W Mass Measurement from DØ

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Fermilab

(for the DØ Collaboration)

— all results are preliminary —

Wine & Cheese Seminar, Fermilab,
3/28/1997

Introduction

- Discovery of the W (1983)
  - "Experimental Observation of Isolated Large Transverse Energy Electrons with Associated Missing Energy at $\sqrt{s} = 540$ GeV"

    UA1 collaboration, Phys. Lett. 122B, 103 (1983)
  - "Observation of Single Isolated Electrons of High Transverse Momentum in Events with Missing Transverse Energy at the CERN $\overline{p}p$ Collider"

    UA2 collaboration, Phys. Lett. 122B, 476 (1983)

Introduction

- in the Standard Model at tree level

$$m_W = \left(\frac{\pi\alpha}{\sqrt{2}G_F}\right)^{\frac{1}{2}} \frac{1}{\sin\theta_w}$$

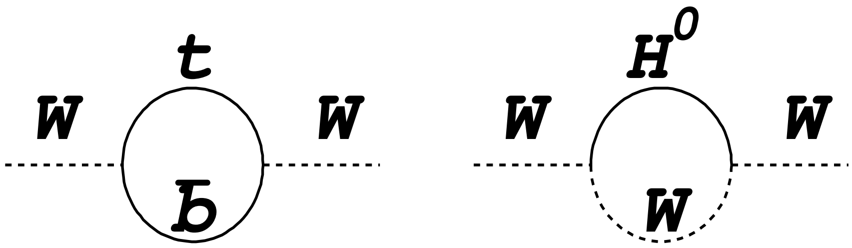
$$m_Z = \frac{m_W}{\cos\theta_w}$$

- m_W is fixed by precisely measured parameters
  - $m_Z = 91.1865 \pm 0.0020$ GeV
  - $G_F = (1.16639 \pm 0.00002) \times 10^{-5}$ GeV^{-2}
  - $\alpha\left(m_Z^2\right) = (128.90 \pm 0.09)^{-1}$

Introduction

- electroweak radiative corrections

$$\frac{m_W}{m_Z} = \cos\theta_w + \alpha V(m_t, m_H) + \mathcal{O}(\alpha^2)$$

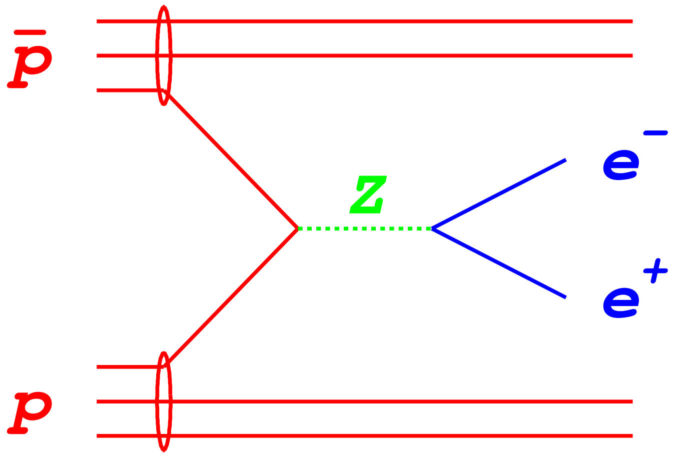


- a precise measurement of the W mass
  - measures radiative corrections
  - constrains Higgs mass
  - tests Standard Model

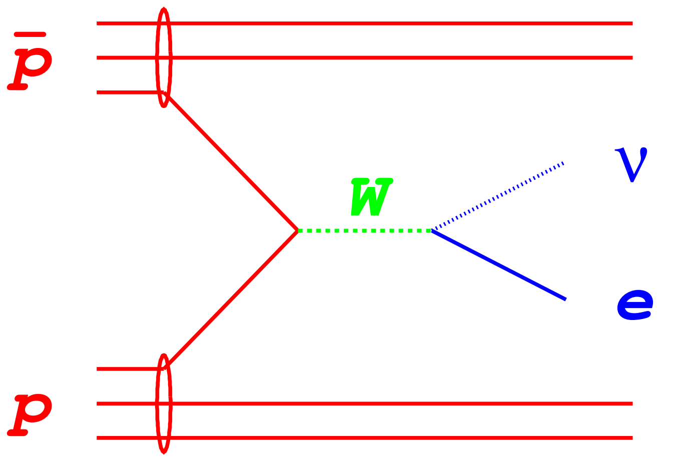
- need precision of $\mathcal{O}$(100 MeV) or better

$\longrightarrow$ challenge: measure W mass to <u>0.1%</u>

W and Z Production

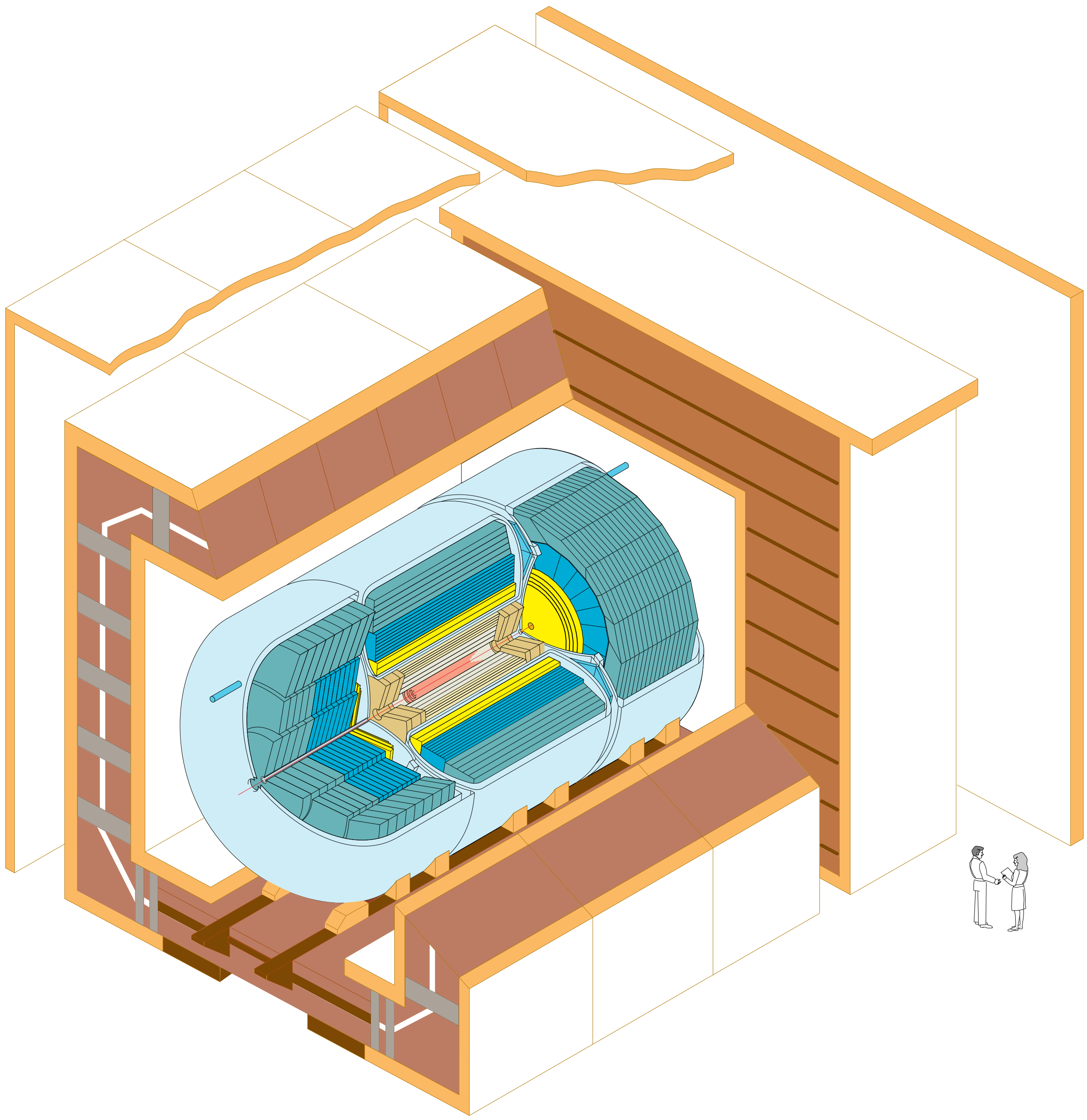


high p_T e^+, e^-



high p_T e
high p_T ν

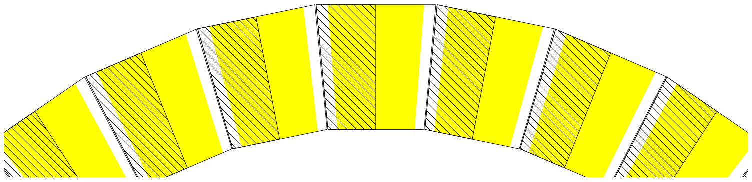
DØ Detector



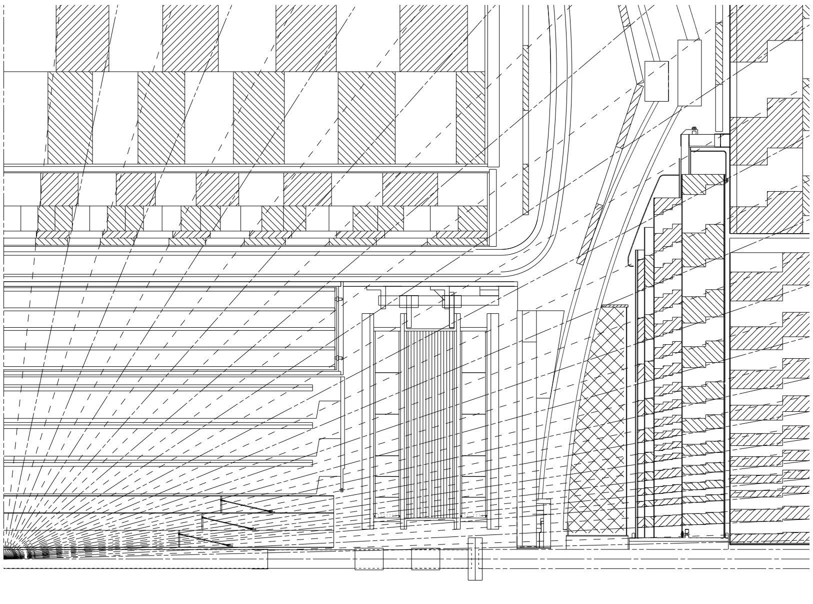
DØ Detector

Electron Identification

- energy clusters in EM calorimeter
- fiducial cuts
  - away from azimuthal module boundaries (20% of acceptance in CC)



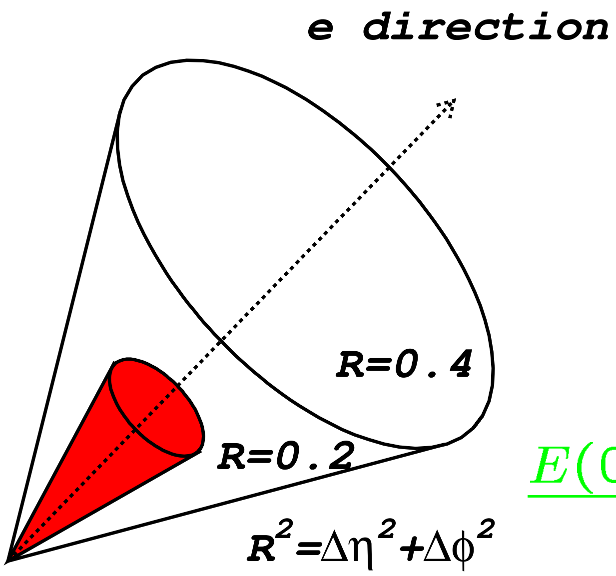
  - $|\eta| < 1.0$ (CC) or $1.5 < |\eta| < 2.5$ (EC)



Electron Identification

- quality cuts
  - spatial match with track in central detector
  - shower shape consistent with Monte Carlo

- isolation

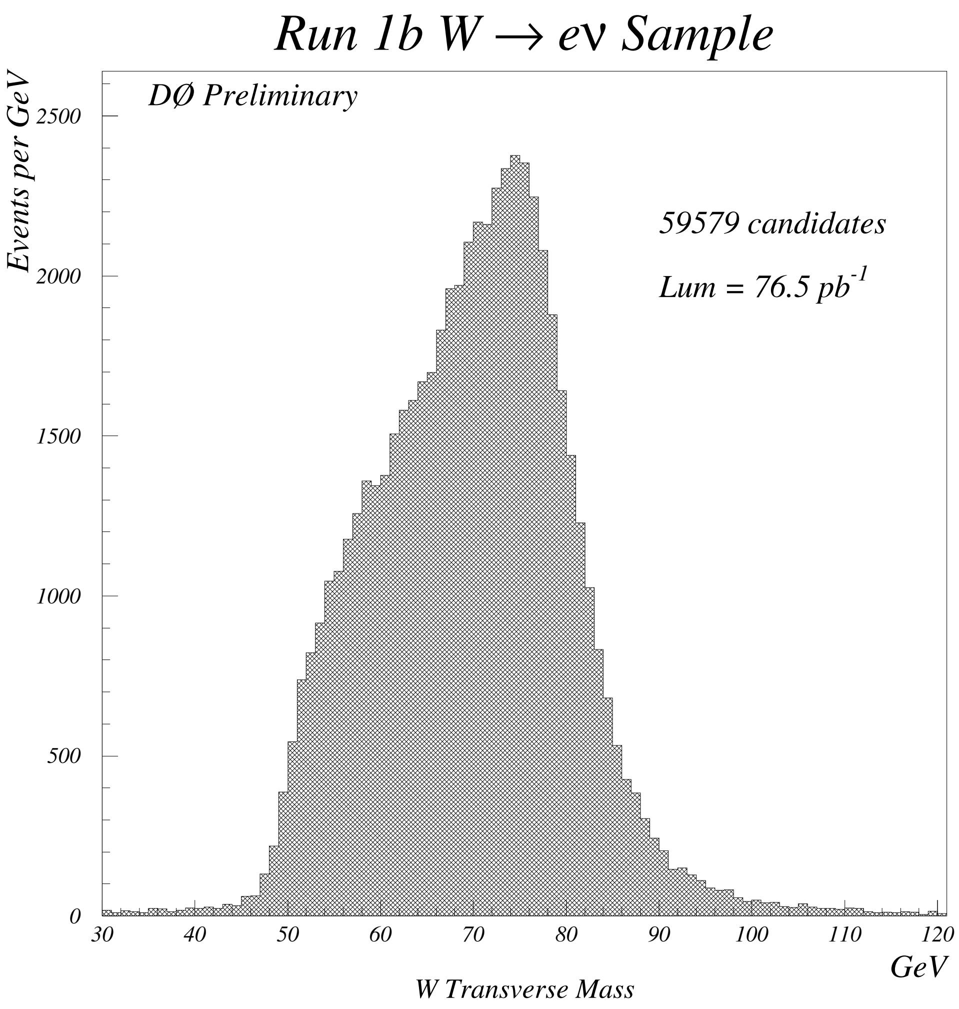


$$\frac{E(0.4)-E(0.2)}{E(0.2)} < 0.15$$

$W \to e\nu$ Selection

- high p_T electron
- high p_T neutrino $\longrightarrow$ high $\not{p}_T$
- transverse mass

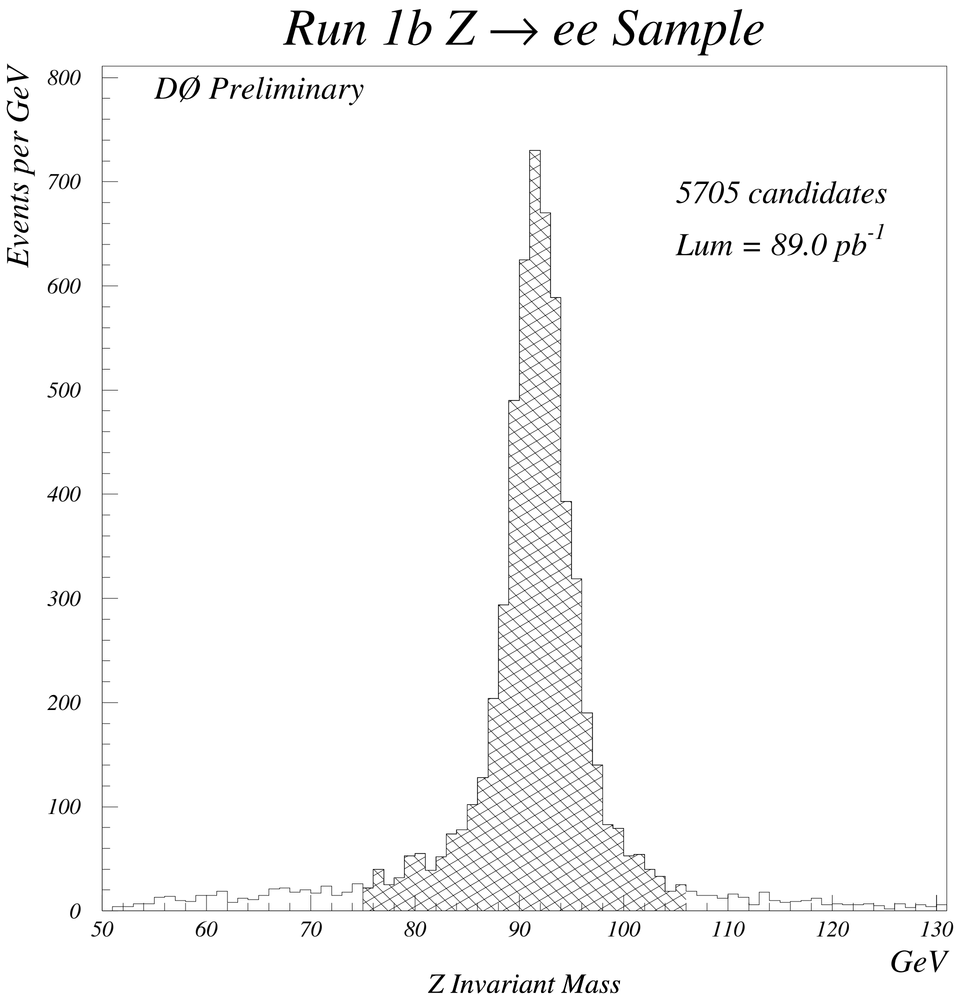
$$m_T = \sqrt{2 p_T(e) \not{p}_T (1 - \cos\phi)}$$



