Diboson Production
At D0

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Introduction

• Most recent Diboson measurements from D0 experiment at Fermilab's Tevatron Collider
  - $ZZ \rightarrow llll$
  - $Z\gamma \rightarrow \nu\nu\gamma$
  - $WW+WZ \rightarrow l\nu qq$
  - $WW \rightarrow l\nu l\nu$
  - $WV$ Combination ($V = \gamma, Z, W$)

• Diboson production at D0
  - The Tevatron is a vector boson factory
    - Able to deliver more than 50 pb^{-1}/week: ~600 $WW$, ~200 $WZ$, and ~100 $ZZ$ events!
  - Hadronic environment not as clean as LEP, but
    - Access to diboson processes not available at LEP ($WZ$ and $W\gamma$)
    - Able to probe higher energies
Introduction

- Probe of new physics above some higher energy scale $\Lambda_{\text{NP}}$
  - Could result in anomalous trilinear gauge-boson couplings (TGCs)
    - Affects cross sections and event kinematics
    - Anomalous TGCs could give clues to the mechanism for electroweak symmetry breaking
  - SM is the low energy limit of a more general theory

$\gamma W W$ and $Z W W$ TGCs
Probed by $W W$, $W Z$, and $W \gamma$ production
General Lagrangian has 14 TGC parameters
Assume EM gauge invariance and C and P conservation
⇒ 5 TGC parameters: $g_1^Z, \kappa_\gamma, \kappa_Z, \lambda_\gamma, \lambda_Z$

$\gamma Z Z$ and $\gamma \gamma Z$ TGCs
Probed by $Z Z$ and $Z \gamma$ production
General Lagrangian has 8 TGC parameters
Assume CP conservation
⇒ 4 TGC parameters: $h_3^\gamma, h_3^Z, h_4^\gamma, h_4^Z$
Introduction

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  - Could result in anomalous trilinear gauge-boson couplings (TGCs)
    - Affects cross sections and event kinematics
    - Anomalous TGCs could give clues to the mechanism for electroweak symmetry breaking
  - In the SM:
    \[
    \lambda_\gamma = \lambda_Z = 0 \quad \text{and} \quad g_1^Z = \kappa_\gamma = \kappa_Z = 1 \implies \Delta \kappa_V \equiv \kappa_V - 1 \\
    h_3^\gamma = h_3^Z = h_4^\gamma = h_4^Z = 0 \implies \Delta g_1^V \equiv g_1^V - 1
    \]
    $\Delta \kappa, \Delta g, \lambda, \text{ or } h \neq 0 \implies \text{anomalous TGCs}$
Introduction

- Probe of new physics above some higher energy scale $\Lambda_{NP}$
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    \[
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    \]
    \[
    h_3^\gamma = h_3^Z = h_4^\gamma = h_4^Z = 0
    \]
    $\Delta \kappa, \Delta g, \lambda,$ or $h \neq 0 \quad \Rightarrow$ anomalous TGCs

- Higgs and SUSY motivations
  - Same or similar final states
    - Vital to understand (often significant) diboson backgrounds
      - E.g., high mass Higgs exclusion dominated by $H \rightarrow WW$
  - Many common analysis techniques
    - Diboson measurements provide proving ground for techniques use in searches
**ZZ→llll**

(PRL 101, 171803 (2008))

- **Selected events in 1.7 fb\(^{-1}\) of Run II data**
  - Four isolated leptons
    - 4e channel: Four electrons with \(p_T > 30, 25, 15, 15\) GeV
    - 4\(\mu\) channel: Four muons with \(p_T > 30, 25, 15, 15\) GeV
    - 2e2\(\mu\) channel: Two electrons and two muons with \(p_T > 25, 15\) GeV
  - That came from a pair for \(Z\) bosons
    - Dilepton mass \(M_{ll} > 70, 50\) GeV
    - (one combo of opposite-charge, like-flavor lepton pairings)

- **Very clean signature**
  - No SM background with four high \(p_T\) leptons!
  - Small \(Z(\gamma)\)+jets background
    - Jets reconstructed as leptons
  - **Predicted background:** \(0.14^{+0.03}_{-0.02}\)
  - **Predicted signal:** \(1.89 \pm 0.08\)
  - ⇒ Observe 3 candidate events
• Production results

Measured cross section:
\[ \sigma(ZZ) = 1.75^{+1.27}_{-0.86}(\text{stat}) \pm 0.13(\text{syst}) \text{ pb} \]
Expected significance: 3.7\(\sigma\)
Observed significance: 5.3\(\sigma\) \(\Rightarrow\) First Tevatron observation!

