

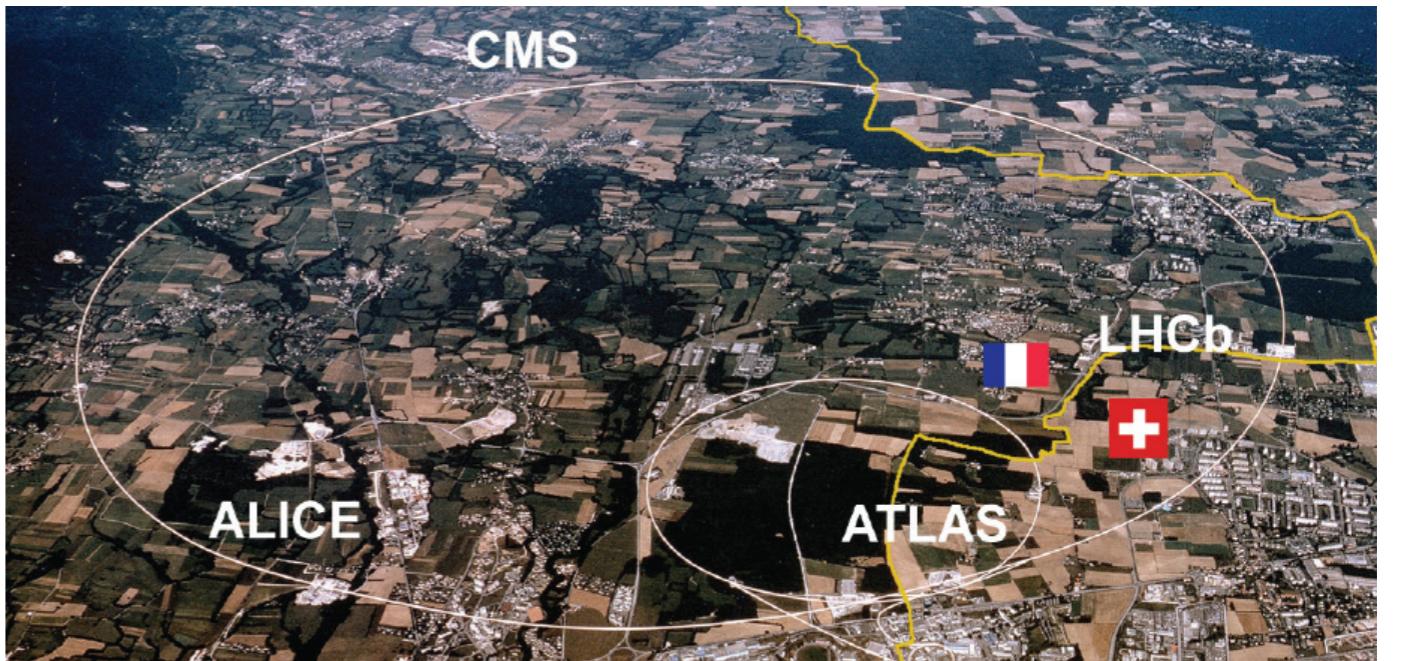
Particle Physics: Introduction

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

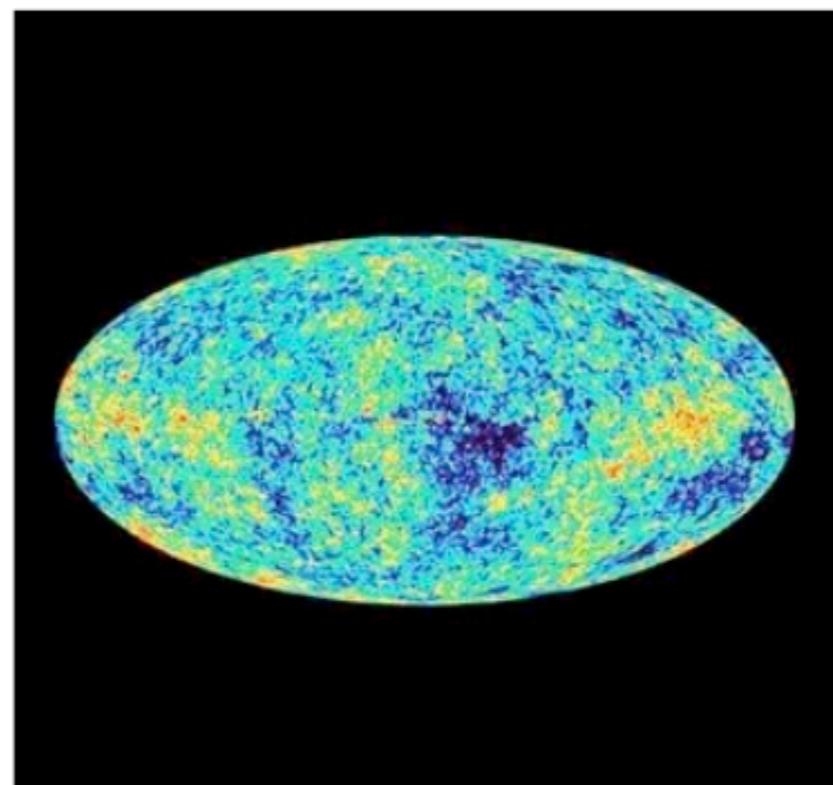
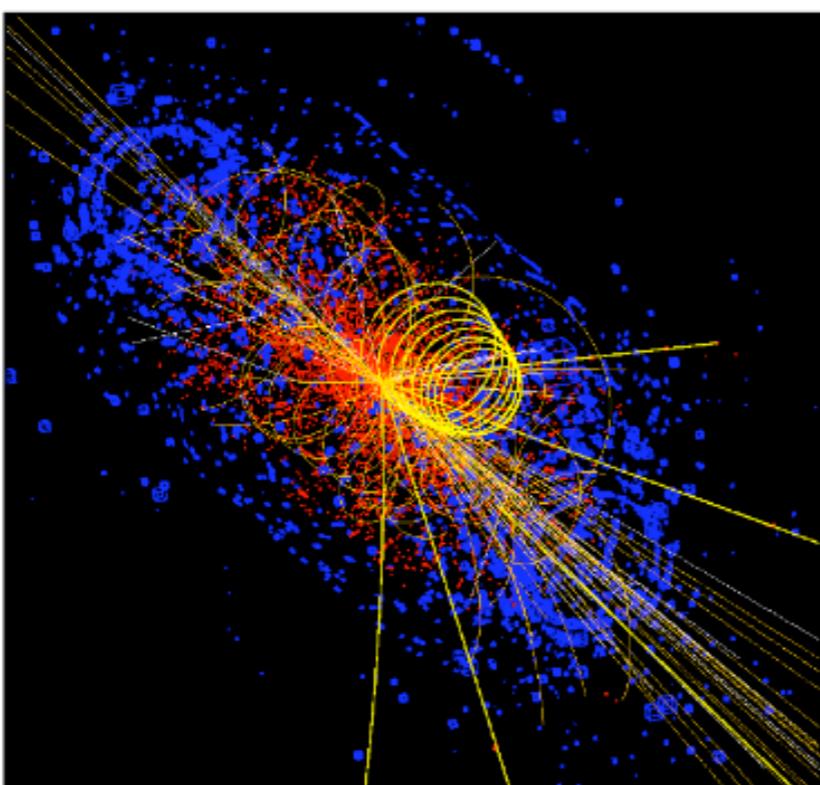
- No cell phone uses during the class.
- Feel free to step outside to the hall way in case of emergencies, bathrooms, starvations.
- Feel free to stop me and ask questions / ask for clarifications.
- Resources for class materials, Research Opportunities + Resources to become a particle physicist

