Direct Measurement of the W Boson Width in $p\bar{p}$ Collisions at $\sqrt{s} = 1.8$ TeV

CDF Collaboration

To be submitted to PRL

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$\Gamma(W)$ in the Standard Model

At tree level,

$$\Gamma(W \to \ell\nu) = \frac{g^2 M_W}{48\pi}$$

Using $G_F/\sqrt{2} = g^2/8M_W^2$, we can rewrite

$$\Gamma(W \to \ell\nu) = \frac{G_F M_W^3}{6\pi\sqrt{2}} \tag{1}$$

Rosner et al. have shown that (1) has only small ($< \frac{1}{2}\%$) SM radiative corrections when measured G_F,M_W are used

Multiplying by $1/B(W \to \ell\nu) =$

$$3 + 6(1 + \alpha_s(M_W^2)/\pi + \mathcal{O}(\alpha_s^2))$$

gives

$$\Gamma(W) = 2.093 \pm 0.002 \text{ GeV}$$

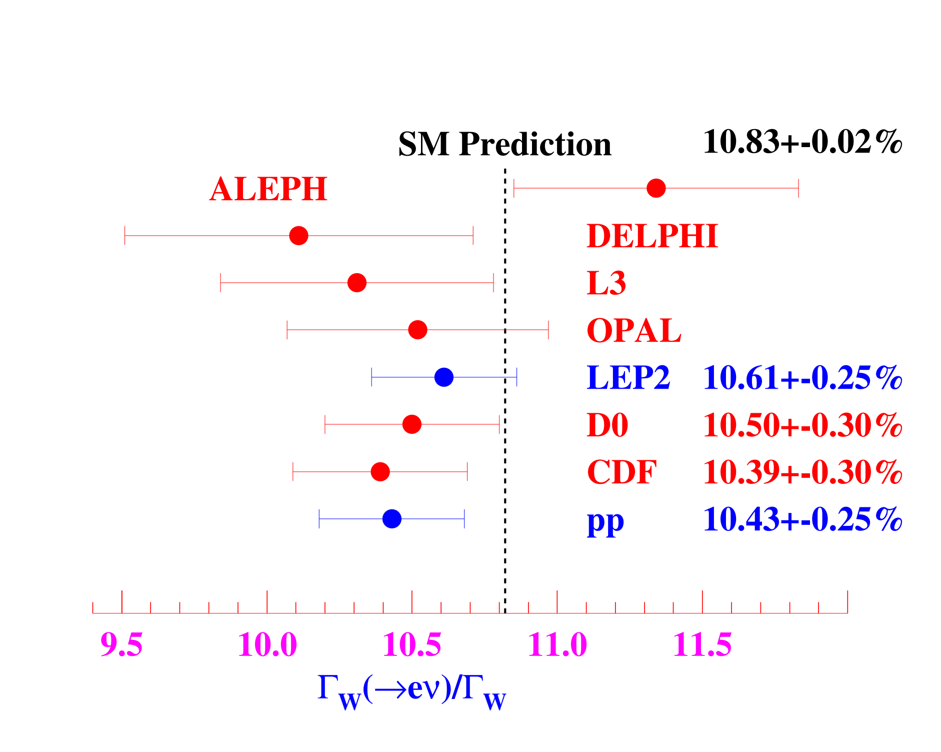
What could change $\Gamma(W)$?

- **New decay channel**
- **Modify $W \to f_1\overline{f_2}$ coupling without affecting τ_μ (unlikely)**
- **In this particular analysis, a new, heavy, W-like particle would change the measured result**

Branching Ratio Method

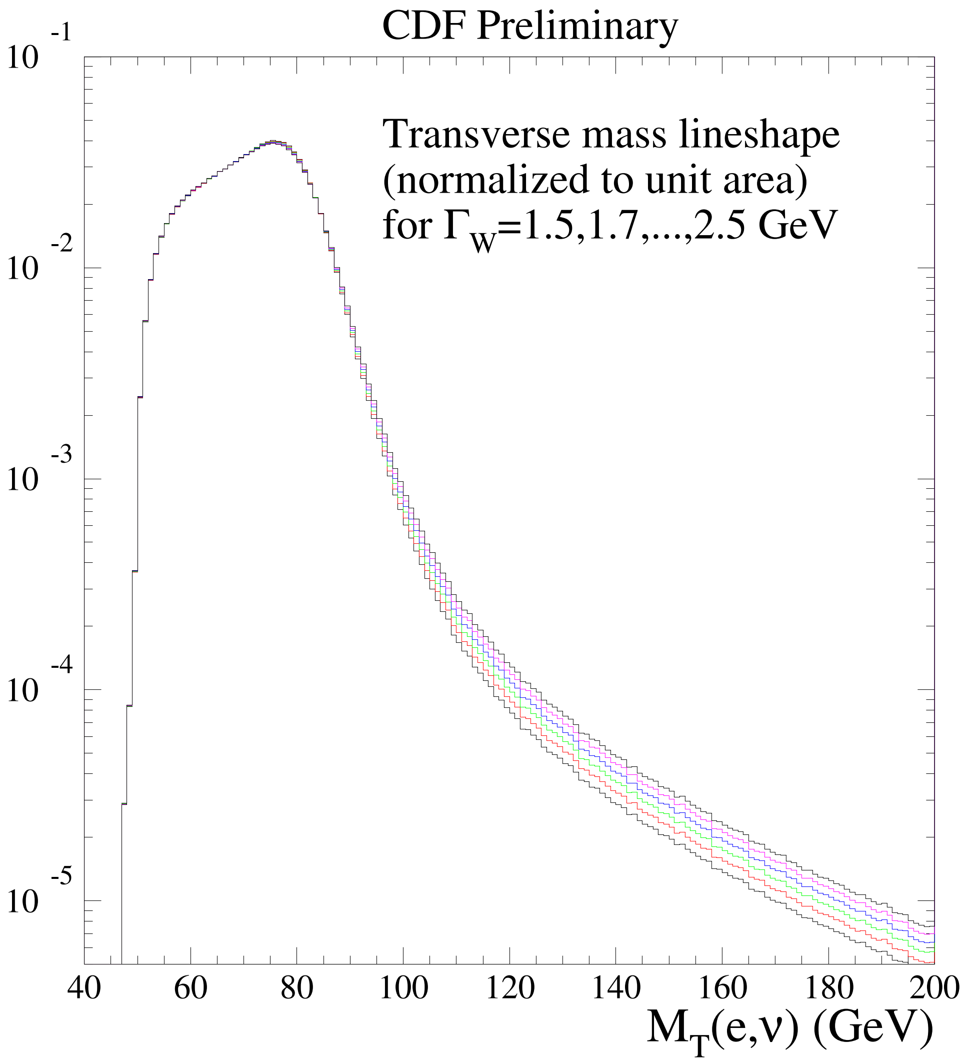
Currently, the most precise way to measure $\Gamma(W)$ is to infer it from $B(W \to \ell\nu)$, using SM $\Gamma(W \to \ell\nu)$

- True for both Tevatron and LEP2
- $\Delta\Gamma \approx 50$ MeV (CDF+DØ $W \to e\nu/Z \to ee$)
- $\Delta\Gamma \approx 50$ MeV (LEP2 $W \to e\nu$)
- $\Delta\Gamma \approx 25$ MeV (LEP2 $W \to \ell\nu$)
- best individual direct measurements ~ 300 MeV



But note that Tevatron $B(W \to e\nu)$ measurement is already systematics dominated: total uncertainty is 2.5%, while statistics + uncorrelated (between CDF and DØ) systematics are only 1.4%