• Combined with previous \(ZZ\to llll\) (1 fb\(^{-1}\)) analysis and \(ZZ\to ll\nu\nu\) (2.7 fb\(^{-1}\))

Measured cross section:
\[ \sigma(ZZ) = 1.60 \pm 0.63(\text{stat})^{+0.16}_{-0.17}(\text{syst}) \text{ pb} \]
Expected significance: 4.8\(\sigma\)
Observed significance: 5.7\(\sigma\)

SM NLO: \[ \sigma(ZZ) = 1.4 \pm 0.1 \text{ pb} \]
Selected events in 3.6 fb\(^{-1}\) of Run II data

- Single high energy photon with \(E_T > 90 \text{ GeV}\)
- Large missing transverse energy \(\not{E}_T > 70 \text{ GeV}\)

Reduce backgrounds:

- \(W \rightarrow l\nu\) and \(Z \rightarrow ll\) background
  - Veto muons, addit'l EM objects, isolated tracks
- Non-collision backgrounds
  (e.g., bremsstrahlung from beam halo)
  - Pointing algorithm: require \(|z_{EM} - z_{vtx}| < 10 \text{ cm}\)
- Mis-measured \(\not{E}_T\)
  - Require no jets (\(p_T > 15 \text{ GeV}\))

Predicted background: \(17.3 \pm 2.4\)
- Predicted signal: \(33.7 \pm 3.4\)
- Observe 51 candidate events
Production results

Measured cross section:
$$\sigma(Z\gamma; E_T^\gamma > 90 \text{ GeV}) \cdot \text{BR}(Z \rightarrow \nu\nu) = 32.9 \pm 9(\text{stat+syst}) \pm 2(\text{lumi}) \text{ fb}$$

Observed significance: $5.1\sigma \Rightarrow$ First Tevatron observation!

95% limits on anomalous $\gamma ZZ$ and $\gamma\gamma Z$ TGCs

- Use photon $E_T$ spectrum
  - Highly sensitive to anomalous TGCs
    $$|h_3^\gamma| < 0.036 \quad |h_3^Z| < 0.0019 \quad (\Lambda_{NP} = 1.5 \text{ TeV})$$
    $$|h_4^\gamma| < 0.035 \quad |h_4^Z| < 0.0019$$

- Combine with $Z\gamma\rightarrow e\gamma e$ and $Z\gamma\rightarrow \mu\mu\gamma$
  $$|h_3^\gamma| < 0.033 \quad |h_3^Z| < 0.0017$$
  $$|h_4^\gamma| < 0.033 \quad |h_4^Z| < 0.0017$$

SM NLO: $\sigma(Z\gamma; E_T^\gamma > 90 \text{ GeV}) \cdot \text{BR}(Z \rightarrow \nu\nu) = 39 \pm 4 \text{ fb}$

(PRL 102, 201802 (2009))
Production results

Measured cross section:
\[ \sigma(Z\gamma; E_T^{\gamma} > 90 \text{ GeV}) \cdot \text{BR}(Z \rightarrow \nu\nu) = 32.9 \pm 9(\text{stat+syst}) \pm 2(\text{lumi}) \text{ fb} \]

Observed significance: \( 5.1\sigma \Rightarrow \text{First Tevatron observation!} \)

95% limits on anomalous \( \gamma ZZ \) and \( \gamma\gamma Z \) TGCs

- Use photon \( E_T \) spectrum
  - Highly sensitive to anomalous TGCs
  \[ |h_{3\gamma}| < 0.036 \quad |h_{3Z}| < 0.0019 \quad (\Lambda_{NP}=1.5 \text{ TeV}) \]
  \[ |h_{4\gamma}| < 0.035 \quad |h_{4Z}| < 0.0019 \]

- Combine with \( Z\gamma \rightarrow e\gamma\gamma \) and \( Z\gamma \rightarrow \mu\mu\gamma \)
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  \[ |h_{4\gamma}| < 0.033 \quad |h_{4Z}| < 0.0017 \]

World best!

