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

John Alison

University of Chicago

http://hep.uchicago.edu/~johnda/ComptonLectures.html
Intermezzo

Taking a lot of flak for remarks associated to:

Realizing Newton’s Dream

- Features of Life
- Evolution
- DNA
- Molecules
- Chemistry
- Atoms
- Electrons
- Quantum Mechanics
- Standard Model
Intermezzo

Taking a lot of flak for remarks associated to:

Realizing Newton’s Dream

Go through a few examples of this kind of reasoning:
- Teeth behind these statements
- Describe world around us in a few basic physical parameters
- Powerful (Fun!) way of estimating ~anything to order of magnitude
Dimensional Analysis and “~”

Put in the right physics to get answers to within “geometric factors”
- Don't worry about factors of 2 or π etc
- Use “~” not “=”
Dimensional Analysis and “∼”

Put in the right physics to get answers to within “geometric factors”
- Don’t worry about factors of 2 or π etc
- Use “∼” not “=“

Examples (Volume of something) ∼ (size)³
Dimensional Analysis and “~”

Put in the right physics to get answers to within “geometric factors”
- Don't worry about factors of 2 or \( \pi \) etc
- Use “~” not “=“

**Examples** (Volume of something) ~ (size)\(^3\)

Cube \( = R^3 \) ~ \( R^3 \)
Dimensional Analysis and “~”

Put in the right physics to get answers to within “geometric factors”
- Don’t worry about factors of 2 or π etc
- Use “~” not “=“

**Examples**  (Volume of something) ~ (size)$^3$

- Cube  = $R^3$  ~ $R^3$
- Sphere = $4/3\pi R^3$  = 4.2 $R^3$  ~ $R^3$
Dimensional Analysis and “~”

Put in the right physics to get answers to within “geometric factors”
- Don’t worry about factors of 2 or \( \pi \) etc
- Use “~” not “=“

**Examples** (Volume of something) \( \sim \) (size)\(^3\)

- **Cube** \( = R^3 \) \( \sim R^3 \)
- **Sphere** \( = \frac{4}{3} \pi R^3 \) \( \sim 4.2 R^3 \)
- \( = \frac{1}{6} \pi (D)^3 \) \( \sim 0.4 D^3 \)
- **Cylinder** \( = R \times \pi R^2 \) \( \sim R^3 \) (if two scales use \( R^2 R \))
Dimensional Analysis and “∼”

Put in the right physics to get answers to within “geometric factors”
- Don’t worry about factors of 2 or π etc
- Use “∼” not “=“

Examples (Volume of something) ∼ (size)$^3$

- Cube $= R^3$ $∼ R^3$
- Sphere $= \frac{4}{3}\pi R^3 = 4.2 R^3$ $∼ R^3$
  $= \frac{1}{6}\pi(D)^3 = 0.4 D^3$ $∼ D^3$
- Cylinder $= R \times \pi R^2 = \pi R^3$ $∼ R^3$ (if two scales use $r^2R$)
Dimensional Analysis and “~”

Put in the right physics to get answers to within “geometric factors”
- Don’t worry about factors of 2 or $\pi$ etc
- Use “~” not “=“

**Examples** (Volume of something) $\sim$ (size)$^3$

- Cube $= R^3 \sim R^3$
- Sphere $= 4/3\pi R^3 = 4.2 \ R^3 \sim R^3$
  $= 1/6\pi(D)^3 = 0.4 \ D^3 \sim D^3$
- Cylinder $= R \times \pi R^2 = \pi \ R^3 \sim R^3$ (if two scales use $r^2R$)

Kinematic energy $= 1/2 \ mv^2 \sim mv^2$
Dimensional Analysis and “~”

Put in the right physics to get answers to within “geometric factors”
- Don’t worry about factors of 2 or π etc
- Use “~” not “=“

**Examples** (Volume of something) ~ (size)$^3$

Cube $= R^3$ ~ $R^3$
Sphere $= \frac{4}{3}\pi R^3 = 4.2 R^3$ ~ $R^3$
  $= \frac{1}{6}\pi (D)^3 = 0.4 D^3$ ~ $D^3$
Cylinder $= R \times \pi R^2 = \pi R^3$ ~ $R^3$ (if two scales use $r^2R$)

Kinematic energy $= \frac{1}{2} mv^2$ ~ $mv^2$

I’ve been doing this already: “$\Delta p \Delta x \geq h$”
  ($\ldots$ it is really $\Delta p \Delta x \geq h/(4\pi)$)
Units

*I hate units!* All numbers are really unit-less
Always comparing some quantity relative to some standard
We will work in “Natural Units”
Units

*I hate units!* All numbers are really unit-less
Always comparing some quantity relative to some standard
We will work in “Natural Units”

Natural Units
- The right way to think about the world
  *(How physicists think, what makes them seem smart to other people)*
- Very easy. Much easier than Metric/British/cgm/mks …
- Standard is set by basic physical principles
  ⇒ numbers have direct physical interpretations
Units

*I hate units!* All numbers are really unit-less
Always comparing some quantity relative to some standard
We will work in “Natural Units”

Natural Units
- The right way to think about the world
  *(How physicists think, what makes them seem smart to other people)*
- Very easy. Much easier than Metric/British/cgm/mks …
- Standard is set by basic physical principles
  \[ \Rightarrow \text{numbers have direct physical interpretations} \]

\( c \equiv 1: \ \text{[Distance]}/[\text{Time}] \equiv 1 \)
- Time and distance have same units
- \( E = m \)
Units

I hate units! All numbers are really unit-less
Always comparing some quantity relative to some standard
We will work in “Natural Units”

Natural Units
- The right way to think about the world
  (How physicists think, what makes them seem smart to other people)
- Very easy. Much easier than Metric/British/cgm/mks …
- Standard is set by basic physical principles
  ⇒ numbers have direct physical interpretations

\[ c \equiv 1: \frac{\text{Distance}}{\text{Time}} \equiv 1 \]
- Time and distance have same units
- \( E = m \)

You are already familiar with this:
“Its about an hour from here”
Units

I hate units! All numbers are really unit-less
Always comparing some quantity relative to some standard
We will work in “Natural Units”

Natural Units
- The right way to think about the world
  \((How \text{ physicists think, what makes them seem smart to other people})\)
- Very easy. Much easier than Metric/British/cgm/mks …
- Standard is set by basic physical principles
  \(\Rightarrow\) numbers have direct physical interpretations

\[c \equiv 1: \frac{\text{Distance}}{\text{Time}} \equiv 1\]
- Time and distance have same units
- \(E = m\)

\[h \equiv 1: \text{Energy} \times \text{Time} = 1 \text{ and } \text{Energy} \times \text{Distance} = 1\]
- Energy (or Mass) is inversely related to distance or time.

