Measurement of the W Mass using the DØ Detector

Kathleen Streets

New York University, USA

- Introduction
- Detector
- W and Z event topology
- Event Selection
- Monte Carlo Description
- Results
- Consistency Checks

Measurement based on Run 1A of Fermilab Tevatron Collider

Data Collected: $\mathcal{L} \approx 15\ \mathrm{pb}^{-1}$

Why Measure W Mass?

Standard Model of electroweak interactions $\Rightarrow$

- $\star$ **fundamental parameters precisely specified at tree level:**
  $\Rightarrow$ **all known accurately:** α_{em}, G_F, M_Z
- $\star$ **large radiative corrections due to higher order diagrams**

$\Rightarrow$ **direct measurement of W mass:**

defines size of radiative corrections

constrains M_{top} & M_{Higgs}

tests the SM beyond the tree level

W and Z Production

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

At $\sqrt{s} = 1.8$ TeV: valence-sea contribution $\approx 55\%$
sea-sea contribution $\approx 20\%$

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

$$W \rightarrow l\nu$$
$$Z \rightarrow ll$$

DØ $\quad l = e$

Experimental Measurement

Experimentally Measure:
lepton (l) momentum
recoil (R) transverse momentum

$\underline{W}$ events:
have: $\vec{P}(l), \vec{P}_T(R)$

$$\vec{P}_T(R) = -\vec{P}_T(W) - \vec{u}$$

infer: $\vec{P}_T(\nu) = -\vec{P}_T(R) - P_T(l)$

$$M_T(W) = \sqrt{2P_T^l P_T^\nu (1 - \cos\phi)}$$

$\underline{Z}$ events:
have: $\vec{P}(l1), \vec{P}(l2), \vec{P}_T(R)$

$$\vec{P}_T(R) = -\vec{P}_T(Z) - \vec{u}$$

$$M(Z) = \sqrt{2P_1^l P_2^l (1 - \cos\phi)}$$

Electron Identification - DØ

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

Event Selection

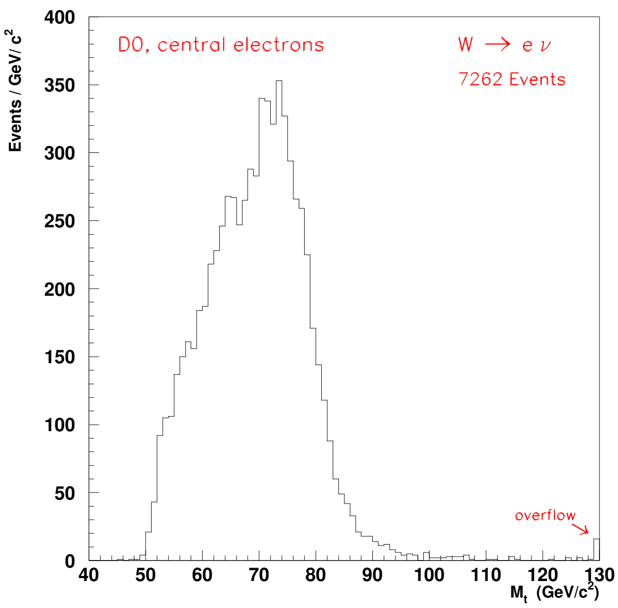
$W \to e\nu$

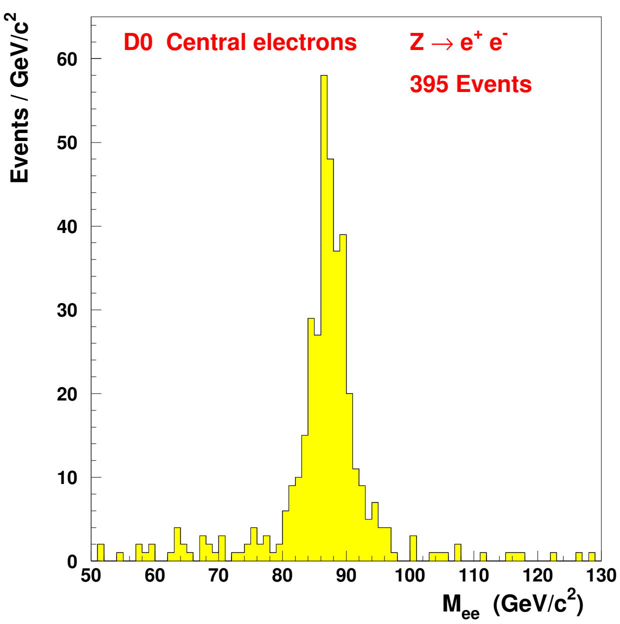
- ⋆ CC calorimeter: $|\eta| < 1.2$
- ⋆ isolated electron: $P_T(e) > 25$ GeV
- ⋆ neutrino: $\not{E}_T > 25$ GeV
- ⋆ W transverse momentum: $P_T(W) < 30$ GeV
- ⋆ transverse mass $50 < M_T(W) < 110$ GeV

$Z \to ee$

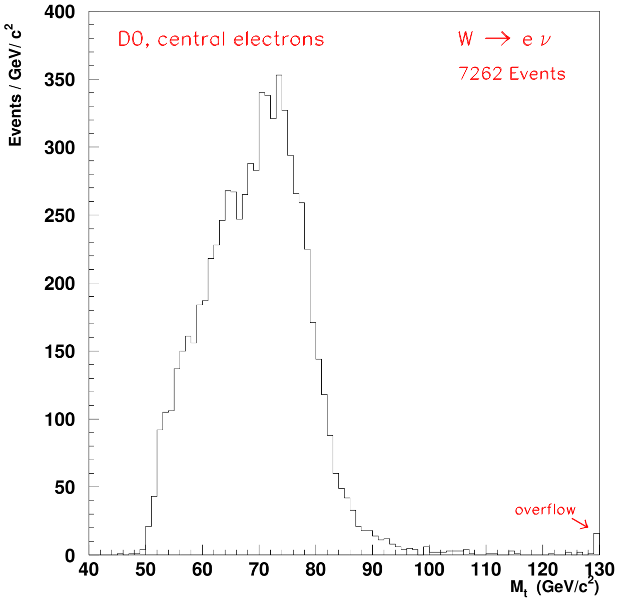
- ⋆ CC calorimeter: $|\eta| < 1.2$
- ⋆ 2 isolated electrons: $P_T(e) > 25$ GeV
- ⋆ invariant mass $70 < M(Z) < 110$ GeV

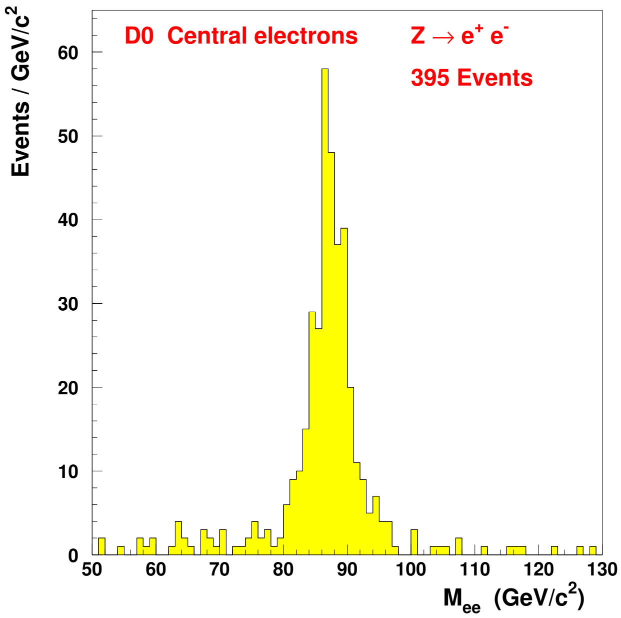
Run 1A - spectra:





DØ Run 1A - spectra:





Event Sample

	$W \to e\nu$	$W \to \mu\nu$	$Z \to ee$	$Z \to \mu\mu$
DØ	7234		395	
CDF	5718	3268	287	330

Measurement Technique

- **Longitudinal momentum of ν unknown**

- **Transverse mass distribution exhibits Jacobian peak**

which contains the mass information

Measurement Technique:

Generate $M_T(W)$ distributions for different M_W values and do a maximum likelihood fit to the data.

Event Modelling

Description of Fast Monte Carlo
- must model data:

- W production and decay $\longrightarrow \vec{P}_T(l)$ & $\vec{P}_T(W)$
- lepton energy scale
- hadronic energy scale
- energy & angular smearing
- underlying event modelling
- selection biases (efficiencies)
- kinematic cuts

(Z events modelled in analagous way)

DØ $\longrightarrow$ calibrate EM calorimeter response to Z's
$\Rightarrow$ measure ratio of W/Z mass

$\longrightarrow$ use data to set most MC parameters

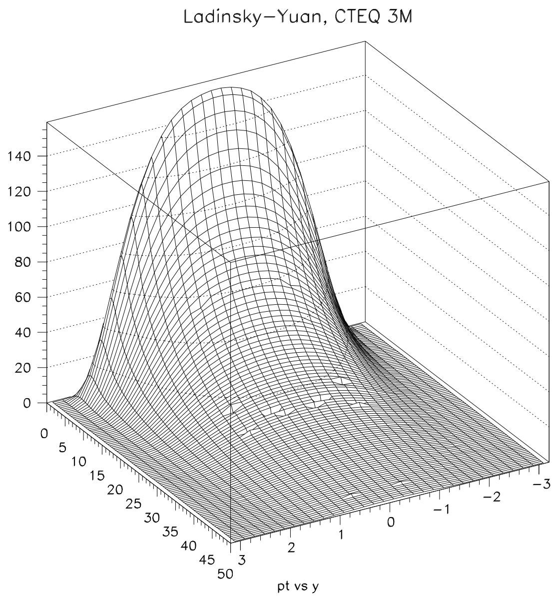
$\longrightarrow$ errors set using large statistics samples of MC data

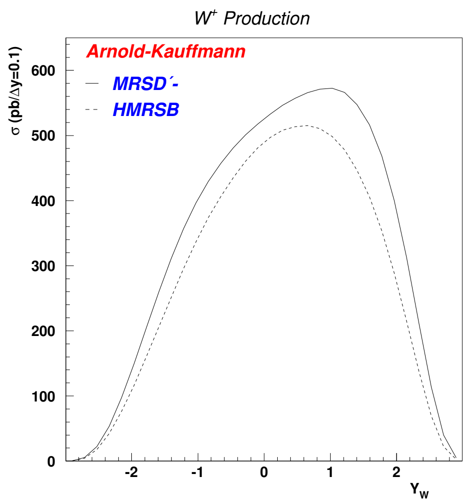
W Production:

- Ladinsky-Yuan (NLO) with **MRSA** pdf [PRD 50,4239(1994)]

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

- W resonance generated with relativistic Breit-Wigner, skewed by mass dependence of parton luminosity





W **Decay:**

- decay of polarized W in rest frame - then boosted to lab

- radiative decays: $W \to e\nu\gamma$
  [Berends & Kleiss, Z. Phys. C 27, 365(1985)]

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

$P_T(e)$ Scale

→ **Absolute calibration of calorimeter not known**

→ **Calibrate calorimeter to LEP/SLC Z mass**

→ **Measure ratio**

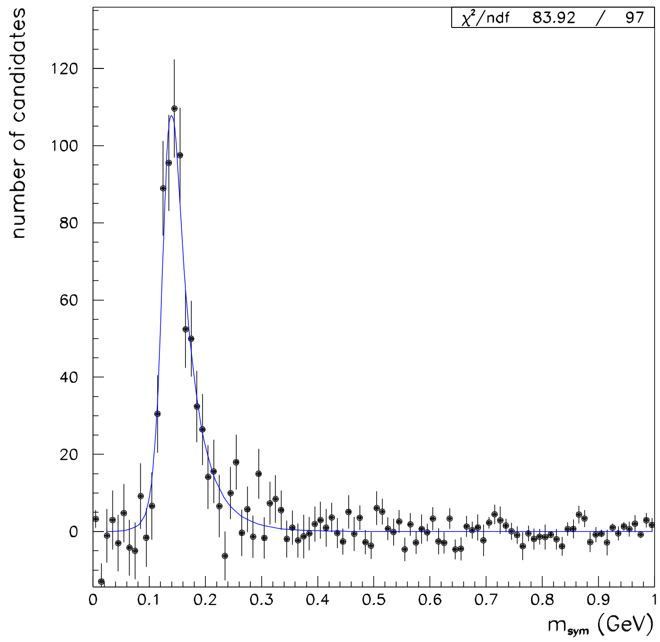
$$\left(\frac{M_W}{M_Z}\right) \cdot M_Z^{\mathrm{LEP}}$$

