Standard Model of particle physics

Ricardo González López

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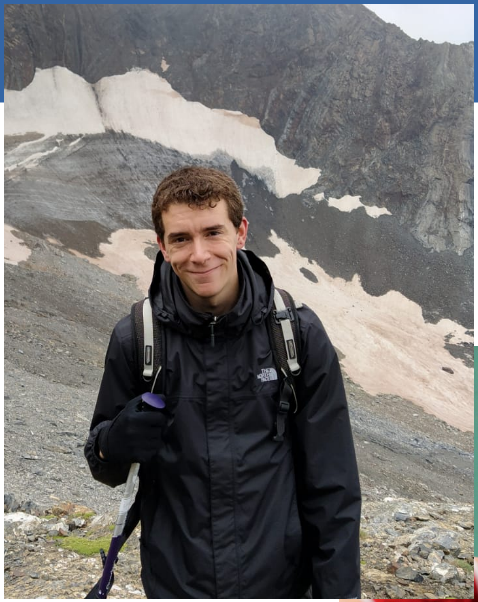
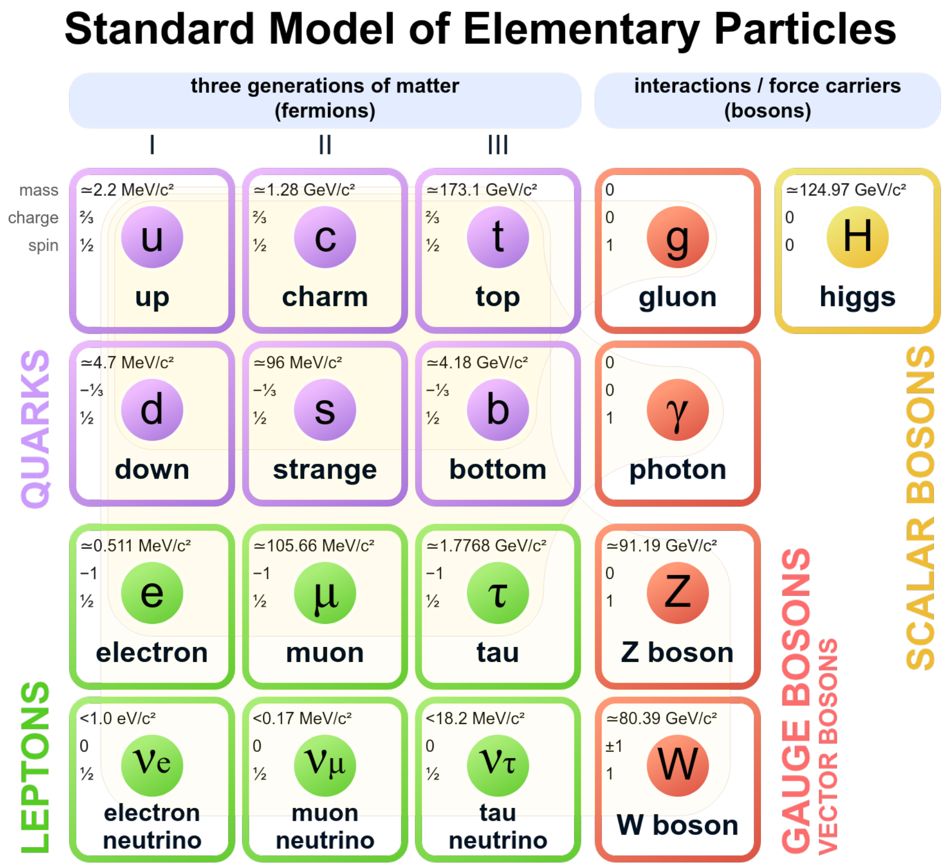
About me

- Hi! I'm Ricardo Gonzalez
- Born in Zaragoza, Spain, where I took undergrad Physics
- Took a master in Advanced Physics in Valencia
- Now a 4^{th} year PhD student at the University of Liverpool
- Working at the ATLAS experiment
  - Precision W and Z boson measurements
  - Pixel tracker upgrade
- Interests: basketball, videogames, hiking...



Standard Model of particle physics – What is it?

- It is the theory that best encapsulates our current understanding of the universe:
  - What is it made of?
  - What are the fundamental forces that reign it?



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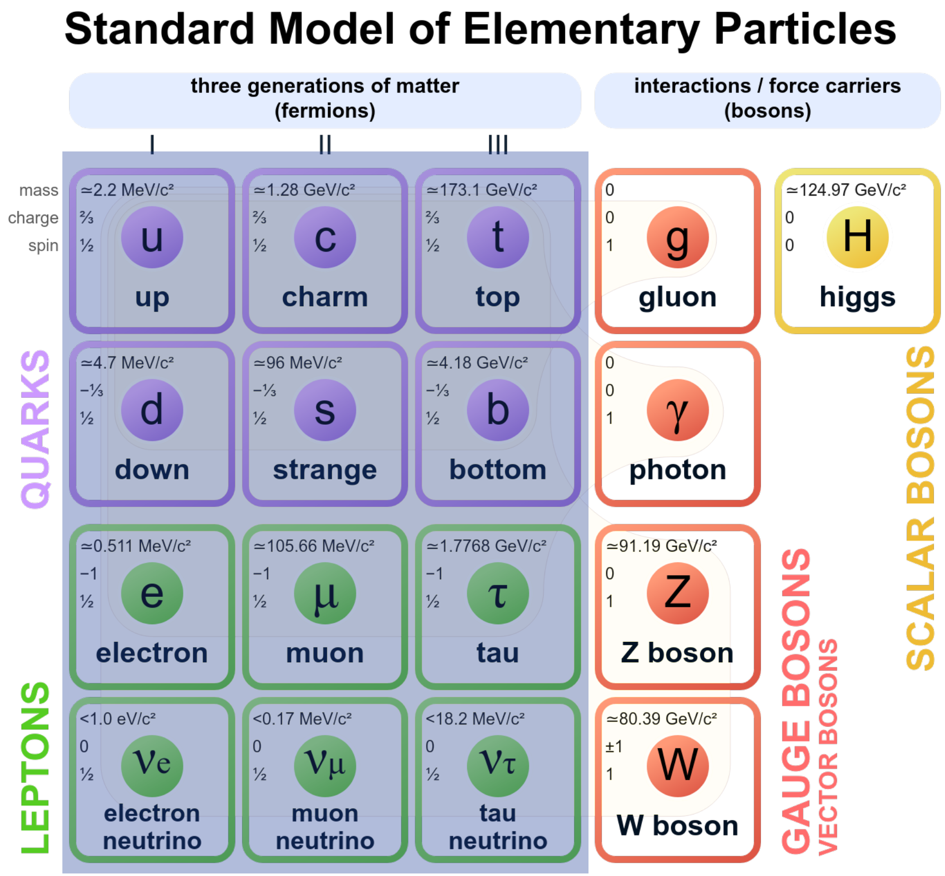

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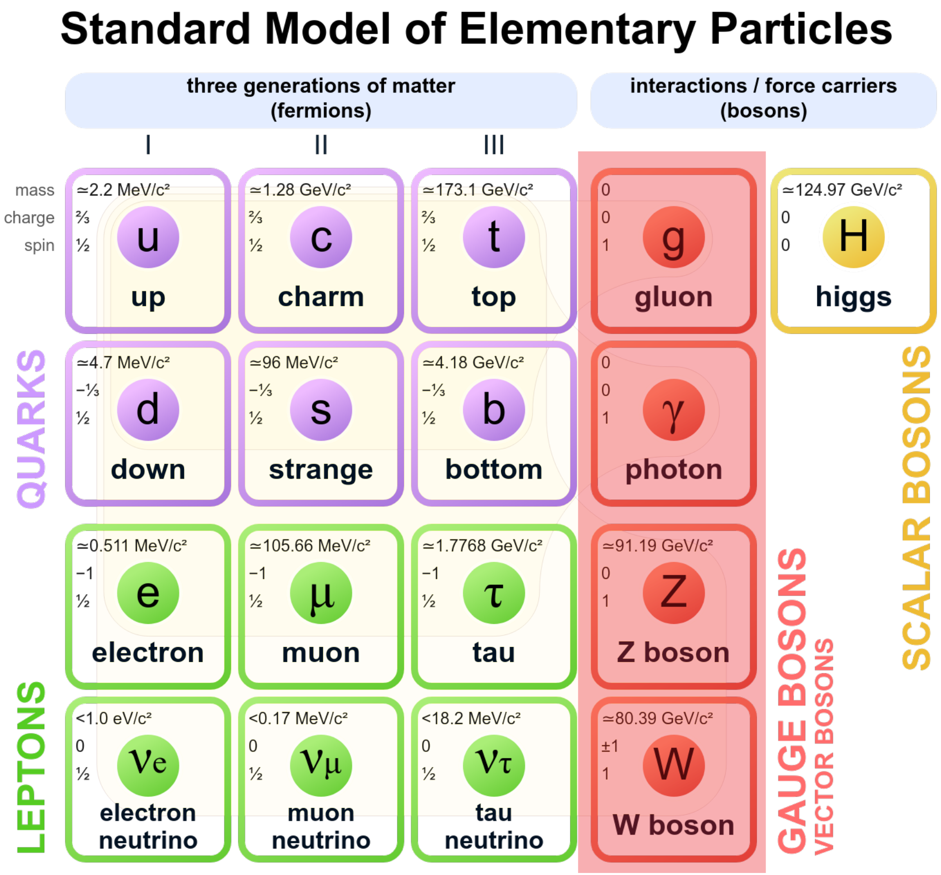
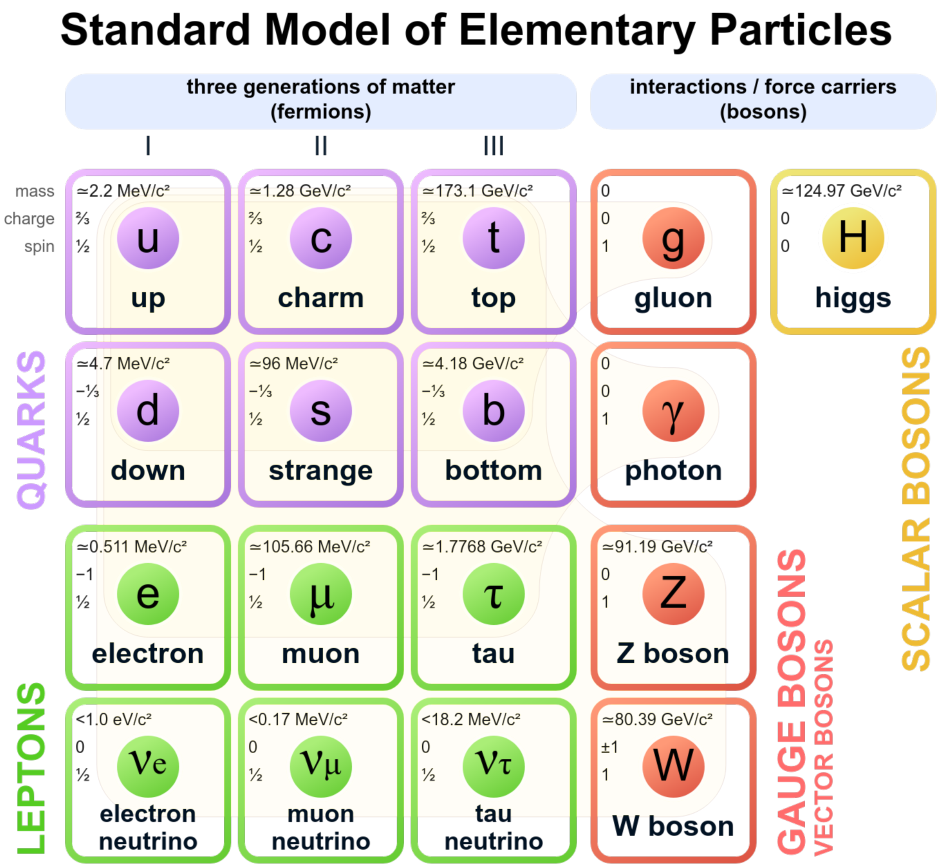


What is matter made of?