<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

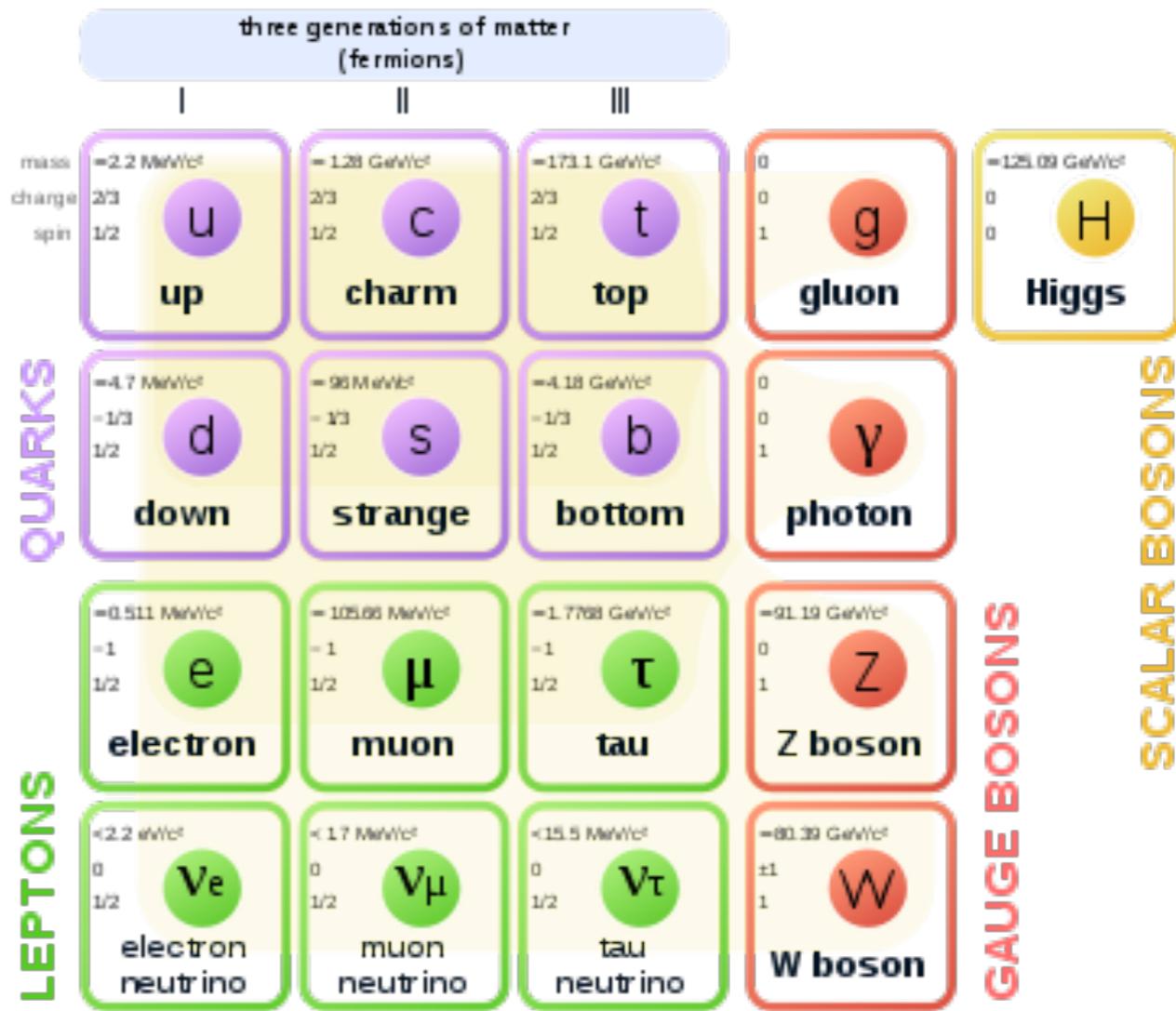
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18																																																																								
1 H Hydrogen 1.00794	2 He Helium 4.002602	3 Li Lithium 6.941	4 Be Beryllium 9.01162	5 B Boron 10.811	6 C Carbon 12.0107	7 N Nitrogen 14.0067	8 O Oxygen 15.9994	9 F Fluorine 18.998422	10 Ne Neon 20.1797	11 Na Sodium 22.98979828	12 Mg Magnesium 24.3205	13 Al Aluminum 26.9815399	14 Si Silicon 28.0955	15 P Phosphorus 30.973762	16 S Sulfur 32.065	17 Cl Chlorine 35.453	18 Ar Argon 39.949	19 K Potassium 39.0983	20 Ca Calcium 40.078	21 Sc Scandium 44.959512	22 Ti Titanium 47.887	23 V Vanadium 50.9415	24 Cr Chromium 51.9951	25 Mn Manganese 54.938045	26 Fe Iron 55.845	27 Co Cobalt 58.933195	28 Ni Nickel 58.934	29 Cu Copper 63.545	30 Zn Zinc 65.38	31 Ga Gallium 69.723	32 Ge Germanium 72.64	33 As Arsenic 74.92165	34 Se Selenium 75.95	35 Br Bromine 79.904	36 Kr Krypton 83.788	37 Rb Rubidium 84.419	38 Sr Strontium 87.62	39 Y Yttrium 88.9065	40 Zr Zirconium 91.224	41 Nb Niobium 92.90938	42 Mo Molybdenum 95.95	43 Tc Technetium 97.902	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.96501	46 Pd Palladium 106.42	47 Ag Silver 107.8692	48 Cd Cadmium 112.411	49 In Indium 114.819	50 Sn Tin 118.710	51 Sb Antimony 121.795	52 Te Tellurium 127.95	53 I Iodine 126.90447	54 Xe Xenon 131.293	55 Cs Cesium 132.904519	56 Ba Barium 137.327	57-71	72 Hf Hafnium 178.49	73 Ta Tantalum 180.94788	74 W Tungsten 183.84	75 Os Osmium 188.207	76 Ir Iridium 190.23	77 Pt Platinum 191.217	78 Pt Platinum 195.084	79 Au Gold 196.96659	80 Hg Mercury 200.59	81 Tl Thallium 204.3833	82 Pb Lead 207.2	83 Bi Bismuth 208.96840	84 Po Polonium (208.9624)	85 At Astatine (210.9631)	86 Rn Radium (222.0178)	87 R Radium 226.0259	88 Rf Rutherfordium 261.0259	89-103	104 Rf Rutherfordium 261.0259	105 Db Dubnium 264.0259	106 Bh Berkelium 265.0259	107 Hs Hassium 266.0259	108 Mt Mendelevium 268.0259	109 Ds Darmstadtium 281.0259	110 Rg Rutherfordium 283.0259	111 Uub Ununbium 284.0259	112 Uup Ununtrium 285.0259	113 Uut Ununpentium 286.0259	114 Uuo Ununhexium 287.0259	115 Uup Ununtrium 288.0259	116 Uuh Ununpentium 289.0259	117 Uus Ununhexium 290.0259	118 Uuo Ununtrium 291.0259

For elements with no stable isotopes, the mass number of the isotope with the longest half-life is in parentheses.