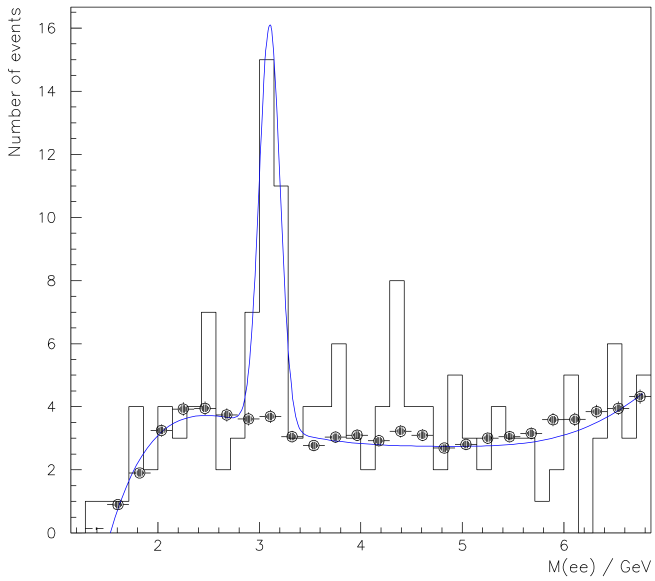
→ **Set EM energy scale using J/ψ, π^0, and Z events**

→ **EM energy response:**

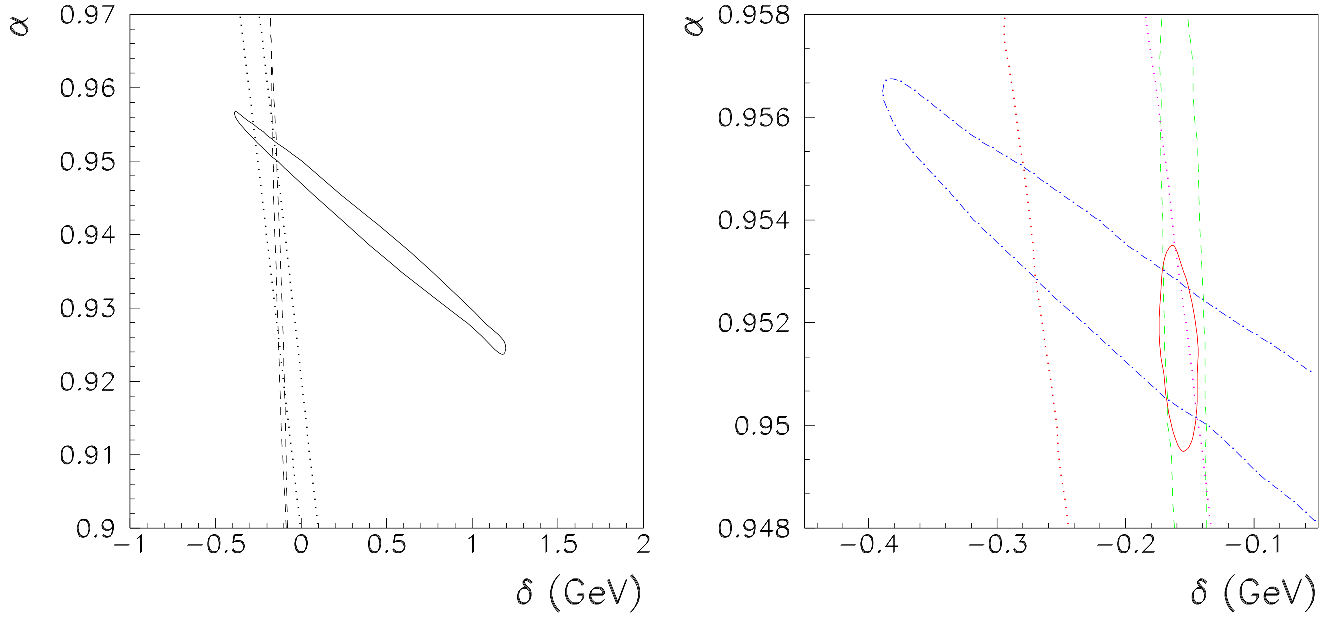
$$E^{meas} = \alpha E^{true} + \delta$$

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





$P_T(e)$ Scale



Measure Ratio:

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

$\rightarrow$ **Ratio insensitive to scale (first order)**

- error from offset suppressed

- error dominated by limited Z statistics

$$\alpha = 0.9514 \pm 0.0018 \qquad \delta = -0.158 \pm 0.015 \ {}^{+.030}_{-.210} \ \text{GeV}$$

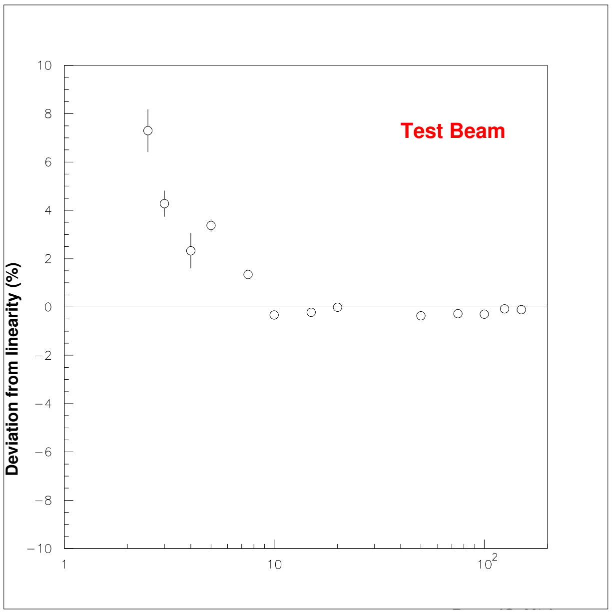
error due to EM scale: $\sigma(M_W) = 160 \ \text{MeV}$

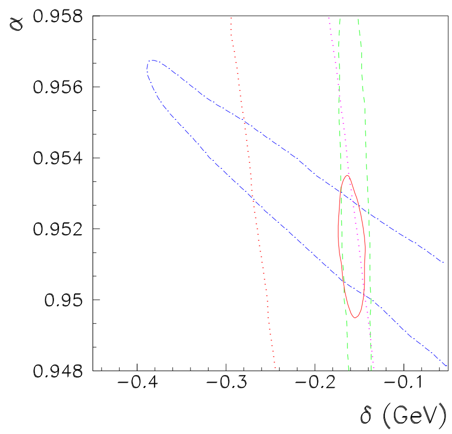
DØ EM energy scale - nonlinearity

constrained by test beam, $2.5 < p < 150$ GeV

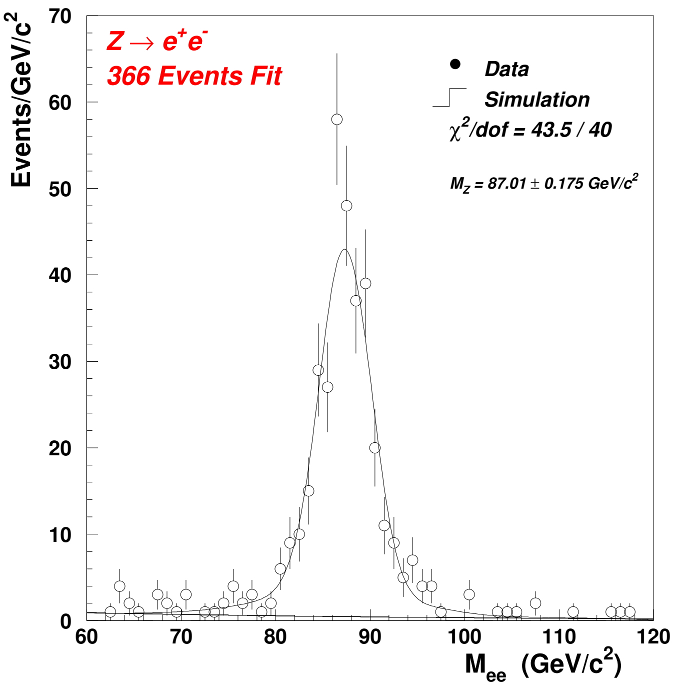
linear to better than 0.5% for $p > 10$ GeV

assume $E^{meas} = \alpha E + \delta + \xi(E - 45)^2$





$P_T(e)$ Scale and Resolution



Use $Z \longrightarrow ee$ events:

- peak of M_Z sets EM scale: $\alpha = .95$
- width of M_Z constrains EM energy resolution:

EM Energy resolution:

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

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

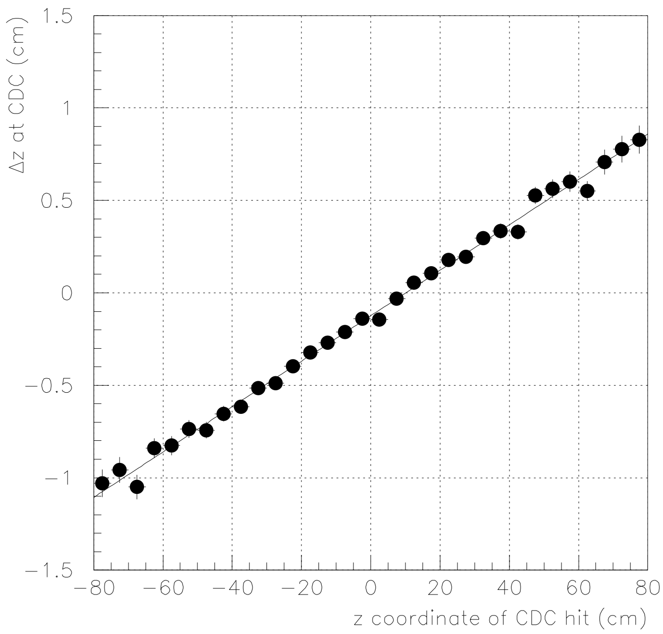
$$Z \text{ data} \Rightarrow C = (1.5 \ ^{+0.6}_{-1.5})\%$$

error due to EM energy resolution: $\sigma(M_W) = 70$ MeV

Electron Angle Determination

Electron direction determined using:
track center-of-gravity & calorimeter cluster position

- calorimeter extensively studied in test beam
- bias in z_{CD} position exists - extensively studied using:
  collider muon data & cosmic ray muons
  $\Rightarrow z_{CD}^{true} = (0.988 \pm 0.002) z_{CD}^{meas}$



error due to electron angle determination:
$\sigma(M_W) = 50$ MeV

Underlying Event Correction to $P_T(e)$

Electron energy $\Rightarrow 5 \times 5$ towers with $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$

