#### Precision Measurements in High Energy Physics and the Higgs Boson Ashutosh Kotwal Duke University



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## Spontaneous Symmetry Breaking

• 2008 Nobel Prize in Physics

"for the discovery of the mechanism of spontaneously broken symmetry in subatomic physics"



Yoichiro Nambu

• Experimentally, jury is still out on Higgs mechanism of Electroweak Symmetry Breaking in the Standard Model of Particle Physics

## Outline

- The Standard Model of Particle Physics how did we get here?
- The role of the Higgs boson in the Standard Model
- What do we know about the Higgs boson
- Importance of precision electroweak observables
- Summary



Peter Higgs

### Why Build Accelerators? From Atoms to Quarks

• Scattering of probe particles off matter to investigate substructure, i.e. "look inside"

Radius

- Rutherford did it, shooting α particles at a gold foil, to tell us the structure of the atom (1911)
- Quantum mechanics:  $\Delta r \sim h / \Delta p$



atom	10 <sup>-10</sup> m	10 electron-volts (eV)
nucleus	10 <sup>-15</sup> m	10 <sup>6</sup> eV (MeV)
proton, neutron	10 <sup>-18</sup> m	10 <sup>9</sup> eV (GeV)
quarks	<10 <sup>-18</sup> m	>GeV

- 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



- 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

• The "charm quark" (*c*) discovered at SLAC in 1974

- The heaviest lepton, " $\tau$ " was also discovered at SLAC in 1975



• 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  $\upsilon_{\tau}$  beam established at Fermilab



- 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



- Success # 2: gauge invariance predicts the properties of fundamental forces
  - matter particles (quarks and leptons) transform in internal spaces
    - Electroweak: SU(2) x U(1)
    - QCD: SU(3)

• Analogous to the Coriolis and Centrifugal forces generated in rotating frames of reference



- 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

$$\Psi(x) \longrightarrow \mathrm{e}^{i\varphi(x)} \Psi(x)$$



- 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

- As generators of gauge transformations, gauge bosons should be massless
  - Obviously not true in nature for weak interaction
  - W and Z gauge bosons very massive (W ~ 80 GeV, Z ~ 91 GeV)
- Unconfirmed postulate of scalar Higgs field which develops a vacuum expectation value via spontaneous symmetry breaking





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

## Standard Model Higgs Boson Production and Decay

### Light Higgs Boson Production and Decay



## Particle Detection

Drift chamber: reconstuct particle trajectory by sensing ionization in gas on high voltage wires

Electromagnetic (EM) calorimeter: lead sheets cause *e*/**g** shower, sense light in alternating scintillator sheets



Muon chambers: detect penetrating particles behind shielding

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

### Collider Detector at Fermilab (CDF)



## **CDF** Tracking Chamber



Reconstruction of particle trajectories, calibration to  $\sim 2 \ \mu m$  accuracy:

AVK, H. Gerberich and C. Hays, NIM A506, 110 (2003)

C. Hays et al, NIM A538, 249 (2005)

## 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

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 nonlinear function of kinematics
- Decision trees: event classification using sequential cuts







## Heavy Higgs Boson Production and Decay



## **SM Higgs Boson Production Limits**

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





Tevatron Run II Preliminary, L=2.0-5.4 fb<sup>-1</sup>

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

### **Contributions from Supersymmetric Particles**

(or any other model of new physics with calculable radiative corrections)



# Standard Model Calculation

• The electroweak gauge sector of the standard model is constrained by three precisely known parameters

$$- \alpha_{\rm EM} \, ({\rm M_Z}) = 1 \, / \, 127.918(18)$$

$$-G_{\rm F} = 1.16637$$
 (1) x 10<sup>-5</sup> GeV<sup>-2</sup>

 $M_Z = 91.1876 (21) \text{ GeV}$ 

- Without quantum virtual corrections, these parameters are related to  $M_W$  by

$$- M_W^2 = \pi \alpha_{\text{EM}} / \sqrt{2G_F \sin^2 \vartheta_W}$$

- Where  $\vartheta_{W}$  is the weak mixing angle, defined by

$$\cos\vartheta_{\rm W} = M_{\rm W}/M_{\rm Z}$$

Top Quark Mass Measurement

### Top Quark Pair Production at the Tevatron



## Top Mass Measurement in Dilepton Decay Channel



• An interesting conceptual problem: how can we select top quark events from the data such that we obtain the most precise measurement of the top quark mass?

