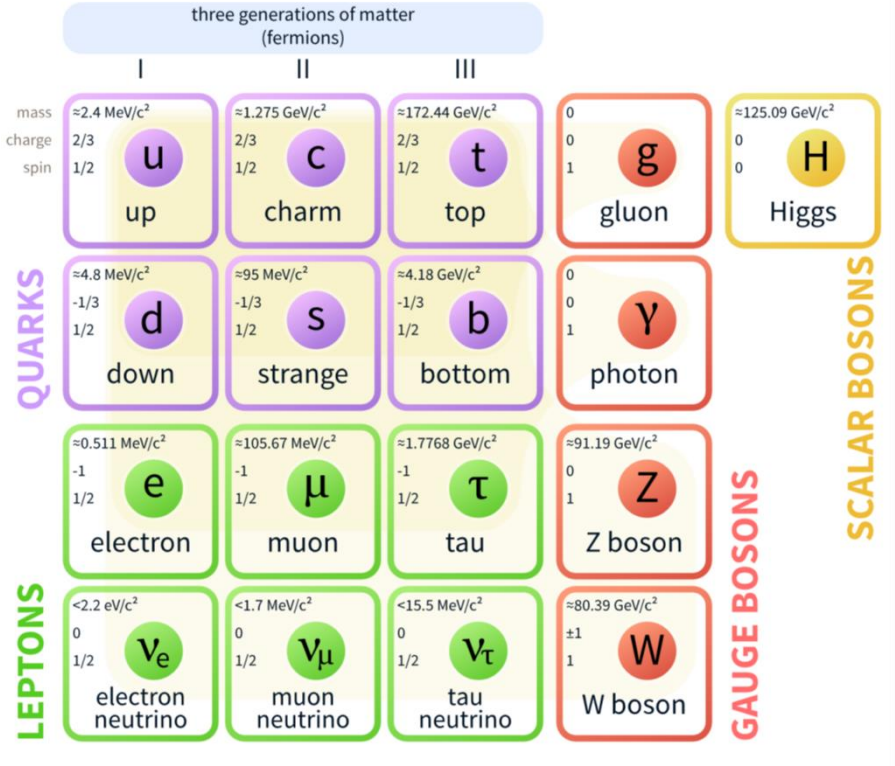
Particles and fields – The standard model

