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

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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)

J. J. Sakurai Prize 2010

Higgs Kibble Guralnik Hagen Englert Brout†

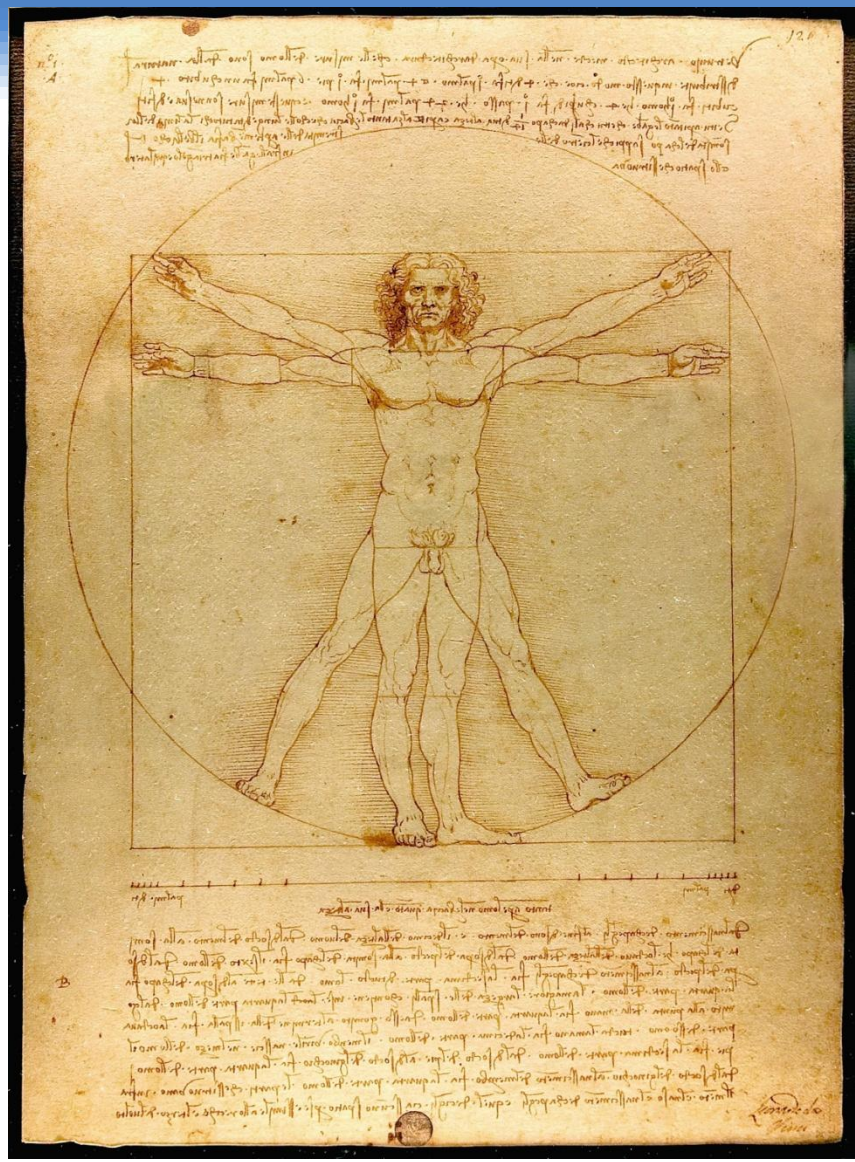
"for elucidation of the properties of ***spontaneous symmetry breaking*** in four-dimensional relativistic gauge theory and of the mechanism for the consistent generation of vector boson masses" (emphasis added)

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?

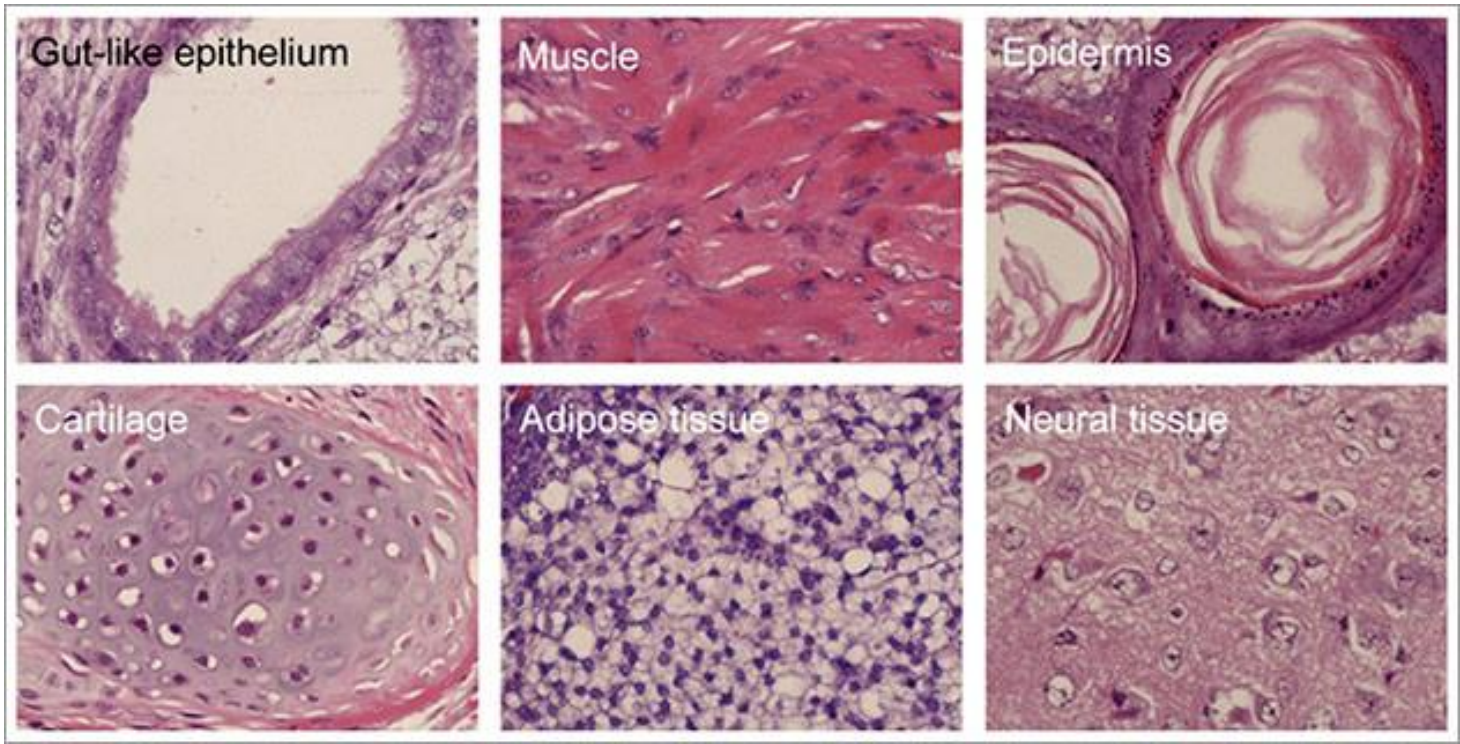
- Beneath our **skin, organs, bones, blood, etc.**, we're all made of…



Picture credit: wikipedia.org

What are we made of?