You are already familiar with this:
“\text{It's about an hour from here}”
Units

*I hate units!* All numbers are really unit-less
Always comparing some quantity relative to some standard
We will work in “Natural Units”

**Natural Units**
- The right way to think about the world
  *(How physicists think, what makes them seem smart to other people)*
- Very easy. Much easier than Metric/British/cgm/mks …
- Standard is set by basic physical principles
  ⇒ numbers have direct physical interpretations

\[ c \equiv 1: \quad \text{[Distance]/[Time]} \equiv 1 \]
- Time and distance have same units
- \( E = m \)

\[ h \equiv 1: \quad \text{[Energy]×[Time]} = 1 \quad \text{and} \quad \text{[Energy]×[Distance]} = 1 \]
- Energy (or Mass) is inversely related to distance or time.

You are already familiar with this: “Its about an hour from here”

Write everything in terms of [Energy]: use 1 GeV ~ mp as basic unit
Examples

Everything in terms of GeV. Use conversions to get back to human units

**Conversions:**

\[
\text{GeV} = 10^{-27} \text{ kg}
\]

\[
\text{GeV}^{-1} = 10^{-16} \text{ m}
\]

\[
\text{GeV}^{-1} = 6 \cdot 10^{-25} \text{ s}
\]
Examples

Everything in terms of GeV. Use conversions to get back to human units

Conversions:

\[
\text{GeV} = 10^{-27} \text{ kg}
\]

\[
\text{GeV}^{-1} = 10^{-16} \text{ m}
\]

\[
\text{GeV}^{-1} = 6 \cdot 10^{-25} \text{ s}
\]

Proton Weight: GeV
Examples

Everything in terms of GeV. Use conversions to get back to human units.

Conversions:

\[
\text{GeV} = 10^{-27} \ \text{kg}
\]

\[
\text{GeV}^{-1} = 10^{-16} \ \text{m}
\]

\[
\text{GeV}^{-1} = 6 \cdot 10^{-25} \ \text{s}
\]

Proton Weight: GeV

Proton Size: GeV^{-1}
Examples

Everything in terms of GeV. Use conversions to get back to human units

Conversions:

GeV = $10^{-27}$ kg

GeV$^{-1}$ = $10^{-16}$ m

GeV$^{-1}$ = $6 \cdot 10^{-25}$ s

Proton Weight: GeV

Proton Size: GeV$^{-1}$

My height: 1 m $\sim 10^{16}$ GeV$^{-1}$
Examples

Everything in terms of GeV. Use conversions to get back to human units.

Conversions:

GeV = $10^{-27}$ kg
GeV$^{-1}$ = $10^{-16}$ m
GeV$^{-1}$ = $6 \cdot 10^{-25}$ s

Proton Weight: GeV

Proton Size: GeV$^{-1}$

My height: 1 m $\sim$ $10^{16}$ GeV$^{-1}$

My weight: 100 kg $\sim$ $10^{29}$ GeV
Examples

Everything in terms of GeV. Use conversions to get back to human units

Conversions:

GeV = $10^{-27}$ kg

GeV$^{-1}$ = $10^{-16}$ m

GeV$^{-1}$ = $6 \cdot 10^{-25}$ s

Proton Weight: GeV

Proton Size: I am as tall as $10^{16}$ protons stacked on top of each other

My height: 1m $\sim 10^{16}$ GeV$^{-1}$

My weight: 100 kg $\sim 10^{29}$ GeV
Examples

Everything in terms of GeV. Use conversions to get back to human units

Conversions:

GeV = \(10^{-27}\) kg

GeV\(^{-1}\) = \(10^{-16}\) m

GeV\(^{-1}\) = \(6 \cdot 10^{-25}\) s

Proton Weight: GeV

Proton Size: GeV\(^{-1}\)

My height: 1m \(\sim\) \(10^{16}\) GeV\(^{-1}\)

My weight: 100 kg \(\sim\) \(10^{29}\) GeV

I am made of \(\sim10^{29}\) protons
Electromagnetic Energy

\[ E = - \frac{e^2}{4\pi} \frac{1}{r} \]
EM and Gravitation Interactions

Electromagnetic Energy

\[ E = - \frac{e^2}{4\pi} \frac{1}{r} \]

GeV
EM and Gravitation Interactions

Electromagnetic Energy

\[ E = -\frac{e^2}{4\pi} \frac{1}{r} \]  

GeV  

GeV
EM and Gravitation Interactions

Electromagnetic Energy

\[ E = -\frac{e^2}{4\pi} \frac{1}{r} \]

GeV \quad \text{GeV}

Pure number: \( \alpha \)
Its small: 1/137
EM and Gravitation Interactions

Electromagnetic Energy

\[ E = -\frac{e^2}{4\pi} \frac{1}{r} \]  
GeV  

Gravitational Energy

\[ E = -G_N \frac{m_p^2}{r} \]  
GeV

Pure number: \( \alpha \)  
Its small: 1/137
**Electromagnetic Energy**

\[ E = -\frac{e^2}{4\pi} \frac{1}{r} \]  
GeV \[ \downarrow \]  
GeV

**Gravitational Energy**

\[ E = -G_N \frac{m_p^2}{r} \]  
GeV \[ \downarrow \]  
GeV \[ \downarrow \]  
GeV^3

Pure number: \( \alpha \)  
Its small: 1/137
EM and Gravitation Interactions

Electromagnetic Energy

\[ E = -\frac{e^2}{4\pi} \frac{1}{r} \]

Gravitational Energy

\[ E = -G_N \frac{m_p^2}{r} \]

Pure number: \( \alpha \)
Its small: 1/137

Dimensionful number
\[ G_N m_p^2 = 10^{-39} \]
The world with 4 numbers

Claim: ~everything in world combination of these numbers

\[ m_p \sim 1 \text{ GeV} \quad \alpha = \frac{1}{137} \sim 10^{-2} \]

\[ m_e \sim 10^{-3} \text{ GeV} \quad \alpha_G \equiv G_N m_p^2 = 10^{-39} \]

*Will work through some quick examples.*
Atoms

\[ E \sim -\frac{Z\alpha}{r} + \frac{p^2}{m_e} \]
Atoms

\[ E \sim -\frac{Z\alpha}{r} + \frac{p^2}{m_e} \]

\[ p \times r \sim 1 \]

\[ E \sim -\frac{Z\alpha}{r} + \frac{1}{m_e r^2} \]
Atoms

\[ p \times r \sim 1 \]

\[ E \sim -\frac{Z\alpha}{r} + \frac{p^2}{m_e} \]

\[ r_{\text{atom}} \sim \frac{1}{Z\alpha m_e} \]
Atoms

\[ p \times r \sim 1 \]

\[ E \sim -\frac{Z\alpha}{r} + \frac{p^2}{m_e} \quad E \sim -\frac{Z\alpha}{r} + \frac{1}{m_e r^2} \]

\[ r_{\text{atom}} \sim \frac{1}{Z\alpha m_e} \]

<table>
<thead>
<tr>
<th>Z</th>
<th>Prediction</th>
<th>Actual Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>( \sim 10^{-11} \text{m} )</td>
<td>2.5 ( \cdot ) ( 10^{-11} \text{m} )</td>
</tr>
<tr>
<td>10</td>
<td>( \sim 10^{-12} \text{m} )</td>
<td>4.0 ( \cdot ) ( 10^{-11} \text{m} )</td>
</tr>
<tr>
<td>&gt;10</td>
<td>( \sim 10^{-12} \text{m} )</td>
<td>( \sim 10^{-10} \text{m} )</td>
</tr>
</tbody>
</table>

