EWK physics at the Tevatron

P. Murat (FNAL) for the CDF and D0 collaborations

- physics of the gauge bosons - W, Z, photons
  - single boson production: couplings to the fermions
  - diboson production: self- or triple gauge couplings
- Tevatron vs LEP:
  - LEP: Z pole, WW and ZZ production
  - Tevatron: more W’s, WZ pairs, large sqrt(s) and Pt
- precision measurements
  - Properties of the W’s: mass, width, branching ratios
  - W’s vs Z’s - consistency of SM
  - Probe QCD and internal structure of the proton
- Signature-based searches
Tevatron today

~800 pb\(^{-1}\) delivered

CDF

Peak luminosities above \(1 \times 10^{32}/\text{cm}^2/\text{sec}\)

CDF

- Tevatron as a vector boson factory: *)
  - \(~30,000 \ W\rightarrow e\ \text{events/week}\)
  - \(~2500 \ Z\rightarrow ee\ \text{events/week}\)
  - \(120 \ WW, 40 \ WZ\ \text{events/week}\)

*) for \(L \sim 10\ \text{pb}^{-1}/\text{week}\)

P. Murat, Aspen Winter Conference, 2005/02/14
**EWK results’ 2004**

- **Single boson production**
  - $Z \rightarrow \tau \tau \tau$
  - $W$ charge asymmetry

- **Diboson physics**
  - $W\gamma$ and $Z\gamma$ cross sections
  - $W\gamma/Z\gamma$: limits on anomalous couplings
  - $WW$ production
  - $WZ/ZZ$ results

- **Properties of the $W$-boson: mass (status) and width**
**pp → Z → ττ cross section**

- **Taus very important**
  - H→τττ, SUSY at large tan(β)
- **Z→τττ** establishes the baseline
  - Learn if accuracy better than 10%

\[
p \bar{p} \rightarrow Z \rightarrow \tau(\mu \nu \bar{\nu})\tau(e/hadrons \nu)
\]

**D0 measurement:**

- Single muon trigger, neural network-based τID
- \(P_{\text{t}}(\mu) > 12\) GeV, \(E_{\text{T}}(\tau) > 10(5)\) GeV
- ~2000 events, S/B ~ 1
- **Z→τττ** signal: 914+/−24 events

\[
\sigma(p \bar{p} \rightarrow ZZ) \times BR(Z \rightarrow \tau\tau) = (252 \pm 16^{\text{STAT}} \pm 19^{\text{SYST}} \pm 17^{\text{LUM}}) \text{ pb}
\]

\([m(\tau\tau) > 60 \text{ GeV/c}^2]\) **hep/ex 0412020**

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Inclusive $p\bar{p}\rightarrow W/Z$ cross sections

**Tevatron $W \rightarrow l\nu$ cross section measurements**

- CDF'04 ($\mu$)  $2768 \pm 16 \pm 67 \pm 166$ pb
- CDF'04 (e)  $2780 \pm 14 \pm 56 \pm 167$ pb
- CDF'04 (e+\mu)  $2780 \pm 14 \pm 56 \pm 167$ pb
- CDF'04 (e, plug) (preliminary)  $2874 \pm 34 \pm 167 \pm 172$ pb
- CDF'03(\tau) (preliminary)  $2620 \pm 70 \pm 210 \pm 160$ pb

- D0'04 (e) (preliminary)  $2865 \pm 8 \pm 75 \pm 186$ pb
- D0'03 (\mu) (preliminary)  $3226\pm128\pm100\pm322$ pb

**Tevatron $Z \rightarrow l^+l^-$ cross section measurements**

- CDF'04 (e)  $255.8 \pm 3.9 \pm 0.6 \pm 15.4$ pb
- CDF'04 (\mu)  $248.0 \pm 5.9 \pm 0.7 \pm 14.9$ pb
- CDF'04 (e+\mu)  $253.9 \pm 3.3 \pm 4.6 \pm 15.2$ pb
- CDF'04 (\tau) (preliminary)  $242 \pm 48.0 \pm 26 \pm 15$ pb

- D0'04 (e) (preliminary)  $264.9 \pm 3.9 \pm 9.9 \pm 17.2$ pb
- D0'04 (\mu) (preliminary)  $291.3 \pm 3.0 \pm 6.9 \pm 18.8$ pb
- D0'04 (\tau)  $252 \pm 16 \pm 19 \pm 17$ pb

- **Good agreement with the NNLO calculations**
- **Accuracy limited by the systematic effects, dominant sources:**
  - luminosity measurements (~6%), correlated
  - PDF uncertainties (~2%)
**W charge asymmetry**

