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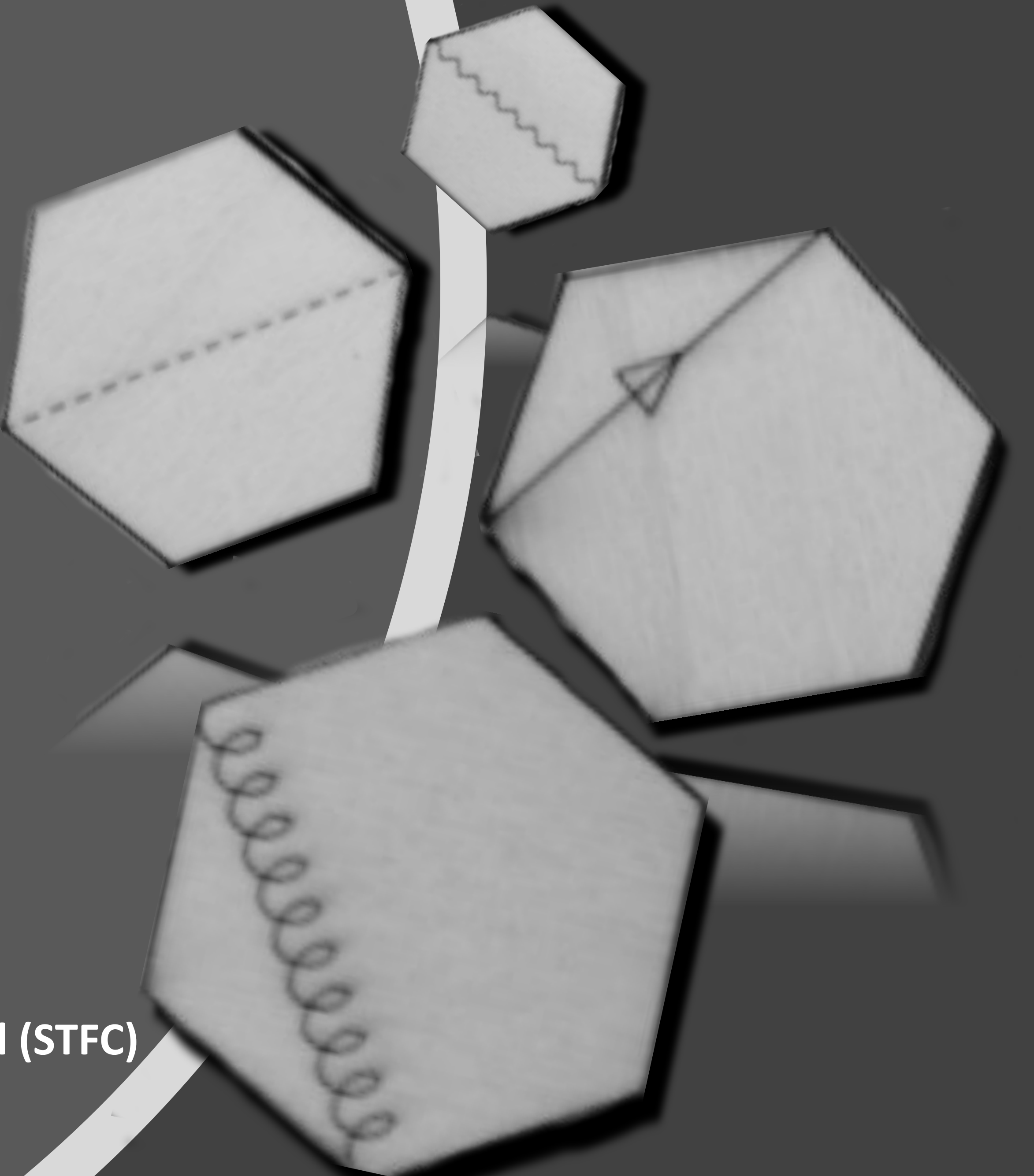
Higgs Boson Dominoes



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From Queen Mary University of London

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https://www.qmul.ac.uk/spcs/engage/outreach/in-school/physics-activities/higgs-boson-dominoes/

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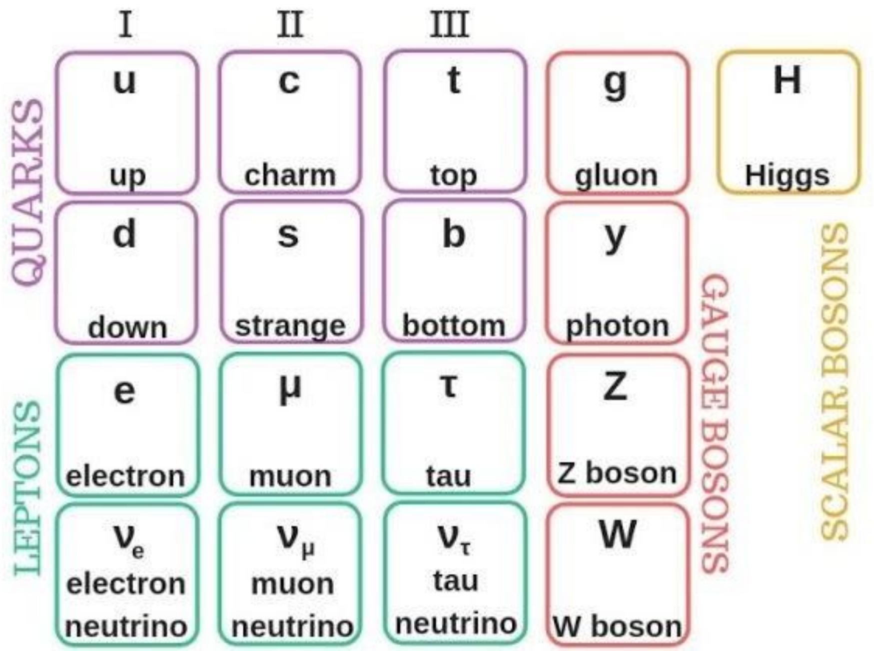
The standard model

- All currently known fundamental particles are grouped in what’s called the Standard Model
- Matter in the universe is made up of fermions (quarks and leptons), which have 3 generations (labelled I II III in vertical columns)
- Forces in the universe are carried by gauge bosons like the photon
- The Higgs boson allows particles to have mass via interactions with its field

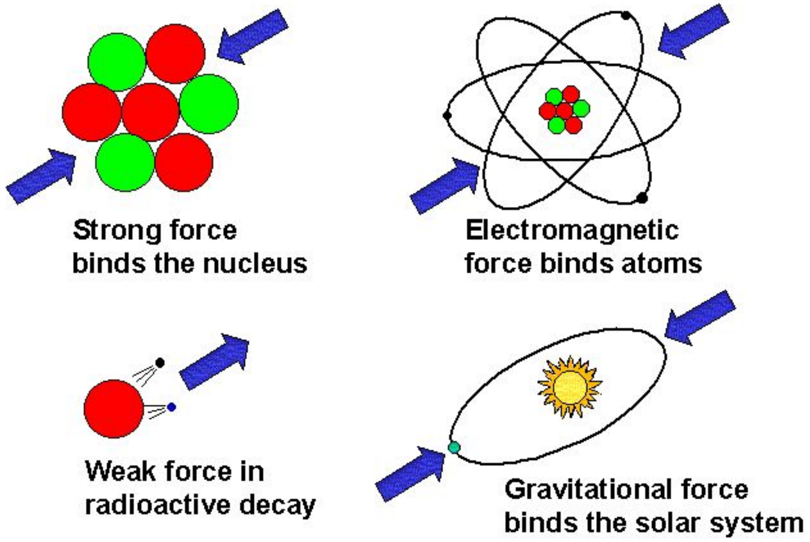


The Fundamental Forces

- The four fundamental forces are carried by the gauge bosons – the bosons take part in interactions involving those forces
- The graviton has not been found (yet!)

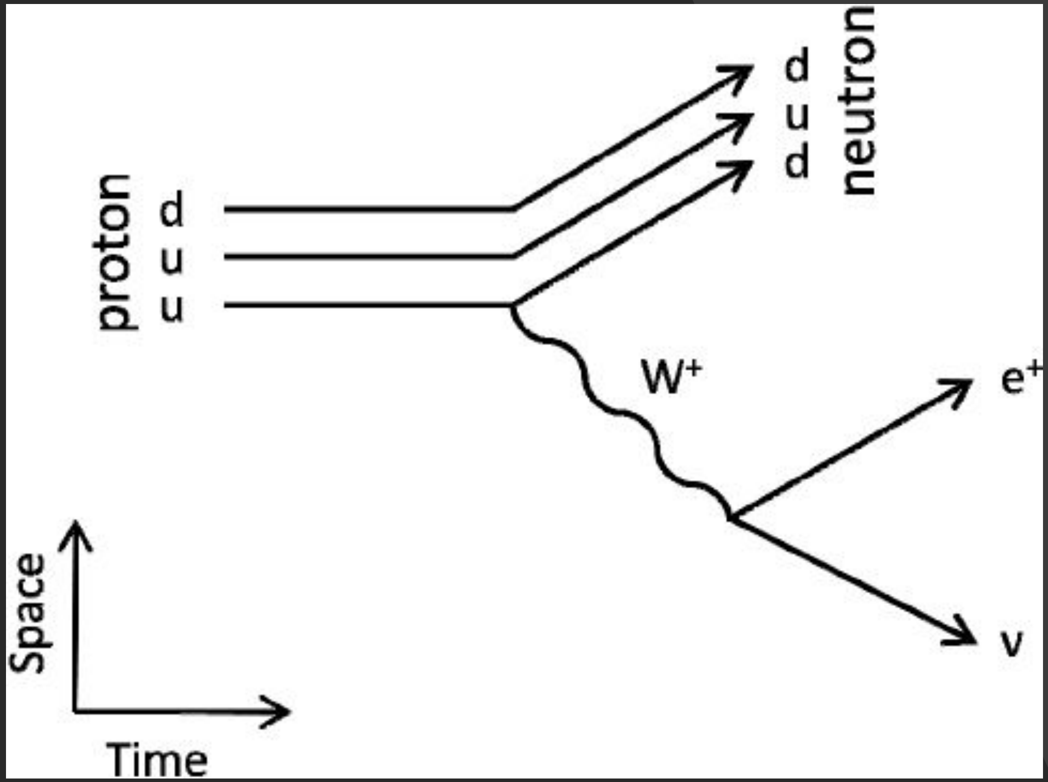
Fundamental Forces

Force	Associated Property	Effect	Range	Carrier Particle	Relative Strength
Gravitational	Mass	All masses attract each other	Infinite but weakens with distance	Graviton	10^{-36}
Electromagnetic	Electric charge	Opposites attract, likes repel	Infinite but weakens with distance	Photon	1
Strong	Color charge	Three colors combine to make neutral combinations	≈ 10^{-15} meters (distance between protons in atomic nucleus)	Gluon	102
Weak	Weak charge	Massive particles decay to lower mass particles	≈ 10^{-18} meters (1/1000th proton diameter)	W & Z	10^{-7}

