Before and After - Consequences of the Higgs Discovery

Travis Martin, TRIUMF

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Edmonton, Alberta
Overview

• On the necessity for a Higgs boson

• Confirming “a Higgs boson”

• State of theory after the discovery
  • Little Higgs
  • Supersymmetry

• What this all means for the future of particle physics
### Standard Model

#### Light
- Electromagnetism
- Chemical Binding
- Substance/Structure

#### Nucleus Binding
- Quark Binding

#### Beta Decay
- Neutrino recoil

Developed in the 1960s

<table>
<thead>
<tr>
<th>Quarks</th>
<th>Leptons</th>
</tr>
</thead>
<tbody>
<tr>
<td>I: up</td>
<td>0 $V_e$ electron neutrino</td>
</tr>
<tr>
<td>II: charm</td>
<td>0 $V_\mu$ muon neutrino</td>
</tr>
<tr>
<td>III: top</td>
<td>0 $V_\tau$ tau neutrino</td>
</tr>
<tr>
<td>mass $\rightarrow$</td>
<td>2.4 MeV/c$^2$</td>
</tr>
<tr>
<td>charge $\rightarrow$</td>
<td>$\frac{3}{2}$</td>
</tr>
<tr>
<td>spin $\rightarrow$</td>
<td>$\frac{1}{2}$</td>
</tr>
<tr>
<td>name $\rightarrow$</td>
<td>up</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>I: down</td>
<td>0 electron</td>
</tr>
<tr>
<td>II: strange</td>
<td>0 $\mu$ muon</td>
</tr>
<tr>
<td>III: bottom</td>
<td>0 $\tau$ tau</td>
</tr>
<tr>
<td>mass $\rightarrow$</td>
<td>$\frac{3}{2}$</td>
</tr>
<tr>
<td>charge $\rightarrow$</td>
<td>$\frac{1}{2}$</td>
</tr>
<tr>
<td>spin $\rightarrow$</td>
<td>$\frac{1}{2}$</td>
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<tr>
<td>name $\rightarrow$</td>
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<tr>
<td>I: $V_e$ electron neutrino</td>
<td>0.511 MeV/c$^2$</td>
</tr>
<tr>
<td>II: $V_\mu$ muon neutrino</td>
<td>105.7 MeV/c$^2$</td>
</tr>
<tr>
<td>III: $V_\tau$ tau neutrino</td>
<td>1.777 GeV/c$^2$</td>
</tr>
<tr>
<td>mass $\rightarrow$</td>
<td>$\frac{1}{2}$</td>
</tr>
<tr>
<td>charge $\rightarrow$</td>
<td>$-1$</td>
</tr>
<tr>
<td>spin $\rightarrow$</td>
<td>$\frac{1}{2}$</td>
</tr>
<tr>
<td>name $\rightarrow$</td>
<td>electron</td>
</tr>
</tbody>
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<thead>
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<th>Quarks</th>
<th>Leptons</th>
</tr>
</thead>
<tbody>
<tr>
<td>I: $V_\mu$ muon</td>
<td>0.17 MeV/c$^2$</td>
</tr>
<tr>
<td>II: $V_\tau$ tau</td>
<td>0.51 MeV/c$^2$</td>
</tr>
<tr>
<td>III: $W^+$ W boson</td>
<td>80.4 GeV/c$^2$</td>
</tr>
<tr>
<td>mass $\rightarrow$</td>
<td>$\frac{1}{2}$</td>
</tr>
<tr>
<td>charge $\rightarrow$</td>
<td>$1$</td>
</tr>
<tr>
<td>spin $\rightarrow$</td>
<td>$\frac{1}{2}$</td>
</tr>
<tr>
<td>name $\rightarrow$</td>
<td>muon</td>
</tr>
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<tbody>
<tr>
<td>I: $V_e$ electron neutrino</td>
<td>2.2 eV/c$^2$</td>
</tr>
<tr>
<td>II: $V_\mu$ muon neutrino</td>
<td>4.2 GeV/c$^2$</td>
</tr>
<tr>
<td>III: $Z^0$ Z boson</td>
<td>91.2 GeV/c$^2$</td>
</tr>
<tr>
<td>mass $\rightarrow$</td>
<td>$\frac{1}{2}$</td>
</tr>
<tr>
<td>charge $\rightarrow$</td>
<td>$0$</td>
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<tr>
<td>spin $\rightarrow$</td>
<td>$0$</td>
</tr>
<tr>
<td>name $\rightarrow$</td>
<td>electron neutrino</td>
</tr>
</tbody>
</table>

