Finding a new (Higgs?) boson at the Large Hadron Collider

Peter Onyisi

*UT Physics Colloquium, 31 Oct 2012*
The **Higgs Boson** is the theoretical particle of the Higgs mechanism, which physicists believe will reveal how all matter in the universe gets its mass. Many scientists hope that the Large Hadron Collider in Geneva, Switzerland, which collides particles at 99.99% the speed of light, will detect the elusive Higgs Boson.

Wool felt, fleece with gravel fill for maximum mass. Made in China.
The big picture

What is particle physics about?

- What is the Lagrangian of the universe?
  - What are the matter and force particles? How big are the coefficients of the terms?

- What principles guide the terms that are present?
  - Symmetries and conserved charges: not everything goes

- How do we go from the small to the large?
  - Protons and neutrons (e.g.) are not fundamental particles, but we had best be able to explain them!
  - Physics at the smallest and largest scales is intimately related
The Modern Universe

- 74% Dark Energy
- 22% Dark Matter
- 4% Atoms

NASA/WMAP
What you're made of

Gauge bosons: carriers of fundamental forces
electromagnetism, strong and weak nuclear forces
Interactions determined by gauge symmetries
Massive carriers of the weak force

Still very mysterious: Gravity? Dark matter? Dark energy? Baryon asymmetry? ...

1 GeV = 1.07 protons
125 GeV ≈ 1 Cs atom
Gauge Theory

• Forces in the particle physics Standard Model are specified by *symmetries*
  
  – Particles that feel a force are affected by its symmetry transformations
  
  – Constrains possible interactions very strongly

• If a particle interacts with a force, it has a charge for that force. *Charge conservation applies!*

Classical electrodynamics has a gauge symmetry:

\[ A^\mu = (\phi, \vec{A}) \rightarrow A^\mu + \partial^\mu \chi \]

Leaves \( E \) and \( B \) unchanged
The Weak Force is Weird

- The weak force carriers are massive.
- The weak force carriers form a triplet $W^+, Z^0, W^-$ (as expected from their symmetry), but they do not all have the same mass, and they do not all have the same interactions.
- The weak force distinguishes left- and right-handed particles.
The Weak Force Carriers

We even use the W and Z masses for experimental calibration

Detection mode:
W decays to a charged lepton + neutrino
Z decays to charged lepton + antilepton
Parity and Chirality

• The weak force treats left and right handed electrons (and all fermions) differently
  – left handed fermions and right handed antifermions have weak interactions. Their antiparticles don't.

• Left and right handed fermions are different particles.

OK!

\[ W^- \quad \text{left-handed electron} \quad \text{OK!} \quad \text{right-handed electron} \quad \text{W}^- \]
So, the Problems...

- Gauge invariance forbids the Standard Model from having explicit masses for the W and Z

\[
\frac{1}{2} m_Z^2 Z_\mu Z^\mu
\]

- Gauge invariance forbids explicit (Dirac) fermion mass terms, as these would create/destroy weak charge.

\[
-m e^\dagger R e^L
\]

How do we get a realistic model of the weak force without abandoning gauge theory?
Add a weak-charged scalar field $\phi = (v+h)/\sqrt{2}$, where $v \neq 0$ in the vacuum state. Then the required interaction becomes

$$\frac{g^2}{4} (W^+ \phi)^\dagger (W^+ \phi)$$

becomes

$$\frac{1}{2} \frac{g^2 v^2}{4} \left( W^- W^+ \left( 1 + 2 \frac{h}{v} + \frac{h^2}{v^2} \right) \right)$$

**W mass**

$m_w = gv/2$

**WWH coupling**

$\propto gm_w$

**WWHH coupling**

$\propto g^2$

*Englert and Brout; Higgs; Guralnik, Hagen, and Kibble (1964)*

*Weinberg; Salam (1967-8)*
Fermion Masses

Since $\phi$ field has weak charge the following is ok:

$$-y_e \left( e_R^\dagger e_R \phi + e_L^\dagger e_L \phi^* \right)$$

which becomes

$$-y_e v \left( e_R^\dagger e_R + e_L^\dagger e_L \right) \left( 1 + \frac{h}{v} \right)$$

$e$ mass

$m_e = y_e v$

$e_R e_L h$

coupling $\propto y_e$

$y_e$ (the “Yukawa coupling”) is not predicted from theory but determined from observed masses.
Getting $v \neq 0$

Arrange so it is energetically favorable for the ground state to break a symmetry of the potential (pretty standard!)