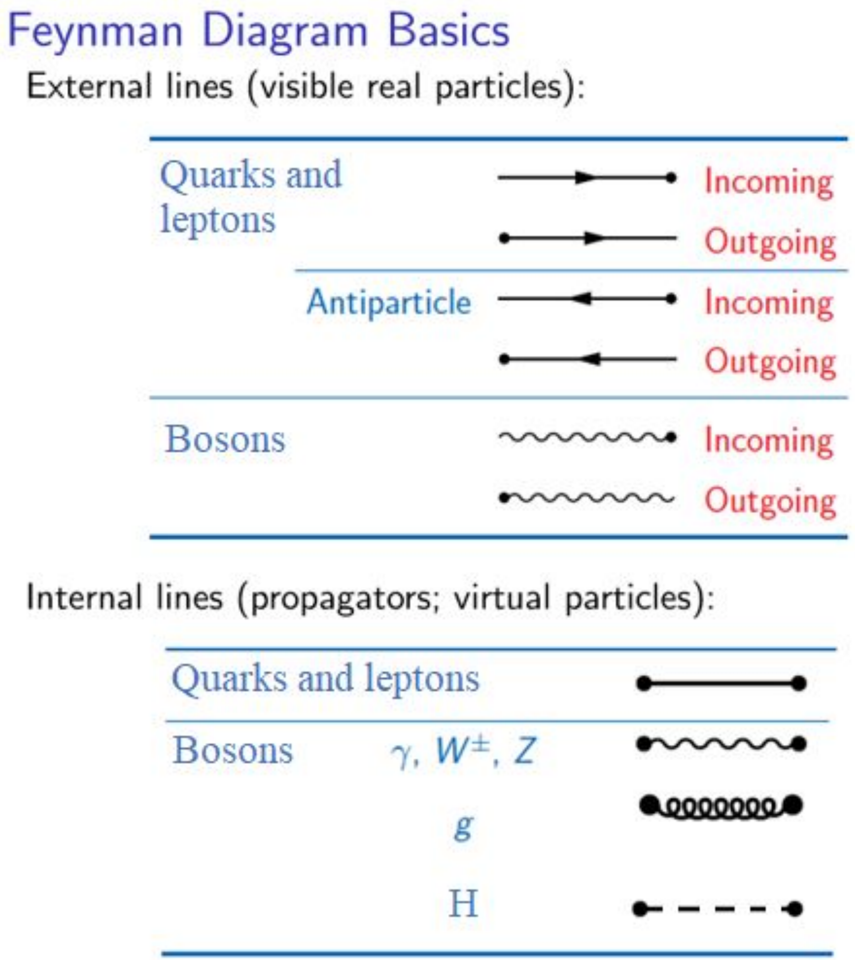


Particles and forces - interactions

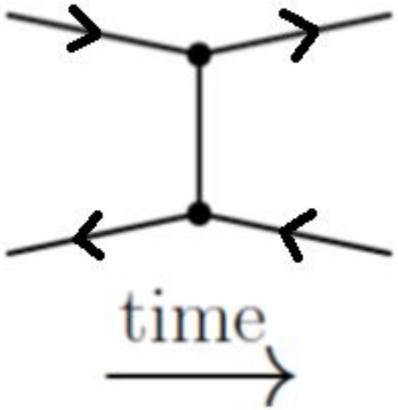
- Particles interact with each other via the four fundamental forces
- You can write a process (such as beta decay) as:
  $p \rightarrow n + e^{+} + v_{e}$
- To show what force takes part you need to draw a diagram that includes the vector bosons (photons, gluons, gravitons etc)
- A diagram can tell us what actually happens when a proton turns into a neutron



Introduction to Feynman diagrams

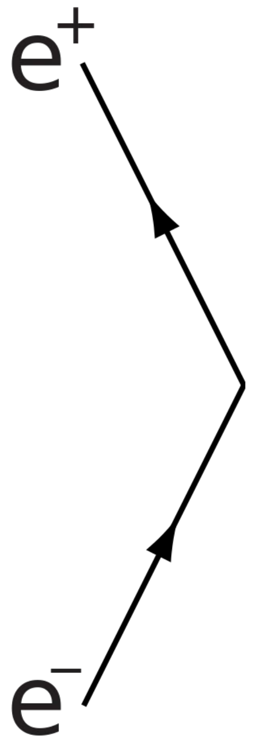


- Feynman diagrams help explain how interactions happen
- By convention antiparticles have arrows in opposite direction to particles
- Arrows always “flow” through a vertex
- Original/starting particles are on the left
- Products of the interaction are on the right
- A particle is exchanged in the process
- Time flows to the right (convention)



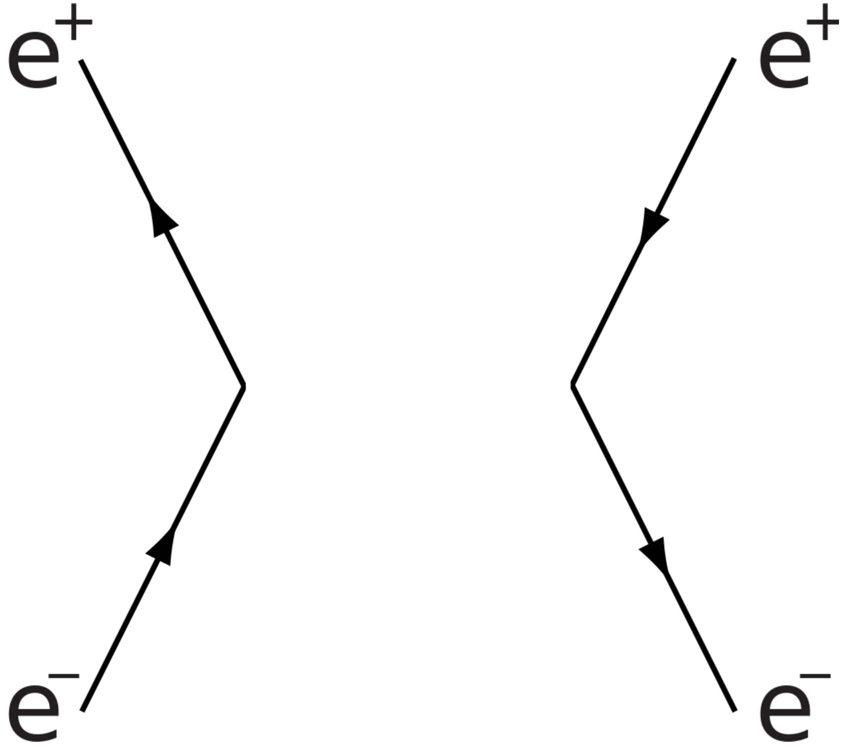
Example – constructing $e^+ e^- \to e^+ e^-$

- As an example let us construct a diagram for an electron and a positron annihilating each other and producing a new pair of an electron and positron via an electromagnetic interaction
- Start by putting initial particles on the left side



Example – constructing $e^+ e^-$ -> $e^+ e^-$

- Put the products on the right side



Example – constructing $e^+ e^- \rightarrow e^+ e^-$

- Fill in the intermediate particle
- Since this is an electromagnetic interaction we use the carrier for that force – the photon

