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UNIVERSITY OF
LIVERPOOL

Standard Model of particle physics

Ricardo González López

Liverpool@CERN Summer School - 22/08/2022

About me

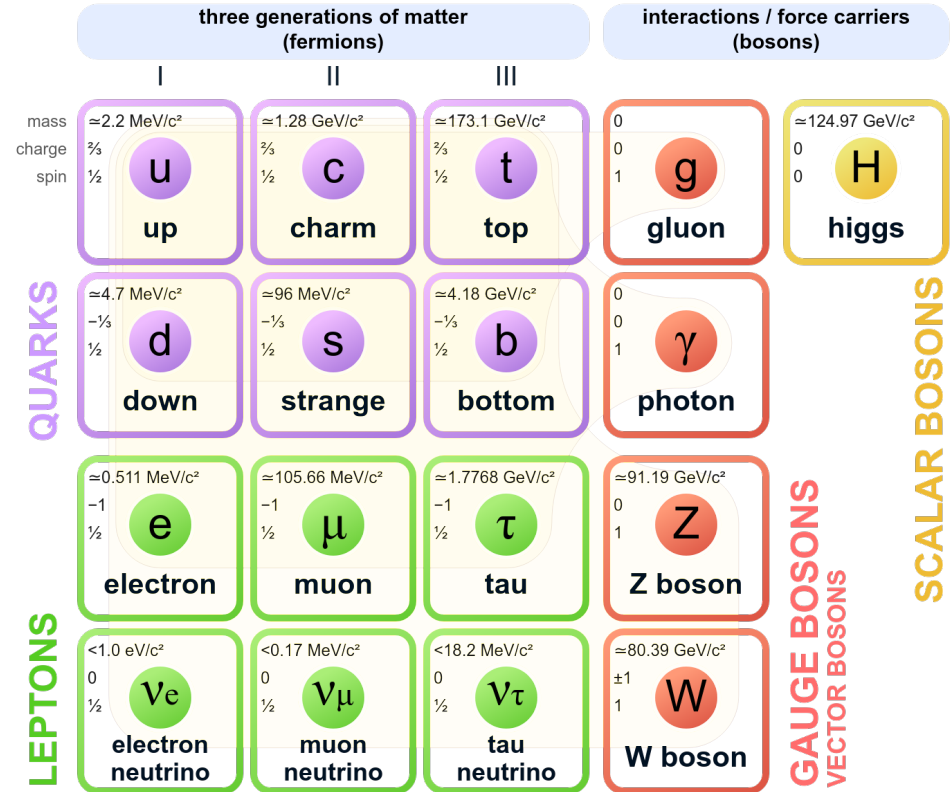
- Hi! I'm Ricardo Gonzalez
- Born in Zaragoza, Spain, where I took undergrad Physics
- Took a master in Advanced Physics in Valencia
- Now a 4th year PhD student at the University of Liverpool
- Working at the ATLAS experiment
 - Precision W and Z boson measurements
 - Pixel tracker upgrade
- Interests: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

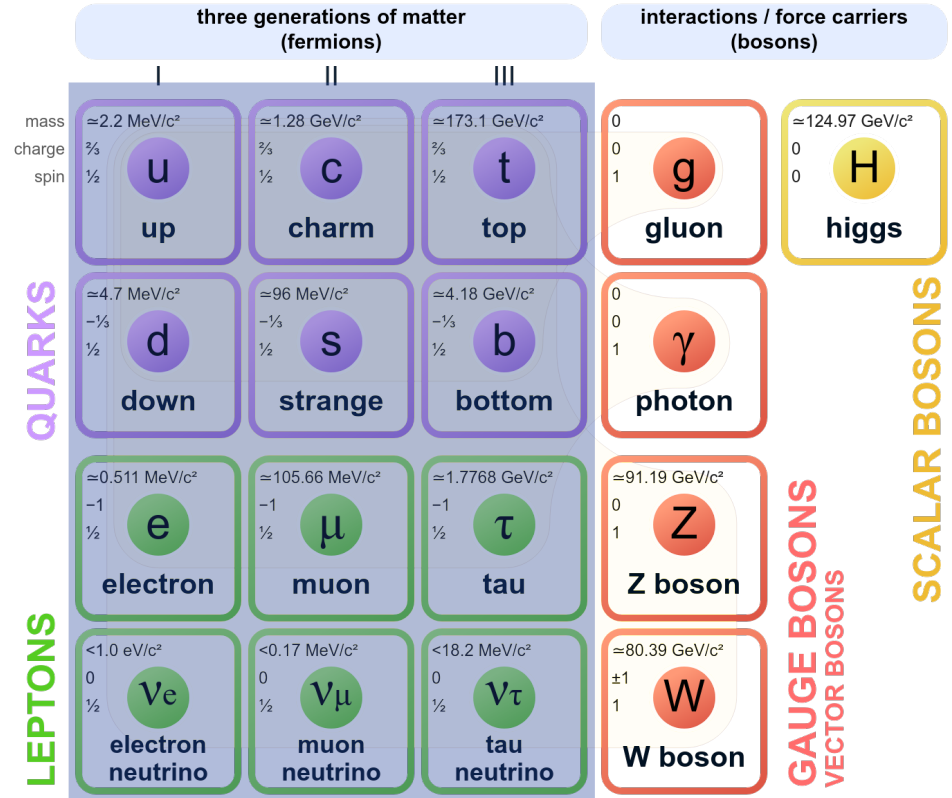
Standard Model of Elementary Particles



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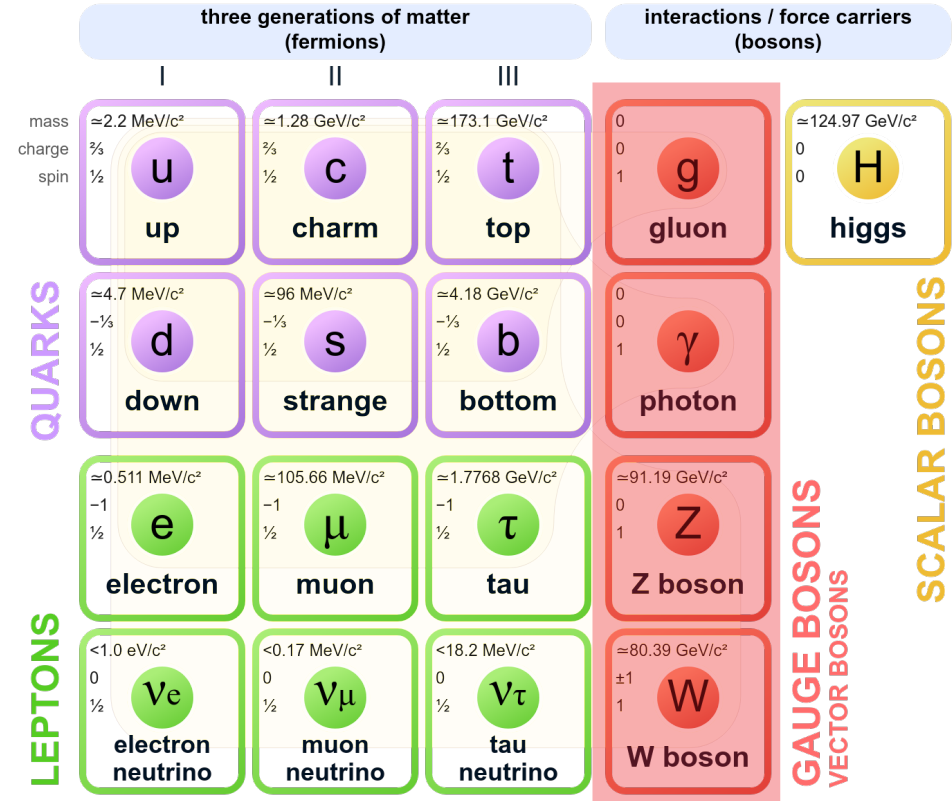
Standard Model of Elementary Particles



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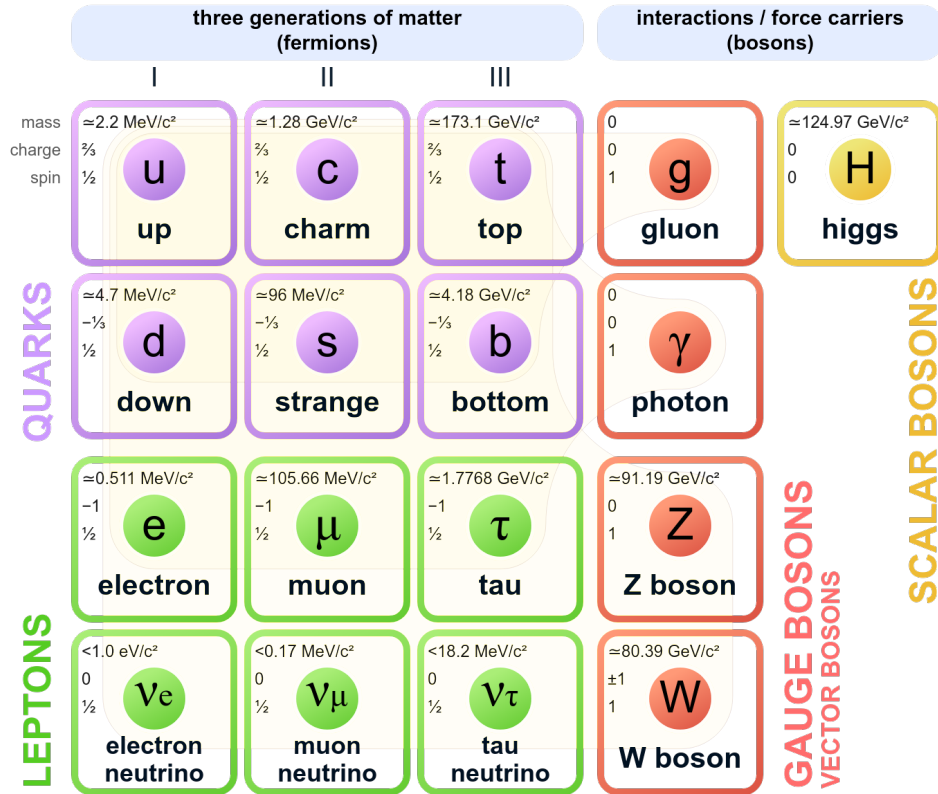
Standard Model of Elementary Particles



What is matter made of?