## Optimizing Event Selection for Top Mass Measurement

• Artificial Neural Networks: use to construct non-linear function of event kinematics



• First use in particle physics: training neural network using genetic evolution algorithm

## Genetic Neuro-Evolution

- Goal: single multi-variate selection criterion yielding most precise measurement of the top quark mass
- Genetic evolution:
  - Random initial set of neural networks
  - Evaluate resulting M<sub>top</sub> precision using each network
  - Discard networks yielding low precision
  - Mutate and breed high-precision networks







### Genetic Neural Network Mutation and Breeding

#### [K. Stanley, R. Miikkulainen]



### Measurement of $M_{top}$ in the dilepton channel

Neural Network for optimized event selection



Best  $M_{top}$  measurement in dilepton channel:  $M_{top} = 171.2 \pm 4.0 \text{ GeV}$ 

W Boson Mass Measurement

### W Boson Production at the Tevatron



information, can be measured precisely (achieved 0.03%)

Initial state QCD radiation is O(10 GeV), measure as soft 'hadronic recoil' in calorimeter (calibrated to ~1%)

## W Boson Production at the Tevatron



Lepton  $p_T$  carries most of *W* mass information, can be measured precisely (achieved 0.03%)

Initial state QCD radiation is O(10 GeV), measure as soft 'hadronic recoil' in calorimeter (calibrated to ~1%)

## Quadrant of Collider Detector at Fermilab (CDF)



Select W and Z bosons with central (  $| \mathbf{\eta} | < 1$  ) leptons

### Data Fit for W boson mass



### W Boson Mass Measurements



(D0 Run II: PRL 103:141801, 2009) (CDF Run II: PRL 99:151801, 2007; PRD 77:112001, 2008)

### Improvement of M<sub>w</sub> Uncertainty with Sample Statistics



Next target: 15-20 MeV measurement of  $M_w$  from the Tevatron

M<sub>W</sub> vs M<sub>top</sub>



# Summary

- The *W* boson mass and top quark mass are very interesting parameters to measure with increasing precision
- W boson mass measurement from the Fermilab Tevatron and LEP data:

 $- M_W = 80399 \pm 23 \text{ MeV}$ 

• Top quark mass measurement from the Tevatron data:

 $- M_{top} = 173.1 \pm 1.3 \text{ GeV}$ 

- Tevatron sensitivity to Higgs boson soon to extend upto Higgs mass of 200 GeV
- Learning as we go: Tevatron  $\rightarrow$  LHC may produce  $\delta M_W$  ~ 5-10 MeV and  $\delta m_{top}$  ~ 0.5 GeV
- Looking forward to a definitive statement on the Higgs mechanism soon

# A possible Future Scenario



Higgs discovery with a large Higgs mass

# Collaborators

- Heather Gerberich (Duke Ph.D, now at University of Illinois, Urbana-Champaign)
- Christopher Hays (Duke Postdoc, now at University of Oxford)
- Bodhitha Jayatilaka (Duke Postdoc)
- Ben Kilminster (Fermilab)
- Larry Nodulman (Argonne National Laboratory)
- Jan Stark (Universite Joseph Fourier Grenoble)
- Oliver Stelzer-Chilton (Ph.D. Toronto, now at TRIUMF, Canada)
- William Trischuk (University of Toronto)
- Ian Vollrath (Ph.D. University of Toronto)
- Daniel Whiteson (University of California, Irvine)
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