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?
Study of the spin of the Higgs-like particle in the $H \to WW(\tau\tau)\to e\nu\mu\nu$ channel with 20.7 fb$^{-1}$ 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 126 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 disfavours a spin-0 hypothesis. This note reports on the compatibility of the observed excess in the $H \to WW(\tau\tau)\to e\nu\mu\nu$ search arising from either a spin-9 or a spin-\(-\frac{3}{2}\) particle with positive charge/parity. Data collected in 2019 with the ATLAS detector favours a spin-9 signal, and results in the exclusion of a spin-\(-\frac{3}{2}\) signal at 95\% confidence level if one assumes a production fraction larger than 0.1 for a spin-\(-\frac{3}{2}\) particle, and at 90\% confidence level if one assumes pure $gg$ production.

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The Basic Outputs:

- Inner Tracking System
- Electro-Magnetic Calorimeter
- Hadronic Calorimeter
- Muon Tracking System

A lot of work goes into making/understanding these basic outputs.
What do we know about the Higgs Particle: \textbf{A Lot}

Higgs is excitations of $\nu$-condensate
$\Rightarrow$ Couples to matter / W/Z just like $\nu$

Spin: \hspace{1cm} 0 \hspace{1cm} 1/2 \hspace{1cm} 1 \hspace{1cm} 3/2 \hspace{1cm} 2

Only thing we don’t \textit{(didn’t!)} know is the value of $m_H$
Today’s Lecture

The Discovery of the Higgs Boson
How to Make Higgs Bosons?

Collide Protons! (Really Quarks/gluons)

Higgs interactions (couplings) matter known:

\text{matter} \ (e \ μ \ τ \ q) \ \sim \ \text{(mass of matter)} \quad \text{W/Z} \quad \sim \ \text{(mass of W or Z)}
How to Make Higgs Bosons?

Collide Protons!

Really Quarks / Gluons

Higgs interactions (couplings) matter known:

\[
\text{matter} \approx \text{(mass of matter)}
\]

\[
\text{W/Z} \approx \text{(mass of W or Z)}
\]

Top quark / W / Z are heaviest things in theory

Have the highest probability of producing Higgs

⇒ small of a coupling to Higgs

⇒ small of a probability to produce Higgs
How to Make Higgs Bosons

We really want to use processes like:

- **Gluon-fusion**
- **Vector-Bosons Fusion**

This is why the higgs was so hard to find!
- Couples very weakly to particles we have lying around
- Need to first create pair of (unstable!) massive particles
- These then interact to form a Higgs

Problem is we don’t have Top/W/Z colliders
⇒ *Have to make tops and W/Z from protons first*
Where to look for the Higgs Boson?

Mass constraints pre-LHC

$50 < m_H < 150 \text{ GeV} \quad (95\%)$

$m_H > 115 \text{ GeV}$

Limits from direct search Large Electron-Positron collider (LEP)

$50 < m_H < 150 \text{ GeV} \quad (95\%)$

$m_H > 115 \text{ GeV}$
How to look for the Higgs Boson?

Higgs Boson quickly decays to other particles.
- Basic Higgs interactions control how the Higgs can decay
- Fraction of decays to particular particle is: *Branching Ratio*

\[
\text{Branching Ratio} = \sum_i \left( \frac{h}{i} \right) \quad \text{(for particle P)}
\]

Higgs wants to decay to heaviest particle around \(m_x < m_H/2\)
How to look for the Higgs Boson?

Higgs Boson quickly decays:
- Basic Higgs interactions
- Fraction of decays to particular particle is: Branching Ratio.

\[ \text{Branching Ratio} = \frac{\text{mass of particle } P}{\text{mass of higgs boson}} \]

\[ m_\gamma/m_g = 0 \text{ but } h \to \gamma\gamma/gg \text{ through loops} \]

Higgs wants to decay to heaviest particle around (provided: \( m_X < m_H/2 \))
Higgs decays

- $H \rightarrow bb$: $\sim 60\%$
- $H \rightarrow WW$: $\sim 20\%$
- $H \rightarrow ZZ$: $\sim 2\%$
- $H \rightarrow \tau\tau$: $\sim 5\%$
- $H \rightarrow jj$: $\sim 10\%$
- $H \rightarrow \gamma\gamma$: $0.2\%$

**Hopeless:**
- Too much background
- Can’t Trigger
- in $gg \rightarrow h$
- VBF hard, doable.
- Not used discovery

Higgs search focused on these three signatures.
How much data do we need?