SM NLO: \( \sigma(Z\gamma; E_T^{\gamma} > 90 \text{ GeV}) \cdot \text{BR}(Z \rightarrow \nu\nu) = 39 \pm 4 \text{ fb} \)
**WW/WZ → ℓνqq**  

(PRL 102, 161801 (2009))

- **Selected events in 1.1 fb⁻¹ of Run II data**
  - One isolated lepton with $p_T > 20$ GeV
  - Missing transverse energy $E_T > 20$ GeV
  - Two jets with $p_T > 30, 20$ GeV

- **Reduce backgrounds:**
  - Multijet backgrounds
    - “Transverse” $W$ mass $> 35$ GeV
  - $W+$jets ($Z+$jets, top)
    - “Random Forest” multivariate discriminant
  - Fit to determine cross section

- **Production results**
  
  Measured cross section:
  \[ \sigma(WW+WZ) = 20.2 \pm 4.4(\text{stat+syst}) \pm 1.2(\text{lumi}) \text{ pb} \]
  Expected significance: $3.7\sigma$
  Observed significance: $5.3\sigma \Rightarrow$ First Tevatron evidence!

  SM NLO: $\sigma(WW+WZ) = 16.1 \pm 0.9 \text{ pb}$
95% limits on $\gamma_{WW}$ and $Z_{WW}$ TGCs

- Use $p_T$ of dijet system
- Requiring SU(2)$\times$U(1) symmetry (a.k.a. LEP parameterization):

$$\Delta \kappa_Z = \Delta g_1^Z - \Delta \kappa_{\gamma} \cdot \tan^2 \theta_W$$

and $\lambda_{\gamma} = \lambda_Z$

$\Rightarrow$ Three independent parameters

$$-0.44 < \Delta \kappa_{\gamma} < 0.55$$  \hspace{1cm} ($\Lambda_{NP}=2$ TeV)

$$-0.10 < \lambda < 0.11$$

$$-0.12 < \Delta g_1^Z < 0.20$$

- Equal couplings scenario (a.k.a. $\gamma_{WW}=Z_{WW}$)

$$\Delta \kappa_Z = \Delta \kappa_{\gamma}, \ \Delta g_1^Z = \Delta g_1^\gamma = 1,$$ \hspace{0.2cm} and $\lambda_{\gamma} = \lambda_Z$

$\Rightarrow$ Two independent parameters

$$-0.16 < \Delta \kappa < 0.23$$

$$-0.11 < \lambda < 0.11$$
• Selected events in 1 fb\(^{-1}\) of Run II data
  - Two isolated leptons
    - \(ee\), \(e\mu\), or \(\mu\mu\) of opposite charge
    - Leading lepton \(p_T > 25\) GeV
    - Trailing lepton \(p_T > 15\) GeV

  • Reduce backgrounds:
    - \(Z\rightarrow ll\) backgrounds
      - Optimized \(E_T\) cuts for each channel
    - \(tt\) and \(W+\text{jets}\)
      - Require balanced event
        - \(|p_T^{l_1} + p_T^{l_2} + E_T| < 20 (ee), 25 (e\mu), 16 (\mu\mu)\)

<table>
<thead>
<tr>
<th>Process</th>
<th>(ee)</th>
<th>(e\mu)</th>
<th>(\mu\mu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal</td>
<td>12.38 ± 0.62</td>
<td>44.43 ± 0.86</td>
<td>7.89 ± 0.35</td>
</tr>
<tr>
<td>Background</td>
<td>11.08 ± 1.80</td>
<td>24.21 ± 3.78</td>
<td>2.91 ± 0.46</td>
</tr>
<tr>
<td>Total expected</td>
<td>23.46 ± 1.90</td>
<td>68.64 ± 3.88</td>
<td>10.79 ± 0.58</td>
</tr>
<tr>
<td>Data</td>
<td>22</td>
<td>64</td>
<td>14</td>
</tr>
</tbody>
</table>
• **Production results**

  Measured cross section:  
  \[ \sigma(WW) = 11.5 \pm 2.1\text{(stat+syst)} \pm 0.7\text{(lumi)} \text{ pb} \]

• **95% limits on }\gamma_{WW} and Z_{WW} TGCs**
  
  - Use 2-dimensional distribution of lepton pT
  
  - Requiring SU(2)xU(1) symmetry:
    \[ \Delta \kappa_Z = \Delta g_1^Z - \Delta \kappa_{\gamma} \tan^2 \theta_W \text{ and } \lambda_{\gamma} = \lambda_Z \]

    \[
    \begin{align*}
    &-0.54 < \Delta \kappa_{\gamma} < 0.83 \\
    &-0.14 < \lambda < 0.18 \\
    &-0.14 < \Delta g_1^Z < 0.30
    \end{align*}
    \] (\(\Lambda_{NP}=2\text{ TeV}\))

