Diboson Production and Drell-Yan Forward-Backward Asymmetry Measurements using the DØ Detector at Fermilab

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The Tevatron

- DØ data recorded to date $\sim 0.7 \text{ fb}^{-1}$
- Results shown in this talk are based on $\sim 150–320 \text{ pb}^{-1}$
- Expect $\sim 1 \text{ fb}^{-1}$ by Fall 2005
- $\sim 4-8 \text{ fb}^{-1}$ by 2009
The DØ Detector
The $WW\gamma$ and $WWZ$ Vertices

- Standard model $U(1)_Y \times SU(2)_L$ predicts existence of gauge boson self-interactions
- Direct measurement:
  - Demonstrate SM predictions are correct, or not...
  - Use as probe of new physics
- **Effective Lagrangian**
  parametrization of new physics in terms of coupling parameters
  - SM tree-level values:
    \[
    g_1^V = 1 \quad (\Delta g_1^V = g_1^V - 1 = 0)
    \]
    \[
    \kappa_V = 1 \quad (\Delta \kappa_V = \kappa_V - 1 = 0)
    \]
    \[
    \lambda_V = 0
    \]
- Unitarity violation avoided by use of **form factor**
  \[
  a(\hat{s}) = \frac{a_0}{(1 + \hat{s}/\Lambda_{FF}^2)^2}
  \]
  \[
  \hat{s} = \text{subprocess CM energy}
  \]
  \[
  \Lambda_{FF} = \text{form factor scale related to scale of new physics}
  \]

\[
L_{WWV} / g_{WWV} = i g_1^V \left( W_{\mu\nu}^+ W_{\nu\mu} - W_{\mu\nu}^+ V_{\nu} W_{\mu\nu} \right) + i \kappa_V W_{\mu}^+ W_{\mu} V_{\nu} + i \frac{\lambda_V}{m_w^2} W_{\mu}^+ W_{\mu} V_{\nu}^2 + \text{CP-violating terms}
\]

- $WW\gamma$ couplings related to magnetic dipole and electric quadrupole **moments of the $W$**
  \[
  \mu_w = \frac{e}{2m_w} (1 + \kappa_\gamma + \lambda_\gamma)
  \]
  \[
  Q_w^e = -\frac{e}{m_w^2} (\kappa_\gamma - \lambda_\gamma)
  \]

John Ellison, UCR

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Expectations for Couplings

• Expected values of $WW\gamma$ couplings in SM and some models beyond the SM

| Model            | $|\Delta\kappa_\gamma|$ | $|\lambda_\gamma|$ | $|\tilde{\kappa}_\gamma|$ |
|------------------|--------------------------|---------------------|--------------------------|
| standard model   | 0.008 [33, 34]           | 0.002 [34]          | $10^{-22}$ [35, 36]     |
| 2HDM             | 0.016 [37]               | 0.0014 [37]         | –                        |
| Multi-doublet    | –                        | –                   | $4 \times 10^{-6}$ [38, 35] |
| E6               | $2.5 \times 10^{-5}$ [39] | 0.003 [39]          | –                        |
| SUSY             | 0.005 [40]               | $5 \times 10^{-5}$ [40] | $3 \times 10^{-4}$ [41] |
| TC               | 0.002 [42]               | –                   | $7 \times 10^{-6}$ [42]  |
| 4th generation   | –                        | –                   | $5 \times 10^{-3}$ [43]  |

– See JE and J. Wudka, hep-ex/9804322
Diboson Production

- Effect of anomalous couplings:
  - Increased *diboson production cross section*
  - Increased *boson transverse momentum* in diboson production

- Cross sections in the standard model at 1.96 TeV:
  \[
  \begin{align*}
  \sigma(W\gamma \rightarrow l\nu \gamma) &= 16 \text{ pb}^* \\
  \sigma(Z\gamma \rightarrow ll\gamma) &= 3.9 \text{ pb}^* \\
  \sigma(WW) &= 13 \text{ pb} \\
  \sigma(WZ) &= 3.7 \text{ pb}
  \end{align*}
  \]
  * $E_T^\gamma > 8 \text{ GeV}$, $\Delta R(l\gamma) > 0.7$

