The Standard Model

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19th August 2025

1. Context and Objective
2. Language and Key Ideas
3. The Standard Model Revisited
4. How do we do it?
5. What do we not know?

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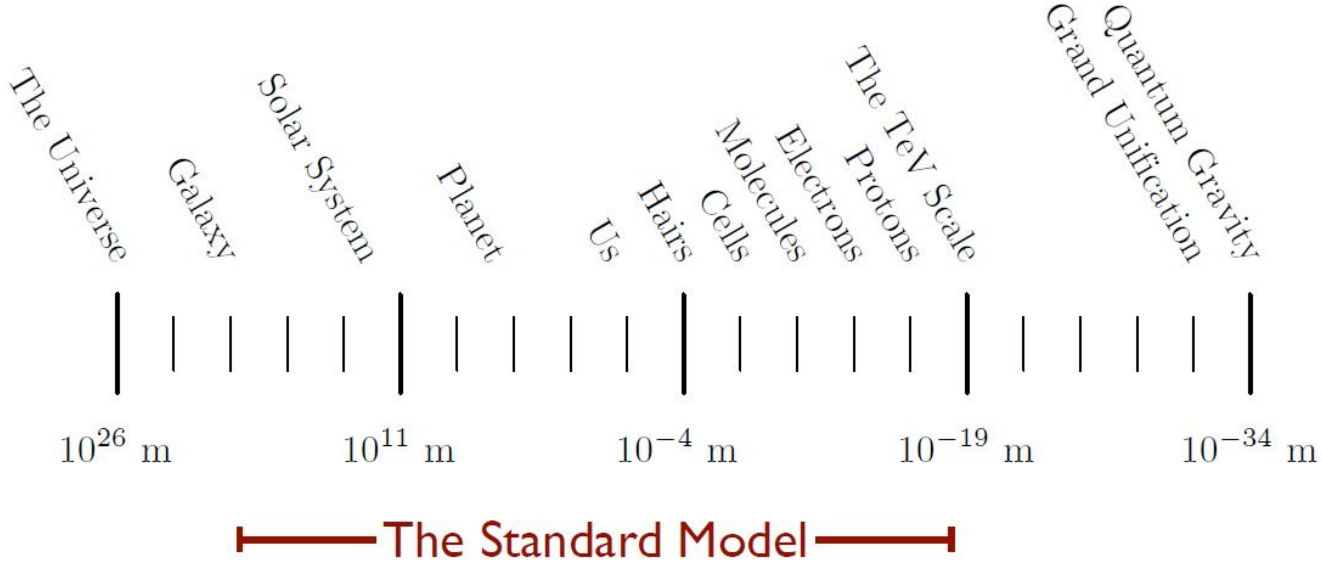
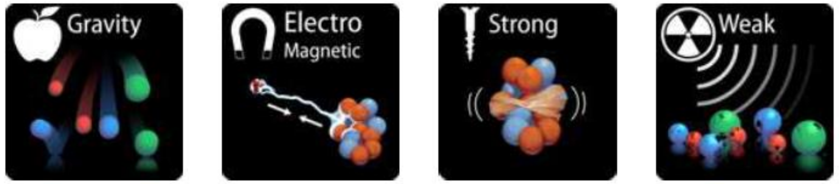


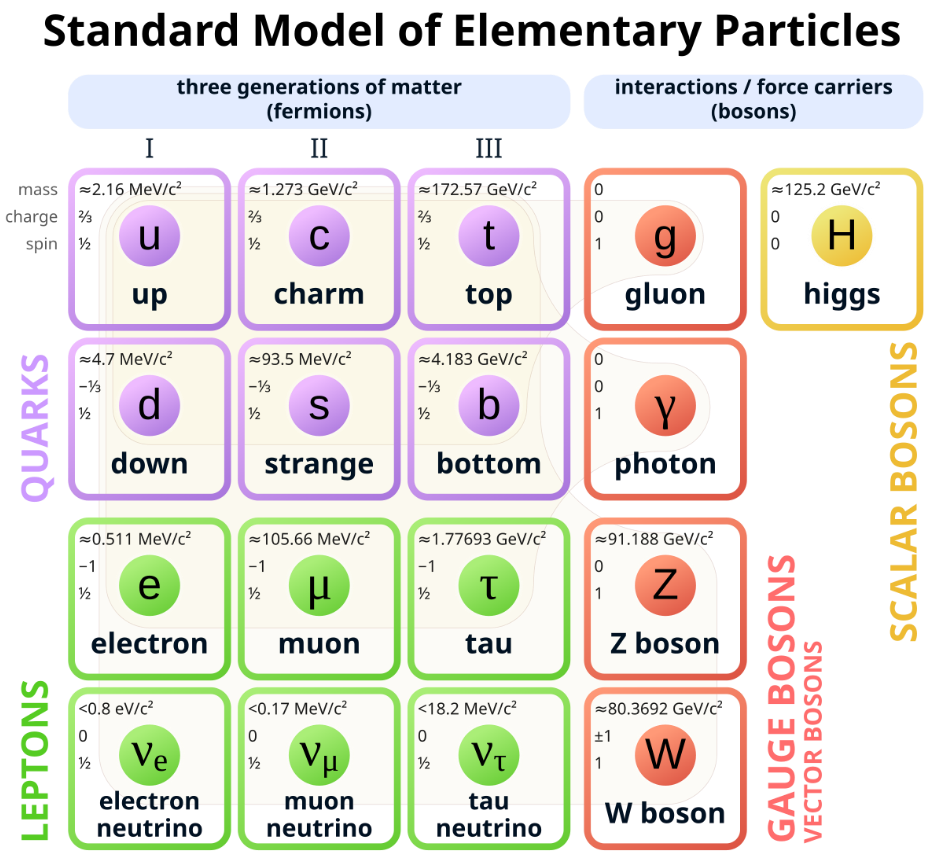


4 fundamental forces

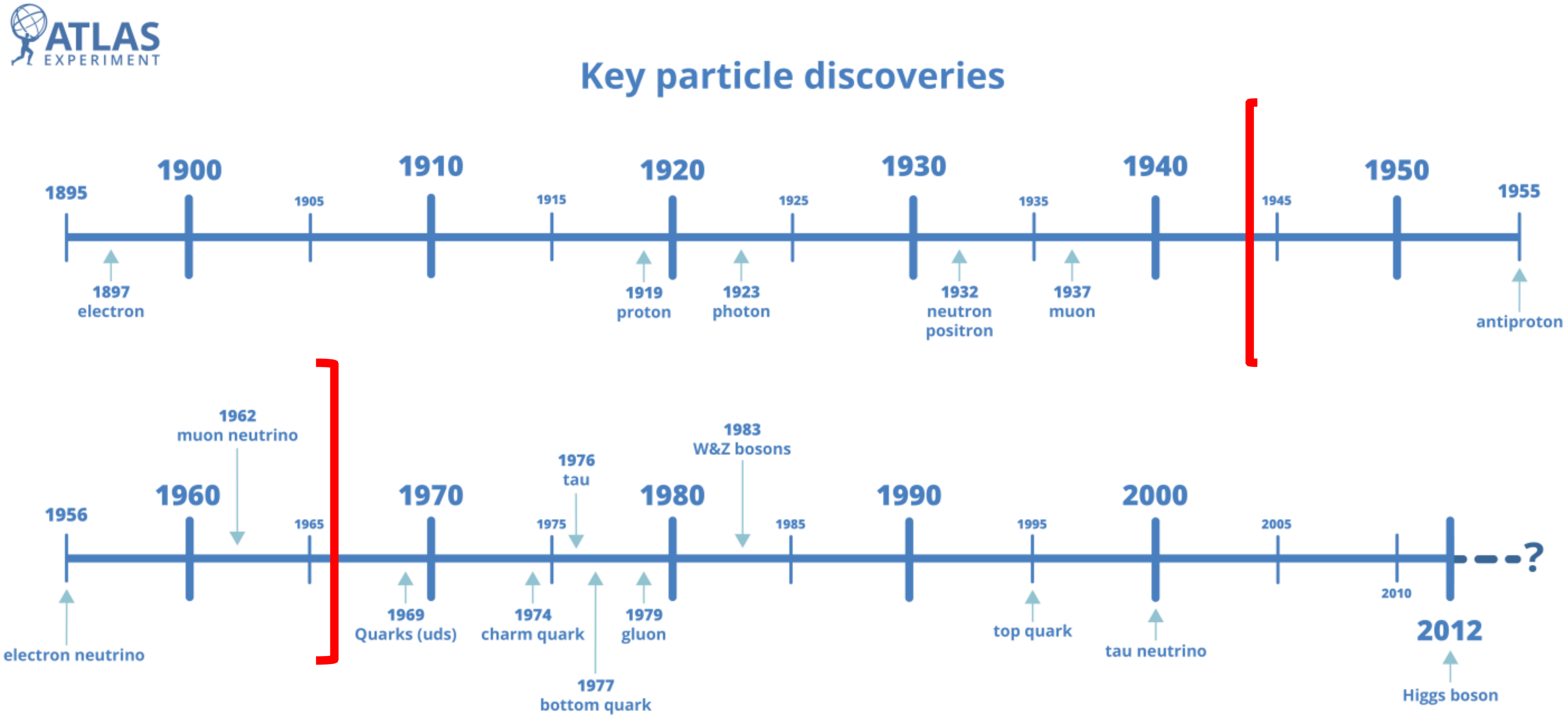
- Naïve overview – Physics is the only subject that spans a huge variety of phenomena over vast distance scale