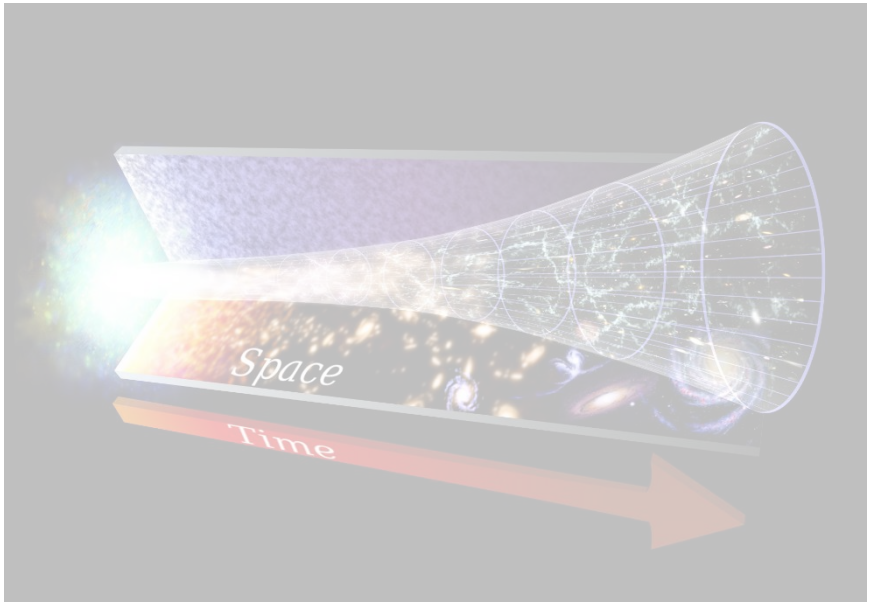
Edvard Mörtsell

Cosmology and Astroparticle Physics FK7050

Standard models of Particle physics and Cosmology

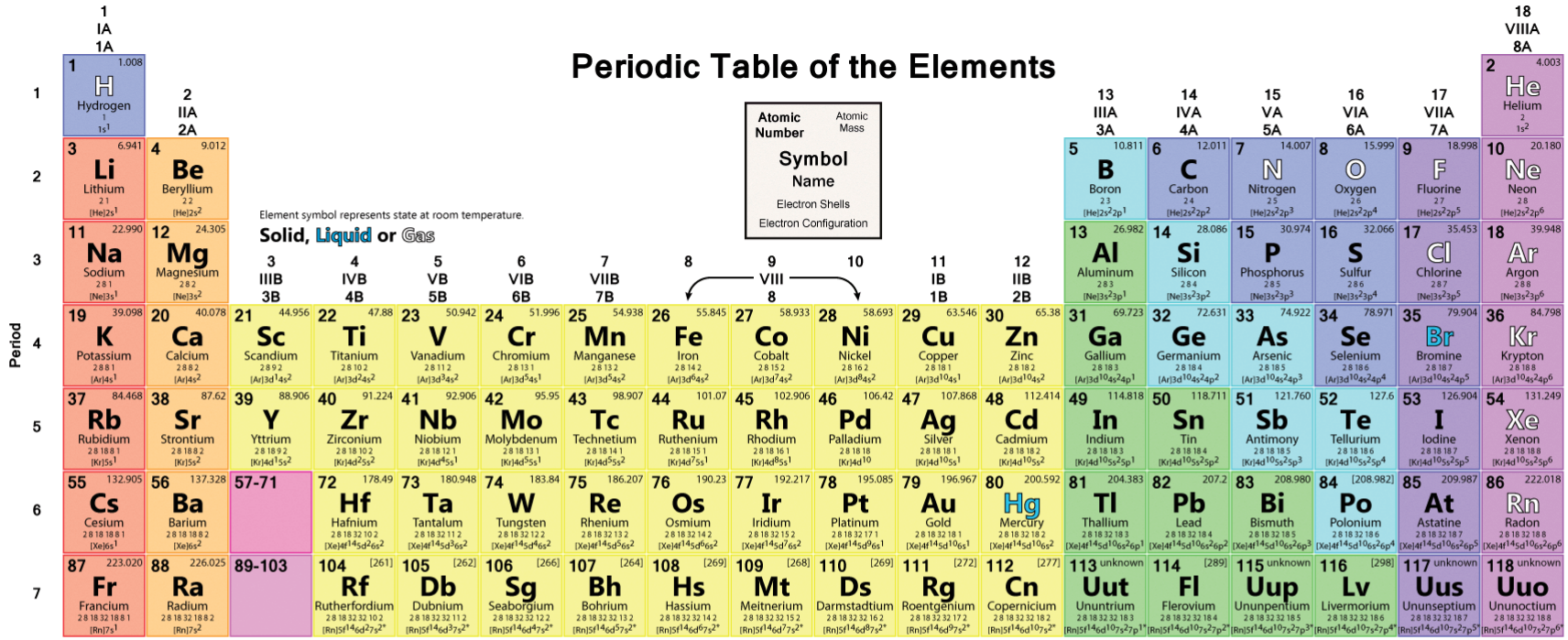


Particle Physics



Cosmology

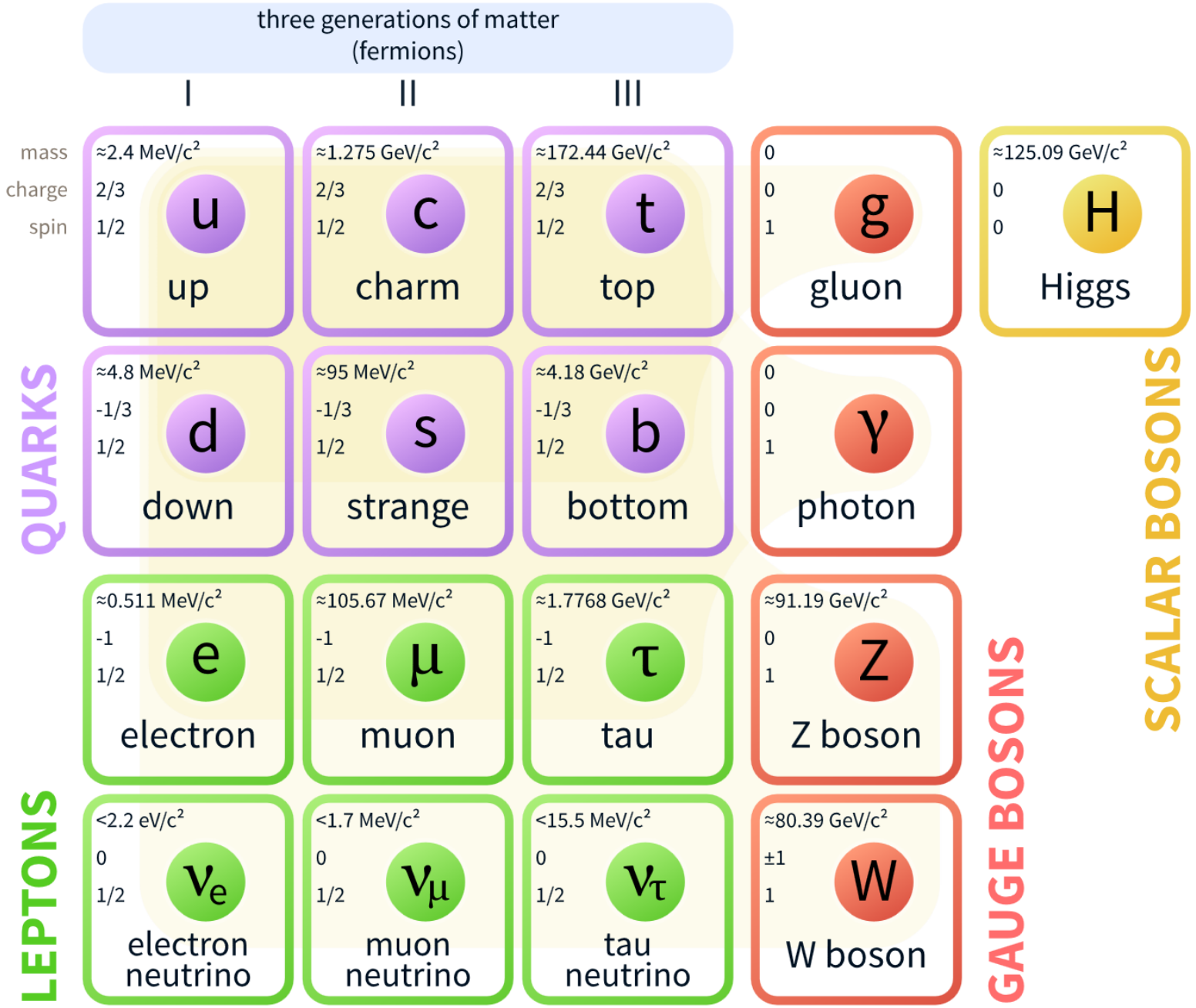
Periodic Table of the Elements



Some Particles and Their Properties

Category	Particle Name	Symbol	Anti-particle	Mass (MeV/c^2)	B	L_e	L_μ	L_τ	S	Lifetime(s)	Principal Decay Modes[a]
Leptons	Electron	e^-	e^+	0.511	0	+1	0	0	0	Stable	
	Electron–neutrino	ν_e	$\overline{\nu}_e$	$< 7eV/c^2$	0	+1	0	0	0	Stable	
	Muon	μ^-	μ^+	105.7	0	0	+1	0	0	2.20×10^{-6}	$e^- \overline{\nu}_e \nu_\mu$
	Muon–neutrino	ν_μ	$\overline{\nu}_\mu$	< 0.3	0	0	+1	0	0	Stable	
	Tau	τ^-	τ^+	1 784	0	0	0	+1	0	$< 4 \times 10^{-13}$	$\mu^- \overline{\nu}_\mu \nu_\tau$, $e^- \overline{\nu}_e \nu_\tau$
	Tau–neutrino	ν_τ	$\overline{\nu}_\tau$	< 30	0	0	0	+1	0	Stable	
Hadrons											
Mesons	Pion	π^+	π^-	139.6	0	0	0	0	0	2.60×10^{-8}	$\mu^+ \nu_\mu$
		π^0	Self	135.0	0	0	0	0	0	0.83×10^{-16}	2γ
	Kaon	K^+	K^-	493.7	0	0	0	0	+1	1.24×10^{-8}	$\mu^+ \nu_\mu$, $\pi^+ \pi^0$
		K^0_S	K^0_S	497.7	0	0	0	0	+1	0.89×10^{-10}	$\pi^+ \pi^-$, $2\pi^0$
		K^0_L	K^0_L	497.7	0	0	0	0	+1	5.2×10^{-8}	$\pi^\pm e^\mp \overline{\nu}_e$, $3\pi^0$ $\pi^\pm \mu^\mp \overline{\nu}_\mu$
	Eta	η	Self	548.8	0	0	0	0	0	$< 10^{-18}$	2γ, 3π
		η'	Self	958	0	0	0	0	0	2.2×10^{-21}	$\eta \pi^+ \pi^-$
Baryons	Proton	p	$\overline{p}$	938.3	+1	0	0	0	0	Stable	
	Neutron	n	$\overline{n}$	939.6	+1	0	0	0	0	920	$p e^- \overline{\nu}_e$
	Lambda	Λ^0	$\overline{\Lambda}^0$	1 115.6	+1	0	0	0	−1	2.6×10^{-10}	$p\pi^-$, $n\pi^0$
	Sigma	Σ^+	$\overline{\Sigma}^-$	1 189.4	+1	0	0	0	−1	0.80×10^{-10}	$p\pi^0$, $n\pi^+$
		Σ^0	$\overline{\Sigma}^0$	1 192.5	+1	0	0	0	−1	6×10^{-20}	$\Lambda^0 \gamma$
		Σ^-	$\overline{\Sigma}^+$	1 197.3	+1	0	0	0	−1	1.5×10^{-10}	$n\pi^-$
	Xi	Ξ^0	$\overline{\Xi}^0$	1 315	+1	0	0	0	−2	2.9×10^{-10}	$\Lambda^0 \pi^0$
		Ξ^-	Ξ^+	1 321	+1	0	0	0	−2	1.64×10^{-10}	$\Lambda^0 \pi^-$
	Omega	Ω^-	Ω^+	1 672	+1	0	0	0	−3	0.82×10^{-10}	$\Xi^0 \pi^0$, $\Lambda^0 K^-$

[a]Notations in this column, such as $p\pi^-$, $n\pi^0$, mean two possible decay modes. In this case the two possible decays are $\Lambda^0 \rightarrow p + \pi^-$ and $\Lambda^0 \rightarrow n + \pi^0$.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I
II
III
mass
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1/2
u
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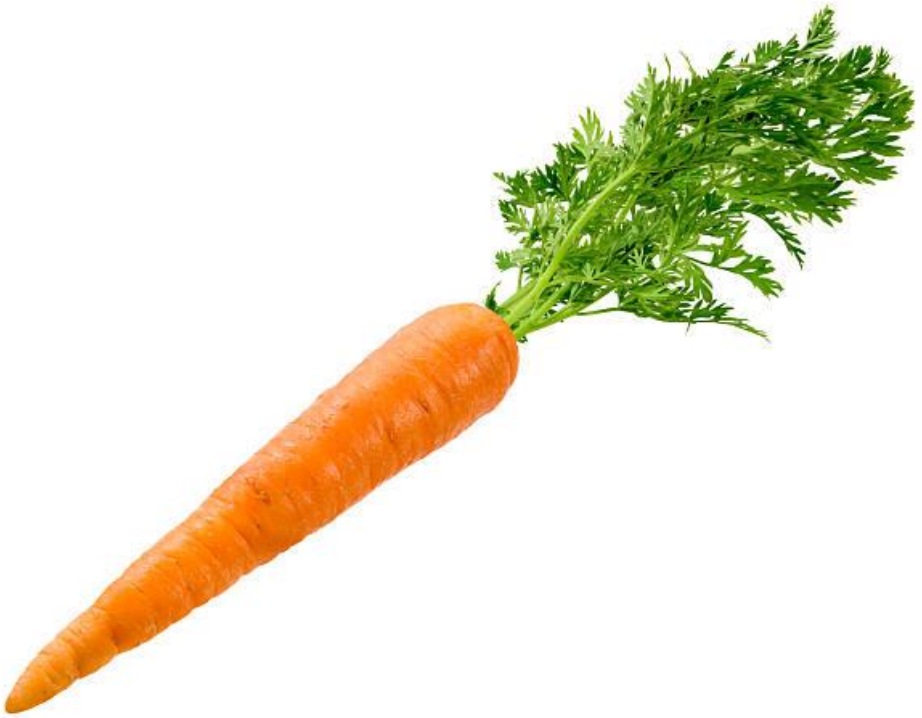
How many atoms are there in a carrot?

- ❑ 10^6
- ❑ 10^{16}
- ❑ 10^{25}
- ❑ 10^{50}



Particles and fields - Quarks

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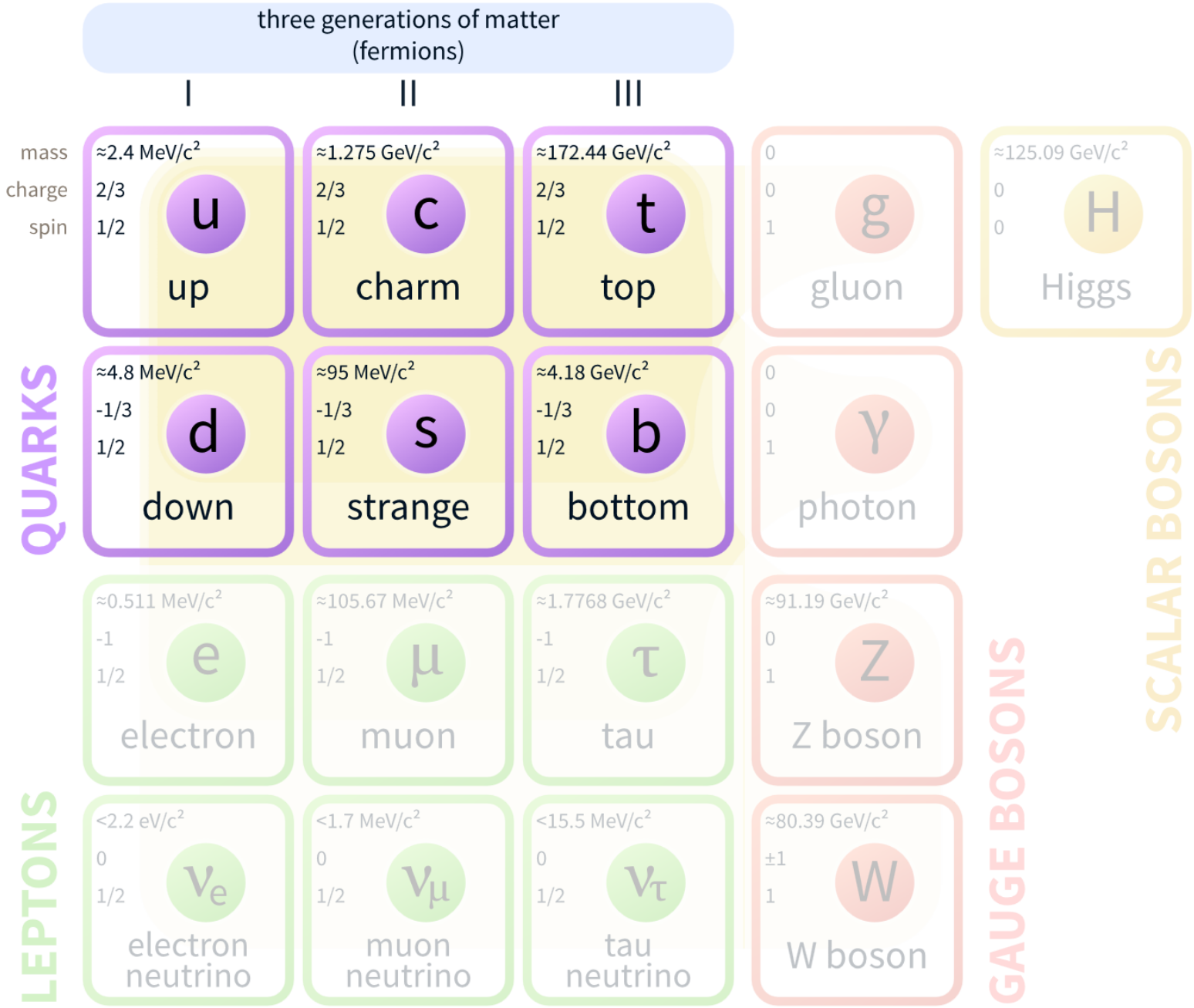
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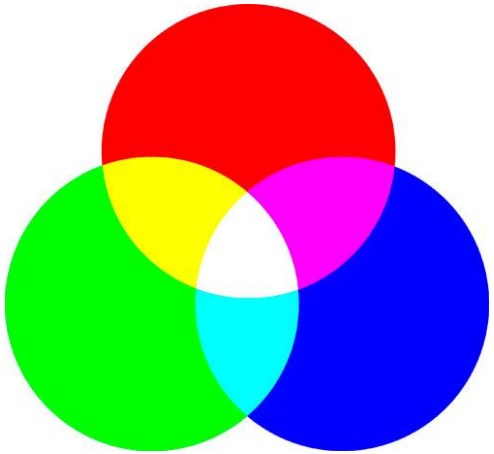
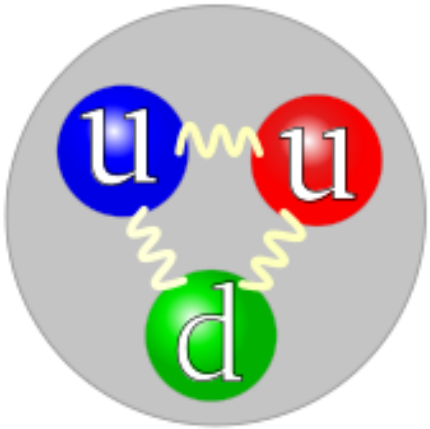
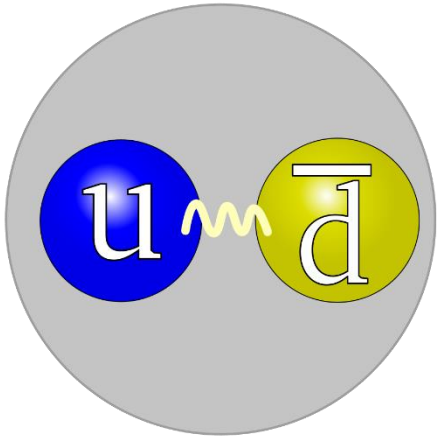
Quarks and colour

