The Standard Model of Particle Physics

Particle Physics Masterclass

Imperial College London, 17th July 2026

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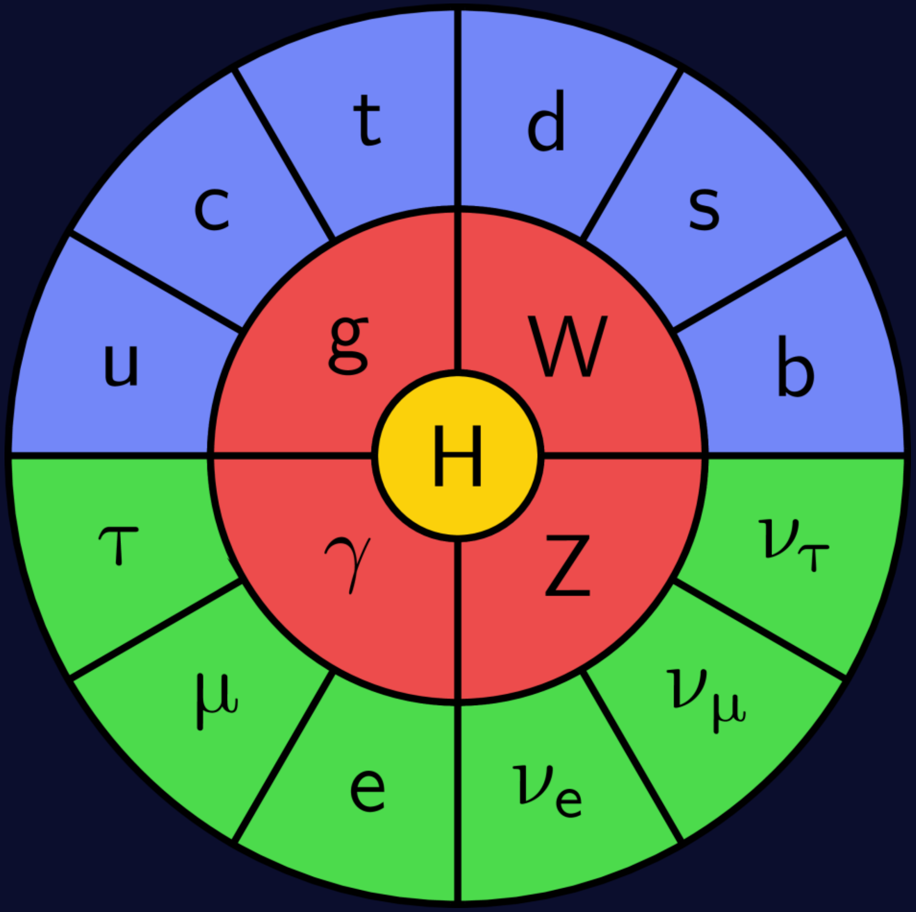
$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\psi} \not{D} \psi + \psi_i y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$

Introduction

- The Standard Model is our best theory of the fundamental building blocks of the universe, and the forces between them
- Developed through the 1960s and 70s, and tested to extraordinary precision ever since
- It describes all known matter, and the forces that dominate at the subatomic level with just 17 fundamental particles



What we’ll cover

1 **What is matter made of?** *Fermions: quarks & leptons*

2 **How do particles interact?** *Forces & their bosons*

3 **Why do particles have mass?** *The Higgs mechanism*

4 **What don't we know yet?** *Open questions*

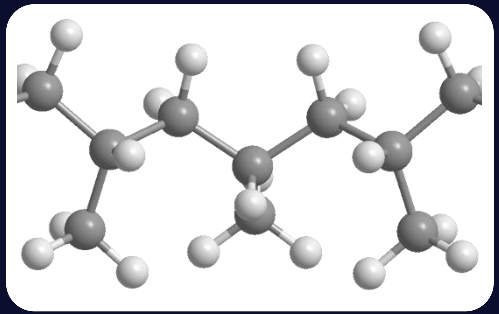
Part 1

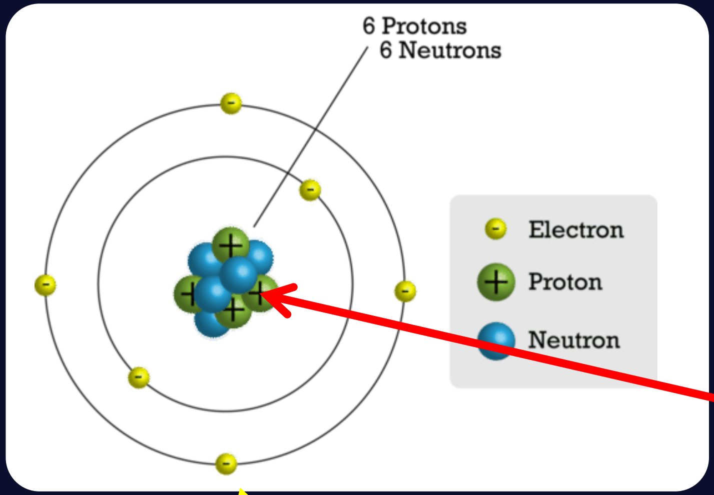
What is matter made of?

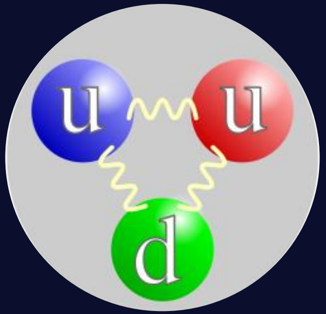
How small can you go?

Take an object, and split it in half, then split that half again, and again, and again….

→ Could you go on forever?







Protons and **neutrons** are **composite**, and formed of **quarks**

Electrons are **fundamental particles (leptons)**

→ These fundamental “matter“ particles are called **fermions**

Quarks

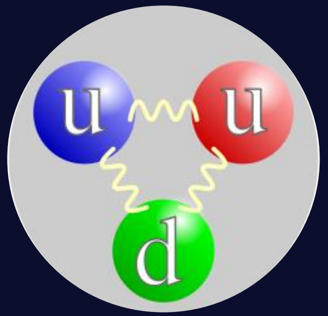
- There are three generations of quarks:

"Heavy flavour"

	I	II	III
Charge +2/3	u up $m = 2.16$ MeV	c charm $m = 1.27$ GeV	t top $m = 173$ GeV
Charge -1/3	d down $m = 4.7$ MeV	s strange $m = 94$ MeV	b bottom $m = 4.18$ GeV

In particle physics we typically use **natural units** ($c = \hbar =$ 1), and express energy/momentum/mass in MeV/GeV (eV=electronvolts) → 1 GeV = 1.783×10^{-27} kg

Proton



Charge: +2/3 +2/3 -1/3 =+1

→All fermions have an intrinsic angular momentum called spin, with value 1/2

Leptons

- There are three **generations** of leptons:

