Standard Model of Particle Physics

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Saturday Morning Physics

Spring 2021

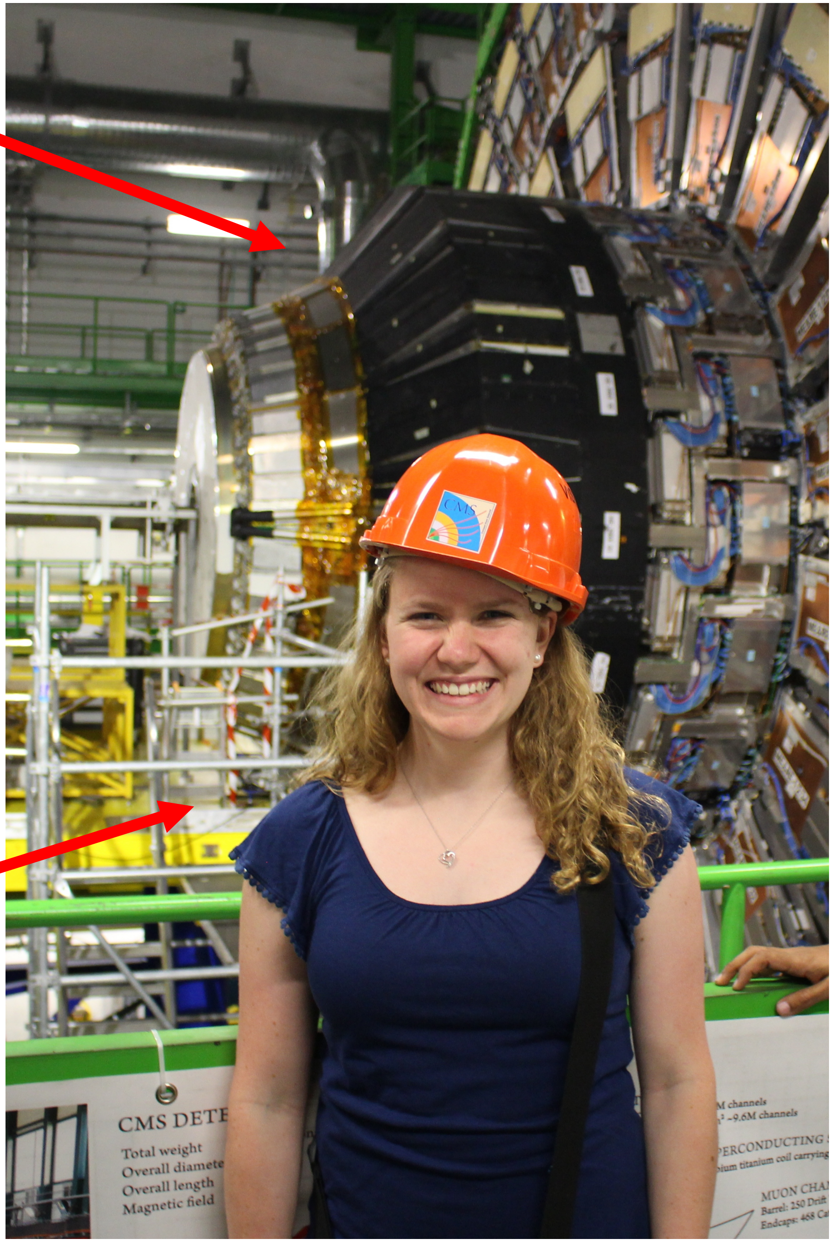
*Thanks to Javier Duarte, Cecilia Gerber, and Bo Jayatilaka!

A little about me

- Highschool in Des Moines, Iowa
- Majored in Physics at the College of St. Benedict in Minnesota
  - Summer internships (paid!) in physics and engineering research
  - Graduated 2013
- Ph.D. in experimental particle physics from the University of Notre Dame in Indiana
  - Grad school = get paid to take classes and do research!
  - Graduated 2018
- Now: Postdoc at Fermilab
  - Working on CMS experiment, including searches for dark matter and optimizing CMS code

