Di-Boson Measurements at the Tevatron

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for the CDF and DØ Collaborations
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Physics Motivation

Di-boson final states:
Charged: WW, WZ, Wγ
Neutral: ZZ, Zγ, (γγ)

Similar to WH, ZH, gg→H→WW.

• Test the electroweak sector:
  – cross-sections, kinematic distributions, gauge-boson couplings
• Search for new particles decaying to the same final state
• Known benchmarks for Higgs search
  – demonstrate sensitivity and constrain backgrounds
Di-Boson Cross-Sections

So far, the primary measurement channel is through leptonic decays. This means that we are probing $\sigma \cdot B$ values orders of magnitude smaller. Example: $\sigma \cdot B \approx 1.5$ fb for $ZZ \rightarrow \mu\mu\mu\mu$.

In practice, we measure final state topologies like: lepton+photon+MET ($W\gamma$), di-lepton + photon ($Z\gamma$), photon+MET ($Z\gamma$), di-leptons + MET ($WW$), tri-leptons+MET ($WZ$), lepton+jets+MET ($WW+WZ$), jets+MET ($WW+WZ+ZZ$), four-leptons ($ZZ$). We often retain acceptance for new physics sources of the same final state topology: eg. Higgs, SUSY, technicolor.
Outline

• Introduction
• $Z\gamma +$ anomalous neutral gauge couplings
• $W\gamma$
• $WW$
• $WZ$
• $ZZ$
• Jets + MET ($WW+WZ+ZZ$)
• $l\nu jj$ ($WW+WZ$)
• Combining charged gauge boson coupling measurements
• Summary
Charged Triple Gauge Couplings

One of the potentially most sensitive tests of the SM is the self-interactions of the gauge bosons

\[ \mathcal{L}_{WWV}^{WWV} = \frac{g_{WWV}}{\sqrt{2}} \left( W_{\mu}^{\dagger} W_{\nu}^{\mu} V_{\mu}^{\nu} - W_{\mu}^{\dagger} V_{\nu}^{\mu} W_{\mu}^{\nu} \right) + i \kappa_{V} W_{\mu}^{\dagger} W_{\nu}^{\mu} V_{\mu}^{\nu} + \frac{i \lambda_{V}}{M_{W}^{2}} W_{\lambda}^{\dagger} W_{\mu}^{\mu} V_{\lambda}^{\nu} V_{\mu}^{\nu} \]

• Analyses usually use this C,P, and CP conserving form of an effective Lagrangian for the \( WW\gamma \) and \( WWZ \) vertices with up to 5 free parameters. \( g_{1\gamma} = 1 \)
• In the SM, \( g_{1V} = \kappa_{V} = 1 \) and \( \lambda_{V} = 0 \) for \( V = \gamma, Z \)
• Analyses often use reduced parameter sets based on additional constraints.

(as used at LEP2) 3-parameter

2-parameter

\[ \gamma WW = Z WW: \quad \Delta \kappa_{\gamma} = \Delta \kappa_{z}, \quad \lambda_{\gamma} = \lambda_{z} \]

\[ \alpha(s) = \frac{\alpha_0}{(1 + s/\Lambda_{NP}^{2})^{\gamma}} \]
Complementarity to LEP2

Experiments at LEP2 primarily tested a combination of WWγ and WWZ TGCs in ee → WW by full reconstruction of the event kinematics and cross-section measurements at √s ≤ 209 GeV.

Many of the collisions producing di-bosons extend significantly above the √s explored at LEP2.

The Tevatron provides clean signatures in the leptonic decay modes to test directly WWγ couplings in the Wγ final state and to test directly WWZ couplings in the WZ final state (in addition to channels like WW).

68% CL
Zγ + Anomalous Neutral TGCs

\[ \mathcal{L}_{Z\gamma} = -ie \left[ (h_1^{\nu}\bar{F}_{\mu\nu} + h_3^{\nu}\tilde{F}_{\mu\nu}) Z_\mu \left( \frac{1 + m_V^2}{m_Z^2} \right) V_\nu 
\quad + (h_2^{\nu}\bar{F}_{\mu\nu} + h_4^{\nu}\tilde{F}_{\mu\nu}) Z^\alpha \left( \frac{1 + m_V^2}{m_Z^4} \right) \partial_\alpha \partial_\nu V_\nu \right] \]

For Zγ, explore using eeγ, μμγ and ννγ final states. Lots of ISR and FSR (l+1γ) to deal with.