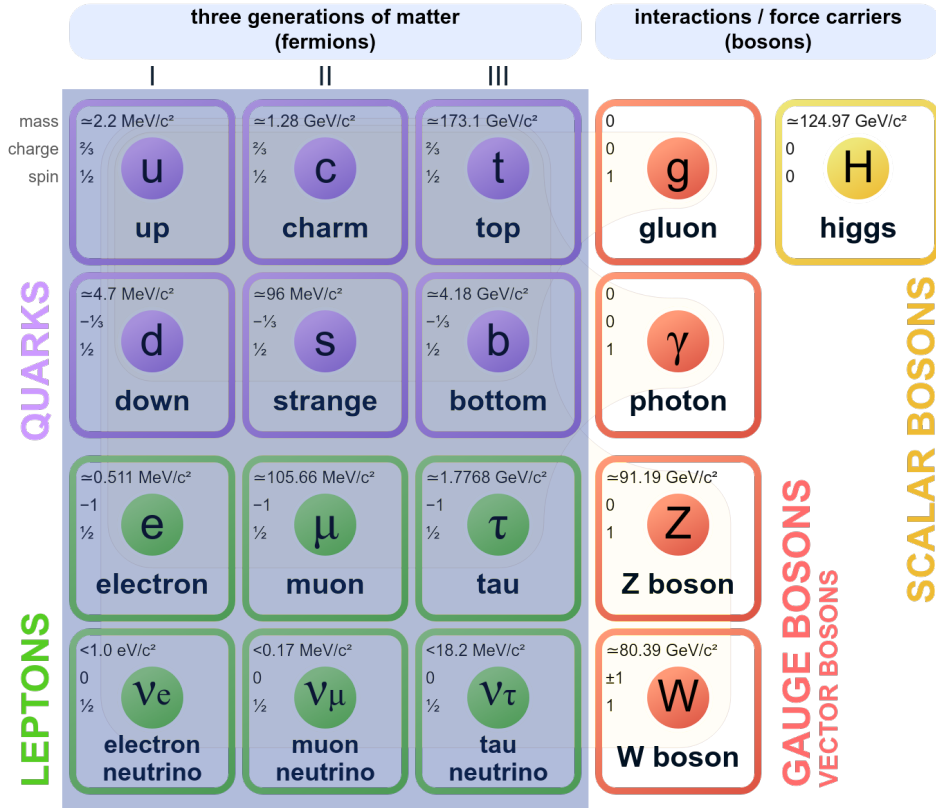
One picture, many views!

Standard Model of Elementary Particles



One picture, many views!

Standard Model of Elementary Particles



Fermions

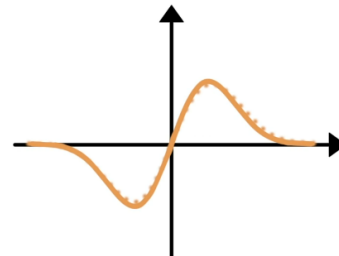
Matter particles

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

Spin 1/2

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

ANTISYMMETRIC



One picture, many views!

Standard Model of Elementary Particles

three generations of matter (fermions)			interactions / force carriers (bosons)		
	I	II	III		
mass	$\approx 2.2 \text{ MeV}/c^2$	$\approx 1.28 \text{ GeV}/c^2$	$\approx 173.1 \text{ GeV}/c^2$	0	$\approx 124.97 \text{ GeV}/c^2$
charge	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0	0
spin	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	0
	u up	c charm	t top	g gluon	H higgs
	$\approx 4.7 \text{ MeV}/c^2$	$\approx 96 \text{ MeV}/c^2$	$\approx 4.18 \text{ GeV}/c^2$	0	
	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	0	
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
QUARKS	d down	s strange	b bottom	γ photon	
	$\approx 0.511 \text{ MeV}/c^2$	$\approx 105.66 \text{ MeV}/c^2$	$\approx 1.7768 \text{ GeV}/c^2$	$\approx 91.19 \text{ GeV}/c^2$	
	-1	-1	-1	0	
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
	e electron	μ muon	τ tau	Z Z boson	
LEPTONS	$< 1.0 \text{ eV}/c^2$	$< 0.17 \text{ MeV}/c^2$	$< 18.2 \text{ MeV}/c^2$	$\approx 80.39 \text{ GeV}/c^2$	
	0	0	0	± 1	
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	
				GAUGE BOSONS VECTOR BOSONS	SCALAR BOSONS

Fermions

Bosons

Matter particles

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

Force carriers*

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

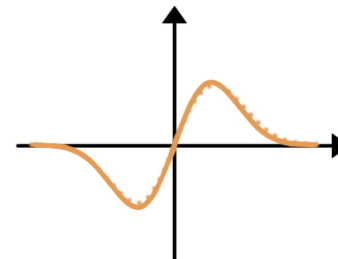
Spin 1/2

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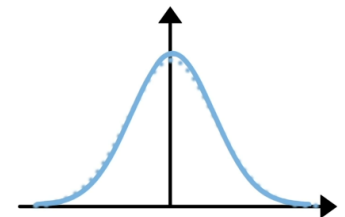
Integer spin: 0, 1, 2

- Mathematically described by a symmetric function.

ANTISYMMETRIC

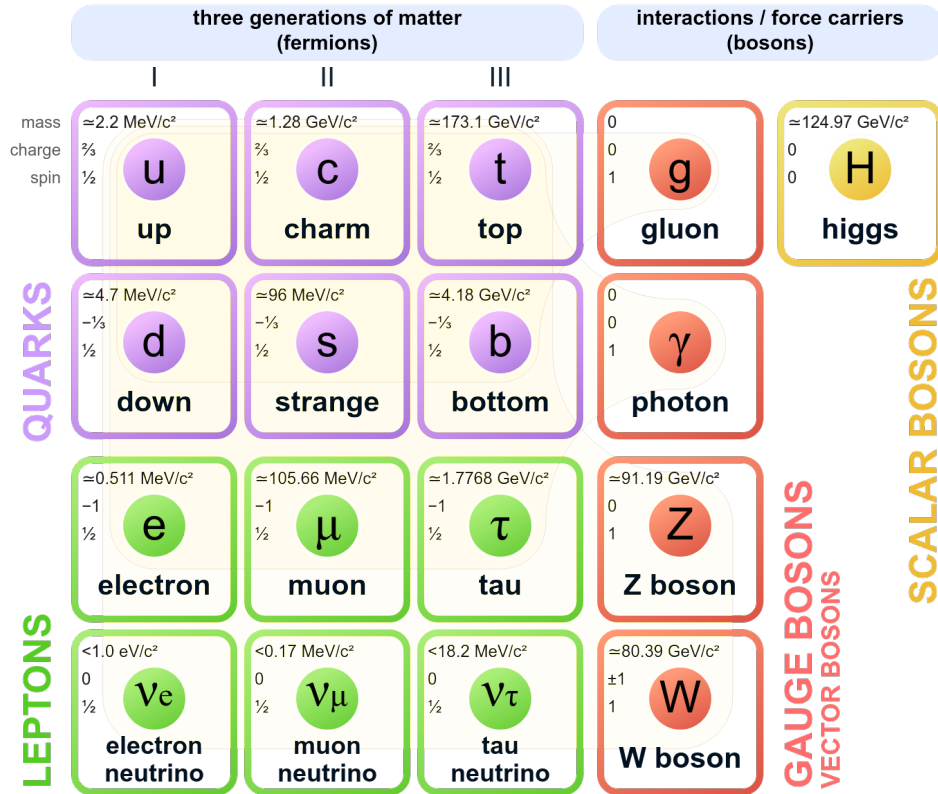


SYMMETRIC



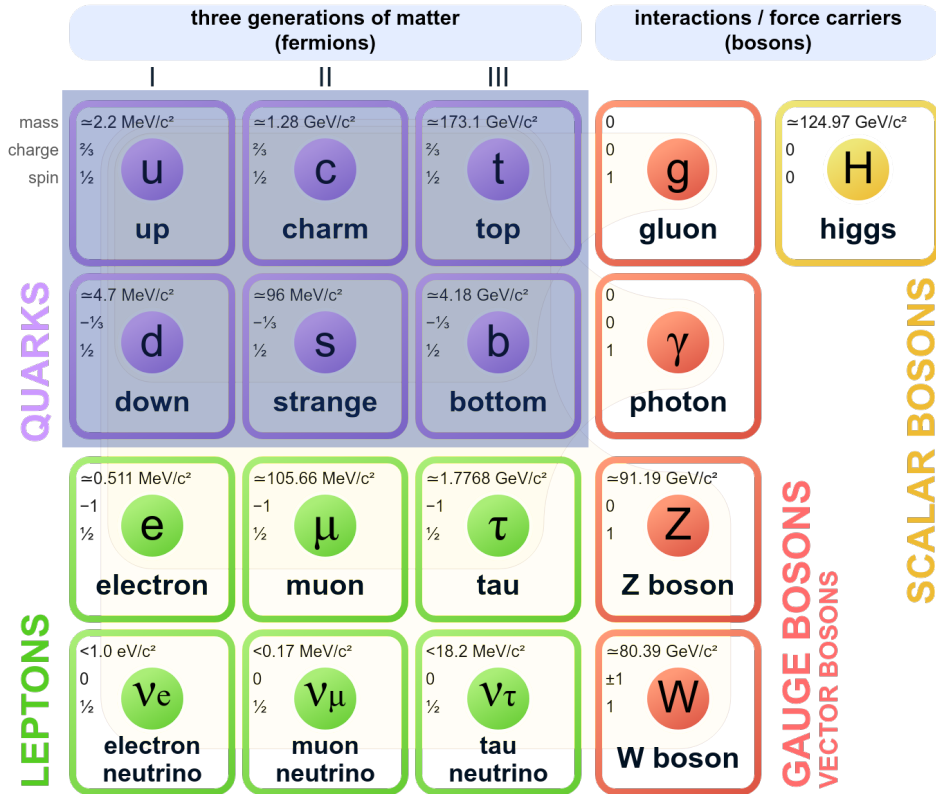
One picture, many views!