CMS Detector

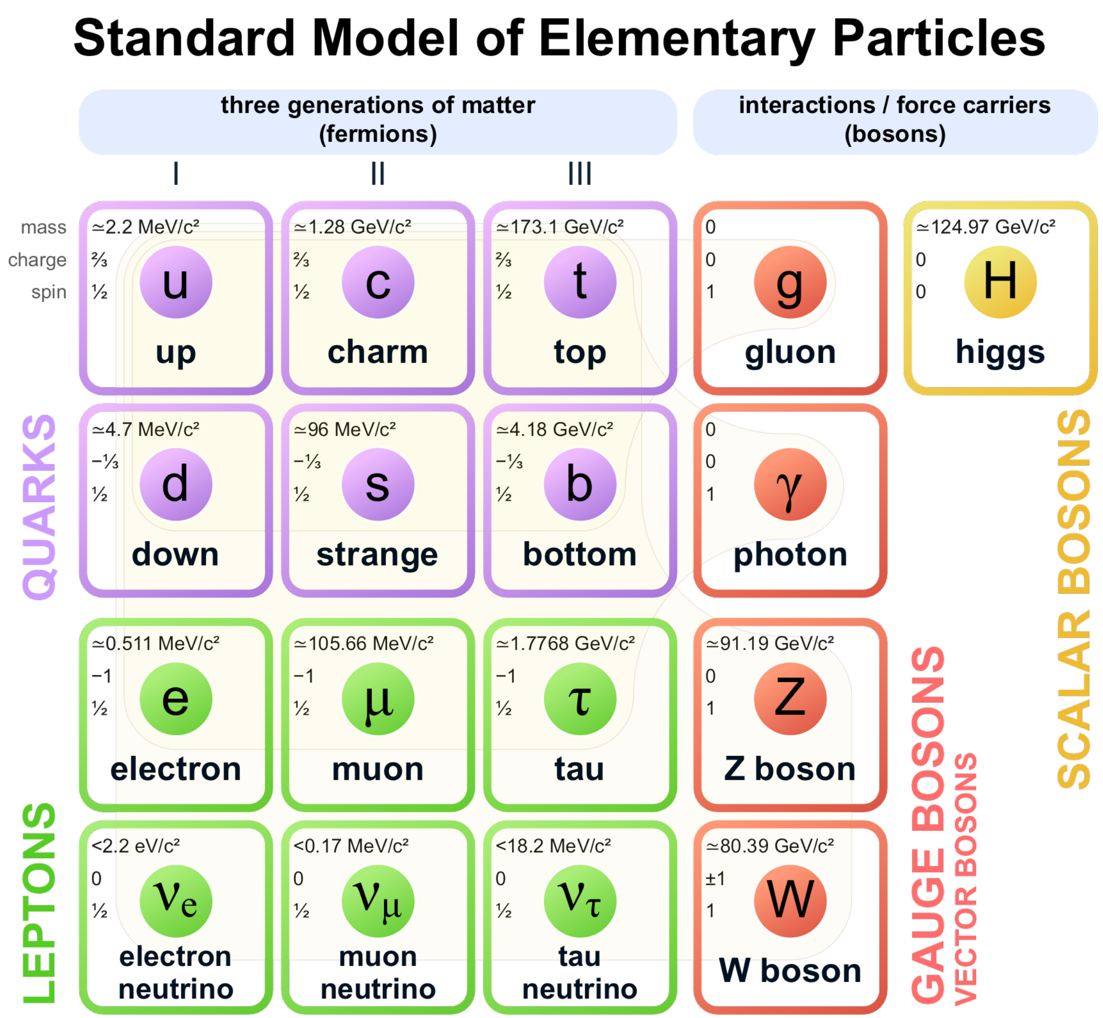
CMS Physicist



Zoom etiquette in breakout rooms

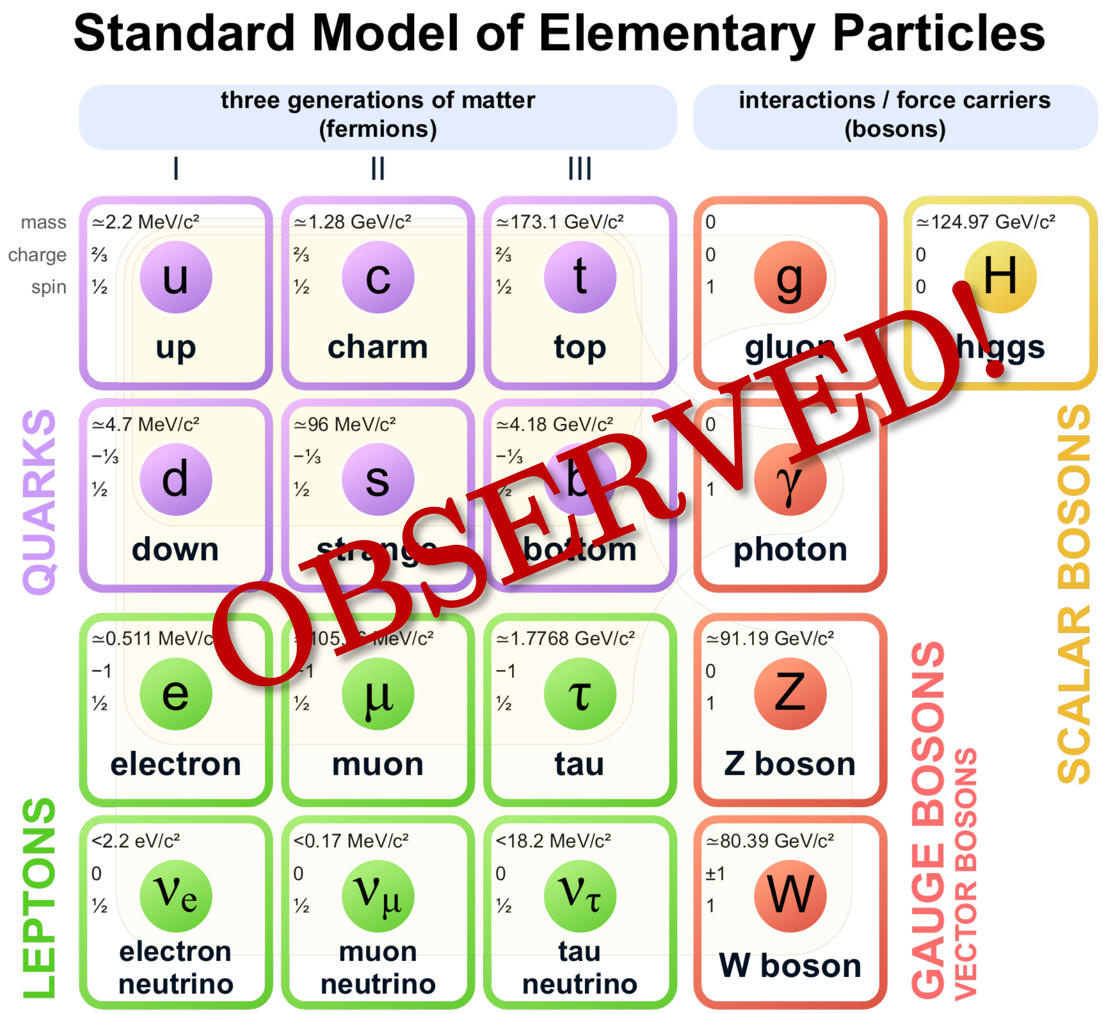
- Avoid monopolizing the conversation; give everyone a chance to talk
- Everyone should feel comfortable talking
  - There are no stupid questions; everyone has a different amount of physics background, but we are all here to learn more
- Try to avoid talking at the same time as other participants.
- Check the chat for what the discussion questions.
  - Should be an option to call me into the breakout room if needed

Preview: Standard Model



Everything we understand today about fundamental particles and their interactions is incorporated into the **Standard Model**

Preview: Standard Model



Observations:

- electron: 1897 by JJ Thomson
- muon: 1937 by Anderson & Neddermeyer
- electron neutrino: 1956 by Cowan & Reines
- muon neutrino: 1962@BNL
- up, down, strange quark: 1968@SLAC
- charm quark: 1974@SLAC, BNL
- tau lepton: 1975@SLAC
- bottom quark: 1977@FNAL
- gluon: 1979@DESY
- W and Z bosons: 1983@CERN
- top quark: 1995@FNAL
- tau neutrino: 2000@FNAL
- Higgs boson: 2012@CERN

Overview

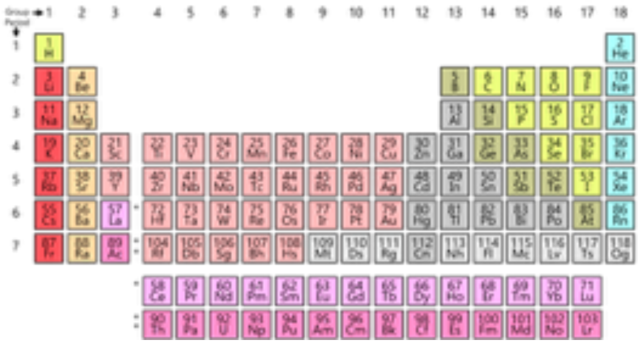
- Historical view of particle physics
  - What are fundamental particles?
  - How were electrons, protons, neutrinos, and quarks discovered?

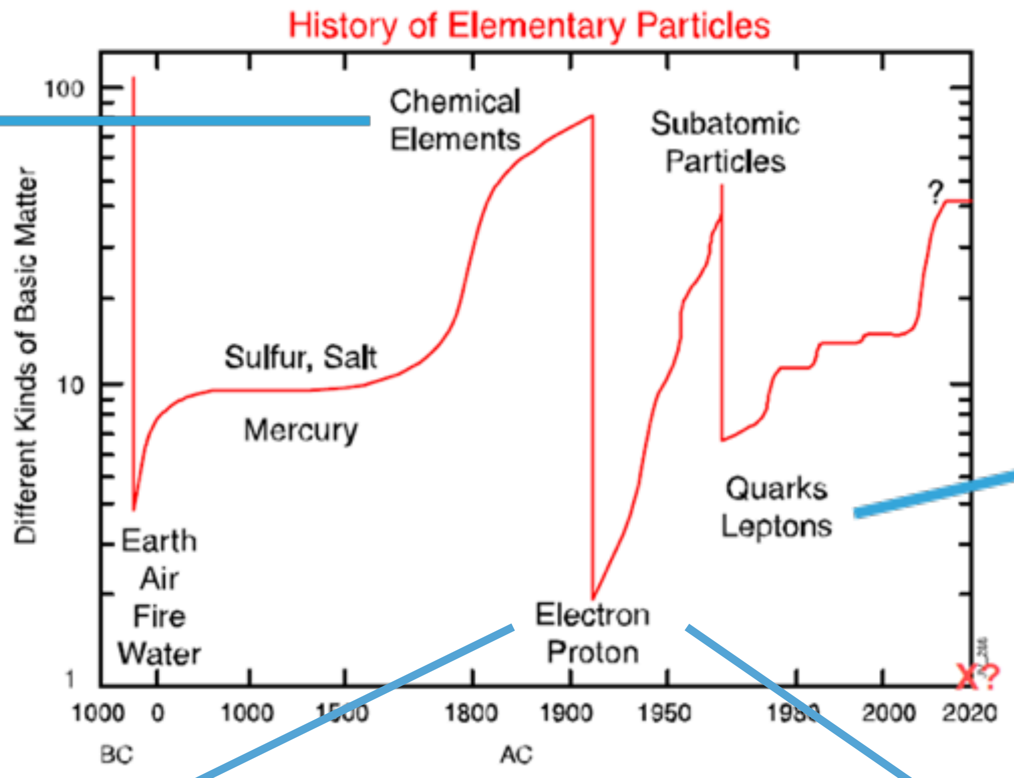
- Overview of the Standard Model
  - Particles in the SM: matter particles and force carriers
  - Feynman diagrams

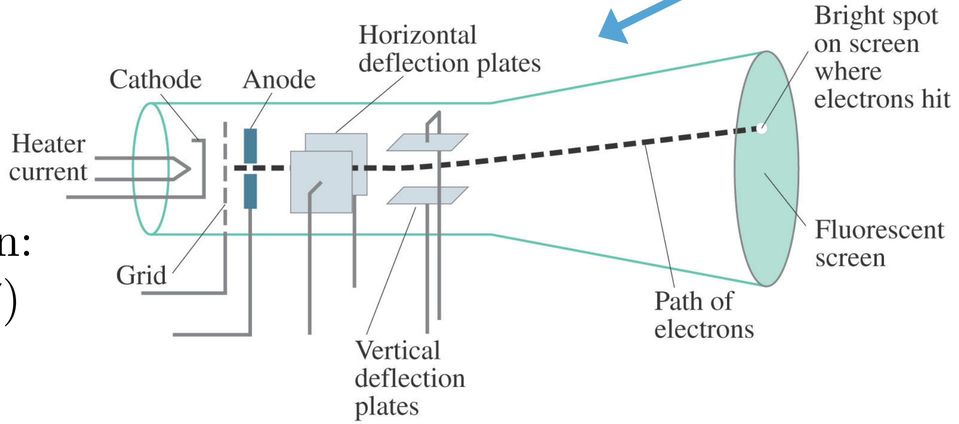
What is particle physics?

