Diboson production cross sections at the Tevatron

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Tevatron

- Most recent Diboson measurements from the CDF and DØ experiments
  - $W\gamma \rightarrow l\nu\gamma$
  - $Z\gamma \rightarrow ll\gamma$
  - $WZ \rightarrow ll\nu$
  - $ZZ \rightarrow llll, ll\nu\nu$
  - $WZ+ZZ \rightarrow lvbb/vvbb$

- Tevatron is a vector boson factory
  - Delivering $\sim 50$ pb$^{-1}$/week
    - $\sim 600$ WW, $\sim 200$ WZ, $\sim 100$ ZZ
  - Access to charged final states (not possible at LEP)
    - $W\gamma \rightarrow l\nu\gamma$, $WZ \rightarrow l\nu ll$, $l\nu qq$
Motivations for Diboson Physics

- Test of Standard Model
  - SM provides precise predictions of Diboson production cross sections

- New physics can enhance Diboson production
  - Enhancement of triple gauge couplings (TGCs)
  - Resonances decaying to pairs of bosons

- Measurement of SM Diboson Production is important step in hunt for Higgs boson
  - $H \rightarrow WW$ / $H \rightarrow ZZ$: Higgs can decay to Dibosons
  - Associated $WH$ / $ZH$ production: also same final states
$\sigma_{\text{NLO}} = 16.0 \pm 0.4 \text{pb}$
- $p_T(\gamma) > 8 \text{ GeV}, \Delta R(\gamma, l) > 0.7$
- Use 3-body mass $M_{l\nu\gamma}$ to distinguish Final State Radiation
- $\gamma W W$ vertex $\Rightarrow \kappa_\gamma$ and $\lambda_\gamma$
Wγ Cross Section (DØ)

- Unique test of the SM: Radiation amplitude zero
  - Destructive interference between tree-level diagrams
  - Dip in sign(l) × | η(γ) − η(l) |
    - In agreement with SM

- Cross section measurement
  - 4.2 fb⁻¹ of data
  - High p_Τμ, high p_Τγ, and MET
    - 492 Wγ candidates
    - Expected signal: 376 ± 42
    - Expected background: 134 ± 9
      - ~100 from W+jets

\[ \sigma(p\bar{p} \rightarrow W\gamma) = (15.2 \pm 1.6(stat + syst)) \text{ pb} \]

\[ \sigma_{NLO} = (16.0 \pm 0.4) \text{ pb} \]
Photon ET spectrum sensitive to anomalous TGCs
- Set 95% CL limits on anomalous TGCs ($\Lambda_{NP} = 2$ TeV)

1D Limits:
- $-0.14 < \Delta \kappa_\gamma < 0.15$
- $-0.02 < \lambda_\gamma < 0.02$

2D Limits:

68% Limits

|                  | $-0.1 < \Delta \kappa_\gamma < 0.029$ | $-0.043 < \lambda_\gamma < 0.014$
<table>
<thead>
<tr>
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<tbody>
<tr>
<td>ALEPH</td>
<td></td>
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<tr>
<td>L3</td>
<td>$-0.049 &lt; \Delta \kappa_\gamma &lt; 0.095$</td>
<td>$-0.062 &lt; \lambda_\gamma &lt; 0.019$</td>
</tr>
<tr>
<td>OPAL</td>
<td>$-0.1 &lt; \Delta \kappa_\gamma &lt; 0.018$</td>
<td>$-0.097 &lt; \lambda_\gamma &lt; 0.024$</td>
</tr>
<tr>
<td>LEP2 combined</td>
<td>$-0.072 &lt; \Delta \kappa_\gamma &lt; 0.017$</td>
<td>$-0.049 &lt; \lambda_\gamma &lt; 0.008$</td>
</tr>
<tr>
<td>$D\O \ 4.2 \text{ fb}^{-1}$</td>
<td>$-0.07 &lt; \Delta \kappa_\gamma &lt; 0.07$</td>
<td>$-0.012 &lt; \lambda_\gamma &lt; 0.011$</td>
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Zγ Production

- No s-channel at the tree-level
- Zγγ and ZZγ vertices $\Rightarrow h_3^γ, h_3^Z, h_4^γ, h_4^Z$
Zγ Production (CDF)

- Photon ET spectra sensitive to TGCs
  - Combination of two selections
    - $Z\gamma \rightarrow ll\gamma$: $5.1 \text{ fb}^{-1}$, $\text{ET}(\gamma) > 50 \text{ GeV}$
    - $Z\gamma \rightarrow \nu\nu\gamma$: $4.9 \text{ fb}^{-1}$, $\text{ET}(\gamma) > 100 \text{ GeV}$
  - Observe 176 candidate events
  - Expected signal: $140 \pm 9$
  - Small background (mostly cosmic $\mu$)
- Set 95% CL limits