Standard Model of Elementary 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

One picture, many views!

Standard Model of Elementary Particles

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	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
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	0	0	0	± 1	
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	

QUARKS

LEPTONS

SCALAR BOSONS

GAUGE BOSONS
VECTOR BOSONS

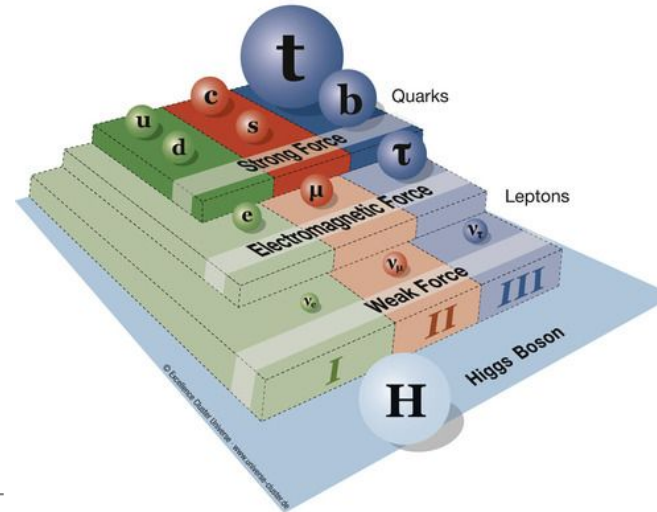
Fermions

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.

mass	$\approx 2.2 \text{ MeV}/c^2$	$\approx 1.28 \text{ GeV}/c^2$	$\approx 173.1 \text{ GeV}/c^2$
charge	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$
spin	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$
	u	c	t
	up	charm	top
QUARKS	$\approx 4.7 \text{ MeV}/c^2$	$\approx 96 \text{ MeV}/c^2$	$\approx 4.18 \text{ GeV}/c^2$
	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$
	d	s	b
	down	strange	bottom
	$\approx 0.511 \text{ MeV}/c^2$	$\approx 105.66 \text{ MeV}/c^2$	$\approx 1.7768 \text{ GeV}/c^2$
	-1	-1	-1
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$
	e	μ	τ
	electron	muon	tau
LEPTONS	$< 2.2 \text{ eV}/c^2$	$< 0.17 \text{ MeV}/c^2$	$< 18.2 \text{ MeV}/c^2$
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	electron neutrino	muon neutrino	tau neutrino

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

Antiparticles

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

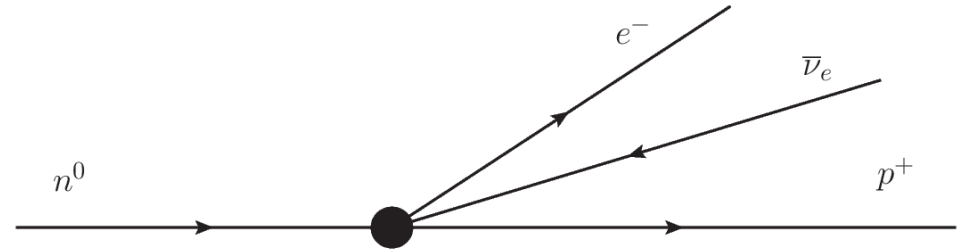
	mass	charge	spin							
QUARKS	$=2.2 \text{ MeV}/c^2$	$\frac{2}{3}$	$\frac{1}{2}$	u	up	$=1.28 \text{ GeV}/c^2$	$\frac{2}{3}$	$\frac{1}{2}$	c	charm
	$=173.1 \text{ GeV}/c^2$	$\frac{2}{3}$	$\frac{1}{2}$	t	top	$=2.2 \text{ MeV}/c^2$	$-\frac{2}{3}$	$\frac{1}{2}$	\bar{u}	antiup
	$=1.28 \text{ GeV}/c^2$	$-\frac{2}{3}$	$\frac{1}{2}$	\bar{c}	anticharm	$=173.1 \text{ GeV}/c^2$	$-\frac{2}{3}$	$\frac{1}{2}$	\bar{t}	antitop
	$=4.7 \text{ MeV}/c^2$	$-\frac{1}{3}$	$\frac{1}{2}$	d	down	$=4.7 \text{ MeV}/c^2$	$\frac{1}{3}$	$\frac{1}{2}$	\bar{d}	antidown
	$=96 \text{ MeV}/c^2$	$-\frac{1}{3}$	$\frac{1}{2}$	s	strange	$=96 \text{ MeV}/c^2$	$\frac{1}{3}$	$\frac{1}{2}$	\bar{s}	antistrange
	$=4.18 \text{ GeV}/c^2$	$-\frac{1}{3}$	$\frac{1}{2}$	b	bottom	$=4.18 \text{ GeV}/c^2$	$\frac{1}{3}$	$\frac{1}{2}$	\bar{b}	antibottom
LEPTONS	$=0.511 \text{ MeV}/c^2$	-1	$\frac{1}{2}$	e	electron	$=0.511 \text{ MeV}/c^2$	1	$\frac{1}{2}$	e^+	positron
	$=105.66 \text{ MeV}/c^2$	-1	$\frac{1}{2}$	μ	muon	$=105.66 \text{ MeV}/c^2$	1	$\frac{1}{2}$	$\bar{\mu}$	antimuon
	$=1.7768 \text{ GeV}/c^2$	-1	$\frac{1}{2}$	τ	tau	$=1.7768 \text{ GeV}/c^2$	1	$\frac{1}{2}$	$\bar{\tau}$	antitau
	$<2.2 \text{ eV}/c^2$	0	$\frac{1}{2}$	ν_e	electron neutrino	$<2.2 \text{ eV}/c^2$	0	$\frac{1}{2}$	$\bar{\nu}_e$	electron antineutrino
	$<0.17 \text{ MeV}/c^2$	0	$\frac{1}{2}$	ν_μ	muon neutrino	$<0.17 \text{ MeV}/c^2$	0	$\frac{1}{2}$	$\bar{\nu}_\mu$	muon antineutrino
	$<18.2 \text{ MeV}/c^2$	0	$\frac{1}{2}$	ν_τ	tau neutrino	$<18.2 \text{ MeV}/c^2$	0	$\frac{1}{2}$	$\bar{\nu}_\tau$	tau antineutrino

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

How do particles interact?