- additional energy due to spectator interactions
  $= 9.2$ MeV per tower
- additional energy due to zero suppression of asymmetric pedestal
  $= 7.6$ MeV per tower
- energy lost due to zero suppression cut-off = -150 MeV
- correct for 8 towers not zero suppressed = -60 MeV
- corrections in electron direction:

$$P_T(e) + 25(9.2 + 7.6) - 150 - 60$$

$$= P_T(e) + \vec{u}(e) - 210 \text{ MeV};\ \vec{u}(e) = 420 \text{ MeV}$$

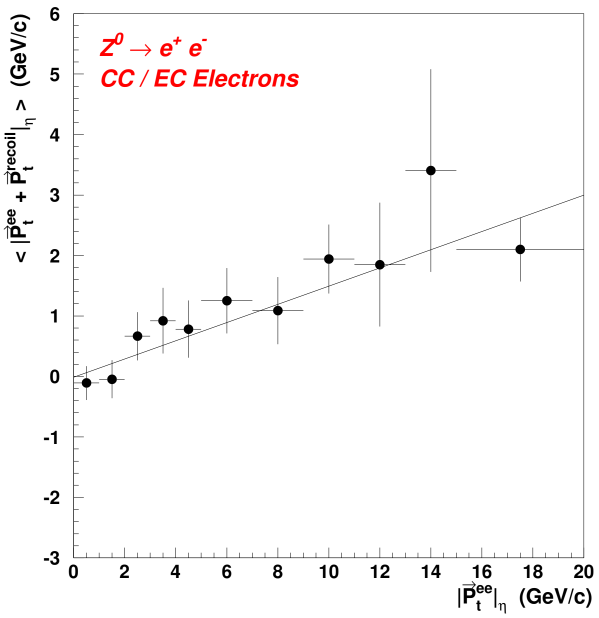
error due to underlying event modelling: $\sigma(M_W) = 35$ MeV

$\vec{P}_T(R)$ Scale

$\Longrightarrow$ hadronic energy scale relative to EM scale

$\Longrightarrow$ from Z events have

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



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

error due to hadronic energy scale: $\sigma(M_W) = 50$ MeV

$\vec{P}_T(R)$ Energy Resolution

$\Longrightarrow$ use jet resolution from test beam:

$$S = 0.80 \pm 0.20,\ N = 1.5,\ C = 0.04$$

error due to hadronic energy resolution: $\sigma(M_W) = 65$ MeV

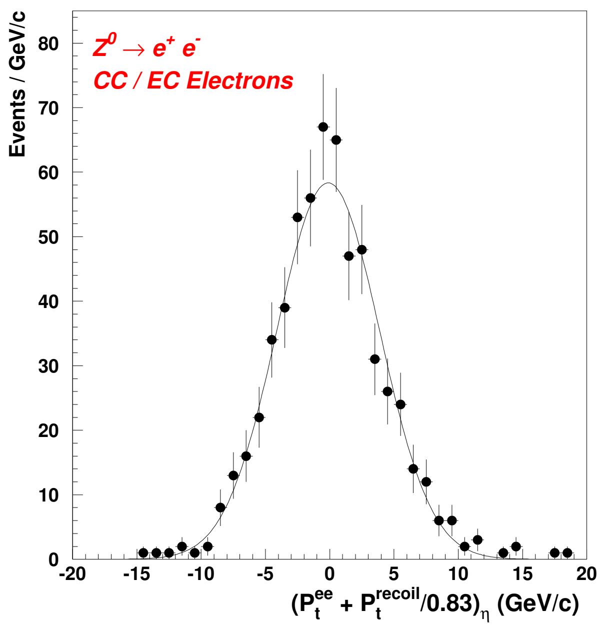
$\vec{P}_T(R)$ Resolution and Underlying Event

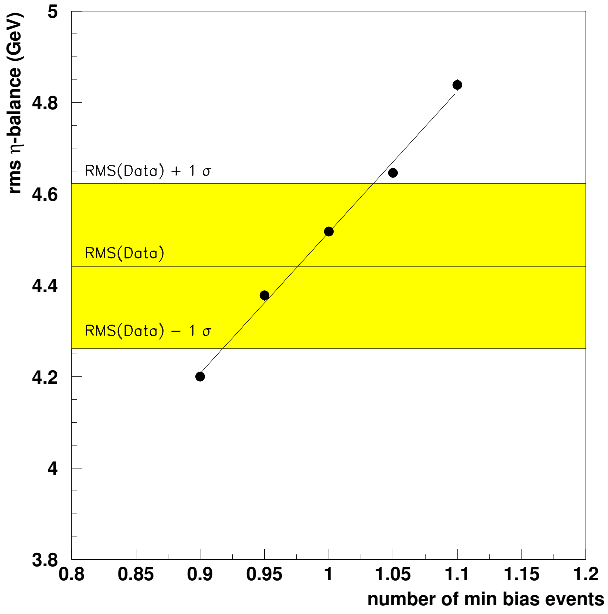
Underlying event affects magnitude and smears the $\vec{P}_T(R)$

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

$$\vec{P}_T(R) = -\vec{P}_T(W) - C\vec{u}_{mb}$$

- $\vec{u}_{mb}$ is total $\vec{P}_T$ of minimum bias event
- luminosity distribution of data is modelled
- $C = \#$ minbias events needed to model W underlying event
- resolution of $\eta-$balance of Z data constrains $C \rightarrow 0.98 \pm 0.06$





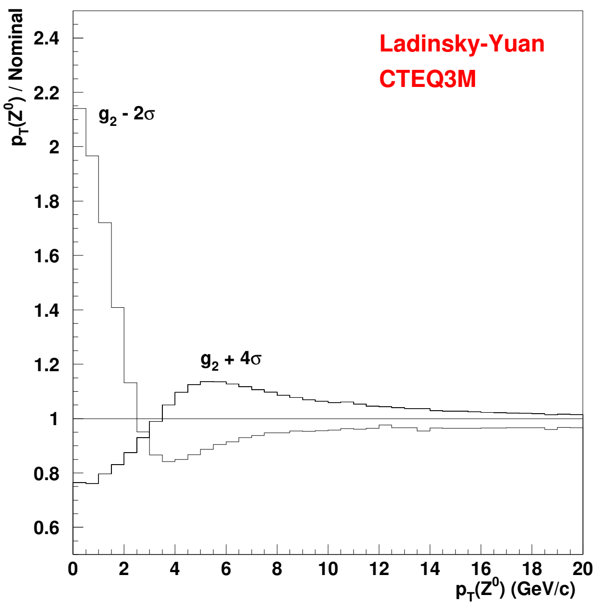
error due to # min bias events: $\sigma(M_W) = 60$ MeV

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

Use Ladinsky-Yuan model input $P_T(W)$ spectrum
- correlated with pdf choice

$\star$ g's are phenomenological parameters in model
$\longrightarrow$ P_T most sensitive to g_2
$\star$ CDF W Asymmetry data contrains pdf's

$Rightarrow$ Allow 2σ variation in data to set error



error due to $P_T(W)$ spectrum and pdfs: $\sigma(M_W) = 65$ MeV

$P_T(W)$ spectrum and pdf's

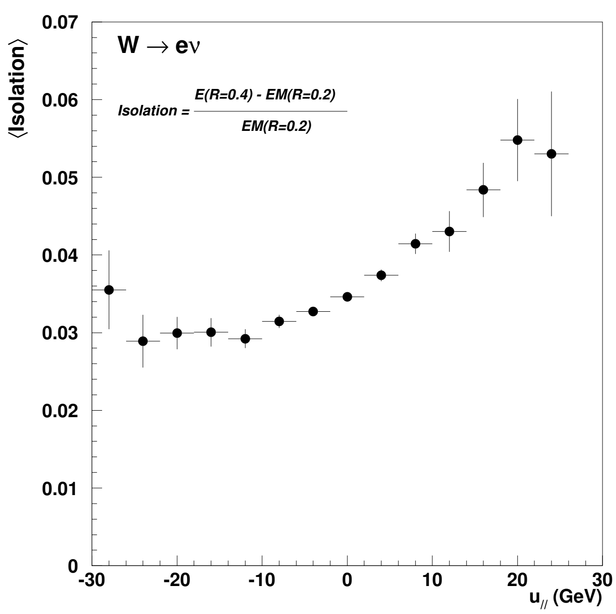
Change in M_W from varying pdf's g parameters independently:

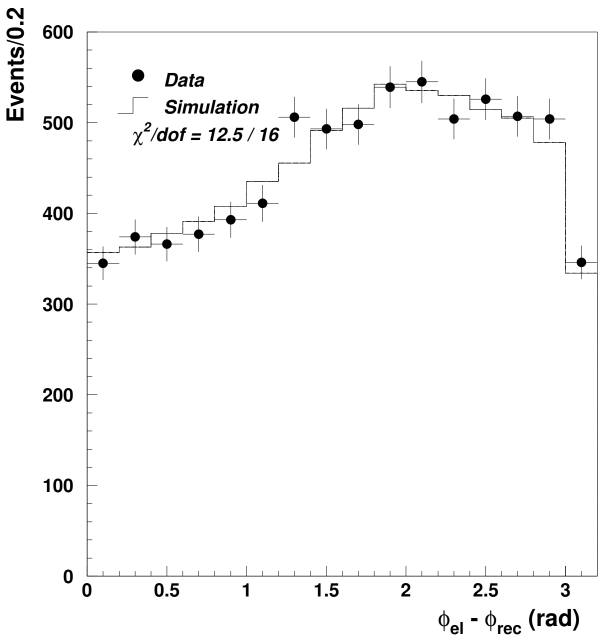
	ΔM_W (MeV)
MRSH	$+30 \pm 15$
MRSD'-	$+31 \pm 15$
CTEQ2M	-20 ± 15
CTEQ3M	$+37 \pm 15$
GRV H0	$+47 \pm 15$
HMRSB	$+157 \pm 15$
$g_2 - 2\sigma$	-14 ± 15
$g_2 + 2\sigma$	-37 ± 15
$g_2 + 4\sigma$	-30 ± 15

Event Selection Bias - $u_{\|}$ Efficiency

$$u_{\|} \equiv \vec{P}_T(R) \cdot \hat{e}$$

- $u_{\|} > 0 \longrightarrow$ recoil close to $e \longrightarrow$ events lost due to shape cuts
- $u_{\|} < 0 \longrightarrow$ recoil away from $e \longrightarrow$ no bias



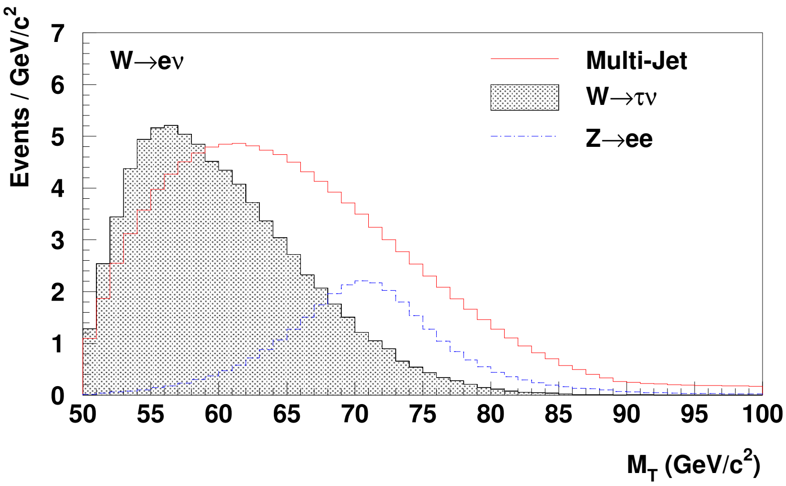


Also:

- model trigger efficiencies
- model efficiency of electron ID in radiative decays
- fiducial and kinematic cuts as in data

error due to radiative decays: $\sigma(M_W) = 20$ MeV
error due to efficiencies: $\sigma(M_W) = 30$ MeV

