8.882 LHC Physics
Experimental Methods and Measurements

Higgs Physics and Other Essentials
[Lecture 22, April 29, 2009]
Organization

Next week lectures:
• Monday 2pm and Tuesday 9:30am (which room?)

Project 3
• remember, due May 2

Conference Schedule
• worked out
A Physics and EAPS joint Colloquium
Thursday, April 30 at 4:15 pm in room 34-101

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"The Dwarf Planets of the Outer Solar System"

For a full listing of this semester’s colloquia, please visit our website at web.mit.edu/physics
Outline

Higgs Search and Other Essentials

- the fundamental question
- state-of-the-art
- Higgs boson production and decay @ LHC
- closer look at specific channels
- beyond the Standard Model (BSM)
- in 5 years from now - Higgs Boson Properties
The Fundamental Question

What is the origin of elementary particle masses?
The Fundamental Question

What is around us?

proton mass: \( m_p = 938 \text{ MeV} \)

quark masses:
\( m_u = 1.5\text{-}4.5 \text{ MeV} \)
\( m_d = 5.0\text{-}8.5 \text{ MeV} \)

rest mass:
kinecetic energy & QCD effects
The Fundamental Question

How are we effected by elementary particle mass?

electron mass (105 MeV) (Bohr radius $r = \frac{1}{\alpha_{\text{em}} m_e}$): massless electrons would result in no atomic binding

u, d quark mass (~1-10MeV): massless quark or $m_u = m_d$ would result in proton decays, different nucleosynthesis, ...

W mass: massless or small mass would result in rapid fusion in stars

Mass values for electron, u quark, d quark, W boson are fine tuned for the creation of the universe and life on our planet.

Principle of mass creation: Higgs mechanism (our best guess)
Origin of elementary particle mass: completely unknown

- consistent description of nature seems to be based gauge symmetries
- problem: $SU(2)_L \times U(1)_Y$ gauge symmetry $\rightarrow$ no masses for $W/Z$ boson
- ad hoc mass terms spoil theory

- incorporated in the Standard Model using a complex scalar field (4 components)
- self interaction creates potential
- vacuum break symmetry spontaneously

- three components absorbed by $Z/W$ bosons.
- one scalar field component is not absorbed resulting in physical particle: **Higgs Boson**
The Fundamental Question

- interaction of particles with Higgs generates mass
- couplings are proportional to masses
\( \nu \sim 246 \text{ GeV} \) (vacuum expectation value)

Fermions (Yukawa coupling):

\[ m_f \sim g_f \nu \]

Higgs boson (self coupling):

\[ M^2 = \lambda \nu^2 \]

**Diagram:**

1. **Fermions (Yukawa coupling):**
   - Fermion: \( g_f \) coupling to the Higgs boson \( \nu \). The interaction generates mass.
   - \( m_f \sim g_f \nu \)

2. **Higgs boson (self coupling):**
   - The Higgs self-coupling is given by \( M^2 = \lambda \nu^2 \).

3. **W/Z bosons (gauge coupling):**
   - \( W/Z \) bosons have a gauge coupling to the Higgs field \( \nu \).
   - \( M \sim g \nu \)

**Graphical Representation:**

- Fermions are connected to the Higgs boson with a Higgs coupling \( g_f \).
- The Higgs boson is shown with a self-coupling \( \lambda \).
- \( W/Z \) bosons interact with the Higgs field through a gauge coupling \( g \).
The Fundamental Question

$W$ and $Z$ masses result from couplings to the Higgs field

Gluon and photon have no such couplings $\rightarrow$ massless

Quark and lepton masses are determined by the strength of their coupling to the Higgs field

What about neutrinos? Do they have the same nature?

Couplings determine quark mixing, CP violation, ...

Is the Higgs field responsible for matter dominance?

We have no understanding of the origin of those couplings
What do we know about the Standard Model Higgs Boson?

**theory:** unitarity in $WW$ scattering requires $M_H < 1$ TeV

**direct searches at LEP:** $M_H < 114.4$ GeV excluded with 95% CL
(talk by itself: ALEPH candidate events; end of LEP data taking in 2000)

**indirect prediction in SM:**
$M_H > 144$ GeV excluded with 95% CL

$$M_W(\text{Phys}) = M_W(\text{Born}) + m_t^2 + \ln(M_H)$$
What do we know about the Standard Model Higgs Boson?