Ptable
com

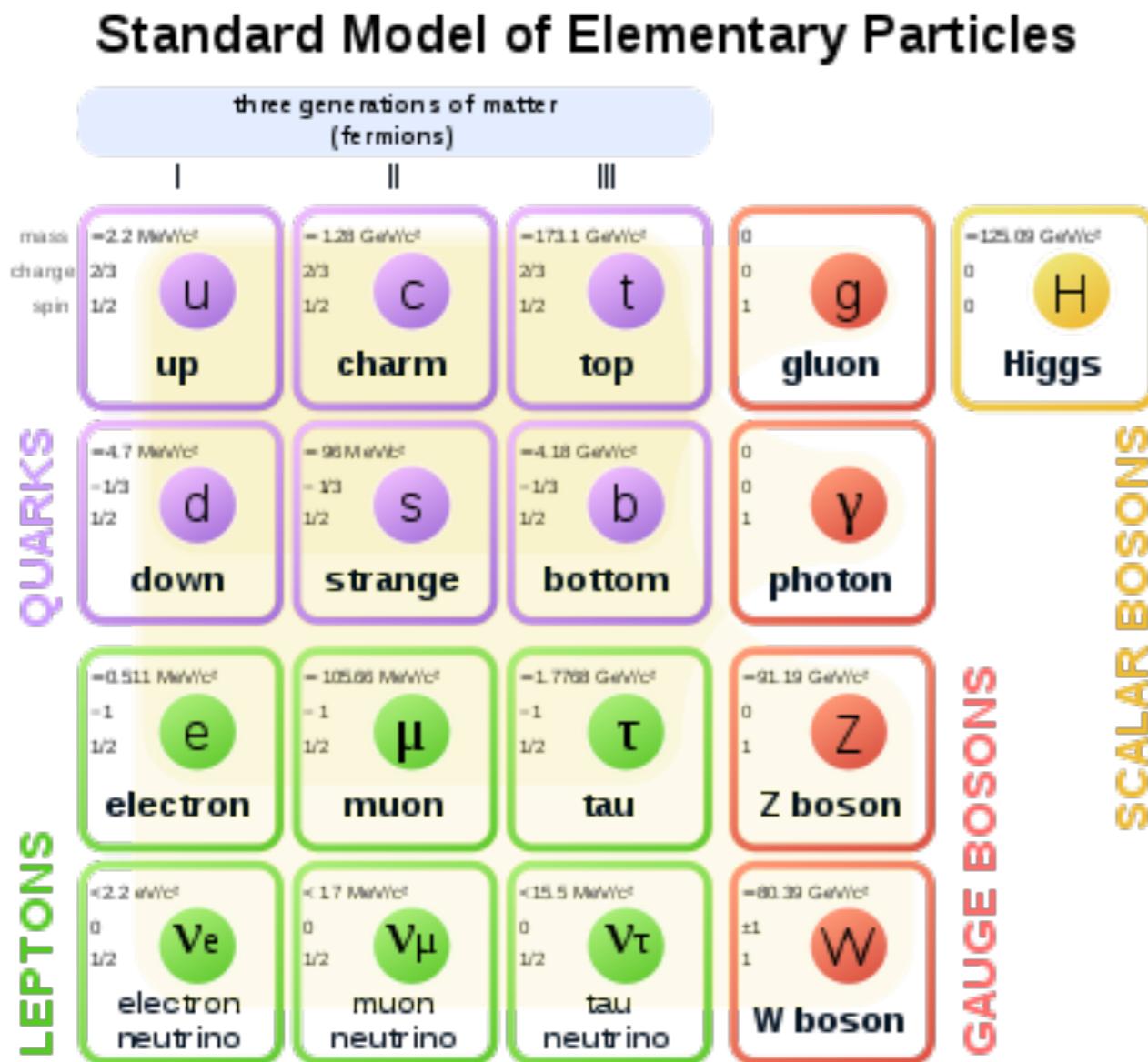
From a physicist's point of view

Standard Model of Elementary Particles



Quarks, leptons, gauge bosons, scalar bosons

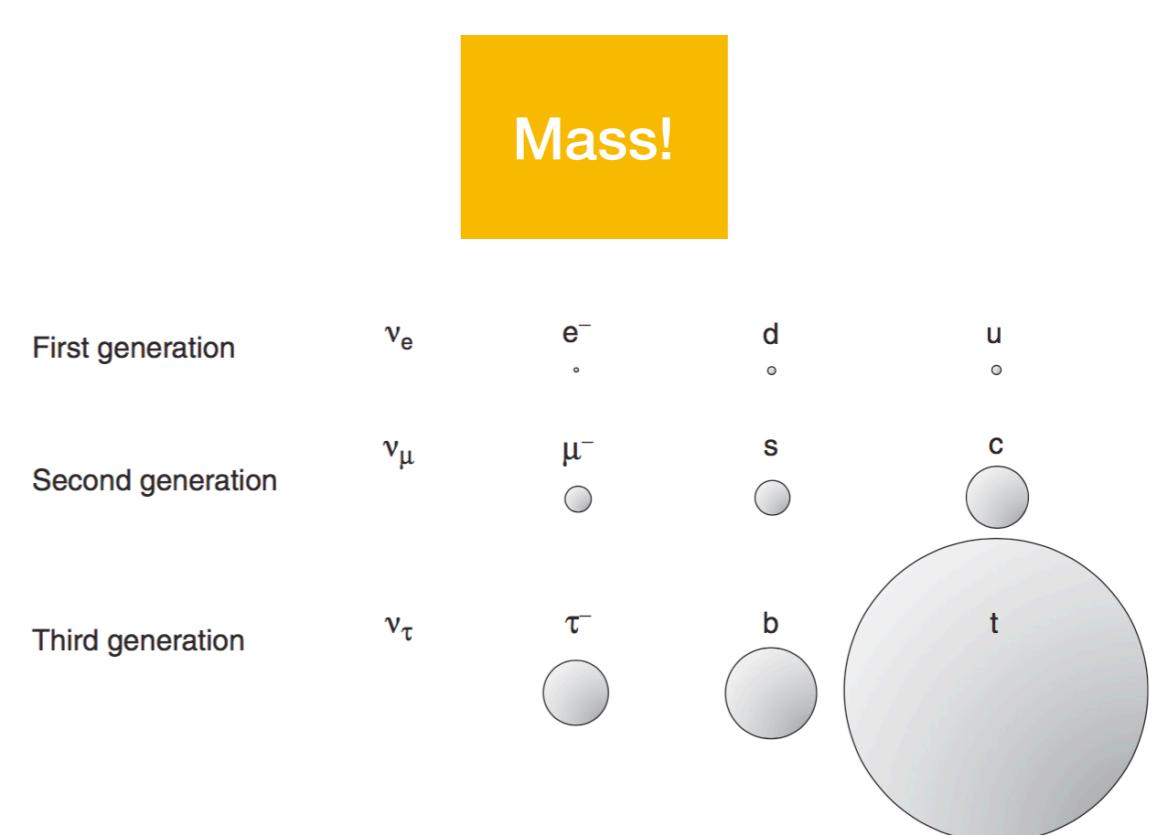
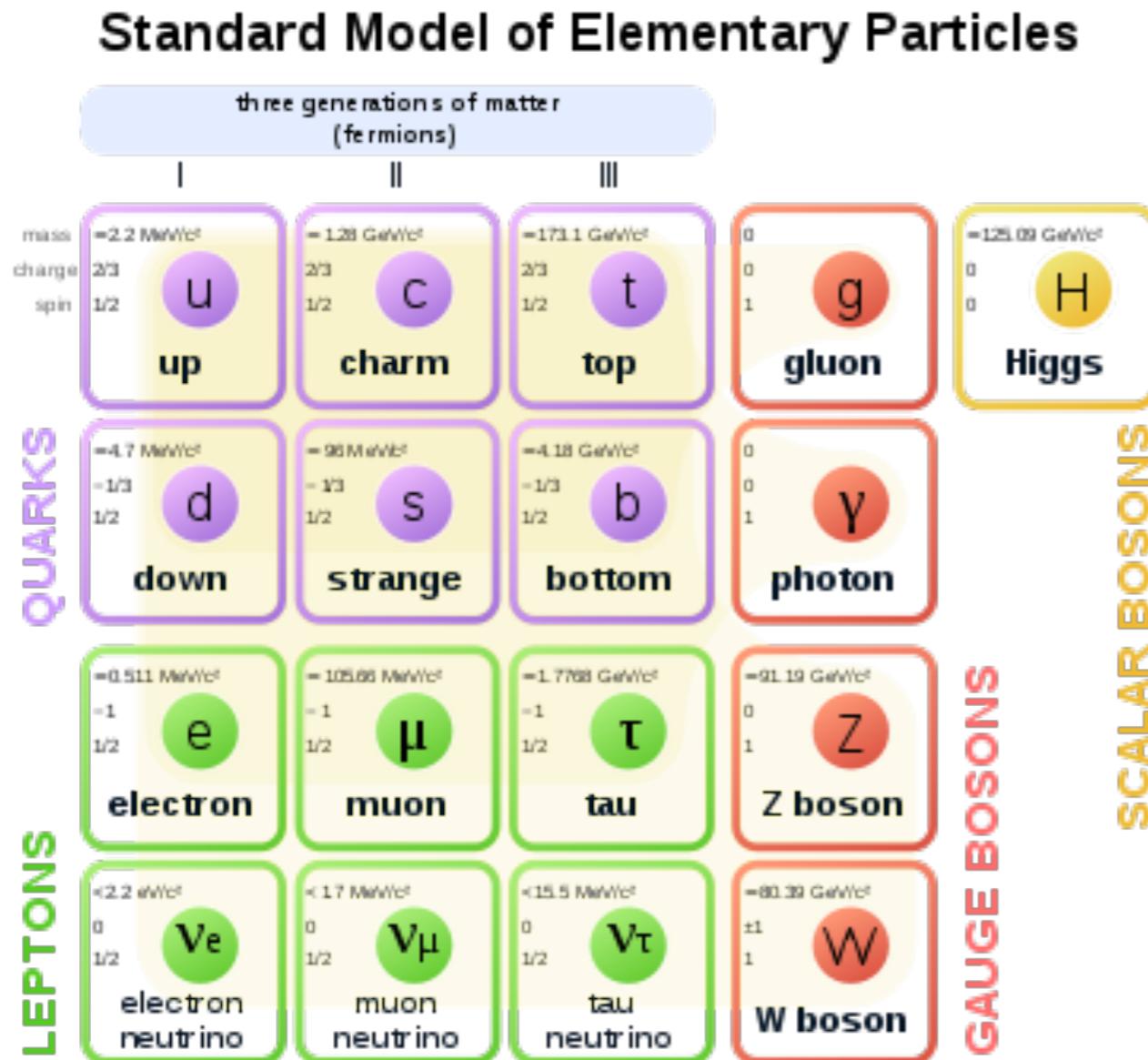
What consists the universe?