  - Equal couplings:
    \[ \Delta \kappa_Z = \Delta \kappa_{\gamma}, \quad \Delta g_1^Z = \Delta g_1^{\gamma} = 1, \text{ and } \lambda_{\gamma} = \lambda_Z \]

    \[
    \begin{align*}
    &-0.12 < \Delta \kappa < 0.35 \\
    &-0.14 < \lambda < 0.18
    \end{align*}
    \]
**WV Combination**

- Combination of four analyses with \( \sim 1 \, \text{fb}^{-1} \)

**WZ\rightarrow l\nu l\nu** (PRD 76, 111104 (2007))

**WW\rightarrow l\nu l\nu** (arXiv.org:0904.0673)

**Wγ\rightarrow l\nu γ** (PRL 100, 241805 (2008))

**WW+WZ\rightarrow l\nu jj** (preliminary)
Combination of four analyses with $\sim 1 \text{ fb}^{-1}$

95% limits on $\gamma_{WW}$ and $Z_{WW}$ TGCs $(\Lambda_{NP}=2 \text{ TeV})$

- Requiring SU(2)xU(1) symmetry:
  \[
  \Delta \kappa_Z = \Delta g_1^Z - \Delta \kappa \cdot \tan^2 \theta_W \quad \text{and} \quad \lambda_{\gamma} = \lambda_Z
  \]
  
  \[-0.29 < \Delta \kappa_{\gamma} < 0.38\]
  
  \[-0.08 < \lambda < 0.08\]
  
  \[-0.07 < \Delta g_1^Z < 0.16\]

- Equal couplings:
  \[
  \Delta \kappa_Z = \Delta \kappa_{\gamma}, \quad \Delta g_1^Z = \Delta g_1^\gamma = 1, \quad \text{and} \quad \lambda_{\gamma} = \lambda_Z
  \]
  
  \[-0.11 < \Delta \kappa < 0.18\]
  
  \[-0.08 < \lambda < 0.08\]

$\Rightarrow$ Approaching sensitivity of the LEP2 experiments
Conclusions

- So far everything agree with the Standard Model
- Many of the measurements are firsts or bests from a hadron collider
Conclusions

- So far everything agree with the Standard Model
- Many of the measurements are firsts or bests from a hadron collider

First evidence of $WW + WZ \rightarrow lvqq$

First observation of $Z\gamma \rightarrow \nu\nu\gamma$

New measurement of $\sigma(WW)$

First observation of $ZZ$
Conclusions

- So far everything agree with the Standard Model
- Many of the measurements are firsts or bests from a hadron collider

And we now have over 6 fb$^{-1}$ of reconstructed data

⇒ The future is bright for Diboson physics at D0!
thank you
Anomalous Couplings

- **ZWW** and **γWW** couplings:
  - General Lorentz invariant Lagrangian has 14 couplings
  
  \[
  \frac{L_{WWV}}{g_{WWV}} = ig_1^Z (W_\mu^* W^\mu V^\nu - W_\mu V^\nu W^{\mu\nu}) + ig_1^\gamma W_\mu^* W_\nu V^\mu + i \frac{\lambda_1}{M_W^2} W_\mu^* W_\nu V^\nu
  \]
  
  \[- g_4^Z W_\mu W_\nu (\partial_\mu V^\nu + \partial_\nu V^\mu) + g_5^\gamma \epsilon^{\mu\nu} \left( W_\mu^* \partial_\nu W_\nu - \partial_\nu W_\mu^* W_\nu \right) V_\rho \]
  
  \[+ i \kappa_1^Z W_\mu^* W_\nu \tilde{V}^{\mu\nu} + i \frac{\lambda_1}{M_W^2} W_\mu^* W_\nu \tilde{V}^{\mu\nu} \]

- **γZZ** and **γγZ** couplings:
  - General Lorentz invariant Lagrangian has 8 couplings
  
  \[
  L_{V\gamma V} = -ie \left[ \left( h_1^\gamma F_\mu^\nu + h_3^\gamma \tilde{F}_\mu^\nu \right) V_\nu \left( \Box + m_\nu^2 \right) V_\nu + \left( h_3^Z F_\mu^\nu + h_4^Z \tilde{F}_\mu^\nu \right) Z_a \left( \Box + m_\nu^2 \right) \partial_a \partial_\mu V_\nu \right]
  \]

