Electroweak Physics at the TeVatron

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RADCOR-2000
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1. Introduction, Goals, Musings
2. On-Shell Physics
   - $W$ Properties
   - Multi-Boson Final States
3. Off-Shell Physics
   - NuTeV $\sin^2 \theta_W$
   - Drell-Yan
4. Discovering a Higgs
5. Conclusions
Status of TeVatron

Where's CDF?

Cosmic in COT, Calorimeter
Status of TeVatron (cont’d)

- TeVatron has achieved \( p\bar{p} \) collisions with Main Injector
  - \( \sqrt{s} = 1960 \text{ GeV} \)
  - \( \mathcal{L} \sim 10^{27} \), c.f. design \( \mathcal{L} \) of \( 2 \times 10^{32} \)

- CDF being installed for (short) “commissioning” run
- CDF/D0 to be ready for beam by March 1, 2001
  - “or else”

- Initial running with 36 bunch operation in machine
  - Occupancy a concern

  ![Graph](image)

  ▶ Hope for quick transition to 99 bunch operation, \( \delta t = 132 \text{ ns} \)
Status of Precision Electroweak Measurements: A Three Hour Tour?

A dozen years ago...

- The *basic structure* of the electroweak Standard Model appeared correct
  - Low-energy measurements of $\gamma - Z$ interference and $Z$ exchange
  - Crude boson masses
- Time was ripe for a quick **BIG SURPRISE**
  - Fat $Z$?
  - Generation dependence in couplings?
  - Physics at $TeV$ mass scales appearing in precision measurements?
  - Other

- **Who ordered this?**
  - *Certainly not an experimentalist!*
### Osaka 2000

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Pull</th>
<th>Pull</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_Z$ [GeV]</td>
<td>91.1875 ± 0.0021</td>
<td>.05</td>
</tr>
<tr>
<td>$\Gamma_Z$ [GeV]</td>
<td>2.4952 ± 0.0023</td>
<td>-.42</td>
</tr>
<tr>
<td>$\sigma^0_{\text{hadr}}$ [nb]</td>
<td>41.540 ± 0.037</td>
<td>1.62</td>
</tr>
<tr>
<td>$R_l$</td>
<td>20.767 ± 0.025</td>
<td>1.07</td>
</tr>
<tr>
<td>$A_{tb}^{0,l}$</td>
<td>0.01714 ± 0.00095</td>
<td>.75</td>
</tr>
<tr>
<td>$A_e$</td>
<td>0.1498 ± 0.0048</td>
<td>.38</td>
</tr>
<tr>
<td>$A_T$</td>
<td>0.1439 ± 0.0042</td>
<td>-.97</td>
</tr>
<tr>
<td>$\sin^2\theta^\text{lept}$</td>
<td>0.2321 ± 0.0010</td>
<td>.70</td>
</tr>
<tr>
<td>$m_W$ [GeV]</td>
<td>80.427 ± 0.046</td>
<td>.55</td>
</tr>
<tr>
<td>$R_b$</td>
<td>0.21653 ± 0.00069</td>
<td>1.09</td>
</tr>
<tr>
<td>$R_c$</td>
<td>0.1709 ± 0.0034</td>
<td>-.40</td>
</tr>
<tr>
<td>$A_{tb}^{0,b}$</td>
<td>0.0990 ± 0.0020</td>
<td>-2.38</td>
</tr>
<tr>
<td>$A_{tb}^{0,c}$</td>
<td>0.0689 ± 0.0035</td>
<td>-1.51</td>
</tr>
<tr>
<td>$A_b$</td>
<td>0.922 ± 0.023</td>
<td>-.55</td>
</tr>
<tr>
<td>$A_c$</td>
<td>0.631 ± 0.026</td>
<td>-1.43</td>
</tr>
<tr>
<td>$\sin^2\theta^\text{eff}$</td>
<td>0.23098 ± 0.00026</td>
<td>-1.61</td>
</tr>
<tr>
<td>$\sin^2\theta_W$</td>
<td>0.2255 ± 0.0021</td>
<td>1.20</td>
</tr>
<tr>
<td>$m_W$ [GeV]</td>
<td>80.452 ± 0.062</td>
<td>.81</td>
</tr>
<tr>
<td>$m_t$ [GeV]</td>
<td>174.3 ± 5.1</td>
<td>-.01</td>
</tr>
<tr>
<td>$\Delta\alpha^{(5)}_{\text{had}}(m_Z)$</td>
<td>0.02804 ± 0.00065</td>
<td>-.29</td>
</tr>
</tbody>
</table>

