Diboson Production at the Tevatron

Michael Cooke (Fermilab, DØ) on behalf of the CDF and DØ Collaborations

DIS 2009, April 28th, Madrid, Spain
Diboson processes have low cross sections

- Provide natural series of goals for detector sensitivity
- Probe fundamental details of the SM EW sector directly

Direct window to SM Higgs decay

- Higgs can decay directly into $WW$, $ZZ$, $Z\gamma$
- Associated $WH$, $ZH$ production
Search for Anomalous Couplings

- SM includes two triple gauge-boson vertices
  - Contribute directly to $W\gamma$, $WW$, $WZ$ production

Assuming EM gauge invariance and C and P conservation, the most general Lorentz invariant effective Lagrangian for triple gauge couplings is:

$$\frac{L_{WWV}}{g_{WWV}} = ig^W_1 \left( W_{\mu\nu}^\dagger W^\mu V^\nu - W_\mu W_\nu V^{\mu\nu} \right) + i \kappa_V W_{\mu\nu} W^\mu V^{\mu\nu} + i \frac{\lambda_V}{M_W^2} W_{\lambda\mu\nu} W^\mu V^{\nu\lambda}$$

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

- In SM: $g_1^V = \kappa_V = 1$, $\lambda_V = 0$
Search for Anomalous Couplings

- Equivalent triple-gauge boson vertex does not exist in SM for $Z\gamma\gamma/ZZ\gamma$
  - Can probe for this anomalous tree-level diagram in $Z\gamma$ production
  - Most general Lagrangian has CP-odd and CP-even couplings

$$\frac{L_{yZV}}{-ie} = (h_1^V F^{\mu\nu} + h_3^V \tilde{F}^{\mu\nu}) Z_\mu \frac{\Box + m_V^2}{M_Z^2} V_\nu + (h_2^V F^{\mu\nu} + h_4^V \tilde{F}^{\mu\nu}) Z_\alpha \frac{\Box + m_V^2}{M_Z^4} \partial_\alpha \partial_\mu V_\nu$$

...where $F^{\mu\nu}$ is the photon field, "~" denotes antisymmetry, $\Box = \partial^2/\partial t^2 - \nabla^2$

- To preserve partial-wave unitarity and avoid divergent cross-sections, TGCs are introduced as form factors:
  - Limits set in terms of $A_0$
  - $A$ sets scale of new physics

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

- $n = 2$ for $\kappa_V, \lambda_V, g_1^Z$
- $n = 3$ for $h_1^V, h_3^V$
- $n = 4$ for $h_2^V, h_4^V$
Creating Dibosons at Fermilab

- Tevatron produces $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV
  - CDF and DØ detectors measure the created particles

36-on-36 particle bunches
with 396 ns spacing
1.7 million collisions per second
Tevatron Performance

Tevatron has delivered 6.5 fb\(^{-1}\) of integrated luminosity to each experiment so far in RunII!

- Record weekly int. lumi. (April 13\(^{th}\)–20\(^{th}\)): 73.1 pb\(^{-1}\)
- 1992-95 (RunI) int. luminosity: \(\sim\)110 pb\(^{-1}\)
- Results presented today correspond to 1.0–3.6 fb\(^{-1}\)

Thank you, Accelerator Division!
The CDF and DØ Detectors

- Silicon vertex detector
- Wire drift chamber tracking
- Pb/Fe-scintillator calorimetry
- Muon chambers

- Silicon vertex detector
- Scintillating fiber tracking
- LAr-U compensating cal.
- Muon chambers
Only ISR diagram contributes to $Z\gamma \rightarrow \nu\nu\gamma$ at tree level

- SM NLO $\sigma_{Z\gamma}^{[E_T^\gamma > 90 \text{ GeV}]} = 39 \pm 4 \text{ fb}$; selection:
  - Missing $E_T > 70 \text{ GeV}$
  - Central calorimeter $\gamma$ candidate with $E_T > 90 \text{ GeV}$
    - Use EM shower pointing to confirm vertex & estimate backgrounds
  - Veto on: Jet or 2$^{\text{nd}}$ EM object with $E_T > 15 \text{ GeV}$; muons; iso. tracks

