Gauge Boson Studies at the Tevatron

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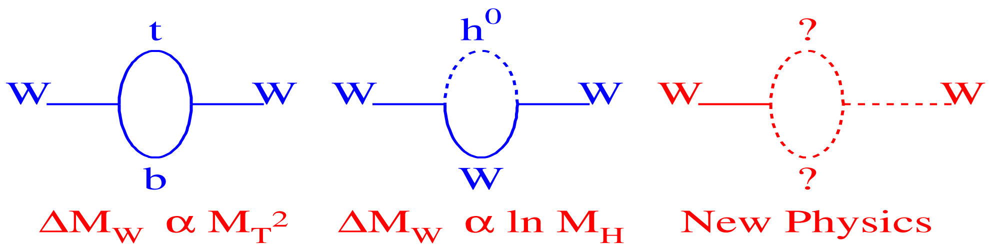
for the CDF & DØ Collaborations

Outline:

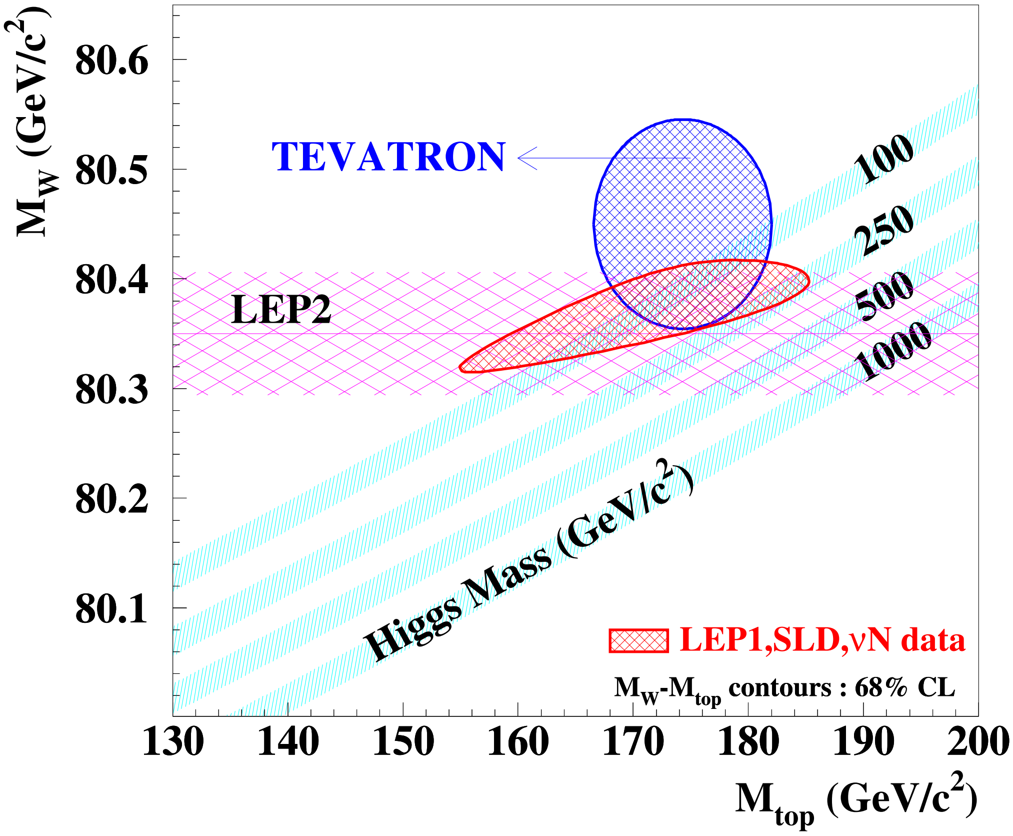
- ***W*** **mass measurements (∼ 1/2 of talk)**
- ***W*, *Z*** **cross-sections, BR, and Γ(*W*)**
- **Trilinear gauge-boson couplings**
- **Drell-Yan measurements**

W Mass – Overview



Given M_Z, G_F, and α_{QED} as SM inputs, M_W is predicted, but depends on $M_{\rm top}$, $M_{\rm Higgs}$

Measuring M_W, M_t constrains M_H; checks SM consistency



Tevatron $\delta M_t = 5.1$ GeV, $\delta M_W = 63$ MeV

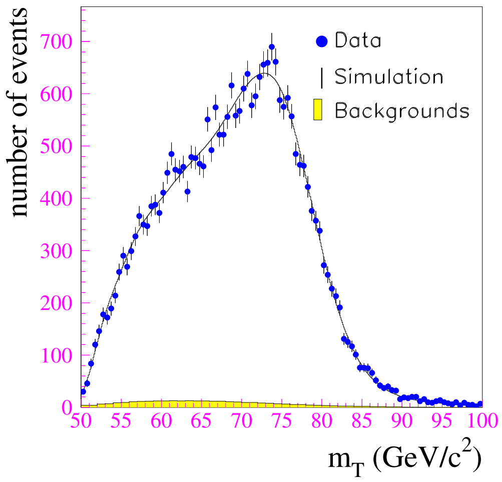
W Mass – Recent Tevatron Results

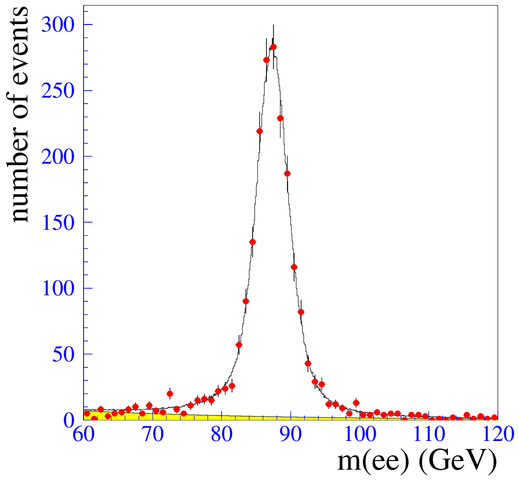
New Tevatron M_W results in past year:

- **CDF completed analysis of 1994-95 data set**
  - **electron channel now included**
  - **W,Z production model now constrained more directly from CDF data**
  - **improved "recoil model" used to derive P_T^ν**
  - **E, p scales fixed to LEP M_Z**
  - **shown last March; draft article circulating within CDF**
- **DØ added endcap electrons from 1994-95 data set**
  - **extends rapidity coverage into $1.5 < |\eta| < 2.5$ region**
  - **combined fit including CC+EC data, M_T, P_T^e, P_T^ν spectra**
  - **final results published PRL {84} 222 (2000) and submitted to PRD (hep-ex/9908057)**

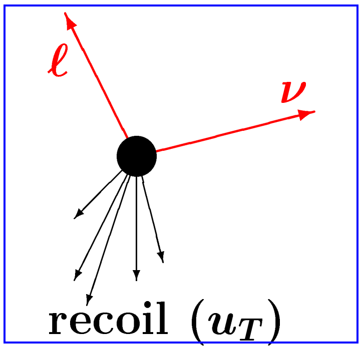
W Mass – Event Selection

Event Selection for CDF/DØ W Mass Measurements: well-measured events, low BG





- **Leptonic decays $W \to e\nu$ (both), $W \to \mu\nu$ (CDF)**
- **Transverse momentum balance $\Rightarrow$ P_T^ℓ, 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 $\vec{P}_T^\nu = -(\vec{P}_T^\ell + \vec{u}_T)$**
- **$M_T^W = \sqrt{2P_T^\ell P_T^\nu(1 - \cos\Delta\phi_{\ell,\nu})}$**
- **$P_T^\ell >$25–30, $|\eta_\ell| < 1$ (DØ also 1.5–2.5), $u_T <$15–20**
- **u_T cut reduces BG, improves P_T^ν resolution**