### Gauge Bosons

- $U(1)_{\text{em}}$}
- $SU(3)_{\text{c}}$}
- $SU(2)_{\text{w}}$
Forbidden Mass

- Mass in nucleons, matter: mostly binding energy

- **Fundamental mass** terms forbidden for standard model fermions/gauge bosons

- Mass terms for fermions/gauge bosons violate the fundamental conservation laws/symmetries upon which the standard model is based

\[ f_L \times f_R \]

\[ Z \times Z \]
Not Forbidden: Scalar

- Scalar fundamental mass, self coupling not forbidden
  \[ V \supset \mu^2 H \dagger H + \lambda (H \dagger H)^2 \]

- Can include interactions between scalars & fermions/gauge bosons
Spontaneous Symmetry Breaking

\[ V \supset \mu^2 H^\dagger H + \lambda (H^\dagger H)^2 \]
Spontaneous Symmetry Breaking

\[ V \supset \mu^2 H^\dagger H + \lambda (H^\dagger H)^2 \]

Unbroken Symmetry
Spontaneous Symmetry Breaking

\[ V \supset \mu^2 H^\dagger H + \lambda (H^\dagger H)^2 \]

- Unbroken Symmetry
- \( \mu^2 > 0, \lambda > 0 \)

- Broken Symmetry
- \( \mu^2 < 0, \lambda > 0 \)
Spontaneous Symmetry Breaking

\[ V \supset \mu^2 H\dagger H + \lambda(H\dagger H)^2 \]

\[ H \rightarrow h + \nu \]
Mass terms

\[ H \rightarrow h + v \]
Previous Searches

\[
e^{-} \rightarrow Z^{*} \rightarrow h \rightarrow e^{+} Z
\]
Previous Searches

Search for the Higgs Particle
Status as of July 2010

Excluded by LEP Experiments
95% confidence level

Excluded by Tevatron Experiments

Excluded by Indirect Measurements
95% confidence level

Higgs mass values

100 114 120 140 158 175 185 200 GeV/c²

95% confidence level
Before and After - Consequences of the Higgs Discovery
“Discovery”, July 4, 2012

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Spin
Production

June 2015
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Decays

June 2015
Before and After - Consequences of the Higgs Discovery
**Measurements**

**ATLAS Preliminary**

\[ m_H = 125.36 \text{ GeV} \]

<table>
<thead>
<tr>
<th>DECAY</th>
<th>( \mu_{\text{obs}} )</th>
<th>( \mu_{\text{exp}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( H \to \gamma\gamma )</td>
<td>1.17^{+0.28}_{-0.26}</td>
<td>1.00^{+0.25}_{-0.23}</td>
</tr>
<tr>
<td>( H \to ZZ^* )</td>
<td>1.46^{+0.40}_{-0.34}</td>
<td>0.99^{+0.31}_{-0.26}</td>
</tr>
<tr>
<td>( H \to WW^* )</td>
<td>1.18^{+0.24}_{-0.21}</td>
<td>1.00^{+0.21}_{-0.19}</td>
</tr>
<tr>
<td>( H \to bb )</td>
<td>0.63^{+0.39}_{-0.37}</td>
<td>1.00^{+0.41}_{-0.38}</td>
</tr>
<tr>
<td>( H \to \tau\tau )</td>
<td>1.44^{+0.42}_{-0.37}</td>
<td>1.00^{+0.36}_{-0.32}</td>
</tr>
<tr>
<td>( H \to \mu\mu )</td>
<td>-0.7^{+3.7}_{-3.7}</td>
<td>1.0^{+3.4}_{-3.5}</td>
</tr>
<tr>
<td>( H \to Z\gamma )</td>
<td>2.7^{+4.6}_{-4.5}</td>
<td>1.0^{+4.2}_{-4.2}</td>
</tr>
</tbody>
</table>

