Electroweak Precision Measurements and Direct Higgs Searches at the Tevatron

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on behalf of the CDF & DØ Collaborations

- W Mass
- Top Physics
- Direct Higgs Searches

More details in parallel sessions:
- Knoepfel (27/am)
- Soustruznik (27/pm)
- Vellidas (27/pm)
- Head (27/pm)
- Riddick (28/pm)
- Peters (29/am)
Tevatron Run II

1st March 2001 – 30th September 2011

- 12 fb\(^{-1}\) delivered to CDF and DØ \(\approx\) ~10 fb\(^{-1}\) good data on tape.
- A enormous wealth of physics and much still to come.

Thank You!
Drift chamber outer tracker:
\[ \delta p_T / p_T \approx 0.0005 \times p_T \] [GeV/c; beam constrained]; \( |\eta| < 1 \)

Silicon vertex detector:
tracking coverage out to \( |\eta| < 2.8 \)

Central calorimeter: \( \delta E_T / E_T \approx 13.5\% / \sqrt{E_T} \oplus 1.5\% \) \( |\eta| < 1.1 \)

Plug calorimeter: coverage out to \( |\eta| < 3.0 \)

Muon chambers: coverage out to \( |\eta| < 1.0 \)
Central Fiber Tracker:
Tracking out to $|\eta|<1.8$ in 2 T B-field

**Silicon Tracker:**
Coverage out to $|\eta|<3$

**Muon System:**
Near hermetic coverage out to $|\eta|<2$
Momentum measurement in 1.8 T toroidal magnet

**Calorimetry:**
Liquid Argon/Uranium; covers $|\eta|<4$
• Electroweak standard model relates precisely known parameters and less well known parameters through radiative corrections:

\[ G_F = 1.16637(1) \times 10^{-5} \text{ GeV}^{-2} \]

\[ \alpha^{em}(0) = \frac{1}{137.03599911(46)} \]

\[ M_Z = 91.1876(21) \text{ GeV} \]

\[ M_W = f(\alpha^{em}(0), G_F, M_Z, \Delta r) \]

\[ \Delta r : \text{ radiative corrections} \]

\( \Delta r \) : radiative corrections (zero at tree level)

exquisitely well known

what goes into \( \Delta r \) ?
W Mass : Playing Precision Catch-Up

• Radiative corrections to $M_W$ include those due to top and Higgs:

$$\Delta M_W \propto M_{top}^2$$

$$\Delta M_W \propto \ln M_H$$

• Equivalently, measuring $M_W$ and $M_{top}$ places constraints on the missing piece, $M_H$.

$$M_H = 92^{+34}_{-26} \text{ GeV} \quad \text{(LEP EWWG, 2011)}$$

• How do $M_W$ and $M_{top}$ inputs compare?
• Current top mass precision:

$$\Delta (M_{TOP}) = 0.9 \text{ GeV} \ (0.54\%)$$

• Equivalent constraint on $M_H$ would come from:

$$\Delta (M_W) = 6 \text{ MeV} \ (0.001\%)$$

• The most important measurement for us to improve now is the W mass!
Even after a Higgs discovery at the Tevatron or LHC, precision EWK measurements will enable powerful Standard Model consistency fits.

May be possible to distinguish SM from MSSM and in general constrain the properties of new physics at higher mass scales.
\[ p\bar{p} \rightarrow W(\rightarrow l\nu) + X \]

- **Lepton**: Measure 4-vector as precisely as possible.
- **Hadronic Recoil**: Measure in transverse plane only
  \[ \vec{u}_T = \{u_x, u_y\} \]
- **Neutrino**: Infer transverse momentum:
  \[ \vec{p}_T^\nu = - (\vec{p}_T^l + \vec{u}_T) \]
- **Transverse Mass**:
  \[ M_T = \sqrt{2 p_T^l p_T^\nu (1 - \cos(\Delta\phi^{l\nu}))} \]

New!