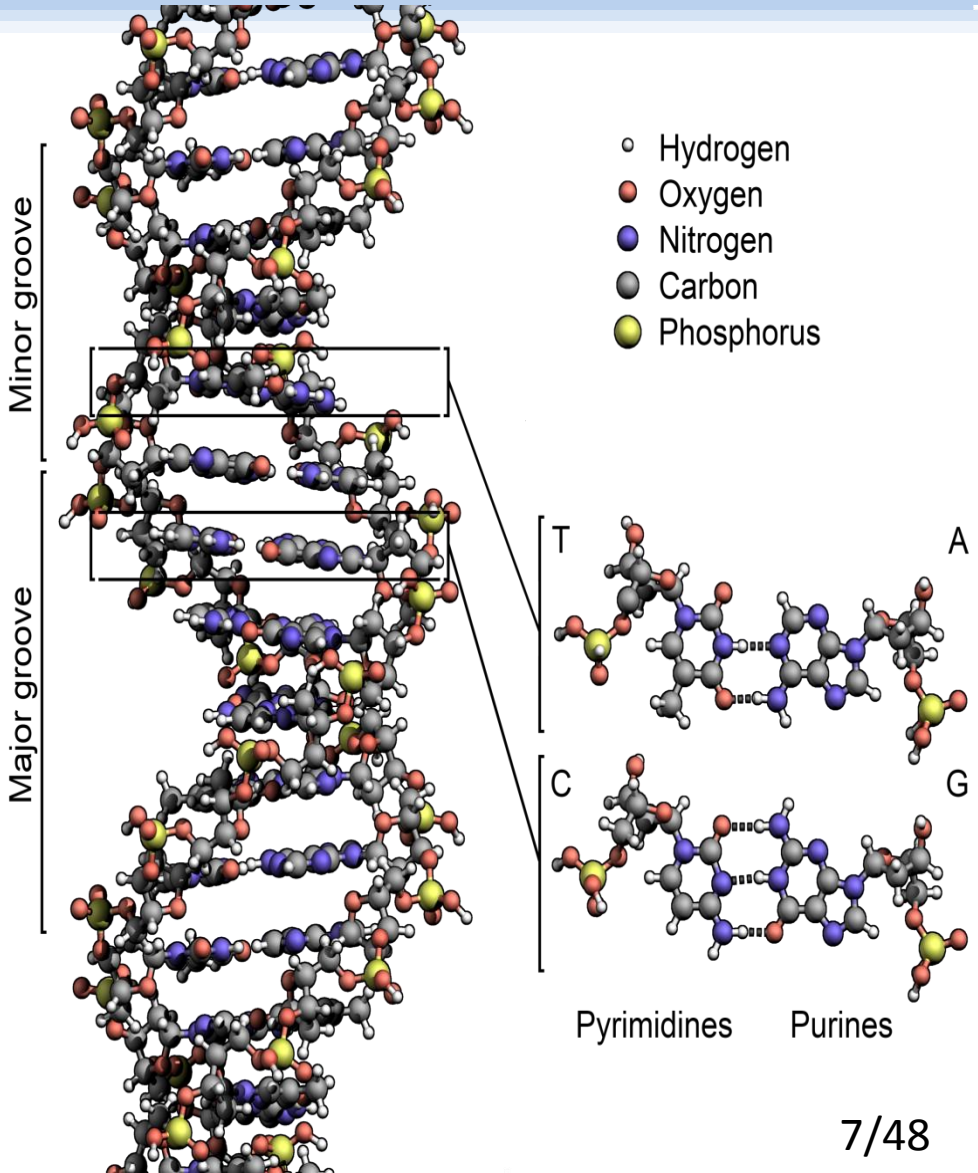
- Beneath our skin, organs, bones, blood, etc., we're all made of…
- **Cells**, which in turn are made of…



Picture credit: wikipedia.org

What are we made of?

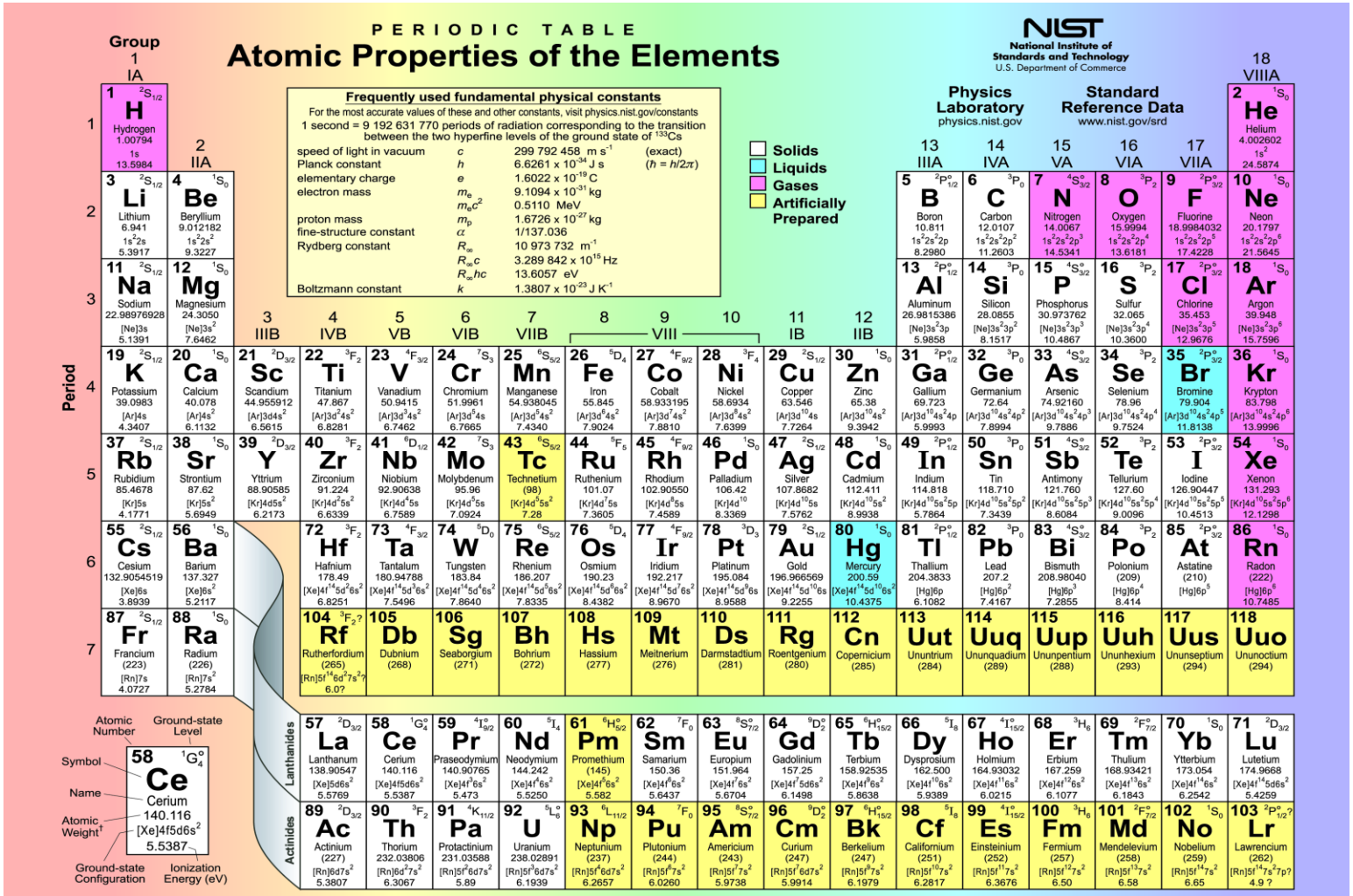
- Beneath our skin, organs, bones, blood, etc., we're all made of…
- Cells, which in turn are made of…
- **Molecules**, which themselves are composed of…



Picture credit: wikipedia.org

What are we made of?

