

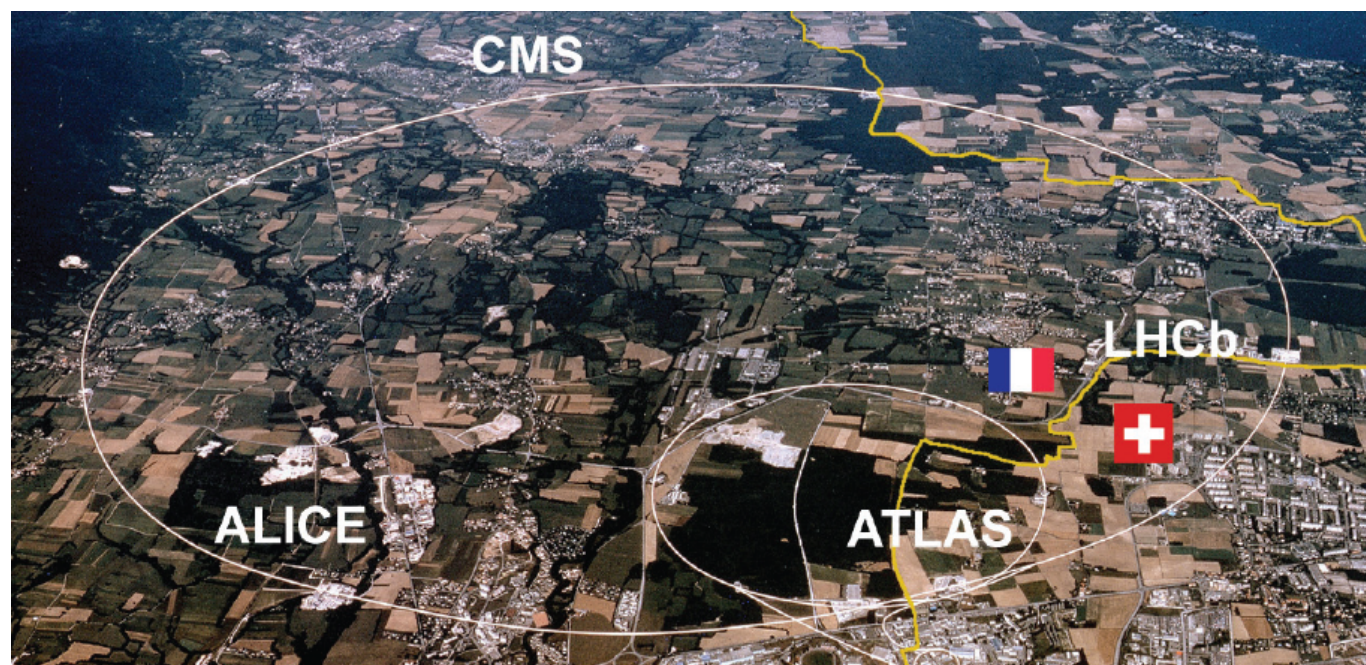
Particle Physics: Introduction

Yeon-jae Jwa

Week 1: September 22nd, 2018
Columbia University Science Honors Program

Welcome!

- Yeon-jae Jwa
- 3rd year graduate student in physics in MicroBooNE, DUNE @ Fermilab
- Master's thesis in CMS experiment @ CERN



Class Schedule

Date	Topic
Week 1 (9/22/18)	Introduction
Week 2 (9/29/18)	History of Particle Physics
Week 3 (10/6/18)	Special Relativity
Week 4 (10/13/18)	Quantum Mechanics
Week 5 (10/20/18)	Experimental Methods
Week 6 (10/27/18)	The Standard Model - Overview
Week 7 (11/3/18)	The Standard Model - Limitations
Week 8 (11/10/18)	Neutrino Theory
Week 9 (11/17/18)	Neutrino Experiment
Week 10 (12/1/18)	LHC and Experiments
Week 11 (12/8/18)	The Higgs Boson and Beyond
Week 12 (12/15/18)	Particle Cosmology

Class Policy

- Classes from 10:00 AM to 12:30 PM (10 min break at ~ 11:10 AM).
- Attendance record counts.
- Up to four absences
- Lateness or leaving early counts as half-absence.
- Send email notifications of all absences to shpattendance@columbia.edu.

Class Policy

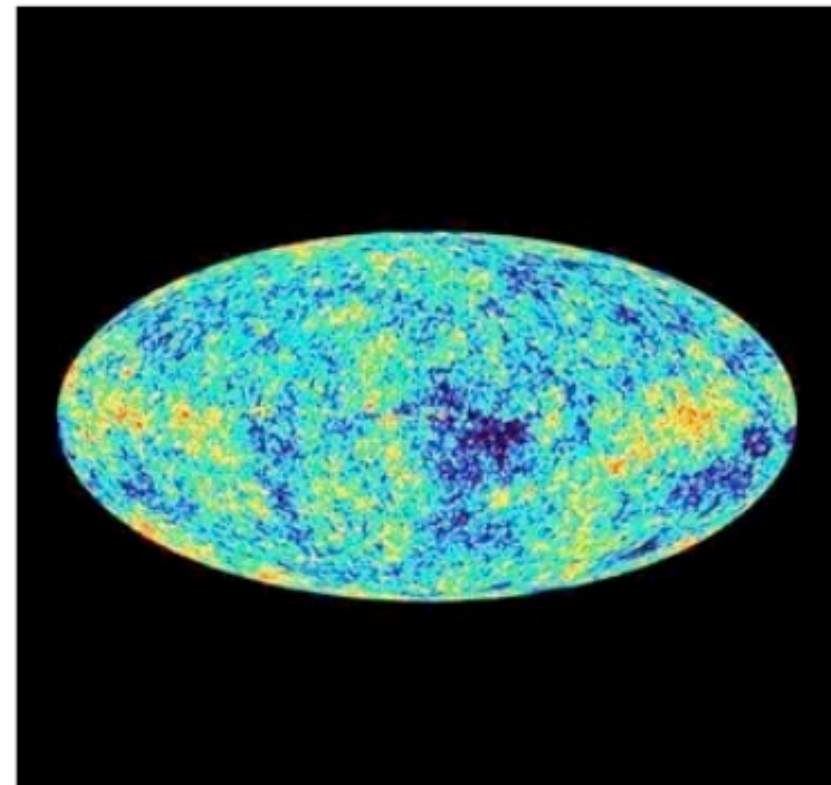
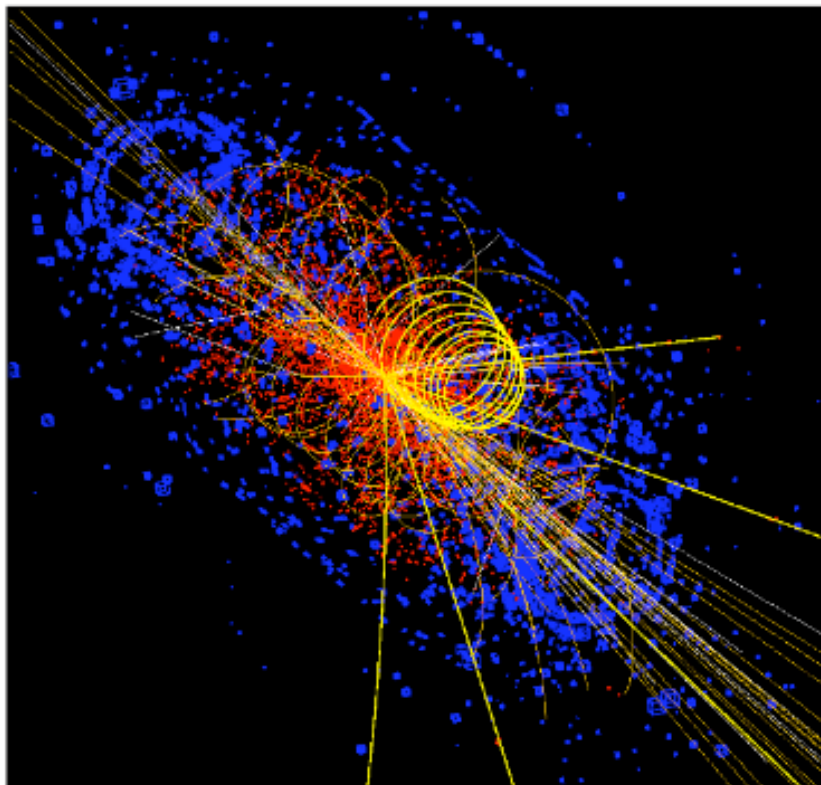
- No cell phone uses during the class.
- Feel free to step outside to the hall way in case of emergencies, bathrooms, starvations.
- Feel free to stop me and ask questions / ask for clarifications.
- Resources for class materials, Research Opportunities + Resources to become a particle physicist

<https://twiki.nevis.columbia.edu/twiki/pub/Main/ScienceHonorsProgram>

**Introduce yourself to
the class**

What is Particle Physics?