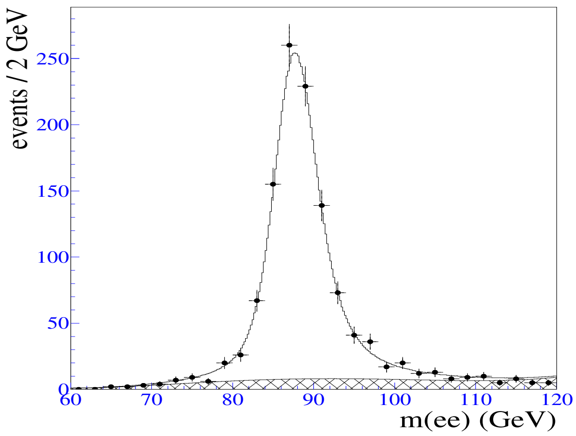
	W	Z
CDF e	30115	1559
CDF μ	14740	1840
DØ CC	28323	2179
DØ EC	11089	1265(CF) + 422(FF)

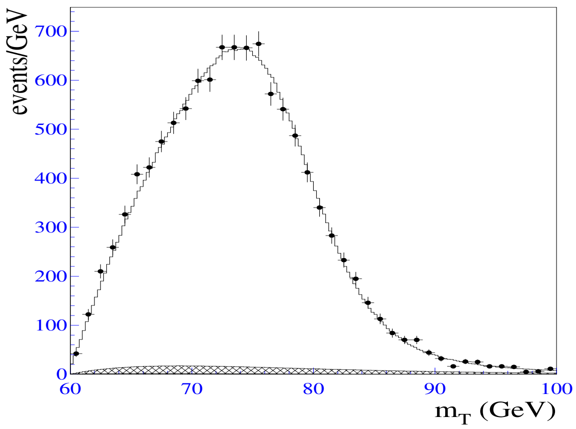
CDF/DØ M_W – Method

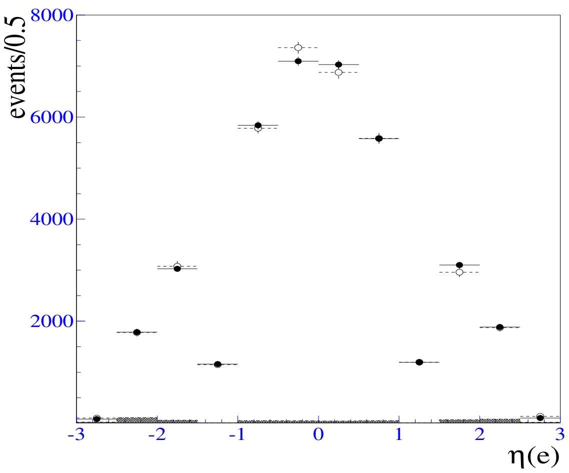
- **Need to model three basic ingredients: W prodn/decay, P_T^ℓ measurement, u_T measurement**
- **Use Z samples to tune prodn model, u_T model, P_T^ℓ resns & scales (no $E_{\rm beam}$ constraint!)**
- **Fast MC generator & detector simulation**
  - **Relativistic Breit-Wigner lineshape convol w/ PDF**
  - **y, P_T of W, Z (or W/Z ratio) from calculation+PDF (LY; Ellis et al), tuned to match Z data**
    - **CDF,DØ 1992–95 Z P_T spectra now published!**
  - **$W \to \ell\nu\gamma$, $Z \to \ell^+\ell^-\gamma$ (BK, PHOTOS, Baur et al)**
  - **Parametric models of P_T^ℓ, u_T meas, tuned to data**
  - **CDF includes bremsstrahlung, pair production, dE/dx, to model p_T^e (spectrometer), low-mass $\mu\mu$ resonances**
- **Small BG (1–5% total, varying by detector/channel) (0.4–4% multijet, 0.1–4% $Z \to \ell\not\ell$, 1% τ) incl in spectra**
- **PDF $\Rightarrow d\sigma/dy \Rightarrow$ acceptance $\Rightarrow$ lineshape $\Longrightarrow$**
  - **use PDFs spanning exptl $d\sigma/dy^W$ bounds**
  - **extend $\eta(\ell)$ coverage to reduce impact (DØ)**

DØ Endcap M_W

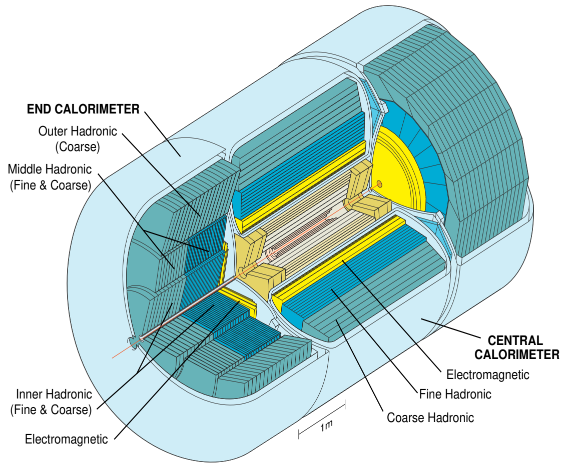
- added statistics; some complementary systematics
- EC electrons allow $|\eta^e|$ check of PDF
- $\boxed{80.691 \pm 0.227 \text{ GeV}}$: combining fits to M_T, P_T^e, P_T^ν
- $\boxed{80.498 \pm 0.095 \text{ GeV}}$: combining with Ib(central), w/correlations
- $\boxed{80.482 \pm 0.091 \text{ GeV}}$: combining with Ia measurement





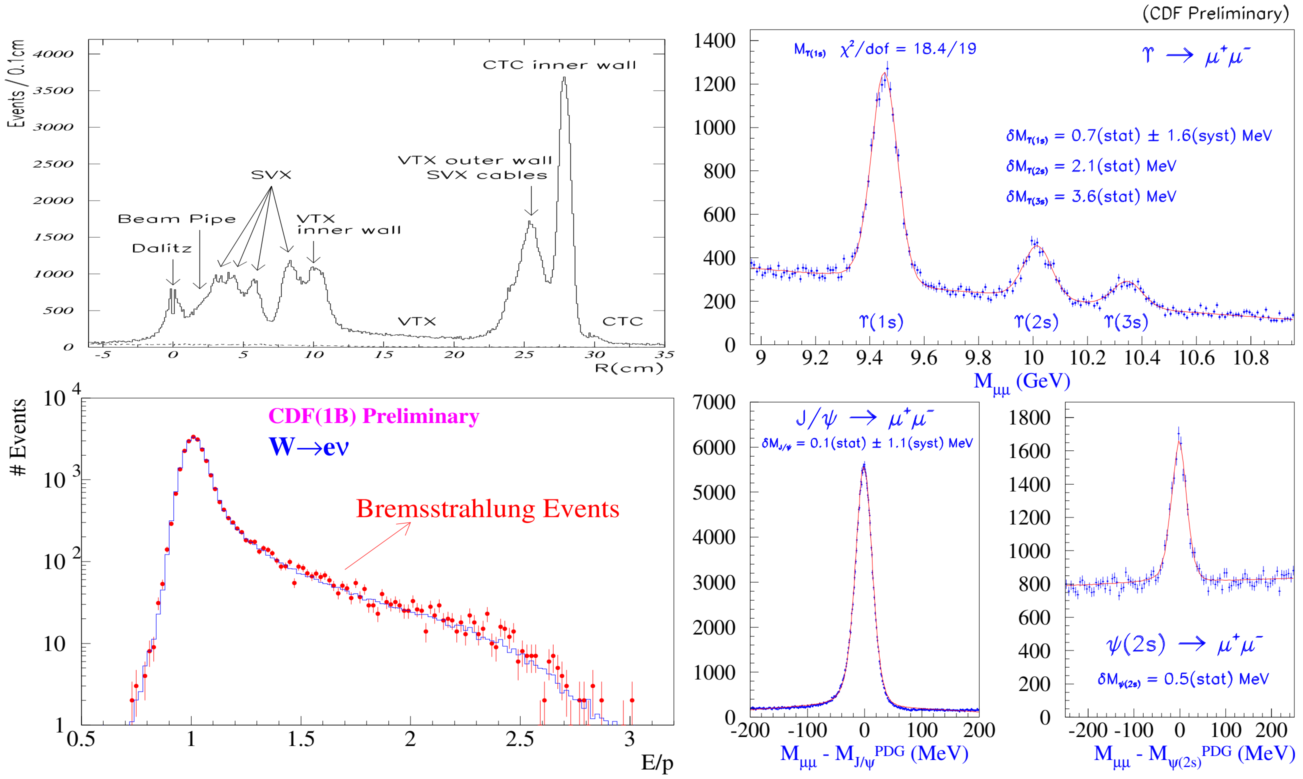


Uncertainty	CC	EC	CC+EC
W stats	70	108	61
Z stats	65	181	59
cal. linearity	20	52	25
cal. uniformity	10	–	8
e resolution	25	42	19
e angle calib.	30	20	10
e removal	15	4	12
selection bias	5	5	3
u_T resolution	25	42	25
u_T response	20	17	25
backgrounds	10	20	9
P_T^W spectrum	10	25	15
PDF	20	17	7
parton lumi	10	2	4
radiative decays	15	1	12
W width	10	10	10
Total	115	227	95