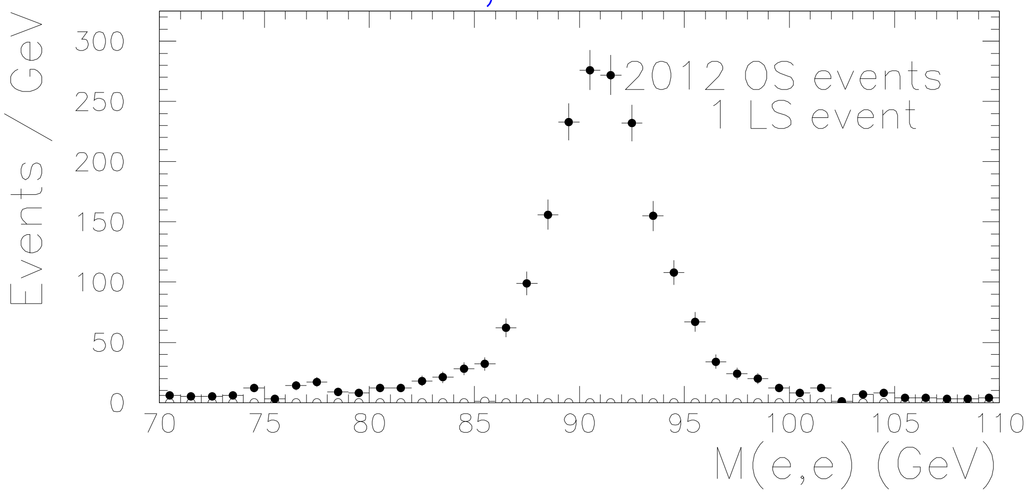
Lineshape-Based $\Gamma(W)$ Measurement



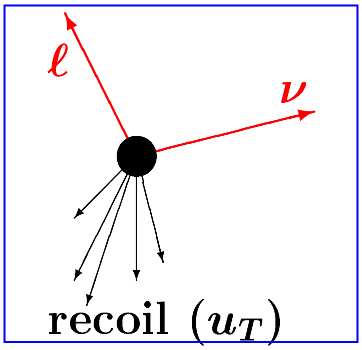
- **High-M_T events are mostly off-shell, since Breit-Wigner falls much more slowly than resolution**
- **Basically, extract width by comparing off-shell and on-shell W production**
- **Large overlap with M_W analysis**
- **Less precise than B.R. method, but still statistics-limited**
- **CDF Run Ia $W \to e\nu$: $\Delta\Gamma = 320$ MeV**
- **LEP2 lineshape-based analyses: 375 MeV best single expt so far**

Event Selection

Nearly identical to W mass event selection: well-measured events, low BG



- **Leptonic decays $W \to e\nu$, $W \to \mu\nu$**
- **Transverse momentum balance $\Rightarrow P_T^\ell$, P_T^ν, M_T**
- **$P_T^\ell = E_T^e$ (calorimeter) or p_T^μ (spectrometer)**
- **$\vec{u}_T = \Sigma_{\text{cell}} E_{\text{cell}} \sin\theta_{\text{cell}} (\cos\phi_{\text{cell}}, \sin\phi_{\text{cell}})$, excluding ℓ**
- **Infer $\vec{P}_T^\nu = -(\vec{P}_T^\ell + \vec{u}_T)$**
- **$M_T^W = \sqrt{2 P_T^\ell P_T^\nu (1 - \cos\Delta\phi_{\ell,\nu})}$**
- **$P_T^\ell > 25$, $|\eta_\ell| < 1$, $u_T < 20$**
- **u_T cut reduces BG, improves P_T^ν resolution**



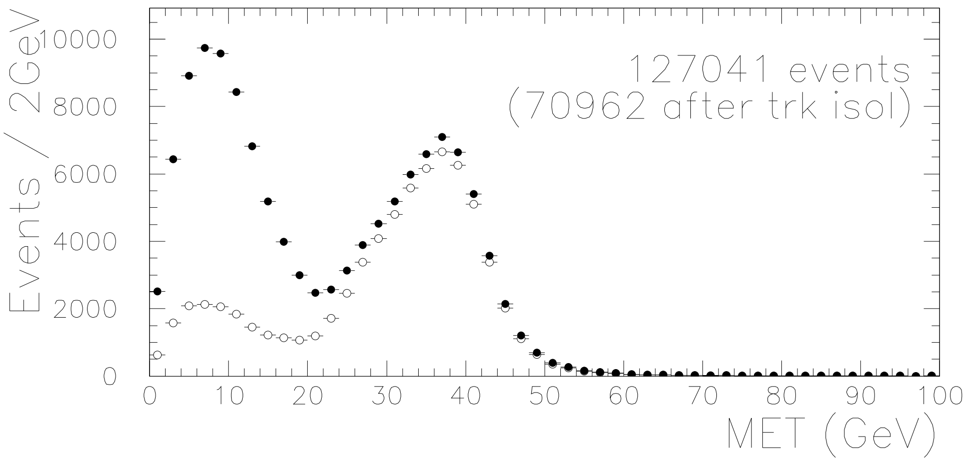
	W	Z
e	49844	2012
μ	21806	1840

$W \to e\nu$ Selection—Details

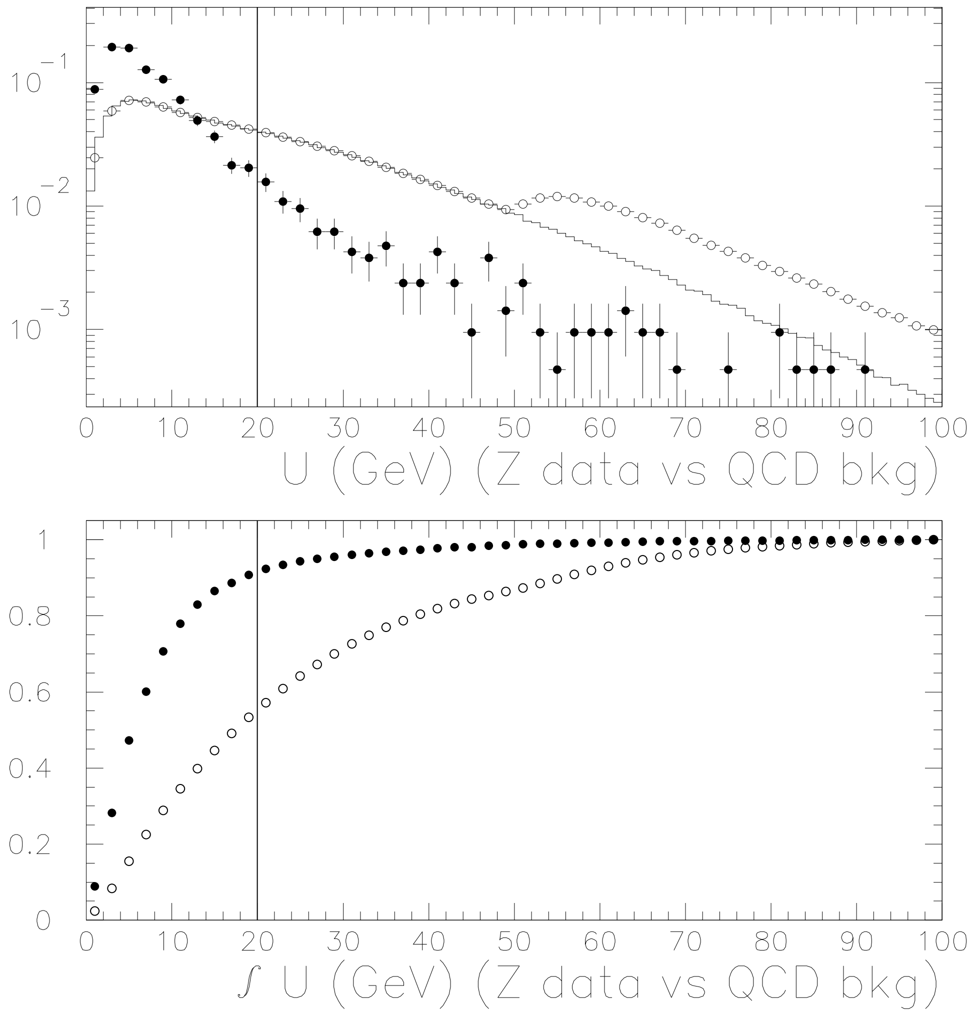
	Cut	# pass	% fail	if last
A	Run Ib W central electron dataset	232909	—	—
B	No known detector problems	225402	3.2	2.9
C	Passes CEM $W \to e\nu$ trigger	225051	0.16	0.0
D	Central electron found by reconstruction software	225048	0.001	—
E	Electron in CEM fiducial volume	201995	10.2	8.2
F	$E_T > 25$ GeV	187249	7.3	4.1
G	Electron track $\mathbf{P_T^{BC}} > 15$ GeV	118870	36.5	4.2
H	z-vertex in fiducial region	105338	11.4	5.6
I	CTC fiducial volume	103030	2.2	2.5
J	$\not{\mathbf{E}}_\mathbf{T} > 25$ GeV	70143	31.9	5.1
K	$u < 20$ GeV	58182	17.1	8.3
L	CTC impact parameter < 0.5 cm	57900	0.5	0.2
M	$Z \to ee$ removal	57201	1.2	1.2
N	$E_{\rm hadron}/E_{\rm EM}$ consistent with electron	55741	2.6	1.0
O	Track/CEM position match (z-view)	54813	1.7	1.0
P	Transverse shower shape (z-view)	53643	2.1	1.4
Q	Electron track is isolated	49851	7.1	7.1
R	$M_T < 200$ GeV	49843	0.02	0.02