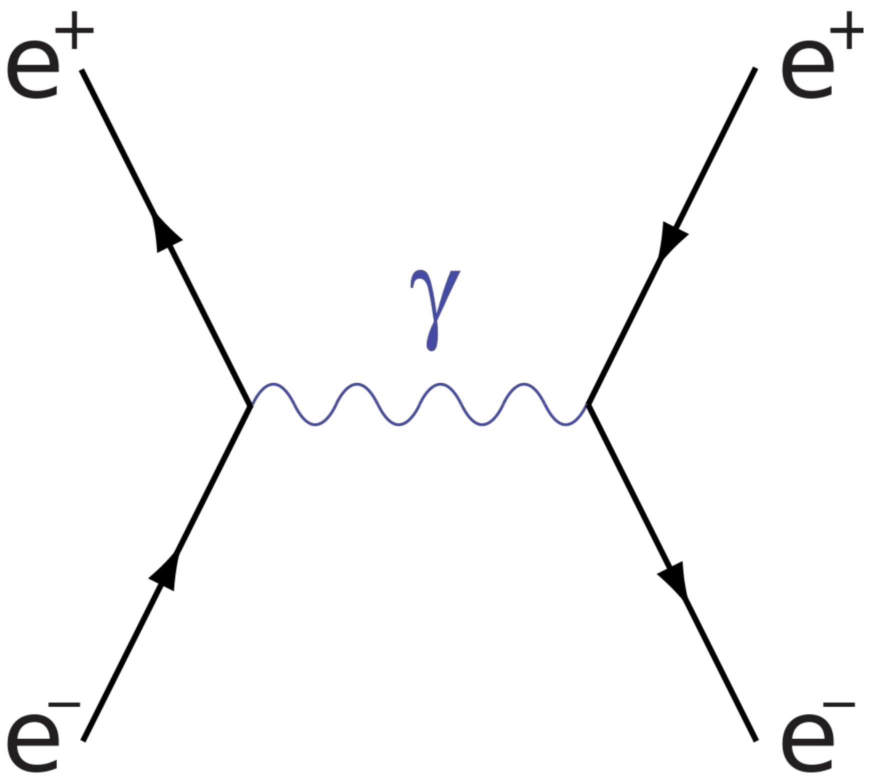
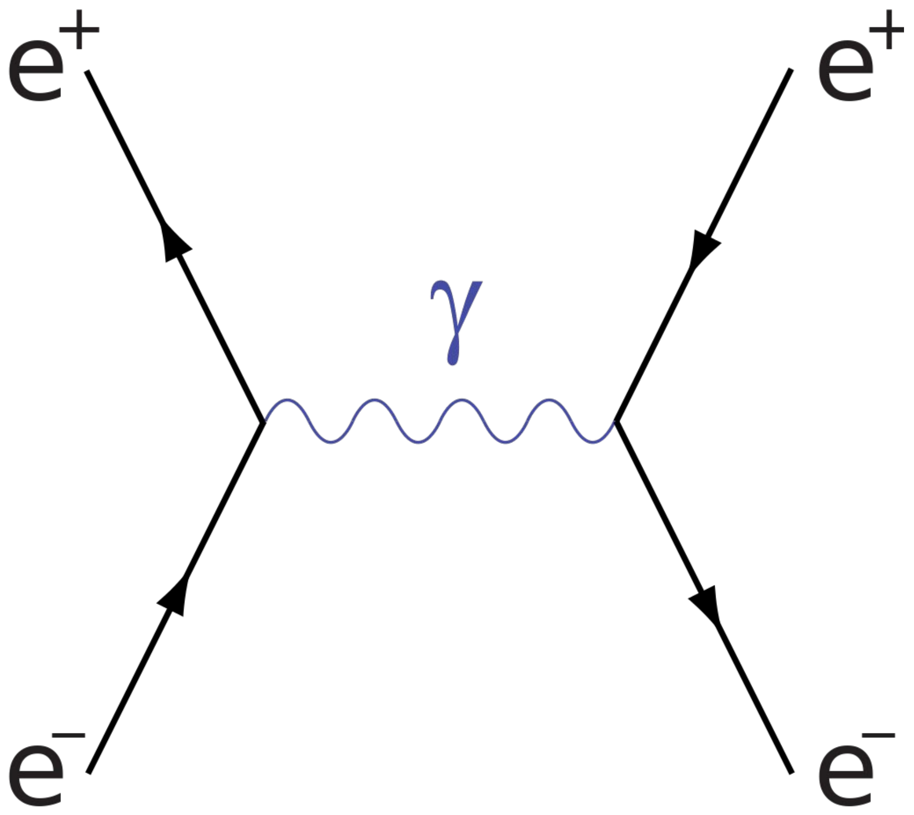
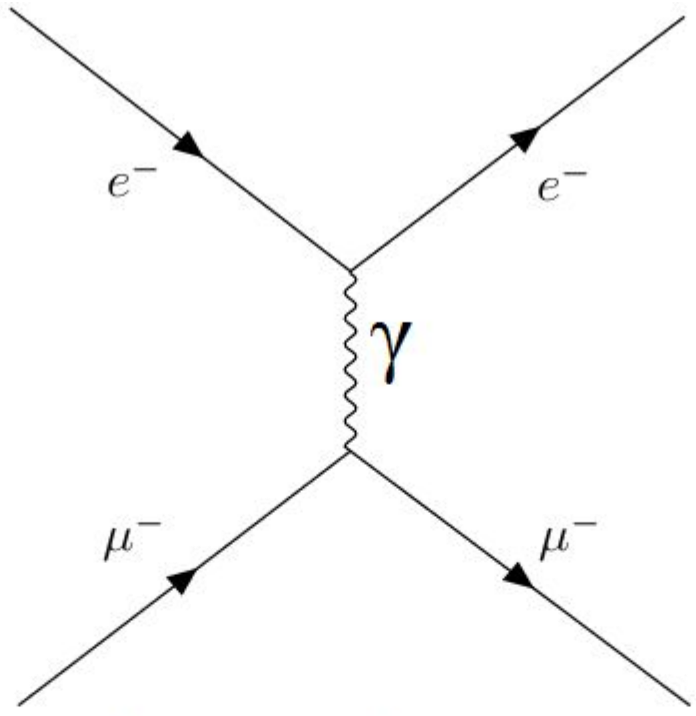


Diagram type examples

- Annihilation $e^+ e^- \to e^+ e^-$

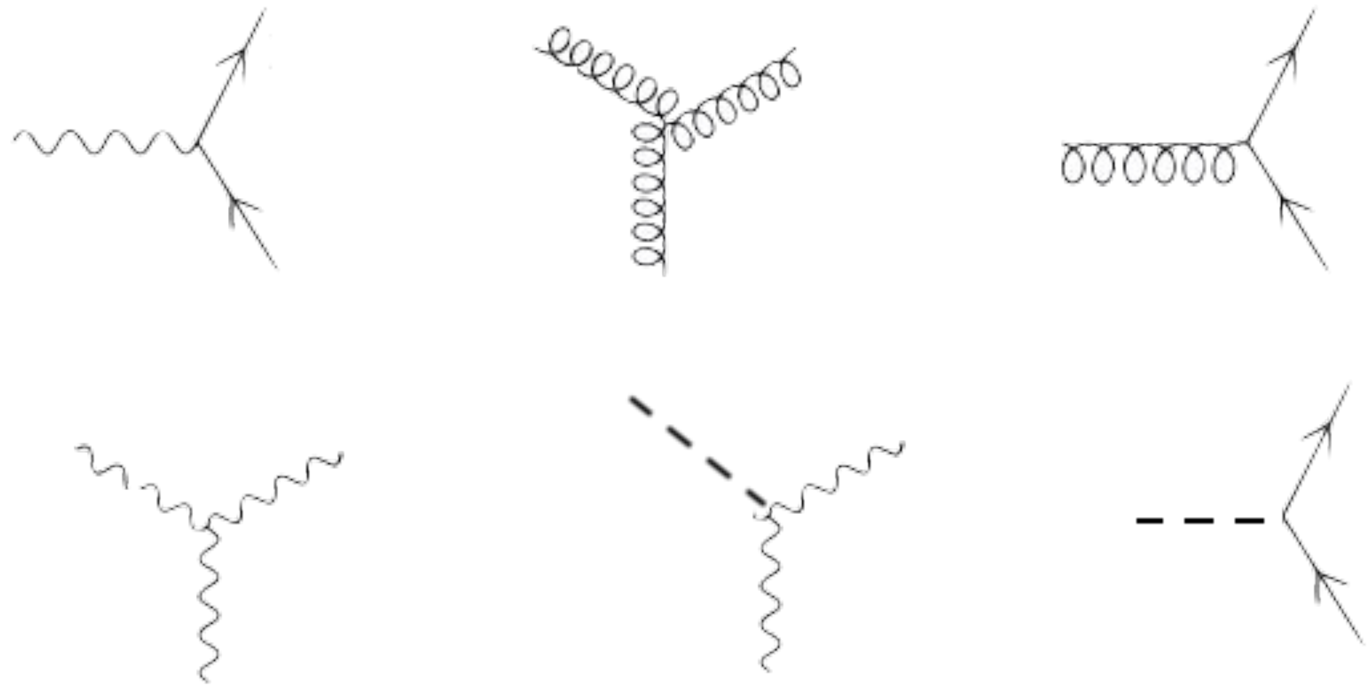


- Scattering $\mu^- e^- \to \mu^- e^-$



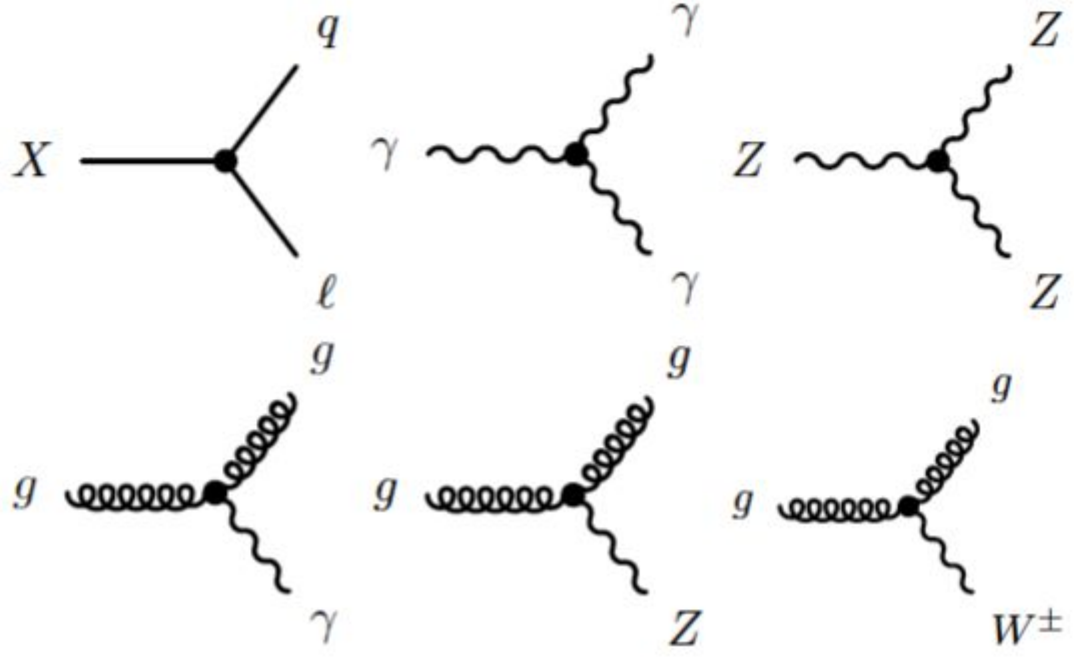
An electron and a muon exchange a photon