- Diboson production is an important background in many high-$p_T$ analyses
  - e.g. $H \rightarrow WW$, top, trileptons

- **$W\gamma$ Production**
  - Probes $WW\gamma$ vertex
  - Main background is from $W + \text{jet}$ production; jet mimics a photon
  - Radiative decays suppressed by requiring $E_T^\gamma > 8 \text{ GeV}$, $\Delta R(l\gamma) > 0.7$
Wγ Production

- Event selection \( \int Ldt = 162 (e), 134(\mu) \, \text{pb}^{-1} \)
  - High \( p_T \) electron or muon
  - Missing \( E_T > 25,20 \, \text{GeV} \)
  - Isolated photon with
    - \( E_T > 8 \, \text{GeV}, |\eta| < 1.1 \)
    - \( \Delta R(l,\gamma) > 0.7 \)
- Background estimation
  - \( W + \text{jet} \) events from data
  - Probability for a jet to be misidentified as a photon
    - Estimated from multijet events in data
- SM predictions: Baur and Berger MC generator + parametrized detector simulation

<table>
<thead>
<tr>
<th>Channel</th>
<th>( e )</th>
<th>( \mu )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( N_{obs} )</td>
<td>112</td>
<td>161</td>
</tr>
<tr>
<td>( N_{bkg} )</td>
<td>60.8 ± 4.5</td>
<td>71.3 ± 5.2</td>
</tr>
<tr>
<td>( N_{obs} - N_{bkg} )</td>
<td>51.2 ± 11.5</td>
<td>89.7 ± 13.7</td>
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</table>
Results: $W\gamma$ Cross Section, $WW\gamma$ Couplings

- Measured cross sections for $W\gamma$ production with $E_T > 8$ GeV and $\Delta R(l\gamma) > 0.7$:

  \[ \sigma(W\gamma \to e\nu\gamma) = 13.9 \pm 2.9 \text{ (stat)} \pm 1.6 \text{ (syst)} \pm 0.9 \text{ (lum)} \text{ pb} \]
  \[ \sigma(W\gamma \to \mu\nu\gamma) = 15.2 \pm 2.0 \text{ (stat)} \pm 1.1 \text{ (syst)} \pm 1.0 \text{ (lum)} \text{ pb} \]

  **Combined Result:**
  \[ \sigma(W\gamma \to l\nu\gamma) = 14.8 \pm 1.6 \text{ (stat)} \pm 1.0 \text{ (syst)} \pm 1.0 \text{ (lum)} \text{ pb} \]

  Standard Model (Baur and Berger):
  \[ \sigma(W\gamma \to l\nu\gamma) = 16.0 \pm 0.4 \text{ pb} \]

- Limits on couplings obtained from likelihood fit to photon $E_T$ spectrum

  - 95% CL 1-d limits for $\Lambda_{FF} = 2$ TeV:
    \[ -0.88 < \Delta \kappa_\gamma < 0.96 \]
    \[ -0.20 < \lambda_\gamma < 0.20 \]


**Wγ Radiation Zero**

- Radiation zero in all helicity amplitudes for $W\gamma$ production in SM
  - For $u\bar{d} \rightarrow W^+\gamma$, amplitudes **vanish** for $\cos\theta = -1/3$
  - $\theta$ = scattering angle of photon w.r.t. quark direction in $W\gamma$ rest frame
  - Corresponds to dip at $\eta(\gamma) - \eta(l^+) \approx -0.4$

- In practice, zero is partially filled in
  - Effects of pdf’s, higher-order QCD corrections, final state photon radiation

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**DØ preliminary, muon channel**