One picture, many views!



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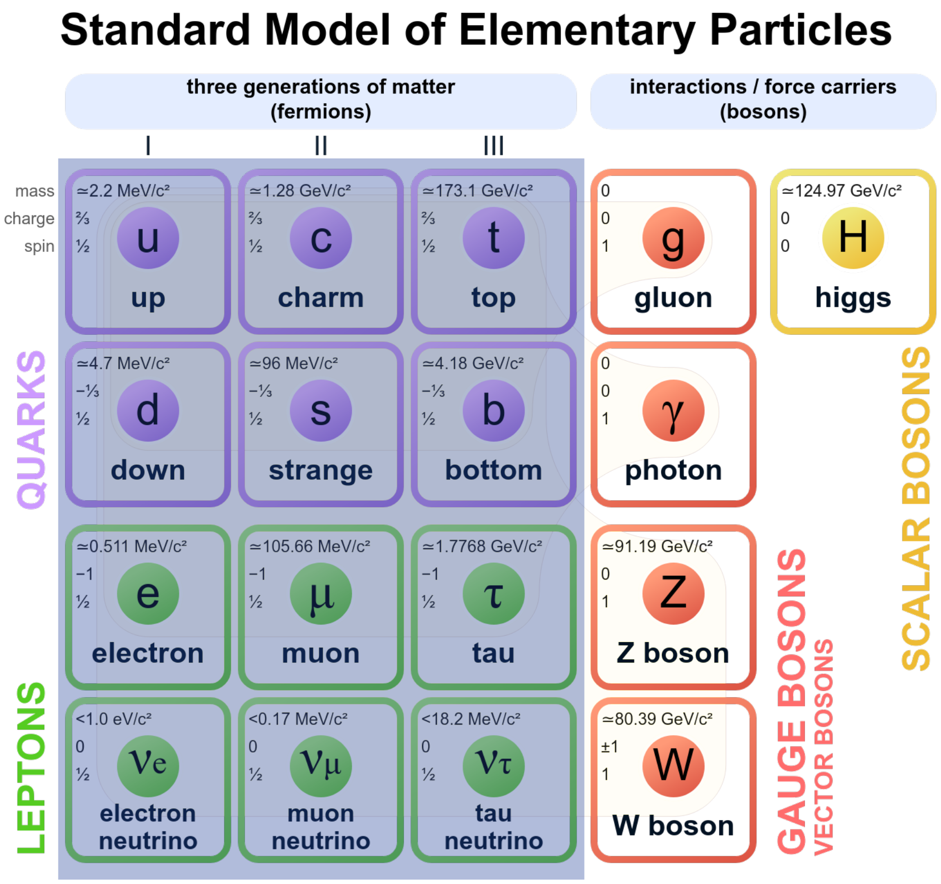


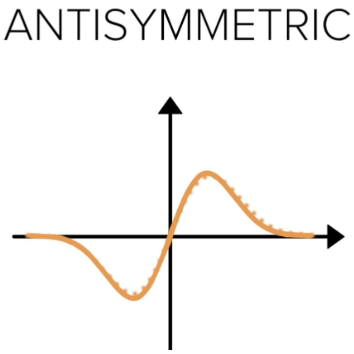
Fermions

Matter particles

- Can further combine into more complex particles (protons, neutrons and a <u>very</u> long etc)

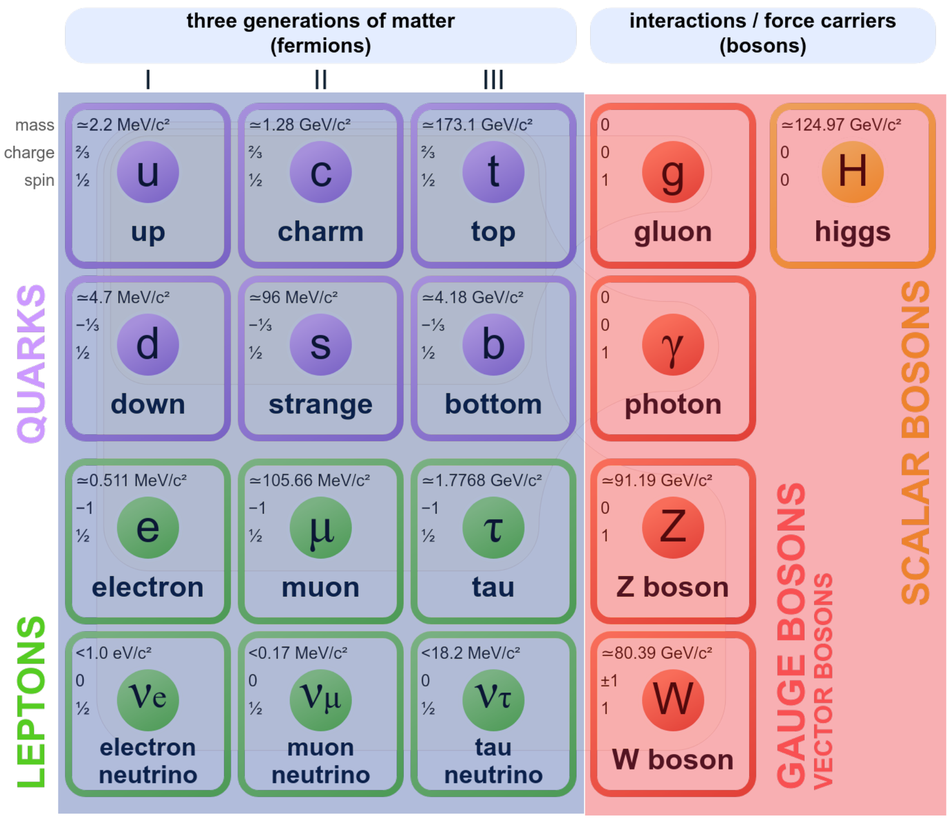
Spin 1/2

- Mathematically described by an antisymmetric function.
- Can't find two identical together → Pauli exclusion principle



One picture, many views!

Standard Model of Elementary Particles



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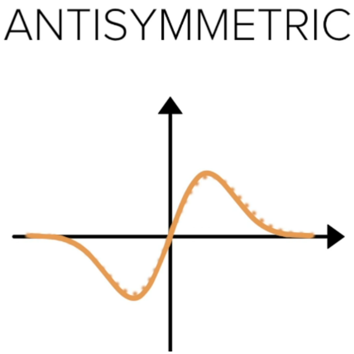


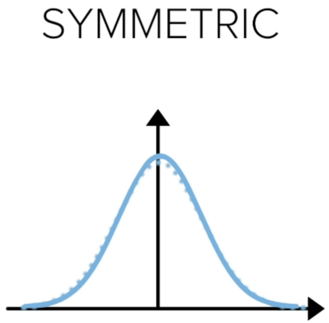
Bosons

Force carriers*

- Particle interactions are represented by bosons' exchange
- * Higgs is not associated to any force

Integer spin: 0, 1, 2

- Mathematically described by an symmetric function.



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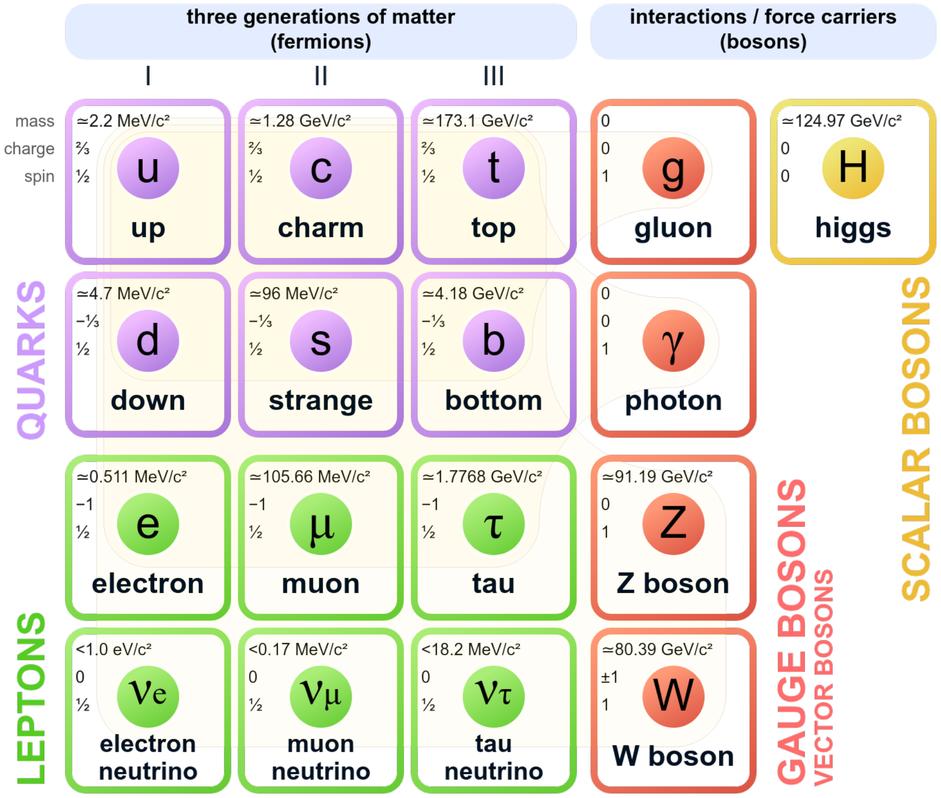