- Trying to understand the basic building blocks of our universe
- “Fundamental” or “elementary” particles
  - Cannot be divided into any smaller pieces
  - No internal structure

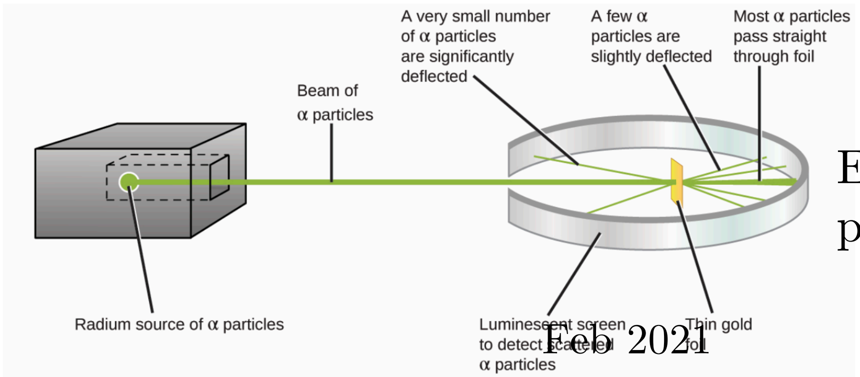
Brief history of particle physics







J.J. Thompson: electron (1897)



E. Rutherford: proton (1909)

Physics at the turn of the century

- Common belief: all physical phenomena could be described using Newton's Laws
- Maxwell's equations for electromagnetism had been established and experimentally verified
- Chemical elements were believed to be **fundamental** particles

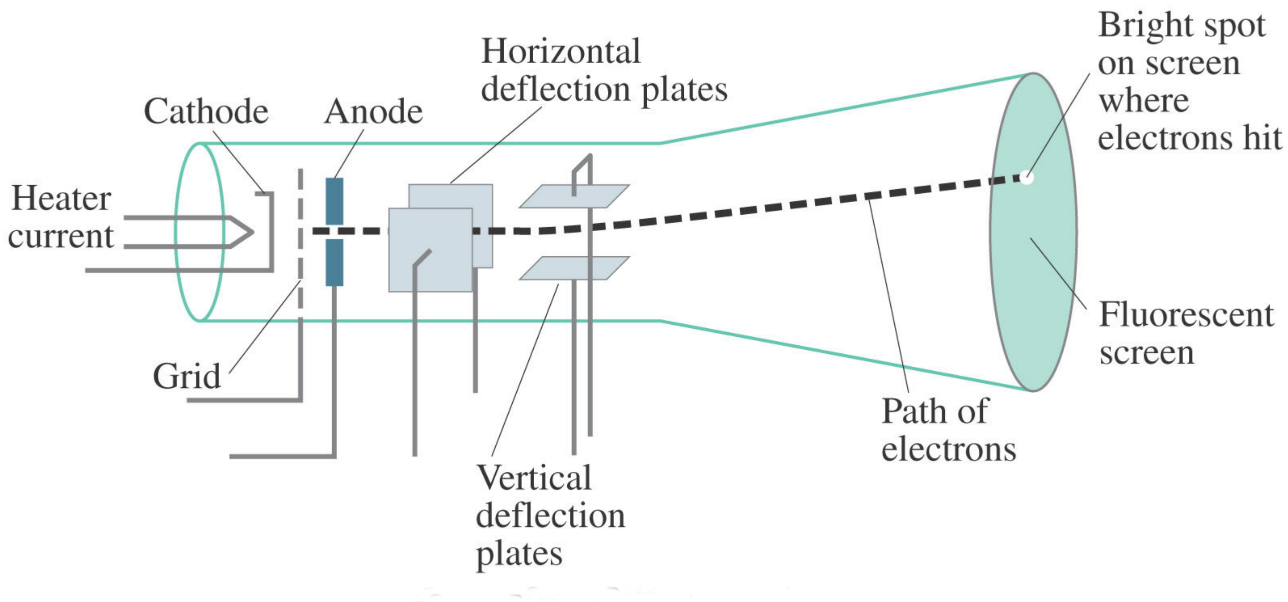
	1	2	3†		4	5	6	7	8	9	10	11	12‡	13	14	15	16	17	18
1	1 H																		2 He
2	3 Li	4 Be												5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg												13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc		22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y		40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	57 La	58-71	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	89 Ac	90-103	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og

58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

Discovery of the electron

- J.J. Thomson (1856– 1940): explored cathode rays in an evacuated glass tube

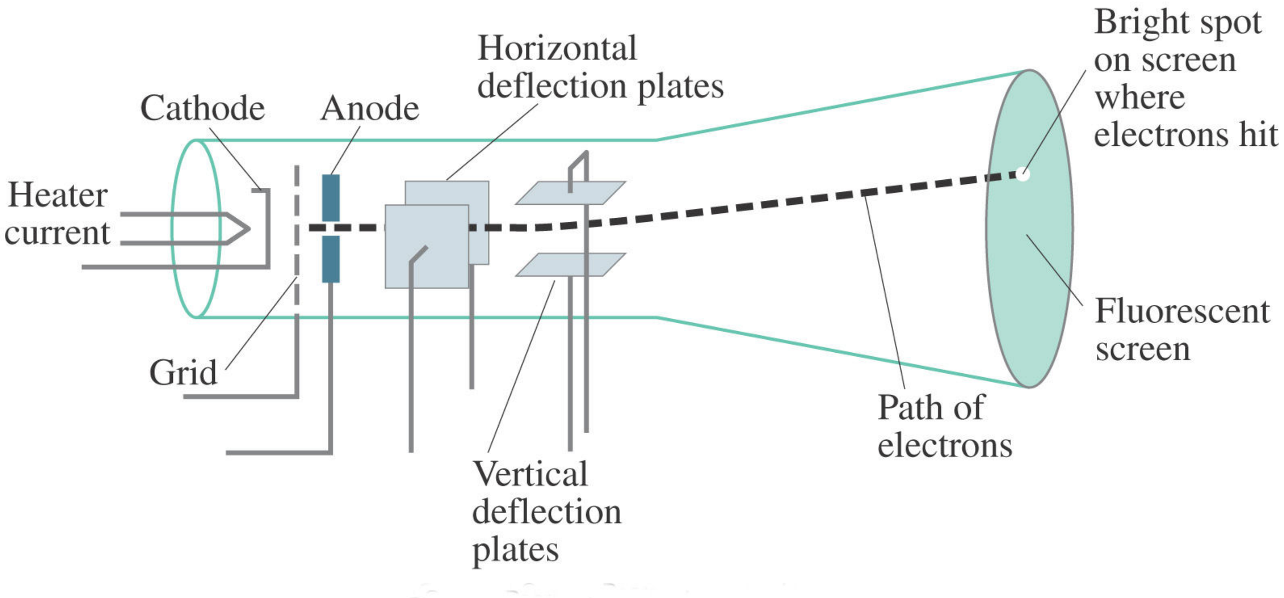
- What is the beam?
  - Massless electromagnetic vibrations in the aether?
    - Beam was deflected by electric fields = negatively charged particles!
  - Charged gas molecules?
    - Applied known E and B fields, measured e/m ratio
    - Same measured value of e/m even for **different** gas and cathode materials



$\rightarrow$ 1897: New fundamental particle that is present in all atoms!

Discovery of the electron

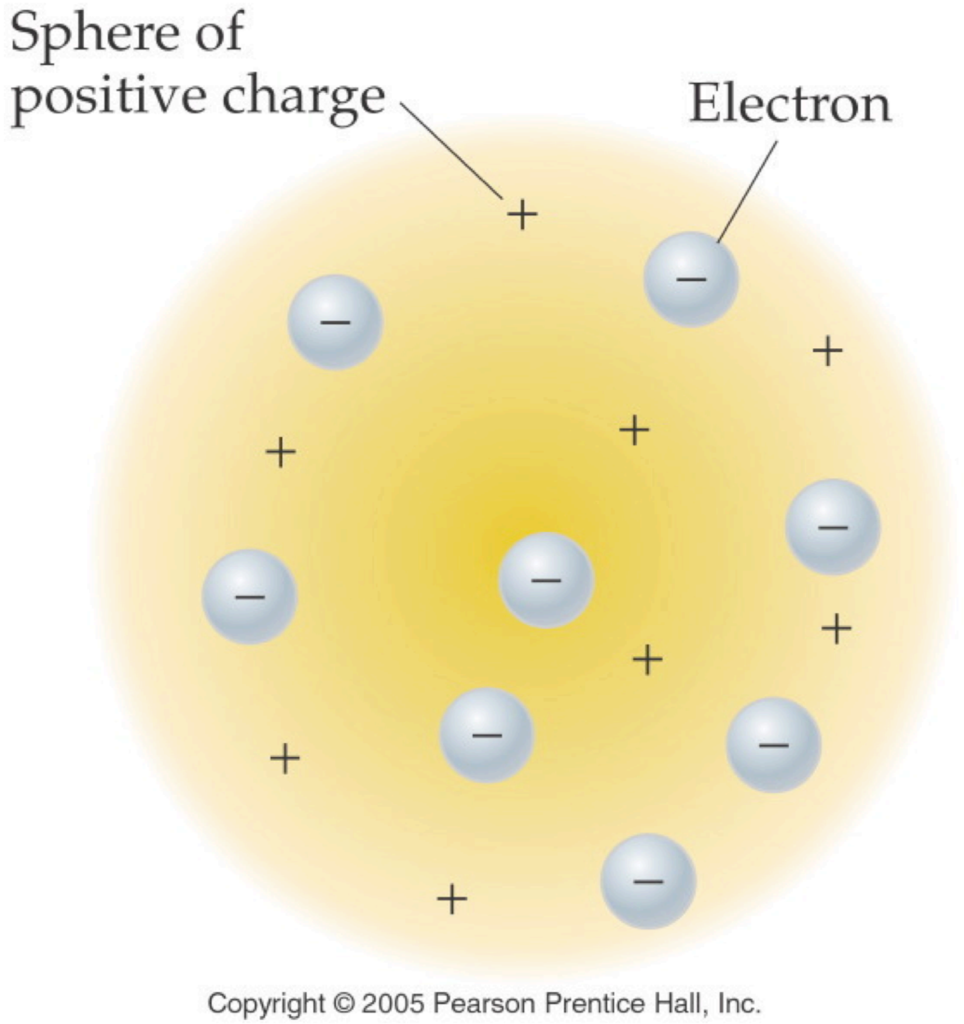
J.J.Thomson (1856 - 1940)



First solid evidence that the chemical atom was not the structureless, fundamental particle that scientists thought!

