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: The Standard Model

Description fundamental constituents of Universe and their interactions
Triumph of the 20th century
Quantum Field Theory: Combines principles of Q.M. & Relativity

Constituents (Matter Particles)

Leptons: \[
\begin{pmatrix}
\nu_e \\
e
\end{pmatrix},
\begin{pmatrix}
\nu_\mu \\
\mu
\end{pmatrix},
\begin{pmatrix}
\nu_\tau \\
\tau
\end{pmatrix}
\]

Quarks: \[
\begin{pmatrix}
u \\
u
\end{pmatrix},
\begin{pmatrix}
\nu_\tau \\
\tau
\end{pmatrix}
\]

Interactions Dictated by principles of symmetry

QFT \Rightarrow Particle associated w/each interaction (Force Carriers)

\[\gamma, W, Z, g\]
## Reminder: The Standard Model

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### Constituents (Matter Particles)

<table>
<thead>
<tr>
<th>Leptons:</th>
<th>Quarks:</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \nu_e )</td>
<td>( u )</td>
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<tr>
<td>( \nu_\mu )</td>
<td>( c )</td>
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<tr>
<td>( \nu_\tau )</td>
<td>( t )</td>
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<tr>
<td>( e )</td>
<td>( d )</td>
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<tr>
<td>( \mu )</td>
<td>( s )</td>
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<tr>
<td>( \tau )</td>
<td>( b )</td>
</tr>
</tbody>
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### Interactions

Dictated by principles of symmetry

QFT ⇒ Particle associated w/each interaction (Force Carriers)

### Consistent theory of electromagnetic, weak and strong forces ...

... provided **massless** Matter and **Force Carriers**
Reminder: \textit{The Standard Model}

Description fundamental constituents of Universe and their interactions
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\textbf{Constituents} (\textit{Matter Particles})

Leptons: \( \begin{pmatrix} \nu_e \\ e \end{pmatrix}, \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}, \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix} \)

Quarks: \( \begin{pmatrix} u \\ d \end{pmatrix}, \begin{pmatrix} c \\ s \end{pmatrix}, \begin{pmatrix} t \\ b \end{pmatrix} \)

\textbf{Spin} = 1/2

\textbf{Interactions} Dictated by principles of symmetry

QFT \( \Rightarrow \) Particle associated w/each interaction (\textit{Force Carriers})

\( \gamma, W, Z, g \)

\textbf{Spin} = 1

Consistent theory of electromagnetic, weak and strong forces ...
... provided \textbf{massless} Matter and \textit{Force Carriers}

\textit{Serious problem: matter and W, Z carriers have Mass}!
New field (Higgs Field) added to the theory
Allows massive particles while preserve mathematical consistency
Works using trick: “Spontaneously Symmetry Breaking”

Ground state (vacuum of Universe) filled will Higgs field
Leads to particle masses: Energy cost to displace Higgs Field / $E=mc^2$
Additional particle predicted by the theory:
Generally Expected / Needed for Logical Consistency!

Higgs boson: $H$  Spin = 0
What do we know about the Higgs Particle: **A Lot**

Higgs is excitations of v-condensate

⇒ Couples to matter / W/Z just like v

Higgs

\[ h \]

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

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

**Spin:**

\[ 0 \quad 1/2 \quad 1 \quad 3/2 \quad 2 \]

Only thing we don’t (**didn’t**) know is the value of mH
History of Prediction and Discovery

Late 60s: Standard Model takes modern form. Predicts massive W/Z bosons
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1983: W/Z discovered at CERN:

\[
\begin{array}{c}
\text{u} \\
\text{Z} \\
\text{u}
\end{array} \quad \begin{array}{c}
\text{e} \\
\text{d} \\
\text{e}
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\text{u} \\
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2000s: W/top quark and used to predict the Higgs.
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50 < mH < 150 GeV (95%)
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Now introduced basic theory.
Switch gears discuss what it takes to test it.