Backgrounds



Backgrounds included in likelihood fitting procedure

multi − jet ⇒ QCD event with $\not{E}_T$ and where one jet fakes an electron

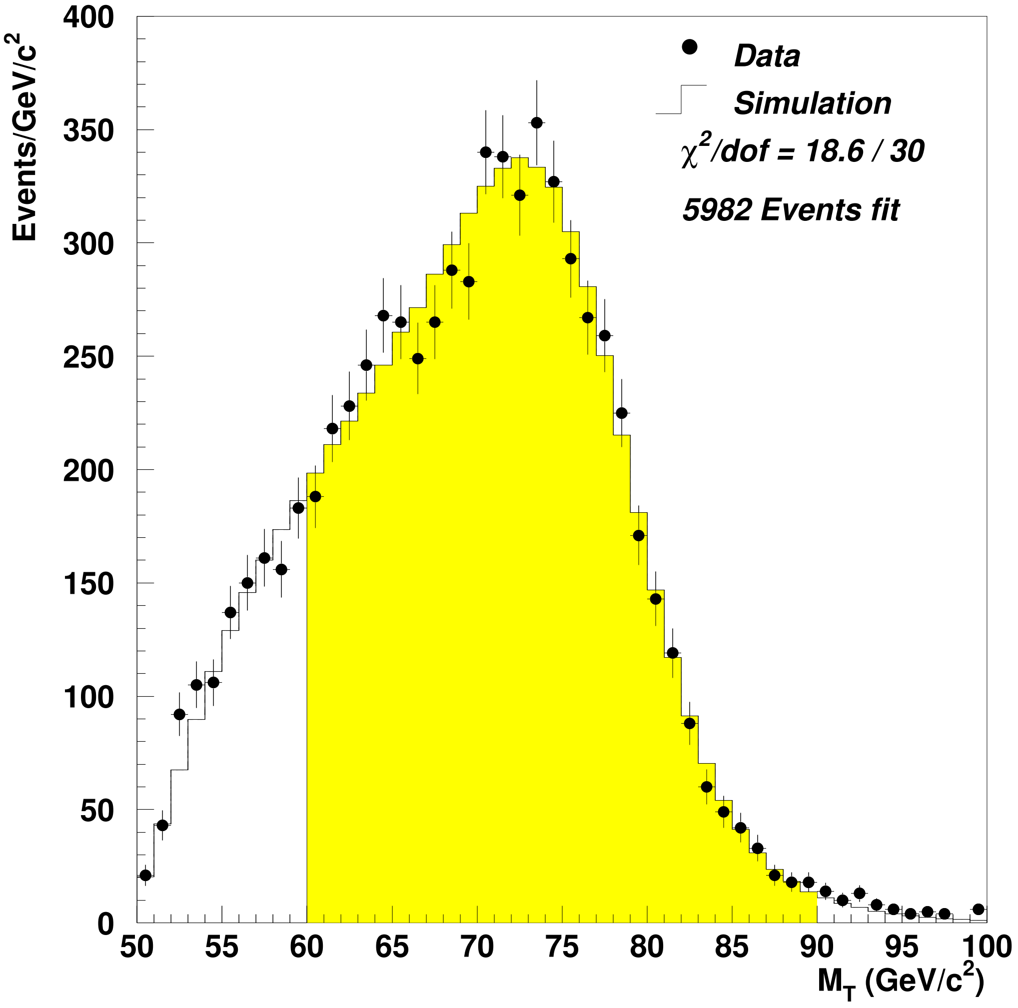
$Z \rightarrow ee \Rightarrow Z$ event in which one electron lost

$W \rightarrow \tau\nu \Rightarrow$ included in MC event generation

background	fraction (%)
QCD multi-jet	1.6 ± 0.8
$Z \rightarrow ee$	0.45 ± 0.04
$W \rightarrow \tau\nu \rightarrow e\nu\nu\nu$	1.1 ± 0.1

error due to backgrounds: $\sigma(M_W) = 35$ MeV

Fit to Transverse Mass of W



$$M_W = 80.330 \pm 0.140 \ \mathrm{GeV/c^2}$$

(DØ Preliminary)

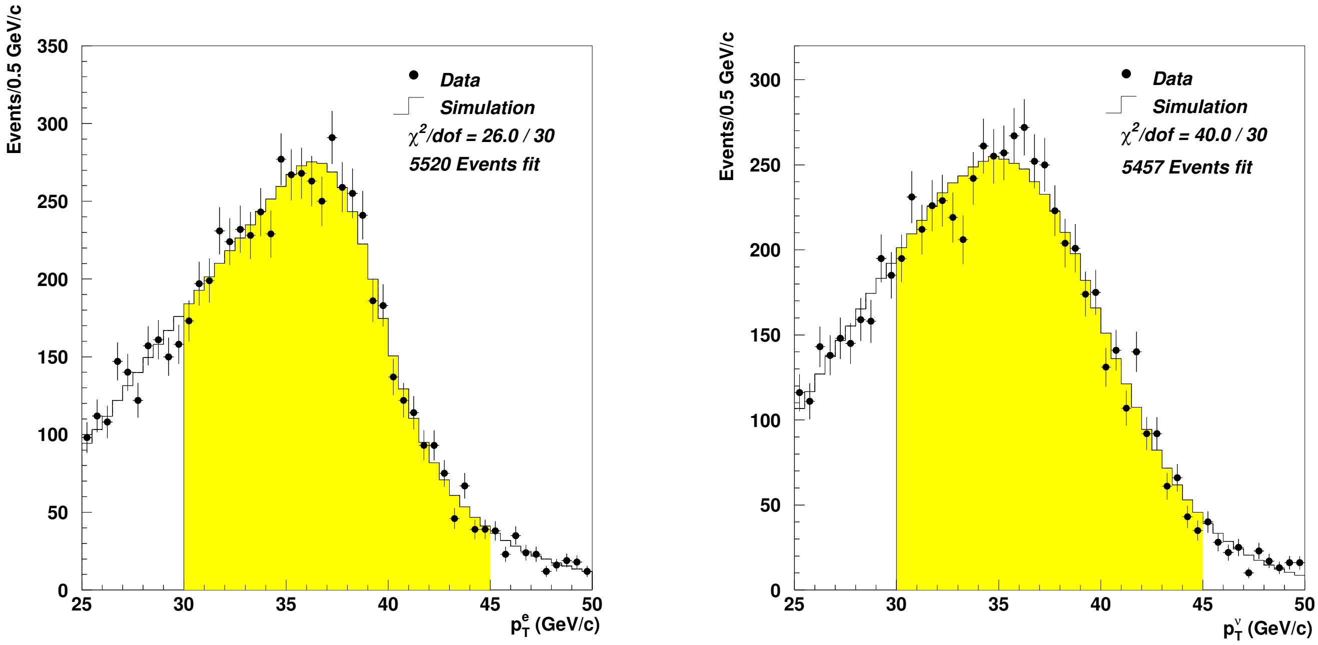
Errors on Fit to $M_T(W)$

Error	$\sigma(M_W)$ MeV
Statistical	140
EM energy scale	160
Systematic	165
EM energy resolution	70
hadronic energy scale	50
hadronic energy resolution	65
# min bias events	60
input $P_T(W)$ & pdf	65
electron angle determination	50
W-width	20
underlying event	35
non-uniform response	10
backgrounds	35
efficiencies	30
radiative decays	20
fit error	5
TOTAL	270

$$M_W = 80.330 \pm 0.140(stat.) \pm 0.160(scale) \pm 0.165(syst.) \ \mathrm{GeV/c^2}$$

(DØ Preliminary)

Fits to Transverse Momenta
$\rightarrow$ Consistency Check



$$\mathrm{P_T(e)fit} \Rightarrow M_W = 80.280 \pm 0.190(stat.)\ \mathrm{GeV/c^2}$$

$$\mathrm{P_T}(\nu)\mathrm{fit} \Rightarrow M_W = 80.040 \pm 0.260(stat.)\ \mathrm{GeV/c^2}$$

systematic error on $P_T(\nu)$ large

Conclusions

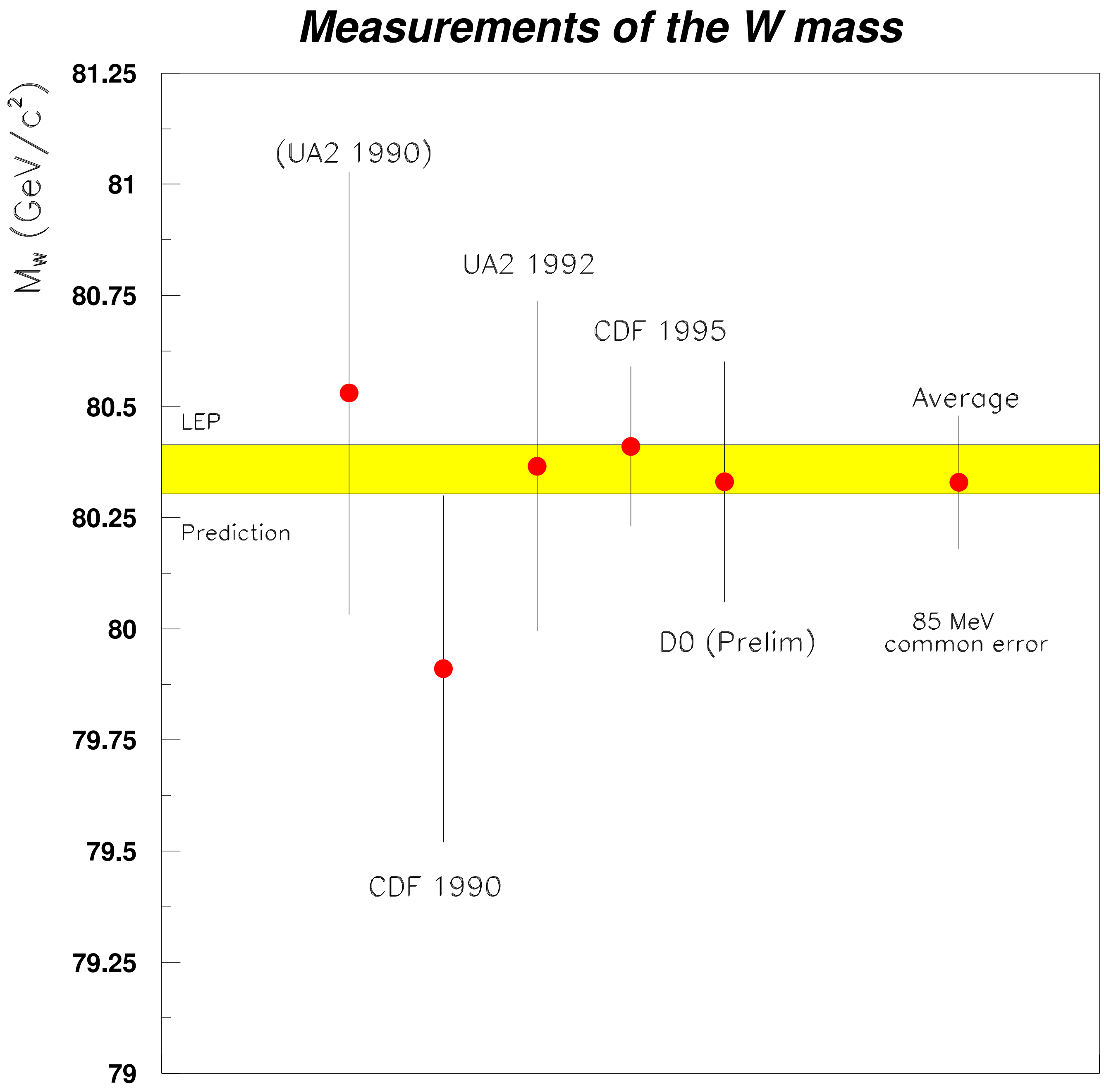
- have collected $\approx 100\ pb^{-1}$ of data in Runs 1A & 1B

- from analysis of partial data sample have
  $\Rightarrow$ measured W mass (DØ: e channel):