- More details see T. Phillips’ talk at ICHEP and Y. Maravin’s talk at Blois.
- SM has no ZZZ, ZZγ or Zγγ couplings.
- h3, h4 couplings conserve CP

\[ \begin{array}{ccc}
\h_3^{Z} & 0.017 & \h_4^{Z} & 0.0006 \\
\h_3^{\gamma} & 0.017 & \h_4^{\gamma} & 0.0006 \\
\end{array} \]

CDF Prel.
5 fb\(^{-1}\)
Λ=1.5 TeV

\[ \sigma(p\bar{p} \rightarrow l^+l^-\gamma + X) = 4.6 \pm 0.2 \pm 0.3 \pm 0.3 \text{pb} \]
\[ \text{cf 4.5 ± 0.5 pb (NLO)} \]
\[ \text{with } E_\gamma > 7 \text{ GeV, } m_\perp > 40 \text{ GeV} \]

arXiv:1004.1140
Interference leads to radiation amplitude zero in the photon angular distribution.

Studied by D0: PRL 100, 241805 (2008)

\[ \Lambda = 2\text{TeV} \]

Direct test of \( WW\gamma \) couplings alone
Future measurements will likely take advantage of considerable progress on improving the sensitivity for these channels in the context of the Higgs search.
CDF         WW (lνlν)

PRL 104.20180 (2010)

<table>
<thead>
<tr>
<th>Process</th>
<th>Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z/\gamma^*$ (Drell-Yan)</td>
<td>79.8 ± 18.4</td>
</tr>
<tr>
<td>$WZ$</td>
<td>13.8 ± 1.9</td>
</tr>
<tr>
<td>$W\gamma$</td>
<td>91.7 ± 24.8</td>
</tr>
<tr>
<td>$W$ + 1-jet</td>
<td>112.7 ± 31.2</td>
</tr>
<tr>
<td>$ZZ$</td>
<td>20.7 ± 2.8</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>1.3 ± 0.2</td>
</tr>
<tr>
<td>Total Background</td>
<td>320.0 ± 46.8</td>
</tr>
<tr>
<td>$W^+W^-$</td>
<td>317.6 ± 43.8</td>
</tr>
<tr>
<td>Total Expected</td>
<td>637.6 ± 73.0</td>
</tr>
<tr>
<td>Data</td>
<td>654</td>
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</tbody>
</table>

3.6 fb$^{-1}$

95% CL limits

<table>
<thead>
<tr>
<th>$\Delta$ (TeV)</th>
<th>$\lambda_Z$</th>
<th>$\Delta g_1^Z$</th>
<th>$\Delta \kappa$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expected</td>
<td>1.5</td>
<td>-0.05,0.07</td>
<td>-0.23,0.31</td>
</tr>
<tr>
<td>Observed</td>
<td>1.5</td>
<td>-0.09,0.17</td>
<td>-0.24,0.034</td>
</tr>
<tr>
<td>Expected</td>
<td>2.0</td>
<td>-0.05,0.06</td>
<td>-0.08,0.15</td>
</tr>
<tr>
<td>Observed</td>
<td>2.0</td>
<td>-0.14,0.15</td>
<td>-0.22,0.30</td>
</tr>
</tbody>
</table>

Note: observed > expected

$\sigma(p\bar{p} \rightarrow W^+W^- + X) = 12.1 \pm 0.9 \text{ (stat)} ^{+1.6}_{-1.4} \text{ (syst)} \text{ pb}$
WW Cross-section Summary

NLO prediction: $11.7 \pm 0.8$ pb

($+ \text{Higgs}(165): +0.4$ pb)

Current and future measurements are taking advantage of ongoing $H\rightarrow WW$ experimental developments.
CDF WZ→lνll Cross-Section I

- CDF has two recent measurements of WZ cross-section.

- 12-variable NN plus ML fit to WZ Likelihood Ratio formed from ME for WW,ZZ, W+jet, Wγ using control regions to constrain background normalizations

$$\sigma(p\bar{p} \rightarrow WZ) = 3.7 \pm 0.6\,(\text{stat})^{+0.6}_{-0.4}\,(\text{syst})(\text{pb})$$
CDF WZ$\rightarrow$lνll Cross-Section II

- CDF’s second measurement normalizes to the NNLO Z cross-section reducing some systematics.
- Demonstrate reasonable detector stability with time wrt lumi, acceptance, lepton ID and trigger

\[ \text{ee, } \mu\mu \text{ combined} \]
Measure $\sigma_Z \cdot B(Z \rightarrow ll) = 247 \pm 4 \text{ pb}$ consistent with NNLO prediction of $251.3 \pm 5.0 \text{ pb}$

\[ \sigma(p\bar{p} \rightarrow WZ) = (4.1 \pm 0.6(stat) \pm 0.4(syst)) \text{ pb} \]
Select 3 leptons (l=e,μ) each with pT > 15 GeV. Require MET > 20 GeV.