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$(\Lambda = 1.2 \text{ TeV})$</th>
<th>$(\Lambda = 1.5 \text{ TeV})$</th>
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</thead>
<tbody>
<tr>
<td>$h_3^Z$</td>
<td>$-0.018, 0.020$</td>
<td>$-0.017, 0.016$</td>
</tr>
<tr>
<td>$h_4^Z$</td>
<td>$-0.0009, 0.0009$</td>
<td>$-0.0006, 0.0005$</td>
</tr>
<tr>
<td>$h_3^\gamma$</td>
<td>$-0.021, 0.021$</td>
<td>$-0.017, 0.016$</td>
</tr>
<tr>
<td>$h_4^\gamma$</td>
<td>$-0.0009, 0.0010$</td>
<td>$-0.0006, 0.0006$</td>
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Tightest limits on $\gamma ZZ/\gamma\gamma Z$ couplings
WZ Production

- $\sigma_{NLO} = 3.5 \pm 0.3$ pb
- Not directly accessible at LEP
- No SM backgrounds with three leptons and MET
  - Small background from $ZZ \rightarrow llll$, $Z+$jets, $tt$
- $WWZ$ vertex $\Rightarrow \kappa_Z, \lambda_Z, g_1^Z$
$WZ \rightarrow l\nu l\ell$ (CDF)

- Signature: three isolated, high-$p_T$ leptons with MET
- Build $Z$ from two opposite-sign, same-flavor leptons, require invariant mass to be close to $Z$ mass

\[ \frac{\sigma(p\bar{p} \rightarrow WZ)}{\sigma(p\bar{p} \rightarrow Z)} = (5.5 \pm 0.9) \times 10^{-4} \]

\[ \sigma(p\bar{p} \rightarrow WZ) = (4.1 \pm 0.7) \text{ pb} \]
In 4.1 fb$^{-1}$, expect ~23 signal and ~6 BG events, observe 34, $\sigma(WZ) = 3.90^{+1.06}_{-0.90}$ pb

Use pT of Z boson to set limit on aTGCs: best limit from direct measurement of WWZ vertex

In the SM:
$g_1^Z, \kappa_\gamma, \kappa_Z \equiv 1$ and $\lambda_\gamma, \lambda_Z \equiv 0$
\( \sigma(p\bar{p} \rightarrow ZZ) = 1.26^{+0.47}_{-0.37} \text{(stat)} \pm 0.14 \text{(syst)} \text{ pb} \)

- Two pairs of opposite-sign, same flavor leptons → very clean signature
- First observation of ZZ in 2008 with three four-lepton events
- Now in 6.4 fb\(^{-1}\)
  - Expect ~9 signal events, ~0.4 BG events
  - Observe 10 events
ZZ → llll (CDF)

- In 6.1 fb⁻¹, expect ~10 signal events ~0.26 BG events
- Observe 14 events

\[ \sigma(p\bar{p} \rightarrow ZZ) = 2 \pm 29\% (\text{stat}) \pm 16\% (\text{syst}) \pm 6\% (\text{lumi}) \text{ pb} \]
ZZ Kinematics

- Azimuthal angle between Z decay planes can distinguish different Scalar models
  - Higgs-like, CP violating/conserving scalar
Azimuthal angle between Z decay planes can distinguish different Scalar models
- Higgs-like, CP violating/conserving scalar
$ZZ \rightarrow llvv$ (CDF)

- **Z → l+l- plus high MET**
  - Not as clean as $Z \rightarrow llll$: background from Drell-Yan production

- **To reduce D-Y background, require MET to be back-to-back with Z boson in transverse plane**
  - 5.9 fb$^{-1}$
  - Expect ~50 signal events
  - Expect ~1100 BG events
  - Observe 1162 events

- **Use neural network to separate signal and background**
  - $\sigma(p\bar{p} \rightarrow ZZ) = 1.45^{+0.45}_{-0.42}(\text{stat})^{+0.41}_{-0.30}(\text{syst}) \text{ pb}$
VV with Hadronic Decays

- $\sigma_{\text{NLO}}(WZ+ZZ) = 4.9 \pm 0.3 \text{ pb}$
- Larger hadronic branching ratios
- Much larger background contamination
  - $W/Z+$jets: same final states, orders of magnitude larger cross sections
VV with Hadronic Decays

- **2009**: observed $VV \rightarrow \text{MET} + \text{jets}$ final states
  - $WW \rightarrow l\nu qq$, $WZ \rightarrow l\nu qq/qq\nu\nu$, $ZZ \rightarrow vvqq/qq\nu\nu$

![Graph showing dijet mass distribution](image-url)