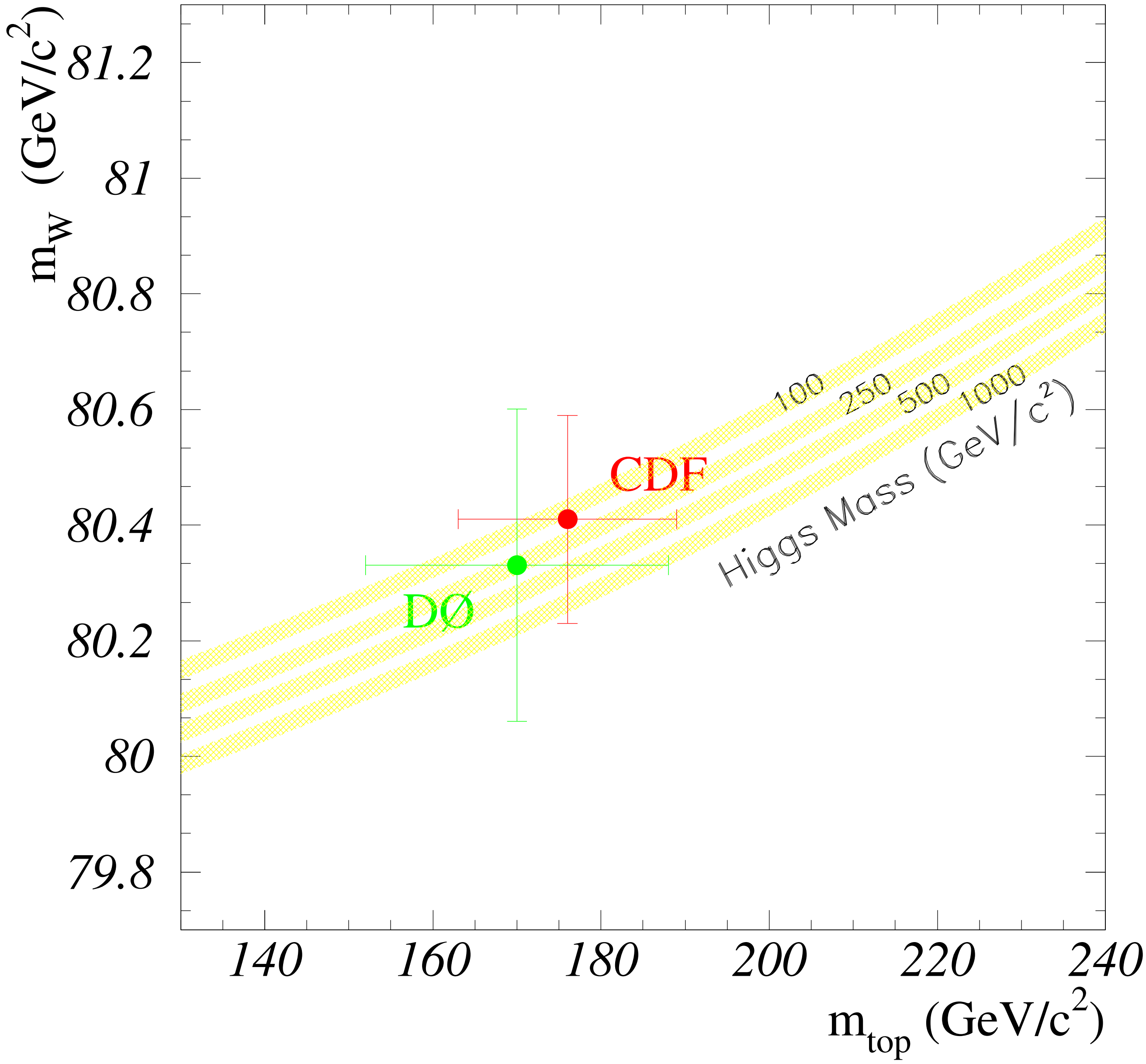
$$M_W = 80.330 \pm .270 \text{ GeV}$$

(Preliminary)

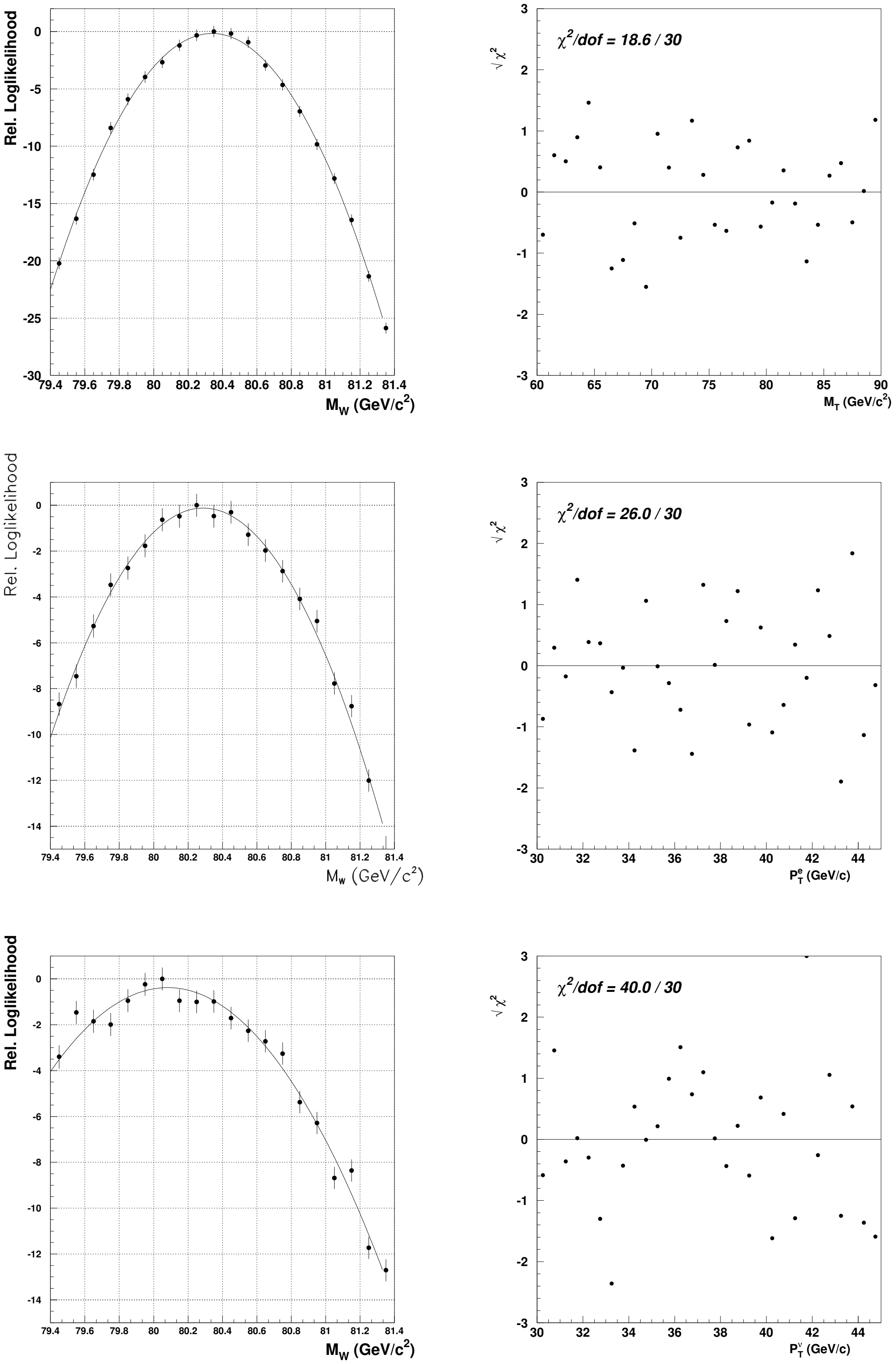
- analysis of the full data sample is in progress

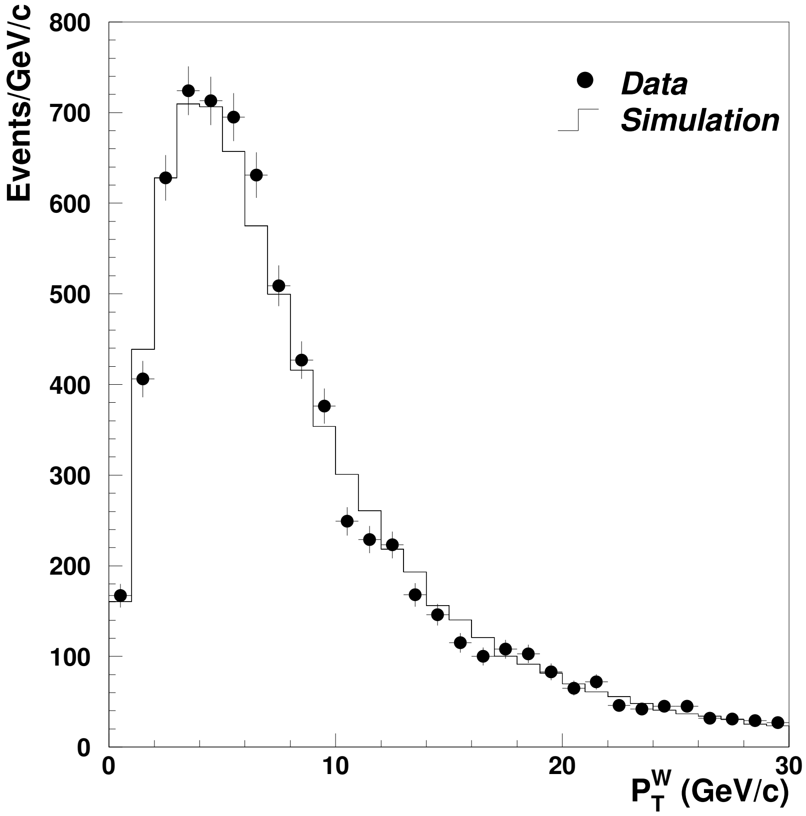


Measurements of the W mass
M_W (GeV/c^2)
81.25
81
80.75
80.5
80.25
80
79.75
79.5
79.25
79
(UA2 1990)
UA2 1992
CDF 1995
Average
LEP
Prediction
CDF 1990
D0 (Prelim)
85 MeV
common error

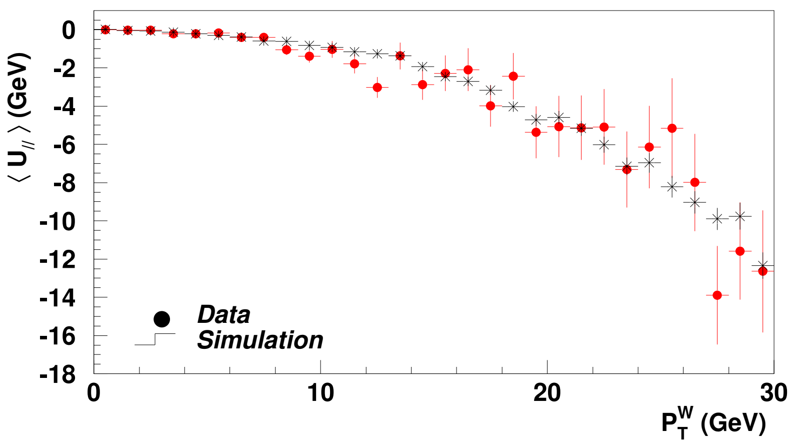


m_W (GeV/c^2)
81.2
81
80.8
80.6
80.4
80.2
80
79.8
140
160
180
200
220
240
m_{top} (GeV/c^2)
CDF
DØ
100
250
500
1000
Higgs Mass (GeV/c^2)