- **Wide $\eta$ coverage essential**; extend for electrons and photons in future

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*SM, no det. effects*
WW Cross Section

- **WW production**
  \[ p\bar{p} \rightarrow W^+W^- \rightarrow \ell^+\nu\ell'^-\nu' \]
  in three decay modes: ee, μμ, eμ

- **Selection**
  - \[ \int Ldt = 252 (ee), 224 (\mu\mu), 235 (e\mu) \text{ pb}^{-1} \]
  - Two oppositely charged leptons with \( p_T > 15 \text{ GeV} \)
  - At least one with \( p_T > 20 \text{ GeV} \)

- **Additional selection based on**
  - Missing \( E_T, m_T, \Delta\phi(\text{jet, } E_T), \Delta\phi(\mu,\mu), \Sigma E_T^{\text{jet}}, Z \text{ mass window} \)

- **Good agreement of data with SM WW production + backgrounds**

- **Monte Carlo**
  - PYTHIA + parametrized detector simulation

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Graphs showing data for different lepton pairs ee, μμ, eμ.
**WW Cross Section Results**

- Probability of background fluctuation is very low: 5.2σ

- **Measured cross section**
  \[ \sigma(p\bar{p} \rightarrow W^+W^-) = 13.8^{+4.3}_{-3.8}\text{(stat)}^{+1.2}_{-0.9}\text{(syst)} \pm 0.9\text{(lum)} \text{ pb} \]

- Good agreement with NLO calculations 12.0-13.5 pb
  - Ohnemus/Campbell and Ellis

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<th>eμ</th>
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<tr>
<td>( N_{obs} )</td>
<td>6</td>
<td>4</td>
<td>15</td>
</tr>
<tr>
<td>( N_{bkg} )</td>
<td>2.30 ± 0.21</td>
<td>1.95 ± 0.41</td>
<td>3.81 ± 0.17</td>
</tr>
<tr>
<td>( N_{WW(SM)} )</td>
<td>3.42 ± 0.05</td>
<td>2.10 ± 0.05</td>
<td>11.10 ± 0.10</td>
</tr>
</tbody>
</table>
WZ Production

- Sensitive to WWZ vertex
  - cf. WW production, which depends on WWZ and WWγ
  - Allows study of WWZ coupling parameters with **no assumptions** about WWγ couplings

- SM cross section is 3.7 pb

- WZ → ℓν ℓ⁺ℓ⁻ mode is clean and unambiguous
  - But has low branching fraction 1.5%

- WZ → ℓν jj mode has larger branching fraction (15%)
  - But cannot distinguish WZ from W+jets, WW
WZ → Trileptons

- Event selection
  - $\int L dt = 320 \ (eeee), 290 \ (\mu\nu\nu\mu)$
    - $280 \ (e\nu\mu\mu), 290 \ (\mu\nu\mu\mu) \ \text{pb}^{-1}$
  - 3 charged leptons $p_T > 15 \ \text{GeV}$, missing $E_T > 20 \ \text{GeV}$, $M_Z$ window
- Candidates:
  - 2 $\mu\nu\mu\mu$ events, 1 $e\nu$ ee event

- Total estimated background
  - $0.71 \pm 0.08$
  - $Z+$jet background estimated from dilepton + jet events and $P(j \rightarrow e), P(j \rightarrow \mu)$
  - Other backgrounds are from $Z\gamma, ZZ,$ and $ttbar$
Results and Limits on WWZ Coupling

- Probability of background of 0.71 events to fluctuate to three or more candidates is 3.5%
  - Assume excess events due to WWZ signal: Cross section
    \[ \sigma(p\bar{p} \rightarrow WZ) = 4.5 \pm^{+3.8}_{-2.6} \text{ pb} \]
    <13.3 pb at the 95% C.L.
  - Agrees with SM (Campbell+Ellis)
    \[ \sigma^{NLO}_{SM}(p\bar{p} \rightarrow WZ) = 3.7 \pm 0.1 \text{ pb} \]

