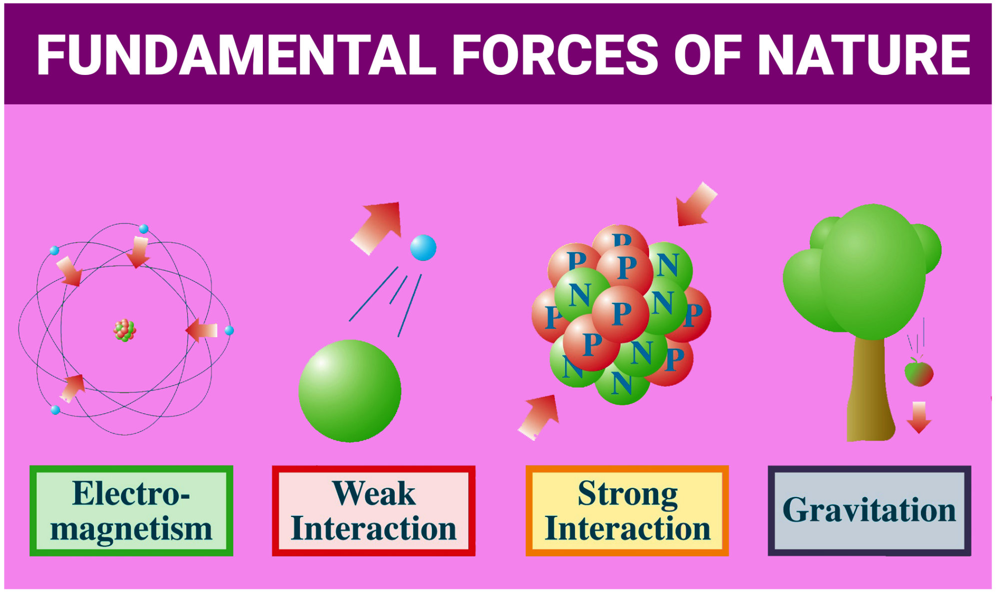
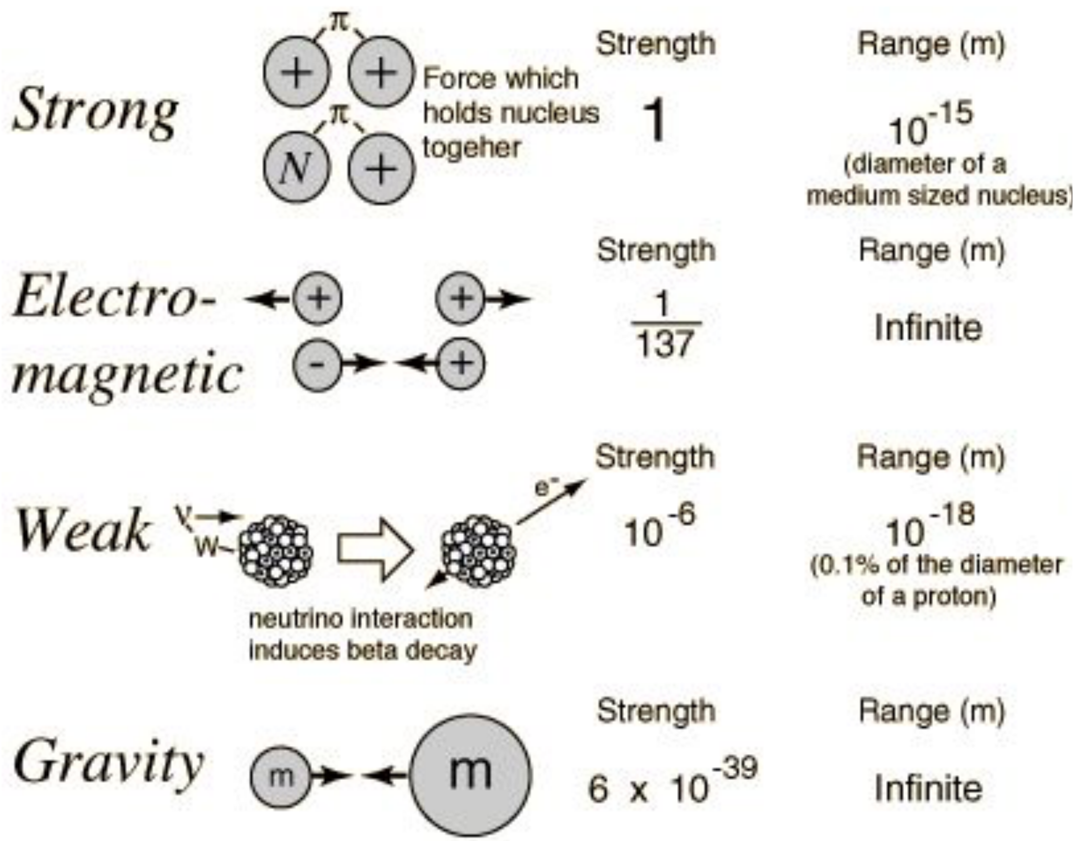
PHY20004 Particle Physics Class 2:
The Fundamental Forces

