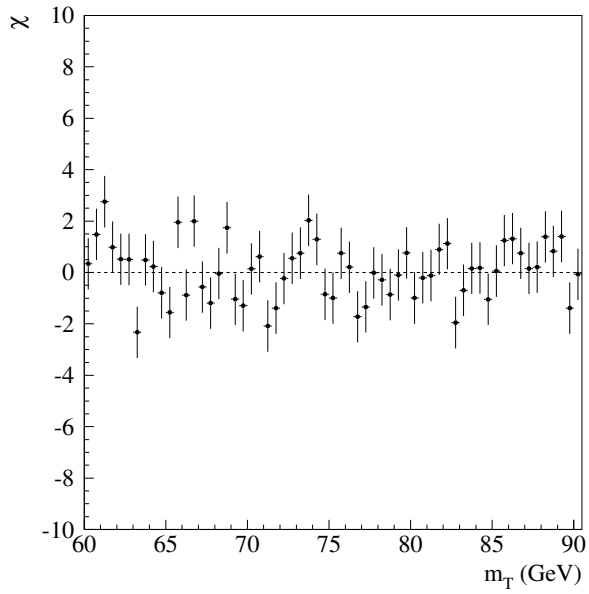
Errors from $P_T(W)$ spectrum and pdf's

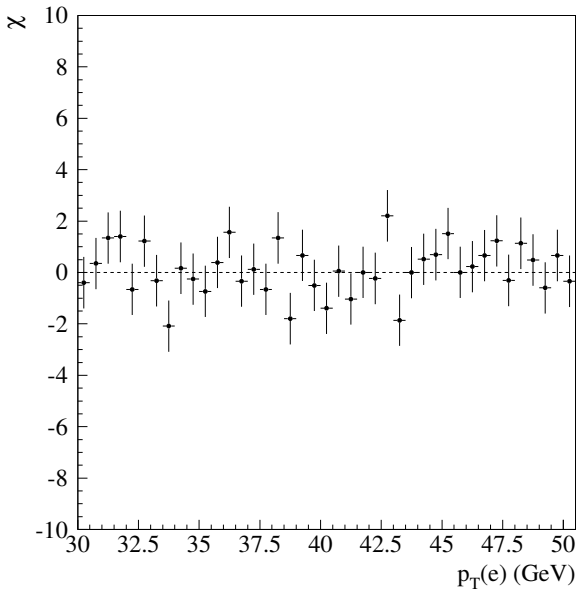
Use Ladinsky-Yuan calculation of $\frac{d^2\sigma}{dydP_T}$
- correlated with pdf choice

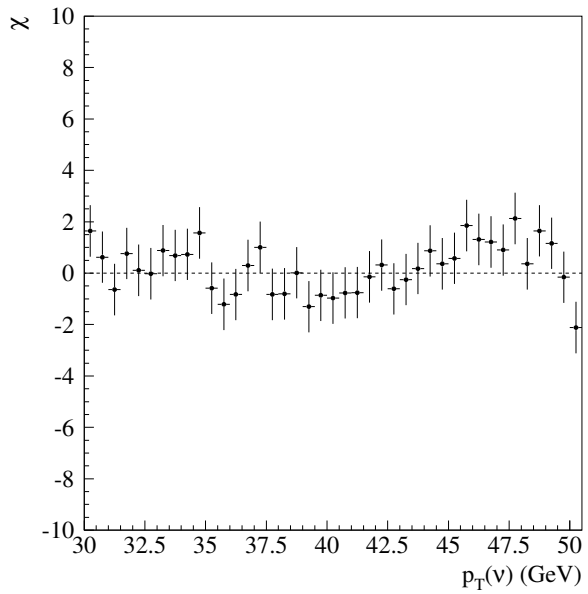
- **new parametrization of non-perturbative (low P_T) region of the resummed cross section**
- **based on resummed calculation by Collins, Soper & Sterman**
- **modified to include perturbative high P_T part - Arnold & Reno**

