Electroweak Results
from the
Tevatron

presented by:

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representing the
CDF and DØ Collaborations

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Outline

- $W$ and $Z$ production
  - $\sigma \cdot B(W, Z \rightarrow e, \mu)$
  - $\Gamma_W$ - indirect, direct
  - $\sigma \cdot B(W \rightarrow \tau \nu)$

- Rare $W$ decays
  - $W \rightarrow \pi \gamma$
  - $W \rightarrow D, \gamma$

- Drell-Yan production: quark/lepton substructure

- Latest results for $M_W$

- Trilinear Gauge Boson Couplings
  - $W \gamma, WW/Z, Z\gamma$
  - Combined limits

- Conclusions
Run I Detectors

DØ: Hermetic, high-resolution Ur/LAr calorimetry ($|\eta| < 4.0$)

CDF: Extensive magnetic inner tracking volume (1.4 T)
W Bosons Detected

Number of W bosons detected

Years of Collider Runs (SPS, Tevatron and LEP II)

<table>
<thead>
<tr>
<th>Tevatron Run</th>
<th>Year</th>
<th>$\int \mathcal{L} dt$ (pb$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;0&quot;</td>
<td>1988-89</td>
<td>4 (CDF only)</td>
</tr>
<tr>
<td>1A</td>
<td>1992-93</td>
<td>20</td>
</tr>
<tr>
<td>1B</td>
<td>1994-95</td>
<td>90</td>
</tr>
<tr>
<td>1C</td>
<td>1995-96</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td></td>
<td>~ 130 total</td>
</tr>
<tr>
<td>2</td>
<td>begins April, 2000</td>
<td>&gt; 2 fb$^{-1}$ (×20)</td>
</tr>
</tbody>
</table>
Typical Candidate Samples

- Mass of $Z$ measured directly from invariant mass:
  \[ M_Z = \sqrt{2E_{t_1}E_{t_2}(1 - \cos \theta_{t_1,t_2})} \]

- Mass of $W$ extracted from $M_T^W$:
  \[ M_T^W = \sqrt{2E_T^lE_T^{\nu}(1 - \cos \Delta \phi^{l\nu})} \]

- Background contamination:
  $\leq 15\%$ for $W$, $\leq 5\%$ for $Z$
  (QCD, cosmic rays, etc.)

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Run 1b $W \rightarrow ev$ Sample

- 59579 candidates
- Lum = 76 pb$^{-1}$

Run 1b $Z \rightarrow ee$ Sample

- 5705 candidates
- Lum = 89 pb$^{-1}$
W and Z Production

\[ p\bar{p} \rightarrow W + X \quad p\bar{p} \rightarrow Z + X \]

\[ l\nu \quad ll \]

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

- \( W/Z \) identified via leptonic decays: \( l = e, \mu, (\tau) \)
  - \textit{Isolated, high-}\( p_T \) (>20-25 GeV/c) charged lepton(s)
  - \textit{Neutrino in W decays “detected” via} \( \not{E}_T \) :

\[ \not{E}_T \equiv -(\text{observed } E_T) = E^\nu_T \text{ (>20-25 GeV)} \]
\[ \sigma \cdot B = \frac{N_C - N_B}{\mathcal{L}} \cdot \frac{1}{\mathcal{A}\varepsilon} \]

- \( N_C \) = number of candidates
- \( N_B \) = estimated background
- \( \mathcal{L} \) = integrated luminosity
- \( \mathcal{A} \) = acceptance
- \( \varepsilon \) = efficiencies

- Measurements available from:
  - **DØ**: \( e, \mu \) channels
    (Run 1A and Run 1B data samples)
  - **CDF**: \( e \) channel
    (Run 1A (W), Run 1A+1B (Z) data samples)

- **Theoretical prediction at \( \mathcal{O}(\alpha_s^2) \) (CTEQ2M)**

<table>
<thead>
<tr>
<th></th>
<th>DØ (e)</th>
<th>CDF (e)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \int \mathcal{L}dt ) (pb(^{-1}))</td>
<td>75.9 \pm 6.4</td>
<td>19.7 \pm 0.7</td>
</tr>
<tr>
<td>( W ) candidates</td>
<td>59,579</td>
<td>13,796</td>
</tr>
<tr>
<td>( \mathcal{A}_W ) (%)</td>
<td>43.4 \pm 1.5</td>
<td>34.2 \pm 0.8</td>
</tr>
<tr>
<td>( \varepsilon_W ) (%)</td>
<td>70.0 \pm 1.2</td>
<td>72.0 \pm 1.3</td>
</tr>
<tr>
<td>Bkg ( W ) (%)</td>
<td>8.1 \pm 0.9</td>
<td>12.3 \pm 1.2</td>
</tr>
</tbody>
</table>
$W$ & $Z$ Cross Sections (cont.)

![Graph showing $\sigma \cdot B$ values for $e$, $\mu$, and $e$ events for DØ and CDF experiments.]

- Dominant uncertainties:
  - Theory: pdf's (3-5%)
  - Data: luminosity

<table>
<thead>
<tr>
<th></th>
<th>$\sigma \cdot B(W \rightarrow l\nu)$ (nb)</th>
<th>$\sigma \cdot B(Z \rightarrow ll)$ (nb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DØ(e) (Run 1B)</td>
<td>2.38 ± 0.01 ± 0.09 ± 0.20</td>
<td>±0.003 ± 0.005 ± 0.020</td>
</tr>
<tr>
<td>DØ(μ) (Run 1B)</td>
<td>2.38 ± 0.03 ± 0.17 ± 0.13</td>
<td>±0.011 ± 0.020 ± 0.009</td>
</tr>
<tr>
<td>CDF(e)</td>
<td>2.49 ± 0.02 ± 0.08 ± 0.09</td>
<td>±0.004 ± 0.004 ± 0.018</td>
</tr>
<tr>
<td>(Run 1A)</td>
<td></td>
<td>(Run 1A+1B)</td>
</tr>
<tr>
<td>Standard Model</td>
<td>2.42 ± 0.12</td>
<td>0.226 ± 0.010</td>
</tr>
</tbody>
</table>
Extracting $\Gamma_W$

$$R_\ell = \frac{\sigma \cdot B(W \to \ell\nu)}{\sigma \cdot B(Z \to \ell\ell)} = \frac{\sigma_W}{\sigma_Z} \frac{\Gamma(Z)}{\Gamma(Z \to \ell\ell)} \times \frac{\Gamma(W \to \ell\nu)}{\Gamma(W)}$$

$$\downarrow$$

$$B^{-1}(Z \to \ell\ell)$$

- Measure $R_\ell$ directly (expt'nl errors tend to cancel)
- Obtain remaining quantities on RHS to extract $\Gamma_W$:

