Particle Physics: Introduction

Yeon-jae Jwa

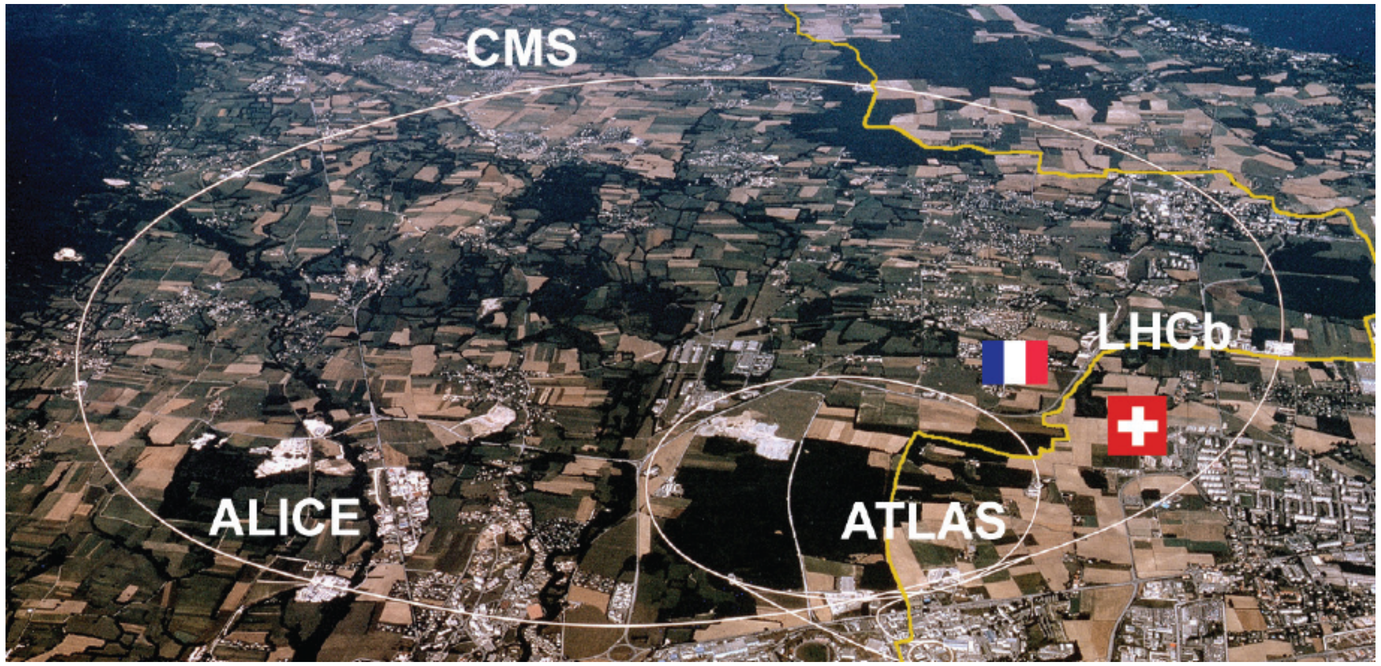
Week 1: September 22nd, 2018
Columbia University Science Honors Program

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

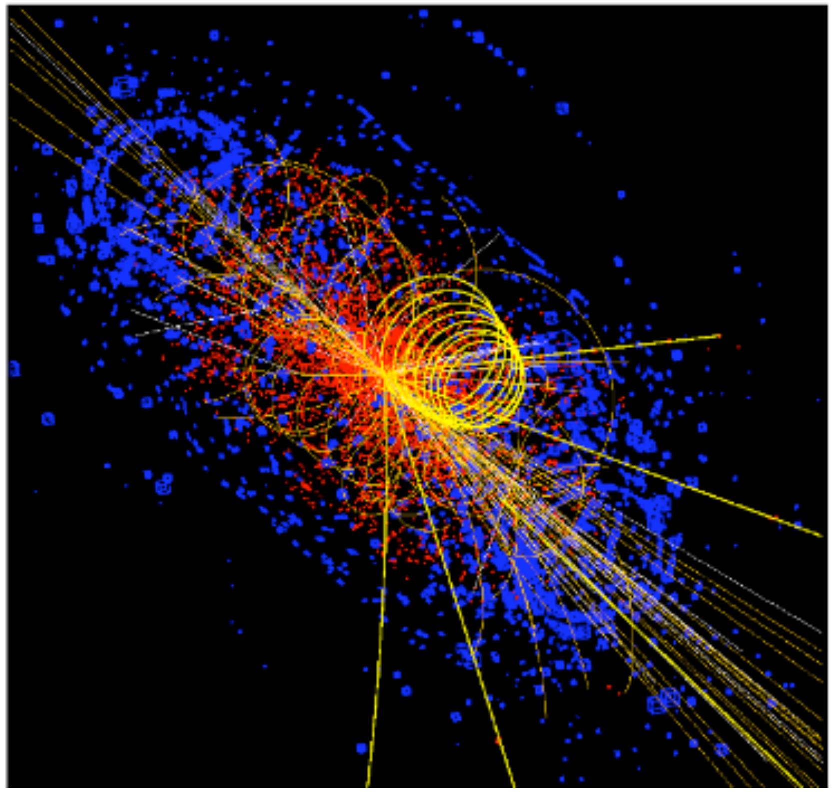
- No cell phone uses during the class.
- Feel free to step outside to the hall way in case of emergencies, bathrooms, starvations.
- Feel free to stop me and ask questions / ask for clarifications.
- Resources for class materials, Research Opportunities + Resources to become a particle physicist

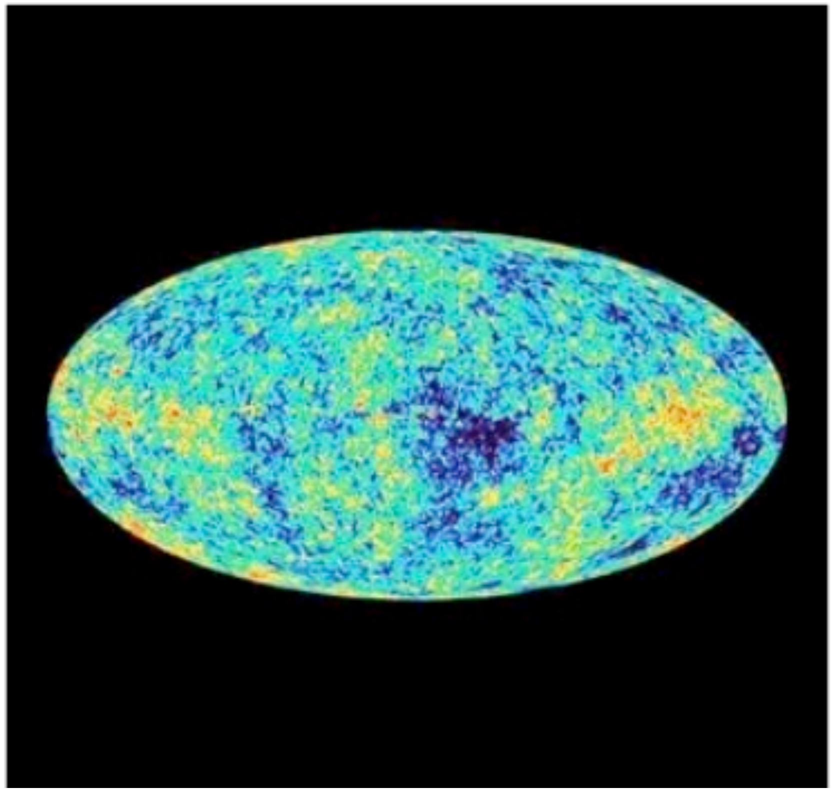
https://twiki.nevis.columbia.edu/twiki/pub/Main/ScienceHonorsProgram

Introduce yourself to the class

What is Particle Physics?