Details of electron screening needed for high Z
(Will use \( 10^{\sim-10} \) when \( Z > 10 \))
Atoms

\[ p \times r \sim 1 \]

\[ E \sim -\frac{Z\alpha}{r} + \frac{p^2}{m_e} \]

\[ r_{\text{atom}} \sim \frac{1}{Z\alpha m_e} \]
Atoms

\[ p \times r \sim 1 \]

\[ E \sim -\frac{Z\alpha}{r} + \frac{p^2}{m_e} \]

\[ r_{\text{atom}} \sim \frac{1}{Z\alpha m_e} \]

\[ E \sim -\frac{Z\alpha}{r} + \frac{1}{m_e r^2} \]

\[ r_{\text{nucleus}} \sim \frac{Z^{1/3}}{m_p} \]
Atoms

\[ p \times r \sim 1 \]

\[ E \sim -\frac{Z\alpha}{r} + \frac{p^2}{m_e} \]

\[ E \sim -\frac{Z\alpha}{r} + \frac{1}{m_e r^2} \]

\[ r_{\text{atom}} \sim \frac{1}{Z\alpha m_e} \]

\[ r_{\text{nucleus}} \sim \frac{Z^{1/3}}{m_p} \]

\[ \frac{r_{\text{nucleus}}}{r_{\text{atom}}} \sim \frac{\alpha m_e}{Z^{2/3} m_p} \sim 10^{-5} \]
Atoms

\[ p \times r \sim 1 \]

\[ E \sim - \frac{Z\alpha}{r} + \frac{p^2}{m_e} \quad \text{or} \quad E \sim - \frac{Z\alpha}{r} + \frac{1}{m_e r^2} \]

\[ r_{\text{atom}} \sim \frac{1}{Z\alpha m_e} \quad \text{or} \quad r_{\text{nucleus}} \sim \frac{Z^{1/3}}{m_p} \]

\[ \frac{r_{\text{nucleus}}}{r_{\text{atom}}} \sim \frac{\alpha m_e}{Z^{2/3} m_p} \sim 10^{-5} \]

\[ p_e \sim \frac{1}{r_{\text{atom}}} \sim m_e (Z\alpha) \quad \text{or} \quad v_e \sim (Z\alpha) \]
Atoms

\[ p \times r \sim 1 \]

\[ E \sim -\frac{Z\alpha}{r} + \frac{p^2}{m_e} \]

\[ r_{\text{atom}} \sim \frac{1}{Z\alpha m_e} \]

\[ E \sim -\frac{Z\alpha}{r} + \frac{1}{m_e r^2} \]

\[ r_{\text{nucleus}} \sim \frac{Z^{1/3}}{m_p} \]

\[ \frac{r_{\text{nucleus}}}{r_{\text{atom}}} \sim \frac{\alpha m_e}{Z^{2/3} m_p} \sim 10^{-5} \]

Number of different atoms \(\sim 1/\alpha\)

\[ p_e \sim \frac{1}{r_{\text{atom}}} \sim m_e (Z\alpha) \quad v_e \sim (Z\alpha) \]
Atoms

\[ p \times r \sim 1 \]

\[ E \sim -\frac{Z\alpha}{r} + \frac{p^2}{m_e} \]

\[ r_{\text{atom}} \sim \frac{1}{Z\alpha m_e} \]

\[ r_{\text{nucleus}} \sim \frac{Z^{1/3}}{m_p} \]

\[ \frac{r_{\text{nucleus}}}{r_{\text{atom}}} \sim \frac{\alpha m_e}{Z^{2/3} m_p} \sim 10^{+5} \]

Number of different atoms \( \sim 1/\alpha \)

\[ p_e \sim \frac{1}{r_{\text{atom}}} \sim m_e (Z\alpha) \]

\[ v_e \sim (Z\alpha) \]

- Why we could do QM first without relativity: \( (v \ll 1 \text{ for } Z \sim 1) \)
- Why electricity is more stronger everyday than magnetism.
Atoms

\[ p \times r \sim 1 \]

\[ E \sim -\frac{Z\alpha}{r} + \frac{p^2}{m_e} \]

\[ r_{\text{atom}} \sim \frac{1}{Z\alpha m_e} \]

\[ r_{\text{nucleus}} \sim \frac{Z^{1/3}}{m_p} \]

\[ \frac{r_{\text{nucleus}}}{r_{\text{atom}}} \sim \frac{\alpha m_e}{Z^{2/3} m_p} \sim 10^{-5} \]

\[ p_e \sim \frac{1}{r_{\text{atom}}} \sim m_e(Z\alpha) \quad v_e \sim (Z\alpha) \]
Atoms

\[ p \times r \sim 1 \]

\[ E \sim -\frac{Z\alpha}{r} + \frac{p^2}{m_e} \quad E \sim -\frac{Z\alpha}{r} + \frac{1}{m_e r^2} \]

\[ r_{\text{atom}} \sim \frac{1}{Z\alpha m_e} \quad r_{\text{nucleus}} \sim \frac{Z^{1/3}}{m_p} \]

\[ \frac{r_{\text{nucleus}}}{r_{\text{atom}}} \sim \frac{\alpha m_e}{Z^{2/3} m_p} \sim 10^{-5} \]

\[ p_e \sim \frac{1}{r_{\text{atom}}} \sim m_e (Z\alpha) \quad v_e \sim (Z\alpha) \]

\[ E_{\text{atom}} \sim \frac{Z\alpha}{r_{\text{atom}}} \sim Z^2 \alpha^2 m_e \]
Atoms

\[
p \times r \sim 1
\]

\[
E \sim -\frac{Z\alpha}{r} + \frac{p^2}{m_e}
\]

\[
r_{\text{atom}} \sim \frac{1}{Z\alpha m_e}
\]

\[
r_{\text{nucleus}} \sim \frac{Z^{1/3}}{m_p}
\]

\[
\frac{r_{\text{nucleus}}}{r_{\text{atom}}} \sim \frac{\alpha m_e}{Z^{2/3} m_p} \sim 10^{-5}
\]

\[
p_e \sim \frac{1}{r_{\text{atom}}} \sim m_e (Z\alpha)
\]

\[
v_e \sim (Z\alpha)
\]

\[
E_{\text{atom}} \sim \frac{Z\alpha}{r_{\text{atom}}} \sim Z^2 \alpha^2 m_e
\]

For Hydrogen

\[
10^{-4} \; 0.5 \; \text{MeV} \sim 50 \; \text{eV}
\]

(Actually is 13.6 eV)
Atoms

For Atoms Electron mass is king! (mp doesn't make an appearance)

\[ E \sim -\frac{Z\alpha}{r} + \frac{p^2}{m_e} \]

\[ r_{\text{atom}} \sim \frac{1}{Z\alpha m_e} \quad r_{\text{nucleus}} \sim \frac{Z^{1/3}}{m_p} \]

\[ \frac{r_{\text{nucleus}}}{r_{\text{atom}}} \sim \frac{\alpha m_e}{Z^{2/3} m_p} \sim 10^{-5} \]

\[ p_e \sim \frac{1}{r_{\text{atom}}} \sim m_e (Z\alpha) \quad v_e \sim (Z\alpha) \]

\[ E_{\text{atom}} \sim \frac{Z\alpha}{r_{\text{atom}}} \sim Z^2 \alpha^2 m_e \]