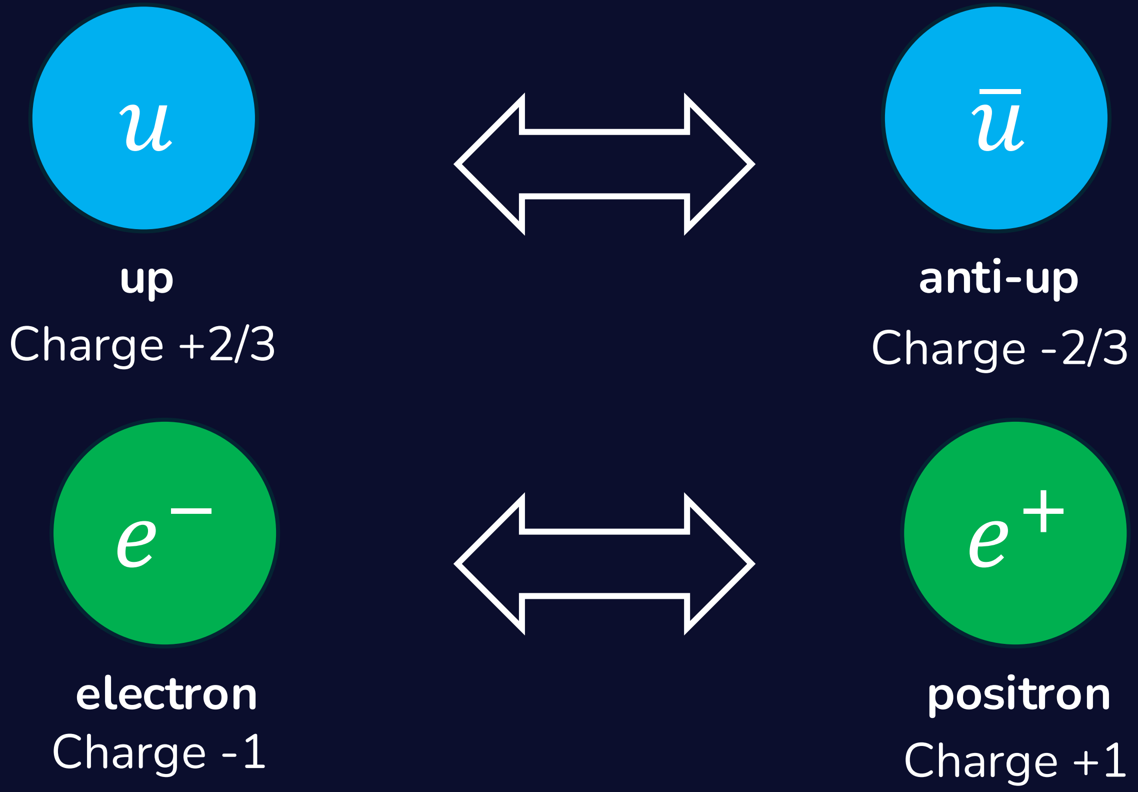
	I	II	III
Charge -1	e^- **electron** $m = 0.511$ MeV	μ^- **muon** $m = 106$ MeV	τ^- **tau** $m = 1.78$ GeV
Charge 0	ν_e **electron neutrino** $m \approx 0$	ν_μ **muon neutrino** $m \approx 0$	ν_τ **tau neutrino** $m \approx 0$

Neutrinos are light neutral particles *predicted* to have zero mass in the Standard Model

→All fermions have an intrinsic angular momentum called spin, with value 1/2

Anti-particles

- All fermions have an **anti-particle equivalent**, with opposite quantum numbers such as **electric charge**

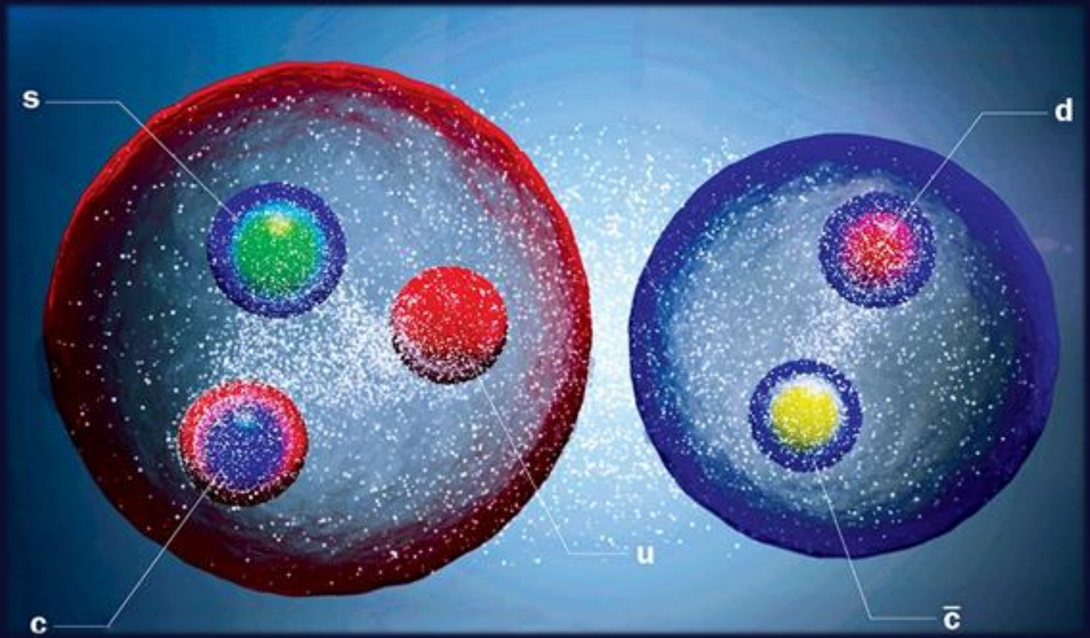


→ When matter and antimatter meet, they **annihilate**, releasing energy

Bound states

- Quarks are bound together by the strong force, forming hadrons:
  - **Baryons:** 3 quarks (or 3 antiquarks) (e.g. proton = uud, neutron = udd)
  - **Mesons**: 1 quark + 1 antiquark (e.g. $\pi^+ = u\bar{d}$)

- Each quark has a colour charge (R/G/B) , hadrons must be **colour neutral** (e.g. RGB , $\mathrm{R\bar{R}}$, ...)



→ These hadrons are typically quite short-lived and decay to other, lighter particles - only the proton is stable

Part 2

How do particles interact?