- The Standard Model plays a central role over a large spectrum

$$
\begin{aligned}
\mathcal{L} \;=\; & -\frac{1}{2}\mathrm{Tr}\, G_{\mu\nu}G^{\mu\nu} - \frac{1}{2}\mathrm{Tr}\, W_{\mu\nu}W^{\mu\nu} - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} \\
& + (D_\mu\phi)^\dagger D^\mu\phi + \mu^2\phi^\dagger\phi - \frac{1}{2}\lambda\left(\phi^\dagger\phi\right)^2 \\
& + \sum_{f=1}^{3}\left(\bar{\ell}^f_L i\not{D}\ell^f_L + \bar{\ell}^f_R i\not{D}\ell^f_R + \bar{q}^f_L i\not{D} q^f_L + \bar{d}^f_R i\not{D} d^f_R + \bar{u}^f_R i\not{D} u^f_R\right) \\
& - \sum_{f=1}^{3} y^f_\ell \left(\bar{\ell}^f_L \phi \ell^f_R + \bar{\ell}^f_R \phi^\dagger \ell^f_L\right) \\
& - \sum_{f,g=1}^{3}\left(y^{fg}_d \bar{q}^f_L \phi d^g_R + (y^{fg}_d)^* \bar{d}^g_R \phi^\dagger q^f_L + y^{fg}_u \bar{q}^f_L \tilde{\phi} u^g_R + (y^{fg}_u)^* \bar{u}^g_R \tilde{\phi}^\dagger q^f_L\right)
\end{aligned}
$$

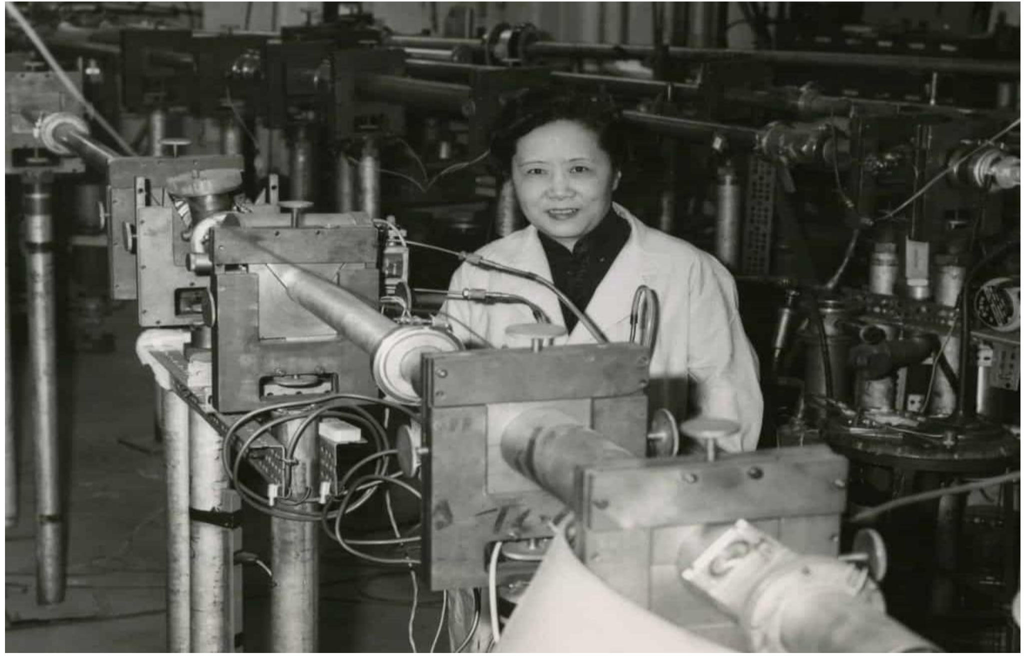


- Spoiler alert: This is **The Standard Model**
- A consistent model to describe matter content of the universe
  - Contains 19 free parameters
- We will try and understand some of the central ideas behind the model



- Journey has taken a long time to find, validate and organize
- Particularly the 1950's and 1960's and the "Particle Zoo"
- **"the finder of a new elementary particle used to be rewarded by a Nobel Prize, but such a discovery now ought to be punished by a $10,000 fine" – Willis Lamb (1955 Nobel Prize in Physics)**

Parity Violation - 1956



Chien-Shiung Wu – Not awarded Nobel Prize which went to her two colleagues Lee and Yang instead

- Wu measured beta decay in the process:

$$^{60}_{27}\mathrm{Co} \rightarrow \, ^{60}_{28}\mathrm{Ni} + \mathrm{e}^- + \bar{\nu}_e + 2\gamma$$

- She measured the spin direction of the emitted electron
- She found that the spin of the electron is emitted preferentially in a certain direction and therefore the Weak interaction violates “parity”
  - Particles have a property called “Left” or “Right” handedness
- This is very important. Left handed particles interact differently to Right handed particles
  - The Standard Model is Chiral
  - This can help in solving the matter/anti-matter asymmetry problem

