

Particles and fields – The standard model

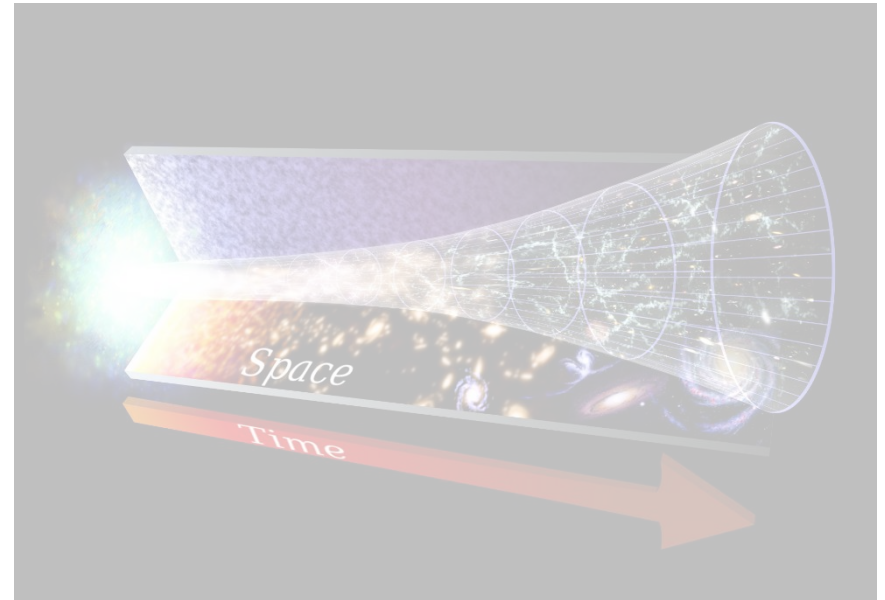
Edvard Mörtzell

Cosmology and Astroparticle Physics FK7050

Standard models of Particle physics and Cosmology

		three generations of matter (fermions)				
		I	II	III		
mass		$\approx 2.4 \text{ MeV}/c^2$	$\approx 1.275 \text{ GeV}/c^2$	$\approx 172.44 \text{ GeV}/c^2$	0	$\approx 125.09 \text{ GeV}/c^2$
charge		2/3	2/3	2/3	0	0
spin		1/2	1/2	1/2	1	0
	QUARKS	u up	c charm	t top	g gluon	H Higgs
		d down	s strange	b bottom	γ photon	
		e electron	μ muon	τ tau	Z Z boson	
	LEPTONS	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	
		$< 2.2 \text{ eV}/c^2$	$< 1.7 \text{ MeV}/c^2$	$< 15.5 \text{ MeV}/c^2$	$\approx 80.39 \text{ GeV}/c^2$	
		0	0	0	± 1	
		1/2	1/2	1/2	1	
						GAUGE BOSONS
						SCALAR BOSONS