- Particle physicists explore the most basic components of our natural world:
 - **Particles!**
- Not just particles though, also their **interactions**, and how they become the things we see around us.
- This leads us from the littlest things to the the biggest things: from the Big Bang and the basic constituents of our universe, to its large scale structure, the interiors of stars and even extra dimensions of space.



Power of tens

<https://www.youtube.com/watch?v=0fKBhvDjuy0>

Quiz: What is a particle?

- Elementary(fundamental) particles; unbreakable
 - - Quarks, leptons, gauge bosons, scalar boson
- Composite particles; breakable
 - - Hadrons (Baryons, Mesons), Atomic nuclei, Atoms, Molecules

**Can you tell
(electron, proton, neutron, neutrino, anti-electron)
are composite particles or elementary particles?**

What consists the universe?

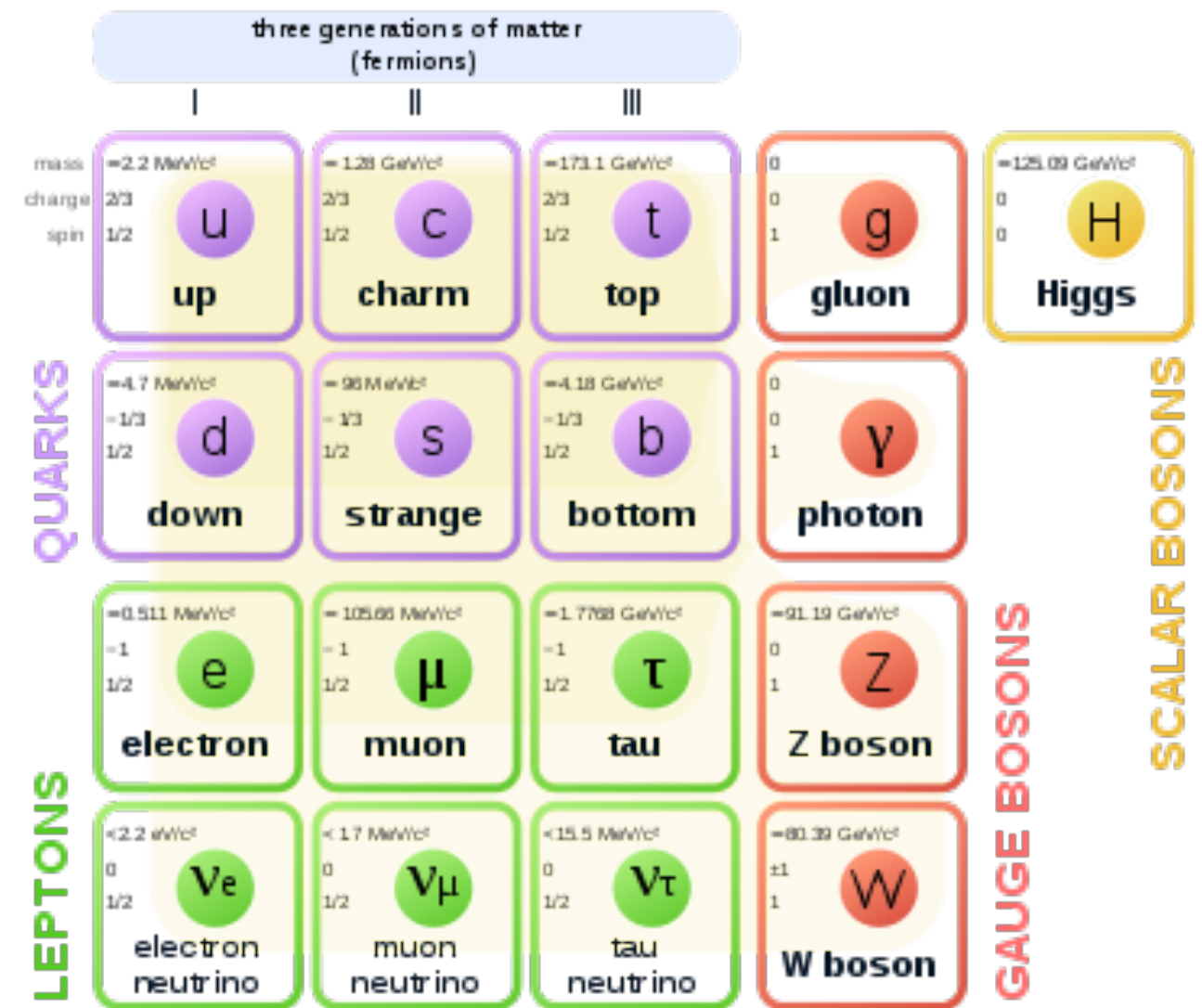
From a chemist's point of view

Periodic Table of Elements

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18														
1 H Hydrogen 1.00794	2 He Helium 4.002602																														
		[C] Solid		Metals										Nonmetals				2 He Helium 4.002602													
3 Li Lithium 6.941	4 Be Beryllium 9.012182	[Hg] Liquid		Alkali metals				Lanthanoids		Transition metals	Poo metals		Other nonmetals	Noble gases		9 F Fluorine 18.9984032	10 Ne Neon 20.1797														
5 B Boron 10.811	6 C Carbon 12.0107	7 N Nitrogen 14.0067	8 O Oxygen 15.9994											13 Al Aluminum 26.9815386	14 Si Silicon 28.0855	15 P Phosphorus 30.973762	16 S Sulfur 32.065	17 Cl Chlorine 35.453	18 Ar Argon 39.948												
9 Na Sodium 22.98976928	10 Mg Magnesium 24.3050	[Rf] Unknown												19 K Potassium 39.0983	20 Ca Calcium 40.078	21 Sc Scandium 44.955912	22 Ti Titanium 47.867	23 V Vanadium 50.9415	24 Cr Chromium 51.9961	25 Mn Manganese 54.938045	26 Fe Iron 55.845	27 Co Cobalt 58.933195	28 Ni Nickel 58.6934	29 Cu Copper 63.546	30 Zn Zinc 65.38	31 Ga Gallium 69.723	32 Ge Germanium 72.64	33 As Arsenic 74.92160	34 Se Selenium 78.96	35 Br Bromine 79.904	36 Kr Krypton 83.798
37 Rb Rubidium 85.4678	38 Sr Strontium 87.62	39 Y Yttrium 88.90585	40 Zr Zirconium 91.224	41 Nb Niobium 92.90638	42 Mo Molybdenum 95.94	43 Tc Technetium (97.9072)	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.90550	46 Pd Palladium 106.42	47 Ag Silver 107.8682	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.710	51 Sb Antimony 121.760	52 Te Tellurium 127.60	53 I Iodine 126.90447	54 Xe Xenon 131.293														
55 Cs Cesium 132.9054519	56 Ba Barium 137.327	57–71		72 Hf Hafnium 178.49	73 Ta Tantalum 180.94788	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.222	78 Pt Platinum 195.084	79 Au Gold 196.966569	80 Hg Mercury 200.59	81 Tl Thallium 204.3833	82 Pb Lead 207.2	83 Bi Bismuth 208.98040	84 Po Polonium (209)	85 At Astatine (210)	86 Rn Radon (222.0176)													
87 Fr Francium (223)	88 Ra Radium (226)	89–103		104 Rf Rutherfordium (261)	105 Db Dubnium (262)	106 Sg Seaborgium (266)	107 Bh Bohrium (264)	108 Hs Hassium (277)	109 Mt Meitnerium (268)	110 Ds Darmstadtium (271)	111 Rg Roentgenium (272)	112 Uub Ununbium (285)	113 Uut Ununtrium (284)	114 Uuq Ununquadium (289)	115 Uup Ununpentium (288)	116 Uuh Ununhexium (292)	117 Uus Ununseptium (294)	118 Uuo Ununoctium (294)													
For elements with no stable isotopes, the mass number of the isotope with the longest half-life is in parentheses.																															
Design and Interface Copyright © 1997 Michael Dayah (michael@dayah.com). http://www.ptable.com/																															
57 La Lanthanum 138.90547	58 Ce Cerium 140.116	59 Pr Praseodymium 140.90765	60 Nd Neodymium 144.242	61 Pm Promethium (145)	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.92535	66 Dy Dysprosium 162.50	67 Ho Holmium 164.93032	68 Er Erbium 167.259	69 Tm Thulium 168.93421	70 Yb Ytterbium 173.054	71 Lu Lutetium 174.965	89 Ac Actinium 227.0277	90 Th Thorium 232.0377	91 Pa Protactinium 231.03688	92 U Uranium 238.02891	93 Np Neptunium 237.04817	94 Pu Plutonium 244	95 Am Americium 243	96 Cm Curium 247	97 Bk Berkelium 247	98 Cf Californium 251	99 Es Einsteinium 252	100 Fm Fermium 257	101 Md Mendelevium 258	102 No Nobelium 259	103 Lr Lawrencium 262		