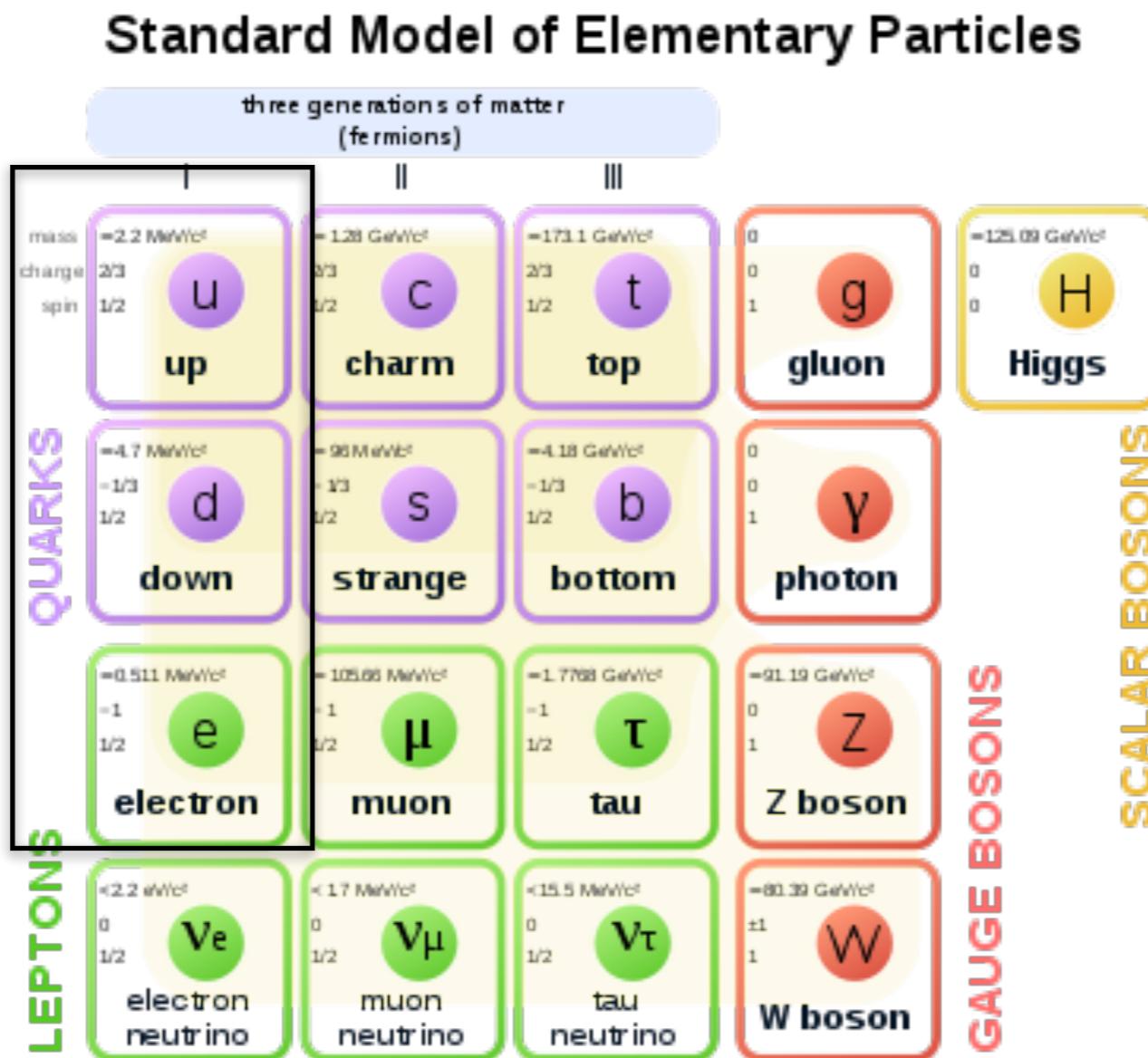
Our current model of matter consists of point-like particles (<10-18m), interacting through four forces.
-> More about this later

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

What consists the universe?