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

M_W(Run 1B) - χ^2 of fits

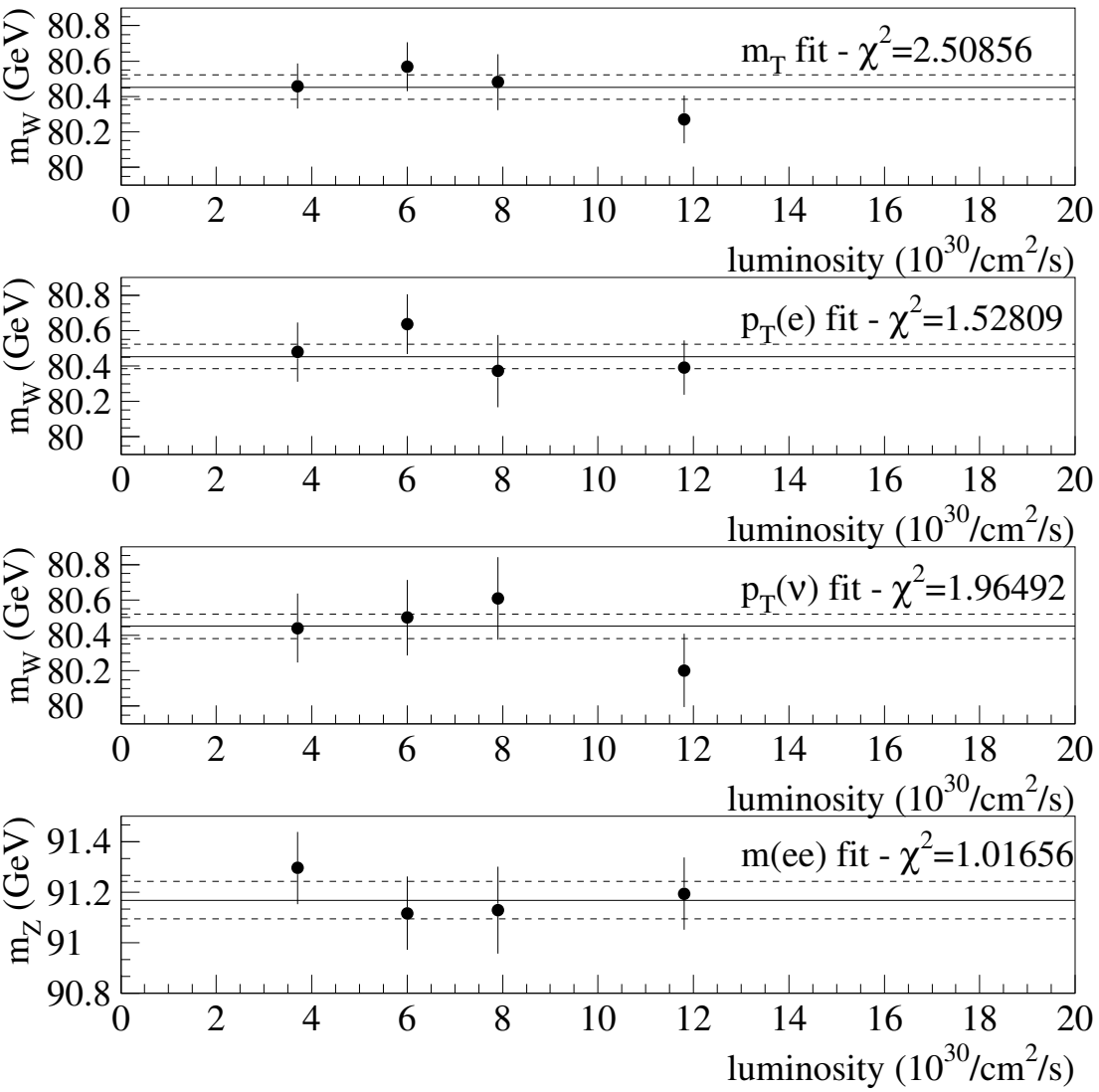






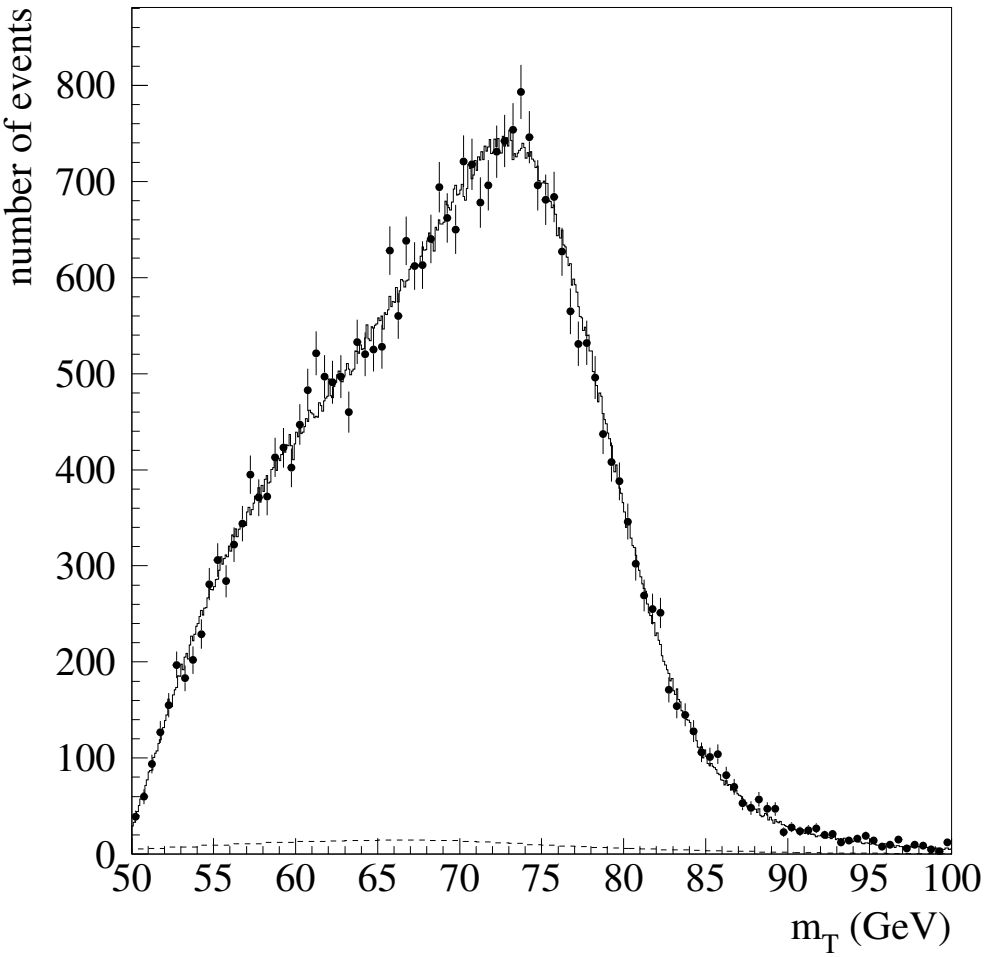
$M_T(W)$ **fit,** $\chi^2/dof = 77/59$
$P_T(e)$ **fit,** $\chi^2/dof = 38.7/39$
$P_T(\nu)$ **fit,** $\chi^2/dof = 36/39$

M_W(Run 1B) - Cross Checks
M_W(Run 1B) - variation with luminosity



Cross Checks

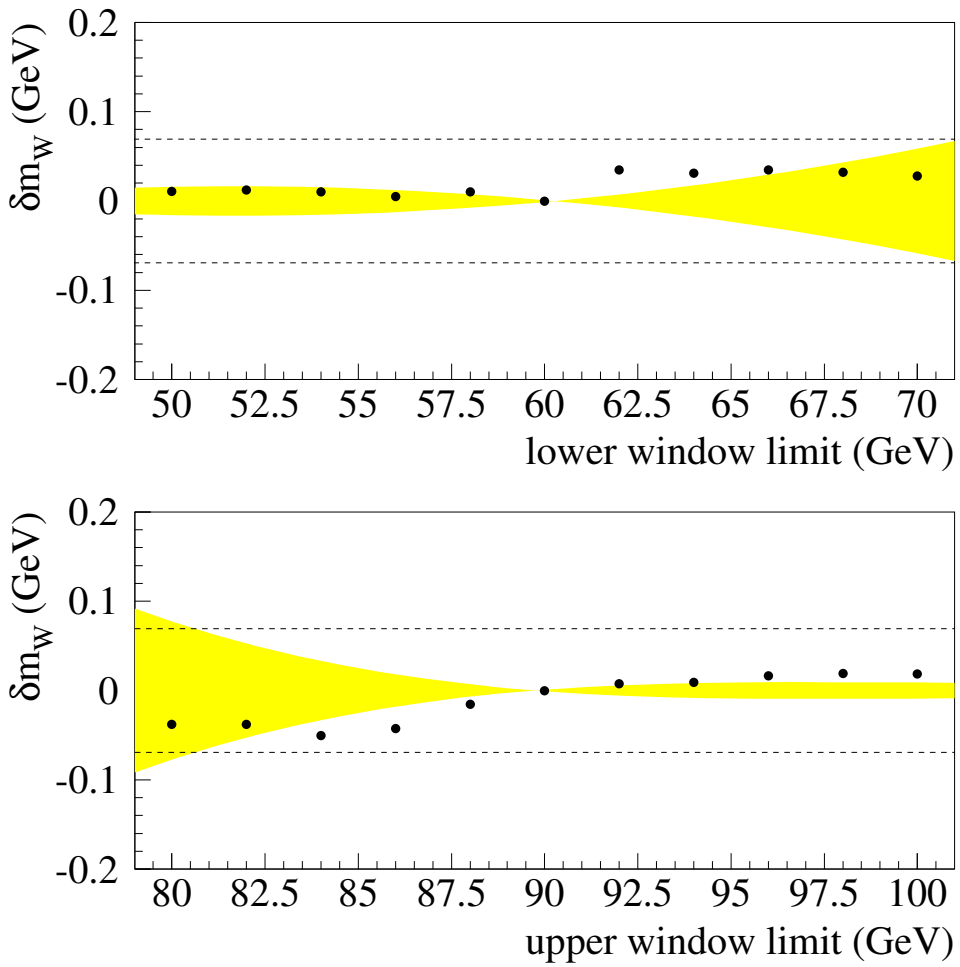
- **fit W data with requirement $p_T(W) < 30$ GeV**