Plum Pudding Model of the Atom

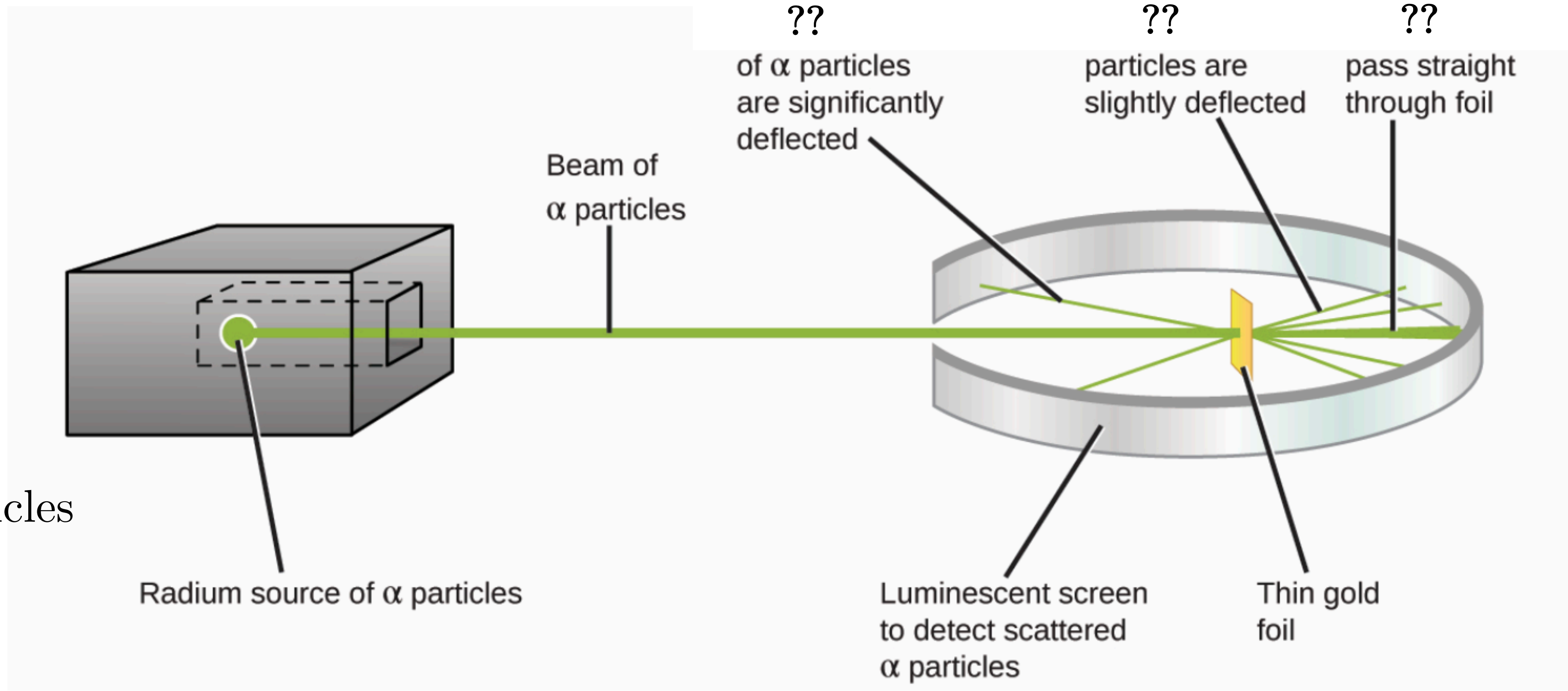
J.J. Thomson (1904)



Electrons were embedded in a positively charged atom like plums in a pudding

Rutherford scattering experiment

- Ernest Rutherford (1909): Wanted to study the structure of the nucleus
  - Sent α particles toward a thin gold foil, observed angles at which they were deflected
- **Go to online demo:** https://phet.colorado.edu/sims/html/rutherford-scattering/latest/rutherford-scattering_en.html



Alpha (α) particles are ${}^{4}_{2}He$ ions (+2 charge)

Discussion questions

First, introduce yourself to your group, including what school you attend.

Test the simulation and answer the following questions:

1. Compare the paths of the α particles in both models. Try to explain any differences.
2. What would have happened if neutrons had been used in Rutherford's experiment instead of α particles? Explain your answer.

Bonus:

3. How does altering the energy of the α particle affect the direction of the paths in each model?
4. In the Rutherford mode of the atom, what effect does changing the number of protons and neutrons have on the paths of the α particles?

Rutherford Scattering

- **Results** of Rutherford's experiment: 1 in 8000 α's were deflected back towards the source.

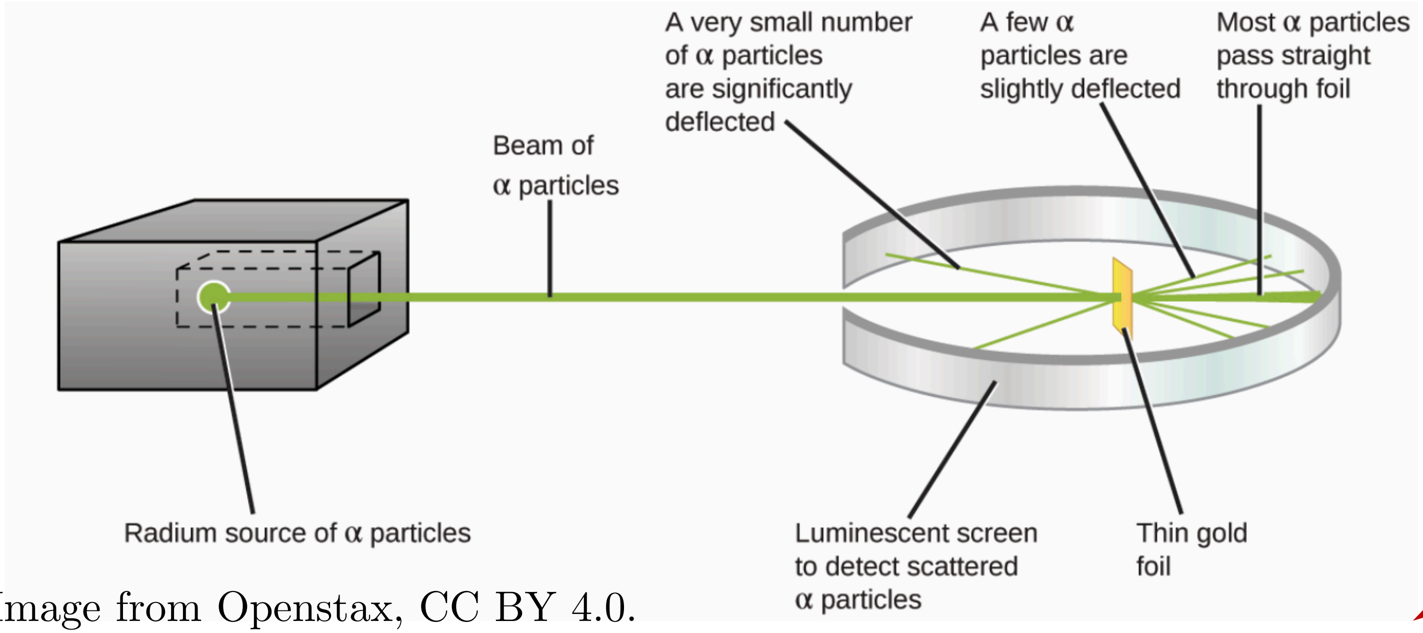


Image from Openstax, CC BY 4.0.

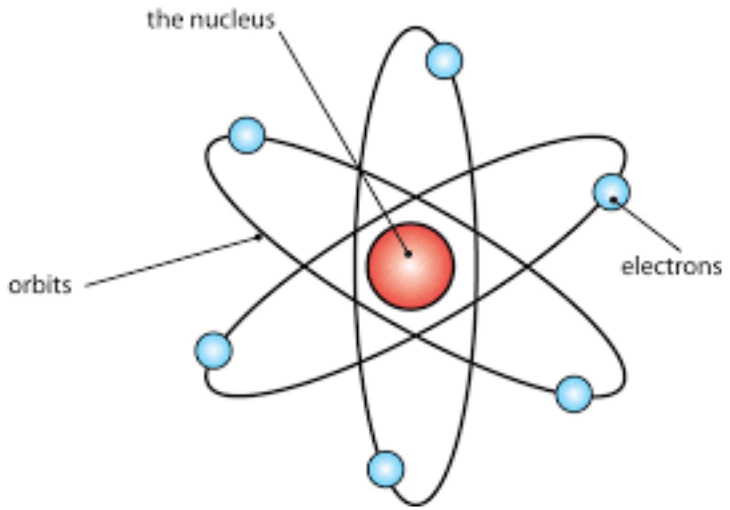
"It was quite the most incredible event that has ever happened to me in my life. It was almost as incredible as if you fired a 15-inch shell at a piece of tissue paper and it came back and hit you.