In this class we will introduce the fundamental interactions between the elementary particles: the electromagnetic, weak, strong and gravitational forces



What are fundamental forces?

- Elementary particles interact through the **fundamental forces**: the electromagnetic, weak, strong and gravitational forces

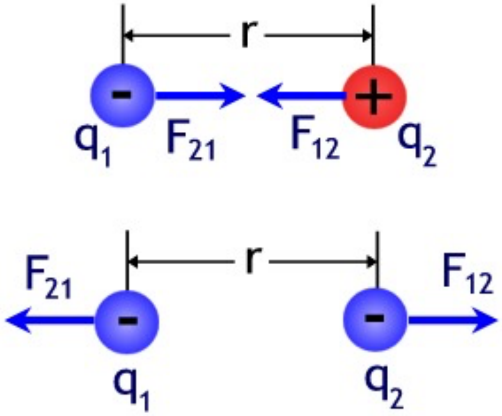


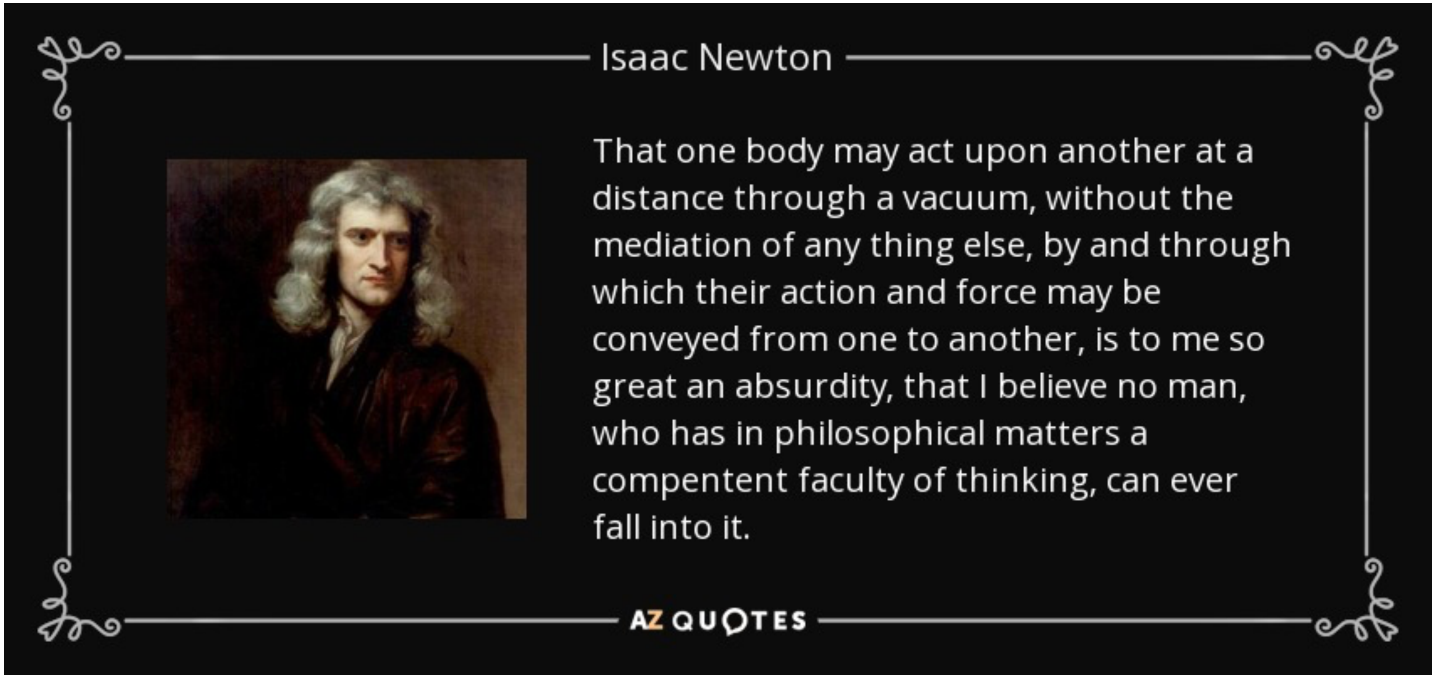
- The illustration shows some general properties of these forces
- The **strength** and **range** of the forces varies dramatically
- Gravity is negligible for particle physics, so we generally ignore it!