Fundamental forces

- There are 4 fundamental forces in the universe:
  - Gravity
  - Strong Force
  - Weak Force
  - Electromagnetism

Fundamental forces

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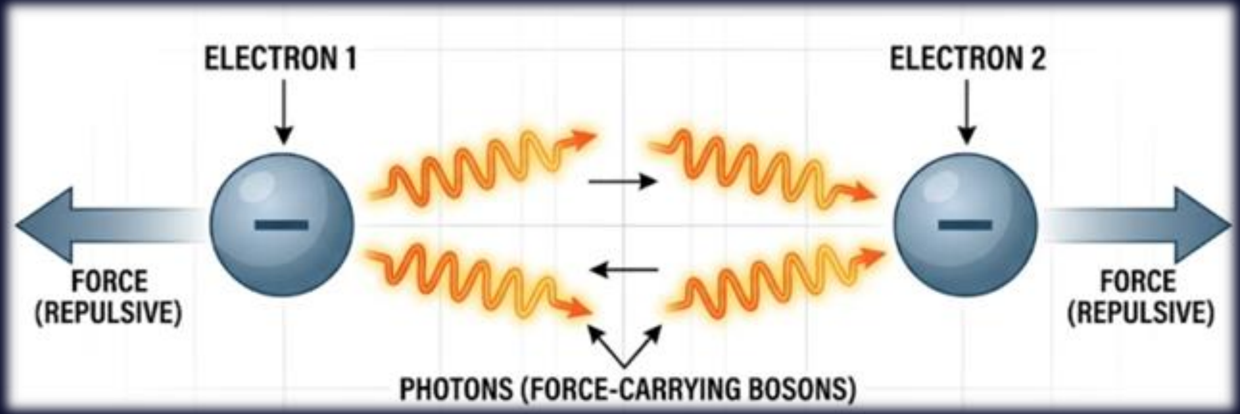
The Standard Model describes the behaviour of the **forces that dominate at the subatomic level**

- These forces are described in quantum field theory
  → Interactions occur via the exchange of **force-carrier particles** called **bosons**



Fundamental forces

Electromagnetism

- Responsible for electric and magnetic fields
- Attraction and repulsion of charged particles

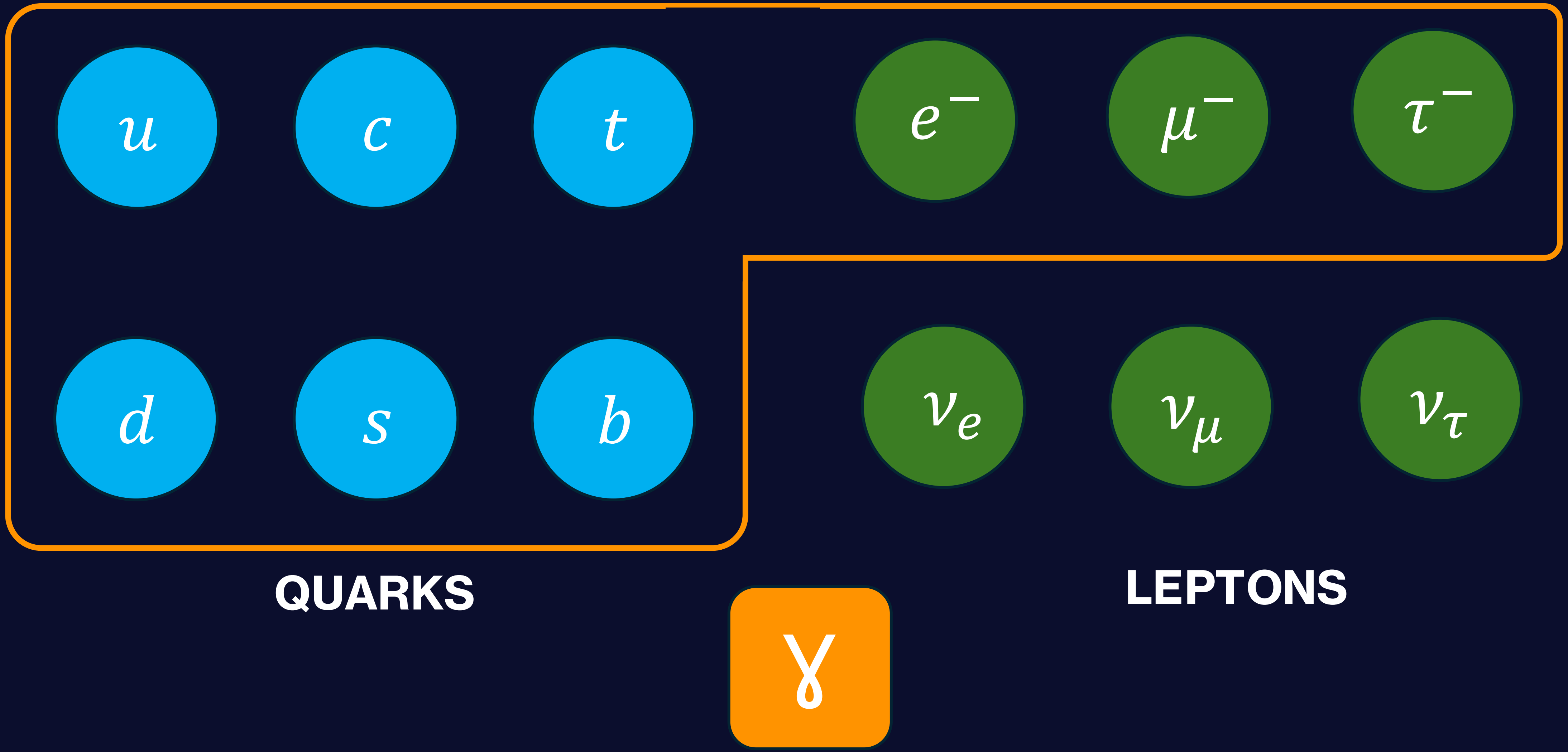
γ

Charge = 0

$m = 0$

Range: ∞

Interactions with Fermions



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Strong Force

- Holds protons and neutrons together inside the nucleus
- Binds quarks together to form hadrons