Particle Physics



Cosmology

Periodic Table of the Elements

Period	1 IA 1A	2 IIA 2A											13 IIIA 3A	14 IVA 4A	15 VA 5A	16 VIA 6A	17 VIIA 7A	18 VIIIA 8A	
1	1 1.008 H Hydrogen 1s ¹																		2 4.003 He Helium 1s ²
2	3 6.941 Li Lithium 2s ¹ [He]2s ¹	4 9.012 Be Beryllium [He]2s ²											5 10.811 B Boron 2s ² [He]2s ² 2p ¹	6 12.011 C Carbon 2s ² [He]2s ² 2p ²	7 14.007 N Nitrogen 2s ² [He]2s ² 2p ³	8 15.999 O Oxygen 2s ² [He]2s ² 2p ⁴	9 18.998 F Fluorine 2s ² [He]2s ² 2p ⁵	10 20.180 Ne Neon 2s ² [He]2s ² 2p ⁶	
3	11 22.990 Na Sodium 2s ¹ [Ne]3s ¹	12 24.305 Mg Magnesium [Ne]3s ²	3 IIIIB 3B	4 IVB 4B	5 VB 5B	6 VIB 6B	7 VIIB 7B	8 VIII 8	9 VIII 8	10 VIII 8	11 IB 1B	12 IIB 2B	13 26.982 Al Aluminum [Ne]3s ² 3p ¹	14 28.086 Si Silicon [Ne]3s ² 3p ²	15 30.974 P Phosphorus [Ne]3s ² 3p ³	16 32.066 S Sulfur [Ne]3s ² 3p ⁴	17 35.453 Cl Chlorine [Ne]3s ² 3p ⁵	18 39.948 Ar Argon [Ne]3s ² 3p ⁶	
4	19 39.098 K Potassium 3s ¹ [Ar]4s ¹	20 40.078 Ca Calcium 2s ² [Ar]4s ²	21 44.956 Sc Scandium [Ar]3d ¹ 4s ²	22 47.88 Ti Titanium 2s ¹ [Ar]3d ² 4s ²	23 50.942 V Vanadium 2s ¹ [Ar]3d ³ 4s ²	24 51.996 Cr Chromium 2s ¹ [Ar]3d ⁵ 4s ¹	25 54.938 Mn Manganese 2s ¹ [Ar]3d ⁵ 4s ²	26 55.845 Fe Iron 2s ¹ [Ar]3d ⁶ 4s ²	27 58.933 Co Cobalt 2s ¹ [Ar]3d ⁷ 4s ²	28 58.693 Ni Nickel 2s ¹ [Ar]3d ⁸ 4s ²	29 63.546 Cu Copper 2s ¹ [Ar]3d ¹⁰ 4s ¹	30 65.38 Zn Zinc [Ar]3d ¹⁰ 4s ²	31 69.723 Ga Gallium 2s ¹ [Ar]3d ¹⁰ 4s ² 4p ¹	32 72.631 Ge Germanium [Ar]3d ¹⁰ 4s ² 4p ²	33 74.922 As Arsenic 2s ¹ [Ar]3d ¹⁰ 4s ² 4p ³	34 78.971 Se Selenium [Ar]3d ¹⁰ 4s ² 4p ⁴	35 79.904 Br Bromine 2s ¹ [Ar]3d ¹⁰ 4s ² 4p ⁵	36 84.798 Kr Krypton 2s ¹ [Ar]3d ¹⁰ 4s ² 4p ⁶	
5	37 84.468 Rb Rubidium 3s ¹ [Kr]5s ¹	38 87.62 Sr Strontium [Kr]5s ²	39 88.906 Y Yttrium [Kr]4d ¹ 5s ²	40 91.224 Zr Zirconium 2s ¹ [Kr]4d ² 5s ²	41 92.906 Nb Niobium [Kr]4d ⁴ 5s ¹	42 95.95 Mo Molybdenum [Kr]4d ⁵ 5s ¹	43 98.907 Tc Technetium [Kr]4d ⁵ 5s ²	44 101.07 Ru Ruthenium [Kr]4d ⁷ 5s ¹	45 102.906 Rh Rhodium [Kr]4d ⁸ 5s ¹	46 106.42 Pd Palladium [Kr]4d ¹⁰	47 107.868 Ag Silver [Kr]4d ¹⁰ 5s ¹	48 112.414 Cd Cadmium [Kr]4d ¹⁰ 5s ²	49 114.818 In Indium [Kr]4d ¹⁰ 5s ² 5p ¹	50 118.711 Sn Tin [Kr]4d ¹⁰ 5s ² 5p ²	51 121.760 Sb Antimony [Kr]4d ¹⁰ 5s ² 5p ³	52 127.6 Te Tellurium [Kr]4d ¹⁰ 5s ² 5p ⁴	53 126.904 I Iodine [Kr]4d ¹⁰ 5s ² 5p ⁵	54 131.29 Xe Xenon [Kr]4d ¹⁰ 5s ² 5p ⁶	
6	55 132.905 Cs Cesium 2s ¹ [Xe]6s ¹	56 137.328 Ba Barium 2s ¹ [Xe]6s ²	57-71 Lanthanide Series	72 178.49 Hf Hafnium 2s ¹ [Xe]4f ¹⁴ 5d ² 6s ²	73 180.948 Ta Tantalum 2s ¹ [Xe]4f ¹⁴ 5d ³ 6s ²	74 183.84 W Tungsten [Xe]4f ¹⁴ 5d ⁴ 6s ²	75 186.207 Re Rhenium 2s ¹ [Xe]4f ¹⁴ 5d ⁵ 6s ²	76 190.23 Os Osmium 2s ¹ [Xe]4f ¹⁴ 5d ⁶ 6s ²	77 192.22 Ir Iridium 2s ¹ [Xe]4f ¹⁴ 5d ⁷ 6s ²	78 195.085 Pt Platinum 2s ¹ [Xe]4f ¹⁴ 5d ⁹ 6s ¹	79 196.967 Au Gold 2s ¹ [Xe]4f ¹⁴ 5d ¹⁰ 6s ¹	80 200.592 Hg Mercury [Xe]4f ¹⁴ 5d ¹⁰ 6s ²	81 204.383 Tl Thallium 2s ¹ [Xe]4f ¹⁴ 5d ¹⁰ 6s ² 6p ¹	82 207.2 Pb Lead 2s ¹ [Xe]4f ¹⁴ 5d ¹⁰ 6s ² 6p ²	83 208.980 Bi Bismuth 2s ¹ [Xe]4f ¹⁴ 5d ¹⁰ 6s ² 6p ³	84 [208.982] Po Polonium [Xe]4f ¹⁴ 5d ¹⁰ 6s ² 6p ⁴	85 209.987 At Astatine [Xe]4f ¹⁴ 5d ¹⁰ 6s ² 6p ⁵	86 222.018 Rn Radon [Xe]4f ¹⁴ 5d ¹⁰ 6s ² 6p ⁶	
7	87 223.020 Fr Francium 2s ¹ [Rn]7s ¹	88 226.025 Ra Radium 2s ¹ [Rn]7s ²	89-103 Actinide Series	104 [261] Rf Rutherfordium 2s ¹ [Rn]5f ¹⁴ 6d ² 7s ² *	105 [262] Db Dubnium 2s ¹ [Rn]5f ¹⁴ 6d ³ 7s ² *	106 [262] Sg Seaborgium [Rn]5f ¹⁴ 6d ⁴ 7s ² *	107 [264] Bh Bohrium [Rn]5f ¹⁴ 6d ⁵ 7s ² *	108 [269] Hs Hassium 2s ¹ [Rn]5f ¹⁴ 6d ⁶ 7s ² *	109 [269] Mt Meitnerium [Rn]5f ¹⁴ 6d ⁷ 7s ² *	110 [269] Ds Darmstadtium [Rn]5f ¹⁴ 6d ⁸ 7s ² *	111 [272] Rg Roentgenium [Rn]5f ¹⁴ 6d ⁹ 7s ² *	112 [277] Cn Copernicium [Rn]5f ¹⁴ 6d ¹⁰ 7s ² *	113 unknown [289] Uut Ununtrium [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 7p ¹ *	114 [289] Fl Flerovium [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 7p ² *	115 unknown [289] Uup Ununpentium [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 7p ³ *	116 [289] Lv Livermorium [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 7p ⁴ *	117 unknown [289] Uus Ununseptium [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 7p ⁵ *	118 unknown [289] Uuo Ununoctium [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 7p ⁶ *	

Atomic Number	Atomic Mass
Symbol Name	
Electron Shells	
Electron Configuration	

Element symbol represents state at room temperature.

Solid, Liquid or Gas


















- Alkali Metal
- Alkaline Earth
- Transition Metal
- Basic Metal
- Metalloid
- Nonmetal
- Halogen
- Noble Gas
- Lanthanide
- Actinide

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	$\bar{\nu}_e$	$< 7\text{eV}/c^2$	0	+1	0	0	0	Stable		
	Muon	μ^-	μ^+	105.7	0	0	+1	0	0	2.20×10^{-6}	$e^- \bar{\nu}_e \nu_\mu$	
	Muon-neutrino	ν_μ	$\bar{\nu}_\mu$	< 0.3	0	0	+1	0	0	Stable		
	Tau	τ^-	τ^+	1 784	0	0	0	+1	0	$< 4 \times 10^{-13}$	$\mu^- \bar{\nu}_\mu \nu_\tau, e^- \bar{\nu}_e \nu_\tau$	
	Tau-neutrino	ν_τ	$\bar{\nu}_\tau$	< 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_S^0	K_S^0	497.7	0	0	0	0	+1	0.89×10^{-10}	$\pi^+ \pi^-, 2\pi^0$	
		K_L^0	K_L^0	497.7	0	0	0	0	+1	5.2×10^{-8}	$\pi^\pm e^\mp \bar{\nu}_e, 3\pi^0$ $\pi^\pm \mu^\mp \bar{\nu}_\mu$	
	Eta	η	Self	548.8	0	0	0	0	0	$< 10^{-18}$	$2\gamma, 3\pi$	
		η'	Self	958	0	0	0	0	0	2.2×10^{-21}	$\eta\pi^+ \pi^-$	
	Baryons	Proton	p	\bar{p}	938.3	+1	0	0	0	0	Stable	
Neutron		n	\bar{n}	939.6	+1	0	0	0	0	920	$p e^- \bar{\nu}_e$	
Lambda		Λ^0	$\bar{\Lambda}^0$	1 115.6	+1	0	0	0	-1	2.6×10^{-10}	$p\pi^-, n\pi^0$	
		Sigma	Σ^+	Σ^-	1 189.4	+1	0	0	0	-1	0.80×10^{-10}	$p\pi^0, n\pi^+$
			Σ^0	Σ^0	1 192.5	+1	0	0	0	-1	6×10^{-20}	$\Lambda^0 \gamma$
Xi		Σ^-	Σ^+	1 197.3	+1	0	0	0	-1	1.5×10^{-10}	$n\pi^-$	
		Ξ^0	$\bar{\Xi}^0$	1 315	+1	0	0	0	-2	2.9×10^{-10}	$\Lambda^0 \pi^0$	
		Ξ^-	$\bar{\Xi}^+$	1 321	+1	0	0	0	-2	1.64×10^{-10}	$\Lambda^0 \pi^-$	
Omega	Ω^-	$\bar{\Omega}^+$	1 672	+1	0	0	0	-3	0.82×10^{-10}	$\Xi^0 \pi^0, \Lambda^0 K^-$		