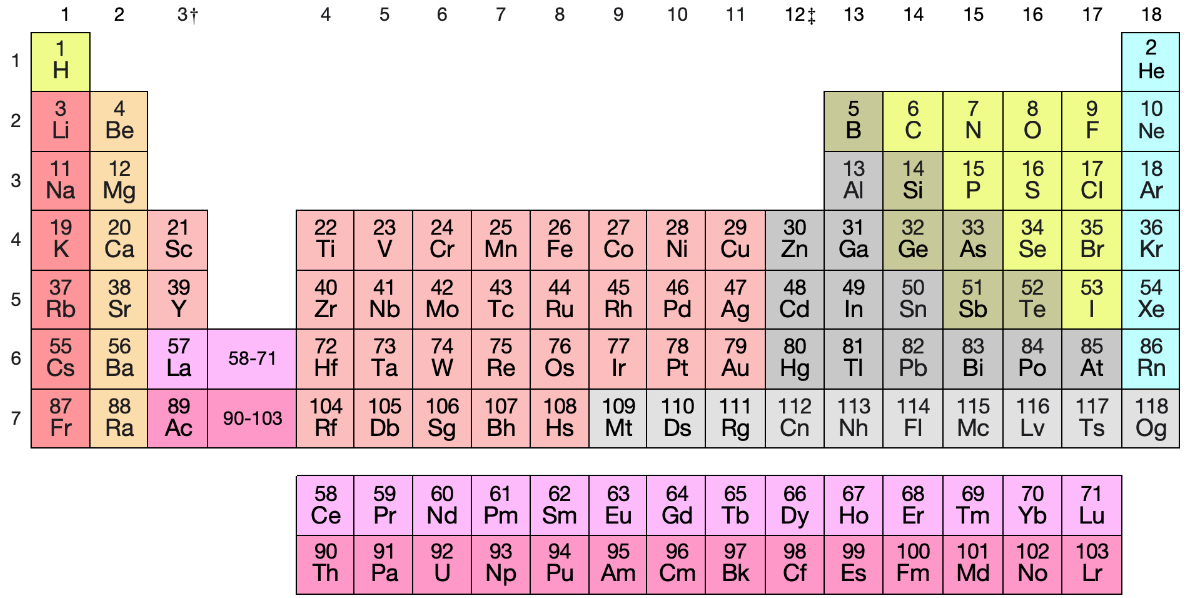
E. Rutherford (1909)

- Conclusion: positive matter is concentrated in an incredibly small volume (10^{-13} cm)

Planetary Model of the Atom

- Atoms are made up of a central positive charge surrounded by a cloud of orbiting electrons
    - As you heard last week, this model isn't quite right either and fails to account for quantum mechanics
- 1917: Rutherford proved that the nucleus of all atoms includes protons
- 1932: Neutrons discovered by James Chadwick





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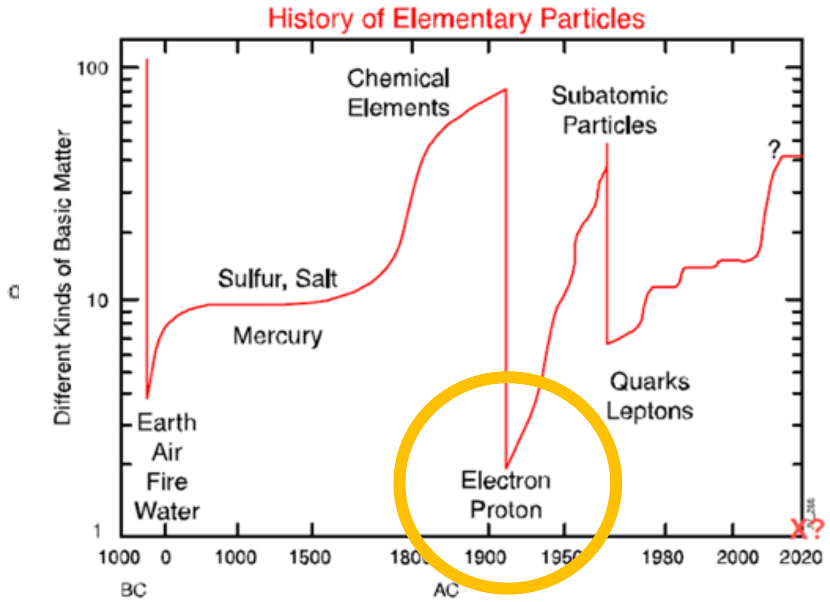
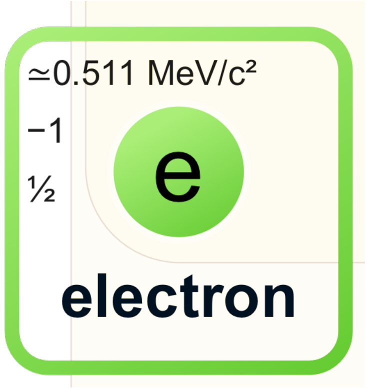
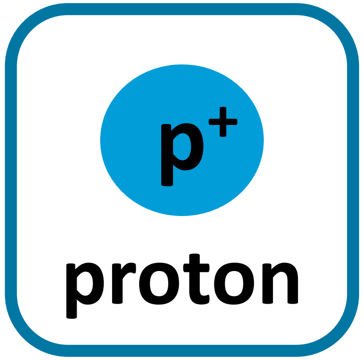
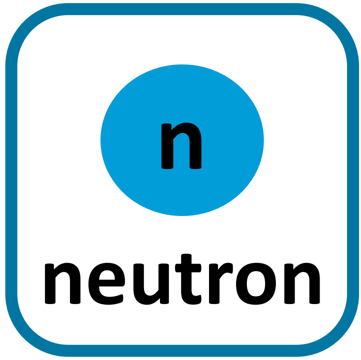
- All atoms are made of protons, neutrons and electrons
  - Only 3 fundamental particles, life is good!



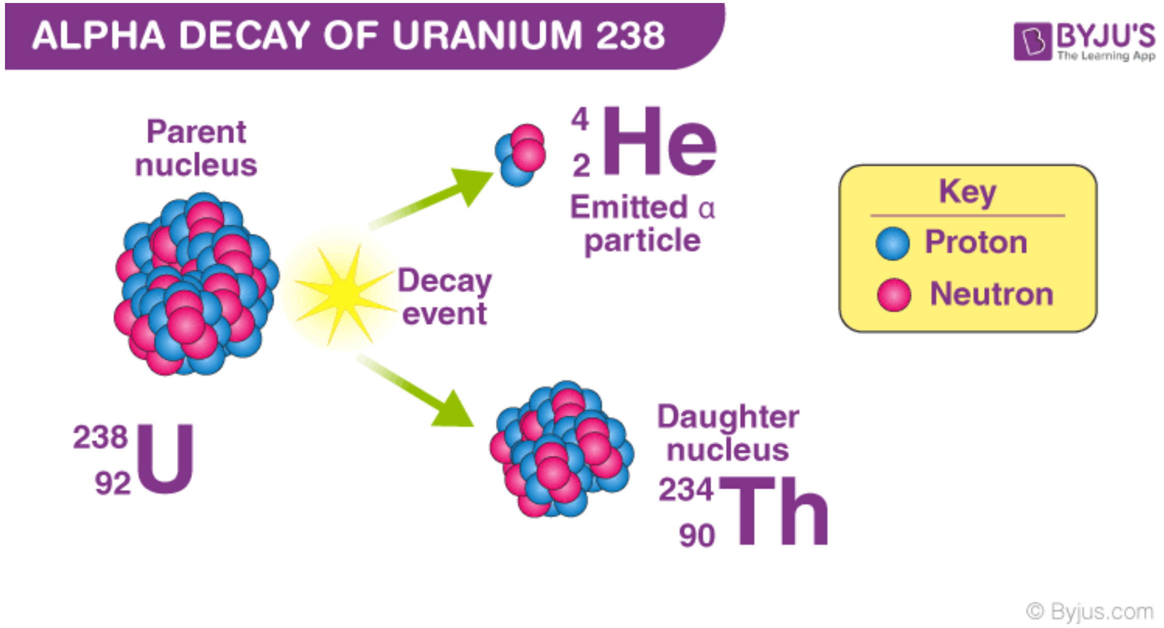






Case study: alpha (α) decay

- α decay is when the original nucleus ($^{238}_{92}U$) breaks into a smaller nucleus ($^{234}_{90}Th$) and an α particle ($^{4}_{2}He$)