  - $\frac{\sigma_W}{\sigma_Z} = 3.33 \pm 0.03$ (theory)
    

  - $B(Z \to \ell\ell) = (3.367 \pm 0.006)\%$ (LEP/SLC)

  - $\Gamma(W \to \ell\nu) = \frac{G_F M_W^2}{\sqrt{2} \pi} (1 + \delta) = 225.2 \pm 1.5$ MeV
    
    Rosner et al., PRD49, 1363 (1994)

<table>
<thead>
<tr>
<th>DØ $(e+\mu)$</th>
<th>Run 1B Preliminary</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_\ell$</td>
<td>10.48 ± 0.43</td>
</tr>
<tr>
<td>$B(W \to \ell\nu)%$</td>
<td>10.59 ± 0.44</td>
</tr>
<tr>
<td>$\Gamma_W$ (GeV)</td>
<td>2.126 ± 0.092</td>
</tr>
<tr>
<td>Standard Model (GeV)</td>
<td>2.077 ± 0.014</td>
</tr>
</tbody>
</table>

* Expect $\sim \times 2$ reduction in error for final result
Direct Measurement of $\Gamma_W$ (CDF)

- High tail region of $M_T$ distribution sensitive to $\Gamma_W$
  - Breit-Wigner shape > calorimeter resolutions
  - Measurement independent of theoretical input

CDF Preliminary

Transverse mass lineshape (normalized to unit area) for $\Gamma_w = 1.5, 1.7, ..., 2.5$ GeV

- Log-likelihood fit to Monte Carlo-generated templates with varying $\Gamma_W$
- Fit window: $110 < M_T < 200$ GeV (210 events - Run 1B)
- $e$ channel only
Direct Measurement of $\Gamma_W$ (cont’d)

CDF Preliminary

$\Gamma_W = 2.19 \pm 0.17 \pm 0.09$ GeV

$(\Gamma_W^{SM} = 2.077 \pm 0.014$ GeV$)$

- Systematic errors dominated by:
  - $W$ recoil modeling – 55 MeV
  - electron energy scale – 55 MeV
  - backgrounds – 40 MeV
Summary of $\Gamma_W$

\[ \Gamma_W = 2.062 \pm 0.059 \quad \text{World Average} \]
\[ \Gamma_W = 2.077 \pm 0.014 \quad \text{SM Prediction} \]

\[ \Delta \Gamma_W^{\text{non-SM}} < 109 \text{ MeV (95\% CL)} \]

Upper limit on unexpected contributions to $\Gamma_W$
(supersymmetric charginos or neutralinos, heavy quarks)
Lepton Universality

\[
\left( \frac{g_\tau^W}{g_e^W} \right)^2 = \frac{\sigma \cdot B(W \rightarrow \tau \nu)}{\sigma \cdot B(W \rightarrow e\nu)}
\]

- Select hadronic decays of \( \tau \):
  - Isolated, narrow, high-\( E_T \) jet (> 15-25 GeV)
  - Few associated charged tracks (1, 3 prong decays)
  - Large \( E_T \) (> 20-25 GeV)
  - No jet opposite in azimuth (QCD background)

- Recent preliminary DØ result:
  - 17 pb\(^{-1}\), 1202 candidates, 222 ± 16 background:
    \[
    \sigma \cdot B(W \rightarrow \tau \nu) = 2.38 \pm 0.09 \pm 0.10 \text{ nb}
    \Rightarrow \frac{g_\tau^W}{g_e^W} = 1.004 \pm 0.019 \pm 0.026
    \]

![Graph showing values of \( \frac{g_\tau^W}{g_e^W} \) for different experiments and the world average](image)

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>UA1</td>
<td>1.01 ± 0.117</td>
</tr>
<tr>
<td>UA2</td>
<td>1.02 ± 0.057</td>
</tr>
<tr>
<td>CDF</td>
<td>0.97 ± 0.07</td>
</tr>
<tr>
<td>DØ</td>
<td>1.004 ± 0.032</td>
</tr>
<tr>
<td>World Average</td>
<td>1.003 ± 0.025</td>
</tr>
</tbody>
</table>
Rare $W$ Decays

$W^\pm \rightarrow \pi^\pm \gamma$

- Theory: $\Gamma(W \rightarrow \pi\gamma)/\Gamma(W \rightarrow e\nu) \sim 3 \times 10^{-8}$
  

- Previous experimental limits:
  
  * UA2: $\leq 5 \times 10^{-3}$ (1992)
  * CDF: $\leq 2 \times 10^{-3}$ (Run 1A)
    
    - One isolated high-$p_T$ photon ($>23$ GeV/c)
    - Jet with isolated high-$p_T$ charged track ($>15$ GeV/c)
    - CDF Run 1B: $\varepsilon \times A \sim 4\%$, $\int \mathcal{L} dt = 83$ pb$^{-1}$

\[8\]
\[7\]
\[6\]
\[5\]
\[4\]
\[3\]
\[2\]
\[1\]

- 3 events in $\pi\gamma$ mass spectrum within $M_W \pm 3\sigma$

- Est. background: $(5.2 \pm 1.5)$ events (QCD direct photons)

\[\Rightarrow \sigma_W \cdot B(W \rightarrow \pi\gamma) \leq 1.7$ pb (95\% CL)

\[\Gamma(W \rightarrow \pi\gamma)/\Gamma(W \rightarrow e\nu) \leq 7 \times 10^{-4}\]
Rare $W$ Decays (cont'd)

