How and Why to go Beyond the Discovery of the Higgs Boson

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http://hep.uchicago.edu/~johnda/ComptonLectures.html
Lecture Outline

April 1st:   Newton’s dream & 20th Century Revolution
April 8th:  Mission Barely Possible: QM + SR
April 15th: The Standard Model
April 22nd: Importance of the Higgs
April 29th: Guest Lecture
May 6th:    The Cannon and the Camera
May 13th:   The Discovery of the Higgs Boson
May 20th:   Problems with the Standard Model
May 27th:   Memorial Day: No Lecture
June 3rd:   Going beyond the Higgs: What comes next?
Reminder: Last Week

Quantum Mechanics + Space-time leads us to expect:

Planck scale ~ weak scale ~ Hubble scale

We observe:

Planck scale ~ weak scale ~ Hubble scale

Current theory accounts for huge difference w/implausible cancellation.

*Need modifications QM or Space-time to avoid fine tuning*
Reminder: Last Week

Problems associated to each fundamental scale.

**Planck Scale:**
*What replaces spacetime?* ("Quantum Gravity")

**Weak Scale:**
*Why is Gravity so weak?* ("Hierarchy Problem")

**Hubble Scale:**
*Why is the universe so big?* ("Cosmological Constant Problem")

Current theory accounts for huge difference w/implausible cancellation
*Need modifications QM or Space-time to avoid fine tuning*
Today’s Lecture

Going beyond the Higgs Discovery:

What comes next?
Focus: Problem associated w/weak scale

(Standard Model (Before Higgs Discovery))

Failure WW scattering

~unexplored

LHC Directly Probed Experimentally

Standard Model (After Higgs Discovery)

Most tractable now:
- Currently directly probing this scale with the LHC
- Understand the physics at this scale incredibly well

Working theory thats been verified experimentally

- $10^{-20}$ GeV$^{-1}$
  \(10^{-36} \text{ m}\)

- $10^{-3}$ GeV$^{-1}$
  \(10^{-19} \text{ m}\)

- $10^{41}$ GeV$^{-1}$
  \(10^{25} \text{ m}\)

Planck scale
\(\sqrt{G_N}\)

weak scale
observable universe
Focus: Problem associated w/weak scale

Reminder: Vacuum fluctuations of Higgs mass \( (m_H^2) \)

Top

\[ h \quad \sim \Lambda^2 \Rightarrow m_H \sim 10^{20} \text{ GeV} \]

Very different type problem than we discussed before: "Naturalness" Problem:
- Theory is fully logically consistent
- Need bizarre (un-natural) choice of input parameters

Un-like situation before Higgs where theory broke down

\[ P(\omega\omega \rightarrow \omega\omega) > 1 / \text{Inconsistent mass description} \]
What scale do we need Modification?

\[ mH^2 = \square + \square \]

\[ \sim (\text{weak-scale})^2 \quad mH^2_{\text{Classical}} \sim \Lambda^2 \]

Can avoid need for fine tuning only if \( \Lambda \sim \text{weak-scale} \).

Need changes to stop vacuum fluctuations below: \( 10^{-3} \text{ GeV}^{-1} \)

\( (10^{-19} \text{ m}) \)

\( mX \sim 1000 \text{ GeV} \)

\( \text{new particle} \)

\( \text{(Pencil metaphor: analogous to the pencil glue/string)} \)
Naturalness Problems in History

Same type of problems have occurred before in history of physics

Same types of arguments for scale of new physics worked

**Example:** Energy stored in the electric field around electron

\[ E \sim \frac{\alpha}{r} \sim \frac{\alpha}{\Lambda} \]

*Naively seems infinite*

Energy of electron at rest: \( \sim m_e \)

Introduce cut off

Need \( \Lambda \geq \alpha/E \) to avoid fine tuning
Naturalness Problems in History

Same type of problems have occurred before in history of physics. Some types of arguments for scale of new physics worked.

Naturalness requires new physics kick in $\Lambda \geq \alpha/m_e$

Picture of point like electron must break down at this scale

Solution was Anti-particles:
- Direct result of extension of Space-time (adding QM)
- Doubled the number of particles in the theory

Exactly what happens!

At scale $\Lambda \sim 1/m_e$ start seeing particle-anti-particle cloud
Potential Solutions

"Compositeness" Higgs made of smaller particles
Weak scale not fundamental / Similar to size of the proton
New underlying physics responsible for Higgs/Higgs potential
⇒ New forces / New matter

Extra dimensions
Planck scale is really at the weak scale
Gravity appears weak b/c gravitons can propagate in extra dim.