arXiv:1203.0742 (CDF)
arXiv:1203.0293 (DØ)
W Mass : Yields

<table>
<thead>
<tr>
<th>Channel (Exp.)</th>
<th>Luminosity</th>
<th>#Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W \to e\nu$</td>
<td>2.2 fb$^{-1}$</td>
<td>470, 126</td>
</tr>
<tr>
<td>$W \to \mu\nu$</td>
<td>2.2 fb$^{-1}$</td>
<td>624, 708</td>
</tr>
<tr>
<td>$Z \to ee$</td>
<td>2.2 fb$^{-1}$</td>
<td>16,134</td>
</tr>
<tr>
<td>$Z \to \mu\mu$</td>
<td>2.2 fb$^{-1}$</td>
<td>59,738</td>
</tr>
<tr>
<td>$W \to e\nu$</td>
<td>4.3 fb$^{-1}$</td>
<td>1,677,394</td>
</tr>
<tr>
<td>$Z \to ee$</td>
<td>4.3 fb$^{-1}$</td>
<td>54,512</td>
</tr>
</tbody>
</table>

$W \to \ell\nu$ Kinematic Cuts

\[ 30 < p_T^{\ell}, p_T^{\nu} < 55 \text{ GeV} \]
\[ |\vec{u}| < 15 \text{ GeV} \]
\[ p_T^{\ell}, p_T^{\nu} > 25 \text{ GeV} \]
\[ |\vec{u}| < 15 \text{ GeV} \]

- Selection efficiencies are small compared to cross-section analyses: 3% (Z) - 12% (W).
- We are trading statistics for systematics - tight fiducial and ID cuts.

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My Ph.D. Thesis

3 $W \to e\nu$ events in 48 pb$^{-1}$

\[ \sigma(e^+ p \to e^+ W^{\pm} X) = 0.9^{+1.0}_{-0.7} \pm 0.2 \text{ pb} \]
$d\sigma_{p\bar{p}\to W/Z\to \ell\bar{\ell}} = \int \sum_{i,j=u,d,s,(c,b)} [f_i^q(x_p)f_j^q(x_{\bar{p}}) + f_i^\bar{q}(x_p)f_j^\bar{q}(x_{\bar{p}})] \times d\sigma_{q\bar{q}\to W/Z\to \ell\bar{\ell}} \ d\bar{p} \ dx_p$
• The heart of the CDF analysis is the extremely good $p_T$ measurement from the tracker.
• Start with a detailed cosmic ray internal alignment of the COT to $\sim 5 \mu m$
• Use precisely known resonances spanning a large range of curvature.

Flatness over a large $p_T$ range is also a test of dE/dx modelling.

$$\Delta M_W(\mu) = 7 \text{ MeV}$$

$$\delta p/p = 0.00009$$
Electron Energy Scale

- Transfer p-scale to E-scale using E/p:
  - Take advantage of large statistics in the W sample.
  - Fit the peak region for the energy scale.
  - E/p tail due to Bremsstrahlung in detector material \( \rightarrow \) constrain radiative material.

- Use \( Z \rightarrow ee \) events and precisely known \( M_Z \):
  - Effectively measuring \( M_W/M_Z \)
  - Luminosity dependence
  - Overall: \( \Delta M_W(e) = 16 \text{ MeV} \)

- Use dynamic range of E within the Z data to constrain parameters:
  \( E^{\text{meas}} = \alpha E^{\text{true}} + \beta \)
**M_Z Cross-Checks**

- Z mass fits blinded until the p-scale (from J/ψ and Υ) and E-scale (from E/p) were finalised.
- Comparison of unblinded Z mass fits with PDG is a very powerful cross-check.
- Subsequently Z constraints are included in p/E-scale determinations.

\[
\Delta M_W(e) = 10 \text{ MeV}
\]

combined with E/p to give:

\[
\Delta M_W(\mu) = 7 \text{ MeV}
\]

combined with J/ψ and Υ to give:
Recoil Modelling

- “Recoil” from W/Z $p_T$, UE, overlapping MB events and any lepton energy leakage/FSR.
- Tune using Z data and minimum-bias data.