- **Atoms…**



Picture credit: NIST

What is ***everything*** made of?

- **Atoms…**

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

Picture credits:
FNAL and NASA

What is ***everything*** made of?

- **Atoms…**

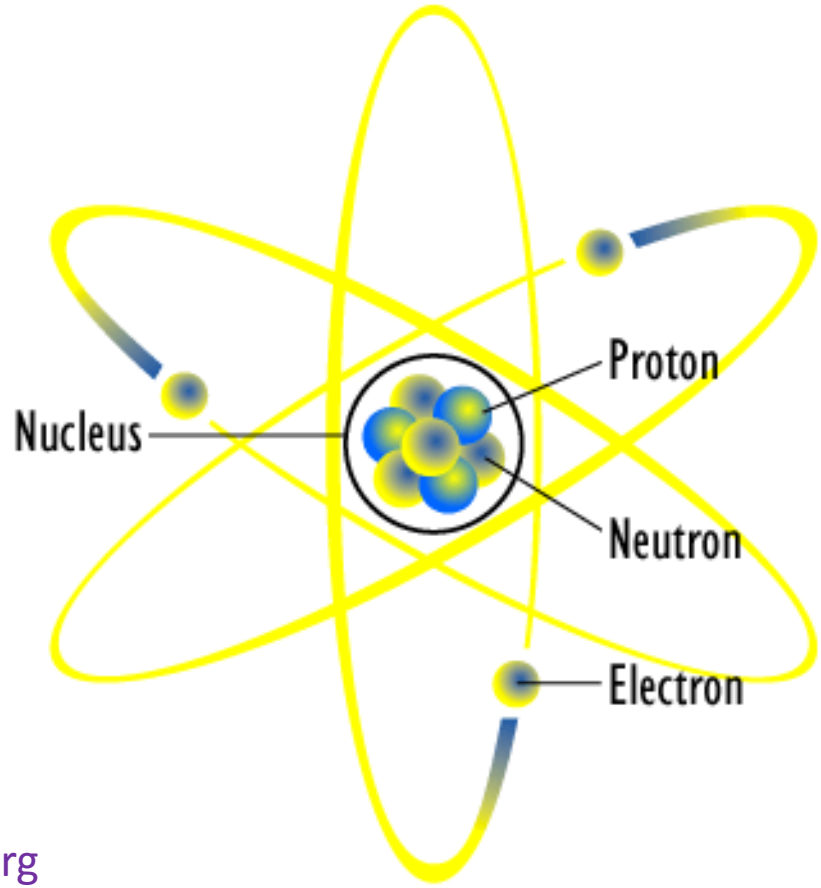
shocking to realize that everything you can hold and touch is made of atoms (!)

Notable exception: Light!

Picture credits:
FNAL and NASA

What are atoms made of?

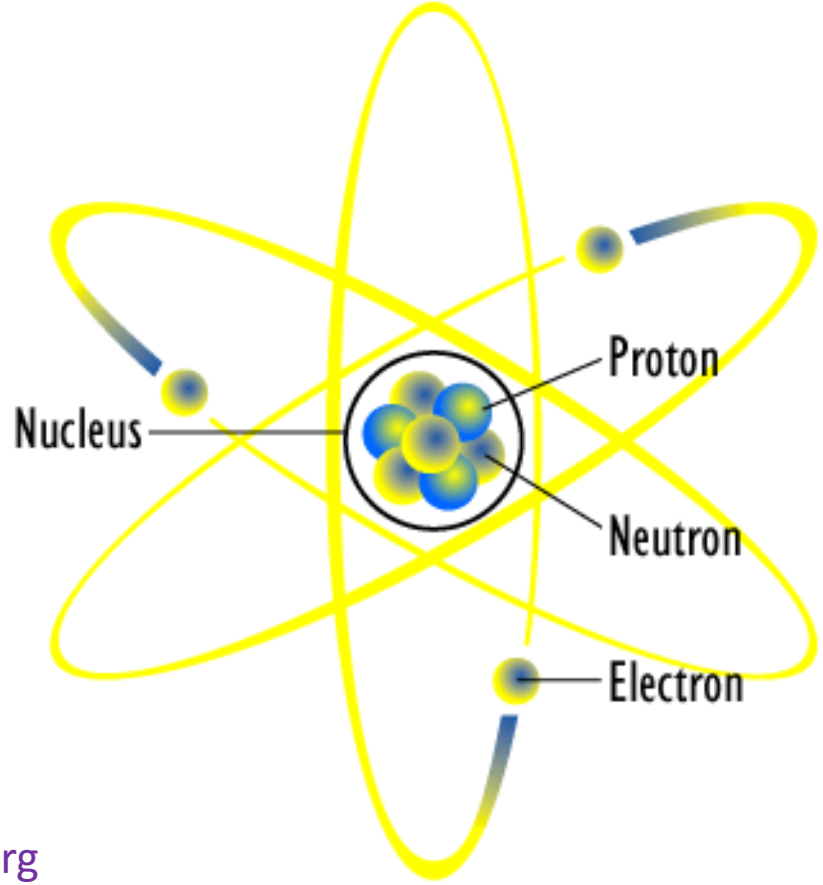
- Atoms are composed of **protons, neutrons, and electrons**