- Particle physicists explore the <u>most basic components</u> 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

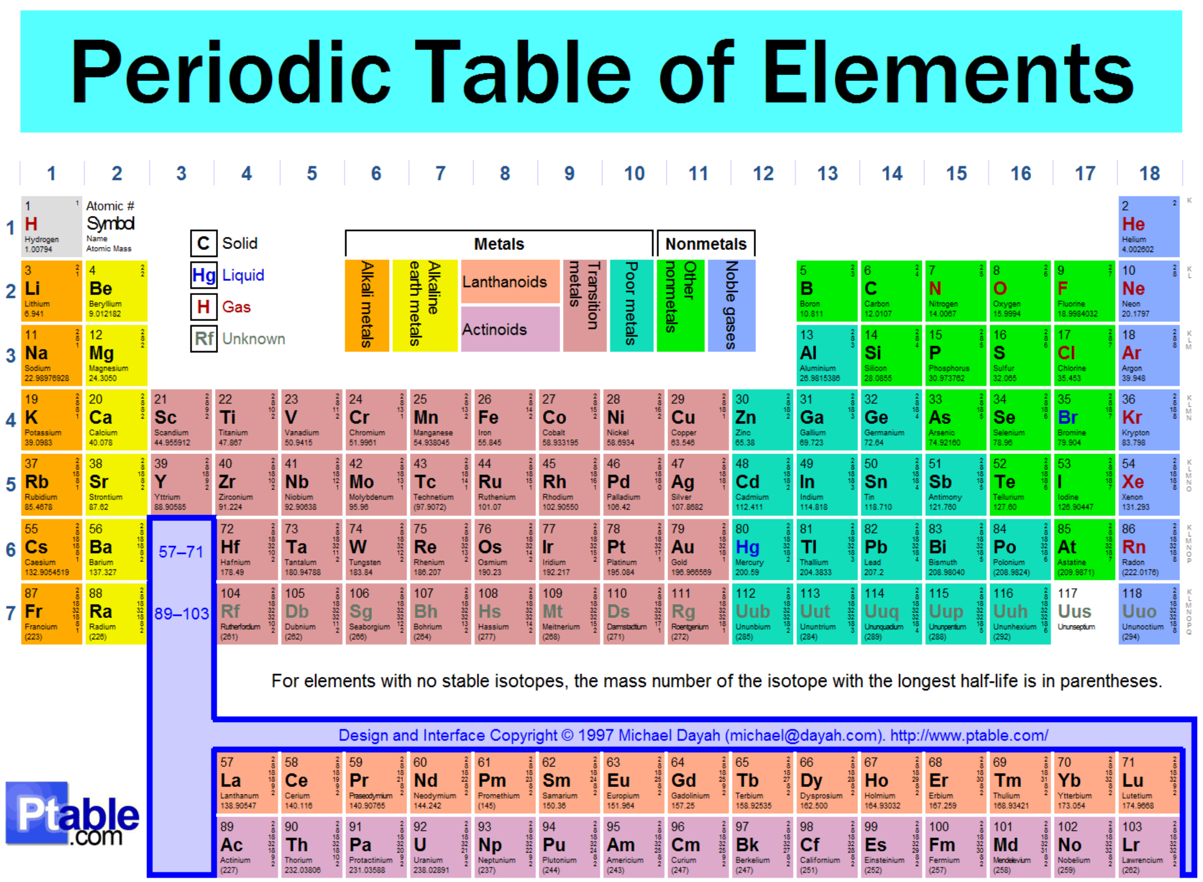
Quiz: What is a particle?

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

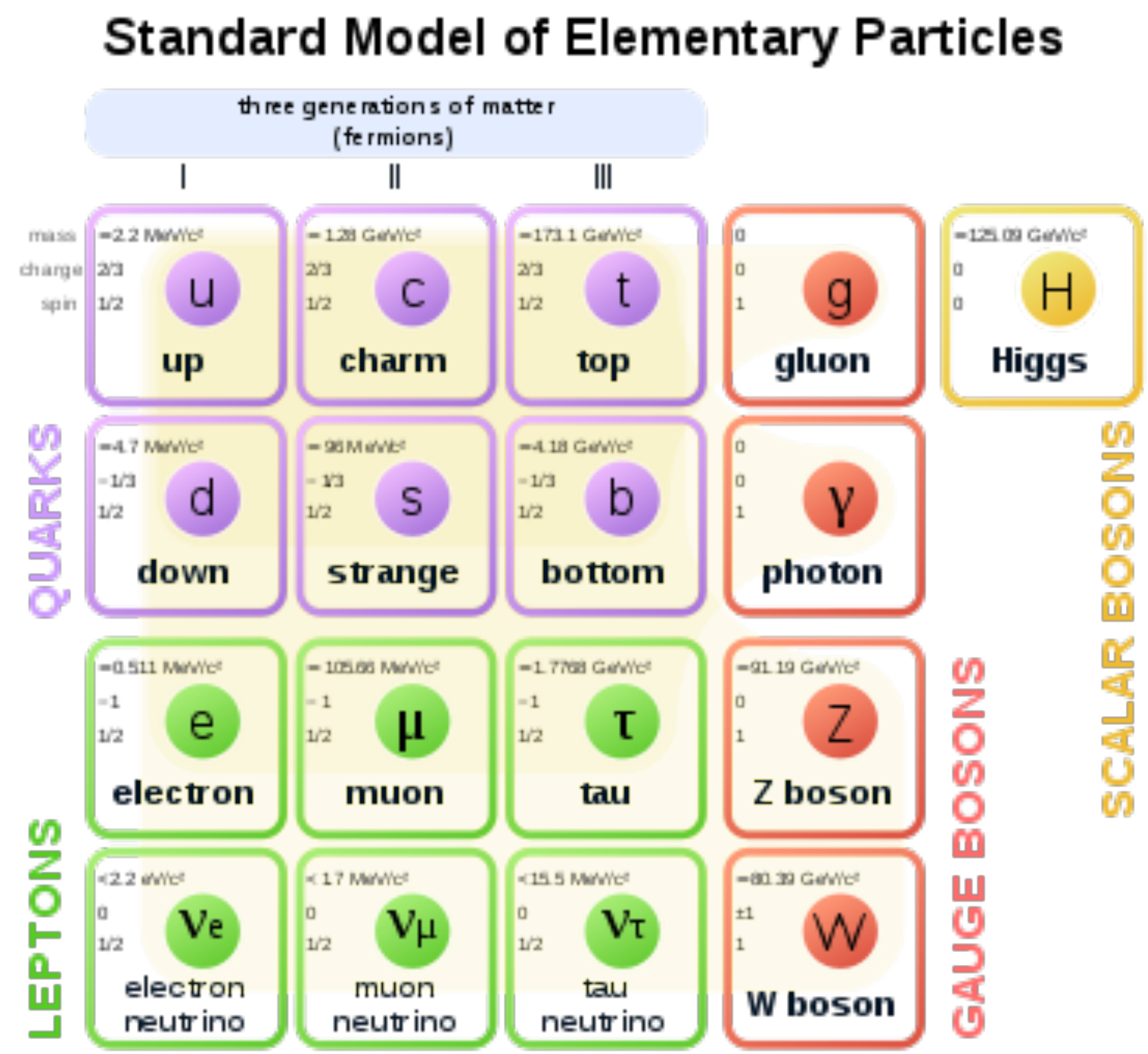
Can you tell
(electron, proton, neutron, neutrino, anti-electron)
are composite particles or elementary particles?

What consists the universe?