Supersymmetry
Vacuum corrections suppressed below weak scale

Go through example of how works in detail
Has been a favorite within the field
**Super Symmetry**

Modification of Space-time

**Distance measured in “quantum” numbers:**

\[ x \times y = -y \times x \]

\[ \Rightarrow x^2 = 0 \]

Can only take one step

**Doubles number of particles:**
- Standard Model particles
- Super-partners w/step in extra dimension

Measured in normal numbers

\[ x \times y = y \times x \]

All regular rules of QFT apply / Symmetry relating particles/Super particles
Super Symmetry

Modification of Space-time

Distance measured in “quantum” numbers:

\[ x \times y = - y \times x \]

\[ \Rightarrow x^2 = 0 \]

Can only take one step

- Haven't seen super-partners
- Could be another example of long-distance illusion:
  
  **eg: difference between forces**

- Idea: going to short enough distances start seeing symmetry
- To avoid fine-tuning needs to happen around weak scale

All regular rules of QFT apply / Symmetry relating particles/Super particles
How Does This Help?

\[ m_{H^2} \approx \text{m}_{H^2_{\text{Classical}}} + \ldots \]

\[ \sim (\text{weak-scale})^2 \]

\[ \sim (\text{weak-scale})^2 \]

\[ \text{SM particle} \]

\[ \text{Super-particle} \]
Super Symmetry at the LHC

Quantum Dimension

Super-top

proton → ~t

Super-top

proton → ~t

“Super-photon”
- Massive
- Stable
- Weakly interacting

Perfect candidate for Dark Matter
Interaction Strengths

\[ e \xrightarrow{\gamma} e \quad \alpha = 1/137 \]

\[ e \xrightarrow{Z} e \quad \alpha_{\text{Weak}} = 1/50 \]

\[ q \xrightarrow{\text{gluon}} q \quad \alpha_{\text{Strong}} = 1/10 \]

**Did not have to happen!**
- Not put in by hand
- Could be coincidence
- Seems like strong sign we are the right track
Searching For Solutions at the LHC
Higgs as Window to New Physics

Higgs boson directly related to the Higgs field.
Problem fundamentally related to Higgs field.
Higgs Boson is the harbinger of the Higgs field (how we study it).

Compositeness:
- Deeper origin for shape of potential
  (probe experimentally with $hh$ events)

Extra Dimensions:

SuperSymmetry:
- New particle(s)
Reconstructed the event from the observed b-jets
- Work backward from $4b \rightarrow 2h \rightarrow G$
- Study the “reconstructed” graviton mass
**Enhanced Higgs Production**

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### Signal

- **ATLAS Preliminary**
  - $\sqrt{s} = 13$ TeV, 2016, 10.1 fb$^{-1}$
  - Signal Region: Resolved

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- **Data**
- **Multijet**
- **$t\bar{t}$**
- **$G(300) \times 10$**
- **$G(800) \times 10$**
- **SM $hh \times 500$**
- **Stat+Syst Uncertainty**

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![Graph](image_url)

---

**Figure 5**: Distributions of $m_{4j}$ in the signal region of the resolved analysis for (a) 2015 data and (b) 2016 data, compared to the predicted backgrounds. The hatched bands shown in the data/background ratio in the bottom panels represent the combined statistical and systematic uncertainties in the total background estimates. The expected signal distributions for SM non-resonant $hh$ production and $G_{KK}$ resonances with masses of 300 and 800 GeV are also shown.

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1st August 2016 – 13:47 14
Expect contributions from new physics to correct higgs mass:

If new physics interacts with the **electro-magnetic**:

- **Strong force**:
  - Modifies rate at which higgs bosons decay to photons.
  - Modifies rate at which higgs bosons are produced at LHC.

Modified Higgs Couplings
Expect contributions from new physics to correct higgs mass:

If new physics interacts with the electromagnetic:

- Modifies rate at which higgs bosons are produced at LHC
- Modifies rate at which higgs bosons decay to photons.

