Studying EWSB at the Tevatron
Lecture #1

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CDF Experiment

SLAC Summer Institute
August 13-24, 2001

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Energy Frontier Accelerators

LEP (Z, W)

Tevatron (W, Top)

900 GeV p on 900 GeV p

1: 45 GeV e- on 45 GeV e+
2: 80~103 GeV e- on 80~103 GeV e+

SLC (Z)

45 GeV e- on 45 GeV e+
Energy Frontier Accelerators necessary to understand EWSB

1991 → 2001 → 2011 (year)

- LEP (e^+e^-) Ecm up to 208 GeV
- SLC (e^+e^-) ~ 90 GeV
- Run I
- Run II
- Tevatron (p\bar{p}) Ecm = 2 TeV
- LHC (p\bar{p}) Ecm = 14 TeV
- LC (e^+e^-) ? Ecm = 0.5~1 TeV

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Outline of Lectures

Status of Tevatron Run II Experimental Program

- Lecture #1
  - Tevatron Run II has begun
  - Physics Potential for Tevatron Run II (selected highlights)
  - Tevatron and accelerator complex
  - CDF and DO experiments
  - A first look at Run II data

Studying Electroweak Symmetry Breaking

- Lecture #2
  - Electroweak Precision Measurements & their Implication
    - $M_W, M_{top}, ...$

- Lecture #3
  - Direct Searches for EWSB Mechanisms
    - SM Higgs, MSSM Higgs, ...
What's New at Fermilab?
The Fermilab Accelerator Complex

- Run IIa (2001 - 4): 2 fb-1
  - Main Injector: x5
    - 150 GeV proton storage ring replaces Main Ring, the original Fermilab accelerator.
  - Recycler: x 2–3 (2003 - 4)
    - Re-cools p-bar from Tevatron

- Run IIb (2005 - 7): 15 fb-1
  - Electron cooling, crossing angle, electron lens: x 2–3
  - Increased # of p and p-bar bunches:
    - 6 (3500 ns) → 36 (396 ns) → ~100 (132 ns)

- Higher energy collisions:
  - $E_{\text{proton}} = 900 \rightarrow 980$ GeV

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Physics Potential for Tevatron Run II

The details depend on specific physics channels, but it is easy to understand the big picture.

A = \frac{\text{Accelerator improvements}}{\text{Detector upgrades}} \approx 200 - 300 \text{ (top, Higgs, B physics)}

D = \text{Detector Capabilities}
- L1 (10k - 50k Hz) \rightarrow L2 (0.5k - 1k Hz) \rightarrow L3 (\sim 50 Hz)
- Tracking in Level-1, B hadrons in Level-2
- b-tagging, Lepton coverage, Particle ID's

E = \text{Experience working with the data} > 1

e.g. attained \sim 2 \text{ in Run I top studies}

I = \text{new Ideas} > 1

[Run I Physics Results] \times A \times D \times E \times I > 400 \sim 900
Tevatron Improvement

\[ L = \frac{3\gamma_r f_0 N_B N_p}{\beta^*} \left( \frac{N_p}{\epsilon_p} \right) F\left( \beta^*, \theta_x, \theta_y, \epsilon_p, \epsilon_{\overline{p}}, \sigma_z \right) \left( 1 + \frac{\epsilon_{\overline{p}}}{\epsilon_p} \right) \]

**Total Antiprotons**

<table>
<thead>
<tr>
<th>Run</th>
<th>Ib(93-95) (6x6)</th>
<th>IIa (36x36)</th>
<th>IIa (140x103)</th>
<th>IIb (140x103)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( N_p )</td>
<td>2.3 \times 10^{11}</td>
<td>2.7 \times 10^{11}</td>
<td>2.7 \times 10^{11}</td>
<td>2.7 \times 10^{11}</td>
</tr>
<tr>
<td>( N_{\overline{p}} )</td>
<td>5.5 \times 10^{10}</td>
<td>3.0 \times 10^{10}</td>
<td>4.0 \times 10^{10}</td>
<td>1.0 \times 10^{11}</td>
</tr>
<tr>
<td>( N_B N_{\overline{p}} )</td>
<td>3.3 \times 10^{11}</td>
<td>1.1 \times 10^{12}</td>
<td>4.2 \times 10^{12}</td>
<td>1.1 \times 10^{13}</td>
</tr>
<tr>
<td>( \overline{p} ) prod. rate</td>
<td>6.0 \times 10^{10}</td>
<td>1.0 \times 10^{11}</td>
<td>2.1 \times 10^{11}</td>
<td>5.2 \times 10^{11}</td>
</tr>
<tr>
<td>( L_{\text{peak}} )</td>
<td>0.16 \times 10^{31}</td>
<td>0.86 \times 10^{32}</td>
<td>2.1 \times 10^{32}</td>
<td>5.2 \times 10^{32}</td>
</tr>
<tr>
<td>Int. Luminosity</td>
<td>3.2</td>
<td>17.3</td>
<td>42</td>
<td>105</td>
</tr>
<tr>
<td>Bunch spacing</td>
<td>\sim 3500</td>
<td>396</td>
<td>132</td>
<td>132</td>
</tr>
<tr>
<td>( N_{\text{int}} / \text{crossing} )</td>
<td>2.5</td>
<td>2.3</td>
<td>1.9</td>
<td>4.8</td>
</tr>
</tbody>
</table>