<table>
<thead>
<tr>
<th>Event Type</th>
<th>Number of events</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W \rightarrow e\nu$</td>
<td>$9.67 \pm 0.30 \text{(stat.)} \pm 0.48 \text{(syst.)}$</td>
</tr>
<tr>
<td>non-collision</td>
<td>$5.33 \pm 0.39 \text{(stat.)} \pm 1.91 \text{(syst.)}$</td>
</tr>
<tr>
<td>$W/Z$ + jet</td>
<td>$1.37 \pm 0.26 \text{(stat.)} \pm 0.91 \text{(syst.)}$</td>
</tr>
<tr>
<td>$W\gamma$</td>
<td>$0.90 \pm 0.07 \text{(stat.)} \pm 0.12 \text{(syst.)}$</td>
</tr>
<tr>
<td>Total background</td>
<td>$17.3 \pm 0.6 \text{(stat.)} \pm 2.3 \text{(syst.)}$</td>
</tr>
<tr>
<td>$N_{\nu\nu\gamma}^{\text{SM}}$</td>
<td>$33.7 \pm 3.4$</td>
</tr>
<tr>
<td>$N_{\text{obs}}$</td>
<td>51</td>
</tr>
</tbody>
</table>

OBSERVATION ($5.1\sigma$): $[E_T^\gamma > 90 \text{ GeV}]$

$\sigma_{Z\gamma} = 32 \pm 9 \text{ (stat+syst)} \pm 2 \text{ (lumi) fb}$
Photon $E_T$ spectrum used to examine anomalous TGCs

- No distinction between CP-even/odd couplings ($h_{1,2}^V$ vs $h_{3,4}^V$)
- Combined with DØ $Z\gamma\rightarrow\nu\nu\gamma$ [PLB 653, 378 (2007); 1.1 fb$^{-1}$]

Tightest limits from hadronic collider!

- $3\times$ improvement vs $Z\gamma\rightarrow\ell\ell\gamma$
- All but $h_{30}^\gamma$ improve upon LEP2
Individual channel cuts optimized for $\sigma_{WW}$ measurement

- SM NLO $\sigma_{WW} = 12.4 \pm 0.7$ pb:
  - Lepton $p_T > 25, 15$ GeV
  - $E_T > 45$ (ee), 20 (e$\mu$), 35 ($\mu\mu$) GeV
  - Maximum $p_T^{WW}$ cut suppresses $Z$ and $t\bar{t}$

| $WW \to \ell\ell'$ | 10.98 ± 0.59 | 39.25 ± 0.81 | 7.18 ± 0.34 |
| $WW \to \ell\tau/\tau\tau \to \ell\ell'$ | 1.40 ± 0.20 | 5.18 ± 0.29 | 0.71 ± 0.10 |
| Total expected | 23.46 ± 1.90 | 68.64 ± 3.88 | 10.79 ± 0.58 |
| Data | 22 | 64 | 14 |

$\sigma_{WW} = 11.5 \pm 2.1$ (stat+syst) $\pm 0.7$ (lumi) pb

Most precise at hadronic collider when submitted Apr. 3rd!

TGC limits based on lepton $p_T$:

$\Lambda = 2$ TeV

LEP: -0.54 < $\Delta \kappa_\gamma$ < 0.83, -0.14 < $\lambda$ < 0.19, -0.14 < $\Delta g_1 \gamma$ < 0.30

EQUAL: -0.12 < $\Delta \kappa_\gamma = \Delta \kappa_Z$ < 0.35, -0.14 < $\lambda_\gamma = \lambda_Z$ < 0.19
Matrix element based likelihood ratio analysis

- SM NLO $\sigma_{WW} = 12.4 \pm 0.7$ pb:
  
  - Event kinematics are used to assign a probability based on LO ME cross section calculation for the $WW$, $ZZ$, $W\gamma$ and $W+\text{jet}$ processes

<table>
<thead>
<tr>
<th>CDF Run II Preliminary</th>
<th>$\int L = 3.6$ fb$^{-1}$</th>
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</thead>
<tbody>
<tr>
<td>Process</td>
<td>Events</td>
</tr>
<tr>
<td>$Z/\gamma^*$</td>
<td>79.8 $\pm$ 18.4</td>
</tr>
<tr>
<td>$WZ$</td>
<td>13.8 $\pm$ 1.9</td>
</tr>
<tr>
<td>$W\gamma$</td>
<td>91.7 $\pm$ 24.8</td>
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<tr>
<td>$W+\text{jets}$</td>
<td>112.7 $\pm$ 31.2</td>
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<tr>
<td>$tt$</td>
<td>20.7 $\pm$ 2.8</td>
</tr>
<tr>
<td>Total Background</td>
<td>320.1 $\pm$ 46.8</td>
</tr>
<tr>
<td>$WW$</td>
<td>317.6 $\pm$ 54.1</td>
</tr>
<tr>
<td>Signal+Background</td>
<td>637.6 $\pm$ 79.6</td>
</tr>
<tr>
<td>Data</td>
<td>654</td>
</tr>
</tbody>
</table>