- To each quark (u) comes an anti-quark ($\bar{u}$)
- Each (anti-)quark comes in three (anti-)colours: red, blue and green
- Quarks combine to give colour-less particles: *hadrons*
- Red + blue + green (baryon)
- Colour + anti-colour (meson)

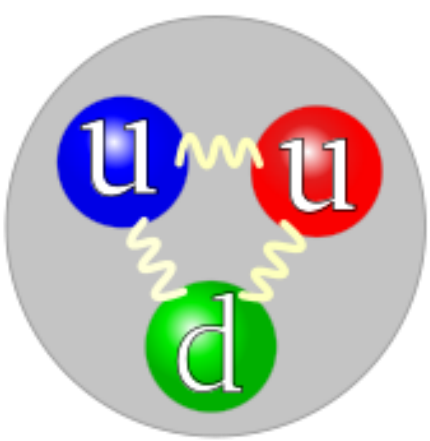


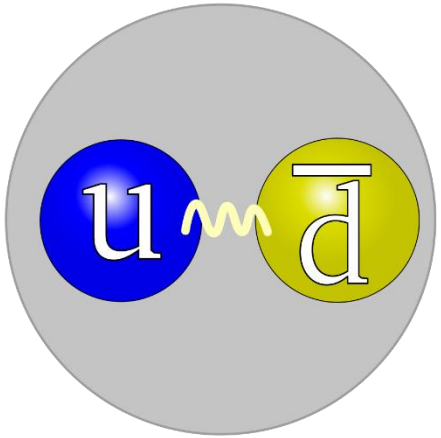




What are the charges of the particles below?

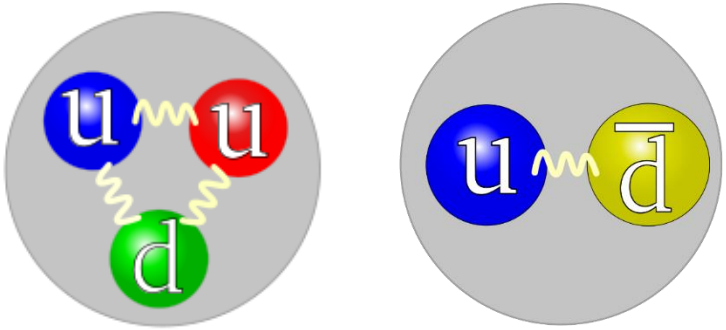
- ❑ +1 and +1
- ❑ -1 and +1
- ❑ +1 and -1
- ❑ -1 and -1





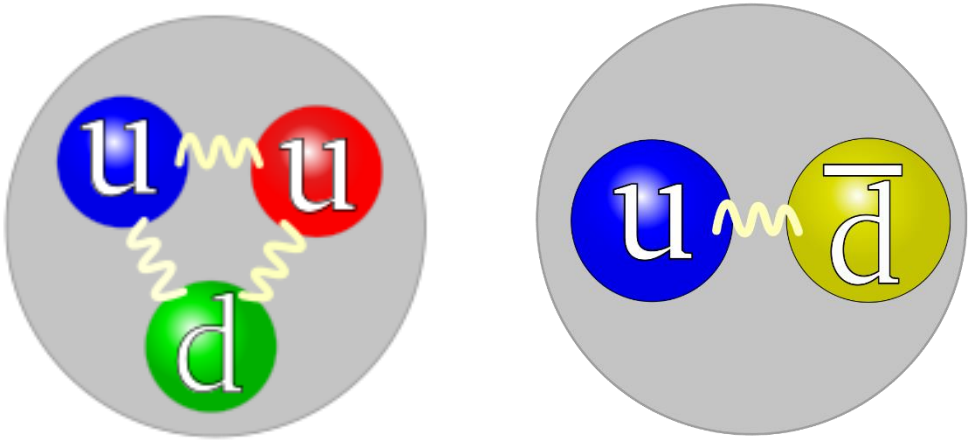
Which are the particles below?

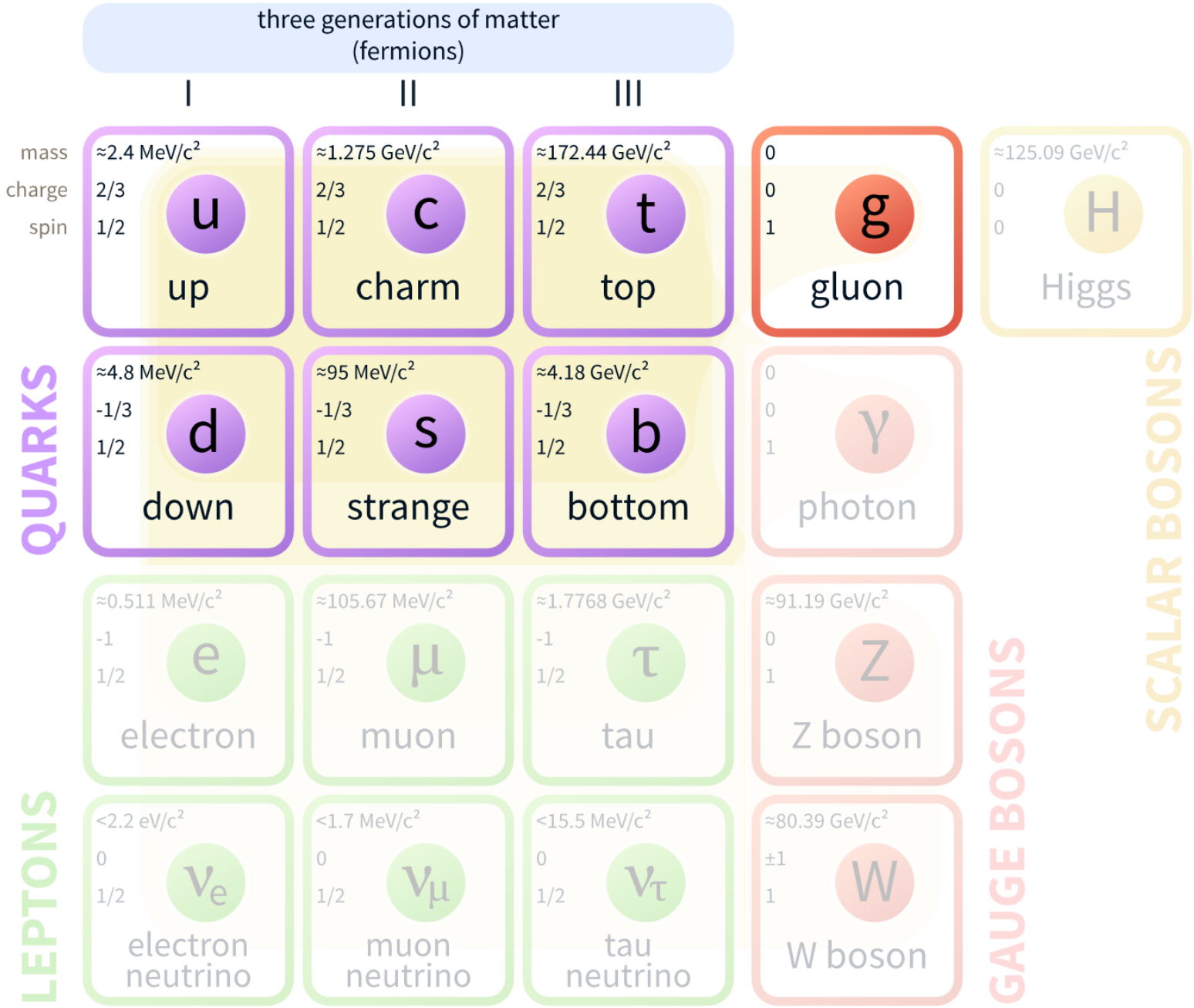
- ❑ A neutron and a proton
- ❑ A lepton and a gluino
- ❑ A proton and a pion
- ❑ A kaon and a D meson



The strong force

- Force mediators are bosons
- Baryons and mesons are kept together by the strong force
- The strong force is mediated by gluons

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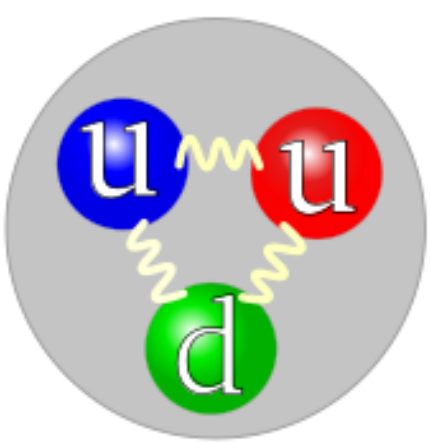
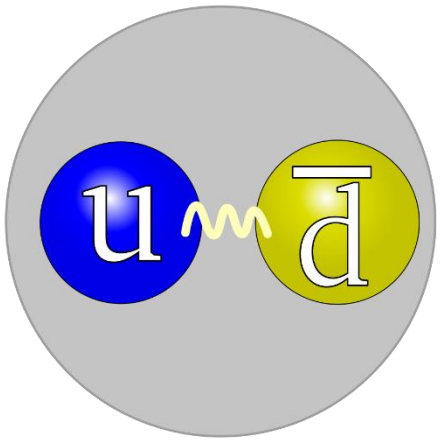
GAUGE BOSONS

How could you make a neutron out of u and d-quarks?