Cut	data % fail	% predict	how
CEM fiducial volume	8.2	6.7	simulation
$E_T > 25$ GeV	4.1	—	Figure ??
$p_T^{\rm BC} > 15$ GeV	4.2	3.8	simulation
z-vertex fiducial volume	5.6	2.4	simulation
CTC fiducial volume	2.5	2.6	simulation
$\not{\mathbf{E}}_\mathbf{T} > 25$ GeV	5.0	—	Figure ??
$u < 20$ GeV	8.3	8.2	Z data+sim+bkg
CTC impact parameter	0.2	0.2	Z data
Z removal	1.2	1.1	simulation
$\mathbf{E}_{\rm hadron}/\mathbf{E}_{\rm EM}$	1.0	1.3	Z data
$\mathbf{\Delta z}_{\rm track,CES}$	1.0	0.1	Z data
transverse shower profile	1.4	1.5	Z data
track isolation cut	7.1	7.3	W data+sim+bkg

$W \to e\nu$ Selection—More Details



(Motivating track isolation cut)



(Motivating $u < 20$ cut)

$W \to \mu\nu$ Selection—Details

Cut	**# pass**
Event passes one of the high-p_T muon triggers	164510
Detector at full operational capacity	157271
$\lvert z_{\mathrm{vertex}} \rvert < 60.0$ cm	145795
$\lvert z_\mu \rvert < 60.0$ cm	145485
$E_{\mathrm{CEM}} < 2$ GeV	110727
$E_{\mathrm{CHA}} < 6$ GeV	110070
Track in CTC matches a hit in muon detector	98254
$p_T^\mu > 25$ GeV/c	46452
$p_T^\nu > 25$ GeV/c	34430
$\lvert \mathbf{u} \rvert < \mathbf{20}$ GeV	31908
Number of hits on stereo layers ≥ 12	26156
$z_\mu(r = 130\text{ cm})\rvert < 150.0$ cm	25913
$Z \to \mu^+\mu^-$ events removed	23482
Cosmic events are removed	22959
Impact parameter $\lvert D_0 \rvert < 0.15$ cm	21824
$0 < M_T < \infty$ GeV	21824

Backgrounds

Sources are largely the same for e and μ:

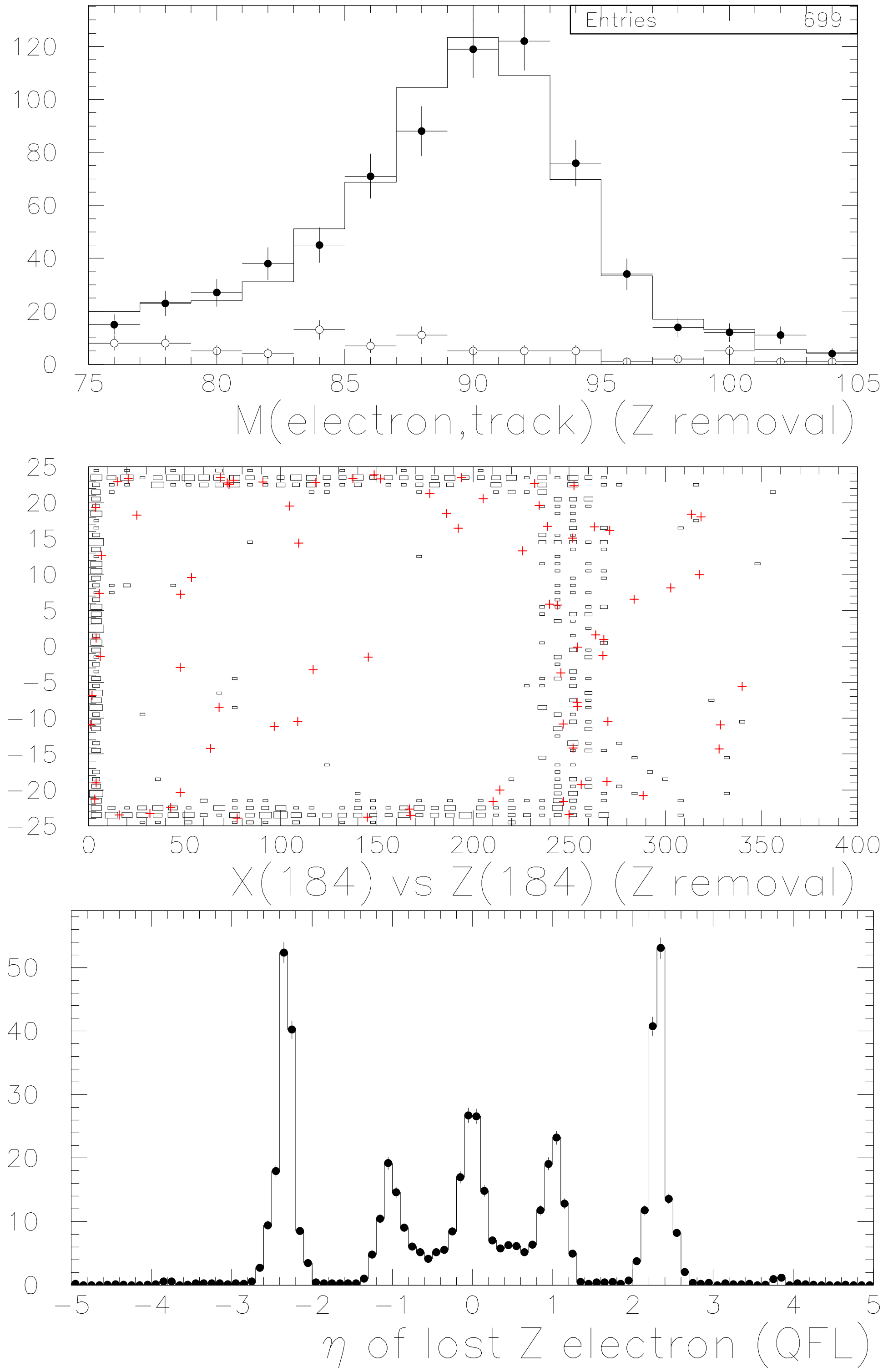
- $W \to \tau\nu \to \ell\nu\nu\nu$
- $Z \to \ell\not\ell$
- **Multijets from QCD processes**
- **Cosmic rays (e negligible)**