**Combined**

\[ \mu = 1.00^{+0.14}_{-0.14} \]

\[ \mu_{\text{exp}} = 1.00^{+0.13}_{-0.12} \]

\[ \sigma = 7 \text{ TeV}, 4.5-4.7 \text{ fb}^{-1} \]

\[ \sigma = 8 \text{ TeV}, 20.3 \text{ fb}^{-1} \]

**CMS**

\[ m_H = 125 \text{ GeV} \]

**Backgrounds**

- \( \gamma\gamma \) (untagged)
- \( \gamma\gamma \) (VBF tag)
- \( \gamma\gamma \) (VH tag)
- \( \gamma\gamma \) (ttH tag)
- \( ZZ \) (0/1-jet)
- \( ZZ \) (2-jet)
- \( WW \) (0/1-jet)
- \( WW \) (VBF tag)
- \( WW \) (VH tag)
- \( WW \) (ttH tag)
- \( \tau\tau \) (0/1-jet)
- \( \tau\tau \) (VBF tag)
- \( \tau\tau \) (VH tag)
- \( \tau\tau \) (ttH tag)
- \( bb \) (VH tag)
- \( bb \) (ttH tag)
Stability

Degrassi et al. arXiv:1205.6497
Fine Tuning/Hierarchy

\[ m_h^2 = m_0^2 + \delta m^2 \]

Bare mass:

\[ \Lambda \approx \text{Scale of New Physics (Gravity?)} \]
\[ \Lambda \gg m_h \rightarrow \text{Hierarchy Problem} \]

1 loop correction:

\[ \delta m^2 = \frac{3}{64\pi^2} (3g^2 + g'^2 + 8\lambda - 8\lambda_t^2) \Lambda^2 \]
• Introduce new particles, new symmetries

• Possibilities:
  • Little Higgs
  • Supersymmetry
  • Extra Dimensions
  • many more

http://www.theguardian.com/science/2013/jun/16/has-physics-gone-too-far
Two-Higgs Doublets

- 2HDM: $H_1$ for up-type, $H_2$ for down-type
- Search for heavy Higgs bosons ($h, H, A, H^\pm$)

arXiv:1409.6064

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CMS-PAS-HIG-15-001
Little Higgs

- New gauge symmetries, vector-like particles
- Collective cancellation of Higgs divergence

\[ \Lambda = \text{scale of new physics} \]
\[ f = \text{vev of BSM model} \]
\[ \Lambda \sim 4\pi f \]
Bestest Little Higgs

SO(6)xSO(6)
New:
6 fermions
3 gauge bosons
20 scalars

2 Higgs Doublets
(h, H, A, H±)

Kalyniak, Martin & Moats, arXiv:1310.5130
Bestest Little Higgs

\[ f \gtrsim 4 v \]
• **Boson - Fermion symmetry**
• Boson - Fermion symmetry
• Bozon - Fermion symmetry

\[ m_{h^0} < m_Z \left| \cos(2\beta) \right| \]

\[ \Delta(m_{h_0}^2) = \frac{3}{4\pi^2} \cos^2 \alpha \ y_t^2 m_t^2 \ln \left( \frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2} \right) \]

Draper et al. arXiv:1112.3068
Minimal Supersymmetry

- MSSM not ruled out!
Minimal Supersymmetry

- MSSM not ruled out!
- MSSM not ruled out!