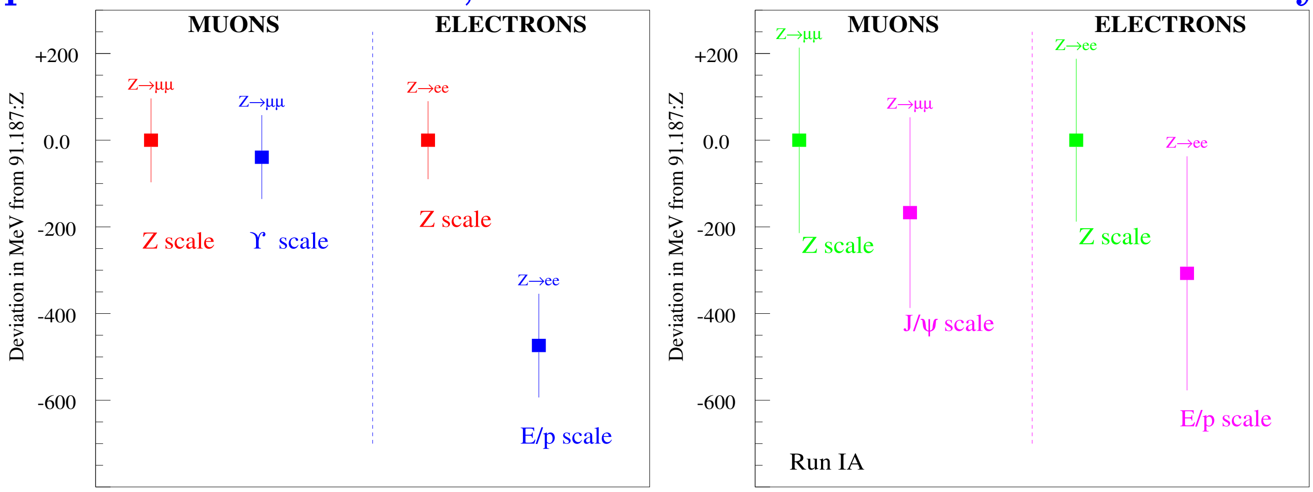


CDF – P_T^ℓ Scales (Plan A)

\# X_0 ($R < 30$ cm) $= 7.20 \pm 0.38\%$ (γ conv), $7.55 \pm 0.37\%$ (brem tail)

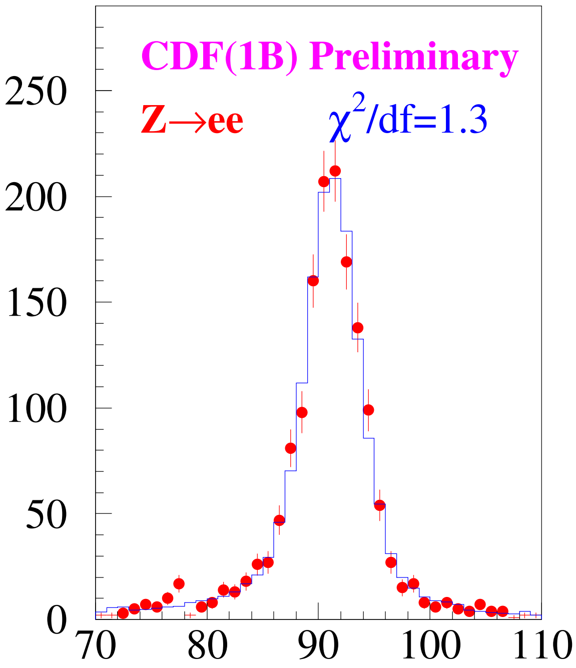


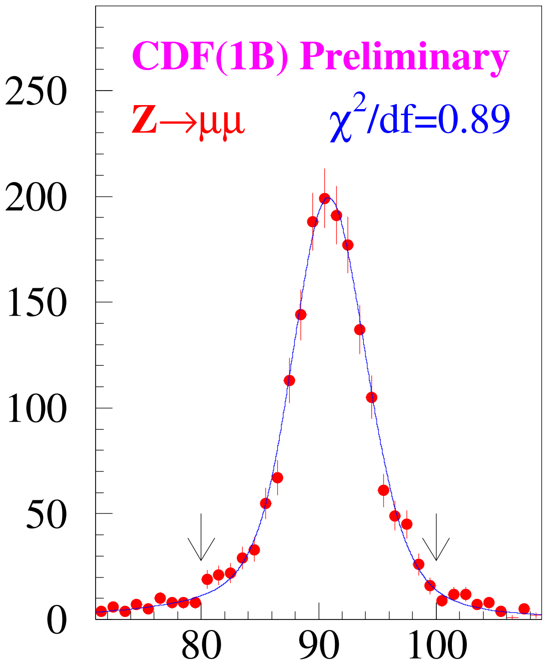
High-statistics resonances + material map + E/p allow precise E calibration, but Z mass check shows inconsistency.

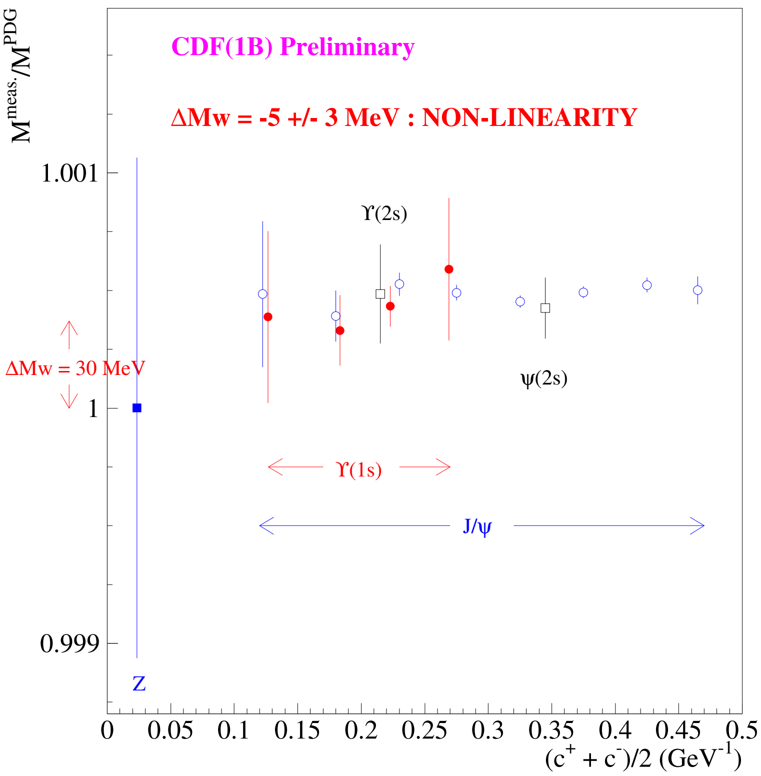


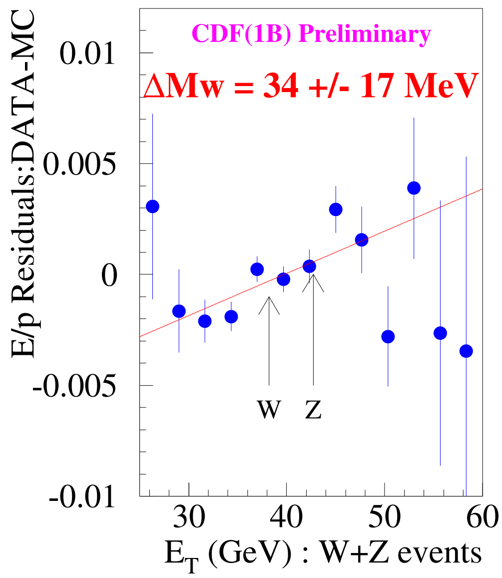
1992–93 data (right) do not distinguish presence/absence of 1994–95 E/p problem (left). We hope to understand/fix with 2001– data. For now, we normalize to M_Z.