Credit: http://hyperphysics.phy-astr.gsu.edu

Forces in particle physics

- In classical physics, forces are described as direct interactions between objects
- Newton didn't like it!

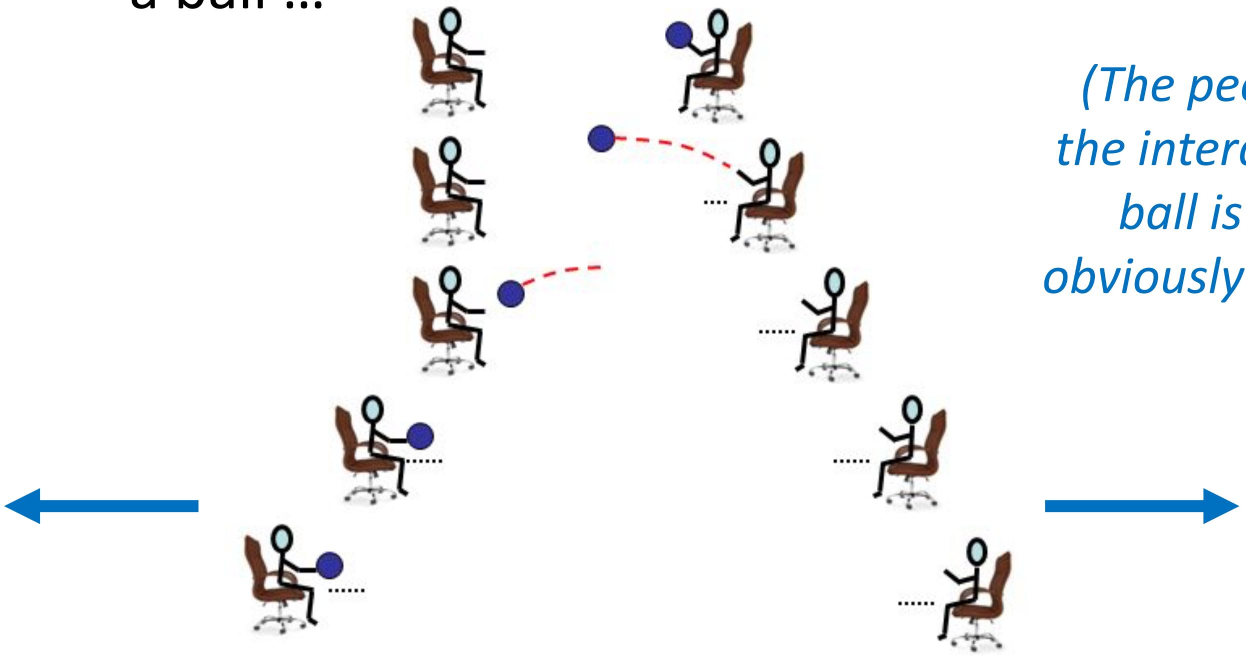




Forces in particle physics

- In modern particle physics, objects interact by **exchanging particles known as force carriers**

- A typical analogy is people sitting in wheely-chairs throwing a ball …



(The people in the chairs are the interacting objects and the ball is the force carrier … obviously not a perfect analogy, but still…!)