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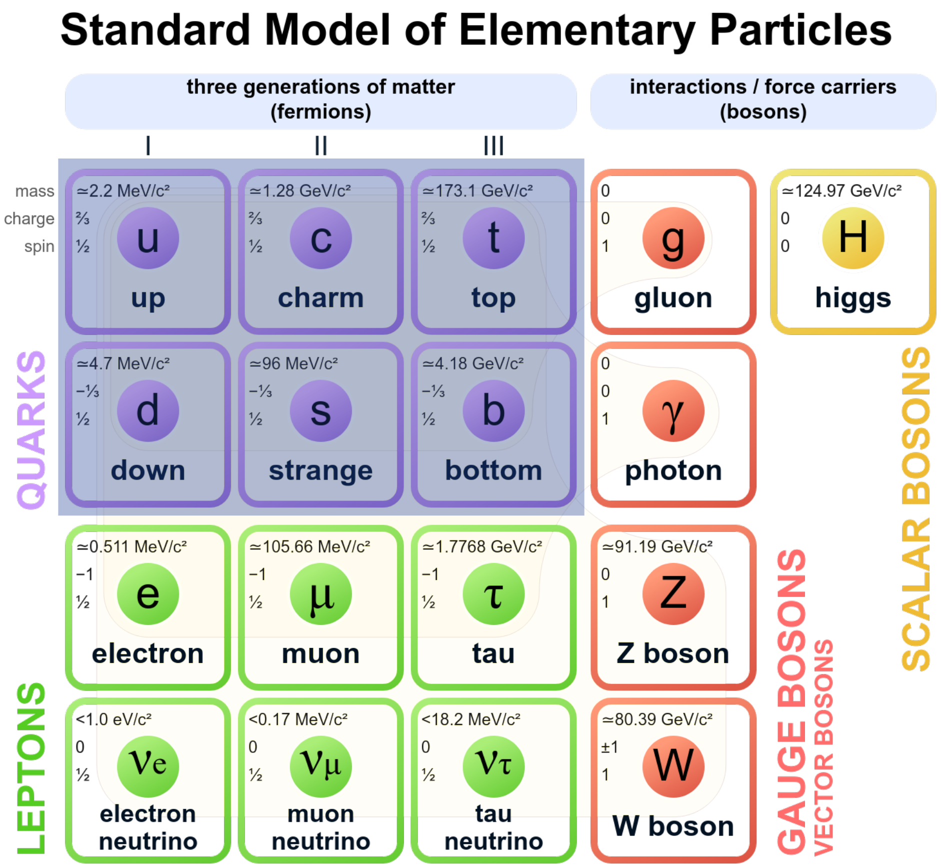


Fermions

Quarks

Massive particles

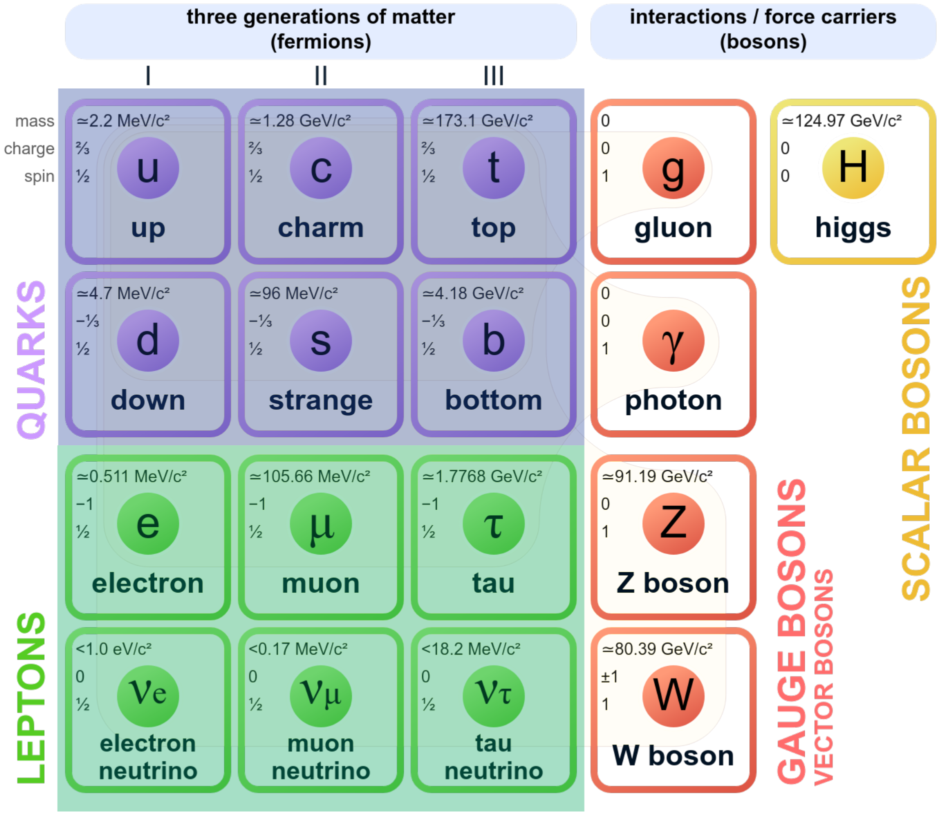
Fractional electric charge

Carry colour charge

Never observed as free particles

One picture, many views!

Standard Model of Elementary Particles



Fermions

Quarks

Massive particles

Fractional electric charge

Carry colour charge

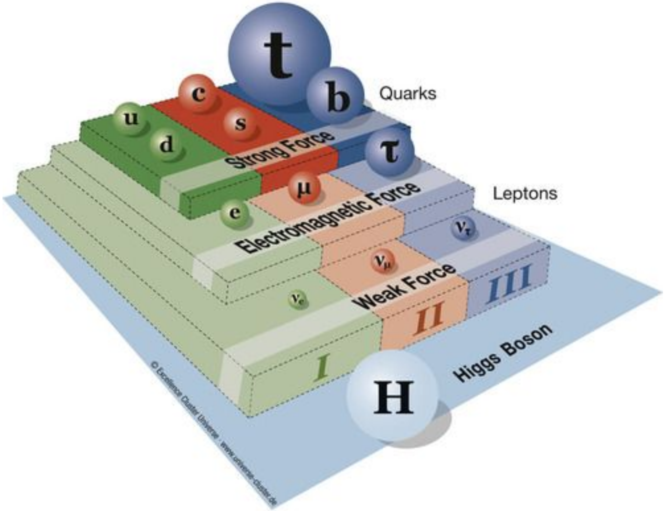
Never observed as free particles

Leptons

Don’t interact strongly

Integer charges

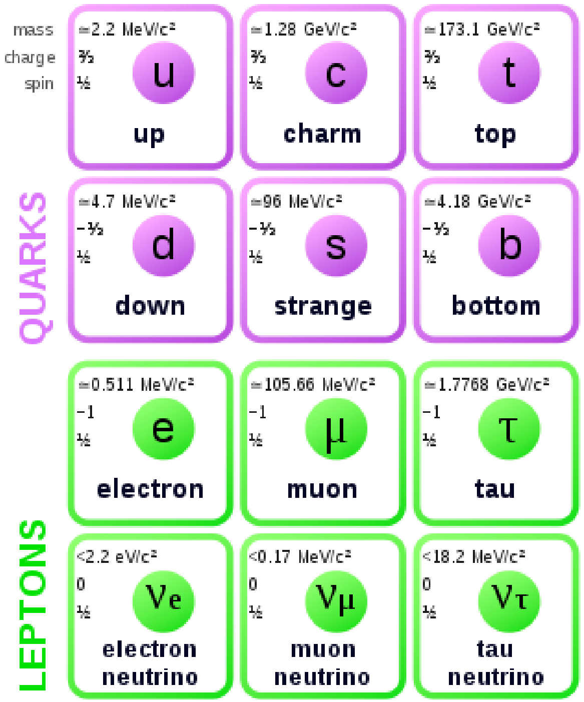
Each charged lepton is associated to a neutrally-charged neutrino



Fermions tend to organise in generations!

Antiparticles

- Every fermion in the Standard Model has its own antiparticle.
- Each antiparticle has the same mass, but opposite charge as its corresponding particle.



You will hear more about antiparticles in Joe's talk tomorrow!

Antiparticles

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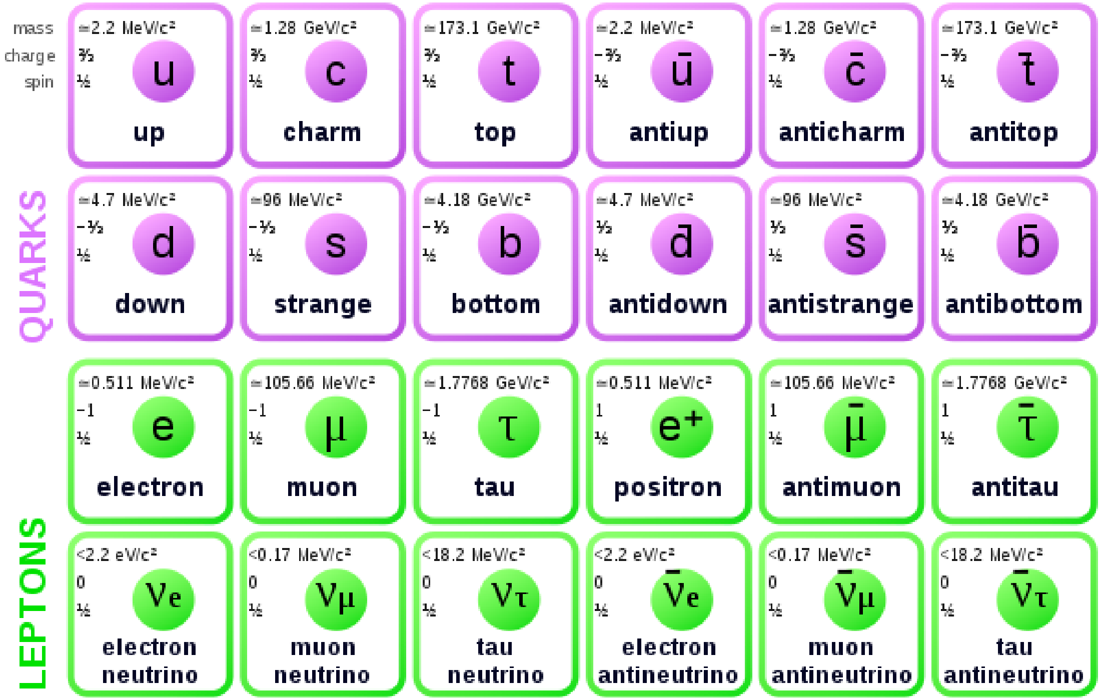

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How do particles interact?