$Z \rightarrow ee$ **Selection**

- two high p_T electrons
- invariant mass

$$m(ee) = \sqrt{2p(e^{+})p(e^{-})(1 - \cos\phi)}$$



W Mass Data Sample

- Run 1b data sample ($\int \mathcal{L}dt \approx 80$ pb^{-1})

- $W \to e\nu$
  - $p_T(e) > 25$ GeV
  - $\not{p}_T > 25$ GeV
  - $p_T(W) < 15$ GeV
  - electron in central calorimeter
  - main ring veto

28323 events

- $Z \to ee$
  - $p_T(e) > 25$ GeV
  - $70 < m(ee) < 110$ GeV

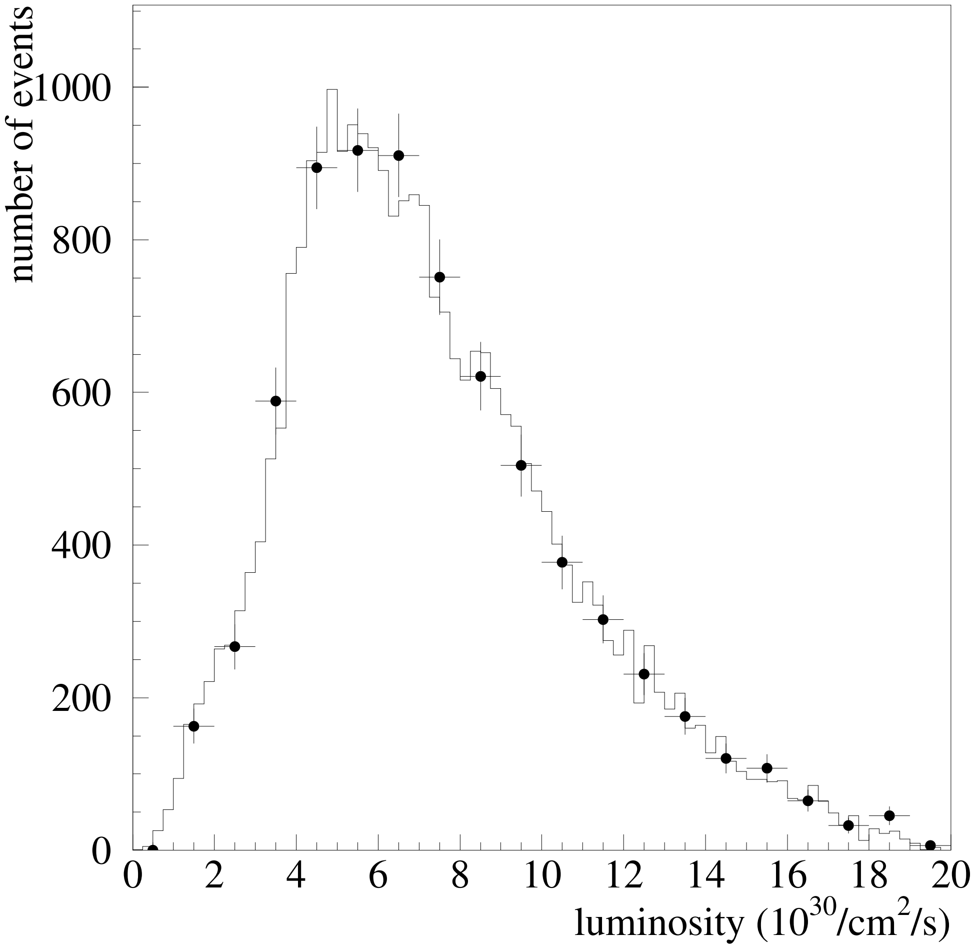
	CC/CC loose	CC/CC tight	CC/EC
main ring veto	537	1225	1116
no main ring veto	107	310	268

2179 (e calibration)

2341 (recoil calibration)

W Mass Data Sample

- luminosity profile

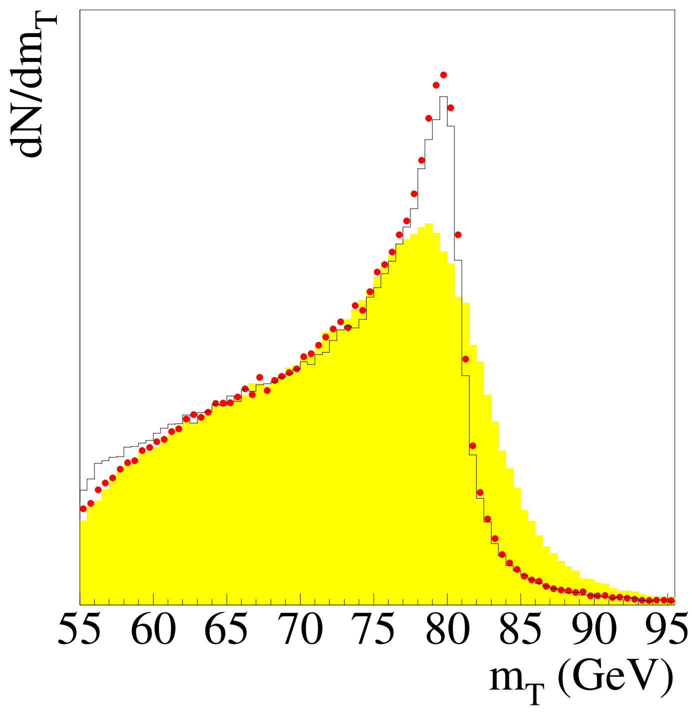


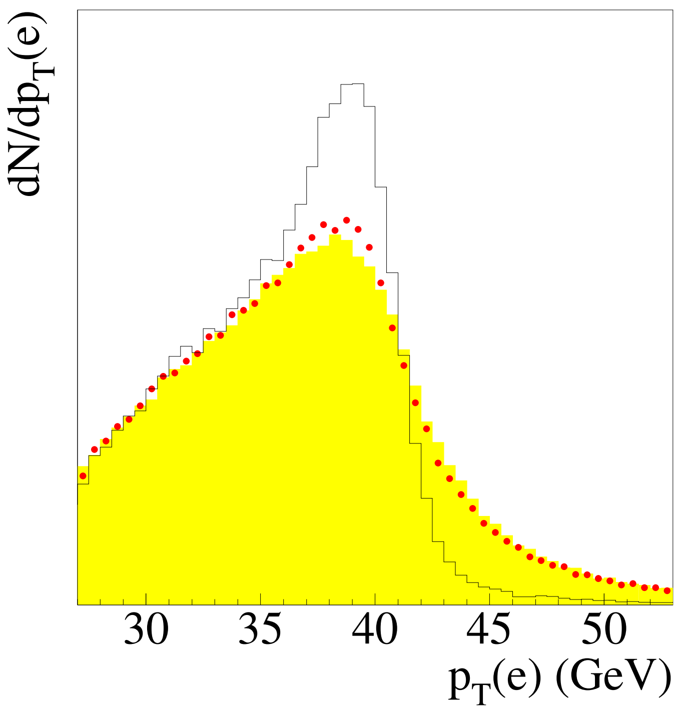
Measurement Strategy

$Z \to ee$: reconstruct invariant mass
$\longrightarrow$ electron energy response ①

$W \to e\nu$: infer neutrino p_T from $\not{p}_T$
$\longrightarrow$ response of hadron calorimeter ②
cannot reconstruct Lorentz invariant
$\longrightarrow$ production dynamics of W bosons ③

- measure m_W/m_Z to cancel ①
- electron p_T spectrum $\longrightarrow$ ③
- transverse mass spectrum $\longrightarrow$ ②

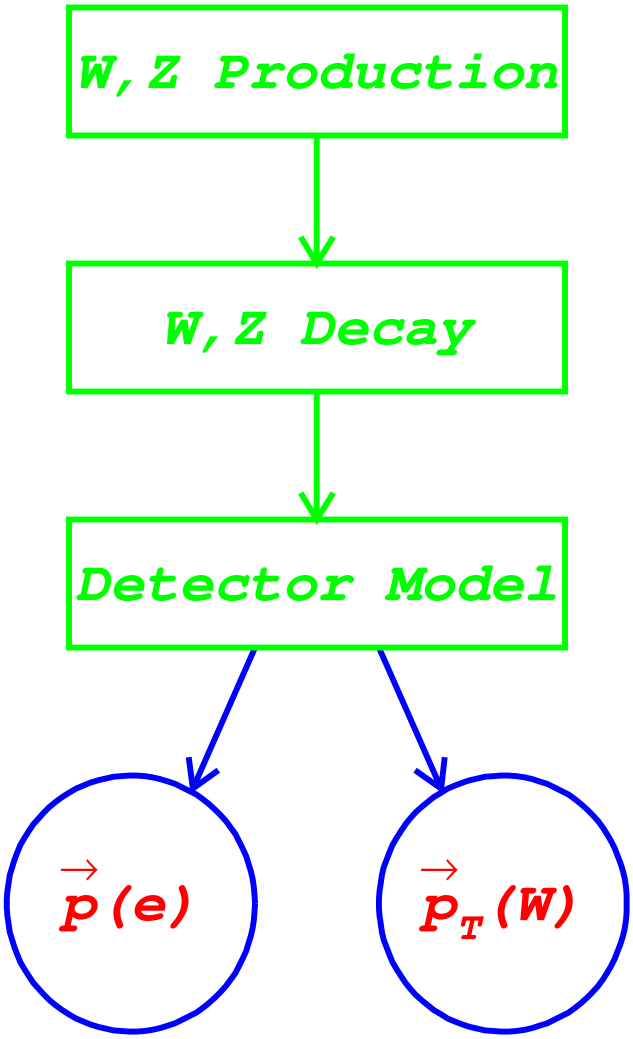




Measurement Strategy

- Monte Carlo Model
- tune electron response $\rightarrow p_T(e)$ fit
- tune recoil response $\rightarrow m_T$ fit
- systematic uncertainties, cross checks
- result

Fast Monte Carlo



$\approx$ 50 events/s

W Production Model

- specify W in terms of
  - q_T - transverse momentum
  - y - rapidity
  - m - mass

$$\frac{d\sigma}{dq_T\,dy\,dm}$$

$$\swarrow \qquad \searrow$$

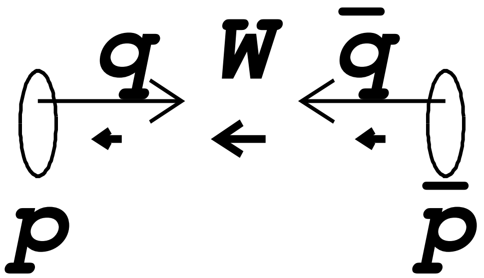
$$\left|\frac{d\sigma}{dq_T\,dy}\right|_{m=m_W} \quad \times \quad \frac{d\sigma}{dm}$$

Ladinsky & Yuan
PRD 50, 4239 (1994)

$$\frac{e^{-\beta m}}{m}\frac{m^2}{(m^2-m_W^2)^2+\frac{m^4\Gamma_W^2}{m_W^2}}$$

W Decay Model

- at lowest order $p_T(W) = 0$ and the W is completely polarized along the beam

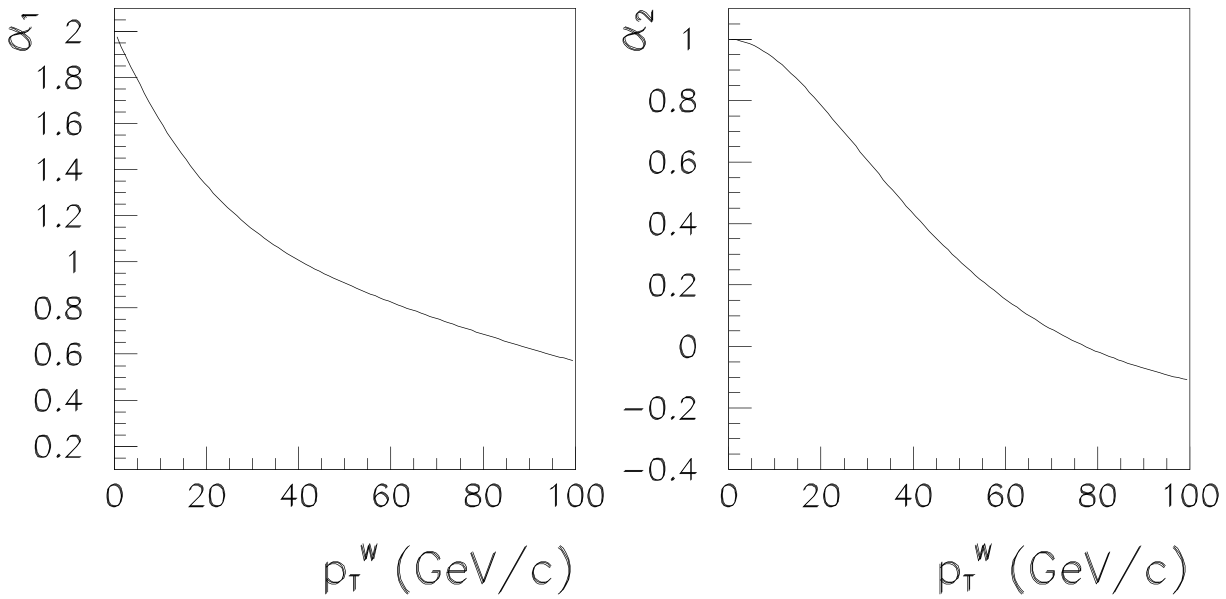


$$\frac{d\sigma}{d\cos\theta^*} \propto (1 \pm \cos\theta^*)^2$$

- at $\mathcal{O}(\alpha_s)$ $p_T(W) > 0$ and

$$\frac{d\sigma}{d\cos\theta^*} \propto \left(1 + \alpha_1 \cos\theta^* + \alpha_2 \cos^2\theta^*\right)$$

[E. Mirkes, Nucl. Phys. B 387, 3 (1992)]



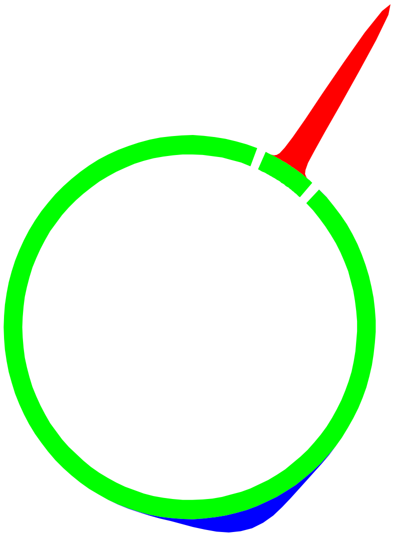
W Decay Model

- generate $W \longrightarrow e\gamma\nu$

  Berends & Kleiss, Z.Phys. C27, 365 (1985)

- generate $W \longrightarrow \tau\nu \longrightarrow e\nu\nu\nu$

Detector Model



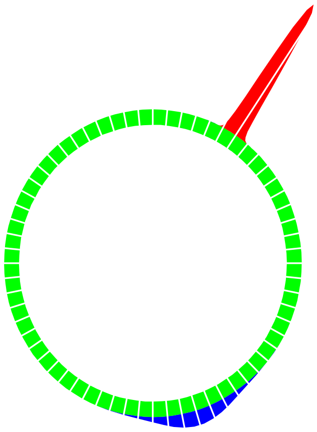
- electron

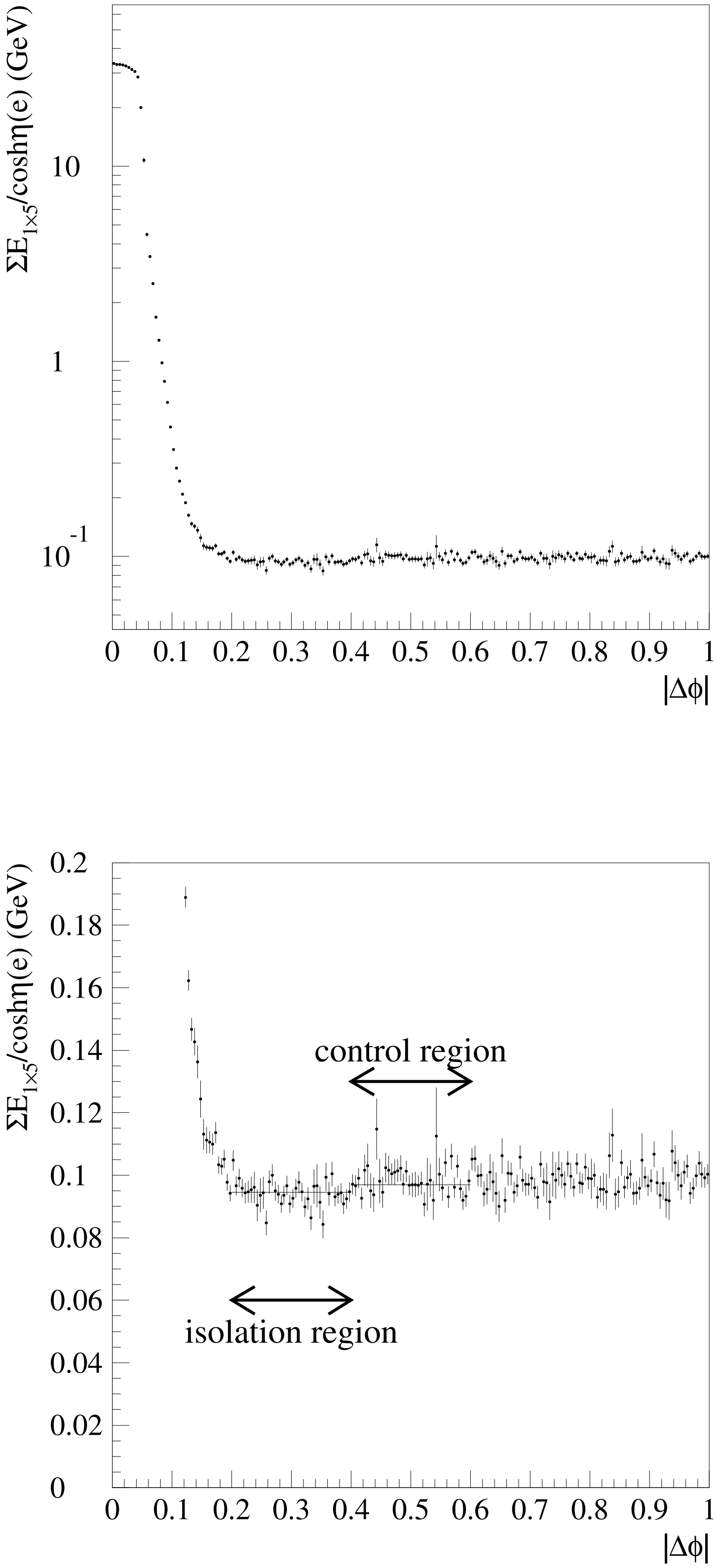
$$E = (\mathcal{R}_{EM}(E_0) \oplus \text{resolution}) + \Delta E$$