$W^\pm \rightarrow D_s^\pm \gamma$

- Theory: $\Gamma(W \rightarrow D_s \gamma)/\Gamma(W \rightarrow e\nu) \sim 1 \times 10^{-6}$
- First experimental limit on this branching fraction
  - One isolated high-$p_T$ photon ($>22$ GeV/c)
  - One isolated high-$p_T$ $D_s$ candidate ($>22$ GeV/c):
    - $D_s^\pm \rightarrow \phi \pi^\pm$, $\phi \rightarrow K^+ K^-$
    - $D_s^\pm \rightarrow K^{*0} K^\pm$, $K^{*0} \rightarrow K^{\pm} \pi^\mp$
  - CDF Run 1B: $\epsilon \times \mathcal{A} \sim 7\%$, $\int \mathcal{L} dt = 82$ pb$^{-1}$

- 4 candidates in $D_s^\pm \gamma$ mass spectrum within $M_W \pm 3\sigma$
- Estimated background of 4 events (QCD direct photons)
  \[ \Rightarrow \sigma_W \cdot B(W \rightarrow D_s \gamma) \leq 27.4 \text{ pb (95\% CL)} \]
  \[ \Gamma(W \rightarrow D_s \gamma)/\Gamma(W \rightarrow e\nu) \leq 1.1 \times 10^{-2} \]

With 10 fb$^{-1}$, expect $\leq 10^{-6}$ for these types of processes. Long shot, but Run 2 may reveal something new here...
Drell-Yan Probe of Substructure

\[ q\bar{q} \rightarrow (\gamma, Z) \rightarrow l^+l^- \]

- Broad range of partonic cms energies available in \( \bar{p}p \) collisions
  - Low mass \( \Rightarrow \) low \( x \) probe (\( x \approx 0.006 \))
  - High mass \( \Rightarrow \) high \( x \), partonic substructure

- Contact interaction:

  Erichsen et al., PRL 50, 911 (1983)

  \[
  \mathcal{L} = \mathcal{L}_{SM} + \eta_{ij} \frac{g^2}{\Lambda_{ij}^2} (\bar{\psi}_i \gamma^\mu \psi_i) (\bar{\psi}_j \gamma_\mu \psi_j)
  \]

  - \( \Lambda_{ij} \) = compositeness scale
  - \( \eta_{ij} = +(-)1 \) destructive (constructive) interference
  - \( i, j = L, R \) chirality

- Gives rise to predicted Drell-Yan cross section of form:

  \[
  \frac{d\sigma}{dm} = \left( \frac{d\sigma}{dm} \right)_{DY} + \beta I + \beta^2 C
  \]

  - \( m \) = dilepton invariant mass
  - \( \beta = 1/((\Lambda_{ij}^2)^2) \)
  - \( I \) = Drell-Yan/contact term interference
  - \( C \) = pure contact term contribution to \( \text{xsec} \)
  - enhancement at high mass

- Measure \( M_{l\bar{l}} \geq 40 \text{ GeV} \)
  - Isolated \( ee, \mu\mu \) pairs, \( p_T^i > 20-25 \text{ GeV} \)
  - Backgrounds: dijets, \( Z \rightarrow \tau\tau \), cosmic rays
Drell-Yan (cont'd)

- Normalize predictions to observed cross section for $50 < M_{ll} < 150$ GeV (removes luminosity dependence)

- Binned likelihood fit as function of $\Lambda_{ij}^\pm$:

![Graph showing $d^2\sigma/dMdy$ for different models and mass values.]

<table>
<thead>
<tr>
<th>Model $(i,j)$</th>
<th>$\Lambda^+$ (TeV)</th>
<th>$\Lambda^-$ (TeV)</th>
<th>$\Lambda^+$ (TeV)</th>
<th>$\Lambda^-$ (TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LL</td>
<td>3.3</td>
<td>4.2</td>
<td>3.1</td>
<td>4.3</td>
</tr>
<tr>
<td>RR</td>
<td>3.3</td>
<td>4.0</td>
<td>3.0</td>
<td>4.2</td>
</tr>
<tr>
<td>LR</td>
<td>3.4</td>
<td>3.6</td>
<td>3.3</td>
<td>3.9</td>
</tr>
<tr>
<td>RL</td>
<td>3.3</td>
<td>3.7</td>
<td>3.3</td>
<td>3.7</td>
</tr>
<tr>
<td>VV</td>
<td>4.9</td>
<td>6.1</td>
<td>5.0</td>
<td>6.3</td>
</tr>
<tr>
<td>AA</td>
<td>4.7</td>
<td>5.5</td>
<td>4.5</td>
<td>5.6</td>
</tr>
</tbody>
</table>

- Other (representative) measurements:
  - $qqqq \Rightarrow 2.4$-2.7 TeV (DØ - submitted to PRL)
  - $eeqq \Rightarrow 2.0$-4.9 TeV (ZEUS - ICHEP '98)
  - $eeqq \Rightarrow 2.8$-6.3 TeV (OPAL - ICHEP '98)
  - $eell \Rightarrow 5.2$-11.8 TeV (ALEPH - ICHEP '98)
  - $\nu\nuqq \Rightarrow 4.2$-8.3 TeV (CCFR)
  - $\nu\nu\mu\mu \Rightarrow 3.1$ TeV (TRIUMF E185)

- Fundamental composition of matter being probed in variety of reactions; limits from $\sim 2$ - 11 TeV
\[ M_W^2 = \frac{\pi\alpha(M_Z^2)}{\sqrt{2}G_F} \cdot \frac{1}{1 - \frac{M_W^2}{M_Z^2}} \cdot \frac{1}{1 - \Delta r} \]

