Millennial Physics at Fermilab

The high energy physics program at the U.S. Premier platform for

DISCOVERY

- Introduction
- Standard Model
- Accelerator complex and detectors
- Remembrance of Things Past
  - with an emphasis on the top quark
- The future

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Michigan State University
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I’m going to present the Fermilab proton-antiproton collider program in two lectures, past and future:

Lecture 1: A review of the physics of the Tevatron Collider in its first running

- introduction to the Standard Model of elementary particle physics
- introduction to the accelerator and the experiments

Lecture 2: Results and prospects

- Run I results
- Run II prospects

“Run I”, from 1193-1996, $L = 100 \text{ pb}^{-1}$
“Run IIa”, from 3/01 - ~03, $L \sim 3,000-5,000 \text{ pb}^{-1}$
“Run IIb”, from ~03 - LHC physics, $L \sim 20,000 \text{ pb}^{-1}$
Lecture 2: Fermilab Collider Physics: Results and Prospects
Run I

CDF’s second run...DØ’s first.
Run I physics, a (tiny) snapshot

Top quark– Discovery!

\[ m_t = 174.3 \pm 3.2 \text{ (stat)} \pm 4.0 \text{ (sys)} \text{ GeV/c}^2 \]

- Beginnings of detailed studies (cross sections, distns, BR, etc.)

W/Z bosons

\[ M_W = 80.45 \pm 0.063 \text{ GeV/c}^2 \]

- \( V-V-V \) couplings studied
- \( W/Z + \) soft gluon radiation

Bottom quarks – a new field

- 100’s B → J/\( \Psi \) - K\( _S \)
- \( B_C \) discovered
- Production \( \Psi \)’s & BR’s

Quantum Chromodynamics

- Substructure probed, \( 10^{-18} \text{ cm} \)
- Radiative corrections confirmed
- Colorless exchange - Pomeron

Exotic physics – searches

- supersymmetry
- leptoquarks
- Higgs boson
- additional W/Z’s

Over 250 papers published in PRL, PR, NP
The Top Quark at Fermilab

it’s big.
Who ordered that? – the extraordinary mass of $175 \times m_p$ distorts one’s expected picture of (just) a quark...

The decay of a quark, $Q$, with $m_Q > M_W + m_q$ is straightforward:

$$\Gamma(Q \rightarrow qW^+) = \frac{G_F m_Q^3}{8\sqrt{2}} |V_{tb}|^2 \left( \frac{M_W^2}{m_Q^2} \right)^2 + \frac{2M_W^2}{m_Q}$$

$V_{tb}$ is an element of the quark mixing matrix, bounded by the requirement of Unitarity and weak interaction phenomenology.

$$\begin{array}{ccc}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{array} \begin{array}{c}
0.9745 \pm 0.0045 \\
0.217 \pm 0.024 \\
0.004 \pm 0.013
\end{array}$$

SO, the fraction of decay of $t \rightarrow W b$ is almost 100%.
SO, $\Gamma_{top} \approx 0.4 \times 10^{-24}$ s … QCD confinement scale $\approx 1/\Lambda_{QCD} \approx \text{few } \times 10^{-24}$ s
Which means…top quarks decay before they form top-mesons…bare fermion… unprecedented and surely a clue to something?
TOP manifests itself three ways, depending on the W decay:

- **bℓq bq'** 30% “lepton + jets”

  - Charged lepton
  - Missing energy
  - 2 jets
  - 2 b quarks

  Serious backgrounds: QCD $Wjjbb$ w/ S/B $\sim$2/1, 4/1 with $b$ tagging

- **bℓq bq'** 5% “dilepton”

  - 2 Charged leptons
  - Missing energy
  - no jets
  - 2 b quarks

  Low backgrounds: QCD $Wjjbb$, (fake e, missing j) w/ S/B~3-4/1

- **bqq' bq'** 44% “dijet”

  - no lepton
  - no Missing energy
  - 4 jets
  - 2 b quarks

  Huge backgrounds: QCD multijets w/ S/B~1/1

But wait, there’s more:
Getting to the bottom of the top quark...