Picture credit: wikipedia.org

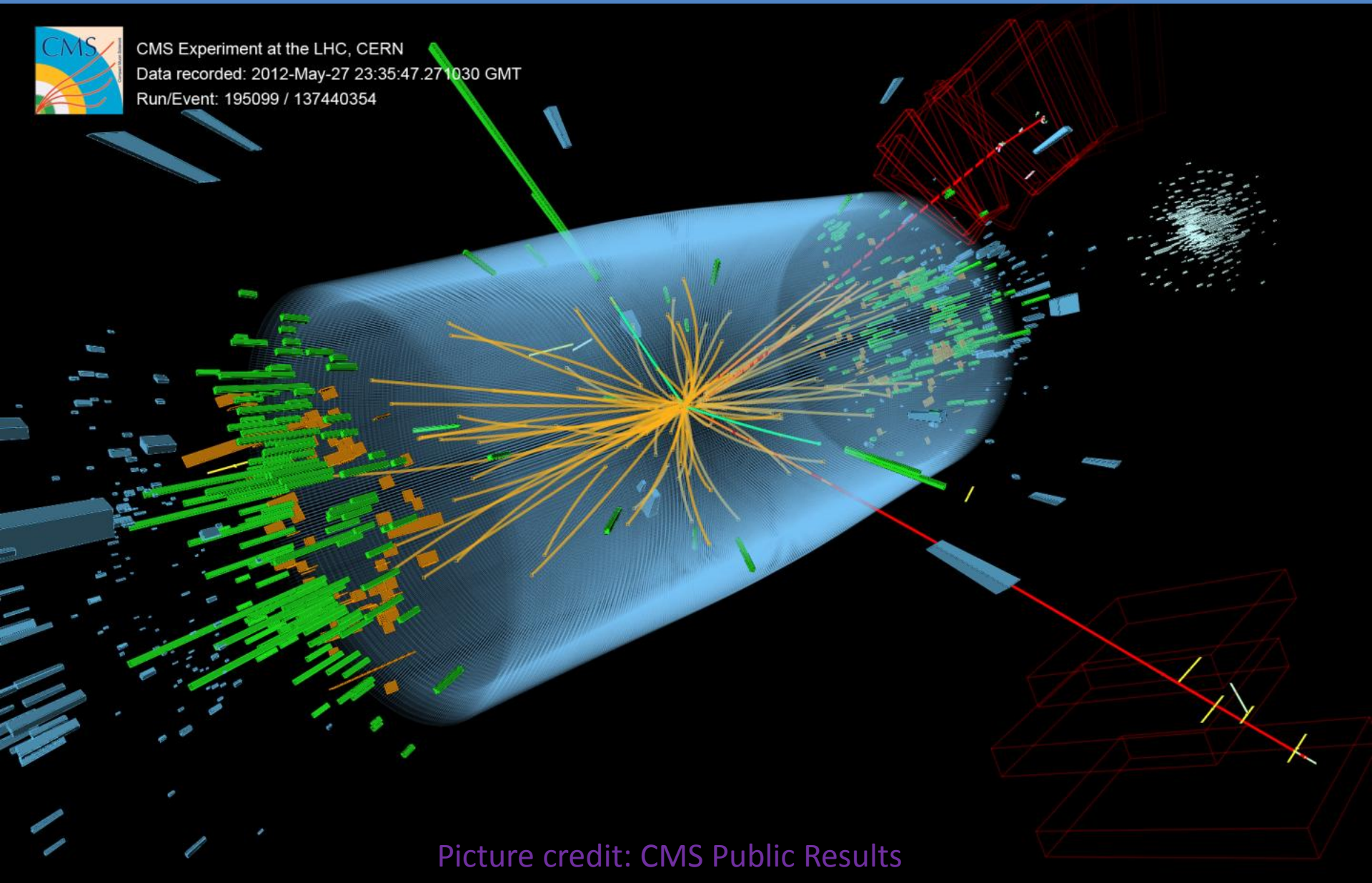
What are atoms made of?

- Atoms are composed of **protons, neutrons, and electrons**
  - Electrons are fundamental… but what about protons and neutrons?