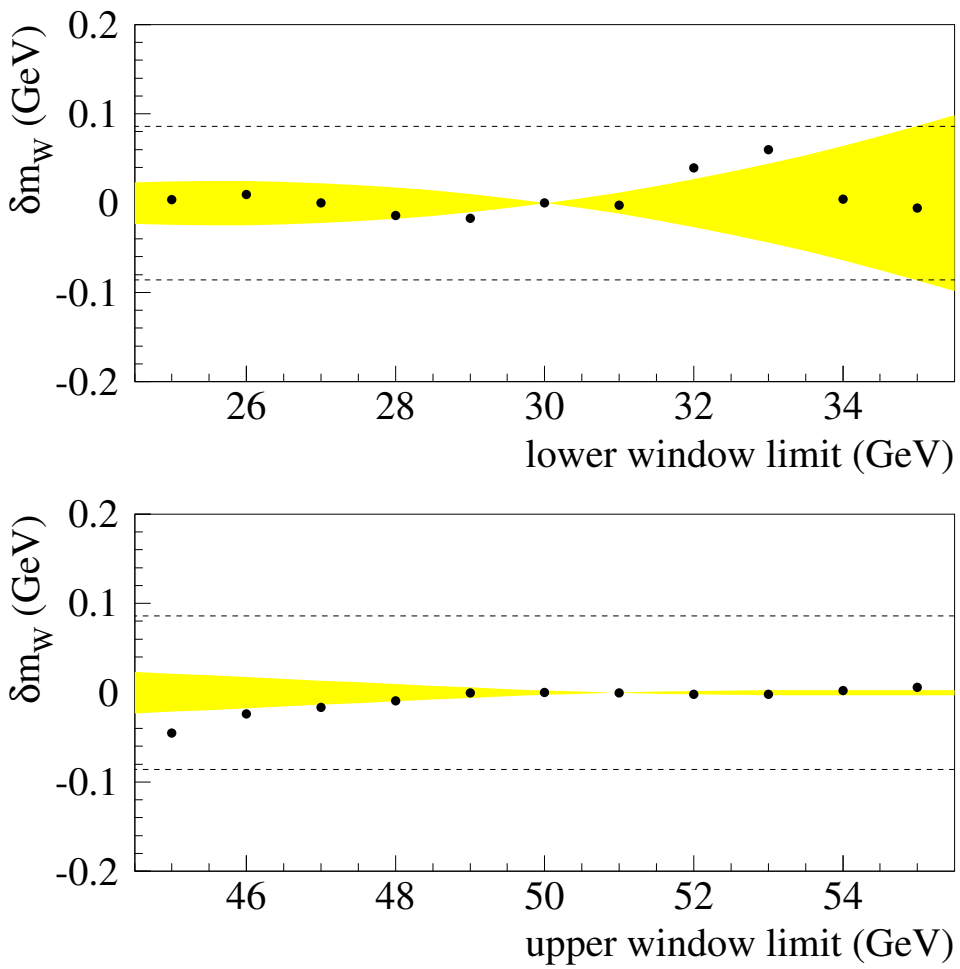
$M_T(W)$ **fit** $\Rightarrow 80.48 \pm 0.07(stat)$ **GeV**
$P_T(e)$ **fit** $\Rightarrow 80.45 \pm 0.09(stat)$ **GeV**
$P_T(\nu)$ **fit** $\Rightarrow 80.30 \pm 0.11(stat)$ **GeV**

CROSS CHECK

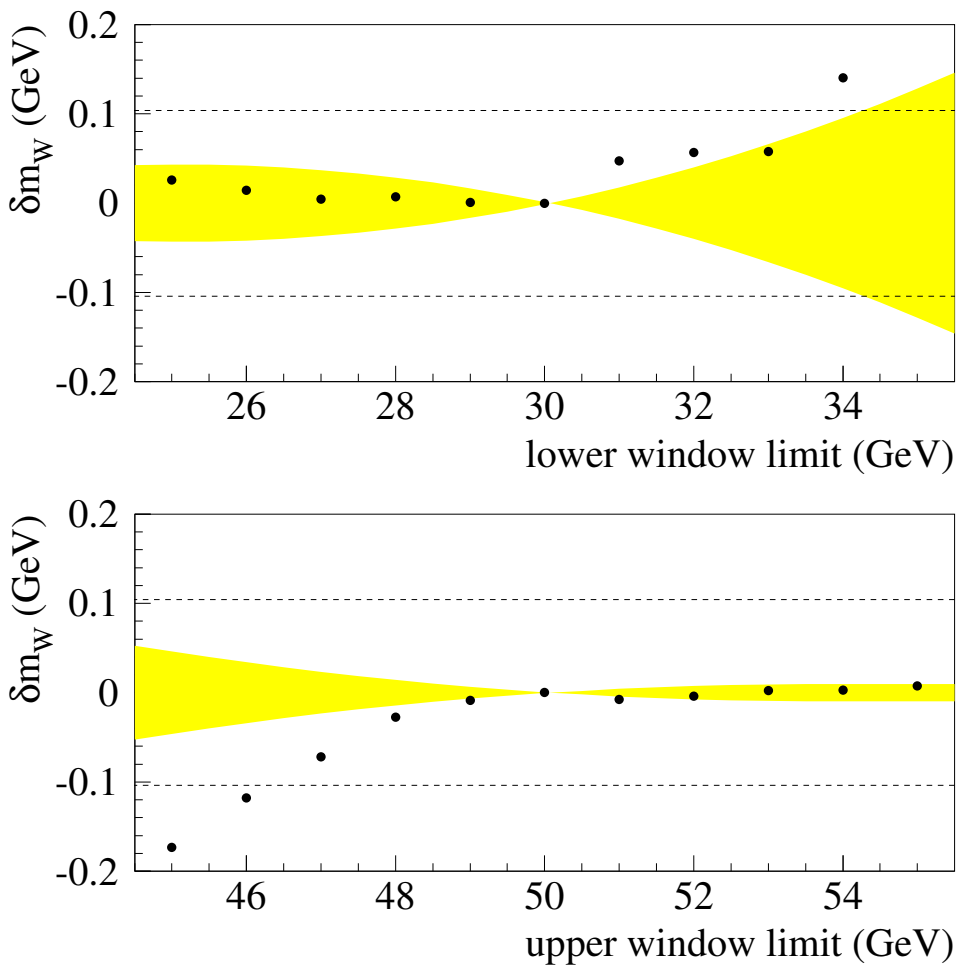
M_W - variation with fitting window, fit to $M_T(W)$



M_W - variation with fitting window, fit to $P_T(e)$



M_W - variation with fitting window, fit to $P_T(\nu)$



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

* this error combined with another one

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

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

M_W - Summary of Errors

Source	$\sigma_{M(W)}$ in MeV/c^2	
	$M_T(W)$ fit	$P_T(e)$ fit
Statistical (W events)	69	86
Statistical (Z events)	65	65
Non-Uniform energy response (η)	10	10
Electron Angle Calibration	28	28
Electron Energy Resolution	23	14
Electron Energy Linearity	20	20
Electron Underlying Event	16	16
Selection Biases/Efficiencies	-	9
Hadronic Energy Scale	20	16
Hadronic Resolution	33	9
$P_T(W)$ Spectrum	5	28
pdf	21	48
parton luminosity	10	10
W Width	9	7
Radiative Decays	20	20
QCD background	11	16
Z background	5	8
Systematic Total	70	79
Total	118	134

$M_W(\mathrm{P_T(e)\ fit}) = 80.49 \pm 0.09(stat.) \pm 0.065(scale) \pm 0.079(syst.)\ \mathrm{GeV/c^2}$

$M_W(\mathrm{M_T(W)\ fit}) = 80.45 \pm 0.070(stat.) \pm 0.065(scale) \pm 0.070(syst.)\ \mathrm{GeV/c^2}$