**Protons per bunch**

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Tevatron Physics Potential
Run II vs Run I
(accelerator upgrade only)

<table>
<thead>
<tr>
<th>Process</th>
<th>Mass $\gamma$ GeV/c²</th>
<th>Production sensitivity increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>$pp \rightarrow \gamma \gamma$</td>
<td>120</td>
<td>$1.2 \times 150$</td>
</tr>
<tr>
<td>$\bar{t}t$</td>
<td>175</td>
<td>$1.4 \times 150$</td>
</tr>
<tr>
<td>$\bar{q}q$</td>
<td>300</td>
<td>$1.8 \times 150$</td>
</tr>
<tr>
<td>$\bar{g}g$</td>
<td>300</td>
<td>$2.1 \times 150$</td>
</tr>
</tbody>
</table>

Energy $\times$ Lum.

Sensitivity increase of Run II vs Run I = 200 - 300

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Tevatron History and Future

Discovery of top, $B_c$, ...
$M_W$, $M_{top}$, $\sin2\beta$, ... measurements

Tevatron Collider Luminosity

- $5 \times 10^{32}$ cm$^{-2}$ s$^{-1}$
- $2 \times 10^{32}$ cm$^{-2}$ s$^{-1}$
- We are here!
- $2$ fb$^{-1}$
- $15$ fb$^{-1}$

Run: 0 Ia Ib
Run: IIa IIb

$\sqrt{s} : 1.8$ TeV
$\sqrt{s} : 1.96$ TeV

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Recent Machine Performance

Peak Lum (1E30)

- Luminosity (1E30) vs Store number
  - Feb. 02: 5E31
  - Sept.: 1E31
  - Aug.: 1E31

Projected

- Int. Lum (nb^-1)
  - 1-Jul-01: Delivered
  - 8-Jul-01: Data on Tape (CDF)

Projected July 02 ~0.2 fb^-1

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The Fermilab Particle Menu

- High b rates
  - $15k$ (IIa) - $100k$ (IIb) $B \rightarrow J/\psi K_S \rightarrow \mu\mu K_S$
  - 400 events in Run I
  - $9k$ (IIa) $B_s \rightarrow J/\psi \phi$
  - $1.6k$ (IIa) $B_s \rightarrow D_s \pi$
  - challenge: triggers, flavor tagging

- Large $W$ boson sample:
  - $10^7$ (IIa) - $10^8$ (IIb) events

- Largest/only $t\bar{t}$ sample:
  - $10k$ (IIa) - $75k$ (IIb) events
  - challenge: $b$ tagging, jet energy scale

- Searches for Higgs, SUSY, ...
  - challenge: backgrounds, statistics

Comparison of $\times$-sections at Tevatron

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Run II Physics Goals

- Study Electroweak Symmetry Breaking
  - Precision EW Measurements ($M_W, M_{top}$), Top properties
  - Direct Searches for EWSB mechanisms
    - the Standard Model Higgs
    - SUSY

- Searches for New Phenomena
  - SUSY
  - Large Extra Dimension
  - QCD tests: probe distance scales below 1 milli fermi.

- Study CP Violation and the CKM Matrix
  - $\chi s$ Measurement
  - $\sin 2\beta$ Measurement, + $\alpha, \gamma$

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Study CP Violation and CKM Matrix

B_s mixing measurement (unique to Tevatron) is important for complete picture of the Unitary triangle.