- recoil

$$\begin{aligned} \vec{u}_T &= \mathcal{R}_{rec}(\vec{p}_T(W)) \oplus \text{resolution} \\ &+ \alpha_{mb} \vec{\not{p}}_T \\ &- \Delta u \end{aligned}$$

Underlying Event



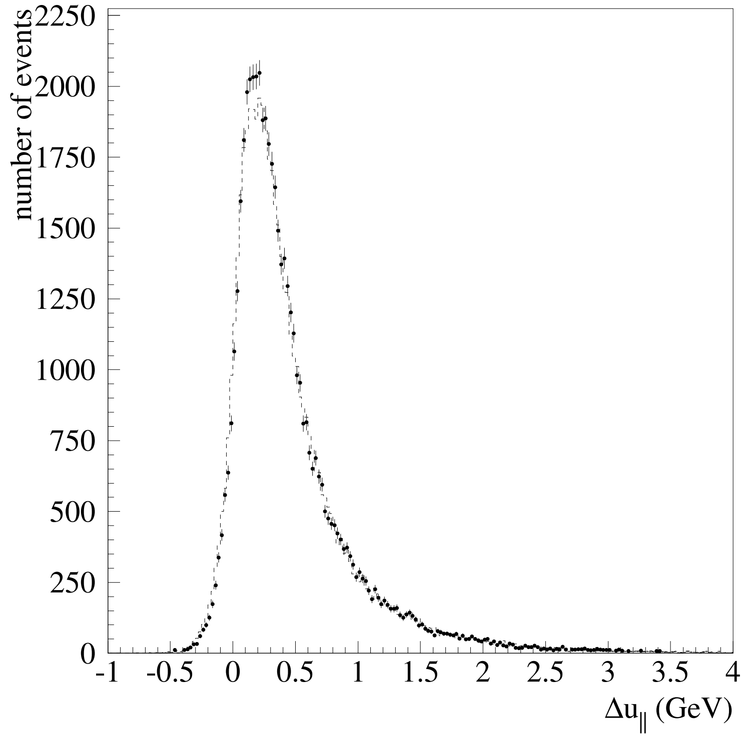


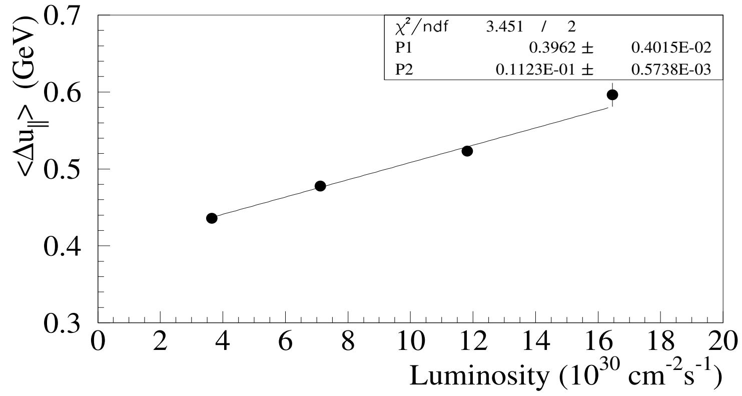
$\sum E_{5\times5}/\cosh\eta$

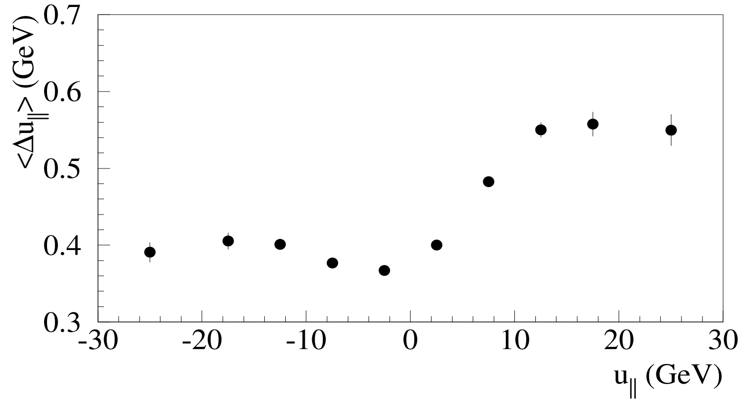
W: 479±6 MeV

Z: 468±9 MeV

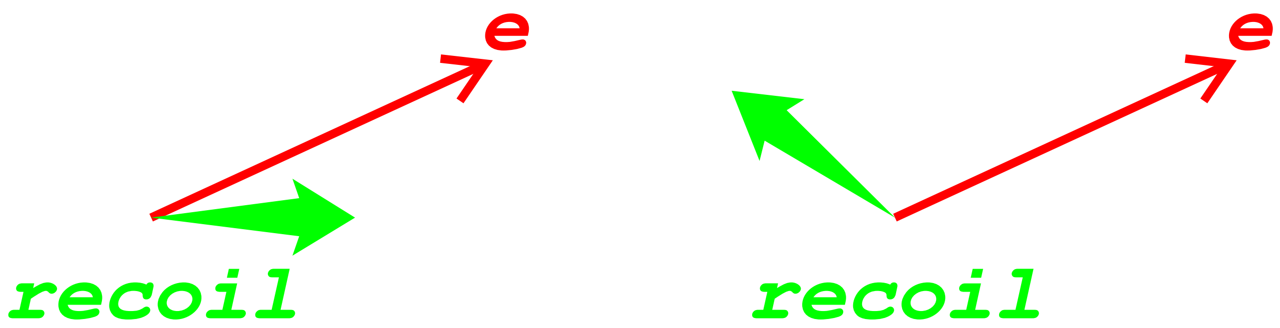
Underlying Event



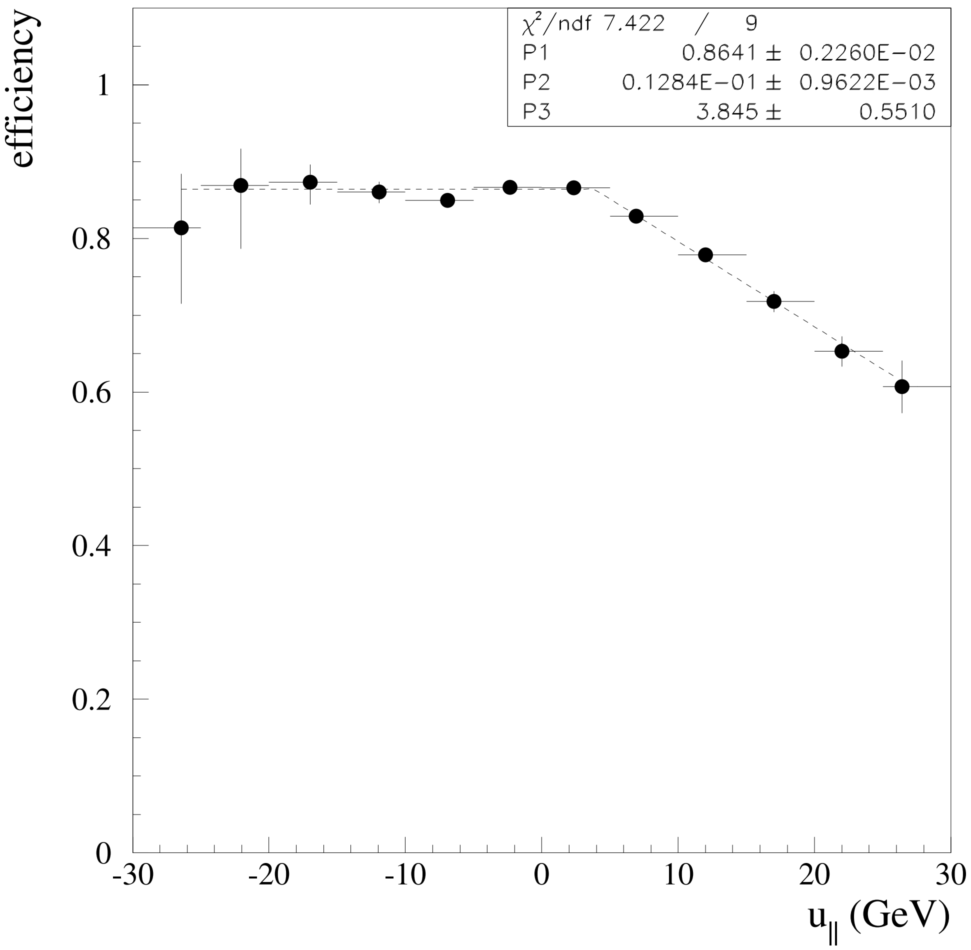




$u_{||}$ Efficiency



- overlap MC electrons on W data



Electron Response

- electron beam tests of central calorimeter

$$\sigma/p = \frac{n}{p} \oplus \frac{s}{\sqrt{p_T}} \oplus c$$

$n \approx 0.4$ GeV

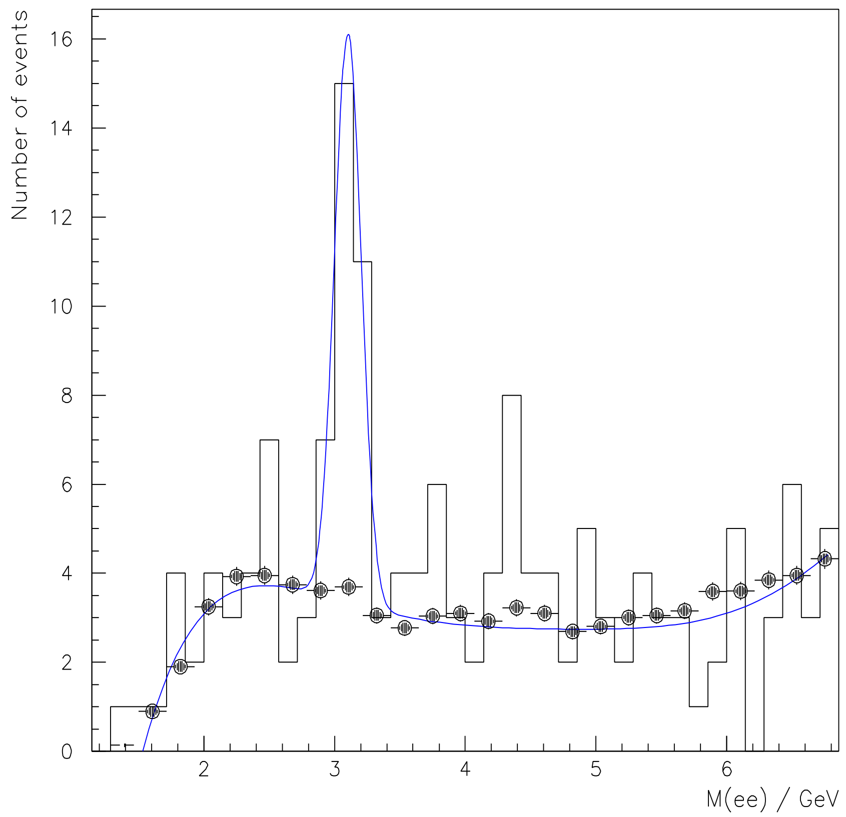
$s \approx 0.13$ GeV$^{1/2}$

$c \approx 0.003$

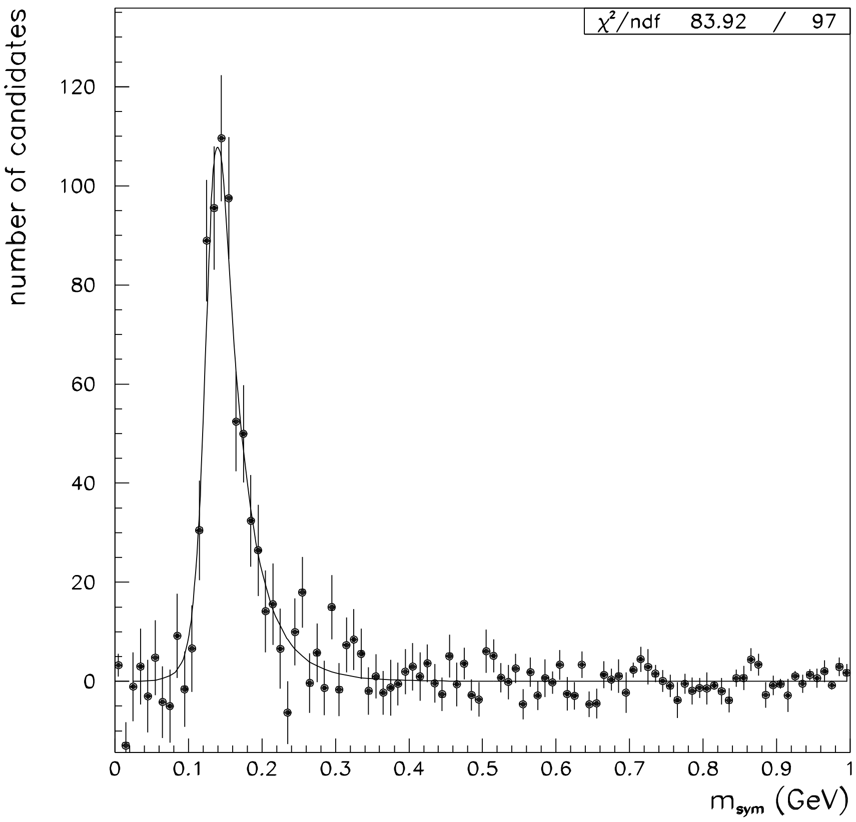
$$p = \alpha_{EM} p_{beam} + \delta_{EM}$$

Electron Response

$J/\psi \rightarrow ee$



$\pi^0 \rightarrow \gamma\gamma$

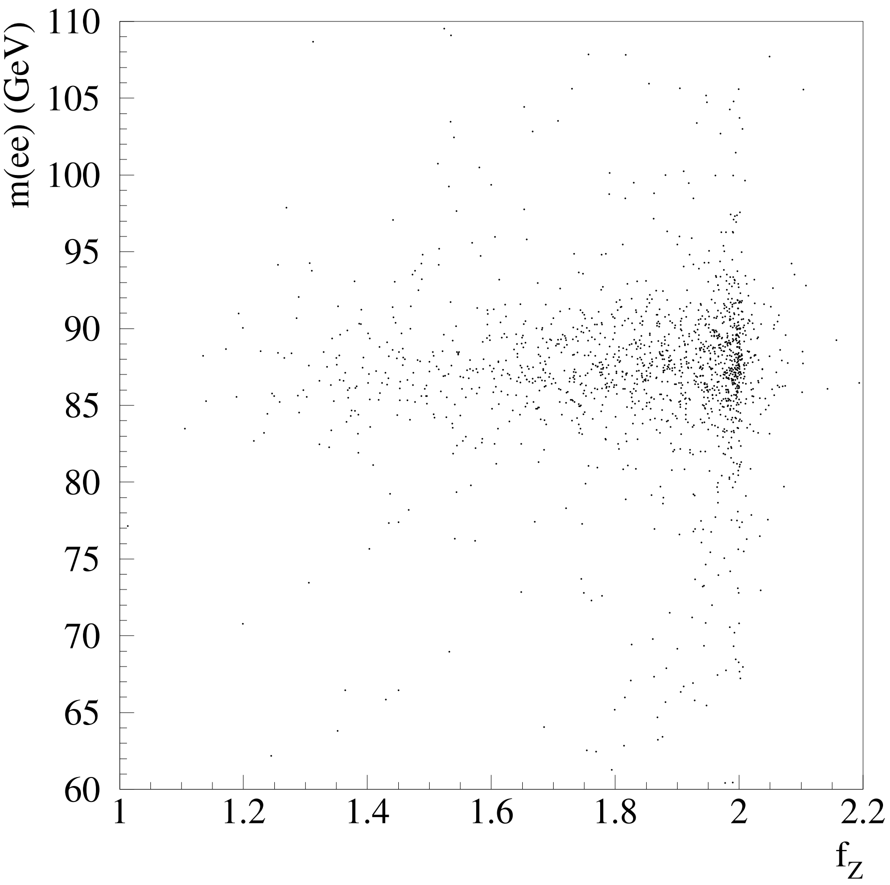


Electron Response

- if $p = \alpha_{EM} p_0 + \delta_{EM}$ for electrons

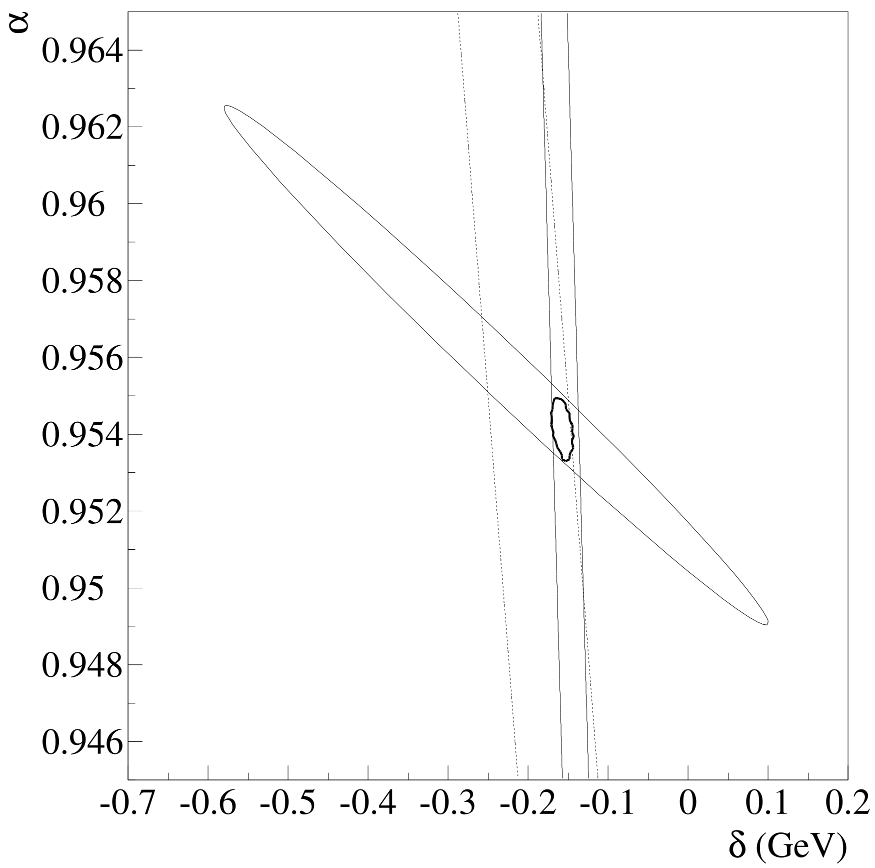
$$\longrightarrow \; m \approx \alpha_{EM} m_0 + \delta_{EM} \underbrace{\frac{(p_1 + p_2)(1 - \cos\omega)}{m}}_{f}$$

