Di-boson production at the Tevatron

Outline

• Introduction
• WW cross section
• WZ cross section and WWZ couplings
• W_\gamma cross section and WW_\gamma couplings
• Z_\gamma cross section and tri-neutral couplings
• Conclusions
Motivations

- Non-Abelian structure of SM $\Rightarrow$ triple and quartic gauge boson couplings $\exists (ZZ_\gamma & Z_{\gamma\gamma} = 0)$

- Diboson production
  $\Rightarrow$ test of Triple Gauge Couplings ($WW_\gamma, WWZ, ZZ_\gamma, Z_{\gamma\gamma}$)

- Tevatron is complementary to LEP:
  - Tevatron probes different coupling combinations than LEP
  - Tevatron explores higher $S$

- New physics probe
- Background of numerous analyses $(H\rightarrow WW, SUSY, \bar{t}t)$
- Knowledge of diboson cross section important for many LHC analyses
- At Run I, low statistics, low significance on diboson signal
**WWγ & WWZ Anomalous couplings AC**

- All possible interactions terms (WWV; V = γ or Z) in $L_{\text{eff}}$:

  \[
  L_{WWV} / g_{WWV} = \sum g_{V}^{1}(W_{\mu}^{\dagger} W^{\mu} V^{\nu} - W_{\mu}^{\dagger} V W^{\mu} V^{\nu})
  \]

  \[
  + K_{V} W_{\mu}^{\dagger} W V^{\mu} V^{\nu} + \frac{\lambda_{V}}{M_{W}^{2}} W_{\lambda}^{\dagger} W_{\mu}^{\mu} V_{\nu}^{\nu}
  \]

- $L_{\text{eff}}$ characterized by 5 CP conserving parameters:

  $\lambda_{Z} = \lambda_{\gamma} = 0$; $\Delta \kappa_{Z} = \Delta \kappa_{\gamma} = 0$ ($\Delta \kappa = \kappa - 1$) and $\Delta g^{1}_{Z} = 0$ ($\Delta g^{1}_{Z} = g^{1}_{Z} - 1$)

- $\kappa$ and $\lambda$ related to magnetic dipole and electric quadrupole moments of W:

  \[
  \mu_{W} = e(1+\kappa+\lambda) / 2M_{W}
  \]

  \[
  Q_{W}^{e} = -e(\kappa-\lambda) / M_{W}^{2}
  \]

- Form-factor scale $\Lambda$ to avoid unitarity violation

- WW to probe WWγ and WWZ coup.

- Wγ to probe WWγ coupling

- WZ to probe WWZ coupling

- AC effect: X-section increases for high $E_{T}$ boson

\[\text{Events/Mb} \]

\[\log_{10}(E_{T}/\text{GeV}) \]

\[\Lambda = 1.5 \text{ TeV} \]

\[\Delta \kappa = 0, \lambda = 0 \]

\[\Delta \kappa = 0, \lambda = 1 \]

\[\Delta \kappa = 1, \lambda = 0 \]

\[\Delta \kappa = 0, \lambda = 0 \]

\[\Delta \kappa = 0, \lambda = 1 \]

\[\Delta \kappa = 1, \lambda = 0 \]
Cut definitions

- CDF and D0 use similar cuts
- W/Z selections are based on selection of high-$P_T$ leptons
  - $Z\rightarrow ll$, $W\rightarrow l\nu$
- High-$P_T$ leptons
  - Electron or muon with $P_T > 20-25$ GeV/c
  - Isolated = $E_T$ in cone $R=0.4$ less than $0.1*E_T(\text{lepton})$
  - Central = $|\eta|<1$ (1.1)

- Neutrinos result in mis-balance of transverse energy
  - Large missing $E_T$: $\not{E}_T > 20-25$ GeV
**WW production**

- Important background for Higgs searches
- Self interaction of heavy bosons (WWγ/Z)
- Probe for new heavy bosons
- Large statistics at LEPII (10K evts/exp.)
- @ Run I, one result (CDF) w/ limited significance: 5 evts observed with 1.3±0.3 bkgrd.

\[ \sigma (WW) = 10.2^{+6.3}_{-5.1} \text{ (stat)} \pm 1.6 \text{ (syst)} \text{ pb} \]

- Dileptons: \(e\mu\nu\nu, \mu\mu\nu\nu\) 
  - Br = 2.5 and 1.2%
  - Pure and efficient
  - Low branching frac.