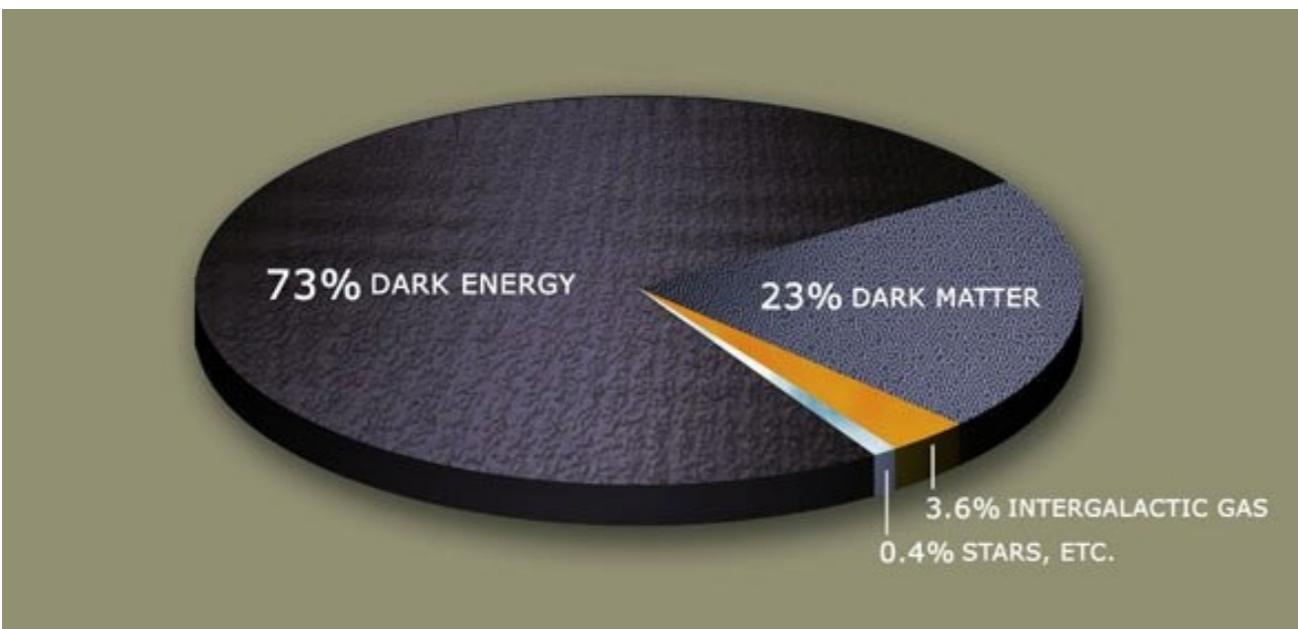
What consists our body?



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

three generations of matter (fermions)					
mass	=2.2 MeV/c ²	= 1.29 GeV/c ²	= 173.1 GeV/c ²	0	= 125.09 GeV/c ²
charge	2/3	2/3	2/3	0	0
spin	1/2	1/2	1/2	1	0
	U	C	t	g	H
	up	charm	top	gluon	Higgs
QUARKS					
mass	=4.7 MeV/c ²	= 98 MeV/c ²	= 4.18 GeV/c ²	0	= 91.19 GeV/c ²
charge	-1/3	-1/3	-1/3	0	0
spin	1/2	1/2	1/2	1	1
	d	s	b	γ	Z
	down	strange	bottom	photon	Z boson
LEPTONS					
mass	=0.511 MeV/c ²	= 105.66 MeV/c ²	= 1.7768 GeV/c ²	0	= 80.39 GeV/c ²
charge	-1	-1	-1	1	1
spin	1/2	1/2	1/2	1	1
	e	μ	τ	Z	W
	electron	muon	tau	Z boson	W boson
SCALAR BOSONS					
mass	<2.2 MeV/c ²	<17 MeV/c ²	<15.5 MeV/c ²	0	<15.5 MeV/c ²
charge	0	0	0	±1	±1
spin	1/2	1/2	1/2	1	1
	ν _e	ν _μ	ν _τ		
	electron neutrino	muon neutrino	tau neutrino		
GAUGE BOSONS					

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 “dark matter” that is increasing rapidly?
- Why was there matter in the universe?
- Why do particles have mass?
- Why is gravity so weak?
- How do neutrinos interact?
- 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.)
- 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).



The Standard Model

How matter interacts

		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
Electromagnetism	10^{-3}	Photon	γ	1
Weak	10^{-8}	W boson	W^\pm	1
Gravity	10^{-37}	Z boson	Z	80.4
		Graviton?	G	91.2
				0