Cahill-Rowley et al. arXiv:1407.7021
• Holding our breath for Run II of the LHC!

<table>
<thead>
<tr>
<th>Year</th>
<th>Period</th>
<th>Energy</th>
<th>Luminosity</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>Run 1</td>
<td>7-8 TeV</td>
<td>$0.7 \times 10^{34}$ ($\mu=20$), 25 fb$^{-1}$</td>
<td>LS1</td>
</tr>
<tr>
<td>2015</td>
<td>Run 2</td>
<td>13-14 TeV</td>
<td>$1.6 \times 10^{34}$ ($\mu=43$), 150 fb$^{-1}$</td>
<td>LS2 Phase-I Install</td>
</tr>
<tr>
<td>2020</td>
<td>Run 3</td>
<td>14 TeV</td>
<td>$2-3 \times 10^{34}$ ($\mu=50-80$), 350 fb$^{-1}$</td>
<td>LS3 Phase-II Install</td>
</tr>
<tr>
<td>2025</td>
<td>Run 4</td>
<td>14 TeV</td>
<td>$5-7 \times 10^{34}$ ($\mu=140-200$), 3000 fb$^{-1}$</td>
<td>LS4</td>
</tr>
</tbody>
</table>

• The HL-LHC running starts in 2025 and continues beyond LS4 until 2035
Holding our breath for Run II of the LHC!

- **The HL-LHC running starts in 2025 and continues beyond LS4 until 2035**
Conclusions?

• Higgs discovered - YAY!
• Looks like the SM Higgs - Yay?
• Fine tuning not resolved - Umm...
• Meta stable Higgs - Uh oh...
• BSM models not ruled out - YAY!
Standard Model

Light Electromagnetism
Chemical Binding
Substance/Structure
Nucleon Binding

Protons and neutrons are fundamental particles.

Leptons: electron (0.511 MeV/c^2, -1, 1/2).

SU(2)_F for nucleon binding.
Origin of the SM

Quark model proposed
Higgs Mechanism proposed
Electroweak theory proposed

LHC Era

Jim Pivarsky, Texas A&M
Allowed Interactions

Standard Model Interactions
(Forces Mediated by Gauge Bosons)

- Z
  - X
  - X
  - X is any fermion in the Standard Model.

- γ
  - X
  - X
  - X is electrically charged.

- g
  - g
  - g
  - X is any quark.

- W
  - D
  - U
  - U is a up-type quark; D is a down-type quark.

- W
  - ν
  - L
  - L is a lepton and ν is the corresponding neutrino.

- W^+
  - W^-
  - X
  - X is a photon or Z-boson.

- W^+
  - W^-
  - X
  - X and Y are any two electroweak bosons such that charge is conserved.
Previous Searches

Tevatron Run II, $L_{\text{int}} \leq 9.7 \text{ fb}^{-1}$

1+2 b-Tagged Jets

- Data - Bkgd
- WZ
- ZZ
- Higgs Signal

$m_H = 125 \text{ GeV}/c^2$

$H > bb$

CDF Run II Preliminary

OS 0 Jets

$M_H = 160 \text{ GeV}/c^2$

$H > WW$
Little Higgs

\( f \gtrsim 50 \, v \)

\( v/f \)

\( \Lambda = \text{scale of new physics} \)

\( f = \text{vev of BSM model} \)

\( \Lambda \sim 4\pi \, f \)

Littlest Higgs

Simplest Little Higgs

Reuter & Tonini, arXiv:1212.5930
Trade-offs

Baroque-ness: measure of model complexity

Strangeness: measure of fine-tuning

from the Resonaances Blog
Trade-offs

Baroque-ness: measure of model complexity

Strangeness: measure of fine-tuning

Naturalness

from the Resonaances Blog
Baroque-ness: measure of model complexity

Strangeness: measure of fine-tuning

Naturalness

Occam’s Razor

Trade-offs from the Resonances Blog

June 2015

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