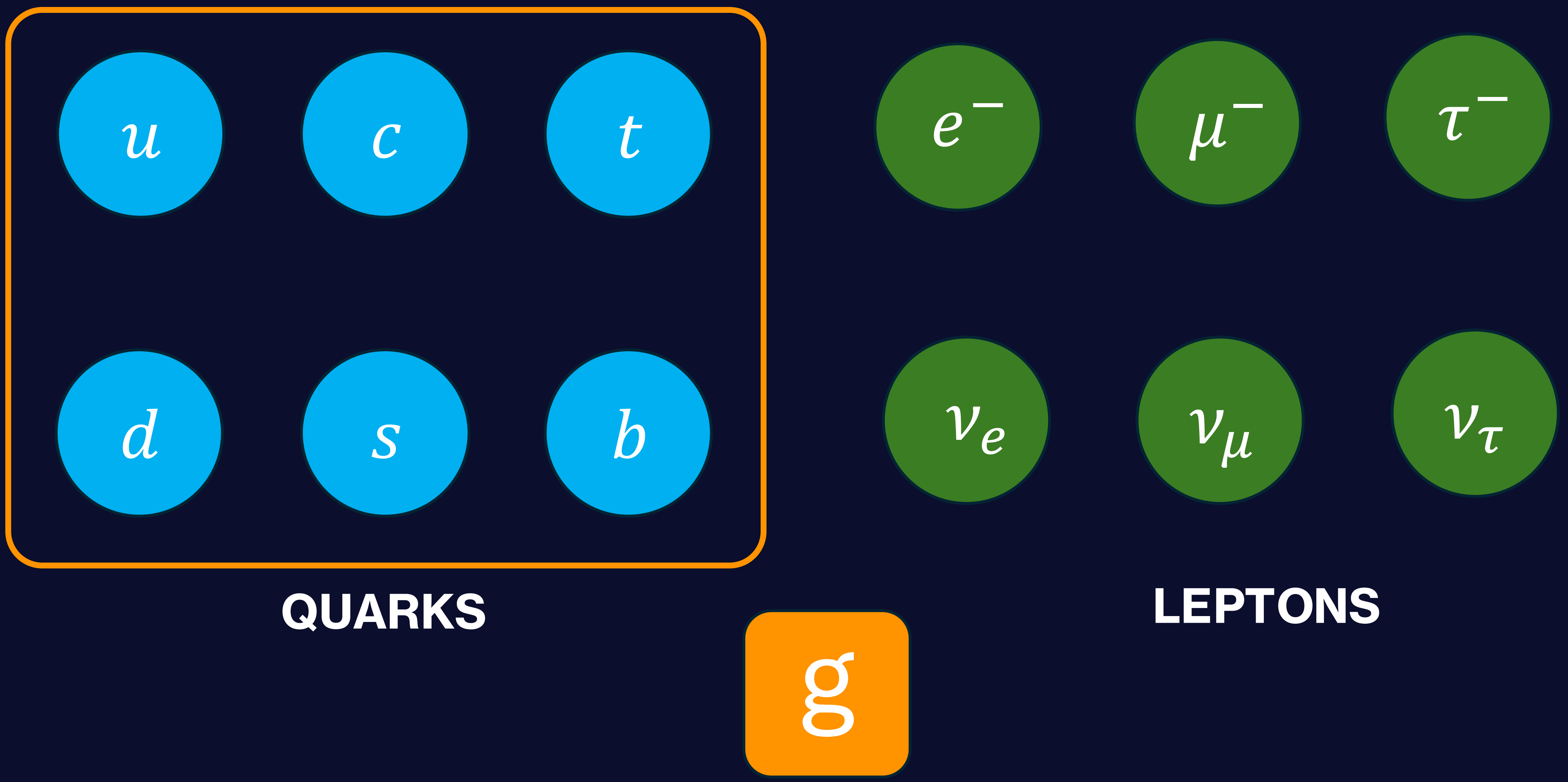
g

Charge = 0

$m = 0$

Range: $\sim 10^{-15}$ m

Interactions with Fermions



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$m = 0$
Range: $\sim 10^{-15}$ m

Weak Force

- Responsible for radioactive decays (e.g. β decay)
- Responsible for nuclear fusion (e.g. the creation of heavier elements in stars)

Z

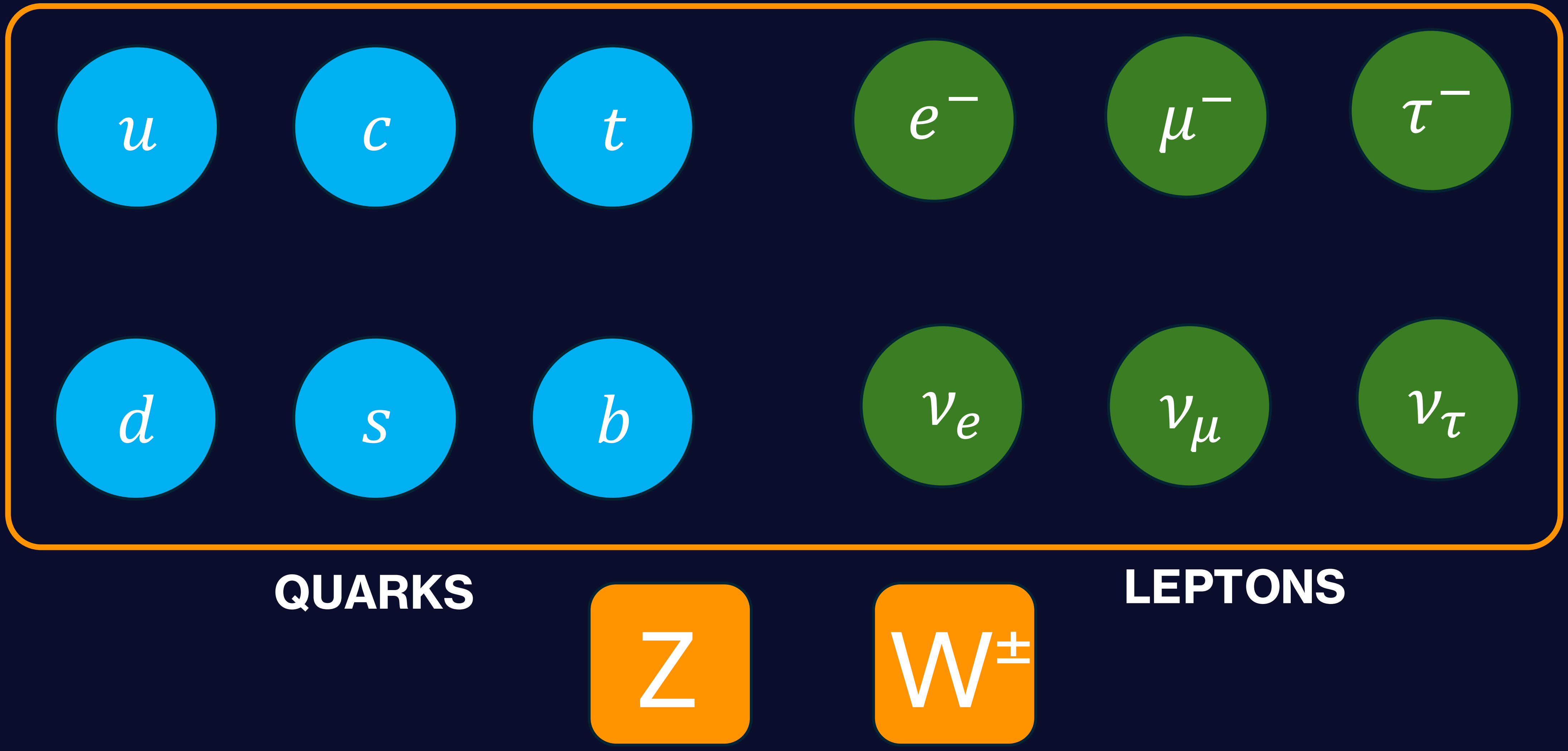
Charge = 0
$m = 91.2$ GeV
Range: $\sim 10^{-18}$ m