- The “force” is the net result of all the particle exchanges

Summary of force carriers

- The following table summarises these different force carrier particles: **photons, W and Z bosons, and gluons!**

Fundamental Force Particles

Force	Particles Experiencing	Force Carrier Particle	Range	Relative Strength*
Gravity acts between objects with mass	all particles with mass	graviton (not yet observed)	infinity	much weaker
Weak Force governs particle decay	quarks and leptons	W^+, W^-, Z^0 (W and Z)	short range	
Electromagnetism acts between electrically charged particles	electrically charged	γ (photon)	infinity	
Strong Force** binds quarks together	quarks and gluons	g (gluon)	short range	much stronger

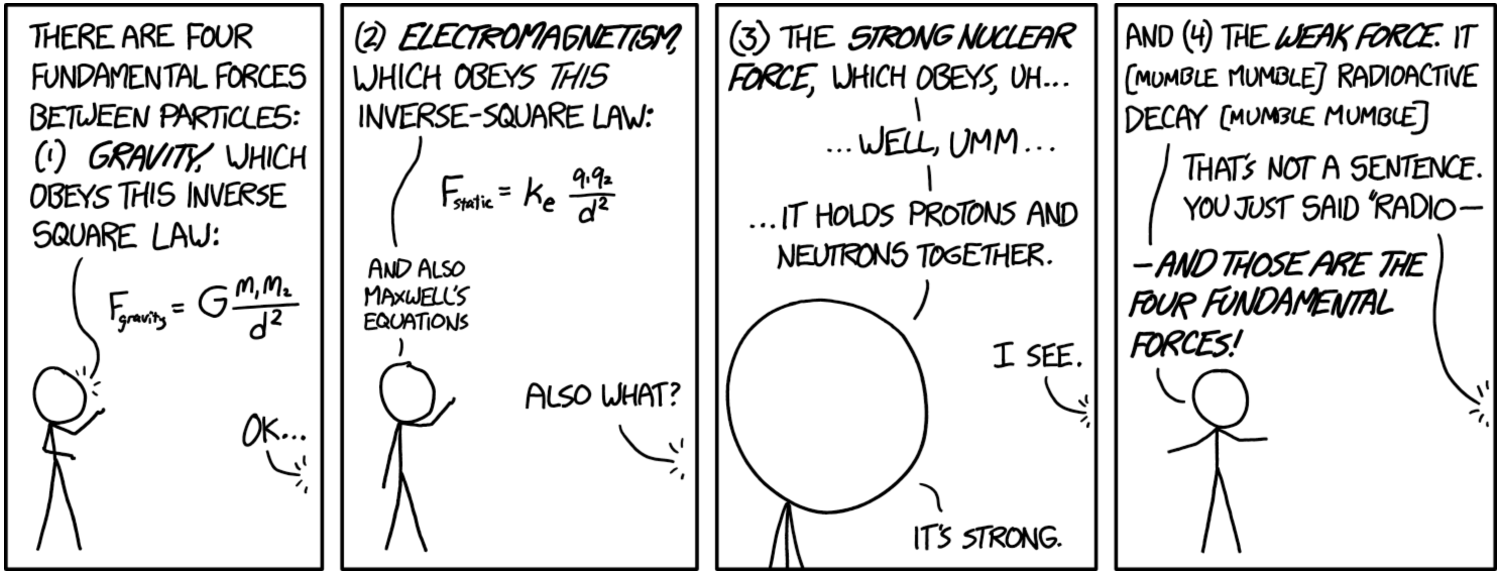
- All the force-carrier particles are **bosons** – you will sometimes see them called "gauge bosons"