- $Z \to ee$ data



Electron Response

- combine constraints on α_{EM} and δ_{EM}

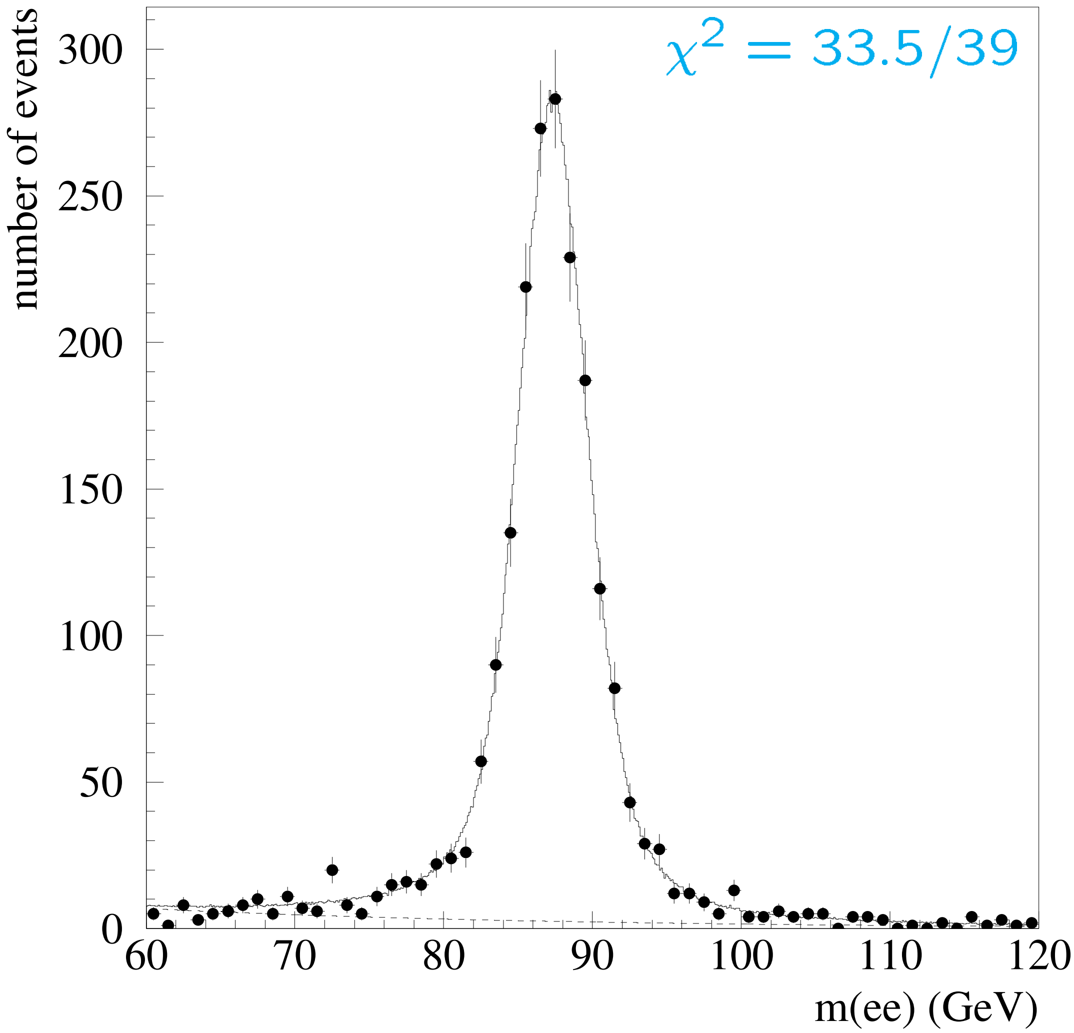


- systematic uncertainties

underlying event	± 30 MeV
response to photons	± 50 MeV
low energy response	-200 MeV

$$\delta_{EM} = -160 \pm 16(stat) \pm {}^{60}_{210}(syst) \text{ MeV}$$

Electron Response

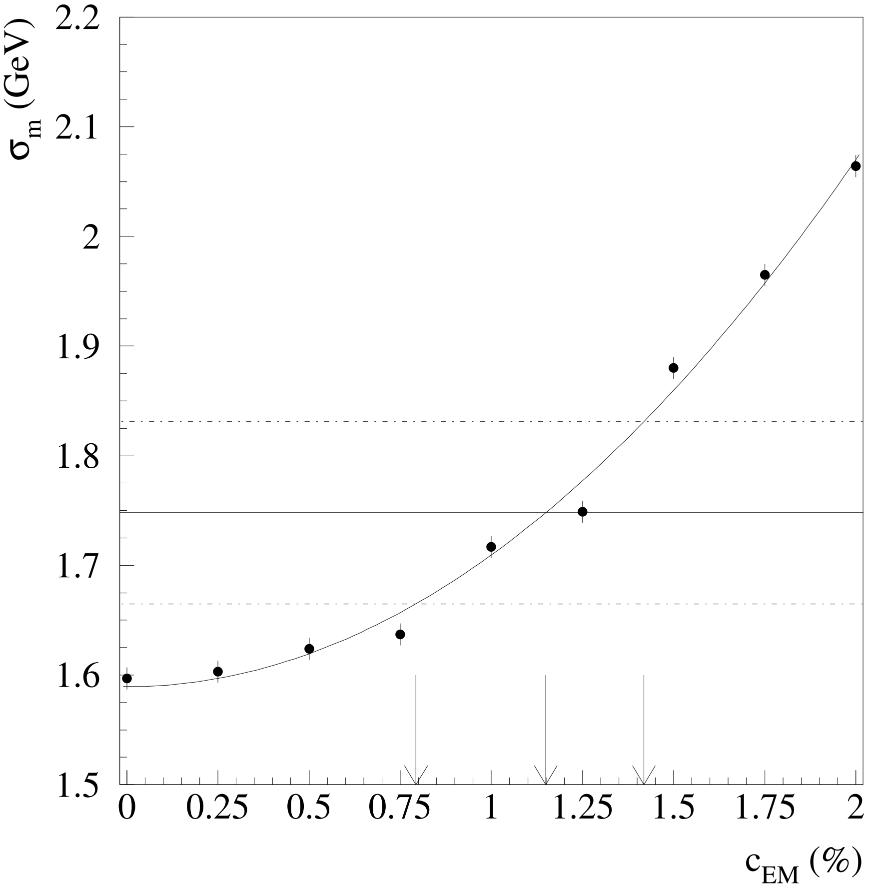


$$\alpha_{EM} = 0.95329 \pm 0.00077$$
for $\delta_{EM} = 160$ MeV

Electron Resolution

- fit Gaussian $\otimes$ Breit-Wigner to data

$\longrightarrow \sigma_m = 1.75 \pm 0.08$ GeV

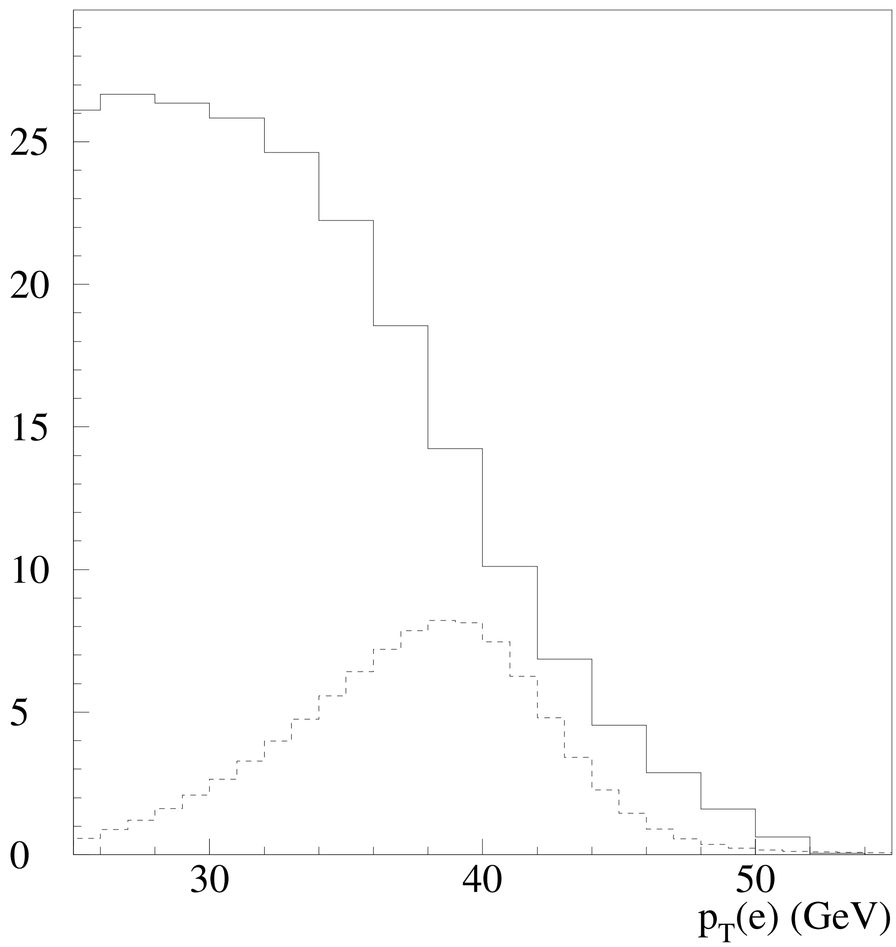


$$c_{EM} = 0.0115^{+0.0027}_{-0.0036}$$

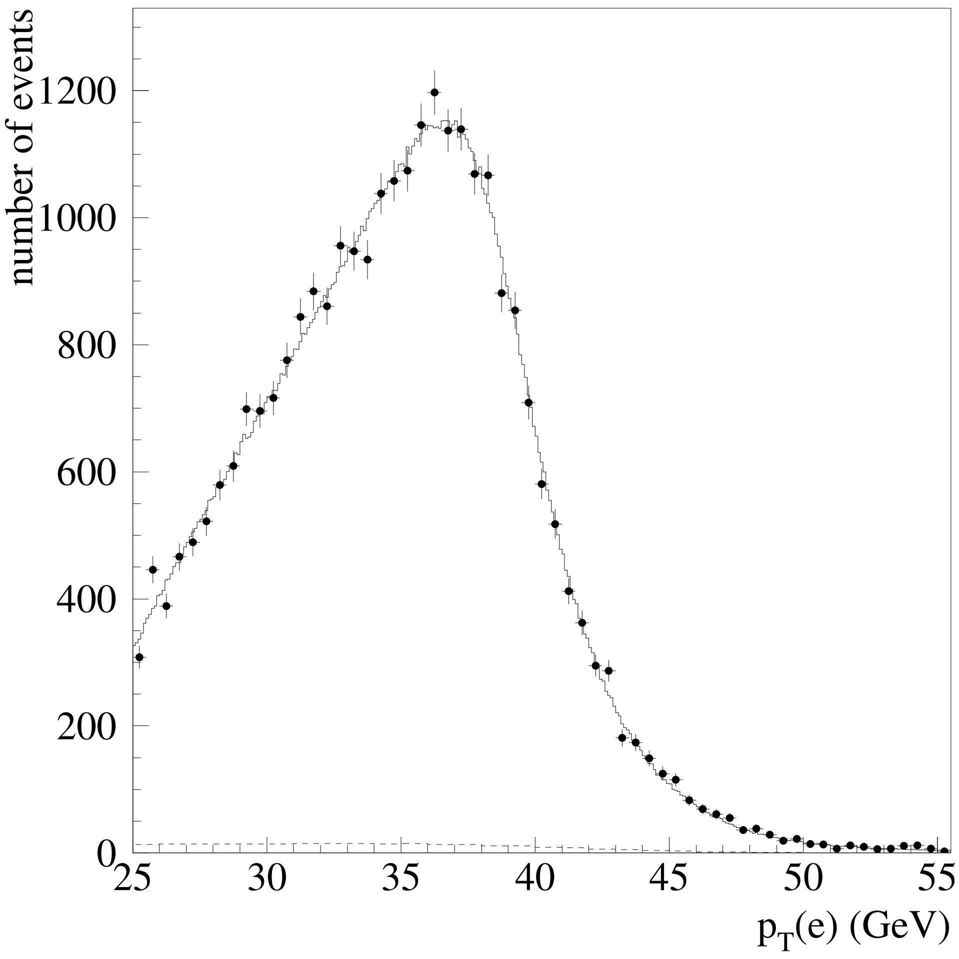
Backgrounds

- background sources

$W \to \tau\nu, \tau \to e\nu\nu$	(included in Monte Carlo)
$Z \to ee$	(0.33±0.06 %)
QCD	(1.4±0.2 %)



Fit to $p_T(e)$ Spectrum

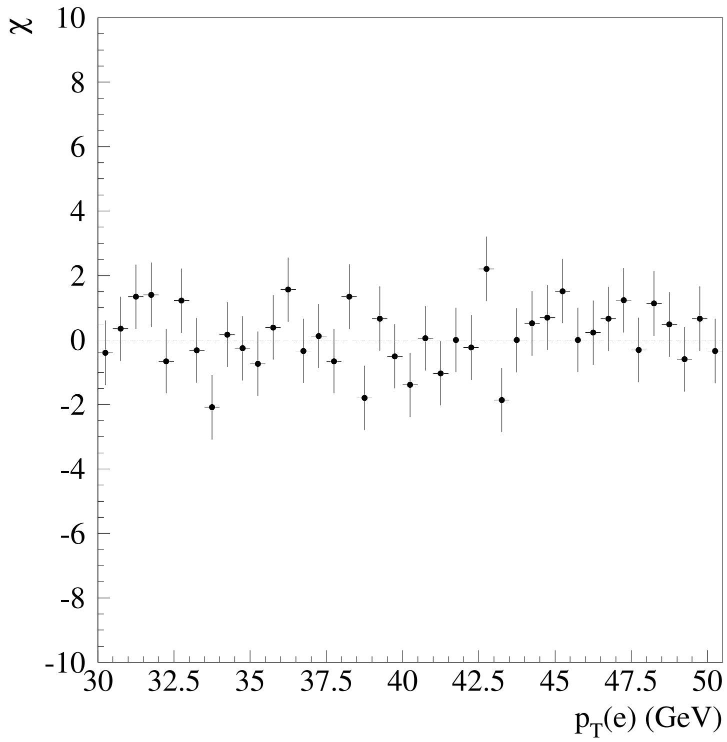


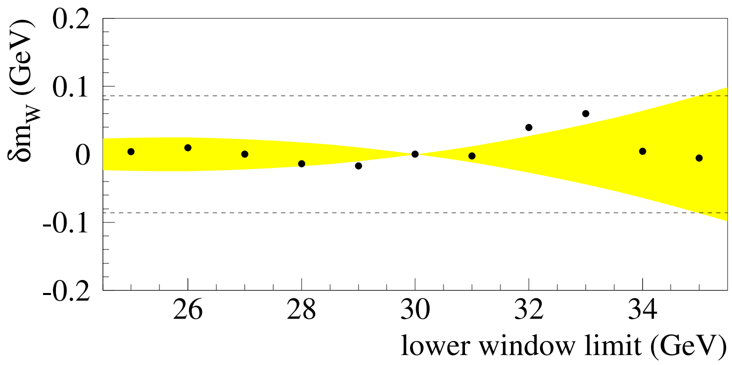
- goodness of fit

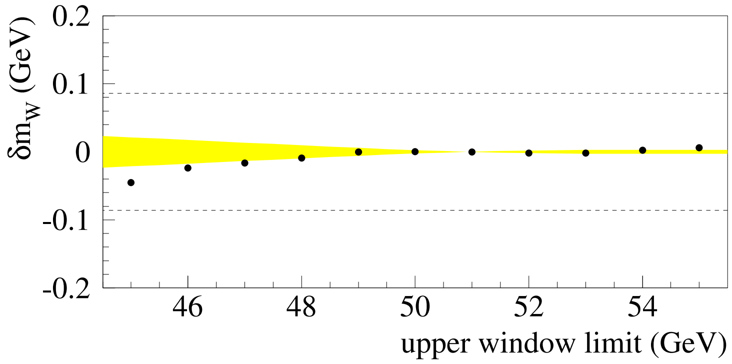
χ^2 test	38.7/39 d.o.f.
Kolmogorov-Smirnov test	47 %