  - C and P conserving: \( g_1^\gamma = g_1^Z = \kappa = \kappa_\gamma = 1 \) and all others are zero
  - C and P violating, but CP conserving: \( g_5^Z, h_3^\gamma, h_3^Z, h_4^\gamma, h_4^Z \)
  - CP violating: \( g_4^Z, g_4^\gamma, \kappa, \kappa_\gamma, \lambda, \lambda_\gamma, h_1^\gamma, h_1^Z, h_2^\gamma, h_2^Z \)
**Anomalous Couplings**

- **ZWW and γWW couplings**
  - In the SM:
    - γWW and ZWW TGCs
      - $g_1^Z = \kappa_\gamma = \kappa_Z = 1$ and $\lambda_\gamma = \lambda_Z = 0$
    - No γZZ and γγZ TGCs
      - $h_{3\gamma} = h_{3Z} = h_{4\gamma} = h_{4Z} = 0$
  - Measure deviations from SM
    - $\Delta \kappa_V \equiv \kappa_V - 1$, $\Delta g_1^V \equiv g_1^V - 1$
    - $\Delta \lambda_V = \lambda_V$, $\Delta h_{3V} = h_{3V}$, $\Delta h_{4V} = h_{4V}$
    - $\Delta x \neq 0 \Rightarrow$ anomalous TGC
### $ZZ \rightarrow llll$

- Three candidate events

<table>
<thead>
<tr>
<th>4$e$ candidate 1</th>
<th>$e_1^+$</th>
<th>$e_2^+$</th>
<th>$e_3^-$</th>
<th>$e_4^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T$ (GeV)</td>
<td>107</td>
<td>59</td>
<td>52</td>
<td>16</td>
</tr>
<tr>
<td>$\eta$</td>
<td>0.66</td>
<td>0.25</td>
<td>-0.64</td>
<td>-0.85</td>
</tr>
<tr>
<td>$\phi$</td>
<td>4.10</td>
<td>1.08</td>
<td>0.46</td>
<td>2.62</td>
</tr>
<tr>
<td>$M_{lll}$ (GeV)</td>
<td>$e_1^+ e_4^-$</td>
<td>$e_2^+ e_3^-$</td>
<td>89 ± 3</td>
<td>61 ± 2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>4$e$ candidate 2</th>
<th>$e_1^+$</th>
<th>$e_2^+$</th>
<th>$e_3^-$</th>
<th>$e_4^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T$ (GeV)</td>
<td>83</td>
<td>75</td>
<td>35</td>
<td>26</td>
</tr>
<tr>
<td>$\eta$</td>
<td>0.64</td>
<td>0.40</td>
<td>0.85</td>
<td>1.17</td>
</tr>
<tr>
<td>$\phi$</td>
<td>6.16</td>
<td>3.80</td>
<td>3.83</td>
<td>1.40</td>
</tr>
<tr>
<td>$M_{lll}$ (GeV)</td>
<td>$e_1^+ e_3^-$</td>
<td>$e_2^+ e_4^-$</td>
<td>99 ± 3</td>
<td>90 ± 4</td>
</tr>
</tbody>
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<tr>
<th>4$\mu$ candidate</th>
<th>$\mu_1^+$</th>
<th>$\mu_2^+$</th>
<th>$\mu_3^-$</th>
<th>$\mu_4^+$</th>
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<tbody>
<tr>
<td>$p_T$ (GeV)</td>
<td>115</td>
<td>77</td>
<td>42</td>
<td>24</td>
</tr>
<tr>
<td>$\eta$</td>
<td>0.04</td>
<td>-1.01</td>
<td>0.77</td>
<td>-1.93</td>
</tr>
<tr>
<td>$\phi$</td>
<td>1.69</td>
<td>4.26</td>
<td>5.29</td>
<td>0.36</td>
</tr>
<tr>
<td>$M_{lll}$ (GeV)</td>
<td>$\mu_1^+ \mu_3^-$</td>
<td>$\mu_2^+ \mu_4^+$</td>
<td>148$^{+32}_{-18}$</td>
<td>90$^{+12}_{-8}$</td>
</tr>
</tbody>
</table>