^aNotations 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 $\Lambda^0 \rightarrow n + \pi^0$.

three generations of matter
(fermions)

	I	II	III		
mass	$\approx 2.4 \text{ MeV}/c^2$	$\approx 1.275 \text{ GeV}/c^2$	$\approx 172.44 \text{ GeV}/c^2$	0	$\approx 125.09 \text{ GeV}/c^2$
charge	$2/3$	$2/3$	$2/3$	0	0
spin	$1/2$	$1/2$	$1/2$	1	0
QUARKS	 up	 charm	 top	 gluon	 Higgs
	 down	 strange	 bottom	 photon	
	 electron	 muon	 tau	 Z boson	
LEPTONS	 electron neutrino	 muon neutrino	 tau neutrino	 W boson	
	$\approx 0.511 \text{ MeV}/c^2$	$\approx 105.67 \text{ MeV}/c^2$	$\approx 1.7768 \text{ GeV}/c^2$	$\approx 91.19 \text{ GeV}/c^2$	
	-1	-1	-1	0	
	$1/2$	$1/2$	$1/2$	1	
	$< 2.2 \text{ eV}/c^2$	$< 1.7 \text{ MeV}/c^2$	$< 15.5 \text{ MeV}/c^2$	$\approx 80.39 \text{ GeV}/c^2$	
	0	0	0	± 1	
	$1/2$	$1/2$	$1/2$	1	
					SCALAR BOSONS
					GAUGE BOSONS

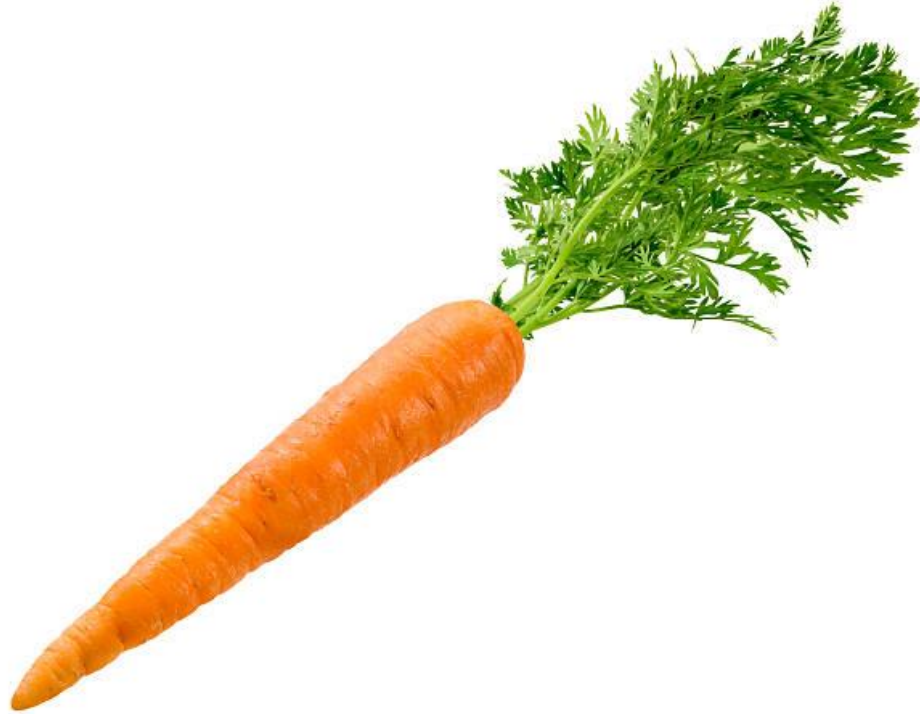
How many atoms are there in a carrot?

10^6

10^{16}

10^{25}

10^{50}



Particles and fields - Quarks

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three generations of matter
(fermions)

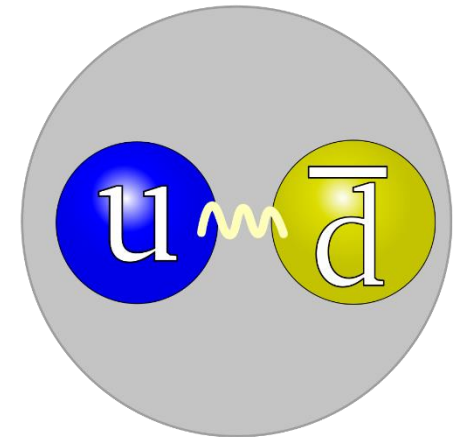
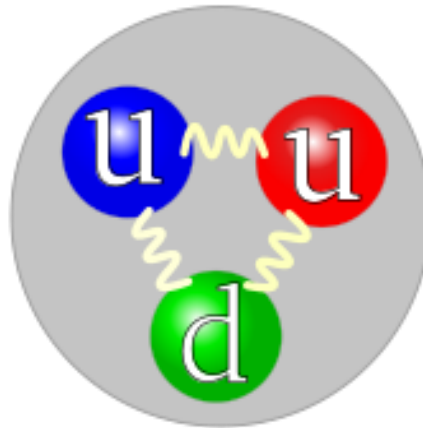
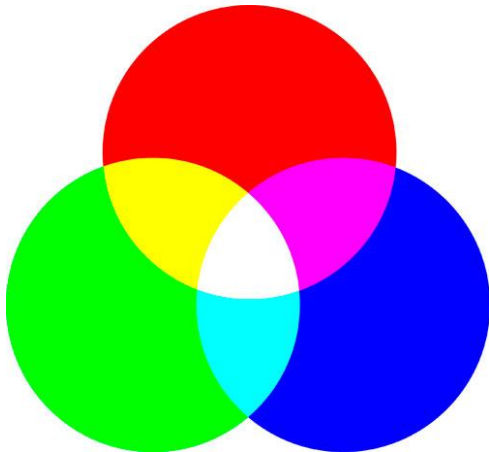
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charge	$2/3$	$2/3$	$2/3$	0	0
spin	$1/2$	$1/2$	$1/2$	1	0
QUARKS	u up	c charm	t top	g gluon	H Higgs
	d down	s strange	b bottom	γ photon	
LEPTONS	e electron	μ muon	τ tau	Z Z boson	
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	

SCALAR BOSONS

GAUGE BOSONS

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)



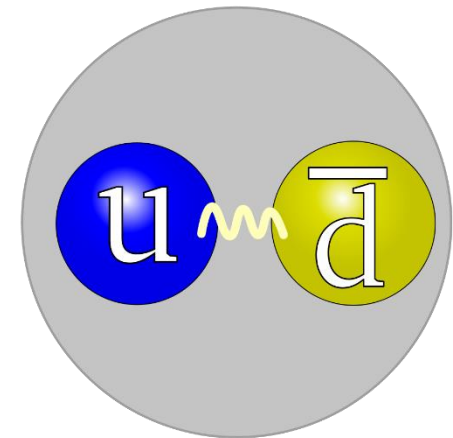
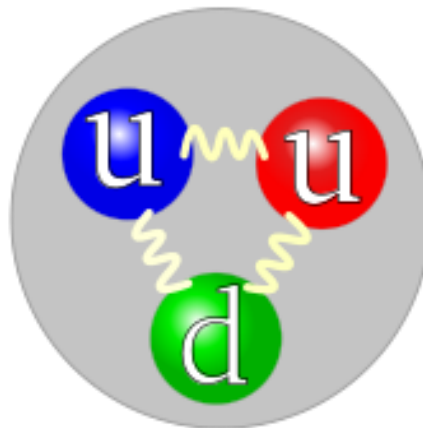
What are the charges of the particles below?