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]**

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

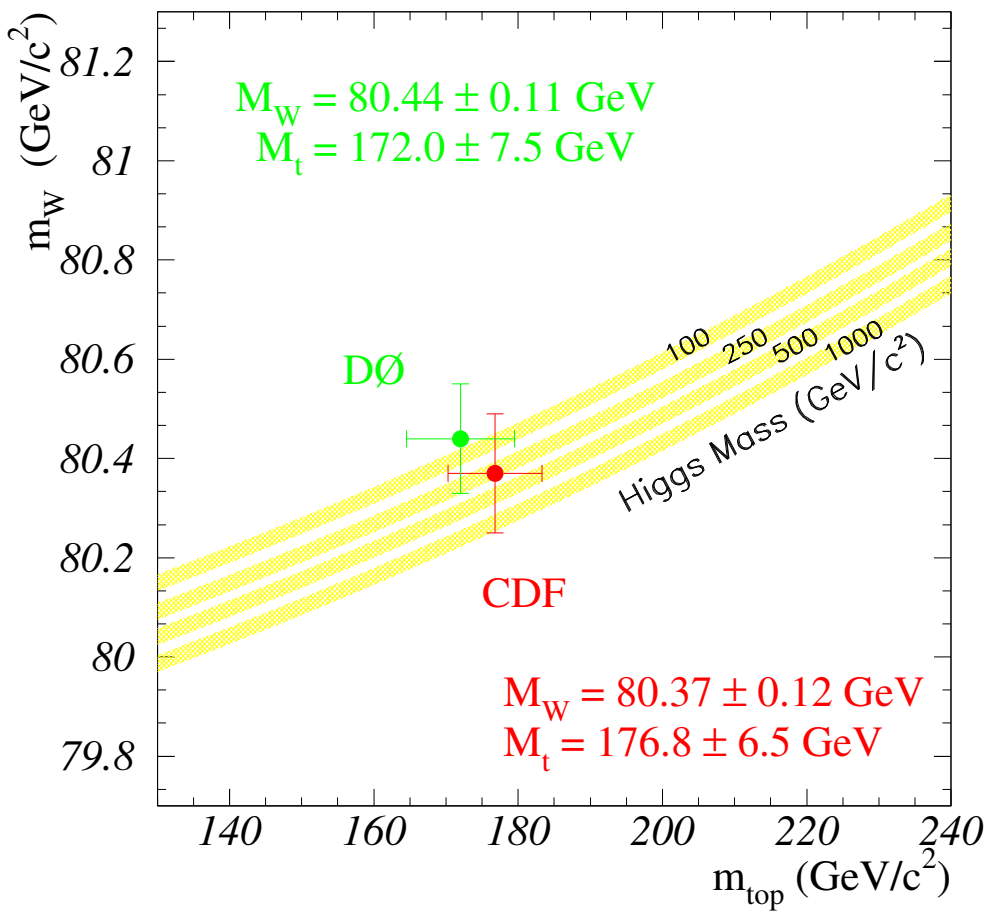
- **CDF Combined 1A + 1B data [prelim., Feb 97]**

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

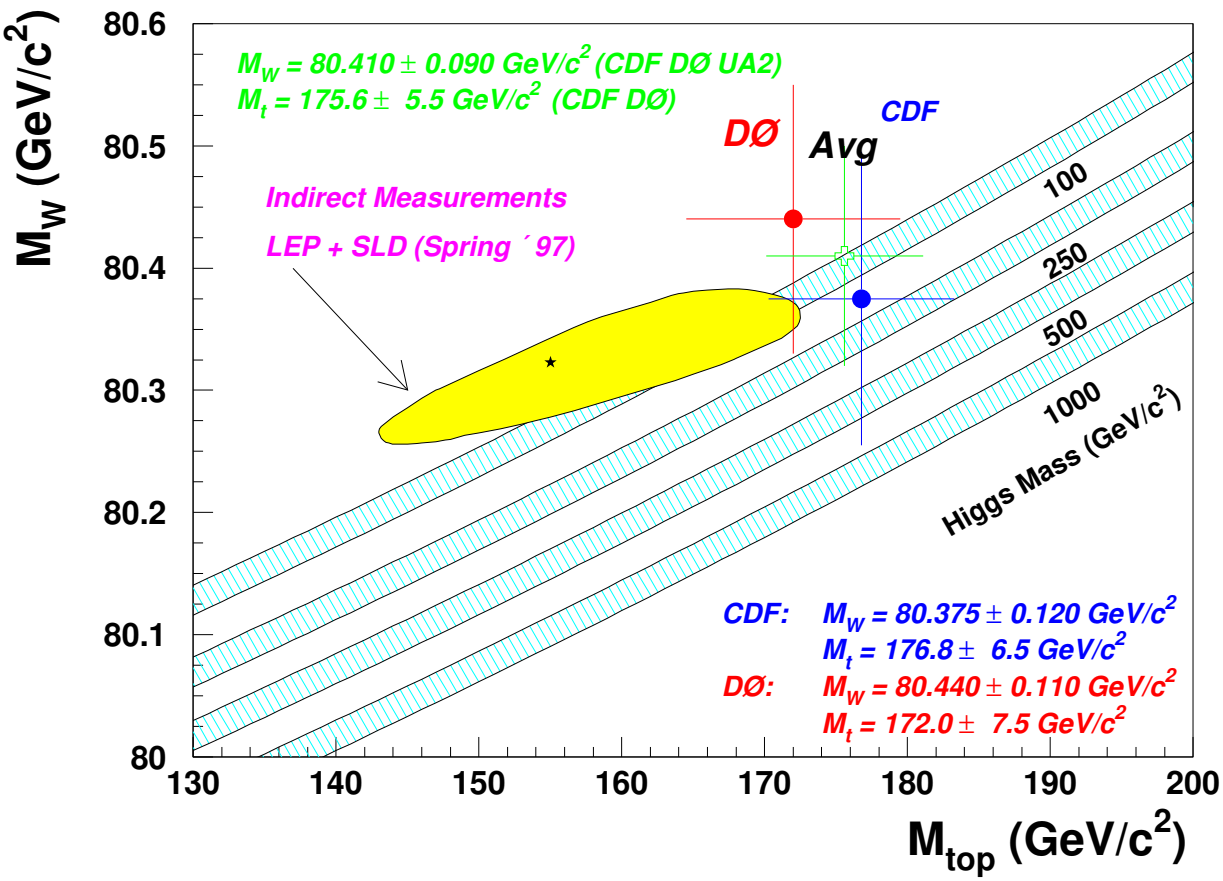
- **expect CDF error to decrease with addition of $W \to e\nu$ events $\Rightarrow$**