- ❑ u, u and d
- ❑ u, d and d
- ❑ $u, \bar{u}$ and d
- ❑ $u, \bar{d}$ and d





Particles and fields - Leptons

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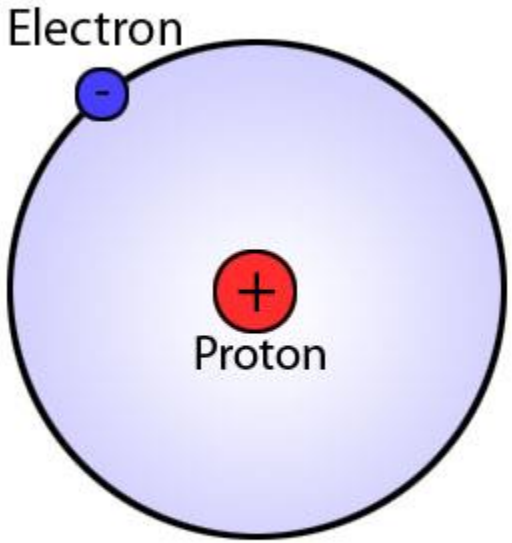
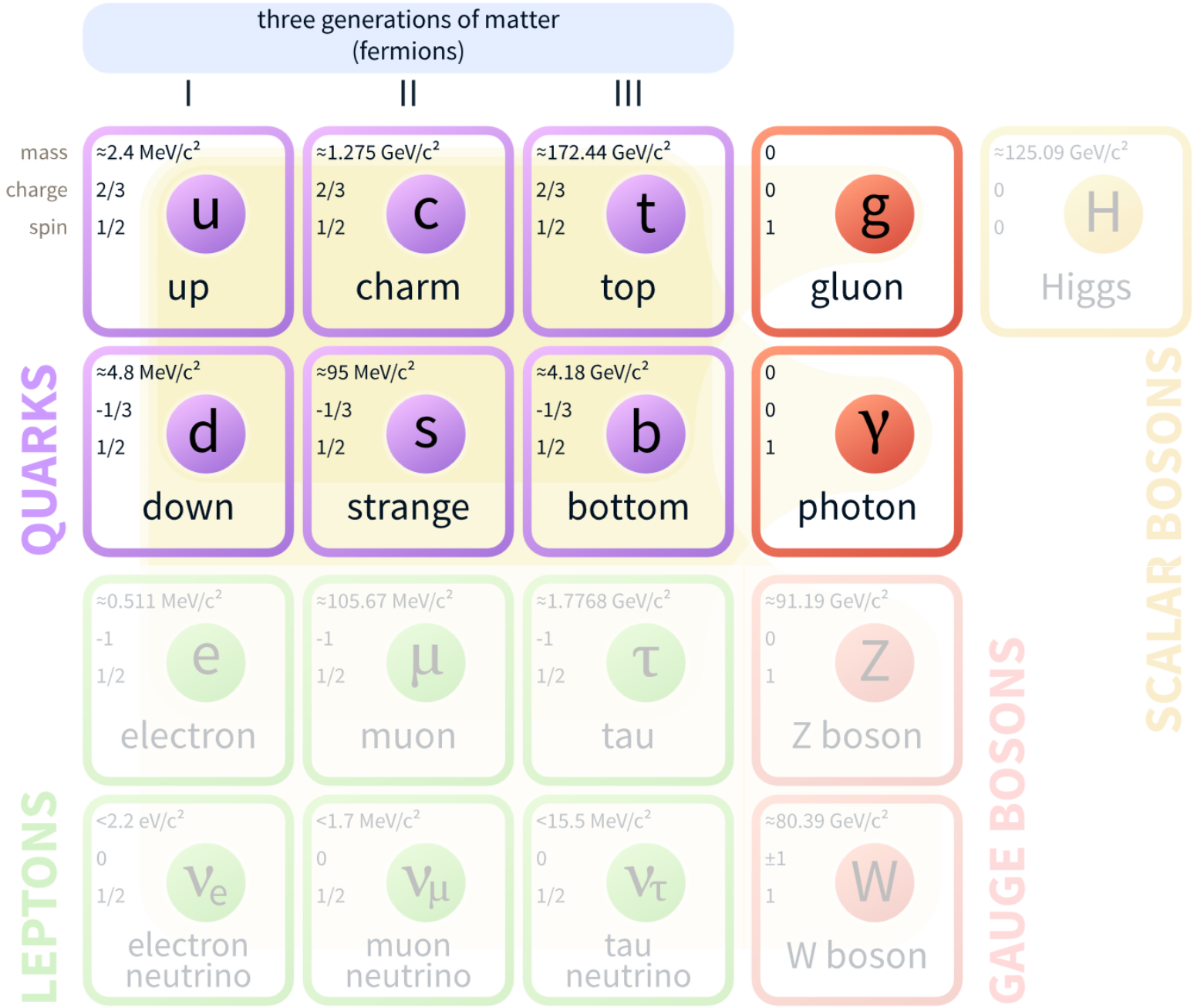
The electromagnetic force

- Atoms are held together by the electromagnetic (EM) force
- The electromagnetic force is mediated by photons

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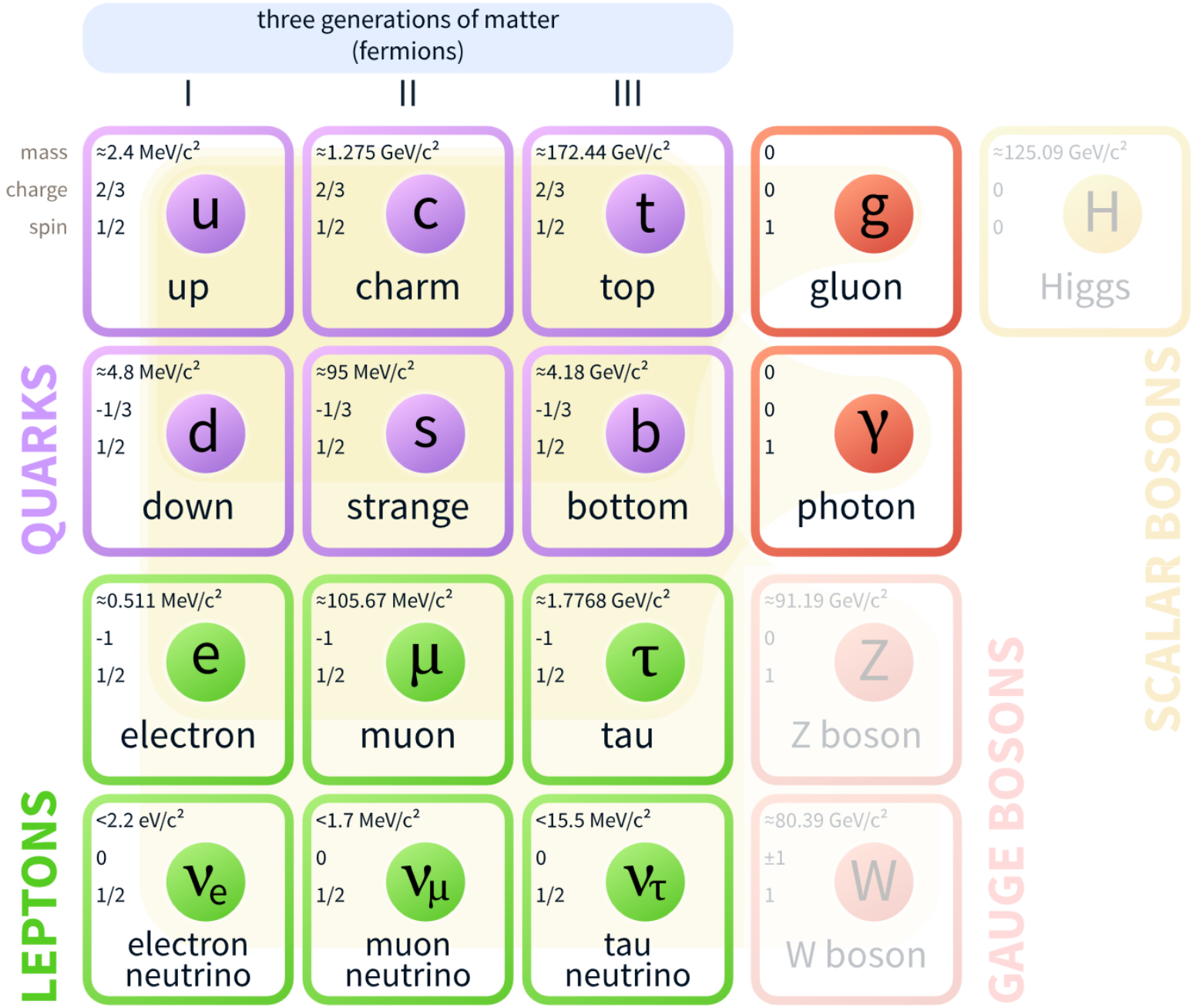
GAUGE BOSONS

Leptons

To each family, there are also two leptons (and anti-leptons):