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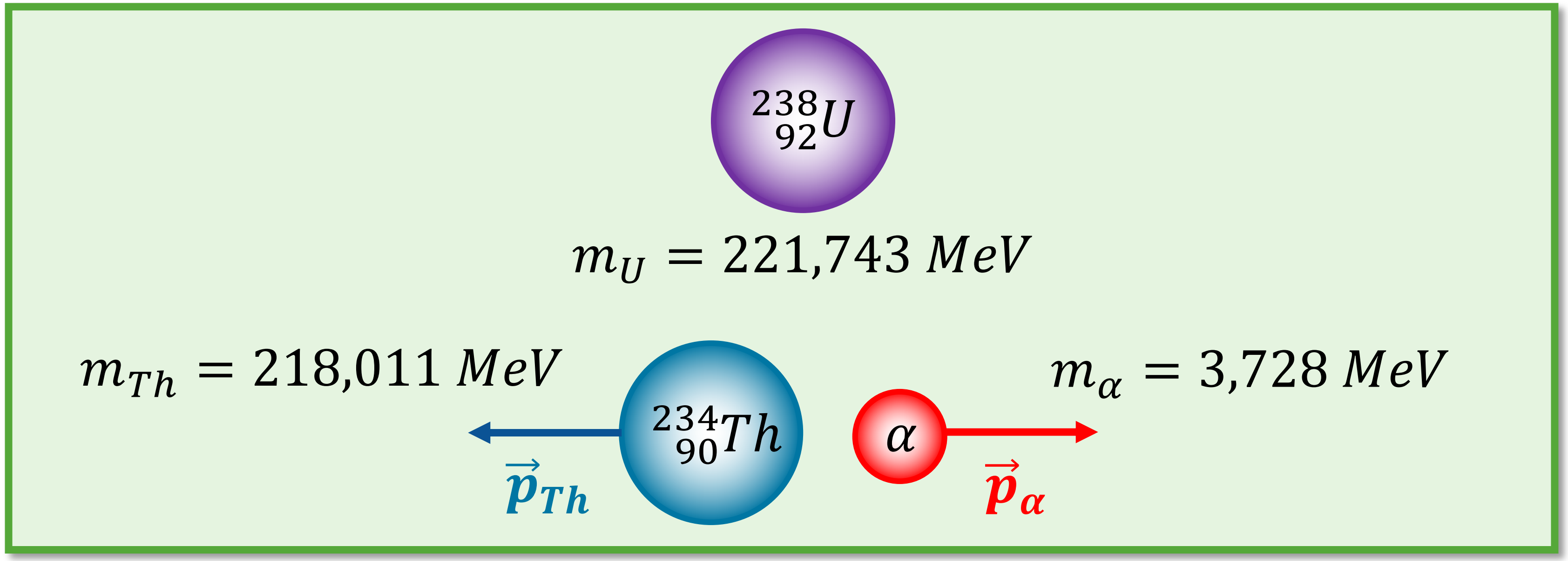
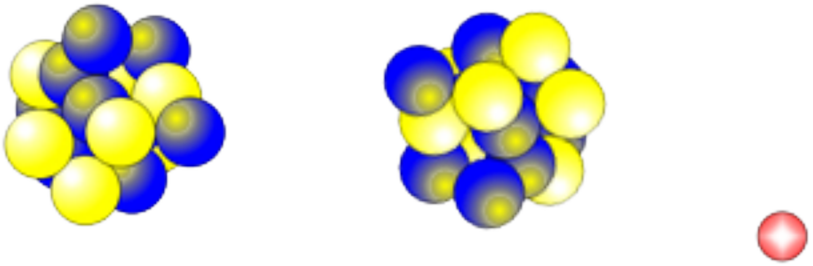


- Two equations and two unknowns:
  - Energy conservation: energy from mass difference ($E = mc^2$) gets converted into kinetic energy of *Th* and α
  - Momentum conservation: $\vec{p}_\alpha$ must balance $\vec{p}_{Th}$

$\rightarrow$ Energy of α particle is uniquely determined

Case study: beta (β) decay

- β decay is when a neutron is converted into a proton and an electron is emitted
  - Original nucleus $^{234}_{90}Th$ becomes $^{234}_{91}Pa$



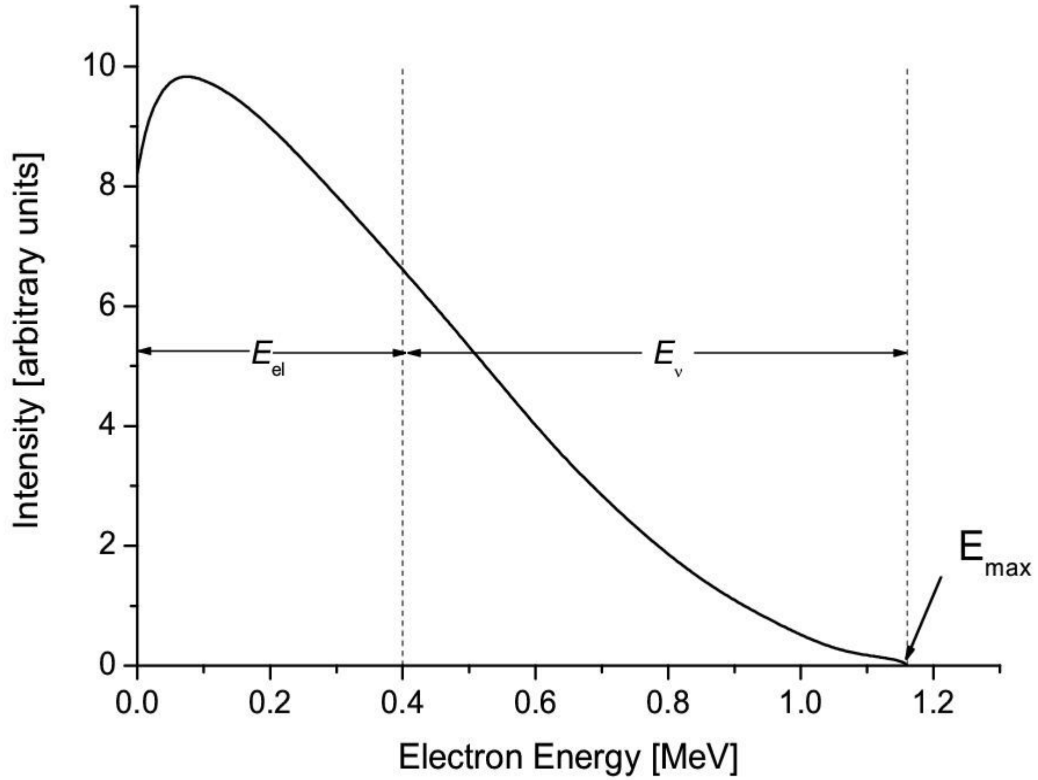
$$^{234}_{90}Th \rightarrow {}^{234}_{91}Pa + {}^{0}_{-1}e$$

- Two equations and two unknowns:
  - Energy conservation: energy from mass difference ($E = mc^2$) gets converted into kinetic energy of Pa and e
  - Momentum conservation: $\vec{p}_e$ must balance $\vec{p}_{Pa}$

  $\rightarrow$ Energy of e particle is uniquely determined

β decay mystery

- As expected, α particles from a decay always have the same energy
- But for β decay, a **range of energies** is observed!
  - First observed by Lise Meitner, Jean Danysz in 1913
  - Is energy conserved??
- 1930: "desperate remedy" by Pauli
  - Maybe there is an undetectable third particle involved in the decay – the **neutrino**
  - Then there are 2 equations and >3 unknowns; energy is not uniquely determined
- 1933: Fermi published his theory of beta decay
  - Neutrino & electron are created in the decay



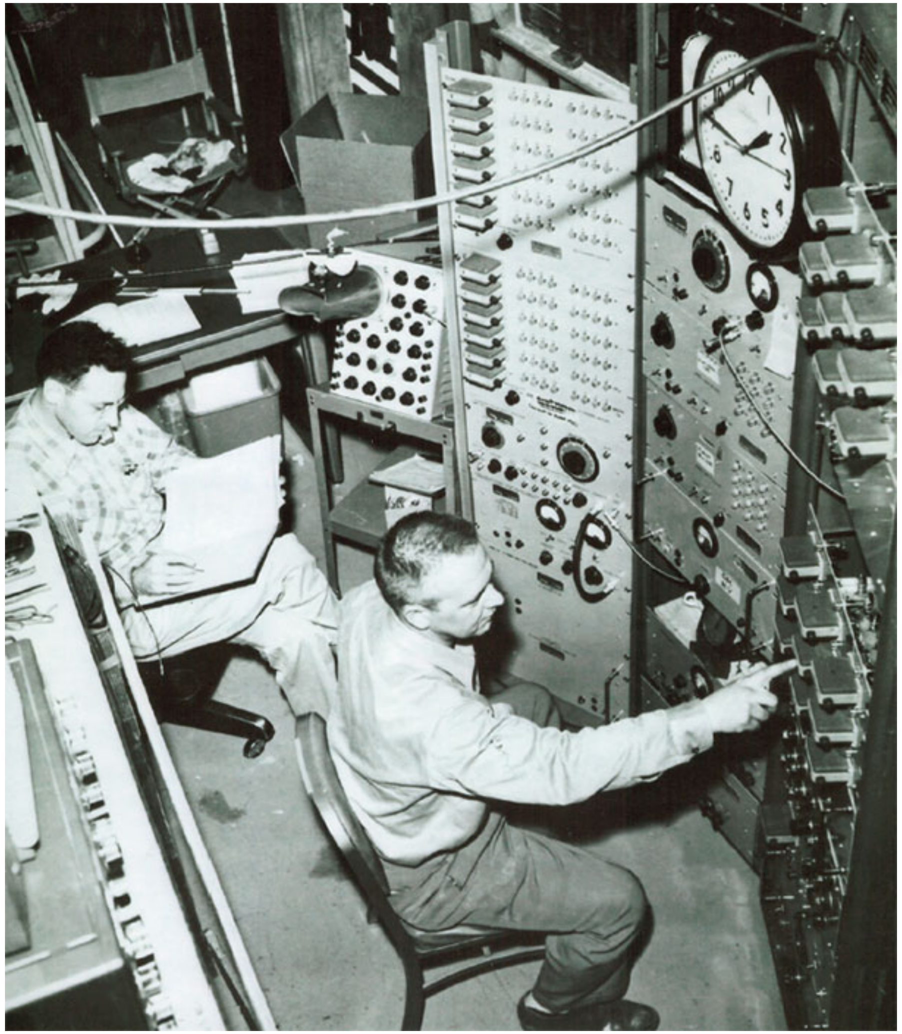
Neutrinos

- Neutrinos only interact via the weak force
- Would need a light year of lead to have a 50% chance of interacting