50 < mH < 150 GeV (95%)
Today’s Lecture

The Cannon and the Camera
Particle Physics for 3rd Graders
Everything

Molecules

Atoms

No Body Knows

Quarks

Protons

Protons

Atoms

Molecules

Everything

No Body Knows

Quarks

Protons
What's in the Lunch Box?
What’s in the Lunch Box?

Look inside.

No Fun!
What’s in the Lunch Box?

SMASH THEM!!!

Bang!
What's in the Lunch Box?

Bang!
What’s in the Proton?

Protons are Too small to look inside.
What’s in the Proton?

Protons are too small to look inside.

SMASH THEM!!!
The World's Biggest Cannon

Philadelphia

CERN
Switzerland/France
The World's Biggest Cannon
The World's Biggest Cannon
The World's Biggest Cannon
Really Big Camera!!!
Really Big Camera!!!
Really Big Camera!!!
Really Big Camera!!!
Figure 3.2: Event display of a $t\bar{t}$ di-lepton candidate in the $e\mu$-channel with two b-tagged jets. The electron is shown by the green track pointing to a calorimeter cluster, the muon by the long red track intersecting the muon chambers, and the $E_{\text{miss}}$ direction is indicated by the blue dotted line in the $x$-$y$ view. The secondary vertices of the two b-tagged jets are indicated by the orange ellipses in the upper right.
3rd Grade Explanation is Essentially Correct

Some Caveats:
- More sophisticated analog to “what are quarks made of?”
- What comes out of the lunch box is there to begin with…
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However, basic concepts/methods something that anyone understands

One of the great things about this business!
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One of the great things about this business!

Rest of lecture:
- Refine basic notions of camera and cannon
- Discuss challenges in collecting/analyzing pictures
- Talk about how we use picture to test SM
The ATLAS Experiment

Figure 3.1: Cutaway view of the ATLAS detector

Signed to measure the energy of electrons, photons, and hadrons. They are sensitive to both charged and neutral particles.

The Muon Spectrometer (MS) surrounds the calorimeters. All particles except muons and neutrinos are stopped by the calorimeter system. The MS is designed to measure the trajectories of muons leaving the calorimeter. The MS is composed of muon chambers operating in a magnetic field provided by the toroid magnets.

A common coordinate system is used throughout ATLAS. The interaction point is defined as the origin of the coordinate system. The z-w axis runs along the beam line. The x-w plane is perpendicular to the beam line and is referred to as the transverse plane. The positive x-w axis points from the interaction point to the center of the LHC ring; the positive y-w axis points upward to the surface of the earth. The detector half at positive z-w values is referred to as the "A" side; the other half the "C" side. The transverse plane is often described in terms of r*w* coordinates. The azimuthal angle w* is measured from the x-w axis, around the beam. The radial dimension r*v measures the distance from the beam line. The polar angle v* is defined as the angle from the positive z-w axis. The polar angle is often reported in terms of pseudorapidity, defined as \( \eta = \ln \tan \frac{v}{2} \). The distance R is defined.
ATLAS NOTE

February 03, 2019

Study of the spin of the Higgs-like particle in the $\mathcal{H} \to WW^\ast \to e\nu\mu\nu$ 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 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 disfavours a spin-0 hypothesis. This note reports on the compatibility of the observed excess in the $\mathcal{H} \to WW^\ast \to e\nu\mu\nu$ search arising from either a spin-1/2 or a spin-3/2 particle with positive charge/parity. Data collected in 2018 with the ATLAS detector favours a spin-1/2 signal and results in the exclusion of a spin-3/2 signal at 95% confidence level if one assumes a $q\bar{q}$ production fraction larger than 0.1 for a spin-3/2 particle, and at 90% confidence level if one assumes pure $gg$ production.

