BTeV Experiment

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# Weak Interactions of Quarks

<table>
<thead>
<tr>
<th>Generation</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
</table>
| **Quarks** | \[
\begin{pmatrix}
up(0.001) \\
\down(0.003)
\end{pmatrix}
\] | \[
\begin{pmatrix}
\text{charm}(1.3) \\
\text{strange}(0.015)
\end{pmatrix}
\] | \[
\begin{pmatrix}
top(175) \\
bottom(5)
\end{pmatrix}
\] |
| **Leptons** | \[
\begin{pmatrix}
e^-(0.0005) \\
\nu_e(< 1 \times 10^{-8})
\end{pmatrix}
\] | \[
\begin{pmatrix}
\mu^-(0.1) \\
\nu_\mu(< 0.00017)
\end{pmatrix}
\] | \[
\begin{pmatrix}
\tau^-(1.8) \\
\nu_\tau(< 0.018)
\end{pmatrix}
\] |
| **Antiquarks** | \[
\begin{pmatrix}
\bar{u}(0.001) \\
\bar{d}(0.003)
\end{pmatrix}
\] | \[
\begin{pmatrix}
\bar{c}(1.3) \\
\bar{s}(0.015)
\end{pmatrix}
\] | \[
\begin{pmatrix}
\bar{t}(175) \\
\bar{b}(5)
\end{pmatrix}
\] |
| **Antileptons** | \[
\begin{pmatrix}
e^+(0.0005) \\
\bar{\nu}_e(< 1 \times 10^{-8})
\end{pmatrix}
\] | \[
\begin{pmatrix}
\mu^+(0.1) \\
\bar{\nu}_\mu(< 0.00017)
\end{pmatrix}
\] | \[
\begin{pmatrix}
\tau^+(1.8) \\
\bar{\nu}_\tau(< 0.018)
\end{pmatrix}
\] |
Fundamental Forces

1. **Strong**: Binds colored quarks into colorless hadrons (particles that feel the strong force, quark+antiquark (mesons such as the $B^0(bd)$) or three quarks and antiquarks (baryons such as the proton($uud$)), holds nucleus together, carried by the gluon(massless).

2. **Electromagnetic**: Acts on charges, carried by the photon, $\gamma(< 2 \times 10^{-16}$eV).

3. **Weak**: Responsible for radioactive decay of nuclei, carried by the $W^\pm$ (80.41 GeV) and $Z^0$ (91.187 GeV), study of this force led to discovery of the neutrinos and CP violation.

4. **Gravity**: Mass attraction, carried by the graviton(massless), we do not yet have a proper quantum theory of gravity.
Weak Quark Interactions

The weak force connects quarks across generations:

**Semileptonic Decays**

\[ \begin{array}{c}
\text{b} & \text{W}^- & \bar{\nu} & \text{c} \\
V_{cb} & & & \\
\text{b} & \text{W}^- & \bar{\nu} & \text{c} \\
V_{cb} & & & \\
\end{array} \]

**Hadronic Decays**

\[ \begin{array}{c}
\text{b} & \text{W}^- & \bar{u}, \bar{c} & \bar{u}, \bar{c} \\
V_{qq} & & & \\
\text{b} & \text{W}^- & \bar{u}, \bar{c} & \bar{u}, \bar{c} \\
V_{qq} & & & \\
\end{array} \]

The CKM matrix gives the strength of the interaction:

\[
\begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{pmatrix}
\]
CKM Matrix

Measurements show a pattern that as yet has no compelling explanation:

\[
\begin{pmatrix}
0.9742 - 0.9757 & 0.219 - 0.226.002 - 0.005 \\
0.219 - 0.225 & 0.9734 - 0.9749.037 - 0.043 \\
0.004 - 0.014 & 0.035 - 0.0430.9990 - 0.9993
\end{pmatrix}
\]

And the theory behind the Weak Force implies that the matrix elements are not independent, but can be described with 4 parameters:

\[
\begin{pmatrix}
1 - \lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\
-\lambda & 1 - \lambda^2/2 & A\lambda^2 \\
A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1
\end{pmatrix}
\]
CKM Triangles and Angles

The theory also predicts relations among the elements that can be displayed as triangles with the elements giving the sides. The angles of the triangles are an alternative way to depict the underlying theory.
CKM Mysteries

1. What are the values of $\rho$ and $\eta$ (equivalently the angles $\alpha, \beta, \gamma, \chi$)?

2. Is the underlying theory of the weak interaction correct? Are four parameters enough?

3. What causes the pattern?

4. Why does it stop at three?

BTeV is an experiment designed to help answer these questions.
Heavy Flavors in $p\bar{p}$ Collisions

Key is decays of the $b$ quark to the $u$ quark as it probes all the parameters of the CKM matrix, $V_{ub} = A\lambda^3(\rho - i\eta)$. The matrix element is small, $|V_{ub}| = 0.002 - 0.005$, meaning that $b$ decays to $u$ are uncommon (1 in 200 or so). So to measure $b \rightarrow u$ to 0.1% one would need $2 \times 10^8$ $b$ decays.

CLEO and its competitors have accumulated $10^7$ $b$ decays in $e^+e^- \rightarrow b\bar{b}$ over the last decade, and struggle to measure $|V_{ub}|$ to 15%.
Need to go to $p\bar{p}$

Need is for much higher statistics and detector like CLEO with very good tracking, ability to see neutral particles (an Electromagnetic Calorimeter), particle identification (RICH), and muon identification.