Modified Higgs Couplings

**Why detailed Higgs measurements are so important:**

![Diagram showing modified Higgs couplings and contour plots for ATLAS and CMS.](image-url)
Modified Higgs Couplings

Expect contributions from new physics to correct higgs mass:

Higgs interaction:

by construction, cannot avoid:

One of the reasons Di-Higgs is so important

Modifies Di-Higgs production
Measuring Higgs Potential

Energy of Higgs field: \textit{Higgs potential}

\[ V(\phi) = -\mu^2 \phi^2 + \lambda \phi^4 \]

Expanding about minimum: \( V(\phi) \to V(\nu + h) \)

\[ V = V_0 + \lambda \nu^2 h^2 + \lambda \nu h^3 + \frac{\lambda}{4} h^4 \]

\[ = V_0 + \frac{1}{2} m_h^2 h^2 + \frac{m_h^2}{2\nu^2} \nu h^3 + \frac{1}{4} \frac{m_h^2}{2\nu^2} h^4 \]

Higgs mass term

- Shape of potential gives relationship between \( \lambda_{hhh} \) and \( m_h, \nu \)
- Measuring \( \lambda_{hhh} \) important probes the shape of the Higgs potential
- \( hh \) production interesting because it measures \( \lambda_{hhh} \)

\[ \frac{\mu}{\sqrt{\lambda}} \equiv \nu \sim \text{weak scale} \]
Need much more data than we currently have to see $hh$

\[ V(\eta) = V(0) + \frac{1}{2} m^2 h^2 + \frac{1}{4} m^2 h^2 v^2 + \frac{1}{4} m^2 h^2 v^2 + \lambda h h h h \]

W bosons: 4 kHz

Top quarks: \(~10\) events/s

1 event/s

\(~4/\text{hour} \sim (1e-3 \text{ Hz})\)

Need much more data than we currently have to see $hh$

Standard Model Total Production Cross Section Measurements

**Status:** August 2016

<table>
<thead>
<tr>
<th>LHC pp</th>
<th>(\sqrt{s} = 7) TeV</th>
<th>Data</th>
<th>4.5 – 4.9 fb(^{-1})</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>LHC pp</td>
<td>(\sqrt{s} = 8) TeV</td>
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**Standard Model Total Production Cross Section Measurement**

SM $h$ production

\(~40\) fb

SM $hh$-production

\(~4/\text{hour} \sim (1e-3 \text{ Hz})\)
Outlook for the Future
What we might know by 2035…
Study of the spin of the Higgs-like particle in the $H \rightarrow \gamma \gamma$ channel with 20.7 fb$^0$ of $\sqrt{s} = 8$ TeV data collected with the ATLAS detector.

The ATLAS Collaboration

Abstract

Recently the ATLAS collaboration reported the observation of a new neutral particle in the search for the Standard Model Higgs boson. The measured production rate of the new particle is consistent with the Standard Model Higgs boson with a mass of about 125 GeV, but its other physics properties are unknown. Presently, the only constraint on the spin of this particle stems from the observed decay mode to two photons, which disfavors a spin-0 hypothesis. This note reports on the compatibility of the observed excess in the $H \rightarrow \gamma \gamma \rightarrow e^\nu \mu^\nu$ search arising from either a spin-0 or a spin-1.5 particle with positive charge-parity. Data collected in 2015 with the ATLAS detector favors a spin-0 signal, and results in the exclusion of a spin-1.5 signal at 95% confidence level if one assumes a $qg$ production fraction larger than 0.1 for a spin-1.5 particle, and at 90% confidence level if one assumes pure $gg$ production.

Future LHC Program

- 8 TeV
- 20/fb

Run I

- Get to 300/fb of 13-14 TeV data
- Up to 75 interactions per crossing

$\times 15$ increase in size of dataset

2010

Run II

- 2020

Run III

- 2026

Run IV

- 2030 →

- 3000/fb of 13-14 TeV data
- Pile-up of up to 150-200

$\times 150$ increase in dataset size

Now
Future LHC Program

25 Interactions

Run I
- Get to 300/ fb of 13-14 TeV data
- Up to 75 interactions per crossing

Run II
- 8 TeV
- 20/fb

Run III
- 10 increase in size of dataset

Run IV
- 3000/fb of 13-14 TeV data
- Pile-up of up to 150-200
- 8 TeV
- 20/fb

Future LHC Program

25 Interactions

Run I
- Get to 300/ fb of 13-14 TeV data
- Up to 75 interactions per crossing

Run II
- 8 TeV
- 20/fb

Run III
- 10 increase in size of dataset

Run IV
- 3000/fb of 13-14 TeV data
- Pile-up of up to 150-200
- 8 TeV
- 20/fb

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This note reports on the compatibility of the observed excess in the $H \rightarrow WW(\tau\tau)$ search arising from either a spin-9/2 or a spin-5/2 particle with positive charge and parity. Data collected in 2019 with the ATLAS detector favours a spin-9/2 signal, and results in the exclusion of a spin-5/2 signal at 95% confidence level if one assumes a $q\bar{q}$ production fraction larger than 0.01 for a spin-5/2 particle, and at 90% confidence level if one assumes pure $gg$ production.

