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: Experimental Challenges
May 27th: Memorial Day: No Lecture
June 3rd: Going beyond the Higgs: What comes next?
Lecture Outline

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Sources:
- Nima Arkani-Hamed
- Steven Weinberg
- …

I will keep this list up to date as we go along.
**Reminder**: Last Lecture

Combining Relativity and Quantum Mechanics
- To preserve causality needed to Anti-particle must exist

- In turn, major implications on the vacuum:

\[ \Delta E > 2m_e c^2 \]

\[ \Delta x \sim \frac{1}{m_e} \]

\[ \Delta E > 2m_\mu c^2 \]

\[ \Delta x \sim \frac{1}{m_\mu} \]
**Reminder**: Last Lecture

Combining Relativity and Quantum Mechanics
- Massive restrictions in types of theories possible

- Forced to talk particle spin:
  
  Integer spin = Bosons / Half-integer = Fermions

  Can only have: 0, 1/2, 1, 3/2, 2

- Major limits to possible interaction:
  Charge conservation / Local in space-time

  Only finite number of specific interactions allowed:

![Diagram showing bosons and fermions](attachment:diagram.png)
Today’s Lecture

The Standard Model:
What the world is made of
Matter

Stuff in the world made of atoms:
Atoms made of:

**Electrons:**

**Nucleus:**

**Matter**

Stuff in the world made of atoms:
Atoms made of:

**Electrons**: Negatively charged  
Responsible for volume of atom  
Thought to be fundamental

**Nucleus**: 
Atoms made of:

**Electrons:** Negatively charged
- Responsible for volume of atom
- Thought to be fundamental

**Nucleus:** Positively charged
- Responsible for the mass of an atom
- Made of protons and neutrons, which are made of quarks
- Quarks also thought to be fundamental
Matter

Stuff in the world made of atoms:

Atoms made of:

**Electrons**: Negatively charged
Responsible for volume of atom
Thought to be fundamental

**Nucleus**: Positively charged
Responsible for the mass of an atom
Made of, protons and neutrons, which are made of quarks
Quarks also thought to be fundamental

**Matter particles (electrons/quarks) fermions**
**Large collections behave like classical particles**
Forces

Gravity:
Known since antiquity / Inverse square law
Always attractive / Irrelevant for atomic/sub-atomic interactions
Forces

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Electromagnetism:
- Known since antiquity / Inverse square law
- Attractive or repulsive / Holds electrons within atoms
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Strong:
Discovered early 1900s / Short distances / No simple relationship
Responsible for holding together the nucleus
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Discovered just before turn of 20th century / Looks nothing like others
Radioactive decay. Heats the sun / earth
Forces

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Radioactive decay. Heats the sun / earth

All forces as important. Look very different from one another.
The Standard Model

Our world both Relativistic and Quantum Mechanical
⇒ described in terms of a Quantum Field Theory (QFT)
The Standard Model

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The particular version of QFT that was found to describe our universe developed in the 1960-70s.
The Standard Model

Our world both Relativistic and Quantum Mechanical
⇒ described in terms of a Quantum Field Theory (QFT)

The particular version of QFT that was found to describe our universe developed in the 1960-70s.

Most accurate theory in all of science
- Describes all matter/interactions down to $10^{-18}$m
  (Distances $100 \times$ smaller than proton)
- Accurate/precise description all observed particle interactions
Output of the Theory

Predict probabilities for various things to happen

Example:
Output of the Theory

Predict probabilities for various things to happen

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Predict probabilities for various things to happen

**Example:**

Stick figure: “Feynman Diagram”
Output of the Theory

Predict probabilities for various things to happen

Example:

Stick figure: “Feynman Diagram”
- Represents one possible way things could have happened
Output of the Theory

Predict probabilities for various things to happen

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Stick figure: "Feynman Diagram"
- Represents one possible way things could have happened
- Theory assigns number to each diagram
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- Add all paths consistent w/input & output
Output of the Theory

Predict probabilities for various things to happen

Example:

Stick figure: “Feynman Diagram”
- Represents one possible way things could have happened
- Theory assigns number to each diagram
- Each diagram only local interactions
- Add all paths consistent w/input & output
- Gives a contribution to $\psi$ (more later)
Output of the Theory

Predict probabilities for various things to happen

Example:

Now on, I’ll use: as short hand for:

\[
\begin{align*}
\text{Space} & \quad e^- \\
\text{Time} & \quad e^- \\
\end{align*}
\]
Forces from Interactions

Forces long-range manifestations of local interactions
No more action at a distance!