$\sigma_{WW} = 12.1 \pm 0.9 \text{ (stat)} ^{+1.6}_{-1.4} \text{ (syst)}$ pb

Public note made available on April 20th, currently most precise measurement at hadronic collider!
Multivariate discriminant separates $WW/WZ$ from $W+j$

- SM NLO $\sigma_{WW+WZ} = 16.1 \pm 0.9$ pb; selection:
  - $e/\mu$ $p_T > 20$ GeV; Missing $E_T > 20$ GeV
  - 2+ jets with $p_T > 30, 20$ GeV
  - Transverse $W$ mass $> 35$ GeV
- Random Forest discriminates S from B
  - Average over many decision trees

Fit to RF output determines signal

- RF fit p-value $= 5.4 \times 10^{-6}$ (4.4$\sigma$)

$\sigma_{WW+WZ} = 20.2 \pm 2.5$ (stat) $\pm 3.6$ (syst) $\pm 1.2$ (lumi) pb

First EVIDENCE in this channel at hadronic collider!
**Dijet mass spectrum used to examine anomalous TGCs**

- Smallest allowed range of values at 95% C.L. from Tevatron

- LEP Constraints conserve $\text{SU}(2)_L \otimes \text{U}(1)_Y$ symmetry
  - Specifically, $\lambda_\gamma = \lambda_Z$ and $\Delta \kappa_Z = \Delta g_Z - \Delta \kappa_\gamma \tan \theta_W$

- LEP Compatible, $\Lambda = 2$ TeV
  - $-0.12 < \Delta g_1^Z < 0.20$
  - $-0.44 < \Delta \kappa_Z < 0.55$
  - $-0.10 < \lambda_Z < 0.11$

- Equal Couplings, $\Lambda = 2$ TeV
  - $-0.16 < \Delta \kappa_\gamma = \Delta \kappa_Z < 0.23$
  - $-0.11 < \lambda_\gamma = \lambda_Z < 0.11$
Three bins in Z boson $p_T$ used to study $\sigma_{WZ}$ and ATGCs

- [105-140] GeV: Control bin
  - Dominated by high $p_T$ Drell-Yan, used to test modeling
  - Used to perform $m_{jj}$ fits to set limits on $\sigma_{WZ}$ and ATGCs

### Medium $p_T$ Bin

<table>
<thead>
<tr>
<th>channel</th>
<th>Total</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>e e</td>
<td>30.0</td>
<td>34</td>
</tr>
<tr>
<td>$\mu \mu$</td>
<td>23.8</td>
<td>36</td>
</tr>
<tr>
<td>e trk</td>
<td>8.5</td>
<td>17</td>
</tr>
<tr>
<td>$\mu$ trk</td>
<td>8.3</td>
<td>10</td>
</tr>
<tr>
<td>Total</td>
<td>71.4 ± 0.5</td>
<td>97</td>
</tr>
</tbody>
</table>

### High $p_T$ Bin

<table>
<thead>
<tr>
<th>channel</th>
<th>Total</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>e e</td>
<td>4.0</td>
<td>5</td>
</tr>
<tr>
<td>$\mu \mu$</td>
<td>3.4</td>
<td>4</td>
</tr>
<tr>
<td>e trk</td>
<td>1.2</td>
<td>2</td>
</tr>
<tr>
<td>$\mu$ trk</td>
<td>1.2</td>
<td>1</td>
</tr>
<tr>
<td>Total</td>
<td>9.74 ± 0.178</td>
<td>12</td>
</tr>
</tbody>
</table>

95% C.L. $\sigma_{WZ}$ Limits:
- Medium Bin: 234 fb
- High Bin: 135 fb
$WZ \rightarrow ℓνℓℓ$: ATGCs

- $Z$ boson $p_T$ spectrum used to set 95% C.L. limits on anomalous TGCs
- Extends PRL 98, 161801 (2007), using 25 observed events

$\Lambda = 1.5 \text{ TeV}$:
- $-0.14 < \Delta g_1^Z < 0.25$
- $-0.81 < \Delta \kappa_Z^Z < 1.29$
- $-0.14 < \lambda_Z^Z < 0.15$

$\Lambda = 2.0 \text{ TeV}$:
- $-0.13 < \Delta g_1^Z < 0.23$
- $-0.76 < \Delta \kappa_Z^Z < 1.18$
- $-0.13 < \lambda_Z^Z < 0.14$
Getting a good handle on Missing $E_T$ is critical!