CDF – P_T^ℓ Scales/Resol/Linearity









	Scale (incl NL)	Resolution
e	$\delta M_W = 72$ MeV	25 MeV
μ	85 MeV	20 MeV

CDF 1994–95 M_W Uncertainties

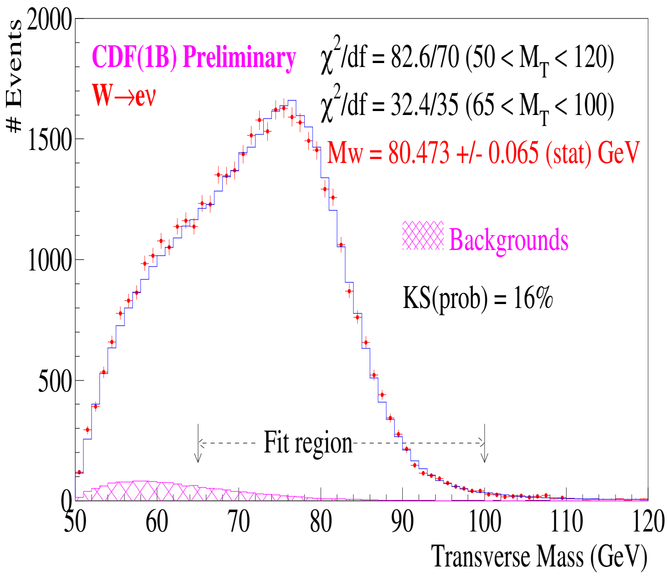
Error Source	$W \to e\nu$		$W \to \mu\nu$	
Statistics	65		100	
Lepton Scale	M_Z	E/p	M_Z	M_Υ
	75	80	85	20
P_T^W, Recoil Model	40		40	
PDFs	15		15	
Higher Order QED	20		10	
Lepton Resolution	25		20	
Trigger+Selection Bias	–		$15 \oplus 10$	
Backgrounds	5		25	
Total(Syst. except Scale)	54		57	
TOTAL	113	117	143	117

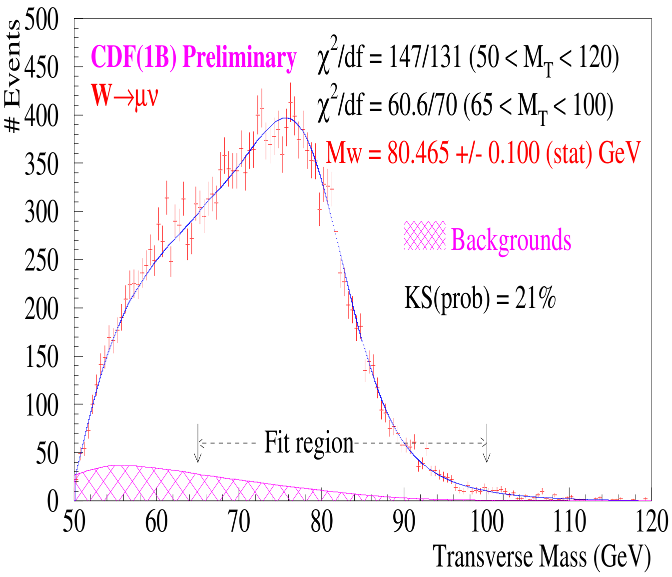
$$M_W = 80.473 \pm 0.113 \text{ GeV (e) using } M_Z$$
$$= 80.465 \pm 0.143 \text{ GeV } (\mu) \text{ using } M_Z$$

Common error : 16 MeV (PDF, QED)

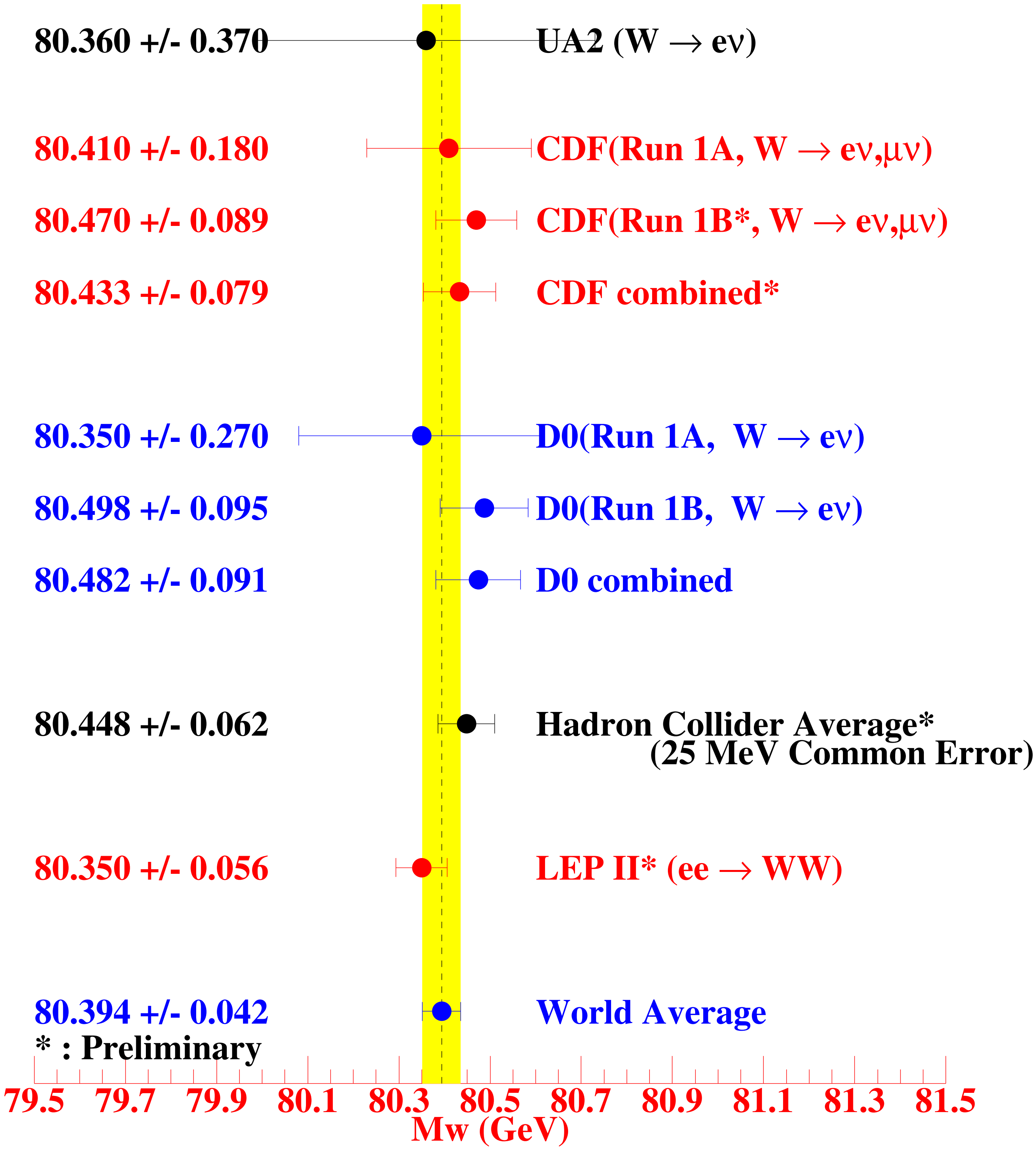
$$\boxed{M_W^{e+\mu} \text{ (1994-95 data)} = 80.470 \pm 0.089 \text{ GeV}}$$