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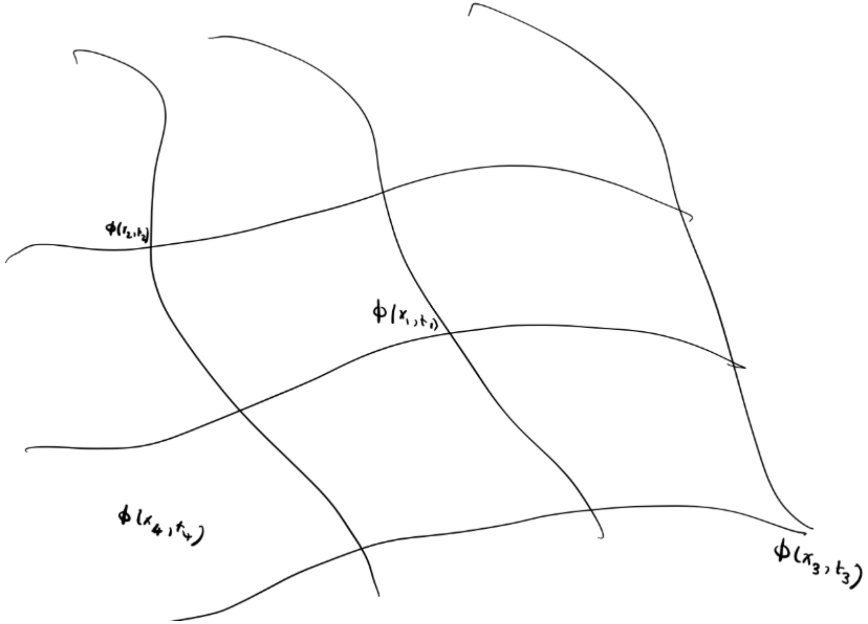
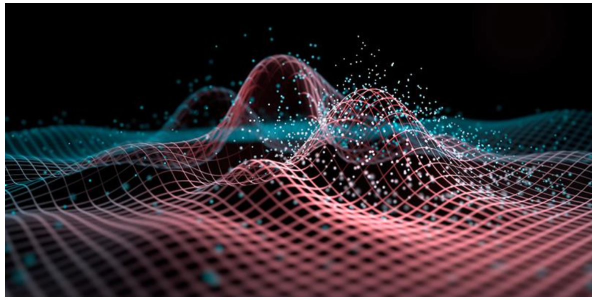
What is a Quantum Field Theory?

- A field is a mathematical function which has a value at every point in space-time

$$\phi(\vec{x}, t)$$



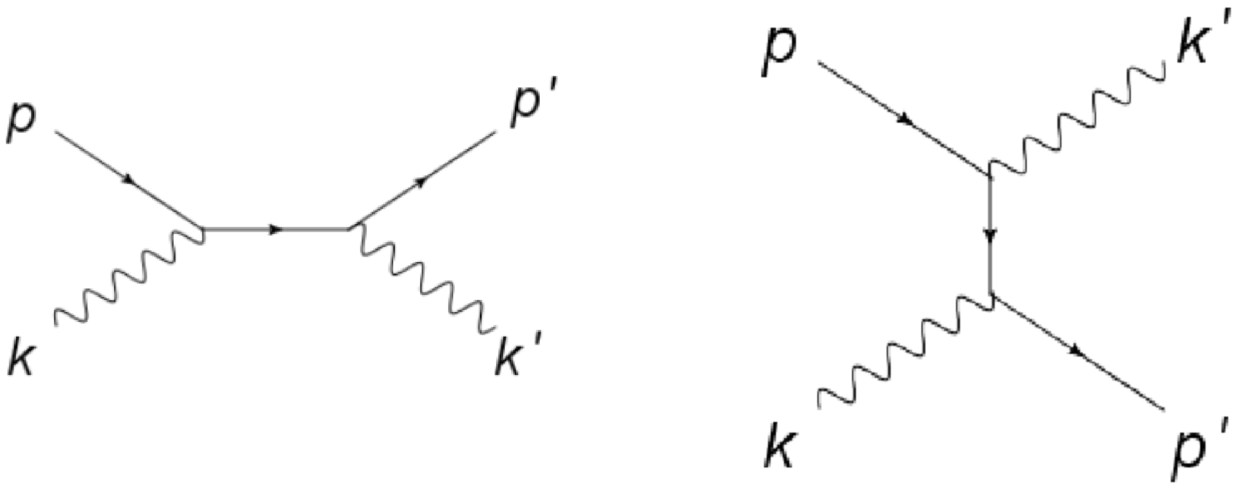


- A quantum field will have “discretized” excitations/lumps which correspond to particles

- A quantum field theory is the theoretical framework that mathematically describes quantum fields and their interactions in a unique way that incorporates Quantum Mechanics and Special Relativity

What do we calculate with Quantum Field Theory?

- Our universe is Quantum → therefore we can only calculate probabilities of events occurring



$$\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta} = \frac{1}{32\pi}\left(\frac{\omega'}{m_e\omega}\right)^2 |\mathcal{M}_1 + \mathcal{M}_2|^2$$

- The probabilities of processes can be represented by Feynmann diagrams
  - We can calculate the cross section of an events, etc

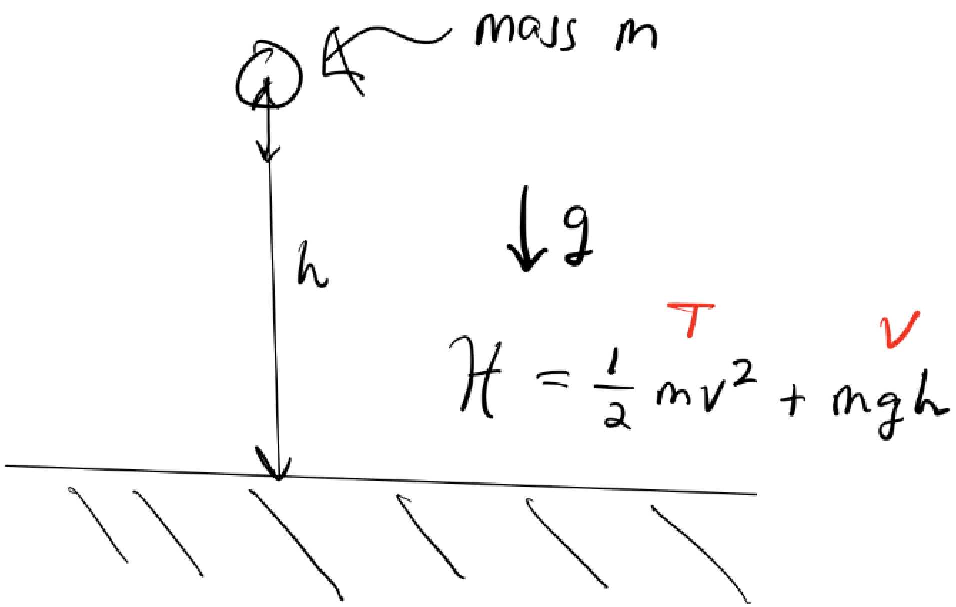
A Brief Chat About Classical Physics

- You can describe a theory/ system if you know the energy → we call this the "Hamiltonian":

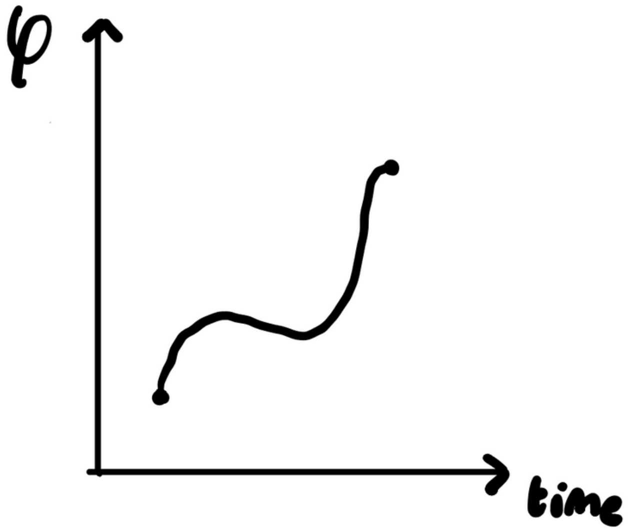
$$\mathcal{H} = T + V$$

- This is related to something called a "Lagrangian"

$$\mathcal{L}(\phi, \partial_\mu \phi) = \pi(x)\,\dot{\phi}(x) - \mathcal{H}(\phi, \pi), \quad \pi(x) = \frac{\partial \mathcal{L}}{\partial \dot{\phi}(x)}$$



- Using the Lagrangian we can derive the “equations of motion” of a particle/field



$$\frac{\partial \mathcal{L}}{\partial \varphi} - \partial_\mu \left(\frac{\partial \mathcal{L}}{\partial(\partial_\mu \varphi)} \right) = 0$$

- Great! We can determine the evolution of the system!
  - (Note: moving to quantum systems add a level of complexity and abstraction, but the essence of the idea is the same)
- What else can we do?
  - The Lagrangian is also powerful because it is “invariant” under its symmetries

What are symmetries?