- 95% CL limits on WWZ coupling parameters for \( \Lambda_{FF} = 1.5 \) TeV:

\[
\begin{align*}
\Delta g^Z_1 &= \Delta \kappa_Z = 0 \\
\lambda_Z &= \Delta \kappa_Z = 0 \\
\lambda_Z &= \Delta g^Z_1 = 0 \\
\lambda_Z &= 0, \Delta g^Z_1 = \Delta \kappa_Z \\
\end{align*}
\]

\[
\begin{align*}
-0.53 < \lambda_Z < 0.56 \\
-0.57 < \Delta g^Z_1 < 0.76 \\
-2.0 < \Delta \kappa_Z < 2.4 \\
-0.49 < \Delta g^Z_1 = \Delta \kappa_Z < 0.66 \\
\end{align*}
\]

- Limits are model-independent (no WW\gamma coupling assumptions)
- Factor of \( \sim 3 \) better than Run I

\[
\begin{array}{c}
\text{Condition} \\
\Delta g^Z_1 = \Delta \kappa_Z = 0 \\
\lambda_Z = \Delta \kappa_Z = 0 \\
\lambda_Z = \Delta g^Z_1 = 0 \\
\lambda_Z = 0, \Delta g^Z_1 = \Delta \kappa_Z \\
\end{array}
\]
Anomalous ZZγ and Zγγ Couplings

- **Effective Lagrangian**

\[
L_{Z,V} = -ie \left[ Z^\mu (\begin{array}{c} h_1^V F^{\mu\nu} + h_3^V \tilde{F}^{\mu\nu} \\ \frac{\Box + m_V^2}{m_Z^2} \end{array} ) V_\nu \right] \\
- ie \left[ h_2^V F^{\mu\nu} + h_4^V \tilde{F}^{\mu\nu} \frac{\Box + m_V^2}{m_Z^4} \partial_\alpha \partial_\mu V_\nu \right]
\]

- \( h_1^V \) and \( h_2^V \) violate CP; \( h_3^V \) and \( h_4^V \) conserve CP

- All coupling parameters are zero in the SM at tree-level

- Form factor to ensure unitarity

\[
a(\hat{s}) = \frac{a_0}{\left(1 + \frac{\hat{s}}{\Lambda_{FF}^2}\right)^n}
\]

\( \hat{s} = \) subprocess CM energy \( \Lambda_{FF} = \) form factor scale

\[
n = 3 \text{ for } h_{1,3}^V \text{ and } n = 4 \text{ for } h_{2,4}^V
\]

- ZZγ couplings related to **transition moments of the Z**, e.g.

\[
\mu_w = \frac{-e}{\sqrt{2}m_Z} \frac{E_\gamma^2}{m_Z^2} \left( h_1^Z - h_2^Z \right)
\]

\[
Q_Z^e = \frac{2\sqrt{10}e}{m_Z^2} h_1^Z
\]
Zγ Production

- Two charged leptons
  - p_T > 15/25 GeV (ee)
  - p_T > 15/15 GeV (μμ)
- M(ll) > 30 GeV
- Photon requirements same as in Wγ analysis
  - E_T > 8 GeV
  - ΔR(l,γ) > 0.7
  - |η| < 1.1
- Data sets:
  - 286 pb⁻¹ (μμ), 324 pb⁻¹ (ee)
- Main background is from Z + jet, where jet mimics a photon

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<td>N_bkg</td>
<td>23.6 ± 2.3</td>
<td>22.4 ± 3.0</td>
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<tr>
<td>N_{Zγ(SM)}</td>
<td>95.3 ± 4.9</td>
<td>126.0 ± 7.8</td>
</tr>
</tbody>
</table>