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.
\( \nu_e \nu_\mu \nu_\tau \ u \ c \ t \ e \ \mu \ \tau \ d \ s \ b \)
$\nu_e$, $\nu_\mu$, $\nu_\tau$, $u$, $c$, $t$

e, $\mu$, $\tau$, $d$, $s$, $b$
$\nu_e \quad \nu_\mu \quad \nu_\tau$
\( \nu_e \quad \nu_{\mu} \quad \nu_{\tau} \)

e
\( \mu \)
\( \tau \)

u
\( c \)

\( d \)
\( s \)

b
\[ v_e \quad v_\mu \quad v_\tau \]

\[ u \quad c \quad t \]

\[ d \quad s \quad b \]
Higgs decays

\[ H \rightarrow bb: \sim 60\% \]

\[ H \rightarrow WW: \sim 20\% \]

\[ H \rightarrow \tau\tau: \sim 5\% \]

\[ H \rightarrow ZZ: \sim 2\% \]

\[ H \rightarrow \gamma\gamma: 0.2\% \]
3. Reconstruction and Commissioning

Figure 3.2: Event display of a $t\bar{t}$ di-lepton candidate in the $e\mu$-channel with two b-tagged jets. The electron is shown by the green track pointing to a calorimeter cluster, the muon by the long red track intersecting the muon chambers, and the $E_{\text{miss}}$ direction is indicated by the blue dotted line in the x-y view. The secondary vertices of the two b-tagged jets are indicated by the orange ellipses in the upper right.
Experimental Challenges
b-jet Identification (*b*-Tagging)

Critical as b-jet ubiquitous in Higgs final states.
b-jet Identification (b-Tagging)

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- b-lifetimes \(\sim\) pico-seconds
- Typical speed (time dilation) \(\Rightarrow\) travel \(O(mm)\)
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Drives specs. on detector resolution

*Must know detector positions to \(\sim\mu m\)*
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- b-lifetimes \(~\text{pico-seconds}\)
- Typical speed (time dilation)
  \(\Rightarrow\) travel \(O(mm)\)

Drives specs. on detector resolution
\((\text{Must know detector positions to } \sim \mu m)\)

Detectors size apartment buildings, measure to accuracy of something barely visible to human eye.

Major cost driver
Triggering

- LHC provides orders of magnitude more collisions than can save to disk
- Interesting physics is incredibly rare.
Triggering

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  - Can only keep 1 out of 40,000 events / Discarded data lost forever
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  ~1 Higgs per billion events
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Process of selecting which collisions to save for further analysis.
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**Triggering:**
Process of selecting which collisions to save for further analysis.

**Triggering in ATLAS:**
- Custom Electronics + Commodity CPU
- Fast processing of images (micro-seconds / seconds)
- Events rate from 40 MHz \(\rightarrow\) 1kHz.
- Data rate from 80 TBs (!) \(\rightarrow\) 2 GB/s
Triggering

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*Another major cost driver*
The Cannon

Most of the time protons miss one another
  Cant aim with enough precision to ensure a direct hit each time
Need to collide bunches of tightly packed protons to ensure hit
  LHC: 10^{11} protons per bunch
The Cannon

Most of the time protons miss one another
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Can in principle be calculated by the theory
In practice, calculations extremely hard ($\alpha$ so big)
So extract from measurements in data
What We Measure

Probability for process to happen given in terms of an area: *Cross-section*
What We Measure

Probability for process to happen given in terms of an area: \textit{Cross-section}

Event Rate $= \text{Cross-Section} \times \text{Particle Flux}$

Rate certain pictures
(Directly measured)
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Known input from LHC Protons /area / time
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- Infer “Cross Section”
  Units: area / Probability
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Cross-Section \( (\sigma) \) can be calculated from theory

\[
\sigma \sim \int |\psi(x_1, x_2)|^2 f(x_1) f(x_2)
\]
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Cross-Section ($\sigma$) can be calculated from theory

$$ \sigma \sim \int |\psi(x_1, x_2)|^2 f(x_1) f(x_2) $$

$$ \psi = \sqrt{\alpha} + \sqrt{\alpha} + ... $$

Feynman Diagrams: Pictures of what happens
Invaluable Tool for calculation

Theory give prescription for assigning numerical value to diagram.