Electromagnetic force between two electrons result exchange of a photon
Exchange as local interactions two e-\(\gamma\) interactions
Forces from Interactions

Gravitational Interaction
- e → e
- graviton

Electromagnetic Interaction
- e → e
- γ

Strong Interaction
- q → q
- gluon

Weak Interaction
- e → e
- ν
- Z
- W
Forces from Interactions

Gravitational Interaction

Electromagnetic Interaction

Strong Interaction

Weak Interaction

Force particles are bosons
Large collections behave like classical waves
Force particles believed to be fundamental
Forces from Interactions

Gravitational Interaction

Graviton

Electromagnetic Interaction

Bosons
Fermions

Strong Interaction

Force particles are bosons
Large collections behave like classical waves

Weak Interaction

Force particles believed to be fundamental
Forces from Interactions

**Gravitational Interaction**
- Graviton

**Electromagnetic Interaction**
- Neutrino (fermion)
  - Needed to describe weak interactions
  - Like electron w/no charge/~no mass
  - Believed to be fundamental

**Strong Interaction**
- Force particles are bosons
- Large collections behave like classical waves

**Weak Interaction**
- Force particles believed to be fundamental

- Bosons
- Fermions

- Neutrino
- Gluon
- e
- q
- W
- Z
- v
The Standard Model

Matter Particles (Fermions)

Leptons: \( (\nu_e, \nu, \nu, e) \)

Quarks: \( (u, d) \)

Interactions “Force carriers” (Bosons)

Gauge bosons: \( \gamma, W, Z, g \)
The Standard Model

Matter Particles (Fermions)

Leptons: \( \begin{pmatrix} \nu_e \\ e \end{pmatrix} \)

Quarks: \( \begin{pmatrix} u \\ d \end{pmatrix} \)

Interactions “Force carriers” (Bosons)

Gauge bosons:

\( \gamma \quad W \quad Z \quad g \)

Beautiful (complicated) mathematics governs nature interactions
Dictated by principles of symmetry \((Much \ direct \ consequence \ QM + R)\)
The Standard Model

Matter Particles (Fermions)

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

Quarks: \[ \begin{pmatrix} u \\ d \end{pmatrix}, \begin{pmatrix} c \\ s \end{pmatrix}, \begin{pmatrix} t \\ b \end{pmatrix} \]

Interactions “Force carriers” (Bosons)

Gauge bosons: \( \gamma, W, Z, g \)

Beautiful (complicated) mathematics governs nature interactions
Dictated by principles of symmetry (Much direct consequence QM + R)
Masses

Proton Mass
Masses

These masses are inputs to the theory. Need to determine them from experiment.

Proton Mass
Interaction Strengths

Each interaction vertex characterized by number:

- $\alpha = 1/137$
- $\alpha_{\text{Weak}} = 1/50$
- $\alpha_{\text{Strong}} = 1/10$

Sets the overall strength of the different interactions
- Directly related to the probability for the processes to occur
Interaction Strengths

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These numbers are inputs to the theory
- Need to determine them from experiment
- Then use them as input in other calculations.
Interaction Strengths

Each interaction vertex characterized by number:

Example:
Fix $\alpha$ from measuring properties of atoms, given by:

$\alpha = \frac{1}{137}$

Weak
$\alpha = \frac{1}{50}$

Strong
$\alpha = \frac{1}{10}$
Interaction Strengths

Each interaction vertex characterized by number:

- Directly related to the probability for the processes to occur
- Need to determine them from experiment
- Then use them as input in other calculations.

\[ \alpha_e = \frac{1}{137} \] (Weak)
\[ \alpha_s = \frac{1}{10} \] (Strong)
\[ \alpha = \frac{1}{50} \] (EM)

Example:

Fix \( \alpha \) from measuring properties of atoms, given by:

Then predict all other EM probabilities (e.g., how electrons or anti-electrons scatter).
Output of the Theory (Details)

Feynman Diagrams: Pictures of what happens
Invaluable Tool for calculation
Output of the Theory (Details)

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
Output of the Theory (Details)

**Feynman Diagrams:** Pictures of what happens
Invaluable Tool for calculation

\[ \psi = \sqrt{\alpha} + \sqrt{\alpha} \]