From a chemist’s point of view

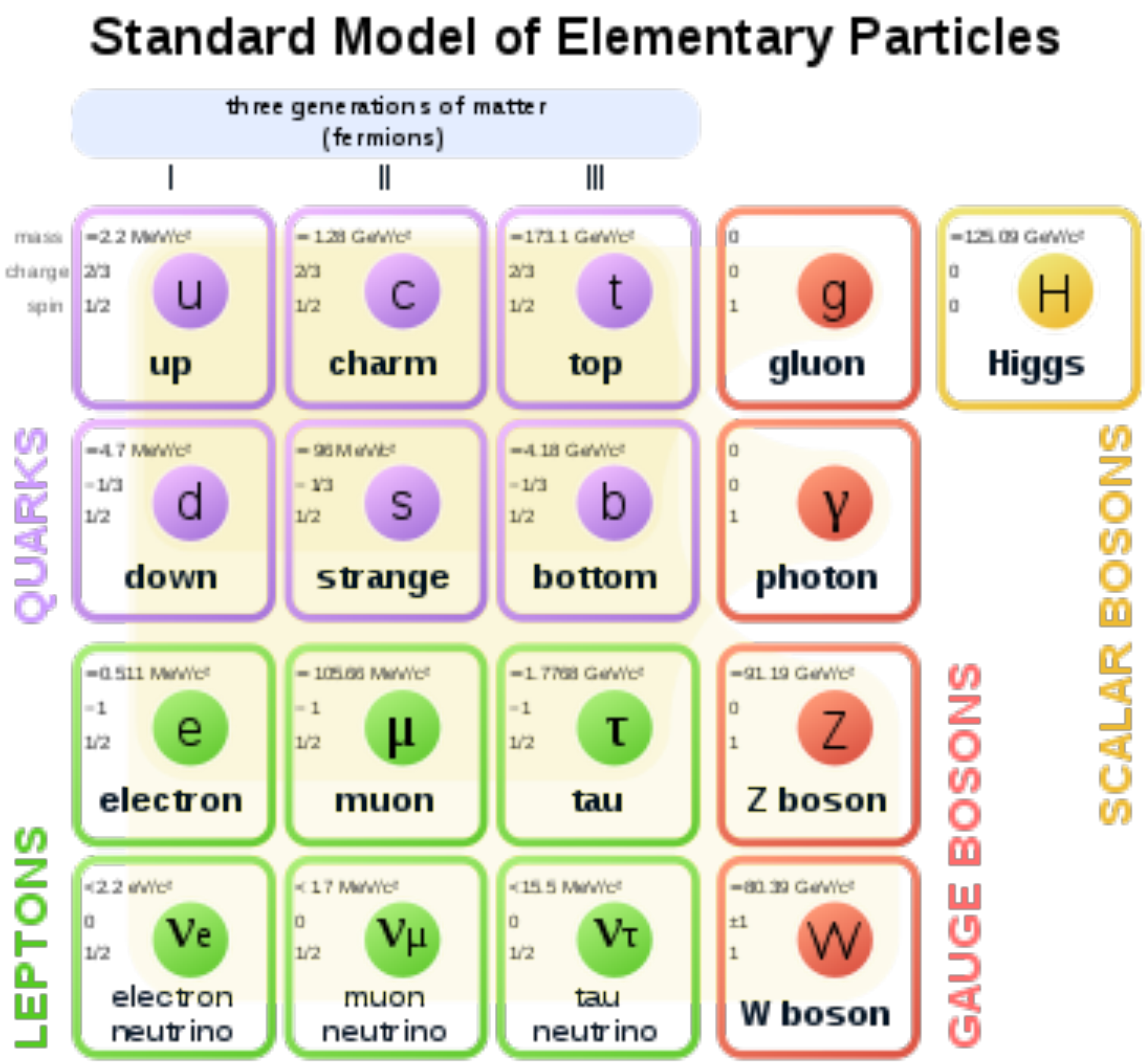


From a physicist’s point of view



Quarks, leptons, gauge bosons, scalar bosons

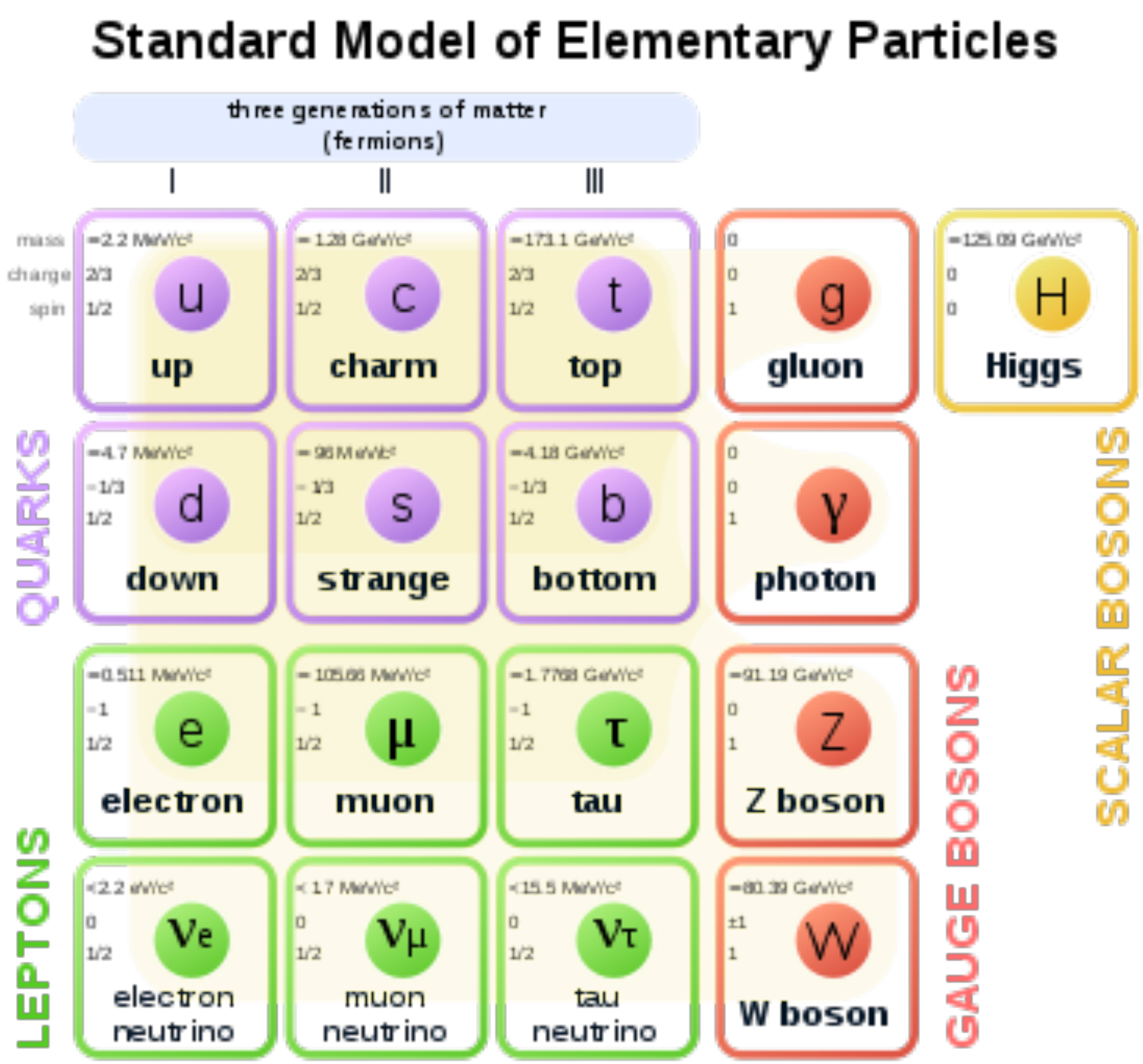
What consists the universe?