- \( M_Z, \alpha, G_F \) known to better than 25 ppm
- \( \Delta r \) measure of higher order corrections in SM
  - \( \gamma \) vacuum polarization (\( \approx 0.06 \))
  - vector boson self-energies (\( M_{t_{top}}^2, \ln(M_H^2/M_W^2) \) terms)
  - new physics (?)
  - \( \Delta r \equiv 0 \) at tree level (on-shell scheme)

\[ \Delta r \propto m_t^2 - m_b^2 \]

\[ \Delta r \propto \ln(m_H) \]

+ Additional corrections in SUSY models
\[ \rightarrow \Delta m_W \propto 250 \text{ MeV} \]

- **Precision measurement of** \( M_W \):
  - measure of radiative corrections in SM
  - with \( M_{t_{top}} \), provides constraint on \( M_H \)
  - tests the SM beyond tree level
**W** Mass (cont’d)

- **Longitudinal momentum of** $\nu$ **unknown ⇒ transverse mass:**
  \[
  M_T = \sqrt{2E_T^l E_T^\nu} (1 - \cos \Delta \phi_{l\nu})
  \]
  (with $E_T^\nu$ inferred from $E_T$)

  - $M_T$ invariant (to 1st order) under transverse Lorentz boosts
    (less sensitive to $p_T^W$)
  - No analytic form for resulting Jacobian ⇒ MC

![Graph showing distribution of $m_T$](image)

- Extract $M_W$ from fits to observed $M_W$ spectra
  - Generate $M_T$ lineshapes as function of $M_W$ via fast MC
  - Perform likelihood fit

- **Fast Monte Carlo**
  - Model $W$ production and subsequent decay
  - Fold in detector response, resolution effects
  - Generate resulting $M_T$ lineshapes for various input values of $M_W$

- Energy scale for both experiments anchored to measured invariant masses of known resonances

- Latest Tevatron results: Run 1B ($\approx$ 80-90 pb$^{-1}$)
  - DØ: $W \rightarrow e\nu$, PRL 80 3000 (1998), PRD accepted
  - CDF: $W \rightarrow \mu\nu$, preliminary
W Mass (cont’d)

- CDF Momentum Scale
  - Normalize observed $J/\Psi \rightarrow \mu\mu$ peak to world average $J/\Psi$ mass (250,000 events)

\[ \Delta M_{\mu^+\mu^-} \text{(MeV)} \]

\[ M_{J/\Psi}^{\text{meas}} = 3096.2 \pm 1.5 \text{ MeV} \]
\[ M_{J/\Psi}^{PDG} = 3096.88 \pm 0.04 \text{ MeV} \]
\[ M_{J/\Psi}^{\text{meas}} / M_{J/\Psi}^{PDG} = 0.99977 \pm 0.00048 \]

- Verified using $\Upsilon \rightarrow \mu\mu$ and $Z \rightarrow \mu\mu$ samples

- Dominant uncertainties are muon upstream energy loss and \( p_T \) dependence over relevant 3–40 GeV range
  \((\Delta M_{J/\Psi} = 1 \text{ MeV}, \Delta M_W = 26 \text{ MeV})\)

\[ \Delta M_W = 40 \text{ MeV/c}^2 \]
W Mass (cont’d)

• DO Electromagnetic Energy Scale
  ▶ Assume energy response of form: $E_{\text{obs}} = \alpha E_{\text{true}} + \delta$
  ▶ Implies $M_{\text{meas}} \approx \alpha M_{\text{true}} + \delta f \left( f = \frac{2(E_1 + E_2)}{m} \sin^2 \gamma/2 \right)$
  ▶ Compare against MC prediction in $(\alpha, \delta)$ grid for resonances reconstructed in situ:
    * $Z \rightarrow ee$
    * $\pi^0 \rightarrow \gamma \gamma \rightarrow eee$
    * $J/\Psi \rightarrow ee$

![Graph showing $\alpha_{EM}$ vs $\delta_{EM}$](image)

• $J/\Psi$ and $\pi^0$ constrain $\delta$; $Z$ constrains $\alpha$

• Including systematic errors from underlying event, non-linearities at low $E$:
  \[
  \alpha = 0.9533 \pm 0.0008 \\
  \delta = -0.16^{+0.03}_{-0.21} \text{ GeV} \\
  \Delta M_W = 70 \text{ MeV}/c^2 \\
  \text{(dominated by } Z \text{ statistics)}
  \]
W Mass (cont’d)

- CDF Momentum Resolution
  
  2-d fit for $M_Z$ and $\sigma(1/p_T)$ in $Z \rightarrow \mu\mu$ events

  \[
  \sigma(1/p_T) = (1.01 \pm 0.05) \times 10^{-3}
  \]

  $\Delta M_W = 25$ MeV/c²

- DØ EM Energy Resolution

  Use width of $Z \rightarrow ee$ to constrain constant term, $C$, in EM energy resolution: $\sigma(E) = \sqrt{C^2 + \frac{E}{\sqrt{E_t}}}$

  $\chi^2$/dof = 33.5/39

  $C = (1.5^{+0.27}_{-0.35})\%$

  $\Delta M_W = 20$ MeV/c²
W Mass (cont’d)

- Recoil Energy Scale and Resolution
  - Hadronic scale and resolution obtained from $p_T$ balance in $Z \rightarrow ee, \mu\mu$ decays (constrained)
    - For equal EM and hadronic response, $p_T^{ee} = p_T^{\mu\mu}$ (on average)
    - Recoil resolution extracted from width of $|p_T^{ee} + p_T^{\mu\mu}|$ distribution
      (Project quantities onto axis defined by inner bisector of $p_T^{ee}$ and $p_T^{\mu\mu}$ ("\(\eta\) axis))
  - Hadronic scale determined relative to scale for charged leptons

- DØ:
  - $\Delta M_W = 20$ MeV/c² (recoil energy scale)
  - $\Delta M_W = 25$ MeV/c² (recoil energy resolution)

- CDF:
  - $\Delta M_W = 90$ MeV/c² (recoil energy scale and resolution)
  - Set conservatively, will improve
**W Production Model**

\( p_T^W \) spectrum constrained by \( p_T^Z \):