Virtual particles

- The process of producing a carrier particle **violates energy and momentum conservation**. However, this is permissible for a short time owing to the **uncertainty principle** $\Delta E \, \Delta t \sim \hbar$
- For this reason, force carriers are known as **"virtual particles"**. The implication is they do not need to satisfy the usual mass-energy-momentum relation, $E^2 = p^2c^2 + m^2c^4$
- To make a real process, two virtual processes are combined such that *energy conservation is only violated for a short amount of time*
- The uncertainty principle time-scale sets the range of the force for a carrier particle of mass m: $R \sim c \, \Delta t \sim \frac{\hbar c}{\Delta E} \sim \frac{\hbar}{mc}$

Force or interaction?

- On the particle scale it can be easier to think in terms of an **interaction** between particles, rather than a **force**
- The Newtonian idea of an action-and-reaction pair of forces does **not** clearly apply in many sub-atomic cases

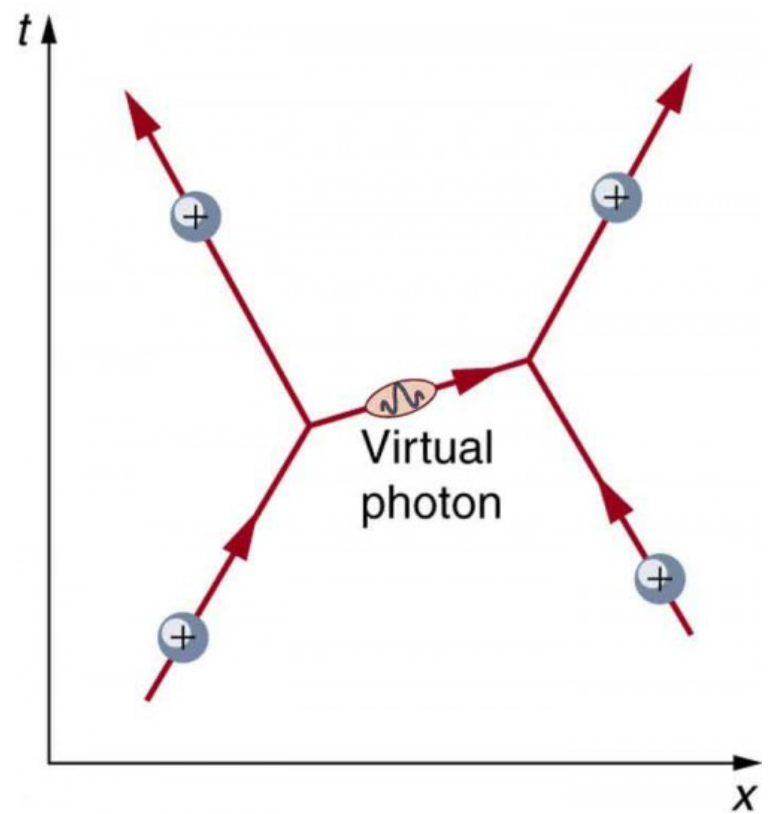


Credit: https://xkcd.com/1489/

The electromagnetic interaction

- The electromagnetic interaction acts between **charged particles**
- The carrier particle for the electromagnetic interaction is the **(virtual) photon**
- Photons have zero mass, and therefore the electromagnetic interaction has **infinite range**
- As a long-range interaction, the electromagnetic force is responsible for *all everyday macroscopic properties*

(The kind of picture below is called a Feynman diagram)



