The Higgs Boson, the Origin of Mass, and the Mystery of Spontaneous Symmetry Breaking

Felix Yu
Theoretical Physics Department
Fermilab

Ask-A-Scientist Public Talk
November 3, 2013
Nobel Prize 2013 – F. Englert, P. Higgs

“for the theoretical discovery of a mechanism that contributes to our understanding of the **origin of mass** of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider”

(emphasis added)
Higgs Kibble Guralnik Hagen Englert Brout†

“for elucidation of the properties of spontaneous symmetry breaking in four-dimensional relativistic gauge theory and of the mechanism for the consistent generation of vector boson masses” (emphasis added)
What does it all mean?

• Origin of mass?
• Spontaneous symmetry breaking?
• My goal is to decipher these phrases for you
• At the end, we’ll see how the Higgs ties it all together
What are we made of?

• Beneath our skin, organs, bones, blood, etc., we’re all made of...
What are we made of?

- Beneath our skin, organs, bones, blood, etc., we’re all made of...
- **Cells**, which in turn are made of...

Picture credit: wikipedia.org
What are we made of?

- Beneath our skin, organs, bones, blood, etc., we’re all made of...
- Cells, which in turn are made of...
- **Molecules**, which themselves are composed of...

Picture credit: wikipedia.org
What are we made of?

- Atoms...

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**Picture credit:** NIST
What is *everything* made of?

- **Atoms...**

shocking to realize that everything you can hold and touch is made of atoms (!)
What is *everything* made of?

- **Atoms...**

  shocking to realize that everything you can hold and touch is made of atoms (!)

Notable exception: Light!

Picture credits: FNAL and NASA
What are atoms made of?

- Atoms are composed of protons, neutrons, and electrons

Picture credit: wikipedia.org
What are atoms made of?

- Atoms are composed of **protons, neutrons, and electrons**
  - Electrons are fundamental... but what about protons and neutrons?
Protons and neutrons are not elementary!

- Instead, they disintegrate into quarks and gluons at very high energies.
- Studying high energy collisions, we have established the existence of six quarks, six leptons, four force-carrier particles (vector bosons), and one Higgs.
  - The quarks and leptons are grouped into three families.
  - The force-carrier particles are grouped into the strong (color) force, the weak force, and the electromagnetic force.
- The graviton (force-carrier for gravity) has not been discovered.
The Standard Model
Particle physics

- Particle physics takes these building blocks and studies how all of these particles *interact* and their properties.
- Critically, we also search for new *particles* and new interactions.

Fermilab is America’s only dedicated particle physics laboratory.

Picture credit: FNAL
The origin of mass question has two aspects
- Masses for the weak force-carriers
- Masses for the quarks and charged leptons

Picture credit: wikipedia.org
The origin of mass question has **three aspects**

- Masses for the weak force-carriers
- Masses for the quarks and charged leptons
- Mass of the Higgs boson: **open question**!
Origin of mass

• The origin of mass question has two four(!) aspects
  – Masses for the weak force-carriers
  – Masses for the quarks and charged leptons
  – Mass of the Higgs boson: open question!
  – Masses of neutrinos: open question!

Picture credit: wikipedia.org
Origin of mass

• The origin of mass question has two four(!) aspects
  – Masses for the weak force-carriers
  – Masses for the quarks and charged leptons
  – Mass of the Higgs boson: open question!
  – Masses of neutrinos: open question!
What's the issue?

- Original papers of Englert, Brout; Higgs from 1964
• We can envision a **probability calculator** (e.g. theorist with a pencil and paper) for **interactions** (e.g. something to happen)

**Start**

**Outcome**

A black card

What’s the probability?
Probability

• We can envision a probability calculator (e.g. theorist with a pencil and paper) for interactions (e.g. something to happen)

Start

Outcome

What’s the probability?

50%

Picture credit:
andyhodgson2000.wordpress.com/2013/02/15/why-people-are-fooled-by-magic-tricks/
Probability

- We can envision a **probability calculator** (e.g. theorist with a pencil and paper) for **interactions** (e.g. something to happen)

![Playing cards](https://andyhodgson2000.wordpress.com/2013/02/15/why-people-are-fooled-by-magic-tricks/)

**Start**

**Outcome**

What’s the probability?

Picture credit: andyhodgson2000.wordpress.com/2013/02/15/why-people-are-fooled-by-magic-tricks/
We can envision a **probability calculator** (e.g. theorist with a pencil and paper) for **interactions** (e.g. something to happen)

**Start**

**Outcome**

- An ace

**What’s the probability?**

1/13
The problem of force-carrier masses in theories without a Higgs field

- What happens if we start with a $W^+$ and $W^-$ pair of massive force-carriers and ask for a final state of a $W^+$ and $W^-$ pair?

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What’s the probability?
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What’s the probability?

Probability > 100% if the interaction energy is about 700 GeV
The problem of force-carrier masses in theories without a Higgs field

- What happens if we start with a $W^+$ and $W^-$ pair of massive force-carrying and ask for a final state of a $W^+$ and $W^-$ pair?

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This nonsensical result of our calculation means the theory is incomplete.

What’s the probability?