- Lepton+jets
  - e\mu\nu\nu, \mu\mu\nu\nu
  - Br = 15%
  - Efficient
  - Not very pure

- All-jets
  - e\mu\nu\nu, \mu\mu\nu\nu
  - Br = 47%
  - Very efficient
  - Never Mind
Event selection

- **First goal:** establish the signal
- **Selection:**
  - 2 isolated leptons
  - Large $E_T$ (2ν)
- **Backgrounds:**
  - Drell-Yan with “fake” $E_T$
    - $\sigma(pp\rightarrow Z/\gamma^*\rightarrow ee) \sim 250 \text{ pb}$
  - $W+$jets/$\gamma$ where jet must fake a lepton
    - $\sigma(pp\rightarrow W(\rightarrow e\nu)+\geq1\text{jet}) \sim 500 \text{ pb}$
  - $tt$ (contains additional jets)
    - $\sigma(pp\rightarrow tt\rightarrow e\nu\nu\bar{b}\bar{b}) \sim 0.1 \text{ pb}$
  - Heavy dibosons ($WZ, ZZ$) production
## WW cross section

<table>
<thead>
<tr>
<th>Process</th>
<th>D0 (224-252 pb⁻¹)</th>
<th>CDF (184 pb⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WW signal</td>
<td>ee</td>
<td>3.42±0.05</td>
</tr>
<tr>
<td></td>
<td>µµ</td>
<td>2.10±0.05</td>
</tr>
<tr>
<td></td>
<td>eµ</td>
<td>11.10±0.10</td>
</tr>
<tr>
<td>Total BKGD</td>
<td>ee</td>
<td>2.30±0.21</td>
</tr>
<tr>
<td></td>
<td>µµ</td>
<td>1.95±0.41</td>
</tr>
<tr>
<td></td>
<td>eµ</td>
<td>3.81±0.17</td>
</tr>
<tr>
<td>Observed</td>
<td>ee</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>µµ</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>eµ</td>
<td>15</td>
</tr>
</tbody>
</table>

### Observed

\[
\sigma(WW) = 13.8^{+4.3}_{-3.8} \text{(stat.)} +1.2_{-0.9} \text{(sys.)}
\pm 0.9 \text{(lum.) pb}
\]

### Combined

\[
\sigma(WW) = 14.6^{+5.8}_{-5.1} \text{(stat.)} +1.8_{-3.0} \text{(sys.)}
\pm 0.9 \text{(lum.) pb}
\]

\[
\sigma(pp\rightarrow WW\rightarrow ll\nu\nu)^{\text{THEORY}}_{NLO} = 12.4\pm0.8 \text{ pb}
\]

- \(P(\text{background fluc.}) = 2.3\times10^{-7}\)
  
  \(\Rightarrow \sim 5.2\) standard deviations

### Systematics (CDF):

- Selection efficiency \(\sim 10\%\)
  
  (signal modelling \(\sim 7\%\))

- Backgrounds \(\sim 40\%\) (D-Y, W+jet)

- Luminosity : 6%
WZ

- Important step towards Higgs searches (significant bkgd)
- Sensitive to the $WWZ$ coupling (and not $WW\gamma$ as in $WW$)
- $W^{\pm}Z$ unavailable at $e^+e^-$ colliders => unique meas. of $WWZ$
- Search for trilepton signature (no other SM process)
- $\sigma_{\text{NLO}}(WZ) \sim 4.0$ pb at 1.96 TeV

Z selection:
- 2 high $P_T$ leptons
- $M_{\text{inv}}(ll)$ consistent w/ $m_Z$

W selection:
- Isolated lepton + $E_T$

Main background:
- $Z/\gamma^* + \text{jet}$
# CDF WZ and ZZ x-sections

<table>
<thead>
<tr>
<th>Process</th>
<th>4 leptons</th>
<th>3 leptons</th>
<th>2 leptons</th>
<th>Combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZZ</td>
<td>0.06±0.01</td>
<td>0.13±0.01</td>
<td>0.69±0.11</td>
<td>0.88±0.13</td>
</tr>
<tr>
<td>ZW</td>
<td>-</td>
<td>0.78±0.06</td>
<td>0.65±0.10</td>
<td>1.43±0.16</td>
</tr>
<tr>
<td>Total signal</td>
<td>0.06±0.01</td>
<td>0.91±0.07</td>
<td>1.34±0.21</td>
<td>2.31±0.29</td>
</tr>
<tr>
<td>WW</td>
<td>-</td>
<td>-</td>
<td>0.40±0.07</td>
<td>0.40±0.07</td>
</tr>
<tr>
<td>Fake</td>
<td>0.01±0.02</td>
<td>0.07±0.06</td>
<td>0.21±0.12</td>
<td>0.29±0.16</td>
</tr>
<tr>
<td>Drell-Yan</td>
<td>-</td>
<td>-</td>
<td>0.31±0.17</td>
<td>0.31±0.17</td>
</tr>
<tr>
<td>tt</td>
<td>-</td>
<td>-</td>
<td>0.02±0.01</td>
<td>0.02±0.01</td>
</tr>
<tr>
<td>Total Bkgd</td>
<td>0.01±0.02</td>
<td>0.07±0.06</td>
<td>0.94±0.22</td>
<td>1.02±0.24</td>
</tr>
<tr>
<td>Signal+Bkgd</td>
<td>0.07±0.02</td>
<td>0.98±0.09</td>
<td>2.28±0.35</td>
<td>3.33±0.42</td>
</tr>
<tr>
<td>#Observed</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>3</td>
</tr>
</tbody>
</table>