2007 sensitivity:

4-12 time SM cross section.

1fb⁻¹ analyzed by CDF
400pb⁻¹ analyzed by D0
< 50% of available data.

~ 8fb⁻¹ needed to exclude
SM ~ 160GeV
What do we know about the Standard Model Higgs Boson?

Winter 2008 first tangible results on the Higgs from the Tevatron.

Dedicated effort combines CDF and D0 and finds first new exclusion 'point' since the LEP2 experiments (finished 2001).
What do we know about the Standard Model Higgs Boson?

Winter 2009 brought exciting new results.

Dedicated effort combines CDF and D0 and finds first new exclusion area since the LEP2 experiments (finished 2001).

C.Paus, LHC Physics: Higgs Physics and Other Essentials
Higgs Boson Production and Decay

Job Description (for experimentalist):

Discover the Higgs Boson and explore its properties.

In more Detail:

Does the Higgs Boson exist? One or more?

Is the Higgs Boson a scalar boson?

Does the Higgs Boson generate the masses of gauge bosons and fermions?

Does the Higgs Boson couple to itself?
Higgs Boson Production and Decay

LHC: pp collisions @ 14 TeV
Higgs Boson Production and Decay

\[ K = \frac{\sigma_{(N)\text{NLO}}}{\sigma_{\text{LO}}} \]

K ~ 2

K ~ 1.2

K ~ 1.4

K ~ 1.1
Some more words on K-factors - $K = \sigma_{(N)NLO} / \sigma_{LO}$

Leading Order $O(\alpha_s^2)$:
$gg \rightarrow H$

Next to Leading Order $O(\alpha_s^3)$:
$gg \rightarrow gH, \ gq \rightarrow qH, \ ...$

$\Delta \sigma \sim 4\text{-}15\% \ + \ \Delta \sim 5\text{-}15\% \ \text{from PDF}$
Higgs Boson Production and Decay

- $\Gamma_{Hff} \sim m_f^2$
- $\Gamma_{HVV} \sim m_V^4$

$m_H < 135$ GeV:
- $bb, \tau\tau$ dominant

$m_H > 135$ GeV:
- $WW, ZZ$ dominant
Higgs Boson Production and Decay

Branching fraction reminder:

W boson decays:

- in $e\nu$, $\mu\nu$, $\tau\nu$, $3^*ud$, $3^*sc$
- $\text{BR}(l\nu) \sim 11\%$
- $\text{BR}(\text{hadrons}) \sim 68\%$

Z boson decays:

- in $e^+e^-$, $\mu^+\mu^-$, $\tau^+\tau^-$, $\nu\bar{\nu}$, hadronic
- $\text{BR}(l\nu) \sim 3.3\%$
- $\text{BR}(\nu\bar{\nu}) \sim 20\%$
- $\text{BR}(\text{hadrons}) \sim 70\%$

$\tau$ decays:

- in $e\nu\nu$, $\mu\nu\nu$, hadronic+$\nu$
- $\text{BR}(l\nu\nu) \sim 18\%$
- $\text{BR}(\text{hadrons}) \sim 64\%$
m_H = 150 GeV: S/B ~ 10^{-10}

trigger: 10^{-7} reduction, on leptons, photons and missing ET

no track trigger @ L1

Considerations for discovery channel:

- sufficient signal rate
- efficient trigger
- Higgs mass reconstruction
- control of background
A Closer Look at Specific Channels

$H \rightarrow \gamma \gamma$: \quad \sigma_H = 44.2 \text{ pb} \quad \text{BR} (H \rightarrow \gamma \gamma) = 0.0022 \ (m_H = 120 \text{ GeV})

\( \downarrow \sim 100 \text{ evts/fb} \)

signal: \quad 2 \text{ isolated high pT photons}

background: irreducible \quad pp \rightarrow \gamma \gamma + x

reducible \quad pp \rightarrow \gamma j + x, jj + x

exp. challenge: \quad \text{mass resolution} \quad \sigma_M / M \sim 0.7\%

vertex constraint

photon conversions

$\pi^0$ rejection

background estimation

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A Closer Look at Specific Channels