- We have a magical key...
- The $b$ quark lives a long time... $\tau_b \approx 1.5$ ps

**Si vertex detectors are magic**
1. lifetime is long enough to measure
2. Important for top physics
3. Important in it’s own right for B hadron physics
4. now a precision industry
   - Efficiency for 1 Si vertexing (SVX) tag is $\approx 50\%$ and essentially $p(b)$ independent
   - Can double tag with $\approx 40\%$
   - also can detect the presence of a soft lepton (SLT) from $b \rightarrow c \ell \nu$
Top, revealed

\[ t \rightarrow W (e \bar{e}) \ b \]

\[ \bar{t} \rightarrow W (q q) \ b \]
physics at fermilab

DØ top as art
Top’s bare bottom revealed by CDF

Two jets tagged by SVX
fit top mass is 170 ± 10 GeV

e^+, Missing E_t, jet #4 from top
jets 1,2,3 from top (2&3 from W)

Tracking View

seeing the bottom quark decay
Top quark physics: cross section

A cross section is a basic measurement:

$$\sigma(p\bar{p} \rightarrow X \rightarrow \text{channel}_i) = \frac{N_{\text{obs}}^i - N_{\text{background}}^i}{\epsilon_i \cdot \int \mathcal{L} \, dt}$$

A complicated theoretical effort for comparison

- Stresses QCD understanding at a deep level
- Heavy quark QCD calculations are tough

CDF: $6.5^{+1.7}_{-1.4}$ pb
DO: $5.9 \pm 1.7$ pb

---

**Top Cross Sections**

- **CDF preliminary**
  - 7.6^{+3.5}_{-2.7} pb
  - 5.1^{+1.6}_{-1.4} pb
  - 9.2^{+4.8}_{-4.0} pb
  - 8.4^{+4.3}_{-3.5} pb
  - 6.5^{+1.7}_{-1.4} pb

- **Theory (4.7 - 5.5)**
  - HAD
  - SVX
  - SLT
  - DIL
  - Combined

- **D0**
  - 6.4^{+3.4}_{-3.2} pb
  - 4.1^{+2.1}_{-1.9} pb
  - 8.3^{+3.6}_{-3.2} pb
  - 7.1^{+3.2}_{-3.0} pb
  - 5.9^{+1.7}_{-1.4} pb

- **Combined**
  - L+J (topo)
  - L+J (μ-tag)
  - HAD

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Millennial Physics

Chip Brock, Michigan State University

2001
Top quark physics: mass determination

Full kinematical fitting of lepton+jets, dilepton, all jets candidates
- A serious challenge for background simulation
- in particular, the QCD production of $W^+$ multiple jets w/b’s

<table>
<thead>
<tr>
<th>Channel</th>
<th>DO</th>
<th>DO</th>
<th>CDF</th>
<th>CDF</th>
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<tbody>
<tr>
<td></td>
<td>sample</td>
<td>bckgnd</td>
<td>sample</td>
<td>bckgnd</td>
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<tr>
<td>Di-lepton</td>
<td>5</td>
<td>1.4 ± 0.4</td>
<td>9</td>
<td>2.4 ± 0.5</td>
</tr>
<tr>
<td>Lep+jets SVX</td>
<td>11</td>
<td>2.4 ± 0.5</td>
<td>34</td>
<td>9.2 ± 1.5</td>
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<tr>
<td>Lep+jets SLT</td>
<td>19</td>
<td>8.7 ± 1.7</td>
<td>40</td>
<td>22.6 ± 2.8</td>
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<tr>
<td>Lep+jets top</td>
<td>41</td>
<td>24.8 ± 2.4</td>
<td>184</td>
<td>142 ± 12</td>
</tr>
<tr>
<td>All jets</td>
<td>4</td>
<td>1.2 ± 0.4</td>
<td>4</td>
<td>≈2</td>
</tr>
<tr>
<td>$en$</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>$et, mt$</td>
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Very sophisticated likelihood combinations of samples are now done
- eg., CDF combined 4 independent samples for their best result
- DO employs complicated kinematical and topological cuts
lepton plus jets mass results

<table>
<thead>
<tr>
<th>systematics</th>
<th>(GeV/c^2)</th>
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<tbody>
<tr>
<td>jet energy determination</td>
<td>4.0</td>
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<tr>
<td>bckgnd model</td>
<td>2.5</td>
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<tr>
<td>signal model</td>
<td>1.9</td>
</tr>
<tr>
<td>fitting tech.</td>
<td>1.5</td>
</tr>
<tr>
<td>cal. noise</td>
<td>1.3</td>
</tr>
<tr>
<td>Total</td>
<td>5.5</td>
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(CDF)
Top Quark Mass