Estimate out how often we make a Higgs.

Warm-up: *How often do we make a W/Z?*

\[
\sigma_{W/Z} \sim \frac{\alpha_W}{(m_{W/Z})^2} \sim \left( \frac{1}{50} \right) \left( \frac{1}{100} \right)^2 \text{ GeV}^{-2}
\]

\[
\sim 2 \cdot 10^{-6} \text{ GeV}^{-2}
\]

\[
\sigma_{pp} \sim \text{GeV}^{-2} \Rightarrow 1 \text{ W/Z for every 1 million proton collisions}
\]
How much data do we need?

First estimate out how often we make a Higgs.

Same game for the Higgs

\[
\sigma_H \sim \frac{1}{16\pi^2} \frac{\alpha_S^2 \alpha_W}{(m_H)^2} \sim \frac{1}{160} \left( \frac{1}{10} \right)^2 \left( \frac{1}{50} \right) \left( \frac{1}{100} \right)^2 \text{GeV}^{-2}
\]

\[
\sim 1 \cdot 10^{-10} \text{ GeV}^{-2}
\]

\[
\sigma_{pp} \sim \text{GeV}^{-2} \Rightarrow 1 \text{ Higgs for every billion proton collisions}
\]

**Good target:**

\[
\sim 100 \frac{h \rightarrow \gamma\gamma}{\text{year}} \sim 10^5 \frac{h}{\text{year} \epsilon \cdot 10^7 \text{s}} \sim 1 \frac{h}{\text{second}}
\]

\[
\Rightarrow \text{need billion proton collisions per second}
\]

*Only have beams crossing 40 million times per second ... \Rightarrow Need \sim 25 \text{ proton collisions per crossing}!\]
Higgs Discovery
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 126 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 $H \rightarrow WW^{\ast} \rightarrow e\mu$ search arising from either a spin-0 or a spin-1/2 particle with positive charge and parity. Data collected in 2010 with the ATLAS detector favors a spin-0 signal and results in the exclusion of a spin-1/2 signal at 95% confidence level if one assumes a $q\bar{q}$ production fraction larger than 0.5 for a spin-1/2 particle, and at 90% confidence level if one assumes pure $gg$ production.
Study of the spin of the Higgs-like particle in the $H \rightarrow WW^{(*)} \rightarrow e^+e^-\mu^+\mu^-$ channel with 20.7 fb$^0$ of $\sqrt{s} = 8$ TeV data collected with the ATLAS detector.

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 0.4 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 disfavours a spin-0 hypothesis. This note reports on the compatibility of the observed excess in the $H \rightarrow WW^{(*)}$ search arising from either a spin-0 or a spin-1/2 particle with positive charge and parity. Data collected in 2019 with the ATLAS detector favours a spin-0 signal, and results in the exclusion of a spin-1/2 signal at 95% confidence level if one assumes a production fraction larger than 0.05 for a spin-1/2 particle, and at 90% confidence level if one assumes pure $gg$ production.
Study of the spin of the Higgs-like particle in the channel with 20.7 fb

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\[ \nu \nu WW^\tau \rightarrow e^\tau \nu \nu \]

assumes pure production fraction larger than the spin of a particle and at 90% confidence level if one results in the exclusion of a spin signal at 90% confidence level if one assumes a charge-parity Data collected in 2010 with the ATLAS detector favours a spin signal. This note reports on the compatibility of the observed excess in the spin of this particle stems from the observed decay mode to two photons which disfavoursGeV but its other physics properties are unknown. Presently, the only constraint on the new particle is consistent with the Standard Model Higgs boson with a mass of about 125 GeV. The measured production rate of the Higgs to WW channel with 20.7 fb recently the ATLAS collaboration reported the observation of a new neutral particle gg + \rightarrow \nu \nu WW^\tau\rightarrow e^\tau \nu \nu \] which disfavours the SM Higgs boson. The expected excess of events over the predicted background is seen. The observed excess is consistent with the backgrounds along with the corresponding signal distribution with leptons and the measured momentum imbalance. The data is shown after subtracting the estimated events. The ATLAS Collaboration

Abstract

The results are interpreted statistically as described above. The dominant backgrounds are continuum background estimation.