Other rules associated to the lines / Sum overall possible configurations

- Sum of diagrams (# associated with diagrams) is
- Really infinite sum. In practice, only the first few terms dominate
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Cross-Section (\(\sigma\)) can be calculated from theory

\[ \sigma \sim \int |\psi(x_1, x_2)|^2 f(x_1)f(x_2) \]

\[ \psi = \frac{\sqrt{\alpha}}{q} + \frac{\sqrt{\alpha}}{q} + \text{e- e+} + \ldots \]
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Cross-Section (σ) can be calculated from theory

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\[
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Quote $\sigma$ (areas) in funny units: \textit{barns}

1 barn = cross section for neutron to interact with Uranium \textit{- Enrico Fermi -}
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238 (n+p)
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$$\sigma(n \rightarrow U^{238}) \sim 1 \text{ barn}$$
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\[
\sigma(n \rightarrow U^{238}) \sim 1 \text{ barn} \sim (238)^{2/3} \times \sigma(p, p)
\]

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$\sigma(n \rightarrow U^{238}) \sim 1 \text{ barn} \sim (238)^{2/3} \times \sigma(p, p)$

$\Rightarrow \sigma(p \rightarrow p) \sim 0.03 \text{ barn (30 millibarn)}$
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\[
\sigma(n \rightarrow U^{238}) \sim 1 \text{ barn} \sim (238)^{2/3} \times \sigma(p, p)
\]

\[
\implies \sigma(p \rightarrow p) \sim 0.03 \text{ barn} (30 \text{ millibarn}) \sim \text{GeV}^{-2}
\]
What We Measure

Count pictures ("Events")
Compare events selected w/particular signature to prediction from theory

SM Prediction:

$$N_{\text{Signal Events}} = \sigma \times \mathcal{L}$$

- $\sigma$: Probability of process to happen (SM calculation)
- $\mathcal{L}$: Size of the dataset (Total number of events)
What We Measure

Count pictures ("Events")
Compare events selected w/particular signature to prediction from theory

SM Prediction:

\[ N_{\text{Signal Events}} = \sigma \times L \]

Probability of process to happen

(SM calculation)

Size of the dataset

(Total number of events)

Measurement:

\[ N_{\text{Observed Events}} = N_{\text{Signal Events}} + N_{\text{Background Events}} \]
What We Measure

Count pictures ("Events")
Compare events selected w/particular signature to prediction from theory

SM Prediction:

\[ N_{\text{Signal Events}} = \sigma \times L \]

\( \sigma \) calculated (SM calculation)
\( L \) is size of the dataset
\( L \) is total number of events

Measurement:

\[ N_{\text{Observed Events}} = N_{\text{Signal Events}} + N_{\text{Background Events}} \]

Report measured probabilities (cross sections) / Compare directly to theory

\[ \sigma_{\text{Measured}} = \frac{N_{\text{Observed Events}} - N_{\text{Background Events}}}{L} \]
Standard Model Total Production Cross Section Measurements

ATLAS Preliminary
Run 1,2 $\sqrt{s} = 7, 8, 13$ TeV

$\sigma [\text{pb}] = 10^{-12}$ barn

LHC pp $\sqrt{s} = 7$ TeV
- Data 4.5 – 4.9 fb$^{-1}$
- Theory

LHC pp $\sqrt{s} = 8$ TeV
- Data 20.3 fb$^{-1}$

LHC pp $\sqrt{s} = 13$ TeV
- Data 0.08 – 13.3 fb$^{-1}$

Total Production Cross Section Measurement Status: August 2016

ATLAS Preliminary
Run 1,2 $\sqrt{s} = 7, 8, 13$ TeV

$\sigma [\text{pb}] = 10^{-12}$ barn
Advantage of Higher Energy

\[ N_{\text{Events}} = \sigma \times \mathcal{L} \]

