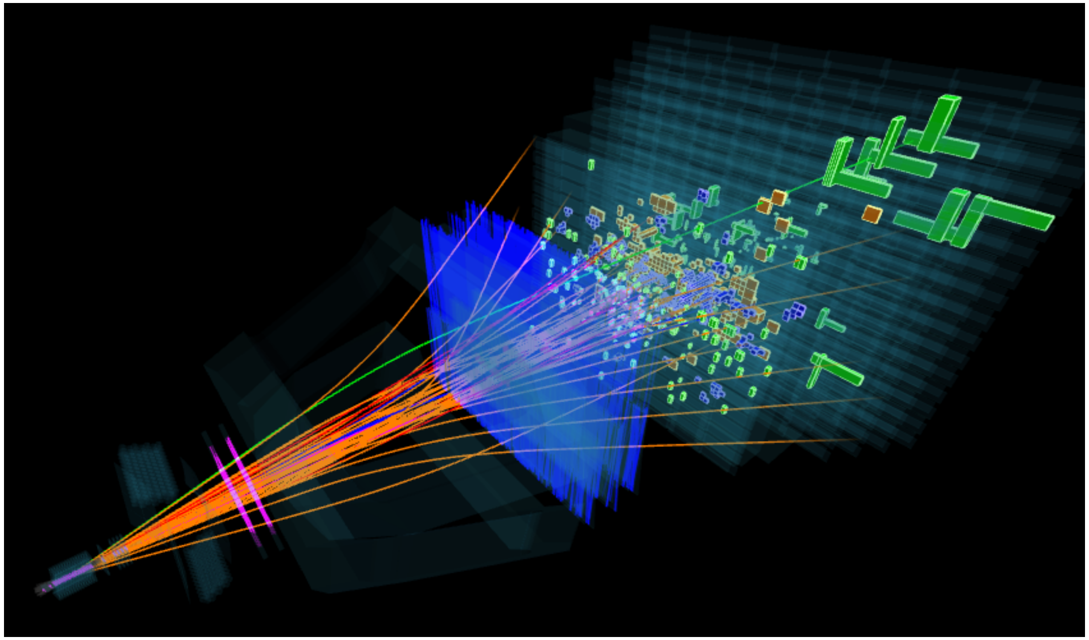
PHY20004 Particle Physics Class 5:
Discoveries and Puzzles

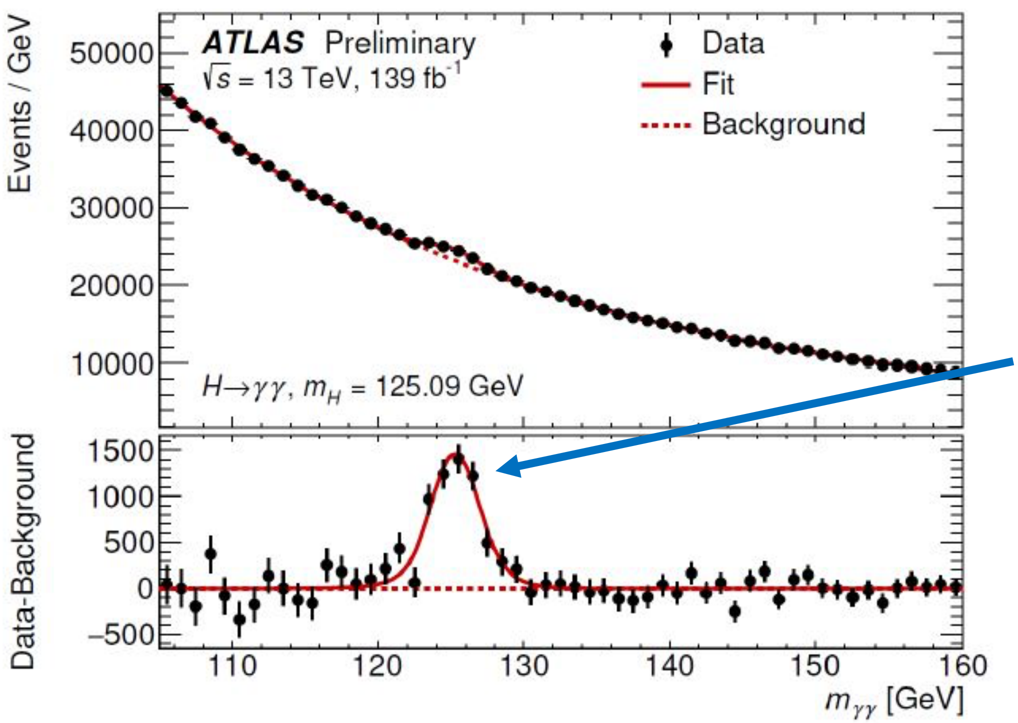
In this class we'll summarise some recent, important discoveries in particle physics, and the outstanding mysteries of the standard model