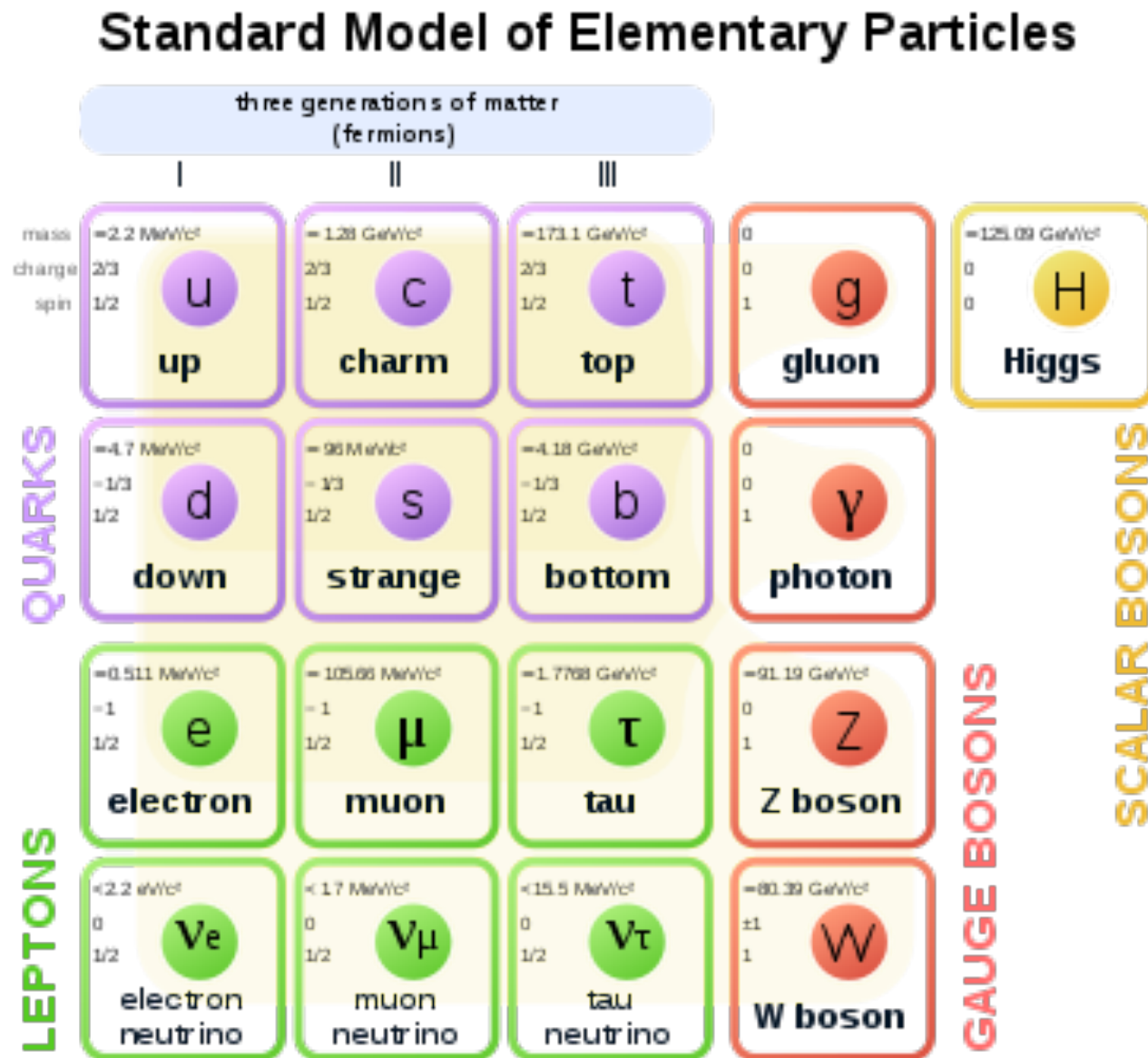
From a physicist's point of view

Standard Model of Elementary Particles



Quarks, leptons, gauge bosons, scalar bosons

What consists the universe?

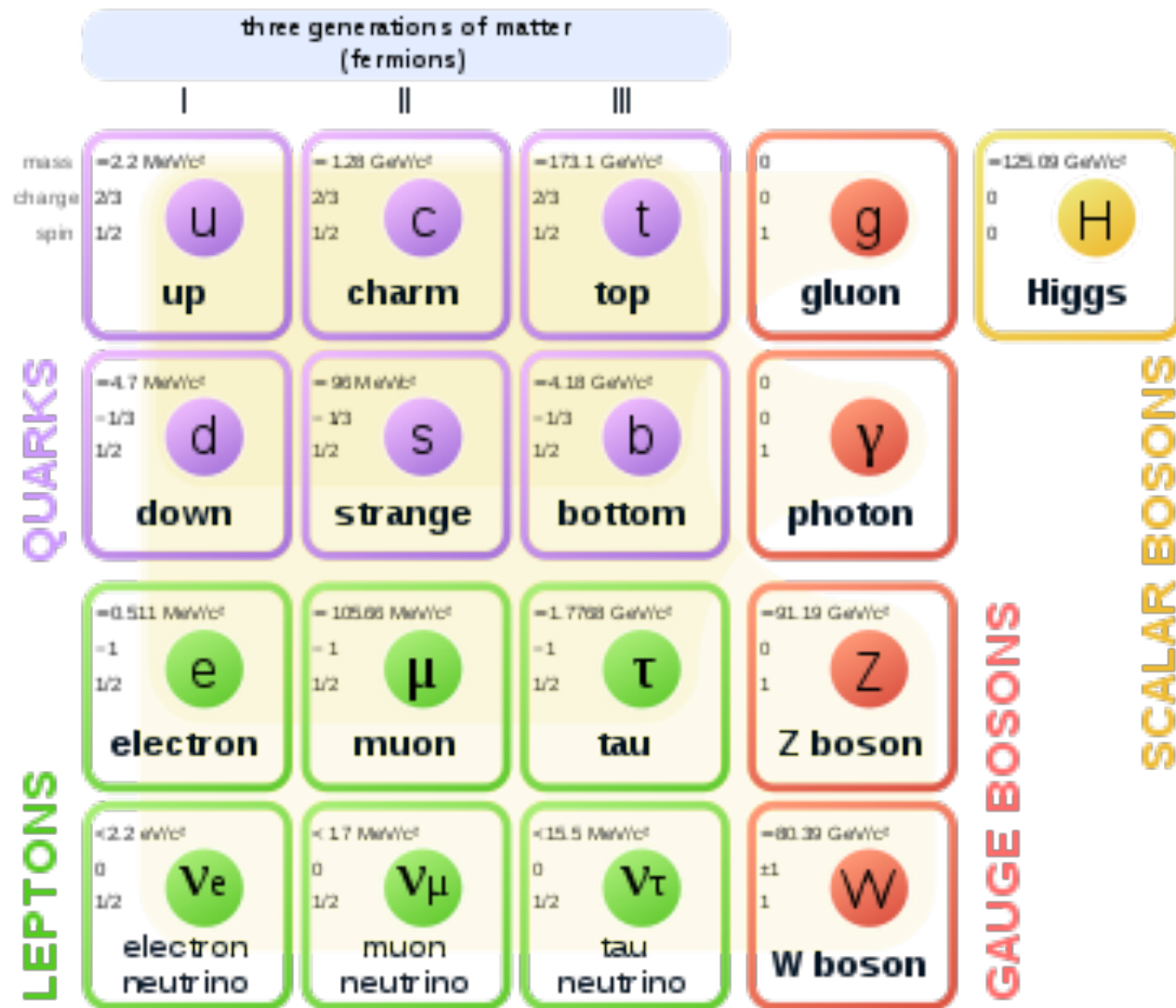


Our current model of matter consists of point-like particles ($<10^{-18}\text{m}$), *interacting* through four forces.
 -> More about this later

