New England Particle Physics Student Retreat VI
Cape Cod, August 13-17, 2007
A week-long retreat for students interested in pursuing graduate study in experimental particle physics or astrophysics
http://physics.bu.edu/neppsr
Outline

- Fermilab
- QCD
- b-quark physics
- electroweak physics
- top quark physics
- the Higgs boson
- new physics
- summary
Fermilab

• accelerator
• experiments
  – D0
  – CDF
Fermilab

The proton source and linac

E = 750 keV

E = 400 MeV
Fermilab

The main injector

$E = 150$ GeV
The Tevatron

- collides beams of protons and antiprotons
- beam energy = 980 GeV
- $2 \times 10^{11}$ protons in 36 bunches
- $2 \times 10^{10}$ antiprotons in 36 bunches
- time between collisions = 396 ns

$E = 1\,\text{TeV}$
The accelerator complex

CDF

DØ

2 km
The CDF experiment

- Central Muon
- Central Calorimeter (E/H)
- Wall Calorimeter (H)
- Plug Calorimeter (E/H)
- Forward Muon
- Forward Calorimeter (E)
- Silicon
- Central Tracker
- TOF
- Solenoid

Fermilab
Tevatron performance

peak luminosity = \(2.8 \times 10^{32}\text{cm}^{-2}\text{s}^{-1}\)

most luminous hadron collider ever

D0 recorded 2.8 fb\(^{-1}\) by August 2007

expect 6-7 fb\(^{-1}\) by 2009
why is the Tevatron interesting?

we have data at the highest com energy
the physics landscape in 1984

1974: J/Ψ discovery (BNL/SPEAR)
1975: SPEAR jets observed
1976: Open charm, tau discoveries (SPEAR)
1977: Upsilon discovery (FNAL)
1982: Open beauty meson discovery (CLEO)
1983: W/Z discoveries (CERN)
1984: High p_{T} jets seen at UA2
    UA1: Monojets (jets with large missing E_{T}) ?
    UA1/UA2: anomalous Z → ℓ^{+} ℓ^{-} γ ?
    UA1: W → t b  top evidence ?

There was a sense of excitement and discovery in the air - skepticism about tantalizing fluctuations was suspended.

Paul Grannis
QCD allows to calculate production cross sections.
b-quark physics

- $B_s$ mixing
- new states
B_s mixing

mixing measurements in B_d and B_s systems allow access to CKM elements

\[ \Delta m_d \text{ is well measured} \]
\[ 0.509 \pm 0.004 \text{ ps}^{-1} \]
**B_{s} mixing**

- **measurement of production flavor**
  - OS kaon charge $b!c!K^{-}$
  - SS kaon charge
  - lepton charge $b!X^{l}$ but $b!c!X^{+}$
  - jet charge

- **measurement of decay flavor**
  - reconstruct specific decay mode

- **measurement of proper decay time**
  - $\tau = m_{B} L_{T}/p_{T}$
$\Delta m_s = 17.77 \pm 0.10 \text{ (stat)} \pm 0.07 \text{ (syst)} \text{ ps}^{-1}$

$|V_{td}/V_{ts}| = 0.2060 \pm 0.0007 \text{ (exp)} \pm^{0.0081}_{-0.0060} \text{ (theor)}$
b-physics

B_s mixing

DØ Run II Preliminary
Semileptonic + Hadronic

χ² / ndf = 2.99772 / 8
p0 = 221.65781 ± 30.45230
p1 = -24.39616 ± 3.30910
p2 = 0.65733 ± 0.08937

Δm_s = 18.56 ± 0.87 ps⁻¹

Δm_s = 18.6 ± 0.8
(Δ log(L))ₘᵢₙₚ = -4.70

3.1σ statistical significance
Wolfenstein parametrization of CKM matrix

\[
\begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
1 - \lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\
V_{cd} & V_{cs} & V_{cb} \\
-\lambda & 1 - \lambda^2/2 & A\lambda^2 \\
V_{td} & V_{ts} & V_{tb} \\
A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1
\end{pmatrix}
\]
b-physics

discovery of the $\Xi_b$ baryon

how to discover a new particle?

