The Higgs Boson
Triumph of the Standard Model

Jesse Thaler

Higgs-like Celebration — Oct 11, 2012
Higgs-like Discovery

July 4, 2012

This talk: Why the Higgs is such a big deal

= Affiliated (past or present) with MIT
8.05 = Shout out to my recitation students

Culminating a century of particle physics!
Defining next 25 years of fundamental physics!
The Standard Model

- Graviton
- Photon
- Gluon
- W/Z Bosons

Quarks: u, d, s, c, t, b
Leptons: e, ν_e, ν_μ, ν_τ, μ, τ
The Standard Model

+ Higgs!

Graviton  |  Photon  |  Gluon  |  W/Z Bosons

Quarks  |  Leptons

u  d  e  νe  s  c  μ  νμ  t  b  τ  ντ
Weak Alchemy

Electromagnetic

\[ e \quad \text{photon} \quad p \quad \text{(unchanged)} \]

Weak Force

\[ e \quad \text{W boson} \quad p \quad \Rightarrow \quad n \quad (\nu_e) \]

Essential for Stellar Burning

Deuteron

\[ p_n \quad \text{W boson} \quad p \quad \nu_e \quad e \]
Three Bizarre Properties

1. Massive Carrier

\[ \text{Massless Photon} = \text{Two Polarizations} \quad \text{vs.} \quad \text{Massive W Boson} = \text{Three Polarizations} \]

2. Self-Interacting

\[ \text{Photon} \rightarrow \text{Pass right through} \quad \text{vs.} \quad \text{Collision} \]

3. (Parity-Violating)

\[ x \rightarrow -x \text{ is not a symmetry of weak force} \]

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Why is Weak Force so Weird?

Because Weak Force is Broken

8.325: “Spontaneous Symmetry Breaking”
8.05: Weak charge is not conserved
Analogy: “Why is ice so weird compared to water?”
Why is Weak Force so Weird?

Because Weak Force is Broken

8.325: “Spontaneous Symmetry Breaking”
8.05: Weak charge is not conserved
Analogy: “Why is ice so weird compared to water?”

Caused by the Higgs!
A Little History

Energy Not Conserved in Weak Decays??

$\text{n} \rightarrow \text{p} \, \text{e}$

Chadwick, et al.

Expt: 1920s

Theory:
Energy Not Conserved in Weak Decays??

\[ n \rightarrow p \, e \]

Chadwick, et al.

Expt: 1920s

Theory: 1930 1933
Pauli  Fermi

\[ n \rightarrow p \, e \, \nu ? \]
Energy Not Conserved in Weak Decays??

\[ n \rightarrow p e \]

Chadwick, et al.
Expt: 1920s

\[ n \rightarrow p e \nu \]

Pauli
Fermi
Theory: 1930 1933

Cowan/Reines
1956

\[ n \rightarrow p e \nu \]?
Energy Not Conserved in Weak Decays??

\[ n \rightarrow p + e^- \]

Chadwick, et al.

Expt: 1920s

Theory: 1930 1933

Pauli  Fermi

\[ n \rightarrow p + e^- + \nu \]

Cowan/Reines

1956

Lessons:

- New Particle \( \leftrightarrow \) Fundamental Principle
- Neutrino \( \leftrightarrow \) Energy Conservation

Have to take the long view
A Little History

Energy Not Conserved in Weak Decays??

\[ n \rightarrow p e \]

Chadwick, et al. 1920s

\[ \nu! \]

Cowan/Reines 1956

\[ n \rightarrow p e \nu? \]

Pauli 1930 1933
Fermi
A Little History

Energy Not Conserved in Weak Decays??

\[ n \rightarrow p\ e \]

Chadwick, et al.
Expt: 1920s

\[ n \rightarrow p\ e\ ν? \]

Cowan/Reines
1956

Theory:

1930 1933
Pauli Fermi

1967
Weinberg/Salam/Glashow

\[ n \rightarrow p\ e\ ν \]
via New Weak Force?

Three New Force Carriers:

\[ W^-? \] Weak Alchemy
\[ W^+? \] (Reverse) Weak Alchemy
\[ Z? \] Zomething else...

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A Little History

Energy Not Conserved in Weak Decays??

\[ n \rightarrow p e \]
Chadwick, et al.
Expt: 1920s

Theory:

1930 1933
Pauli Fermi

\[ n \rightarrow p e \nu \]?

Cowan/Reines
1956

\[ W/\bar{Z}! \]
SPS @ CERN
Rubbia/van der Meer
1983

1967
Weinberg/Salam/Glashow

\[ n \rightarrow p e \nu \]
via New Weak Force?