Use MC normalized to $W \to \ell\nu$ or $Z \to \ell\ell$ to predict τ and Z BG

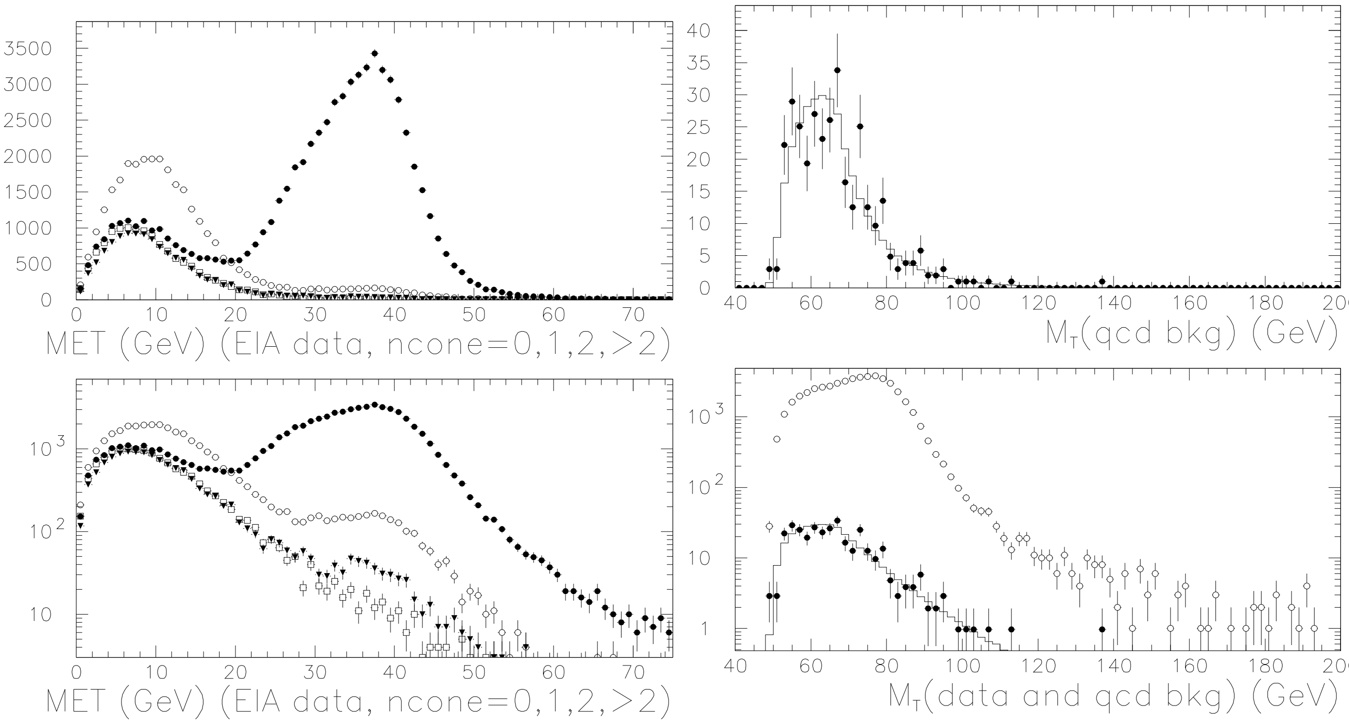
Use non-isolated lepton candidates to estimate QCD BG

Use large-impact-parameter e, μ to estimate cosmic BG

Backgrounds—Lost $Z \to ee$

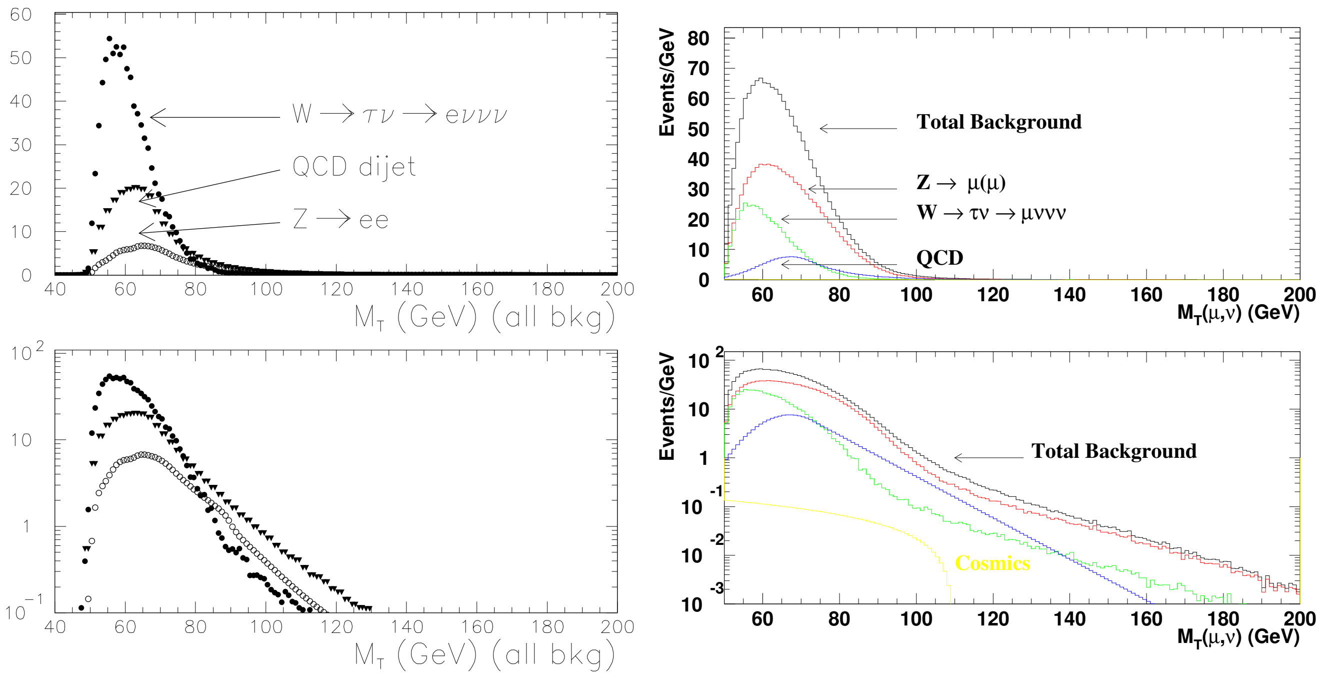


Backgrounds—QCD Multijet



- e analysis uses $N_{\text{cone}} > 2$ sample as "pure BG," and scales it based on N_{cone} distribution of low $\not{E}_T$ region to estimate total BG beneath W signal
- μ analysis does a similar extrapolation, but between isolation and $\Delta\phi(\mu, \text{jet})$ instead of between isolation and $\not{E}_T$

Backgrounds—Summary



Channel	$W \to e\nu$		$W \to \mu\nu$	
M_T region	40–200	100–200	40–200	100–200
Events	49844	438	21806	196
$W \to \tau\nu$	870 ± 100	4 ± 2	440 ± 20	2 ± 2
$Z \to ll$	170 ± 85	5 ± 3	760 ± 30	5 ± 2
QCD multijets	450 ± 110	10 ± 4	175 ± 15	4 ± 3
cosmic rays	0	0	4 ± 2	0
Backgrounds	1490 ± 170	19 ± 5	1379 ± 40	11 ± 4