take events with $\mu^+\mu^-$

combine any other two oppositely charged tracks

“jay-sigh”

Fermilab press release

$J/\psi!\mu^+\mu^-$

$\Lambda!\pi-p$
b-physics

discovery of the $\Xi_b$ baryon

how to discover a new particle?

take events with $\mu^+\mu^-$

combine the "jay-sigh" and the $\Lambda$

combine any other two oppositely charged tracks

$\chi^2$/dof = 0.24

$N_{\Lambda_b} = 61 \pm 12$

$\Lambda_b \rightarrow J/\psi + \Lambda$
discovery of the $\Xi_b$ baryon

how to discover a new particle?

combine the $\Lambda$ and yet another track

combine any other two oppositely charged tracks

take events with $\mu^+\mu^-$

"zigh"

$J/\psi!\mu^+\mu^-$
b-physics

discovery of the $\Xi_b$ baryon

how to discover a new particle?

now take events with a jay-sigh and a zigh

![Graph showing $M(\Xi_b^\pm)$ and $M(\Lambda\pi^-)$ distributions with fit and data points.](image)
b-physics

discovery of the $\Xi_b$ baryon

how to discover a new particle?

now take events with a jay-sigh and a zigh

"zigh sub b"

J/ψ $\rightarrow \Xi_b^- \mu^+ \mu^-$
discovery of the Ξ_b baryon
discovery of the $\Xi_b$ baryon

Run 179200, Event 55278820, $M(\Xi_b) = 5.788$ GeV
**b-physics**

**is one event enough to discover a particle?**

V. Barnes et al., PRL 204 (1964)

electroweak physics

• W boson mass
• diboson couplings
electroweak physics

W boson mass

at tree level

with

\[ m_W = 1.18 \	imes 10^{-3} \text{ MeV} \]

\[ m_Z = 1.1 \text{ MeV} \]
electroweak physics

W boson mass

at tree level

loop corrections

\[
W \to tX \\
\frac{1}{m_t^2} \quad \frac{1}{\ln m_H}
\]
electroweak physics

Higgs mass constraint

![Graph showing Higgs mass constraint](image)
electroweak physics

how to measure the W boson mass?
electroweak physics

how to measure the W boson mass?
electroweak physics

$m_T$ fit

<table>
<thead>
<tr>
<th></th>
<th>W$\rightarrow$e$\nu$</th>
<th>W$\rightarrow$µ$\nu$</th>
<th>common</th>
</tr>
</thead>
<tbody>
<tr>
<td>stat</td>
<td>48</td>
<td>54</td>
<td>0</td>
</tr>
<tr>
<td>lepton energy</td>
<td>30</td>
<td>17</td>
<td>17</td>
</tr>
<tr>
<td>pdf</td>
<td>11</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>QED radiation</td>
<td>11</td>
<td>12</td>
<td>11</td>
</tr>
<tr>
<td>syst</td>
<td>39</td>
<td>27</td>
<td>26</td>
</tr>
<tr>
<td>total error</td>
<td>62</td>
<td>60</td>
<td></td>
</tr>
</tbody>
</table>

CDF II preliminary

$M_W = (80493 \pm 48_{\text{stat}})$ MeV

$\chi^2/\text{dof} = 86 / 48$
electroweak physics

lepton energy calibration

calibrate track momentum with $\mu^+\mu^-$ resonances
electroweak physics

lepton energy calibration

transfer momentum calibration to electron energy with electrons from W decays
electroweak physics

W boson mass

- CDF Run I: $80433 \pm 79$
- DØ Run I: $80483 \pm 84$
- DELPHI: $80336 \pm 67$
- L3: $80270 \pm 55$
- OPAL: $80416 \pm 53$
- ALEPH: $80440 \pm 51$
- CDF Run II (prel.): $80413 \pm 48$
- World Average 2007: $80398 \pm 25$
Electroweak physics

Trilinear gauge couplings are uniquely specified by the SM.