Credit: LHC

The Higgs boson …

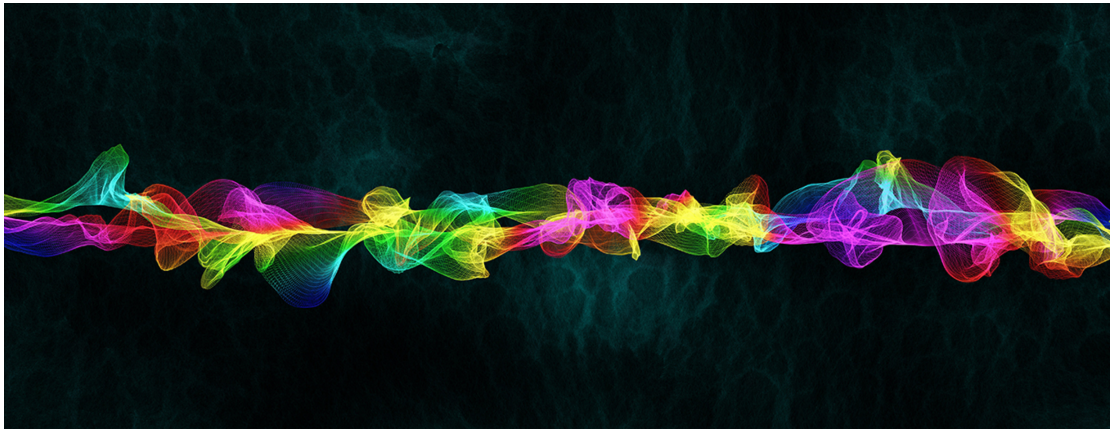
- The discovery of the **Higgs boson** in 2012, by the ATLAS and CMS experiments at LHC, is celebrated as one of the most important recent discoveries in physics. *Why is this? And how does the Higgs fit into the standard model we've been describing?*



- The Higgs bosons produced in LHC collisions decay in $\sim 10^{-22}$ s, so we can only observe the **decay products**, not the boson itself
- Here we are seeing one of these possible decays, into a pair of photons, causing a small increase in the background event rate
- The sum of energies tells us the Higgs mass, ≈ 125 GeV!

… or rather the Higgs field!

- What's important here is not the Higgs boson itself, but rather the associated **Higgs field**
- Let's back up … what is a (quantum) field?
  - A continuous fluid-like entity present everywhere in space and time
  - If the field is non-zero somewhere, it can cause physical effects
  - The field contains waves, and these waves are made up of particles; an individual particle is the least intense possible wave



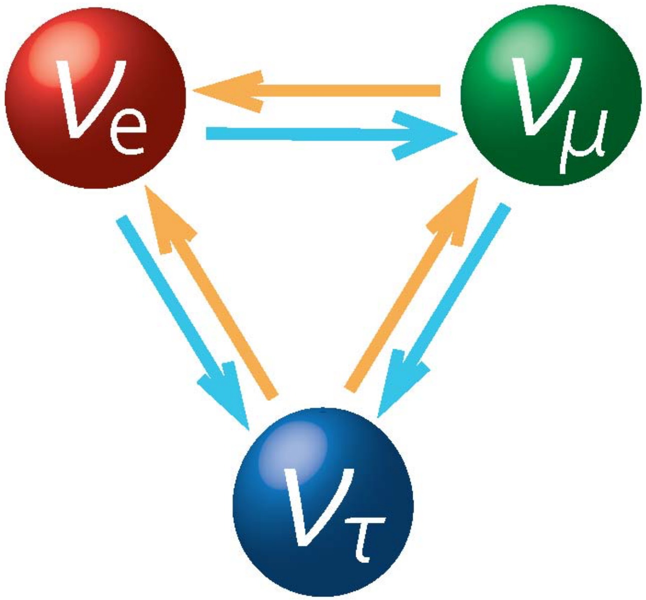
In the quantum field theory which describes the fundamental interactions, particles are considered as ripples or excitations in a field

… or rather the Higgs field!