For Hydrogen

\[ 10^{-4} \quad 0.5 \text{ MeV} \sim 50 \text{ eV} \]

(Actually is 13.6 eV)
Solids

(To within our ~) Solids just atoms stacked next to each other
Solids

(To within our ~) Solids just atoms stacked next to each other

Mass Density: Mass/Volume

\[ \rho_{\text{solid}} \sim \frac{Zm_p}{(r_{\text{atom}})^3} \sim Z^4 \alpha^3 m_pm_e^3 \]
Solids

(To within our ~) Solids just atoms stacked next to each other

Mass Density: Mass/Volume

\[ \rho_{\text{solid}} \sim \frac{Z m_p}{(r_{\text{atom}})^3} \sim Z^4 \alpha^3 m_p m_e^3 \]

Pressure of Solid: Force/Area or Energy/Volume

\[ P_{\text{solid}} \sim \frac{Z^2 \alpha^2 m_e}{(r_{\text{atom}})^3} \sim Z^5 \alpha^5 m_e^4 \]
Solids

(To within our ~) Solids just atoms stacked next to each other

Mass Density: Mass/Volume

$$\rho_{\text{solid}} \sim \frac{Z m_p}{(r_{\text{atom}})^3} \sim Z^4 \alpha^3 m_p m_e^3$$

Pressure of Solid: Force/Area or Energy/Volume

$$P_{\text{solid}} \sim \frac{Z^2 \alpha^2 m_e}{(r_{\text{atom}})^3} \sim Z^5 \alpha^5 m_e^4$$

(Ratio of two give the speed of sounds)

$$V_{\text{sound}} \sim \sqrt{\frac{P_{\text{solid}}}{\rho_{\text{solid}}}} \sim \sqrt{\frac{\alpha}{m_p r_{\text{atom}}}}$$

**Predict:** ~25,000 m/s
- Beryllium 12,890 m/s
- Diamond 12,000 m/s
- Steel 6000 m/s
Planets

Solids where gravitational pressure balanced by solid pressure
Planets

Solids where gravitational pressure balanced by solid pressure

\[ E_{\text{Gravity}} \sim \frac{G_N M_P^2}{R_P} \quad \text{P}_{\text{Gravity}} \sim \frac{E_{\text{Gravity}}}{V_{\text{Planet}}} \sim \frac{G_N M_P^2}{R_P^4} \]
Planets

Solids where gravitational pressure balanced by solid pressure

\[ E_{\text{Gravity}} \sim \frac{G_N M_P^2}{R_P} \quad P_{\text{Gravity}} \sim \frac{E_{\text{Gravity}}}{V_{\text{Planet}}} \sim \frac{G_N M_P^2}{R_P^4} \]

\[ M_{\text{Planet}} \sim \rho_{\text{solid}} \times R_P^3 \sim \frac{Z m_p R_P^3}{r_{\text{atom}}^3} \]
Planets

Solids where gravitational pressure balanced by solid pressure

\[ E_{\text{Gravity}} \sim \frac{G_N M_P^2}{R_P} \quad P_{\text{Gravity}} \sim \frac{E_{\text{Gravity}}}{V_{\text{Planet}}} \sim \frac{G_N M_P^2}{R_P^4} \]

\[ M_{\text{Planet}} \sim \rho_{\text{solid}} \times R_P^3 \sim \frac{Z m_P R_P^3}{r^3_{\text{atom}}} \]

\[ P_{\text{Gravity}} \sim \frac{G_N Z^2 m_P^2 R_P^2}{r^6_{\text{atom}}} \]
Planets

Solids where gravitational pressure balanced by solid pressure

\[ E_{\text{Gravity}} \sim \frac{G_N M_p^2}{R_p} \quad P_{\text{Gravity}} \sim \frac{E_{\text{Gravity}}}{V_{\text{Planet}}} \sim \frac{G_N M_p^2}{R_p^4} \]

\[ M_{\text{Planet}} \sim \rho_{\text{solid}} \times R_p^3 \sim \frac{Z m_p R_p^3}{r_{\text{atom}}^3} \]

\[ P_{\text{Gravity}} \sim \frac{G_N Z^2 m_p^2 R_p^2}{r_{\text{atom}}^6} \]

\[ P_{\text{Gravity}} \sim P_{\text{solid}} \frac{G_N Z^2 m_p^2 R_p^2}{r_{\text{atom}}^6} \sim \frac{Z \alpha}{r_{\text{atom}}^4} \]
Planets

Solids where gravitational pressure balanced by solid pressure

\[ E_{\text{Gravity}} \sim \frac{G_N M_P^2}{R_p} \quad P_{\text{Gravity}} \sim \frac{E_{\text{Gravity}}}{V_{\text{Planet}}} \sim \frac{G_N M_P^2}{R_p^4} \]

\[ M_{\text{Planet}} \sim \rho_{\text{solid}} \times R_P^3 \sim \frac{Z m_p R_P^3}{r_{\text{atom}}^3} \]

\[ P_{\text{Gravity}} \sim \frac{G_N Z^2 m_p^2 R_P^2}{r_{\text{atom}}^6} \]

\[ P_{\text{Gravity}} \sim P_{\text{solid}} \quad \frac{G_N Z^2 m_p^2 R_P^2}{r_{\text{atom}}^6} \sim \frac{Z \alpha}{r_{\text{atom}}^4} \]

\[ R_{\text{Planet}} \sim \sqrt{\frac{1}{G_N m_p^2 Z^3 \alpha m_e^2}} \sim \sqrt{\frac{\alpha}{\alpha_G}} \times r_{\text{atom}} \]
Planets

Solids where gravitational pressure balanced by solid pressure

\[ E_{\text{Gravity}} \sim \frac{G_N M_{\text{P}}^2}{R_{\text{P}}} \quad P_{\text{Gravity}} \sim \frac{E_{\text{Gravity}}}{V_{\text{Planet}}} \sim \frac{G_N M_{\text{P}}^2}{R_{\text{P}}^4} \]

\[ M_{\text{Planet}} \sim \rho_{\text{solid}} \times R_{\text{P}}^3 \sim \frac{Z m_p R_{\text{P}}^3}{r_{\text{atom}}^3} \]

\[ P_{\text{Gravity}} \sim \frac{G_N Z^2 m_p^2 R_{\text{P}}^2}{r_{\text{atom}}^6} \]

\[ P_{\text{Gravity}} \sim P_{\text{solid}} \]

\[ R_{\text{Planet}} \sim \sqrt{\frac{1}{G_N m_p^2 Z^3 \alpha m_e^2}} \sim \sqrt{\frac{\alpha}{\alpha_G}} \times r_{\text{atom}} \]