- SM NLO $\sigma_{ZZ} = 1.4 \pm 0.1$ pb; selection:
  - Select $ee/\mu\mu$ events with lepton $p_T > 15$ GeV
  - Veto extra EM clus. (5 GeV), muons, iso. tracks, > 2 jets (10 GeV)
- Create “corrected $E_T$” discriminant
  - Minimize effect of mismeasured jets/\mu
    
    $$\hat{E}_T = \sqrt{\hat{E}_l^2 + (1.5 \hat{E}_t)^2} - \delta_{\text{LeptonTrks}} - \delta_{\text{JetTrks}}$$
- Expect 7.4 ZZ, 26.5$\pm$0.5 bkgd; 43 data

LLR p-value = $4.2 \times 10^{-3}$ (2.6$\sigma$):

$$\sigma_{ZZ} = 2.01 \pm 0.93 \ (\text{stat}) \pm 0.29 \ (\text{syst}) \ \text{pb}$$
Analysis focused on optimization of lepton selection

- SM NLO $\sigma_{ZZ} = 1.4 \pm 0.1$ pb; selection:
  - Study $eeee$, $ee\mu\mu$, $\mu\mu\mu\mu$ channels, with tighter cuts on lepton $p_T$, lepton isolation and dilepton mass than previous DØ analysis
    - $4e/4\mu$ require $p_T > 30, 25, 15, 15$ GeV ($ee\mu\mu$ 25, 15); all $> 15$ GeV before
    - Dilepton mass pairs $> 70, 50$ GeV vs. $> 30, 30$ GeV in previous analysis

Comparison to previous 1 fb$^{-1}$ analysis (no data overlap):

- 1 fb$^{-1}$: expect $1.71 \pm 0.15$ ZZ, $0.13 \pm 0.03$ bkgd; observed 1 event
- 1.7 fb$^{-1}$: expect $1.89 \pm 0.08$ ZZ, $0.14 \pm 0.03$ bkgd; observed 3 events
1.7 fb\(^{-1}\) ZZ→ℓℓℓℓ observations: p-value 4.3×10\(^{-8}\) (5.3σ)

- \(\sigma_{ZZ} = 1.75^{+1.27}_{-0.86}\) (stat) ± 0.13 (syst) pb

Three analyses combined into final \(\sigma_{ZZ}\) measurement:

- Non-overlapping 1.0 fb\(^{-1}\) and 1.7 fb\(^{-1}\) ZZ→ℓℓℓℓ
  - 1.0 fb\(^{-1}\): Phys. Rev. Lett. 100, 131801 (2008)
- Complimentary 2.7 fb\(^{-1}\) ZZ→ℓℓνν
- Combined p-value = 6.2×10\(^{-9}\) (5.7σ)
  \(\sigma_{ZZ} = 1.60 \pm 0.63\) (stat) \(+0.16_{-0.17}\) (syst) pb

First OBSERVATION of ZZ at hadronic collider!

- CDF: 1.4 \(+0.7_{-0.6}\) (stat+syst) pb (4.4 σ) [PRL 100, 201801 (2008)]
Summary

Diboson production results are in agreement with SM
- Cross section measurements remain consistent with SM
- No evidence of anomalous triple gauge-boson couplings

Recently, the Tevatron has provided:
- EVIDENCE for $WW + WZ \rightarrow \ell \nu jj$ (4.4$\sigma$)
- OBSERVATION of $Z\gamma \rightarrow \nu \nu \gamma$ (5.1$\sigma$)
- OBSERVATION of $ZZ$ production (5.7$\sigma$)
- MOST PRECISE $WW \rightarrow \ell \nu \ell \nu$ cross section at hadronic collider
  • ...twice in April!
- MOST STRINGENT LIMITS on $h_{30}^Z$, $h_{40}^\gamma$, $h_{40}^Z$
- INCREASINGLY STRINGENT LIMITS on $\kappa_V$, $\lambda_V$, $g_1^Z$ from hadronic collisions