+1 and +1

-1 and +1

+1 and -1

-1 and -1



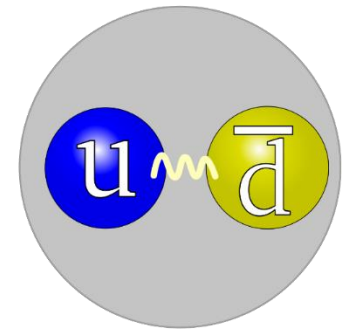
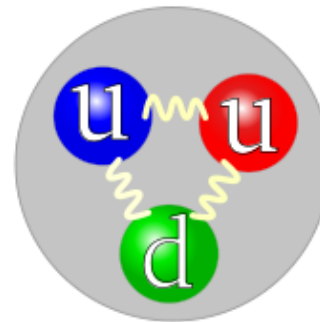
Which are the particles below?

A neutron and a proton

A lepton and a gluino

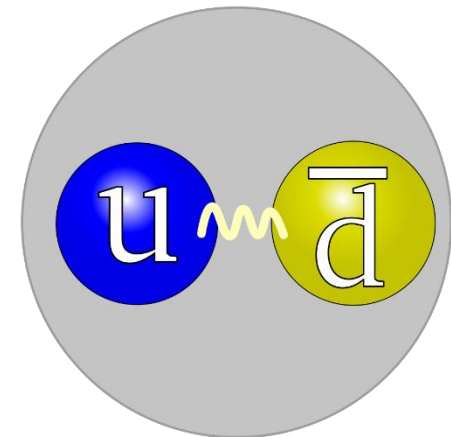
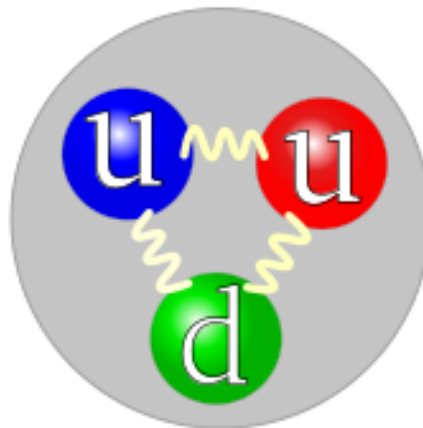
A proton and a pion

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



three generations of matter
(fermions)

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charge	$2/3$	$2/3$	$2/3$	0	0
spin	$1/2$	$1/2$	$1/2$	1	0
QUARKS	u up	c charm	t top	g gluon	H Higgs
	$\approx 4.8 \text{ MeV}/c^2$	$\approx 95 \text{ MeV}/c^2$	$\approx 4.18 \text{ GeV}/c^2$	0	
	$-1/3$	$-1/3$	$-1/3$	0	
	$1/2$	$1/2$	$1/2$	1	
	d down	s strange	b bottom	γ photon	
	$\approx 0.511 \text{ MeV}/c^2$	$\approx 105.67 \text{ MeV}/c^2$	$\approx 1.7768 \text{ GeV}/c^2$	$\approx 91.19 \text{ GeV}/c^2$	
	-1	-1	-1	0	
	$1/2$	$1/2$	$1/2$	1	
	e electron	μ muon	τ tau	Z Z boson	
LEPTONS	$< 2.2 \text{ eV}/c^2$	$< 1.7 \text{ MeV}/c^2$	$< 15.5 \text{ MeV}/c^2$	$\approx 80.39 \text{ GeV}/c^2$	
	0	0	0	± 1	
	$1/2$	$1/2$	$1/2$	1	
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	
					GAUGE BOSONS
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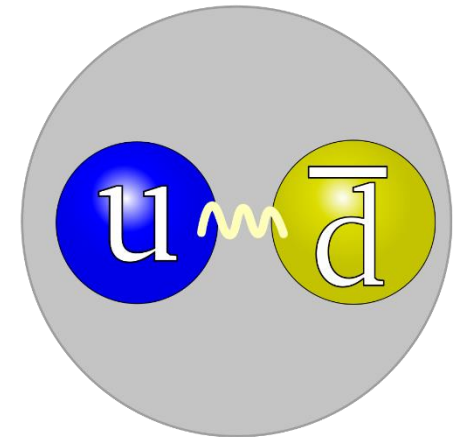
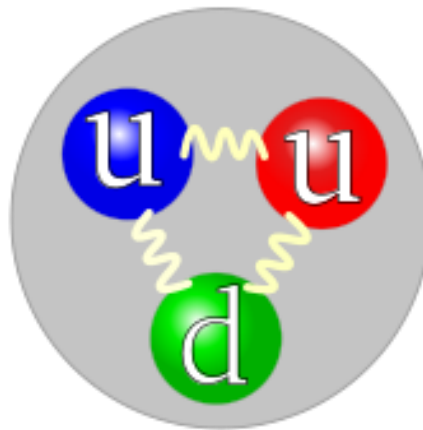
How could you make a neutron out of u and d-quarks?

u, u and d

u, d and d

u, \bar{u} and d

u, \bar{d} and d



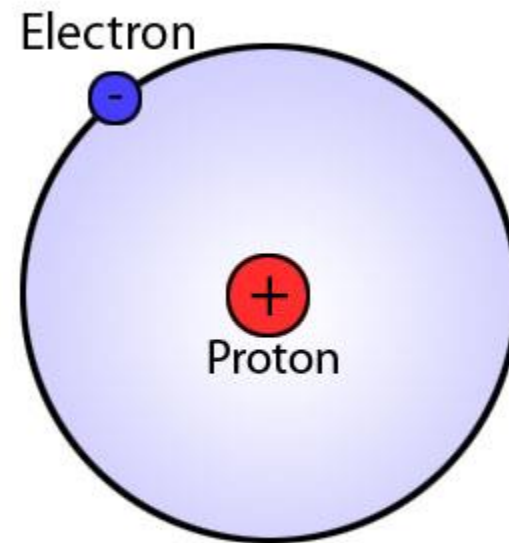
Particles and fields - Leptons

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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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QUARKS	u up	c charm	t top	g gluon
	d down	s strange	b bottom	γ photon
	e electron	μ muon	τ tau	Z Z boson
LEPTONS	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson
				H Higgs
				SCALAR BOSONS
				GAUGE BOSONS

Leptons

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

- One with zero charge
- One with charge $-e = -1$

three generations of matter
(fermions)