$$\boxed{M_W^{e+\mu} \text{ (1988-95 data)} = 80.433 \pm 0.079 \text{ GeV}}$$

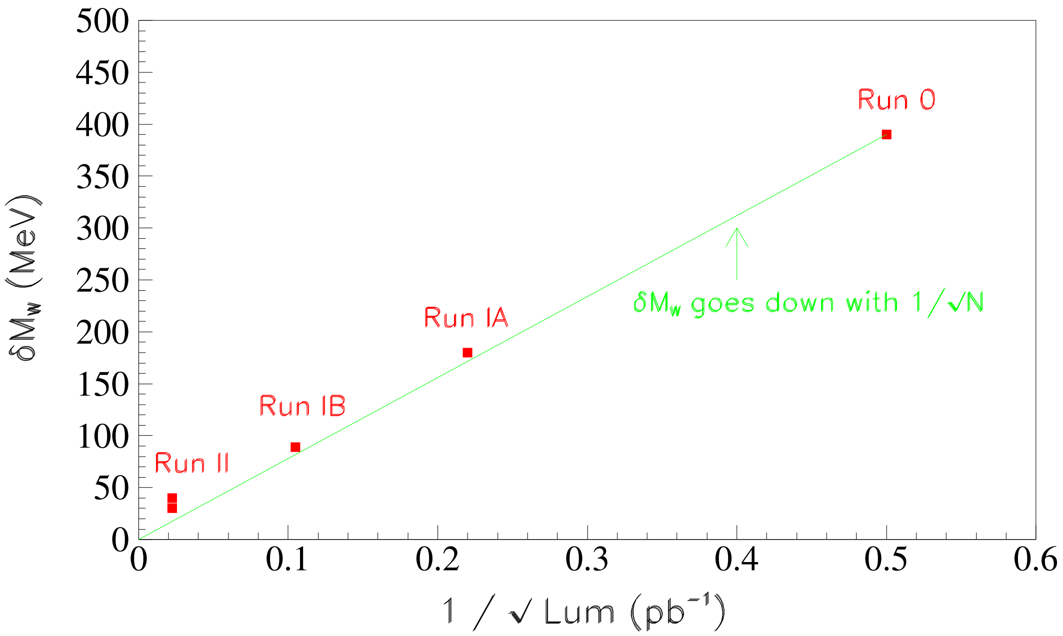




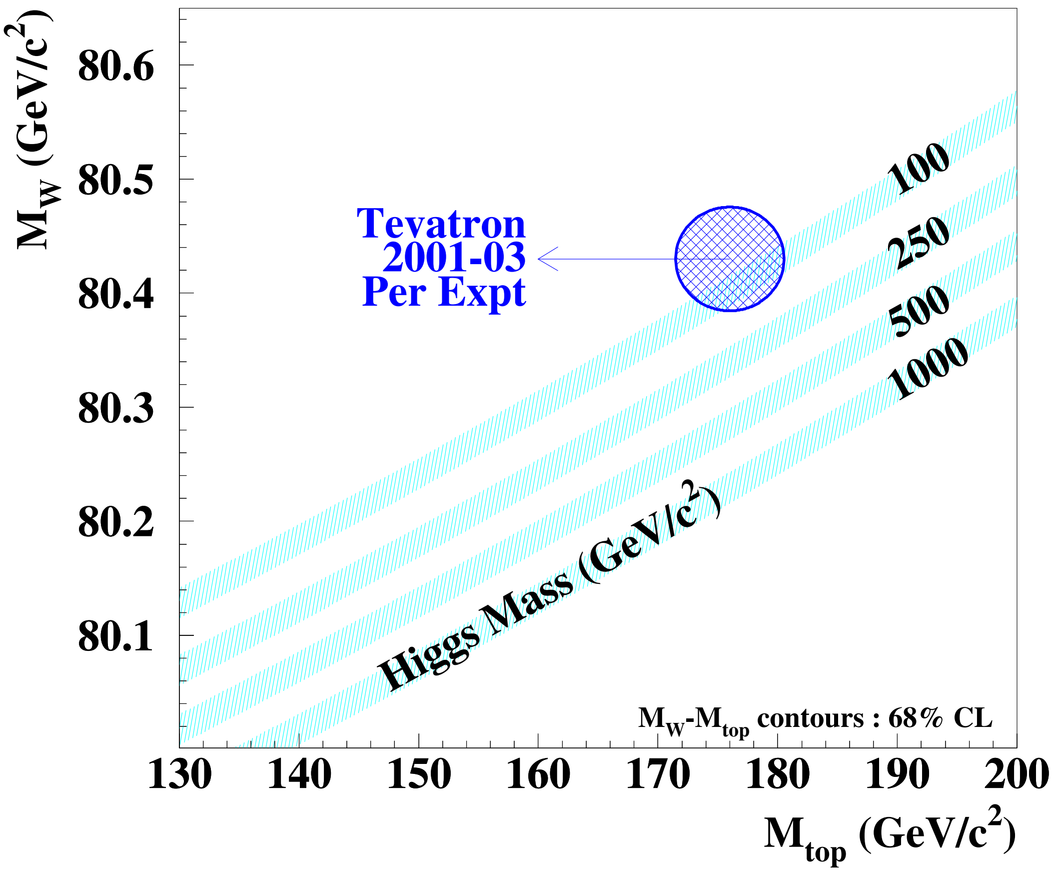
W Mass – Combined Results



Tevatron Run II (2001–) Prospects



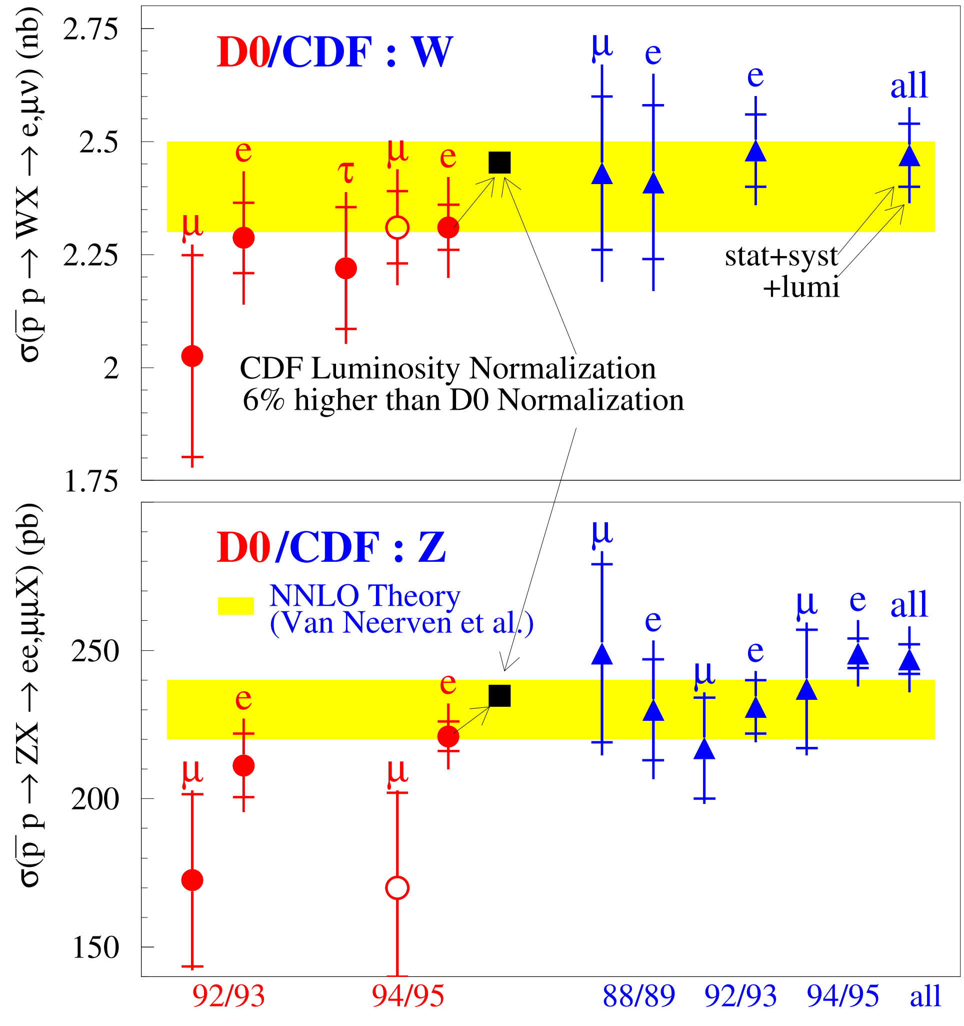
New challenges with each new dataset, but $1/\sqrt{\mathcal{L}}$ rule has worked so far. Anticipate 20–40 MeV (CDF+DØ) from first 2 fb^{-1}.