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

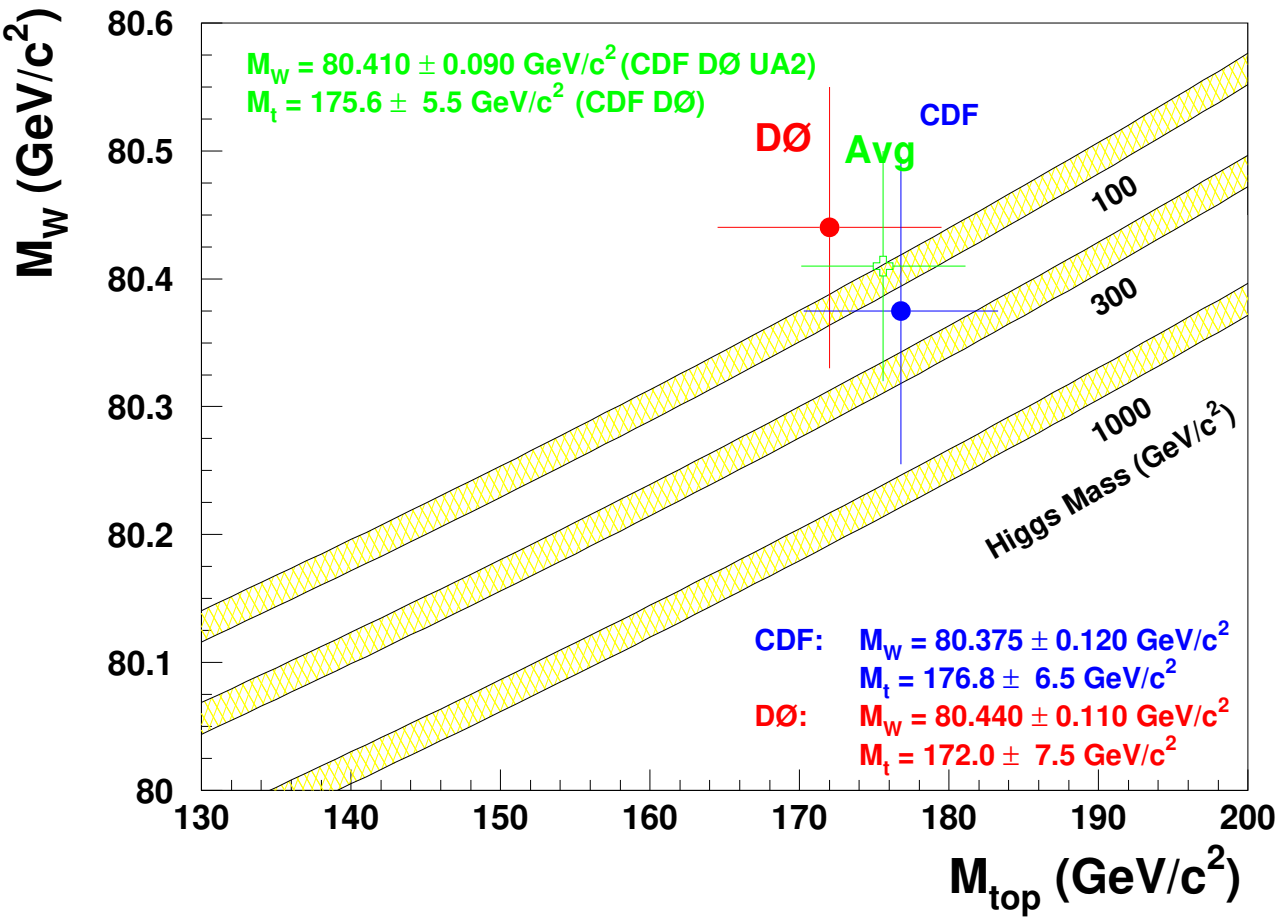
Constraints on Higgs Mass - May 1997



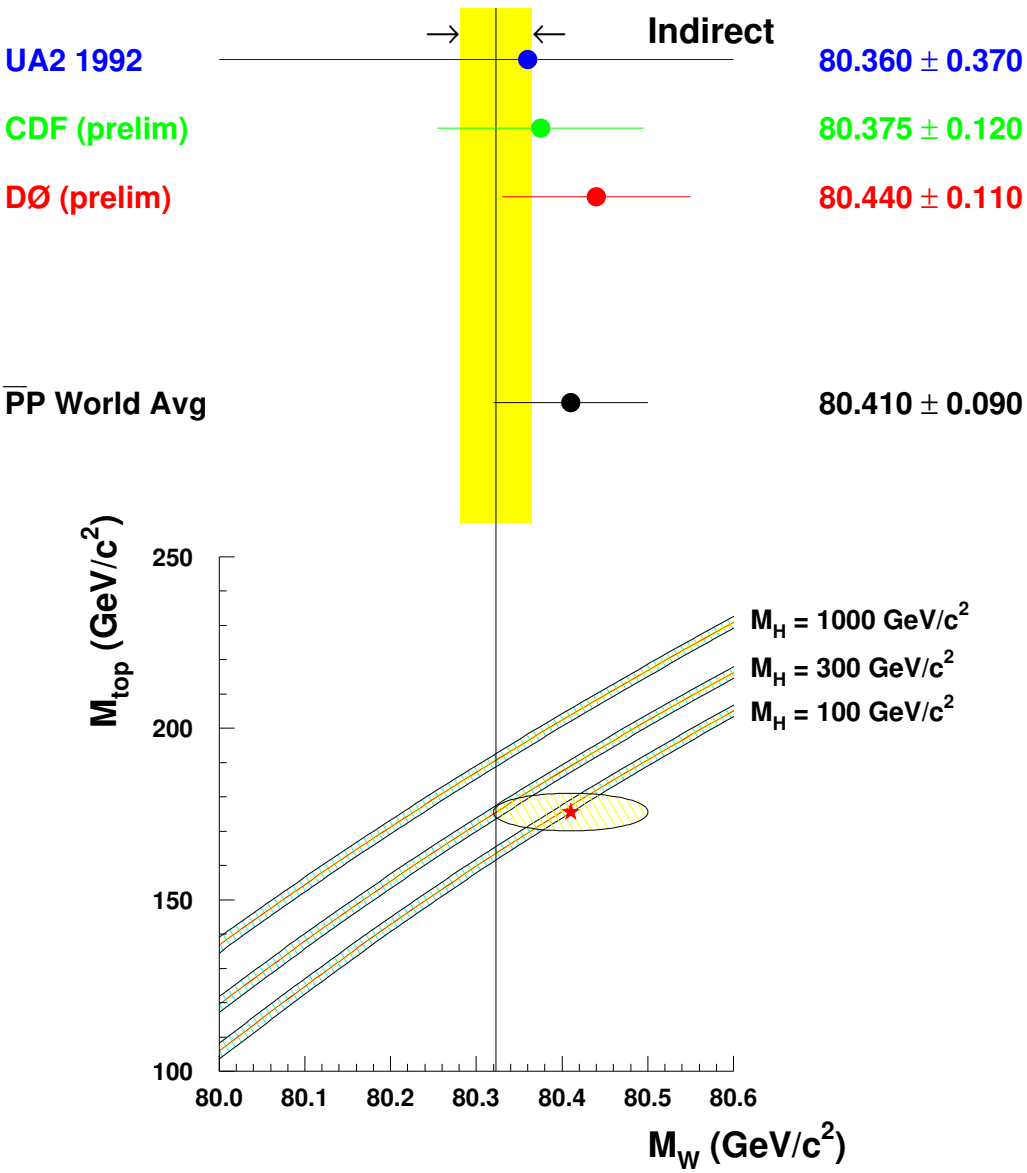