Recipe for neutrino experiment

1. Use an intense neutrino source to produce neutrinos to study
2. Build the biggest detector possible to increase chances of interacting
3. Minimize backgrounds from other sources (go underground)
4. Collect data over a long period and analyze results

- Experimental observation in 1956 by Clyde Cowan, Frederick Reines



Cowan and Reines at the 1956 Savannah River experiment; Image Credit: Los Alamos National Laboratory

Particle zoo

- Charged Pion (1947)
- Charged Kaon (1947)
- Neutral Pion (1950)
- Neutral Kaon (1950)
- Lambda (1950)
- Charged Sigma (1950)
- Delta (1952)
- Charged Xi (1953)

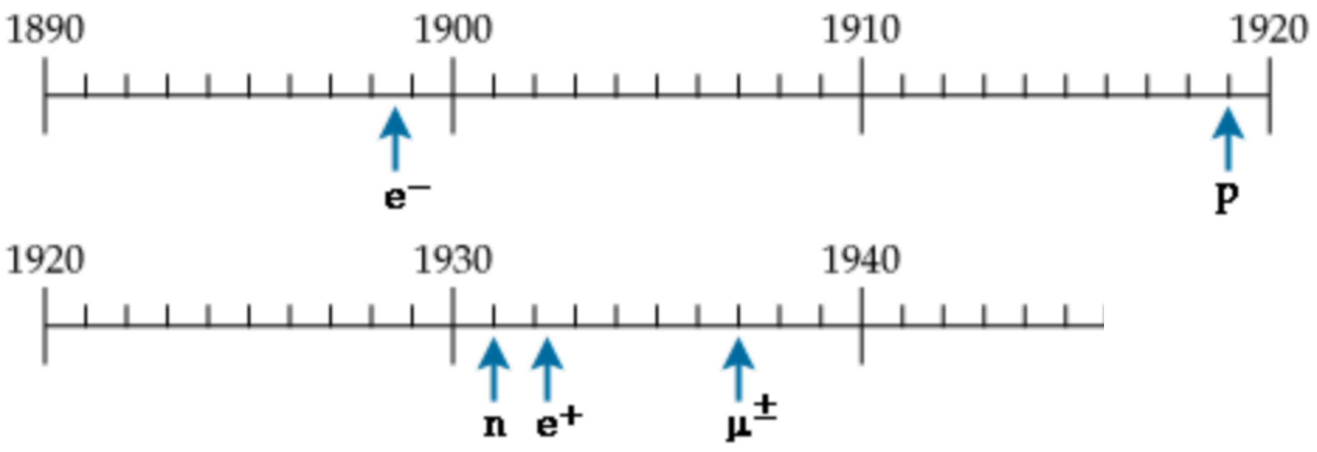


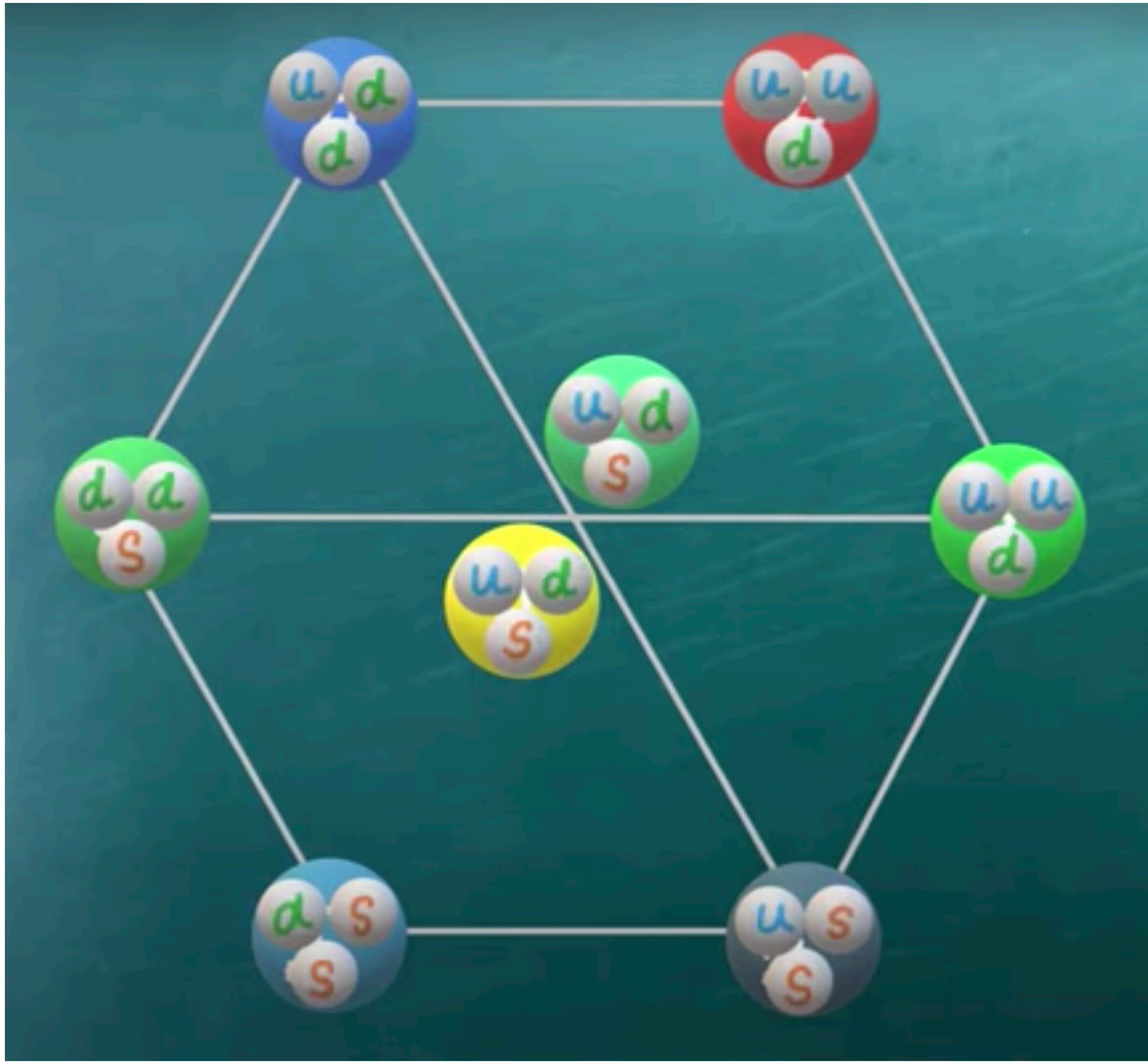
Image from the particle adventure

- Trying to make sense and organize all the new particles:
  - "Strangeness" quantum # proposed by Gell-Man, Tadao Nakano and Kazuhiko Nishijima in 1953

Eightfold way

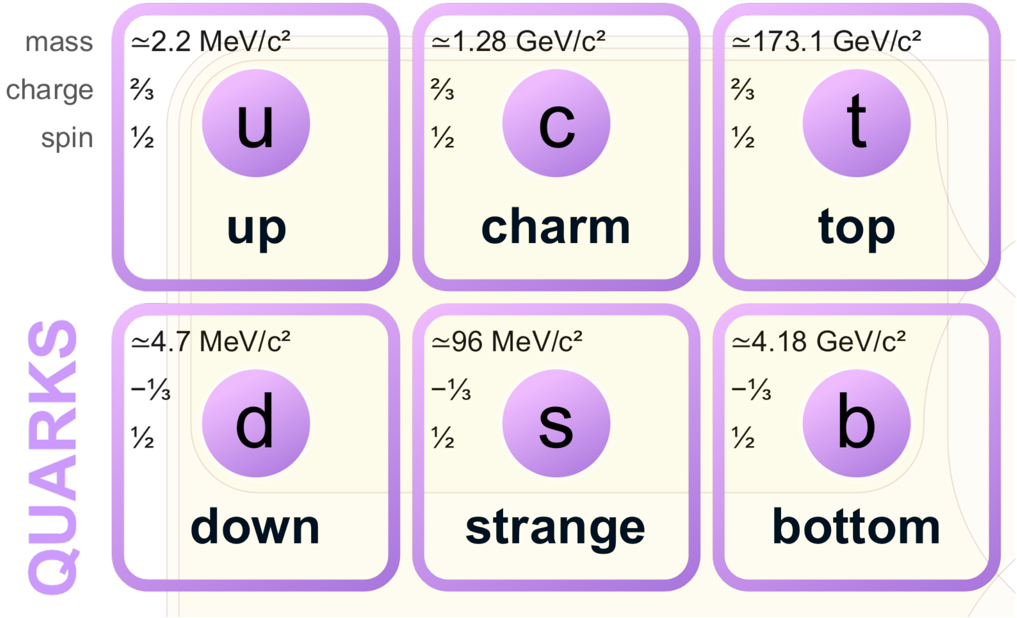
- Scheme proposed by Gell-Mann and Ne'eman in 1961
  - Organize hadrons by charge and strangeness
- Predicted Ω^- particle that was later discovered in 1964