3 generations in elementary particles
 - 1st, 2nd, 3rd generations

What consists the universe?

Standard Model of Elementary Particles



Mass!

First generation

 v_e e^{-}

d

u

Second generation

 v_μ μ^-

S

C

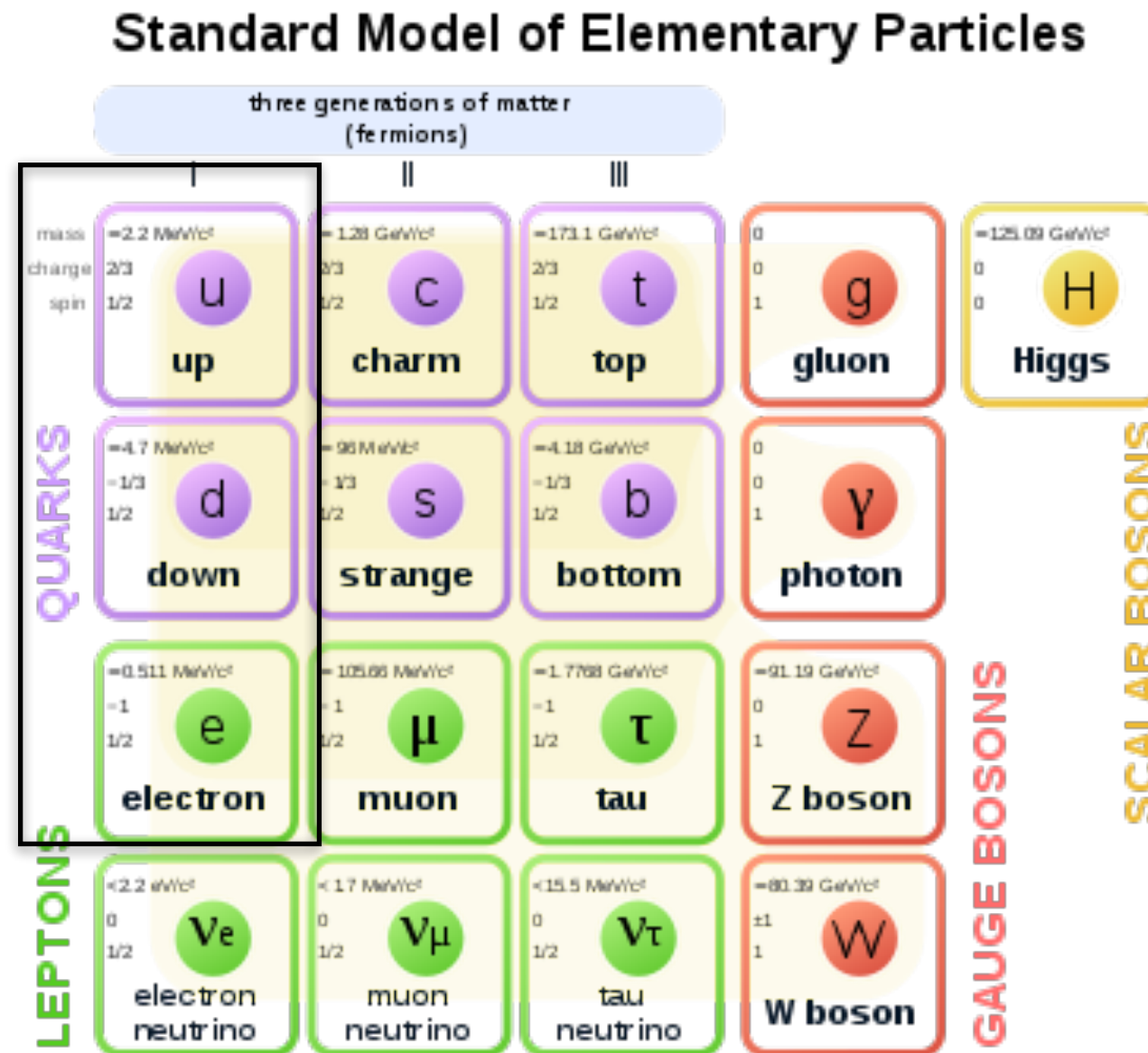
Third generation

 v_τ τ^-

b

t

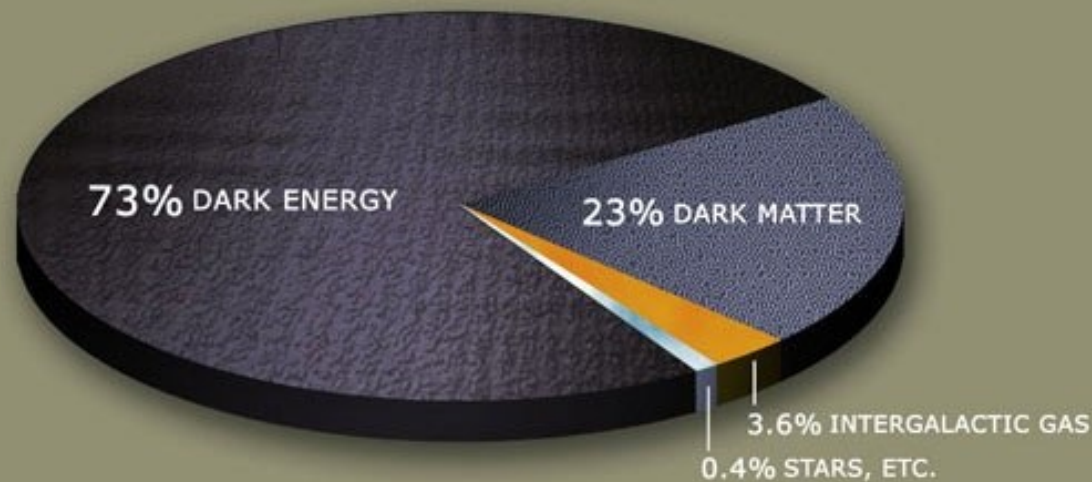
What consists our body?



Is that all?

Do we truly know what consists the universe?

73% of dark energy, 23% of dark matter, 4% of ordinary matter



Not even close!