$H \rightarrow ZZ^*$:

$\sigma_H = 21.6 \text{ pb}$ \hspace{0.5cm} $\text{BR} (H \rightarrow ZZ) = 0.058 \text{ (mH=180GeV)}$

$\text{BR}(ZZ \rightarrow 4l) = 0.005$

$\approx 7 \text{ evts/fb}$

signal: 4 isolated leptons

background: irreducible $pp \rightarrow ZZ \rightarrow 4l$

reducible $tt, Zbb$

exp. challenge: mass resolution $\sigma_M / M < 1\%$

background estimation

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A Closer Look at Specific Channels

\( H \rightarrow WW^* : \sigma_H = 26.6 \text{ pb} \quad \text{BR} (H \rightarrow WW) = 0.9 \quad (m_H=160 \text{GeV}) \)

\[ \text{BR}(WW \rightarrow 2l 2\nu) = 0.05 \]
\[ \Rightarrow \sim 1200 \text{ evts / fb} \]

signal:
- 2 isolated leptons,
- missing transverse energy
- no mass peak

\[ m_T = \sqrt{2 P_T \ell \ell E_T} (1 - \cos \Delta \phi) \]

→ use transverse mass

background: WW, WZ, tt, QCD

exp. challenge: missing energy resolution
- tt (or jet) – veto
A Closer Look at Specific Channels

Vector Boson Fusion: $pp \rightarrow qqH$

signature: $\times$ 2 forward jets with large rapidity gap
$\times$ only Higgs decay products in central det.

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A Closer Look at Specific Channels

$qqH \rightarrow qq\tau\tau$:

$\sigma_H = 4.5 \text{ pb}$  \hspace{1em} $\text{BR} (H \rightarrow \tau\tau) = 0.069 \ (mH=120\text{GeV})$

$\downarrow \sim 180 \text{ evts/fb}$

<table>
<thead>
<tr>
<th>$\tau\tau$ decay mode</th>
<th>BR</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\ell\ell \nu$</td>
<td>12%</td>
</tr>
<tr>
<td>$\ell\text{jet}\nu$</td>
<td>46%</td>
</tr>
<tr>
<td>jet jet $\nu$</td>
<td>42%</td>
</tr>
</tbody>
</table>

signal: VBF signature

high pT lepton, hadronic, missing energy or two high pT leptons, missing energy

background: $pp \rightarrow Z \rightarrow \tau\tau$ (EWK, QCD)

$tt$, $WW$, $bbjj$

exp. challenge: missing Et resolution (Higgs mass)

central jet veto

forward jet tagging

all detector components involved
A Closer Look at Specific Channels

Hadronic $\tau$ reconstruction:

- $c\tau \sim = 87 \mu m$,  
  $m_\tau = 1.78$ Gev/c$^2$

- Leptonical decays
  - $\tau \rightarrow e(\mu) \nu \nu : \sim 35.2 \%$
    - Identification done through the final lepton

- Hadronical decays
  - 1 prong
    - $\tau \rightarrow \nu_\tau + \pi^{+/0} + n(\pi^0) : 49.5 \%$
  - 3 prongs
    - $\tau \rightarrow \nu_\tau + 3\pi^{+/0} + n(\pi^0) : 15.2 \%$
  - “$\tau$–jet” is produced
Higgs mass reconstruction:

\[ p(l) = x \cdot p(\tau) \], collinear approximation

\[ p_T(H) = p_T(\tau_1) + p_T(\tau_2) = p_T(e) + p_T(\mu) + p_T \]

\[ m_{\tau\tau}^2 = m_{e\mu}^2 \times (x_{e\tau} \times x_{\mu\tau}) \]
other SM Higgs channels of interest:

\[ H \rightarrow WW^* \rightarrow lvjj \]

\[ ttH \rightarrow tt \, bb \]

\[ WH \rightarrow lv \, bb \]

\[ qqH \rightarrow qq \, WW^* \]

\[ qqH \rightarrow qq \, \gamma \gamma \]

\[ qqH \rightarrow qq \, ZZ^* \rightarrow qq \, llvv \]
How much luminosity do we need to find the Higgs?

