The Tevatron’s Legacy: Some Selected Measurements

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- The Tevatron and its Experiments
- Weak Vector Bosons W and Z
  - Cross Sections
  - Asymmetries
  - W mass
- Top Quark Mass
- $B_s$ Mixing
The Tevatron and Associated Accelerators

Cockroft-Walton
Linac
Booster

ppbar collisions at 1.96 TeV
Luminosity up to 400E30 cm\(^{-2}\)s\(^{-1}\)
A very good week: ~80 pb\(^{-1}\)
First CDF p\bar{p} event: 1985
End of operations: 2011

Lepton coverage:
|\eta| < 1.5 (muons)
|\eta| < 2.0 (electrons)

b-tagging with
|\eta| < \sim 1.4

Jets to
|\eta| < 2.8
Higgs analyses restrict to
|\eta| < 2.0

Dijet mass resolution: \sim 16%
The DO Detector

Lepton coverage:
\[ |\eta| < 2 \text{ (muons)} \]
\[ |\eta| < 2.6 \text{ (electrons)} \]

b-tagging with
\[ |\eta| < ~2 \]

Jets to
\[ |\eta| < 3 \]

Scintillating fiber tracker

Trigger similar to CDF’s

Good Feature: Regular Switching of Solenoid Field – Cancels Some Systematic Uncertainties

New Innermost Silicon Layer added between Run IIa and Run IIb

Similar dijet mass resolution to CDF
CDF Run II Trigger System

Bunch Crossing Rate: ~1.7 MHz

Level 1 trigger ~15 KHz
  tracking
  calorimeter: jets & electrons
  muons

Level 2 trigger ~800 Hz
  L1 information (tracks, e, µ)
  calorimeter shower max
  silicon information
  algorithms run in L2 processor

Level 3 trigger ~200 Hz to tape
  full detector readout
  event building
  “offline” processing
The Tevatron, Like All Accelerators, Improved in Performance Over Time

Total delivered luminosity: ~12 fb\(^{-1}\) each to CDF and D0.

Acquired and analyzed: ~10 fb\(^{-1}\) each.
CDF’s W and Z Production Cross Section Measurements

Many additional processes (these are only at NLO)

Measurement of the Forward-Backward Asymmetry of W Bosons with D0

Forward-Backward Asymmetry comes largely from the difference between \( u \) and \( d \) PDF’s. The compton diagram \( gq \rightarrow Wq \) also participates.

\[
A(\eta) = \frac{1}{(1 - 2g)} \left[ \frac{N^+(\eta) - N^-(\eta)}{N^+(\eta) + N^-(\eta)} \right]
\]

Is the LEPTON asymmetry (directly observable). \( p_{z,W} \) ambiguous due to neutrino solution.

Inclusive \( p_{T\mu} > 20 \text{ GeV} \)

\[
20 < p_{T\mu} < 35 \text{ GeV}
\]

\[
p_{T\mu} > 35 \text{ GeV}
\]

\( g \) accounts for the charge misidentification rate, determined with like-sign \( Z \rightarrow \mu\mu \) candidate events. Solenoid reversal results are consistent.
Towards a Measurement of the W boson mass: Calibration of Detector Response

- $m_Z$ known very precisely from LEP
- $Z \rightarrow ee$ lepton rapidity and momentum spectrum similar to $W \rightarrow ev$

- $Z$+hadronic recoil events used to calibrate hadronic response, and electron ID efficiency vs. $P_T$ and proximity to the hadronic recoil

Material tuned in a fast simulation to make electron energies match in $Z \rightarrow ee$ in each calorimeter layer.