Emmy Noether published her seminal work in 1918

- A transformation to the system/theory such that the equations of motions of the system/theory are unchanged

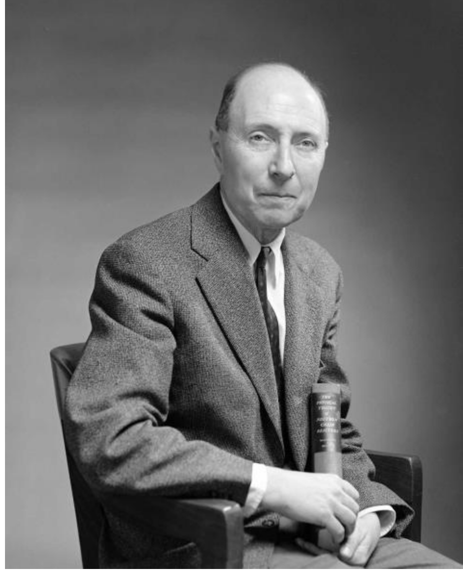
- Why are they powerful?

  - Noethers' Theorem: Every **continuous symmetry** is associated with a corresponding **conservation law**

- Examples:
  - Translation symmetry ←→ Conservation of Energy and Momentum

  - Rotational symmetry ←→ Conservation of Angular Momentum

How will we use Symmetries?



Eugene Wigner

- The Classification of Particles:
  - Particles are defined/characterized by: mass, spin, charge, lepton number, …
  - These quantum numbers are all a consequence of some symmetry (Wigner's theorem)

- The interactions of Particles:
  - Abstract mathematical symmetries called "gauge symmetries" uniquely determine the allowed interactions of particles

An Example: QED

- QED is a theory that involves only electrons and photons

Paul Dirac

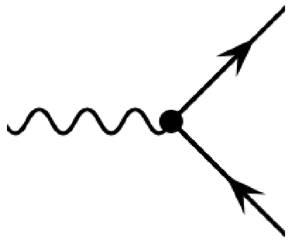
$$\mathcal{L} = -\hbar c \bar{\psi}\left(\gamma_\mu \frac{\partial}{\partial x_\mu} + \frac{mc}{\hbar}\right)\psi - \frac{1}{4}F_{\mu\nu}F_{\mu\nu} - ie\bar{\psi}\gamma_\mu A_\mu \psi$$

T (kinetic terms) V (interaction term)

- **V** corresponds to an interaction term between the photon and electron

- This interaction is a direct consequence of the abstract “gauge symmetry”
  - For QED this is called the “U(1) gauge symmetry”

- All interactions in the SM are determined by gauge symmetries



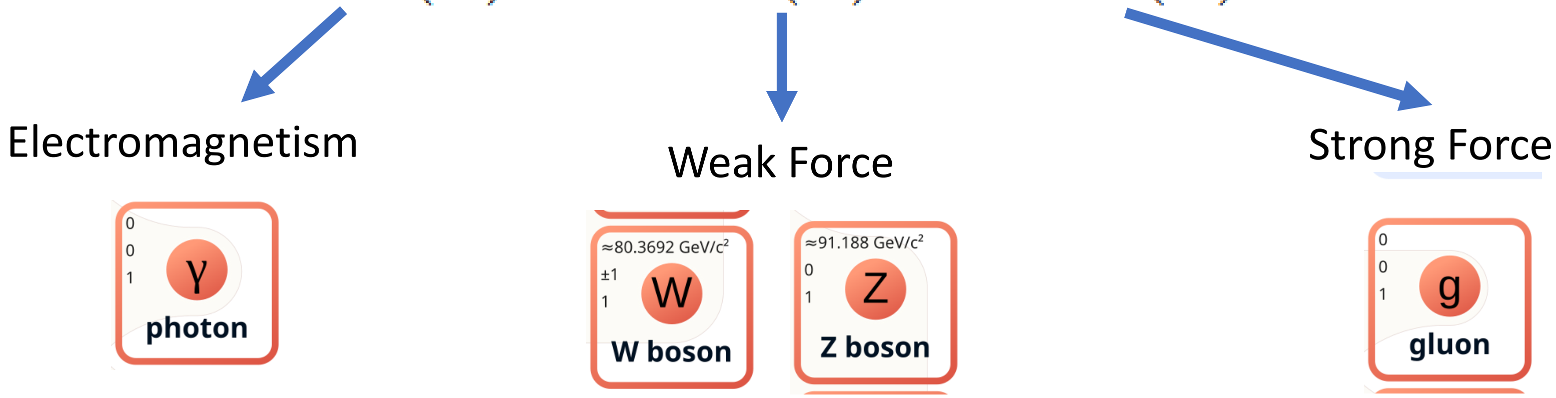
Symmetry and Forces

- For QED the symmetry group was called U(1) and this led to an interaction between the photon and electron

- The mediating particle for QED is the photon and this we call the “force carrier” of the electromagnetic force

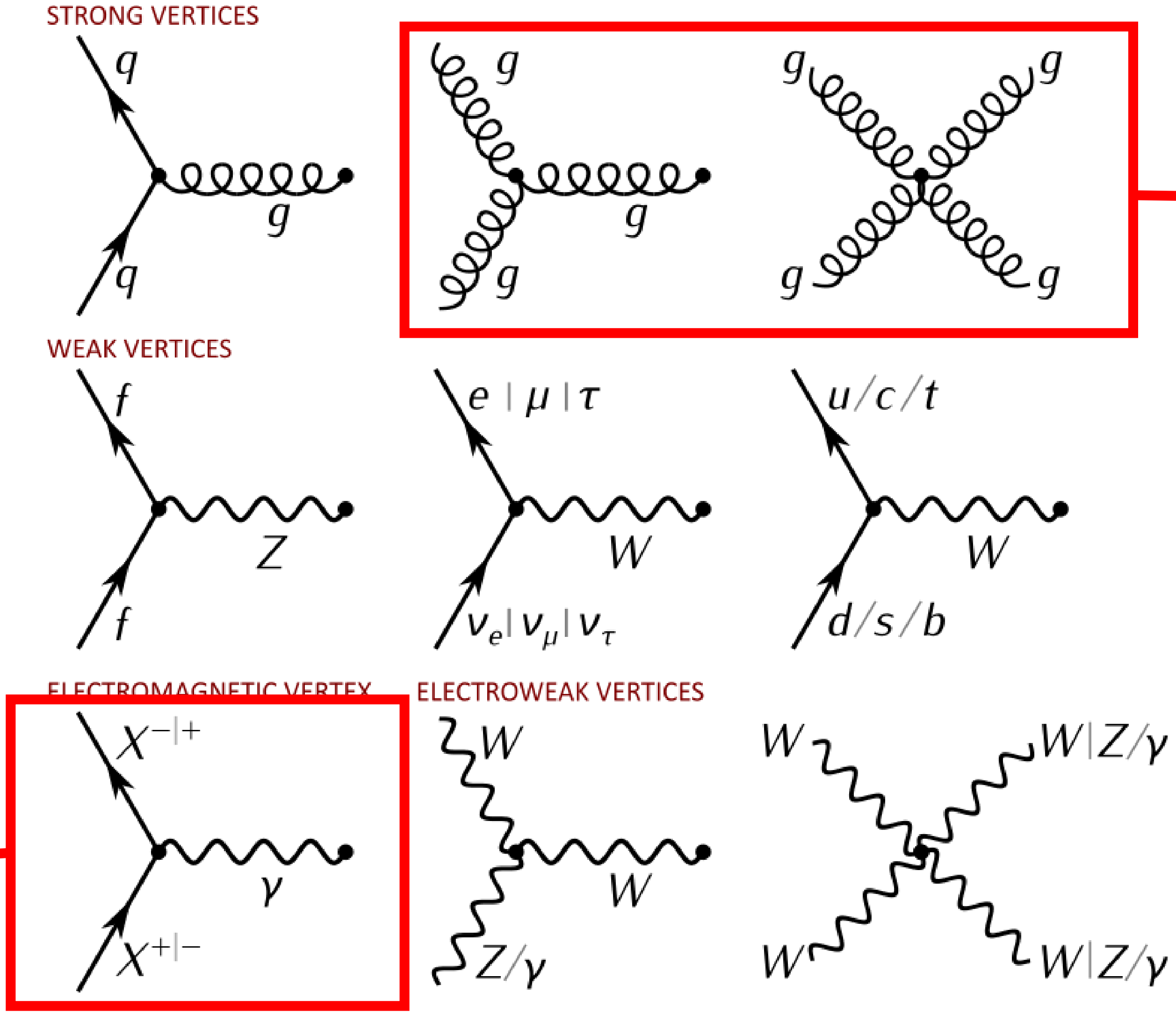
- Similarly, for the full Standard Model the associated symmery is called:

$$U(1) \times SU(2) \times SU(3)$$



Feynmann Diagrams, revisited …

- Diagrammatic way of representing all possible interactions



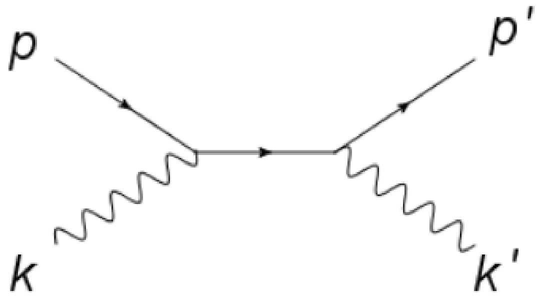
$$-\frac{1}{2}\mathrm{Tr}\, G_{\mu\nu}G^{\mu\nu}$$

$$ie\bar{\psi}\gamma_\mu A_\mu \psi$$

The Story So Far …

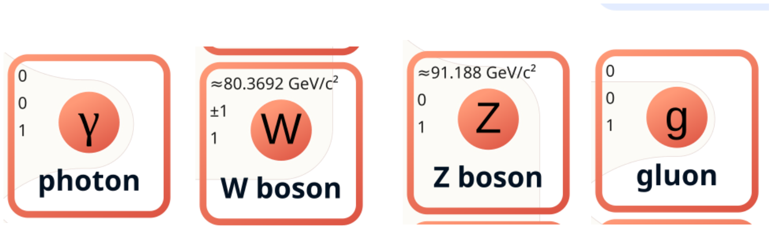
$$\phi(\vec{x}, t)$$

- The Standard Model is a Quantum Field Theory



- Feynman diagrams describe the allowed processes of the Standard Model
  - Calulating these give the probabilities of the process

- Symmetries are responsible for the Strong, Weak, Electromagnetic force and also responsible for the allowed interactions of these forces



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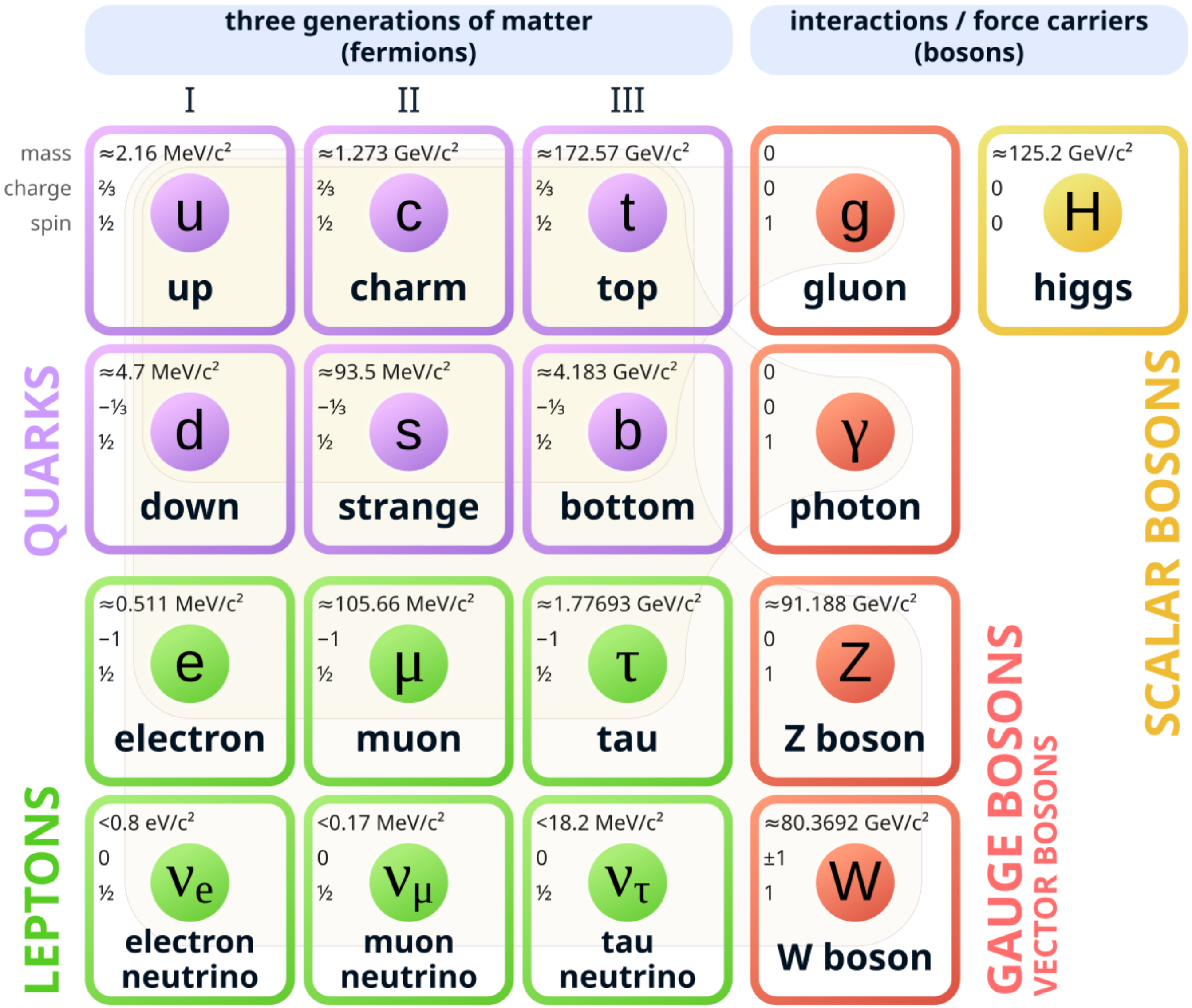
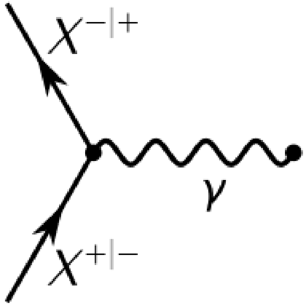
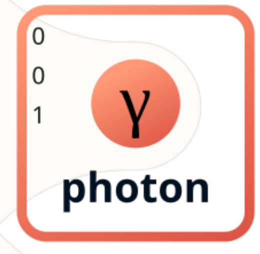
Standard Model of Elementary Particles