Particle interactions

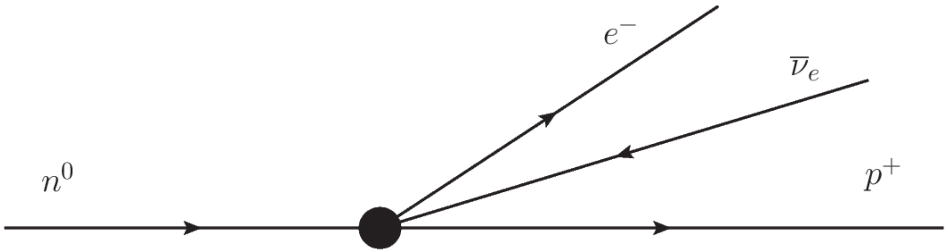
- Particle interactions are represented by the exchange of force carriers.

- Each carrier is associated to a different force:

  - Photons: electromagnetic force carriers

  - W and Z bosons: weak force carriers

  - Gluons: strong force carriers



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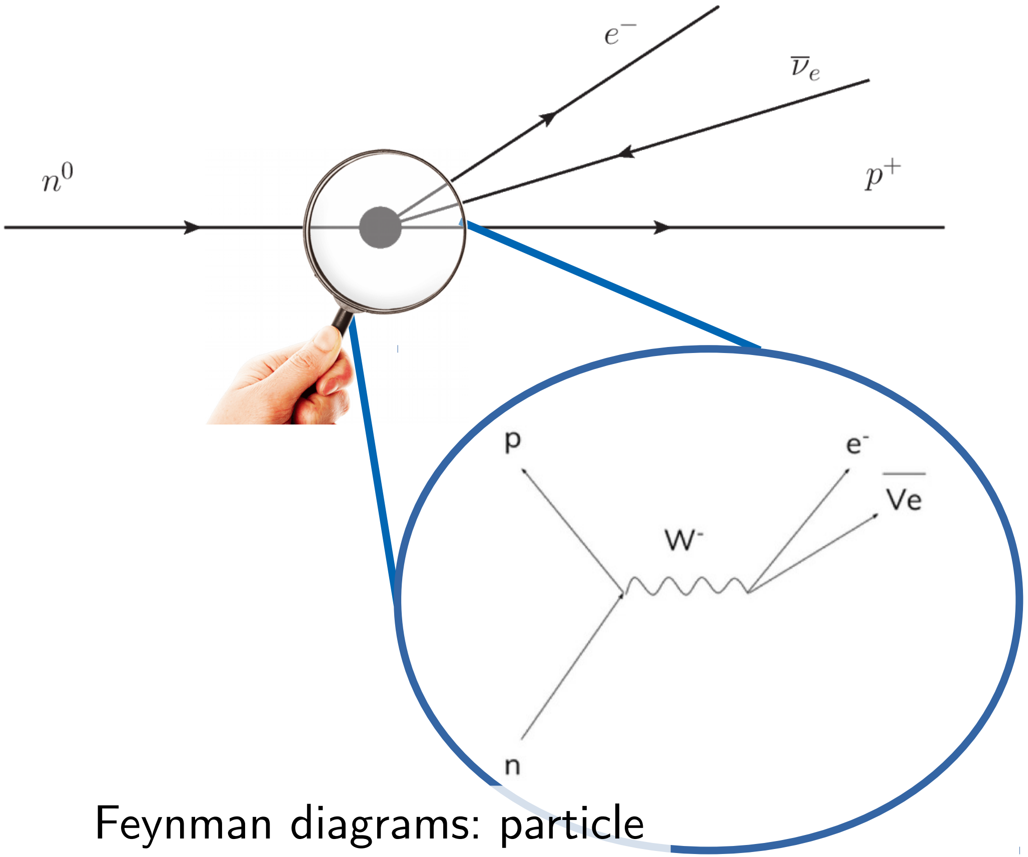
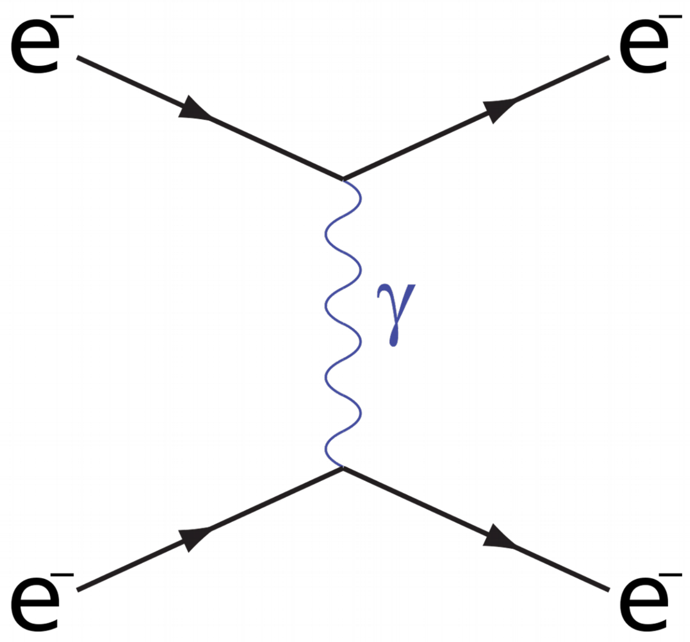


Feynman diagrams: particle physicists' best friends to understand interactions

Particle interactions: electromagnetic force

- Result of the unification of the electric and magnetic forces.
- Occurs between electrically charged particles.
- Carried by massless photons.
- Infinite range.

Electron scattering:



Particle interactions: weak force

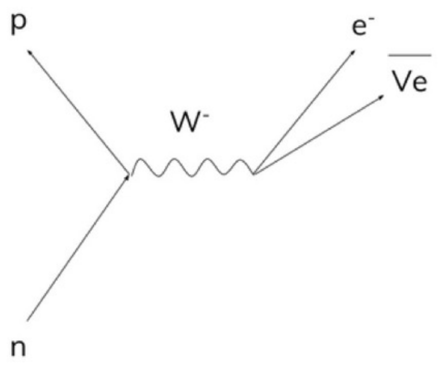
- Occurs between all types of particles.
- Mediated by W and Z bosons.
- Short range due to the bosons' mass.
- Responsible for many nuclear decays.

β decay:

$$^{14}_{6}C \rightarrow ^{14}_{7} N + e^{-} + \bar{\nu}_e$$

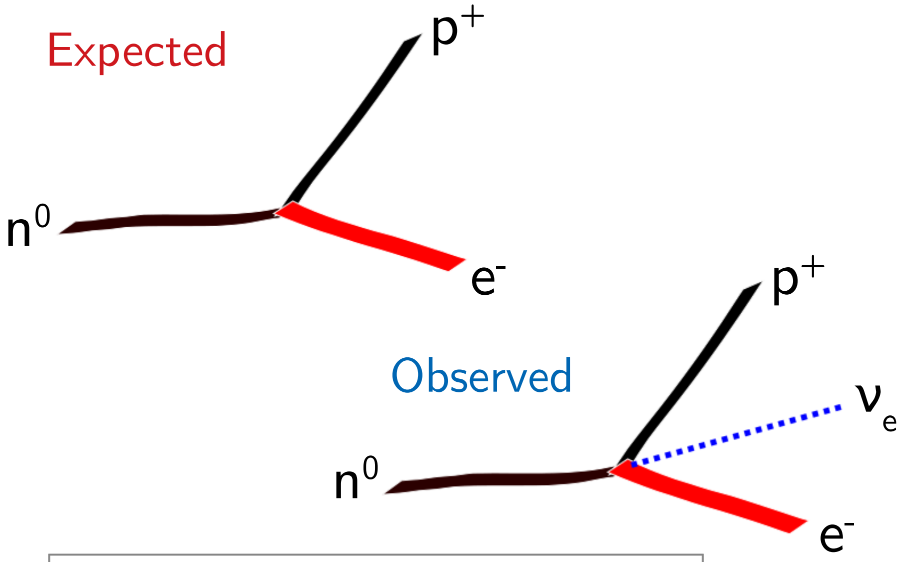
⇓

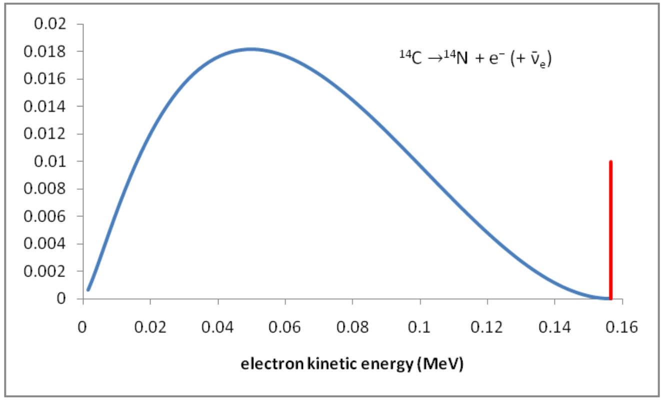
$$^{1}_{0}n \rightarrow ^{1}_{1} p + e^{-} + \bar{\nu}_e$$



Weak force: beta decays and proposal of the neutrino

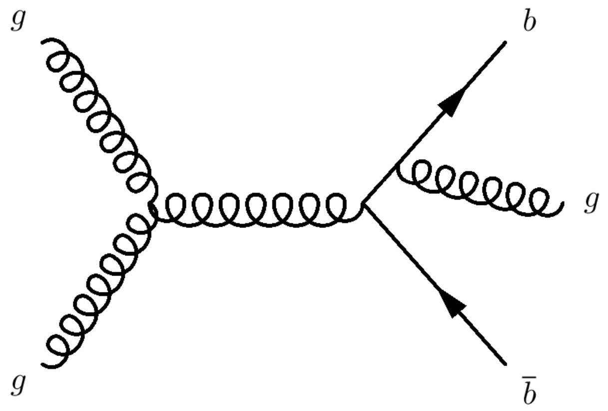
- Beta decays are a very well known reaction in nuclear physics.
- When measuring the electron's energy, physicists expected a single value for it. Instead, they observed a continuous spectrum.
- Something that couldn't be measured was taking part of the electron's energy $\rightarrow$ the neutrino!
  - Neutrinos are very special particles and a research field of their own, more on them in Jaiden's talk!