Fluctuations of $\phi$ around the minimum correspond to a massive particle ("the Higgs boson") with

$$m_h = v \sqrt{2\lambda}$$

quartic term $\rightarrow$ $h$ self-interaction

From known $m_w$ and $g$, $v = 246$ GeV.
Higgs Boson Characteristics

- It is a neutral scalar.
- It has a specific pattern of interactions with the W, Z, and fermions, which depends on their masses.
  - For a given Higgs boson mass, its behavior is predicted.
- It interacts with itself.

(True for the minimal SM Higgs mechanism)

**Q:** why do the W and Z have different masses?

**A:** there are two broken symmetries – the Z gets two mass terms, and the W only gets one
More Complicated Models

- Can add more fields (e.g. two-Higgs doublet models [2HDM], supersymmetry)
- Higgs potential can be fixed by other physics
- The “Higgs field” could be a composite, not a fundamental scalar (e.g. technicolor)

2HDM would give more particles: *light and heavy neutral scalars* h and H, *neutral pseudoscalar* A, *charged scalars* H^+ and H^-

**Fermiophobic** models turn off the fermion couplings
Exotica

- The Higgs could interact with particles outside the Standard Model
  - portal to dark matter or other hidden sectors
  - fourth SM-like generation would strongly affect Higgs production
- These scenarios can modify Higgs production rates or decay patterns

Example "Higgs portal" to dark matter:
Add a SM singlet $S$ with interaction

$$k |\phi|^2 |S|^2$$
How do we look for new particles?

convert kinetic energy to mass energy of new particles

Proton kinetic energy > 4000 times proton mass

Detect “stable” remnants of collisions in detectors, look for patterns
LHC Higgs Production

At 14 TeV, rates are 3x-10x bigger

gluon-gluon fusion
vector boson fusion
W/Z associated production

At 14 TeV, rates are 3x-10x bigger
Directions to See a Higgs

Gauge boson decays: direct probe of EWSB
Rate reduced for Higgs mass below $2M_W, 2M_z$

Tests Yukawa couplings
$\tau\tau$ and $bb$ accessible at LHC, but are tricky experimentally

$\gamma\gamma$ is cleanest mode for low mass Higgs
Rate is sensitive to particles in loop
Behavior varies a lot with $m_H$ – but all very well predicted in the SM!
Knowledge before the LHC

- LEP and Tevatron experiments excluded some mass ranges with direct searches
- Higher-order calculations in the SM relate the Higgs mass to other observables (e.g. $m_W$ and $m_t$) for an indirect prediction of $m_H$
CERN: the European laboratory for particle physics
LHC: collides protons with kinetic energy > 4000 times their rest mass
where it all begins

consumption per day
≈ 2 nanograms
Quantum mechanics:
We only have *probabilities*

Every collision is a *random occurrence*

We're looking for things happening less often than once in a trillion collisions
ATLAS Readout

Can't read out all 40 MHz of collisions

Reduce to 300-500 Hz via hardware and software “trigger system”
“Pileup”: many collisions at once

Needed to get enough collisions

Very tricky to handle!
Over 3000 people work on ATLAS... here are a few (at the Higgs party!)
LHC experiments record billions of collisions, tens of petabytes of data per year

Need to search through them with computers throughout the globe

How do we take advantage of new computing technologies in HEP? Area of interest here at UT
The Pace of Higgses

At the absolute best collision rate we have had so far, we get

- a $H \rightarrow WW \rightarrow \ell\nu\ell\nu$ event every 20 minutes
- a $H \rightarrow \gamma\gamma$ event every 45 minutes
- a $H \rightarrow ZZ \rightarrow 4\ell$ event every 13 hours

We're not 100% efficient at catching them, and we need a lot to separate them from other processes.

In short, it takes a long time.
Simultaneous ATLAS and CMS papers

PL B716, 1
$m(\gamma\gamma) = 126.6$ GeV

$H \rightarrow \gamma\gamma$
candidate
The Discovery Plots: $H \rightarrow 2\gamma$

$x$ axis is invariant mass of $\gamma\gamma$ system: bump is a signature of a particle

Impossible to tell if any given event is from Higgs decay: use smoothness of non-Higgs contributions

“Weighted” plot: events weighted by expected purity of event category. Enhances events that are (a priori) more likely to be signal.
\[ H \rightarrow ZZ \rightarrow e e \mu \mu \]

candidate

\[ m_{4\ell} = 124.3 \text{ GeV} \]
The Discovery Plots: \( H \rightarrow ZZ \rightarrow 4\ell \)

\( \ell = \) electron or muon

Very clean channel: signal/background \( \approx 1/1 \)

Low rate though
H → WW → eνμν candidate
Neutrinos make this channel harder: signal is a broad lump, background has shape

Use a measurable proxy variable ("transverse mass") instead of Higgs candidate mass
CMS plots

- $H \rightarrow \gamma\gamma$
- $H \rightarrow ZZ$
- $H \rightarrow WW$
Discovery?