- Sample is a factor of 10 larger than in Run I
**Z\gamma Results**

- Measured cross section for $Z\gamma$ production with $E_T^{\gamma} > 8$ GeV, $\Delta R(l_\gamma) > 0.7$, and $M(ll) > 30$ GeV:
  \[
  \sigma(Z\gamma \rightarrow ll\gamma) = 4.2 \pm 0.4\text{(stat+syst)} \pm 0.3\text{(lum)} \text{ pb}
  \]
  - Good agreement with SM (Baur, Han, and Ohnemus):
    \[
    \sigma_{\text{SM}}^{\text{NLO}}(Z\gamma \rightarrow ll\gamma) = 3.9^{+0.1}_{-0.2} \text{ pb}
    \]
- Limits on anomalous couplings set using maximum likelihood fit to photon $E_T$ spectrum
- 95% CL 1-d limits for $\Lambda_{FF} = 1$ TeV:
  - $-0.23 < h_{10,30}^{Z} < 0.23$
  - $-0.020 < h_{20,40}^{Z} < 0.020$
  - $-0.23 < h_{10,30}^{\gamma} < 0.23$
  - $-0.019 < h_{20,40}^{\gamma} < 0.019$
  - Best limits to date
Drell-Yan Production and $A_{FB}$

- Forward-backward asymmetry depends on $v$ and $a-v$ couplings of the quarks and leptons to the Z
  - Sensitive to $\sin^2 \theta_W$, but need high luminosity (see JE, J. Rha, and U. Baur, hep-ex/0011009)
- Can measure $A_{FB}$ at cm energies above LEP II energy
  - Confirm $\gamma^*/Z$ interference (dominates at high cm energy)
  - Study possible new phenomena that affects $A_{FB}$, e.g. $Z'$, extra dimensions, ...
  - $A_{FB} \sim 0.6$ in SM
- Electron angle measured in Collins-Soper frame
- Select ee events
  - Electron $E_T > 25$ GeV, $|\eta| < 1.1$
  - At least one EM cluster must have a track match (with $E/p$)
    - Charge sign measurement
  - Int. lum. = 177 pb$^{-1}$
M_{ee}: Data – Monte Carlo Comparison

- 5259 candidates for M_{ee} > 70 GeV
- Monte Carlo
  - PYTHIA/PHOTOS event generator
  - M_{ee}-dependent K-factor to account for O(\alpha_s^2) QCD corrections
  - Parametrized detector simulation
- Main background is from multijet events; jets mimic electrons
  - N_{QCD} = 62.5 \pm 8.0
- Other backgrounds much smaller
  - Main one is W+jets (11.1 \pm 3.4)
Drell-Yan Differential Cross Section

- Differential Drell-Yan cross section obtained by correcting for:
  - Kinematic acceptance
  - Geometric acceptance
  - Detector resolution
  - QED final state radiation
  - Detection efficiencies
  - Backgrounds

- Observe agreement with NNLO QCD calculations

* $O(\alpha_s^2)$ calculation:
Hamberg, van Neerven and Matsuura, Nucl. Phys. B 359, 343 (1991);
A_{FB} Results

- Data agree with SM Monte Carlo prediction
  - Consistent with A_{FB} \sim 0.6 at high M_{ee}

![Graph showing Raw A_{FB} and Corrected A_{FB} with M_{ee} (GeV/c^2) on the x-axis and A_{FB} on the y-axis. The graph includes data points and Monte Carlo predictions.]
Summary

- Studies of $W\gamma$ production
  - Model-independent limits on $WW\gamma$ couplings
  - Looking for radiation zero
- $WW \rightarrow$ dileptons production cross section is consistent with NLO SM calculation
  - Understanding is important for Higgs search
- Evidence for $WZ$ production (trileptons)
  - Model-independent limits on $WWZ$ couplings
- Studies of $Z\gamma$ production
  - Factor of 10 more statistics than Run I
  - Limits on $h_{20,40}$ are the best to date
- Drell-Yan
  - Differential cross section $d\sigma/dM_{ee}$ and forward-backward asymmetry; consistent with SM predictions