Possible vertices

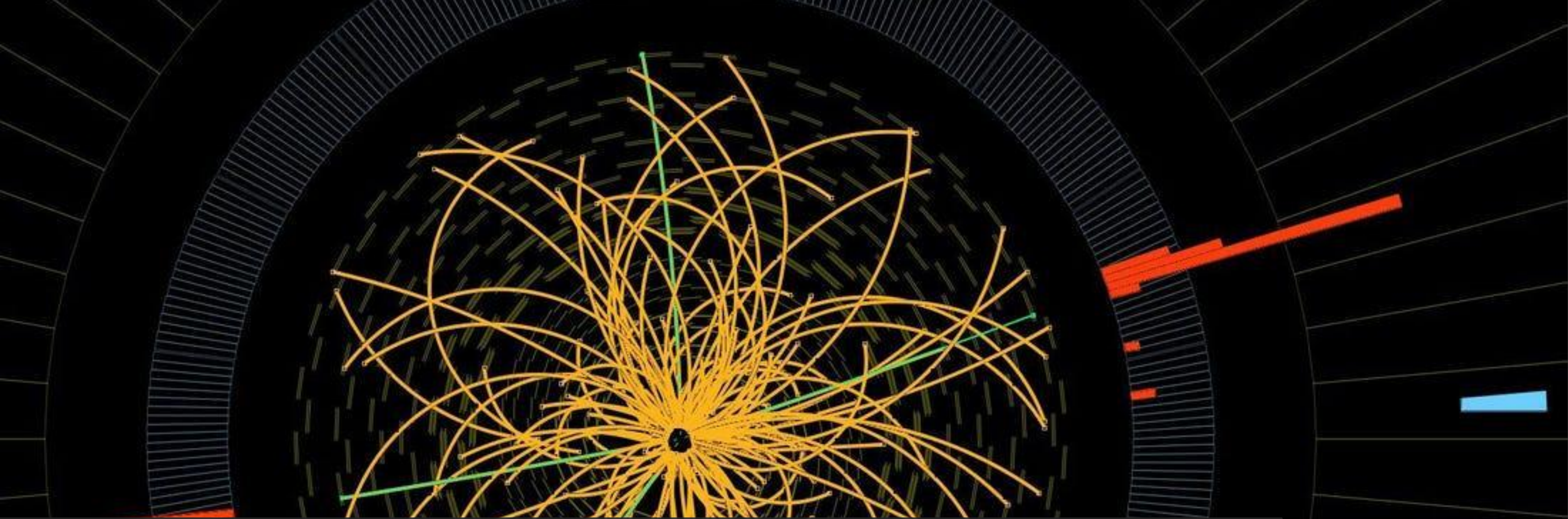


Impossible Vertices

- Quarks and leptons cannot be on the same vertex
- Leptons of different generations cannot be on the same vertex



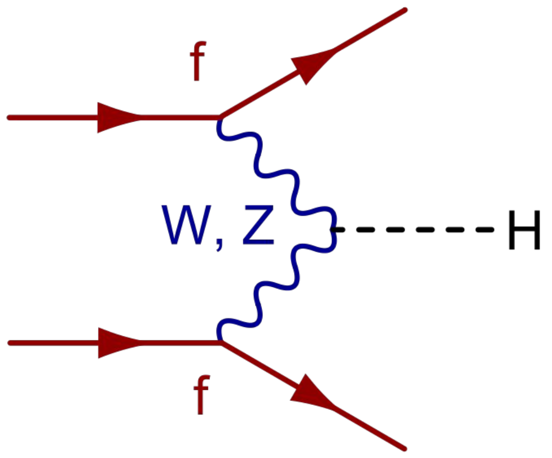
The Higgs Boson



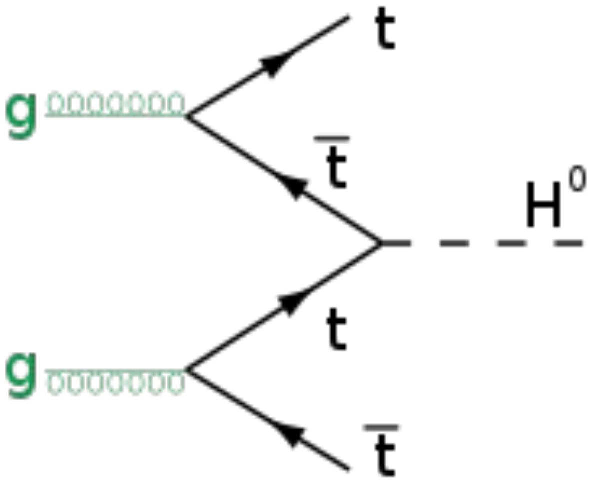
The Higgs Boson

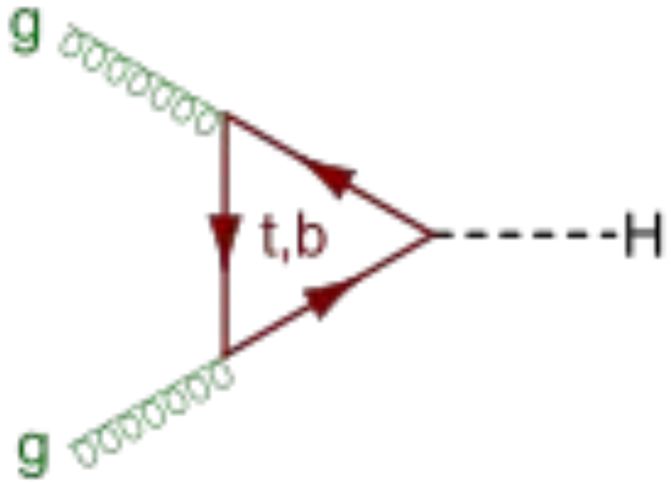
- The Higgs Boson is a relatively newfound particle in the standard model, though predicted in the 1960s
- Particles interacting with the Higgs Boson acquire mass. Those that do not, like photons, remain massless.