Picture credit: wikipedia.org

Smashing protons

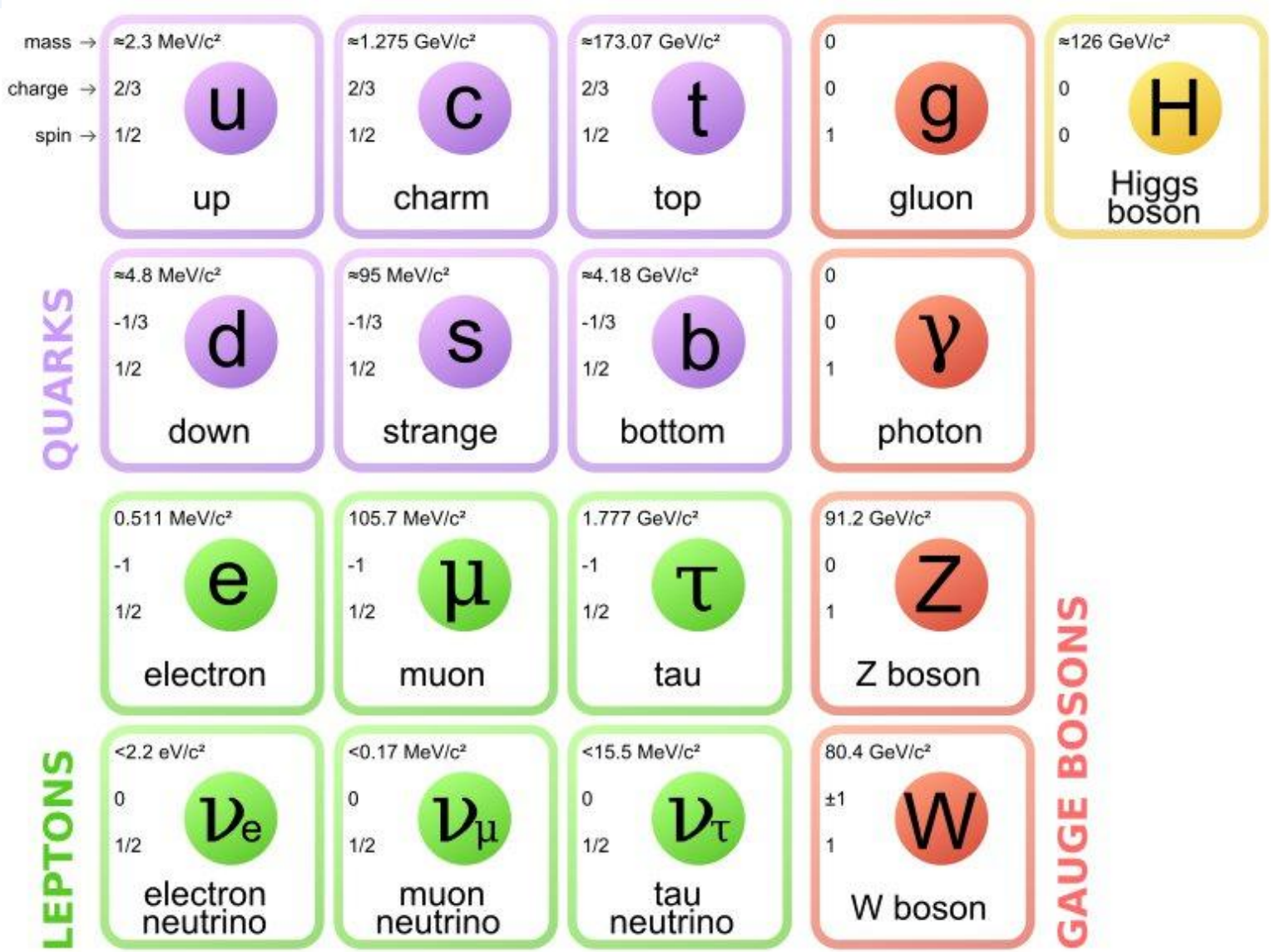


Picture credit: CMS Public Results

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



Picture credit: wikipedia.org

Particle physics

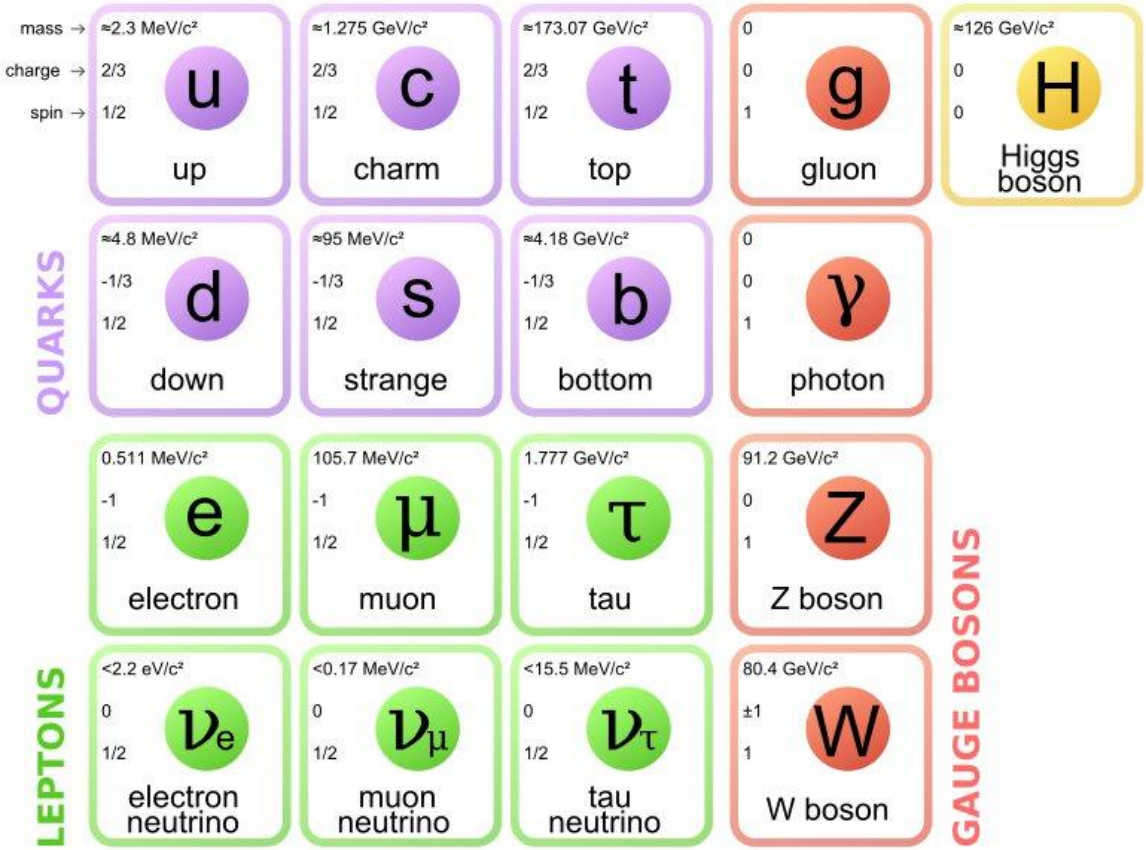
- Particle physics takes these building blocks and studies how all of these particles **interact** and their **properties**
- Critically, we also search for new **particles** and new **interactions**

Fermilab is America's only dedicated particle physics laboratory

Picture credit: FNAL

Origin of mass

- 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

Origin of mass

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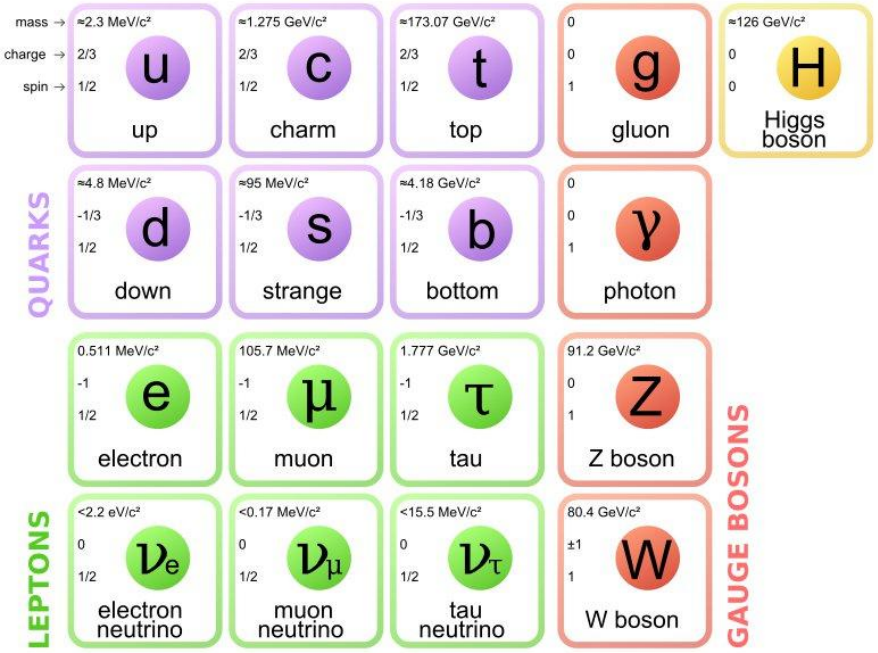
  - Masses for the quarks and charged leptons
  - Mass of the Higgs boson: **open question**!



Picture credit:
wikipedia.org

Origin of mass

- The origin of mass question has ~~two~~ four(!) aspects
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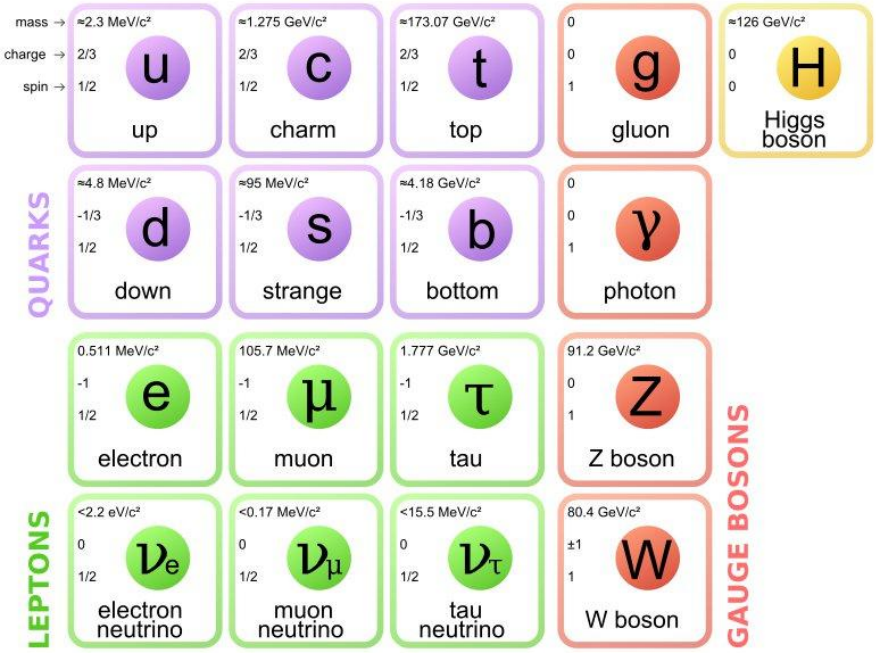
  - Masses of neutrinos: **open question!**