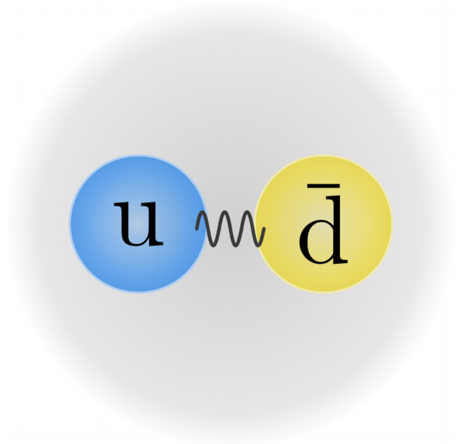




Particle interactions: strong force

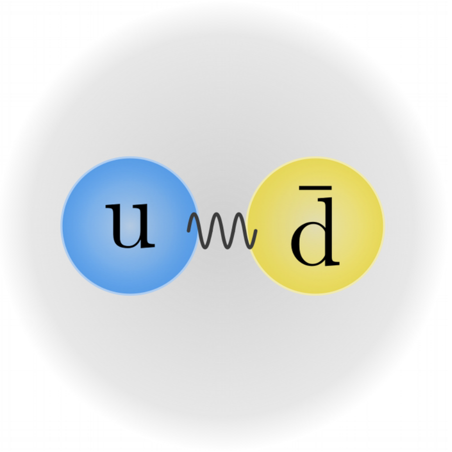
- Occurs between particles carrying colour charge (quarks and gluons).
- Mediated by gluons.
- Stronger at low energies or high distances, weaker at high energies and small distances:
  - Asymptotic freedom + quark confinement
  - No observation of free quarks and gluons

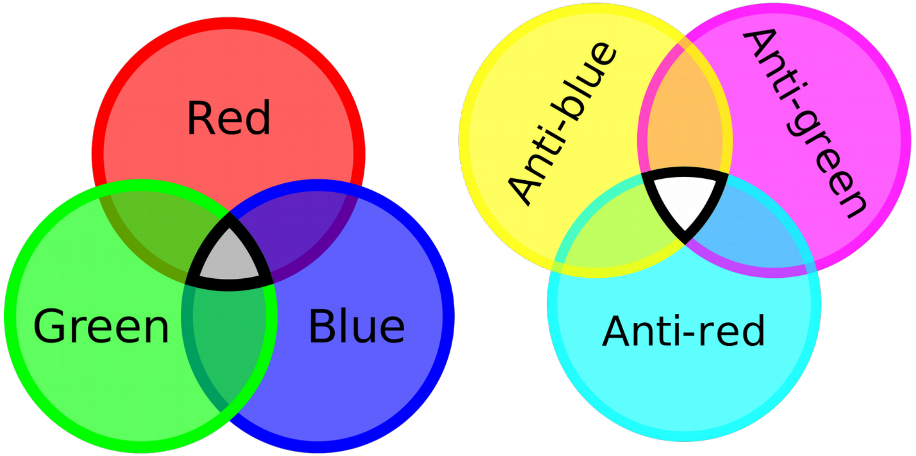




Strong force: colour charge

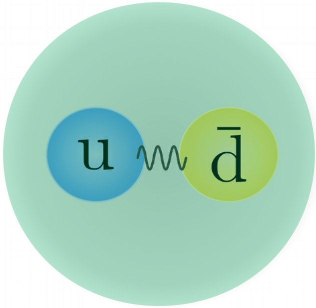
- Proposed to explain the existence of particles made of quarks in seemingly the same states.
  - This would violate Pauli exclusion principle.
- Three possible colours: Red, Green and Blue.
  - Antiquarks have anticolours.
- All stable particle combinations found in nature need to be colourless.
- Not related to visible colours.

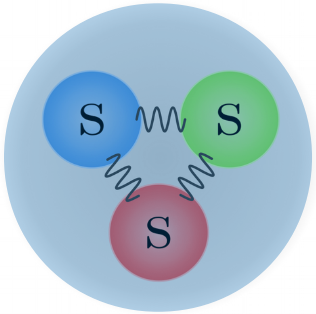


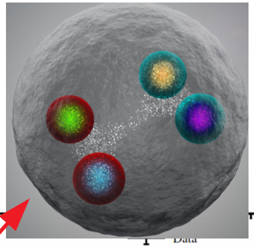


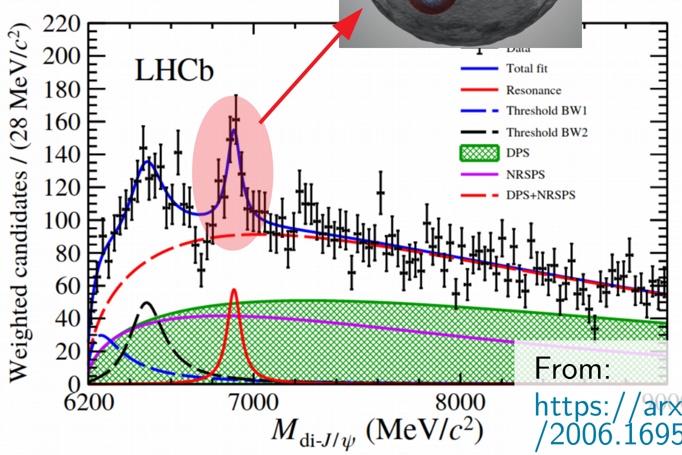
Mesons and baryons

- Particles composed of quarks are hadrons
- 2-quark particles are known as mesons
- 3-quark particles are known as baryons
- Hadrons must be colourless
  - Only colour-anticolour or RGB combinations are allowed
- In July 2020, LHCb published the observation of a candidate to be the first 4-quark particle ever detected (5-quark combinations also observed at LHC!).









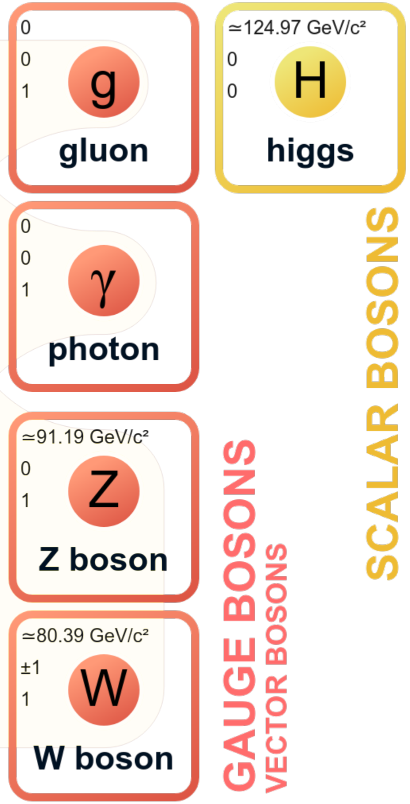
From: https://arxiv.org/pdf/2006.16957.pdf

Force strengths

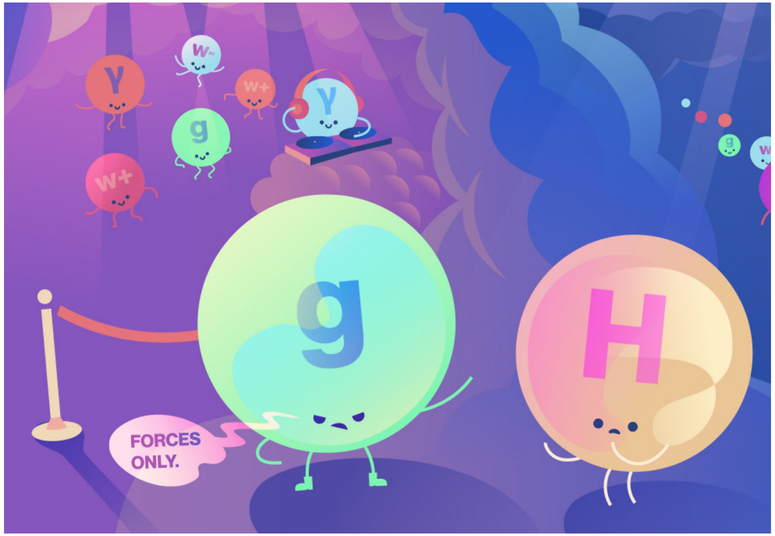
Force	Strength*
Strong	1
Electromagnetic	1/137
Weak	10^{-6}
Gravity	10^{-40}

*All values given for a certain energy point

What about the Higgs boson?



- We've talked about (most) bosons present in SM, but missed a really important one.
- Instead of mediating a force, the Higgs boson "grants mass" to all other particles.
- We'll hear more about it tomorrow, together with a recreation of the analysis that led to its discovery (and the 2013 Physics Nobel Prize)

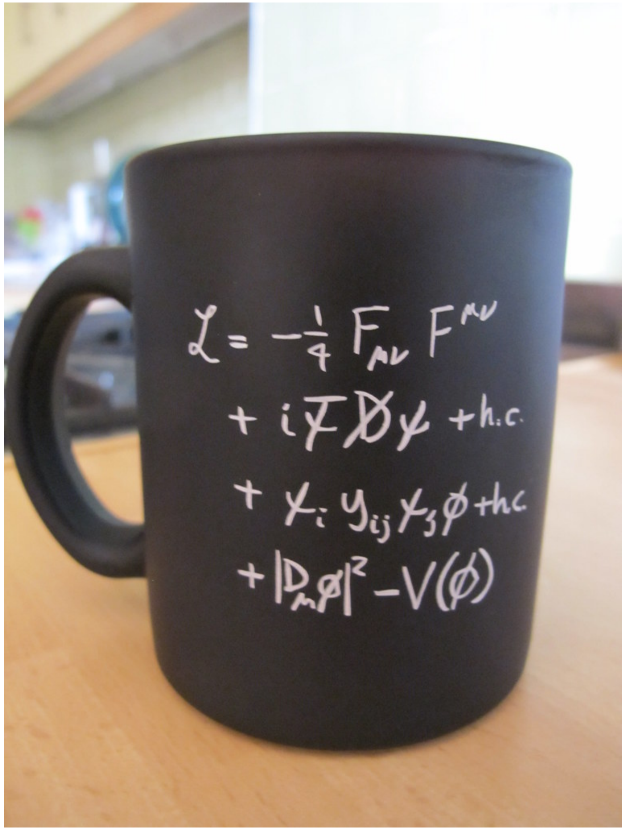


ATLAS EXPERIMENT

How do maths explain all* of our Universe?