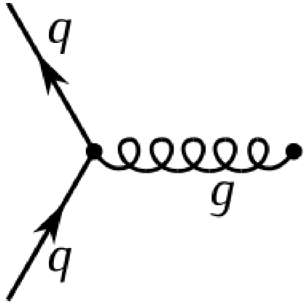
Overview of the Forces

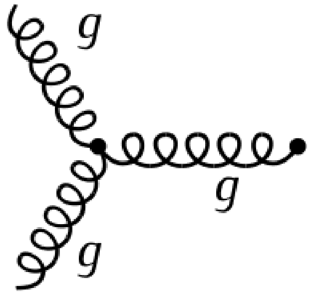
- Electromagnetic:
  - Responsible for light
  - Interacts with particles that have electric charge
  - Carried by the photon



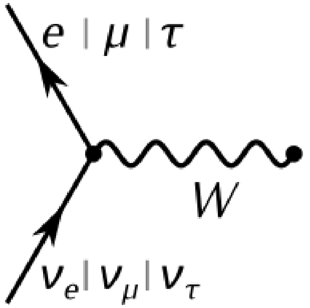


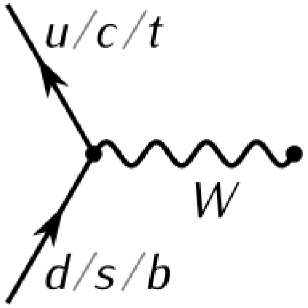
- Strong Nuclear Force:
  - Responsible for the binding of quarks → binds protons/neutrons together
  - Interacts with particles that have "colour" charge → these come in Red, Green and Blue
  - Carried by the Gluon

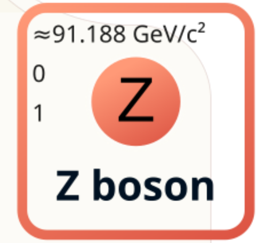


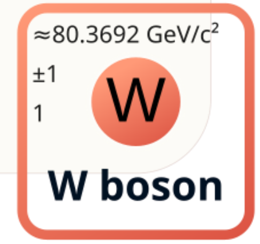


- Weak Nuclear Force
  - Responsible for the decay of particles (i.e beta decay)
  - Interacts with only Left Handed particles
  - Carried by the W and Z bosons



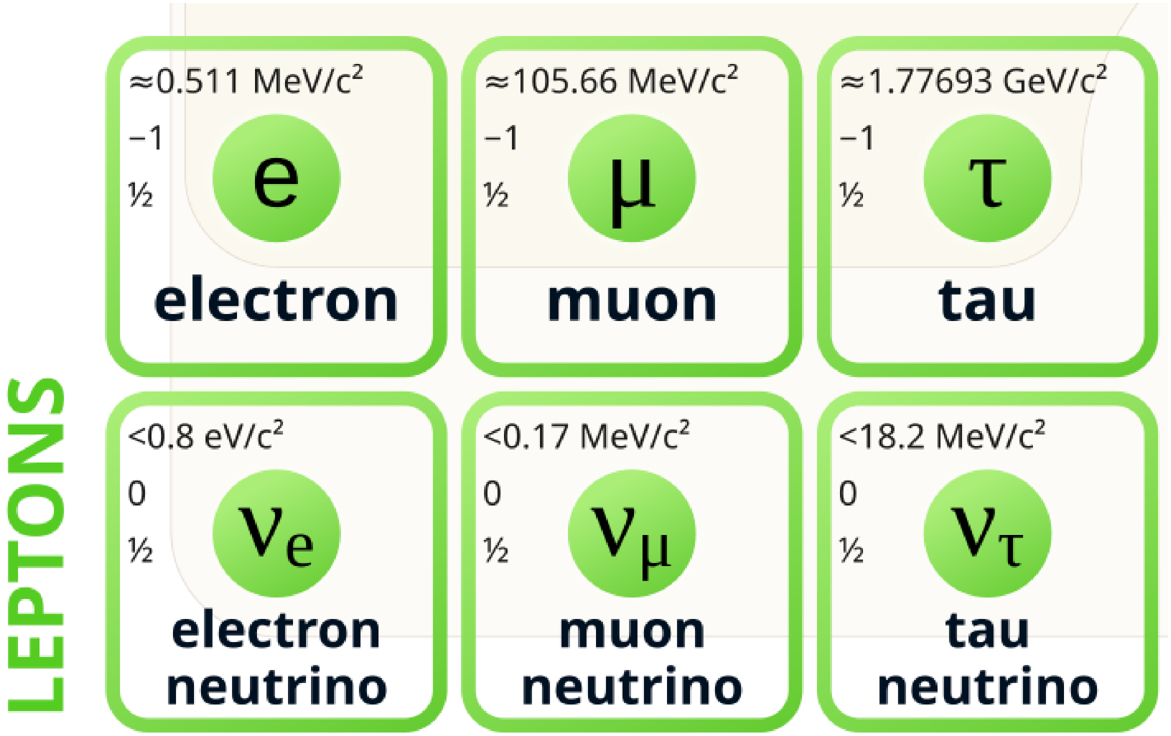






Overview of the Leptons

- Each generation comes in a doublet of a charged and neural lepton
  - i.e electron, electron-neutrino
- Fermions → spin ½ → matter particle
- Interacts with weak and electromagnetic force
  - Does not interact with strong force
- Each generation has sequentially higher mass
- Neutrinos have a very small mass
  - Due to neutrino oscillation experiments
  - Origin of masses is unknown



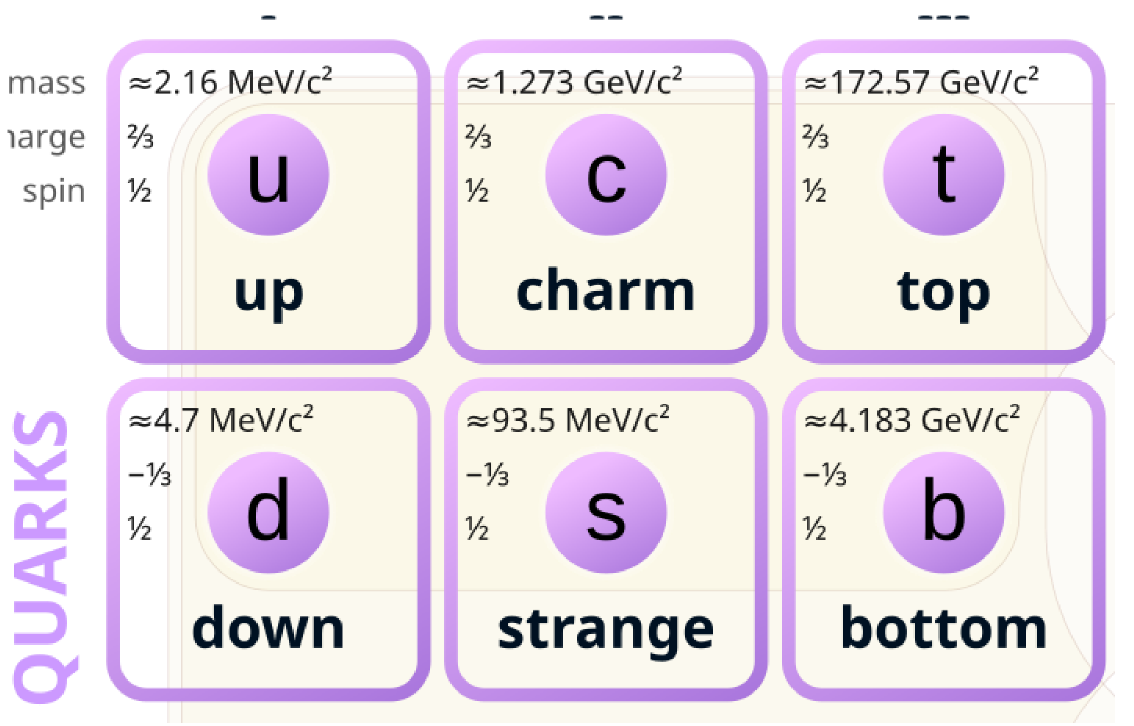
Overview of the Quarks

- Each generation comes in a doublet of an “up” type quark with charge +2/3 and “down” type quark with electric charge -1/3