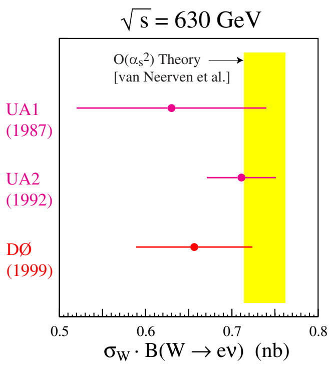


W, Z Cross-Sections

As in M_W measurements, use clean, well-measured leptonic W and Z decays

Principal difference in event selection is that no u_T cut is made, so W and Z can be accompanied by energetic jets





Theory is NNLO, Van Neerven et al, 1991,92; $\sim 4\%$ uncertainty arises from PDFs, α_S, choice of renormalization/factorization scale

W, Z Cross-Sections

Channel	Run	σB $\pm$(s $\oplus$ s) $\pm$ (lum)	Published
CDF			
$Z \to \mu\mu$	92/93	$217 \pm 17 \pm 8$ pb	PRD {59} 052002 (1999)
$Z \to \mu\mu$	94/95	$237 \pm 9 \pm 9$ pb	PRD {59} 052002 (1999) (*)
$Z \to ee$	92/95	$249 \pm 5 \pm 10$ pb	PRL {84} 845 (2000)
DØ			
$Z \to ee$	94/95	$221 \pm 5 \pm 10$ pb	acc PRD, hep-ex/9906025
$W \to e\nu$	94/95	$2310 \pm 51 \pm 100$ pb	acc PRD, hep-ex/9906025
$W \to \tau\nu$	94/95	$2220 \pm 135 \pm 100$ pb	sub PRL, hep-ex/9912065
DØ, $\sqrt{s} = 630$ GeV			
$W \to e\nu$	96	$658 \pm 64 \pm 20$ pb	acc PRD, hep-ex/9906025

(*) CDF 94/95 $Z \to \mu\mu$ luminosity error reduced subsequent to publication; described in $Z \to ee$ paper

Luminosity uncertainty $\sim$ 4%; CDF and DØ normalizations differ by $\sim$ 6%

Dominant uncertainty in many cross-section measurements, in particular $W \to e\nu$, is uncertainty in $\int \mathcal{L}dt$

$\Rightarrow$ $\sigma B(W \to e\nu)$ will probably be used to normalize $\int \mathcal{L}dt$ in future Tevatron runs

W/Z Cross-Section Ratio

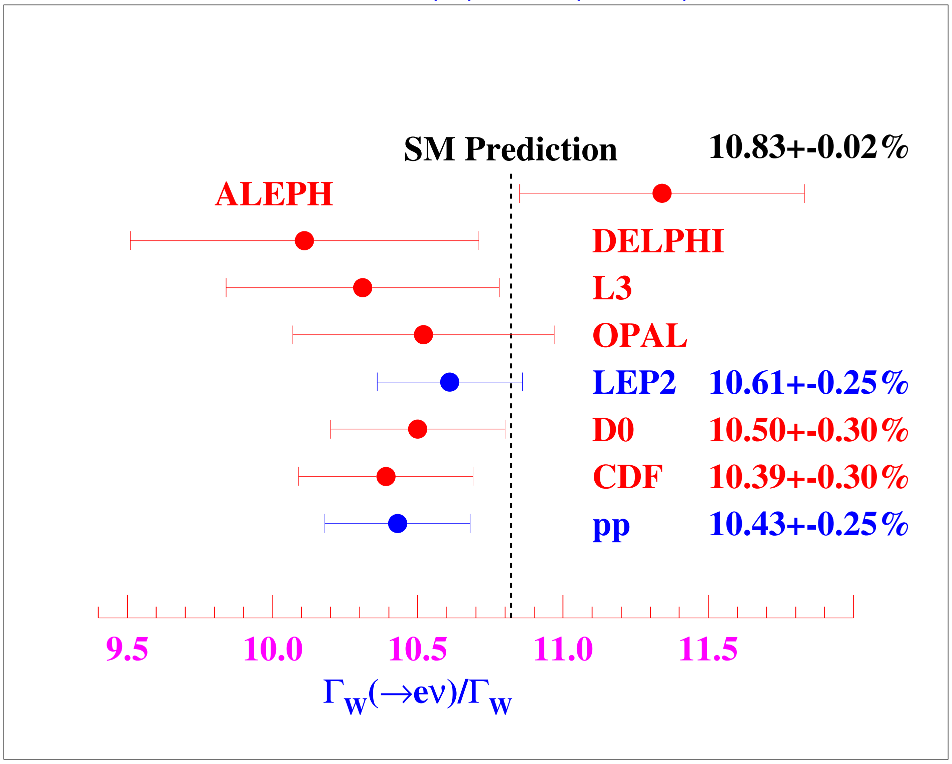
DØ 1994-95:

$\sigma(p\bar{p} \to W + X) \cdot B(W \to e\nu) =$
2310 ± 10 (stat) ± 50 (syst) ± 100 (lum) pb,

$\sigma(p\bar{p} \to Z + X) \cdot B(Z \to ee) =$
221 ± 3 (stat) ± 4 (syst) ± 10 (lum) pb

Statistical errors small; luminosity, many systematics cancel in W/Z ratio; theoretical error smaller on ratio $\sigma(W)/\sigma(Z)$ than $\sigma(W), \sigma(Z)$ individually

$\Rightarrow$ measure $\mathcal{R} \equiv \frac{\sigma(W)}{\sigma(Z)} \cdot \frac{B(W\to e\nu)}{B(Z\to ee)}$; extract $B(W \to e\nu)$



LEP = CERN-EP-2000-016 (summer 99 conf)

DØ pub PRD (op cit)

CDF prelim 6/99 (publ. draft in progress)

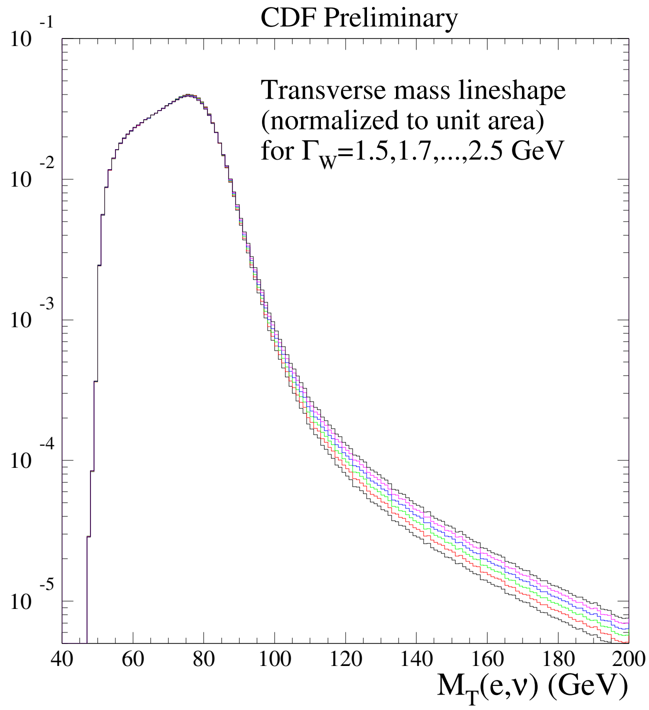
CDF+DØ prelim

CDF+DØ: stat. + uncorrel. $\mathcal{R}$ syst. (1.4%); correl. $\mathcal{R}$ syst. (1.1% EW NLO, 0.3% PDF); $\sigma(W)/\sigma(Z)$ theor. (1.5% EWK corr., 0.5% PDF) = 2.5% combined

W Inclusive Width

Using $B(W \to e\nu)$ from $\mathcal{R}$, $\Gamma(W \to e\nu)$ from SM: extract $\Gamma(W) = 2.171 \pm 0.052$ GeV (CDF+DØ)

