The Collider Detector at Fermilab

Amitabha Lath
Rutgers University
July 25, 2002
What is Fermilab?

A “user” facility with the **Tevatron:**
4 mile ring with superconducting magnets.
- Collides protons with antiprotons.
- Energies up to 2 TRILLION eV achieved.
The Tevatron at Fermilab

- Many stages of boosting.
  - Note p-bar production.
- A “user” facility.
  - Fixed-target or collider.
The Cockroft-Walton and Linac
(where protons start out)
The Tevatron
# The Tevatron in Numbers

<table>
<thead>
<tr>
<th></th>
<th>Run 1B</th>
<th>Run IIa</th>
<th>Run IIb</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Energy/beam</strong></td>
<td>900 GeV</td>
<td>1000 GeV</td>
<td>1000 GeV</td>
</tr>
<tr>
<td><strong>Peak Luminosity</strong></td>
<td>$1.6 \times 10^{31}$</td>
<td>$2.0 \times 10^{32}$</td>
<td>$5.0 \times 10^{32}$</td>
</tr>
<tr>
<td><strong>Number of bunches</strong></td>
<td>6</td>
<td>36/108</td>
<td>~ 108</td>
</tr>
<tr>
<td><strong>Bunch spacing</strong></td>
<td>3500 nsec</td>
<td>396/132 nsec</td>
<td>132 nsec</td>
</tr>
<tr>
<td><strong>Interactions/crossing</strong></td>
<td>2.8</td>
<td>5.8/1.9</td>
<td>4.9</td>
</tr>
<tr>
<td><strong>Run period</strong></td>
<td>1992-96</td>
<td>2001-03</td>
<td>2004-07</td>
</tr>
<tr>
<td><strong>Integral Luminosity</strong></td>
<td>118 pb(^{-1})</td>
<td>2 fb(^{-1})</td>
<td>13 fb(^{-1})</td>
</tr>
</tbody>
</table>

Note integral luminosity given in inverse **barns**. (10\(^{-28}\) m\(^2\))

Some important numbers:
- **pp** total cross-section (2TeV) \(\sim 70\text{mb}\).
- **pp\(\bar{p}\)** \(\rightarrow\) W, (Z) boson production (2TeV) \(\sim 2.5\text{ nb}\), (250 pb) *leptonic decay*.
- **pp\(\bar{p}\)** \(\rightarrow\) t\(\bar{t}\) cross section (2TeV) \(\sim 5\text{ pb}\).
- **pp\(\bar{p}\)** \(\rightarrow\) Higgs +X cross section (2TeV) \(\sim\) few fb (?) *depends on \(M_H\).*
The CDF Collider Detector

- Proton
- Antiproton
- Tracking chamber
- Magnet
- Electromagnetic Calorimeter
- Hadronic Calorimeter
- Muon chambers
Particle Identification (basic)

- **Electron** track, contained cluster, E/P~1 γ, no track
- **Hadron** (p,π,K) track, extended (had) cluster n, no track
- **Muon** penetrating track
- **Short lived (b)** Displaced (mm) vertex.
- **Weak, no charge (ν,LSP)** Missing momentum
The CDF detector
quarter view

- Wire drift chamber (96 hits)

- A new powerful 3D tracking system and vertex detector covering $|\eta|$ out to 2.0.

- A new scintillating tile plug calorimeter covering $|\eta|$ out to 3.6.

Collisions happen here
Silicon Vertex Tracking

- The silicon strip detector is a stand-alone 3D tracking system
- Impact parameter resolution \( \sigma_d = \sqrt{a^2 + \frac{b}{P_t}^2} \) (a = 7\( \mu \)m, b = 20-30\( \mu \)m)
- Increase in B tagging for \( \bar{t}t \):  
  - Run I  
    - single tag  25%  52%  
    - double tag  8%  28%
CDF Silicon Vertex Detector
CDF Rolling into Collision Hall
Z decay to electrons

- All energy contained in **EM calorimeter**.
- 2 hard tracks. *Lots of soft ones.*
- Electron ID?
  - EM energy: 36.97, 39.71 GeV
  - Had energy: 0.73, 0.0 GeV
  - P: 34.65, 61.57 GeV/c
$M_{\mu\mu} = 3.0507$

Jpsi to muons

$M_{\mu\mu} = 3.0859$

Muon hits
Jpsi to muons Mass

CDF Run 2 Preliminary, 13 pb$^{-1}$, 04 Apr 2002

$J/\psi$: Events: 134035, Width: 21 $\pm$ 0.1 MeV/c$^2$

$\Psi(2s)$: Events: 4571, Width: 23$\pm$ 2 MeV/c$^2$
Kshort Mass

\[ \pi \pi \text{Mass} \]

Mass = $496.2 \pm 0.1 \text{ MeV/c}^2$

Energy correction not included
Lambda Mass

Mass = 1115.3 ± 0.1 MeV/c²
Energy correction not included
B MesonLifetime

B -> Jψ
Top Quark Event in Run 1

What happened?

\[ pp \rightarrow t \bar{t} \]

- \( b \ W \rightarrow e \nu \)
- \( b \ W \rightarrow q q' \) (jets)

Keep in mind:

- \( W \rightarrow e, \mu (+\nu) \sim 20\% \)
- \( B \) meson \( c\tau \sim 500 \mu m \)

\[ M_{\text{top}}^{\text{Fit}} = 170 \pm 10 \text{ GeV}/c^2 \]

24 September, 1992
run #40758, event #44414
Basic Idea of Hadron Collider/Detector

• Collide hadrons at highest energy possible.
  – Cross-sections increase with energy.
• Highest collision rates possible.
• General purpose detector that detects and identifies:
  – Electrons, muons, photons, pions, (missing P).
  – Displaced vertices from B mesons.
• Look for final states with specific signatures.
  – Like Higgs. (SM or SUSY).
• Quick identification (in trigger) better than later (in analysis).
CDF Deadtimeless Trigger.

