Search for the Higgs Boson

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The Inter-University Centre for Astronomy and Astrophysics
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Why Build Accelerators?
From Atoms to Quarks

- Scattering of probe particles off matter to investigate substructure, i.e. “look inside”
- Rutherford did it, shooting α particles at a gold foil, to tell us the structure of the atom (1911)
- Quantum mechanics: $\Delta r \sim \hbar / \Delta p$

<table>
<thead>
<tr>
<th>Particle</th>
<th>Radius</th>
<th>Accelerator energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>atom</td>
<td>$10^{-10}$ m</td>
<td>10 electron-volts (eV)</td>
</tr>
<tr>
<td>nucleus</td>
<td>$10^{-15}$ m</td>
<td>$10^6$ eV (MeV)</td>
</tr>
<tr>
<td>proton, neutron</td>
<td>$10^{-18}$ m</td>
<td>$10^9$ eV (GeV)</td>
</tr>
<tr>
<td>quarks</td>
<td>$&lt;10^{-18}$ m</td>
<td>$&gt; \text{GeV}$</td>
</tr>
</tbody>
</table>
A Century of Particle Physics: Standard Model

- Quark constituents of nucleons established in high energy electron scattering experiments at Stanford Linear Accelerator Center (SLAC), 1966-1978
  - Point-like particles explain high scattering rate at large energy and angle
A Century of Particle Physics: Standard Model

• **Success # 1**: discovery of 6 quarks and 6 leptons

• 12 fundamental matter particles (and their antimatter counterparts) fit neatly into an elegant mathematical framework

  **Quarks**

  \[
  \begin{align*}
  u &< 1 \text{ GeV} \quad c \sim 1.5 \text{ GeV} \quad t \sim 175 \text{ GeV} \\
  d &< 1 \text{ GeV} \quad s < 1 \text{ GeV} \quad b \sim 4.5 \text{ GeV}
  \end{align*}
  \]

  But note the intriguing pattern of mass values; not explained:

  **Leptons**

  \[
  \begin{align*}
  \nu_e &< 1 \text{ eV} \quad \nu_\mu < 0.17 \text{ MeV} \quad \nu_\tau < 24 \text{ MeV} \\
  e &0.5 \text{ MeV} \quad \mu 106 \text{ MeV} \quad \tau 1.8 \text{ GeV}
  \end{align*}
  \]
A Century of Particle Physics: Standard Model

• The “charm quark” (c) discovered at SLAC in 1974

• The heaviest lepton, “τ” was also discovered at SLAC in 1975
A Century of Particle Physics: Standard Model

- The heaviest “top quark” ($t$) discovered at Fermilab in 1995

- The next heaviest, “bottom quark” ($b$) was also discovered at Fermilab in 1977

- Appearance of $\tau$ lepton in $\nu_\tau$ beam established at Fermilab
A Century of Particle Physics: Standard Model

- **Success # 2:** a really elegant framework for *predicting* the nature of fundamental forces
  - matter particles (quarks and leptons) transform in *curved* internal spaces
  - The equations of motion *predict* terms that describe particle interactions with force fields

- Analogous to the Coriolis and Centrifugal forces generated in rotating frames of reference
A Century of Particle Physics: Standard Model

- Notion of symmetry of equations under “gauge transformations” not just a theoretical success: beautifully confirmed by large amount of experimental particle physics measurements, for

  - Electromagnetic force \( \psi(x) \rightarrow e^{i\phi(x)} \psi(x) \)

  - Weak force (radioactivity)

  - Strong (nuclear) force: internal space is 3D spherical surface
The “Problem”, thus Excitement, of Particle Physics

- **This highly successful theory predicts that particles should be massless!**
  - Obviously not true in nature
  - Not just “Dark Matter”, we do not know the origin of “Visible Matter”

- **Theory rescued by postulating a new “Higgs” field, which permeates all space**
  - A sticky field, particles moving through space scatter off the Higgs field, thereby *appearing* to be massive

[ Image proposed by David Miller, University College London ]
The “Problem”, thus Excitement, of Particle Physics

- **Proof of the concept: superconductivity**
  - Normally massless photon (quantum of electromagnetic force) becomes massive in a superconductor

- **Conclusion: our vacuum is not a true vacuum**
  - Its a “false vacuum”, behaving like a superconductor
Crossing the Energy Threshold for Discoveries

“Critical Temperature” for superconducting vacuum ~ 1 TeV

Accelerators at Fermilab (running now with 2 TeV energy) and CERN (start running in 2007 with 14 TeV energy) are at the energy at which the “Higgs Boson” is expected to show up

Search for Higgs boson is a key mission of the High Energy Physics program
Collider Detector at Fermilab (CDF)

Muon detector
Central hadronic calorimeter
Central outer tracker (COT)
Particle Detection

Drift chamber (COT): reconstruct particle trajectory by sensing ionization in gas on high voltage wires.

Electromagnetic (EM) calorimeter: lead sheets cause $e/\gamma$ shower, sense light in alternating scintillator sheets.