Events with 3 leptons

Not in SM

3σ hint
electroweak physics

radiation zero in $W_\gamma$

interference between tree level diagrams:

cancellation for $\cos\theta_{q\gamma} = -(1+2Q_d)$
top quark physics

• discovery
• mass
• properties
• single top production
top quark discovery

• need weak isospin partner to the b-quark
• in 1995 CDF and DØ observe an excess of events consistent with
top quark physics

### top quark production

- **top-antitop pair production**
  - $\sigma(tt) \to$ QCD coupling
  - mass
  - branching fractions
  - structure of Wtb vertex

- **electroweak production of top quarks**
  - $s$ channel (tb)
  - $t$ channel (tqb)

  - $|V_{tb}|$
  - width
  - structure of Wtb vertex

- non-standard production or decay?
top quark physics

**lifetime tagging of b-jets**

- **b lifetime \( \frac{1}{4} 1.6 \text{ ps} \)**
  - travels a few mm before decaying
top quark physics

single top quark production

select events with high $p_T$ lepton, missing $p_T$, 2 jets
at least one jet tagged as b-jet

best channels $S/B \approx 1/20$

signal < background uncertainty

need advanced techniques
- decision trees
- neural networks
- matrix element discriminants
top quark physics

decision tree analysis

\[ \sigma(tb+tqb) = 4.9 \pm 1.4 \text{ pb} \]
Compatibiliy with SM = 11%

DØ Run II $\text{preliminary}$

\[
\begin{array}{c}
\text{Event Yield} \\
10^2 \\
10 \\
1 \\
10^{-1} \\
0.6 \\
0.7 \\
0.8 \\
0.9 \\
1 \\
\end{array}
\]

$t\bar{b}+tq\bar{b}$
W+jets
$t\bar{t}$
Multijets
\small{\[\pm 1\sigma \text{ uncertainty on background}\]}

$p$-value = 0.035%

\[ 3.4\sigma! \]
measurement of $|V_{tb}|$

$\sigma(tb,tqb) \propto |V_{tb}|^2 \rightarrow$ calculate a posterior in $|V_{tb}|^2$

**Assume**
- SM top decay: $|V_{td}|^2 + |V_{ts}|^2 \ll |V_{tb}|^2$ and pure V–A coupling
- Three quark families and unitarity of $3 \times 3$ CKM matrix

$$|V_{tb}f_1^L| = 1.3 \pm 0.2$$

$$0.68 < |V_{tb}| \leq 1 \text{ at 95\% C.L. (assuming } f_1^L = 1)$$
the top quark is the most massive quark

leptons

- e
  - $0.5 \text{ MeV}$
- $\mu$
  - $105.7 \text{ MeV}$
- $\tau$
  - $1.777 \text{ MeV}$

- $\nu_e$
- $\nu_\mu$
- $\nu_\tau$

quarks

- d
  - $\approx 7 \text{ MeV}$
- u
  - $\approx 3 \text{ MeV}$
- s
  - $\approx 110 \text{ MeV}$
- c
  - $\approx 1300 \text{ MeV}$
- b
  - $\approx 4300 \text{ MeV}$
- t
  - $\approx 171,000 \text{ MeV}$

volume of spheres $\propto$ mass
no measurable extend ($<10^{-18} \text{ m}$)
lepton+jets event kinematics

tt! Wb Wb
↓ ↓
eν qq

hadrons

jet1 (b)

hadrons

jet2 (b)

hadrons

jet3

e,μ

jet4

hadrons

\[ p_T = -\sum p_T \]

displaced vertex
lepton+jets event kinematics

- 2 unknowns
  - $p_z^\nu$ and $m_t$

- 4 constraints
  - $m(e,\nu) = m_W$
  - quadratic equation for $p_z(\nu)$
    - choose smaller value
  - $m(e,\nu,j_1) = m_t$

