Diboson Production at DØ

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Diboson Production at DØ

Motivation

- Triple Gauge Couplings (TGCs)
- The Tevatron and DØ
- $W\gamma \rightarrow \mu \nu \gamma$
- Radiation Amplitude Zero and TGCs
- $WZ \rightarrow \ell \nu \ell \ell$
- TGCs
- $ZZ \rightarrow \ell \ell \ell \ell$
- Kinematics
Motivation

- Precision test of standard model predictions
- Direct window to SM Higgs ($H \rightarrow WW/ZZ/Z\gamma$)
- Probe for new physics in kinematics
- Anomalous values of triple gauge boson couplings
SM has two charged TG vertices: $WWZ$ & $WW\gamma$

With EM gauge invariance and C and P cons., most general Lorentz inv. Lagrangian is:

$$\frac{\mathcal{L}_{WWV}}{g_{WWV}} = ig_1^V (W^\dagger_{\mu\nu}W^\mu - W^\dagger_{\mu\nu}W^\mu_{\nu})V^\nu$$

$$+ ig_1^V W^\dagger_\mu W_\nu V^{\mu\nu} + i \frac{\lambda_V}{M_W^2} W^\dagger_\mu W_\nu \rho V^\rho_\mu$$

...where $V = \gamma$ or $Z$, $g_{WW\gamma} = -e$, $g_{WWZ} = -e\cot\theta_W$, and $g_1^\gamma = 1$

In SM:

- $\lambda_V = 0$
- $g_1^\gamma = \kappa_V = 1$
- $(\Delta\kappa \equiv \kappa - 1)$
Anomalous TGC Limits

Anomalous TGCs introduced as dipole form factors to preserve partial-wave unitarity and avoid divergent cross sections

\[ A(\hat{s}) = \frac{A_0}{(1 + \hat{s}/\Lambda^2)^2} \]

Constraints may reduce free parameters


Equal coupling between SU(2)×U(1) and Higgs fields

\[ \Delta\kappa_Z = \Delta\kappa_\gamma (1 - \tan^2 \theta_W)/2, \quad \Delta g_1^Z = \Delta\kappa_\gamma /2\cos^2 \theta_W, \text{ and } \lambda_Z = \lambda_\gamma \]
Making Dibosons at Fermilab

The Tevatron produces $p\bar{p}$ collisions at CM energy ($\sqrt{s}$) 1.96 TeV

Thanks to the Accelerator Division for providing excellent performance!

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The DO Detector

\[ \eta = -\ln\left[\tan\frac{\theta}{2}\right] \]

- Silicon vertex detector
- Scintillating fiber tracking & preshower detectors
- LAr-U calorimeter
- Muon chambers

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Wγ → μνγ Production

- Event selection suppresses FSR
  - 1 Isolated μ, p_T > 20 GeV, |η| < 1.6
  - Missing E_T > 20, MET+μ M_T > 40 GeV
  - γ E_T > 10 GeV, |η| < 1.1 or 1.5 < |η| < 2.5
  - NN reduces fakes using CAL, CPS & tracker info
  - 3-body (μ,MET,γ) M_T > 110 GeV, ΔR_{μγ} > 0.7

- eμ+X, W+jet bkgds from data
- Z_{μμ}γ and W_{τν}γ from MC
- SM (p_Tγ > 8): σ = 16 ± 0.4 pb
- σ = 15.2 ± 0.4 (stat) ± 1.6 (syst) pb

<table>
<thead>
<tr>
<th></th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>eμ+X</td>
<td>5.2 ± 1.9</td>
</tr>
<tr>
<td>Z_{μμ}γ</td>
<td>21.3 ± 2.6</td>
</tr>
<tr>
<td>W_{τν}γ</td>
<td>6.2 ± 0.8</td>
</tr>
<tr>
<td>W+jet</td>
<td>101.5 ± 7.7</td>
</tr>
<tr>
<td>total background</td>
<td>134.2 ± 8.6</td>
</tr>
<tr>
<td>data</td>
<td>492</td>
</tr>
<tr>
<td>data - background</td>
<td>357.8 ± 23.8</td>
</tr>
<tr>
<td>signal</td>
<td>375.6 ± 41.5</td>
</tr>
</tbody>
</table>
**Radiation Amplitude Zero**

- From interference between tree level diagrams
  - Zero $\rightarrow$ dip for observables in lab frame
  - Obscured by FSR

- Observe dip consistent with the SM prediction
Anomalous $WW\gamma$ TGCs

- Limits set using $E_T^\gamma$ spectrum ($\Lambda = 2$ TeV)
- Improves previous 0.7 fb$^{-1}$ DØ limits by factor of 3
- Sensitivity comparable to the LEP experiments

68% C.L. Limits:

<table>
<thead>
<tr>
<th>Source</th>
<th>$-0.072 &lt; \Delta \kappa_\gamma &lt; 0.017$</th>
<th>$-0.049 &lt; \lambda_\gamma &lt; 0.008$</th>
<th>$-0.07 &lt; \Delta \kappa_\gamma &lt; 0.07$</th>
<th>$-0.012 &lt; \lambda_\gamma &lt; 0.011$</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEP2 combined</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DØ 4.2 fb$^{-1}$</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>
Four channels ($\ell = e, \mu$) with similar selection