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Electroweak Precision Measurements

Direct measurements of $M_w, M_{top}$

Tevatron Run I:
$M_{top} = 174.3 \pm 5.1 \text{ GeV/c}^2$
$M_w = 80.452 \pm 0.062 \text{ GeV/c}^2$

LEP II:
$M_w = 80.450 \pm 0.039 \text{ GeV/c}^2$

Prediction of $M_w$ & $M_{top}$ using LEP I & SLC data

Current data favor light Higgs:

EW Meas: $M_{Higgs} < \sim 200 \text{ GeV} @ 95\% \text{ CL}$

LEP II Higgs Searches: $M_{Higgs} > 114.1 \text{ GeV} @ 95\% \text{ CL}$

LEP II Hint $M_{Higgs} = 115.6 \text{ GeV}$ (prob. of bgrnd fluctuation $\sim 2.1 \text{ s.d.}$)

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# of Physicists for Particle Discovery

![Graph showing the number of physicists over years](image)

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The New CDF and DO Experiments

A First Look at Run II Data
Tevatron:
\[ \frac{\sigma_{tt}}{\sigma_{inelastic}} \sim 10^{-10} \]
\[ \frac{\sigma_{W}}{\sigma_{inelastic}} \sim 10^{-6} \]

- W, Z, Top events contain e, \( \mu \), \( \nu \), b, ...
- b's are detected by a silicon device.
- \( \nu \)'s will escape, carrying away momentum.
Momentum Measurement of Leptons

40 GeV, s = 3 mm, \( \delta s = 100 \mu m \)
(\( \Delta s \text{ syst} \)) = 3 \( \mu m \)

1 GeV

B = 1.4 T

\[ P_T = |Q| \cdot B \cdot r \]
\[ P_T = 40 \text{ GeV} \rightarrow r \sim 100 \text{ m} \]

Systematic errors:

- Calibration (time)
- Alignment (wire location in \( \phi, r \))
- A rigid body? (twist, deflection)
- B field measurement
- Energy loss (\( \sim 0.005 \text{ GeV} \))
New CDF & DO Experiments

- The CDF and DO experiments have been upgraded to handle the increased collision rate (132 ns crossing time) or \( \sim 10^7 \) collisions per second
  - Fast detector response
  - Ability to quickly decide which of there are interesting and an integrated luminosity up to \( \sim 5 \text{ fb}^{-1} \)

- In addition the experiments have been significantly rebuilt to qualitatively improve performance.

- The transition from Run IIa to IIb will require a shutdown of \( \sim 6 \) months primarily to replace the silicon strip trackers.
DØ

➤ What DØ kept
  o Calorimeters
  o Parts of the muon system

➤ NEW
  o Solenoid
  o Tracking
    ▪ Silicon Tracker
    ▪ Central Fiber Tracker
  o Muon systems
  o Front End Electronics
  o Triggers / DAQ (pipelined)
  o Online and Offline Software

CDF

➤ What CDF kept
  o Solenoid
  o Central calorimeter
  o Parts of the muon system

➤ NEW
  o Tracking
    ▪ Silicon Tracker
    ▪ Central Outer Tracker (Drift)
    ▪ Time of Flight
  o Endplug Calorimeter
  o Muon systems
  o Front End Electronics
  o Trigger / DAQ (pipelined)
  o Online and Offline Software

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DØ Detector Roll-in

Jan 25, 2001

Jan 16, 2001

Jan 26, 2001

Jan 26, 2001
DØ Silicon System

Barrels: $|\eta| < 2$
4 layers

Barrels + disks $|\eta| < 2$

Event with silicon tracks pointing to same vertex

Hit residuals and pulls

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DØ Silicon Performance

Primary vertices reconstructed from tracks in Silicon

\[ <x> = + 0.27 \text{ cm} \]

\[ <y> = + 0.32 \text{ cm} \]

\[ <z> = + 7.04 \text{ cm} \]

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DØ Tracking & Preshower Performance

Scintillating Fiber Tracker
Visible Light Photon Counter Readout

Tracks with fiber tracker & silicon hits
DØ First Reconstructed Muon

Two views of the same muon track:

- Hits in A, B, C layers of mini-drift tubes (magenta dots)
- Hits in A, B, C layer scintillator counters (red lines)
DØ Jet Events

Calorimeter Level-1 Trigger

Jet Et ~ 25 GeV

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CDF Central Outer Tracker Performance

Hit Resolution
~200 μm
Goal: 180 μm

Residual dist. (cm)

Δφ = 6 mrad.
Goal: 8 mrad

ΔC = 0.016 GeV⁻¹
Goal: 0.02 GeV⁻¹

Level-1 Track Trigger

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CDF Tracking Performance

Silicon

West barrel
Central barrel
East barrel

\( D_0 \) (cm)