(Figure courtesy of LEP EWWG)
Status of Precision Electroweak Measurements (cont’d)

\[ \Delta \chi^2 \]

\[ m_H \ [\text{GeV}] \]

\[ \Delta \alpha_{\text{had}} = \Delta \alpha_{\text{had}}^{(5)} = 0.02804 \pm 0.00065 \]

\[ 0.02755 \pm 0.00046 \]

(Figure courtesy of LEP EWWG)
Struggling to Find New Physics

Where, if anywhere in the precision data, are there indications for deviations from Standard Model expectations in the precision data that would guide us as we begin to search again at the TeVatron?

- $\sin^2 \theta_W$, leptons vs $\sin^2 \theta_W$, quarks
- Also $\sigma_\text{had}^0$

Atomic Parity Violation ($^{137}\text{Cs}$)
Atomic Parity Violation

\[ \gamma - Z \text{ Interference} \]

- Interaction suppressed by \( q^2/M_Z^2 \)
- But not in forbidden \((6S \leftrightarrow 7S)\) transitions (parity-violating)
- Magnitude of interference (parity-violating) relative to \( \gamma \)-exchange gives

\[ \langle Q_W \rangle / \langle Q_{EM} \rangle \] (light quarks)

Recent \(^{137}\text{Cs} \) APV measurement


\[ Q_W = -72.06 \pm 0.28 \text{(exp)} \pm 0.34 \text{(theory)} \]

\[ Q_W^{SM} = -73.09 \pm 0.03 \]

“I believe our sigmas mean a bit more than the sigmas that you use [in particle physics].”

Carl Wieman, at an FNAL Seminar
On-Shell or Off-Shell?

- LEP $Z$ pole data disfavors most new physics in the weak neutral current itself

- However, this constraint still allows for new physics in off-shell processes

- New interactions can’t strongly affect $Z$ pole

- E.g., $Z'$ exchange, unmixed

- Global fit shows some $Z-$ $Z'$ mixing allowed
  > $\sim 10^{-3}$ weakly favored?

On-Shell ($W$ Properties)

- $W$ production is dominant source of high $p_t$ leptons at TeVatron

\[
\frac{\sigma(p\bar{p} \to W) \times BR(W \to \ell\nu)}{\sigma(p\bar{p} \to Z) \times BR(Z \to \ell\ell)} \approx 10
\]

- Drell-Yan extends to very high mass $\ell^+\ell^-$ pairs
- Generally clean, “obvious” sample
$W$ Mass

- $\alpha, \ G_F, \ M_Z \Rightarrow M_W$ at tree level
- $M_W$ measurement probes radiative corrections

\[
\begin{array}{c}
W \quad W \\
\uparrow \quad \uparrow \\
b \quad b \\
\downarrow \quad \downarrow \\
W \quad W
\end{array}
\quad \begin{array}{c}
h^0 \\
\quad ?
\end{array}
\quad \begin{array}{c}
W \\
\quad ?
\end{array}
\]

$\Delta M_W \propto M_t^2$  $\Delta M_W \propto \ln M_H$  New Physics

▷ Constraint on Higgs mass
▷ Key consistency check for model

\begin{figure}
\centering
\includegraphics[width=\textwidth]{plot.png}
\caption{Plot showing the relationship between $M_W$, $M_{top}$, and Higgs mass.}
\end{figure}

$\sigma_{M_{top}} = 5.1$ GeV, $\sigma_{M_W} = 63$ MeV
$W$ Mass (cont'd)

CDF/D0 Technique:

- Infer neutrino transverse kinematics from
  \[ \vec{p}_T^\nu = -\vec{u}_T - \vec{p}_T^\ell \]

- Form \( m_T = \sqrt{2p_T^\ell p_T^\nu (1 - \cos(\phi^\ell - \phi^\nu))} \)

- Select events with high \( p_T^\ell \) (25 or 30 GeV) and low \( u_T \) (below 15 or 20 GeV)
  - CDF, D0: central, \(|\eta^\ell| < 1\)
  - D0: endcap \( \ell \), \( 1.5 < |\eta^\ell| < 2.5 \) (\( \sim 30\% \) of sample)
  - \( \approx 4 \times 10^4 \) events per experiment