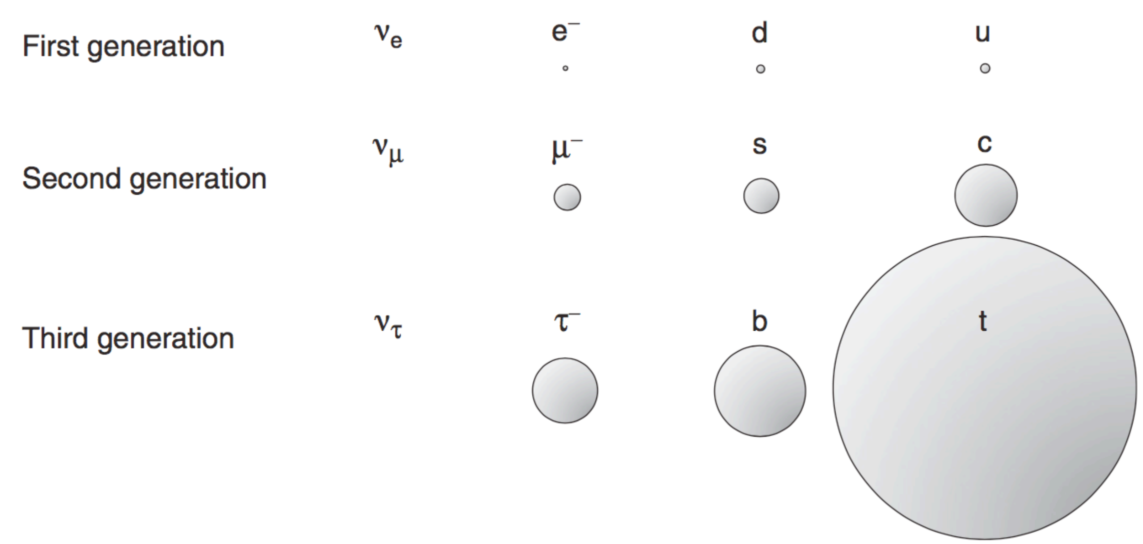
Our current model of matter consists of point-like particles (<10-18m), *interacting* through four forces.
-> More about this later

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

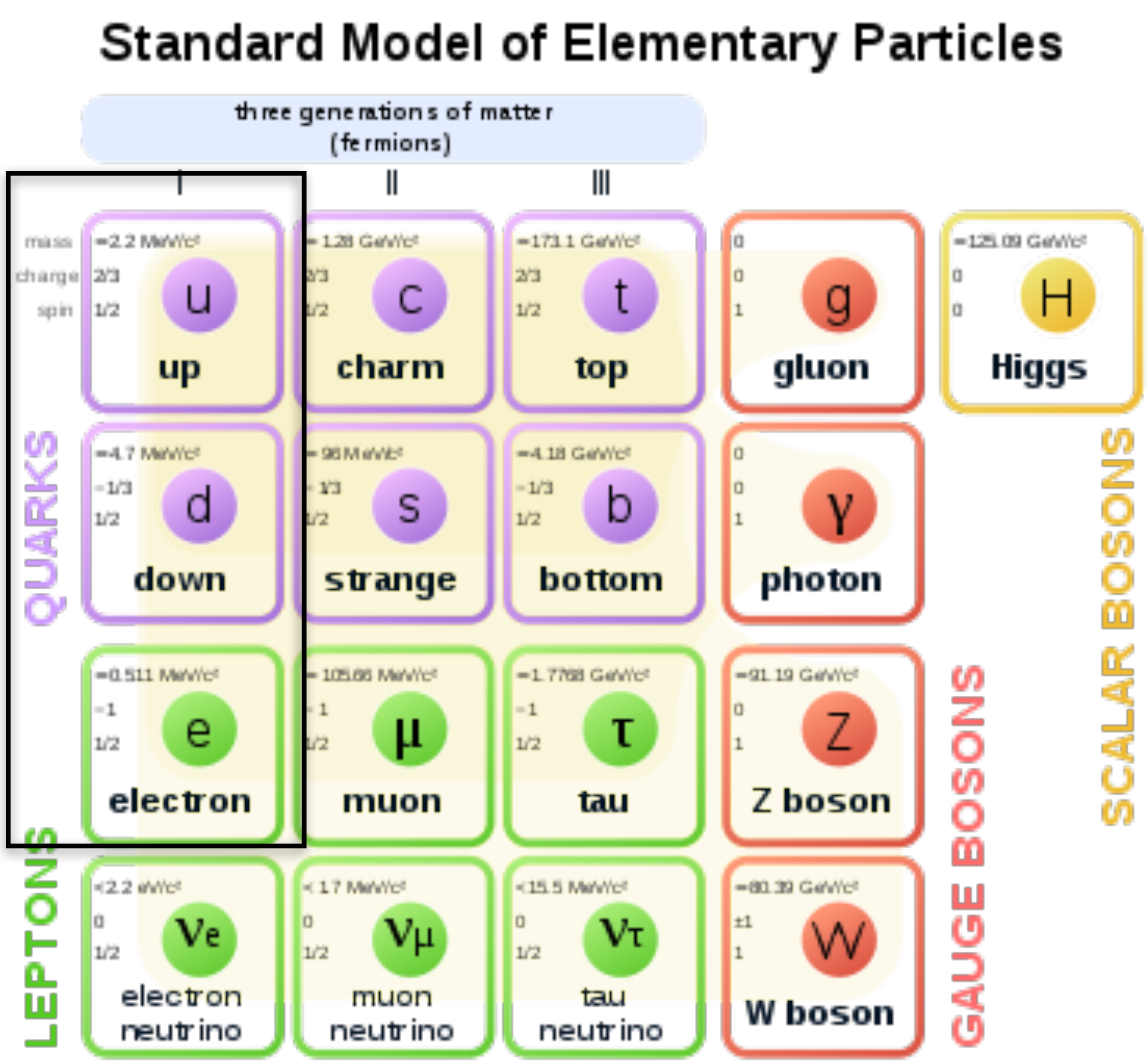
What consists the universe?



Mass!