- Large \( p_T \) region described by pQCD
- Low \( p_T \) region: non-perturbative regime
  - Ladinsky/Yuan: LO QCD matched with resummed calculation (*PRD 50, 4239 (1994)*)
  - 3 parameters describing non-perturbative effects: \( g_1, g_2, g_3 \)
  - \( g_2 \) most sensitive to shape effects
- Use \( p_T^Z \) spectra to fit for \( g_2 \) (and \( \Lambda_{QCD} \)):
  - \( g_2 = 0.59 \pm 0.095 \text{(stat)} \pm 0.052 \text{(sys)} \pm 0.043 \text{(pdf)} \) GeV\(^2\)
- Used to generate \( p_T^W \) spectra
W Charge Asymmetry, PDFs

- W production asymmetry
  - u quarks have larger momentum than d quarks
  - W⁺ boosted along p direction (u̅d → W⁺)
  - W⁻ boosted along p̅ direction (ūd → W⁻)

  \[ A(y_t) = \frac{d\sigma^+/dy_t - d\sigma^-/dy_t}{d\sigma^+/dy_t + d\sigma^-/dy_t} \]

  (Unfold V-A charge asymmetry of decay leptons: \(\sim (1 \pm \cos \theta)^2\))

- Asymmetry measurement provides useful constraints on parton distribution functions in the low x region (0.007 < x < 0.24) at \(Q^2 \approx M_W^2\)

- W production and decay modeling (\(p_T^W\), PDFs, radiative decays, \(\Gamma_W\)):
  - DØ: \(\Delta M_W = 30 \text{ MeV/c}^2\)
  - CDF: \(\Delta M_W = 55 \text{ MeV/c}^2\)
**W Mass (cont’d)**

**Summary of Errors on** $M_W$

(MeV/$c^2$)

<table>
<thead>
<tr>
<th>Source</th>
<th>CDF</th>
<th>DØ</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>($\mu$)</td>
<td>(e)</td>
</tr>
<tr>
<td><strong>Statistical</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$W$ sample</td>
<td>100</td>
<td>70</td>
</tr>
<tr>
<td>$Z$ sample (e energy scale)</td>
<td>–</td>
<td>65</td>
</tr>
<tr>
<td><strong>Total Statistical</strong></td>
<td>100</td>
<td>95</td>
</tr>
<tr>
<td><strong>Systematic</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Muon momentum scale</td>
<td>40</td>
<td>–</td>
</tr>
<tr>
<td>Lepton energy resolution</td>
<td>25</td>
<td>20</td>
</tr>
<tr>
<td>Calorimeter linearity</td>
<td>–</td>
<td>20</td>
</tr>
<tr>
<td>Recoil modeling</td>
<td>90</td>
<td>35</td>
</tr>
<tr>
<td>$W$ production model</td>
<td>55</td>
<td>30</td>
</tr>
<tr>
<td>Backgrounds</td>
<td>25</td>
<td>10</td>
</tr>
<tr>
<td>Lepton angle calibration</td>
<td>–</td>
<td>30</td>
</tr>
<tr>
<td>Fitting</td>
<td>10</td>
<td>–</td>
</tr>
<tr>
<td>Miscellaneous</td>
<td>15</td>
<td>10</td>
</tr>
<tr>
<td><strong>Total Systematic</strong></td>
<td>120</td>
<td>65</td>
</tr>
<tr>
<td><strong>Total Error</strong></td>
<td>155</td>
<td>115</td>
</tr>
</tbody>
</table>
W Mass (cont’d)

Transverse Mass Fits/Results

DO($W \rightarrow e\nu$)

$\chi^2$/dof = 79.5/60
KS Prob = 25%

$M_W^{DO} = 80.440 \pm 0.095$ (stat.) $\pm 0.065$ (syst.) GeV/c$^2$

CDF($W \rightarrow \mu\nu$)

CDF(1B) Preliminary
$\chi^2$/df = 158/139 ($50 < M_T < 120$)
$\chi^2$/df = 62/69 ($65 < M_T < 100$)

$M_W^{CDF} = 80.430 \pm 0.100$ (stat.) $\pm 0.120$ (syst.) GeV/c$^2$
**W Mass (cont’d)**

**Direct W Mass Measurements**

- **80.360 +/- 0.370** \( \rightarrow \) UA2 \((W \rightarrow e\nu)\)
- **80.410 +/- 0.180** \( \rightarrow \) CDF (Run 1A, \(W \rightarrow e\nu, \mu\nu\))
- **80.430 +/- 0.155** \( \rightarrow \) CDF (Run 1B*, \(W \rightarrow \mu\nu\))
- **80.375 +/- 0.120** \( \rightarrow \) CDF combined*
- **80.350 +/- 0.270** \( \rightarrow \) DØ (Run 1A, \(W \rightarrow e\nu\))
- **80.440 +/- 0.115** \( \rightarrow \) DØ (Run 1B*, \(W \rightarrow e\nu\))
- **80.430 +/- 0.110** \( \rightarrow \) DØ combined

- **80.400 +/- 0.090** \( \rightarrow \) Hadron Collider Average* (50 MeV Common Error)
- **80.370 +/- 0.090** \( \rightarrow \) LEP II* (ee \(\rightarrow WW\))