- Use W's to probe the proton structure (quark/gluon momentum distributions)
  \[ A(y) = \frac{d\sigma(W^+)/dy - d\sigma(W^-)/dy}{d\sigma(W^+)/dy + d\sigma(W^-)/dy} \]

- \( A(y) \) is sensitive to \( U(x)/D(x) \)

- Measure lepton charge asymmetry
  \[ A(\eta) = \frac{d\sigma(e^+)/d\eta - d\sigma(e^-)/d\eta}{d\sigma(e^+)/d\eta + d\sigma(e^-)/d\eta} \]

- Deconvolute it to extract information about the parton momentum distributions

- CDF: \( W \rightarrow e\nu \) cross section up to \( |\eta_e| = 2.5 \)

- Lepton asymmetry: W asymmetry\(^*\( (V-A) \)

- Key: lepton charge misID \(~4\%\) at \( |\eta| \sim 2 \)

**Results available for PDF’2005 fits**
Diboson physics: probing gauge sector

- SU(2)xU(1) breaks in the gauge sector W, Z, Higgs
- Probing interactions between the gauge bosons - important test of the SM

\[ L_{WW}^{\text{eff}} = i g_{WW} \left( g_1^V (W_\mu^+ W^- - W_-^+ W_\mu^-) V^\gamma + k_V W_\mu^+ W_-^\gamma V^\mu^\gamma + \frac{\lambda_V}{m_W^2} W_\mu^+ W^-\rho V_\rho^\mu \right) \]

**SM:**
- \( g_1^Z = g_1^\gamma = 1 \)
- \( k_Z = k_\gamma = 1 \)
- \( \lambda_Z = \lambda_\gamma = 0 \)

\( \lambda_\gamma \) and \( k_\gamma \) are related to magnetic and quadrupole moment of the W:
- \( \mu_W = e(1+k_\gamma+\lambda_\gamma)/2m_W \)
- \( q_W = -e(k_\gamma-\lambda_\gamma)/m_W^2 \)

- **Charged couplings** (WWZ/\( \gamma \)): 5 parameters \([g_Z, k_Z, k_\gamma, \lambda_Z, \lambda_\gamma]\)
- **neutral couplings** (ZZ\( \gamma \), Z\( \gamma \gamma \)): 8 parameters \([h_i^Z, h_i^\gamma, i=1,4]\)
- **Stringent limits from LEP**
- **Tevatron:** higher \( \sqrt{s} \), higher \( P_t \)'s \( \Rightarrow \) competitive with \~ few fb-1
**Experimental Language**

- **W/Z selections are based on selection of high-Pt leptons**
  - \( Z \rightarrow ll, \ W \rightarrow l \)

- **high-Pt lepton**
  - \( N(\text{definitions}) = 2 \text{ experiments} \times \text{several analyses} \times 2 \text{ lepton flavors} \)

- **“High-Pt lepton”**
  - Electron or muon with \( \text{Pt} > 25 \ (20, \ 15) \ \text{GeV/c} \)
  - “Isolated” : \( E_T \text{ in cone } R=0.4 \text{ less than } 0.1 \ \cancel{E_T} \text{(lepton)} \)
  - “Central” : \( |\eta| < 1 \ (1.1) \)

- **Neutrinos result in mis-balance of transverse energy,**
  - “large missing \( E_T \): \( \cancel{E_T} > 25 \ (20) \ \text{GeV} \)
**Probe trilinear $WW\gamma$ couplings**

**$W$ selection**
- Isolated high-Pt lepton
- Large missing $E_T$

**Photon identification critical:**
- $|\eta| < 1.1$, $R(\gamma l) > 0.7$

<table>
<thead>
<tr>
<th></th>
<th>$\sigma(pp\rightarrow W\gamma)$, pb</th>
<th>SM expectation, pb</th>
<th>$E_T$, GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDF</td>
<td>$18.1 \pm 1.6^{+2.4}_{-1.2}$ (STAT ± Syst)</td>
<td>$19.3 \pm 1.4$</td>
<td>7</td>
</tr>
<tr>
<td>D0</td>
<td>$14.8 \pm 1.6^{+1.0}_{-1.0}$ (STAT ± Syst)</td>
<td>$16.0 \pm 0.4$</td>
<td>8</td>
</tr>
</tbody>
</table>

*both experiments quote cross section integrated over the acceptance*

hep-ex/0410008
**WWγ couplings (2005)**

D0 preliminary @ 1.96 TeV

\( p \bar{p} \rightarrow Wγ \)

1D limits @ 95% CL:

<table>
<thead>
<tr>
<th></th>
<th>Tevatron Run I</th>
<th>Tevatron Run II (D0)</th>
<th>LEP combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Delta κ_γ )</td>
<td>-0.93, 0.94</td>
<td>-0.93, 0.97</td>
<td>-0.105, 0.069</td>
</tr>
<tr>
<td>( λ_γ )</td>
<td>-0.31, 0.29</td>
<td>-0.22, 0.22</td>
<td>-0.059, 0.026</td>
</tr>
</tbody>
</table>

Tevatron Run I limit for \( λ_γ \) already improved!