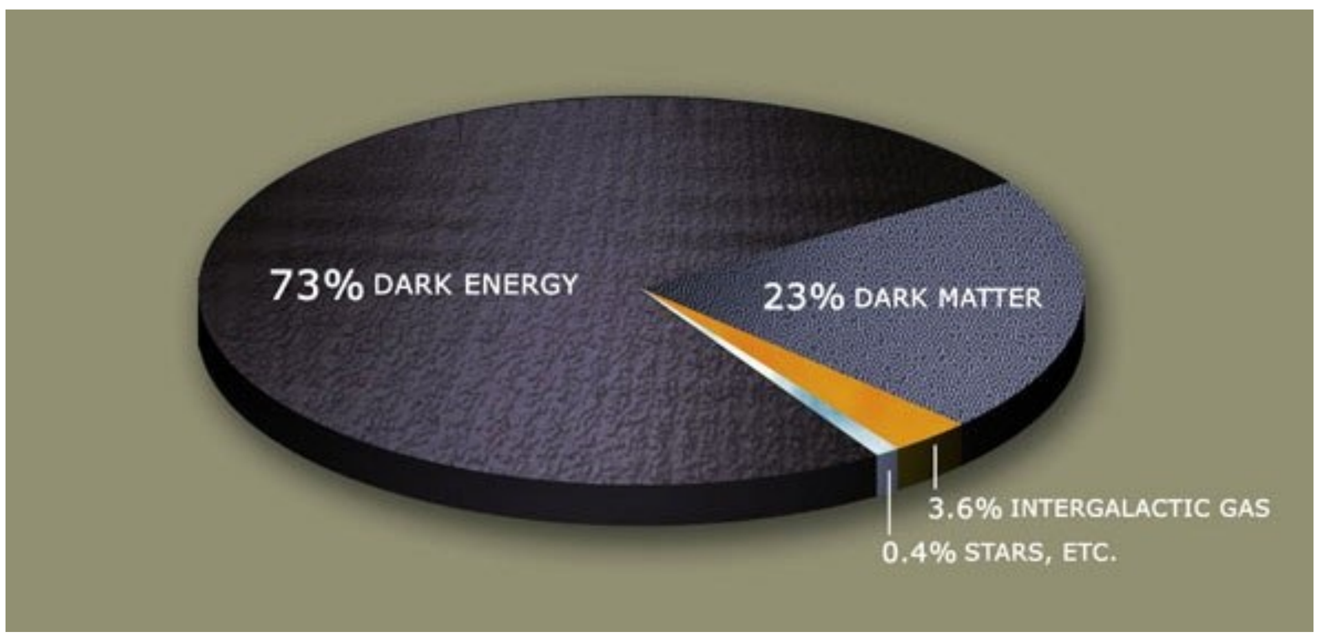


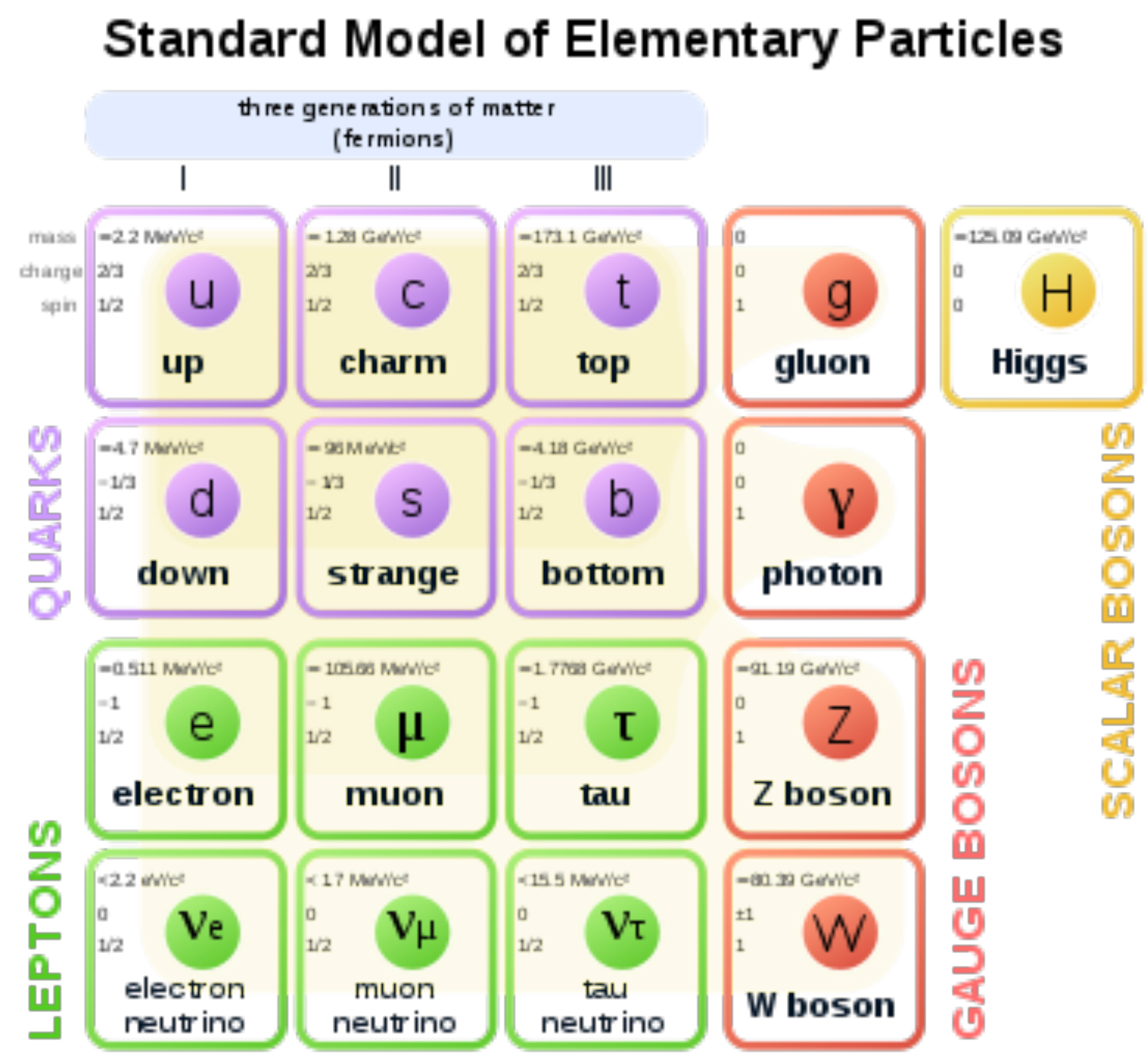
What consists our body?



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

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 rat
- Why was ther 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 fm $= 10^{-15}$ m (roughly the radius of a proton).

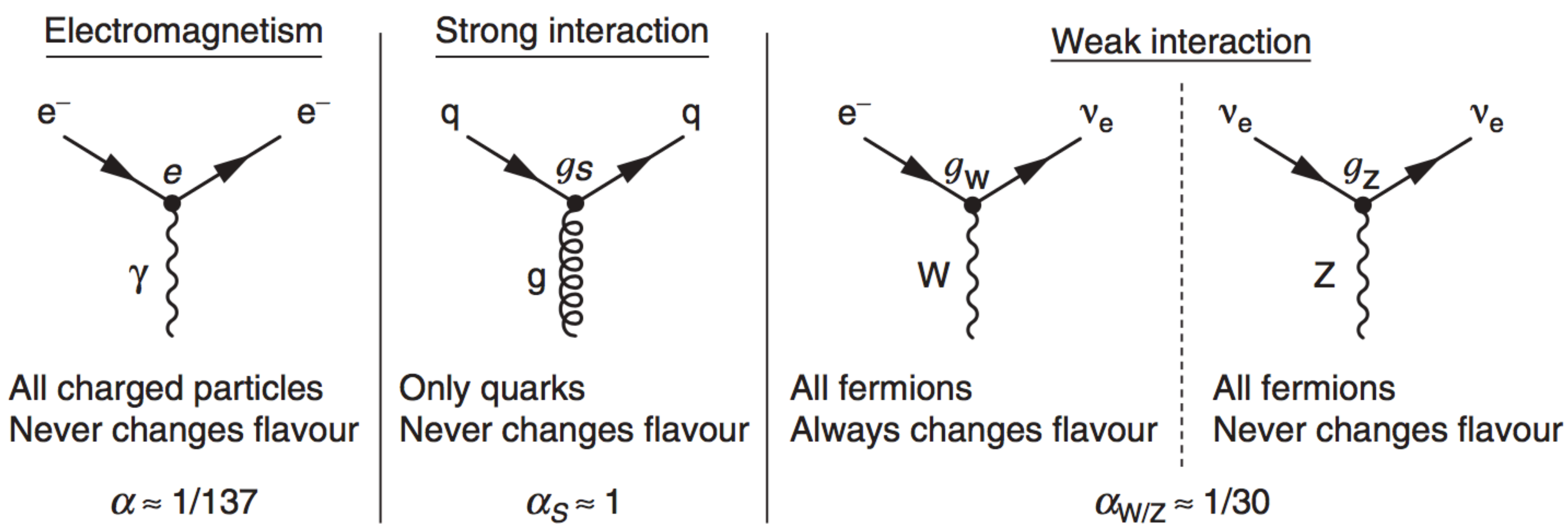
Force	Strength	Boson		Spin	Mass/GeV
Strong	1	Gluon	g	1	0
Electromagnetism	10^{-3}	Photon	γ	1	0
Weak	10^{-8}	W boson	$W^{\pm}$	1	80.4
		Z boson	Z	1	91.2
Gravity	10^{-37}	Graviton?	G	2	0