- **80.385 +/- 0.065** \( \rightarrow \) World Average

* : Preliminary

**World Average** = UA2 + DØ + CDF + LEP2 (Direct)

Including NuTeV \((M_{W}^{\nu T} = 80.250 \pm 0.110 \text{ GeV}/c^2)\) gives:

\[M_{W}^{all} = 80.350 \pm 0.055 \text{ GeV}/c^2\]
Prospects at the Tevatron

- Most systematic errors in $M_W$ are statistically limited
- Further analysis of Run 1 data:
  - DØ: use forward electrons
    $\Rightarrow \Delta M_W \sim 100 \text{ MeV/c}^2$
  - CDF: Finalize $\mu$ result (reduced errors), include $e$ channel
    $\Rightarrow \Delta M_W \sim 90 \text{ MeV/c}^2$
  - Final Tevatron Run 1 result:
    $\Rightarrow \Delta M_W \sim 75 \text{ MeV/c}^2$
- Run 2 with Main Injector – begins April, 2000
  - $\times 20$ more $\mathcal{L}_\text{dt}$ ($> 2 \text{ fb}^{-1}$)
  - $\mathcal{L}_\text{inst} \approx \times 10$
  - bunch spacing: $3.5 \mu\text{s} \rightarrow 400 (132) \text{ nsec}$
- Extensive detector upgrades now in progress:
  - DØ:
    * new solenoid (precision $\mu$'s), new inner tracker
      (silicon, fiber tracker, preshowers), muon upgrade
  - CDF:
    * new inner tracker (silicon and drift chamber), new
      scintillator-based forward calorimeter, extended $\mu$
      coverage
- Each experiment: $\Delta M_W \sim 40 \text{ MeV/c}^2$
- Combined: $\Delta M_W \sim 25 \text{ MeV/c}^2$, $\Delta M_{\text{top}} \sim 2 \text{ GeV/c}^2$
World Avg (Direct) $M_W = 80.385 \pm 0.065$ GeV/c$^2$
(UA2+$D\bar{0}$+CDF+LEP2)

$D\bar{0}$+CDF Top Mass: $M_{top} = 173.9 \pm 5.0$ GeV/c$^2$
(see talk by G. Apollinari)
Trilinear Gauge Boson Couplings

- Direct consequence of $SU(2) \times U(1)$ gauge symmetry
- Reduced Lagrangian described by four coupling parameters in each of the $W$ and $Z$ sectors (CP conserving/violating):
  - $WWV$ ($V = \gamma$ or $Z$): $\kappa, \lambda, \bar{\kappa}, \bar{\lambda}$
  - $ZV\gamma$ ($V = \gamma$ or $Z$): $h_{30}, h_{40}, h_{10}, h_{20}$
- Gauge invariance of SM constrains boson self-couplings:
  - $\Delta \kappa = \kappa - 1 = \lambda = 0$
  - $\bar{\kappa} = \bar{\lambda} = 0$
  - all $h_{i0} = 0$
- $WWV$ parameters related to fundamental properties of the $W$ boson:
  $\mu_W = \frac{e}{2M_W} (1 + \kappa + \lambda)$
  $Q_W = \frac{e}{M_W} (\kappa - \lambda)$
- If couplings anomalous:
  - Gauge cancellations destroyed
  - Increase of production cross section at large $\sqrt{s}$
  - Change in differential distributions (i.e., $p_T^d, p_T^w$)
  - Form factor introduced to avoid violation of unitarity:
    $f f = \left[1/(1 + s/\Lambda^2)\right]^n, n = 2(WWV), 3(h_{1,3}), 4(h_{2,4})$
- Investigation of trilinear couplings provides important test of SM – could provide window to new physics
**Wγ Production**

![Diagrams showing W → lν, Production, Radiative, WWγ vertex]

- **Event selection:**
  - Isolated high $p_T$ muon or electron + large $E_T$
  - Isolated photon with $p_T^γ > 7$ (CDF) or 10 (DØ) GeV/c
  - $ΔR_{lγ} > 0.7$ (suppresses contribution from radiative decays)

- **Primary background:** $W$ + jets
  (with jet → $π^0 → γγ$)

- **Binned likelihood fit to $p_T^γ$ spectrum**

<table>
<thead>
<tr>
<th>$\frac{1}{L} \cdot dt \ (pb^{-1})$</th>
<th>DØ</th>
<th>CDF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of candidates</td>
<td>93</td>
<td>67</td>
</tr>
<tr>
<td>Total background</td>
<td>42.9 ± 5.3</td>
<td>26.4 ± 3.1</td>
</tr>
</tbody>
</table>
$W\gamma$ Production (cont’d)

$D\bar{O} \ p_T^\gamma$ spectrum

- $D\bar{O}$ limits at 95% CL, $\Lambda = 1.5$ TeV:
  
  $-0.93 < \Delta\kappa_\gamma < 0.94$ (for $\lambda_\gamma = 0$)
  
  $-0.31 < \lambda_\gamma < 0.29$ (for $\Delta\kappa_\gamma = 0$)

* Independent of $WWZ$ vertex
  (unlike $WW$ production)

* First direct evidence that photon couples to more
  than just electric charge of the $W$

  ▶ $U(1)_{EM}$-only coupling ruled out at 96% CL
  (assuming $\lambda = \bar{\kappa} = \bar{\lambda} = 0$)
$WW \rightarrow l\nu l\nu \ (l = e, \mu)$

- Event selection:
  - Two isolated high-$p_T$ leptons ($p_T > 15-25$ GeV/c)
  - $E_T > 20-25$ GeV
- Backgrounds: $Z \rightarrow \tau\tau$, Drell-Yan, $t\bar{t}$

<table>
<thead>
<tr>
<th></th>
<th>DØ</th>
<th>CDF</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\int L dt \ (pb^{-1})$</td>
<td>97</td>
<td>108</td>
</tr>
<tr>
<td>Number of candidates</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Total background</td>
<td>3.1 ± 0.4</td>
<td>1.2 ± 0.4</td>
</tr>
<tr>
<td>$N_{SM}$</td>
<td>2.10 ± 0.15</td>
<td>3.5 ± 1.2</td>
</tr>
<tr>
<td>$\sigma_{WW}$</td>
<td>&lt; 37.1 pb (95% CL)</td>
<td>(10.2^{+6.3}_{-5.1} ± 1.6) pb</td>
</tr>
<tr>
<td>Standard Model</td>
<td>$\sigma_{WW} = (9.5 ± 1.0)$ pb</td>
<td></td>
</tr>
</tbody>
</table>

- To obtain limits on anomalous couplings:
  - CDF fits to total number of events
  - DØ fits to lepton $p_T$ spectrum (better limits).
    For $\Lambda = 1.5$ TeV:
    
    \[-0.62 < \Delta\kappa < 0.77 \ (\text{for } \lambda = 0)\]
    \[-0.53 < \lambda < 0.56 \ (\text{for } \Delta\kappa = 0)\]
$WW, WZ \rightarrow l\nu jj$, $lljj$ ($l = e, \mu$)