- **Upper limit at 95%CL:**

$$\sigma(pp_{ZZ}/ZW+X) < 15.2 \text{ pb @95\% C.L.}$$

$$\sigma(pp_{ZZ}/ZW+X)^{\text{THEORY}_{\text{NLO}}} = 5.0 \pm 0.4 \text{ pb}$$
**D0 WZ cross section**

- **Upper limit at 95% CL**
  - $\sigma(pp_{ZW+X})<13.3 \text{ pb @95\% C.L}$

- **WZ cross section estimate**
  - $\sigma(pp_{ZW+X}) = 4.5^{+3.5}_{-2.6}\text{ pb}$

- **Prob (0.71 bkgd->3 candidates) = 3.5\%**

**Table:**

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>D0(285-320pb^{-1})</strong></td>
<td>3 leptons</td>
</tr>
<tr>
<td><strong>WZ signal</strong></td>
<td>$2.04 \pm 0.13$</td>
</tr>
<tr>
<td><strong>Bckgd</strong></td>
<td>$0.71 \pm 0.08$</td>
</tr>
<tr>
<td><strong>Expec. Total</strong></td>
<td>$2.75 \pm 0.15$</td>
</tr>
<tr>
<td><strong>Observed</strong></td>
<td>3</td>
</tr>
</tbody>
</table>
**WWZ anomalous trilinear couplings**

- Generate a grid of WZ M.C.
  (Hagiwara, Woodside, + Zeppenfeld LO generator + Fast Detector Simulation)
- Form Ln(Likelihood)
- Intersect with plane at Max-3.0=> 2D limit at 95%CL

1D limits at 95% CL (D0)

<table>
<thead>
<tr>
<th>$\Lambda = 1.0$ TeV</th>
<th>$\Lambda = 1.5$ TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$-0.53 &lt; \lambda_z &lt; 0.56$</td>
<td>$-0.48 &lt; \lambda_z &lt; 0.48$</td>
</tr>
<tr>
<td>$-0.57 &lt; \Delta g_1^Z &lt; 0.76$</td>
<td>$-0.49 &lt; \Delta g_1^Z &lt; 0.66$</td>
</tr>
<tr>
<td>$-2.0 &lt; \Delta \kappa_z &lt; 2.4$</td>
<td></td>
</tr>
</tbody>
</table>

- Best limits on WWZ couplings in WZ final state
- First 2D limits in $\kappa_Z$ vs $\lambda_Z$ using WZ
- Best limits on $\Delta g_1^Z$, $\Delta \kappa_z$ and $\lambda_Z$ from direct, model independent measur.
- D0 Run II 1D limits are x3 better than Run I
**$W\gamma$ Production**

- Sensitive only to $WW\gamma$ coupling
- Background of Gauge Mediated Supersymmetry Breaking models
- $W$ Selection
  - Isolated high-\(P_T\) lepton
  - Large $\not{E}_T$
- $\gamma$ ID is crucial
  - $|\eta| < 1$, $\Delta R(l, \gamma) > 0.7$

Effect of anomalous couplings more pronounced at high $M_T(W\gamma)$
## Wγ cross section