#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

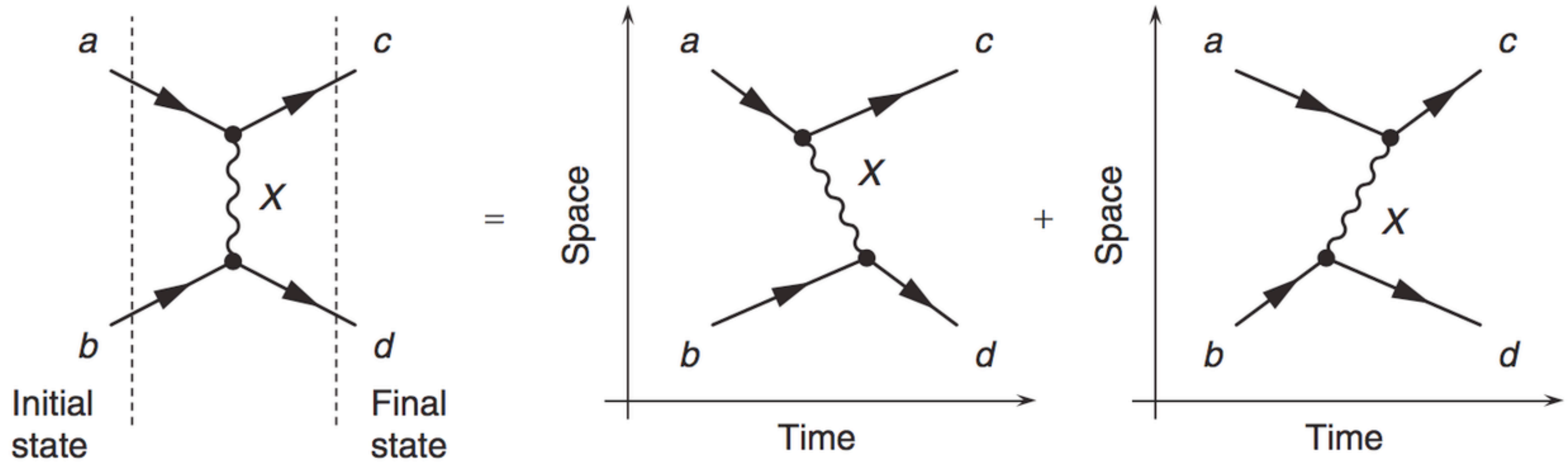
- **The Standard Model vertices**



The strengths of interactions are usually expressed with α

How matter interacts

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

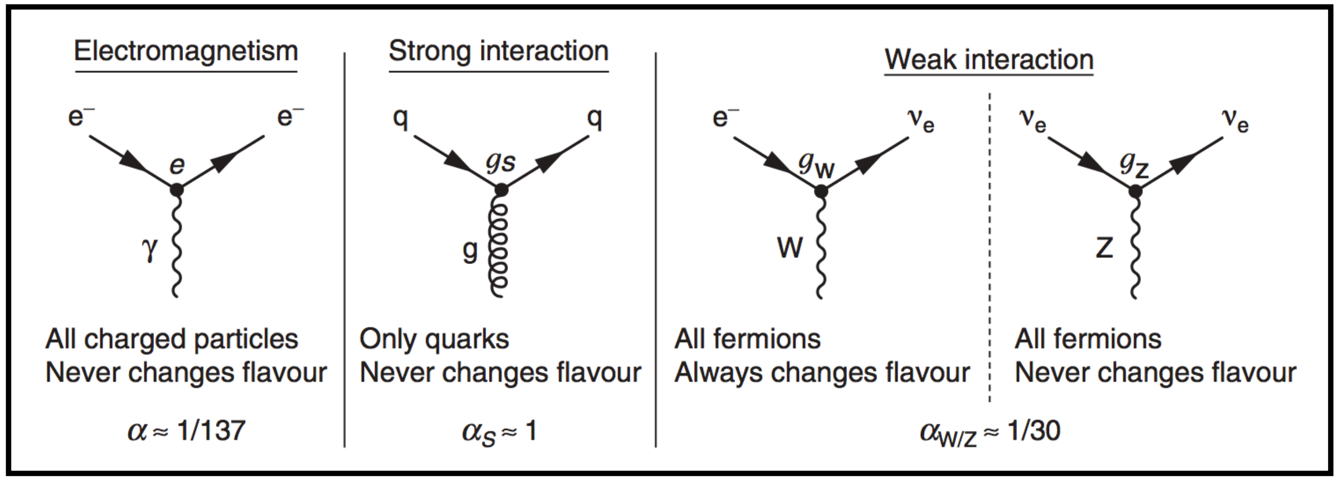


The Feynman diagram for the scattering process $a + b \rightarrow c + d$ and the two time-ordered processes that it represents.