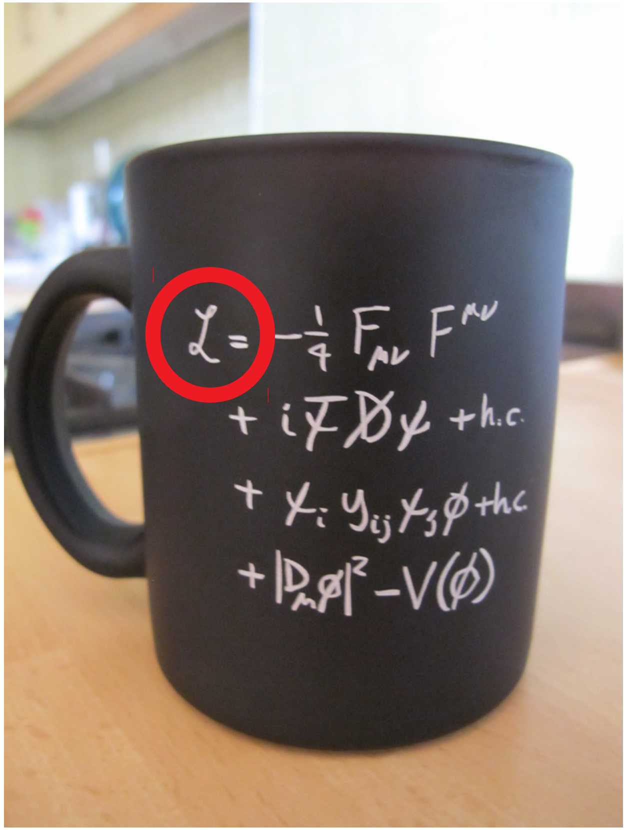
*most

The Universe in a mug



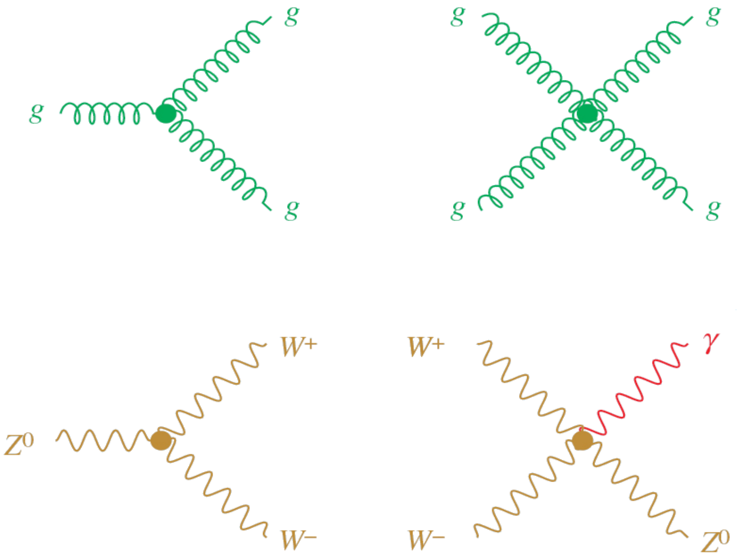
The Universe in a mug

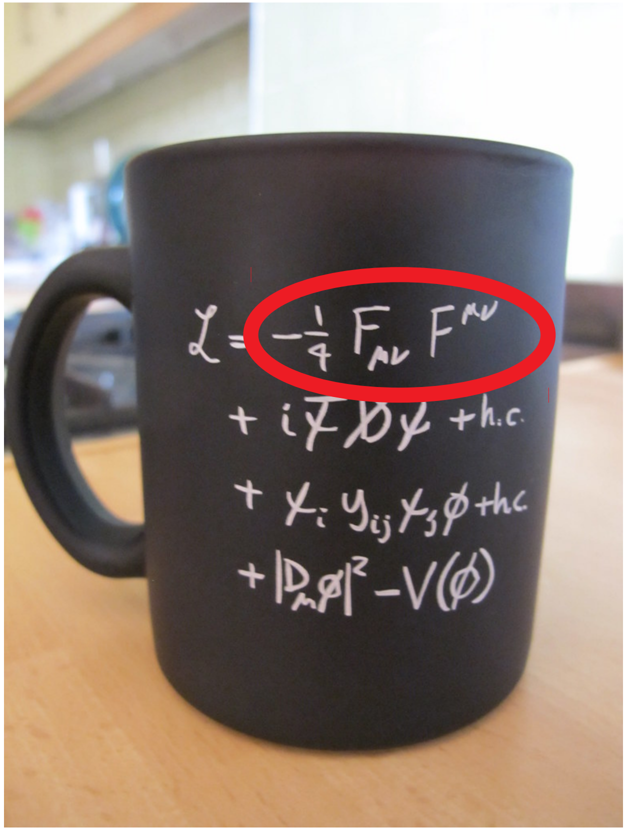
- $\mathcal{L}$ - Lagrangian density
- In classical mechanics, represents the difference between the kinetic and potential energies of a system.
  - Can be used to obtain the equations of motion of a system.
  - For example: springs, slopes...
- In quantum physics, it describes the kinematics of a quantum system.
- These are the rules that will tell us how do our particles behave!



The Universe in a mug

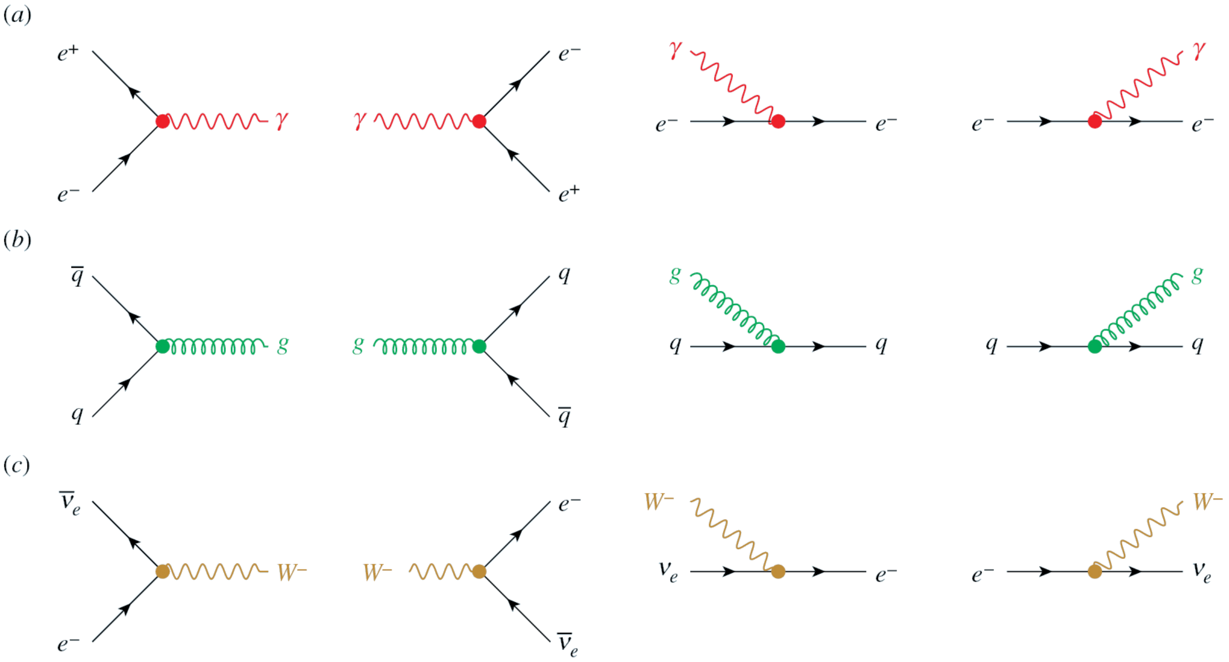
- Describes all interaction particles (all bosons except the Higgs) and how they interact with each other.

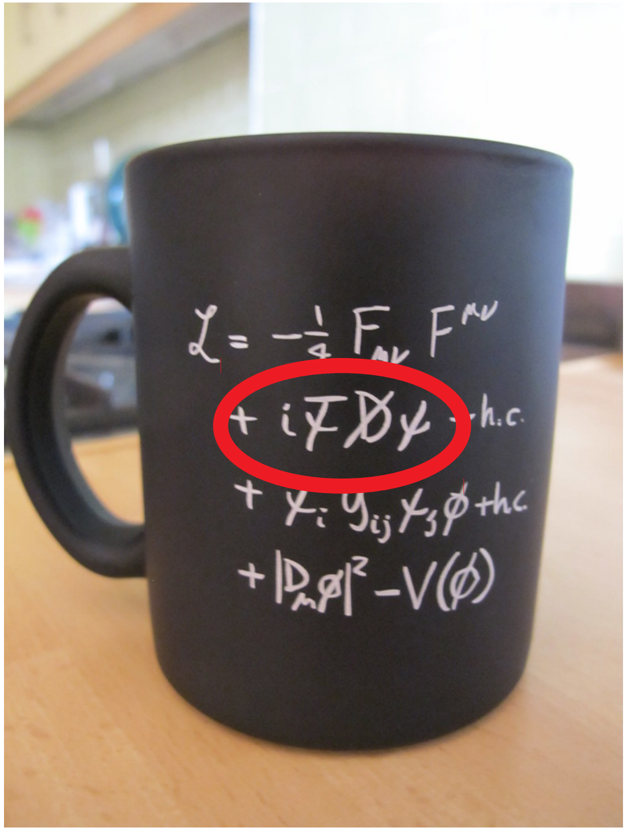




The Universe in a mug

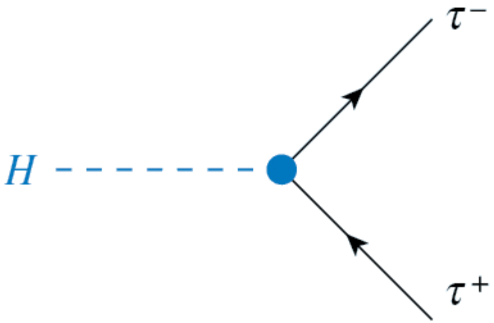
- Describes how interaction particles interact with matter (quarks and leptons).