<table>
<thead>
<tr>
<th>Decay Channel</th>
<th>D0</th>
<th>CDF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lum’y (pb⁻¹)</td>
<td>eνγ 162 (6.5%)  μνγ 134 (6.5%)</td>
<td>eνγ 202-168 (6%)  μνγ 192-175(6%)</td>
</tr>
<tr>
<td>Wγ</td>
<td>51.2 ± 11.5  89.7 ±13.7</td>
<td>126.8 ± 5.8  95.2 ± 4.9</td>
</tr>
<tr>
<td>Total Bkgrd</td>
<td>60.8 ± 4.5  71.3 ± 5.2</td>
<td>67.3 ± 18.1  47.3 ± 7.6</td>
</tr>
<tr>
<td>Sig+Bkgrd</td>
<td>112 ± 12.3  161 ± 14.6</td>
<td>194.1 ± 19.1  142.5 ± 9.5</td>
</tr>
<tr>
<td># Observed</td>
<td>112</td>
<td>195</td>
</tr>
<tr>
<td>A*ε</td>
<td>2.3%</td>
<td>3.3%</td>
</tr>
<tr>
<td>σ(Wγ)*Br</td>
<td>13.9±2.9±1.6 15.2±2.0±1.1</td>
<td>19.4±2.1±2.9 16.3±2.3±1.8</td>
</tr>
</tbody>
</table>

**Combined***:

\[
\sigma(p\bar{p} \to W^\pm\gamma) = 14.8 \pm 1.6\text{(stat.)} \pm 1.0\text{(sys.)} \pm 1.0\text{(lum.) pb}
\]

SM expect: \(\sigma(W_\gamma) = 16.0 \pm 0.4\) pb

\[
\sigma(p\bar{p} \to W^\pm\gamma) = 18.1 \pm 3.1\text{ pb}
\]

SM expect: \(\sigma(W_\gamma) = 19.3 \pm 1.4\) pb

*Both experiments quote x-section integral within acceptance*
**WWγ anomalous coupling**

1D limits at 95% CL (D0):

<table>
<thead>
<tr>
<th></th>
<th>Tev Run I</th>
<th>Tev Run II</th>
<th>LEP comb.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Δκ</td>
<td>-0.93, 0.94</td>
<td>-0.93, 0.97</td>
<td>-0.105, 0.069</td>
</tr>
<tr>
<td>λ</td>
<td>-0.31, 0.29</td>
<td>-0.22, 0.22</td>
<td>-0.059, 0.026</td>
</tr>
</tbody>
</table>

Run I limit on λ already improved!
The tightest at a hadron collider
**Zγ production**

- **Zγ selection:**
  - 2 high-\( P_T \) isolated leptons
  - \( 40 < M_{\text{inv}}(l,l) < 110 \) GeV
  - 1 photon \( |\eta| < 1.1 \) with \( E_T > 7 \) GeV (8 GeV @ D0),

**L\(_{\text{eff}}\)** with 8 couplings parameters \( (h_1^V, h_2^V, h_3^V, h_4^V ; V = Z, \gamma) \).
In SM all these couplings = 0

- **Main Background = Z+jet where jet mimic a photon (see Wγ)**
Zγ cross section

**Summary:**

<table>
<thead>
<tr>
<th>Decay Channel</th>
<th>D0</th>
<th>CDF</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>eeγ</td>
<td>µµγ</td>
</tr>
<tr>
<td>Lum'y (pb⁻¹)</td>
<td>324 (6.5%)</td>
<td>286 (6.5%)</td>
</tr>
<tr>
<td>SM Zγ</td>
<td>109 ± 7</td>
<td>128 ± 8</td>
</tr>
<tr>
<td>Total Bkgrd</td>
<td>23.6 ± 2.3</td>
<td>22.4 ± 3.0</td>
</tr>
<tr>
<td>Sig+Bkgrd</td>
<td>132.6 ± 7</td>
<td>150.4 ± 8</td>
</tr>
<tr>
<td># Observed</td>
<td>138</td>
<td>152</td>
</tr>
<tr>
<td>A*ε</td>
<td>11.3%</td>
<td>11.7%</td>
</tr>
<tr>
<td>σ*Br(pb)</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

**Combined:**

- \( σ(Zγ)\cdot Br(Z \rightarrow ll) = 4.6 \pm 0.6 \text{ pb (CDF)} \)
- \( σ(Zγ)\cdot Br(Z \rightarrow ll) = 4.2 \pm 0.4(\text{stat+syst}) \pm 0.3 (\text{lumi}) \text{ pb (D0)} \)
- SM expectation: 4.5 ± 0.3 (pb)

*Both experiments quote x-section integral within acceptance*
Kin. distributions & tri-neutral coupling