- Fit \( m_T \) to extract \( m_W \)
  (D0 fits \( p_T^\ell \) and \( p_T^\nu \) as well)
**Systematics:** $p_\ell^t$ measurement

- Primary control from $Z \rightarrow \ell^+\ell^-$ data

- Attempt to cross-check this with $E/p$ determination in CDF 1B electron data failed by $4\sigma$, ($\Delta M_Z \sim 500$ MeV)

- Highlights difficulty of measurement

- $\delta M_W \sim 70$–85 MeV (Run I)

**Systematics:** Recoil Model

- Response of detectors to underlying event

- Measured (again) in $Z \rightarrow \ell^+\ell^-$ data

- $\delta M_W \sim 30$–40 MeV (Run I)
Systematics: $d\sigma/dy$

- Direct effect on lineshape in fit

Well constrained from $W$ charge asymmetry

$\delta M_W \sim 10–20$ MeV (Run I)

Systematics: Scaling for Run II

- Most systematics now directly constrained from $W, Z$ data $\Rightarrow$ statistically limited

- Anticipate $\sigma_{M_W}$ of 20–40 MeV from first 2 fb$^{-1}$ (early 2003?) from CDF/D0

- Control of theoretical systematics also key – see talk by D. Wackerth
**W Width**

- TeVatron high statistics $W$ sample ideal for study of $W$ properties
- Run II (2 fb$^{-1}$ per experiment), expect $10^6 W$
- $W$ lineshape as a measure of $\Gamma_W$
- High $m_T$ dominated by Breit-Wigner, not resolution

CDF Preliminary

$\Gamma_W = 2.055 \pm 0.100 \pm 0.075$

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Value (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALEPH</td>
<td>2.17$\pm$0.20</td>
</tr>
<tr>
<td>DELPHI</td>
<td>2.09$\pm$0.15</td>
</tr>
<tr>
<td>L3</td>
<td>2.19$\pm$0.21</td>
</tr>
<tr>
<td>OPAL</td>
<td>2.04$\pm$0.18</td>
</tr>
<tr>
<td>LEP</td>
<td>2.12$\pm$0.11</td>
</tr>
<tr>
<td>CDF</td>
<td>2.06$\pm$0.12</td>
</tr>
</tbody>
</table>

Run II (2 fb$^{-1}$),
$\sigma_{\Gamma_W} \approx 20$–$40$ MeV
\( W/Z \) Production

- \( W, Z \) boson production also is a clean way to probe proton constituents

\[ \begin{align*}
M_V &= \sqrt{x_1 x_2 \frac{s}{2}} \\
\text{Role in precision measurements} \\
\text{e.g., } W \text{ mass and } W \text{ asymmetry}
\end{align*} \]
Forward $e^\pm$ reconstruction key for these measurements
Silicon tracking and EM calorimetry only!
Gauge Boson Couplings

- Standard Model allows for non-zero trilinear Gauge boson couplings
  - $WW\gamma$, $WWZ$ allowed
  - $ZZ\gamma$, $Z\gamma\gamma$, $ZZZ$ zero at tree level
- Search for non-Standard couplings to probe structure of physics beyond Standard Model
- Multi-boson signatures clean if $W, Z \rightarrow$ leptons
  - again, waiting increased $\mathcal{L}$

Run I D0 $WZ$ candidate!
Gauge Boson Couplings (cont’d)

- Expect scaling with $\sqrt{\mathcal{L}}$ (or better)
- $WZ$ signature unique to hadron colliders
Off-Shell: NuTeV

\[ \sigma_{NC} \]
\[ \sigma_{CC} \]
\[ \downarrow \]
\[ \sin^2 \theta_{W}^{\nu N} \]

<table>
<thead>
<tr>
<th>Short (NC) Events</th>
<th>Long (CC) Events</th>
<th>( R_{20} \equiv \text{Short/Long} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \nu )</td>
<td>386K</td>
<td>919K</td>
</tr>
<tr>
<td>( \bar{\nu} )</td>
<td>88.7K</td>
<td>210K</td>
</tr>
</tbody>
</table>
**PRELIMINARY NuTeV $\sin^2 \theta_W$**

**NuTeV measures:**

$$\sin^2 \theta_W^{(\text{on-shell})} = 0.2253 \pm 0.0019(\text{stat}) \pm 0.0010(\text{syst})$$

- The most precise $\nu N$ measurement of the weak mixing angle
- Precision comparable to collider measurements ...