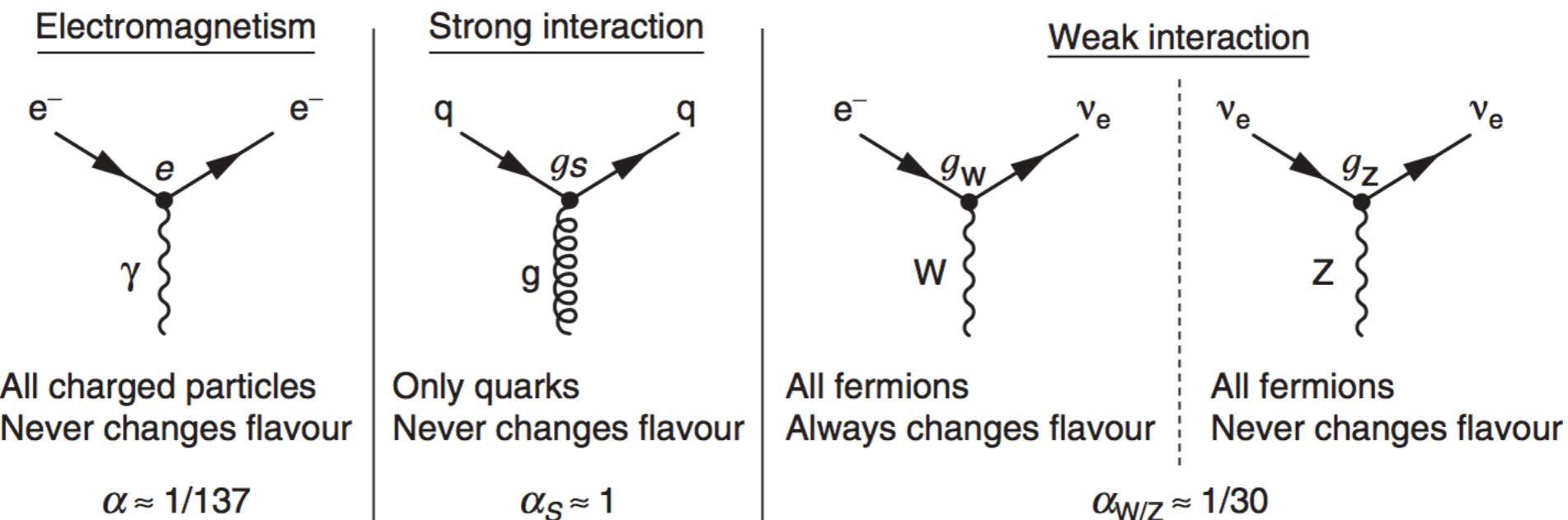
#Note

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

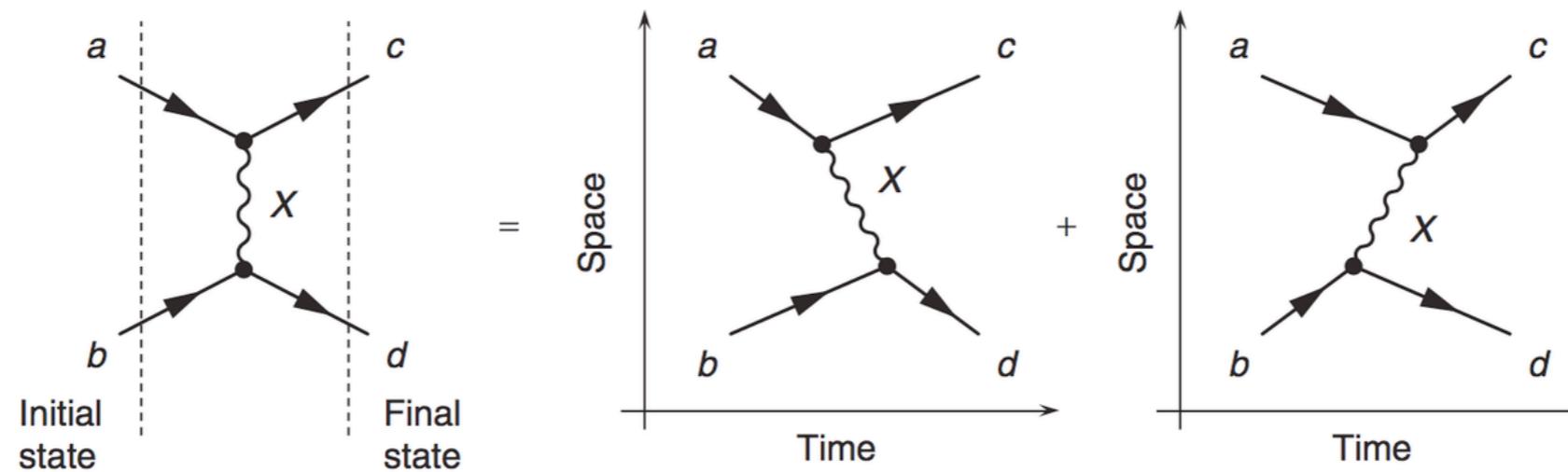
- The Standard Model vertices



The strengths of interactions are usually expressed with α

How matter interacts

- Feynman diagram for $a+b > c+d$



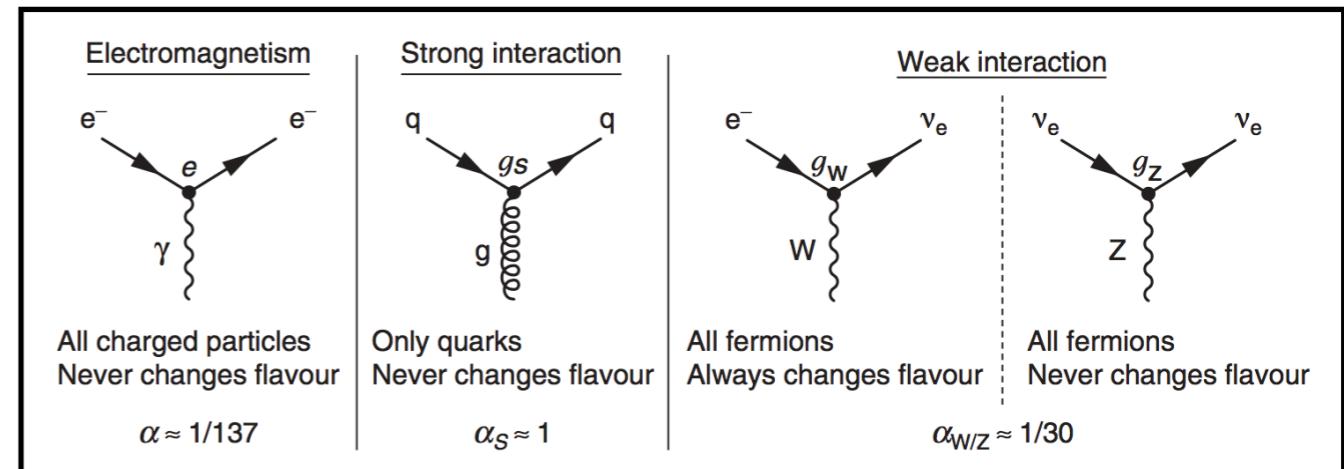
The Feynman diagram for the scattering process $a + b \rightarrow c + d$ and the two time-ordered processes that it represents.