Higgs Mass Constraints



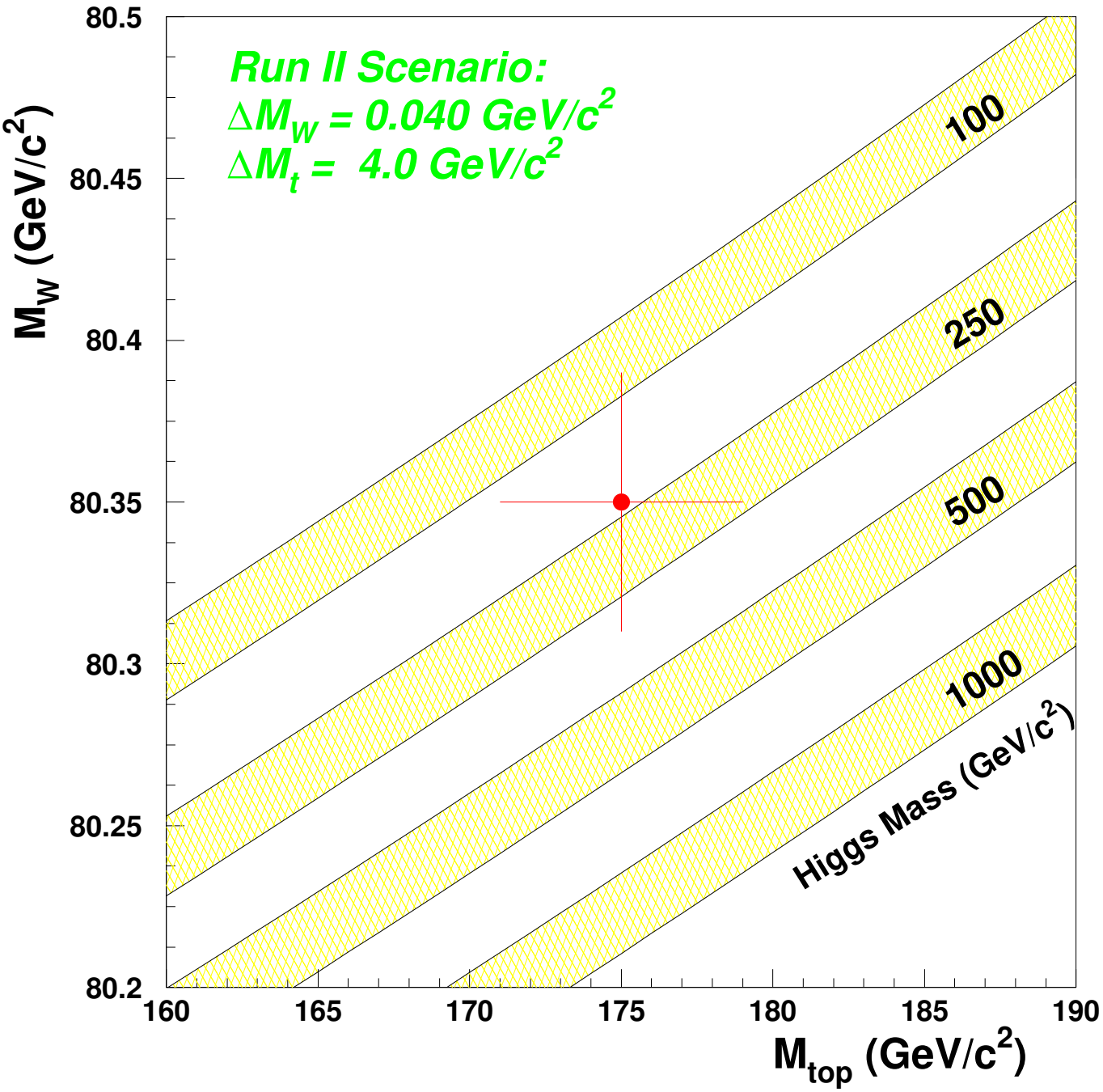
Higgs Mass Constraints



W Mass Results



Higgs Mass Constraints