\[
\begin{align*}
\sin^2 \theta_W^{(\text{on-shell})} &\equiv 1 - \frac{M_W^2}{M_Z^2} \\
80.360 +/- 0.370 &\quad \text{UA2} \\
80.433 +/- 0.079 &\quad \text{CDF*} \\
80.482 +/- 0.091 &\quad \text{D0*} \\
80.449 +/- 0.065 &\quad \text{ALEPH*} \\
80.308 +/- 0.091 &\quad \text{DELPHI*} \\
80.353 +/- 0.088 &\quad \text{L3*} \\
80.446 +/- 0.064 &\quad \text{OPAL*} \\
80.419 +/- 0.038 &\quad \text{World Average} \\
80.26 +/- 0.110 &\quad \text{NuTeV*} \\
\end{align*}
\]

* : Preliminary

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M$_w$ vs M$_{top}$ 68% Confidence Regions

- CDF
- LEP2
- LEP/SLD
- NuTeV
- CCFR
- D0
- FNAL Average

---

79.9 80.1 80.3 80.5 80.7 80.9

Mw (GeV)

79.8 80 80.2 80.4 80.6 80.8 81

M$_{top}$ (GeV/c$^2$)
\( \text{NuTeV } \sin^2 \theta_W \text{(cont'd)} \)

\[
R^- = \frac{\sigma_{NC}^\nu - \sigma_{NC}^\bar{\nu}}{\sigma_{CC}^\nu - \sigma_{CC}^\bar{\nu}} \\
= \left( \frac{1}{2} - \sin^2 \theta_W \right) \\
= u_L^2 + d_L^2 - u_R^2 - d_R^2
\]

**NuTeV measurement → constraint on the \( Z^0 \)-quark couplings:**

\[
0.4530 - \sin^2 \theta_W = 0.2277 \pm 0.0022 = 0.8587u_L^2 + 0.8828d_L^2 - 1.1657u_R^2 - 1.2288d_R^2
\]

**NuTeV \( R^- \) constraint:**

\[-0.0068 \pm 0.006 = + 1.6134 \Delta u_L + 0.9972 \Delta u_R - 2.0631 \Delta d_L - 0.5261 \Delta d_R \]

**APV constraint:**

\[
\left( Q_W^{exp} - Q_W^{SM} \right) / Q_W^{SM} = 0.014 \pm 0.006 = + 5.1436(\Delta u_L + \Delta u_R) + 5.7729(\Delta d_L + \Delta d_R) - 2\Delta g_A^e
\]
Extra Z Bosons?

- Several authors have suggested $E(6)$ $Z'$ as the most natural interpretation of APV data
  - Rosner, Casalbuoni et al, unmixed $Z'$
  - Erler and Langacker, general case

- APV, NuTeV (and $p\bar{p}$ Drell-Yan) all sensitive to direct $Z'$ exchange (interference)

95\% Confidence Level Lower Mass Limits on $Z'$:

$$Z' = Z_\chi \cos\beta + Z_\psi \sin\beta$$

NuTeV Limits (mixing=$-10^{-3}$)

$mZ_\chi \geq 675$ GeV at 95\% CL

$mZ_\eta \geq 380$ GeV at 95\% CL

Rosner hep-ph/9907524
Casalbuoni, et al. hep-ph/0001215
High Mass Drell-Yan

- Search for highest mass $\ell^\pm \ell^\mp$
- Sensitive to $\ell\ell qq$ contact interactions, $Z'$

$\leftarrow$ D0 Run I $e^+e^-$ sample

- Sample is clean, fertile ground for new physics

Comparison of the data with the SM predictions

Limits on Large Spatial Extra Dimensions

95% CL Upper Limit on $F/M_S^2$

- $n = 2, M_S > 1.37 \text{ TeV}$
- $n = 3, M_S > 1.44 \text{ TeV}$
- $n = 4, M_S > 1.21 \text{ TeV}$
- $n = 5, M_S > 1.10 \text{ TeV}$
- $n = 6, M_S > 1.02 \text{ TeV}$
- $n = 7, M_S > 0.97 \text{ TeV}$

D0 (2000)

$F = 2/(n-2), n > 2$

$F = 2\log_{10}(\frac{M_S}{20 \text{ TeV}}), n = 2$

(after Han et al., PRD 59 (1999) 1050060)
High Mass Drell-Yan (cont’d)

- Off-shell, **forward-backward** asymmetry is large

![Diagram of Drell-Yan process]

- Assume Standard Model behavior on $Z$ pole; probe high-mass region and therefore interference
- CDF new result in process; enhanced angular coverage using **forward events**!
High Mass Drell-Yan (cont’d)

- Forward $e^{\pm}$ defined by EM calorimeter...
- ...in conjunction with silicon stub
  ▶ charge determination!