Tevatron Run II (D0): 2D limits

\( \Lambda = 2 \text{ TeV} \)
Event selection:
- Z-boson: 2 high-Pt isolated leptons
- central photon, $\Delta R(\gamma l) > 0.7$

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$\sigma(pp \rightarrow Z\gamma)$, pb</th>
<th>SM expectation, pb</th>
<th>$E_T$, GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDF, ~200 pb$^{-1}$</td>
<td>$4.6 \pm 0.5,<em>{\text{STAT+SYST}},^{0.3},</em>{\text{LUM}}$</td>
<td>$4.5 \pm 0.3$</td>
<td>7</td>
</tr>
<tr>
<td>D0, ~300 pb$^{-1}$</td>
<td>$4.2 \pm 0.4,<em>{\text{STAT+SYST}},^{0.3},</em>{\text{LUM}}$</td>
<td>$3.9 \pm 0.2$</td>
<td>8</td>
</tr>
</tbody>
</table>

*both experiments quote cross section integral within the acceptance*
neutral tri-boson couplings (2005)

\[ \gamma \to Z Z \]

D0 Preliminary

\[ 1D, 95\% \text{CL} \]

Tevatron (D0)

\[ -0.056 < h_{10}^\gamma < 0.055 \]
\[ -0.045 < h_{20}^\gamma < 0.025 \]
\[ -0.049 < h_{30}^\gamma < 0.008 \]
\[ -0.002 < h_{40}^\lambda < 0.034 \]
\[ -0.13 < h_{10}^Z < 0.13 \]
\[ -0.078 < h_{20}^Z < 0.071 \]
\[ -0.20 < h_{30}^Z < 0.07 \]
\[ -0.05 < h_{40}^Z < 0.12 \]

Tevatron already has better limits on \( h_4 \) than LEP
**WW: interesting signal, important background**

- Very important for the Higgs searches:
  \[ gg \rightarrow H \rightarrow WW \]
- Self-interaction of the heavy bosons (WWZ)
- Search for new heavy boson states

- Large statistics of WW events at LEP2 (~10K/expt)
- Run 1: only one measurement with limited sensitivity (CDF):
  \[ \sigma(p \bar{p} \rightarrow WW) = (10.2^{+6.1}_{-5.2} \pm 1.6) \text{ pb} \]
**$p\bar{p}\rightarrow WW$: event selection**

- **First goal for Run II:**
  - establish the signal

- **Prediction for the cross section:**
  \[ \sigma(p\bar{p}\rightarrow WW)_{\text{NLO}} = (12.4 \pm 0.8)\text{pb} \text{ at } 1.96\text{ TeV} \]

- **CDF and DO used dilepton channel**
  - BR~5\%, best sensitivity (S/B)

- **Selection:**
  - 2 isolated leptons, large $E_T(2\nu)$

- **Background sources**
  - Remove Drell-Yan pairs
  - Control rate of fake leptons
  - Veto extra jets

\[
\begin{align*}
\sigma(p\bar{p}\rightarrow WW\rightarrow e\nu e\nu) & \sim 0.15\text{ pb} \\
\sigma(p\bar{p}\rightarrow Z/\gamma^*\rightarrow ee) & \sim 250\text{ pb} \\
\sigma(p\bar{p}\rightarrow (W\rightarrow e\nu)+\text{jets}) & \sim 500\text{ pb} \\
\sigma(p\bar{p}\rightarrow t\bar{t}\rightarrow e\nu e\nu b\bar{b}) & \sim 0.1\text{ pb}
\end{align*}
\]
**WW: the Run II measurements**

<table>
<thead>
<tr>
<th></th>
<th>CDF</th>
<th>D0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity</td>
<td>200pb⁻¹</td>
<td>224-252pb⁻¹</td>
</tr>
<tr>
<td>WW signal</td>
<td>11.3 +/- 1.3</td>
<td>16.6 +/- 0.1</td>
</tr>
<tr>
<td>Background</td>
<td>4.8 +/- 0.7</td>
<td>8.1 +/- 0.5</td>
</tr>
<tr>
<td>Expected total</td>
<td>16.1 +/- 1.6</td>
<td>24.7 +/- 0.5</td>
</tr>
<tr>
<td>Observed</td>
<td>17</td>
<td>25</td>
</tr>
</tbody>
</table>

\[
\sigma(p \bar{p} \to WW)_{CDF} = 14.6_{-5.1}^{+5.8} (stat)_{-3.0}^{+1.8} (syst) \pm 0.9 (lum) \, pb
\]

\[
\sigma(p \bar{p} \to WW)_{D0} = 13.8_{-3.8}^{+4.3} (stat)_{-0.9}^{+1.2} (syst) \pm 0.9 (lum) \, pb
\]