34 candidates

\[ \sigma(WZ) = 3.90^{+1.01}_{-0.85} \text{ (stat + syst)} \pm 0.31 \text{ (lumi) pb} \]

NLO: 3.25 ± 0.19 pb
WZ Candidate Event

\[ WZ \rightarrow \mu \nu \mu \mu \]
D0 WZ $\rightarrow$ lνll

Use $Z$ $p_T$ distribution to test TGCs

Set 95%CL limits in 2D and 1-D

$\Lambda=2$TeV

<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>
• ZZ production at the Tevatron is now well established by both collaborations.
• Use both 4l and llνν final state.
• D0: \[ \sigma(ZZ) = 1.60 \pm 0.63 \text{ (stat.)}^{+0.16}_{-0.17} \text{ (syst.) pb} \]
• CDF: \[ \sigma_{ZZ} = 1.56^{+0.80}_{-0.63} \text{(stat.)} \pm 0.25 \text{(syst.) pb} \]

SM: 1.4 ± 0.1 pb

CDF ZZ→4l update

- Require 4 leptons
- \( p_T > 20, 15, 15, 15 \) GeV
- Require \( |m_{ll} - m_Z| < 15 \) GeV
- Require \( m_{llll} < 300 \) GeV
- Find 4 candidates
- Tiny background (0.01 events.)
- Normalize to \( Z \to ll \)
- Measure:

\[
\sigma(p\bar{p} \to ZZ) = (1.7^{+1.2}_{-0.7}(stat) \pm 0.2(syst)) \text{ pb}
\]

SM : 1.4 ± 0.1 pb
CDF: Jets + MET (WW+WZ+ZZ)

- MET > 60 GeV
- 2 hadronic jets, \( E_T > 25 \text{ GeV}, \mid \eta \mid < 2.0 \)
- \( 40 < m_{jj} < 160 \text{ GeV} \)
- MET significance > 4
- \( \Delta \phi (\text{MET-jet}) > 0.4 \text{ rad} \)
- Use tracking-based MET to constrain QCD MJB model

Acceptances: 2.5% (WW), 2.6% (WZ), 2.9% (ZZ)

Expected \( \sigma \) (pb) = 11.7, 3.6, 1.5

Azimuthal angle between MET and nearest jet

\( \sigma(WW+WZ+ZZ) = 18.0 \pm 2.8(\text{stat}) \pm 2.4(\text{syst}) \pm 1.1(\text{lumi}) \text{ pb} \)

cf 16.8\pm0.5\text{pb} expected

5.3\sigma significance
CDF $l\nu jj$ ($WW+WZ$)

- Recent paper, PRL 104 (2010) 101801 with two separate techniques with little statistical overlap with each other or the jets+MET analysis (only $\approx 15\%$)
  - Di-jet mass fit (3.9 fb$^{-1}$)
  - Matrix-element technique with event-probability discriminant (2.7 fb$^{-1}$) (5.4 $\sigma$)
  - Combined result: $\sigma(WW+WZ) = 16.0\pm 3.3$ pb
  - SM expectation: $16.1 \pm 0.9$ pb.

- Recent updates of both
  - Di-jet mass fit (4.3 fb$^{-1}$) $18.1\pm 3.3 \pm 2.5$ pb
  - ME (4.6 fb$^{-1}$) $16.5 +3.3 - 3.0$ pb
CDF $l_\nu jj \ (WW+WZ)$  Di-jet Mass

Require MET>25 GeV, di-jet $p_T > 40$ GeV. Leads to reasonably smoothly falling background in signal region – and visible bumps!

<table>
<thead>
<tr>
<th>Sample</th>
<th>CEM</th>
<th>CMUP + CMX</th>
</tr>
</thead>
<tbody>
<tr>
<td>MC W+jets</td>
<td>18010 ± 531</td>
<td>16673 ± 482</td>
</tr>
<tr>
<td>MC Z+jets</td>
<td>353 ± 42</td>
<td>966 ± 115</td>
</tr>
<tr>
<td>diboson</td>
<td>750 ± 68</td>
<td>651 ± 59</td>
</tr>
<tr>
<td>top</td>
<td>1324 ± 134</td>
<td>1149 ± 115</td>
</tr>
<tr>
<td>QCD (from data)</td>
<td>2314 ± 462</td>
<td>639 ± 159</td>
</tr>
<tr>
<td>Total MC + QCD</td>
<td>22751</td>
<td>20078</td>
</tr>
<tr>
<td>data</td>
<td>22204 ± 149</td>
<td>19738 ± 141</td>
</tr>
</tbody>
</table>