Event Modeling

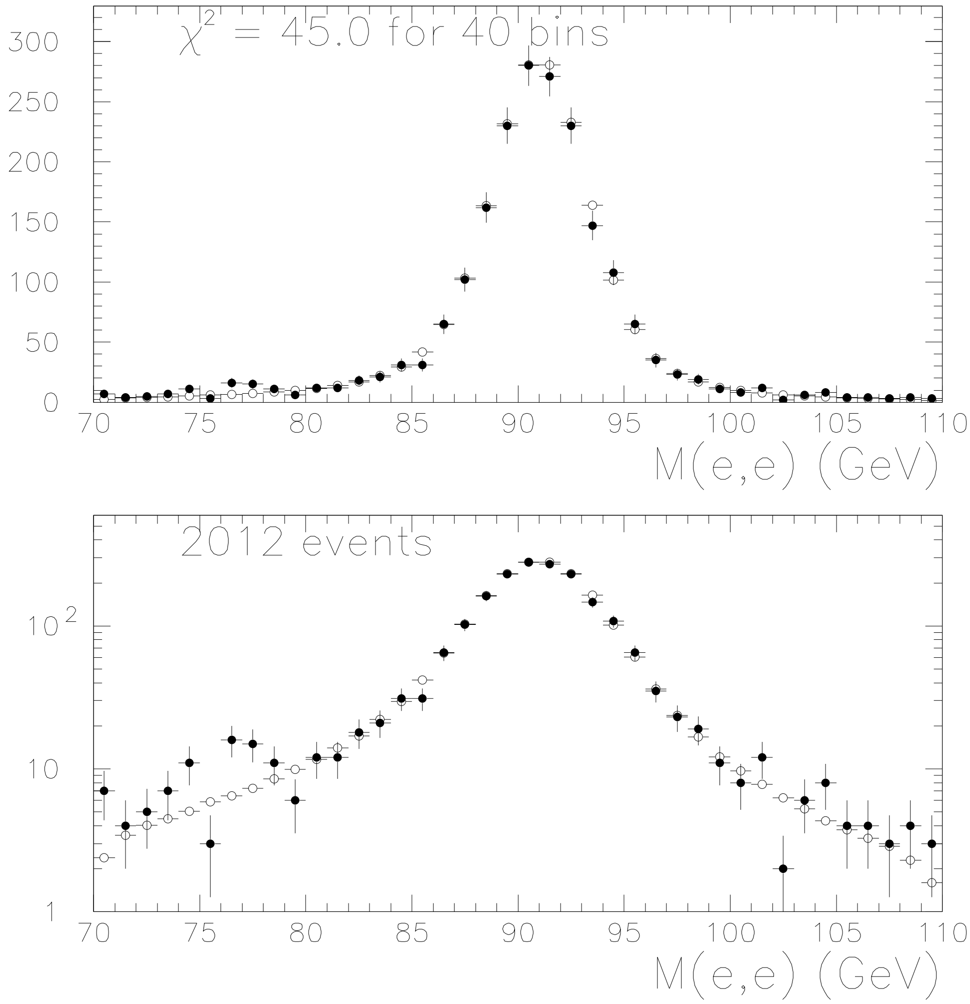
To simulate W signal lineshape, we need to model W production/decay, P_T^ℓ measurement, and u measurement

Since the W and Z bosons share a common production mechanism and are close in mass, $Z \to \ell\ell$ events (which are fully reconstructed) are used extensively to model $W \to \ell\nu$ events

Specifically, we fit

- **E, p scales and resolutions**
- **W, Z p_T spectra**
- **u model**

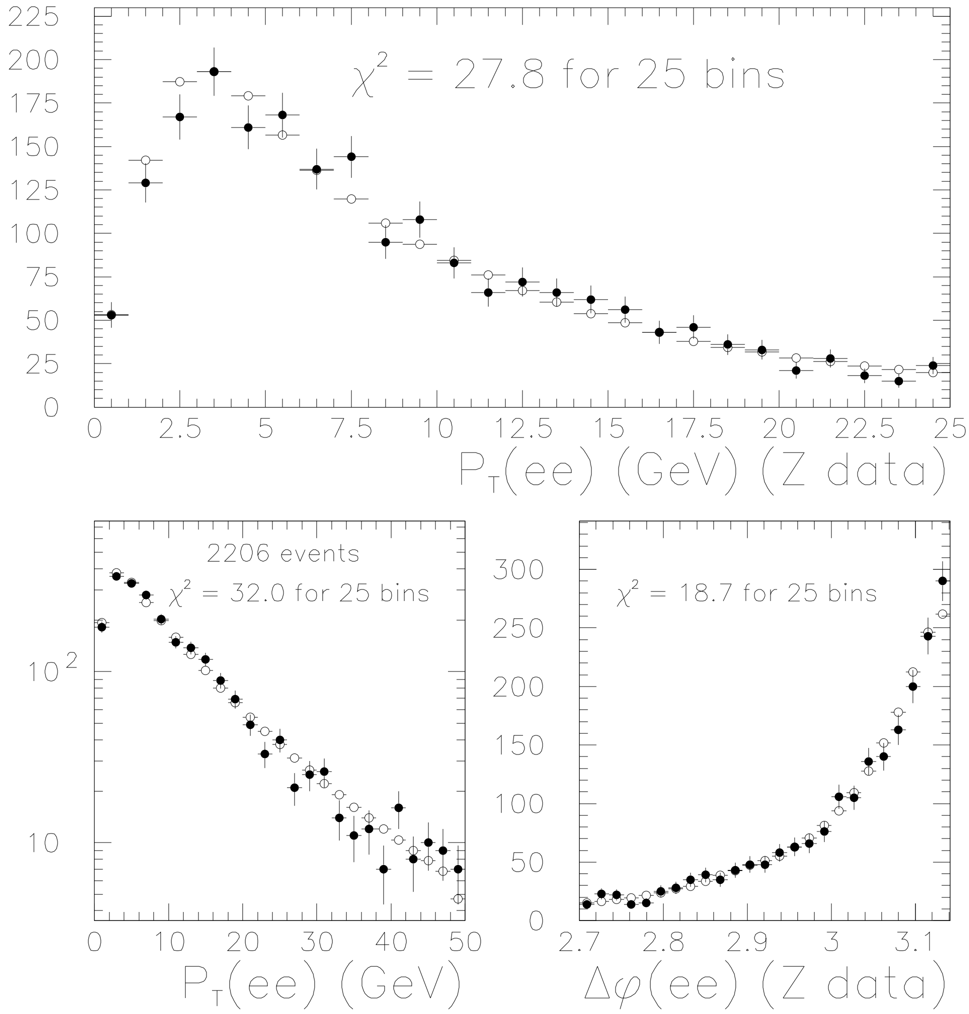
Lepton Scales & Resolutions



For CEM (e), extract $E \to E \times (0.99941 \pm 0.00075$ (stat)), $\kappa = (1.5 \pm 0.3$ (stat+syst))%; use 0.1% (stat+syst) scale error for consistency with M_W analysis

For CTC (μ), fit $p_T \to p_T \times (1.00085 \pm 0.00106$ (stat+syst)), $\delta p_T / p_T^2 = (0.091 \pm 0.004$ (stat))%/GeV