Run II WW signal established  
hep-ex/0410066 (D0)  
hep-ex/0501050 (CDF)

Studies of the mode most sensitive to self-interactions of the W’s

\[ p \bar{p} \to W(l\nu)W(qq) \]

are in progress
\( WZ: \) the selections

- Study of \( WZ \) and \( ZZ \) production at the Tevatron - steps towards Higgs searches
- final state unique for hadron machines

\[
\sigma(p\bar{p} \rightarrow ZW + X)_{\text{NLO}} \sim 4 \text{ pb}
\]

- \( p\bar{p} \rightarrow WZ \): final states with 3 leptons have no irreducible SM backgrounds
- \( Z \) selection: 2 isolated leptons, \( M(\ell\ell) \) consistent with \( M_Z \).
- \( W \) selection: isolated lepton + \( E_T \)
- \( \Delta R(\ell\ell) > 0.2 \)

<table>
<thead>
<tr>
<th>D0(285-320 pb(^{-1})</th>
<th>L_{123}E_T</th>
</tr>
</thead>
<tbody>
<tr>
<td>WZ</td>
<td>2.04 +/- 0.13</td>
</tr>
<tr>
<td>Background</td>
<td>0.71 +/- 0.08</td>
</tr>
<tr>
<td>Expected total</td>
<td>2.75 +/- 0.15</td>
</tr>
<tr>
<td>Observed</td>
<td>3 (1eee, 2 ( \mu \mu \mu ))</td>
</tr>
</tbody>
</table>

71 GeV < \( M(e^+e^-) \) < 111 GeV
50 GeV < \( M(\mu^+\mu^-) \) < 130 GeV
lepton Pt > 15 GeV
missing \( E_T > 20 \) GeV
WZ: the results

The 95% CL upper limits:

**DO:** \[ \sigma(p \bar{p} \rightarrow ZW + X) < 13.3 \text{ pb} \]

**CDF:** \[ \sigma(p \bar{p} \rightarrow ZZ / ZW + X) < 15.2 \text{ pb} \]

3 events \(\Rightarrow\) cross section estimate

\[ \sigma(p \bar{p} \rightarrow ZW + X) = 4.5^{+3.8}_{-2.6} \text{ pb} \]

1D limits [ DØ Preliminary, 95% CL ]

<table>
<thead>
<tr>
<th>(\Lambda = 1.0 \text{ TeV} )</th>
<th>(\Lambda = 1.5 \text{ GeV} )</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 states
- The first and the best 2D limits in \(\kappa_z\) vs \(\lambda_z\) using WZ
- Best limits available on \(\Delta g_1^Z\), \(\Delta \kappa_z\) and \(\lambda_z\) from direct, model-independent measurements.

The DØ Run II 1D limits are \(\times 3\) better than Run I limits.
W mass measurement: work in progress

- Need accuracy better than $10^{-3}$
- fit $M_T(W)$ - the most accurate
- Theoretical / phenomenological inputs:
  - QED radiation
  - QCD: W Pt spectrum, PDF's
  - uncertainties on W mass $\sim 30$ MeV

ICHEP'2004 (CDF):

- $200\,pb^{-1}$: $\sigma(M_W)$ (e+$\mu$ combined) = 76 MeV
- $2\,fb^{-1}$: other sources $\sim 30$ MeV
- $L > 1\,fb^{-1}$: theoretical uncertainties [if not improved] will become important
**W width: direct measurement**

- **Determine W width using the tail of $M_T(\nu)$ distribution**

- **Event counting experiment:**
  - 75K $W \rightarrow e\nu$ candidates total
  - 625 events $100 < M_T < 200$ GeV/$c^2$

- **Result already competitive, a lot of room for improvement**

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P. Murat, Aspen Winter Conference, 2005/02/14
Summary and outlook

- Many new results on diboson production - important steps towards the Higgs searches
- Measurement of $pp \rightarrow Z \rightarrow \tau^+ \tau^-$ - a milestone in collider physics with tau's
- First Run II measurement of the W width
- Looking forward to high precision EWK measurements
  - W mass, width, branching ratios
  - Precision diboson measurements
  - Differential W/Z cross sections - there are interesting predictions to test
- PDF'2005 fits with new W charge asymmetry data included

Tevatron experiments just starting to explore potential of Run II data