- Event selection:
  - One isolated high-$p_T$ lepton ($p_T > 20-25$ GeV/c)
  - Two or more jets with $E_T > 20-30$ GeV, and jet-jet invariant mass consistent with a $W$ or $Z$
  - $p_T > 20–25$ GeV, or a second high-$p_T$ lepton (for $lljj$ events)

- Large backgrounds from $W +$ jets and QCD multi-jets

- To obtain limits on anomalous couplings:
  - CDF: $p_T(jj) > 200$ GeV/c ($110$ pb$^{-1}$)
  - DØ: binned likelihood fit to $p_T^{\ell\nu}$ spectrum ($86$ pb$^{-1}$)

<table>
<thead>
<tr>
<th></th>
<th>DØ</th>
<th>CDF</th>
</tr>
</thead>
<tbody>
<tr>
<td>95% CL Limits</td>
<td>$-0.43 &lt; \Delta \kappa &lt; 0.59$</td>
<td>$-0.49 &lt; \Delta \kappa &lt; 0.54$</td>
</tr>
<tr>
<td>($\Lambda = 2$ TeV)</td>
<td>$-0.33 &lt; \lambda &lt; 0.36$</td>
<td>$-0.35 &lt; \lambda &lt; 0.32$</td>
</tr>
</tbody>
</table>

* Both experiments exclude $U(1)_{EM}$-only point ($\kappa_Z = \lambda_Z = 0$) at 99% CL when SM $WW\gamma$ couplings are assumed
  ⇒ First direct evidence of $WWZ$ coupling
DØ Combined Analysis of $WW\gamma$ and $WWZ$ Couplings

- DØ has performed a simultaneous fit to:
  - $p_T^\gamma$ spectrum in $W\gamma$ data
  - $p_T^l$ distribution in $WW$ dilepton data
  - $p_T^W$ distribution in $WW, WZ \rightarrow e\nu jj$ events

- Limits on coupling parameters extracted from fit, taking into account correlations

![Diagram showing the limits on coupling parameters](image)

- For $\Lambda = 2.0$ TeV, $\lambda_\gamma = \lambda_Z$ and $\Delta\kappa_\gamma = \Delta\kappa_Z$:
  - $-0.30 < \Delta\kappa < 0.43$ ($\lambda = 0$)
  - $-0.20 < \lambda < 0.20$ ($\Delta\kappa = 0$)
**DØ Combined Analysis:**

\(\alpha_{B\phi}, \alpha_{W\phi}, \alpha_W\) Parameterization

- Allows comparison and combined analysis with LEP2 results. LEP2 parameter set:
  
  \[ \alpha_{B\phi} \equiv \Delta \kappa_\gamma - \Delta g_1^Z \cos^2 \theta_W \]
  
  \[ \alpha_{W\phi} \equiv \Delta g_1^Z \cos^2 \theta_W \]
  
  \[ \alpha_W \equiv \lambda_\gamma \]
  
  \[ \text{all } \alpha = 0 \text{ in SM} \]

- with constraints:
  
  \[ \Delta \kappa_Z = -\Delta \kappa_\gamma \tan^2 \theta_W + \Delta g_1^Z \]
  
  \[ \lambda_Z = \lambda_\gamma \]

<table>
<thead>
<tr>
<th>DØ (combined)</th>
<th>LEP2 (combined)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(-0.77 &lt; \alpha_{B\phi} &lt; 0.58)</td>
<td>(-0.44 &lt; \alpha_{B\phi} &lt; 0.95)</td>
</tr>
<tr>
<td>(-0.22 &lt; \alpha_{W\phi} &lt; 0.44)</td>
<td>(-0.12 &lt; \alpha_{W\phi} &lt; 0.13)</td>
</tr>
<tr>
<td>(-0.20 &lt; \alpha_W &lt; 0.20)</td>
<td>(-0.21 &lt; \alpha_W &lt; 0.27)</td>
</tr>
</tbody>
</table>

95% CL, \(\Lambda = 2\) TeV
DØ and LEP2 Combined Analysis

\( \alpha_{B\Phi} \) at LEP+D0 (preliminary)

\begin{align*}
\text{ALEPH} & : 0.28 \pm 0.30 \\
\text{DELPHI} & : 0.31 \pm 0.51 \\
\text{L3} & : -0.43 \pm 0.27 \\
\text{OPAL} & : 0.25 \pm 0.81 \\
\text{LEP} & : -0.04 \pm 0.32 \\
\text{D0} & : -0.08 \pm 0.84 \\
\text{LEP+D0} & : -0.05 \pm 0.22
\end{align*}

\(-0.42 < \alpha_{B\Phi} < 0.43\)

\( \alpha_{W\Phi} \) at LEP+D0 (preliminary)

\begin{align*}
\text{ALEPH} & : -0.14 \pm 0.27 \\
\text{DELPHI} & : 0.01 \pm 0.11 \\
\text{L3} & : -0.12 \pm 0.10 \\
\text{OPAL} & : -0.03 \pm 0.13 \\
\text{LEP} & : -0.04 \pm 0.06 \\
\text{D0} & : 0.11 \pm 0.18 \\
\text{LEP+D0} & : -0.03 \pm 0.06
\end{align*}

\(-0.14 < \alpha_{W\Phi} < 0.10\)

\( \alpha_W \) at LEP+D0 (preliminary)

\begin{align*}
\text{ALEPH} & : 0.04 \pm 0.51 \\
\text{DELPHI} & : -0.11 \pm 0.18 \\
\text{L3} & : -0.25 \pm 0.23 \\
\text{OPAL} & : 0.05 \pm 0.23 \\
\text{LEP} & : -0.09 \pm 0.13 \\
\text{D0} & : 0.00 \pm 0.18 \\
\text{LEP+D0} & : -0.03 \pm 0.08
\end{align*}

\(-0.18 < \alpha_W < 0.13\)

(LEPEWWG/TGC/98-01, DØ Internal Note # 3437 (May, 1998))
$Z\gamma$ Production

- Both DØ and CDF have performed measurements in the $Z(l^+l^-)\gamma$ mode:
  - Two high-$p_T$ leptons (ee or $\mu\mu$)
  - One photon with $E_T^\gamma > 7$–10 GeV
  - Major background: $Z+$ jet (→ fake $\gamma$)

- DØ (CDF) finds 35 (33) events with a background of 5.9 (1.4) in $\sim 105$ (67) pb$^{-1}$.