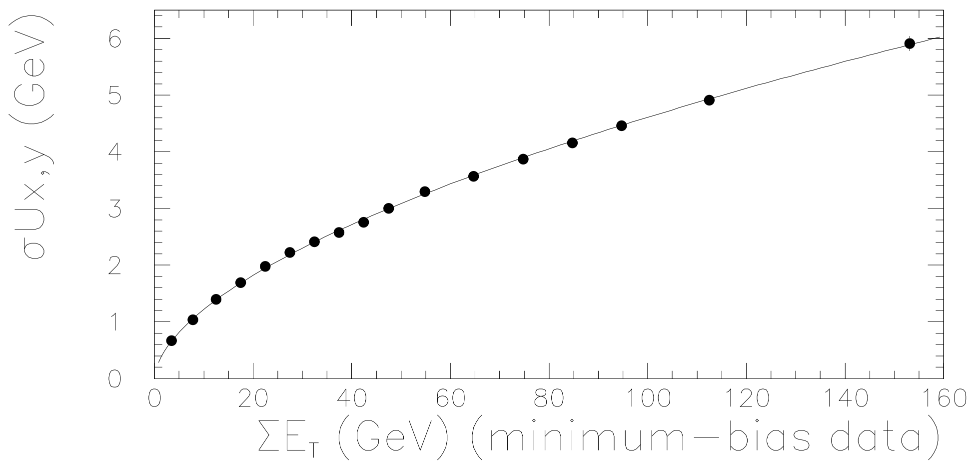
W & Z P_T Spectra



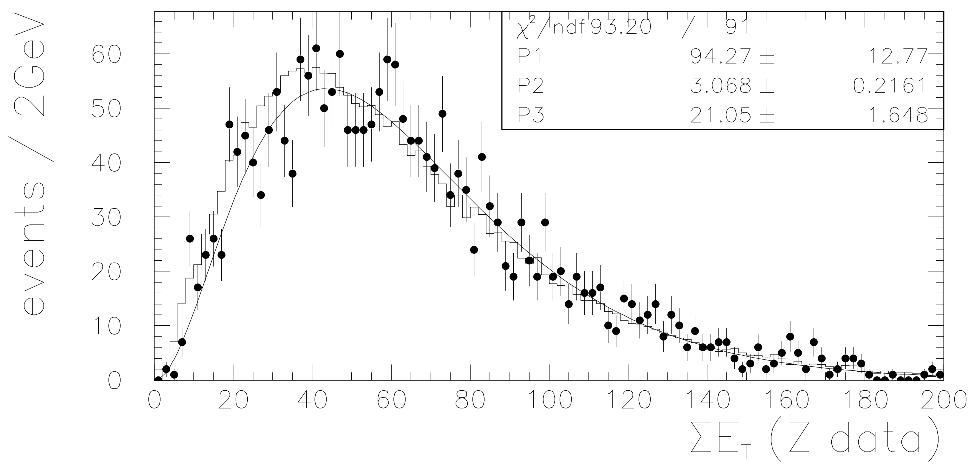
Fit $Z \to \ell\ell$ P_T spectrum, then use theory to relate W and Z spectra

For historical reasons, e analysis fit to Ladinsky-Yuan model, while μ analysis fit to purely empirical form; in any case, W/Z ratio is well predicted

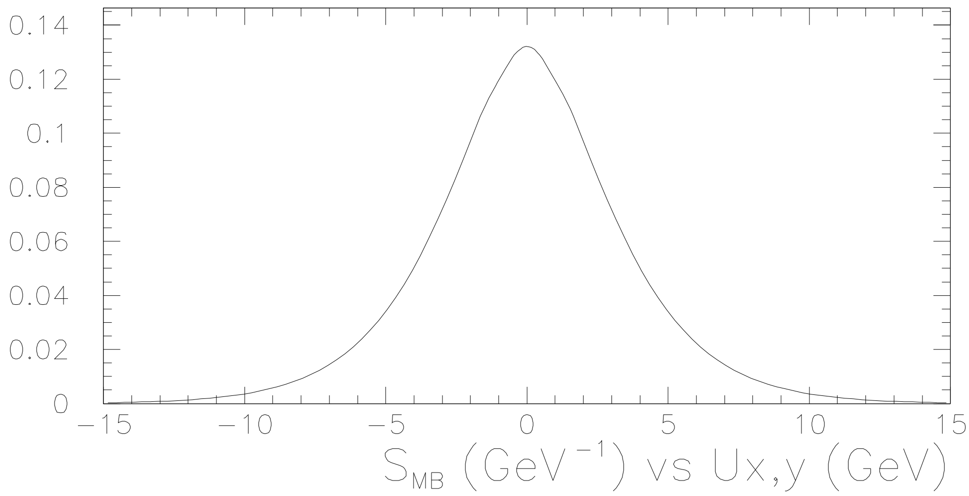
Recoil Model



MB resolution vs $\sum E_T$ . . .

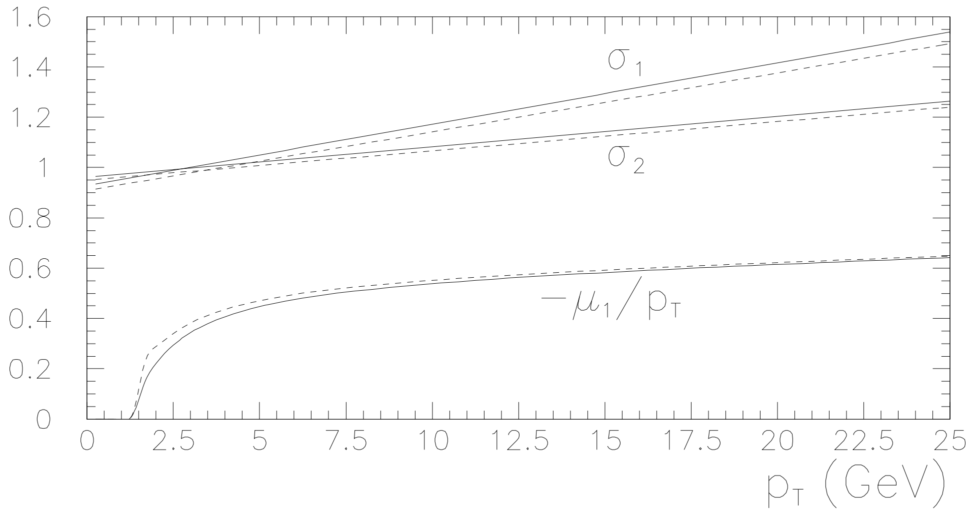


. . . convoluted with $\sum E_T$ spectrum . . .