Can also obtain $\Gamma(W)$ from likelihood fit to high-M_T tail of $W \to \ell\nu$ samples used to measure M_W



$\sigma(W)/\sigma(Z)$, $\Gamma_{SM}(W \to \ell\nu)$ *not* required;

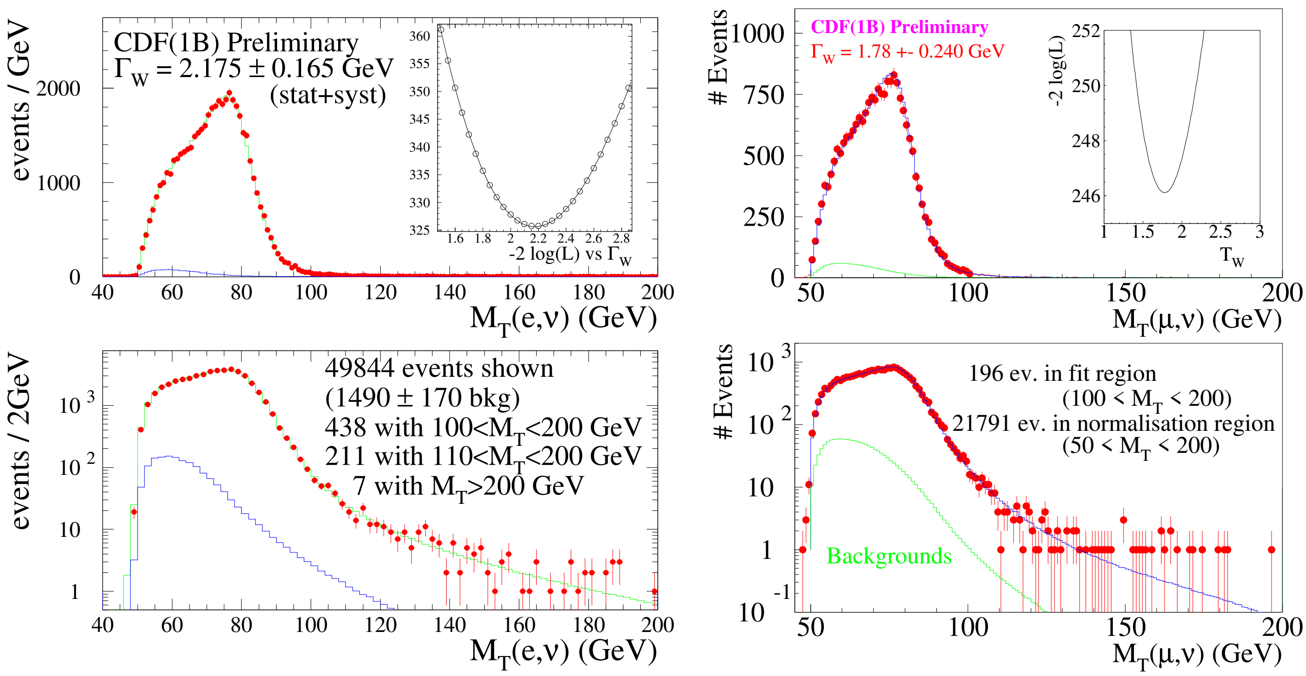
Production model (P_T, y, $\hat{s}$) for off-shell Ws *is* required

Normalize over all M_T; fit $M_T > 100$ GeV

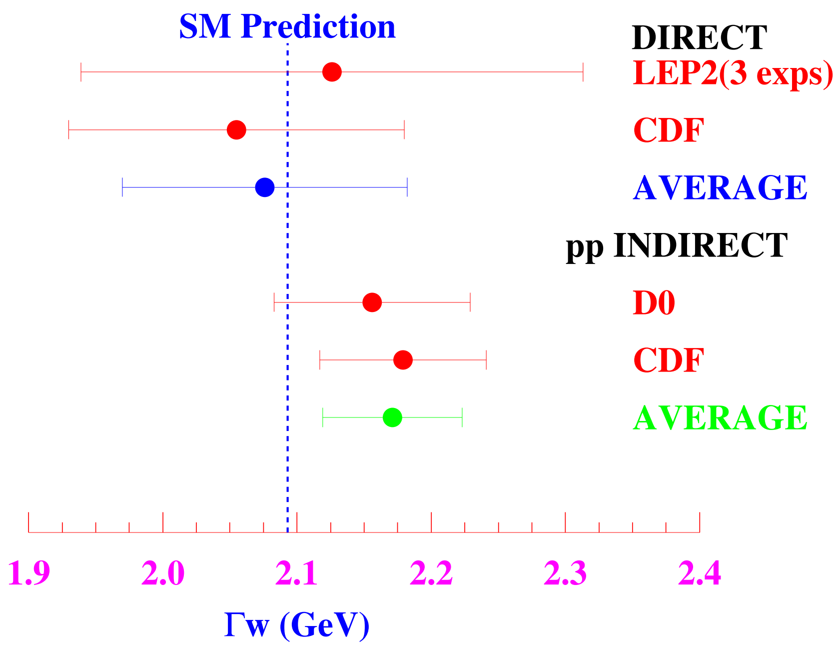
Dominant errors are statistical in nature; expect 20–40 MeV measurement from first ~ 2 fb^{-1} of next Tevatron run

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	65	5
u_T model	60	90
Backgrounds	30	55
W P_T model	30	70
Lepton ID, trigger	30	40
Lepton E or p_T scale	20	15
PDFs	15	15
M_W	10	10
Lepton resolution	10	20
QED	10	10
TOTAL SYST.	105	135
STAT$\oplus$SYST	165	240

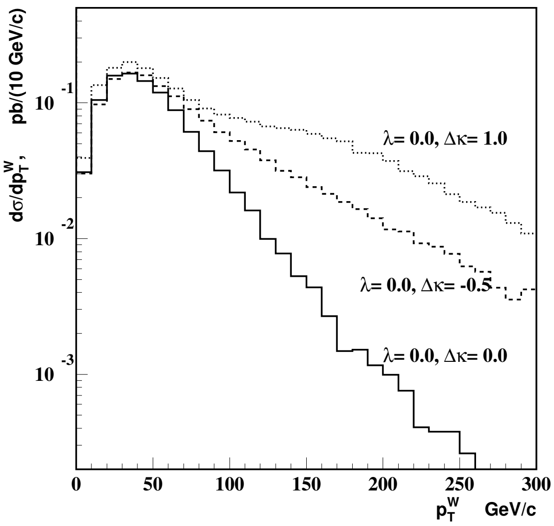
W Width

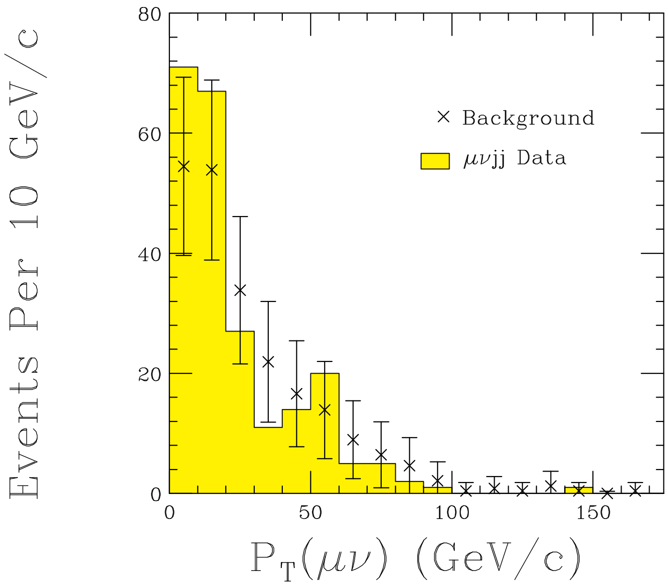


CDF 94–95 $e + \mu$ lineshape (preliminary 7/99):
$\Gamma(W) = 2.055 \pm 0.100$ (stat) ± 0.075 (syst) GeV
draft article circulating within CDF



Trilinear Gauge-Boson Couplings (WWZ,$WW\gamma$)