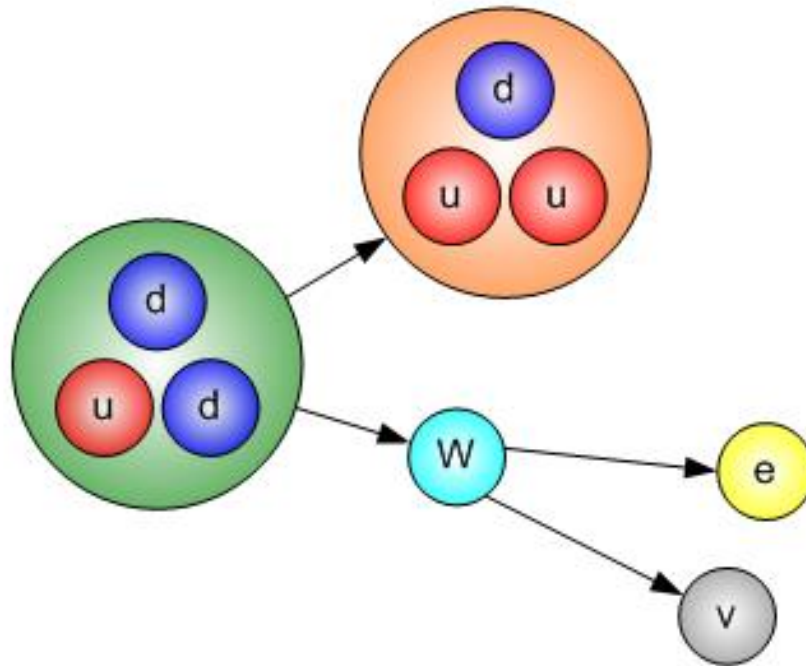
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charge	$2/3$	$2/3$	$2/3$	0	0
spin	$1/2$	$1/2$	$1/2$	1	0
QUARKS	u up	c charm	t top	g gluon	H Higgs
	d down	s strange	b bottom	γ photon	
LEPTONS	e electron	μ muon	τ tau	Z Z boson	
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	

SCALAR BOSONS


















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



three generations of matter
(fermions)

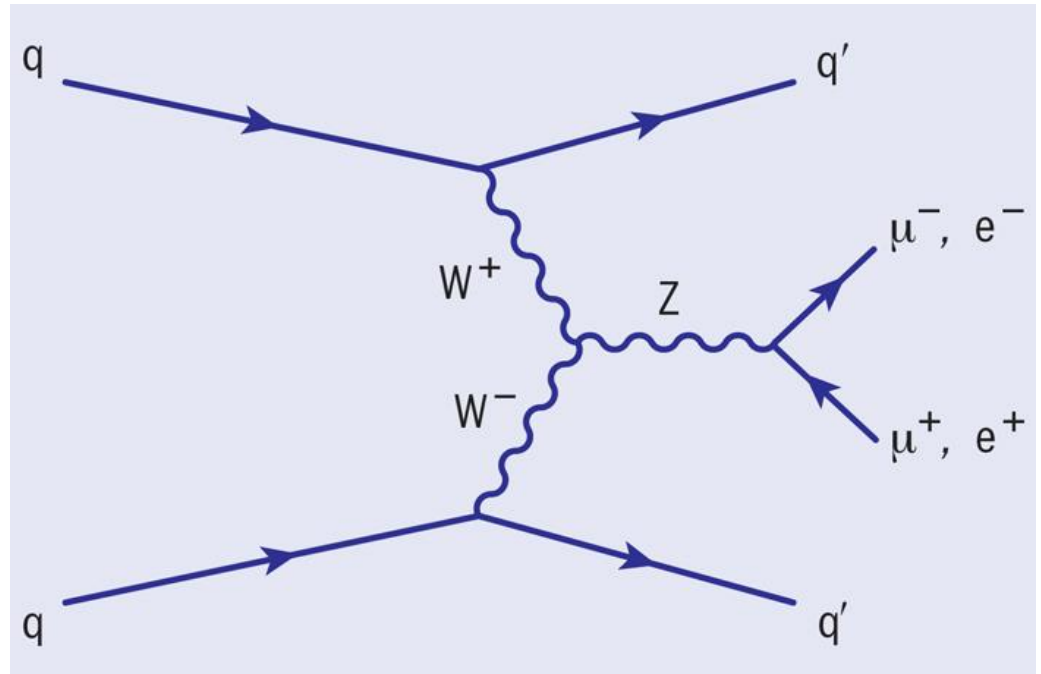
	I	II	III		
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charge	$2/3$	$2/3$	$2/3$	0	0
spin	$1/2$	$1/2$	$1/2$	1	0
QUARKS	 up	 charm	 top	 gluon	 Higgs
	 down	 strange	 bottom	 photon	
LEPTONS	 electron	 muon	 tau	 Z boson	GAUGE BOSONS
	 electron neutrino	 muon neutrino	 tau neutrino	 W boson	
	$\approx 0.511 \text{ MeV}/c^2$ -1 $1/2$	$\approx 105.67 \text{ MeV}/c^2$ -1 $1/2$	$\approx 1.7768 \text{ GeV}/c^2$ -1 $1/2$	$\approx 91.19 \text{ GeV}/c^2$ 0 1	SCALAR BOSONS
	$< 2.2 \text{ eV}/c^2$ 0 $1/2$	$< 1.7 \text{ MeV}/c^2$ 0 $1/2$	$< 15.5 \text{ MeV}/c^2$ 0 $1/2$	$\approx 80.39 \text{ GeV}/c^2$ ± 1 1	

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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	I	II	III		
mass	$\approx 2.4 \text{ MeV}/c^2$	$\approx 1.275 \text{ GeV}/c^2$	$\approx 172.44 \text{ GeV}/c^2$	0	$\approx 125.09 \text{ GeV}/c^2$
charge	$2/3$	$2/3$	$2/3$	0	0
spin	$1/2$	$1/2$	$1/2$	1	0
QUARKS	 up	 charm	 top	 gluon	 Higgs
	$\approx 4.8 \text{ MeV}/c^2$ $-1/3$ $1/2$  down	$\approx 95 \text{ MeV}/c^2$ $-1/3$ $1/2$  strange	$\approx 4.18 \text{ GeV}/c^2$ $-1/3$ $1/2$  bottom	0 0 1  photon	
	$\approx 0.511 \text{ MeV}/c^2$ -1 $1/2$  electron	$\approx 105.67 \text{ MeV}/c^2$ -1 $1/2$  muon	$\approx 1.7768 \text{ GeV}/c^2$ -1 $1/2$  tau	$\approx 91.19 \text{ GeV}/c^2$ 0 1  Z boson	
LEPTONS	$< 2.2 \text{ eV}/c^2$ 0 $1/2$  electron neutrino	$< 1.7 \text{ MeV}/c^2$ 0 $1/2$  muon neutrino	$< 15.5 \text{ MeV}/c^2$ 0 $1/2$  tau neutrino	$\approx 80.39 \text{ GeV}/c^2$ ± 1 1  W boson	GAUGE BOSONS
					SCALAR BOSONS