Hadronic calorimeter: steel sheets cause hadronic showers, sense scintillator light.

Muon chambers: detect penetrating particles behind shielding.
CDF Tracking Chamber
Standard Model Higgs Boson Production and Decay
Higgs Boson Production and Decay

- Different production and decay mechanisms expected for Higgs boson are exploited for its search

![Graph showing Higgs boson production and decay mechanisms](image)

\[ M_H \text{ (GeV/c}^2) \]
Light Higgs Boson Production and Decay

W, Z decay to electrons, muons, τ, and/or neutrinos

Higgs boson decays to bottom quarks
Simulated Higgs Signal on Expected Backgrounds

Key requirements for observing signal:

Excellent lepton identification, good calorimeters for jet and Missing $E_T$ reconstruction, excellent silicon detectors for b jet identification

Good reconstruction of decay particle momentum vectors

Good simulation of signal and background events
Tagging of b-quark jets

**DØ**: Neural Network tagger with multiple operating points

**CDF**: Secondary Vertex tagger, jet probability tagger, and Neural Network flavor separators

50-70% Efficient with 0.3-5% mistag rate

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**Graphs**:

- **SecVtx Tag Efficiency for Top b-Jets**
  - Tight SecVtx
  - Loose SecVtx

- **b-Jet Efficiency (%)**
  - DØ Neural Network tagger
  - CDF SV tagger
Multivariate Techniques for Signal/Background Discrimination

- Likelihood discriminants: Often using Standard Model Matrix Elements to compute differential probability distributions for kinematics
- Artificial Neural Networks: construct non-linear function of kinematics
- Decision trees: event classification using sequential cuts

A simple neural network

Decision Tree

Toy Example
SM Higgs: ZH→llbb

Z + 2 jets background dominant

CDF Run II Preliminary (2.4 fb⁻¹)

Part of my research group activity

Top quark background suppressed by another neural network

Z+2jets ← Neural Network Output → ZH
SM Higgs: VH→vvbb

W (→ lν) + Higgs with lepton undetected also included in signal

Key issue: modelling the shape of QCD background
### SM Higgs: $WH \rightarrow l\nu bb$

**Results at $m_H = 115$ GeV: 95% CL Limits/SM**

<table>
<thead>
<tr>
<th>Analysis</th>
<th>Lum (fb$^{-1}$)</th>
<th>Higgs Events</th>
<th>Exp. Limit</th>
<th>Obs. Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDF NN</td>
<td>2.7</td>
<td>8.3</td>
<td>5.8</td>
<td>5.0</td>
</tr>
<tr>
<td>CDF ME+BDT</td>
<td>2.7</td>
<td>7.8</td>
<td>5.6</td>
<td>5.7</td>
</tr>
<tr>
<td>DØ NN</td>
<td>1.7</td>
<td>7.5</td>
<td>8.5</td>
<td>9.3</td>
</tr>
</tbody>
</table>

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**Key issue: shape of $W+bb$ background**

- Obtained from simulation, with normalization from data control regions
- Most sensitive channel for low-mass Higgs at Tevatron
Heavy Higgs Boson Production and Decay

Most sensitive channel at the Tevatron

Key issue: maximizing lepton acceptance

Spin correlation: Charged leptons go in the same direction
Heavy Higgs Boson Production and Decay

Results at $m_H = 165$GeV : 95%CL Limits/SM

<table>
<thead>
<tr>
<th>Analysis</th>
<th>Lum (fb$^{-1}$)</th>
<th>Higgs Events</th>
<th>Exp. Limit</th>
<th>Obs. Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDF ME+NN</td>
<td>3.0</td>
<td>17.2</td>
<td>1.6</td>
<td>1.6</td>
</tr>
<tr>
<td>DØ NN</td>
<td>3.0</td>
<td>15.6</td>
<td>1.9</td>
<td>2.0</td>
</tr>
</tbody>
</table>

Most sensitive channel at the Tevatron

Key issue: maximizing lepton acceptance
SM Higgs Boson Production Limits

Comparison of Higgs boson production cross section upper limit to the theoretical expectation

Expected Limits on ratio: 1.2 @ 165, 1.4 @ 170 GeV

Tevatron excludes at 95% C.L. the production of a SM Higgs boson of 170 GeV
SM Higgs Boson Production Limits

Comparison of Higgs boson production cross section upper limit to the theoretical expectation

- Low mass combination difficult due to ~70 channels
- Expected sensitivity of CDF/DØ combined: \(<3.0 \times \text{SM} @ 115\text{GeV}\)
Tevatron Higgs Search Projections

- Improvements for low-mass Higgs in progress
  - Dijet mass resolution, increased lepton acceptance and b-tagging efficiency

\[ m_{H} = 160 \text{ GeV} \]

\[ m_{H} = 115 \text{ GeV} \]
Precision Standard Model Measurements
Constraining the Higgs and New Physics
Precision Measurements of W boson and top quark masses