Three New Force Carriers:

\{ \begin{align*}
W^- & \text{ Weak Alchemy} \\
W^+ & \text{(Reverse) Weak Alchemy} \\
Z & \text{Zomething else...} 
\end{align*} \}
History in the Making?

Expt: 1920s

Theory: 1930 1933

n → p e?

ν?

ν!

W/Z!

1956

1983

1967

W/Z?
**History in the Making?**

Higgs boson: Last ingredient of Standard Model

*Prof. Klute’s talk: Higgs or just Higgs-like?*
Tale of Two Higgses

Higgs Mechanism
- Breaks Weak Force
- Gives Mass to Fundamental Particles

Higgs Boson
- New Spin-0 Particle
- Ensures Consistency of Quantum Mechanics

Massive W Boson

W Self-Collisions

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Higgs Mechanism in 2012
Mass for all Fundamental Particles

For Prof. Klute’s talk:

**Higgs Couplings**

,** Particle Masses**

8.05: Composites (like proton) get most mass from strong force
Higgs Mechanism in 1964

The Anderson, Brout/Englert, Higgs*, (1964)
Guralnik/Hagen/Kibble, 't Hooft Mechanism

Two Polarizations
Higgs Mechanism in 1964

The Anderson, Brout/Englert, Higgs*, (1964)
Guralnik/Hagen/Kibble, 't Hooft Mechanism

Two Polarizations

Nambu/Goldstone Bose (1961)
(Necessary consequence of breaking)
Higgs Mechanism in 1964

The Anderson, Brout/Englert, Higgs*, (1964)
Guralnik/Hagen/Kibble, 't Hooft Mechanism

Two Polarizations

Nambu/Goldstone Boson \(\text{MIT}^{(1961)}\)
(Necessary consequence of breaking)

Three Polarizations!
Higgs Mechanism in 1964

The Anderson, Brout/Englert, Higgs*, (1964)
Guralnik/Hagen/Kibble, 't Hooft Mechanism

Two Polarizations

Nambu/Goldstone Boson (1961)
(Necessary consequence of breaking)

Three Polarizations!

* (Optional?) consequence of breaking is extra particle: “Higgs boson”
8.05: Higgs boson is spin-0
Birth of the Standard Model

Killer App for Higgs Mechanism: Electroweak Theory

Photon
Unbroken, Massless,
Long Range

W/Z Bosons
Broken, Massive,
Short Range!

Higgs Boson

= Standard Model

Politzer/Gross/Wilczek
(1973)

Weinberg/Salam/Glashow
(1967)
Higgs Boson?
(Keystone or Appendix?)
Colliding Weak Bosons

Quantum Mechanics = Theory of Probability

\[ P \]

- 100%
- 0%

\[ E_{\text{eff}} \]

- 1 TeV
- 14 TeV
Colliding Weak Bosons

Quantum Mechanics = Theory of Probability

100% chance something will happen

8.05: take 8.06 to learn what “100%” really means

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100% chance something will happen

8.05: take 8.06 to learn what “100%” really means
Prof Klute’s talk: Higgs hunting = “Bump hunting”
The Weak Interaction

A Bizarre Force...

...with a Profound Prediction

0. Weak Alchemy

1. Massive Carrier

2. Self-Interacting

3. (Parity-Violating)

Higgs Mechanism
Breaks Weak Force
Gives Mass to Fundamental Particles

Higgs Boson
New Spin-0 Particle
Ensures Consistency of Quantum Mechanics
The Standard Model

New Particles ⇔ Fundamental Principles

- Neutrino ⇔ Energy Conservation
- W/Z Bosons ⇔ Essential Similarity of All Forces
- Higgs Boson ⇔ Probability Conservation

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The Higgs Boson

Quantum Gravity

Protons

Electrons

Cells

Molecules

The Universe

The TeV Scale

Us

Hairs

Cells

Electrons

Protons

Grand Unification

Solar System

Planet

Galaxy

Hairs

Us

Solar System

Planet

Galaxy

The TeV Scale

10^{26} \text{ m}

10^{11} \text{ m}

10^{-4} \text{ m}

10^{-19} \text{ m}

10^{-34} \text{ m}

The Standard Model

+ Higgs!

New Particles ↔ Fundamental Principles

Neutrino ↔ Energy Conservation

W/Z Bosons ↔ Essential Similarity of All Forces

Higgs Boson ↔ Probability Conservation

Dark Matter? ↔ ??

?? ↔ Supersymmetry?

An exciting future for fundamental physics!

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