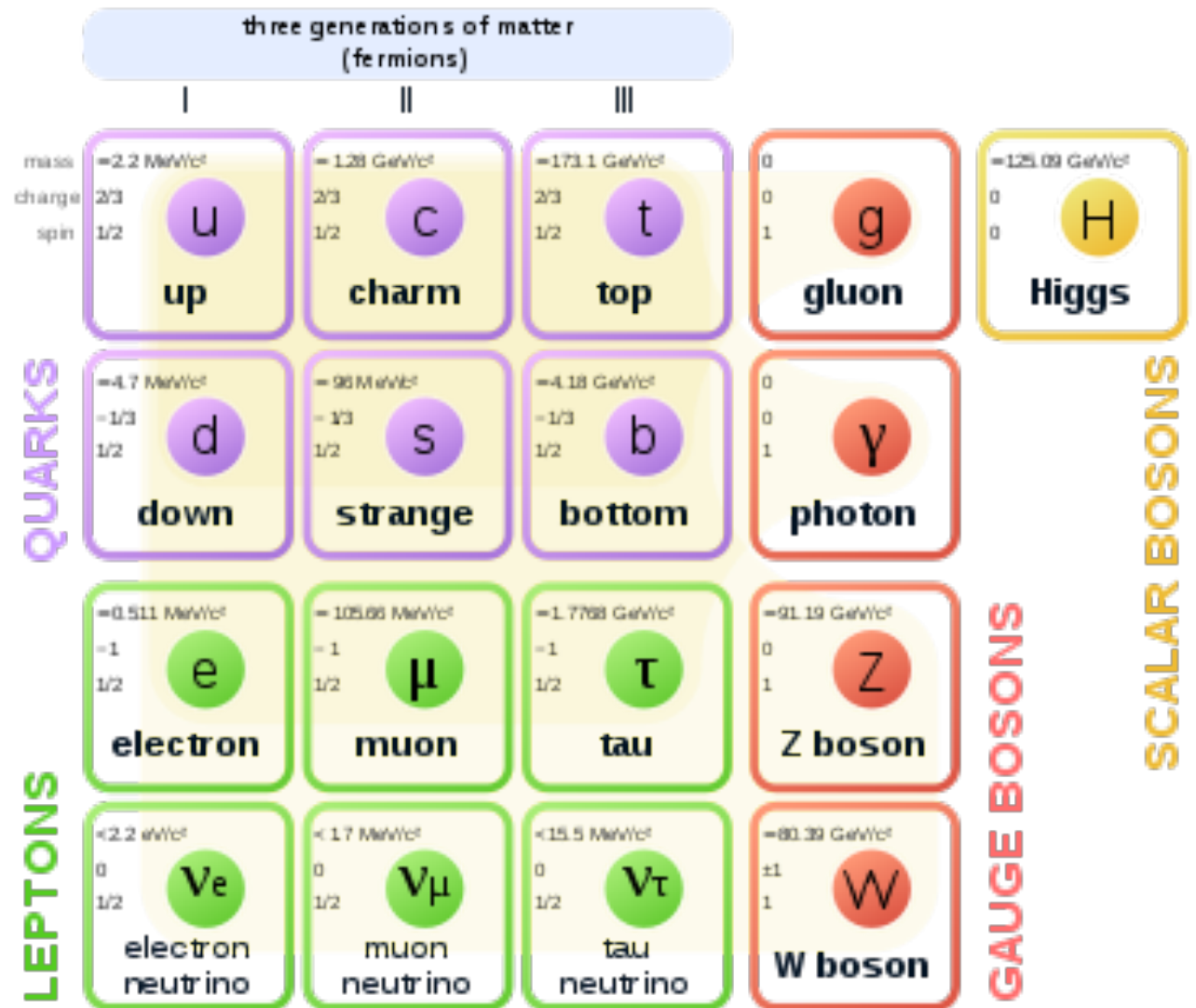
Lol...

What consists the universe :

Ordinary matter Ver. : <https://www.youtube.com/watch?v=CBZH4dMac-Q>

Dark side included Ver. : https://www.youtube.com/watch?v=QAa2O_8wBUQ&t=4s

Standard Model of Elementary Particles



A list of mysteries

- What is the “dark matter” that makes up a quarter of the universe?
- What is the “dark energy” that is causing the universe to expand at an increasing rate?
- Why was there slightly more matter than antimatter in the very early universe?
- Why do particles have the masses that they have?
- Why is gravity much weaker than other forces?
- How do neutrinos fit into the picture?
- And more ...

A list of mysteries

The real perk of being a particle physicist

- What is the “c
- increasing rate
- Why was there
- universe?
- Why do partic
- Why is gravity
- How do neutr
- And more ...



How matter interacts (on the chalk board)



The mediators carry momentum (energy) between two interacting particles, thereby transmitting the force between them.

How matter interacts: the four forces

- Evidence suggests that all interactions in our universe can be understood in terms of four fundamental forces:
 - Electromagnetism (photon exchange)
 - Weak interactions (W, Z exchange)
 - Strong interactions (gluon exchange)
 - Gravity (“graviton” exchange? Not yet observed.)
- } The Standard Model
- This model is phenomenological: we know there are four forces, but we don’t know why.
 - Current thinking: the four forces are actually different manifestations of a single field. This field is unified at sufficiently high energies (e.g., right after the Big Bang).

How matter interacts

Table 1.2 The forces experienced by different particles.

					strong	electromagnetic	weak
Quarks	down-type	d	s	b	✓	✓	✓
	up-type	u	c	t			
Leptons	charged	e^-	μ^-	τ^-		✓	✓
	neutrinos	ν_e	ν_μ	ν_τ			✓

Quarks experience strong, electromagnetic, weak interactions
 Charged leptons experience electromagnetic, weak interactions
 Neutrinos experience weak interactions

Table 1.3 The four known forces of nature. The relative strengths are approximate indicative values for two fundamental particles at a distance of $1 \text{ fm} = 10^{-15} \text{ m}$ (roughly the radius of a proton).

Force	Strength	Boson		Spin	Mass/GeV
Strong	1	Gluon	g	1	0
Electromagnetism	10^{-3}	Photon	γ	1	0
Weak	10^{-8}	W boson	W^\pm	1	80.4
		Z boson	Z	1	91.2
Gravity	10^{-37}	Graviton?	G	2	0

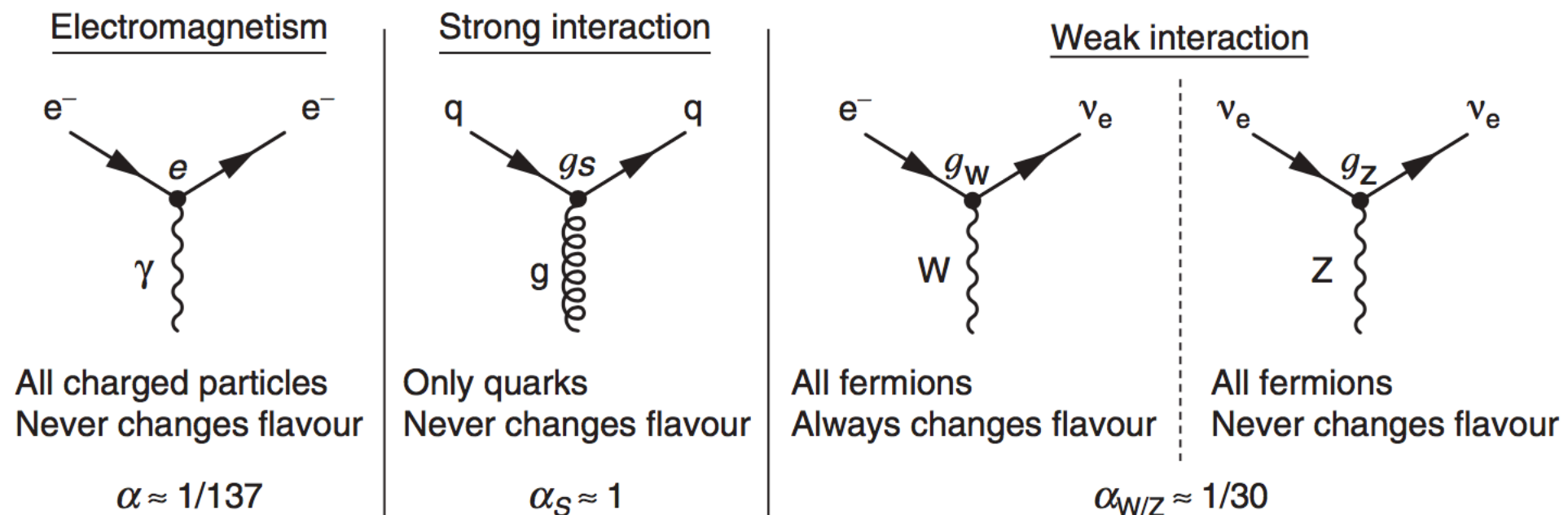
#Note

Boson means a particle with spin value 0, 1, 2, 3, ...
 Fermion means a particle with spin value 1/2, 3/2, ...