- What's the Higgs field in particular?
  - It's a quantum field which has a **non-zero value** everywhere in space
  - Elementary particles such as leptons, quarks, and W and Z bosons acquire their property of **mass** through interaction with the Higgs field *(the stronger the interaction, the greater the mass)*
  - The Higgs field is our best current explanation of **why particles acquire mass**, and hence (in a sense) why our world exists!
  - Not all particles acquire all their mass from the Higgs interaction: e.g. protons & neutrons (binding energy), or the Higgs boson itself!
- Why the big deal about the Higgs boson?
  - The Higgs boson corresponds to excitations of the Higgs field – its discovery **confirms this field exists**, and allows us to **study the field**

Neutrino oscillations

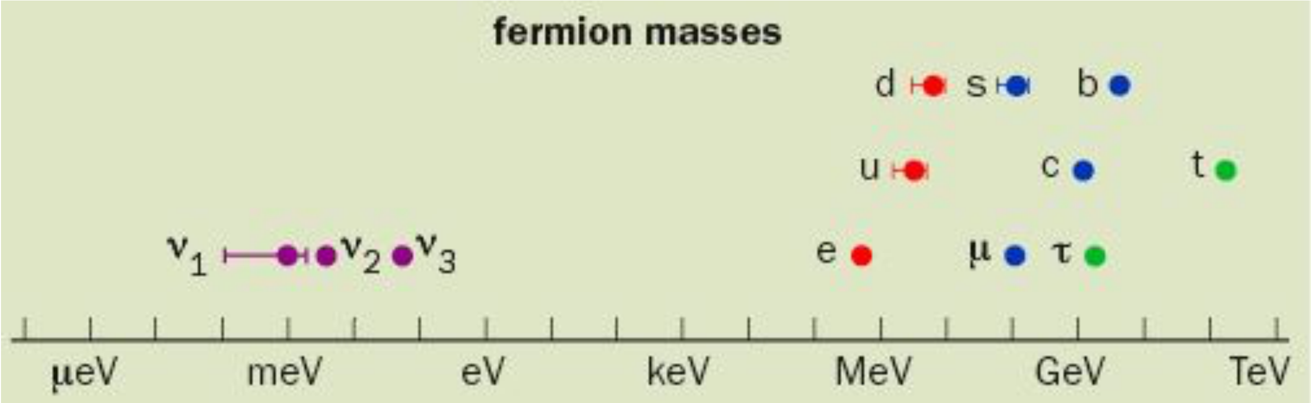
- If a beam of neutrinos of one flavour (electron, muon, tau) is created then, after the beam has propagated a certain distance, **other flavours** start appearing!
- This can be deduced from observations of **solar neutrinos** and in laboratory neutrino experiments



- The solar neutrino problem was a long-standing discrepancy between the neutrino flux predicted to arrive from the Sun, and that measured directly
- The flavour of the electron neutrinos produced in the Sun change during propagation to a mixture of electron, muon and tau neutrinos, with a reduced chance of being detected

Neutrino oscillations

- This strange behaviour can only be explained if neutrinos have a **tiny but non-zero mass** *(not predicted by the standard model!)*
  - More precisely: there are **3 neutrino masses**, and each neutrino flavour exists as a (quantum) mixing of these mass states, which oscillate by quantum theory. We do not yet understand these mixings!