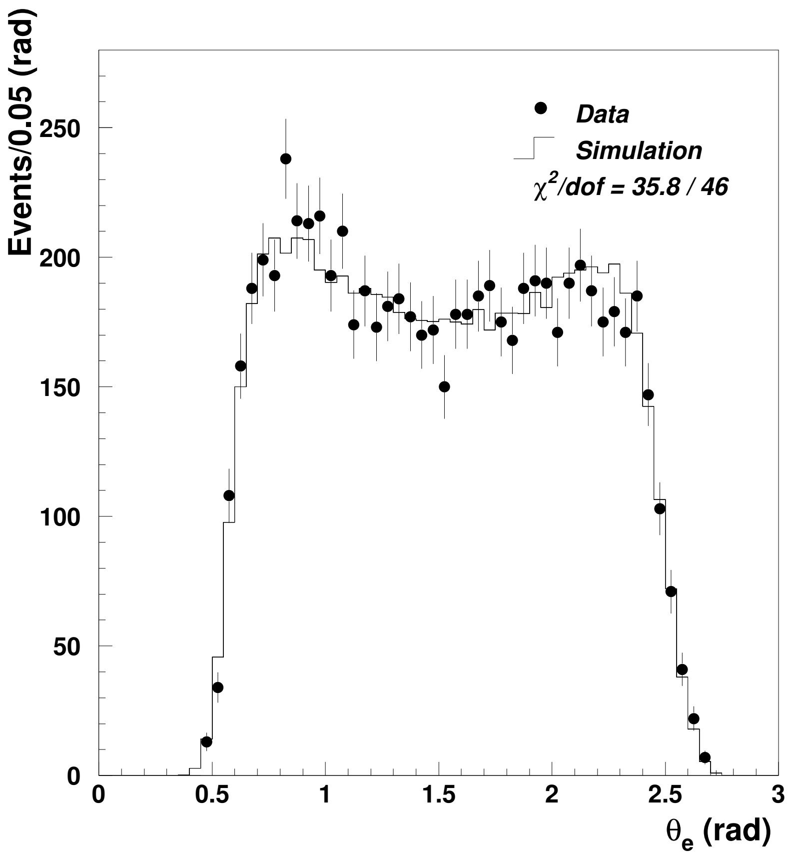

Rel. Loglikelihood
M_W (GeV/c^2)
χ^2/dof = 18.6 / 30
√χ^2
M_T (GeV/c^2)
Rel. Loglikelihood
M_W (GeV/c^2)
χ^2/dof = 26.0 / 30
√χ^2
P_T^e (GeV/c)
Rel. Loglikelihood
M_W (GeV/c^2)
χ^2/dof = 40.0 / 30
√χ^2
P_T^ν (GeV/c)



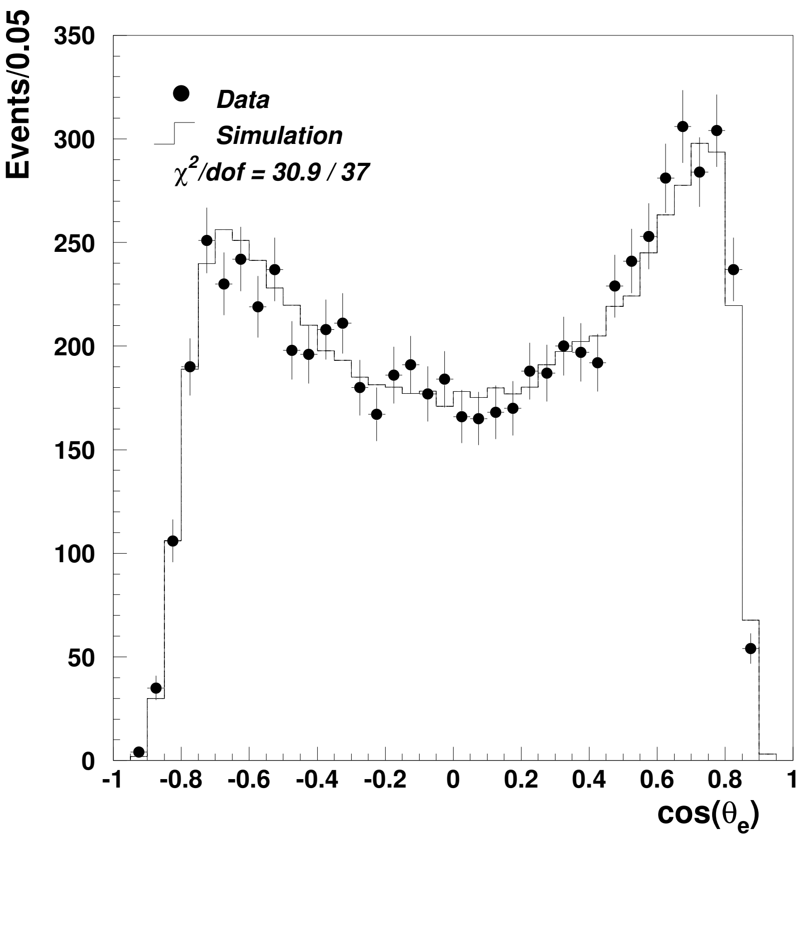
Events/GeV/c
800
700
600
500
400
300
200
100
0
0
10
20
30
P_T^W (GeV/c)
Data
Simulation



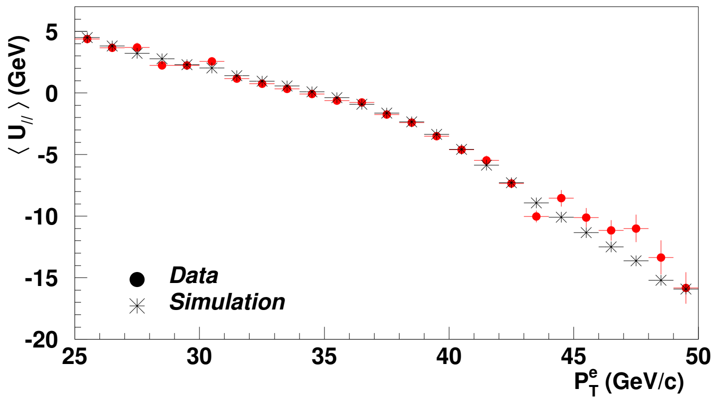
$\langle U_{//} \rangle$ (GeV)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
0
10
20
30
P_T^W (GeV)
Data
Simulation

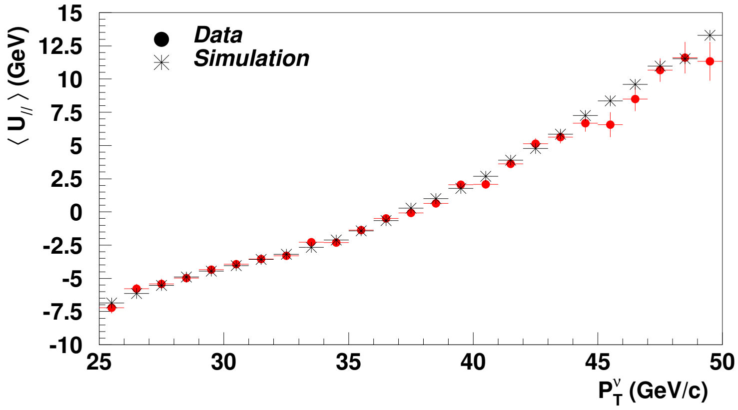


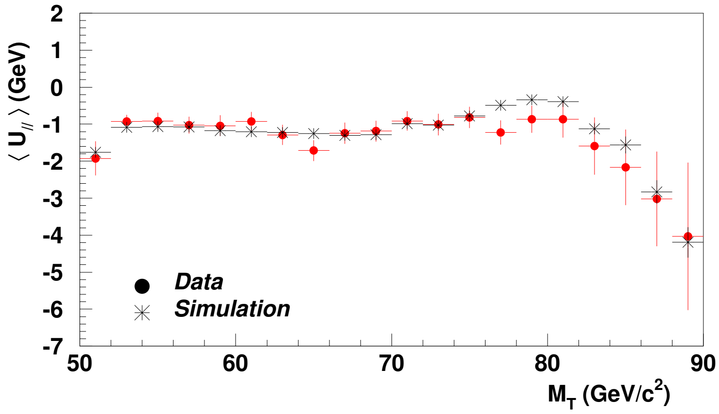
Data
Simulation
$\chi^2/dof = 35.8 / 46$
Events/0.05 (rad)
θ_e (rad)

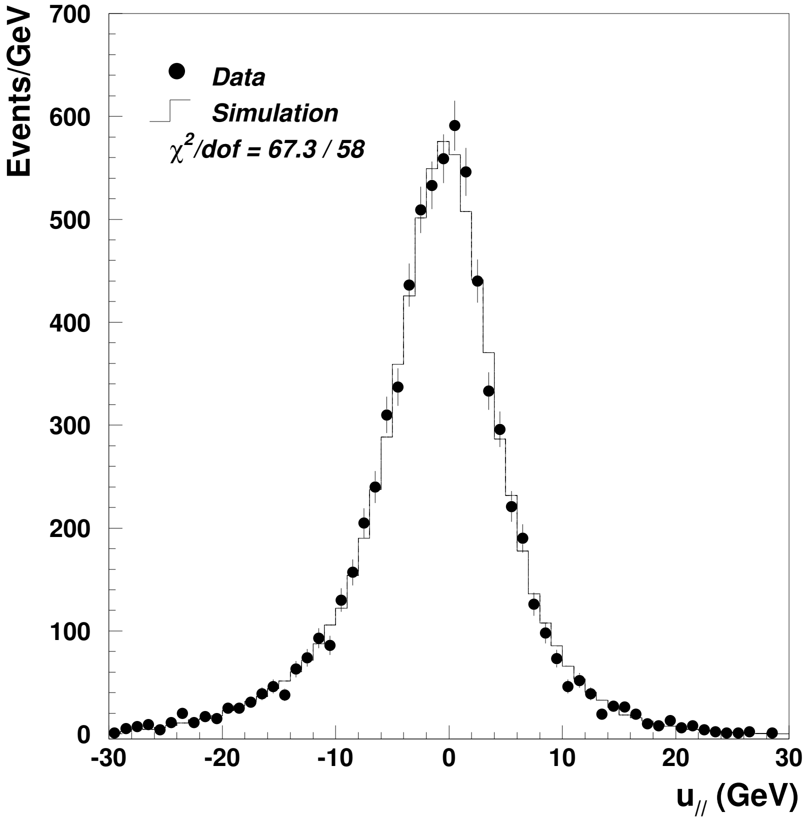


Data
Simulation
$\chi^2/dof = 30.9 / 37$
Events/0.05
$\cos(\theta_e)$

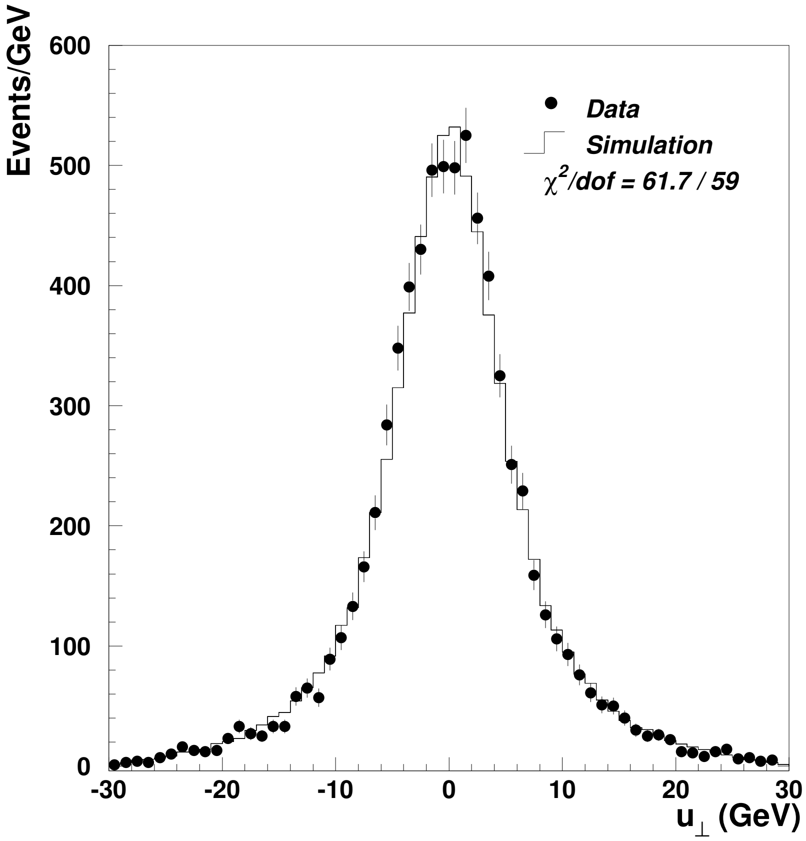

⟨ U// ⟩ (GeV)
Data
Simulation
P$_T^e$ (GeV/c)