$\sigma = 13.5 \pm 4.4 \pm 1.9$ pb

$\sigma = 23.5 \pm 4.9 \pm 3.2$ pb
CDF $l\nu jj$ (WW+WZ) ME Technique

- MET > 40 GeV
- Exactly 2 jets, ET > 25 GeV, $|\eta| < 2.0$
- Form EPD (basically a LR) from ME prob. for WW, WZ and W+jets, single top.
$\nu jj$ WW+WZ (D0)

Use di-jet $p_T$ to constrain TGCs

PRD 80, 053012 (2009)

$\sigma$(WW+WZ) (pb) = 

$20.2 \pm 2.5$ (stat)$ \pm 3.6$ (sys)$ \pm 1.2$ (lum)

D0 lνjj (WW+WZ) TGC constraints

- SU(2)×U(1)
- Equal couplings

Λ=2TeV

PRD 80, 053012 (2009)
D0 Charged TGC combination

Combine 1 fb⁻¹ results from Wγ, WW, WZ, WW+WZ. Recent WZ analysis not included.

Λ=2TeV

SU(2)×U(1)

Equal couplings

arXiv:0907:4952
Outlook & Summary

• With 8 fb\(^{-1}\) per experiment and prospects for doubling the integrated luminosity, diboson physics is very much alive and well at the Tevatron.
  – Current data-sets, once fully analyzed and exploited, promise a wealth of information on interactions at mass scales in the few-100 GeV range.
  – So far all expected di-boson processes have been observed and measurements are in accord with theoretical predictions – but often with relatively large statistical errors – so still room for surprises.

• Increased statistics, and maturing analysis techniques are leading to measurements in challenging channels.
  – Channels like WW, trileptons, jets+MET and \(l\nu jj\), test electroweak interactions, provide benchmark channels relevant to the Higgs quest, and also lend themselves to Higgs searches themselves.

• In a few years, the LHC hopefully will have many more collisions to sift through and at a higher energy. For now, p-pbar at 1.96 TeV at L up to \(4 \times 10^{32}\) may not be that novel – but it sure continues to be fun – and scientifically compelling!
Backup Slides
Tevatron Luminosity

Integrated Luminosity History

Run II Integrated Luminosity

19 April 2002 - 11 July 2010

Delivered
Recorded

9.05
8.07
Detectors

DØ: calorimetry and μ coverage
- 2T Solenoid
- tracker to R = 52 cm
- RunIIb: Layer 0 Silicon

Upgrades to trigger

CDF: general purpose
- 1.4T Solenoid
- High precision tracker (R = 1.4m)

Both detectors have Si VTX detectors optimized for b-tagging

Tevatron: 1.7 MHz BX frequency $\langle n_{\text{int}} \rangle$ on average $\approx 4$ (store start $\approx 10$)
Physics program depends a lot on being able to reconstruct jets reliably and requiring leptons to reduce QCD bkgds. Control lepton-id and trigger efficiencies using $Z \to l\bar{l}$ samples.

All measured cross-sections typically have 6% normalization uncertainty.
• See slides from M. Martinez talk yesterday.
• Previous CDF result

<table>
<thead>
<tr>
<th>Candidate</th>
<th>leptons</th>
<th>$M_{l_l-1}$</th>
<th>$M_{l_l-2}$</th>
<th>4 lepton invariant mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$trk\mu/\mu\mu$</td>
<td>90.5 GeV/c$^2$</td>
<td>88.5 GeV/c$^2$</td>
<td>324.8 GeV/c$^2$</td>
</tr>
<tr>
<td>2</td>
<td>$trk\mu/\mu\mu$</td>
<td>91.6 GeV/c$^2$</td>
<td>94.2 GeV/c$^2$</td>
<td>169.4 GeV/c$^2$</td>
</tr>
<tr>
<td>3</td>
<td>$ee/\mu\mu$</td>
<td>93.0 GeV/c$^2$</td>
<td>86.4 GeV/c$^2$</td>
<td>191.9 GeV/c$^2$</td>
</tr>
<tr>
<td>4</td>
<td>$ee/\mu\mu$</td>
<td>93.3 GeV/c$^2$</td>
<td>79.7 GeV/c$^2$</td>
<td>229.2 GeV/c$^2$</td>
</tr>
<tr>
<td>5</td>
<td>$\mu\mu/\mu\mu$</td>
<td>91.7 GeV/c$^2$</td>
<td>55.1 GeV/c$^2$</td>
<td>325.0 GeV/c$^2$</td>
</tr>
</tbody>
</table>

• Yielded 5 candidates consistent with SM expectation

• ZZ resonance search in $m_{l_l l_l l_l} > 300$ GeV region in progress.