\( \phi \) (radian)

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Si+COT
---

COT

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CDF Secondary Vertex Trigger Performance

Level-2 impact parameter trigger provides access to hadronic B decays for $B_s \to D_s + \pi$ mixing, $B_0 \to \pi^+\pi^-$, or $H \to b\bar{b}$

Level-2 Silicon Trigger measures beam position

Resolution: 56 µm including the beam spread

\begin{align*}
\text{Resolution} \\
D_0 \text{ (cm)} \\
\phi_0 \text{ (radian)}
\end{align*}

\begin{align*}
\text{Resolution} \\
D_0 \text{ (cm)}
\end{align*}

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CDF Performance

\[ J/\psi \rightarrow \mu^+\mu^- \quad \sim 0.7 \text{ pb}^{-1} \]

- Dimuon triggers
- \( \sim 3.5k \) evts

\[ M(J/\psi) = 3.080 \pm 0.001 \text{ MeV} \] (no dE/dx corrections applied)

\[ K_s \rightarrow \pi^+\pi^- \]
\[ \Lambda \rightarrow \pi^-p \]

X-ray the detector with \( \gamma \rightarrow e^+e^- \) conversion

Silicon
COT inner cylinder

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CDF Performance: W candidates

Data (0.6pb$^{-1}$: ~450 W Events)

$E_T\nu$ vs. $E_T^{e,\mu}$ (GeV)

$M_T^W$ (GeV)

1st $W \rightarrow e\nu$ candidate

Missing $E_T = 38$ GeV

$E_T = 35$
CDF Performance: Z Candidates

Z → e⁺e⁻

Points: Data (0.6pb⁻¹)
Hist: PYTHIA (Z/γ*)

Cental e – Central e

Cental e – Plug e

Z → μ⁺μ⁻

Mₜₜ = 88.3 GeV

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CDF Jets

3 jet event

Et of highest energy jet

Jet $E_T$ (GeV)

1.1 million events

Et = 179.24 GeV

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CDF & DØ Summary

- **DØ**
  - Fiber tracker electronics installation in October 2001 (machine shutdown).
  - Silicon, calorimeter, muon systems online.

- **CDF**
  - Detectors fully instrumented.
  - Has been running in stable operational condition.
    - Exception: 1 (out of 6) silicon layer - cooling problem to be fixed.
  - Level-1, 3 Triggers in good shape.
  - Level-2 Trigger commissioning until fall 2001 (for high Lum).
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CP Violation & CKM Matrix with data by next summer,

- $B_s$ mixing: SM prediction region fully covered, unique to Tevatron
- $\delta \sin 2\beta \sim 0.12$: similar to BaBar, Belle LP01 results

200 pb$^{-1}$ (Summer 2002)  
end of 2002  
2 fb$^{-1}$

$\sigma(\sin 2\beta)$

$\sin 2\beta$ (Run II)

$\sin 2\beta$ (TDR)

$\chi_n$ (+TOF+L00, S/B=1)

SM

Int. luminosity (pb$^{-1}$)

CDF (Run I)

0.79 ± 0.41

BaBar + Belle (LP01)

0.79 ± 0.11

BaBar (LP01)

0.59 ± 0.14 ± 0.05

Belle (LP01)

0.99 ± 0.14 ± 0.06

5 $\sigma$ $\chi_n$ Limit

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With 200 pb⁻¹ (next summer), DØ and CDF will achieve
- SM prediction of $B_s$ mixing parameter fully covered.
  - Unique to Tevatron
- $\Delta \sin 2\beta$: similar to BaBar, Belle LP01 results.
- Extend SUSY particle and New Phenomena searches.
- Larger Top and W samples to improve Higgs mass limit.

~2 fb⁻¹ by 2004, ~15 fb⁻¹ by 2007
- Searches for Low Mass Higgs.
- Extend SUSY particle and New Phenomena searches.
- Improve Higgs mass limit from Precision EW meas.s
- Study CP violation and CKM matrix
Lecture #1 Summary: Tevatron Run II has begun!!

- Collisions in April, June - August 2001 demonstrate that CDF and DØ detectors are beginning to produce results.

- Shutdown in October/November, run uninterrupted after that. ~200 pb\(^{-1}\) by summer 2002

- Both DØ and CDF have a goal to present physics results at summer conferences in 2002.

- This is a very ambitious goal but attainable assuming the accelerator meets its luminosity profile.

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