- perform 2-C kinematic fit for $m_t$

$\mathbf{p_T} = -\sum \mathbf{p_T}$
lepton+jets event kinematics

• complications
  – combinatorics
    • \(j_1, j_2, j_3, j_4 \rightarrow b, b, W\) (12 permutations)
    • \(b, j_2, j_3, j_4 \rightarrow b, b, W\) (8 permutations)
    • \(b, b, j_3, j_4 \rightarrow b, b, W\) (2 permutations)
  – gluon radiation
    • initial state radiation
      – momentum from initial quark/antiquark or spectators \(\rightarrow\) overestimate \(m_t\)
    • final state radiation
      – momentum from t or b quarks \(\rightarrow\) underestimate \(m_t\)

• many techniques
matrix element method

• probability density for an event \( o \) if the mass of the top quark is \( m_t \)

• combine all events in a joint likelihood

• and maximize wrt \( m_t, \alpha_{jes}, f_{top} \)

• calculate signal probability

\[ |M|^2 \, dLIPS \]

\[ \text{pdf} \]

normalization

transfer function parametrize detector response

jet scale parameter

top fraction
top quark physics

**top quark mass**

\[ M_{\text{top}} = (170.5 \pm 3.3) \text{ (stat.) GeV} \]

**result for e+jets and \( \mu \)+jets combined:** \( m_{\text{top}} = 170.5 \pm 2.4 \pm 1.2 \text{ GeV} \)
top quark physics

top quark mass

Best Tevatron Run II (preliminary, March 2007)

<table>
<thead>
<tr>
<th>Channel</th>
<th>Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>All-Jets: CDF</td>
<td>171.1 ± 4.3</td>
</tr>
<tr>
<td>(943 pb⁻¹)</td>
<td></td>
</tr>
<tr>
<td>Dilepton: CDF</td>
<td>164.5 ± 5.6</td>
</tr>
<tr>
<td>(1030 pb⁻¹)</td>
<td></td>
</tr>
<tr>
<td>Dilepton: D0</td>
<td>172.5 ± 8.0</td>
</tr>
<tr>
<td>(1000 pb⁻¹)</td>
<td></td>
</tr>
<tr>
<td>Lepton+Jets: CDF</td>
<td>170.9 ± 2.5</td>
</tr>
<tr>
<td>(940 pb⁻¹)</td>
<td></td>
</tr>
<tr>
<td>Lepton+Jets: D0</td>
<td>170.5 ± 2.7</td>
</tr>
<tr>
<td>(900 pb⁻¹)</td>
<td></td>
</tr>
<tr>
<td>Tevatron</td>
<td>170.9 ± 1.8</td>
</tr>
<tr>
<td>(Run I/Run II, March 2007)</td>
<td>(\chi^2/dof = 9.2/10)</td>
</tr>
</tbody>
</table>
top quark physics

Higgs boson mass

![Graphs showing the relationship between top quark mass and Higgs boson mass with statistical and theoretical uncertainties.]
Higgs boson

- standard model Higgs boson searches
The Higgs mechanism

The Higgs field with its “mexican hat” potential breaks the $SU(2) \times U(1)$ symmetry.

Three Higgs degrees of freedom become the longitudinal components of the $W$ and $Z$ bosons.

Fermions acquire mass through their Yukawa couplings to the Higgs.

One Higgs degree of freedom represents a massive scalar particle.