Particles and fields – Quantum numbers

Edvard Mörtzell

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Quantum numbers

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

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

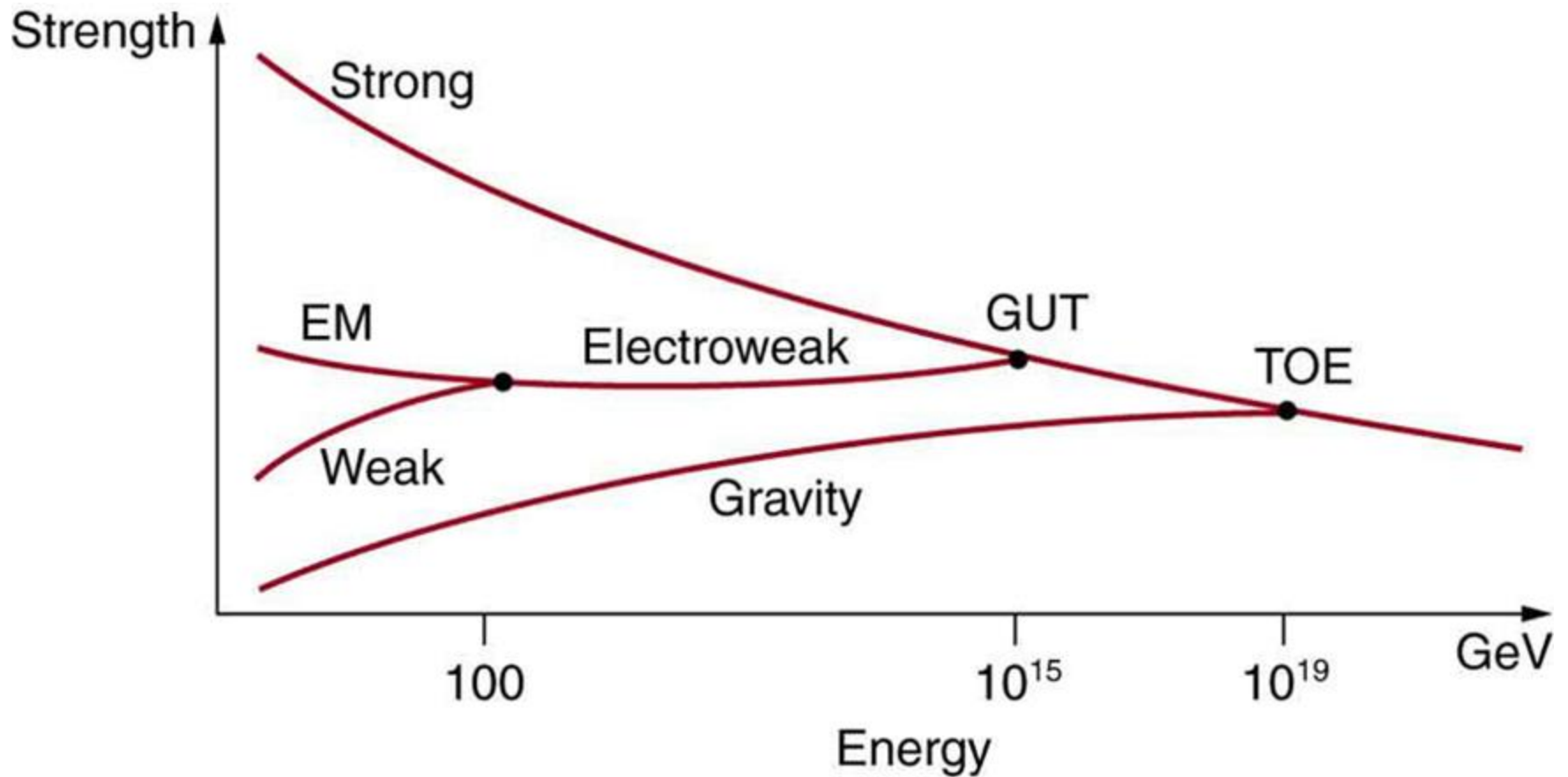
What quantum number conservation is violated in the process below?

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

- 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)

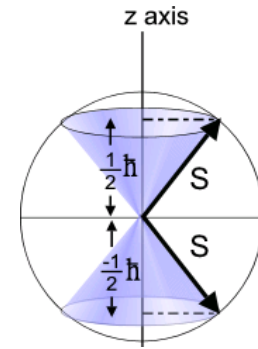


Particles and fields - States

Edvard Mörtzell

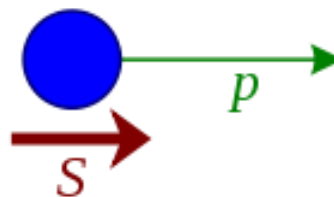
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Spin states

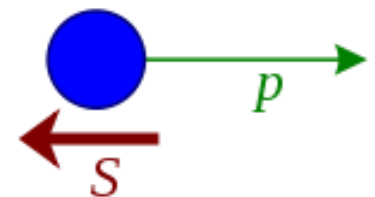


- Two particles with spin s can be in different states depending on the spin direction, e.g., projected on the z -axis
- The projection on the direction of propagation, is denoted *helicity*
- For massive particles, helicity is not unambiguous when changing frame (but the related *chirality* is)
- Massive 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*

Right-handed:



Left-handed:

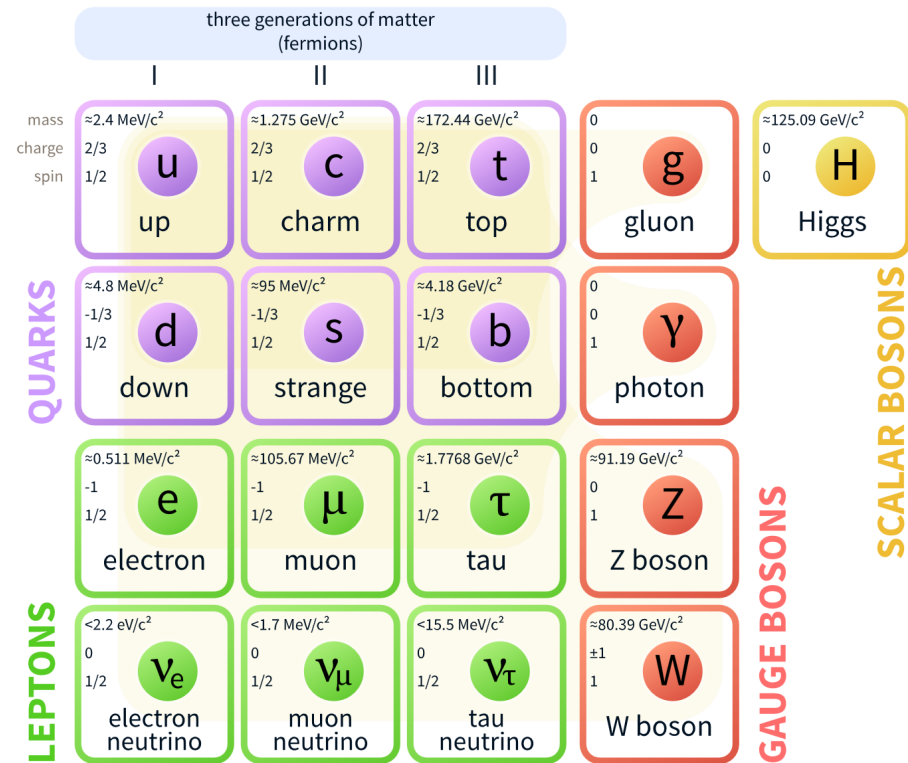


What is the helicity of a particle?