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Origin of mass

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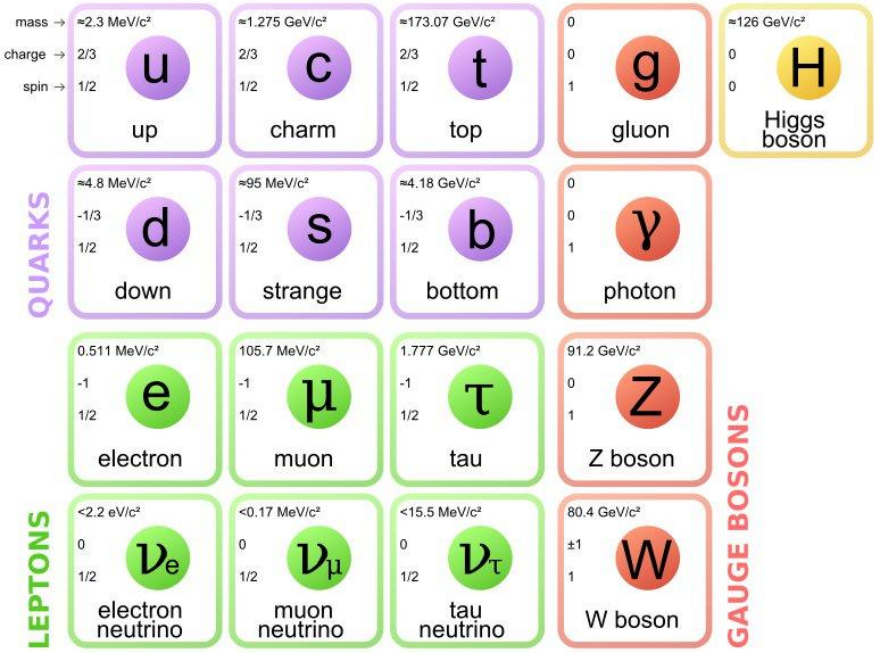

Picture credit: wikipedia.org

What's the issue?

- Original papers of Englert, Brout; Higgs from 1964

VOLUME 13, NUMBER 9 PHYSICAL REVIEW LETTERS 31 AUGUST 1964

BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

F. Englert and R. Brout
Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium
(Received 26 June 1964)

It is of interest to inquire whether gauge vector mesons acquire mass through interaction[1]; by a gauge vector meson we mean a Yang-Mills field[2] associated with of a Lie group from global to loca The importance of this problem r possibility that strong-interactio inates from massive gauge fields system of conserved currents.[3] I we shall show that in certain cas mesons do indeed acquire mass v uum is degenerate with respect t Lie group.

those vector mesons which are coupled to currents that "rotate" the original vacuum are the ones which acquire mass [see Eq. (6)].

VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1964

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)

In a recent note[1] it was shown that the Goldstone theorem,[2] that Lorentz-covariant field theories in which spontaneous breakdown of symmetry under an internal Lie group occurs contain zero-mass particles, fails if and only if the conserved currents associated with the internal group are coupled to gauge fields. The purpose of the present note is to report that, as a consequence of this coupling, the spin-one quanta of some of the gauge fields acquire mass; the longitudinal degrees of freedom of these particles (which would be absent if their mass were zero) go over into the Goldstone bosons when the

about the "vacuum" solution $\varphi_1(x) = 0$, $\varphi_2(x) = \varphi_0$:

$$\partial^\mu\{\partial_\mu(\Delta\varphi_1) - e\varphi_0 A_\mu\} = 0, \tag{2a}$$

$$\{\partial^2 - 4\varphi_0^2 V''(\varphi_0^2)\}(\Delta\varphi_2) = 0, \tag{2b}$$

$$\partial_\nu F^{\mu\nu} = e\varphi_0\{\partial^\mu(\Delta\varphi_1) - e\varphi_0 A_\mu\}. \tag{2c}$$

Equation (2b) describes waves whose quanta have (bare) mass $2\varphi_0\{V''(\varphi_0^2)\}^{1/2}$; Eqs. (2a) and (2c) may be transformed, by the introduction of new variables

Probability

- 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?

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

Probability

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Start

Outcome

A black card

What's the probability?

50%

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

Probability

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Start

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An ace

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Probability

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Start

Outcome

An ace

What's the probability?

1/13

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

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?

Start **Outcome**

W^+W^- W^+W^-

What's the probability?

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?

Start **Outcome**

W^+W^- W^+W^-

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-carriers and ask for a final state of a W^+ and W^- pair?

Start	Outcome
W^+W^-	W^+W^-

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…

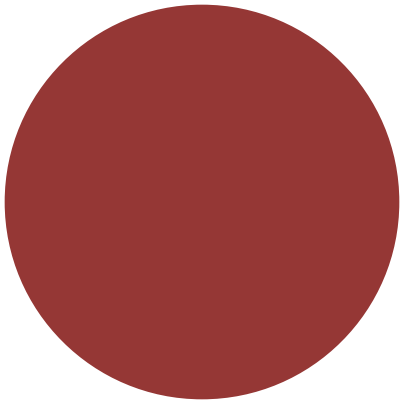
- All fermions (spin ½ particles) **start out massless** in the Standard Model
  - Every massless particle travels at the speed of light
  - Since fermions have spin, their spin can be either along or against their direction of motion
    - This is called **chirality**: right-handed if along, left-handed 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

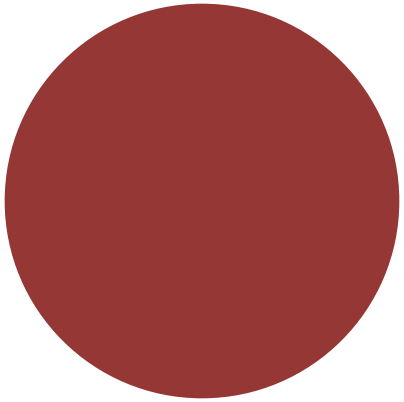
- But **symmetry breaking** is interesting (and fun!)
- “A chain is only as strong as its weakest link”

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?