Only free parameter is its mass.
Higgs at LEP

LEP was supposed to find it…

$m_H > 114.4$ GeV
@ 95% confidence level

Higgs boson

Higgs at Tevatron

… but when it didn’t …
Higgs boson

Higgs boson decay

Higgs couples to mass:

- for $m_H < 130$ GeV, $H \rightarrow bb$ dominates
- for $m_H > 130$ GeV, $H \rightarrow WW$ dominates
Higgs production at the Tevatron

<table>
<thead>
<tr>
<th>Channel</th>
<th>( \sigma ) (pb)</th>
<th>( B_H )</th>
<th>( B_{W/Z} )</th>
<th>( \sigma CFB ) (pb)</th>
<th>( m_H ) (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WH! ( l^+ l^- ) bb</td>
<td>0.18 pb</td>
<td>0.8</td>
<td>0.22</td>
<td>0.032 pb</td>
<td>115 GeV</td>
</tr>
<tr>
<td>ZH! ( \nu \bar{\nu} ) bb</td>
<td>0.11 pb</td>
<td>0.8</td>
<td>0.20</td>
<td>0.018 pb</td>
<td>115 GeV</td>
</tr>
<tr>
<td>ZH! llbb</td>
<td>0.11 pb</td>
<td>0.8</td>
<td>0.067</td>
<td>0.006 pb</td>
<td>115 GeV</td>
</tr>
<tr>
<td>H! WW! ( l^+ l^- )</td>
<td>0.3 pb</td>
<td>1.0</td>
<td>0.047</td>
<td>0.014 pb</td>
<td>160 GeV</td>
</tr>
<tr>
<td>WH!WWW!l( l^+ l^- )X</td>
<td>0.05 pb</td>
<td>1.0</td>
<td>0.083</td>
<td>0.004 pb</td>
<td>160 GeV</td>
</tr>
</tbody>
</table>
Higgs boson

**WH! lν bb**

select events with high $p_T$ lepton, missing $p_T$, 2 jets

- 1 b-tagged jet
- 2 b-tagged jets
Higgs boson

WH! lν bb

select events with high $p_T$ lepton, missing $p_T$, 2 jets

artificial neural network
Higgs boson

WH! lν bb

select events with high $p_T$ lepton, missing $p_T$, 2 jets
Higgs boson

WH ! lν bb

Limit / α(p\overline{p} \rightarrow WH) × BR(H \rightarrow b\overline{b})

DO Preliminary, L = 1.7 fb⁻¹
WH \rightarrow lν bb
Higgs boson

ZH → l⁺l⁻bb

Limit / (α(p→Z) × BR(H→bb))

DO Preliminary, L=1.1 fb⁻¹

m_H (GeV/c²)
Higgs boson

\[ H \rightarrow WW \]

**Graph:**
- **Title:** DO Preliminary, \( L = 1.7 \text{ fb}^{-1} \)
- **Axes:**
  - Y-axis: Limit / SM cross section
  - X-axis: \( m_H \) (GeV/c^2)
- **Legend:**
  - Observed Limit
  - Expected Limit

**Graph Description:**
- The graph shows the limit on the cross section of the Higgs boson decaying into \( WW \) and \( WH \rightarrow WWW \) as a function of the Higgs boson mass, \( m_H \).
- The observed limit and expected limit are depicted by solid and dotted lines, respectively.

**Key Points:**
- The observed limit is lower than the expected limit at most mass points.
- The dip in the observed limit near \( 160 \text{ GeV/c}^2 \) is significant.

**Date:** 8/15/2007
Higgs boson

CDF results

[CDF graph showing 95% CL limits for various processes as a function of Higgs mass. The graph includes expected and observed limits for different decay modes of the Higgs boson.]
Higgs boson

combined limits
where is all the new stuff?

- no leptoquarks
- no heavy W/Z bosons
- no compositeness
- no extra dimensions
- no technicolor
- no SUSY
the legacy of the Tevatron

- significant increase in sophistication of collider physics analyses
- the top quark discovery
- precision electroweak measurements
  - top quark mass
  - W boson mass
- QCD, bottom, charm physics
- no new physics – the sm is rock solid
- Higgs boson (limit/hint/discovery?)