$Z \rightarrow ee$

$W \rightarrow ev$

$\Delta M_W \approx 6 \text{ MeV}$
**M_W Fits**

- Fit the transverse mass in the range $65 < m_T < 90$ GeV:

  \[ M_W (\mu; CDF) = 80379 \pm 16 \text{ (stat.) MeV} \]

  \[ M_W (e; DØ) = 80371 \pm 13 \text{ (stat.) MeV} \]

- Fits are also performed to $p_T^\ell$ and $p_T^\nu$ distributions: all fits are consistent with $\chi^2$ probabilities of $\sim 5\%$ (DØ) and $\sim 25\%$ (CDF).

- $m_T / p_T^\ell$ (DØ) and $m_T / p_T^\ell / p_T^\nu$ (CDF) fit results are combined taking into account (large) correlations.
Uncertainties on Transverse Mass Fits for $M_W$ (MeV)

<table>
<thead>
<tr>
<th>Source</th>
<th>Electron (DØ)</th>
<th>Electron (CDF)</th>
<th>Muon (CDF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lepton Energy Scale + Nonlinearity</td>
<td>17</td>
<td>10</td>
<td>7</td>
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<tr>
<td>Lepton Energy Resolution</td>
<td>2</td>
<td>4</td>
<td>1</td>
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<tr>
<td>Recoil Model</td>
<td>5</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>Lepton Efficiency</td>
<td>1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Backgrounds</td>
<td>2</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>PDF</td>
<td>11</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>QED</td>
<td>7</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Boson $p_T$</td>
<td>2</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td><strong>Total Systematic</strong></td>
<td><strong>22</strong></td>
<td><strong>18</strong></td>
<td><strong>16</strong></td>
</tr>
<tr>
<td>Statistical</td>
<td>13</td>
<td>19</td>
<td>16</td>
</tr>
<tr>
<td><strong>Total Uncertainty</strong></td>
<td><strong>26</strong></td>
<td><strong>26</strong></td>
<td><strong>23</strong></td>
</tr>
</tbody>
</table>

- Modelling uncertainties (especially PDF’s) are starting to dominate.
New $M_W$ Average

Previous World Average (2009) : $M_W = 80399 \pm 23$ MeV
Top Mass : Overview

- Most important channel is lepton + jets
- The final Jet Energy Scale is determined in-situ from $M_W$ constraint.
- Latest measurements beginning to be limited by non-JES systematics (production model uncertainties).

Template Method:
- fit reconstructed mass distributions between simulation and data
- mass determined using a kinematic fit taking into account combinations & smearing

Matrix-Element Method

\[ P_{\text{sig}}(x;m_{\text{top}};\text{JES}) = \frac{1}{\sigma_{\text{obs}}(m_{\text{top}})} \times \int dq_1 dq_2 f(q_1) f(q_2) \cdot \frac{(2\pi)^4 |M(y,m_{\text{top}})|^2}{4\sqrt{q_1 \cdot q_2 - m_1 m_2}} d\phi \cdot W(y,x;\text{JES}) \]

\[ W(y,x;\text{JES}) \]

\[ \text{Transfer Function} \]

\[ \text{parton-level (y)} \otimes \text{detector-resolutions} \Rightarrow \text{measured (x)} \]
Reconstruct the mass for each event using over-constrained kinematics:

\[
\chi^2 = \sum_{i=1,4-jets} \left( \frac{p_T^{i,\text{fit}} - p_T^{i,\text{meas}}}{\sigma_i^2} \right)^2 + \sum_{j=x,y} \left( \frac{U_j^{\text{fit}} - U_j^{\text{meas}}}{\sigma_j^2} \right)^2 + \frac{(M_{jj} - M_W)^2}{\Gamma_W^2} \\
+ \frac{(M_{t\nu} - M_W)^2}{\Gamma_W^2} + \frac{(M_{bij} - M_{\text{reco}}^{\text{top}})^2}{\Gamma_{\text{top}}^2} + \frac{(M_{b\ell\nu} - M_{\text{reco}}^{\text{top}})^2}{\Gamma_{\text{top}}^2}
\]

variables entering mass fit:

- \( M_{jj} \), \( M_{\text{reco}}^{\text{top}} \), \( M_{\text{reco}}^{\text{top},2} \)

- 2-D fit for \( M_{\text{top}} \) and \( \Delta\text{JES} \)

- Result shows a best fit jet-energy scale shifted by about 0.11\( \sigma_C \) with respect to nominal.

- The size of the ellipse shows that the JES is considerably more constrained in-situ: \( \delta(\Delta\text{JES}) \approx 0.15\sigma_C \)
$M_{\text{top}}$ in Lepton+Jets using $8.7 \text{ fb}^{-1}$

$M_{\text{top}} = 172.85 \pm 0.71 \text{ (stat.)} \pm 0.84 \text{ (syst.)} = 172.85 \pm 1.10 \text{ GeV/c}^2$

- JES and generator systematics dominate the total
- Approximately 15% smaller error than $5.8 \text{ fb}^{-1}$ analysis
M_{top} in Dilepton Events with 4.3 fb^{-1}

- Statistically limited \( \times \)
- 2 neutrinos in final state: under-constrained kinematics requires integration over invisible momenta to generate fitting templates \( \times \)
- Precisely measured leptons \( \checkmark \)
- JES is still a critical issue for b-jets.
- A new analysis from DØ transfers the in-situ JES from lepton+jets events taking into account sample differences. [Similar to combined fits across samples from CDF]

\[
M_t = 174.0 \pm 2.4 \text{ (stat.)} \pm 1.4 \text{ (syst.)} = 174.0 \pm 2.8 \text{ GeV/c}^2
\]

- JES and generator systematics dominate the total
- Approximately 7% smaller error than similar analysis w/o new treatment of JES.
### Tevatron $M_t$ Combination with 5.8 fb$^{-1}$

#### Mass of the Top Quark

<table>
<thead>
<tr>
<th>Channel</th>
<th>$m_{top}$ (GeV/c$^2$) ± Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDF-I dilepton</td>
<td>167.4 ± 11.4 (±10.3 ± 4.9)</td>
</tr>
<tr>
<td>DØ-I dilepton</td>
<td>168.4 ± 12.8 (±12.3 ± 3.6)</td>
</tr>
<tr>
<td>CDF-II dilepton</td>
<td>170.6 ± 3.8  (±2.2 ± 1.1)</td>
</tr>
<tr>
<td>DØ-II dilepton</td>
<td>174.0 ± 3.1  (±1.8 ± 2.5)</td>
</tr>
<tr>
<td>CDF-I lepton+jets</td>
<td>176.1 ± 7.4  (±5.1 ± 5.3)</td>
</tr>
<tr>
<td>DØ-I lepton+jets</td>
<td>180.1 ± 5.3  (±3.9 ± 3.6)</td>
</tr>
<tr>
<td>CDF-II lepton+jets</td>
<td>173.0 ± 1.2  (±0.6 ± 1.1)</td>
</tr>
<tr>
<td>DØ-II lepton+jets</td>
<td>174.9 ± 1.5  (±0.8 ± 1.2)</td>
</tr>
<tr>
<td>CDF-I alljets</td>
<td>186.0 ± 11.5 (±10.0 ± 5.7)</td>
</tr>
<tr>
<td>CDF-II alljets *</td>
<td>172.5 ± 2.1  (±1.4 ± 1.5)</td>
</tr>
<tr>
<td>CDF-II track</td>
<td>166.9 ± 9.5  (±9.0 ± 2.9)</td>
</tr>
<tr>
<td>CDF-II MET+Jets *</td>
<td>172.3 ± 2.6  (±1.8 ± 1.8)</td>
</tr>
<tr>
<td>Tevatron combination *</td>
<td>173.2 ± 0.9  (±0.6 ± 0.8)</td>
</tr>
</tbody>
</table>