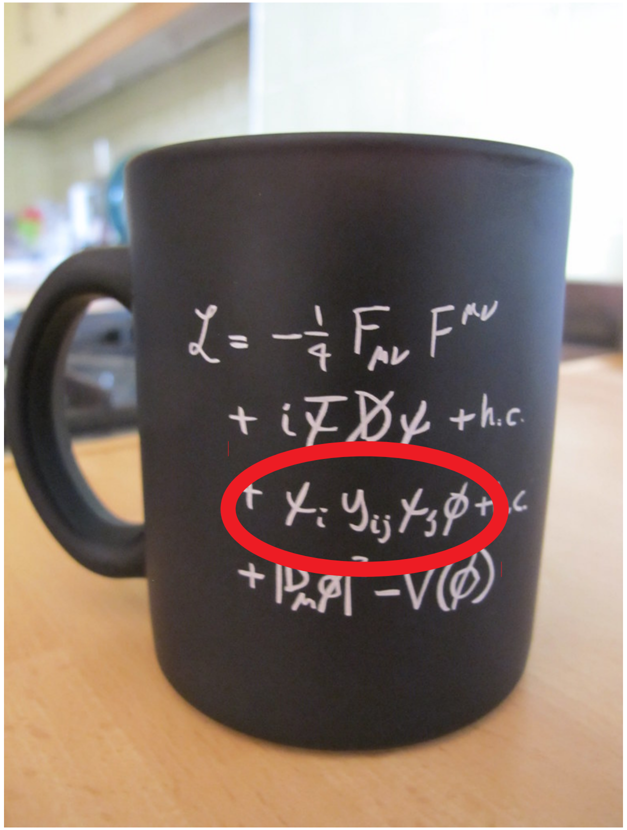




The Universe in a mug

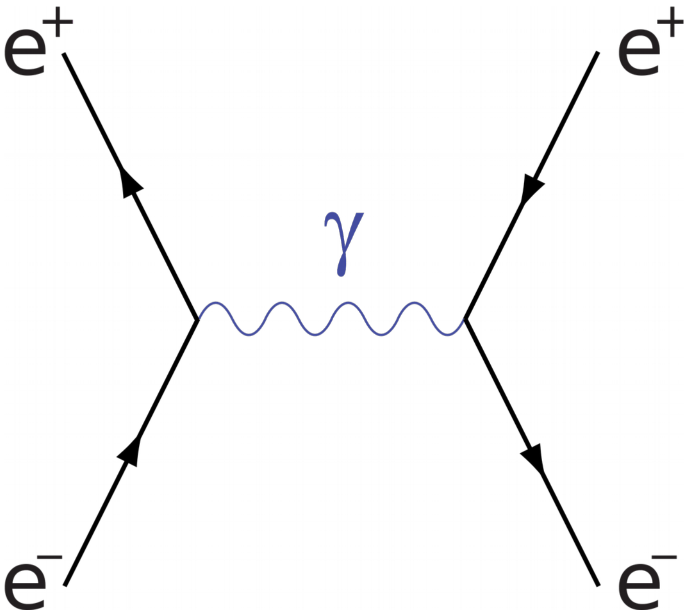
- Describes how matter particles couple to the Higgs field and gain mass.

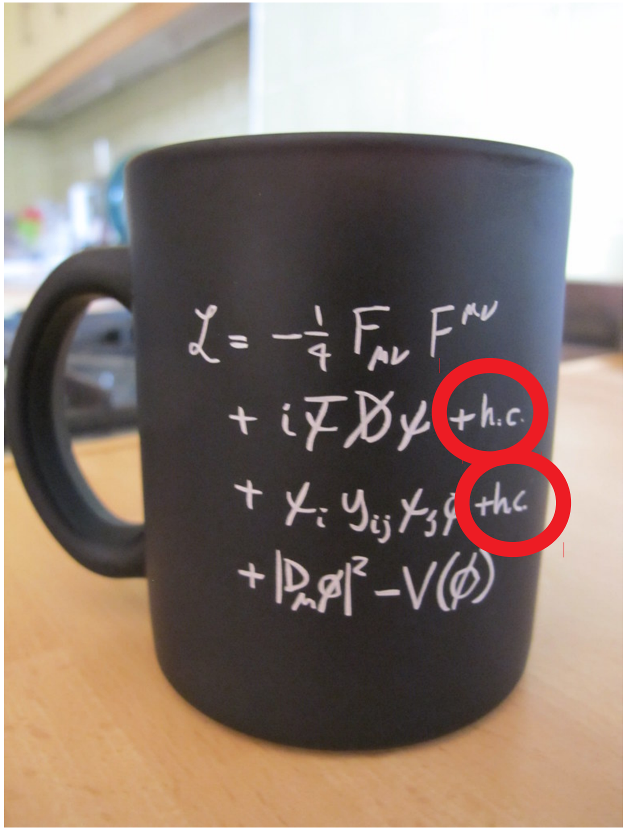




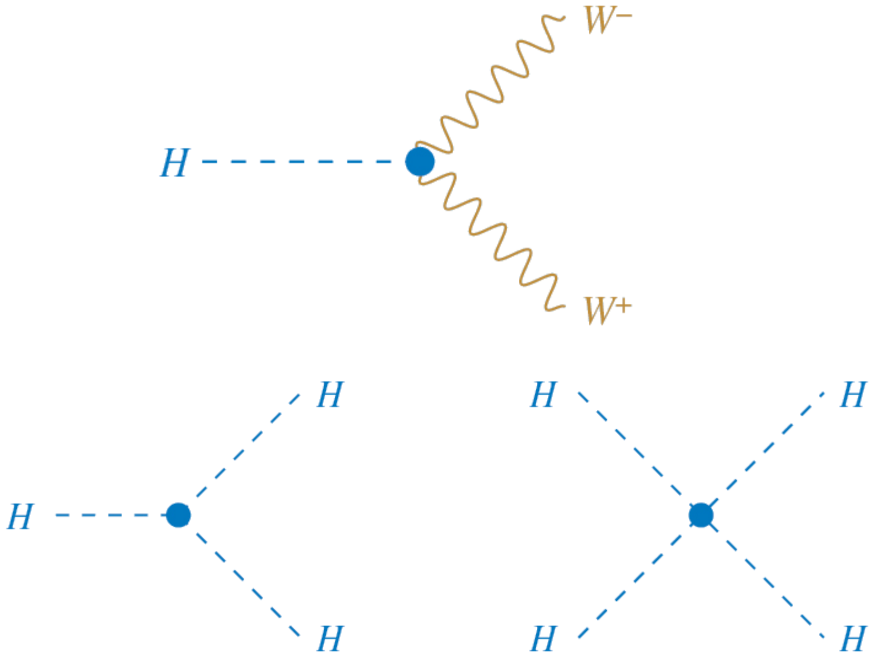
The Universe in a mug

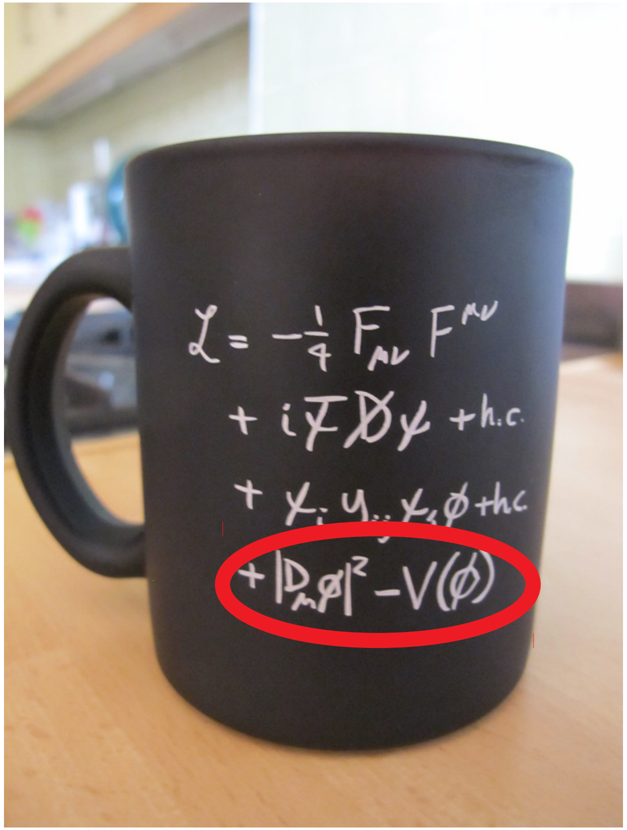
- h.c. stands for hermitian conjugate.
  Describes the same interactions as the main terms, but with antimatter particles.



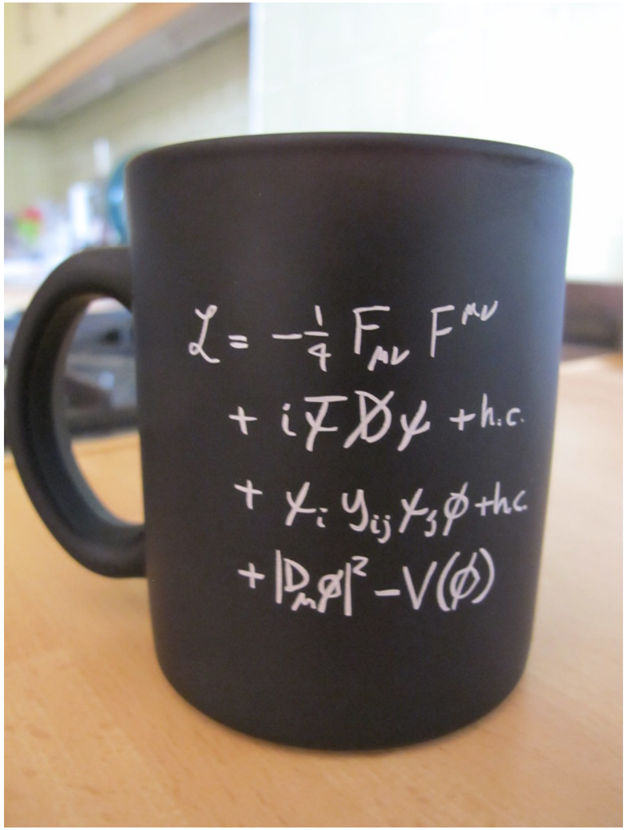


- Describes the Higgs interactions with other bosons and itself.