Much higher statistics compel us to consider $q\bar{q} \rightarrow b\bar{b}$ at 1 TeV (1000 billion eV) with cross section of $\sim 100 \times 10^{-6}$ barns over $e^+e^- \rightarrow b\bar{b}$ at 10 GeV (10 billion eV) with cross section of $\sim 1 \times 10^{-9}$ barns. The cross section increase is $\sim 10^5$.

There are plenty of $b$’s in $p\bar{p}$ collisions at Fermilab’s TeVatron.
Trigger? We don’t need no stinkin’ . . .

There is some bad news. The total cross section for $p\overline{p}$ at 1 TeV is $\sim$ 1 barn. That is while in $e^+e^-$ collisions $b$’s are 1 in 5, in $p\overline{p}$ collisions $b$’s are in 1 in 1000. The detector must include a very powerful trigger to select on $b$ events, events with a $b$ that flies away from the collision point before decaying, or the $b$ signal will be overwhelmed by the other sorts of events.

To make the task easier we can note that most of the $b$’s produced in $p\overline{p}$ collisions go in the same direction as the $p$ or $\overline{p}$ and thus instead of surrounding the collision region we can build a detector along the $p\overline{p}$ beam line.
C0 Detector Hall at Fermilab
Pixel Detector

30 planes of silicon. Bump bonded to readout chips. Gives a 3D view of tracks with resolution of 5 \( \mu \text{m} \). \( 3 \times 10^7 \) channels. Sits in beam vacuum. 3kWatts of Heat. (Fermilab, Iowa, Wayne State)
Intermediate Tracking

Pixel strips in center, straw tube drift chambers on the outside. Connect pixel detector to RICH, calorimeter, and muon ID and measure momentum after magnet bend. (Fermilab, Houston, Italians)
Gas $C_4F_{10}$ and Aerogel radiator.
Gives particle ID out to 70 GeV.
(Syracuse, Italians)
Electromagnetic Calorimeter

\[ PbWO_4 \] Crystals. CLEO-like resolution and ability to reconstruct \( \pi^0 = u \bar{u} = d \bar{d} \). Crucial for measurements of \( b \rightarrow u \) processes (Minnesota, Syracuse)
Muon Identification

Made of proportional tubes arranged in “planks”. Planks are formed into octants. (Illinois, Vanderbilt)
Trigger

Has to reduce data rate by a factor of 2000. Complex interaction between detector hardware and large computer farm to sift for the $b$ events. Selects events with a detached vertex, correlated electron in EM Calorimeter, or correlated muon in Muon ID (Fermilab, Illinois)
# Design and Physics

<table>
<thead>
<tr>
<th>Physics Quantity</th>
<th>Decay Mode</th>
<th>Detector Property</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sin(2\alpha)$</td>
<td>$B^0 \to \rho \pi \to \pi^+ \pi^- \pi^0$</td>
<td>✓</td>
</tr>
<tr>
<td>$\cos(2\alpha)$</td>
<td>$B^0 \to \rho \pi \to \pi^+ \pi^- \pi^0$</td>
<td>✓</td>
</tr>
<tr>
<td>$\text{sign}(\sin(2\alpha))$</td>
<td>$B^0 \to \rho \pi, B^0 \to \pi^+ \pi^-$</td>
<td>✓</td>
</tr>
<tr>
<td>$\sin(\gamma)$</td>
<td>$B_s \to D_s K^-$</td>
<td>✓</td>
</tr>
<tr>
<td>$\sin(\gamma)$</td>
<td>$B^+ \to D^0 K^+$</td>
<td>✓</td>
</tr>
<tr>
<td>$\sin(\gamma)$</td>
<td>$B \to K \pi$</td>
<td>✓</td>
</tr>
<tr>
<td>$\sin(\gamma)$</td>
<td>$B \to \pi^+ \pi^-, B_s \to K^+ K^-$</td>
<td>✓</td>
</tr>
<tr>
<td>$\sin(2\chi)$</td>
<td>$B_s \to J/\psi \eta', J/\psi \eta$</td>
<td>✓</td>
</tr>
<tr>
<td>$\sin(2\beta)$</td>
<td>$B^0 \to J/\psi K_s$</td>
<td>✓</td>
</tr>
<tr>
<td>$\sin(2\beta)$</td>
<td>$B^0 \to \phi K_s, \eta' K_s, J/\psi \phi$</td>
<td>✓</td>
</tr>
<tr>
<td>$\cos(2\beta)$</td>
<td>$B^0 \to J/\psi K^*, B_s \to J/\psi \phi$</td>
<td>✓</td>
</tr>
<tr>
<td>$x_s$</td>
<td>$B_s \to D_s \pi^-$</td>
<td>✓</td>
</tr>
<tr>
<td>$\Delta \Gamma$ for $B_s$</td>
<td>$B_s \to J/\psi \eta', K^+ K^-, D_s \pi^-$</td>
<td>✓</td>
</tr>
</tbody>
</table>
BTeV Conclusion

1. Planned Experiment at Fermilab

2. Jobs this summer are related to test beam measurements on pixel detector prototypes. Students to Fermilab, one working with me and the other with the head of pixel project, Simon Kwan.