$W^{\pm}$

Charge = ±1
$m = 80.4$ GeV
Range: $\sim 10^{-18}$ m

→ These force-carrying bosons have spin 1

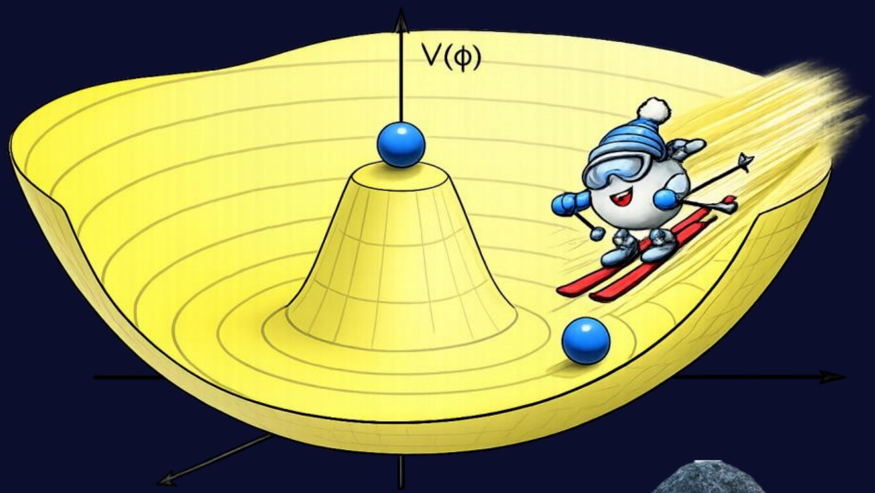
Interactions with Fermions



Part 3

How do particles gain mass?

The Higgs Mechanism



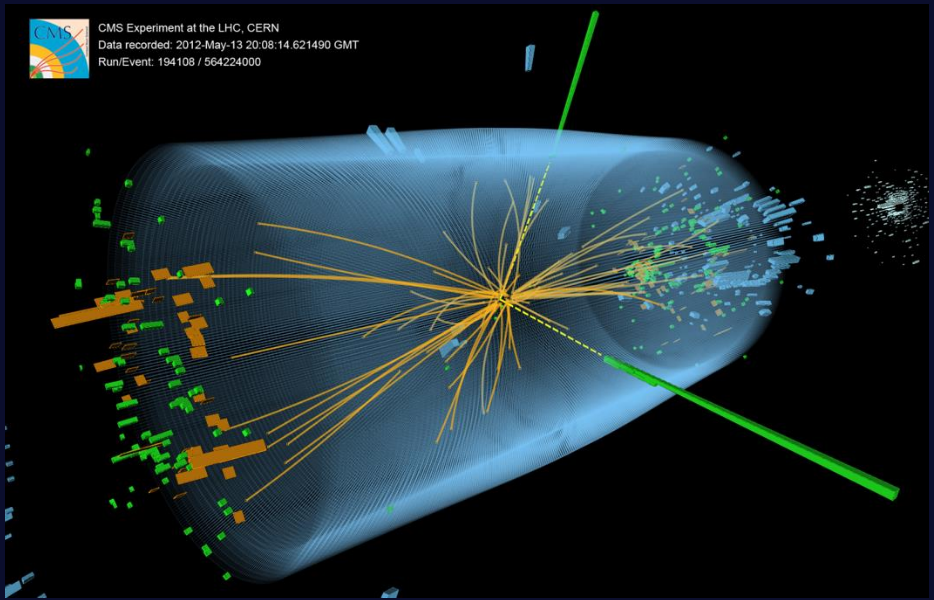
- Before the Higgs mechanism was proposed, the Standard Model could only work for massless particles

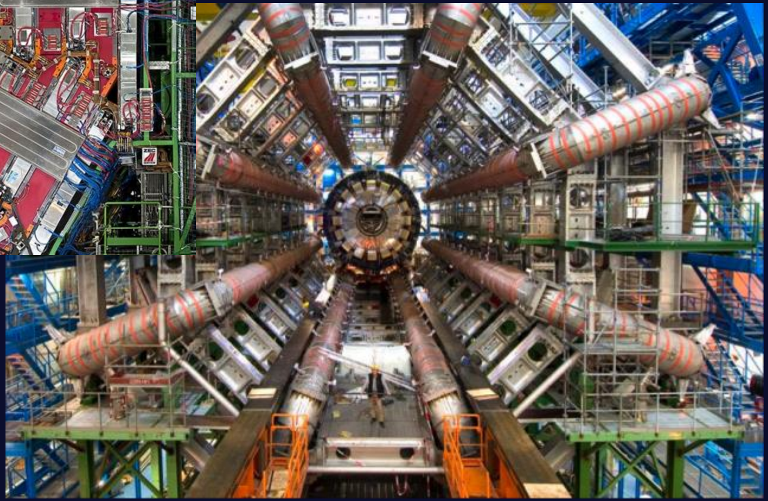
- The Higgs Mechanism was predicted in the 1960s
  - The **Higgs field fills all of space**
  - Particles moving through the Higgs field feel inertia, which is their **mass**

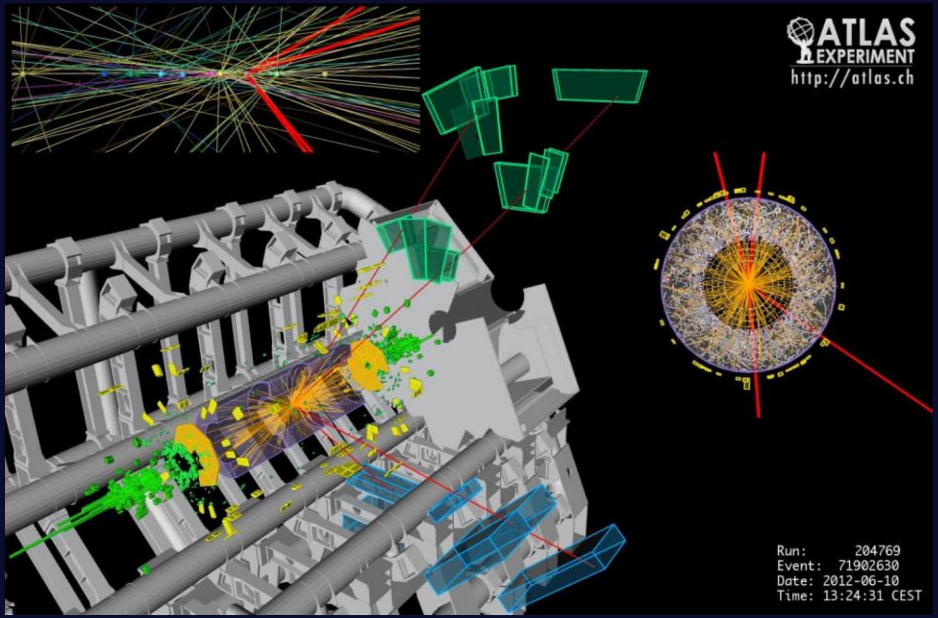
- Predicts the existence of the **Higgs boson** which couples to all massive particles

The Higgs Boson

- The Higgs boson, was discovered by the ATLAS and CMS collaborations in 2012 via the $H \to \gamma\gamma$ and $H \to ZZ^*$ decay channels