**Relative weights of different channels**

$\chi^2$/dof = 8.3/11 (68.5%)  

**Update with 8.7 fb$^{-1}$:**

$M_t = 172.9 \pm 1.1$ GeV/c$^2$

- Precision better than 1.0 GeV (0.54%)
- Consistency between individual measurements and also channels 
  $[\chi^2(\text{dilepton vs. lepton+jets})=1.77/1]$
\[ M_t = 173.2 \pm 0.6\text{(stat.)} \pm 0.8\text{(syst.)} = 173.2 \pm 0.9 \text{ GeV/c}^2 \]

<table>
<thead>
<tr>
<th>Error Source</th>
<th>Tevatron Combined Value (GeV/c^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal Modeling</td>
<td>0.51</td>
</tr>
<tr>
<td>(ISR/FSR, PDF, Generator, Colour-Reconnection)</td>
<td></td>
</tr>
<tr>
<td>Jet Energy Scale (JES) Related</td>
<td>0.49</td>
</tr>
<tr>
<td>Backgrounds</td>
<td>0.26</td>
</tr>
<tr>
<td>Other Experimental</td>
<td>0.18</td>
</tr>
<tr>
<td>(Lepton Energy Scale, Detector Modeling)</td>
<td></td>
</tr>
<tr>
<td>Total Systematic</td>
<td>0.76</td>
</tr>
<tr>
<td>Statistical</td>
<td>0.56</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>0.94</strong></td>
</tr>
</tbody>
</table>

- Some systematics (JES) have statistical components: hence an improvement with the final dataset can still be expected.
Top Forward-Backward Asymmetry

LO production mechanisms are symmetric: $A_{FB}=0$

New physics can be asymmetric:

$A_{FB} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$

where: $\Delta y = y_t - y_{\bar{t}}$

Higher order QCD effects can give a small $A_{FB} \approx 6-7\%$
• Analysis in lepton+jets mode with 5.4 fb\(^{-1}\)

\[
A_{FB} (\text{inclusive}) = 0.196 \pm 0.065
\]

• Analysis in lepton+jets mode with 8.7 fb\(^{-1}\)

\[
A_{FB} (\text{inclusive}) = 0.162 \pm 0.047
\]

• In agreement with previous results with 30% smaller uncertainty.
• Linear empirical parameterisations of \(A_{FB}\) versus \(t\bar{t}\) invariant mass and \(\Delta y\).
Combined Higgs Search with \( \leq 10 \text{ fb}^{-1} \)

- 20 decay channels combined, the most important ones with full luminosity.
- Large number of analysis improvements:
  - Additional acceptance (e.g. loose lepton categories, cut optimisation)
  - Improved b-tagging (boosted decision tree/neural network)
  - Improved multi-variate analysis techniques for a number of different topologies.

\[
M_H < 125 \text{ GeV} \\
\text{Sensitivity dominated by:} \\
VH \rightarrow \ell v b \bar{b}, \ell^+ \ell^- b \bar{b}, \nu \bar{\nu} b \bar{b}
\]

\[
M_H > 125 \text{ GeV} \\
\text{Sensitivity dominated by:} \\
H \rightarrow W^{(*)}W^{(*)}
\]

\[
M_H < 125 \text{ GeV} \\
Sensitivity dominated by:
VH \rightarrow \ell v b \bar{b}, \ell^+ \ell^- b \bar{b}, \nu \bar{\nu} b \bar{b}
\]

\[
M_H > 125 \text{ GeV} \\
Sensitivity dominated by:
H \rightarrow W^{(*)}W^{(*)}
\]

+: VBF, \( t\bar{t}H \)
Higgs Search: Sensitivity Demonstration

- WZ/ZZ production provides an ideal standard candle for low-mass Higgs searches:

\[ VZ \rightarrow \ell^+\ell^- b\bar{b} \]