$$m_W = 80.49 \pm 0.09 \text{ GeV}$$

Fit to $p_T(e)$ Spectrum

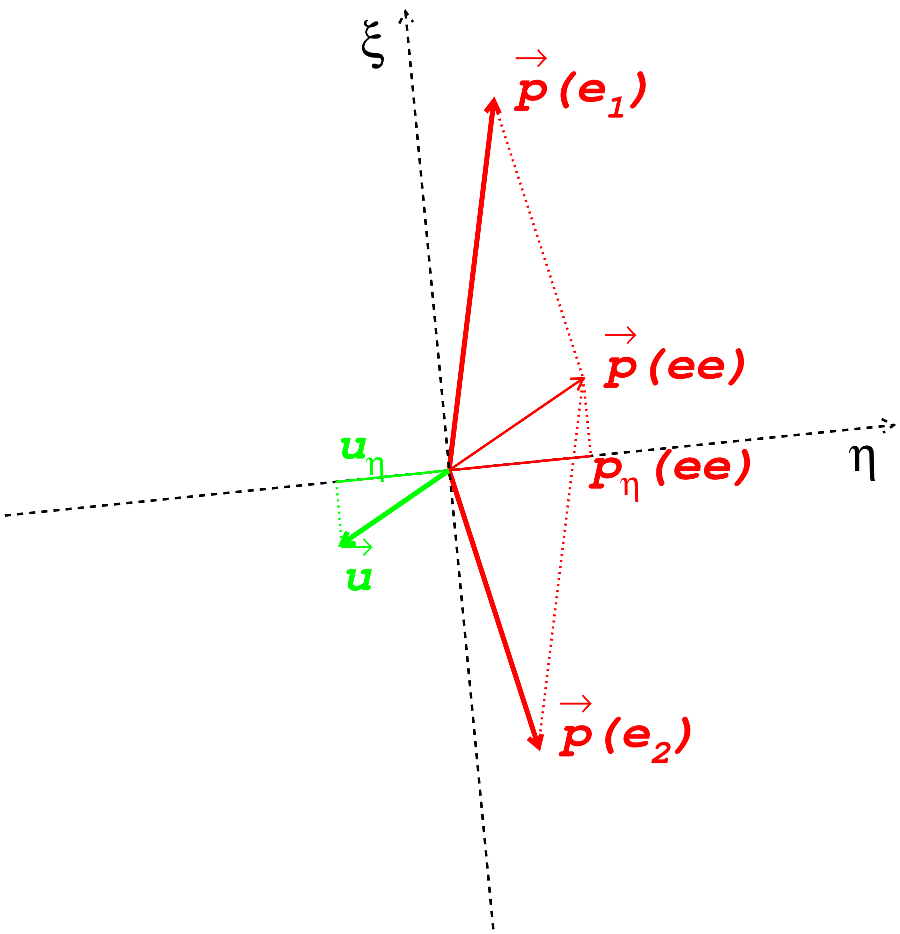






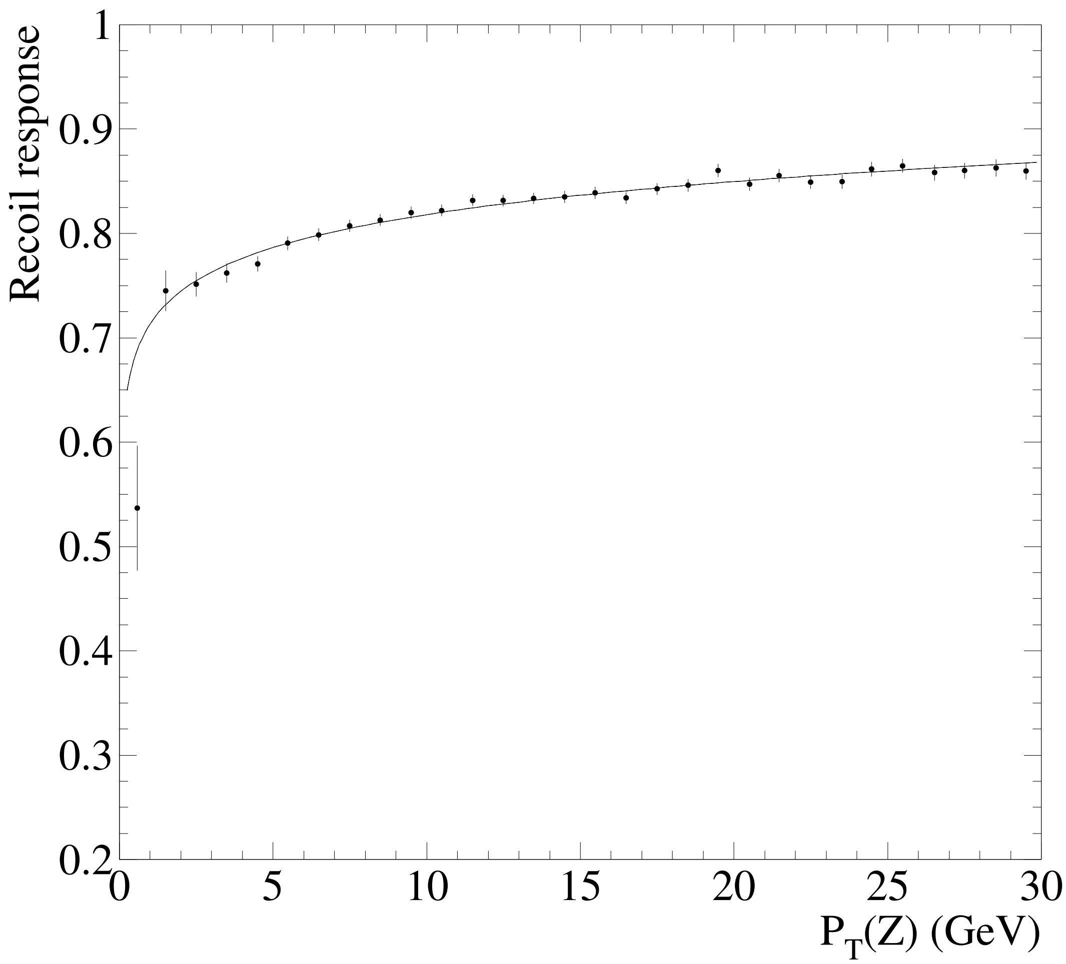
Recoil Response

- calibrate recoil relative to electron response using $Z \to ee$ data



Recoil Response

- HERWIG + GEANT $Z \rightarrow ee$ Monte Carlo sample

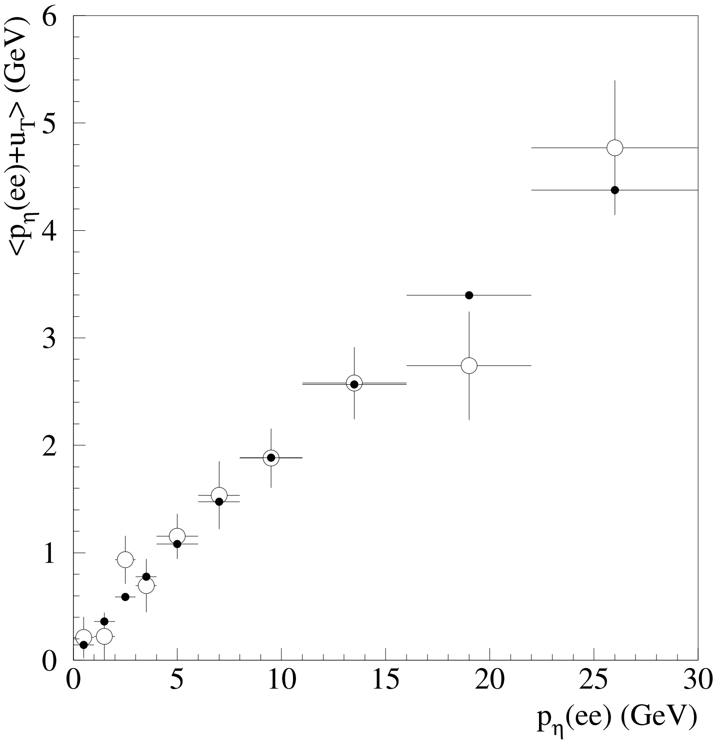


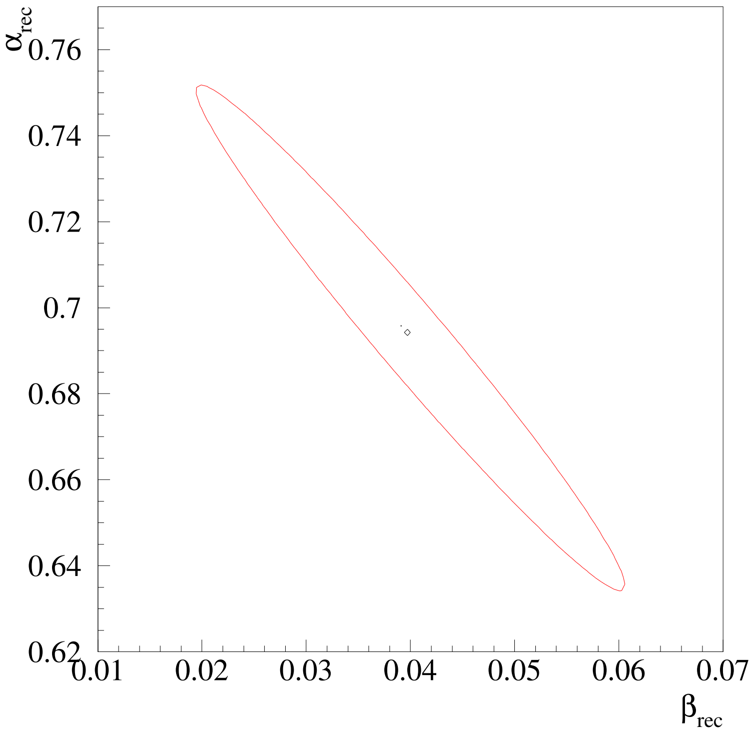
$$\mathcal{R}_{rec} = \alpha_{rec} + \beta_{rec} \log\left(p_T(W)/\mathrm{GeV}\right)$$

- with

$$\alpha_{rec} = 0.71$$
$$\beta_{rec} = 0.046$$

Recoil Response



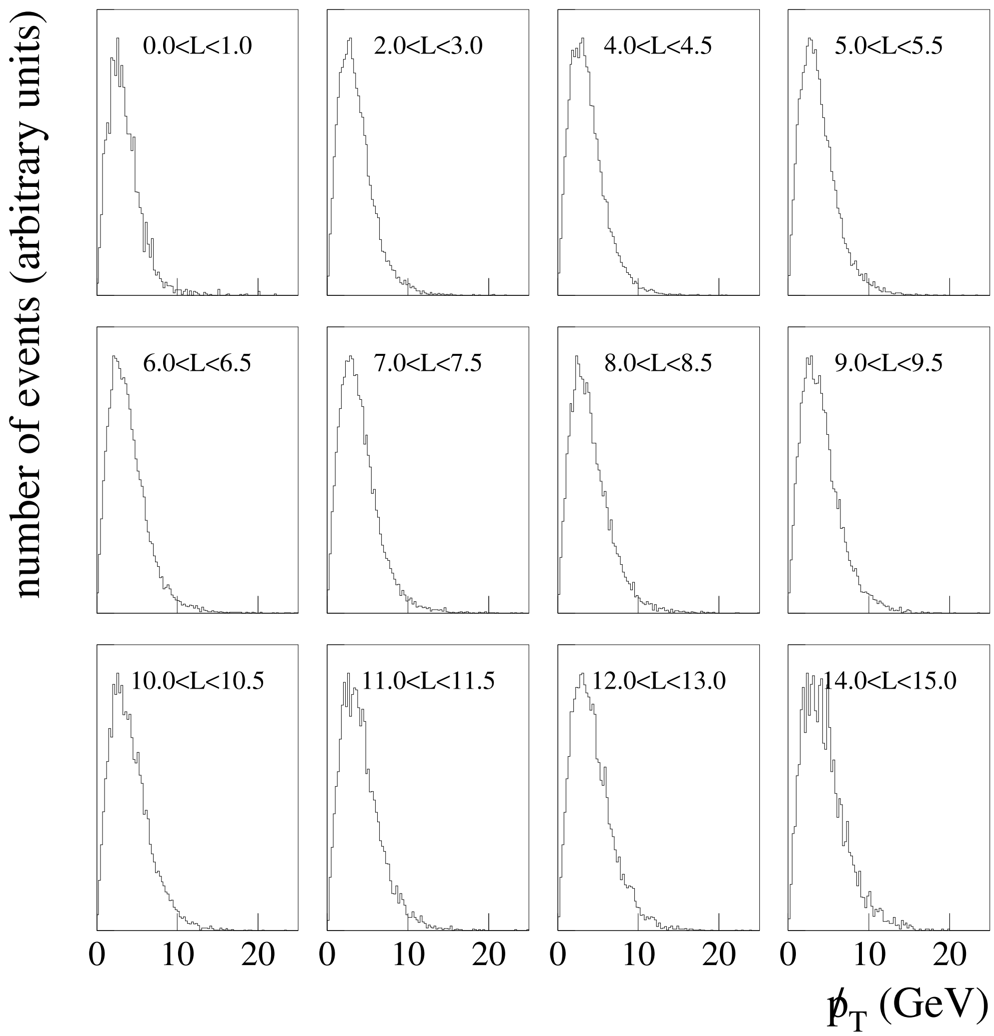


$\alpha_{rec} = 0.69 \pm 0.06$ and $\beta_{rec} = 0.04 \pm 0.02$

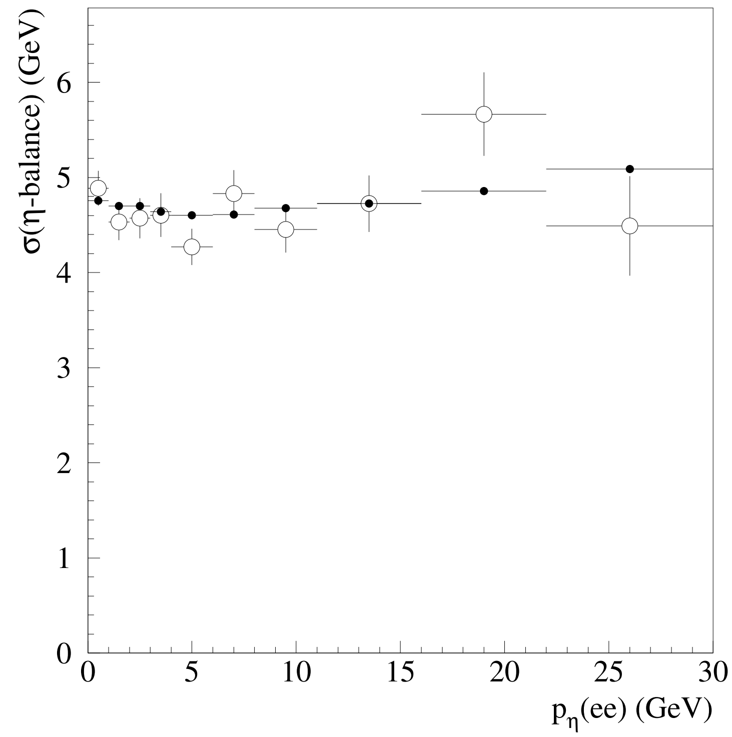
Recoil Resolution

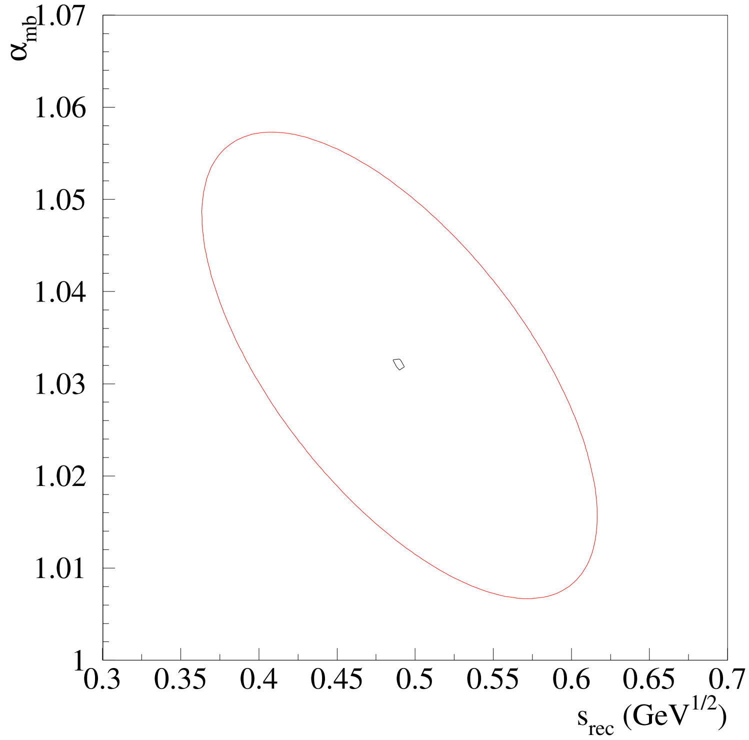
- "hard" component
  - smear $p_T(W)$ by $\sigma_{rec} = s_{rec}\sqrt{p_T(W)}$