Credit: https://courses.lumenlearning.com

The weak interaction

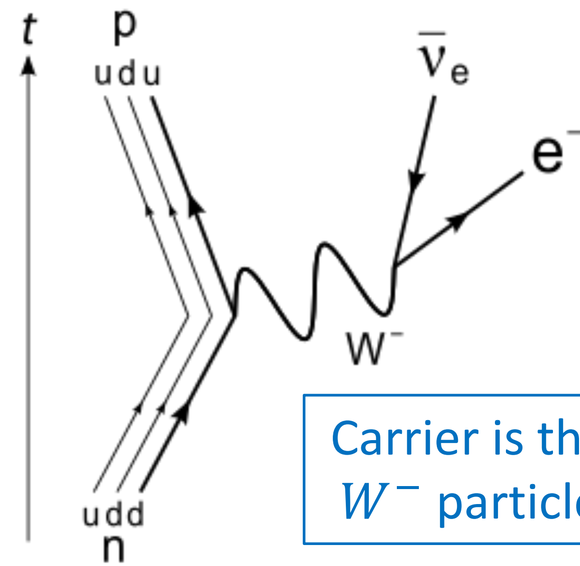
- The weak interaction can occur between **all particles**, but is generally negligible compared to other forces

- It's most significant for **neutrinos**, because these only feel the weak interaction

- The weak interaction is carried by the **W^+, W^- and Z^0 particles**

- The W and Z particles are very massive, hence the weak force is very **short-range** ($\sim 10^{-18}$ m)

The weak interaction mediates β-decay, through which a down quark becomes an up quark, producing an electron and anti-neutrino:



Carrier is the W^- particle

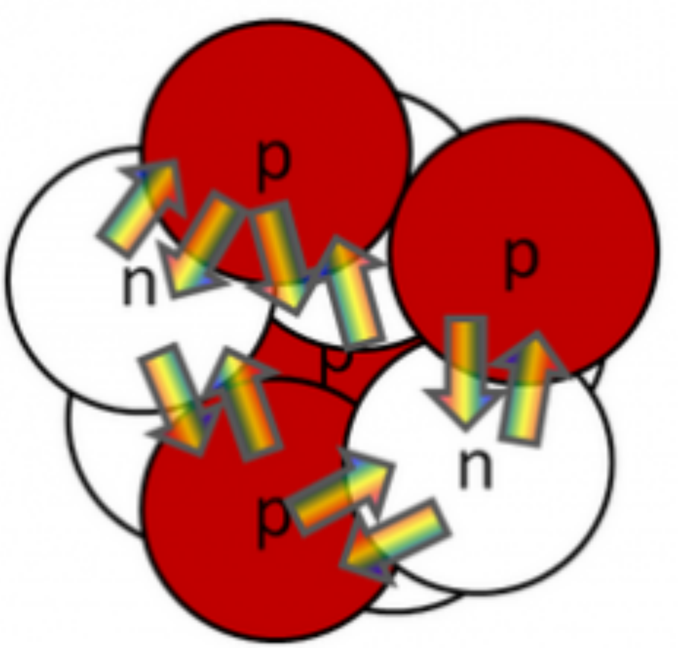
Particle	Charge $[e]$	Mass $[\mathrm{GeV}/c^2]$
W^+	$+1$	80.4
W^-	-1	80.4
Z^0	0	91.2

The strong interaction

- The strong interaction operates between **quarks** (and therefore hadrons) and is responsible for holding the nucleus together

- The carrier particles for the strong interaction are called **gluons**

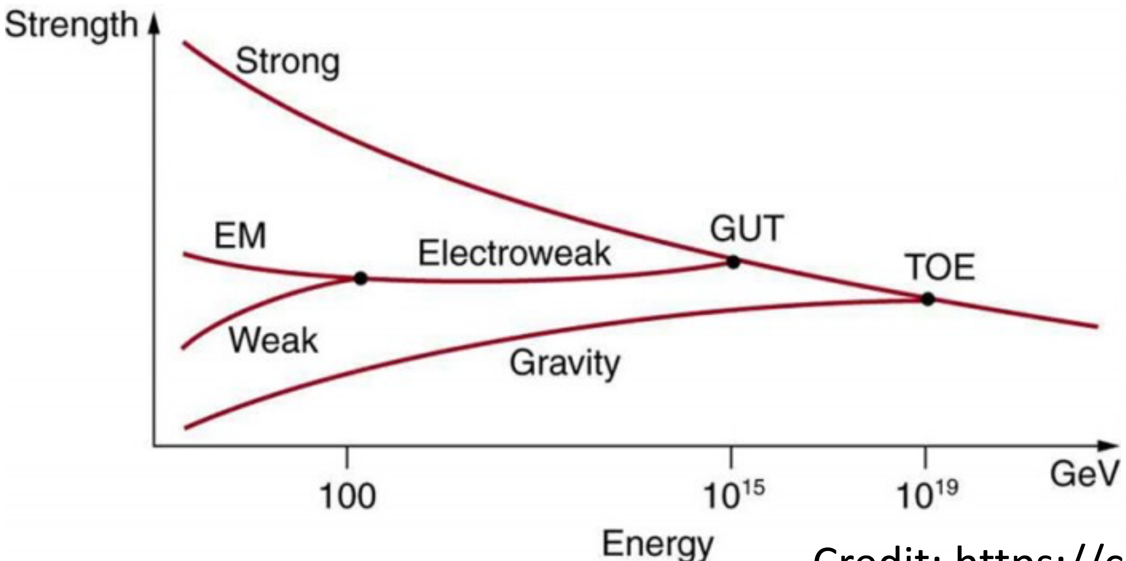
- Gluons have zero mass so the strong interaction would in principle have infinite range, but in practice it's confined to the nucleus *(we won't go into this here!)*