Start

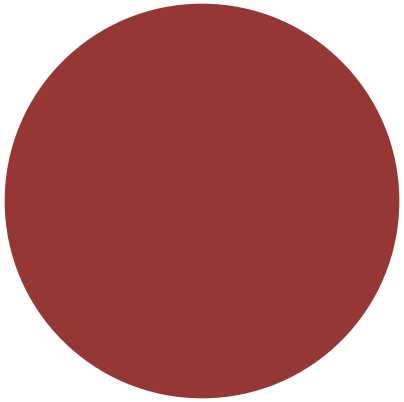


Outcome

Symmetry breaking

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

Start



Outcome

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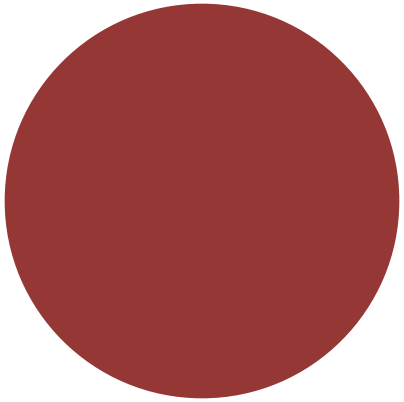
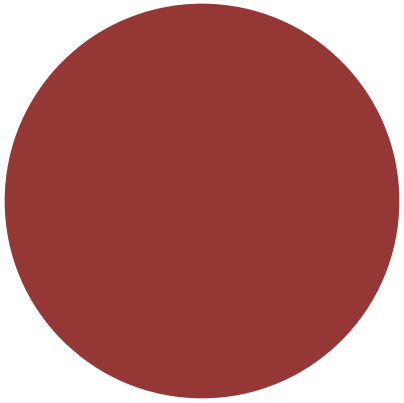


Symmetry breaking

- Suppose we wanted to make a **round** hole with a **square** bit
- Is *this* possible? Yes!

Start

Outcome



- Have to consider the starting point **and** the possible ways to manipulate the starting point (e.g. the possible transformations)

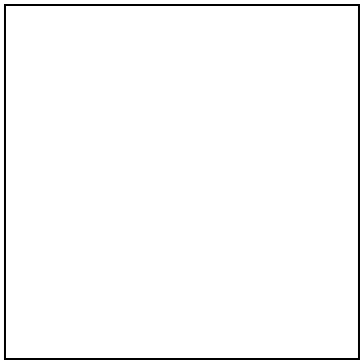
Symmetry and symmetry breaking in laws

- 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
  - "X" represents a North-South mini-magnet
  - "□" represents a South-North mini-magnet