Data (3.5 fb$^{-1}$)
- EWK Uncertainty
- Background
- Diboson Signal
- Signal Uncertainty

PRL 103, 091803 (2009)
WW+WZ \rightarrow lvjj

- One trigger lepton, two jets and MET \rightarrow large W+jets background
- Challenge is to separate signal and BG; model BG well

CDF matrix element:
\[ \sigma(\text{WW}+\text{WZ}) = 17.4 \pm 3.3 \text{ pb} \]
PRD 82, 112001 (2010)

D0 random forest:
\[ \sigma(\text{WW}+\text{WZ}) = 20.2 \pm 4.5 \text{ pb} \]
PRL 102, 161801 (2009)

CDF dijet mass:
\[ \sigma(\text{WW}+\text{WZ}) = 18.1 \pm 4.1 \text{ pb} \]
VV with b-Tagging

- Now apply b-tagging (5.5 fb\(^{-1}\))
  - Try to separate out \(WZ \rightarrow l\nu bb\), \(ZZ \rightarrow \nu\nu bb\)
  - Same analysis tools as low mass Higgs searches
- Fit \(WZ+ZZ\) cross section
  - \(WW\) is constrained to prediction
  - \(W/Z+jet\) normalization free to fit

\[\sigma_{NLO} = 4.9 \pm 0.3 \text{ pb}\]
VV with b-Tagging

- Try to separate out $WZ \rightarrow l\nu bb$, $ZZ \rightarrow \nu \nu bb$
  - Same analysis tools as low mass Higgs searches

- Fit $WZ+ZZ$ cross section
  - $WW$ is constrained to prediction
  - $W/Z+\text{jet}$ normalization free to fit

$$\sigma(p\bar{p} \rightarrow WZ + ZZ) = 5.0^{+3.6}_{-2.5} \text{ pb}$$

$$\sigma(p\bar{p} \rightarrow WZ + ZZ) < 13 \text{ pb at 95\% CL}$$

$\sigma_{\text{NLO}} = 4.9 \pm 0.3 \text{ pb}$
$WW \rightarrow l\nu l\nu$

- Signature: two opposite-sign, isolated, high-$p_T$ leptons and large MET Major BGs from Drell-Yan, $W\gamma$, $W$+jets

- D0: count events, combine $ee$, $e\mu$ and $\mu\mu$ channels
  - $\sim$65 signal, $\sim$40 BG events in 1 fb$^{-1}$
  - $\sigma(WW)= 11.5\pm2.2$ pb

- CDF: matrix element probabilities to separate signal and BG
  - $\sim$300 signal, $\sim$300 BG events (3.6 fb$^{-1}$)
  - $\sigma(WW)= 12.1\pm1.8$ pb

PRL 103, 191801 (2009)

PRL 104, 201801 (2010)
4 – 6 fb⁻¹ of RunII Tevatron data analyzed by each experiment

Measuring very small cross sections

Setting some of the tightest limits on anomalous TGCs

Most results are still statistics limited

Expect ~2 × more data before the Tevatron shuts off
Tevatron Run II $p\bar{p}$ at $\sqrt{s} = 1.96$ TeV

Cross Section (picobarn)

- $W$
- $Z$
- $W_\gamma$
- $Z_\gamma$
- $WW$
- $tt$
- $WZ$
- $t$
- $ZZ$
- $H(150$ GeV)
- $H(120$ GeV)

CDF Run II
D0 Run II
Tevatron Run II Combined
Backup starts right here....
Motivation for Diboson Physics

- **Probe of new physics at some higher energy scale $\Lambda_{NP}$**
  
  - SM is the low energy limit of a more general theory
    - $\gamma WW$ and $ZWW$ TGCs
      General Lagrangian has 14 TGC parameters
      Assume EM gauge invariance and C and P conservation
      $\Rightarrow g_{1Z}^2, \kappa_{\gamma}, \kappa_{Z} \equiv 1$ in the SM
      $\Rightarrow \lambda_{\gamma}, \lambda_{Z} \equiv 0$ in the SM
    - $\gamma ZZ$ and $\gamma\gamma Z$ TGCs
      General Lagrangian has 8 TGC parameters
      Assume CP conservation
      $\Rightarrow h_{3\gamma}, h_{3Z}, h_{4\gamma}, h_{4Z} \equiv 0$ in the SM
Dibosons and the Higgs

- Sensitive Higgs search channels at the Tevatron:
Diboson production cross sections