- "soft" component
  - $\alpha_{mb} \not{E}_T$



Recoil Resolution

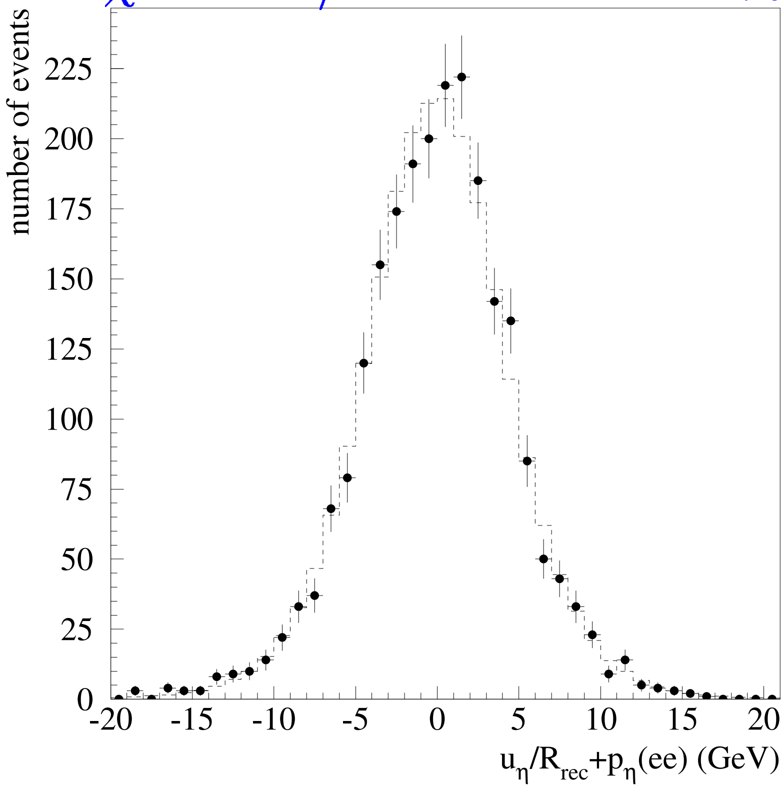




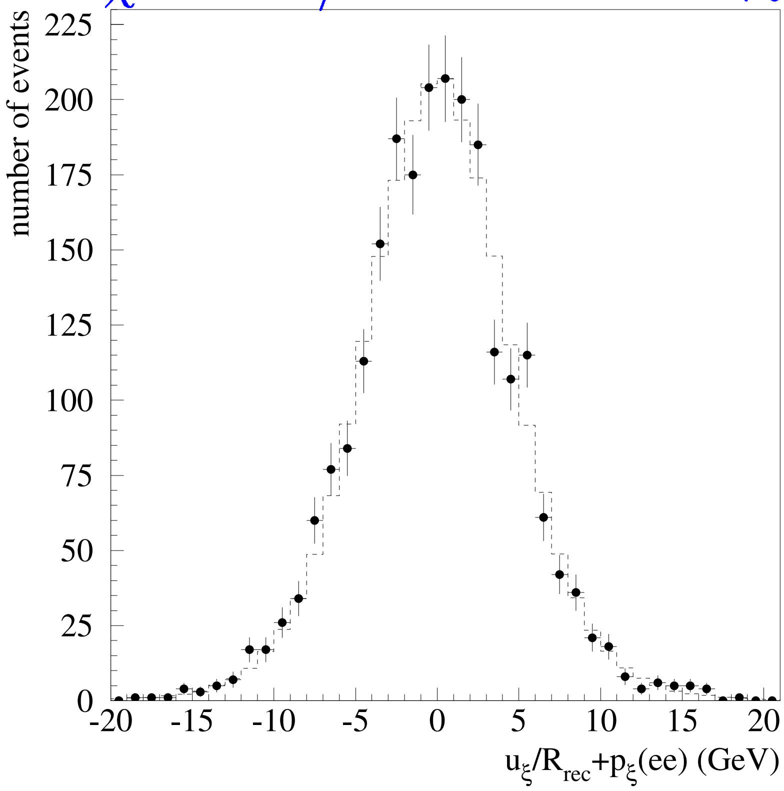
$s_{rec} = 0.49 \pm 0.14$ and $\alpha_{mb} = 1.03 \pm 0.03$

Recoil Resolution

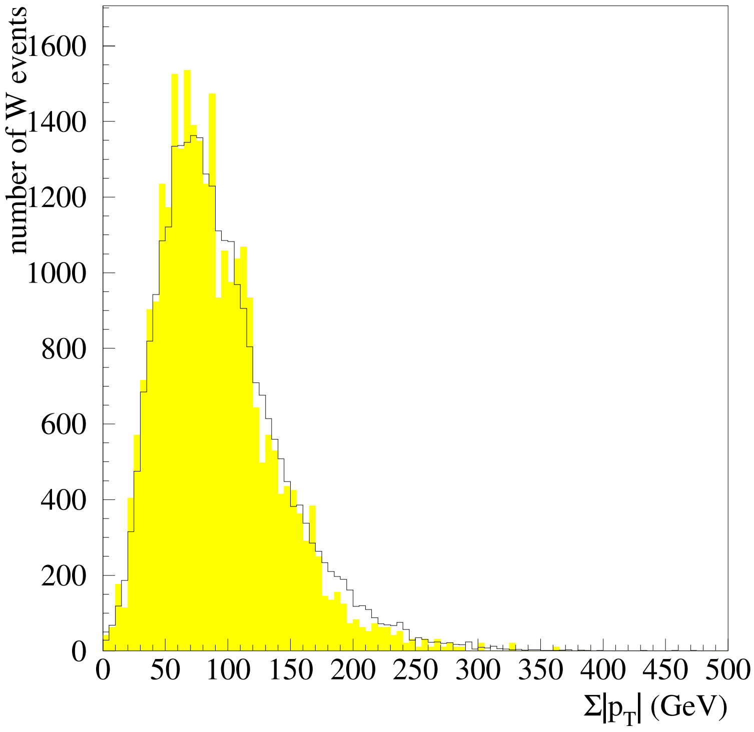
$\chi^2 = 25/40$ and $\kappa = 66\%$

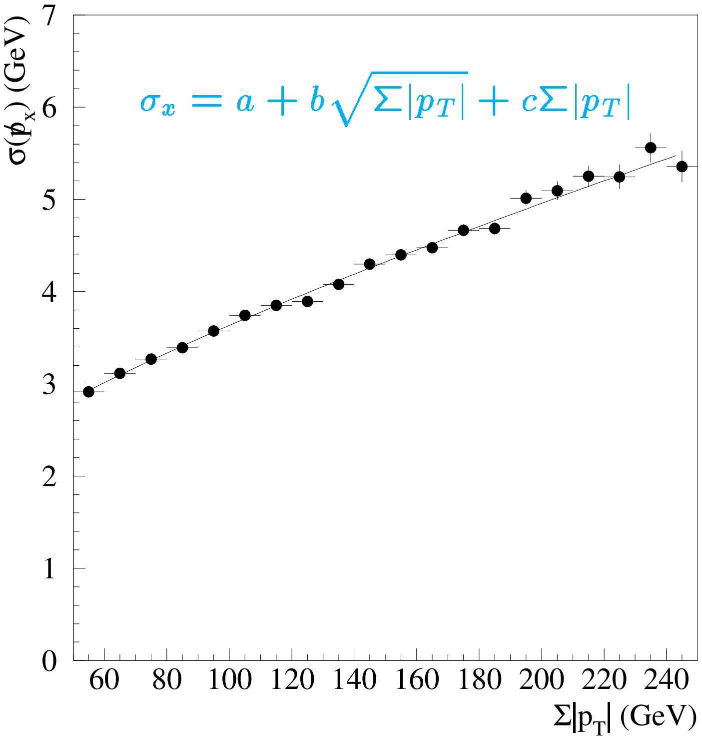


$\chi^2 = 38/40$ and $\kappa = 67\%$



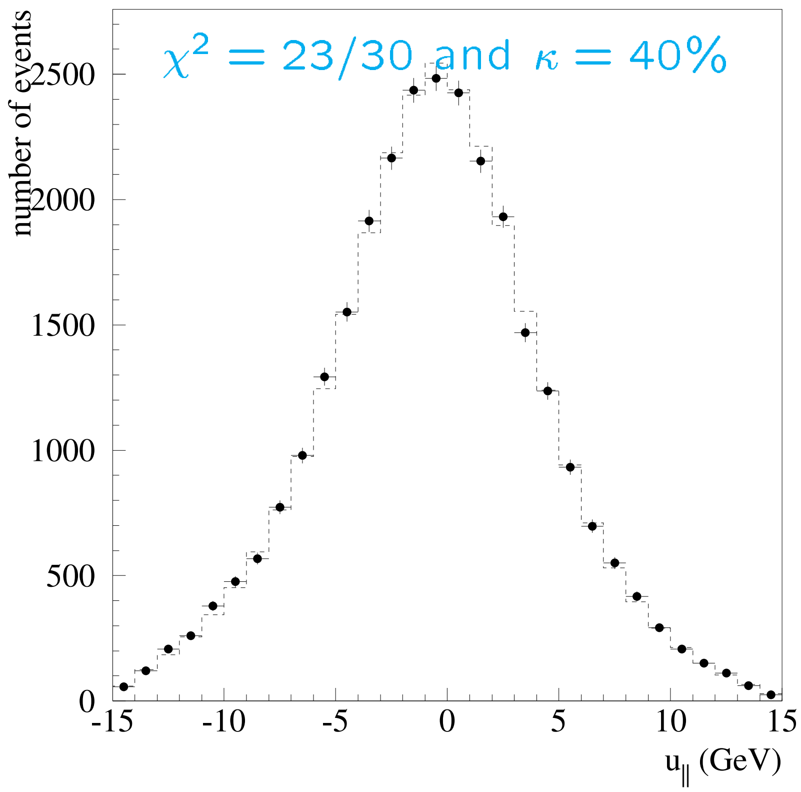
Recoil Resolution

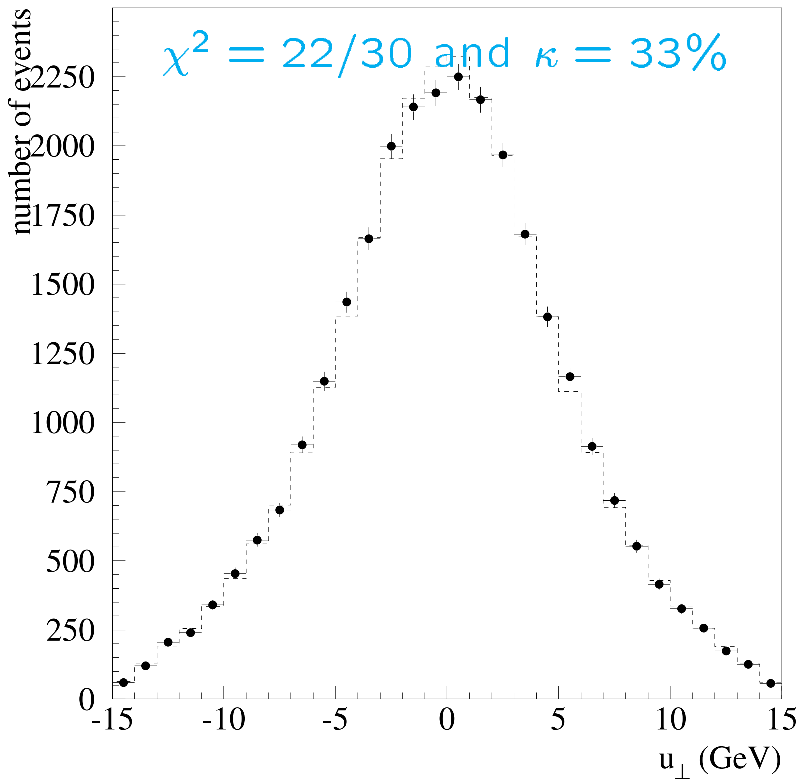




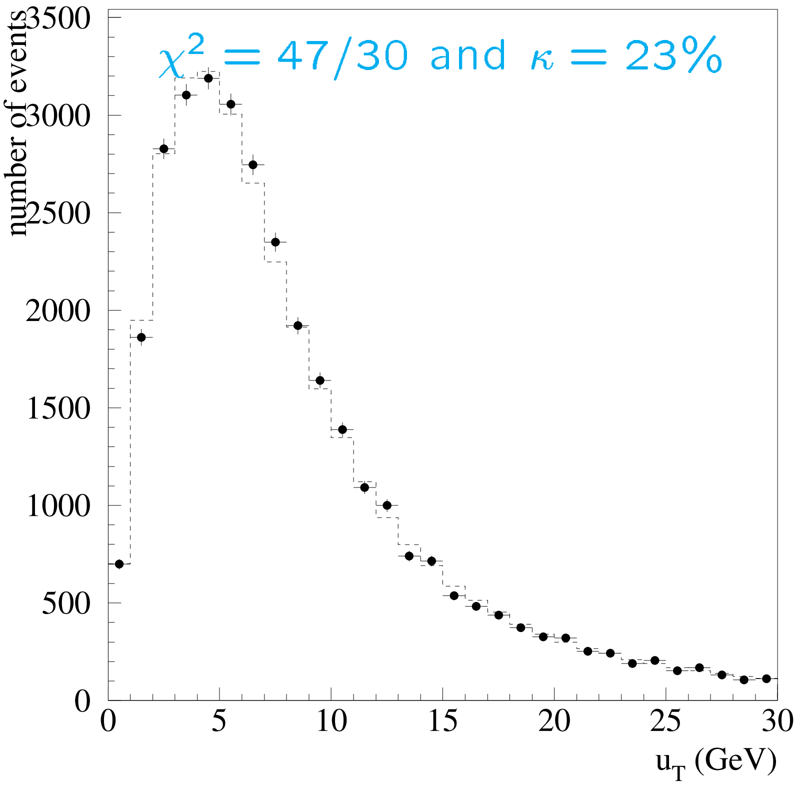
$$\alpha_{mb}(W) = \alpha_{mb}(Z)\,(1.02 \pm 0.02)$$