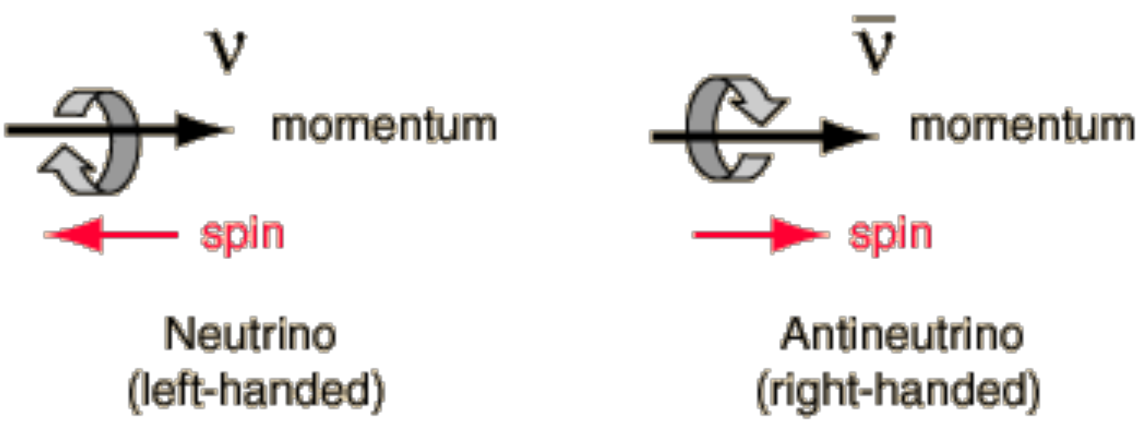
Neutrino masses are very tiny compared to other particles

Credit: http://hitoshi.berkeley.edu /neutrino/neutrino4.html

- Since neutrinos are a very abundant particle (second only to photons), this tiny mass affects the expansion of the Universe!

Neutrinos and their spin

- Particles possess a quantum property known as **spin** – fermions, such as the elementary particles, may be found in either of two possible spin states *(this is the meaning of “spin-$\frac{1}{2}$”)*
- Neutrinos are unusual because their **spin is always aligned opposite to their momentum** (“left-handed”), and the reverse is true for anti-neutrinos (“right-handed”)

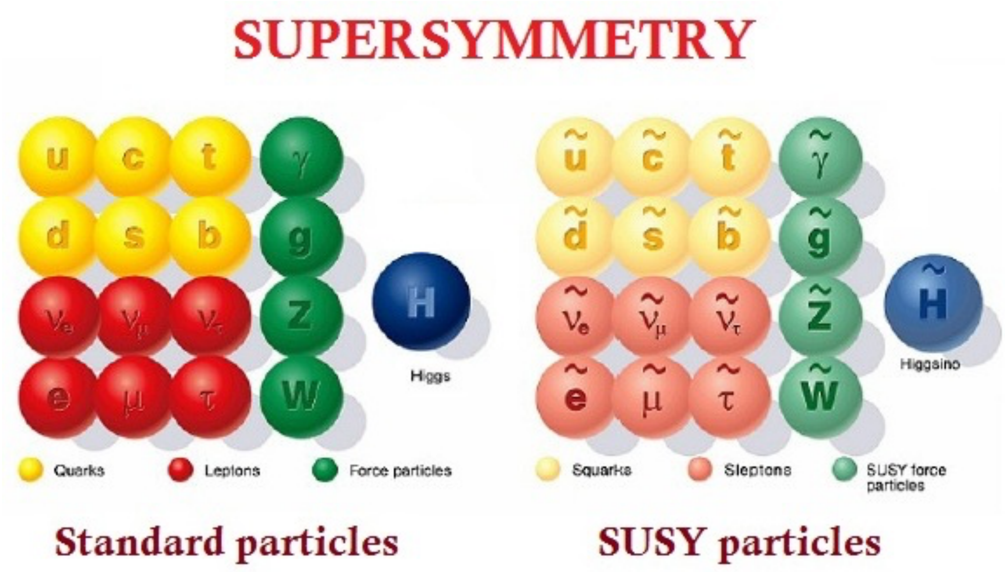


*The mystery of “why are there no right-handed neutrinos” remains unsolved and reflects fundamental questions regarding **matter-antimatter asymmetry***