Tevatron Top Quark Mass Measurements

- $167.4 \pm 11.4$ GeV/c$^2$ Dilepton
- $172.1 \pm 7.1$ GeV/c$^2$ Combined
- $176.1 \pm 7.4$ GeV/c$^2$ Lepton+jets
- $186.0 \pm 11.5$ GeV/c$^2$ All-Hadronic
- $176.1 \pm 6.6$ GeV/c$^2$ Combined
- $174.3 \pm 5.1$ GeV/c$^2$
Electroweak Physics

fraction of a percent experiments with a 5500 ton microscope
Remember, if you don’t see anything, it’s a neutrino...

DØ $W \rightarrow e\nu$
Electroweak Interactions

The physics of W’s, g’s, and Z’s

- \(\frac{g}{g_{\text{EW}}}\) & \(\frac{g_{\text{W}}}{g_{\text{W}}}\) determination
  - Cross section – strong test of QCD
  - “tri-boson couplings”
    - Testing the gauge theory at the vertices – new physics would reveal itself here
- Mass determination (remember the loops?)
  - Requires precision of ±0.06%

Theoretical prediction: \(O\left(\frac{g^2}{s}\right)\) Hamberg, van Neerven, Matsuura; van Neerven & Zijlstra

Dominant uncertainties:
Luminosity, \(\approx 8\%\) (expt) & Parton distribution functions, \(\approx 3\%\) (theory)
物理学在费米实验室

一个棘手的测量

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<tbody>
<tr>
<td>q</td>
<td>g</td>
<td></td>
<td></td>
<td>q</td>
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 Moderately hadronic recoil (~5 GeV/c)

利用两个粒子衰变的 kinematics，通过定义“transverse mass”来识别“Jacobian”边。

\[
m_T^2(\ell,\not p) = \left( |\vec{p}_\ell| + |\vec{p}_p| \right)^2 \left( \vec{p}_\ell + \vec{p}_p \right)^2
= 2E_\ell E_T (1 - \cos \theta_p)
\]

\[
\frac{d\sigma}{dm_T^2} = \frac{V_{qW}^2}{4\sqrt{2}} \left| G_F M_W \right|^2 \left( \frac{1}{s - M_W^2} + \frac{2m_T^2\hat{s}}{(1 - m_T^2\hat{s})^{3/2}} \right)
\]

DØ最新结果

\[
M_W = 80.474 \pm 0.093 \text{ GeV/c}^2 \text{ DO}
\]
\[
= 80.433 \pm 0.079 \text{ GeV/c}^2 \text{ CDF}
\]
\[
= 80.450 \pm 0.063 \text{ GeV/c}^2 \text{ Tevatron}
\]

Millennial Physics

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2001
The full width of the W can be measured in three ways
(SM: $\Gamma_W = 2.077 \pm 0.014$ GeV)

- Indirectly from:

$$R_{W/Z} = \frac{\Gamma_W \cdot BR(W \ell \ell)}{\Gamma_Z \cdot BR(Z \ell \ell)} = \frac{\Gamma_W \cdot BR(W \ell \ell)}{\Gamma_Z \cdot BR(Z \ell \ell) \cdot \Gamma_W}$$

$$\Gamma_W = 2.130 \pm 0.56 \text{ GeV} \quad \text{DØ (new)}$$

$$= 2.064 \pm 0.084 \text{ GeV CDF}$$

- Directly from the tail of the $m_T$ distribution:

$$\Gamma_W = 2.19 \pm 0.19 \text{ GeV CDF}$$

- Simultaneously, in 2 parameter fit with $M_W$
The IVB can couple to one-another due to the non-Abelian nature of the Yang-Mills prescription.

Measurements characterized as parameterized deviations from SM... an anomolous magnetic or electric moment.