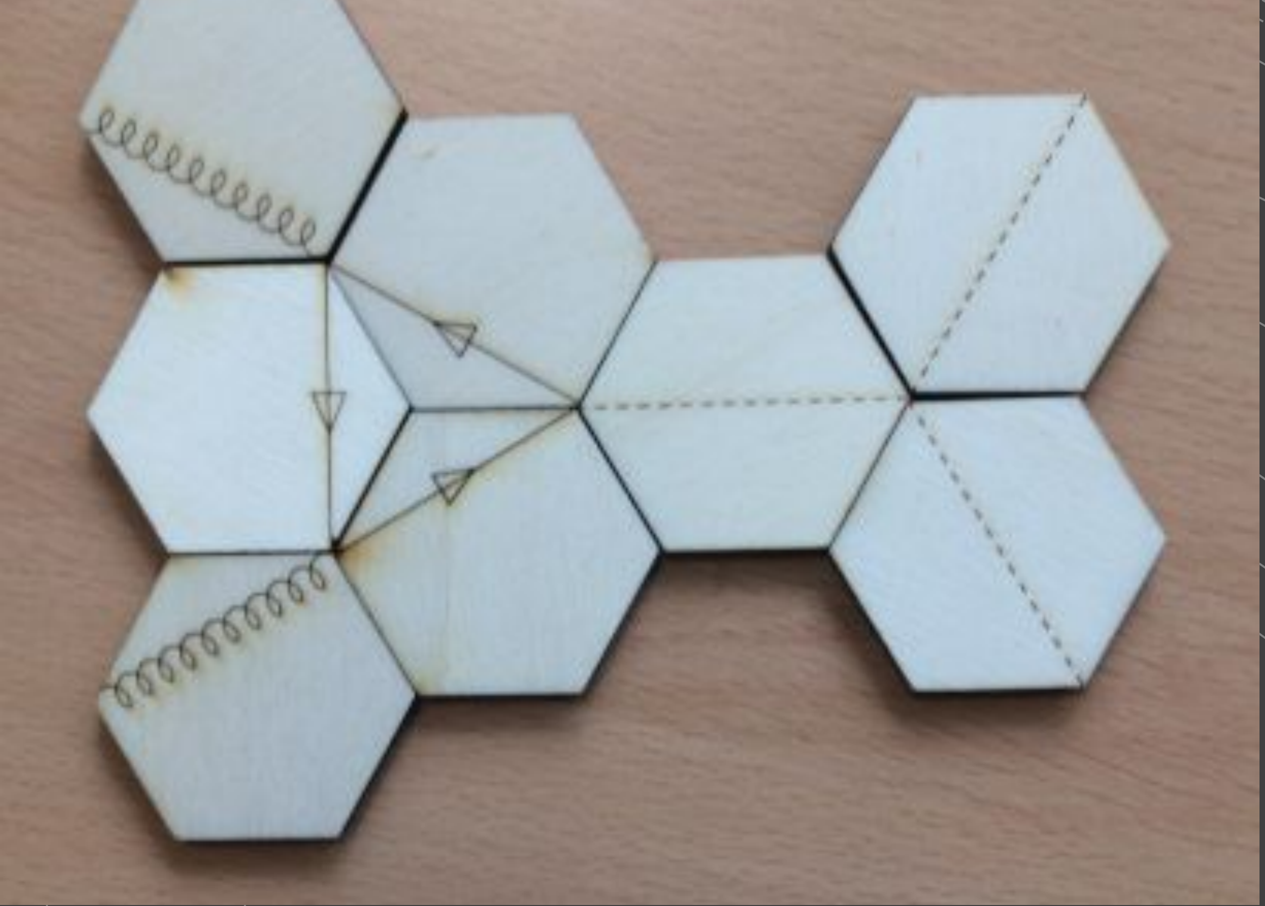
Higgs production diagrams

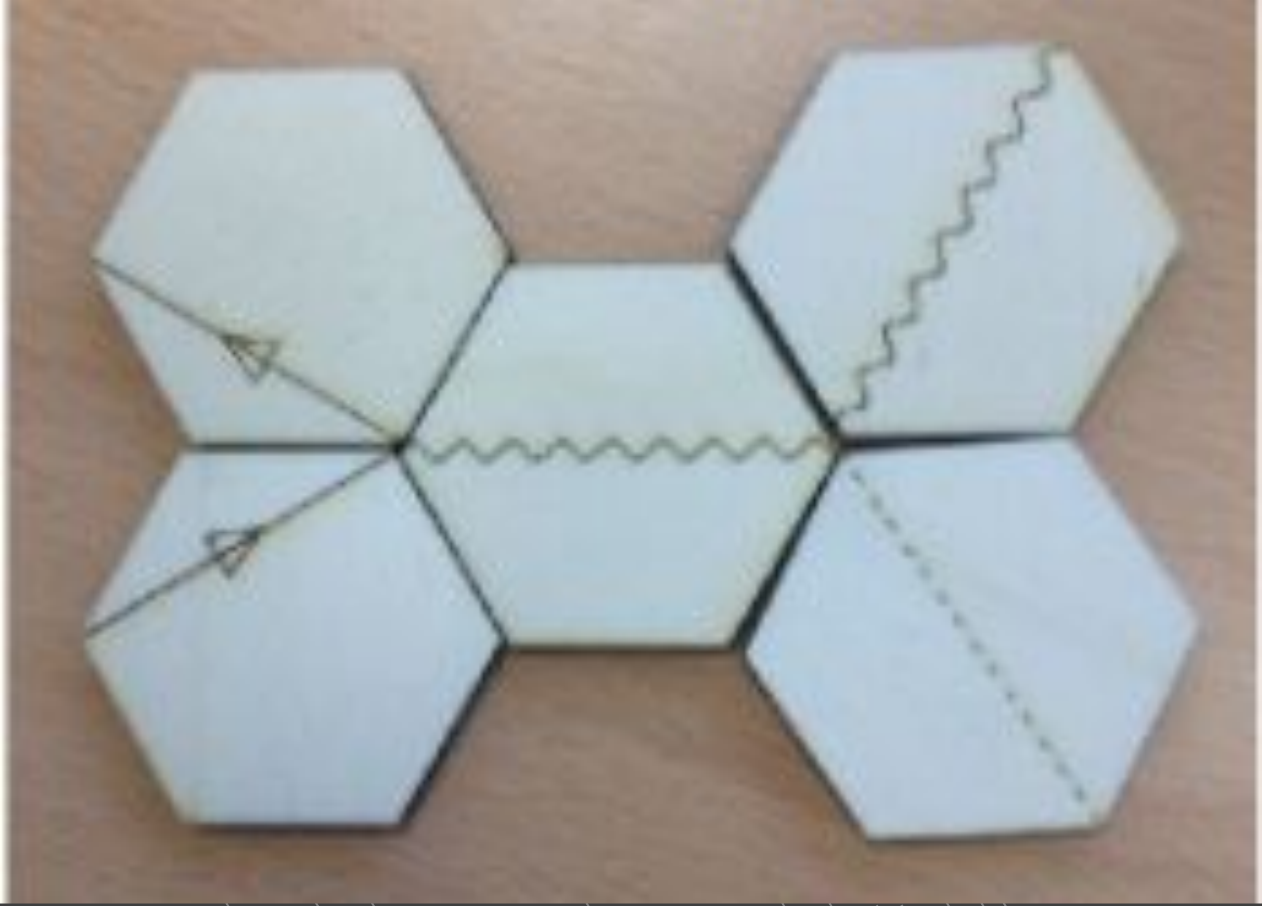


- Diagrams involving Higgs can get really complicated!
- But they are still constructed with the same vertices you've seen before









Feynman Dominoes

- Today you will try to construct some diagrams using the dominoes provided
- The more vertices a diagram involves the lower the probability of that process occurring in reality
- So while you can go crazy with big diagrams the most useful one is often the simplest

Puzzles

- Bhabha Scattering:

  $e^+ e^- \longrightarrow e^+ e^-$

Puzzles

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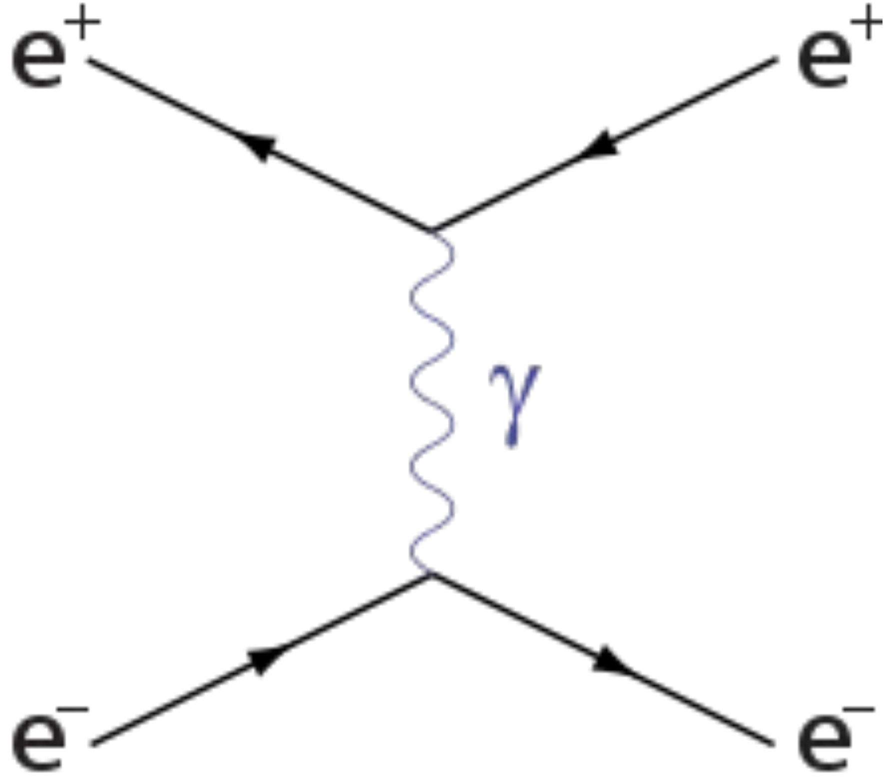


Puzzles

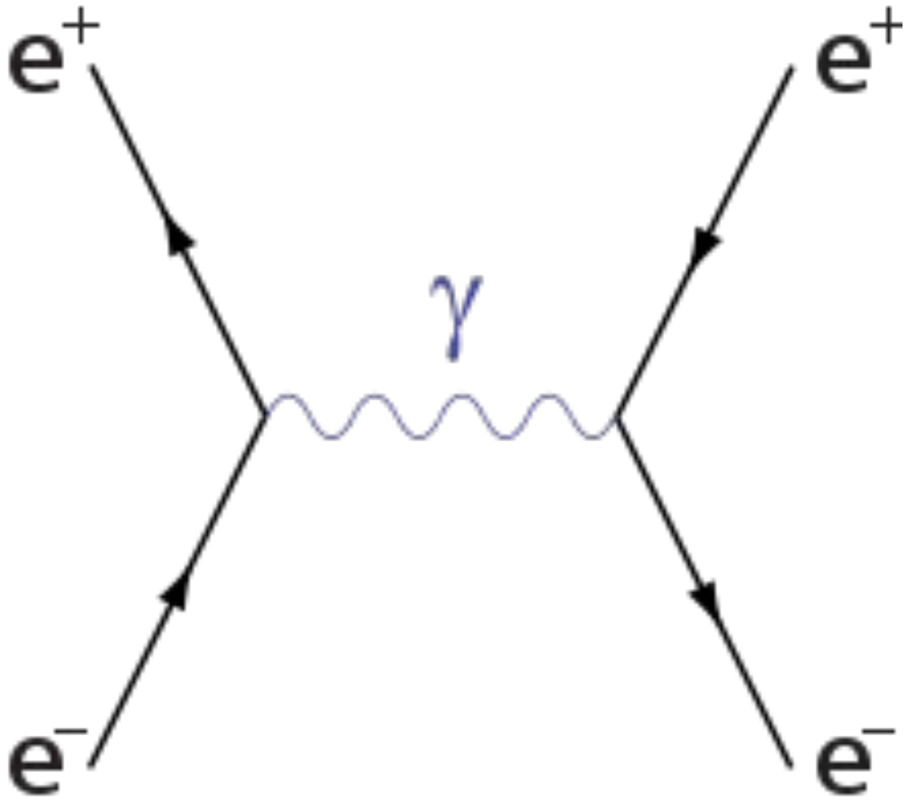
- Electron-Positron annihilation:

  $e^+ e^- \rightarrow e^+ e^-$

Puzzles

- Electron-Positron annihilation:

  $e^+ e^- \longrightarrow e^+ e^-$



Puzzles (harder)

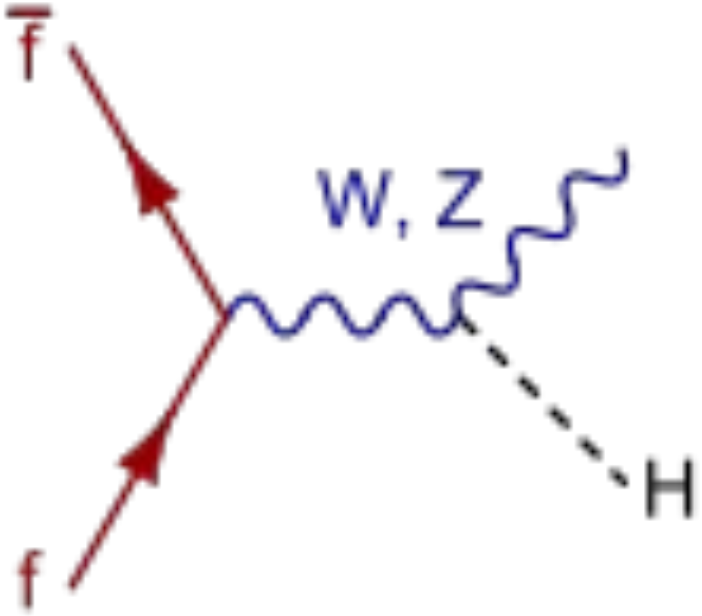
- Fermions to Higgs:

$$f\ \bar{f} \longrightarrow W/Z + H$$

Puzzles (harder)

- Fermions to Higgs:

$$f\ \bar{f} \longrightarrow W/Z + H$$



Puzzles (hardest)