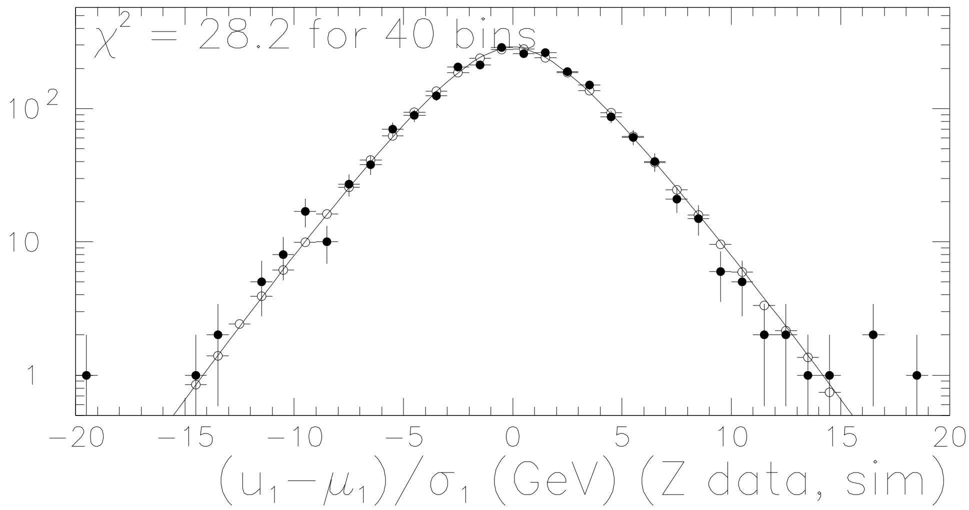


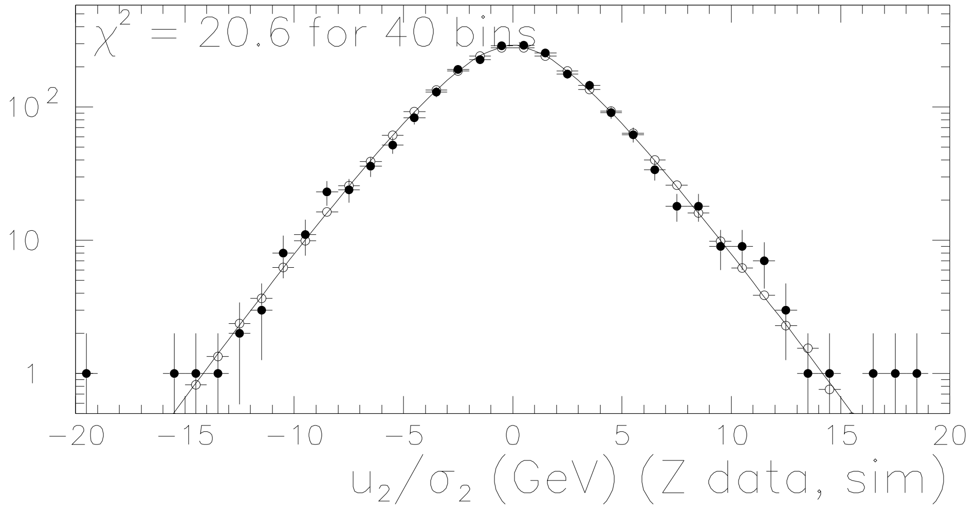
. . . gives a resolution function

Recoil Model, 2



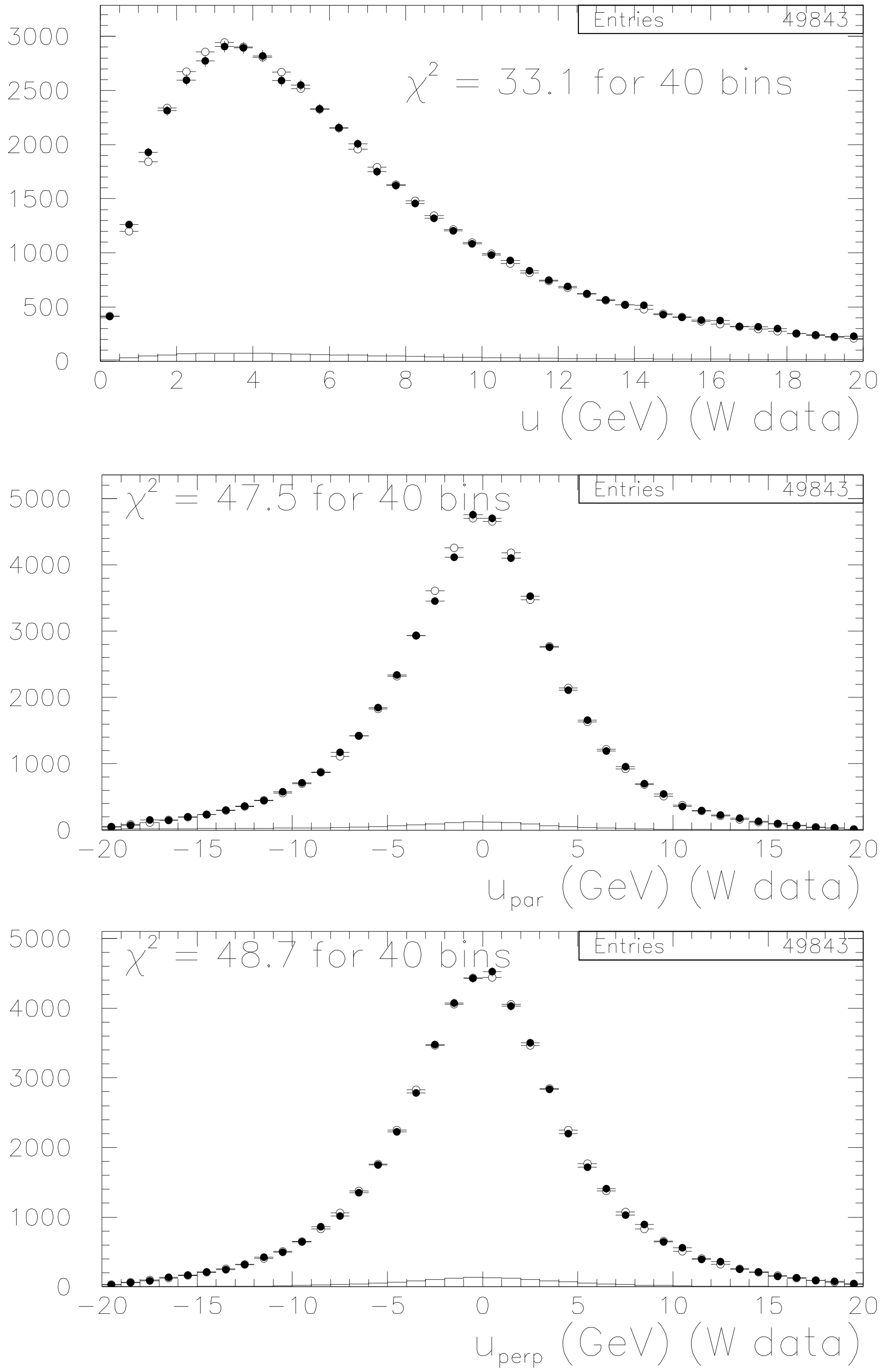
This function is scaled and offset to match $\vec{u}$ vs $\vec{P}_T^{\ell\ell}$ in Z data; note $\perp$ component has no offset, by construction





It then nicely models $\vec{u}$ in Z data . . .

Recoil Model, 3



. . . and in *W* data

Event Generation and Simulation

Same zeroth-order ($p_T(W) = 0$) generator (TOYGEN) as in M_W analysis produces weighted $p\bar{p} \to W \to \ell\nu\gamma$ events

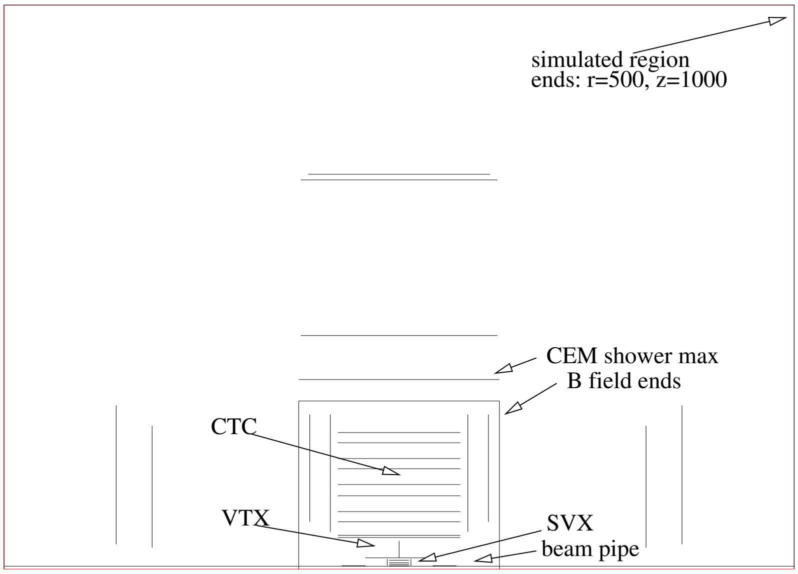
$$\frac{d\sigma}{dx_1 dx_2} \propto \sum_{ij} f_{i/p}(x_1) f_{j/\bar{p}}(x_2) \cdot |V_{ij}|^2 \cdot \frac{\hat{s}}{(\hat{s} - M_W^2)^2 + (\frac{\hat{s}\Gamma_W}{M_W})^2}$$

where i, j = flavors, V_{ij} = CKM matrix, $\hat{s} = x_1 x_2 s$

- $f_i(x)$ from MRS-R2 PDF
- $\ell\nu\gamma$ from BK or PHOTOS
- $P_T(W)$ distribution as described earlier
- reweighting technique handles variation of $\frac{dN}{dp_T}$ with $\sqrt{\hat{s}}$
- no particle-level description of recoil (use u model)