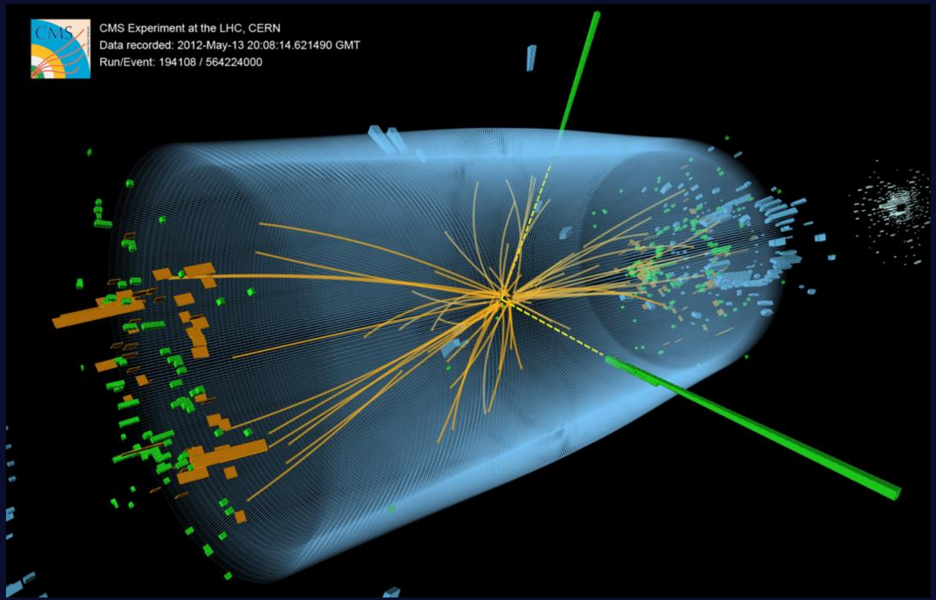
The Higgs Boson

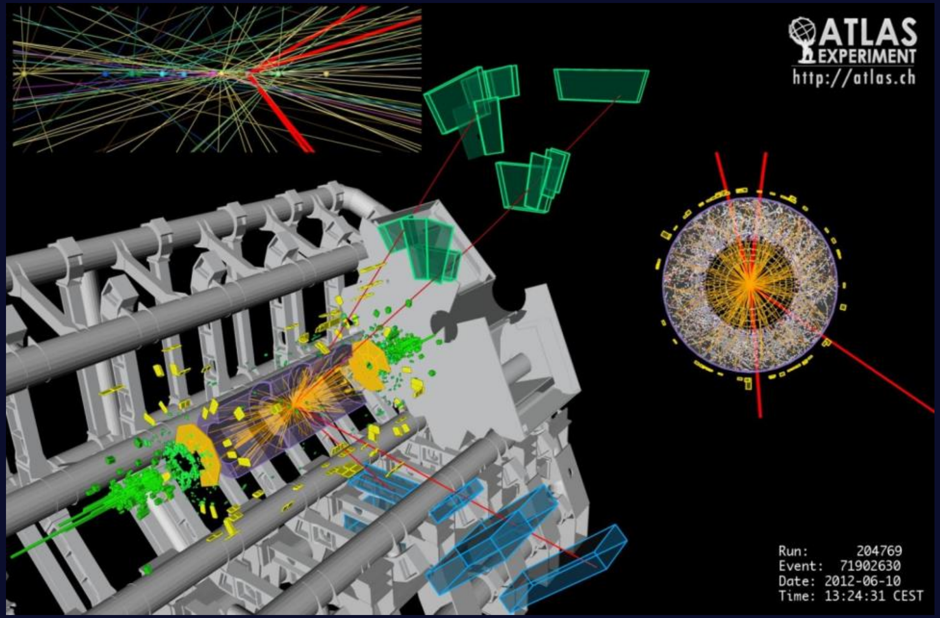
→ Measurements of Higgs properties ongoing!

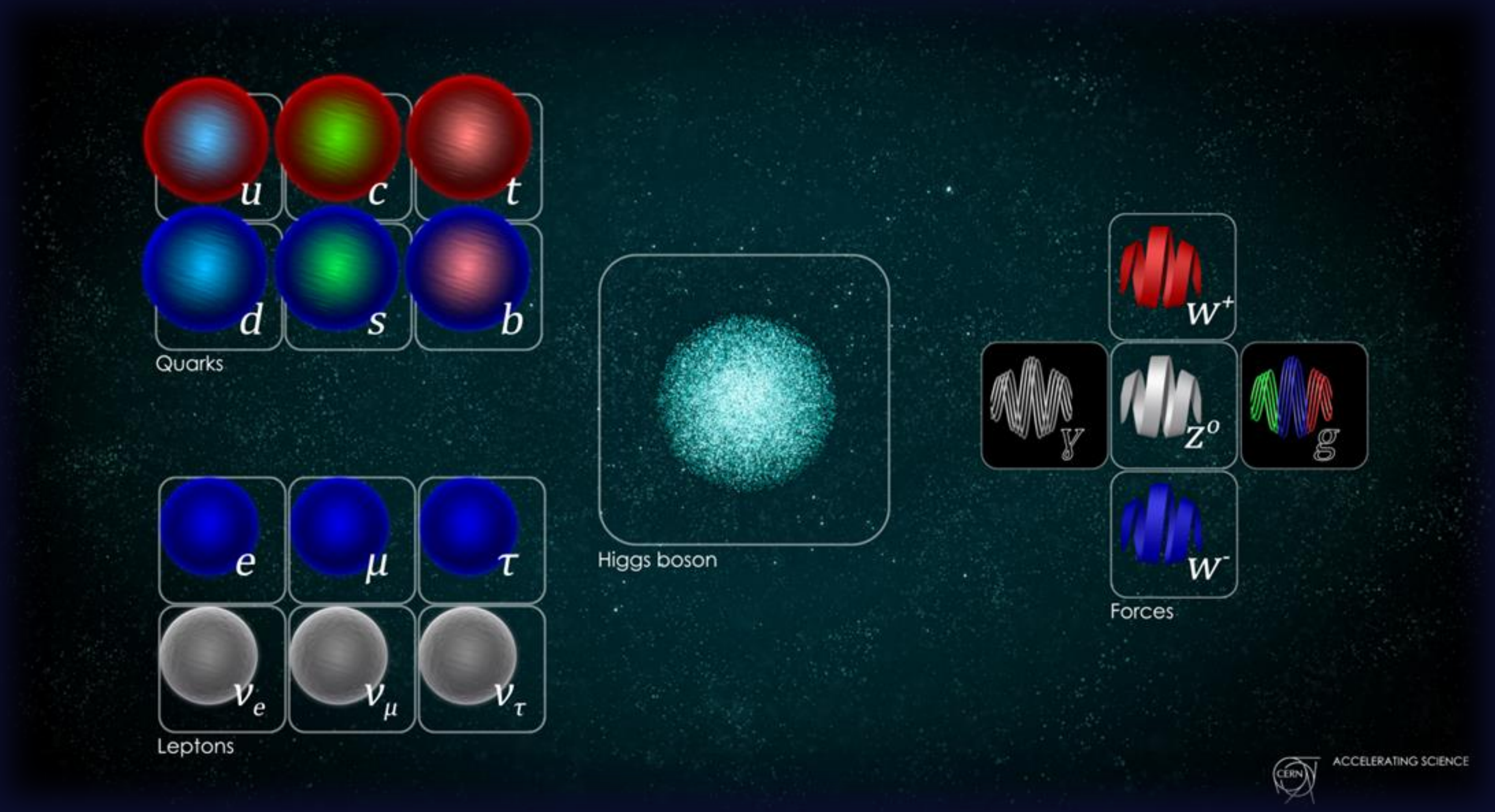
H

Charge = 0
$m = 125$ GeV
Spin 0

- 2013: Nobel prize in physics for theorists Higgs and Englert







u
c
t
d
s
b
Quarks
e
μ
τ
ν_e
ν_μ
ν_τ
Leptons
Higgs boson
W^+
γ
Z^0
g
W^-
Forces
CERN
ACCELERATING SCIENCE