Probability $> 100\%$ if the interaction energy is about 700 GeV.
What’s missing? The Higgs field

• We require some **new interaction** of massive vector particles that **subtracts** from the total probability (**an interference effect**)

• The interaction with **the Higgs field provides this subtraction**

• If the mass of the vector particle is provided in a particular way – i.e. **via spontaneous symmetry breaking** – then **this subtraction is guaranteed**
  
  – More technically: The specific problem arises from the third polarization mode of the \( W^\pm \) and \( Z \) bosons
    
    • This third polarization mode only exists if the boson is massive
  
  – The key is that the third mode is arises from the Higgs field after spontaneous symmetry breaking
Switching to fermions...

- All fermions (spin ½ particles) **start out massless** in the Standard Model
  - Every massless particle travels at the speed of light
  - Since fermions have spin, their spin can be either along or against their direction of motion
    - This is called **chirality**: right-handed if along, left-handed if against
- The underlying symmetry of the $W^\pm$ and $Z$ force-carriers is also chiral
  - So the **same symmetry** that wants to keep the $W^\pm$ and $Z$ force-carriers **massless** also wants to keep the fermions **massless**
- If we break this symmetry spontaneously, we simultaneously give fermions masses
  - The Higgs field serves **double duty** in the origin of mass question
Spontaneous symmetry breaking?

- So the origin of mass relies on the Higgs field spontaneously breaking the weak force symmetry.
- Then what is spontaneous symmetry breaking?
  - We’ll start with “symmetry”
  - Then “symmetry breaking”
  - Finally, “spontaneous symmetry breaking”
Symmetry

- Symmetries abound in everyday life (we’re very good at pattern recognition)
- Symmetries of shapes are easy to spot
Symmetry breaking

• But symmetry breaking is interesting (and fun!)
• “A chain is only as strong as its weakest link”

Picture credit
http://insider.zurich.co.uk/market-expertise/supply-chainshelping-clients-manage-their-weakest-link/
Symmetry breaking

• Suppose we wanted to make a **square** hole with a **round** bit
• Is this possible?
Symmetry breaking

• Suppose we wanted to make a **square** hole with a **round** bit
• Is this possible? **No...**
Suppose we wanted to make a **round** hole with a **square** bit

Is *this* possible?
Symmetry breaking

• Suppose we wanted to make a round hole with a square bit
• Is this possible? Yes!
• Have to consider the starting point and the possible ways to manipulate the starting point (e.g. the possible transformations)
Symmetry and symmetry breaking in laws

• The interactions among the particles of the Standard Model are defined by symmetry properties of the particles
  – like chiral symmetry, weak force symmetry

• But symmetries in laws do not necessarily imply symmetries of outcomes
Symmetries in laws do not necessarily imply symmetries of outcomes

- Ferromagnets spontaneously get a magnetic field
  - “✘” represents a North-South mini-magnet
  - “☐” represents a South-North mini-magnet

To begin, flip a coin

Demonstration taken from C. Quigg – April 4, 2012; Picture credit: wikipedia.org
Neighborly Interactions

• These are the laws that govern how your mini-magnet changes over time.

Demonstration taken from C. Quigg – April 4, 2012
Ising model animation

• We’ve seen how a random starting point can lead to a net magnetization, even though the interactions don’t prefer one magnetization over another (laws are symmetric!)

• Key idea is the interactions enhance any small, local magnetization

In a similar way, the Higgs field starts in a weak symmetric state, but rolls away into a state of broken weak symmetry.
Higgs and spontaneous symmetry breaking

• In a similar way, the Higgs field starts in a weak symmetric state, but rolls away into a state of broken weak symmetry
  – Remember the weak symmetry was exactly the symmetry that required the $W^\pm$ and $Z$ force-carriers to be massless and required the fermions to be massless

• So today, we live in an “initial state” (the ground state of nature) inherently breaks this symmetry

• Thus the Higgs field is responsible for origin of mass via the mechanism of spontaneous symmetry breaking
Switching gears… the fate of the universe

- The universe has a phase diagram

  - The Higgs potential (controls how the Higgs field rolls around) changes depending on the distance scale

Picture credits
http://startswithabang.com/?p=776; Buttazzo, et. al. – 1307.3536
The fate of the universe

- Knowing the Higgs mass and the top quark mass, we can look at the Higgs potential at smaller and smaller length scales

**Stability** – our ground state is the lowest valley in the potential

**Meta-stability** – our ground state is not the lowest valley in the potential, but an intermediate hill exists that keeps us from rolling over (for a long time)

**Instability** – we should have rolled over already

Picture credit: Buttazzo, et. al. – 1307.3536
Summary (1 of 2)

• With the Higgs discovery, the Standard Model of particle physics is complete, but many more discoveries remain.

• The Higgs particle confirms the existence of the Higgs field and the mechanism of spontaneous symmetry breaking generating the masses of elementary particles.
  – Except the Higgs and neutrino masses!

• Particle physicists are eagerly continuing efforts at Fermilab and worldwide to find answers to these modern puzzles and more.
• The primary reason for particle physics is not a commercial benefit to society (unfortunate!)

• Instead, the currency of particle physics is thought
  – Many past examples of how our concept of the universe and how we view ourselves was changed because of a new particle physics discovery
Summary (2 of 2)

• The primary reason for particle physics is not a commercial benefit to society (unfortunate!)
• Instead, the currency of particle physics is thought
  – Many past examples of how our concept of the universe and how we view ourselves was changed because of a new particle physics discovery

Thank you for your time and attention!