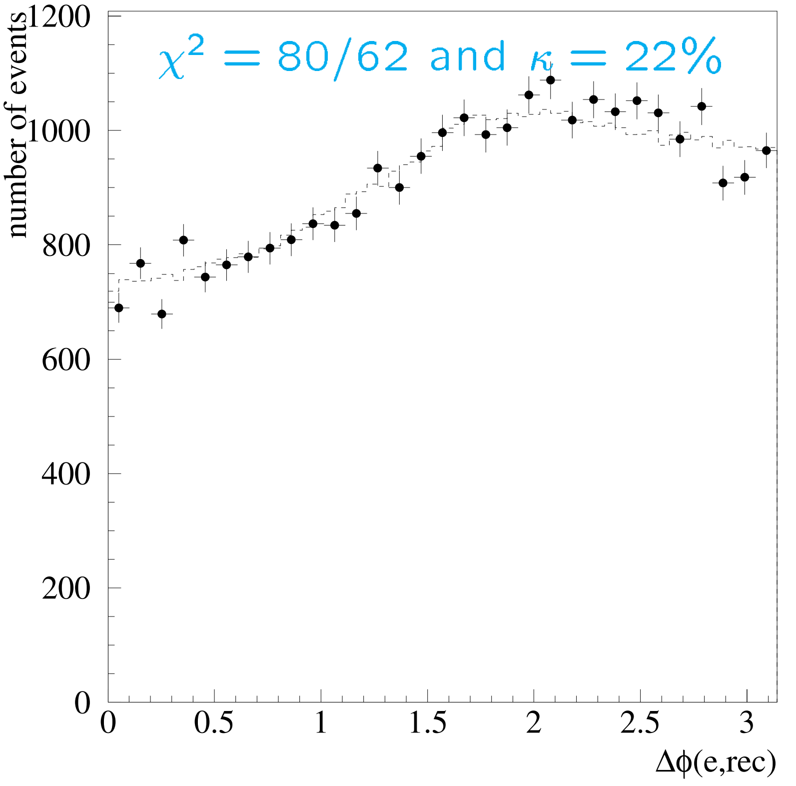
Data–MC Comparisons



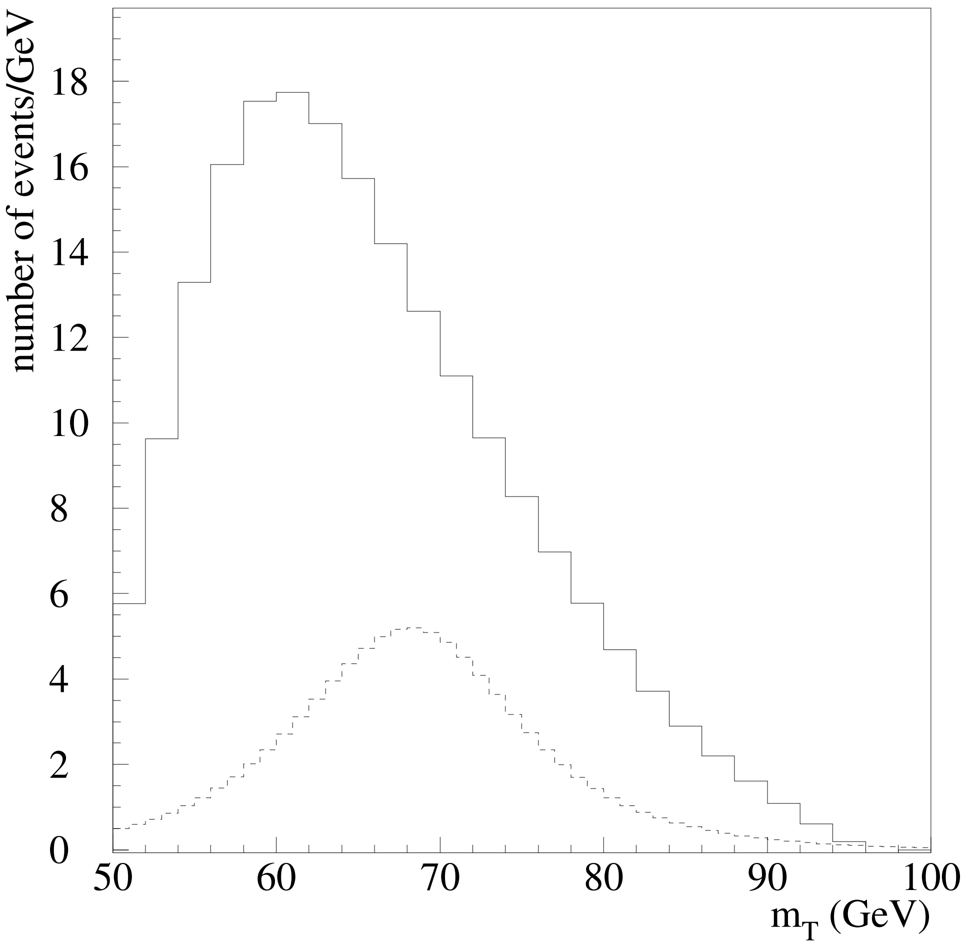


Data–MC Comparisons

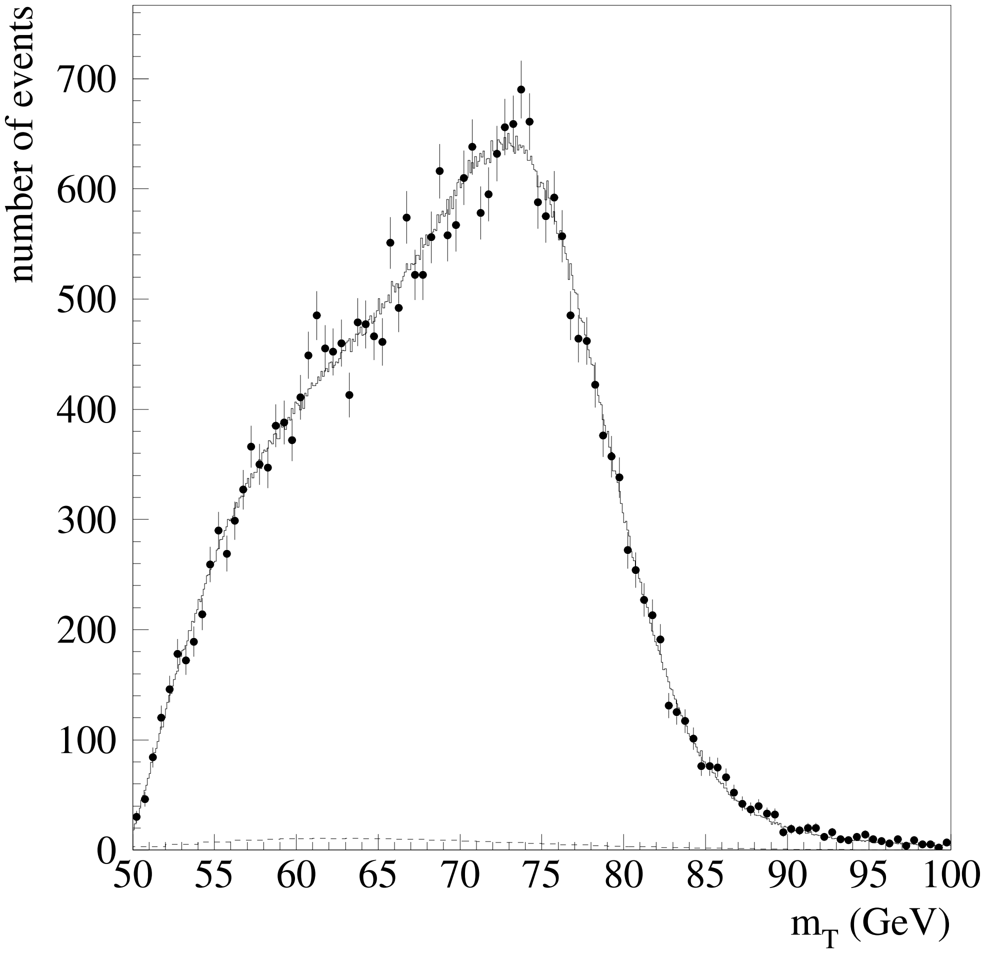




Backgrounds



Fit to m_T Spectrum

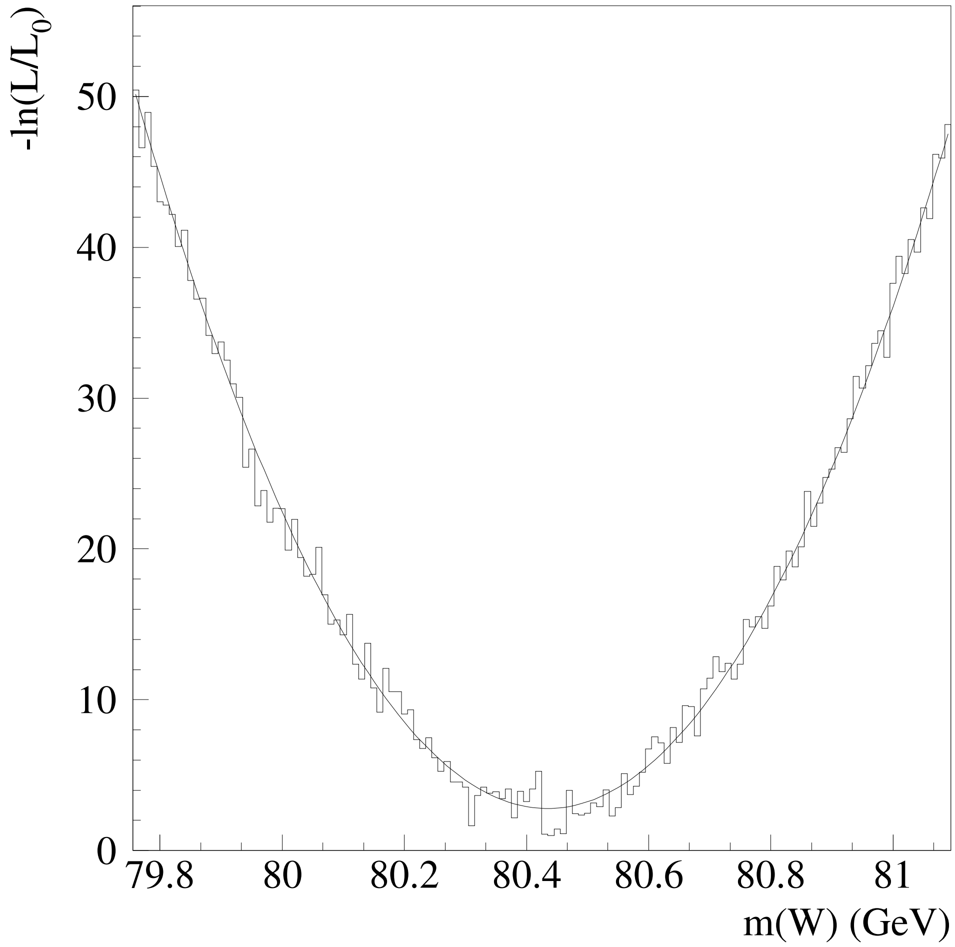


- goodness of fit

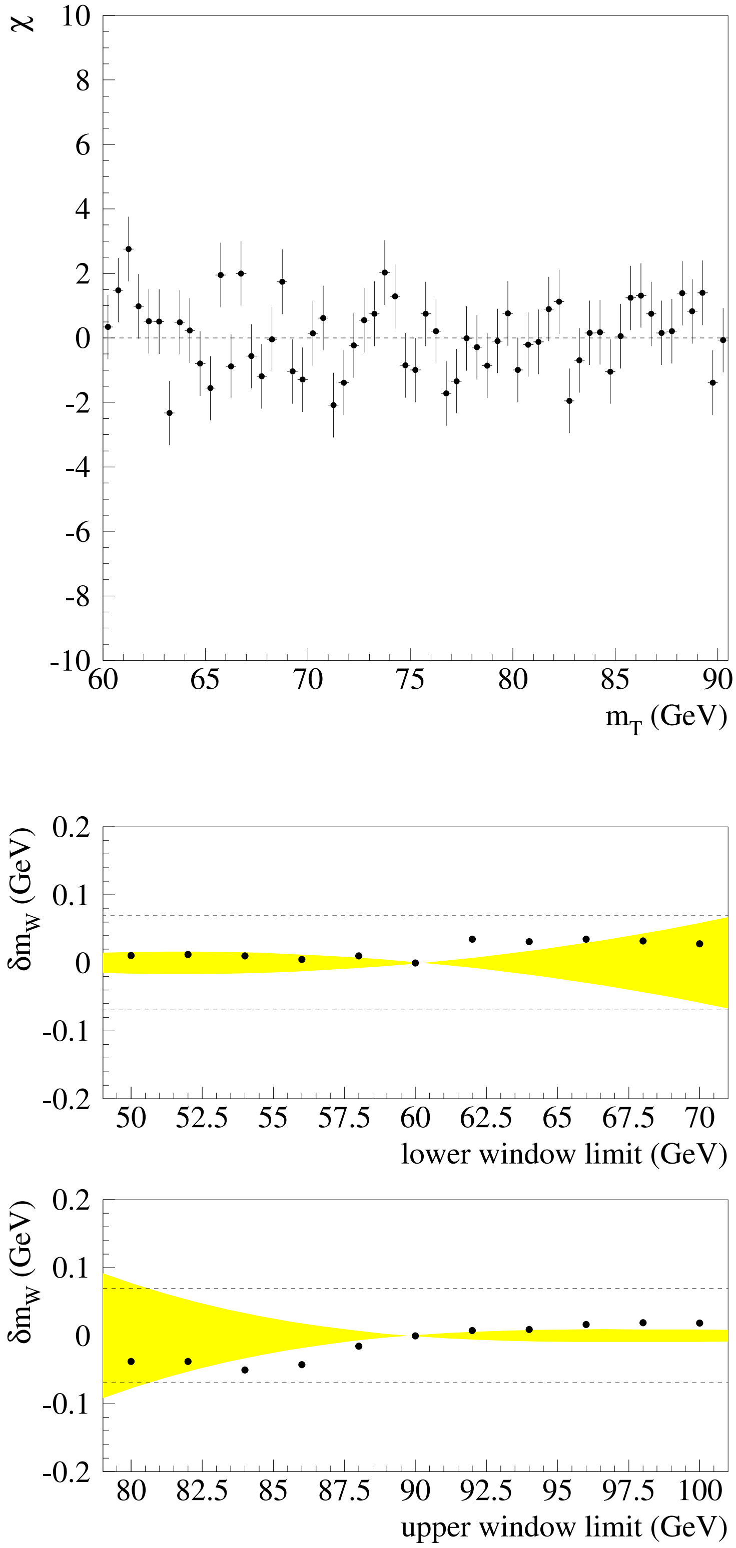
χ^2 test	77/59 d.o.f.
Kolmogorov-Smirnov test	34 %

$$m_W = 80.45 \pm 0.07 \text{ GeV}$$

Fit to m_T Spectrum



Fit to m_T Spectrum



W Production Model

$$\frac{d\sigma}{dQ^2 dy dq_T^2} \propto \int d^2b e^{i\vec{q}_T \vec{b}} W e^{-S} + Y$$

$$S = b^2 \left(g_1 + g_2 \ln \frac{Q}{2Q_0} \right) + b g_1 g_3 \ln (100 x_1 x_2)$$

- from Drell-Yan data with CTEQ2M pdf's

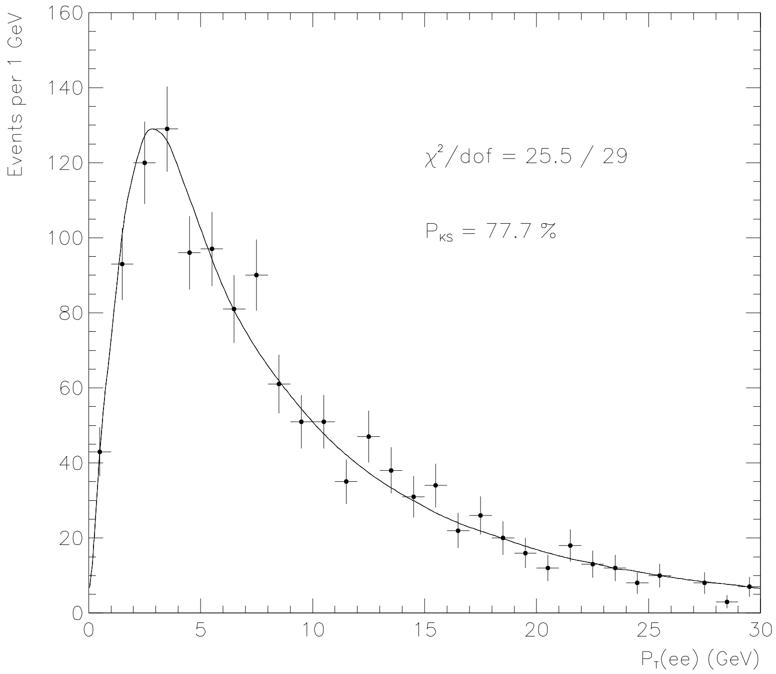
Ladinsky & Yuan, PRD 50, 4239 (1994)

$$g_1 = 0.11^{+0.04}_{-0.03} \text{ GeV}^2$$
$$g_2 = 0.58^{+0.1}_{-0.2} \text{ GeV}^2$$
$$g_3 = -1.5 \pm 0.1 \text{ GeV}^{-1}$$

W Production Model

- fit g_2 using DØ $Z \rightarrow ee$ data

$$\left.\begin{array}{ll} \text{MRSA}' & 0.59 \\ \text{MRSD}-' & 0.61 \\ \text{CTEQ3M} & 0.54 \\ \text{CTEQ2M} & 0.61 \end{array}\right\} \quad \begin{array}{l} \pm 0.10(stat) \\ \pm 0.05(syst)\ \text{GeV}^2 \end{array}$$



- deviations of fitted W mass for different pdf's

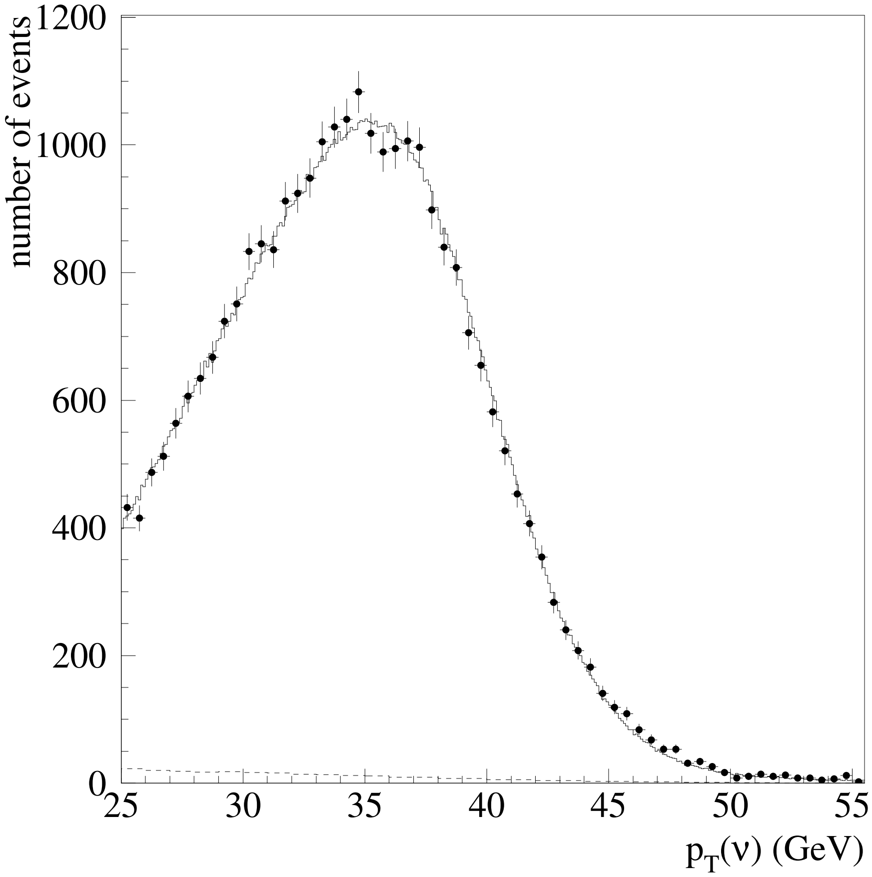
	g_2	m_T fit	$p_T(e)$ fit
MRSA′	0.59	$\equiv 0$	$\equiv 0$
MRSD−′	0.61	+20 MeV	+19 MeV
CTEQ3M	0.54	+5 MeV	+48 MeV
CTEQ2M	0.61	−21 MeV	−17 MeV

Uncertainties

	m_T fit	$p_T(e)$ fit
W stats	69 MeV	86 MeV
Z stats	65 MeV	65 MeV
total stats	95 MeV	108 MeV
calorimeter linearity	20 MeV	20 MeV
calorimeter uniformity	10 MeV	10 MeV
z calibration	28 MeV	28 MeV
electron resolution	23 MeV	14 MeV
lepton removal	16 MeV	16 MeV
selection bias	—	9 MeV
recoil resolution	33 MeV	9 MeV
recoil response	20 MeV	16 MeV
total detector	60 MeV	46 MeV
QCD	11 MeV	16 MeV
Z	5 MeV	8 MeV
total background	12 MeV	18 MeV
W width	9 MeV	7 MeV
parton luminosity	10 MeV	10 MeV
pdf	21 MeV	48 MeV
W p_T spectrum	5 MeV	28 MeV
rad decays	20 MeV	20 MeV
total theory	34 MeV	62 MeV
total syst	70 MeV	79 MeV
syst$\oplus$stat	118 MeV	134 MeV