Unification of the forces

- Physics aims to unify seemingly different phenomena – for example, electricity and magnetism. Can the fundamental forces be unified? – the answer so far is, *yes, partially*

- The electromagnetic and weak interactions become the **"electroweak"** interaction above a certain energy ($\sim 100 \text{ GeV}$)

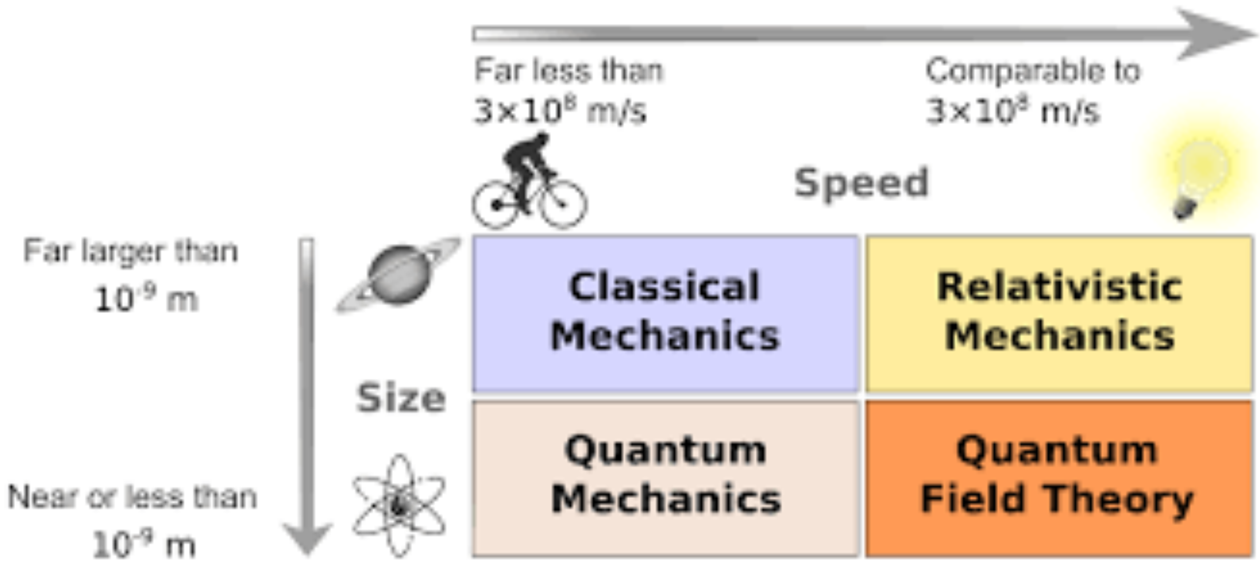


However a "grand unified theory" for the electroweak and strong interactions is not yet known. We also don't know how gravity fits in!

Credit: https://courses.lumenlearning.com

What's in a physics theory?