Standard Model values: $k_g, Z = 1; l_g, Z = 0; h^{Z,g}_{1-4} = 0$

CDF preliminary

DØ

$-0.93 < \frac{k_g}{Z} -1 < 0.94$

$-0.31 < \frac{l_g}{Z} < 0.29$

$-1.8 < \frac{h^{Z,g}_{1-4}}{Z} < 0.94$

$-0.7 < \frac{h^{Z,g}_{1-4}}{Z} < 0.6$

DØ + LEP @ 68% CL

$\frac{h^{Z,g}_{1-4}}{Z} = 0.13 \pm 0.14$

$\frac{h^{Z,g}_{1-4}}{Z} = 0.6 \pm 0.07$
The Standard Model Connection

- LEP2 has final results
- NuTeV ($\square N$ DIS) has preliminary results

$\sin^2\theta_W$, interpreted as $M_W$

**W-Boson Mass [GeV]**

- $\bar{p}p$-colliders: $80.448 \pm 0.062$
- LEP2: $80.401 \pm 0.048$
- Average: $80.419 \pm 0.038$ ($\chi^2$/DoF: 0.4/1)
- NuTeV/CCFR: $80.25 \pm 0.11$
- LEP1/SLD/$\nu N$/$m_t$: $80.382 \pm 0.026$

Run2 uncertainties intentionally plotted at 1996 central values

Good reminder of what $L$ means & reason for growing excitement at Fermilab

IT'S A DIFFERENT GAME NOW – THE SM HIGGS BOSON APPEARS TO BE LIGHT
Quantum Chromodynamics

de the glue that holds us together: it’s everywhere
Quantum Chromodynamics

Study of strong interactions
Most basic measurement—the search for substructure... akin to the original discovery of partons at SLAC

Controversial for a while: was there an excess at high jet $E_T$? could be evidence for substructure

False alarm? Both experiments agree... both agree with theory. Probably a reminder of how hard it is to predict the gluon distribution in the proton
Highest $E_T$ jet event in DO $E_T = 475$ GeV

<table>
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<tbody>
<tr>
<td>Max $E_T$ = 345.4 GeV</td>
<td></td>
</tr>
<tr>
<td>CAEH $E_T$ SUM = 968.0 GeV</td>
<td></td>
</tr>
<tr>
<td>VTX in Z = -5.4 (cm)</td>
<td></td>
</tr>
</tbody>
</table>

![Diagram of physics at Fermilab](image)

![Plot of $E_T$ vs. Dst Etta-Phi](image)
physics at Fermilab

Much more...

Dijet mass spectrum - another substructure search

Excess would suggest a new length scale in 2 parton collisions

$\sigma_s$ running determination at an electron collider

...at a hadron collider!

From CDF inclusive jets:

Blue shows the running of the strong coupling, $\sqrt{s}(E)$, with changing scale, $E_T$. Red, shows the lack of dependence at a fixed scale. Not absolute $\sqrt{s}(E)$.
Gluons are cheap...

Indeed, they radiate like mad from quarks and gluons and accounting for them is complicated in processes in which there are two length scales ...like the $d\sigma/dp_T$ for $W$ and $Z$ production, or $g\bar{g}$ production

Must deal with $\infty$ series of divergences: $\ln(Q^2/p_T^2)$

Turn-over, the effect of QCD radiative corrections and infinite gluon resummation
Bottom Quark Physics

figuring out why we’re matter and not antimatter - or both!
B Physics – HEP with microbarns

Both experiments study B mesons

CDF’s SVX tags the detached vertices of the B’s

Forward production agrees with central production

this is beautiful physics
But wait, there’s more

CDF: lifetimes, eg.

\( t(B^-) = 1.637 \pm 0.058 \pm 0.045/-0.043 \text{ ps} \)
\( t(B^0) = 1.474 \pm 0.039 \pm 0.052/-0.051 \text{ ps} \)
\( t(B^+_s) = 1.34 \pm 0.23/-0.19 \pm 0.05 \text{ ps} \)
\( t(B^0_s) = 1.36 \pm 0.09 \pm 0.06/-0.05 \text{ ps} \)

CDF discovered the \( B_c \) meson

\( M(B_c) = 6.40 \pm 0.39 \pm 0.13 \text{ GeV/c}^2 \)
\( t(B_c) = 0.46 \pm 0.18 \pm 0.05 \text{ ps} \)

CDF observed and measured \( B^0 - B^0 \) oscillation parameters

Combination of 3 tagging techniques:
- SVX “same side” tag
- SLT tag
- Jet charge tag

\( \sin2\phi = 0.79 +0.41 -0.44 \)