- Three isolated $\ell$ with $p_T > 15$ GeV
  - ICR $e$ (1.1 < $|\eta|$ < 1.6) allowed as part of $Z$ decay
- MET > 20 GeV
- Best $M_Z$ from like-flavor opposite-sign leptons make $Z$
  - Other lepton considered as $W$ decay product
  - 92% correct for $eee$, 89% correct for $\mu\mu\mu$
- $V+\text{jets}$, $Z\gamma$ est. from data; $ZZ$, $t\bar{t}$ from MC
Dibosons at DØ

**WZ → ℓνℓℓ Production**

- 34 candidates
  - 23.3 ± 1.5 WZ
  - 6.0 ± 0.6 bkgd

<table>
<thead>
<tr>
<th>Source</th>
<th>eee</th>
<th>eeμ</th>
<th>eμμ</th>
<th>μμμ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total bkg.</td>
<td>1.33 ± 0.21</td>
<td>2.11 ± 0.31</td>
<td>1.13 ± 0.35</td>
<td>1.46 ± 0.24</td>
</tr>
<tr>
<td>WZ signal</td>
<td>5.9 ± 0.8</td>
<td>6.9 ± 0.8</td>
<td>4.7 ± 0.6</td>
<td>5.8 ± 0.8</td>
</tr>
<tr>
<td>Observed</td>
<td>9</td>
<td>11</td>
<td>9</td>
<td>5</td>
</tr>
</tbody>
</table>

- SM σ = 3.25 ± 0.19 pb
- Observed σ = 3.90 $^{+1.01}_{-0.85}$ (stat+syst) ± 0.31 (lumi) pb
**WZ Anomalous TGCs**

- $Z p_T$ spectrum used to set TGC limits
  - Most stringent limits from direct WZ study

<table>
<thead>
<tr>
<th>Coupling relation</th>
<th>95% C.L. Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta g_1^Z = \Delta \kappa_Z = 0$</td>
<td>$-0.075 &lt; \lambda_Z &lt; 0.093$</td>
</tr>
<tr>
<td>$\lambda_Z = \Delta \kappa_Z = 0$</td>
<td>$-0.053 &lt; \Delta g_1^Z &lt; 0.156$</td>
</tr>
<tr>
<td>$\lambda_Z = \Delta g_1^Z = 0$</td>
<td>$-0.376 &lt; \Delta \kappa_Z &lt; 0.686$</td>
</tr>
<tr>
<td>$\Delta \kappa_Z = 0$ (HISZ)</td>
<td>$-0.075 &lt; \lambda_Z &lt; 0.093$</td>
</tr>
<tr>
<td>$\lambda_Z = 0$ (HISZ)</td>
<td>$-0.027 &lt; \Delta \kappa_Z &lt; 0.080$</td>
</tr>
</tbody>
</table>

**HISZ Constrained Limits**
**ZZ → ℓℓℓℓℓ Production**

- Smallest SM diboson $\sigma$ before Higgs
- Selection requires $M_{Z1} > 70$, $M_{Z2} > 50$ GeV
  - Same-flavor opposite-sign $\ell$s used to make Zs
    - 1 flavor: $p_T^{1,2,3,4} > 30, 25, 15, 15$
    - 2 flavors: $p_T^{\ell:1,2} > 20, 15$ each $\ell$
- Largest bkgd. ($W/Z/\gamma+$jets) estimated from data
  - $t\bar{t}$ background from MC
  - Cosmic ray $\mu$ contribution considered for $ee\mu\mu$, $\mu\mu\mu\mu$

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Diboson Production at DØ
Observe 10 events with $0.37 \pm 0.13$ background

SM NLO prediction: $\sigma(Z/γ^* Z/γ^*) = 1.4 \pm 0.1$ pb

Obs. $\sigma = 1.33^{+0.50}_{-0.40}$ (stat) $\pm 0.12$ (syst) $\pm 0.09$ (lumi) pb

Combined with 2.7 fb$^{-1}$ $ℓℓνν$:

$\sigma(ZZ) = 1.40^{+0.43}_{-0.37}$ (stat) $\pm 0.14$ (syst) pb
ZZ Decay Plane Angle

- Decay plane angle of interest for Higgs/BSM search
- Rotates $Z_2$ decay plane into $Z_1$ decay plane

Higgs-like scalar
Heavy scalar
CP-odd scalar
Diboson Production at DØ

- Up to 6.4 fb\(^{-1}\) used to measure dibosons
- No deviation from SM in kinematics & TGCs
- Many analyses will have twice the data by the end of RunII

\[
\begin{align*}
W\gamma \rightarrow \mu\nu\gamma & \quad 4.2 \text{ fb}^{-1} \quad 15.2 \pm 1.6 \text{ pb} \\
WZ \rightarrow \ell\ell\ell\ell & \quad 4.1 \text{ fb}^{-1} \quad 3.90^{+1.06}_{-0.90} \text{ pb} \\
ZZ \rightarrow \ell\ell\ell\ell & \quad 6.4 \text{ fb}^{-1} \quad 1.33^{+0.52}_{-0.43} \text{ pb}
\end{align*}
\]
Diboson Production at DO

Thank you!
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**MVA Validation (WW/WZ)**

- **WW/WZ → ℓνjj** used to verify MVA techniques
  - SM signal with same signature as WH → ℓνjj
  - MVA gives superior results vs. dijet mass