Part 4
What don’t we know yet?

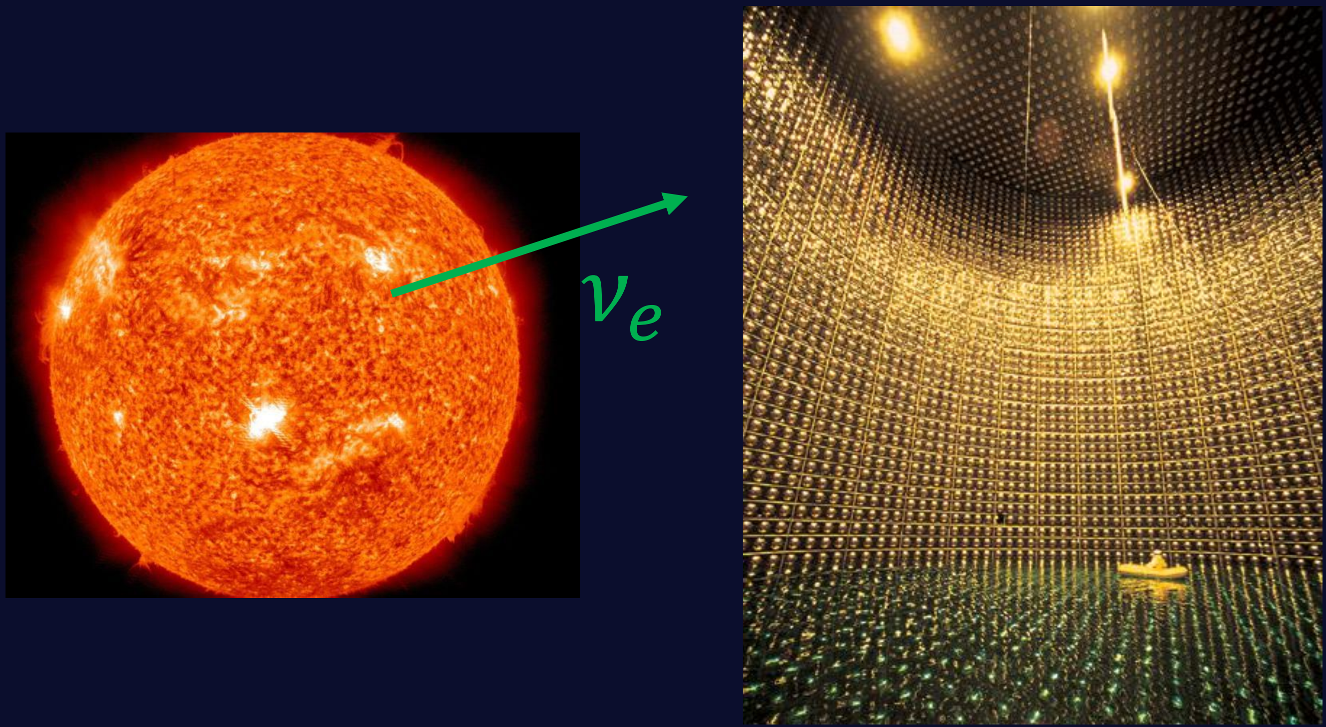
Neutrino Masses

- In the Standard Model, neutrinos are expected to be massless (can’t gain mass via the Higgs mechanism)

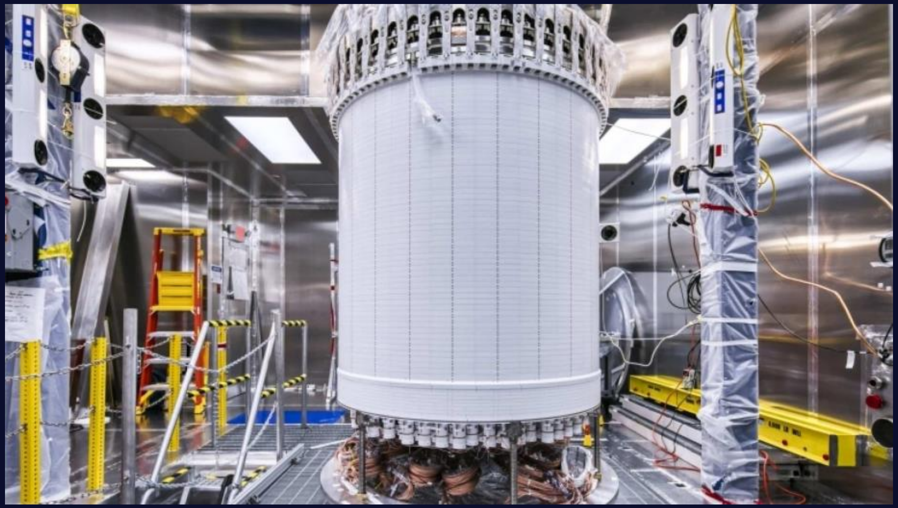
- However, “oscillation” from one flavour of neutrino to another has been observed which means they **must have mass**

  → Nobel prize 2015

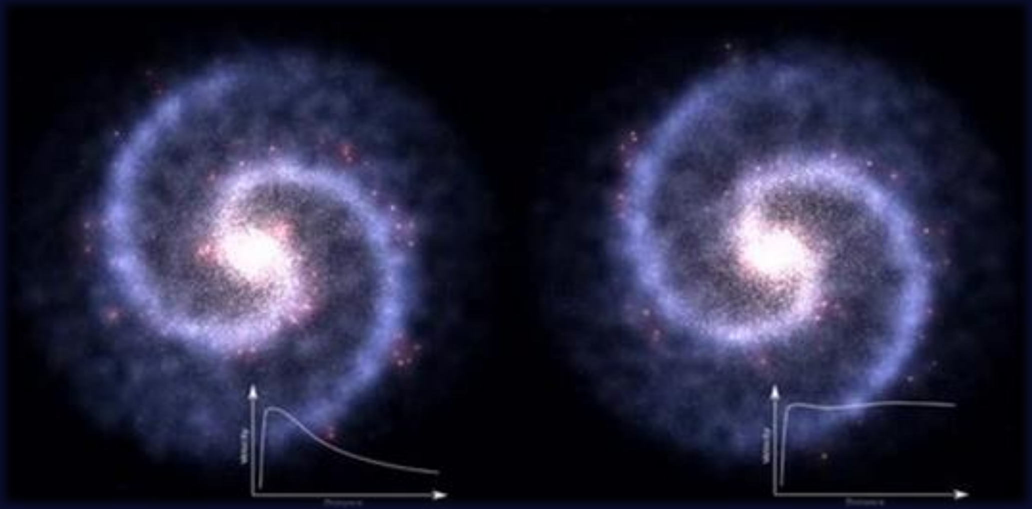
ν_e	ν_μ	ν_τ
electron neutrino	**muon neutrino**	**tau neutrino**