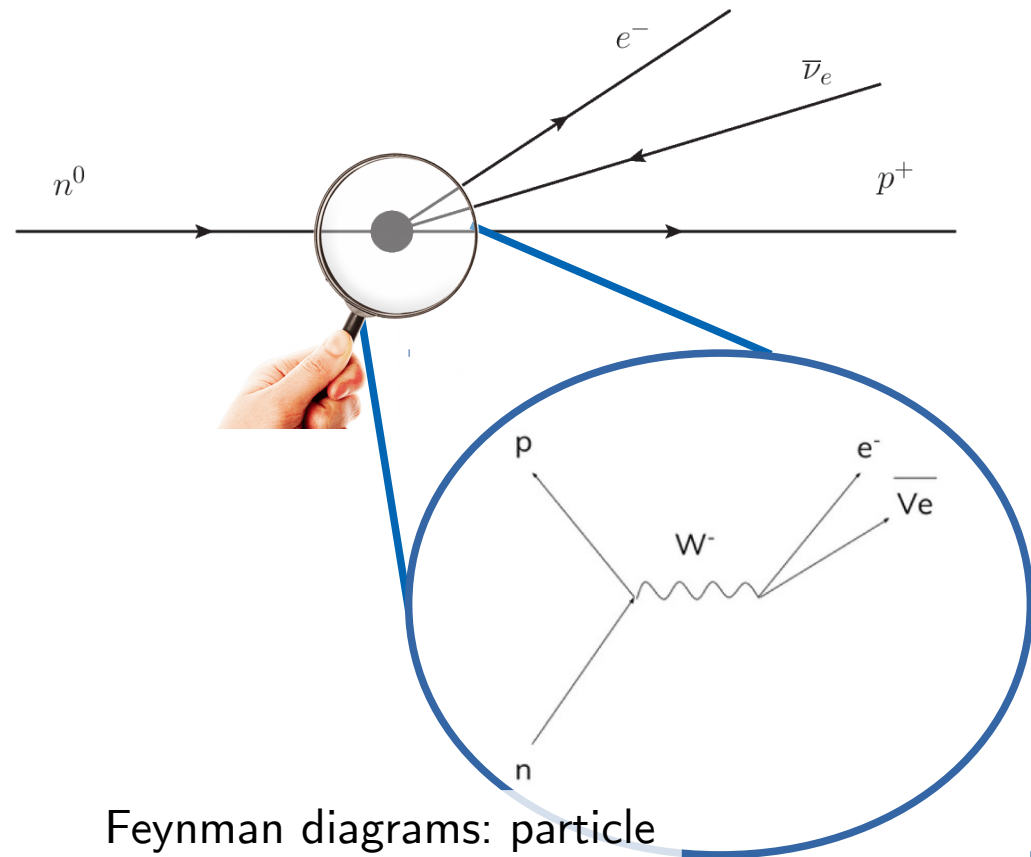
Particle interactions

- 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



Particle interactions

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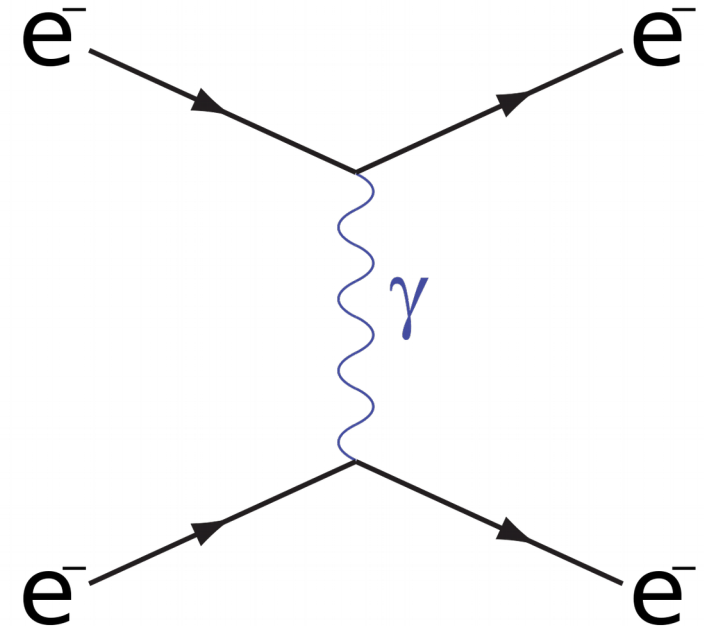


Feynman diagrams: particle physicists' best friends to understand interactions

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.

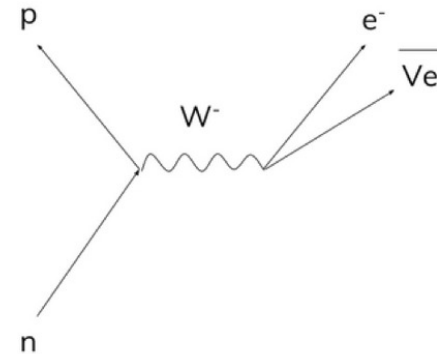
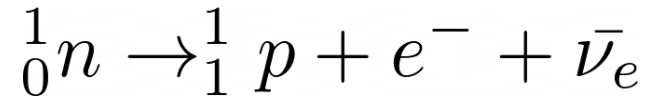
Electron scattering:



Particle interactions: weak force

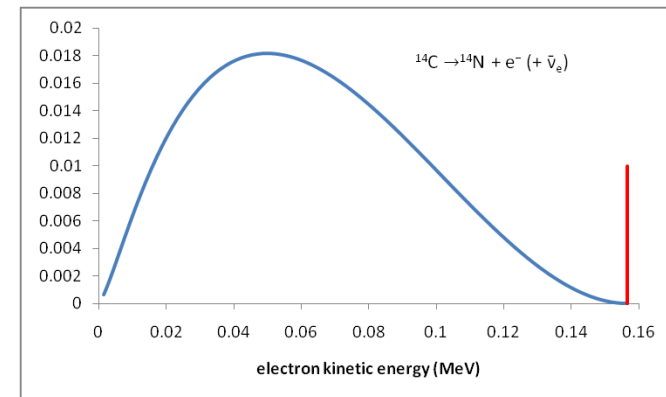
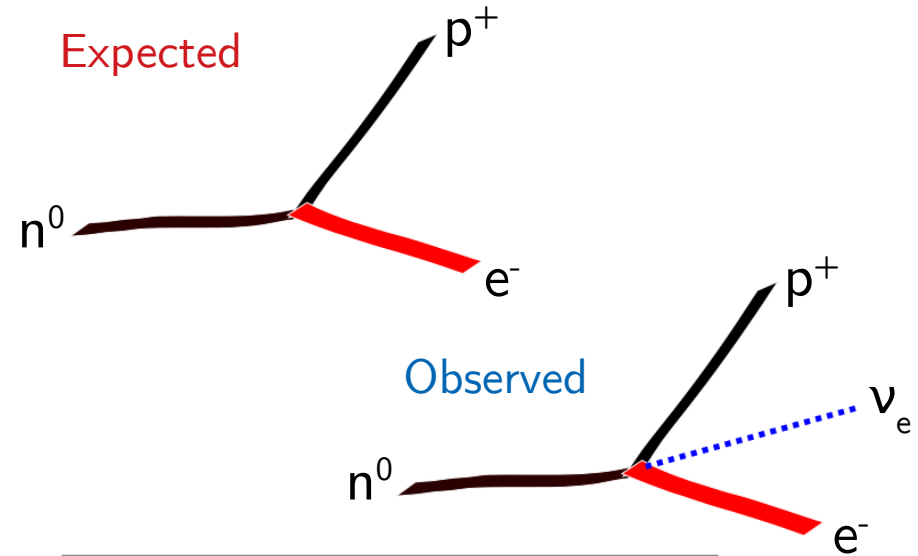
- Occurs between **all types of particles**.
- Mediated by **W and Z bosons**.
- Short range due to the bosons' mass.
- Responsible for many nuclear decays.

β decay:



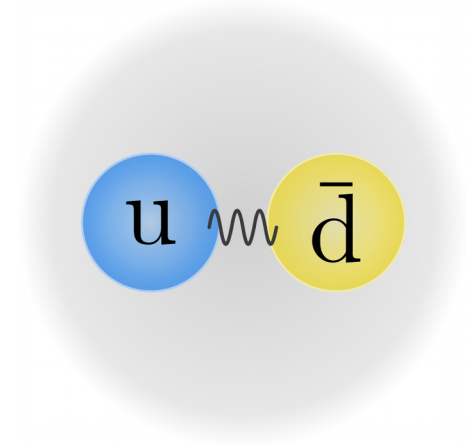
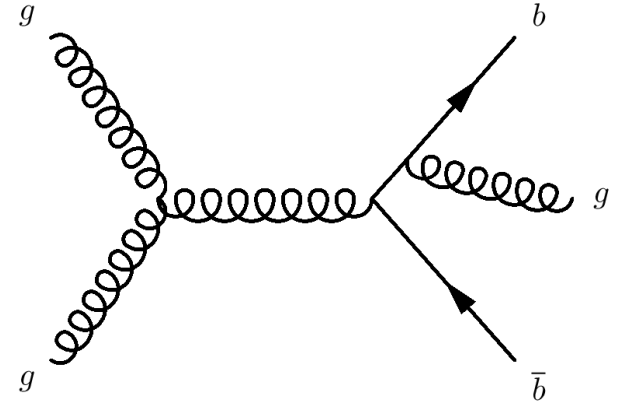
Weak force: beta decays and proposal of the neutrino

- 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 → the neutrino!
 - Neutrinos are very special particles and a research field of their own, more on them in Jaiden's talk!



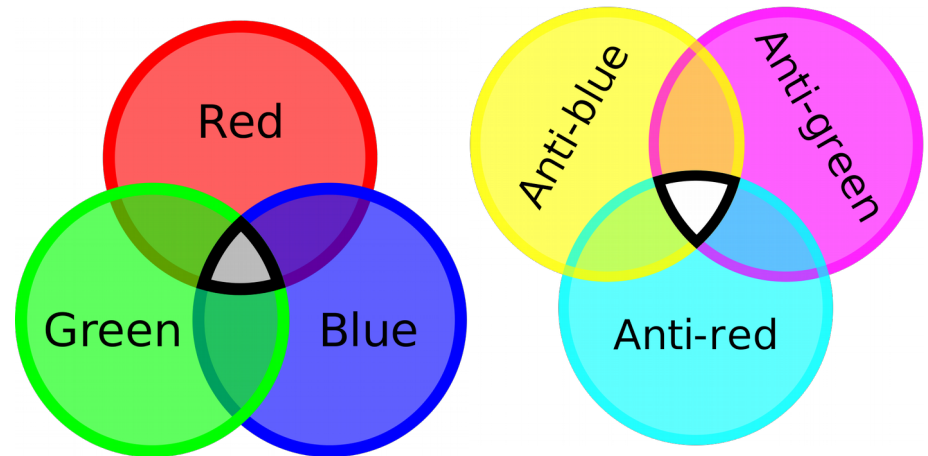
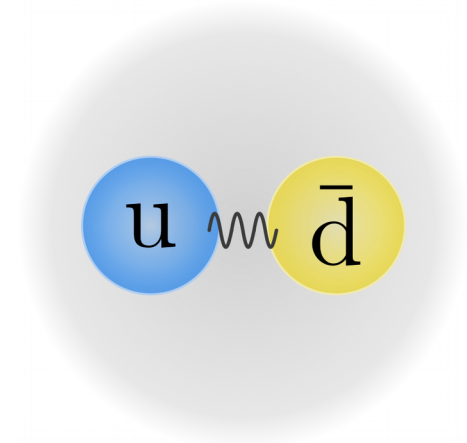
Particle interactions: strong force