- Probing off-shell (interference) key for $Z'$ searches!

- $\gamma^*/Z^*/Z'^*$ interference is signature of $Z'$
- Differentiates among E(6) $Z'$ possibilities
- Just awaiting $\mathcal{L}$...

(Rosner, Phys. Rev. D54 1078)
Standard Model Higgs

- Discovery of the Higgs would complete the experimental verification of the electroweak Standard Model
- SM Higgs:
  - Single doublet of scalar fields
  - Predicts couplings but not Higgs mass

Decay

- For $90 < M_H < 130 \text{ GeV}$, $\text{BR}(H \rightarrow b\bar{b})$ varies between 0.85 and 0.60.
- At $M_H > 140 \text{ GeV}$, $H \rightarrow WW^*$ dominates

Production at TeVatron

- $VH$ production provides additional handle for background rejection.
- $\sigma(WH)/\sigma(ZH) \approx 1.6$
- $gg \rightarrow H$, $H \rightarrow b\bar{b}$
  - hopeless at TeVatron
CDF Run I Searches

No signal observed!

\(W H \rightarrow \ell \nu b \bar{b}\)

Expect: \(30 \pm 5\) 1-tag, \(6.0 \pm 0.6\) 2-tag

Observe: 36 1-tag, 6 2-tag

\(V H \rightarrow qq b \bar{b}\)

Expect: 600 2-tag events

Observe: 589 2-tag events

\(Z H \rightarrow \ell^+ \ell^- b \bar{b}\)

Expect: \(3.2 \pm 0.7\) 1-tag

Observe: 5

\(Z H \rightarrow \nu \nu b \bar{b}\)

Expect: \(39.2 \pm 4.4\) 1-tag, \(3.9 \pm 0.6\) 2-tag

Observe: 40 1-tag, 4 2-tag
CDF Run 1 Searches (cont’d)

- Limits $\sim 50 \times$ SM expectations with $0.1 \text{ fb}^{-1}$
- $2 \text{ fb}^{-1}$ is still not enough
Run II Prospects

- Precision data strongly suggest that Higgs is below 190 GeV
- Suggests opportunity at TeVatron with high luminosity
- Two mass ranges:
  - \( M_H < 130 \text{ GeV} \)
    - \( VH \)
    - \( \ell\nu b\bar{b}, \nu\nu b\bar{b}, \ell^+\ell^- b\bar{b} \)
  - \( M_H > 130 \text{ GeV} \)
    - \( H \rightarrow WW^* \)
    - \( VH \) and \( gg \)
    - \( \ell^+\ell^- jj, \ell^+\ell^-\ell^- \), \( \ell^+\ell^- \)

Low backgrounds make analysis viable, even with low cross-sections and low branching ratios into leptons
Run II Prospects

(Run II Higgs Working Group, All $VH$ Channels and $gg \rightarrow H, H \rightarrow WW^*$)

- With $2 \text{ fb}^{-1}$ can probe $M_H$ up to $\sim 115 \text{ GeV/c}^2$.
- Need $\sim 20 \text{ fb}^{-1}$ for a $3\sigma$ signal for $M_H$ to 180 GeV
- Prospects for luminosity beyond 15 fb$^{-1}$ before LHC are unclear
Conclusions

The TeVatron is Poised for a Long Run!

- “The Signature” for Run II is $W/Z \rightarrow \ell(\nu/\ell)$
  - $10^6 W$ by 2003!
  - Precision measurements: $W$ mass and width
  - Using $W$ as a tool: parton distributions, luminosity calibration for TeVatron
  - Multi-boson production

- “The targets” for New Physics in Run II (2 fb$^{-1}$)
  - $Z'$ (testing Wieman’s “sigma” calibration)
  - Weak couplings of top (Willenbrock’s talk)

- Standard Model Higgs
  - Requires 10–20 fb$^{-1}$ to get in the game
  - TeVatron is a tough place to study a 114.9 GeV Higgs (just to pick a random number)
  - Good news: broad range of masses accessible!
  - More good news: $H \rightarrow WW^*$ clean