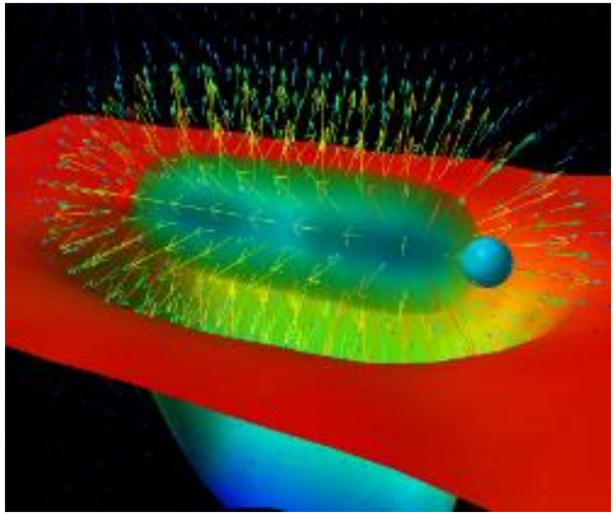
- Fermions → spin ½ → matter particle

- Interacts with strong, weak and electromagnetic force

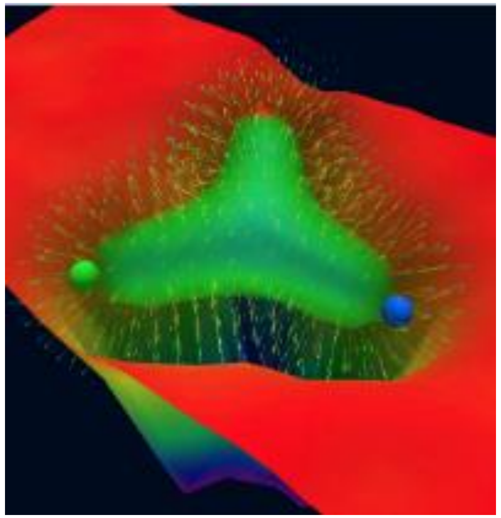
- Each generation has sequentially higher mass



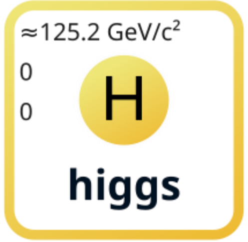
Bound states of the Quarks



- Quarks interact with strong force and therefore gluons
- Due to a feature of the strong force called “confinement”
  - Free quarks cannot exist
  - Quarks can form “colourless” bound states
    - 2 quarks → “meson”
    - 3 quarks → “baryon”
    - “baryon” + “meson” = “hadron”
- Examples are: protons, neutrons, pions, kaons, etc..
  The so called “particle zoo” originated from this



The Higgs Boson



$$
\begin{aligned}
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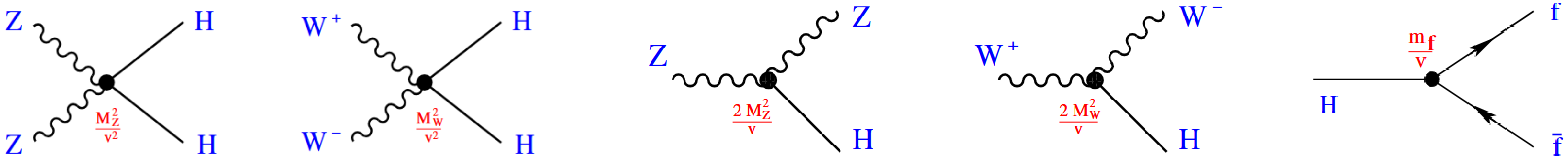
& +(D_\mu\phi)^\dagger D^\mu\phi + \mu^2\phi^\dagger\phi - \frac{1}{2}\lambda\left(\phi^\dagger\phi\right)^2 \\
& +\sum_{f=1}^{3}\left(\bar{\ell}^f_L i\not{D}\ell^f_L + \bar{\ell}^f_R i\not{D}\ell^f_R + \bar{q}^f_L i\not{D} q^f_L + \bar{d}^f_R i\not{D} d^f_R + \bar{u}^f_R i\not{D} u^f_R\right) \\
& -\sum_{f=1}^{3} y^f_\ell\left(\bar{\ell}^f_L\phi\ell^f_R + \bar{\ell}^f_R\phi^\dagger\ell^f_L\right) \\
& -\sum_{f,g=1}^{3}\left(y_d^{fg}\bar{q}^f_L\phi d^g_R + (y_d^{fg})^*\bar{d}^g_R\phi^\dagger q^f_L + y_u^{fg}\bar{q}^f_L\tilde{\phi} u^g_R + (y_u^{fg})^*\bar{u}^g_R\tilde{\phi}^\dagger q^f_L\right)
\end{aligned}
$$

- The Higgs Boson is a spin-0 particle
- Due to this, the possible interactions are not as restricted as the other particles
- This is why most of the SM lagrangian has terms coupling to the Higgs.
  - There are more allowed interactions



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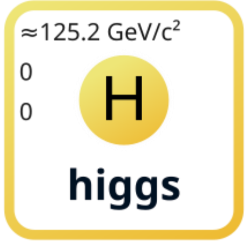
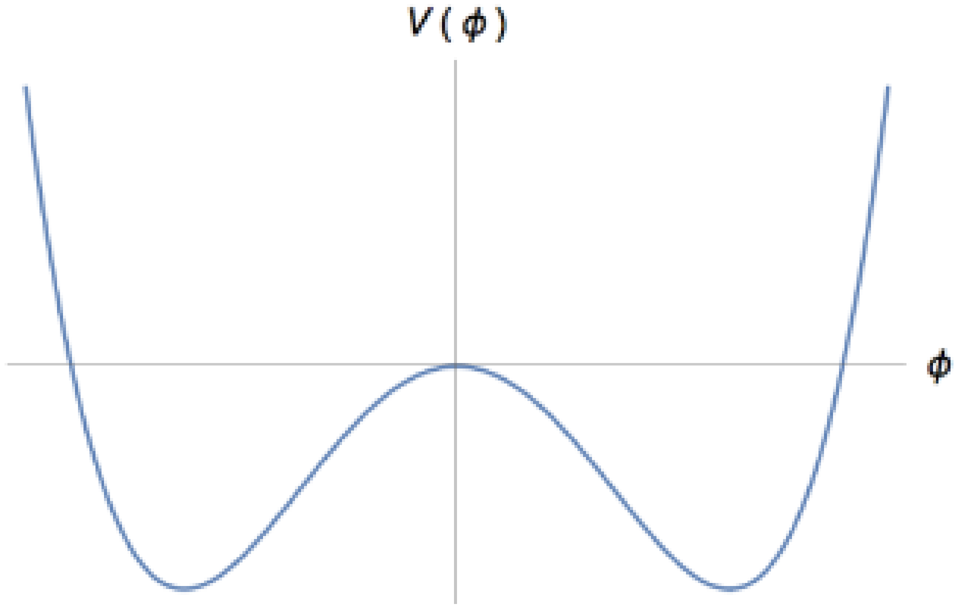


$$\mu^2\phi^\dagger\phi - \frac{1}{2}\lambda\left(\phi^\dagger\phi\right)^2$$

- Because the Higgs is spin-0 it can have a non-zero value in vacuum
- This leads to “spontaneous symmetry breaking”
- And hence the origin of masses for gauge bosons and fermions