18,725 $Z \rightarrow ee$ candidates selected – negligible backgrounds
D0’s Measurement of the W mass in $W \rightarrow e\nu$ Events

499830 candidate events

Background consists of
• $Z \rightarrow ee$ with a missing electron
  (inter-cryostat crack for example)
• Multijets
• $W \rightarrow \tau\nu \rightarrow e\nu\nu$

$m_W^{\text{fit}} = 80.401 \pm 0.023$

$m_W^{\text{fit}} = 80.400 \pm 0.027$

$m_W^{\text{fit}} = 80.402 \pm 0.023$

Tevatron W Mass Combinations

Mass of the W Boson

<table>
<thead>
<tr>
<th>Measurement</th>
<th>$M_W$ [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDF-0/I</td>
<td>$80432 \pm 79$</td>
</tr>
<tr>
<td>DØ-I</td>
<td>$80478 \pm 83$</td>
</tr>
<tr>
<td>DØ-II (1.0 fb⁻¹)</td>
<td>$80402 \pm 43$</td>
</tr>
<tr>
<td>CDF-II (2.2 fb⁻¹)</td>
<td>$80387 \pm 19$</td>
</tr>
<tr>
<td>DØ-II (4.3 fb⁻¹)</td>
<td>$80369 \pm 26$</td>
</tr>
<tr>
<td>Tevatron Run-0/I/II</td>
<td>$80387 \pm 16$</td>
</tr>
<tr>
<td>LEP-2</td>
<td>$80376 \pm 33$</td>
</tr>
<tr>
<td>World Average</td>
<td>$80385 \pm 15$</td>
</tr>
</tbody>
</table>

Very Precise!

Onward to the top quark mass!
Measuring the Top Quark Mass

CDF Collab., PRD 83, 11101 (2011)

Ingredients: Select events, estimate backgrounds. Reconstruct invariant masses: Select assignment of jets to top quarks – or consider all such pairings, weighted with matrix-element probabilities.

Largest source of systematic uncertainty that can be calibrated in the same sample is the jet energy scale. Use $m_{jj}$ (W-candidate jets) to constrain jet energy scale.

CDF Collab.,
PRD 84, 071105 (2011)
**B_s Oscillations**

There are diagrams which allow a B_s meson to transform into its own anti-particle.

\[ |\psi\rangle = e^{-iM_H t} |B_H\rangle + e^{-iM_L t} |B_L\rangle \]

\[ |B_H\rangle = \frac{1}{\sqrt{2}} (|B\rangle - |\bar{B}\rangle), \quad M_H = M + \Delta m/2 \]

\[ |B_L\rangle = \frac{1}{\sqrt{2}} (|B\rangle + |\bar{B}\rangle), \quad M_L = M - \Delta m/2 \]
Measuring the $B_s$ Oscillation Rate

- Make a $B_s$ meson and measure its flavour when it decays
- Identify the flavour at production (tagging)
- Look at oscillation probability vs proper decay time

Fourier component of asymmetry: Mixing amplitude

\[ A(t) = \cos(\Delta m t) \]

Asymmetry:

\[ N_{\text{unmix}} - N_{\text{mix}} / N \]
The Signals
Charge Sign Assignment and Decay Time Resolution

- Opposite side lepton charge
- Opposite side kaon charge
- Opposite side vertex charge
- Same-side kaon charge – fragmentation kaons are correlated in sign with the $B_s$ at production

Decay Time Resolution

$\sigma(ct) = 25.9 \, \mu m$ for fully hadronic decay modes, and $44.6 \, \mu m$ for semileptonic decay modes
The Amplitude Scan for $B_s$ Mixing

$\Delta m_s = 17.77^{+0.10}_{-0.07}(\text{stat})^{+0.07}_{-0.07}(\text{syst}) \, \text{ps}^{-1}$

$|V_{td}/V_{ts}| = 0.2060^{+0.0007}_{-0.0006}(\Delta m_s)^{+0.0081}_{-0.0060}(\Delta m_d^{\text{theor}})$
Summary

The Tevatron has been a very successful accelerator, with two very productive collaborations, CDF and D0.

More than 500 papers in refereed journals per collaboration!

Many joint papers documenting combined results – inter-collaboration cooperation has been very good.

Highlights:
• Discovery of the top quark
• Precise measurement of the masses of the top quark and the W boson
• Observation of $B_s$ mixing and precise measurement of its rate
• Observation of single top quark production and measurement of its rate
• Evidence for the SM Higgs boson and measurement of production rates time decay branching fractions
• And many more: observation of many new hadrons, charm mixing, characterization of top quarks, CP violation in inclusive muon production