- 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



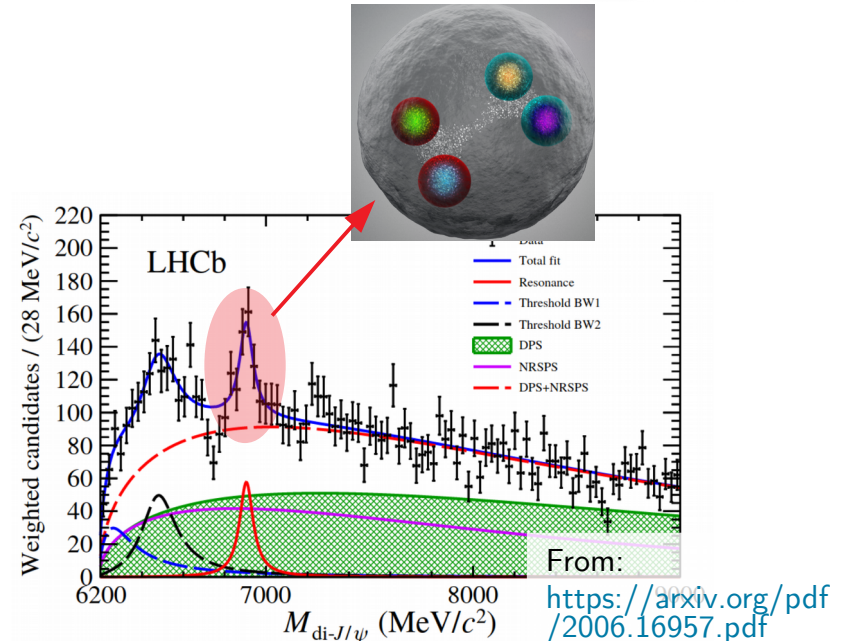
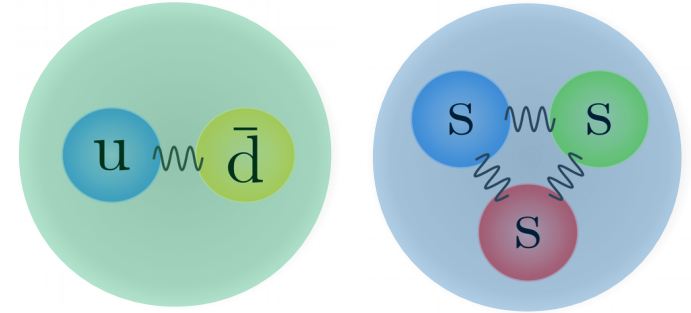
Strong force: colour charge

- 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.

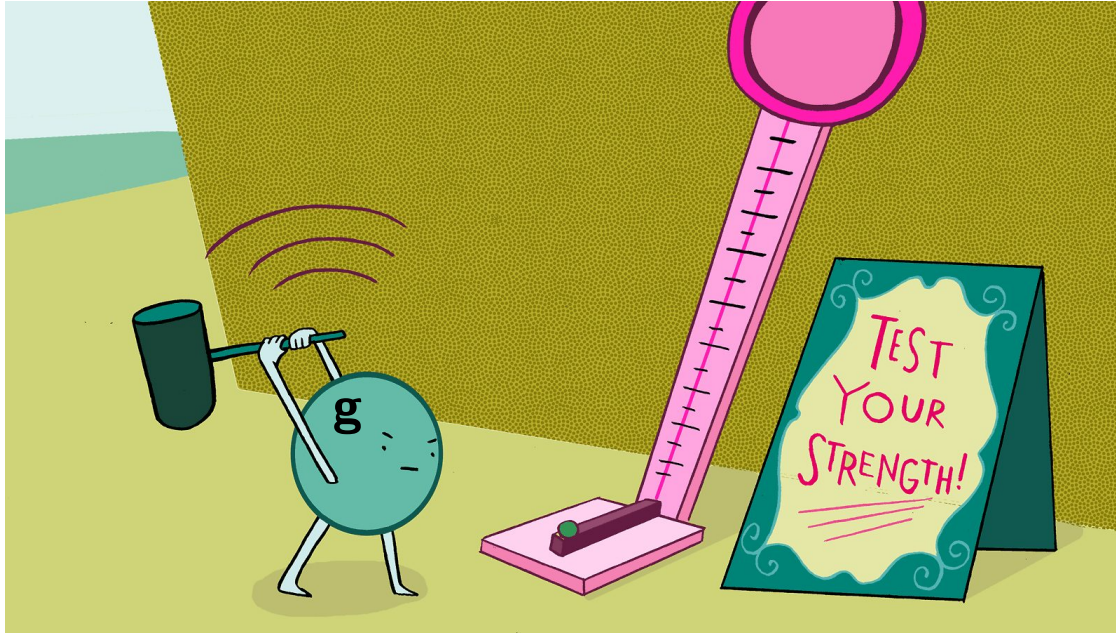


Mesons and baryons

- 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!).



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?

$\begin{matrix} 0 \\ 0 \\ 1 \end{matrix}$ g gluon	$\approx 124.97 \text{ GeV}/c^2$ $\begin{matrix} 0 \\ 0 \\ 0 \end{matrix}$ H higgs
$\begin{matrix} 0 \\ 0 \\ 1 \end{matrix}$ γ photon	SCALAR BOSONS
$\approx 91.19 \text{ GeV}/c^2$ $\begin{matrix} 0 \\ 1 \\ 1 \end{matrix}$ Z Z boson	
$\approx 80.39 \text{ GeV}/c^2$ $\begin{matrix} \pm 1 \\ 1 \end{matrix}$ W W boson	

**GAUGE BOSONS
VECTOR BOSONS**

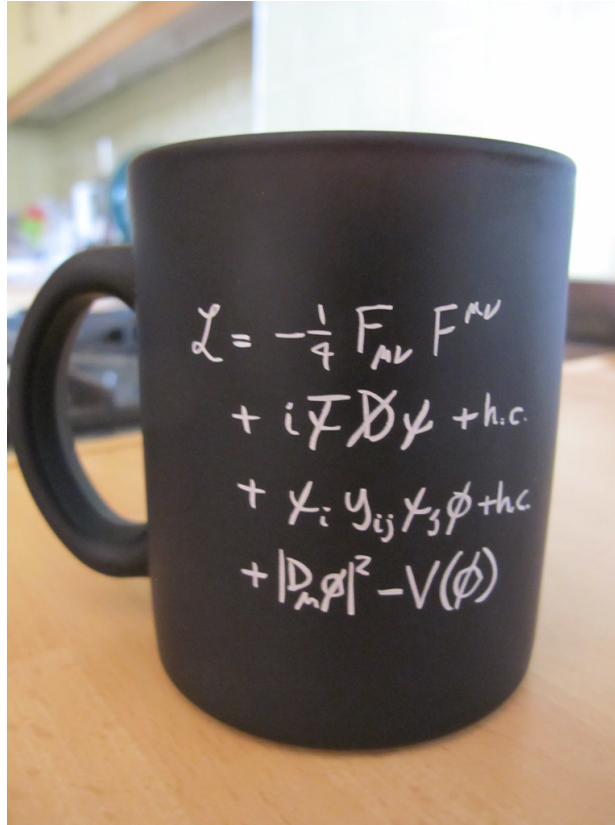
- We've talked about (most) bosons present in SM, but missed a really important one.
- Instead of mediating a force, the Higgs boson “grants mass” to all other particles.
- We'll hear more about it tomorrow, together with a recreation of the analysis that led to its discovery (and the 2013 Physics Nobel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



How do maths explain all* of our Universe?