Cross Checks

- fit $p_T(\nu)$ spectrum

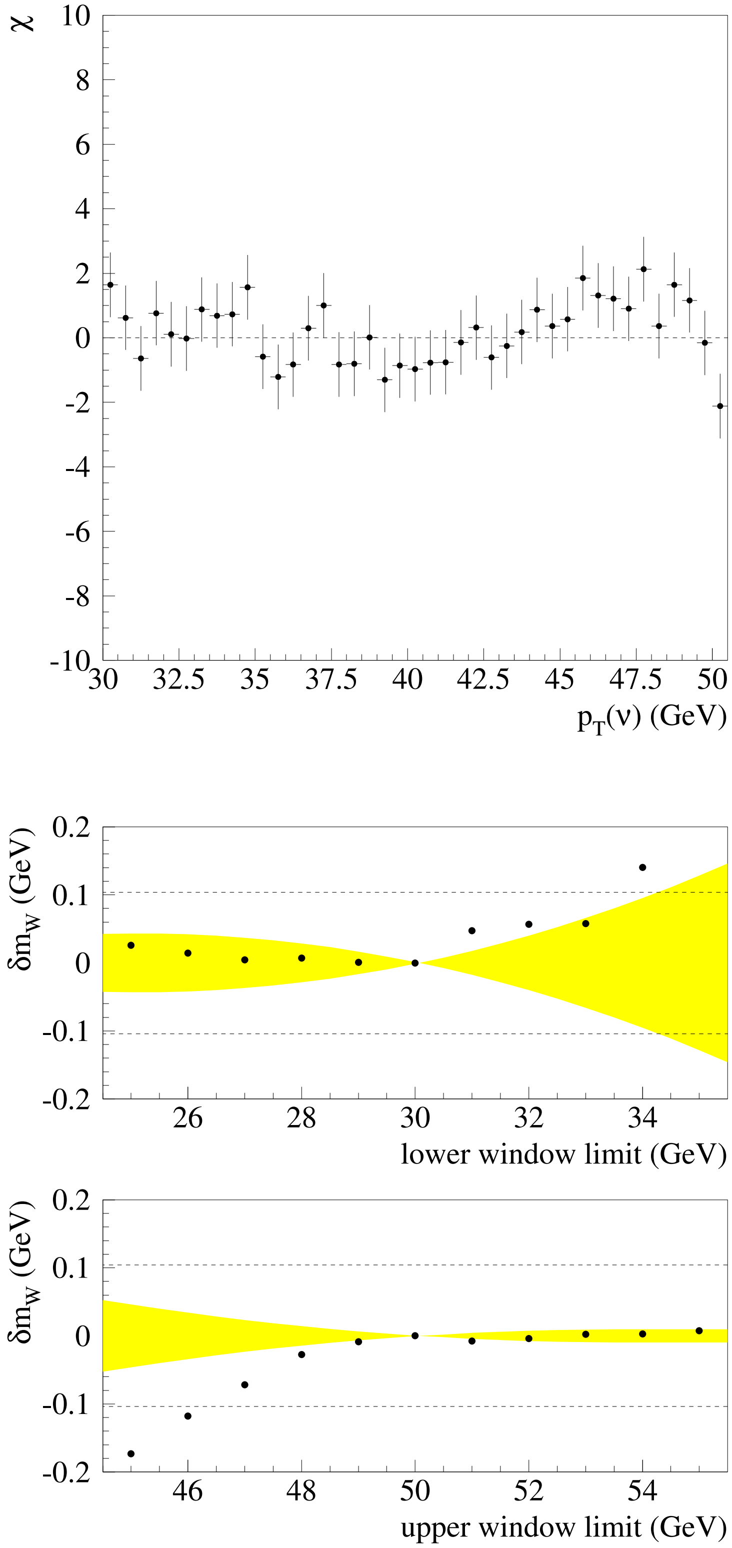


- goodness of fit

χ^2 test	36/39 d.o.f.
Kolmogorov-Smirnov test	32 %

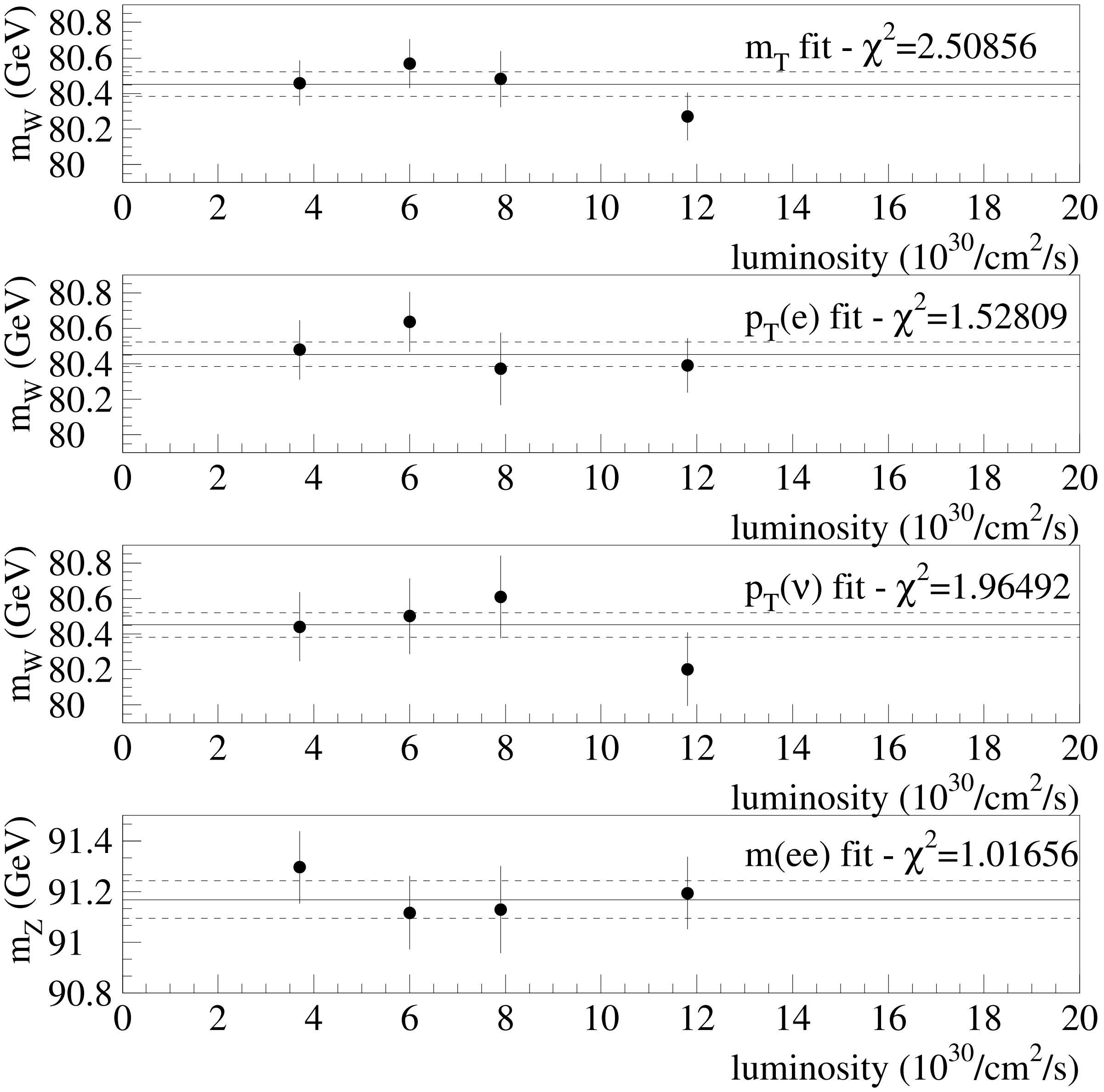
$$m_W = 80.42 \pm 0.10(stat) \pm 0.15(syst) \text{ GeV}$$

Cross Checks



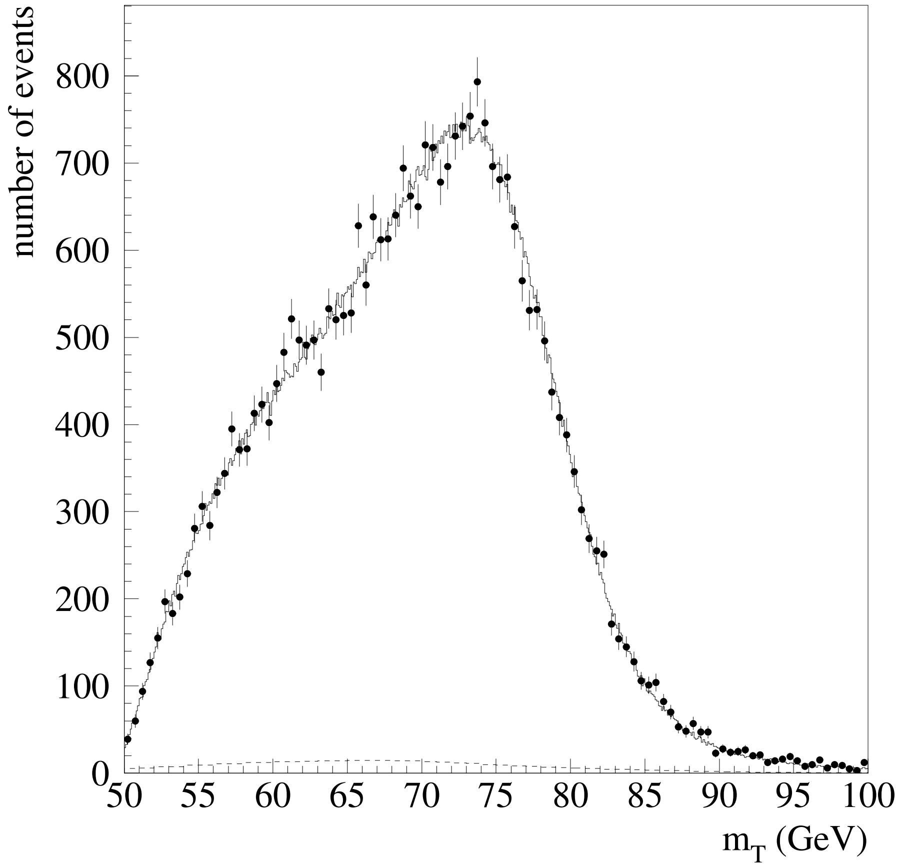
Cross Checks

- fit W sample in four luminosity bins



Cross Checks

- fit W sample with $p_T(W) < 30$ GeV



		χ^2	κ
m_T fit	80.48 ± 0.07 GeV	79/59	48 %
$p_T(e)$ fit	80.45 ± 0.09 GeV	37/39	100 %
$p_T(\nu)$ fit	80.30 ± 0.11 GeV	28/39	86 %
	(stat only)		

Result

- run 1b data [preliminary]
  - from m_T fit

    $m_W = 80.45 \pm 0.10(stat) \pm 0.07(syst)$ GeV

  - from $p_T(e)$ fit

    $m_W = 80.49 \pm 0.11(stat) \pm 0.08(syst)$ GeV

- run 1a data [PRL 77, 3309 (1996)]
  - from m_T fit

    $m_W = 80.35 \pm 0.21(stat) \pm 0.17(syst)$ GeV

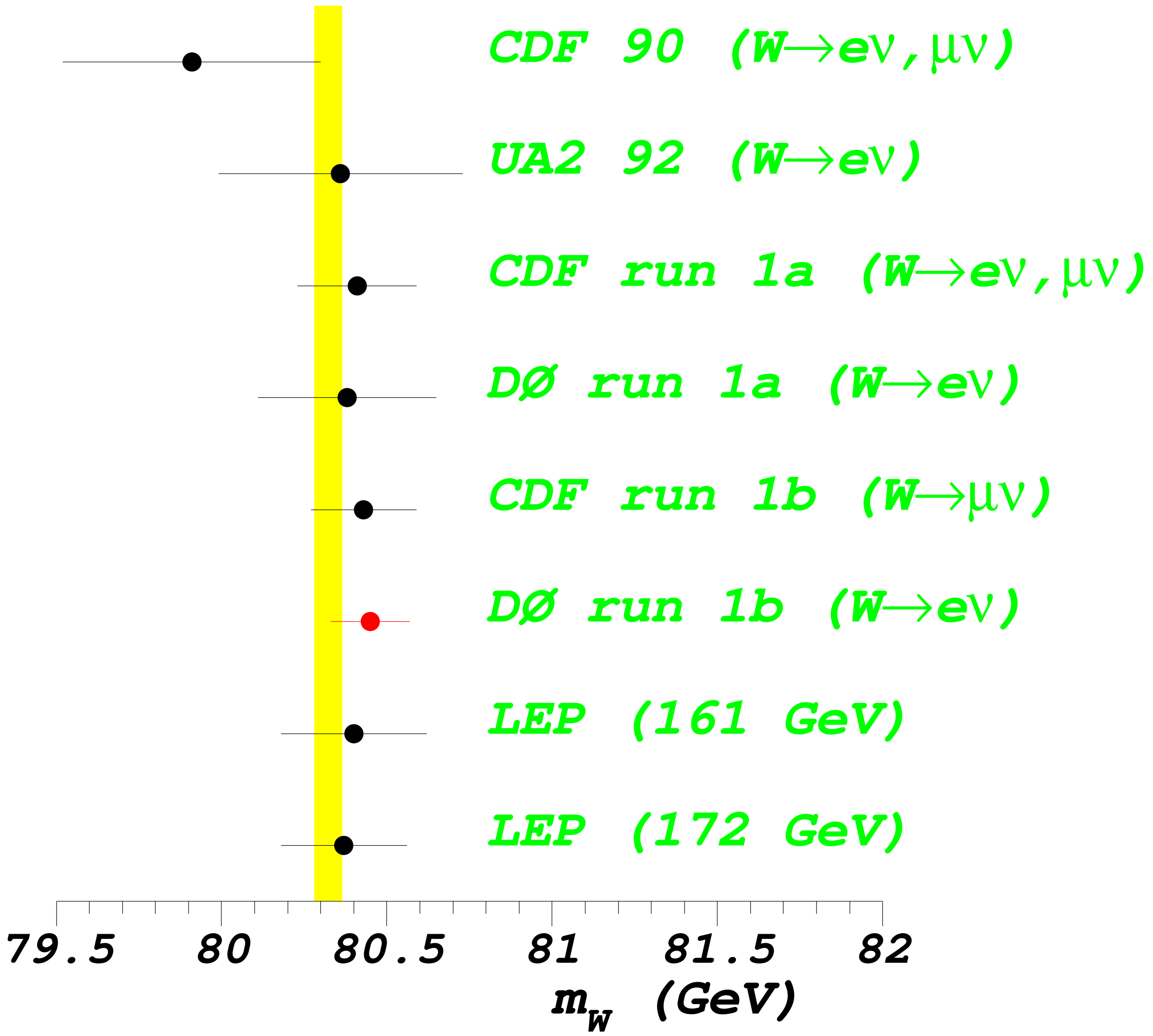
- combined m_T fit
  - common errors:

detector calibrations	36 MeV
W production, decay	34 MeV

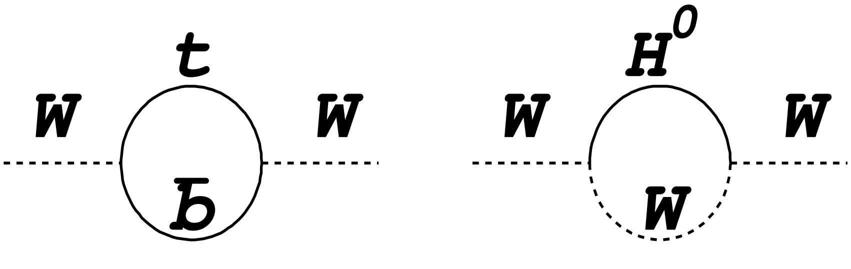
$$\boxed{m_W = 80.44 \pm 0.11 \text{ GeV}}$$

preliminary

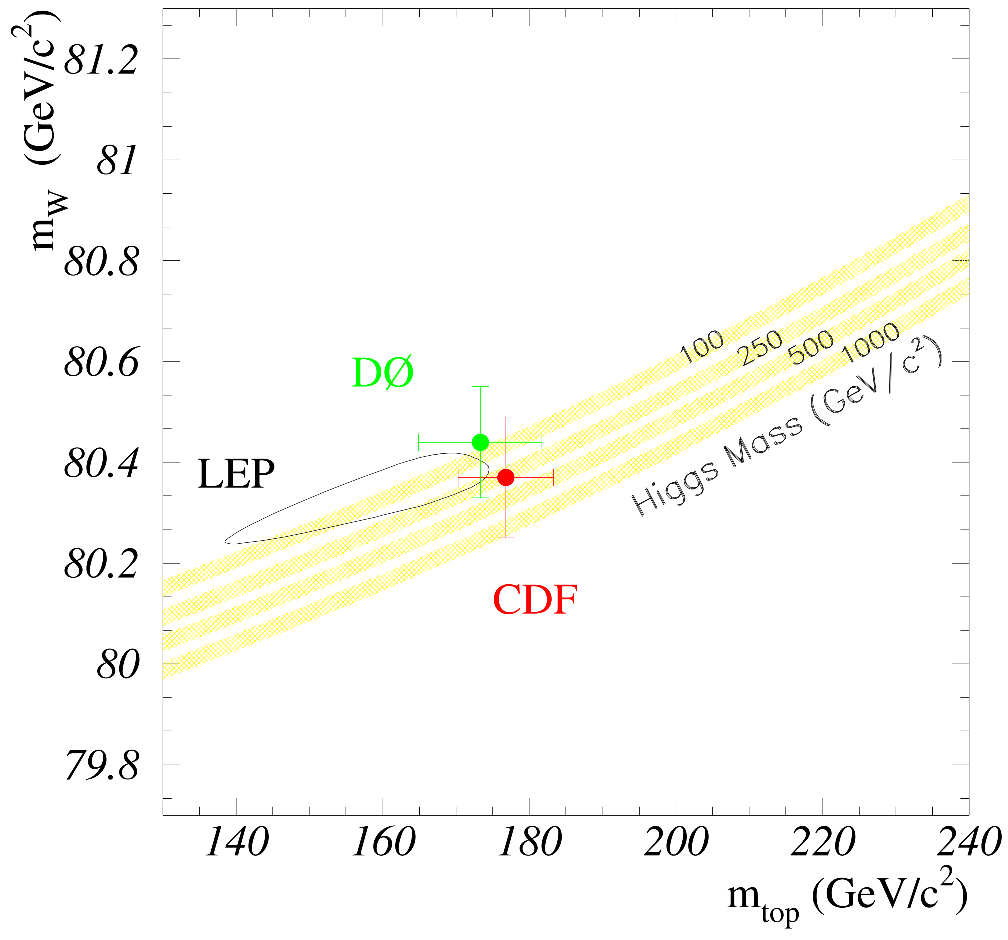
W Mass Measurements



Standard Model



$\propto m_t^2$ $\qquad$ $\propto \ln m_H$



Outlook

Tevatron Run 1	< 100 MeV	$\approx 100\ \text{pb}^{-1}$
LEP2	34 MeV	$4 \times 500\ \text{pb}^{-1}$
Tevatron Run 2	40 MeV	$\approx 1\ \text{fb}^{-1}$
TeV33	20 MeV	$\approx 10\ \text{fb}^{-1}$

Conclusion

- DØ has measured [preliminary]

$$\boxed{m_W = 80.44 \pm 0.11 \text{ GeV}}$$

- in agreement with
  - Standard Model
  - top quark mass