- One with zero charge
- One with charge $-e = -1$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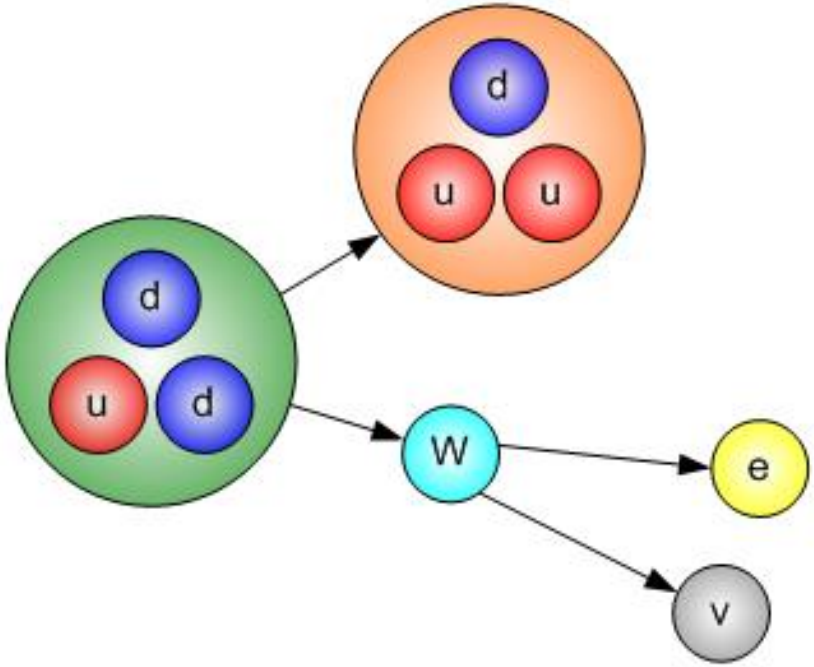
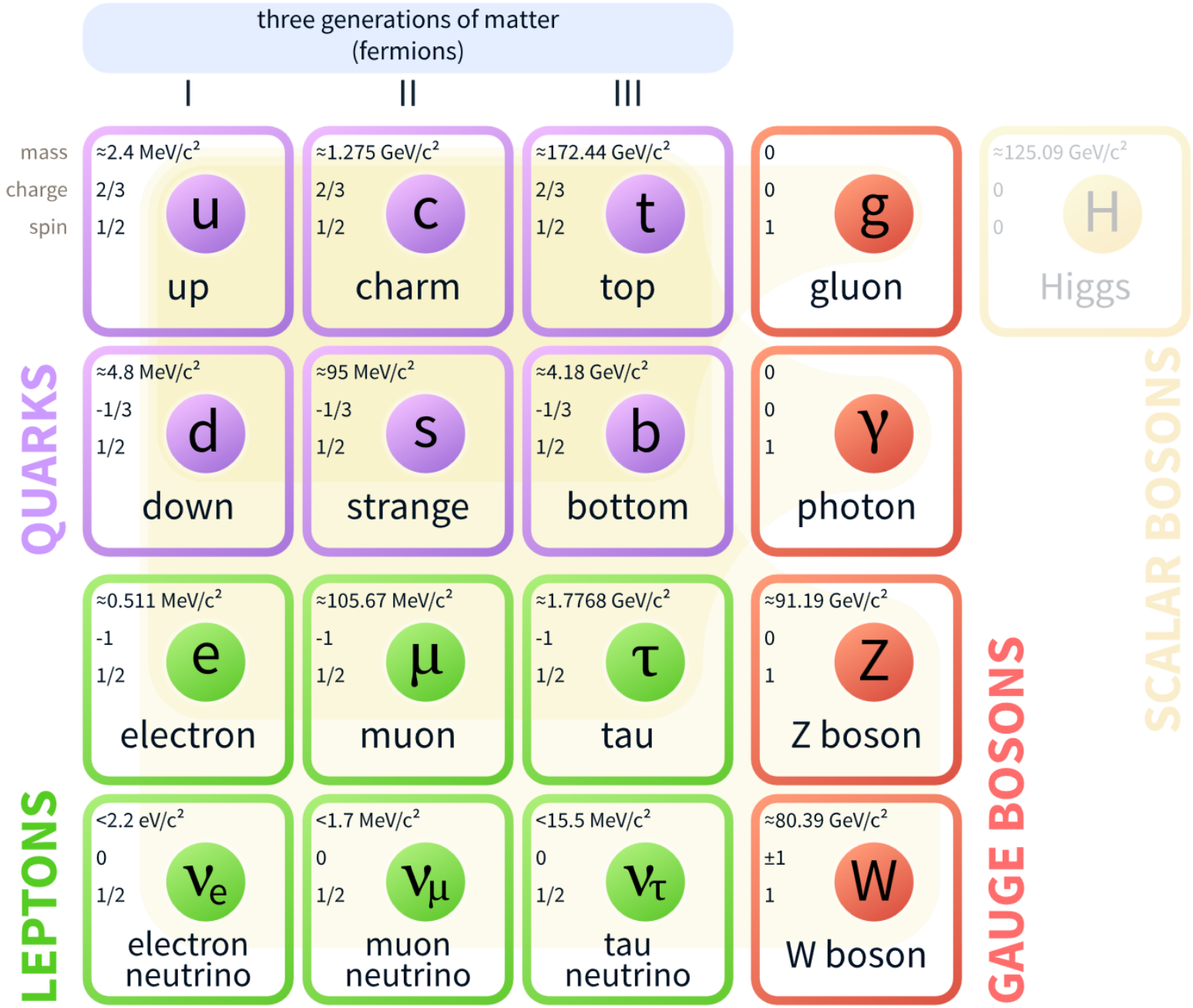
W boson
GAUGE BOSONS

Neutrinos and the weak force

- Neutrinos do not have strong or electromagnetic interactions
- They interact with the weak force
- The weak force is mediated by Z and W bosons

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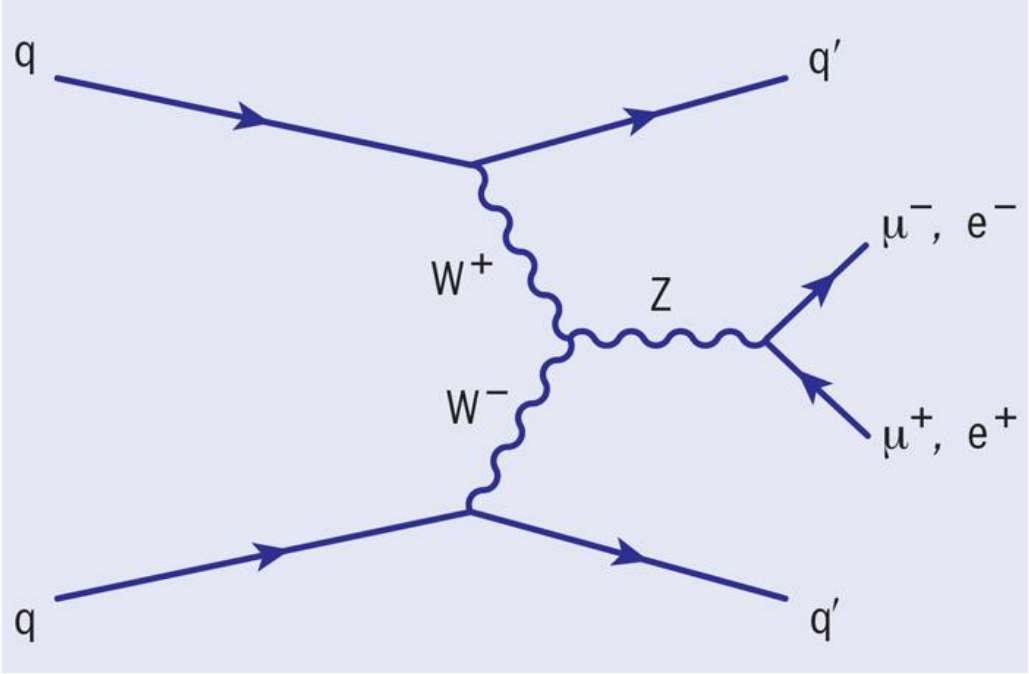
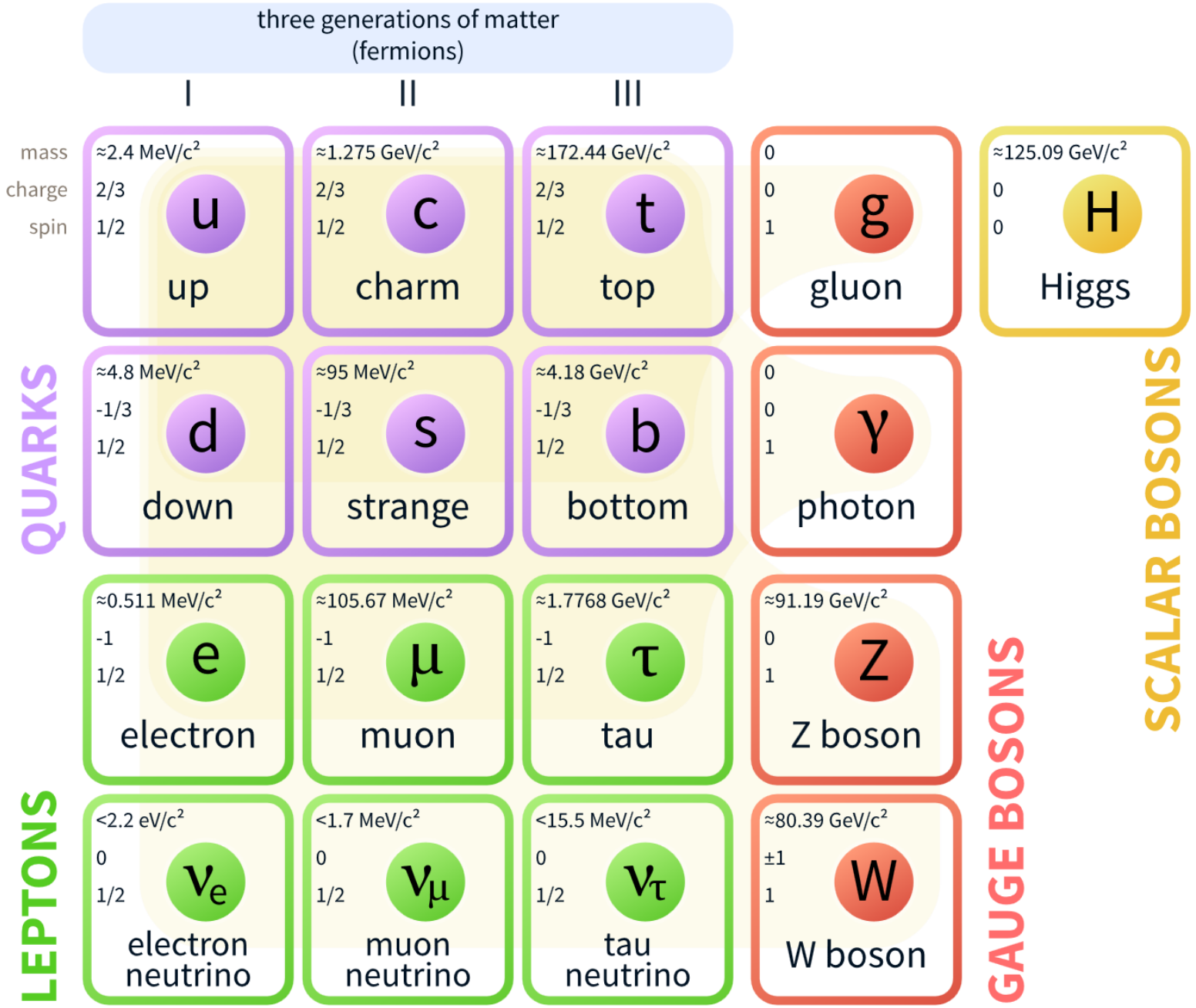
Which is heaviest, the Z or W boson?