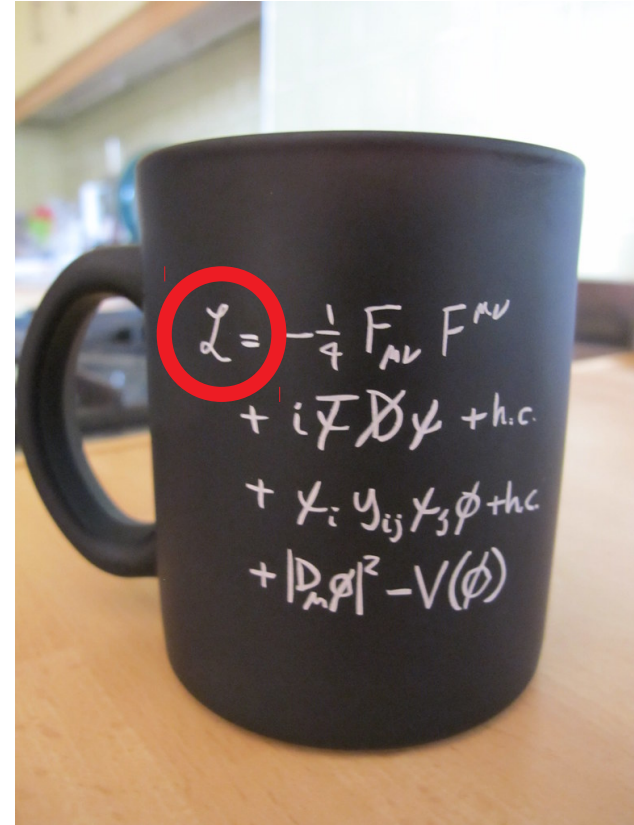
*most

The Universe in a mug



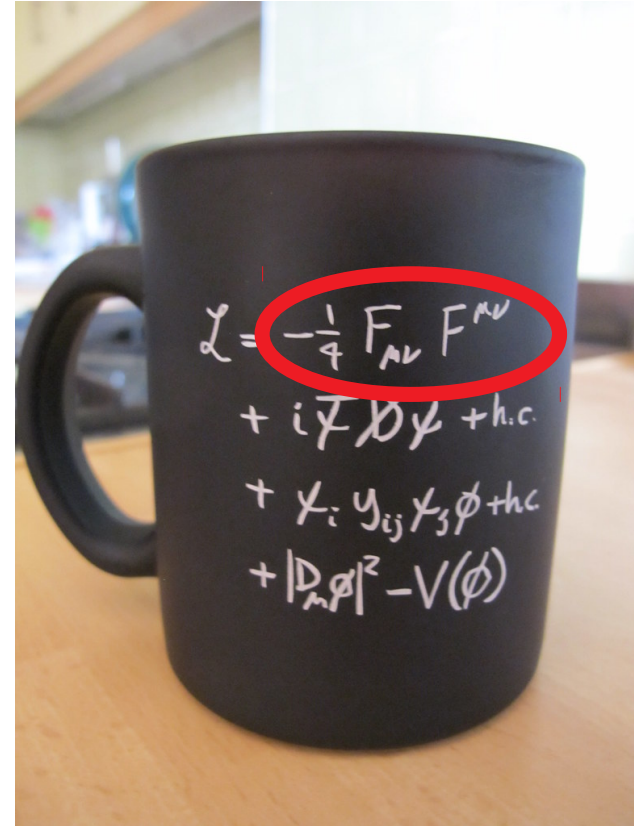
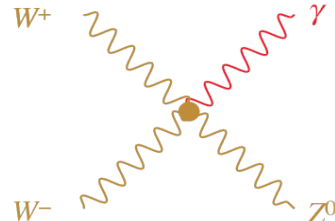
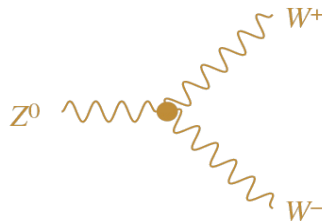
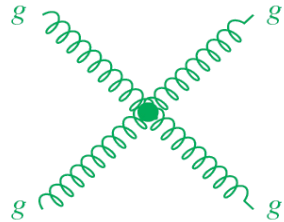
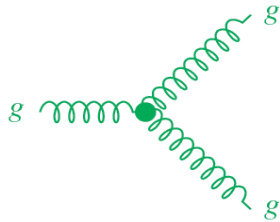
The Universe in a mug

- \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!



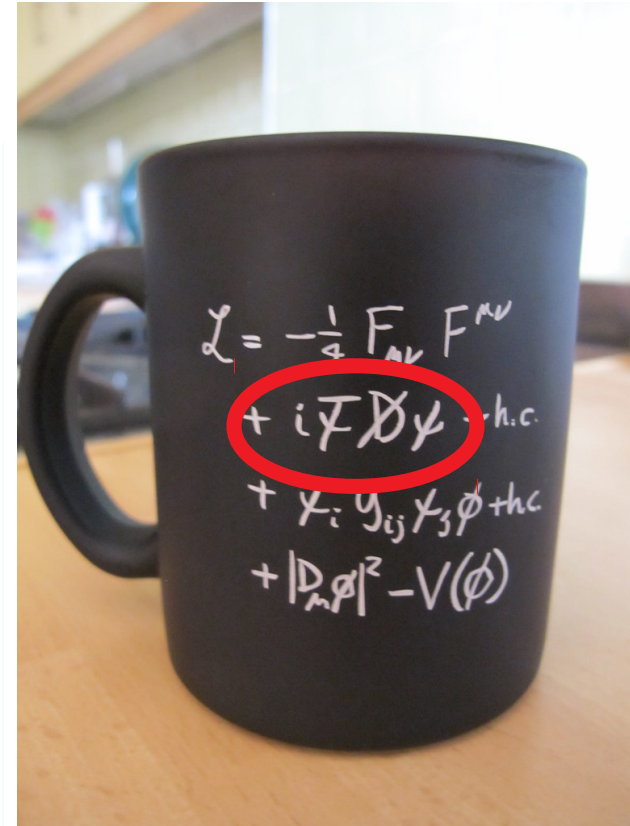
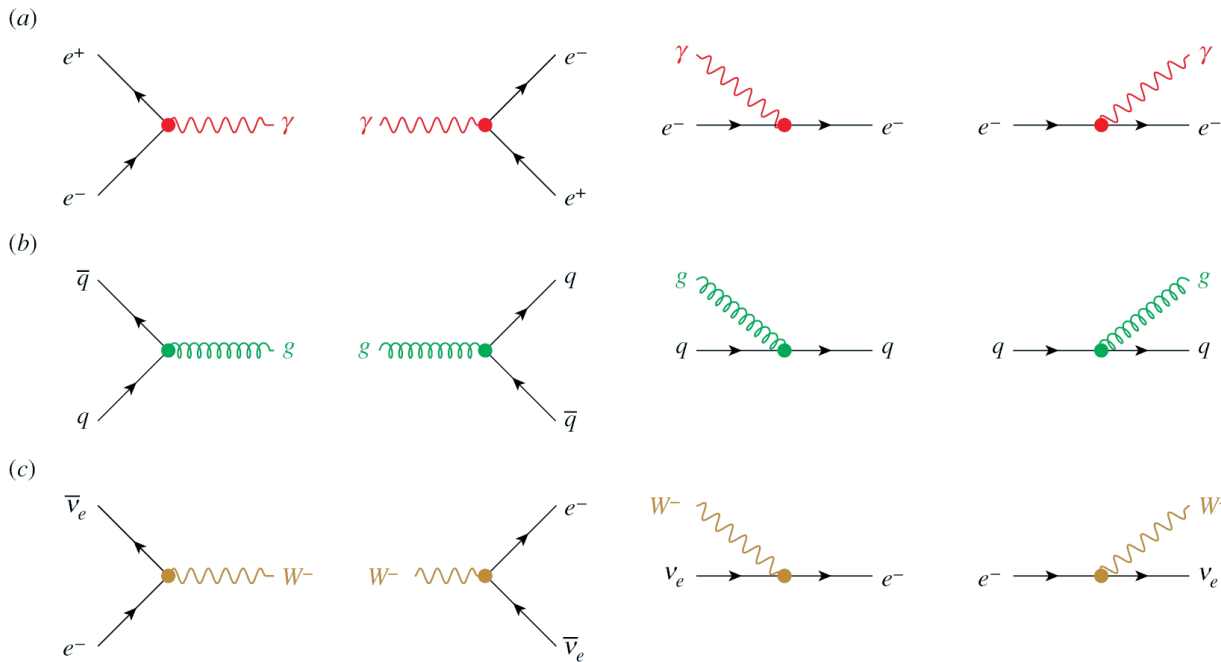
The Universe in a mug

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



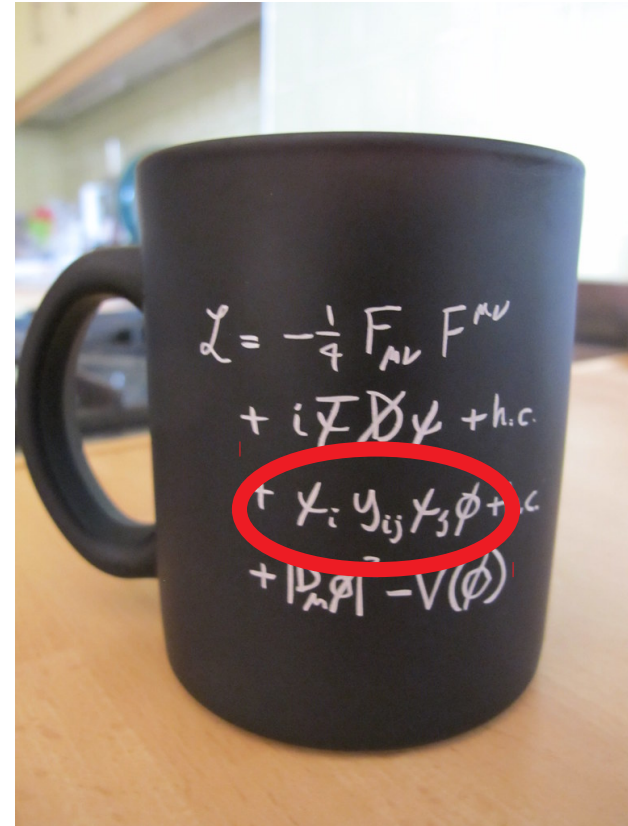
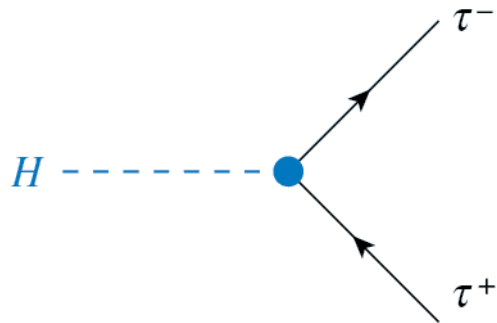
The Universe in a mug