Planets/atoms relative size direct result of EM vs gravity strength
Planets

Solids where gravitational pressure balanced by solid pressure

\[ E_{\text{Gravity}} \sim \frac{G_N M_p^2}{R_p} \quad P_{\text{Gravity}} \sim \frac{E_{\text{Gravity}}}{V_{\text{Planet}}} \sim \frac{G_N M_p^2}{R_p^4} \]

\[ M_{\text{Planet}} \sim \rho_{\text{solid}} \times R_p^3 \sim \frac{Z m_p R_p^3}{r_{\text{atom}}^3} \]

\[ P_{\text{Gravity}} \sim \frac{G_N Z^2 m_p^2 R_p^2}{r_{\text{atom}}^6} \]

\[ P_{\text{Gravity}} \sim P_{\text{solid}} \]

\[ R_{\text{Planet}} \sim \sqrt{\frac{1}{G_N m_p^2 Z^3 \alpha m_e}} \sim \sqrt{\frac{\alpha}{\alpha_G}} \times r_{\text{atom}} \]

This is why things are big, despite being governed by microscopic laws
Planets

Solids where gravitational pressure balanced by solid pressure

\[ E_{\text{Gravity}} \sim \frac{G_N M_P^2}{R_P} \quad P_{\text{Gravity}} \sim \frac{E_{\text{Gravity}}}{V_{\text{Planet}}} \sim \frac{G_N M_P^2}{R_P^4} \]

\[ M_{\text{Planet}} \sim \rho_{\text{solid}} \times R_P^3 \sim \frac{Z m_p R_P^3}{r_{\text{atom}}^3} \]

\[ P_{\text{Gravity}} \sim \frac{G_N Z^2 m_p^2 R_P^2}{r_{\text{atom}}^6} \]

\[ P_{\text{Gravity}} \sim P_{\text{solid}} \]

Planets/atoms relative size direct result of EM vs gravity strength

Prediction: \[ r_e \sim 10^7 \text{m} \quad m_e \sim 10^{25} \text{kg} \]
Actual: \[ 6.4 \times 10^6 \text{m} \quad 5.9 \times 10^{24} \text{kg} \]

This is why things are big, despite being governed by microscopic laws
Life

Estimate limit on size of life: Require don't break bones when fall
Life

Estimate limit on size of life: Require don't break bones when fall

\[ E_{\text{fall}} \sim M_{\text{Ag_local}} L_A \]
Life

Estimate limit on size of life: Require don't break bones when fall

\[ E_{\text{fall}} \sim M_A g_{\text{local}} L_A \]

\[ g_{\text{local}} \sim G_N \frac{M_P}{R_P^2} \sim \sqrt{\alpha_G \alpha} \frac{1}{m_p r_{\text{atom}}^2} \]
Life

Estimate limit on size of life: Require don’t break bones when fall

\[ E_{\text{fall}} \sim M_A g_{\text{local}} L_A \]

\[ g_{\text{local}} \sim G_N \frac{M_P}{R_P^2} \sim \sqrt{\alpha G \alpha} \frac{1}{m_p r_{\text{atom}}^2} \]

<table>
<thead>
<tr>
<th>Prediction:</th>
<th>~5 m/s/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual:</td>
<td>9.8 m/s/s</td>
</tr>
</tbody>
</table>
Life

Estimate limit on size of life: Require don't break bones when fall

\[ E_{\text{fall}} \sim M_A g_{\text{local}} L_A \]

\[ g_{\text{local}} \sim G_N \frac{M_P}{R_P^2} \sim \sqrt{\alpha_G \alpha} \frac{1}{m_p r_{\text{atom}}^2} \]

Prediction: \sim 5 \text{ m/s/s}
Actual: 9.8 \text{ m/s/s}

Break bones along cross sectional areas

\[ E_{\text{Break Bones}} \sim N_{\text{atoms cross-section}} \times E_{\text{atom}} \]
Life

Estimate limit on size of life: Require don’t break bones when fall

\[ E_{\text{fall}} \sim M_A g_{\text{local}} L_A \]

\[ g_{\text{local}} \sim G_N \frac{M_P}{R_P^2} \sim \sqrt{\alpha G} \alpha \frac{1}{m_p r_{\text{atom}}^2} \]

Break bones along cross sectional areas

\[ E_{\text{Break Bones}} \sim N_{\text{atoms cross-section}} \times E_{\text{atom}} \]

\[ \sim \left( \frac{L_A}{r_{\text{atom}}} \right)^2 \times \frac{Z\alpha}{r_{\text{atom}}} \]

Prediction: \(~5\) m/s/s
Actual: \(~9.8\) m/s/s
Life

Estimate limit on size of life: Require don't break bones when fall

\[ E_{\text{fall}} \sim M_A g_{\text{local}} L_A \]

\[ g_{\text{local}} \sim G_N \frac{M_P}{R^2_P} \sim \sqrt{\alpha G \alpha} \frac{1}{m_P r^2_{\text{atom}}} \]

Break bones along cross sectional areas

\[ E_{\text{Break Bones}} \sim N_{\text{atoms}} \text{cross-section} \times E_{\text{atom}} \]

\[ \sim \left( \frac{L_A}{r_{\text{atom}}} \right)^2 \times \frac{Z\alpha}{r_{\text{atom}}} \]

\[ E_{\text{Fall}} \sim E_{\text{Break Bones}} \]

Prediction: \ ~5 \ \text{m/s/s}
Actual: \ 9.8 \ \text{m/s/s}
Life

Estimate limit on size of life: Require don't break bones when fall

\[ E_{\text{fall}} \sim M_A g_{\text{local}} L_A \]

\[ g_{\text{local}} \sim G_N \frac{M_P}{R_P^2} \sim \sqrt{\alpha_G \alpha} \frac{1}{m_p r_{\text{atom}}^2} \]

<table>
<thead>
<tr>
<th>Prediction:</th>
<th>(~5) m/s/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual:</td>
<td>(~9.8) m/s/s</td>
</tr>
</tbody>
</table>

Break bones along cross sectional areas

\[ E_{\text{Break Bones}} \sim N_{\text{atoms cross–section}} \times E_{\text{atom}} \]

\[ \sim \left( \frac{L_A}{r_{\text{atom}}} \right)^2 \times \frac{Z \alpha}{r_{\text{atom}}} \]

\[ E_{\text{Fall}} \sim E_{\text{Break Bones}} \]

\[ L_A \sim \left( \frac{\alpha}{\alpha_G} \right)^{\frac{1}{4}} \times r_{\text{atom}} \]

\[ M_A \sim \left( \frac{\alpha}{\alpha_G} \right)^{\frac{3}{4}} \times Z m_p \]
Life

Estimate limit on size of life: Require don't break bones when fall

\[ E_{\text{fall}} \sim M_A g_{\text{local}} L_A \]

\[ g_{\text{local}} \sim G_N \frac{M_P}{R_P^2} \sim \sqrt{\alpha G \alpha} \frac{1}{m_p r_{\text{atom}}^2} \]

| Prediction: | \( \sim 5 \ \text{m/s/s} \) |
| Actual:     | \( 9.8 \ \text{m/s/s} \) |