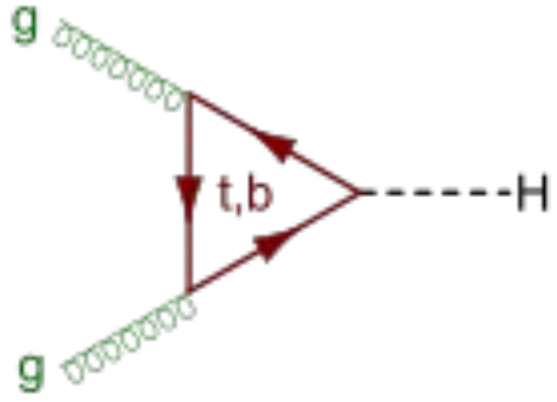
- Gluons to Higgs:

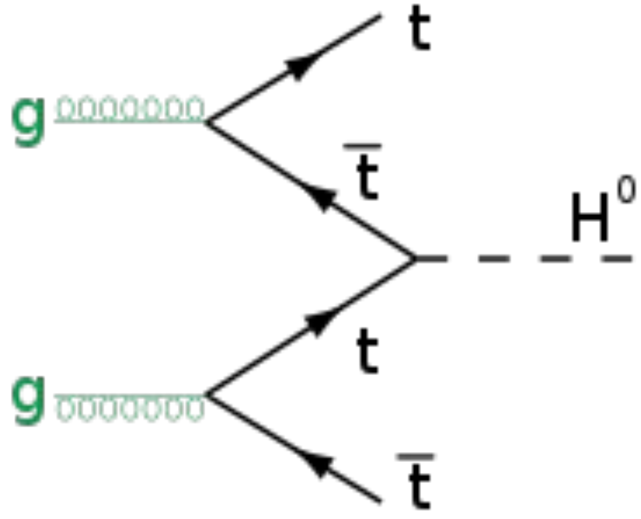
$$g\ g \longrightarrow H$$

Puzzles (hardest)

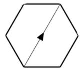
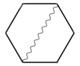
- Gluons to Higgs:

$$g\ g \longrightarrow H$$

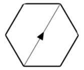
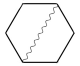
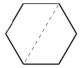


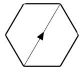
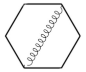


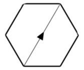
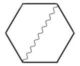
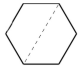
Questions

1. With two  fermion pieces as quark inputs, can you produce a  Z boson? Then use two more fermion pieces to have the Z decay into two leptons

2. Using the same pieces as question 1, change this into a scattering process, where two quarks transfer a vector boson between them, as each then produces another quark.

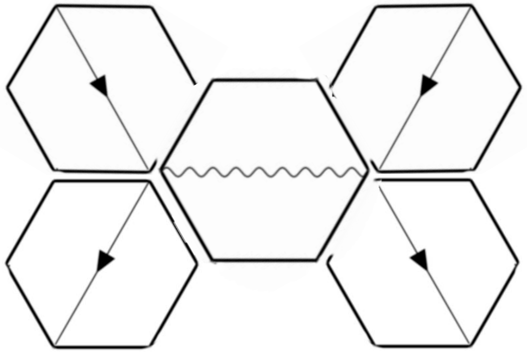
3. Starting with two  fermions colliding, can your form a  vector boson, which then produces a  Higgs boson in association with another vector boson?

4. With a  fermion piece and  gluon piece as inputs, colliding and then decaying to a fermion and gluon, can you produce a total of 3 quarks in the final state? (hint: the gluon could decay to two more quarks!)

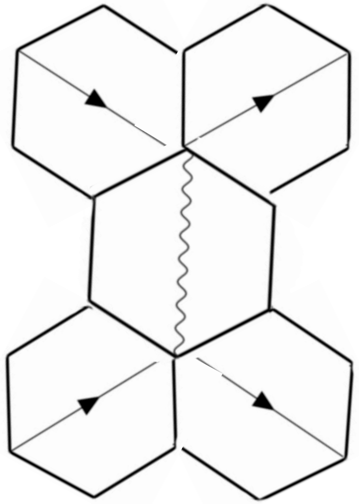
5. Starting from two  fermion pieces each decaying into a quark and  vector boson, where the vector bosons collide, can you produce a  Higgs boson?

Solutions

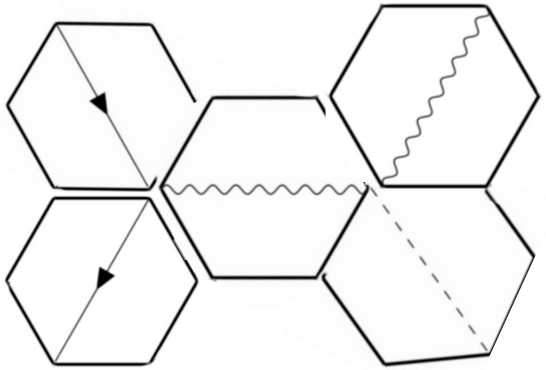
1.



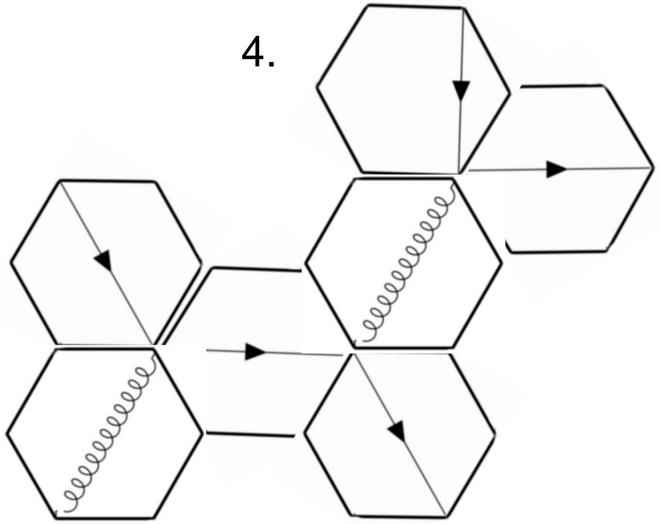
2.



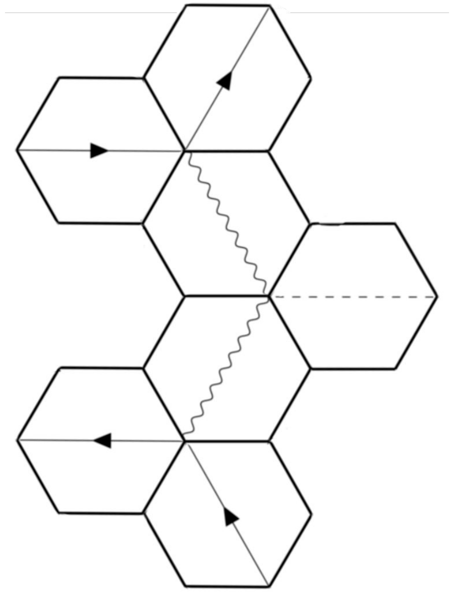
3.



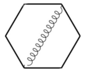
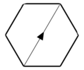
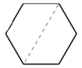
4.

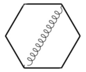
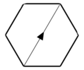
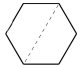


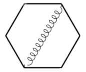
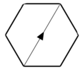
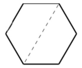
5.

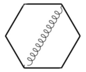
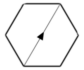
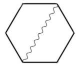


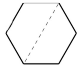
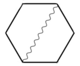
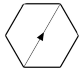
Bonus Questions!

6. Staring with two unjoined  gluon pieces which each decay into two  quarks, collide one quark from each together to give a  Higgs boson (and the un-colliding two fermions) in the final state

7. Starting from two seperate  gluon pieces, join these onto the corners of a box of  fermions. Then attach two  Higgs bosons to the opposite face's corners to finally produce two Higgs bosons.

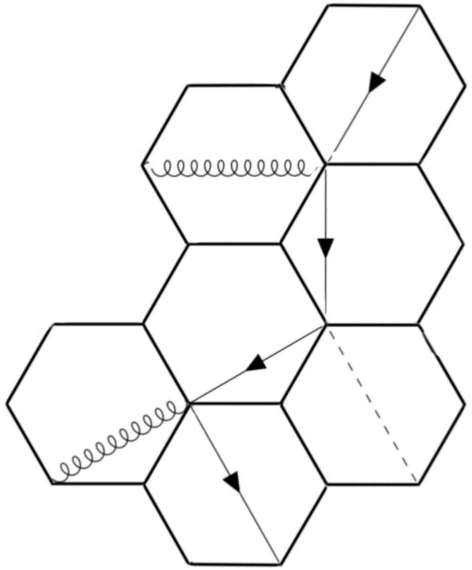
8. Starting from two separate  gluon pieces, join these to corners of a triangle of 3  quark pieces. Then on the remaining corner, decay this into a  Higgs Boson, which can then split into two other Higgs bosons in the final state (hint: you will need two puzzle piece sheets for enough Higgs pieces!)

9. With two  gluon pieces colliding and producing a single gluon, can you produce 2  quarks which each decay into a  vector boson and another quark. These vector bosons then decay to 2 fermions (hint: the final state should have a total of 6 fermions!)