Where the SM predicts 0.66 - 0.84

First observation of CP in the \( B \) system, confirming the large expected asymmetry
Many extensions of the SM are imaginable

- All must be dealt with systematically

Exotica including:
- Extra gauge bosons
- Leptoquarks (bound lepton-quark states)
- Technicolor

*a matter of luminosity...*

Measured limits are right on schedule for 100 pb$^{-1}$
Run II

the standard model has nowhere to hide
Goals of Run II

**Accelerator:**
- To deliver 10-30 x more integrated luminosity

**Experiments:**
- To deal with it...and the required upgrades

**Physics goals:**
- Understand the top quark, measure $\sqrt{m_t} \approx 2 \text{ GeV}/c^2$
- Determine the cross section to $\pm 8\%$
- Determine the $W$ mass to $\sqrt{M_W} \approx 40 \text{ MeV}/c^2$
- Determine the $W$ width to few \%
- Determine $|V_{tb}|$ to $\pm 10\%$
- Refine B physics measurements, extend rare decay searches
- Extend the reach for compositeness to 500 GeV
- Test NNLO QCD and further study the pomeron
- Extend the search reach for Supersymmetry and exotic phenomena
The TOP quark might be Special…we aim to find out.

<table>
<thead>
<tr>
<th>accepted/experiment</th>
<th>2fb(^{-1})</th>
<th>10fb(^{-1})</th>
</tr>
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<tbody>
<tr>
<td>mode</td>
<td></td>
<td></td>
</tr>
<tr>
<td>tt produced</td>
<td>16,000</td>
<td>80,000</td>
</tr>
<tr>
<td>(\ell + 3j / 1b)</td>
<td>1,800</td>
<td>9,000</td>
</tr>
<tr>
<td>(\ell + 4j / 2b)</td>
<td>600</td>
<td>3,000</td>
</tr>
<tr>
<td>(\ell + 2j)</td>
<td>200</td>
<td>1,000</td>
</tr>
<tr>
<td>EW produced top</td>
<td>330</td>
<td>1,650</td>
</tr>
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</table>

With \(\int L dt = 10\ fb^{-1}\), we will:
- determine \(m_{\text{top}}\) to 1-2 GeV/c\(^2\)
- measure \(\mathbb{R}(t\bar{t})\) to 6%
- measure \(\text{BR}(t \rightarrow b\ell)\) to 5%
- probe for \(t\bar{t}\) resonant states to 1 TeV/c\(^2\)
- Michel analysis of top couplings
- isolate EW produced top quarks and:
  - determine \(\mathbb{R}\) to 10%
  - determine \(\mathbb{R}(t \rightarrow Wb)\) to 10%
  - determine \(V_{tb}\) to 5%
  - search for anomalous couplings
  - search for CP
- probe for rare decays to \(10^{-3} - 10^{-4}\)

Fermilab is a top quark factory.
physics at fermilab

With $\sqrt{s}dt = 10 \text{ fb}^{-1}$, we will:

determine $M_W$ to $\sim 30 \text{ MeV/c}^2$
  - which will bound $M_H$ to 40-50% of itself
  - (good timing for direct searches)
measure $\Gamma(W)$ to 15 MeV
refine asymmetries ($W$ and $Z$) and hence, pdf’s
limit $WWV$ and $Z\ell$ couplings
quantify radiation zero in $W\ell$
search for rare $W$ decays
limit CP violation
quantify quartic gauge couplings
study resummation in 2 scale problems
  - $p_T(W)$, $p_T(gg)$

accepted/experiment

<table>
<thead>
<tr>
<th>channel</th>
<th>$2\text{fb}^{-1}$</th>
<th>$10\text{fb}^{-1}$</th>
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<tr>
<td>$W\ell\ell$</td>
<td>1.6M</td>
<td>8M</td>
</tr>
<tr>
<td>$Z\ell\ell$</td>
<td>160k</td>
<td>800k</td>
</tr>
<tr>
<td>$W\ell$</td>
<td>1000</td>
<td>5000</td>
</tr>
<tr>
<td>$Z\ell$</td>
<td>300</td>
<td>1500</td>
</tr>
<tr>
<td>$WW$</td>
<td>100</td>
<td>500</td>
</tr>
<tr>
<td>$WZ$</td>
<td>40</td>
<td>400</td>
</tr>
<tr>
<td>$ZZ$</td>
<td>few</td>
<td>30</td>
</tr>
</tbody>
</table>

Fermilab is a vector boson craft-workshop
With $\mathcal{L} dt = 10 \text{ fb}^{-1}$, we will:

- Study the edge of phase space!
- Probe deep structure beyond 500 GeV
- Measure IVB+jet production with high statistics
- Understand multi-scale physics
- Understand multi-gluon physics
- Heavy quark production kinematics/dynamics
- Probe jet structure
- Understand multi-jet kinematics
- NNLO calculational comparison
- Understand diffractive scattering!