- Measurements agree with SM expectations. Limits found using binned maximum likelihood fit to $E_T^\gamma$ spectrum.

★ Most sensitive limits come from DØ measurement of $Z(\nu\nu)\gamma$:
  - Larger branching ratio than charged leptonic decay modes
  - No final state radiation from final state $l^+l^-$
  - High detection efficiency (one final state particle)
  - Backgrounds much higher ($W \rightarrow e\nu$, cosmic ray and beam halo muon bremsstrahlung) ⇒ tight selection cuts:
    - * $E_T^\gamma > 40$ GeV
    - * $E_T > 40$ GeV
    - * no jets with $E_T > 15$ GeV
  - Bremsstrahlung background reduced using “photon tracking”: “direction” of EM cluster consistent with event vertex
  - $W \rightarrow e\nu$ reduced via “hit counting” in tracking road about photon, and hard cuts on $E_T^\gamma$ and $\not{E}_T$ (above Jacobian peak)
**Z(\nu\nu)\gamma** Candidate from DØ

\[ E_T^Z = 67.9 \text{ GeV} \]
\[ \mathcal{E}_T = 56.6 \text{ GeV} \]
$Z(\nu\nu)\gamma$ (cont'd)

- Find 4 events over background of $5.8 \pm 1.0$ in $13 \text{ pb}^{-1}$. SM expectation: $1.8 \pm 0.2$ events.

- Anomalous coupling limits found using binned maximum likelihood fit to $E_T^\gamma$ spectrum:

<table>
<thead>
<tr>
<th>$\nu\nu$</th>
<th>$h_{40}^Z$</th>
<th>$h_{10}^\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$ee,\mu\mu,\nu\nu$</td>
<td>$</td>
<td>h_{30}^Z</td>
</tr>
<tr>
<td>$</td>
<td>h_{39}^Z</td>
<td>&lt; 0.36$, $</td>
</tr>
</tbody>
</table>

95% CL, $\Lambda = 750 \text{ GeV}$

Most stringent direct limits on these couplings from any experiment.
Summary

- Production cross section $\sigma \cdot B(W \rightarrow l\nu)$ measured for $e$, $\mu$, and $\tau$
  - agree with $\mathcal{O}(\alpha_s^2)$ theory
  - $g^W_\tau/g^W_e = 1.004 \pm 0.032$

- $W$ boson width:
  - Indirect: $\Gamma_W = 2.126 \pm 0.092$ GeV
  - Direct: $\Gamma_W = 2.19 \pm 0.19$ GeV

- Rare $W$ decays:
  - $\Gamma(W \rightarrow \pi\gamma)/\Gamma(W \rightarrow e\nu) \leq 7 \times 10^{-4}$
  - $\Gamma(W \rightarrow D_{s\gamma})/\Gamma(W \rightarrow e\nu) \leq 1.1 \times 10^{-2}$

- Limits on compositeness scale $\Lambda$ from Drell-Yan production range from:
  - $eeqq$: $\Lambda^{+-}_{LL} \geq 3.3$, $\Lambda^{-+}_{VV} \geq 6.1$
  - $llqq$: $\Lambda^{+-}_{RR} \geq 3.0$, $\Lambda^{-+}_{AA} \geq 6.3$

- Trilinear gauge boson couplings:
  - First direct evidence of $WWZ$ coupling
  - First direct evidence that the $W\gamma$ coupling is not purely electromagnetic

- $WW\gamma$, $WWZ$:
  - $-0.30 < \Delta \kappa < 0.43$, $-0.20 < \lambda < 0.20$
  - $-0.77 < \alpha_{B\phi} < 0.58$, $-0.22 < \alpha_{W\phi} < 0.44$
    - $-0.20 < \alpha_W < 0.20$

- $ZZ\gamma$, $Z\gamma\gamma$:
  - $|h_3^Z| < 0.36$, $|h_4^Z| < 0.37$, $|h_4^{Z\gamma}| < 0.05$

- $W$ Mass:
  - Hadron Collider Average: $M_W = 80.400 \pm 0.090$
    - (UA2+DØ+CDF)
  - Direct World Average: $M_W = 80.385 \pm 0.065$
    - (UA2+DØ+CDF+LEP2)
$WW, WZ \rightarrow l\nu jj, lljj \ (l = e, \mu)$

Event selection:

- One isolated high-$p_T$ lepton ($p_T > 20\text{-}25 \text{ GeV/c}$)
- Two or more jets with $E_T > 20\text{-}30 \text{ GeV}$, and jet-jet invariant mass consistent with a $W$ or $Z$
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- Large backgrounds from $W+\text{jets}$ and QCD multi-jets
- To obtain limits on anomalous couplings:
  - CDF: $p_T(jj) > 200 \text{ GeV/c} \ (110 \text{ pb}^{-1})$
  - DØ: binned likelihood fit to $p_T^{\text{enu}}$ spectrum (96 pb$^{-1}$)

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</tr>
<tr>
<td>($\Lambda = 2 \text{ TeV}$)</td>
<td>$-0.33 &lt; \lambda &lt; 0.36$</td>
<td>$-0.35 &lt; \lambda &lt; 0.32$</td>
</tr>
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- Both experiments exclude $U(1)_{EM}$-only point ($\kappa_Z = \lambda_Z = 0$) at 99% CL when SM $WW\gamma$ couplings are assumed
- First direct evidence of $WWZ$ coupling