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Future LHC Program

Future: 200 Interactions

Future LHC Simulation
Study of the spin of the Higgs-like particle in the $H \to WW(\tau\tau)$ channel with $20.7 \, \text{fb}^{-1}$ of $\sqrt{s} = 8$ TeV data collected with the ATLAS detector

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Higgs at the LHC

Uncertainty(%) on $\mu$ (Br)

Run I: ~30/fb / 7-8 TeV
Run II-II: ~300/fb / 13-14 TeV
Run IV: ~3000/fb / 13-14 TeV
Benchmark Coupling Constraints

Sensitivity tested in model with 7 parameters

4 fermion couplings:

\[ K_\tau / K_\mu / K_u \equiv K_t = K_c / K_d \equiv K_b \]

Allow for decays to new particles
Higgs at the LHC

Coupling modifications in “Generic” BSM models (M ~ 1 TeV / Satisfies EWK precision fits)

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<td>$\sim 1%$</td>
<td>$\sim 10%$</td>
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<td>$&lt; 1.5%$</td>
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<td>$\sim -(3 - 9)%$</td>
<td>$\sim -9%$</td>
</tr>
<tr>
<td>Top Partner</td>
<td>$\sim -2%$</td>
<td>$\sim -2%$</td>
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</tr>
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</table>

Run II-III: ~300 fb / 13-14 TeV
Run IV: ~3000 fb / 13-14 TeV

$\delta = 10\%$ deviation

For 10% deviation

2σ CL

5σ CL
Direct search for Super Symmetry

Super-Photon Mass [GeV]
Beyond the LHC

What we might know by 2055…
~100 km tunnel / Operate in two modes
1st-stage: collide electrons: $ee \rightarrow Zh$
2nd-stage: 100 TeV proton collider
Similar idea being pursued in China

Would Also operate in two modes

1st-stage: collide electrons: $ee \rightarrow Zh$

2nd-stage: 50 TeV proton collider

Could be faster time scale if approved
Beyond the LHC

Coupling modifications in “Generic” BSM models (M ~ 1 TeV / Satisfies EWK precision fits)

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For 10% deviation

2σ CL

5σ CL
The early Coleman-Weinberg proposal for symmetry breaking [17]:

$$V(h) = \frac{1}{2} m_h^2 h^2 + \frac{m_h^4}{12} h^4 + \cdots,$$

This possibility is associated with totally different underlying dynamics for electroweak symmetry breaking than the SM, requiring new physics beyond the Higgs around the weak scale. They also have radically different theoretical implications for naturalness, the hierarchy problem and the structure of quantum field theory.

Nature of EW phase transition:
Consider a model $Higgs +$ singlet

Simplest, but also hardest to discover.

Good testing case.

The leading difference between these possibilities shows up in the cubic Higgs self-coupling. In the SM, minimizing the potential gives

$$v^2 = \frac{2 |m_h|^2}{g 
u^2}.$$

Expanding around this minimum

$$h = \frac{v + \delta h}{\sqrt{2} v^2},$$

gives

$$V(H) = \frac{1}{2} m_H^2 H^2 + \frac{1}{6} h^3 h + \cdots,$$

with

$$m_H^2 = v^2 = \frac{2 |m_h|^2}{g 
u^2},$$

$$hhh = \frac{3}{m_H^2 / v^2}.$$

Consider the example with the quartic balancing against a sextic and, for the sake of simplicity to illustrate the point, let us take the limit where the $m_h^2$ term in the potential can be neglected. The potential is now minimized for

$$v^2 = \frac{2 |m_h|^2}{g 
u^2},$$

and we find

$$m_H^2 = v^2 = \frac{2 |m_h|^2}{g 
u^2},$$

$$hhh = \frac{7}{3} m_H^2 / v^2 = \frac{7}{3} \frac{2 |m_h|^2}{g 
u^2},$$

giving an $O(1)$ deviation in the cubic Higgs coupling relative to the SM. In the case with the non-analytic $(h^† h)^2 \log(h^† h)$ potential, the cubic self-coupling

$$hhh = \frac{5}{3} \frac{2 |m_h|^2}{g 
u^2}.$$
100 TeV proton collider

FIG. 5: Projected discovery potential [left] and exclusion limits [right] for 3000 fb

\[ \sqrt{s} = 100 \text{ TeV} \]
\[ \int L dt = 3000 \text{ fb}^{-1} \]
\[ \epsilon_{\text{sys,bkg}} = 20\% \]
\[ \epsilon_{\text{sys,sig}} = 20\% \]
Have only collected \(~1\%\) of total LHC dataset
Next 5-10 years incredibly unique/interesting time!

Bigger rings currently being planned

Thank You