- Theory gives prescription for assigning numerical value to diagram.
  - Other rules associated to the lines / Sum overall possible configurations
- Sum of diagrams (# associated with diagrams) is \( \psi \)
Feynman Diagrams: Pictures of what happens
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\[ \psi = \sqrt{\alpha} + \text{...} \]

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Feynman Diagrams: Pictures of what happens
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\[ \psi = \]

0-loops

1-loops

- 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 \( \psi \)
Output of the Theory (Details)

Feynman Diagrams: Pictures of what happens
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\[ \psi = \]

- 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 \( \psi \)

Example of vacuum fluctuations!
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 $\psi$

\[
\psi = \sqrt{\alpha} \quad + \quad \sqrt{\alpha} \quad + \quad \frac{1}{4\pi} \frac{1}{m_e} \quad + \quad \ldots
\]
Feynman Diagrams: Pictures of what happens
Invaluable Tool for calculation

\[ \psi = \sqrt{\alpha} + \frac{1}{4\pi} \frac{1}{m_e} + \ldots \]

- 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 \( \psi \)
- Really infinite sum. In practice, only the first few terms dominate
Output of the Theory (Details)

Feynman Diagrams: Pictures of what happens
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\[ \psi = \]

- Theory give prescription for assigning numerical value to diagram.
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Output of the Theory (Details)

Just saw example of calculating interaction between particles
Can also calculate basic properties of particles
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**Example:** *Contribution to mass Z boson*

\[ Z \sim Z + Z \sim Z + \ldots \]
Output of the Theory (Details)

Just saw example of calculating interaction between particles
Can also calculate basic properties of particles

**Example:** *Contribution to mass Z boson*

\[ Z \sim Z + Z \sim Z + \ldots \]

- Seems impossible given \( m_{top} > m_Z \)
- Allowed by Quantum theory \( (\text{Uncertainty principle } \Delta E \Delta t \geq \hbar) \)
- “Quantum Corrections” to mass
- Confirmed observable consequences
Forces Common Language

First time that we see that all forces described in same basic way.

\[ \alpha = \frac{1}{137} \]

\[ \alpha_{\text{Weak}} = \frac{1}{50} \]

\[ \alpha_{\text{Strong}} = \frac{1}{10} \]

Forces look very different to us…
EM Strength w/Distance

\[ E \sim \frac{1}{r^{137}} \]

\[ \alpha_{EM} \]

[Diagram showing an electron \( e^- \) and a graph indicating the electromagnetic interaction strength as a function of distance.]
EM Strength w/ Distance

\[ \Delta x \sim \frac{1}{m_e} \]

\[ \alpha_{EM} \sim \frac{1}{137} \]
EM Strength w/Distance

\[ \Delta x \sim \frac{1}{m_e} \]

\[ \alpha_{EM} \sim \frac{1}{137} \]

\[ r \sim \frac{1}{m_e} \]
EM Strength w/Distance

Precisely predict magnetic properties
\[ g/2 = 1.0011596521809(8), \]
(Agree to better than one part in a trillion.)
Strong Interaction w/Distance
Strong Interaction w/ Distance

\[ \Delta x \sim \frac{1}{m_p} \]

\[ \alpha_{\text{Strong}} \]

\[ \frac{1}{10} \]

\[ \sim \frac{1}{m_p} \]
Strong Interaction w/Distance

Unlike photons, gluons can self interact.

\[ \Delta x \sim \frac{1}{m_p} \]

\[ \alpha_{\text{Strong}} \]

\[ \sim \frac{1}{m_p} \]
Strong Interaction w/ Distance

Unlike photons, gluons can self interact.
Strong Interaction w/Distance

Unlike photons, gluons can self interact.

\( \Delta x \sim \frac{1}{m_p} \)

\( x \sim 1 \)

\( \frac{1}{10} \)

\( \sim \frac{1}{m_p} \)
Strong Interaction w/Distance

Unlike photons, gluons can self interact.