- Radiative corrections due to heavy quark and Higgs loops and exotica

- Top quark mass and W boson mass constrain the mass of the Higgs boson, and possibly new particles beyond the standard model
  
  - My research focuses on the precise mass measurements of these two particles
Top Quark Mass Measurement
Top Quark Production at the Tevatron
Progress on $M_{\text{top}}$ at the Tevatron

Reconstructed top mass in 680 pb$^{-1}$ of CDF data, fit with simulated lineshape

Improved top mass precision due to in-situ calibration of jet energy using $W \rightarrow jj$ decays in the same events.
Measurement of $M_{\text{top}}$ in the dilepton channel

Neural Network for optimized event selection

Matrix-element-based likelihood fitting in dilepton channel

Part of my research activities
Progress on $M_{top}$ at the Tevatron

CDF lepton+jets systematics (preliminary)

<table>
<thead>
<tr>
<th>Systematic source</th>
<th>Systematic uncertainty (GeV/c²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calibration</td>
<td>0.1</td>
</tr>
<tr>
<td>MC generator</td>
<td>0.5</td>
</tr>
<tr>
<td>ISR and FSR</td>
<td>0.3</td>
</tr>
<tr>
<td>Residual JES</td>
<td>0.5</td>
</tr>
<tr>
<td>$b$-JES</td>
<td>0.4</td>
</tr>
<tr>
<td>Lepton $P_T$</td>
<td>0.2</td>
</tr>
<tr>
<td>Pileup</td>
<td>0.1</td>
</tr>
<tr>
<td>PDFs</td>
<td>0.2</td>
</tr>
<tr>
<td>Background</td>
<td>0.4</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>1.0</td>
</tr>
</tbody>
</table>

Dominant systematic uncertainties can be reduced with improved understanding of the data and generator models

$\delta M_{top} < 1$ GeV may be possible

contribution of my research group
W Boson Mass Measurement
Motivation for $M_W$ measurement

- SM Higgs fit: $M_H = 84^{+34}_{-26}$ GeV (LEPEWWG & TeVEWWG)

- LEPII direct searches: $M_H > 114.4$ GeV @ 95% CL (PLB 565, 61)

In addition to the Higgs, is there another missing piece in this puzzle?

( $A_{FB}^b$ vs $A_{LR}$: $3.2\sigma$ )

Must continue improving precision of $M_W$, $M_{top}$ ...

Other precision measurements constrain Higgs, equivalent to $\delta M_W \sim 20$ MeV

Motivate direct measurement of $M_W$ at the 20 MeV level
Standard Model Higgs Constraint

$M_W$ and leptonic measurements of $\sin^2\theta$ prefer low SM Higgs mass, hadronic (heavy flavor) measurements of $\sin^2\theta$ prefer higher SM Higgs mass ($A^b_{FB}$ prefers $\sim 500$ GeV Higgs)

Fits to leptonic data

$A^b_{FB}$

$A^e_{FB}$

M. Chanowitz, PRL 97 (2001) 231802
Fitting for the $W$ Boson Mass

Monte Carlo template

$M_W = 80 \text{ GeV}$

$M_W = 81 \text{ GeV}$

Perform fits to kinematic distributions sensitive to the $W$ boson mass

CDF II preliminary

$\int L \cdot dt \approx 200 \text{ pb}^{-1}$

$M_W = (80349 \pm 54_{\text{stat}}) \text{ MeV}$

$\chi^2/\text{dof} = 59/48$
Comparisons

The CDF Run 2 result is the most precise single measurement of the W mass (PRL 99:151801, 2007; Phys. Rev. D 77:112001, 2008) ... and factor of 10 more data being analyzed now by my research group.
$M_W \nu$ \ M_{\text{top}}$

Lightest neutral supersymmetric particle could be dark matter candidate!
Preliminary $M_W$ Studies of 2.4 fb$^{-1}$ Data from Tevatron

$\delta M_W \sim 20$ MeV

$2$ fb$^{-1}$
The Future – Large Hadron Collider at CERN

LHC will start collecting data with 14 TeV collisions in 2009
ATLAS Experiment at Large Hadron Collider

A simulated Higgs boson production event, with Higgs decaying to two $Z$ bosons

I am a member of ATLAS Collaboration and will be studying the Higgs boson with ATLAS data
Summary

- CDF and D0 experiments at the Fermilab Tevatron in pursuit of the mass-generating mechanism:
  - Are closing in on the Higgs boson using direct searches
    - Higgs boson excluded at 170 GeV @ 95% CL
  - Are constraining the Higgs boson mass by making the most precise measurements of the top quark and W boson masses
  - Searching for new fundamental symmetries of nature
    - Supersymmetry
    - Substructure of particles
    - New forces
    - Additional spatial dimensions

- Fermilab continues to collect and analyze x3 more data in the next few years – nature may reveal more of its secrets!

- Large Hadron Collider at CERN is likely to reveal additional hidden symmetries