- 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 $\frac{1}{2}$, all fundamental interactions, fractional EM charge)
- Lepton (Spin $\frac{1}{2}$, 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)

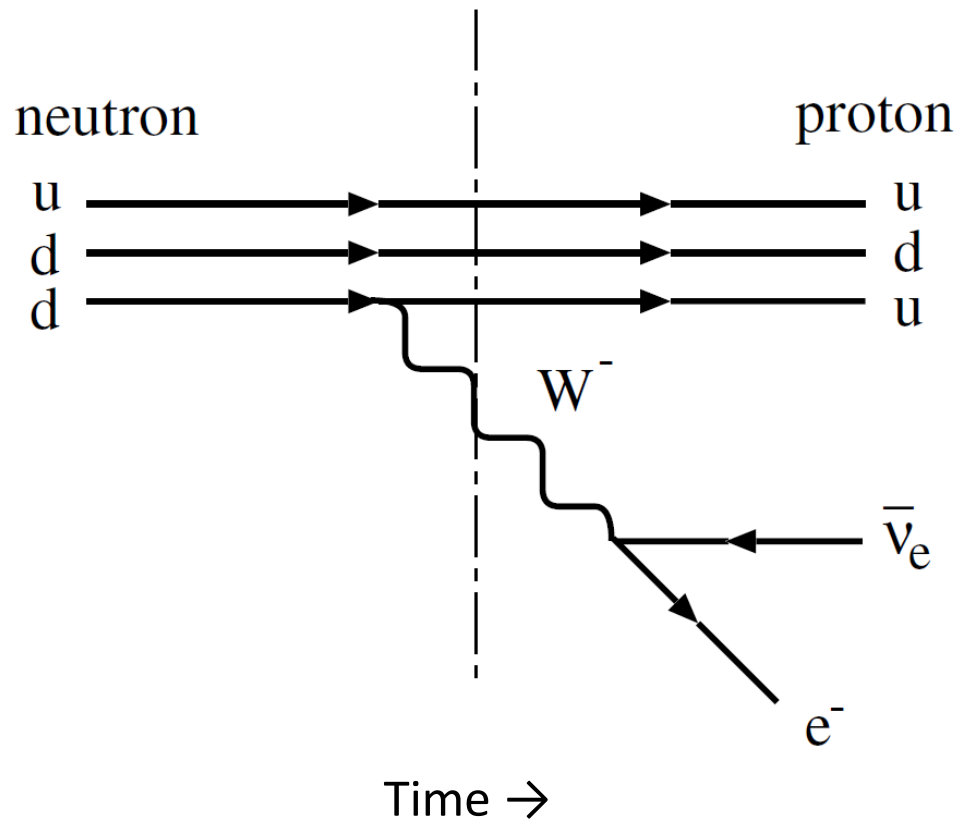
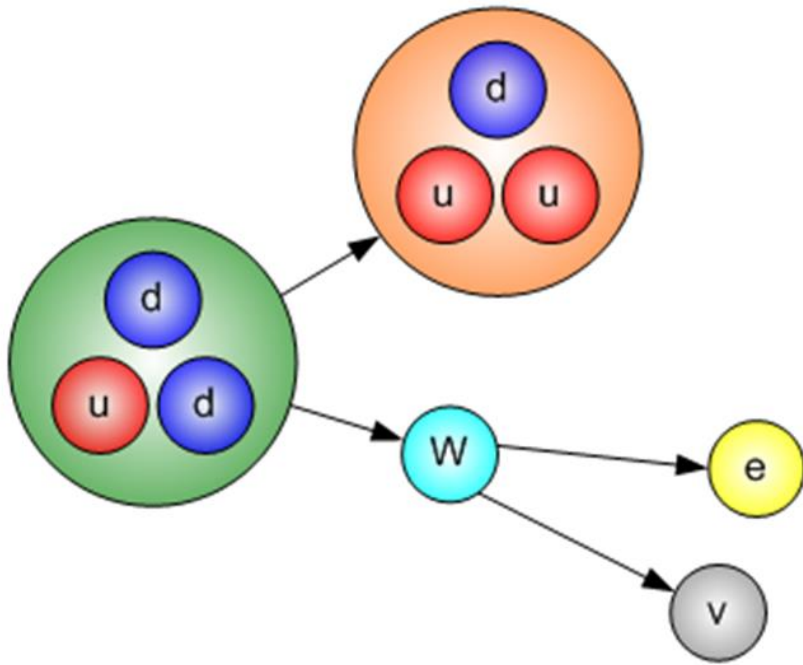
- Quark
- Lepton
- Fermion
- Boson
- Baryon
- Meson
- Hadron

Particles and fields – Cross-sections

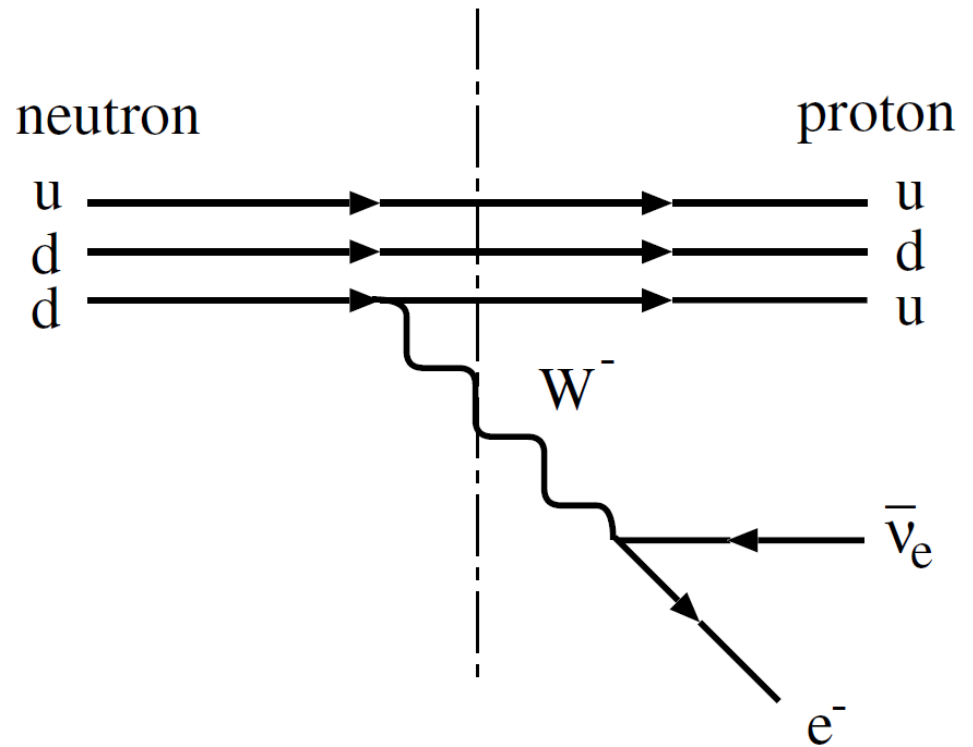
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Feynman diagrams



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 $g_{\text{EM}} = Qe$, where the fine structure constant is given by

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

- The weak coupling constant is

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

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

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

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

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.