- ❑ The Z boson
- ❑ The W boson
- ❑ They have the same mass



Higgs (Englert) boson

- Physics describe particles and their interactions through forces (carried by other particles)
- This can be described by fields and their interactions
- Excitation of the scalar Higgs field: Spin 0
- Gives mass to standard model particles
- Predicted in 1964, found in 2012
- Mass 125 GeV (a proton is 1 GeV)
- Weak and gravitational interactions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νe
electron neutrino
<1.7 MeV/c²
0
1/2
νμ
muon neutrino
<15.5 MeV/c²
0
1/2
ντ
tau neutrino
≈80.39 GeV/c²
±1
1
W
W boson

Particles and fields – Quantum numbers

Edvard Mörtsell

Cosmology and Astroparticle Physics FK7050

Quantum numbers

Conserved quantities (momentum, angular momentum) are related to symmetries (translations, rotations)

- Electric charge
- Spin
- Baryon number (?)
- Lepton number?

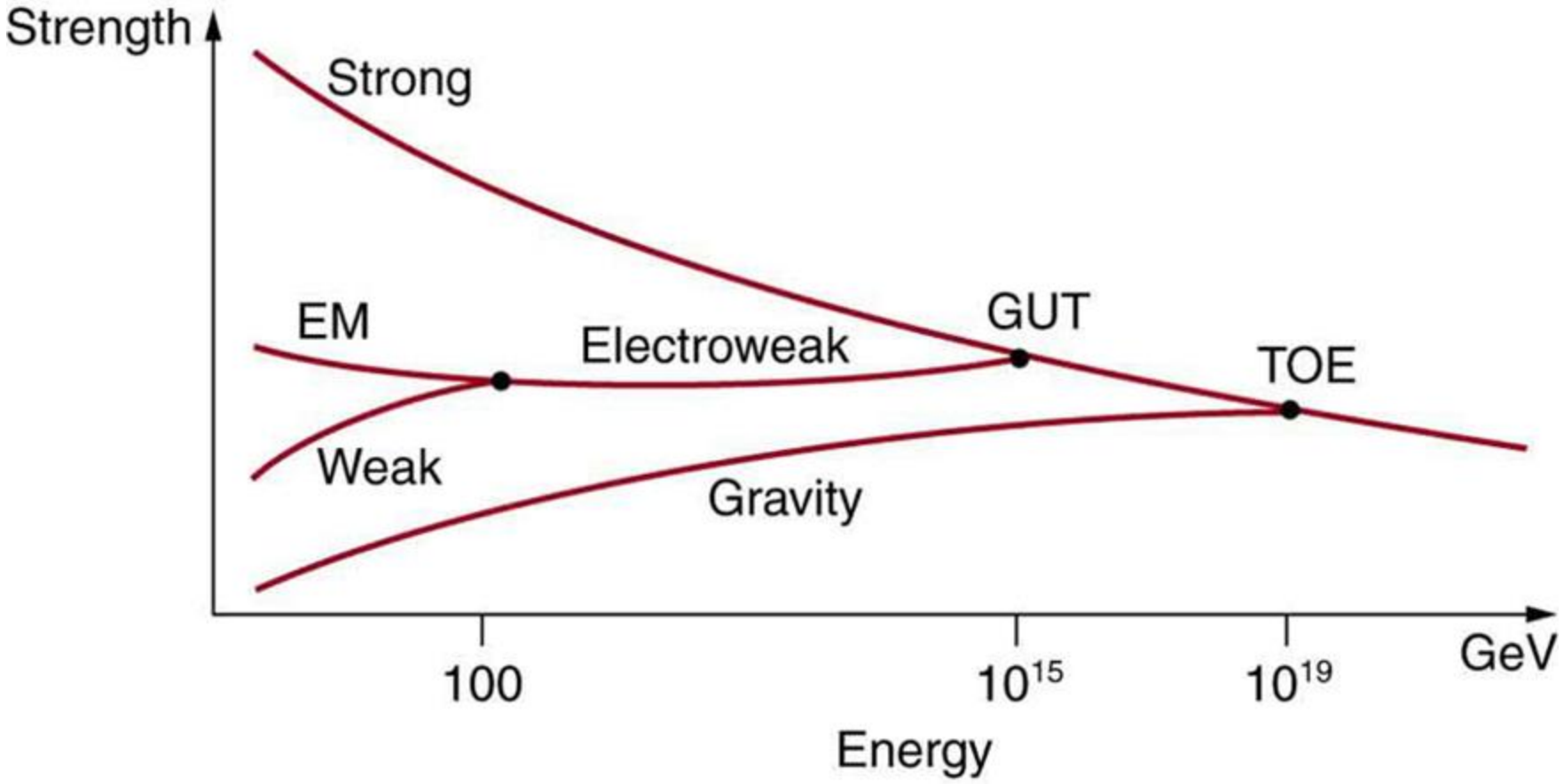
What quantum number conservation is violated in the process below?

$$b \rightarrow \bar{s} + s + d + e^{-} + \bar{\nu}_e$$

- ❑ Lepton number conservation
- ❑ Baryon number conservation
- ❑ Charge conservation

Force	Force mediator	Interaction length	Particles
Strong	Gluon	10^{-15} metres	Quarks, hadrons
Weak	W and Z	10^{-17} metres	Fermions, Higgs
Electromagnetic	Photon	Infinite	Charged particles
Gravity	Graviton?	Infinite	All particles

Grand Unified Theory (GUT) and Theory of Everything (TOE)



Particles and fields - States

Edvard Mörtsell

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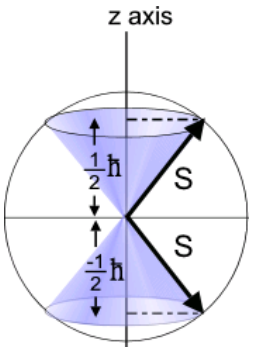
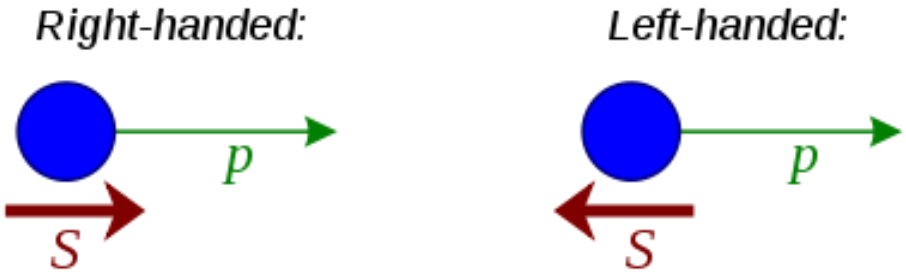
Spin states



- Two particles with spin s can be in different states depending on the spin direction, e.g., projected on the *z*-axis
- The projection on the direction of propagation, is denoted *helicity*
- For massive particles, helicity is not unambigous when changing frame (but the related *chirality* is)
- Massive particles have 2s+1 possible helicity states
- Massless spin-1 particles have only 2 possible helicity states, ±1
- Neutrinos only have helicity -1; they are *left-handed*
- Anti-neutrinos have helicity +1; they are *right-handed*

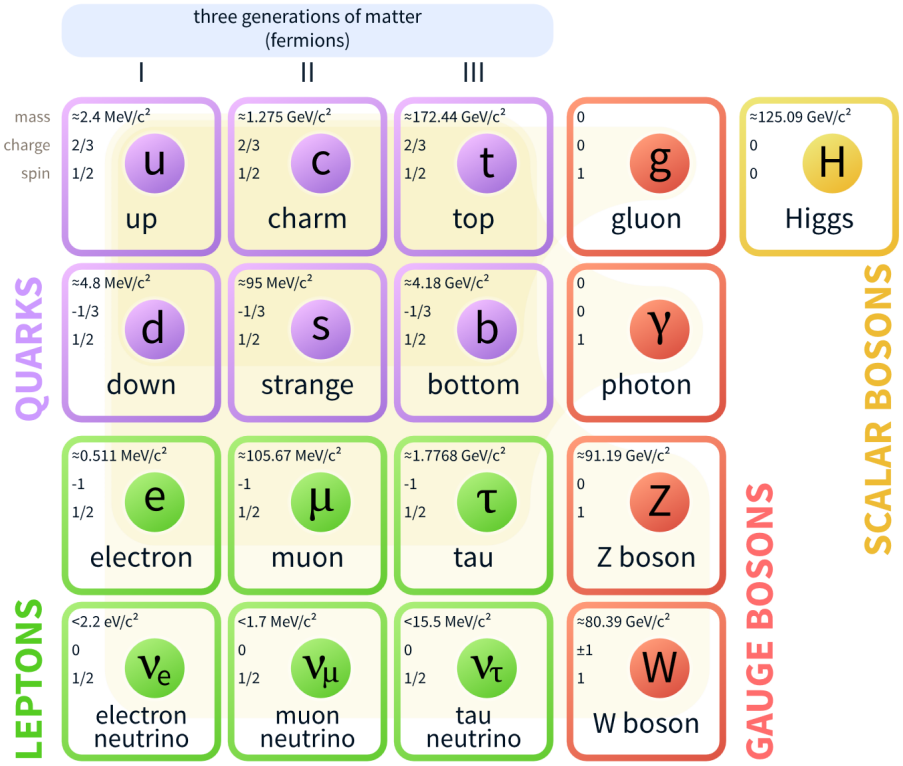


What is the helicity of a particle?

- ❑ The spin of a particle projected on its direction of motion
- ❑ The spin of a particle in units of $\hbar$
- ❑ The angular momentum squared of a particle
- ❑ The inverse mass of a particle

States in the Standard Model

- 12 quarks in 3 colours with 2 spin states = 72
- 6 charged leptons with 2 spin states = 12
- 6 neutrinos
- 90 fermion states
- 8 gluons with 2 spin states = 16
- 1 photon with 2 spin states = 2
- $W^{\pm}$ and Z with 3 spin states = 9
- Higgs = 1
- In total: 118 states



How many boson states are there in the particle standard model?