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<tbody>
<tr>
<td>WW</td>
<td>$11.5 \pm 2.2$</td>
<td>$12.1^{+1.8}_{-1.7}$</td>
<td>$11.7 \pm 0.8$</td>
</tr>
<tr>
<td>WZ</td>
<td>$3.90^{+1.06}_{-0.90}$</td>
<td>$4.1 \pm 0.7$</td>
<td>$3.5 \pm 0.3$</td>
</tr>
<tr>
<td>ZZ</td>
<td>$1.35^{+0.52}_{-0.43}$</td>
<td>$1.56^{+0.84}_{-0.68}$</td>
<td>$1.4 \pm 0.1$</td>
</tr>
</tbody>
</table>

Different measurements use different integrated luminosities, between 1 and 6 fb$^{-1}$
WZ+ZZ →qqll

- 4.8 fb-1 of data
  - Two high pT leptons, two high pT jets, and low MET
  - Expected signal ~202 events
  - Expected background ~13000 events: Dominated by Z+jets
- Use an artificial Neural Network to identify signal like events
- Includes variables to separate quark and gluon jets
  ⇒ Significance ~1 standard deviation above background
$WW \rightarrow lvlv$

- CDF Run II, 184 pb$^{-1}$: 14.6 pb $\pm$ 6.1
- D0 Run II, 224-252 pb$^{-1}$: 13.8 pb $\pm$ 4.6
- CDF Run II, 825 pb$^{-1}$: 13.6 pb $\pm$ 3.0
- D0 Run II, 1000 pb$^{-1}$: 11.5 pb $\pm$ 2.2
- CDF Run II, 3600 pb$^{-1}$: 12.1 pb $\pm$ 1.8

WW Cross Section (pb)
Moving to different kinematical region

- Using exactly the same kinematical cuts as the diboson analysis but:
- We require both jets to have $E_T > 30$ GeV
  1. Energetic jets are measured with better accuracy.
  2. Modeling in this region is expected to be more accurate
  3. A possible heavier particle would be characterized by more energetic jets
- Sample modeling using same processes with different relative contribution
- All cuts chosen “a priori”
CDF Dijet Mass Excess

Fitting procedure

- Combined $\chi^2$ fit to the dijet mass distribution in electron and muon samples.
- 5 templates:
  1. $W + \text{jets}$ (unconstrained, normalization determined from the fit)
  2. QCD (normalization constrained to its fraction with 25% error)
  3. $Z + \text{jets}$ (normalization constrained to the measured cross section)
  4. top & single top (normalization constrained to the theoretical cross section)
  5. $WW/WZ$ (normalization constrained to the theoretical cross section)
CDF Dijet Mass Excess

31/05/2011

Ralf Bernhard - Diboson Production cross sections at the Tevatron

arXiv:1104.0699 [hep-ex]
DZero lνqq Measurement

PRL 102, 161801 (2009)
Anomalous Couplings

- **$ZWW$ and $\gamma WW$ couplings**
  - General Lorentz invariant Lagrangian has 14 couplings

\[
\frac{L_{WWV}}{g_{WWV}} = i g_f^V (W^*_\mu W^\mu V^\nu - W^*_\nu V^\mu W^\mu V^\nu) + i \kappa_\gamma W^*_\mu W^\mu V^\nu + \frac{\lambda_\gamma}{M_W^2} W^*_\mu W^\mu V^\nu V^\rho \\
- g_f^V W^*_\mu W^\mu \left( \partial^{\mu} V^{\nu} + \partial^{\nu} V^{\mu} \right) + g_f^V \varepsilon^{\mu \nu \lambda} \left( W^*_\mu \partial^{\lambda} W^\nu - \partial^{\lambda} W^*_\mu W^\nu \right) V^\rho \\
+ i \kappa_\gamma W^*_\mu W^\mu \bar{V}^\mu V^\nu + i \frac{\lambda_\gamma}{M_W^2} W^*_\mu W^\mu \bar{V}^\mu V^\nu ;
\]

- **C and P conserving:** $g_1^Z, g_1^{Z'}, \kappa_\gamma, \kappa_Z, \lambda_\gamma, \lambda_Z$
- **C and P violating, but CP conserving:** $g_5^Z$
- **CP violating:** $g_4^{Z'}, g_4^{Z}, k_\gamma, k_Z, \lambda_\gamma, \lambda_Z$

SM: $g_1^\gamma = g_1^Z = \kappa = \kappa_Z = 1$ and all others are zero
Any new physics that causes anomalous TGCs must respect unitarity. However, anomalous TGCs in the SM violate unitarity at high energies. Thus, a dipole form factor:

$$a(s) = \frac{a_0}{\left(1 - \frac{s}{\Lambda_{NP}^2}\right)^2}$$

is used to regulate this behavior. $\Lambda_{NP}$ can be interpreted as the energy at which the new physics turns on.
Fermilab

**Tevatron Facts:**
- RunII since 2002
- 36 x 36 bunches
- Average initial luminosity: $>350 \times 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$
- $>50 \text{ pb}^{-1}$ per week