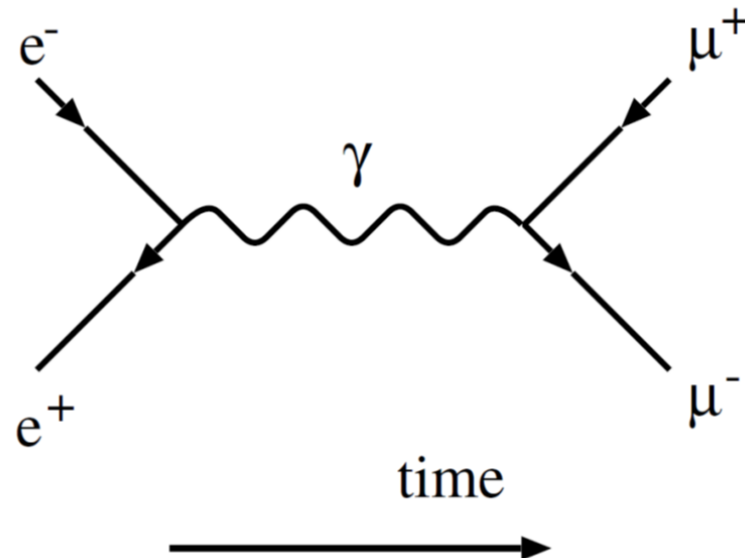
In many cases, $\phi \propto s$ for large energies.

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.

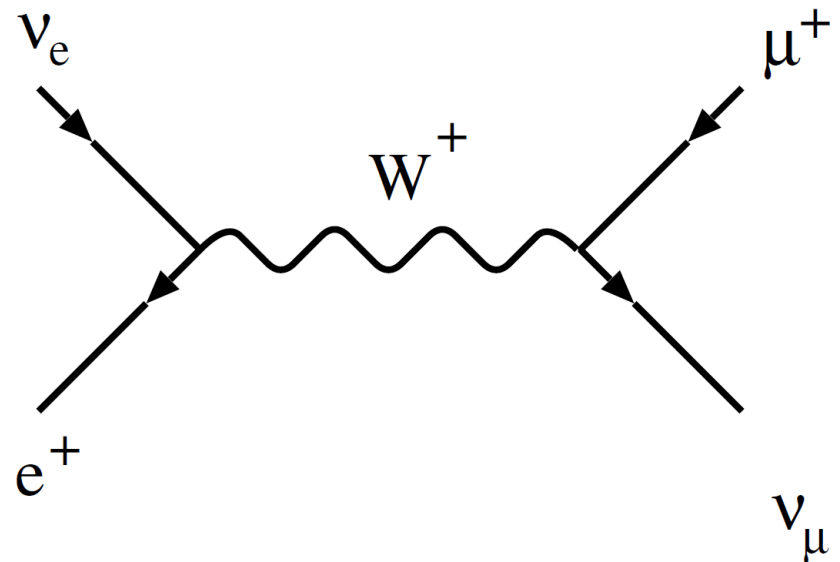


Weak interaction example

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

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

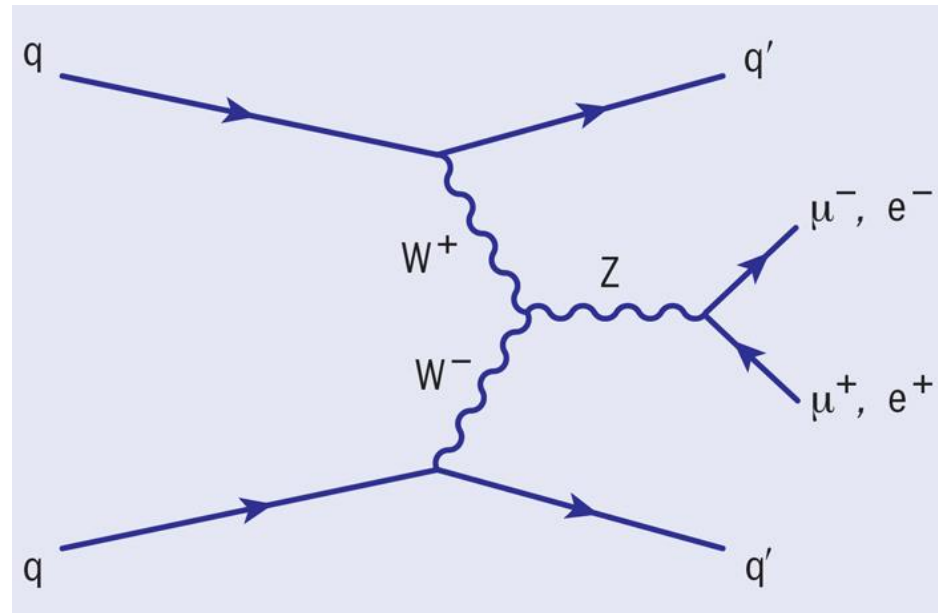
- Putting the cut-off scale to the Planck energy, we obtain

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

- 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

$\approx 2.4 \text{ MeV}/c^2$
2/3
1/2
u
up

$\approx 1.275 \text{ GeV}/c^2$
2/3
1/2
c
charm

$\approx 172.44 \text{ GeV}/c^2$
2/3
1/2
t
top

0
0
1
g
gluon

$\approx 125.09 \text{ GeV}/c^2$
0
0
0
H
Higgs

$\approx 4.8 \text{ MeV}/c^2$
-1/3
1/2
d
down

$\approx 95 \text{ MeV}/c^2$
-1/3
1/2
s
strange

$\approx 4.18 \text{ GeV}/c^2$
-1/3
1/2
b
bottom

0
0
1
 γ
photon

dark energy?

$\approx 0.511 \text{ MeV}/c^2$
-1
1/2
e
electron

$\approx 105.67 \text{ MeV}/c^2$
-1
1/2
 μ
muon

$\approx 1.7768 \text{ GeV}/c^2$
-1
1/2
 τ
tau

$\approx 91.19 \text{ GeV}/c^2$
0
1
Z
Z boson

inflaton?

$< 2.2 \text{ eV}/c^2$
0
1/2
 ν_e
electron neutrino

$< 1.7 \text{ MeV}/c^2$
0
1/2
 ν_μ
muon neutrino

$< 15.5 \text{ MeV}/c^2$
0
1/2
 ν_τ
tau neutrino

$\approx 80.39 \text{ GeV}/c^2$
 ± 1
1
W
W boson

graviton(s)