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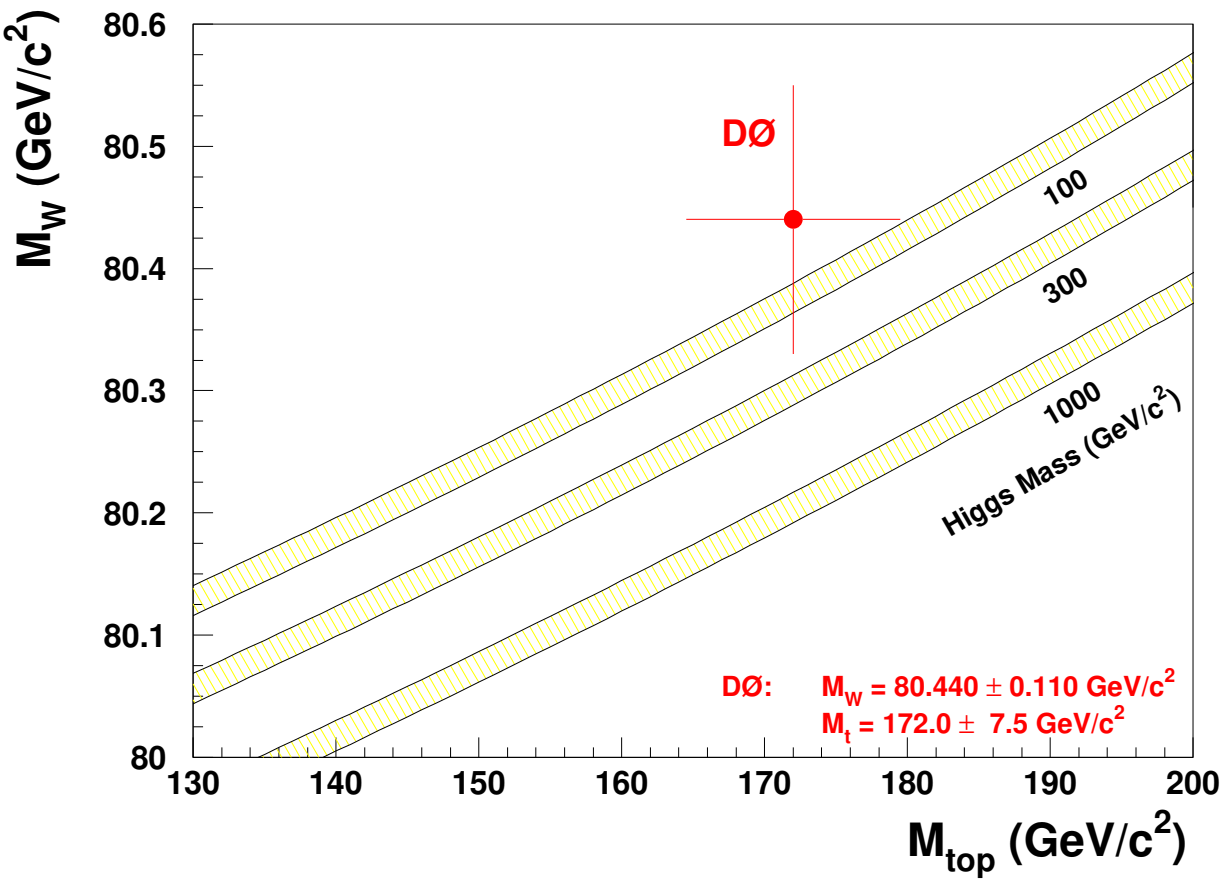
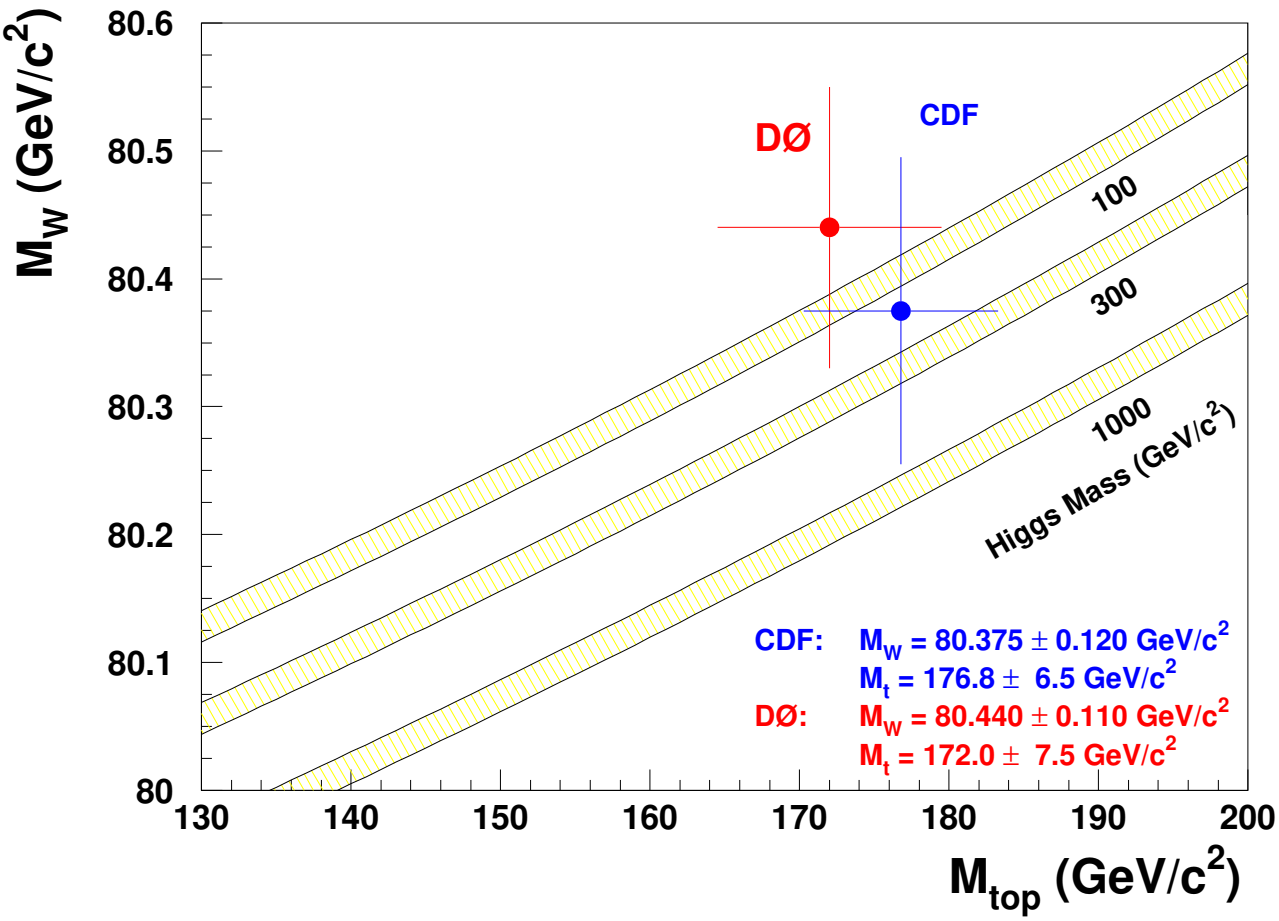
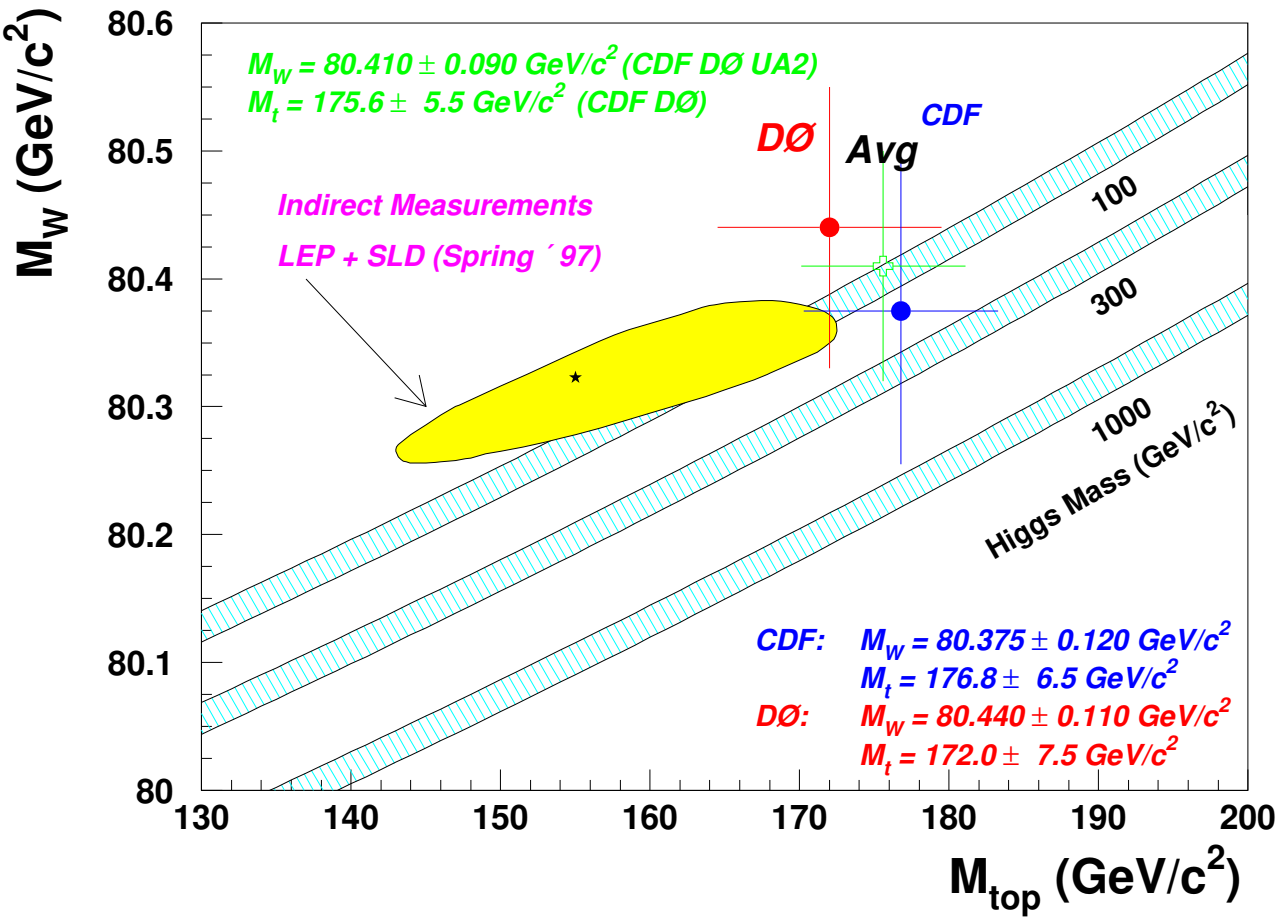