Credit: http://hyperphysics.phy-astr.gsu.edu/hbase/Particles/neutrino3.html

Supersymmetry

- **Supersymmetry** (SUSY) is a conjecture in which every fundamental particle has an **associated massive partner**
  - A key aspect is that the partner *differs by a half-integer in spin*, such that a fermion partners to a boson, and vice versa
  - Supersymmetry solves the *hierarchy problem*, which questions the huge discrepancy in the sizes of the fundamental forces

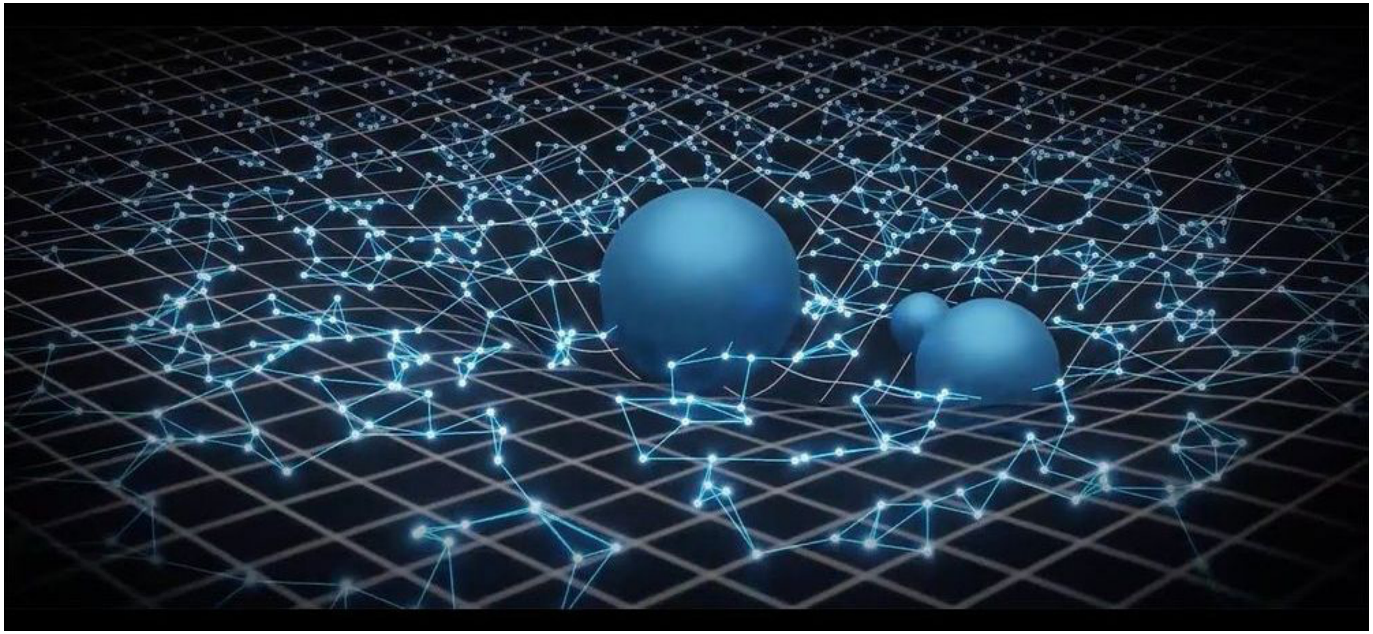


*No supersymmetric particles have yet been detected, but the search continues! An interesting idea is that the mysterious **dark matter** inferred from astronomical observations may be a SUSY particle*

Credit: https://www.quantamagazine.org

How does gravity fit in?

- **Gravity** is the only fundamental interaction which as yet *cannot be described by a quantum field theory* – our leading theory, general relativity, is instead a geometrical theory
- *Do gravitons (the carrier particles for gravity) exist? If not, how can we reconcile gravity with the other fundamental forces?*



Remaining questions!

- The standard model still contains **many unanswered questions** for current and future researchers!
  - *Why are there so many input parameters to the standard model?*
  - *Why are there three generations of leptons and quarks?*
  - *Why is the neutrino mass so much smaller than the quark mass?*
  - *Why are the charges of the electron and proton identical?*
  - *What is responsible for the asymmetry between matter and anti-matter?*
  - *How can we include gravity in this picture?*