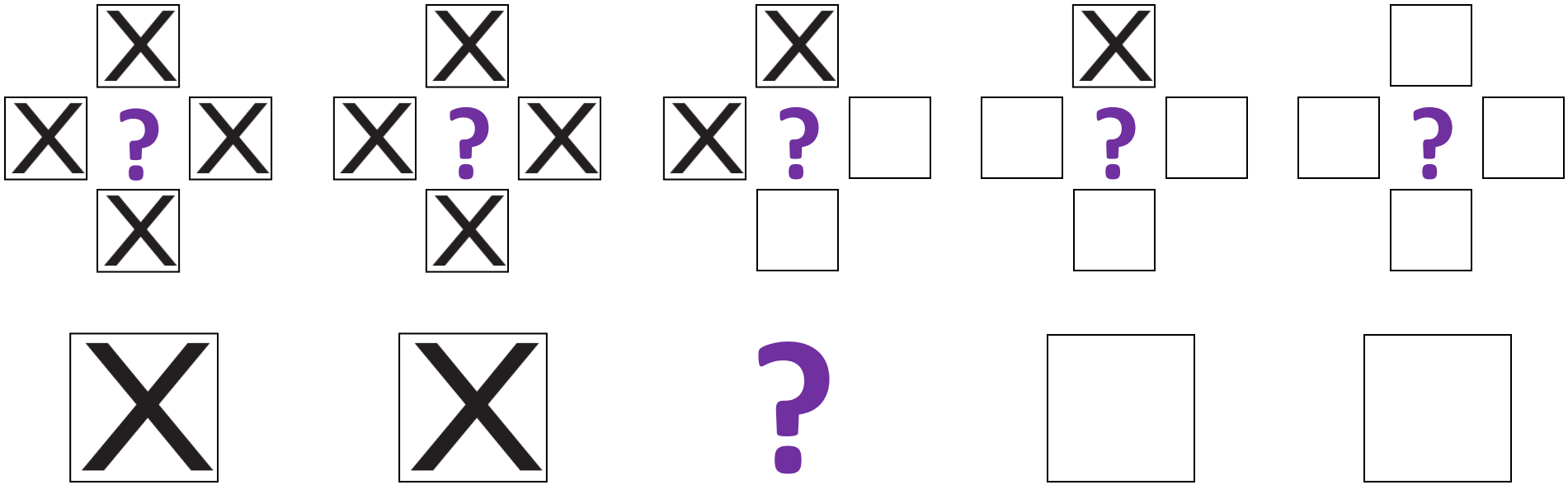
To begin, flip a coin



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

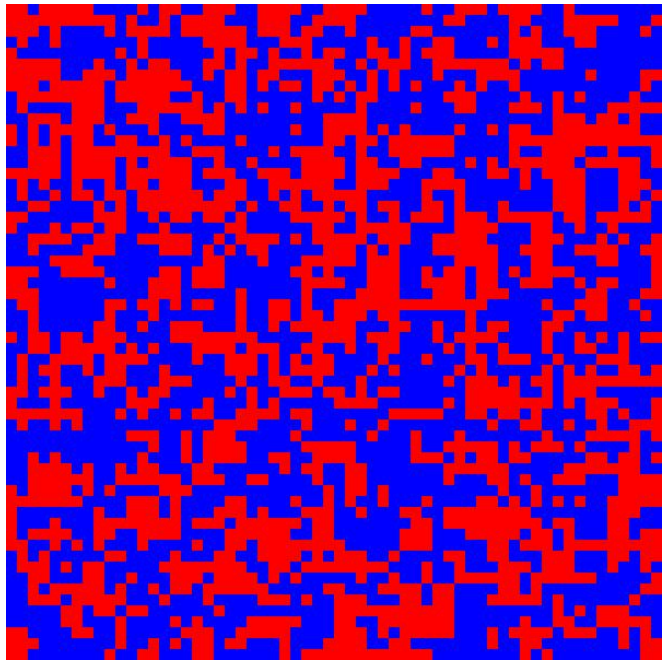
Neighborly Interactions

- These are the laws that govern how your mini-magnet changes over times



Ising model animation

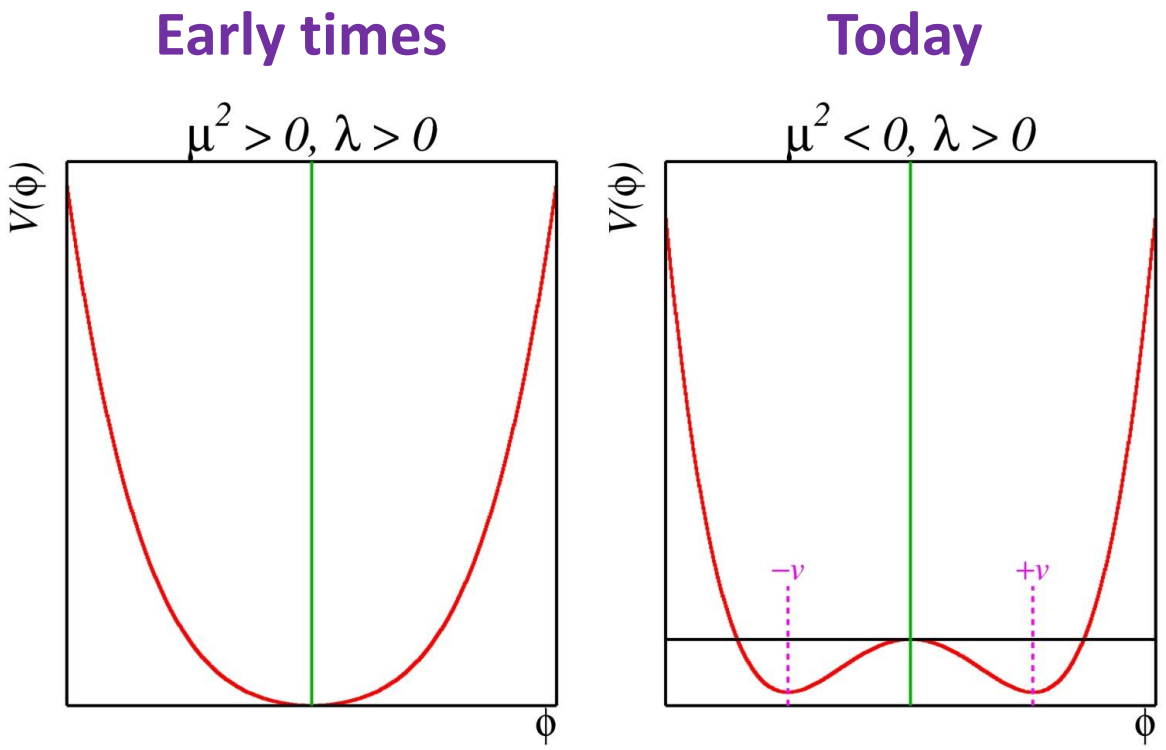
- We've seen how a **random starting point** can lead to **a net magnetization**, even though the interactions don't prefer one magnetization over another (laws are **symmetric**!)
- Key idea is the interactions ***enhance*** any small, local magnetization



Link to http://boudin.fnal.gov/Ising/IsingPage.html

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**



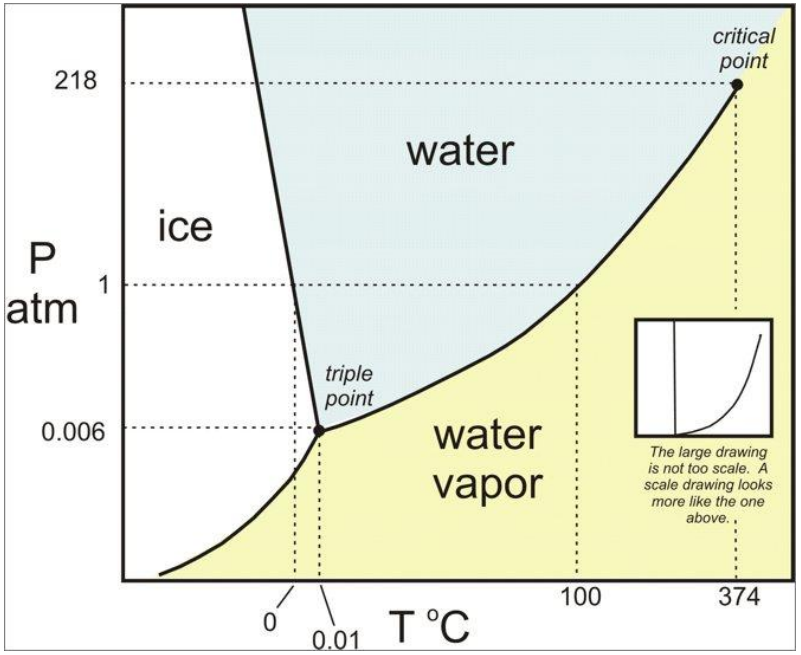
Picture credit
http://dorigo.wordpress.com/2007/11/10/the-goldstone-theorem-for-real-dummies/

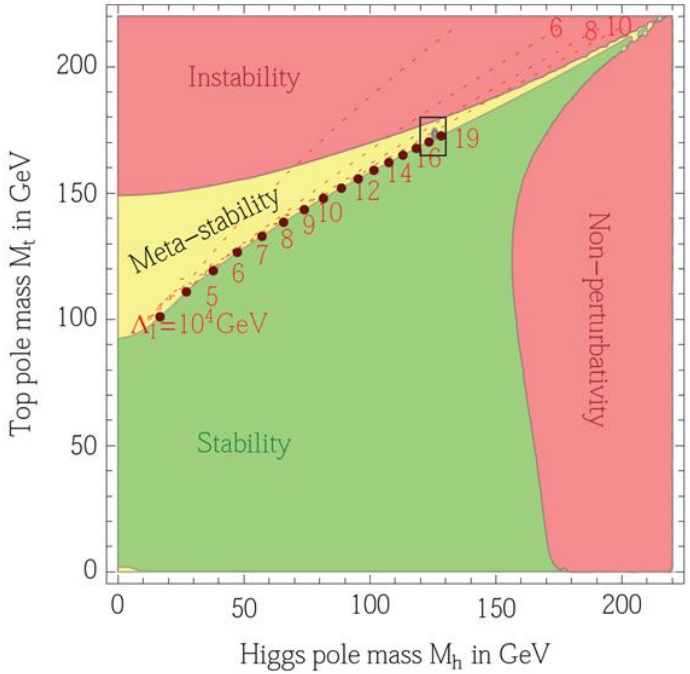
Higgs and spontaneous symmetry breaking

- 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

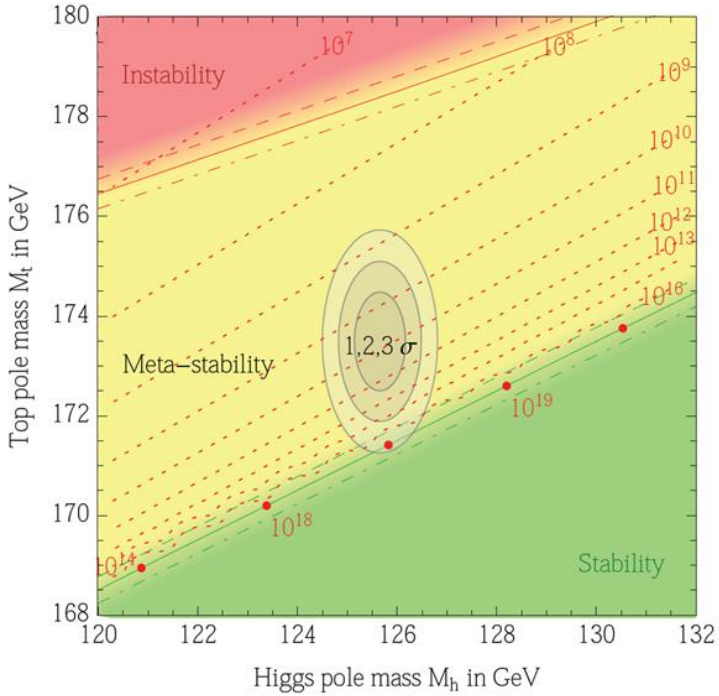
The fate of the universe

- 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

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**

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Thank you for your time and attention!