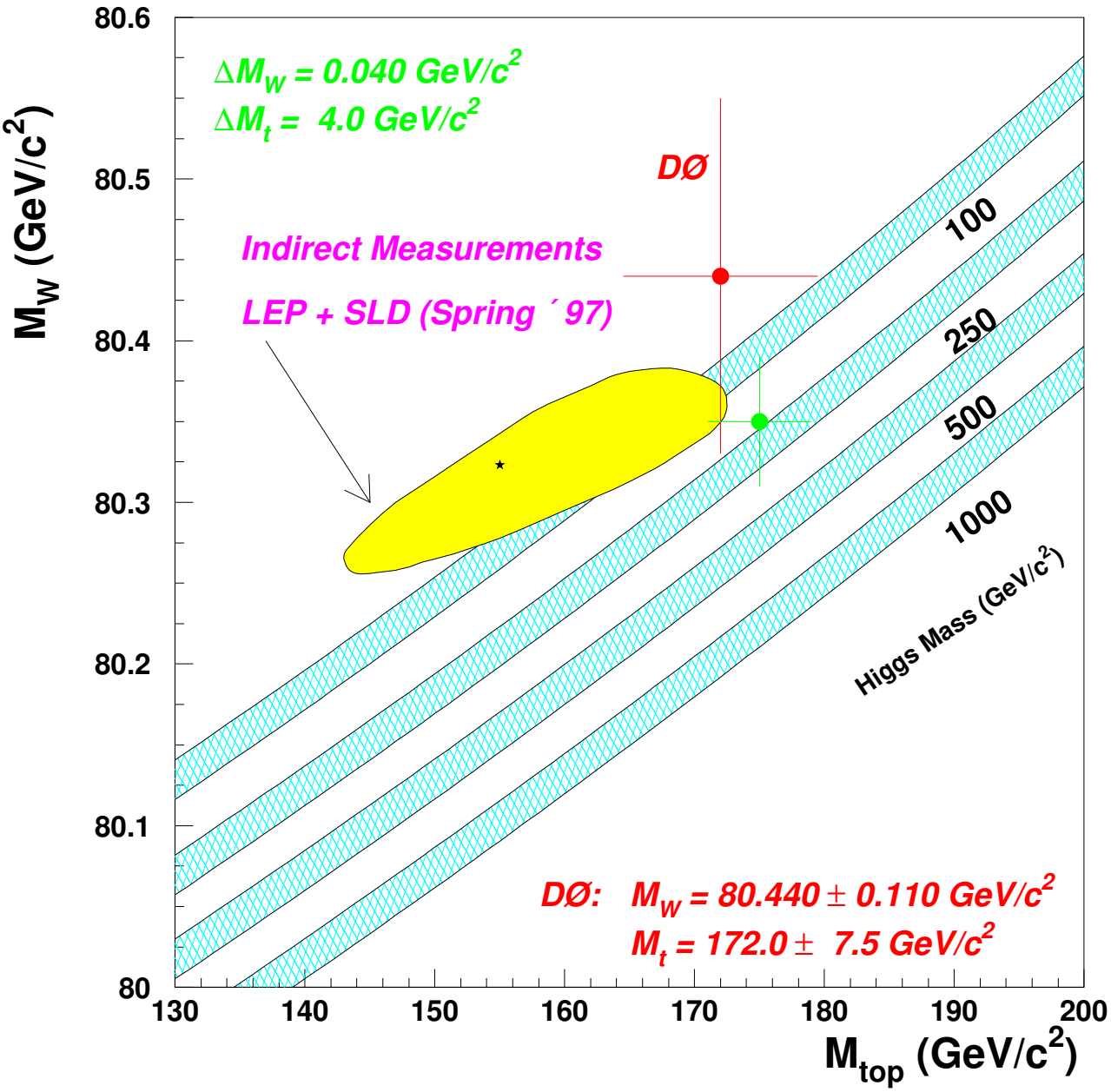
Higgs Mass Constraints



Higgs Mass Constraints



Higgs Mass Constraints



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

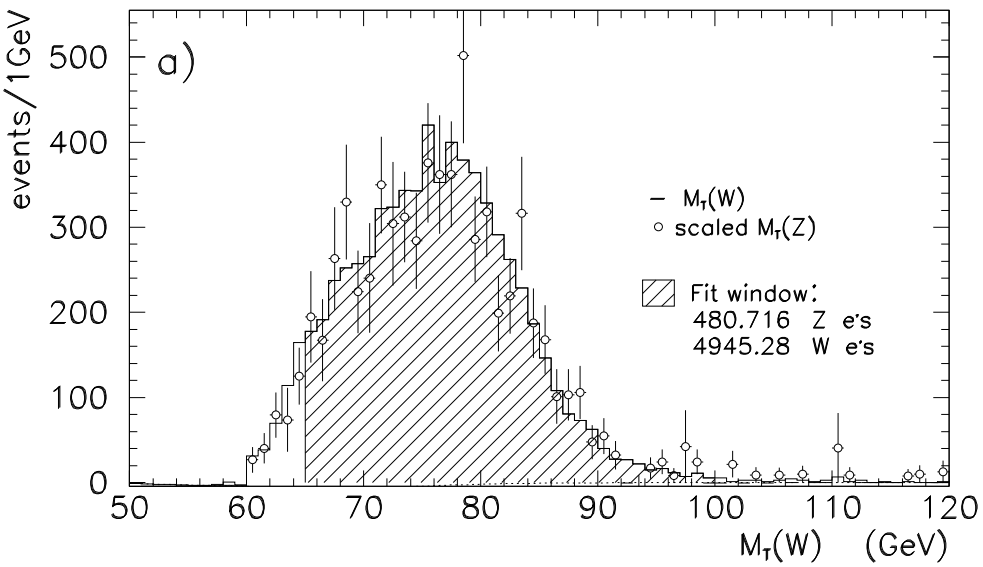
!! Preliminary Results - using run 1A data sample

- **assume W and Z production and decay are similar**
- **treat $Z \to ee$ events as $W \to e\nu$ 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

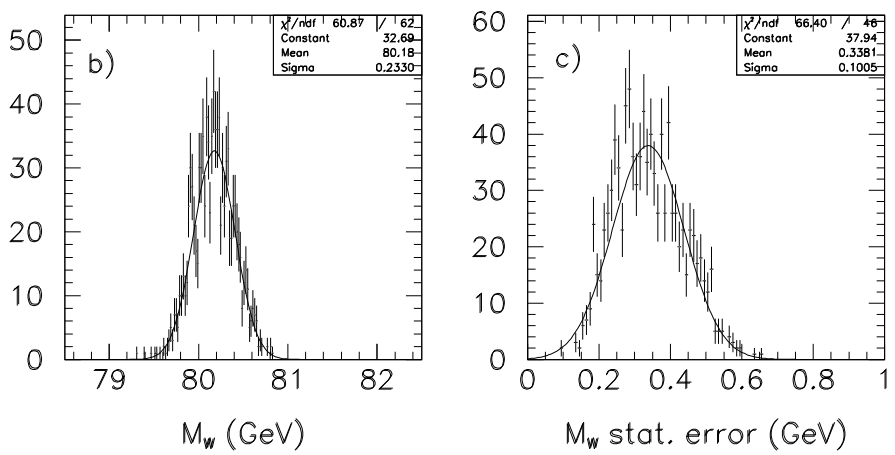
- **lower systematic errors (but higher errors due to Z statistics)**
- **may provide better measurement in higher luminosity, higher statistics running**
- **important cross-check on Standard Method (can also compare p_T^e and p_T^ν)**

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

Systematic Uncertainties

Source	$\sigma M(W)$ (MeV)
EM energy scale	20
EM energy resolution	5
electron underlying event	35
efficiencies	30
Hadronic energy scale and resolution	15
# minimum bias events	30
z position of vertex	15
variation in pdf's	15
input P_T^W distribution	15
radiative decays	15
Monte Carlo statistics	20
Backgrounds	20
Total	75

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



D0 Preliminary

W charge asymmetry - Preliminary

At Tevatron:
W bosons produced primarily by $q\bar{q}$ annihilation

$$u + \bar{d} \rightarrow W^+ \rightarrow \mu^+ + \nu_\mu$$

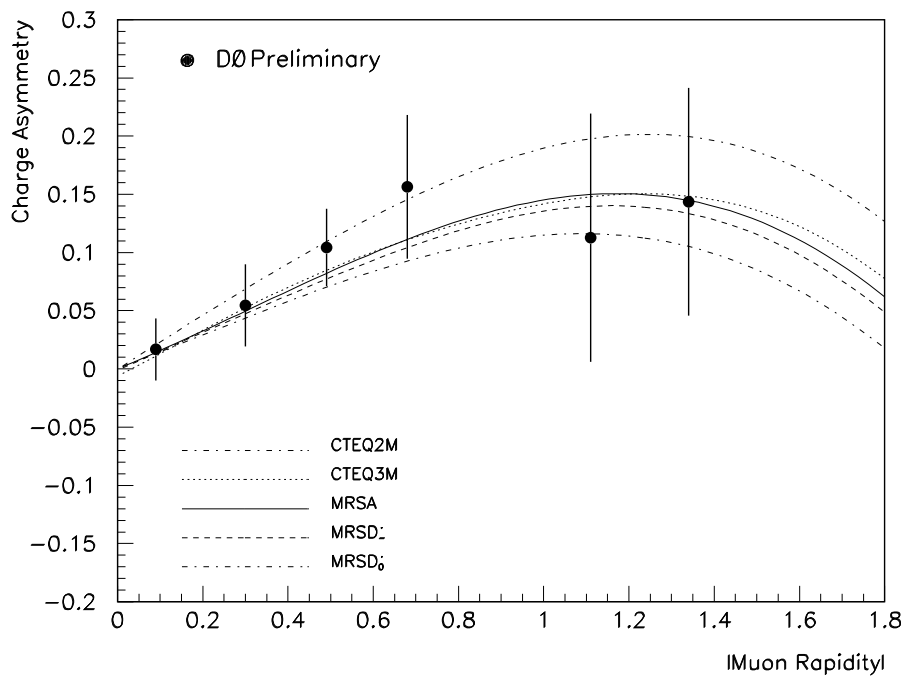
$$\bar{u} + d \rightarrow W^- \rightarrow \mu^- + \bar{\nu_\mu}$$

On average, the $u(\bar{u})$ quarks carry $>$ momentum fraction than $d(\bar{d})$ quarks

$\Rightarrow$ **leads to production asymmetry in rapidity (y)**

$$A(y_w) \equiv \frac{d\sigma_W^+(y)/dy_W - d\sigma_W^-(y)/dy_W}{d\sigma_W^+(y)/dy_W - d\sigma_W^-(y)/dy_W}$$

$\Rightarrow$ **Measure muon charge asymmetry in η**

$$A(\mid \eta \mid) = \frac{N^+(\mid \eta \mid) - N^-(\mid \eta \mid)}{N^+(\mid \eta \mid) + N^-(\mid \eta \mid)},$$

W charge asymmetry - Preliminary