- ❑ 28
- ❑ 90
- ❑ None

Word list

- Quark (Spin ½, all fundamental interactions, fractional EM charge)
- Lepton (Spin ½, no strong interactions, integer EM charge)
- Fermion (Any half-integer spin particle, including composite ones)
- Boson (Any integer spin particle, including composite ones)
  - Fundamental bosons: spin 0 = Higgs, spin 1 = force carriers, spin 2: graviton?
- Baryon (Particle made up of three quarks)
- Meson (Particle made up of a quark and an anti-quark)
- Hadron (Baryon or meson)

A proton is a (multiple answers possible)

- ❑ Quark
- ❑ Lepton
- ❑ Fermion
- ❑ Boson
- ❑ Baryon
- ❑ Meson
- ❑ Hadron

Particles and fields – Cross-sections

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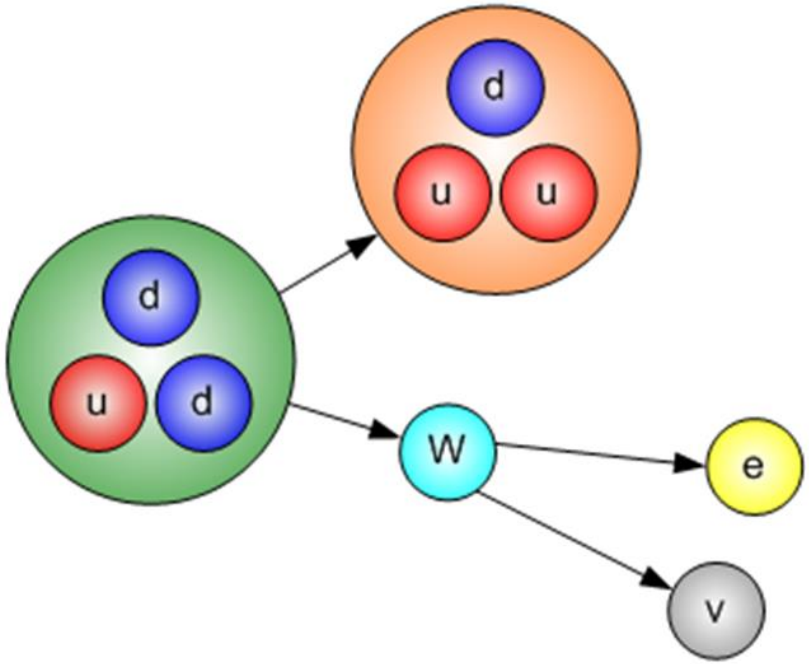
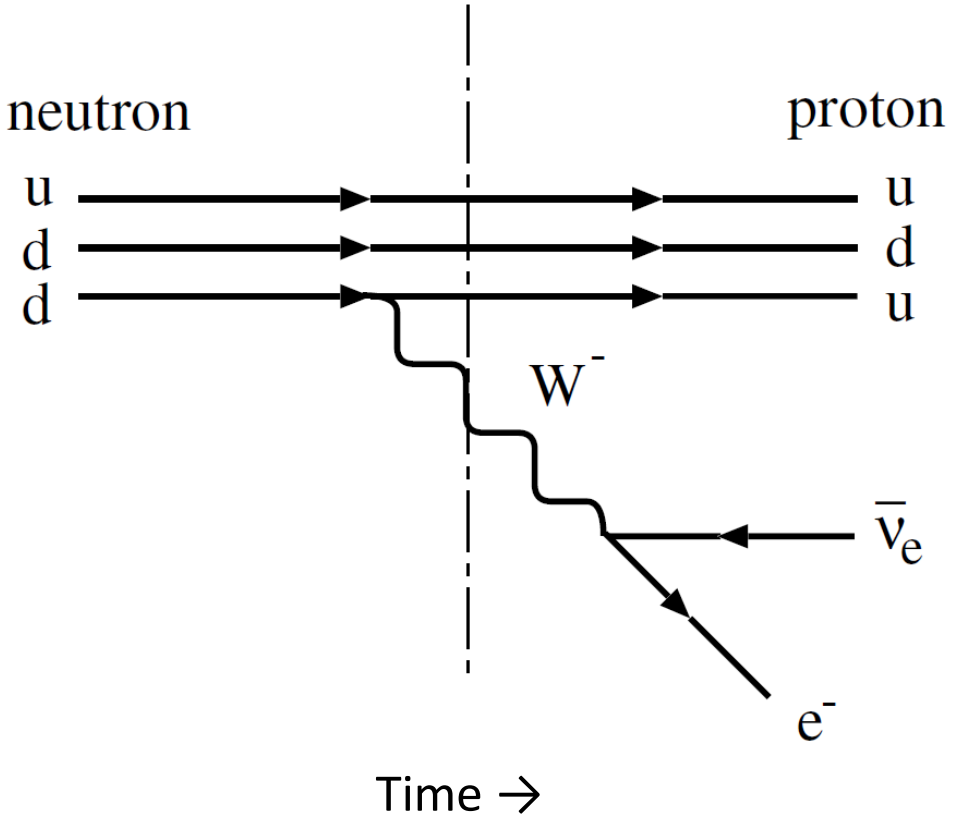
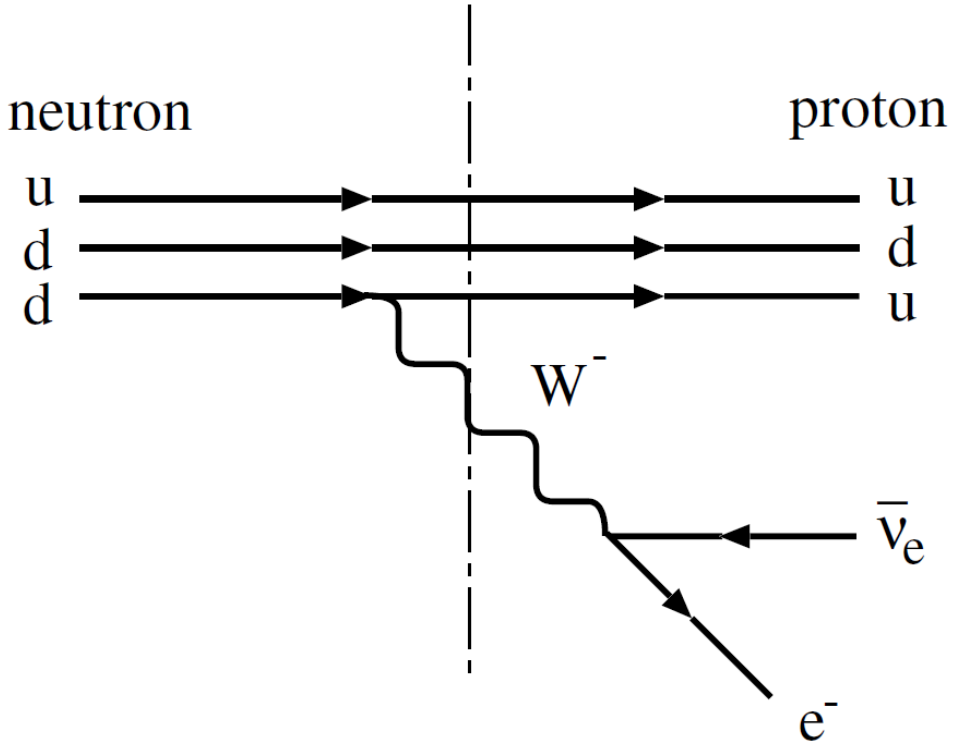
Feynman diagrams





Feynman rules



- The Feynman rules are a prescription for calculating the amplitude for a diagram
- The cross-section is given by the squared amplitude
- Each vertex (where lines meet) gives a factor given by the coupling strength, g
- Each internal line corresponds to a factor of the virtual particle's propagator

Interaction strengths

- The electromagnetic coupling is $g_{\mathrm{EM}} = Qe$, where the fine structure constant is given by

$$\alpha_{\mathrm{EM}} \equiv \frac{e^2}{4\pi} \approx \frac{1}{137}$$

- The weak coupling constant is

$$g_{\mathrm{weak}} = \frac{e}{\sin\theta_{\mathrm{W}}}$$

where the Weinberg angle is $\sin^2\theta_{\mathrm{W}} \approx 0.23$

- The strong coupling constant, g_{S}, is given by (at a few GeV)

$$\alpha_{\mathrm{S}} \equiv \frac{g_{\mathrm{S}}^2}{4\pi} \approx 0.3$$

The propagator and phase space factors

The propagator factor is given by

$$P(s) = \frac{1}{s - m_i^2}$$

where m_i is the (real) mass of the propagator particle and s its virtual mass squared, $s = (p_1 + p_2)^2$.

For fermion propagators, $P \propto m^{-1}$ at low energies.

The phase space factor ϕ , multiplying the cross-section, takes into account that outgoing particles have many possible final states, e.g., different scattering angles.

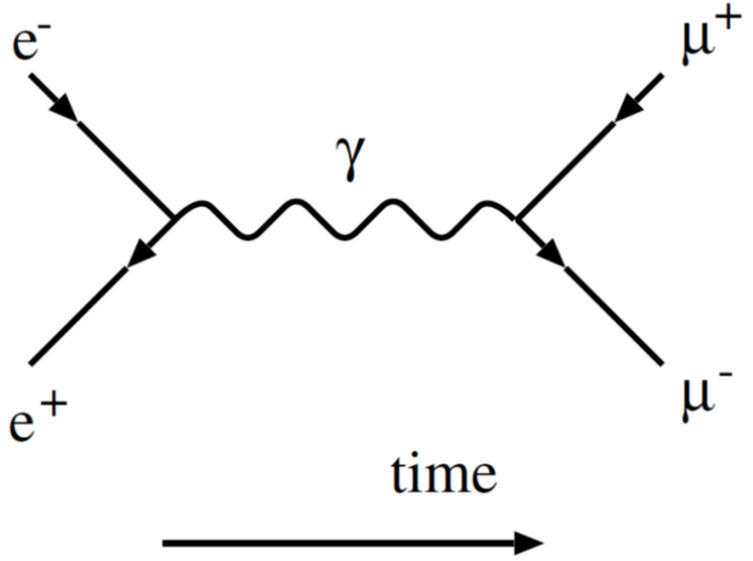
In many cases, $\phi \propto s$ for large energies.

Electromagnetic example

An electron and a positron annihilating and forming a muon and an anti-muon will have a cross-section

$$\sigma \sim \phi \cdot \frac{e^4}{s^2} \sim \phi \cdot \left(\frac{\alpha}{s}\right)^2 \sim \frac{\alpha^2}{s}$$

where the last approximation holds for large energies.