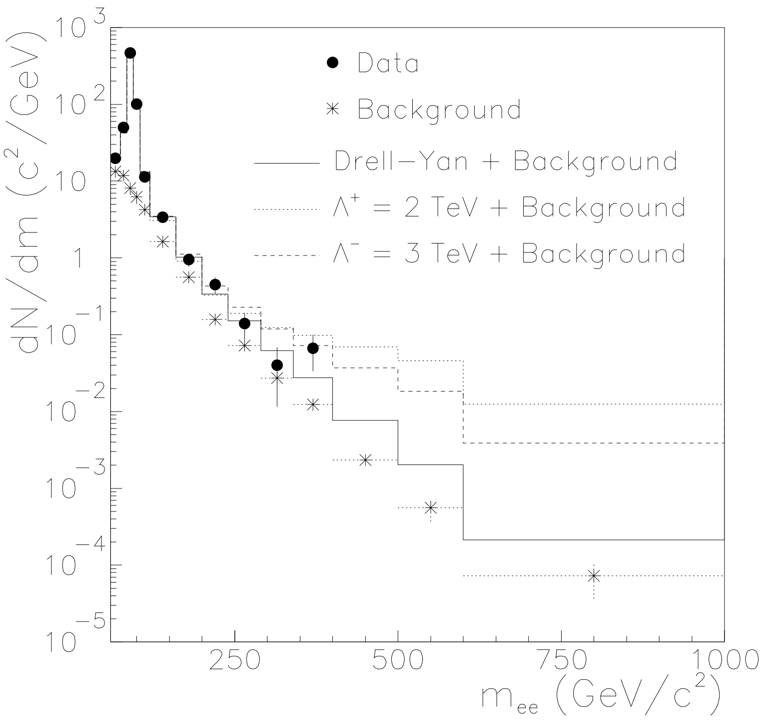




- **DØ $WW, WZ \rightarrow e\nu jj$ subm. PRD, hep-ex/9912033 (long write-up of PRL {79} 1441 (1997))**
- **DØ $WW, WZ \rightarrow \mu\nu jj$, $WZ \rightarrow \mu\nu ee, e\nu ee$ publ. PRD {60} 072002 (1999)**
- **$ee\ell\nu$: SM=.25 $\pm$ .02 evts, BG=.50 $\pm$ .17, obs 1 $e\nu ee$**
- **$\mu\nu jj$ SM=4.5$\pm$0.8, BG=224$\pm$55, obs=224, but $P_T(\mu\nu)$ spectrum sensitive to non-SM signal**
- **DØ comb fit (incl prev pub): $W\gamma$ (P_T^γ); $WW \rightarrow \ell\nu\ell'\nu'$ (P_T^ℓ); $WW, WZ \rightarrow \ell\nu jj$ ($P_T^{\ell\nu}$); $WZ \rightarrow ee\ell\nu$**
- **95% CL ($\Lambda = 2$ TeV, $WW\gamma = WWZ$):**
  $-0.25 \leq \Delta\kappa \leq 0.39$ ($\lambda = 0$),
  $-0.18 \leq \lambda \leq 0.19$ ($\Delta\kappa = 0$)
- **HISZ, for LEP comparison,**
  $-0.29 \leq \Delta\kappa_\gamma \leq 0.53$, LEP2 $-0.11 \leq \Delta\kappa_\gamma \leq 0.20$
  $-0.18 \leq \lambda_\gamma \leq 0.19$, LEP2 $-0.10 \leq \lambda_\gamma \leq 0.03$

High-Mass Drell-Yan Pairs

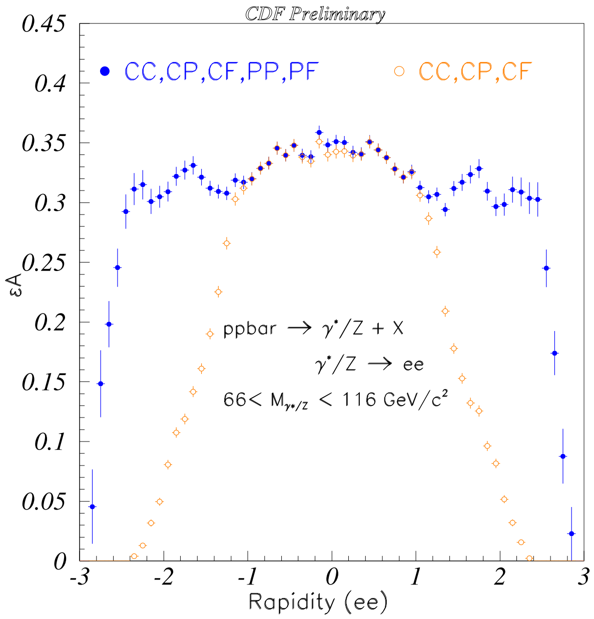
PRL {82} 4769 (1999) (120pb^{-1})

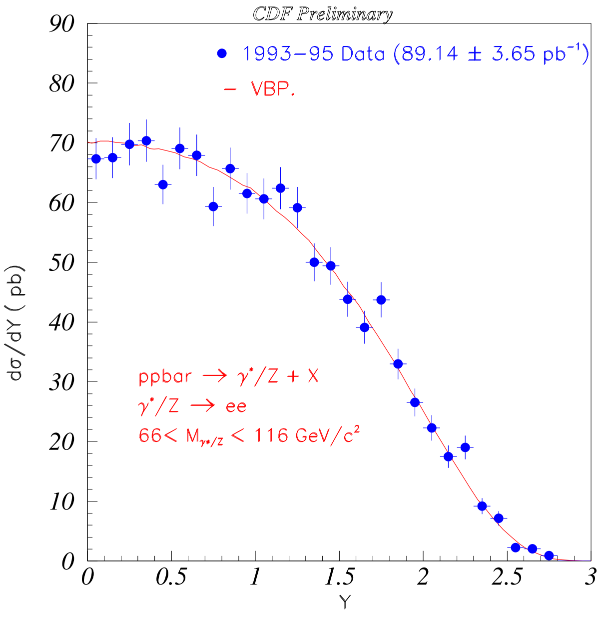


DØ 95% CL		
+=destructive −=constructive	(TeV)	
Term(s)	Λ^+	Λ^-
LL	3.3	4.2
LR	3.4	3.6
RL	3.3	3.7
RR	3.3	4.0
$LL+RR$	4.2	5.1
$LR+RL$	3.9	4.4
$LL-LR$	3.9	4.5
$RL-RR$	4.0	4.3
VV	4.9	6.1
AA	4.7	5.5

- **Most stringent limits to date on qe compositeness scale, except where ruled out ($>$ 10 TeV) by APV measurements**
- **CDF has published similar analyses for qe and $q\mu$ (combined limits in 3–6 TeV range)**
- **LEP2 now has preliminary combined $e\mu$,$e\tau$ limits in the 8–16 TeV range**

Drell-Yan Rapidity Distribution





- **CDF preliminary 3/99; analysis continuing**
- $\boldsymbol{y^{l^+l^-}}$ **distribution may become a useful PDF constraint in the future**
- **One of several recent CDF+DØ analyses making good use of $|\eta| > 1$ leptons**
- **CDF-II will feature new EC calorimeter, substantially improved tracking at high $|\eta|$**
- **Extended y coverage reduces PDF acceptance effects in analyses such as M_W, $\mathcal{R}$**

Outlook

- **Next Tevatron run begins 8/00 (engineering), 3/01 (physics)**
- **$\geq$ 15 fb^{-1} at $\sqrt{s}$=2.0 TeV 2001$\leftrightarrow$LHC turn-on**
  - **$\sim$ 2 fb^{-1} likely in first $\sim$ 2 years**
  - **$\sim$ 12% higher $\sigma(W)$, $\sigma(Z)$**
  - **$\sim$ 40% higher $\sigma(t\bar{t})$**
- **CDF: improved coverage for high-η leptons**
- **DØ: magnetic spectrometer**
- **BOTH: new tracking systems, vertex detectors**
- **Tevatron measurements may reach δM_t $\sim$2–3 GeV, $\delta M_W, \delta\Gamma_W$ $\sim$20–40 MeV with first 2 fb^{-1}**
- **Ws may be our Bhabhas for luminosity calibration!**
- **Measurements provide many challenges: QED/EW radiative corrections; QCD effects in W,Z production; understanding PDF uncertainties; techniques for precise detector calibration**