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

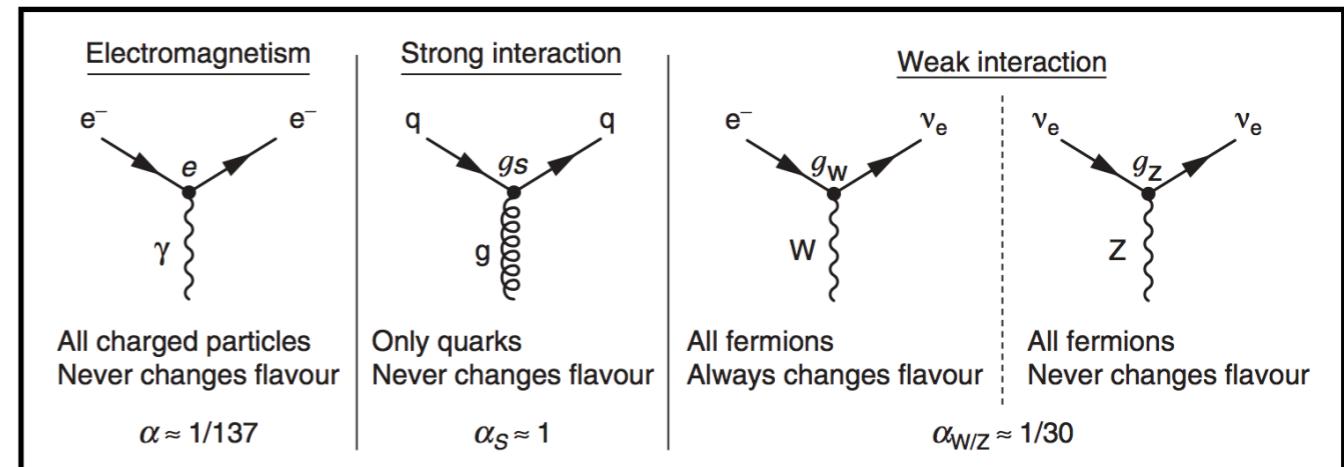
- Examples of Feynman diagrams



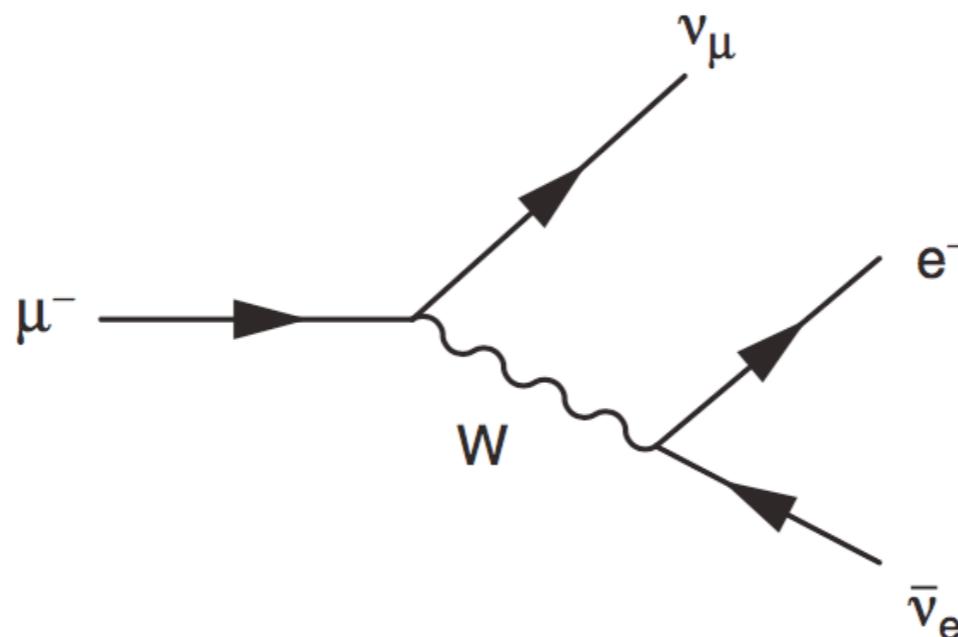
Muon \rightarrow electron + 2 neutrinos

How matter interacts

- Examples of Feynman diagrams

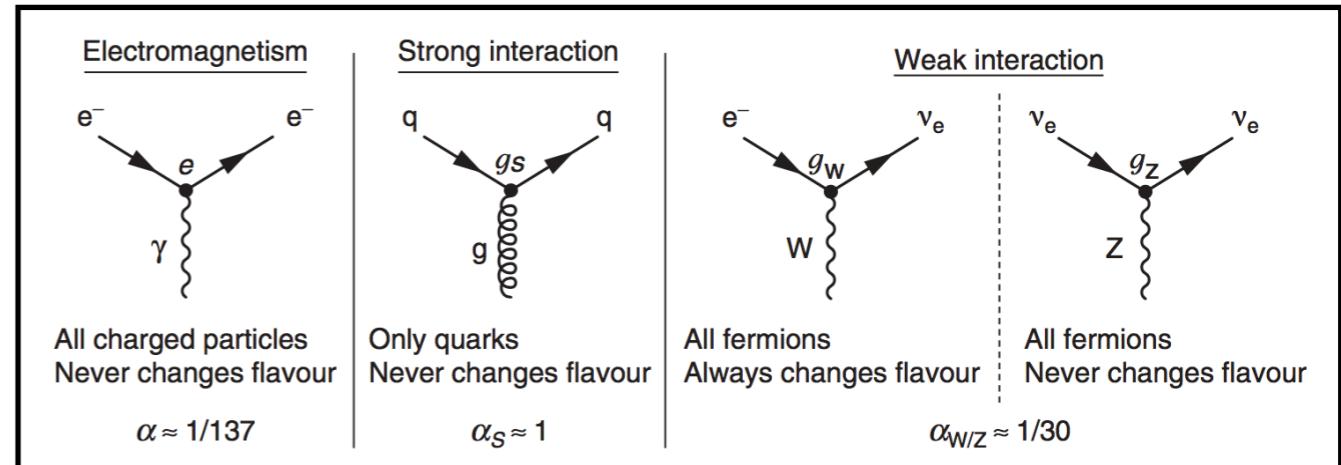


Muon \rightarrow electron + 2 neutrinos



How matter interacts

- Examples of Feynman diagrams



Beta decay

Neutron \rightarrow Proton + electron + neutrino

Hint:

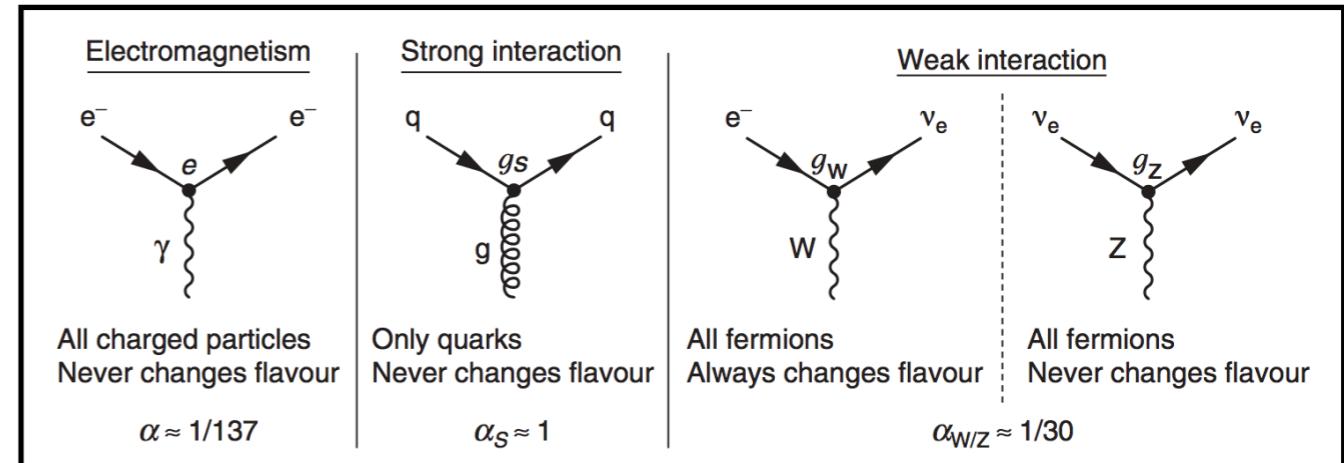
**Neutron has 1 up quark (+2/3 e),
2 down quark (-1/3 e).**