Support all other collider analyses with crucial background studies

Fermilab is a QCD conglomerate

Millions of events, period.
With $\mathcal{L} dt = 2 \text{ fb}^{-1}$, we will:

**Measure CP violation in three modes**
- $B^0 \rightarrow J/\psi K_s$
- $B^0 \rightarrow \phi \phi$
- $B^0 \rightarrow J/\psi \psi$

**Measure $|V_{td}| / |V_{ts}|$** from $B_S$ mixing & $\phi \phi$

**Refine rare decay searches**
- $B \rightarrow \phi \phi K$
- $B \rightarrow \phi \phi K^*$
- $B_d \rightarrow \phi \phi$
- $B_s \rightarrow \phi \phi$

**Completely understand the $B_C$ system**

**Completely understand $B_s$ mixing**

- Semileptonic decays
- Fully hadronic decays

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**accepted/experiment channel**

<table>
<thead>
<tr>
<th></th>
<th>2fb$^{-1}$</th>
<th>10fb$^{-1}$</th>
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</thead>
<tbody>
<tr>
<td>$B$ mesons</td>
<td>$10^{10}$</td>
<td>$5 \times 10^{10}$</td>
</tr>
<tr>
<td>$B$ baryons</td>
<td>$10^8$</td>
<td>$5 \times 10^8$</td>
</tr>
<tr>
<td>$B_c$</td>
<td>$10^9$</td>
<td>$5 \times 10^9$</td>
</tr>
<tr>
<td>$B^0 \rightarrow J/\psi K_s$</td>
<td>15,000</td>
<td>75,000</td>
</tr>
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Fermilab is a bottom quark industry
There’s more

Multiple inverse femtobarns make a qualitative difference:

Supersymmetry

and

the Higgs Boson

are accessible before the LHC
Supersymmetry—In words

The SM is extraordinarily successful
  • nothing seems out of line…and yet nobody is happy.

Digging deeper is troubling
  • SM: physics of the scale of the W/Z masses ~ 100 GeV, or distances of ~ 10^{-18} cm
  • What about deeper scales? What are scale-milestones?

• Higgs is fat, due to radiative corrections
  • problem is due to quartic self-interactions – which correct the mass of the Higgs

\[ M_H^2 \sim \frac{\mathcal{L}_f}{4} \mathcal{D}_f^2 + \frac{\mathcal{L}_f^2}{4} m_f^2 \]

The only high energy scale \( \mathcal{D} \sim M_p \) is the Planck scale of \( 10^{18} \) GeV - no way to renormalize

Ugly...the SM is fundamentally sick due to quadratic divergences
Suppose the theory has Higgs, fermions, and additional scalars

- calculate their mass correction contributions

$$M_H^2 \sim \frac{\Box}{4\Box^2} \overline{q}^2 \Box - \frac{\Box}{4\Box^2} m^2$$

a magical negative sign...cancels the divergent quantity if $\Box = \overline{q}$ ..and there is a pattern of $N(f) = N(\overline{q})$.

Then, the correction is

$$\frac{\lambda^2}{4\pi^2} \left( m_f^2 - m^2 \right)$$

so, equal masses means a total cancellation - a symmetry

Supersymmetry...in which

$$S | F \rangle = | B \rangle$$
 physics at fermilab

In practice, difficult

Supersymmetric partners for all particles

• With a spin flip…and a cute s-prefix
  ▪ Electron (spin $1/2$) becomes selectron (spin 0)
  ▪ Quark (spin $1/2$) becomes squark (spin 0)
  ▪ Photon (spin 1) becomes photino (spin $1/2$)
  ▪ Gluon (spin 1) becomes gluino (spin $1/2$)

• No SUSY at low energies, so supersymmetry is broken…search for their interactions at higher energies

This is not just silly...