The Universe in a mug*



$$
\begin{gathered}
\mathcal{L}_{SM} = -\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4} g^2_s f^{abc} f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - \\
M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c^2_w} M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - igc_w(\partial_\nu Z^0_\mu (W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - Z^0_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu (W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)) - \\
igs_w(\partial_\nu A_\mu (W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + A_\mu (W^+_\nu \partial_\nu W^-_\mu - \\
W^-_\nu \partial_\nu W^+_\mu)) - \tfrac{1}{2} g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \tfrac{1}{2} g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c^2_w (Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - \\
Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2 s^2_w (A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w (A_\mu Z^0_\nu (W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu) - \tfrac{1}{2}\partial_\mu H \partial_\mu H - 2M^2 \alpha_h H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - \tfrac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \\
\beta_h \left(\tfrac{2M^2}{g^2} + \tfrac{2M}{g} H + \tfrac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-) \right) + \tfrac{2M^4}{g^2}\alpha_h - \\
g\alpha_h M \left(H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-\right) - \\
\tfrac{1}{8} g^2 \alpha_h \left(H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2 H^2\right) - \\
gMW^+_\mu W^-_\mu H - \tfrac{1}{2} g \tfrac{M}{c^2_w} Z^0_\mu Z^0_\mu H - \\
\tfrac{1}{2} ig \left(W^+_\mu (\phi^0 \partial_\mu \phi^- - \phi^- \partial_\mu \phi^0) - W^-_\mu (\phi^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^0) \right) + \\
\tfrac{1}{2} g \left(W^+_\mu (H \partial_\mu \phi^- - \phi^- \partial_\mu H) + W^-_\mu (H \partial_\mu \phi^+ - \phi^+ \partial_\mu H) \right) + \tfrac{1}{2} g \tfrac{1}{c_w} (Z^0_\mu (H \partial_\mu \phi^0 - \phi^0 \partial_\mu H) + \\
M \left(\tfrac{1}{c_w} Z^0_\mu \partial_\mu \phi^0 + W^+_\mu \partial_\mu \phi^- + W^-_\mu \partial_\mu \phi^+ \right) - ig \tfrac{s^2_w}{c_w} M Z^0_\mu (W^+_\mu \phi^- - W^-_\mu \phi^+) + igs_w M A_\mu (W^+_\mu \phi^- - \\
W^-_\mu \phi^+) - ig \tfrac{1-2c^2_w}{2c_w} Z^0_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) + igs_w A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \\
\tfrac{1}{4} g^2 W^+_\mu W^-_\mu \left(H^2 + (\phi^0)^2 + 2\phi^+\phi^-\right) - \tfrac{1}{8} g^2 \tfrac{1}{c^2_w} Z^0_\mu Z^0_\mu \left(H^2 + (\phi^0)^2 + 2(2s^2_w - 1)^2 \phi^+\phi^-\right) - \\
\tfrac{1}{2} g^2 \tfrac{s^2_w}{c_w} Z^0_\mu \phi^0 (W^+_\mu \phi^- + W^-_\mu \phi^+) - \tfrac{1}{2} ig^2 \tfrac{s^2_w}{c_w} Z^0_\mu H (W^+_\mu \phi^- - W^-_\mu \phi^+) + \tfrac{1}{2} g^2 s_w A_\mu \phi^0 (W^+_\mu \phi^- + \\
W^-_\mu \phi^+) + \tfrac{1}{2} ig^2 s_w A_\mu H (W^+_\mu \phi^- - W^-_\mu \phi^+) - g^2 \tfrac{s_w}{c_w} (2c^2_w - 1) Z^0_\mu A_\mu \phi^+ \phi^- - \\
g^2 s^2_w A_\mu A_\mu \phi^+ \phi^- + \tfrac{1}{2} ig_s \lambda^a_{ij} (\bar{q}^\sigma_i \gamma^\mu q^\sigma_j) g^a_\mu - \bar{e}^\lambda (\gamma\partial + m^\lambda_e) e^\lambda - \bar{\nu}^\lambda (\gamma\partial + m^\lambda_\nu) \nu^\lambda - \bar{u}^\lambda_j (\gamma\partial + \\
m^\lambda_u) u^\lambda_j - \bar{d}^\lambda_j (\gamma\partial + m^\lambda_d) d^\lambda_j + igs_w A_\mu \left(-(\bar{e}^\lambda \gamma^\mu e^\lambda) + \tfrac{2}{3} (\bar{u}^\lambda_j \gamma^\mu u^\lambda_j) - \tfrac{1}{3} (\bar{d}^\lambda_j \gamma^\mu d^\lambda_j) \right) + \\
\tfrac{ig}{4c_w} Z^0_\mu \{ (\bar{\nu}^\lambda \gamma^\mu (1+\gamma^5) \nu^\lambda) + (\bar{e}^\lambda \gamma^\mu (4s^2_w - 1 - \gamma^5) e^\lambda) + (\bar{d}^\lambda_j \gamma^\mu (\tfrac{4}{3} s^2_w - 1 - \gamma^5) d^\lambda_j) + \\
(\bar{u}^\lambda_j \gamma^\mu (1 - \tfrac{8}{3} s^2_w + \gamma^5) u^\lambda_j) \} + \tfrac{ig}{2\sqrt{2}} W^+_\mu \left((\bar{\nu}^\lambda \gamma^\mu (1+\gamma^5) U^{lep}{}_{\lambda\kappa} e^\kappa) + (\bar{u}^\lambda_j \gamma^\mu (1+\gamma^5) C_{\lambda\kappa} d^\kappa_j) \right) + \\
\tfrac{ig}{2\sqrt{2}} W^-_\mu \left((\bar{e}^\kappa U^{lep\dagger}{}_{\kappa\lambda} \gamma^\mu (1+\gamma^5) \nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\kappa\lambda} \gamma^\mu (1+\gamma^5) u^\lambda_j) \right) + \\
\tfrac{ig}{2M\sqrt{2}} \phi^+ \left(-m^\kappa_e (\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa} (1-\gamma^5) e^\kappa) + m^\lambda_\nu (\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa} (1+\gamma^5) e^\kappa \right) + \\
\tfrac{ig}{2M\sqrt{2}} \phi^- \left(m^\lambda_e (\bar{e}^\lambda U^{lep\dagger}{}_{\lambda\kappa} (1+\gamma^5) \nu^\kappa) - m^\kappa_\nu (\bar{e}^\lambda U^{lep\dagger}{}_{\lambda\kappa} (1-\gamma^5) \nu^\kappa \right) - \tfrac{g}{2} \tfrac{m^\lambda_\nu}{M} H (\bar{\nu}^\lambda \nu^\lambda) - \\
\tfrac{g}{2} \tfrac{m^\lambda_e}{M} H (\bar{e}^\lambda e^\lambda) + \tfrac{ig}{2} \tfrac{m^\lambda_\nu}{M} \phi^0 (\bar{\nu}^\lambda \gamma^5 \nu^\lambda) - \tfrac{ig}{2} \tfrac{m^\lambda_e}{M} \phi^0 (\bar{e}^\lambda \gamma^5 e^\lambda) - \tfrac{1}{4} \bar{\nu}_\lambda \, M^R_{\lambda\kappa} \, (1-\gamma_5) \hat{\nu}_\kappa - \\
\tfrac{1}{4} \bar{\nu}_\lambda \, M^R_{\lambda\kappa} \, (1-\gamma_5) \hat{\nu}_\kappa + \tfrac{ig}{2M\sqrt{2}} \phi^+ \left(-m^\kappa_d (\bar{u}^\lambda_j C_{\lambda\kappa} (1-\gamma^5) d^\kappa_j) + m^\lambda_u (\bar{u}^\lambda_j C_{\lambda\kappa} (1+\gamma^5) d^\kappa_j \right) + \\
\tfrac{ig}{2M\sqrt{2}} \phi^- \left(m^\lambda_d (\bar{d}^\lambda_j C^\dagger_{\lambda\kappa} (1+\gamma^5) u^\kappa_j) - m^\kappa_u (\bar{d}^\lambda_j C^\dagger_{\lambda\kappa} (1-\gamma^5) u^\kappa_j \right) - \tfrac{g}{2} \tfrac{m^\lambda_u}{M} H (\bar{u}^\lambda_j u^\lambda_j) - \\
\tfrac{g}{2} \tfrac{m^\lambda_d}{M} H (\bar{d}^\lambda_j d^\lambda_j) + \tfrac{ig}{2} \tfrac{m^\lambda_u}{M} \phi^0 (\bar{u}^\lambda_j \gamma^5 u^\lambda_j) - \tfrac{ig}{2} \tfrac{m^\lambda_d}{M} \phi^0 (\bar{d}^\lambda_j \gamma^5 d^\lambda_j) + \bar{G}^a \partial^2 G^a + g_s f^{abc} \partial_\mu \bar{G}^a G^b g^c_\mu + \\
\bar{X}^+ (\partial^2 - M^2) X^+ + \bar{X}^- (\partial^2 - M^2) X^- + \bar{X}^0 (\partial^2 - \tfrac{M^2}{c^2_w}) X^0 + \bar{Y} \partial^2 Y + igc_w W^+_\mu (\partial_\mu \bar{X}^0 X^- - \\
\partial_\mu \bar{X}^+ X^0) + igs_w W^+_\mu (\partial_\mu \bar{Y} X^- - \partial_\mu \bar{X}^+ Y) + igc_w W^-_\mu (\partial_\mu \bar{X}^- X^0 - \\
\partial_\mu \bar{X}^0 X^+) + igs_w W^-_\mu (\partial_\mu \bar{X}^- Y - \partial_\mu \bar{Y} X^+) + igc_w Z^0_\mu (\partial_\mu \bar{X}^+ X^+ - \\
\partial_\mu \bar{X}^- X^-) + igs_w A_\mu (\partial_\mu \bar{X}^+ X^+ - \\
\partial_\mu \bar{X}^- X^-) - \tfrac{1}{2} gM \left(\bar{X}^+ X^+ H + \bar{X}^- X^- H + \tfrac{1}{c^2_w} \bar{X}^0 X^0 H \right) + \tfrac{1-2c^2_w}{2c_w} igM \left(\bar{X}^+ X^0 \phi^+ - \bar{X}^- X^0 \phi^- \right) + \\
\tfrac{1}{2c_w} igM \left(\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^- \right) + igMs_w \left(\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^- \right) + \\
\tfrac{1}{2} igM \left(\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0 \right) .
\end{gathered}
$$

* disclaimer: you may actually struggle fitting the whole theory in a mug

ATLAS EXPERIMENT

Summary

- Standard Model is the main theory that describes all known particles and the way they interact.
- Although it was proposed many years ago, it still provides amazing predictions that very well describe our observations in many different experiments.
- However, we do know there's things that fails to explain:
  - Gravity
  - Dark matter and dark energy
  - Matter-antimatter asymmetry
  - ...
- Stay tuned for Matt's talk to hear more about some of these mysteries!

Thanks for your attention!

Further reading

- J. Woithe, G. Wiener, F. Van der Veken, “Let’s have a coffee with Standard Model”
  - https://iopscience.iop.org/article/10.1088/1361-6552/aa5b25/pdf
- R. Oerter (2006). The Theory of Almost Everything: The Standard Model, the Unsung Triumph of Modern Physics
- "Standard Model of Particles and Interactions" – Summary poster
  - https://web.archive.org/web/20160304133522/https://www.pha.jhu.edu/~dfehling/particle.gif