- b-tagging
- di-jet mass reconstruction
- signal & background modelling

\[ \sigma(WZ + ZZ) = 4.47 \pm 0.64 \text{ (stat)} ^{+0.73}_{-0.72} \text{ (syst)} \text{ pb} \]

\[ \sigma(WZ + ZZ)_{SM} = 4.4 \pm 0.3 \text{ pb} \]
Higgs Searches: Example Channels

- Optimise sensitivity by splitting into flavour and jet-multiplicity sub-sets.
- Boosted Decision Tree discriminants.

\[ M_T^{\text{min}} = \min(M_T^{\ell_1}, M_T^{\ell_2}) \]

- New multi-variate b-jet identification, di-jet mass reconstruction and neural network background discrimination.
- 34% increase in signal sensitivity.
Higgs Search : Combining Channels

- Aggregate the discriminant distributions across all channels, combining bins of equal S/B:

- Integrate from $(S/B)_{\text{max}}$ downwards:

Consistent with $(S+B)$ [correlated errors !]
Higgs Search: Combining Channels

- Bayesian:

\[ \mathcal{L}(R, \bar{s}, b | \bar{n}, \theta) \times \pi(\theta) = \prod_{i=1}^{N_C} \prod_{j=1}^{N_b} \mu_{ij} e^{-\mu_{ij}}/n_{ij}! \times \prod_{k=1}^{n_{np}} e^{-\theta_k^2/2} \]

\[ \mu_{ij} = R \times s_{ij}(\theta) + b_{ij}(\theta) \]

- Cross-checked with modified frequentist treatment (i.e. \( \text{CL}_S \)), used to provide p-values.
Combined Higgs Searches : Results

26th March 2012

EWK Precision Measurements at the Tevatron

- Observed exclusion: \(100 < m_H < 106 \text{ GeV/c}^2\) \(147 < m_H < 179 \text{ GeV/c}^2\)
- Expected exclusion: \(100 < m_H < 119 \text{ GeV/c}^2\) \(141 < m_H < 184 \text{ GeV/c}^2\)
The smallest local p-value corresponds to $2.7\sigma$

An estimate of the *look-elsewhere effect* over the full range reduces this to $\sim 2.2\sigma$

[Not a large effect due to the “resolution” of each search point]
confidence level of signal hypothesis larger than expected for background-only

best-fitting signal size is larger than SM but consistent within (large) errors.
• Would such a signal be consistent with the di-boson control sample discussed earlier?
• Overlay the signal prediction for $m_H = 120 \text{ GeV/c}^2$:

The data are *not inconsistent* with such a signal.
Quite compatible with a measurement of $\sigma(WZ+ZZ)$ in agreement with SM (no Higgs) prediction.
Summary

- A new precision measurement of $M_W$ from the Tevatron has reduced the World Average uncertainty by one third:

$$M_W = 80385 \pm 15 \text{ MeV}$$

$$M_{top} = 173.2 \pm 0.9 \text{ GeV}$$

- Almost final Higgs searches using the full Tevatron data have excluded $100 < m_H < 106 \text{ GeV}/c^2$ and $147 < m_H < 179 \text{ GeV}/c^2$.
- There is an excess in the mass range 115-135 GeV with a statistical significance of $2.2 \sigma$. 

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$\text{LEP-2+Run-1!}$
Outlook

• Improvements in $M_{\text{top}}$ precision of between 10-15% are still possible using the full dataset and including the latest analysis improvements.

• The $W$ mass measurement will be further improved – for CDF only $\frac{1}{4}$ of the final dataset has been analysed:

• Model systematics are becoming the limiting factor. New techniques or inputs required to reduce the PDF uncertainty on $M_W$.

• Precision electroweak measurements - especially $M_{\text{top}}$ and $M_W$ - are incredibly difficult and will be an enduring legacy of the Tevatron.