⟨ U// ⟩ (GeV)
Data
Simulation
P$_T^\nu$ (GeV/c)

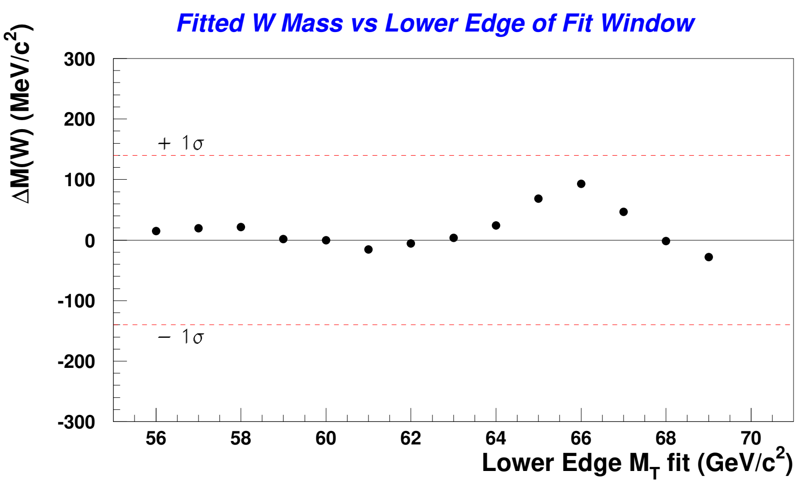

⟨ U// ⟩ (GeV)
Data
Simulation
M$_T$ (GeV/c^2)

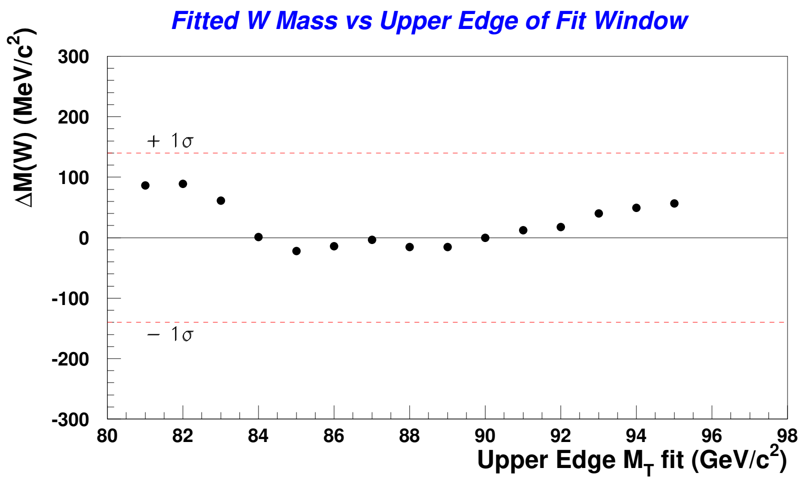


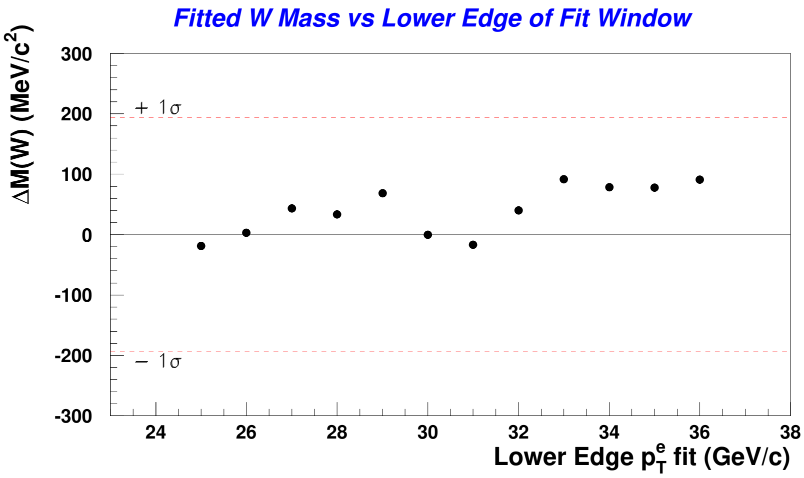
Events/GeV
Data
Simulation
$\chi^2/dof = 67.3 / 58$
0
100
200
300
400
500
600
700
-30
-20
-10
0
10
20
30
$u_{//}$ (GeV)

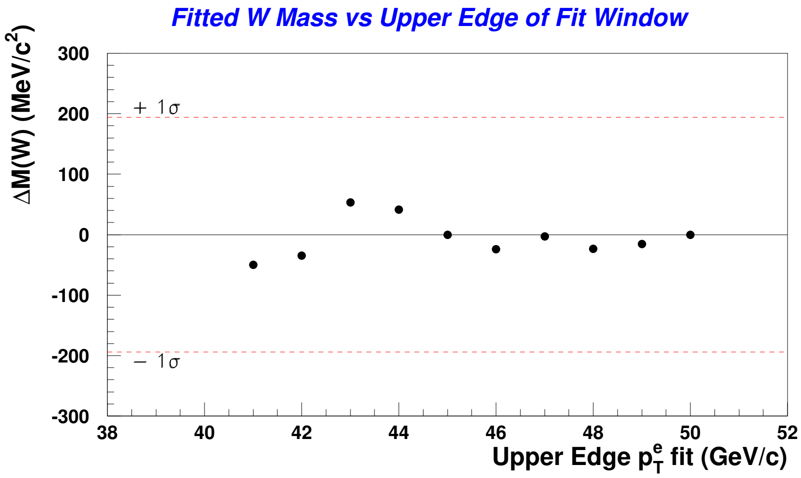


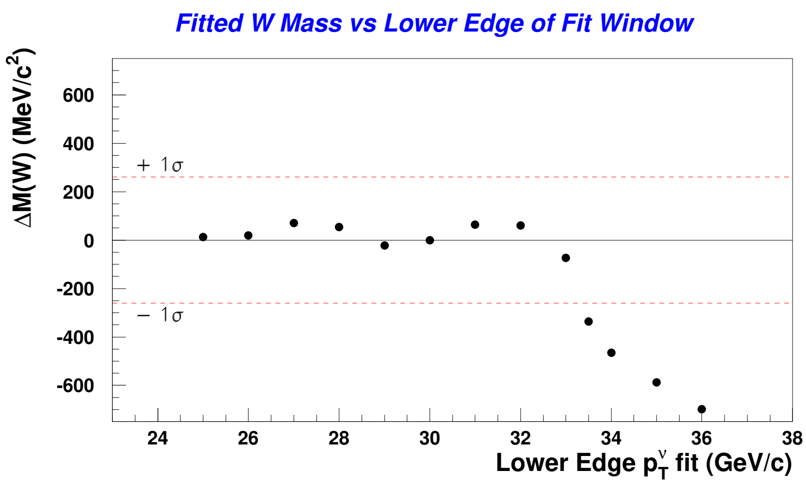
Events/GeV
Data
Simulation
$\chi^2/dof = 61.7 / 59$
0
100
200
300
400
500
600
-30
-20
-10
0
10
20
30
$u_\perp$ (GeV)


Fitted W Mass vs Lower Edge of Fit Window
ΔM(W) (MeV/c²)
300
200
100
0
-100
-200
-300
+ 1σ
− 1σ
56
58
60
62
64
66
68
70
Lower Edge M_T fit (GeV/c²)

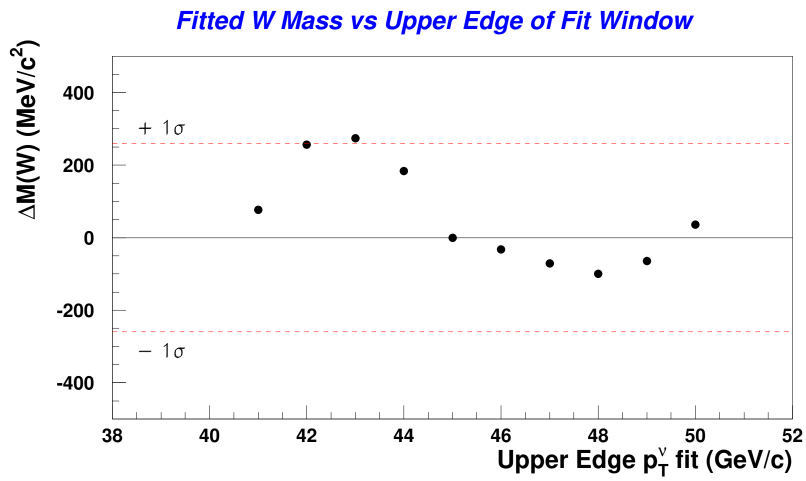

Fitted W Mass vs Upper Edge of Fit Window
ΔM(W) (MeV/c²)
300
200
100
0
-100
-200
-300
+ 1σ
− 1σ
80
82
84
86
88
90
92
94
96
98
Upper Edge M_T fit (GeV/c²)


Fitted W Mass vs Lower Edge of Fit Window
ΔM(W) (MeV/c^2)
+ 1σ
− 1σ
300
200
100
0
-100
-200
-300
24
26
28
30
32
34
36
38
Lower Edge p_T^e fit (GeV/c)

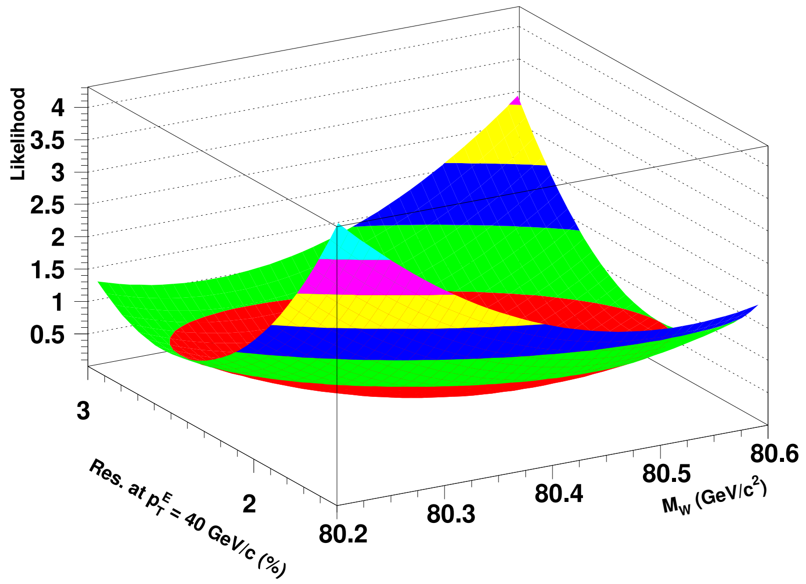

Fitted W Mass vs Upper Edge of Fit Window
ΔM(W) (MeV/c^2)
+ 1σ
− 1σ
300
200
100
0
-100
-200
-300
38
40
42
44
46
48
50
52
Upper Edge p_T^e fit (GeV/c)