The electrons are shown in yellow and correspond to localized high energy deposits in the calorimeter matched to tracks in the inner detector. Under the SM Higgs boson hypothesis the electrons are shown in yellow and correspond to localized high energy deposits in the calorimeter matched to tracks in the inner detector, indicated by the red and orange lines. The dashed line, label and correspond to localized high energy deposits in the calorimeter matched to tracks in the inner detector. Figure 1(b) shows the best estimate of the Higgs mass for selected events using the observed background estimation. The hatched area indicates the systematic uncertainty. The red histogram indicates the predicted background estimation.

The measured momentum imbalance \( E_T^{miss} \) in the plane \( x-y \) is only defined in the calorimeters and the direction of the beam line. The upper right panel shows the projection of the detector along the horizontal and vertical coordinates; as \( \delta \) is arbitrarily placed at the farthest longitudinal position. Figure 2 shows the electron and muon candidates in the 8 TeV data set. The electron candidates are shown in yellow and correspond to localized high energy deposits in the calorimeter matched to tracks in the inner detector, indicated by the red and orange lines. The dashed line, label and correspond to localized high energy deposits in the calorimeter matched to tracks in the inner detector. Under the SM Higgs boson hypothesis the electrons are shown in yellow and correspond to localized high energy deposits in the calorimeter matched to tracks in the inner detector. Under the SM Higgs boson hypothesis the electrons are shown in yellow and correspond to localized high energy deposits in the calorimeter matched to tracks in the inner detector. Under the SM Higgs boson hypothesis the electrons are shown in yellow and correspond to localized high energy deposits in the calorimeter matched to tracks in the inner detector.
Putting It All Together

Triumph of Humanity!

Signal Strength $\mu = \sigma/\sigma_{MC}$
Higgs Post-Discovery

What We Know and Where We are Going
Current Status

\[
\begin{align*}
&\int L dt = 5 \text{ fb}^{-1}, \sqrt{s} = 7 \text{ TeV} \\
&\int L dt = 9.3 \text{ fb}^{-1}, \sqrt{s} = 8 \text{ TeV} \\
&\text{S/B weighted sum} \\
&\text{Signal strength categories}
\end{align*}
\]

**H→γγ**

\[
\begin{align*}
&\sqrt{s} = 7 \text{ TeV}, \int L dt = 4.8 \text{ fb}^{-1} \\
&\sqrt{s} = 8 \text{ TeV}, \int L dt = 5.8 \text{ fb}^{-1}
\end{align*}
\]

**ATLAS**

\[
\begin{align*}
&\sqrt{s} = 7 \text{ TeV}, \int L dt = 4.6 \text{ fb}^{-1} \\
&\sqrt{s} = 8 \text{ TeV}, \int L dt = 20.7 \text{ fb}^{-1}
\end{align*}
\]

**Now**

\[
\begin{align*}
&m_H = 125 \text{ GeV} \\
&H→WW^*→l\nu l\nu + 0/1 \text{ jets}
\end{align*}
\]

**ATLAS**

\[
\begin{align*}
&\sqrt{s} = 7 \text{ TeV}, \int L dt = 4.8 \text{ fb}^{-1} \\
&\sqrt{s} = 8 \text{ TeV}, \int L dt = 5.8 \text{ fb}^{-1}
\end{align*}
\]

**Then**

\[
\begin{align*}
&\sqrt{s} = 7 \text{ TeV}, \int L dt = 4.8 \text{ fb}^{-1} \\
&\sqrt{s} = 8 \text{ TeV}, \int L dt = 5.8 \text{ fb}^{-1}
\end{align*}
\]
Study of the spin of the Higgs-like particle in the $H \rightarrow WW (\gamma \gamma)$ channel with 20.7 fb$^{-1}$ of data collected with the ATLAS detector.

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 0.125 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 $H \rightarrow WW (\gamma \gamma)$ search arising from either a spin-1 or a spin-0 particle with positive charge and parity. Data collected in 2015 with the ATLAS detector favors a spin-1 signal and results in the exclusion of a spin-0 signal at 95% confidence level if one assumes a production fraction larger than 0.05 for a spin-0 particle, and at 90% confidence level if one assumes pure $gg$ production.

Higgs Program Beyond Discovery

Establish signals in harder channels:
- $h \rightarrow \tau \tau$ (done)
- Direct $h \rightarrow tt$ (close)
- $h \rightarrow bb$ (close)

Compare measured/predicted interaction strengths
- Study production cross sections and branching ratios

Measure Spin of new particle

Search for un-predicted decays

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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 → WW → e⌫µ⌫ search arising from either a spin-3/2 or a spin-5/2 particle with positive charge and parity. Data collected in 2016 with the ATLAS detector favors a spin-3/2 signal and results in the exclusion of a spin-5/2 signal at 95% confidence level if one assumes a production fraction larger than 0.1 for a spin-5/2 particle, and at 90% confidence level if one assumes pure ggF + ttH production.