Break bones along cross sectional areas

\[ E_{\text{Break Bones}} \sim N_{\text{atoms cross-section}} \times E_{\text{atom}} \]

\[ \sim \left( \frac{L_A}{r_{\text{atom}}} \right)^2 \times \frac{Z \alpha}{r_{\text{atom}}} \]

\[ E_{\text{Fall}} \sim E_{\text{Break Bones}} \]

\[ L_A \sim 10 \ \text{cm} \ / \ M_A \sim 100 \ \text{kg} \]

\[ L_A \sim \left( \frac{\alpha}{\alpha_G} \right)^{\frac{1}{4}} \times r_{\text{atom}} \]

\[ M_A \sim \left( \frac{\alpha}{\alpha_G} \right)^{\frac{3}{4}} \times Z m_p \]
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?
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

**Sources:**
- Nima Arkani-Hamed
- John Barrow
- Matt Strassler
- Leonard Susskind
- Frank Tipler
- Steven Weinberg

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

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

Interactions Dictated by principles of symmetry
QFT ⇒ Particle associated w/each interaction (Force Carriers)

\[
\gamma, \ W, \ Z, \ g
\]
Last Time: 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** \((\text{Matter Particles})\)

**Leptons:**
\[
\begin{align*}
& \nu_e \\
& e
\end{align*}
\[
\begin{align*}
& \nu_\mu \\
& \mu
\end{align*}
\[
\begin{align*}
& \nu_\tau \\
& \tau
\end{align*}
\]

**Quarks:**
\[
\begin{align*}
& \text{u} \\
& \text{d}
\end{align*}
\[
\begin{align*}
& \text{c} \\
& \text{s}
\end{align*}
\[
\begin{align*}
& \text{t} \\
& \text{b}
\end{align*}
\]

**Interactions** Dictated by principles of symmetry

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

\[
\begin{align*}
& \gamma \\
& \text{W} \\
& \text{Z} \\
& \text{g}
\end{align*}
\]

Consistent theory of electromagnetic, weak and strong forces ...  
... provided **massless** Matter and **Force Carriers**
Last Time: *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*)

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

**Interactions** Dictated by principles of symmetry

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

\[ \gamma \quad W \quad Z \quad g \]

Consistent theory of electromagnetic, weak and strong forces ...  
... provided **massless** Matter and *Force Carriers*

**Serious problem:** matter and W, Z carriers have Mass!
Today’s Lecture

The Importance of the Higgs
Today’s Lecture

The Importance of the Higgs

“The Higgs Boson (or “God Particle”) is Responsible For All Mass in the Universe”
What’s the Problem with Mass?

All goes back spin  *(Forced on us by QM+R)*
What’s the Problem with Mass?

All goes back spin  \((\text{Forced on us by } \text{QM}+\text{R})\)

Matter particles have spin 1/2.  \(\text{QM} \Rightarrow \text{Only two ways they can spin}\)

Aligned with direction of motion

\[\text{“Right-handed”}\]
What’s the Problem with Mass?

All goes back spin  *(Forced on us by QM+R)*
Matter particles have spin 1/2.  *QM ⇒ Only two ways they can spin*

Aligned with direction of motion  
```
 spin
```
```
 motion
```
“Right-handed”

Against with direction of motion  
```
 spin
```
```
 motion
```
“Left-handed”
All goes back spin \textit{(Forced on us by QM+R)}

Matter particles have spin 1/2. \textit{QM} \Rightarrow \textit{Only two ways they can spin}

\begin{itemize}
  \item Aligned with direction of motion
  \item Against with direction of motion
\end{itemize}

QFT tells us that \textit{massive} particles can flip back and forth…
What’s the Problem with Mass?

All goes back spin (Forced on us by QM+R)
Matter particles have spin 1/2.  \( QM \Rightarrow \text{Only two ways they can spin} \)

Aligned with direction of motion

\( \text{“Right-handed”} \)

Against with direction of motion

\( \text{“Left-handed”} \)

QFT tells us that \textbf{massive} particles can flip back and forth…
What’s the Problem with Mass?

All goes back spin \((\text{Forced on us by } QM+R)\)
Matter particles have spin 1/2. \(QM \Rightarrow \text{Only two ways they can spin}\)

Aligned with direction of motion

```
spin
```

```
motion
```

“Right-handed”

Against with direction of motion

```
spin
```

```
motion
```

“Left-handed”

QFT tells us that \textit{massive} particles can flip back and forth…

```
\text{time}
```

… and the size of the mass sets the rate (probability) for flipping. \textit{The heavier the particle the more it flips.}
What’s the Problem with Mass?

All goes back spin (Forced on us by QM+R)
Matter particles have spin 1/2.  $QM \Rightarrow Only\ two\ ways\ they\ can\ spin$

Aligned with direction of motion

```
Spin
```

```
Motion
```

“Right-handed”

Against with direction of motion

```
Spin
```

```
Motion
```

“Left-handed”

QFT tells us that massive particles can flip back and forth…

… and the size of the mass sets the rate (probability) for flipping.

*The heavier the particle the more it flips.*
What’s the Problem with Mass?

Left-handed particles have Hyper-charge = 1
Right-handed particles have Hyper-charge = 0

Now the crazy part ...

H-charge: 0

Because electrons have Charge

Because electrons have Hyper-charge $Z$

$\gamma$

B/c electrons have Charge
What’s the Problem with Mass?

Left-handed particles have Hyper-charge = 1

Right-handed particles have Hyper-charge = 0

Now the crazy part…

This + particle masses immediately leads to contradiction:

\[ H-charge: \frac{1}{0} \]

Because electrons have Charge

Because electrons have Hyper-charge
What’s the Problem with Mass?

Left-handed particles have Hyper-charge = 1
Right-handed particles have Hyper-charge = 0

Now the crazy part…

B/c electrons have Charge

B/c electrons have Hyper-charge
What’s the Problem with Mass?

Left-handed particles have Hyper-charge = 1
Right-handed particles have Hyper-charge = 0

Now the crazy part…
Left-handed particles have Hyper-charge = 1
Right-handed particles have Hyper-charge = 0
What’s the Problem with Mass?

Left-handed particles have Hyper-charge = 1
Right-handed particles have Hyper-charge = 0

Now the crazy part...
Left-handed particles have Hyper-charge = 1
Right-handed particles have Hyper-charge = 0

B/c electrons have Charge
B/c electrons have Hyper-charge

Only left-handed particles have hyper-charge change!
What’s the Problem with Mass?

Left-handed particles have Hyper-charge = 1
Right-handed particles have Hyper-charge = 0

Now the crazy part...
Left-handed particles have Hyper-charge = 1
Right-handed particles have Hyper-charge = 0

This + particle masses immediately leads to contradiction:

Only left-handed particles have hyper-charge change!
What's the Problem with Mass?

Left-handed particles have Hyper-charge = 1
Right-handed particles have Hyper-charge = 0

Now the crazy part...
Left-handed particles have Hyper-charge = 1
Right-handed particles have Hyper-charge = 0

One hand:
QFT tells us that massive particles can flip back and forth.
SM these have different H-charges ⇒ H-charge not conserved

Other hand:
QFT tells us that all charge must be conserved! (Basic conseq. QM+R)
Get around this with the Higgs Field

Field: mapping of number (or set of numbers) to each point in space

You are familiar with fields:

- Temperature map: number at each location
- Wind map: arrow (pair of numbers) at each location

Warm-up with example of how a field can affect mass
Get around this with the Higgs Field

What is a field?
Field: mapping of number (or set of numbers) to each point in space
Get around this with the Higgs Field

What is a field?
Field: mapping of number (or set of numbers) to each point in space
You are familiar with fields:
- Temperature map: number at each location
- Wind map: arrow (pair of numbers) at each location
Get around this with the Higgs Field

What is a field?