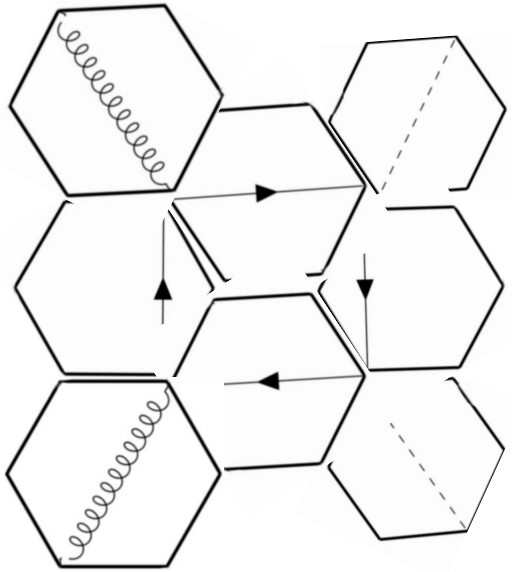
10. Use your  Higgs production from Question 8 to, instead of decaying into two Higgs, instead join this with production of two  Z bosons that each decay into two  leptons (fermions)

Solutions

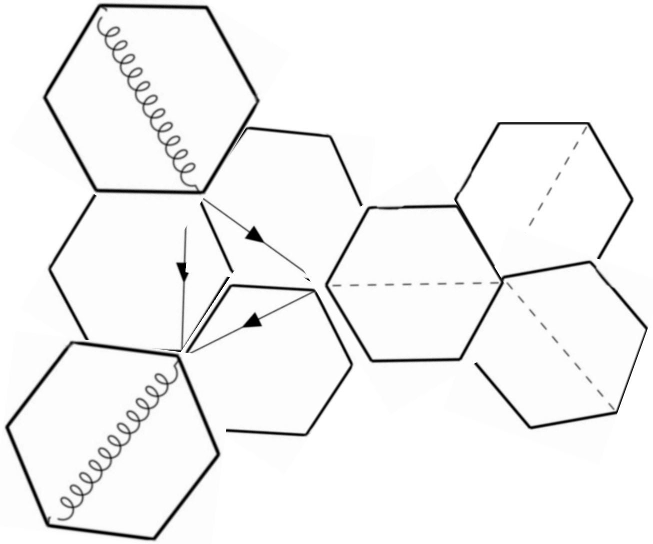
6.



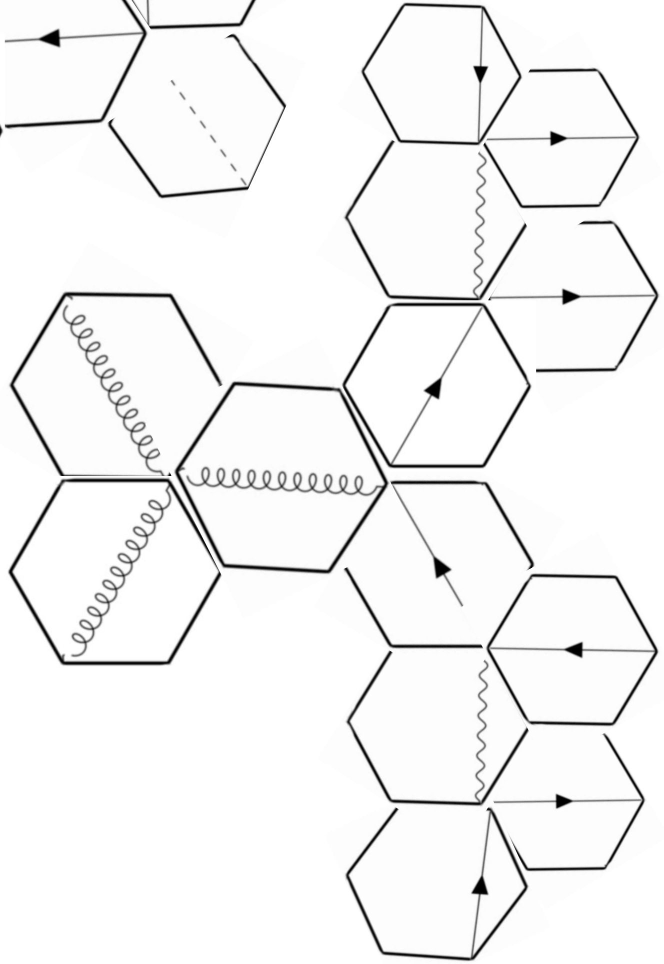
7.



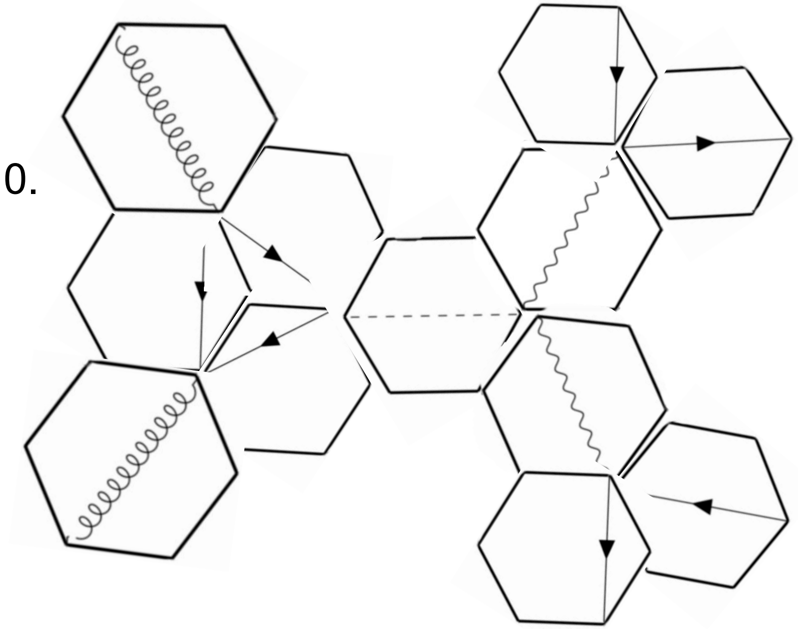
8.



9.



10.

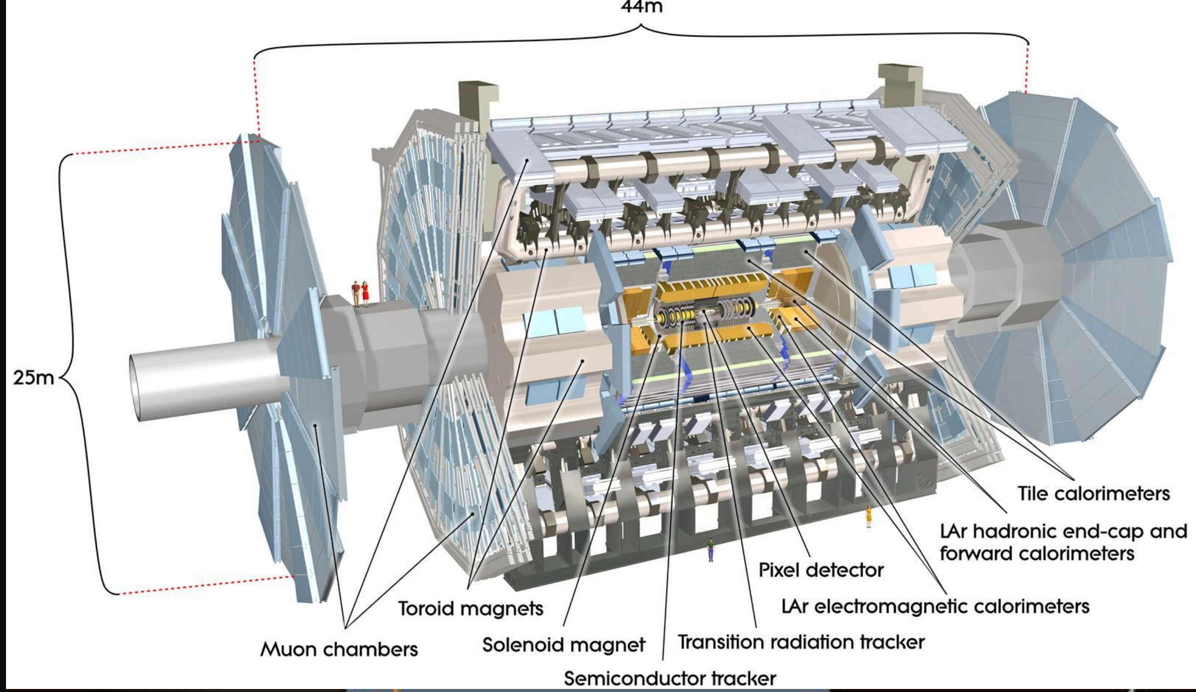


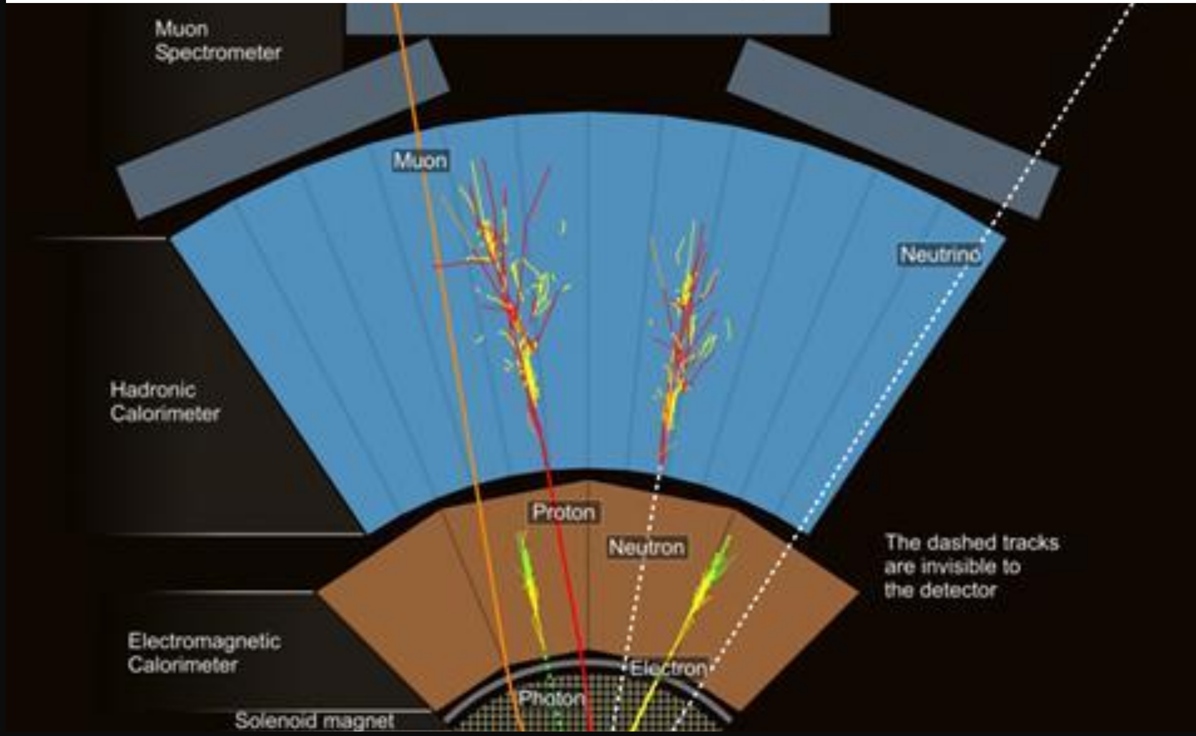
Interactions in real life experiments - The Large Hadron Collider