Results: Production Cross Section

[Diagram showing the compatibility of the observed excess in the H → WW → e⌫µ⌫ search with either a spin-3/2 or a spin-5/2 particle.]
Results: Interaction Strengths

\[ \text{Interaction Strength} \]

\[ \log_{10}(\text{Interaction Strength}) ] \]

\[ \text{Particle mass [GeV]} \]

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

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

\[ \text{ATLAS} \]

\[ \text{Observed} \]

\[ \text{SM Expected} \]

\[ \mu, \tau, b, Z, W, t \]

\[ \text{m} \]

\[ \text{W/Z} \]

\[ \sim \text{mass} \]

\[ h \]

\[ \sim \text{mass} \]

\[ h \]

\[ \text{m} \]

\[ \text{W/Z} \]
Results: Spin

- Massive Spin 1 resonance cannot decay to $\gamma\gamma$ (QM+Relativity)
- Use decay angle to separate spin 0 and 2

$H \rightarrow WW \rightarrow e\nu\mu\nu$

**Spin-0**

**Spin-2**

![Graph showing distributions of $\Delta\phi$ for Spin 0 and Spin 2]

**ATLAS** Preliminary
Simulation, $\sqrt{s} = 8$ TeV
$H \rightarrow WW(\gamma) \rightarrow e\mu/\mu e + 0$ jets

- $H^0$ [125]
- $H^2$ [125]

Spin 0+
Spin 2+ (graviton-like)
Compatibility w/SM Higgs Couplings

Current statistics allow a limited number of tests of data w.r.t expectation.

In practice introduce coupling modifiers “κ”, where κ = 1 is SM.

Examples:

Test against few specific benchmark scenarios.
Compatibility w/SM Higgs Couplings

Test for differences in boson and fermion couplings: assume \((\kappa_w = \kappa_z)\)

Assume:
- no decays to unknown particles
Compatibility w/SM Higgs Couplings

Test loops diagrams

Assume:
- $\kappa_F = \kappa_V = 1$
- no decays to unknown particles
Compatibility w/SM Higgs Couplings

Test loops diagrams and unknown decays

Allow decays to unknown particles

Assume:
- $\kappa_F = \kappa_V = 1$
What we don’t know

- If established couplings modified at level of ≤ 20%
- If Higgs decays in unexpected way ≤ 30% of the time
- Lots of un-observed interactions

Leptons: 
(\(v_e\)) (\(v_\mu\)) (\(v_\tau\))
\(e\) \(\mu\) \(\tau\)
\(\gamma\) \(W\) \(Z\)
Quarks:
(\(u\)) (\(d\)) (\(c\)) (\(s\)) (\(t\)) (\(b\))
\(u\) \(d\) \(c\) \(s\) \(t\) \(b\)

d - Very important unobserved interaction: \(H\)

\textit{Higgs self-interaction:}
Measure Potential with $hh$

Energy of Higgs field: *Higgs potential*

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

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

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

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

- 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 $\lambda_{hhh}$

\[ \frac{\mu}{\sqrt{\lambda}} \equiv \nu \quad 246 \text{ GeV} \]

- Higgs mass term
- $hh$-production
- $hhh$-production

Standard Model:

\[ \lambda_{hhh} = \frac{m_h^2}{2\nu^2} \]
SM $hh$ Production at the LHC

Small in Standard Model
- Leading $hh$ diagrams higher order in series (have extra vertices)
- 2 heavy particles (fraction of proton energy needed larger)
- Two diagrams with relative minus sign

Production Diagrams:
SM $hh$ production at the LHC

SM $hh$ sensitivity interesting only w/full LHC dataset (more on this later)

W bosons: 4 kHz

top quarks: $\sim$10 events/s

1 event/s

$\times \sim$1000

$\sim$40 fb

$\sim$4/hour $\sim$ (1e-3 Hz)
Rich set of final states.

Larger Br-$h$ decay

Rarer Br-$h$ decay
Di-Higgs

Ultimate goal in the program to measure the Higgs
- Direct probe of shape of Higgs potential
- Deep connections w/fundamental problems associated to the Higgs boson.

*Pick up here next time.*