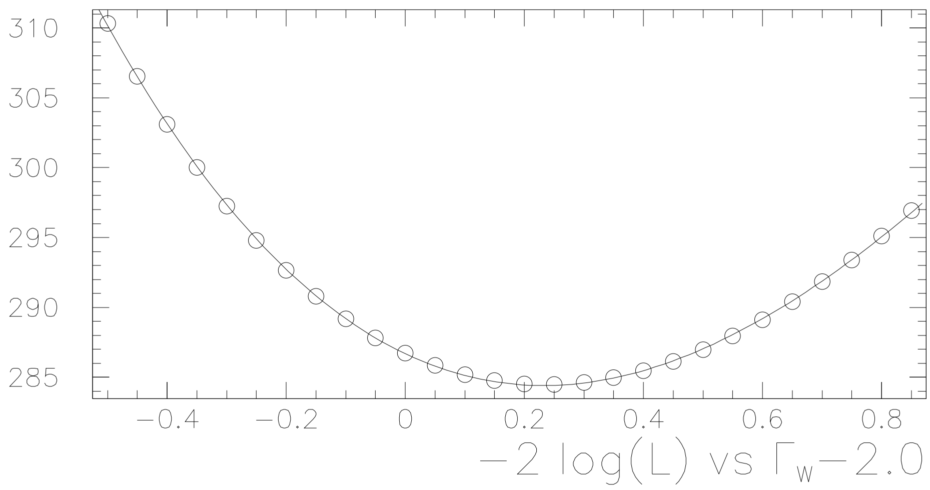
μ analysis uses same custom simulation program used in $M_W(\mu)$ analysis

e analysis uses both a custom QFL-like simulation and QFL itself; track lists from W data are used to model effect of overlap on track isolation variable



Fit Procedure

- **Generate M_T spectra for $\Gamma(W)$ from 1.0 to 3.0 GeV in 50 MeV intervals (by reweighting)**
- **Normalize to observed minus BG in region $M_T < 200$; add BG to templates**
- **Binned likelihood fit in 1 GeV M_T bins in the region $100 < M_T < 200$**
- **e analysis considered $M_T > 90$, > 100, > 110: starting at 100 GeV minimizes total error ((200, 165, 180) MeV in thesis)**
- **Check bias by applying fit to templates themselves**



Sample fit

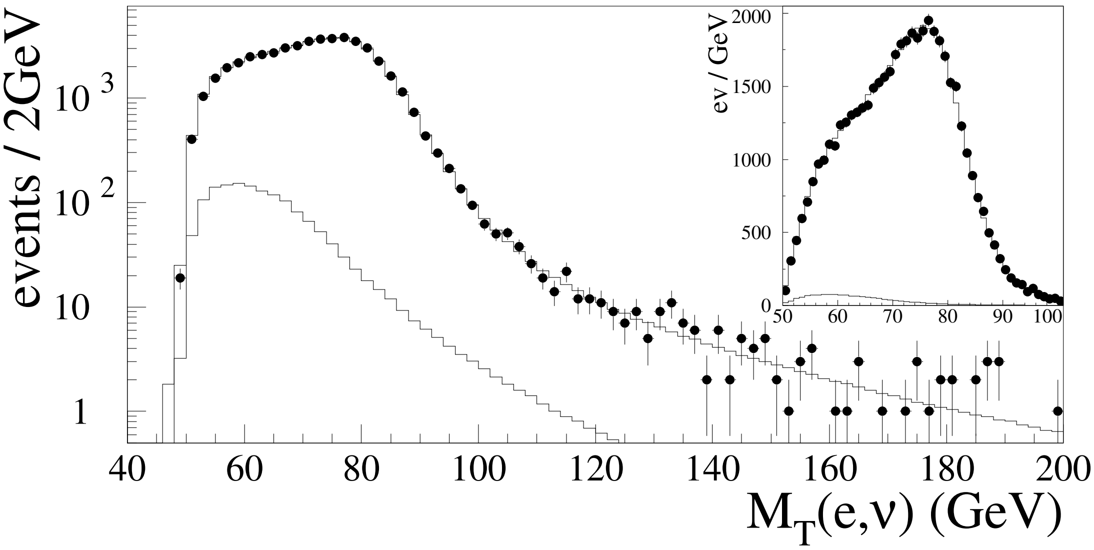
- **Evaluate systematic X by generating MC sample with effect X altered, then fitting to unaltered templates**

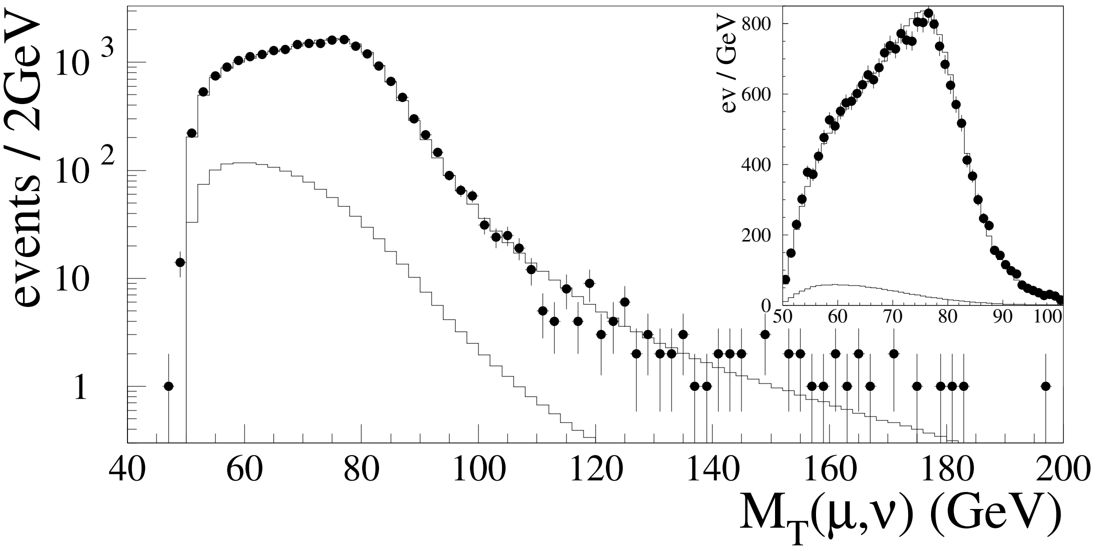
Systematics

CDF 1994-95 $e + \mu$	(MeV)	(MeV)
Error Source	$W \to e\nu$	$W \to \mu\nu$
Statistics	125	195
Lepton E,p_T linearity	60	5
u_T model	60	90
W P_T model	55	70
Backgrounds	30	50
Lepton ID, trigger	30	40
Lepton E or p_T scale	20	15
Lepton resolution	10	20
PDFs (common)	15	15
M_W (common)	10	10
QED (common)	10	10
Total Syst.	115	135
Stat$\bigoplus$Syst	170	235

- Use M_W CEM non-linearity correction, but inflate error to cover zero ($\approx \times 2$)
- Throw from u, P_T model covariance matrices
- For μ, "lepton ID" means varying ID cuts; for e, it means a check using QFL (consistent)
- Take RMS shift from range of PDFs used in M_W analysis

Result





$$\Gamma_W(e) = 2.175 \pm 0.125 \text{ (stat) } \pm 0.115 \text{ (syst) GeV}$$
$$\Gamma_W(\mu) = 1.780 \pm 0.195 \text{ (stat) } \pm 0.135 \text{ (syst) GeV}$$

Result

CDF $e + \mu$ (including Ia e result):

$$\begin{aligned}\Gamma(W) &= 2.05 \pm 0.10\ (\mathrm{stat}) \pm 0.08\ (\mathrm{syst})\ \mathrm{GeV} \\ &= 2.05 \pm 0.13\ \mathrm{GeV}\end{aligned}$$