• The Higgs mechanism is accounted for in a natural way and the Weinberg angle is predicted
• Unification of forces appears to work
• Superstrings contain SUSY...

A bold theoretical suggestion, on par with Dirac’s positron, or Weinberg’s Z !!
SUSY provides a unification of couplings

Unification – a goal – requires serious tinkering

Each force (electromagnetic, strong, and weak) is characterized by a coupling,
\[ \alpha_q(I = 1, 2, s), \]
for 2 EW couplings and 1 QCD coupling

Unification requires that
\[ \alpha_1(M_X) = \alpha_2(M_X) = \alpha_s(M_X) \]

Modern analyses suggest \( \alpha_s \approx 0.13 \)
SUSY is not the only solution...

• composite Higgs can protect itself from infinities (technicolor)

However, it is taken very, very seriously

• Many flavors of models…thousands
• A particular brand is especially promising, called the Minimal SuperSymmetric Model (MSSM) contains definite predictions

1. 4 Higgs bosons, one of which is SM-like and must be lighter than $\approx 125$ GeV/c$^2$
2. A supersymmetric “number” is conserved, so decays of SUSY particle result in another SUSY particle
3. A mass spectrum is conceivable, so there is a sterile Lightest SUSY state…which is missing energy in a detector
4. Signals are many leptons, and/or jets with significant missing energy
physics at Fermilab

**Model space**

The time is right...

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Each dot, an allowed supersymmetric model:

- $\chi^-$
  - Predicted: Run I 2fb-1, 10fb-1
  - Actual: Run I
- $g$
  - Predicted: 65, $\sim 220, 235$
  - Actual: 70
- $t_1$
  - Predicted: 48, 150
  - Actual: 155, 145

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Dozens of limits have been set already by both experiments

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Fermilab could be a SUSY venture startup...
Hints appeared in September - a 1 month extension of the final running period was authorized...

- it experienced more than the average downtime, so it must have been frustrating
- Signal is associate production, $H(bb)Z(jj \text{ or } ll)$.

the hint is a $2.9\sigma$ signal (all 4 experiments) at a mass of 115 GeV/$c^2$, with a 0.4% probability of it being background.
The HIGGS is the thing...

The Higgs couples to fermions via $m_f$
- Big is beautiful.

- electron (or muon)
- missing energy
- two $b$’s, at $M_H$

The Golden Mode:
associated production

the cross section is large enough...

So, we expect a standard model Higgs boson:
- to be produced with an $W$ and
- decay overwhelmingly to
  - $b$ pairs (if light),
  - or 2W’s (if slightly heavier...)

The issue is background from $pp \rightarrow W+b+b$
Higgs could be ours...

**Need:**
- Luminosity
- Ability to tag b’s of relatively high $p_T$
- Ability to form $M(bb)$ with good resolution

Mass resolutions will be acceptable

CDF study of $Z \rightarrow bb$

CDF MC extrapolation to Run II

2fb$^{-1}$
Higgs will be surrounded

\[ M(bb) \text{ in } 10 \text{ fb}^{-1} \]

\[ M \approx 8 \text{ GeV} \]

S/B \approx 1/1, dependent on cuts

Mass resolution is key
top events

\[ Z \rightarrow bb \]

Recently, a year-long workshop at Fermilab:

Fermilab could be a
Higgs cottage industry
The plan is clear...

**Run IIa**
- Provides an ability to take the top quark apart
- Uncover CP violation in the B system
- Determine the $W$ mass to precision necessary to corner the Higgs

**Run IIb, above a critical $\ell$ threshold of about 20pb$^{-1}$**
- Maybe discover supersymmetry
- Maybe discover the Higgs Boson

If not there, then the more promising SUSY model is wrong, the SM EW model will be in jeopardy,
- and a whole new era in elementary particle physics will have opened.

If it is there, it will be studied at LHC, NLC, and/or a collider
- and a whole new era in elementary particle physics will have opened.

*A familiar no-lose situation again for Fermilab physics!*
Conclusion

I’ve not talked about the Kaon CP program or the neutrino oscillation experiments. The whole program leads to evolutionary measurements blended with significant discovery potential - it’s complete.

This is a great time to be at Fermilab.