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

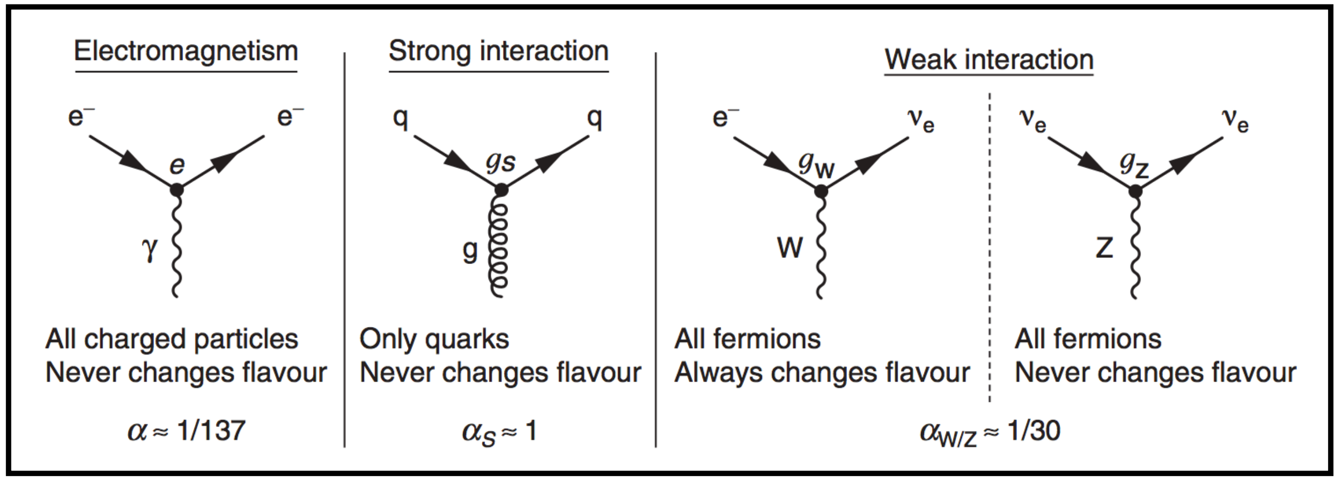
- **Examples of Feynman diagrams**



Muon -> electron + 2 neutrinos

How matter interacts

- **Examples of Feynman diagrams**



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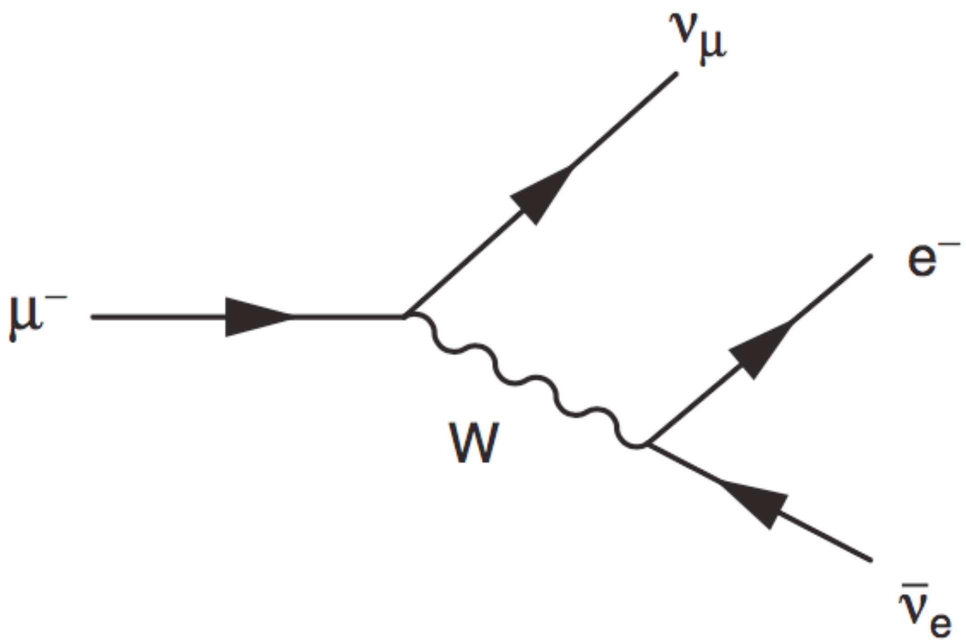
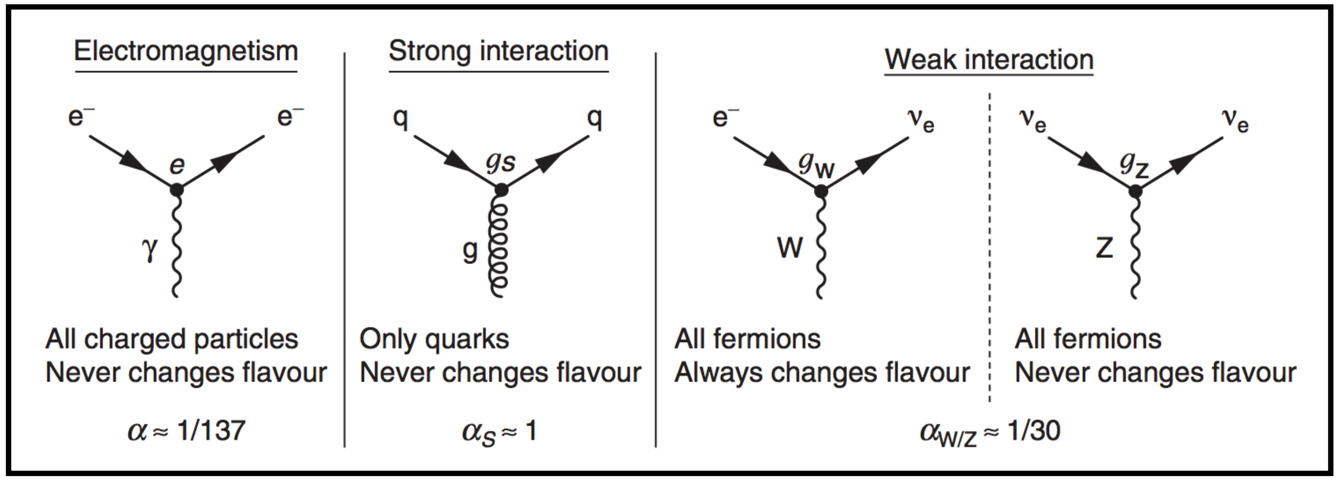


How matter interacts

- **Examples of Feynman diagrams**

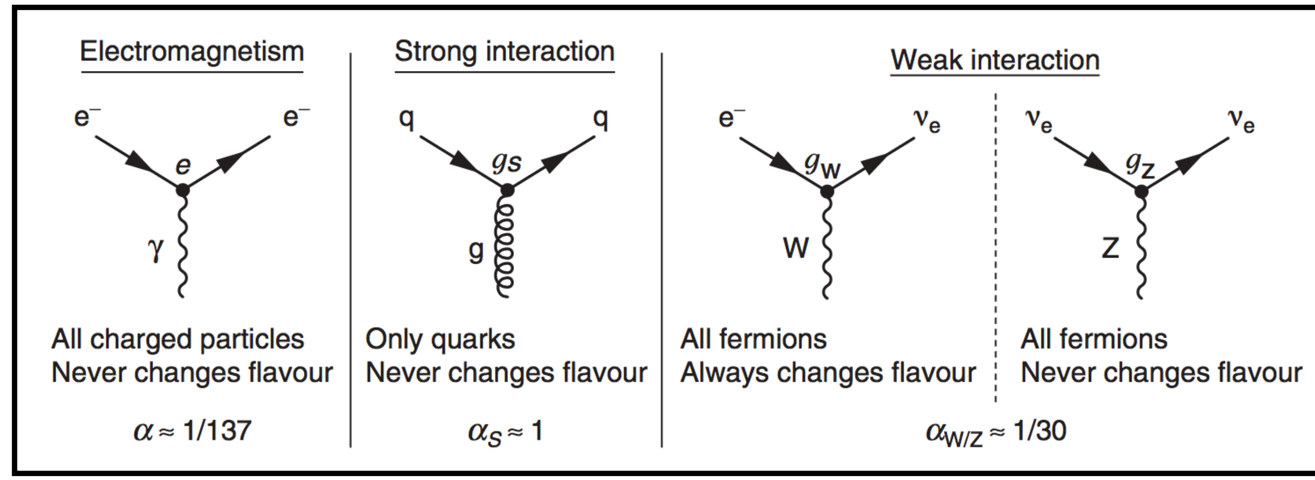


Beta decay
Neutron -> Proton + electron + neutrino

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**



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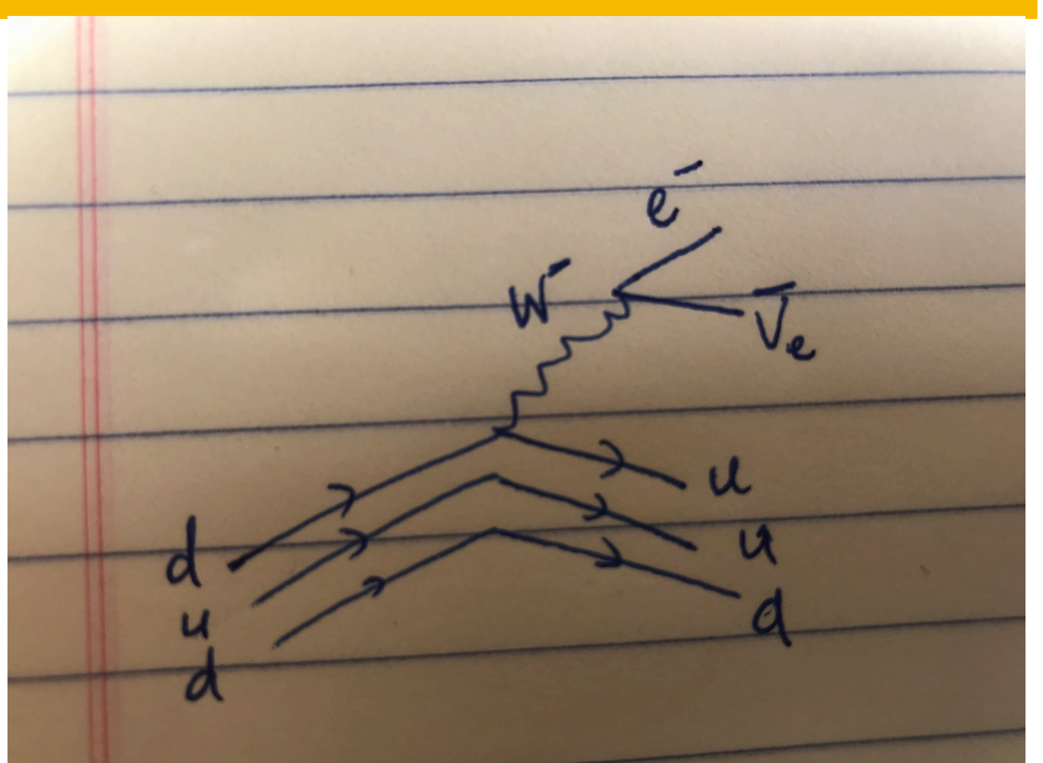