Interaction become very strong $\sim 1/mp$

Proton:

- $q$ and gluons “confined”
- Sets the size of protons (neutrons)

B/c force grows with distance:
- Cant pull them out of the proton

$\frac{1}{mp} \approx 1$
Electron high probability to emit $\gamma$ when:

$$E \times r < \frac{h}{c}$$

(consistent with $\Delta E \Delta t > h$)

$$r < \frac{h}{p c^2}$$

When $p \to 0$ then $r \to \infty$

$F (= -\Delta p)$ on $q$ can extends to $r = \infty$

Of course, force get smaller ($p \to 0$)

(Gives precisely inverse square law)
Back to EM Interaction

Electron high probability to emit $\gamma$ when:
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Back to EM Interaction

Electron high probability to emit $\gamma$ when:

$E \times r < h/c$ (consistent with $\Delta E \Delta t > h$)

$r < h/Ec$

Electro-magnetic Force

\[ \begin{array}{c}
\text{e} \\
\text{q}
\end{array} \quad \gamma \quad \begin{array}{c}
\text{q} \\
\text{e}
\end{array} \]
Electron high probability to emit $\gamma$ when:

$E \times r < h/c$ (consistent with $\Delta E \Delta t > h$)

$r < h/Ec$

$r < h/pc^2$

$r \rightarrow \infty$ when $p \rightarrow 0$.

Electro-magnetic Force on $q$ can extends to $r = \infty$.

Of course, force get smaller ($p \rightarrow 0$) (Gives precisely inverse square law)
Back to EM Interaction

Electron high probability to emit $\gamma$ when:
- $E \times r < h/c$ (consistent with $\Delta E \Delta t > h$)
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(Gives precisely inverse square law)
Weak Interaction

Electron high probability to emit $\gamma$ when:
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$r < \frac{h}{Ec}$
$r < \frac{h}{pc^2}$
when $p \to 0$ then $r \to \infty$
F ($= -\Delta p$) on q can extends to $r = \infty$
Of course, force get smaller ($p \to 0$)
(Gives precisely inverse square law)

Weak Force

Exactly same except $mZ \neq 0$

Electron high probability to emit $Z$ when:
$E \times r < \frac{h}{c}$ (consistent with $\Delta E \Delta t > h$)
$r < \frac{h}{Ec}$
Weak Interaction

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Weak Force

Electron high probability to emit $Z$ when:
- $E \times r < h/c \ (consistent \ with \ \Delta E \Delta t > h)$
- $r < h/Ec$
- $r < h/\sqrt{(pc + mZc^2)c}$

Exactly same except $mZ \neq 0$
Weak Interaction

Electron high probability to emit $\gamma$ when:

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$r < h/\sqrt{(pc + mZc^2)c}$

when $p \to 0$ then $r \to \sim 1/mZ$
Weak Interaction

Electron high probability to emit $\gamma$ when:
1. $E \times r < h/c$ (consistent with $\Delta E \Delta t > h$)
2. $r < h/Ec$
3. $r < h/pc^2$
   when $p \to 0$ then $r \to \infty$
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2. $r < h/Ec$
3. $r < h/\sqrt{(pc + mzc^2)c}$
   when $p \to 0$ then $r \to \sim 1/mZ$
F ($= -\Delta p$) on q cannot extend to $r = \infty$
Mass of $Z$ makes weak force short ranged.
Forces Common Language

First time that we see that all forces described in same basic way.

\[
\begin{align*}
\alpha &= 1/137 \\
\alpha_{\text{Weak}} &= 1/50 \\
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Forces look very different to us…
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Forces look very different to us… is a long distance illusion!
Forces look very different to us… **is a long distance illusion!**
- Strong force: anti-screening / confinement
- Weak force: massing force carriers

At short distance (~1/mZ) all look the forces start to look the same
Forces look very different to us… **is a long distance illusion!**
- Strong force: anti-screening / confinement
- Weak force: massing force carriers
At short distance (~1/mZ) all look the forces start to look the same

**This is the reason we build colliders! Unity at small scales.**
The Standard Model

The Standard Model took on modern form in 60s - 70s.

Makes very precise predictions, shown to be highly accurate.

Consistent theory of electromagnetic, weak and strong forces ...
The Standard Model

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... provided massless Matter and Force Carriers
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*Serious problem as matter and W, Z known to be massive!*
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**Serious problem as matter and W, Z known to be massive!**

**Pick up here next time.**
Bonus
Number of Parameters

Vertex interaction strength input to the theory
- Taken from data

QFT $\Rightarrow$ Only this “three point” interaction relevant

All calculations done by just stitch together this one basic vertex

One parameter (●) is enough to calculate all graphs
Each term introduces a new unknown parameter.
Lose predictive power