Forces are mediated by gauge bosons

How matter interacts

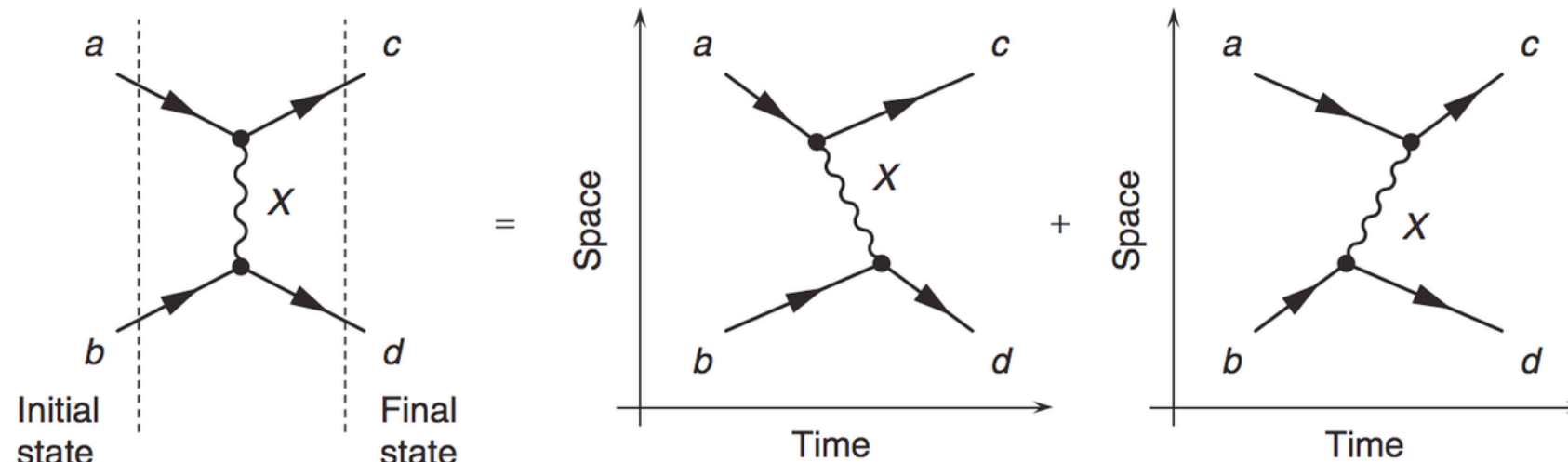
- The Standard Model vertices



The strengths of interactions are usually expressed with α

How matter interacts

- Feynman diagram for $a+b \rightarrow c+d$



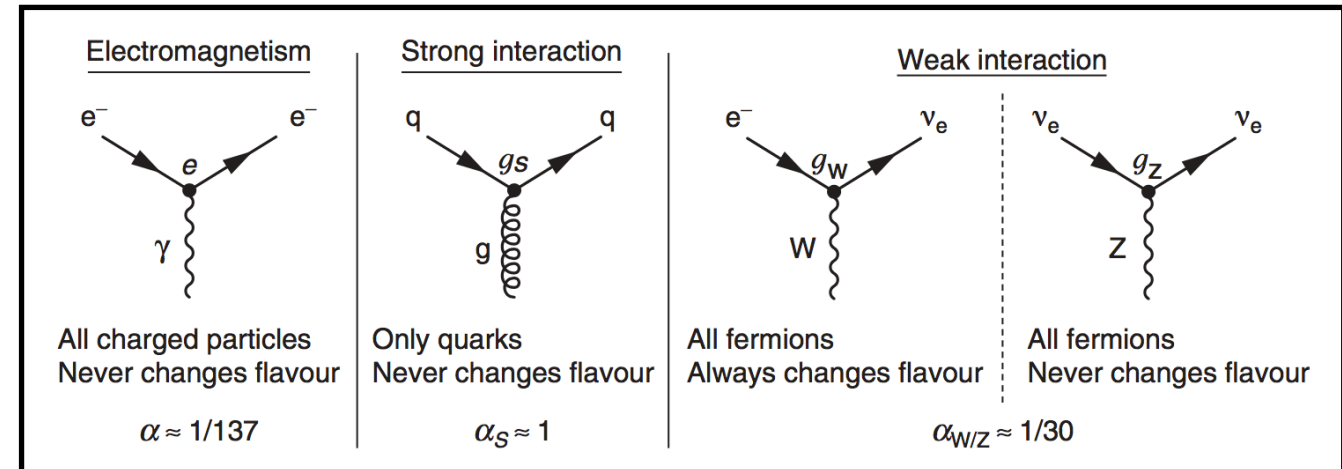
The Feynman diagram for the scattering process $a + b \rightarrow c + d$ and the two time-ordered processes that it represents.

Graphical representation of particle interactions

Momentum transfer (by gauge boson) is in the middle, outer lines are incoming particles and outgoing particles. In this example, there are two possible time ordering. However, since the exchanged particle is not observed, only the combined effect of these two time-ordered diagrams is physically meaningful.