DØ Preliminary

1D limits at 95% CL

<table>
<thead>
<tr>
<th>LEP</th>
<th>Tevatron (D0)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.049 &lt; ( h_{\gamma}^{30} ) &lt; 0.008</td>
<td>-0.23 &lt; ( h_{\gamma}^{30} ) &lt; 0.23</td>
</tr>
<tr>
<td>-0.002 &lt; ( h_{\gamma}^{40} ) &lt; 0.034</td>
<td>-0.019 &lt; ( h_{\gamma}^{40} ) &lt; 0.019</td>
</tr>
<tr>
<td>-0.20 &lt; ( h_{Z}^{30} ) &lt; 0.07</td>
<td>-0.23 &lt; ( h_{Z}^{30} ) &lt; 0.23</td>
</tr>
<tr>
<td>-0.05 &lt; ( h_{Z}^{40} ) &lt; 0.12</td>
<td>-0.020 &lt; ( h_{Z}^{40} ) &lt; 0.020</td>
</tr>
</tbody>
</table>

Already better than LEP!
Conclusions

- Most of Run I measurements re-established and/or already improved + new Run II results:
  - Significant number of diboson candidate events
  - Very good agreement with SM
  - CDF and D0 have measured $\sigma(WW)$ at 1.96 TeV using the dilepton decay channel
  - CDF and D0 have 95% CL on $\sigma(WZ/W+ZZ)$ and D0 has first evidence of WZ production
  - D0 has tightest limit on WWZ anomalous coupling using WZ events.
  - Both CDF and D0 study the $W\gamma$ and $Z\gamma$ production
    - tightest limit on $WW\gamma$ anomalous coupling at hadron collider

- More to come:
  - CDF and D0 start only exploring the potential of Tevatron Data
  - Radiation amplitude zero ($WW\gamma$ AC)
  - Use jet channel $WW\rightarrow l\gamma jj$
  - Quartic couplings
  - ...
Backup slides
CDF detector

New
Old
Partially new

Central calorimeters
Solenoid
Central muon

Front end
Trigger
DAQ
Offline

TOF

Forward muon
Endplug calorimeter
Silicon and drift chamber trackers
D0 detector

- Forward Mini-drift chambers
- Central Scintillator
- Forward Scintillator
- Shielding
- New Solenoid, Tracking System: Si, SciFi, Preshower
- + New Electronics, Trig. DAQ

D0 Detector: Quarter r-z View:

- CC
- GPS
- Superconducting Coil
- CPS
- FPS
- ICD

p. 21
**WW →eeνν Event Selection**

- **ee channel criteria**
  - Minimal Transverse Mass > 60 GeV/c².
  - NOT. 76<M(ee)<106 GeV/c².
  - “Scaled MET” > 15 rootGeV
  - $H_T$ (jets w/ $E_T$>20 & $|\eta|<2.5$) <50 GeV.

- Background is 2.30±0.21 events and is 60% W+jets, 40% mixed heavy.
- Eff’y is 8.76±0.13%.
- Expected signal is 3.42±0.05 events.
- 6 Candidates Observed.
$WW\rightarrow e\nu+\mu\nu_\mu$

Run 155364 Event 3494901: $WW \rightarrow e^+\nu e^-\bar{\nu}_\mu$ Candidate

$p_T(e) = 42.0 \text{ GeV}/c; \quad p_T(\mu) = 20.0 \text{ GeV}/c; \quad M_{e\mu} = 81.5 \text{ GeV}$

$E_T = 64.8 \text{ GeV}; \quad \Phi(E_T) = 1.6$

$\Delta\Phi(E_T, \text{lepton}) = 1.3; \quad \Delta\Phi(e, \mu) = 2.4; \quad \text{Opening Angle}(e, \mu) = 2.6$

- $e\mu$ channel has little Standard Model background
- Signal/Background $= 4$
The 3 events
Wγ production

Cluster transverse mass:

\[ M_T^2(l_\gamma, \slashed{E_T}) = \left( M_{T,\gamma}^2 + |\slashed{p_T}(l) + \slashed{p_T}(\gamma)|^2 \right)^{1/2} + \slashed{E_T}^2 - |\slashed{p_T}(l) + \slashed{p_T}(\gamma) + \slashed{E_T}|^2 \]

CDF \( E_\gamma > 7 \text{ GeV} \)

DØ \( E_\gamma > 8 \text{ GeV} \)

\( \Delta R(\gamma, l) > 0.7 \)

\( |\eta_\gamma| < 1.1 \)

Cal & trk-iso

Jet → γ fake rate
0.2%

0.06%
For COS(θ*), the angle between incoming quark and photon in the Wγ rest frame, = −1/3, SM has “amplitude zero”.

For events w/ \( M_T(\text{cluster}) > 90 \) GeV/c². One could guess the Wγ rest frame. We use charge-signed \( \Delta \eta(l, \gamma) \).

We plot the background-subtracted muon data vs. MC \( \Delta \eta(l, \gamma) \) => hints of the Rad. Zero.

It will help to extend the eta-coverage of electrons and especially of photons.