The Precision Measurement of the W Mass using the DØ Detector

Dr. Kathleen Streets

New York University

- The electroweak Standard Model (SM)
- Measurements of:
  - W & Z production cross sections
  - Γ_W
  - W mass
- Comparisons to other measurements and SM
- Future Prospects

Lawrence Berkeley Laboratory

23 January 1997

ElectroWeak Standard Model

- Glashow, Weinberg, Salam (1967-1968)
  - SU(2)× U(1) model of electroweak interactions

- massless interacting vector particles: W^+, W^-, W°, B
  (Yang-Mills)
  W°, B mix to produce γ, Z° with mixing angle θ_W

  $$\gamma = \sin\theta_W W^\circ + \cos\theta_W B; \; Z^\circ = \cos\theta_W W^\circ - \sin\theta_W B$$

  - interactions mediated by $\gamma, W^\pm, Z$

- gauge symmetry of electroweak model implies:
  W, Z and fermions have $mass = 0$

→ break the electroweak symmetry by introducing Higgs boson:

Higgs' mechanism gives mass to $W^\pm, Z$ and fermions

Verification of ElectroWeak theory

⋆ existence of neutral weak currents (1973 - CERN)

⋆ ratio of neutral-current to charged-current events (1973 - CERN)

⋆ interference between electromagentic and neutral weak currents (1978 - SLAC) - parity violation in what seemed to be purely QED interaction

⋆ discovery and properties of W, Z (1983 - UA1,UA2 at CERN)

SM has survived all experimental tests so far!

⋆ **TOP quark recently (1994) discovered at Fermilab**

DØ and CDF current results
(from DPF in August 96):

DØ $\rightarrow M_T = 169 \pm 11$ **GeV**
CDF $\rightarrow M_T = 176.8 \pm 6.5$ **GeV**
Combined $\rightarrow M_T = 175 \pm 6$ **GeV**

⋆ **Higgs (H) is only undiscovered SM particle**

ElectroWeak Standard Model

Specified by 3 parameters:

- $\alpha = (137.03599 \pm .09)^{-1}$ $(\delta\alpha/\alpha = 0.045\ ppm)$
  but $\alpha(M_Z^2) \approx 1/128$ known to $(\delta\alpha/\alpha \approx 700\ ppm)$

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

- $M_Z = 91.1863 \pm .0020\mathrm{GeV}$ $(\delta M_Z/M_Z = 22\ ppm)$

Then can evaluate

$$M_W = A/\sin\theta_W$$

$$M_Z = A/\sin\theta_W\cos\theta_W$$

where

$$A = (\pi\alpha/\sqrt{2}G_F)^{1/2}$$

EW Radiative Corrections:

→ Data is sufficiently precise - must include radiative corrections

define: (on-shell scheme, Sirlin)

$$sin^2\theta_W = 1 - \frac{M_W^2}{M_Z^2}$$

then lump radiative corrections into Δr

$$M_W = \frac{A_o}{\sin\theta_W(1-\Delta r)^{1/2}} \quad \text{with} \quad A_o = (\frac{\pi\alpha}{\sqrt{2}G_F})^{1/2}$$

⇒ Dominate contributions to Δr due to

- running of $\alpha \rightarrow \alpha(M_Z^2)$ - vacuum polarization diagrams
- W, Z self-energy diagrams
- bosonic loop diagrams

$$\Delta r \sim \Delta r_o - \rho_t / \tan\theta_W \quad \text{with}$$

$$\Delta r_o \approx 1 - \frac{\alpha}{\alpha(M_Z)} \approx 0.06 \quad \text{and}$$

$$\rho_t \approx 0.01 (M_T / 180 \text{ GeV})^2$$

also contributions from bosonic loops which $\propto (\ln M_H)$

Motivation

⇒ **Precision Measure of M_W**

- ⋆ test of SM at level of radiative corrections
- ⋆ Improvement in precision can further constrain allowed values of M_H in SM or parameter space of other models
- ⋆ A precise value of M_W from direct measurement could contradict the value determined indirectly, indicating breakdown of SM

Fermilab $p\bar{p}$ Tevatron Collider

⇒ **Oct. 1985 - test run**

⇒ **1987 - first operating run (CDF only),** $\mathcal{L} \approx 4.3\ pb^{-1}$

⇒ **1992-1993: Run 1A,** $\mathcal{L} \approx 15\ pb^{-1}$

⇒ **1994-1995: Run 1B,** $\mathcal{L} \approx 89\ pb^{-1}$

⇒ **1999? start Run 2,** $\mathcal{L} \approx 2000\ pb^{-1}$

Peak luminosity: Run 1A, $\approx 0.8 \times 10^{31} (cm^{-2} s^{-1})$

Peak luminosity: Run 1B, $\approx 2.4 \times 10^{31} (cm^{-2} s^{-1})$

900 GeV protons **900 GeV anti-protons**

DØ Detector at Fermilab:

→ **large multi-purpose detector designed to study top, electroweak, QCD, new physics, etc.**

⋆ **mid 1984, experiment approved**

⋆ **Feb 1992, detector completed**

⋆ **May 1992, first collisions**

⋆ **Aug 1992, commissioning completed, run 1 starts**

Inclusive W and Z Production

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

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

$W \longrightarrow l\nu$ signature: high p_T lepton + large $\not{E}_T$
$Z \longrightarrow ll$ signature: 2 high p_T leptons

Inclusive W and Z Production

Event Selection

electrons:	muons:
$\lvert\eta\rvert < 1.2$ or $1.5 < \lvert\eta\rvert < 2.5$	$\lvert\eta\rvert < 1.0$
$W \rightarrow e\nu : E_T^e > 25, \not\!E_T > 25$ GeV	$W \rightarrow \mu\nu : p_T^\mu > 20, \not\!E_T > 20$ GeV
$Z \rightarrow ee : E_T^e > 25$ GeV	$Z \rightarrow \mu\mu : p_T^{\mu 1} > 20, p_T^{\mu 2} > 15$ GeV

$$\sigma \cdot B = \frac{N_{obs} - N_{bkg}}{A \epsilon \mathcal{L}}$$

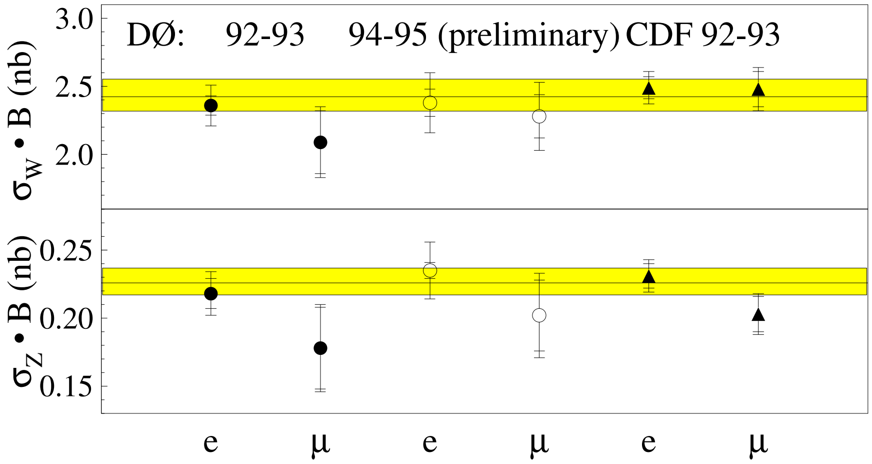
D0 1B - Preliminary Results

	$W \rightarrow e\nu$	$Z \rightarrow ee$	$W \rightarrow \mu\nu$	$Z \rightarrow \mu\mu$
# events	59579	5702	4477	173
Background(%)	8.1 ± 0.9%	4.8 ± 0.5%	18.6 ± 2.0%	8.0 ± 2.1%
Acceptance(%)	43.4 ± 1.5%	34.2 ± 0.5%	20.1 ± 0.7%	5.7 ± 0.5%
Efficiency(%)	70.0 ± 1.2%	75.9 ± 1.2%	24.7 ± 1.5%	43.2 ± 3.0%
$\mathcal{L}$ (pb^{-1})	75.9 ± 6.4	89.1 ± 7.5	32.0 ± 2.7	32.0 ± 2.7
$\sigma \cdot B$ (stat)	2.38 ± 0.01	0.235 ± .003	2.28 ± 0.04	0.202 ± .016
(syst) (lum) [nb]	±0.09 ± 0.20	±.005 ± .020	±0.16 ± 0.19	±.020 ± .017

D01A [PRL 75, 1456(1995)]

$\sigma \cdot B$ (stat)	2.36 ± 0.02	0.218 ± .008	2.09 ± 0.06	0.178 ± .022
(syst) (lum) [nb]	± 0.07 ± 0.13	± .008 ± .012	± 0.22 ± 0.11	± .021 ± .009

Inclusive W and Z Production



Results consistent with SM predictions (band)