- In order to see those interactions we need particles at high energies
- To get them there we speed them up in huge accelerators – travelling around rings being accelerated by magnets

The ATLAS detector

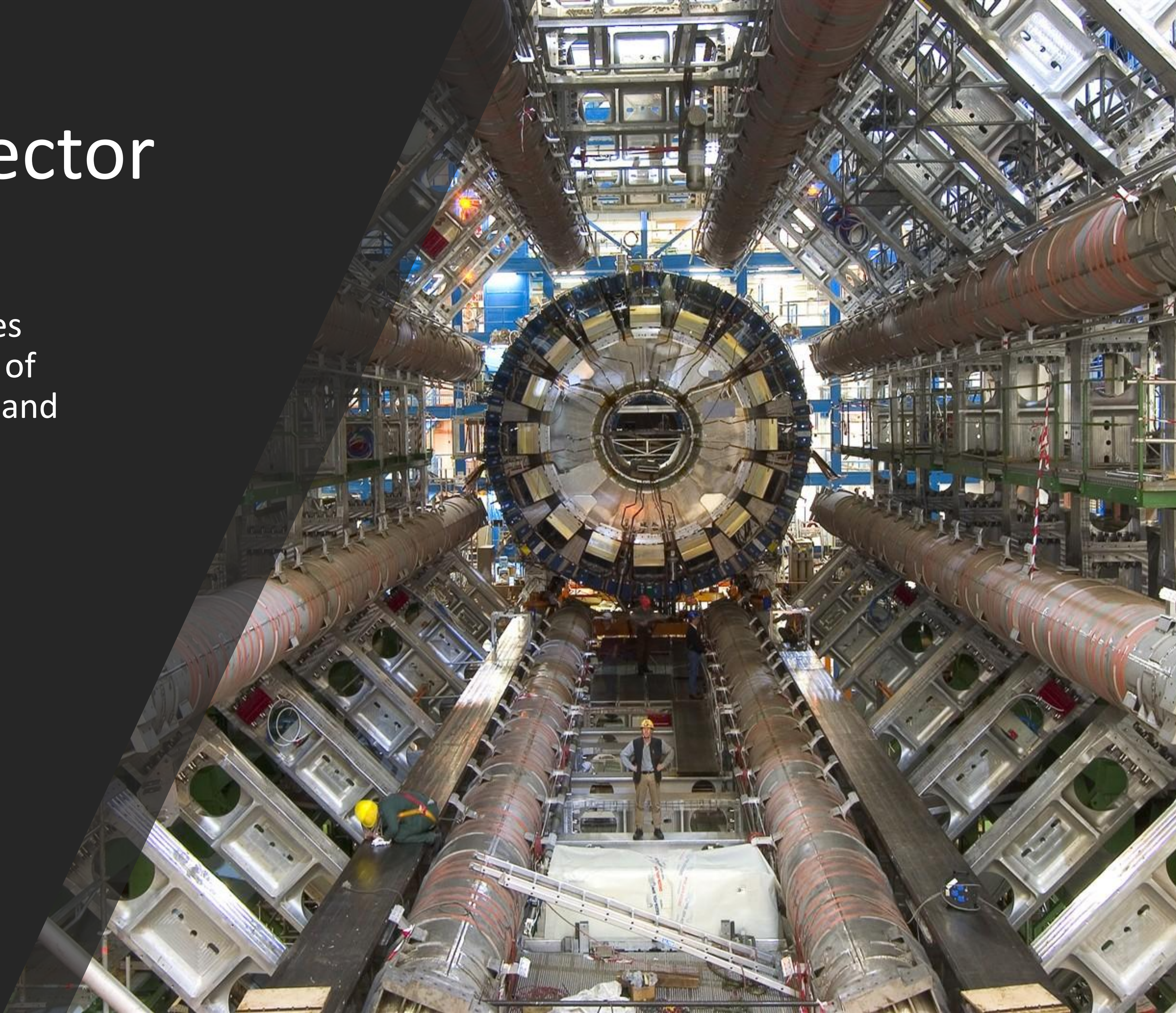
- The detector systems have to be very complex just to see the outcome of the collisions.





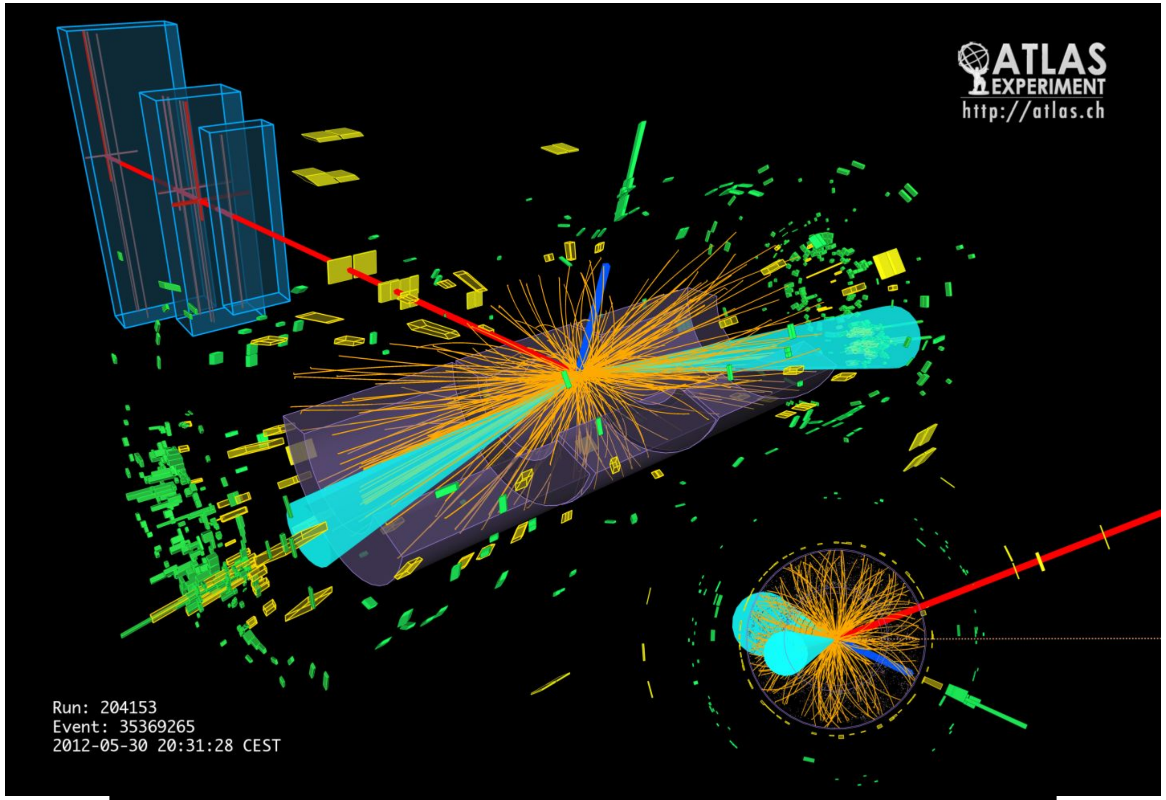
The ATLAS detector

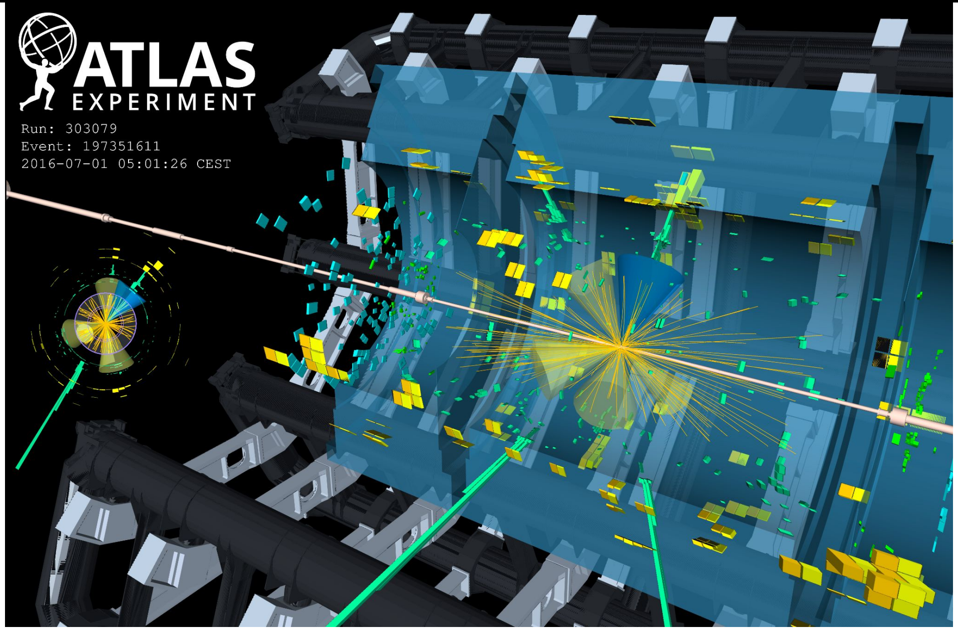
- Building this is a task that takes many years and requires a lot of work from the best physicists and engineers



Higgs event in a detector

- This is what a reconstructed Higgs event looks like
- This uses the data received from the detector once it has been analysed to produce an image of what happens inside the detector.





Thank you

Queen Mary
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