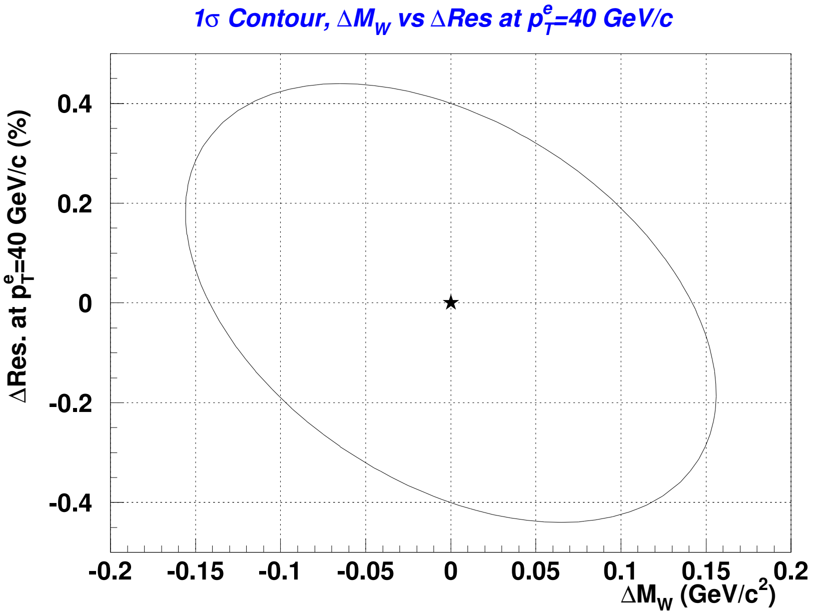
Fitted W Mass vs Lower Edge of Fit Window
ΔM(W) (MeV/c²)
600
400
200
0
-200
-400
-600
+ 1σ
− 1σ
24
26
28
30
32
34
36
38
Lower Edge p_T^ν fit (GeV/c)



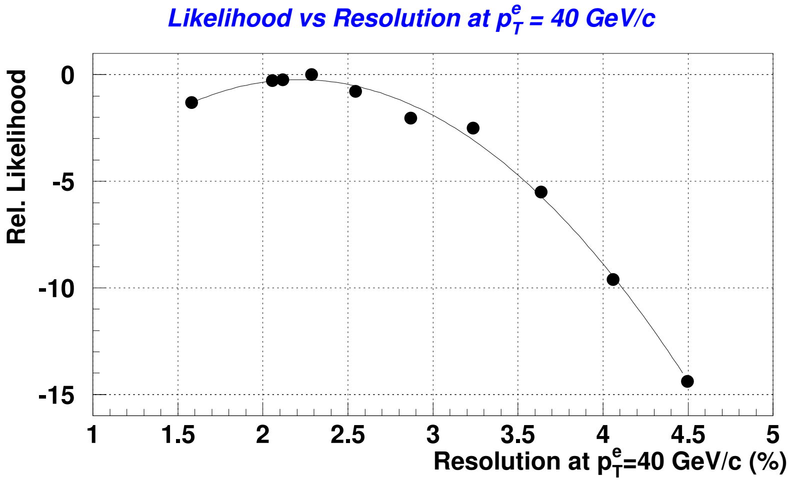
Fitted W Mass vs Upper Edge of Fit Window
ΔM(W) (MeV/c²)
400
200
0
-200
-400
+ 1σ
− 1σ
38
40
42
44
46
48
50
52
Upper Edge p_T^ν fit (GeV/c)

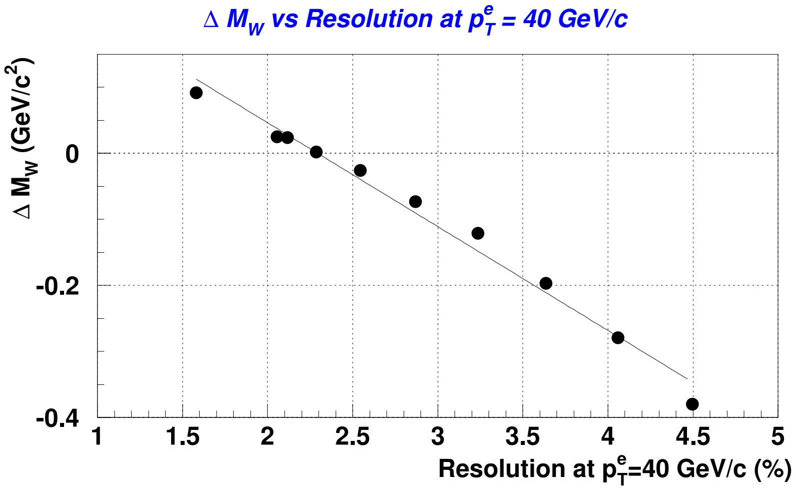


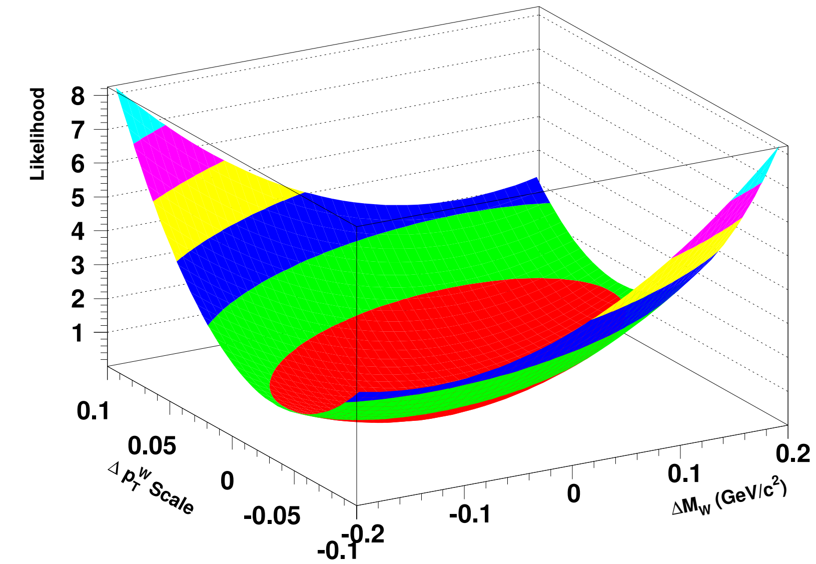
Likelihood
4
3.5
3
2.5
2
1.5
1
0.5
3
2
Res. at p_T^E = 40 GeV/c (%)
80.2
80.3
80.4
80.5
80.6
M_W (GeV/c^2)

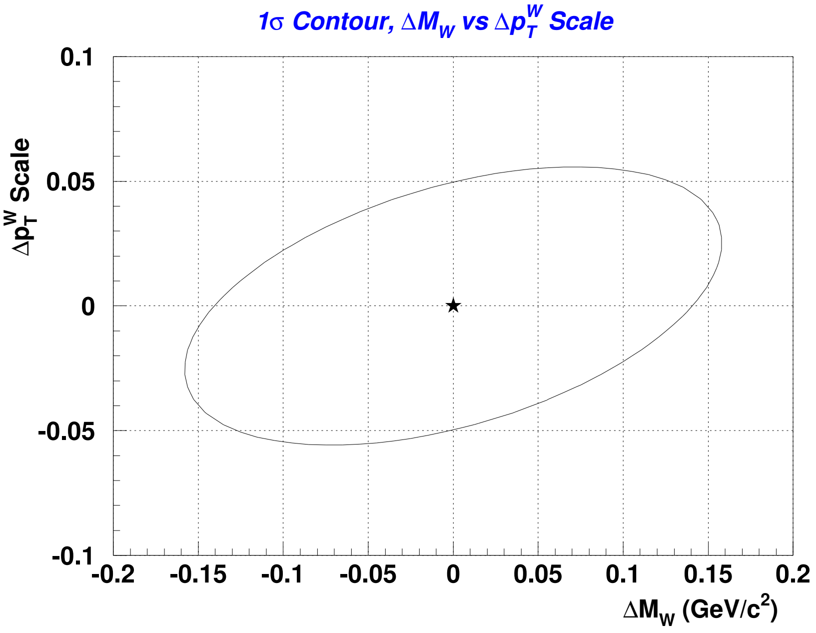


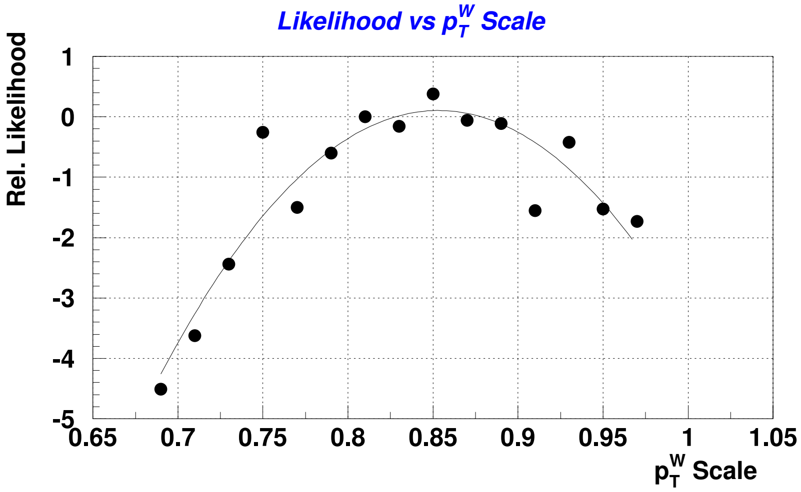
1σ Contour, ΔM_W vs ΔRes at p_T^e=40 GeV/c
ΔRes. at p_T^e=40 GeV/c (%)
0.4
0.2
0
-0.2
-0.4
-0.2
-0.15
-0.1
-0.05
0
0.05
0.1
0.15
0.2
ΔM_W (GeV/c^2)

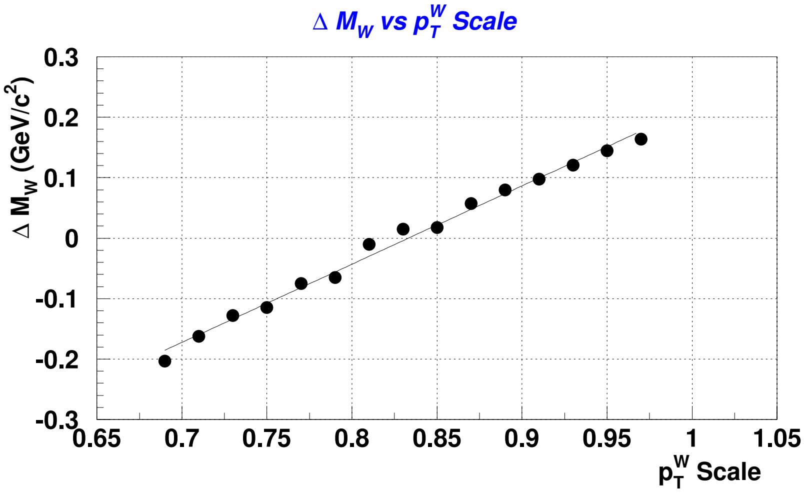

Likelihood vs Resolution at p_T^e = 40 GeV/c
Rel. Likelihood
0
-5
-10
-15
1
1.5
2
2.5
3
3.5
4
4.5
5
Resolution at p_T^e=40 GeV/c (%)


Δ M_W vs Resolution at p_T^e = 40 GeV/c
Δ M_W (GeV/c^2)
0
-0.2
-0.4
1
1.5
2
2.5
3
3.5
4
4.5
5
Resolution at p_T^e=40 GeV/c (%)


Likelihood
8
7
6
5
4
3
2
1
0.1
0.05
0
-0.05
-0.1
Δp_T^W Scale
-0.2
-0.1
0
0.1
0.2
ΔM_W (GeV/c^2)


1σ Contour, ΔM_W vs Δp_T^W Scale
0.1
0.05
0
-0.05
-0.1
Δp_T^W Scale
-0.2
-0.15
-0.1
-0.05
0
0.05
0.1
0.15
0.2
ΔM_W (GeV/c^2)


Likelihood vs p_T^W Scale
Rel. Likelihood
1
0
-1
-2
-3
-4
-5
0.65
0.7
0.75
0.8
0.85
0.9
0.95
1
1.05
p_T^W Scale


ΔM_W vs p_T^W Scale
ΔM_W (GeV/c^2)
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
0.65
0.7
0.75
0.8
0.85
0.9
0.95
1
1.05
p_T^W Scale