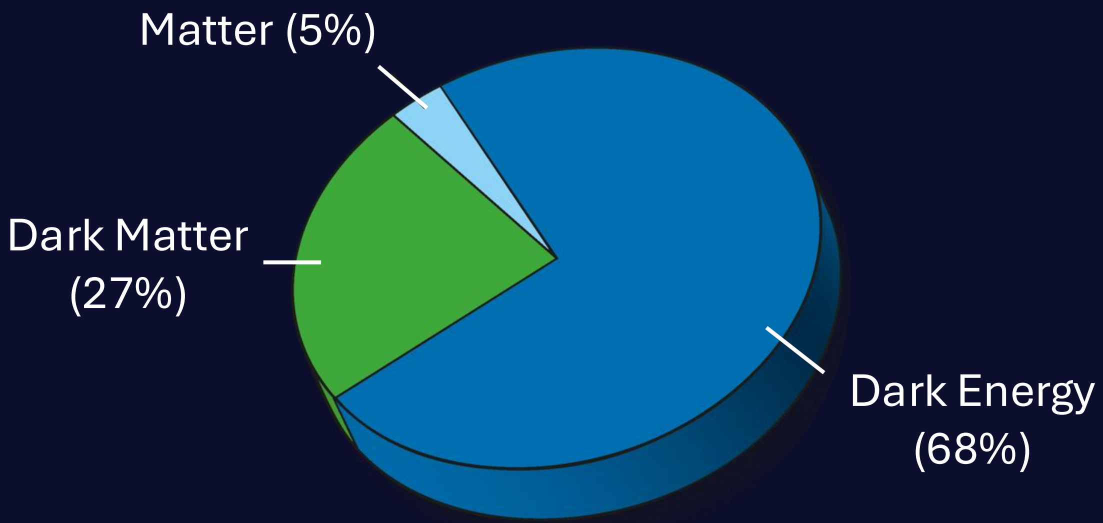


Dark Matter



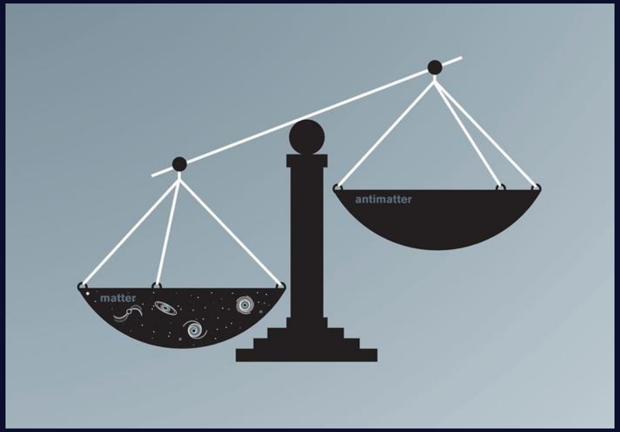
- Ordinary matter only makes up a small part of the universe (< 5%)
- The presence of dark matter is hinted at by various cosmological observations
  →This mysterious mass doesn’t seem to interact via any force except gravity





Matter-antimatter asymmetry

→ Where did all the antimatter go?

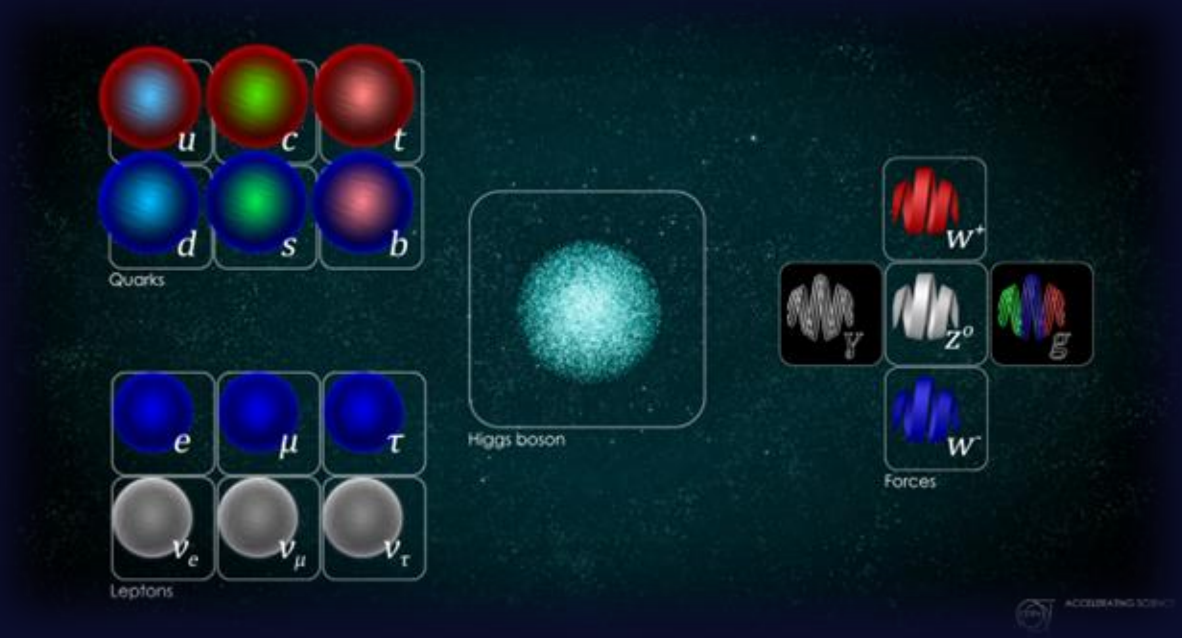


- Matter and antimatter were produced in nearly equal proportions at the Big Bang according to the Standard Model

- This is because almost all the predicted interactions obey CP symmetry, which implies that a process would look the same if viewed in a special mirror that swaps left/right, up/down, and positive/negative charges.
    → There isn’t enough CP violation to explain the differences we see, there must be new physics!

Conclusion

- The Standard Model is an extremely successful theory that has predicted many fundamental particle interactions to a very high precision



→ Nonetheless, there are various unexplained phenomena - new and precise measurements are essential to further understanding our universe

Thank you!

Any questions?