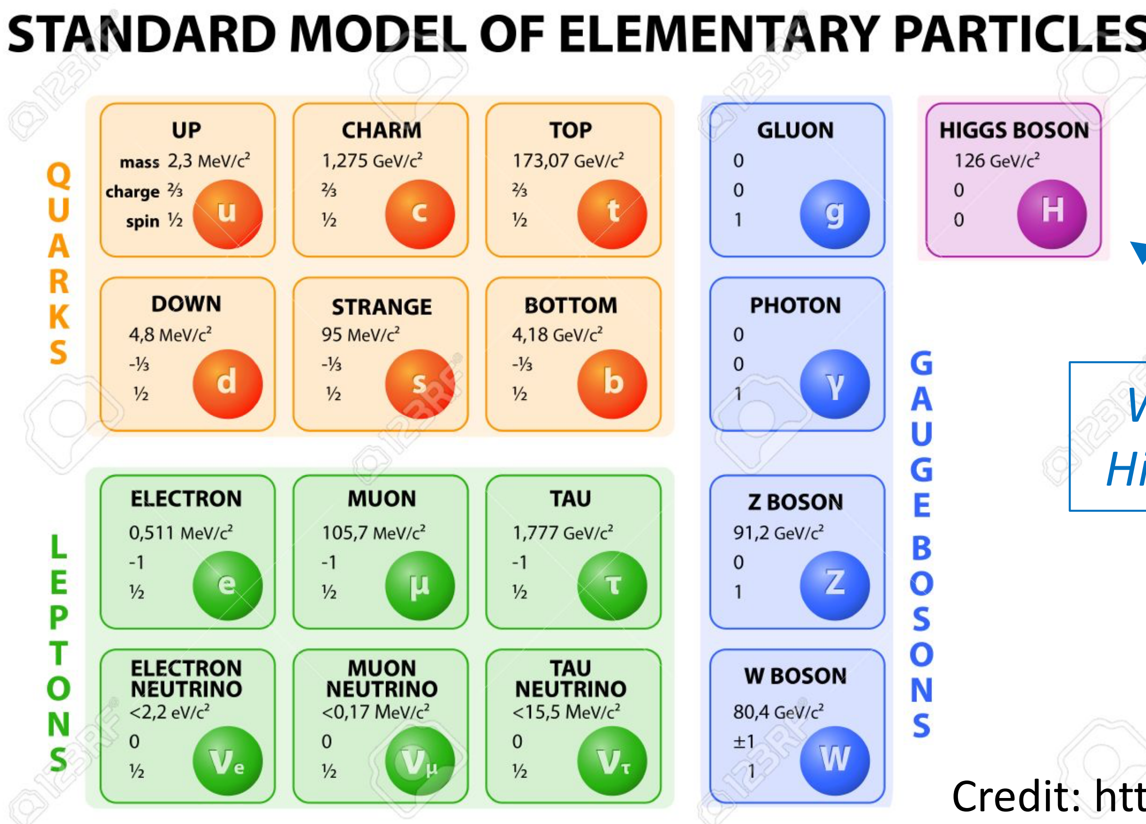
- What about the equations that govern the fundamental interactions? We are in the domain of *relativistic physics on a microscopic scale*, so **quantum field theory** applies



- The quantum theory of the electromagnetic interaction is called **Quantum Electrodynamics** (QED), and the theory of the strong interaction is **Quantum Chromodynamics** (QCD)

The standard model

- The **standard model of particle physics** unifies our picture of the fundamental particles and interactions, categorising them in as simple a manner as possible



We'll discuss the Higgs boson later!

Credit: https://www.123rf.com

Key take-aways

- There are four fundamental forces or interactions in nature: the **electromagnetic**, **weak**, **strong** and **gravitational**
- Fundamental interactions involve the **exchange of carrier particles**: photons, W and Z bosons, and gluons!
- Force carriers are **virtual particles** which violate energy-momentum conservation. They therefore only exist for a short amount of time, which sets the range of the force
- The EM, weak and strong interactions act between charged particles, all particles and quarks, respectively
- Fundamentally, these interactions are modelled as a **quantum field theory** (QED, QCD)