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

**Electromagnetic charge should
be conserved.**

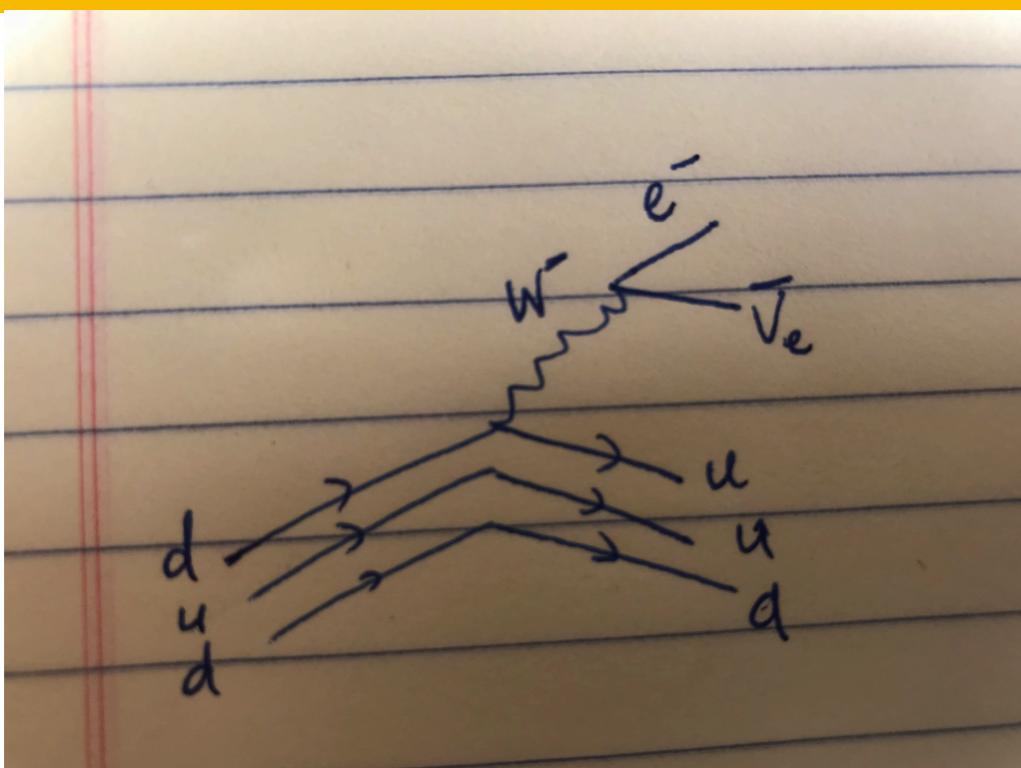
How matter interacts

- Examples of Feynman diagrams



Beta decay

Neutron \rightarrow Proton + electron + neutrino



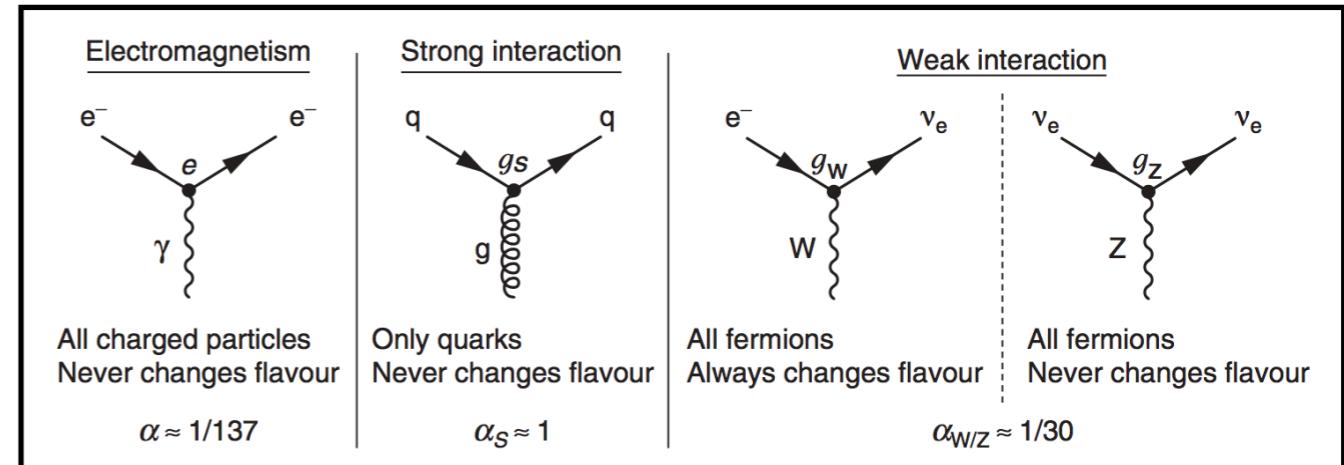
Hint:

**Neutron has 1 up quark (+2/3 e),
2 down quark (-1/3 e).
Proton has 2 up quarks and 1
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**Electromagnetic charge should
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How matter interacts

- Examples of Feynman diagrams

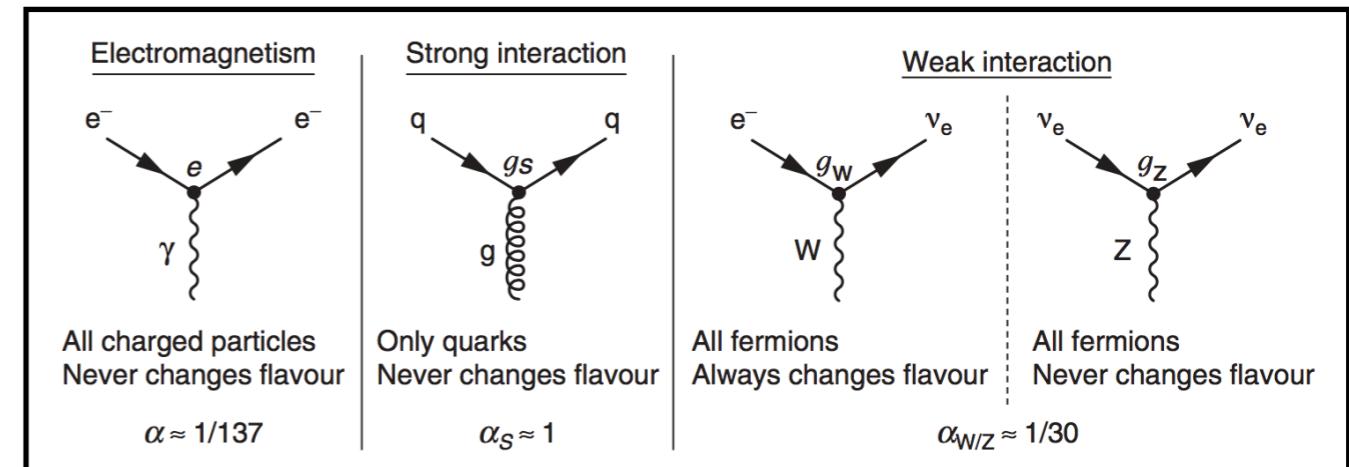


e+, e- pair annihilation

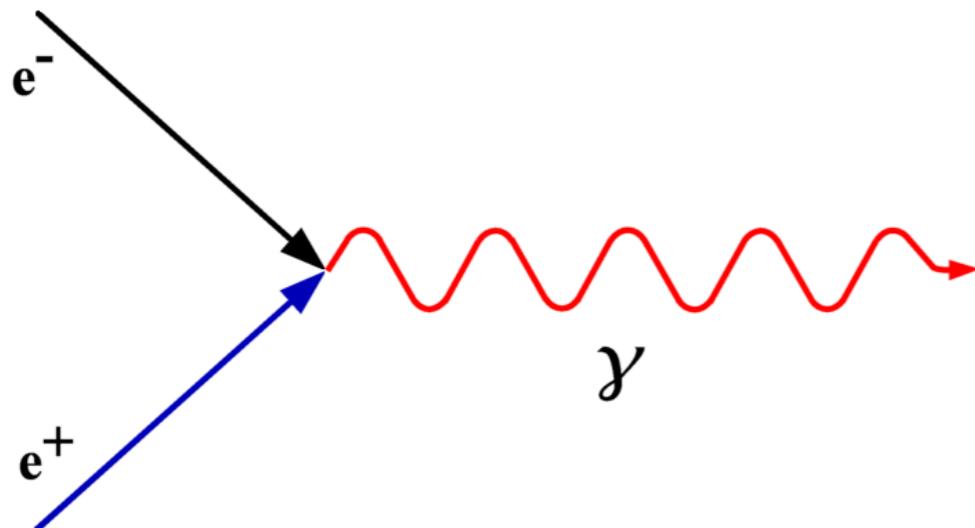
Hint:
Elementary particle and its anti-particle can annihilate

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**.

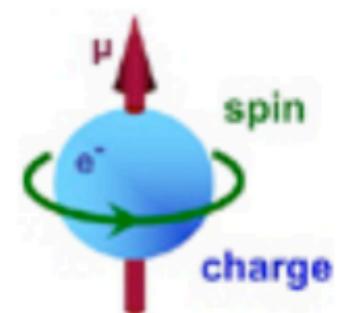
Field Theory and the Standard Model

- 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.

$\mu_{\text{electron}} = 1.00115965219 \pm 0.00000000001 \mu_B$ (measured)

$\mu_{\text{electron}} = 1.00115965217 \pm 0.00000000003 \mu_B$ (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)