Calorimeter energy
Central Tracker (Pt, \(\phi\))
Muon stubs

132 ns -> 7.6 Mhz

50 kHz

Cal Energy-track match
E/P, EM shower max
Silicon secondary vertex
Multi object triggers

300 Hz

Farm of PC’s running
fast versions of
Offline Code \(\rightarrow\) more
sophisticated selections

Mass Storage
(1 Pb in 2 years)

30 – 50 Hz
CDF Secondary Vertex Trigger

NEW for Run 2  --  level 2 impact parameter trigger

SVT  Provides access to hadronic B decays

Data from commissioning run

COT defines track ➔ SVX measures

at level 1  impact parameter

σ ~ 87 μm

ONLINE!
In Run 1, b-quark decays were tagged by decays to leptons.

In Run 2, we hope to tag hadronic decays of B.

Approx 5x increase in B acceptance possible.
Physics Analyses

Sample of main results

➤ QCD
  - Properties of jets and photons
  - Is there quark substructure?

➤ B
  - Bc discovery (The “last meson”)
    - Lifetimes, mixing
  - \( \sin(2\beta) \) (CP violation in the B system)

➤ Top/Electroweak.
  - Top quark discovery
  - Top mass, W mass

➤ Searches for new particles (EXOTICS).
  - Several limits set
    ➤ \( Z' \), \( W' \), SM/MSSM Higgs
    ➤ SUSY, Technicolor, Leptoquarks
Why do all this?

Isn't this good enough?
Go Back 100+ Years.

\[ \nabla \cdot \vec{E} = \rho / \varepsilon_0 \]

\[ \nabla \cdot \vec{B} = 0 \]

\[ \nabla \times \vec{\omega} = -\frac{d\vec{B}}{dt} \]

\[ \nabla \times \vec{E} = -\frac{d\vec{B}}{dt} - \nabla \cdot \vec{B} = \mu_0 j + \varepsilon_0 \mu_0 \frac{d\vec{E}}{dt} \]

\[ \vec{F} = q(\vec{E} + \vec{v} \times \vec{B}) \]

Isn’t this good enough?
Even before QED, we knew that classical electrodynamics could not be the whole story . . .

The classical theory predicts its own demise with an infinite electron self-energy

(This is a recurring and important theme)
**Nonsensical predictions, and solutions**

**Fermi theory of the 1930’s**

This process violates unitarity at high energies. (Simple muon decay, for instance).

What do we do?

Modify the diagram to cancel the divergence.

Add the W boson

(observed at CERN in 1983)
Nonsensical predictions, and solutions cont.

But now this process violates unitarity at high energies! (Simple e+e- annihilation).

What do we do?
Introduce another diagram that cancels the divergence

(ally observed at CERN in 1983)
Nonsensical predictions, and solutions cont 2.

But now these processes violate unitarity at high energies! (not so simple \(W^+W^-\) scattering)

What do we do?

Introduce other diagrams to cancel the divergence

The Higgs boson!
Nonsense Predictions don’t stop here!

Thus far we have **no direct evidence** for the Higgs boson*

but so what:

If the Higgs exists, this process violates unitarity at high energies ("fine-tuning" or "universe is size of basketball" problem)

What do we do?

Introduce other diagrams to cancel the divergence without fine-tuning

\{ 
\begin{align*}
\text{supersymmetry} \\
\text{strong dynamics} \\
\text{extra dimensions}
\end{align*}
\}
The Higgs Boson.

Even though we know the simple (Standard Model) Higgs Boson is not viable, it makes a good benchmark.

- **Weak Boson masses:** $M_z$, $M_w$.
- **Electroweak asymmetries:** $\sin^2 \theta_w$.
- **Top quark mass.**

If higgs exists, then

$$113 < m_h < 170 \text{ GeV}$$
Higgs Discovery Potential

Luminosity is key

(LEP “hint”)

(Luminosity is key)
But you just said Higgs has problems…

The simple Higgs theory does have problems but it solves the many problems quite elegantly, so we are loath to throw it out entirely.

**What do we hope/expect to find?**
Whatever is responsible for EW symmetry breaking - obviously not SM Higgs - should be at $M \sim 150$ GeV (see Steve Schnetzer’s talk). These should be observable.
Possibilities at 1 TeV

Logically, the possible options now are:

a) A Higgs-like field does not exist
   \( \rightarrow \exists \) other interesting physics at \( \approx 1 \) TeV

b) A Higgs-like field does exist
   
   i) A parameter is tuned to 1 part in \( 10^{16} \)
      \( \rightarrow \) No need for new physics at \( \approx 1 \) TeV
   
   ii) The parameter is not tuned to 1 part in \( 10^{16} \)
      \( \rightarrow \exists \) other interesting physics at \( \approx 1 \) TeV

Hence the excitement!
Conclusion

- CDF is a good general purpose detector.
  - Good tracking: electron, muon id.
  - Good vertex finding: b-tagging.
  - Smart trigger.
- We need this, since we cannot be certain of the signature of the new physics.
  - SM Higgs? SUSY? Technicolor? N-dim?
- Indirect indicators are encouraging.
- Watch this space!