- Mass $m_H \approx 125$ GeV
- Condensate $\langle\phi\rangle \approx 246$ GeV

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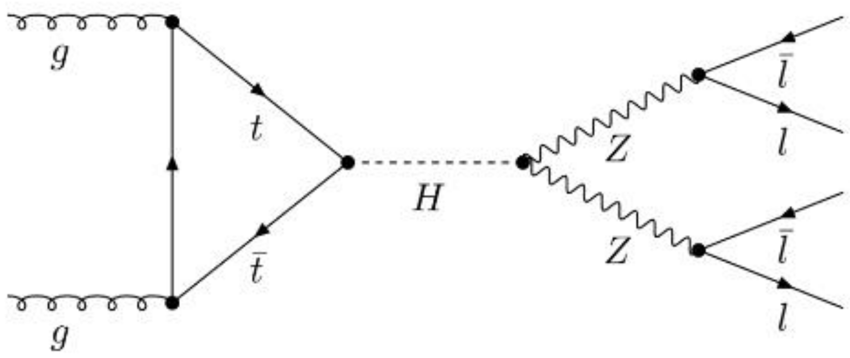

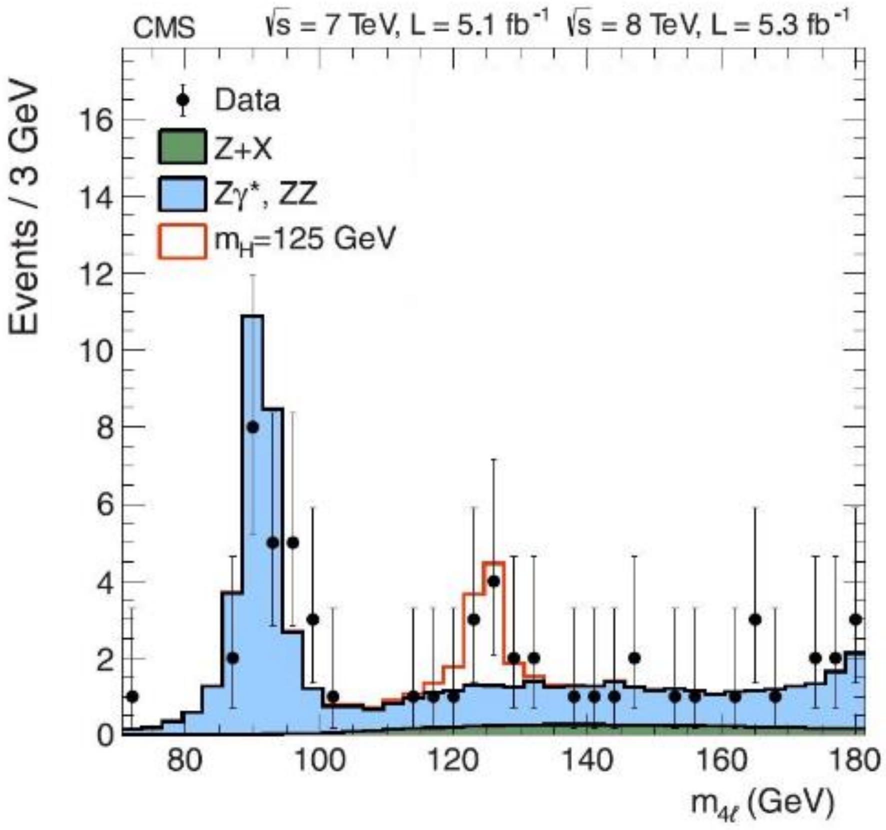

- Choose a process and channel to look for your signal in
- Find and model the background processes which give the same final state
- Count the number of events observed in data and compare to the expectations and make a statistically significant conclusion

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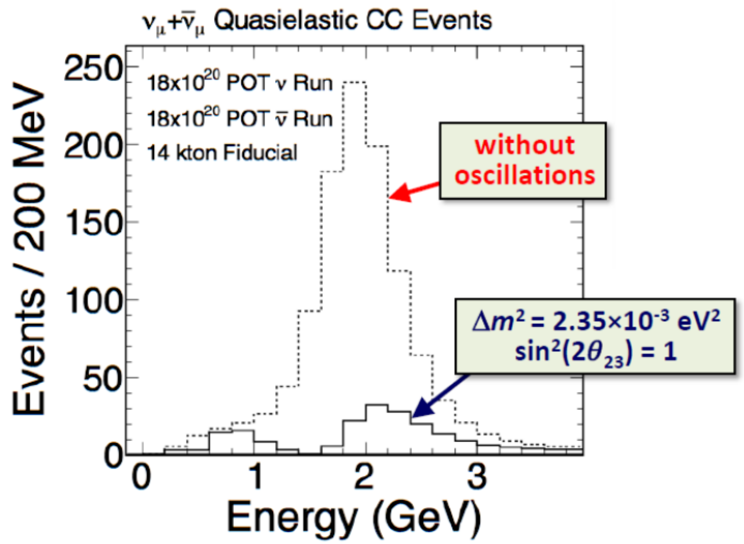
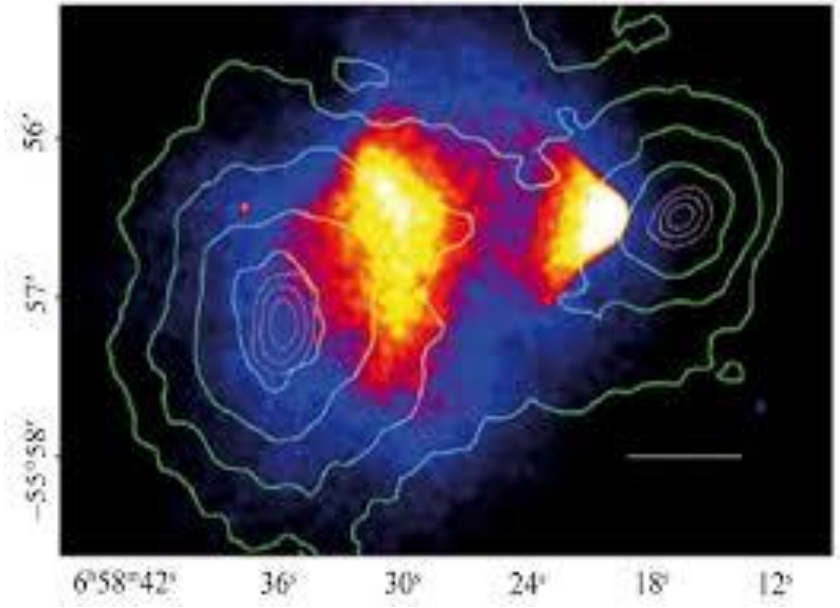
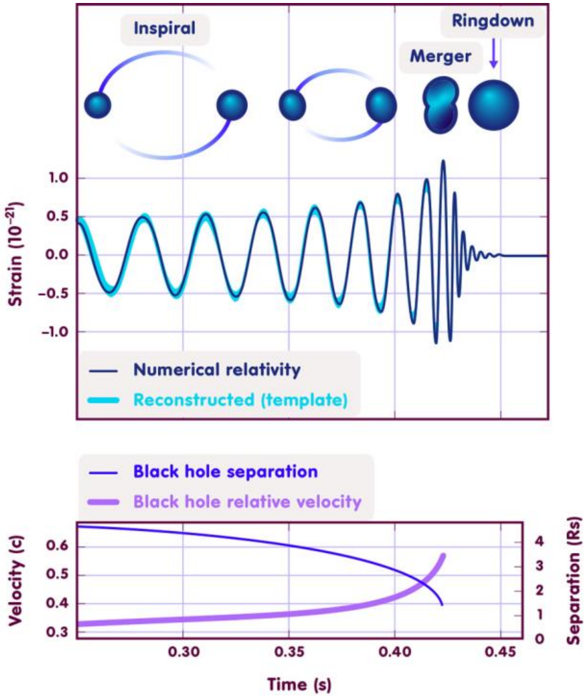
What do we not know?

- Neutrino masses
- Dark Matter
- Quantum Gravity
- Much more







Thank you for Listening! Questions?