Cross sections calculated to $\mathcal{O}(\alpha_s^2)$ using CTEQ2M - (van Neerven *et al.*, Nucl. Phys. B382, 1992)

Indirect Measurement of W Width

measure ratio - many errors cancel

$$R_{e+\mu} = \frac{\sigma_W \cdot B(W \rightarrow l\nu)}{\sigma_Z \cdot B(Z \rightarrow ll)} = 10.32 \pm 0.43$$

and extract

$$B(W \rightarrow l\nu) = \frac{B(Z \rightarrow ll)\sigma_Z}{\sigma_W} \cdot R_{e+\mu} = 10.44 \pm 0.44\%$$

inputs: $\frac{\sigma_W}{\sigma_Z} = 3.33 \pm 0.03$ → from theory - error dominated by pdfs

$B(Z \rightarrow ll) = (3.367 \pm 0.006)\% \rightarrow$ LEP

and use

$$\Gamma_W = \frac{\Gamma(W \rightarrow l\nu)}{B(W \rightarrow l\nu)}$$

input: $\Gamma(W \rightarrow l\nu) = 225.2 \pm 1.5$ MeV → SM prediction

- Rosner *et al.*, PRD49 (1994) 1363.

Indirect Measurement of W Width

DØ 1A Result [PRL 75, 1456(1995)]

$$\Gamma_W = 2.044 \pm 0.093 \text{ GeV}$$

DØ 1B Result [Preliminary]

$$\Gamma_W = 2.159 \pm 0.092 \text{ GeV}$$

Standard Model Prediction

$$\Gamma_W = 2.077 \pm 0.014 \text{ GeV}$$

⇒ Comparison of world average (not including 1B result) $\Gamma_W = 2.062$ with SM prediction gives limit on unknown decay modes of W:

95% CL upper limit of $\Delta\Gamma < 109$ MeV on unexpected decays

M_W - Direct Measurement by DØ

⇒ **Analysis based on Run 1A data sample (published)**
  - **PRL 77 (1996) 3309**
  - **PRD in progress**
  - **will concentrate on this measurement**

⇒ **Preliminary results based on Run 1B data**

⇒ **Preliminary results using ratio method**

⇒ **Comparisons to other Measurements**

⇒ **Standard Model Implications**

⇒ **Future**

⋆ **for M_W measurement use:**

$W \to e\nu$ **and** $Z \to ee$ **data samples**

with electrons in central calorimeter (CC)

M_W - Quantities Measured

electron (e) momentum (+ underlying event)

recoil (R) transverse momentum (+ underlying event)

recoil longitudinal momentum not known

→ particles escape down beamline

W events:	*Z events:*
have: $\vec{P}(e), \vec{P}_T(R)$	have: $\vec{P}(e1), \vec{P}(e2), \vec{P}_T(R)$
$\vec{P}_T(R) = -\vec{P}_T(W)$	$\vec{P}_T(R) = -\vec{P}_T(Z)$

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

→ Cannot reconstruct W invariant mass
Instead study p_T^e and M_T^W distributions:
At current luminosities, best to use M_T^W

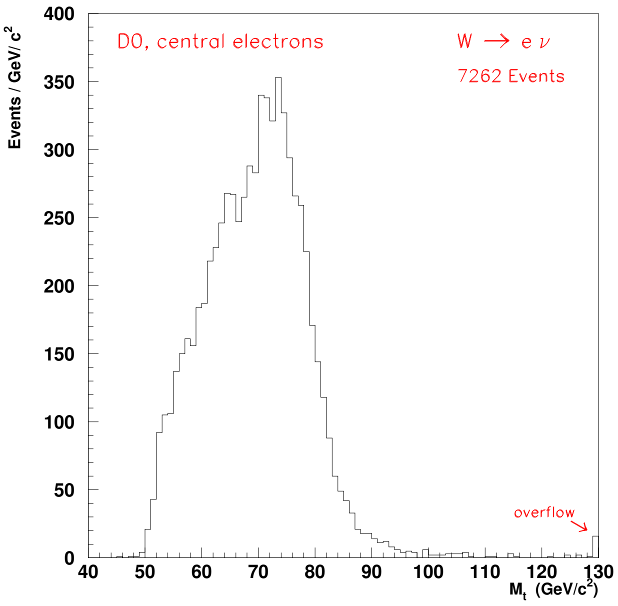
Measure quantities:

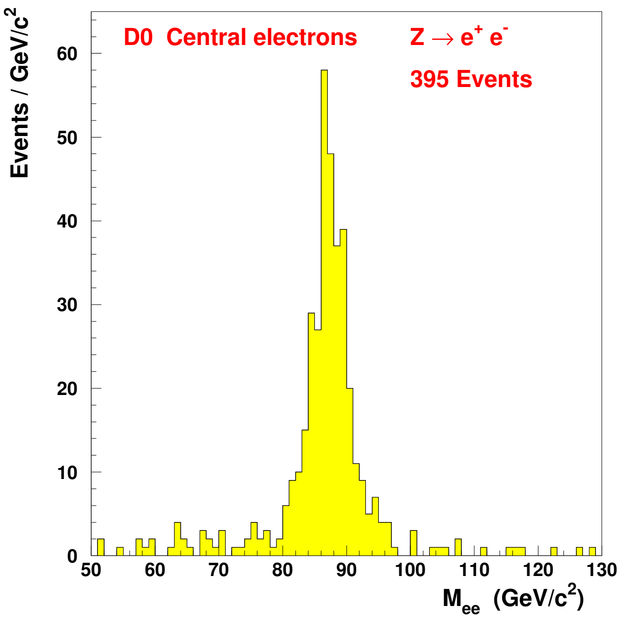
$M_T^W = \sqrt{2E_T^e E_T^\nu (1 - \cos\varphi)}$ $\qquad$ $M_Z = \sqrt{2E^{e1} E^{e2} (1 - \cos\varphi)}$

M_W - Event Sample

		# events: 1A	1B
$W \rightarrow e\nu$		7234	32856
⋆ e in CC:	$\lvert\eta\rvert < 1.2$		
⋆ electron:	$p_T^e > 25$ GeV		
⋆ neutrino:	$\not{E}_T > 25$ GeV		
⋆ W transverse momentum:	$P_T^W < 30$ GeV		
⋆ transverse mass (1A)	$50 < M_T^W < 110$ GeV		
$Z \rightarrow ee$		366	1562
⋆ e's in CC:	$\lvert\eta\rvert < 1.2$		
⋆ 2 isolated electrons:	$p_T(e) > 25$ GeV		
⋆ invariant mass (1A)	$70 < M_Z < 110$ GeV		

Run 1A - spectra:





⋆ Also have data sample of $Z \rightarrow ee$ in CC/CC and CC/EC

- to ensure equivalent event topologies for some studies

M_W - Measurement Technique

No analytic description of the $M_T(W)$ distribution... therefore

- model data with fast Monte Carlo simulation
- generate $M_T(W)$ distributions as a function of M_W
  - do for 21 values of M_W, 100 MeV apart
- extract value of M_W by doing event-by-event max-likelihood fit of data to simulation
- backgrounds included during fitting

M_W - Fast Monte Carlo

⋆ **model what is measured in data!**

⋆ **will discuss main features shown below:**

- W production and decay ⟶ to get $\vec{P}_T(e)$ & $\vec{P}_T(W)$
- electron and hadronic energy scale
- energy & angular resolution
- additional energy due to underlying event
- selection biases & efficiencies
- kinematic cuts

(Z events modelled in analagous way)

⇒ **Points to Note!!**

⟶ **calibrate EM calorimeter response to Z's**

⟶ **measure ratio of W/Z mass:**

$$M_W = \frac{M_W^{meas}}{M_Z^{meas}} \cdot M_Z^{LEP}$$

⟶ **use $Z \rightarrow ee$ and other data to set most parameters**

⟶ **systematic errors set using large statistics samples of MC data - vary parameter within its errors**

M_W -Monte Carlo W Production

- Events generated using 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:

$$\frac{d\sigma}{dm} \sim \frac{e^{-\beta\cdot m}}{m} \cdot \frac{m^2}{(m^2-M^2)^2+\frac{m^4\Gamma^2}{M^2}}$$

- angular decay of W, respecting polarization

$$\frac{d^2\sigma}{dyd\cos\theta} \sim (1-\cos\theta_{cm})^2\cdot(\frac{1}{2}\frac{d\sigma_s^{W+}}{dy}+\frac{d\sigma_v^{W+}}{dy})+(1+\cos\theta_{cm})^2\cdot(\frac{1}{2}\frac{d\sigma_s^{W+}}{dy})$$

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

- τ decays: $W \rightarrow \tau\nu \rightarrow e\nu\nu\nu$ generated in MC - cannot differentiate in data from $W \rightarrow e\nu$

M_W - $P_T(e)$ Scale

→ **Absolute calibration of calorimeter not known**

→ **Measure ratio**

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

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

→ **EM energy response:**

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

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

$\star$ **π^0 & J/ψ events determine δ**

$\star$ **Z data determines α**