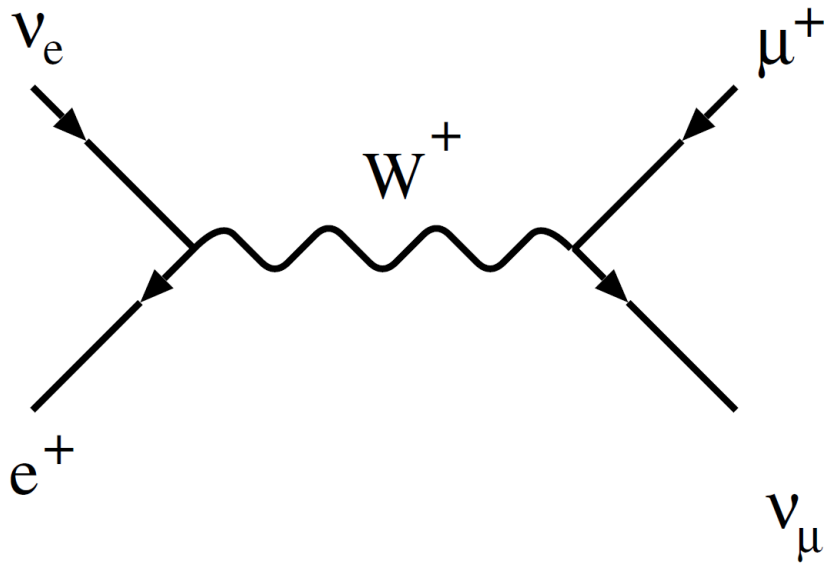


Weak interaction example

An electron neutrino and a positron annihilating and forming a muon neutrino and an anti-muon will have a cross-section

$$\sigma \sim \phi \cdot \frac{e^4}{\sin^4 \theta_W \, (s - m_W^2)^2} \sim \phi \cdot \left(\frac{\alpha}{s - m_W^2} \right)^2 \sim \frac{s\alpha^2}{(s - m_W^2)^2}$$

being very small for $s \ll m_W^2$.



Particles and fields – The dark sectors

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Vacuum energy density

- The energy of a massless scalar field is the sum of all possible ground state energies $E_0 = \sum_i (\hbar\omega_i)/2$
- In a box with side L, we can fit harmonic oscillators with $\lambda_i \cdot n_i = L$
- In terms of the wave vector $k_i = (2\pi)/\lambda_i = \omega_i, n_i = L \cdot k_i/(2\pi)$
- Summing the number of modes at each k, we obtain

$$E_0 = \frac{\hbar}{2}\frac{L^3}{(2\pi)^3}\int k d^3k = \frac{\hbar}{16\pi^2}\, L^3 k_{\text{max}}^4$$

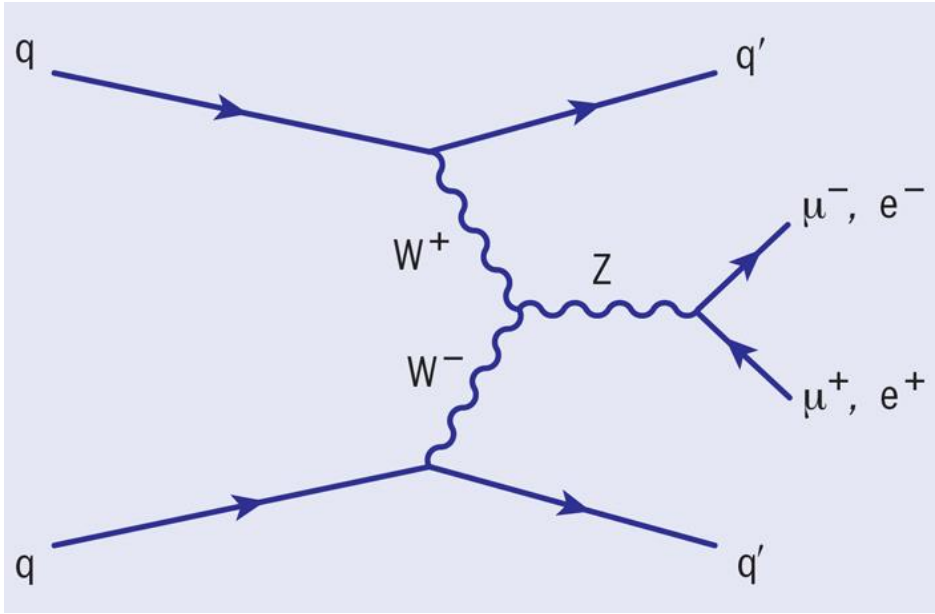
- Putting the cut-off scale to the Planck energy, we obtain

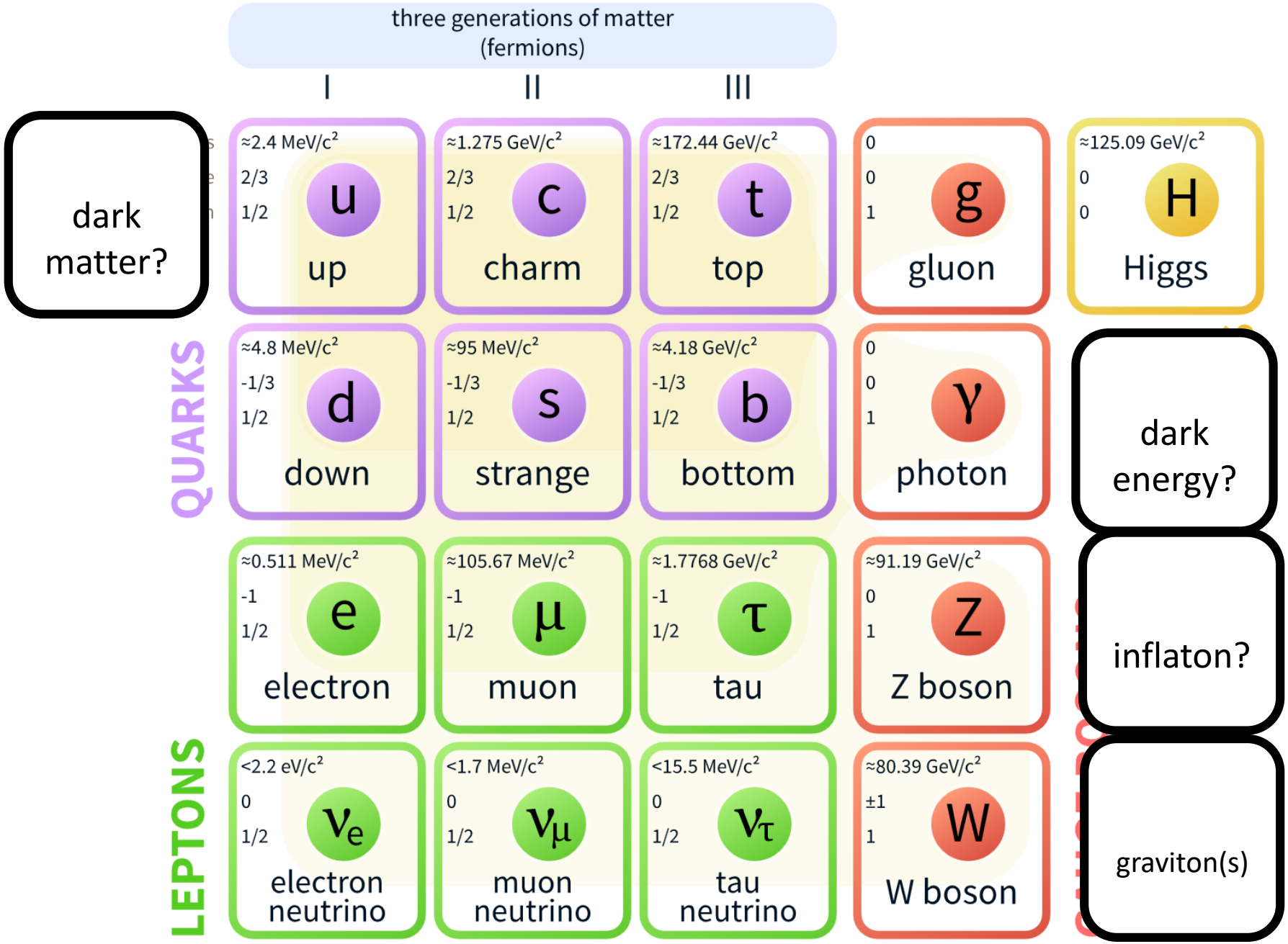
$$\rho_{\text{vac}} = \frac{E_0}{L^3} \sim 10^{95}\ \text{kg/m}^3$$

- The fact that this is a factor of 10^{122} too high is referred to as the *cosmological constant problem*

Imagine we put the cut-off scale for our field theory treatment of the vacuum energy to that of the W and Z bosons instead (that we know exist and we believe we understand well). What is the corresponding vacuum energy contribution?

- ❑ $\rho_{\text{vac}} \sim 1\ \text{kg/m}^3$
- ❑ $\rho_{\text{vac}} \sim 10^{27}\ \text{kg/m}^3$
- ❑ $\rho_{\text{vac}} \sim 10^{78}\ \text{kg/m}^3$
- ❑ $\rho_{\text{vac}} \sim 10^{120}\ \text{kg/m}^3$




three generations of matter
(fermions)
I
II
III
dark matter?
QUARKS
LEPTONS
≈2.4 MeV/c²
2/3
1/2
u
up
≈1.275 GeV/c²
2/3
1/2
c
charm
≈172.44 GeV/c²
2/3
1/2
t
top
0
0
1
g
gluon
≈125.09 GeV/c²
0
0
H
Higgs
≈4.8 MeV/c²
-1/3
1/2
d
down
≈95 MeV/c²
-1/3
1/2
s
strange
≈4.18 GeV/c²
-1/3
1/2
b
bottom
0
0
1
γ
photon
dark energy?
≈0.511 MeV/c²
-1
1/2
e
electron
≈105.67 MeV/c²
-1
1/2
μ
muon
≈1.7768 GeV/c²
-1
1/2
τ
tau
≈91.19 GeV/c²
0
1
Z
Z boson
inflaton?
<2.2 eV/c²
0
1/2
νe
electron neutrino
<1.7 MeV/c²
0
1/2
νμ
muon neutrino
<15.5 MeV/c²
0
1/2
ντ
tau neutrino
≈80.39 GeV/c²
±1
1
W
W boson
graviton(s)