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



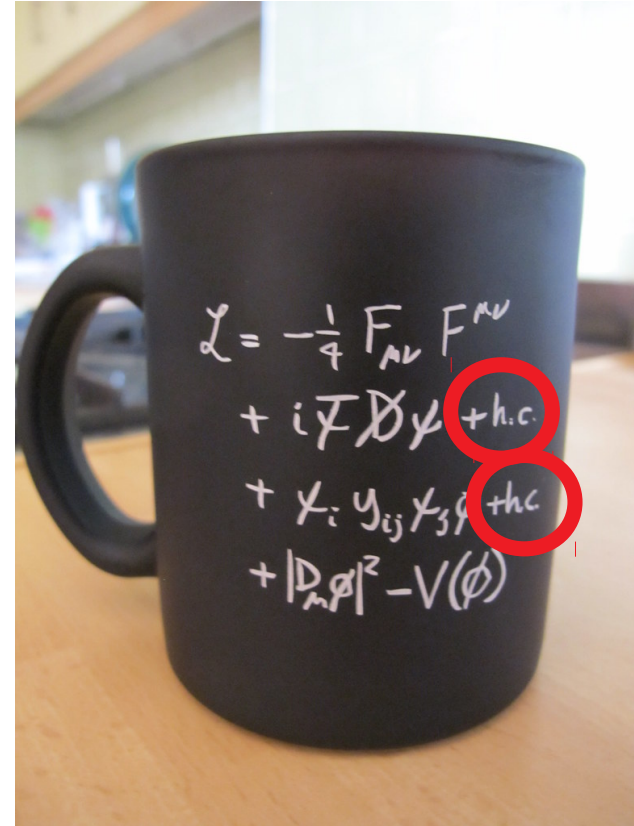
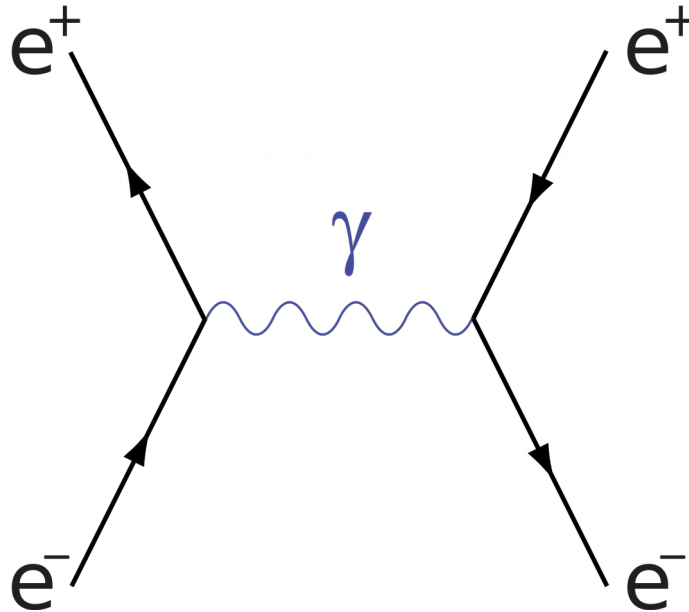
The Universe in a mug

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



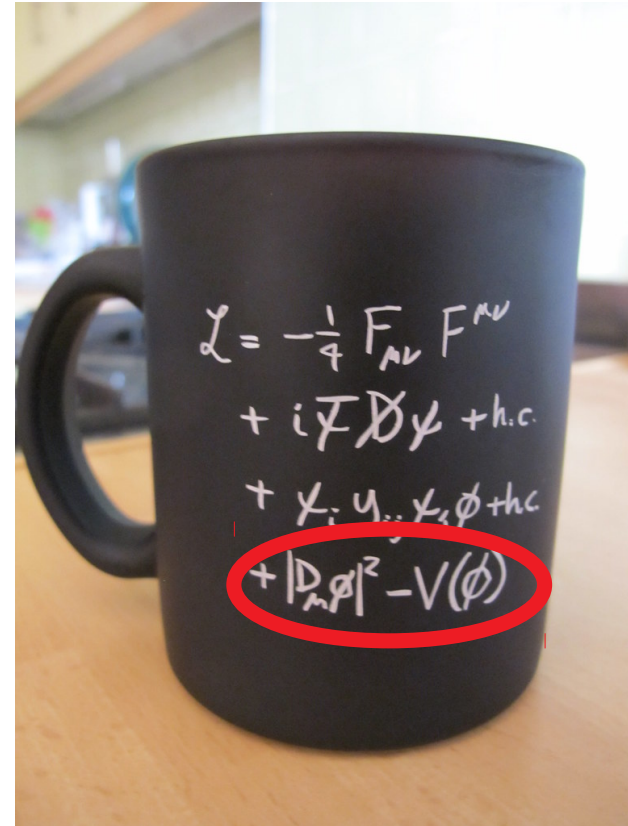
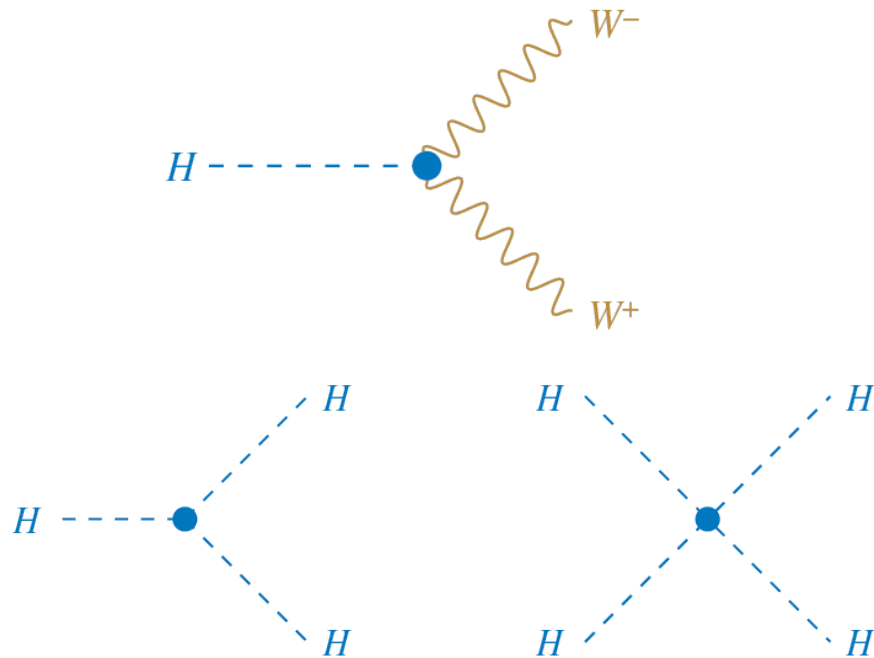
The Universe in a mug

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

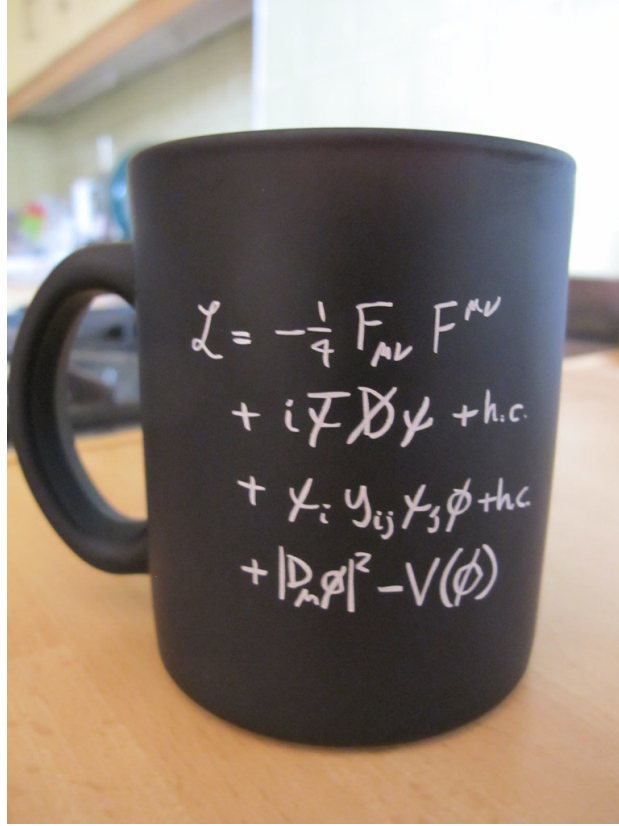


The Universe in a mug

- Describes the Higgs interactions with other bosons and itself.