Field: mapping of number (or set of numbers) to each point in space

You are familiar with fields:
- Temperature map: number at each location
- Wind map: arrow (pair of numbers) at each location

Most fields cost energy for being on:
What is a field?

Field: mapping of number (or set of numbers) to each point in space

You are familiar with fields:
- Temperature map: number at each location
- Wind map: arrow (pair of numbers) at each location

Most fields cost energy for being on:

Warm-up with example of how a field can affect mass
Mass from Field: Example

Water molecules are little dipoles:
Mass from Field: *Example*

Water molecules are little dipoles:

Consider only two orientations

- Up-water
- Down-water
Mass from Field: *Example*

Water molecules are little dipoles:

- *Up*-water
- *Down*-water

Consider only two orientations

- Mass of *Up* and *Down* water same
- Space is symmetric
Mass from Field: *Example*

Water molecules are little dipoles:
Consider only two orientations

- *Up-water*
- *Down-water*

- Mass of *Up* and *Down* water same
- Space is symmetric

Now, break the symmetry by external electric field pointing up:

Battery forms Electric Field
Mass from Field: \textit{Example}

Water molecules are little dipoles:

Consider only two orientations

- \textit{Up}-water
- \textit{Down}-water

- Mass of \textit{Up} and \textit{Down} water same
- Space is symmetric

Now, break the symmetry by external electric field pointing up:

- Now, \textit{Down} water more energy (= mass) than \textit{Up} water
Mass from Field: *Example*

Water molecules are little dipoles:

Consider only two orientations

- *Up*-water  
- *Down*-water

- Mass of *Up* and *Down* water same  
- Space is symmetric

Now, break the symmetry by external electric field pointing up:

- Now, *Down* water more energy (= mass) than *Up* water

*Example of how a field can creates mass for a particle*

*Note:* No net force on the water molecule  
Not like the water getting stuck in some kind of molasses!
Mass from Field: *Example*

We know this electric force mediated by photons $\gamma$

Battery forms Sea of $\gamma$
Mass from Field: *Example*

We know this electric force mediated by photons $\gamma$

Photons are constantly being created/absorbed by the charged plates
Mass from Field: *Example*

We know this electric force mediated by photons $\gamma$

Photons are constantly being created/absorbed by the charged plates

Point of view of water molecule:
- Lives in place where can add or remove $\gamma$ with changing anything
- Space (“vacuum”) filled with *Condensate* of photons
Mass from Field: Example

We know this electric force mediated by photons $\gamma$

Photons are constantly being created/absorbed by the charged plates

Point of view of water molecule:
- Lives in place where can add or remove $\gamma$ with changing anything
- Space (“vacuum”) filled with Condensate of photons

Down-water
Mass from Field: *Example*

We know this electric force mediated by photons $\gamma$

Photons are constantly being created/absorbed by the charged plates

Point of view of water molecule:
- Lives in place where can add or remove $\gamma$ with changing anything
- Space (“vacuum”) filled with *Condensate* of photons

In this example, $\gamma$ *condensate* is created by the battery ("Turns field On")
Turning the Higgs Field On

For the Higgs field don't use batteries or charged plate, instead…
Use a trick called “Spontaneous Symmetry Breaking”
Turning the Higgs Field On

For the Higgs field don't use batteries or charged plate, instead…
Use a trick called “Spontaneous Symmetry Breaking”
Turning the Higgs Field On

For the Higgs field don't use batteries or charged plate, instead… Use a trick called “Spontaneous Symmetry Breaking”

Potential Energy of Higgs Field

Zero Field value not minimum

Higgs Field Value
Turning the Higgs Field On

For the Higgs field don't use batteries or charged plate, instead… Use a trick called “Spontaneous Symmetry Breaking”

Potential Energy of Higgs Field

Zero Field value not minimum

The form of the Higgs potential energy enough to turn the field on
Turning the Higgs Field On

For the Higgs field don't use batteries or charged plate, instead… Use a trick called “Spontaneous Symmetry Breaking”

The form of the Higgs potential energy enough to turn the field on

This functional form is also an input to the theory
Turning the Higgs Field On

For the Higgs field don't use batteries or charged plate, instead…
Use a trick called “Spontaneous Symmetry Breaking”

Potential Energy of Higgs Field

Zero Field value not minimum

The form of the Higgs potential energy enough to turn the field on
This functional form is also an input to the theory

Form a condensate (\textit{v-condensate}) just as in our previous example
QM effect related to shape of potential. (Analogous to Superconductivity)
Does all mass come from Higgs Field?
Does all mass come from Higgs Field?

**No!**

Example:

Ultra-light reflective walls

photons (no mass)
Does all mass come from Higgs Field?

No!

Example:

Ultra-light reflective walls

photons (no mass)

Proton:
Does all mass come from Higgs Field?

No!

Example:

Ultra-light reflective walls

photons (no mass)

Proton:

Most of the mass in the universe (protons) not from the Higgs Field!
Higgs Field: Mass to Matter

How does it work for matter particles?
   As in the example, but using the v-condensate
Higgs Field: Mass to Matter

How does it work for matter particles?
   As in the example, but using the v-condensate

Critical Point: v-condensate has hyper-charge = 1
Higgs Field: Mass to Matter

How does it work for matter particles?
As in the example, but using the v-condensate

Critical Point: v-condensate has hyper-charge = 1
Higgs Field: Mass to Matter

How does it work for matter particles?
As in the example, but using the $v$-condensate

Critical Point: $v$-condensate has hyper-charge $= 1$
Higgs Field: Mass to Matter

How does it work for matter particles?
As in the example, but using the $v$-condensate

Critical Point: $v$-condensate has hyper-charge = 1
**Higgs Field: Mass to Matter**

How does it work for matter particles? As in the example, but using the v-condensate

**Critical Point:** v-condensate has hyper-charge = 1
Higgs Field: Mass to Matter

How does it work for matter particles?
As in the example, but using the v-condensate

Critical Point: v-condensate has hyper-charge = 1

Interaction of matter particles w/v-condensate that allows mass
Can change between right and left-handed in a way that conserves charge
Higgs Field: Mass to W & Z

Similar effect gives mass to W/Z particles: One crucial difference. Both Left and Right states of W/Z have hyper charge 0
Higgs Field: Mass to W & Z

Similar effect gives mass to W/Z particles: One crucial difference. Both Left and Right states of W/Z have hyper charge 0

H-charge: 0 1
Similar effect gives mass to W/Z particles: One crucial difference. Both Left and Right states of W/Z have hyper charge 0. Need new particles: “Ω”.