\[ \frac{N_{13 \, \text{TeV}}}{N_{8 \, \text{TeV}}} = \frac{\sigma_{13 \, \text{TeV}}}{\sigma_{8 \, \text{TeV}}} \times \frac{\mathcal{L}_{13 \, \text{TeV}}}{\mathcal{L}_{8 \, \text{TeV}}} \]
Advantage of Higher Energy

\[ N_{\text{Events}} = \sigma \times L \]

\[ \frac{N_{13 \text{ TeV}}}{N_{8 \text{ TeV}}} = \frac{\sigma_{13 \text{ TeV}}}{\sigma_{8 \text{ TeV}}} \times \frac{L_{13 \text{ TeV}}}{L_{8 \text{ TeV}}} \]

Now ~ 10
(linear w/dataset size)
Advantage of Higher Energy

\[ N_{\text{Events}} = \sigma \times L \]

\[ \frac{N^{13 \text{ TeV}}_{\text{Events}}}{N^{8 \text{ TeV}}_{\text{Events}}} = \frac{\sigma^{13 \text{ TeV}}}{\sigma^{8 \text{ TeV}}} \times \frac{L^{13 \text{ TeV}}}{L^{8 \text{ TeV}}} \]

ratios of LHC parton luminosities: 13 TeV / 8 TeV

Now ~ 10
(linear w/dataset size)
Advantage of Higher Energy

\[ N_{\text{Events}} = \sigma \times \mathcal{L} \]

\[
\frac{N_{13 \text{ TeV}}}{N_{8 \text{ TeV}}} = \frac{\sigma_{13 \text{ TeV}}}{\sigma_{8 \text{ TeV}}} \times \frac{\mathcal{L}_{13 \text{ TeV}}}{\mathcal{L}_{8 \text{ TeV}}}
\]

ratios of LHC parton luminosities: 13 TeV / 8 TeV

Now \sim 10 (linear w/dataset size)

new physics

1.5 TeV

MSTW2008NLO

WJS2013

Events = \lambda \times L

13 TeV Events \ll 100 \times 8 \text{ TeV Events}
Advantage of Higher Energy

\[ N_{\text{Events}} = \sigma \times \mathcal{L} \]

\[ \frac{N^{13 \text{ TeV}}_{\text{Events}}}{N^{8 \text{ TeV}}_{\text{Events}}} = \frac{\sigma^{13 \text{ TeV}}}{\sigma^{8 \text{ TeV}}} \times \frac{\mathcal{L}^{13 \text{ TeV}}}{\mathcal{L}^{8 \text{ TeV}}} \]

Ratios of LHC parton luminosities: 13 TeV / 8 TeV

Now ~ 10
(linear w/dataset size)
Advantage of Higher Energy

\[ N_{\text{Events}} = \sigma \times \mathcal{L} \]

\[ \frac{N_{13 \text{ TeV}}}{N_{8 \text{ TeV}}} = \frac{\sigma_{13 \text{ TeV}}}{\sigma_{8 \text{ TeV}}} \times \frac{\mathcal{L}_{13 \text{ TeV}}}{\mathcal{L}_{8 \text{ TeV}}} \]

Now ~ 10
(linear w/dataset size)

\[ N_{13 \text{ TeV}} \sim 20 \times N_{8 \text{ TeV}} \]
Advantage of Higher Energy

\[ N_{\text{Events}} = \sigma \times \mathcal{L} \]

\[ \frac{N_{\text{13 TeV Events}}}{N_{\text{8 TeV Events}}} = \frac{\sigma_{\text{13 TeV}}}{\sigma_{\text{8 TeV}}} \times \frac{\mathcal{L}_{\text{13 TeV}}}{\mathcal{L}_{\text{8 TeV}}} \]

Pick up next time discussing how these tools used to discover and study the Higgs Boson

Now ~ 10 (linear w/dataset size)