The Universe in a mug*



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

$$\begin{aligned}
 \mathcal{L}_{SM} = & -\frac{1}{2}\partial_\nu g_\mu^\alpha \partial_\nu g_\mu^\alpha - g_s f^{abc} \partial_\mu g_\nu^a g_\mu^b g_\nu^c - \frac{1}{4} g_s^2 f^{abc} f^{ade} g_\mu^b g_\nu^c g_\mu^d g_\nu^e - (\partial_\nu W_\mu^+ \partial_\nu W_\mu^- - \\
 & M^2 W_\mu^+ W_\mu^- - \frac{1}{2}\partial_\nu Z_\mu^0 \partial_\nu Z_\mu^0 - \frac{1}{2c_w^2} M^2 Z_\mu^0 Z_\mu^0 - \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - igc_w (\partial_\nu Z_\mu^0 (W_\mu^+ W_\nu^- - \\
 & W_\nu^+ W_\mu^-) - Z_\nu^0 (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^+ \partial_\nu W_\nu^-) + Z_\mu^0 (W_\nu^+ \partial_\nu W_\mu^- - W_\nu^+ \partial_\nu W_\nu^-)) - \\
 & ig s_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_\nu^-) + A_\mu (W_\nu^+ \partial_\nu W_\mu^- - \\
 & W_\nu^+ \partial_\nu W_\nu^-)) - \frac{1}{2} g^2 W_\mu^+ W_\mu^- W_\nu^+ W_\nu^- + \frac{1}{2} g^2 W_\mu^+ W_\nu^- W_\mu^- W_\nu^+ + g^2 c_w^2 (Z_\mu^0 W_\mu^+ Z_\nu^0 W_\nu^- - \\
 & Z_\mu^0 Z_\nu^0 W_\mu^+ W_\nu^-) + g^2 s_w^2 (A_\mu W_\mu^+ A_\nu W_\nu^- - A_\mu A_\nu W_\mu^+ W_\nu^-) + g^2 s_w c_w (A_\mu Z_\nu^0 (W_\mu^+ W_\nu^- - \\
 & W_\nu^+ W_\mu^-) - 2A_\mu Z_\mu^0 W_\nu^+ W_\nu^-) - \frac{1}{2}\partial_\mu H \partial_\mu H - 2M^2 \alpha_h H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - \frac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \\
 & \beta_h \left(\frac{2M^2}{g^2} + \frac{2M}{g} H + \frac{1}{2}(H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^-) \right) + \frac{2M^4}{g^4} \alpha_h - \\
 & g \alpha_h M (H^3 + H \phi^0 \phi^0 + 2H \phi^+ \phi^-) - \\
 & \frac{1}{8} g^2 \alpha_h (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) - \\
 & g M W_\mu^+ W_\mu^- H - \frac{1}{2} g \frac{M}{c_w^2} Z_\mu^0 Z_\mu^0 H - \\
 & \frac{1}{2} ig (W_\mu^+ (\phi^0 \partial_\mu \phi^- - \phi^- \partial_\mu \phi^0) - W_\mu^- (\phi^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^0)) + \\
 & \frac{1}{2} g (W_\mu^+ (H \partial_\mu \phi^- - \phi^- \partial_\mu H) + W_\mu^- (H \partial_\mu \phi^+ - \phi^+ \partial_\mu H)) + \frac{1}{2} g \frac{1}{c_w} (Z_\mu^0 (H \partial_\mu \phi^0 - \phi^0 \partial_\mu H) + \\
 & M (\frac{1}{c_w} Z_\mu^0 \partial_\mu \phi^0 + W_\mu^+ \partial_\mu \phi^- + W_\mu^- \partial_\mu \phi^+) - ig \frac{s_w^2}{c_w} M Z_\mu^0 (W_\mu^+ \phi^- - W_\mu^- \phi^+) + ig s_w M A_\mu (W_\mu^+ \phi^- - \\
 & W_\mu^- \phi^+) - ig \frac{1-2c_w^2}{2c_w} Z_\mu^0 (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) + ig s_w A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \\
 & \frac{1}{4} g^2 W_\mu^+ W_\mu^- (H^2 + (\phi^0)^2 + 2\phi^+ \phi^-) - \frac{1}{8} g^2 \frac{1}{c_w^2} Z_\mu^0 Z_\mu^0 (H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2 \phi^+ \phi^-) - \\
 & \frac{1}{2} g^2 \frac{s_w^2}{c_w} Z_\mu^0 \phi^0 (W_\mu^+ \phi^- + W_\mu^- \phi^+) - \frac{1}{2} ig^2 \frac{s_w^2}{c_w} Z_\mu^0 H (W_\mu^+ \phi^- - W_\mu^- \phi^+) + \frac{1}{2} g^2 s_w A_\mu \phi^0 (W_\mu^+ \phi^- + \\
 & W_\mu^- \phi^+) + \frac{1}{2} ig^2 s_w A_\mu H (W_\mu^+ \phi^- - W_\mu^- \phi^+) - g^2 \frac{s_w}{c_w} (2c_w^2 - 1) Z_\mu^0 A_\mu \phi^+ \phi^- - \\
 & g^2 s_w^2 A_\mu A_\nu \phi^+ \phi^- + \frac{1}{2} ig s_w \lambda_{ij}^a (\bar{q}_i^a \gamma^\mu q_j^a) g_\mu^a - \bar{e}^\lambda (\gamma \partial + m_e^\lambda) e^\lambda - \bar{\nu}^\lambda (\gamma \partial + m_\nu^\lambda) \nu^\lambda - \bar{u}_j^\lambda (\gamma \partial + \\
 & m_u^\lambda) u_j^\lambda - \bar{d}_j^\lambda (\gamma \partial + m_d^\lambda) d_j^\lambda + ig s_w A_\mu (-\bar{e}^\lambda \gamma^\mu e^\lambda) + \frac{2}{3} (\bar{u}_j^\lambda \gamma^\mu u_j^\lambda) - \frac{1}{3} (\bar{d}_j^\lambda \gamma^\mu d_j^\lambda) + \\
 & \frac{ig}{4c_w} Z_\mu^0 \{ (\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{e}^\lambda \gamma^\mu (4s_w^2 - 1 - \gamma^5) e^\lambda) + (\bar{d}_j^\lambda \gamma^\mu (\frac{4}{3}s_w^2 - 1 - \gamma^5) d_j^\lambda) + \\
 & (\bar{u}_j^\lambda \gamma^\mu (1 - \frac{8}{3}s_w^2 + \gamma^5) u_j^\lambda) \} + \frac{ig}{2\sqrt{2}} W_\mu^+ ((\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) U^{lep}{}_{\lambda\kappa} e^\kappa) + (\bar{u}_j^\lambda \gamma^\mu (1 + \gamma^5) C_{\lambda\kappa} d_j^\kappa)) + \\
 & \frac{ig}{2\sqrt{2}} W_\mu^- ((\bar{e}^\kappa U^{lep}{}_{\kappa\lambda} \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{d}_j^\kappa C_{\kappa\lambda}^\dagger \gamma^\mu (1 + \gamma^5) u_j^\lambda)) + \\
 & \frac{ig}{2M\sqrt{2}} \phi^+ (-m_e^\kappa (\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa} (1 - \gamma^5) e^\kappa) + m_\nu^\lambda (\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa} (1 + \gamma^5) e^\kappa) + \\
 & \frac{ig}{2M\sqrt{2}} \phi^- (m_e^\lambda (\bar{e}^\lambda U^{lep}{}_{\lambda\kappa} (1 + \gamma^5) \nu^\kappa) - m_\nu^\kappa (\bar{e}^\lambda U^{lep}{}_{\lambda\kappa} (1 - \gamma^5) \nu^\kappa) - \frac{g}{2} \frac{m_\lambda^\lambda}{M} H (\bar{\nu}^\lambda \nu^\lambda) - \\
 & \frac{g}{2} \frac{m_\lambda^\lambda}{M} H (\bar{e}^\lambda e^\lambda) + \frac{ig}{2} \frac{m_\lambda^\lambda}{M} \phi^0 (\bar{\nu}^\lambda \gamma^5 \nu^\lambda) - \frac{ig}{2} \frac{m_\lambda^\lambda}{M} \phi^0 (\bar{e}^\lambda \gamma^5 e^\lambda) - \frac{1}{4} \bar{\nu}_\lambda M_{\lambda\kappa}^R (1 - \gamma_5) \hat{\nu}_\kappa - \\
 & \frac{1}{4} \bar{\nu}_\lambda M_{\lambda\kappa}^R (1 - \gamma_5) \hat{\nu}_\kappa + \frac{ig}{2M\sqrt{2}} \phi^+ (-m_d^\kappa (\bar{u}_j^\lambda C_{\lambda\kappa} (1 - \gamma^5) d_j^\kappa) + m_u^\lambda (\bar{u}_j^\lambda C_{\lambda\kappa} (1 + \gamma^5) d_j^\kappa) + \\
 & \frac{ig}{2M\sqrt{2}} \phi^- (m_d^\lambda (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 + \gamma^5) u_j^\kappa) - m_u^\kappa (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 - \gamma^5) u_j^\kappa) - \frac{g}{2} \frac{m_\lambda^\lambda}{M} H (\bar{u}_j^\lambda u_j^\lambda) - \\
 & \frac{g}{2} \frac{m_\lambda^\lambda}{M} H (\bar{d}_j^\lambda d_j^\lambda) + \frac{ig}{2} \frac{m_\lambda^\lambda}{M} \phi^0 (\bar{u}_j^\lambda \gamma^5 u_j^\lambda) - \frac{ig}{2} \frac{m_\lambda^\lambda}{M} \phi^0 (\bar{d}_j^\lambda \gamma^5 d_j^\lambda) + \bar{G}^a \partial^2 G^a + g_s f^{abc} \partial_\mu \bar{G}^a G^b g_\mu^c + \\
 & \bar{X} + (\partial^2 - M^2) X^+ + \bar{X} - (\partial^2 - M^2) X^- + \bar{X}^0 (\partial^2 - \frac{M^2}{c_w^2}) X^0 + \bar{Y} \partial^2 Y + ig c_w W_\mu^+ (\partial_\mu \bar{X}^0 X^- - \\
 & \partial_\mu \bar{X}^+ X^0) + ig s_w W_\mu^+ (\partial_\mu \bar{Y} X^- - \partial_\mu \bar{X}^+ Y) + ig c_w W_\mu^- (\partial_\mu \bar{X}^- X^0 - \\
 & \partial_\mu \bar{X}^0 X^+) + ig s_w W_\mu^- (\partial_\mu \bar{X}^- Y - \partial_\mu \bar{Y} X^+) + ig c_w Z_\mu^0 (\partial_\mu \bar{X}^+ X^+ - \\
 & \partial_\mu \bar{X}^- X^-) + ig s_w A_\mu (\partial_\mu \bar{X}^+ X^+ - \\
 & \partial_\mu \bar{X}^- X^-) - \frac{1}{2} g M (\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c_w^2} \bar{X}^0 X^0 H) + \frac{1-2c_w^2}{2c_w^2} ig M (\bar{X}^+ X^0 \phi^+ - \bar{X}^- X^0 \phi^-) + \\
 & \frac{1}{2c_w} ig M (\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-) + ig M s_w (\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-) + \\
 & \frac{1}{2} ig M (\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0) .
 \end{aligned}$$

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>