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

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

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

2012: Discovered new particle consistent with expectations

Since then: Significant improvement in sensitivity
Agreement with Higgs interpretation ~20% level
No sign of any deviations
What it Took: In Numbers

- >10,000 scientists and engineers from 85 countries
- 27 kilometer particle accelerator
- Protons moving at 99.9999993% the speed of light
- ~1 billion proton collisions / second (for 2 years)
- Total budget: ~10 billions dollars
- Detectors - size of apartment buildings - operating at 40 MHz
- Generate 80 TB/s (~10 × size of library of congress )
- (Salary of physicist) << (Salary of banker or engineer)

What is the Higgs boson ?!?
Why did we need such extremes to find it ?
Why look for the Higgs boson in the first place ?
Are we done now that we have found it ?

Focus of last two lectures
Today’s Lecture

Problems with the Standard Model
Length Scales

Standard Model (After Higgs Discovery)

Standard Model (Before Higgs Discovery)

Failure WW scattering

~unexplored

LHC Directly Probed Experimentally

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

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

Planck scale \( \sqrt{G_N} \)

weak-scale

nuclei

atoms

cells

animals

planets

stars

solar systems

galaxies

observable universe

Length Scales

~unexplored

Failure WW scattering

(In principle)
Fundamental Length Scales

Standard Model (After Higgs Discovery)
- Directly Probed Experimentally

Standard Model (Before Higgs Discovery)
- Failure WW scattering
- ~unexplored
- LHC

Planck scale
- $10^{-20}$ GeV$^{-1}$
- $(10^{-36}$ m

Weak scale
- $10^{-3}$ GeV$^{-1}$
- $(10^{-19}$ m

LHC exciting both because:
- it is the frontier but also
- exploring fundamental scale of nature

Weak scale: Fundamental scale in physics
- Scale associated with fundamental particle masses
- Typical at which massive particles interact with Higgs field
- The first time start seeing the forces have same underlying structure
- Large range, but not infinite.
- Claim: Everything we know, *and can possibly know*, within this range
- Upper bound set by finite upper speed limit (finite age of universe)
- Talk about lower bound, next. Believed to really be hard lower bound
- Deep mysteries/problems with SM directly associated with each fundamental scale
Problem with the Planck Scale
Relative Strength of Gravity

Electromagnetic Interaction

At short distances, (comparable to \( \ell_{\text{Pl}} \)) gravitational interaction dominates - \( \ell_{\text{Pl}} \) the scale at which gravity is becoming strong

\[
F_{\text{EM}} = \frac{e^2}{4\pi r^2}
\]

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

Gravitational Interaction

Distance GeV\(^{-1}\)

\[
G_N \sim (l_{\text{Pl}})^2 \sim (10^{-20} \text{ GeV}^{-1})^2
\]

Uncertainty principle kicks in. Takes E (=m) to keep together
Probing Smaller Distance Scales

- Say we decided to probe smaller and smaller distance scales
- Build collider, go to higher and higher energies
- Eventually reach point where gravitational interaction dominates
- Continue to smaller distance … then something new happens…
Some point put so much energy into collisions that you create black hole
Estimate scale when this happens:

\[ G_N \frac{m^2}{r} \sim mc^2 \]

At high energies, mass dominated by E associated w/uncertainty principle

\[ m \sim \frac{1}{r} \]

\[ G_N \frac{1}{r^3} \sim \frac{1}{r} \]

\[ r \sim \sqrt{G_N} \sim l_{Pl} \]
Probing Smaller Distance Scales

- Go to higher-higher energies... Gravity begins to dominate
- At ℓ_{Pl} make blackhole / Cant tell what's happening in blackhole
- Even higher energies gives bigger blackhole
- Nothing can do (in principle) to get information about smaller scales
  - *Physics telling us that smaller scales don't exist*

(Seen kind of thing before in QM and Relativity)
Probing Smaller Distance Scales

Lower Limit to Spacetime
Notion of space-time breaking down $\ell_{Pl}$ /Not clear what replaces it.

Major issue:
- Understanding of these short scales needed for:
  - Early universe: *What happened when universe curvature $\ell_{Pl}$*
  - Details of blackholes
- Physics is about what happens in space-time

Other hints that some dramatic need ("Holographic Principle")
- Black hole information scales like area
- Observables with QM can in principle perfectly predict
- Toy models where see space emerging
- …

(Seen kind of thing before in QM and Relativity)
Problems with Weak and Hubble Scales

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

- In turn, major implications on the vacuum:

\[ \Delta E > 2m_e c^2 \]
\[ \Delta E > 2m_\mu c^2 \]
Vacuum Fluctuations ARE REAL!

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

50 \quad 150 \text{ GeV} 

115 \text{ GeV} \quad \text{(Discovered)}
Vacuum Has Energy

Classically (w/o QM)

Minimum non-zero energy: $E \sim h\omega$

Lowest possible energy is 0

Quantum World

Estimate energy density in region of empty space: Dimensional Analysis

Smaller Box

Reach: Cut-off

$\Lambda \sim \frac{E}{V} \sim \frac{1}{L^4}$

$(V \sim L^3)$

$(E \sim \frac{1}{L})$

$\Lambda$ much bigger

$\ell_{Pl} \sim \frac{1}{L^4}$

$\Lambda \sim \frac{1}{\ell_{Pl}^4}$

...this is a problem
Cosmological Constant Problem

Without gravity constant energies ($\Lambda$) can be ignored \textit{(overall offset)}
With gravity, constant energy warps space-time, interacts gravitationally