How matter interacts

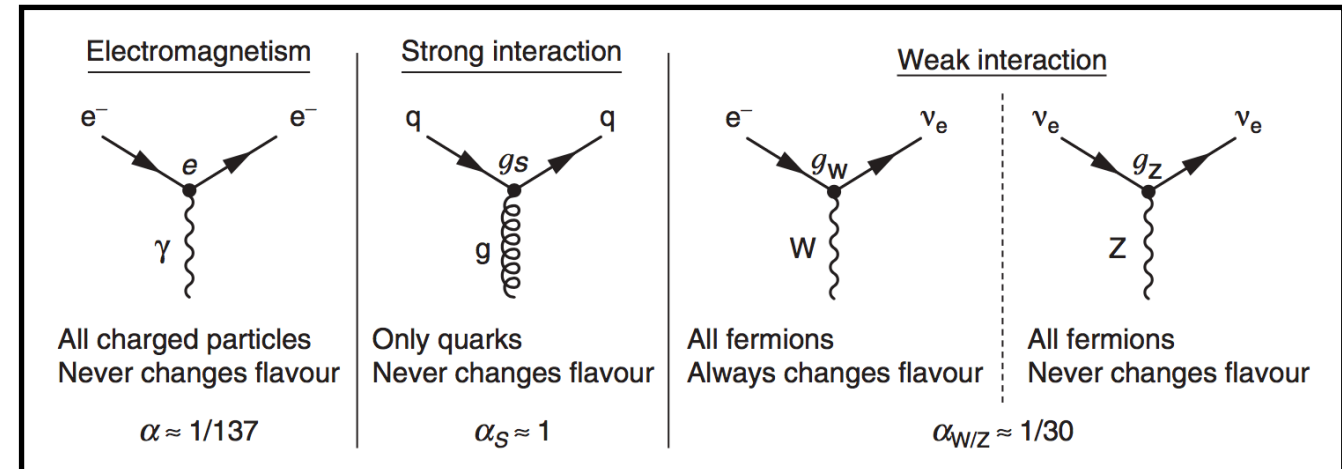
- **Examples of Feynman diagrams**



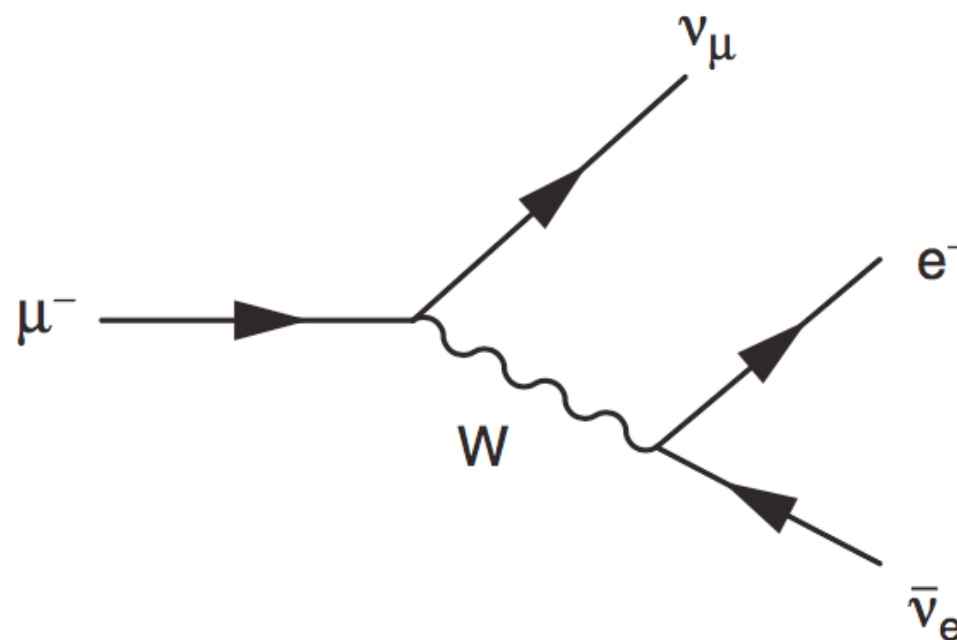
Muon -> electron + 2 neutrinos

How matter interacts

- Examples of Feynman diagrams

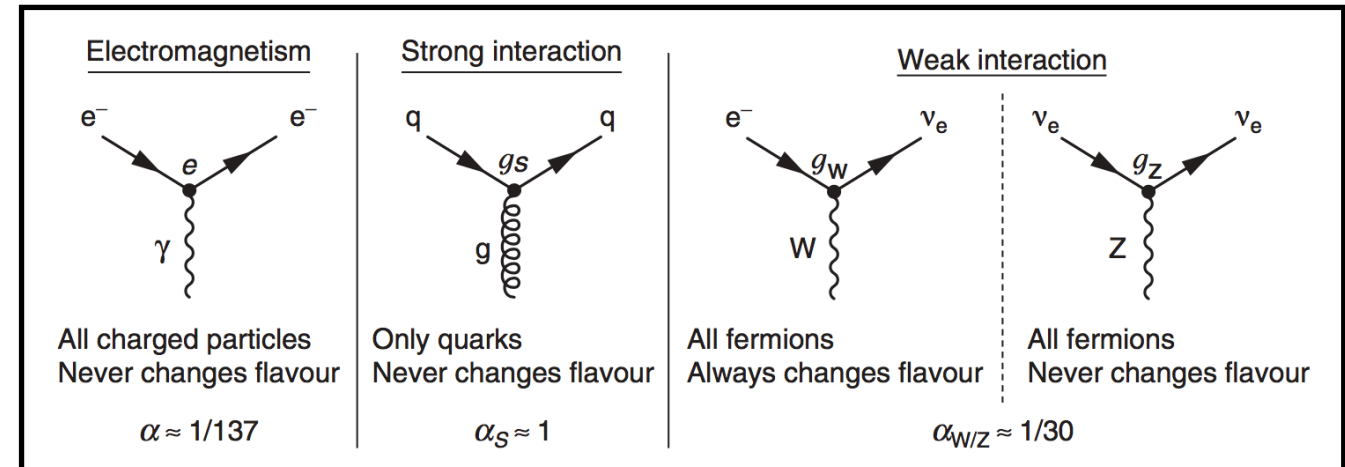


Muon \rightarrow electron + 2 neutrinos



How matter interacts

- **Examples of Feynman diagrams**



Beta decay

Neutron \rightarrow Proton + electron + neutrino

Hint:

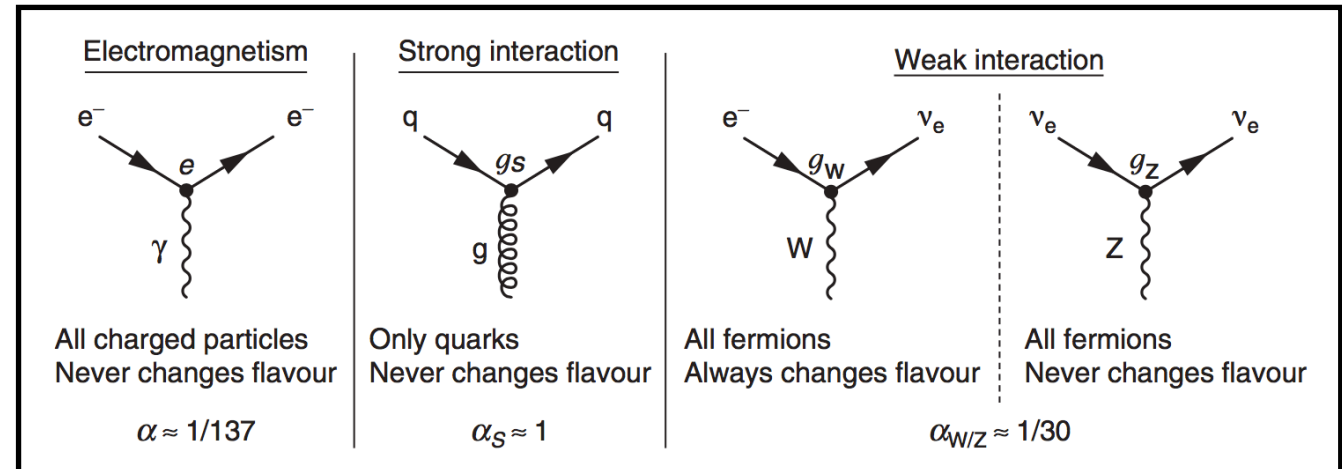
**Neutron has 1 up quark (+2/3 e),
2 down quark (-1/3 e).**

**Proton has 2 up quarks and 1
down quark.**

**Electromagnetic charge should
be conserved.**

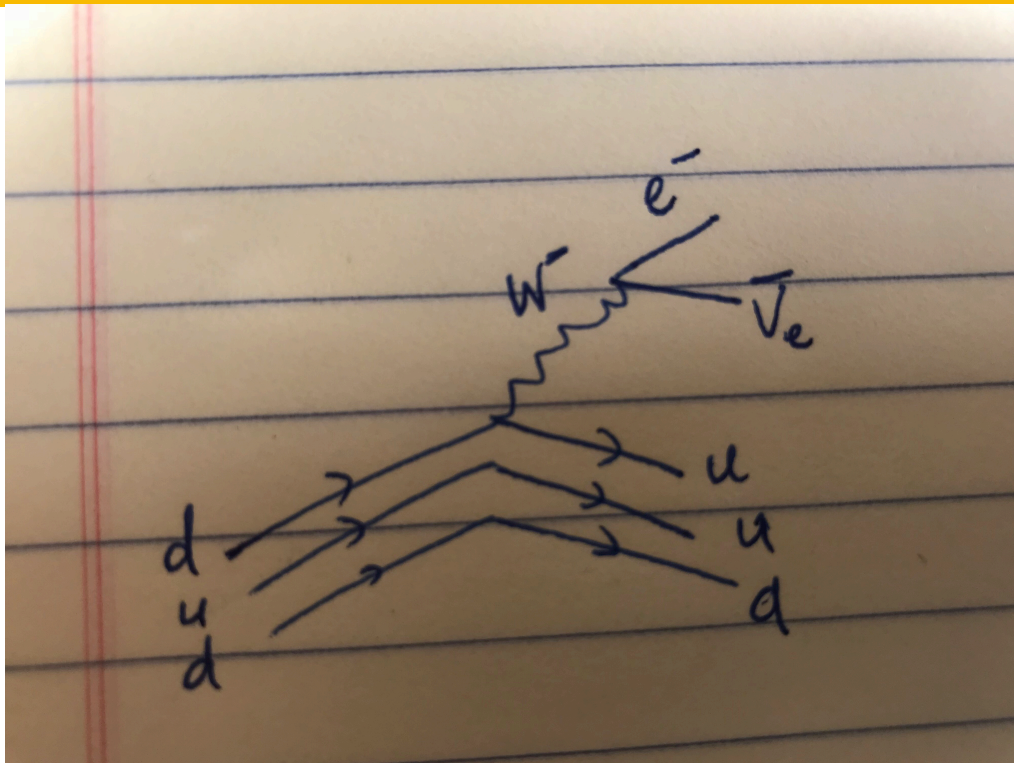
How matter interacts

- Examples of Feynman diagrams



Beta decay

Neutron \rightarrow Proton + electron + neutrino



Hint:

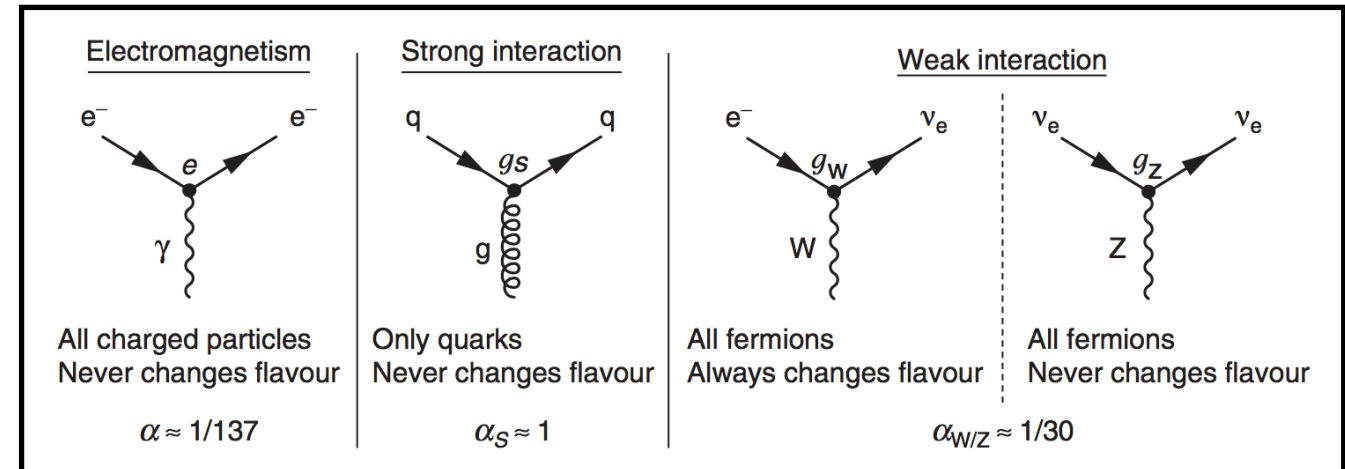
**Neutron has 1 up quark (+2/3 e),
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How matter interacts

- Examples of Feynman diagrams

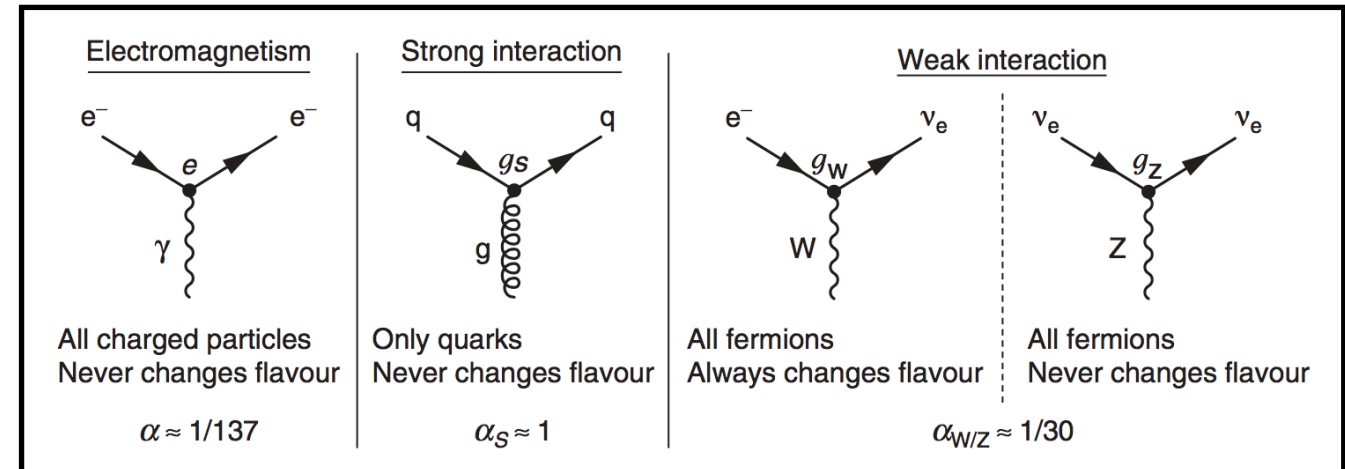


e+, e- pair annihilation

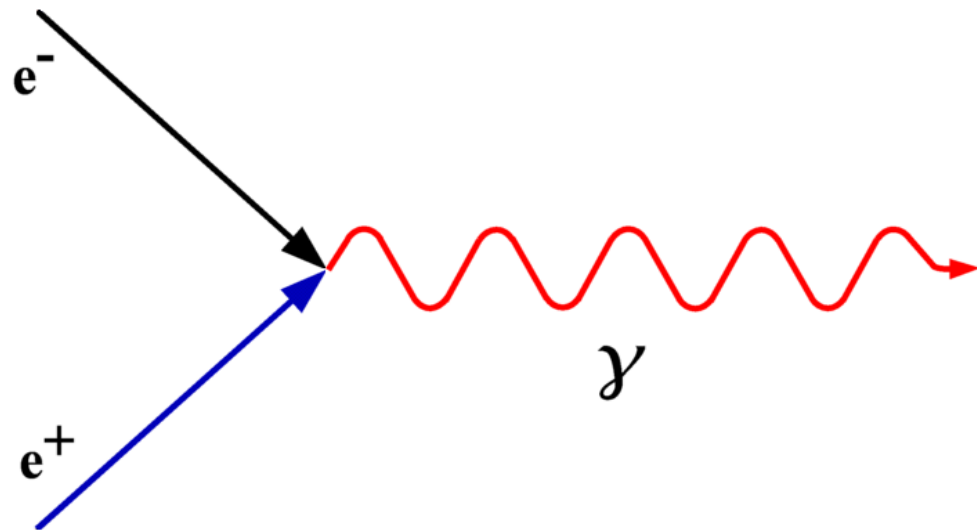
Hint:
Elementary particle and its anti-particle can annihilate

How matter interacts

- Examples of Feynman diagrams



e+, e- pair annihilation



Hint:
Elementary particle and its anti-particle can annihilate

Foundations of Particle Theory

- Particle physics is the study of the smallest constituents of matter.
- At these size scales, matter behaves quite differently than in the macroscopic world.
 - Here, particles obey the rules of quantum mechanics.
 - Moreover, to observe the smallest size scales, we must accelerate particles to very high energies, near the speed of light, c . At these speeds, Newtonian mechanics is superseded by special relativity.
- Elementary particle physics describes objects that are both *very small and very fast*.
- Physicists developed a theoretical framework that incorporates relativistic and quantum principles: **Quantum Field Theory**.

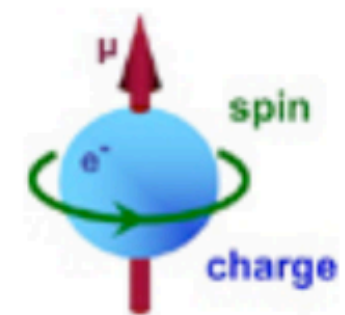
Field Theory and the Standard Model

- Quantum field theory (QFT) is the sophisticated mathematical infrastructure of particle physics. It tells us the dynamics of elementary particles - that is, how to use force laws to describe subatomic behavior.
- While QFT is itself quite challenging, its main product - **the Standard Model of particle physics** - is conceptually straightforward.
- Some parts of the Standard Model perform incredibly well, for example, Quantum Electrodynamics. Its predictions match experiment with **stunning** accuracy!
 - Actually, these are the most precise predictions and measurements in Science.

$$\mu_{\text{electron}} = 1.00115965219 \pm 0.000000000001 \mu_B \text{ (measured)}$$

$$\mu_{\text{electron}} = 1.00115965217 \pm 0.000000000003 \mu_B \text{ (QED prediction)}$$

(PDG, 2002)



Quiz: Interactions

- Name 4 interactions
- Name the mediating particles for those interactions
- Classify them to fermions or bosons

Class Survey

- Name / Year
- Favorite subject
- What made you register for SHP particle physics?
- What are you most excited to learn from this class?
- What is the most exciting thing in physics for you?
- Any physics/ research in physics related questions?
(Optional)