H-charges: 0 1
Higgs Field: Mass to W & Z

Similar effect gives mass to W/Z particles: One crucial difference.
Both Left and Right states of W/Z have hyper charge 0
Need new particles: “Ω”

H-charge: 0

\[ 1 \ 1 \ 0 \]

Diagram:
- W/Z particles are shown with hyper charges.
- "Ω" is introduced as a new particle.
- The diagram illustrates the mass-giving effect through the Higgs field.
Higgs Field: Mass to W & Z

Similar effect gives mass to W/Z particles: One crucial difference. Both Left and Right states of W/Z have hyper charge 0. Need new particles: “Ω”.

H-charge: 0  1  0  1  0
Higgs Field: Mass to W & Z

Similar effect gives mass to W/Z particles: One crucial difference. Both Left and Right states of W/Z have hyper charge 0. Need new particles: “Ω” and “ω”
Higgs Field: Mass to W & Z

Similar effect gives mass to W/Z particles: One crucial difference. Both Left and Right states of W/Z have hyper charge 0

Need new particles: “Ω” and “ω”

Ω and ω are also referred to as “Longitudinal polarizations of W/Z”
What about the Higgs Boson?
What about the Higgs Boson?

What is the probability to scatter $\omega^{+/-}$?

$$\psi = \begin{array}{c}
\omega^+ \\
\omega^+ \\
\omega^+ \\
\omega^+
\end{array} \sim \frac{1}{50} \frac{\text{Energy}}{m_W}$$
What about the Higgs Boson?

What is the probability to scatter $\omega^{+/-}$?

$$\psi = \omega^+ \to \omega^+$$

$$P = |\psi|^2 = \left(\frac{1}{50} \frac{\text{Energy}}{m_W}\right)^2 > 1 \text{ at high E}$$
What about the Higgs Boson?

What is the probability to scatter $\omega$+/-?

$$\psi = \omega^+ \times \omega^+ \times \omega^+ \times \omega^+$$

$$P = |\psi|^2 = \left(\frac{1}{50}\frac{\text{Energy}}{m_W}\right)^2 > 1 \text{ at high } E$$

(putting all the correct factors)

- $P > 1$ when $E \sim 1200$ GeV
- Theory breaking down at $\sim 1$ TeV
- Something clearly missing when we get to 1 TeV
The Higgs Boson

Requires another new particle: $h$
That couples to $\omega^+$

$h$ sound waves is the Higgs field condensate
What about the Higgs Boson?

Have to include all terms:

\[ \psi = \omega^+ \times \omega^+ + \omega^+ \rightarrow h \sim < 1 ! \]

Fixes the inconsistent behavior at high Energy
Have sensible theory again!
The Higgs Boson

What do we know about the Higgs Particle: *A Lot*
The Higgs Boson

What do we know about the Higgs Particle: *A Lot*

Higgs is excitations of $\nu$-condensate

$\Rightarrow$ Couples to matter / W/Z just like $\nu$...
The Higgs Boson

What do we know about the Higgs Particle: \textit{ALot}

Higgs is excitations of $\nu$-condensate
\[ \Rightarrow \text{Couples to matter / W/Z just like } \nu \]

\begin{itemize}
  \item matter: e $\mu$ $\tau$ / quarks
  \item W/Z
  \item $h$ \sim (mass of W or Z)
\end{itemize}

\begin{itemize}
  \item matter \sim (mass of matter)
\end{itemize}
The Higgs Boson

What do we know about the Higgs Particle: A Lot

Higgs is excitations of v-condensate
⇒ Couples to matter / W/Z just like v

Spin: 0 1/2 1 3/2 2
What do we know about the Higgs Particle: \textbf{ALot}

Higgs is excitations of \(v\)-condensate

\[ \Rightarrow \text{Couples to matter} / \text{W/Z just like} \ v \]

\[ \begin{array}{c}
\text{matter: e \(\mu\) \(\tau\) / quarks} \\
\text{bosons} \\
\text{fermions}
\end{array} \]

\[ \begin{array}{c}
\text{Spin:} \\
0 \quad 1/2 \quad 1 \quad 3/2 \quad 2
\end{array} \]
What do we know about the Higgs Particle: *A Lot*

Higgs is excitations of \( \nu \)-condensate

\[ \Rightarrow \text{Couples to matter} / \text{W/Z just like } \nu \]

- **Spin:** 0, 1/2, 1, 3/2, 2

- **Mass/coupling needed for Higgs inconsistent**

- **Graviton**

- Massive Spin-1 in a reason we are in this mess!

- Would need another condensate to explain \( m_H \)

- Spin-0 only thing left / Can have an input mass
The Higgs Boson

What do we know about the Higgs Particle: *ALot*

Higgs is excitations of v-condensate
⇒ Couples to matter / W/Z just like v

- QM+R ⇒ Only 1 Spin-2 interaction allowed: *Graviton*
  Mass/coupling needed for Higgs inconsistent
  Massive Spin-1 in a reason we are in this mess!
  Would need another condensate to explain mH

Spin: 0  1/2  1  3/2  2

matter: e µ τ / quarks

\[ W/Z \]
The Higgs Boson

What do we know about the Higgs Particle: *A Lot*

Higgs is excitations of v-condensate
⇒ Couples to matter / W/Z just like v

\[ \text{matter: } e \mu \tau / \text{quarks} \]

- QM+R ⇒ Only 1 Spin-2 interaction allowed: *Graviton*
  - Mass/coupling needed for Higgs inconsistent
  - Massive Spin-1 in a reason we are in this mess!
    - Would need another condensate to explain mH
  - *Spin-0 only thing left / Can have an input mass*

\[ \text{Spin: } 0 \quad 1/2 \quad 1 \quad 3/2 \quad 2 \]

\[ \text{W/Z} \]
The Higgs Boson

What do we know about the Higgs Particle: **A Lot**

Higgs is excitations of \( \nu \)-condensate

\[ \Rightarrow \text{Couples to matter} / \text{W/Z just like} \nu \]

- **Spin:**
  - 0
  - 1/2 
  - 1
  - 3/2
  - 2

Only thing we don’t *(did\(\text{n’t}!)* know is the value of \(m_H\)

- **Bosons**
  - QM+R \( \Rightarrow \) Only 1 Spin-2 interaction allowed: *Graviton*
  - Mass/coupling needed for Higgs inconsistent
  - Massive Spin-1 in a reason we are in this mess!
  - Would need another condensate to explain \(m_H\)

- **Fermions**

\(\nu\): e \(\mu\) \(\tau\) / quarks
“The Higgs Boson (or “God Particle”) is Responsible For All Mass in the Universe”
“The Higgs Boson (or “God Particle”) is Responsible For All Mass in the Universe”
Field

^

“\textit{The Higgs Boson (or \textit{“God Particle”}) is Responsible For All Mass in the Universe}”
“The Higgs Boson (or “God Particle”) is Responsible For All Mass in the Universe”

Some (Very Important!) Mass
Field

“The Higgs Boson (or “God Particle”) is Responsible For All Mass in the Universe”

Some (Very Important!) Mass

\[ L_A \sim \left( \frac{\alpha}{\alpha_G} \right)^{\frac{1}{4}} \times \frac{1}{Z\alpha m_e} \]