Uniform matter/energy controls size/expansion of overall Universe

$$t_{\text{Double}} \sim \frac{1}{\sqrt{G_N \Lambda}}$$
$$\sqrt{\ell_{\text{Pl}}^2 \Lambda}$$

- Naive cut off at $\ell_{\text{Pl}}$: $t_{\text{Double}} \sim 10^{-43} \text{ s}$
  (would be bad for atoms/planets/people…)

- Conservative cut-off at 100 GeV: $t_{\text{Double}} \sim 10 \text{ ns}$
  (would be bad for atoms(?)/planets/people…)

Measured: $t_{\text{Double}} \sim 10^{10} \text{ years} \Rightarrow \text{cut off of } 10\mu\text{m}$!
Cosmological Constant Problem

How do we deal with this in the current theory?

\[ \Lambda = \Lambda_{\text{QM}} + \Lambda_{\text{Classical}} \]

- \( \Lambda_{\text{QM}} = 3.342\,862\,210 \ldots 554\ldots \times \ell_{\text{Pl}}^{-4} \)
- \( \Lambda_{\text{Classical}} = 3.342\,862\,210 \ldots 541\ldots \times \ell_{\text{Pl}}^{-4} \)

from the vacuum fluctuations

Constant. Input parameter to theory
Cosmological Constant Problem

How do we deal with this in the current theory?

\[ \Lambda_{\text{QM}} + \Lambda_{\text{Classical}} = 3.342862210\ldots 554\ldots - 3.342862210\ldots 541\ldots \]

How do we deal with this in the current theory?

- from the vacuum fluctuations
- Classical
- Input parameter to theory

“Fine Tuning”

Planck scale: \(10^{-20} \text{ GeV}^{-1} (10^{-36} \text{ m})\)
Weak scale: \(10^{-3} \text{ GeV}^{-1} (10^{-19} \text{ m})\)
Hubble scale: \(10^{41} \text{ GeV}^{-1} (10^{25} \text{ m})\)

\[\text{?}\]

Why is the universe so big?
Vacuum Fluctuations: Higgs Particle

Closely related problem

Vacuum fluctuations of Higgs mass ($m_H^2$)

$$m_H^2 = 2.569678321 \ldots 554\ldots \times \ell_{Pl}^2$$

+ 60 digits

- $2.569678321 \ldots 453\ldots \times \ell_{Pl}^2$

60 digits

- Estimated mass corrections unreasonably large
- Instability of the Higgs mass

Particular to Spin-0 particles
- Spin 1/2 Protected by charge conservation.
  Need interactions with $\nu$ to get their mass
- Spin 1, 3/2, 2: need needed the extra particles $\omega/\Omega$-from

$$\sim \Lambda^2 \Rightarrow m_H \sim 10^{20} \text{ GeV}$$

new heavy particle

$$m_H \sim m_X$$
Vacuum Fluctuations: Higgs Particle

Closely related problem

Vacuum fluctuations of Higgs mass ($m_H^2$)

Without “small scale” physics
(only gravity + pencil DoF)
- Bizarre, but stable
- Suggests fine tuning

Higgs mass in SM

Including physics at smaller scales
(vibrations/ air molecules / atoms)
- Quickly lead to instability
- Suggests active mechanism
  (eg: glue / string)

Higgs mass including new, high mass scale physics

- Bizarre, but stable
- Suggests fine tuning

Without "small scale" physics

Instability of the Higgs mass

New heavy particle

$m_H \approx m_X$
Vacuum Fluctuations: Higgs Field

Another way of talking about same problem
Can perform similar estimate for scale of interaction with condensate $v$
Same logic $\Rightarrow$ Scale should be set by the cut-off in the theory

Naively, $\Lambda \sim \ell_{\text{Pl}}$ :

$\sim \frac{1}{\Lambda}$

$\sim \frac{1}{\ell_{\text{Pl}}} \sim 10^{-20} \text{ GeV}^{-1} \sim 10^{-36} \text{ m}$

Measured scale of: $\sim 10^{-3} \text{ GeV}^{-1} \sim 10^{-19} \text{ m}$

$\Lambda \sim \ell_{\text{Pl}}$ would be bad for atoms/planets/people... all blackholes

$\frac{F_G}{F_{\text{EM}}} \sim (\ell_{\text{Pl}}^2 \Lambda^2)$

Expect: $\sim 1$

Observe: $\sim 10^{-34}$
Vacuum Fluctuations: Higgs Field

Another way of talking about same problem

Weakness of gravity directly responsible
\sim all structure around us

\[ R_{\text{Planet}} \sim \sqrt{\frac{\alpha}{\alpha_G}} \times r_{\text{atom}} \]

Why is gravity so weak?

"Hierarchy Problem"

Observe: \sim 10^20 GeV^{-1} (10^{-36} m)

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

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

Planck scale
weak scale
Hubble scale
Length Scales

Quantum Mechanics + Space-time leads us to expect:

Planck scale ~ weak scale ~ Hubble scale

We observe:

Planck scale  $\sim 10^{17}$  weak scale  $\sim 10^{44}$  Hubble scale

Current theory accounts for huge difference w/implausible cancellation

*Need modifications QM or Space-time to avoid fine tuning*
What scale do we need Modification?

\[ m_H = \text{--------------------------------} + \text{--------------------------------} \]

\[ \sim \text{weak-scale} \]

\[ m_{H_{\text{Classical}}} \sim \Lambda^2 \]

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

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

\( (10^{-19} \text{ m}) \)
Most natural explanation requires new physics at $10^{-3} \text{ GeV}^{-1}$ ($10^{-19} \text{ m}$)