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How matter interacts

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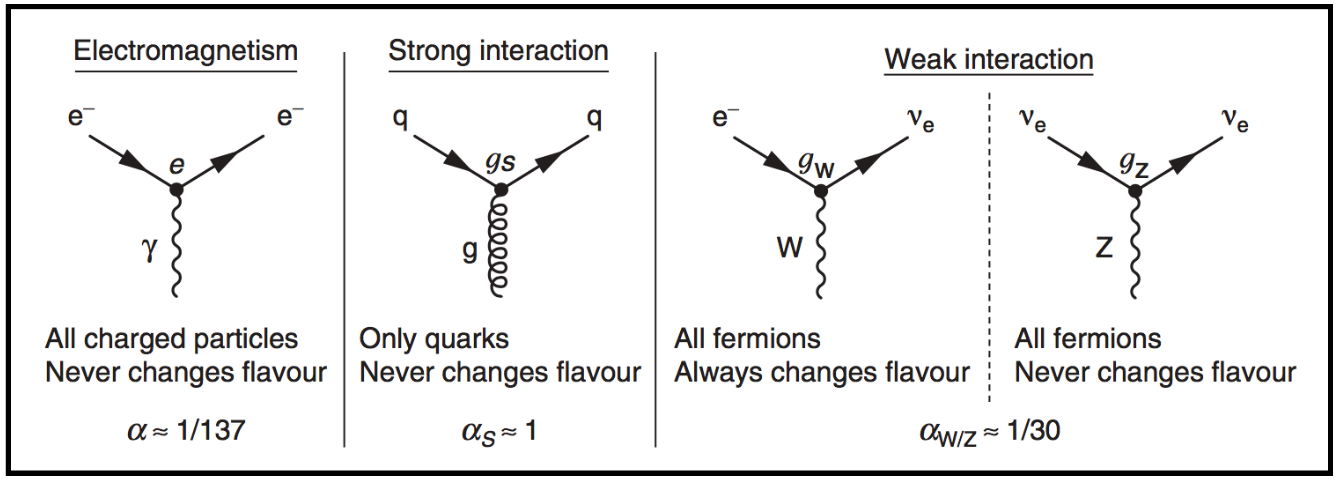
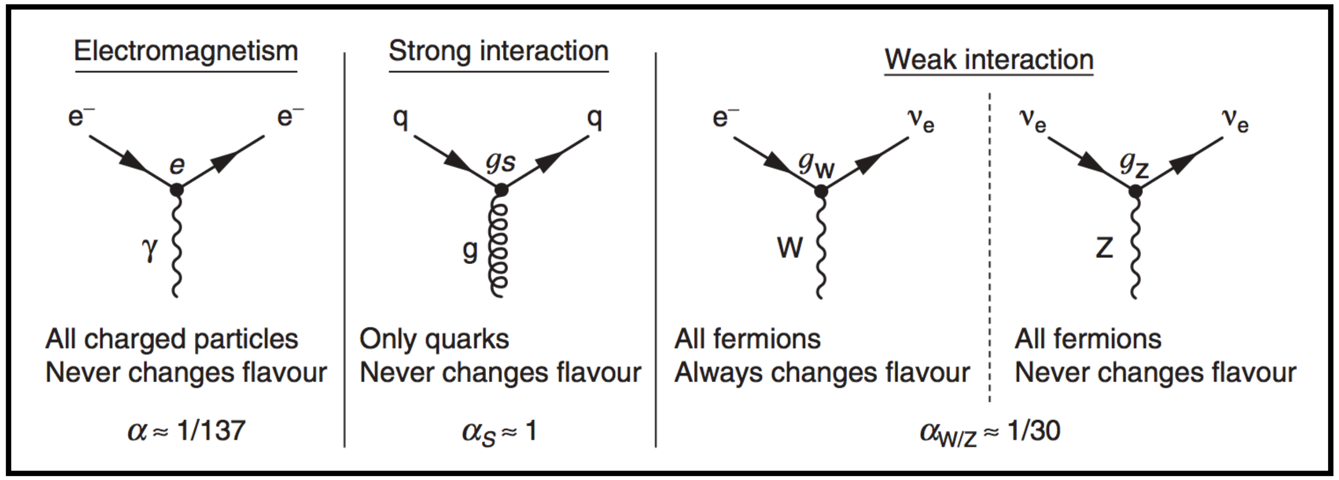


e+, e- pair annihilation

Hint:
Elementary particle and its anti-particle can annihilate

How matter interacts

- **Examples of Feynman diagrams**



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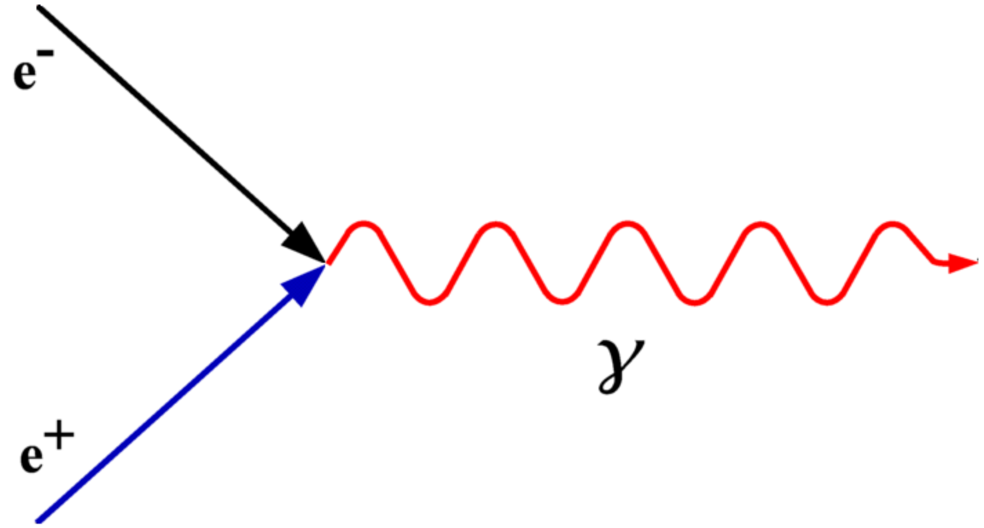


Hint:
Elementary particle and its anti-particle can annihilate

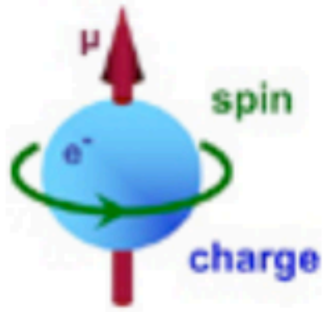
Foundations of Particle Theory

- 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.

$\mu_{electron}$= 1.00115965219 ±0.000000000001 μ_B (measured)
$\mu_{electron}$= 1.00115965217 ±0.00000000003 μ_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)