**SM Higgs**

Working plots with updated statistical methods.

**CMS**

Luminosity for 5$\sigma$ discovery, fb$^{-1}$

- $H\rightarrow\gamma\gamma$ cuts
- $H\rightarrow\gamma\gamma$ opt
- $H\rightarrow ZZ\rightarrow 4l$
- $H\rightarrow WW\rightarrow lv lv$
- Combined

$\int L\,dt = 30\,fb^{-1}$
Why are the discovery potential plots so different?

ATLAS: \( K = 1 \) and LO MC for signal and background  
CMS: K-factors for gluon fusion and estimates for background  

Both: instrumental backgrounds are not fully considered

Result:  
\( \times \) More signal for CMS  
\( \times \) More background for CMS  
\( \times \) Imbalance between GF and VBF channels

How do we have to read those plots?  
- very carefully!
A Closer Look at Specific Channels

Sensitivity with 30 fb\(^{-1}\):
Beyond the Standard Model

Why do we want to go beyond the Standard Model?
- hierarchy problem: why $\nu = 246$ GeV $<<$ Mpl. $= 10^{19}$ GeV
- origin of all this new couplings
- dark matter and baryon asymmetry

SUSY might be a solution but has large problems itself:
- it is broken & 105 new parameters

Study constrained models:
- MSSM with 5 (6) additional parameter

Very rich phenomenology:
- minimal Higgs sector has 5 physical boson $h$, $H$, $A$, $H^+$, $H^-$
- Higgs bosons can decay into particles and sparticles

More on (Higgs-) physics beyond the Standard Model in the following lectures
In 5 Years from Now

These could be the topics of your thesis!!

ATLAS and CMS have datasets of $\sim 100 \text{ fb}^{-1}$

The Higgs Boson was discovered 2010, confirmed by both experiments and in different channels (topic of your thesis if you come here right away!!)

Nothing else but the Higgs Boson was discovered so far

Obvious three interesting topics
- measure Higgs Boson properties
- other SM precision measurements
- keep searching for new physics
Higgs Boson Properties

Higgs Boson mass:

direct mass peaks from:
\[ H \rightarrow \gamma\gamma, \ H \rightarrow bb, \ H \rightarrow \tau\tau, \ H \rightarrow ZZ \rightarrow 4l \]

indirect from fits to transverse mass spectrum:
\[ H \rightarrow WW \rightarrow l \nu l \nu, \ WH \rightarrow WW\rightarrow l \nu l \nu l \nu \]

uncertainties:
  a) statistical  
  b) absolute energy scale  
  c) background

estimated precision:
\[ \Delta M / M : 0.1\text{-}1.0\% \]
Higgs Boson Properties

Higgs Boson couplings:
production:
\[ \sigma_{Hx} = \text{const} \times \Gamma_{Hx} \]
decay:
\[ \text{BR}(H \rightarrow yy) = \frac{\Gamma_{Hy}}{\Gamma_{\text{tot}}} \]

event rate:
\[ \sigma_{Hx} \times \text{BR} = \text{const} \times \Gamma_{Hx} \times \frac{\Gamma_{Hy}}{\Gamma_{\text{tot}}} \]

coupling:
\[ \Gamma_{Hz} \sim g_{Hz}^2 \]

challenge:
disentangle contributions from production and decay
Projects

a) $H \rightarrow ZZ^* \rightarrow 4l$
b) $H \rightarrow WW^* \rightarrow l\nu l\nu$
c) $qqH \rightarrow qqWW^* \rightarrow \text{jet jet } l\nu l\nu$

Goal 1:
How much luminosity to you need as a function of $m_H$ (two point) to discover the Higgs boson.

Goal 2:
Measure the relative fraction of Higgs production cross section in vector boson fusion.

Details are on the twiki. Feel free to ask questions!
Conclusion

Fundamental question
   What is the origin of elementary particle mass?

Principal of mass creation
   Higgs mechanism

LHC experiments will find the SM Higgs boson with 1-10fb-1.

Able to measure or at least constrain Higgs Boson properties
Next Lecture