“5.9σ”: probability of fluctuation is $1.7 \times 10^{-9}$
What have we seen?

Decays to $\gamma\gamma$:
has integral spin ($\neq 1$)

Mass compatible
between all channels

ATLAS

$\sqrt{s} = 7$ TeV: $\int L dt = 4.7$-4.8 fb$^{-1}$
$\sqrt{s} = 8$ TeV: $\int L dt = 5.8$-5.9 fb$^{-1}$

+ Best fit
68% CL
95% CL

$H \rightarrow \gamma\gamma$
$H \rightarrow ZZ^{(*)} \rightarrow 4l$
$H \rightarrow WW^{(*)} \rightarrow lvlv$

Signal strength (μ)

$m_H$ [GeV]
**ATLAS 2011 - 2012**

**W, Z, H → bb**
- $\gamma s = 7$ TeV: $\int L dt = 4.7$ fb$^{-1}$
- $H → \tau\tau$
  - $\gamma s = 7$ TeV: $\int L dt = 4.6$-4.7 fb$^{-1}$
  - $\gamma s = 8$ TeV: $\int L dt = 5.8$ fb$^{-1}$
- $H → WW^{(*)} → l\nu l\nu$
  - $\gamma s = 7$ TeV: $\int L dt = 4.7$ fb$^{-1}$
  - $\gamma s = 8$ TeV: $\int L dt = 5.8$ fb$^{-1}$
- $H → γγ$
  - $\gamma s = 7$ TeV: $\int L dt = 4.8$ fb$^{-1}$
  - $\gamma s = 8$ TeV: $\int L dt = 5.9$ fb$^{-1}$
- $H → ZZ^{(*)} → 4l$
  - $\gamma s = 7$ TeV: $\int L dt = 4.8$ fb$^{-1}$
  - $\gamma s = 8$ TeV: $\int L dt = 5.8$ fb$^{-1}$

**Combined**
- $\mu = 1.4 \pm 0.3$

$\gamma s = 8$ TeV: $\int L dt = 5.8 \cdot 5.9$ fb$^{-1}$

---

Signal strength = observed/SM rate

**Remember observed modes have x 40 difference in expected total rates**

Agreement with SM is not trivial!
Compatible with Standard Model?

Observed Higgs mass consistent with indirect predictions
The Higgs discovery paper author list
Discovery of a SM Higgs-like particle at 125 GeV already limits “new physics” models

- Technicolor: gone
- Supersymmetry: strongly constrained (prefers lower \( m_H \) if “natural”)

Arbey, Battaglia, Djouadi, Mahmoudi
JHEP 1209 (2012) 107

\[
M_h (\text{GeV}) = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}
\]
Is our vacuum stable?

Renormalization drives quartic term negative at high energy

Perhaps we are not in the true minimum of the Higgs potential?

New physics at $10^{10}$ GeV?

$\lambda = 0$ boundary condition?

Degrassi et al, arxiv:1205.6497
Higgs effective potential @ NNLO
Higgs and Inflation?

- For (very) special choices of the Higgs and top quark masses, a second minimum develops in the potential at high vev.
- Could this drive primordial inflation ("false vacuum")?

---

Degrassi et al, arxiv:1205.6497
Towards the Future

What else do we need to study about the Higgs?

- Detect it in as many decay channels as possible
  - e.g. we do not know yet if it couples to leptons
- Show that the couplings are those of the Standard Model (or not)
  - Huge uncertainties right now
  - Lots of theoretical excitement over “high” $H \rightarrow \gamma\gamma$ rate...
- Show it couples to itself
  - Necessary for electroweak symmetry breaking mechanism to work
- Non-SM decays? (Dark matter?)
- Precision mass

(and then there's the hierarchy problem ...)

Potential Futures

Wring more collisions out of the LHC?
300 fb\(^{-1}\) ~ 2020
3000 fb\(^{-1}\) ~ 2030 (“HL-LHC”)

New lepton “Higgs Factory”?
e\(^{+}\)e\(^{-}\), \(\mu^{+}\)\(\mu^{-}\), \(\gamma\gamma\) collider?
Circular or linear?

\[ H \rightarrow \mu\mu \]

Very Large Hadron Collider?

Something totally new, like plasma acceleration?
Summary

- ATLAS and CMS have found a new particle, mass ~ 125 GeV, with properties consistent with the minimal Standard Model Higgs boson.
- This already strongly constrains the parameter space for physics beyond the Standard Model, and has implications for physics at very high energies.
- With more data we will improve the measurements of production and decay parameters of the particle, and see if it is embedded in a larger symmetry breaking sector.