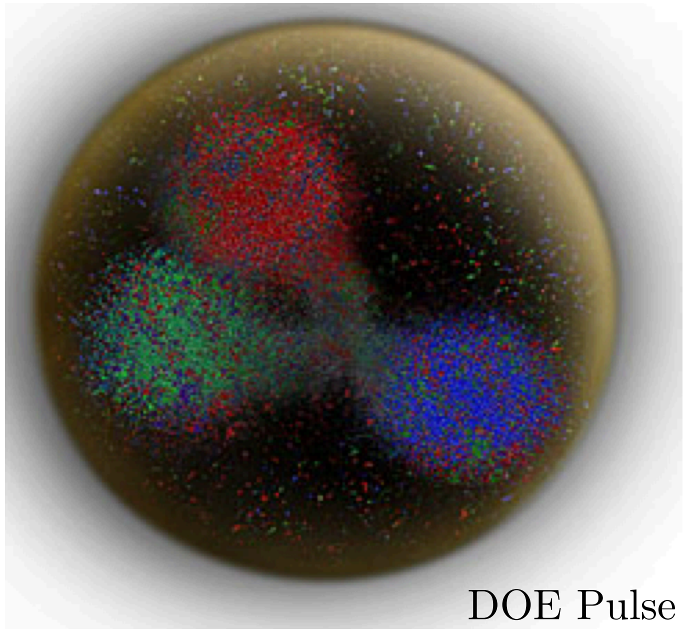
- **Quarks:** proposed by Gell-Mann and Zweig in 1964
  - All of the hadrons made up of **up, down,** and **strange** quarks
  - Fractional charges: 1/3 or 2/3



Quarks

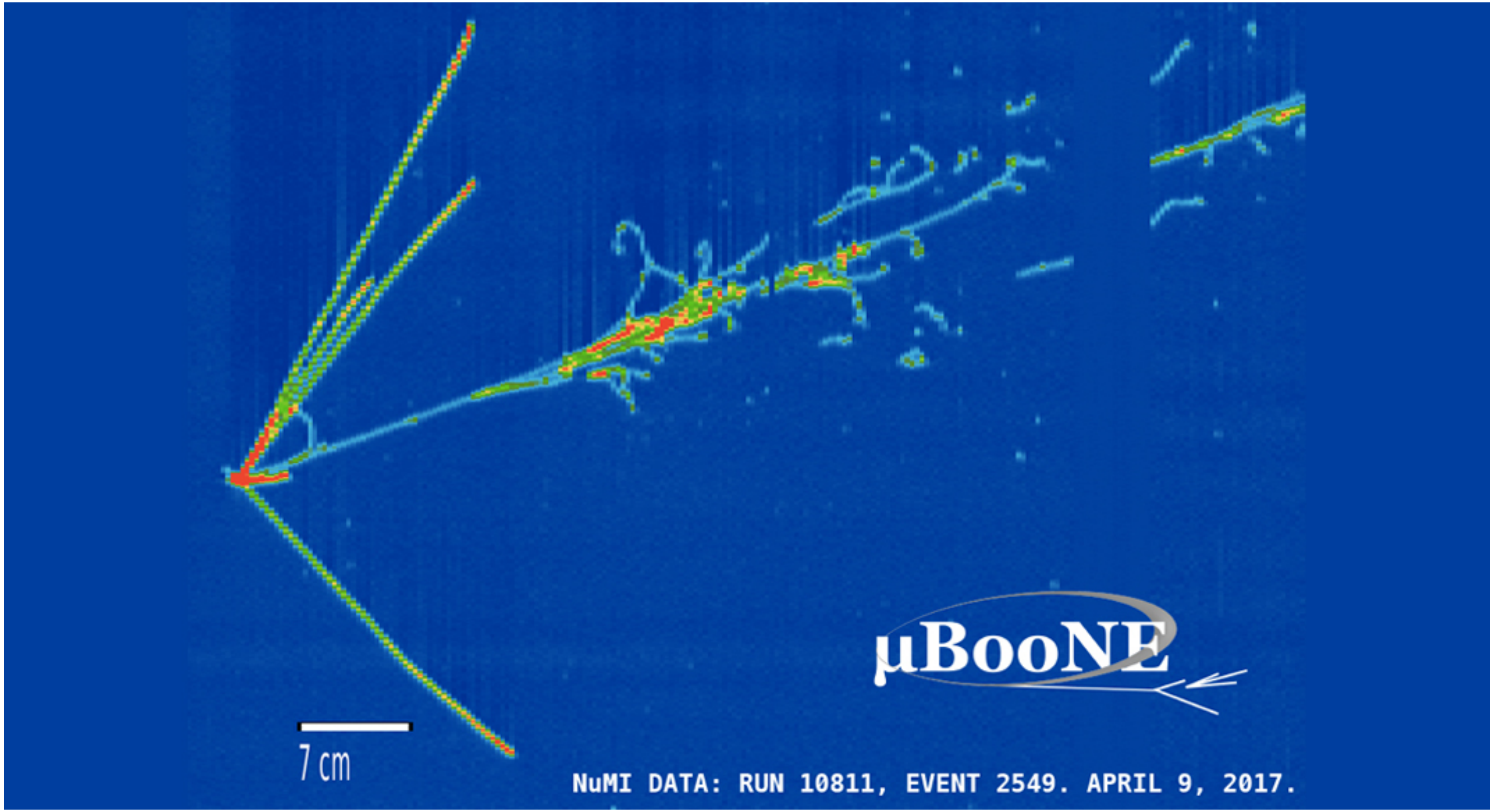
- Mathematical framework or the way the world actually works?
  - Direct evidence for quarks within proton came from experiments at SLAC in 1968
- Discovery of the J/ψ particle at SLAC and Brookhaven in 1974 showed there was a 4$^{\text{th}}$ quark: **charm** quark
  - Bottom quark discovered in 1977
  - Top quark discovered in 1995





DOE Pulse

Liquid Argon neutrino interaction



Overview of the Standard Model

Overview

- Historical view of particle physics
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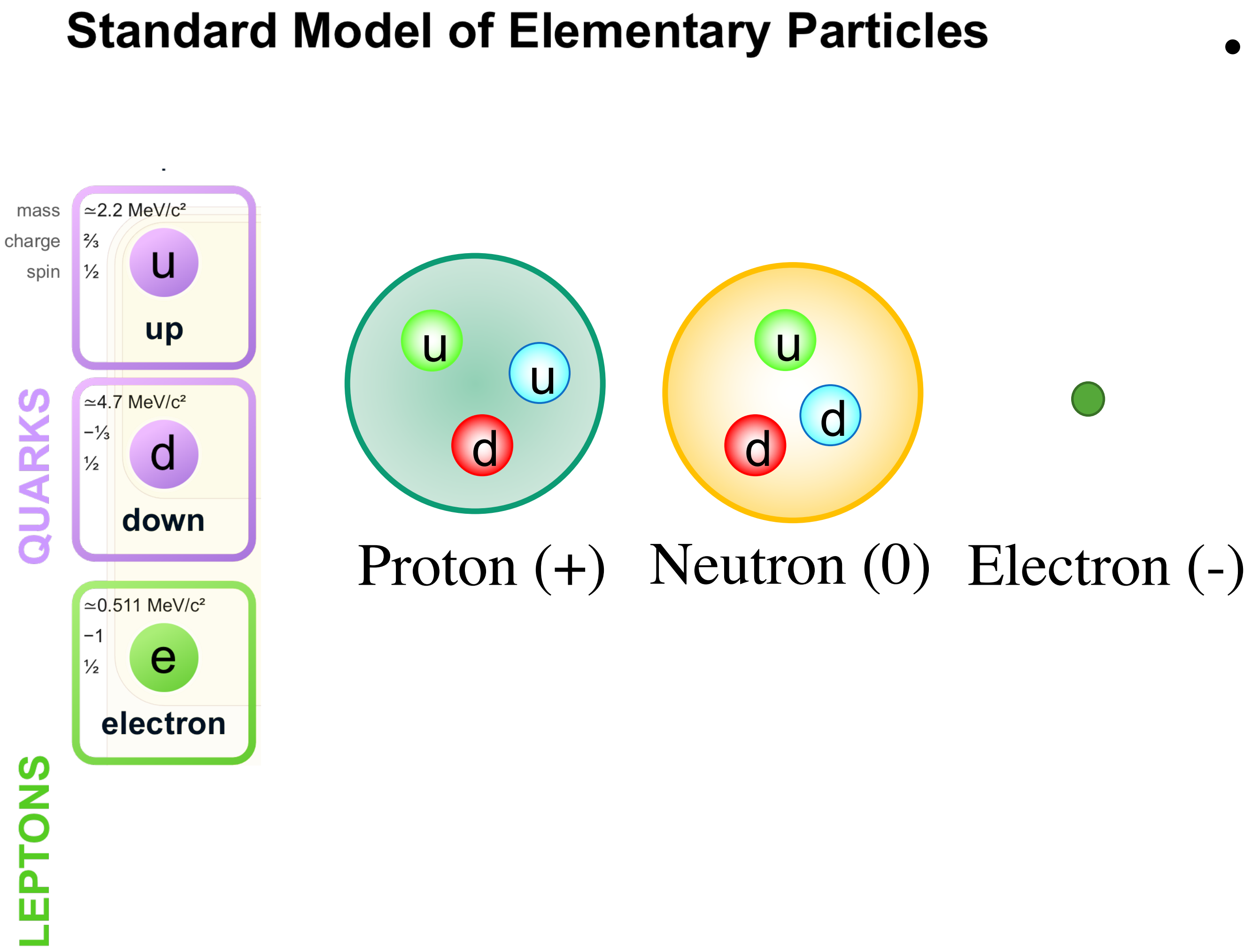
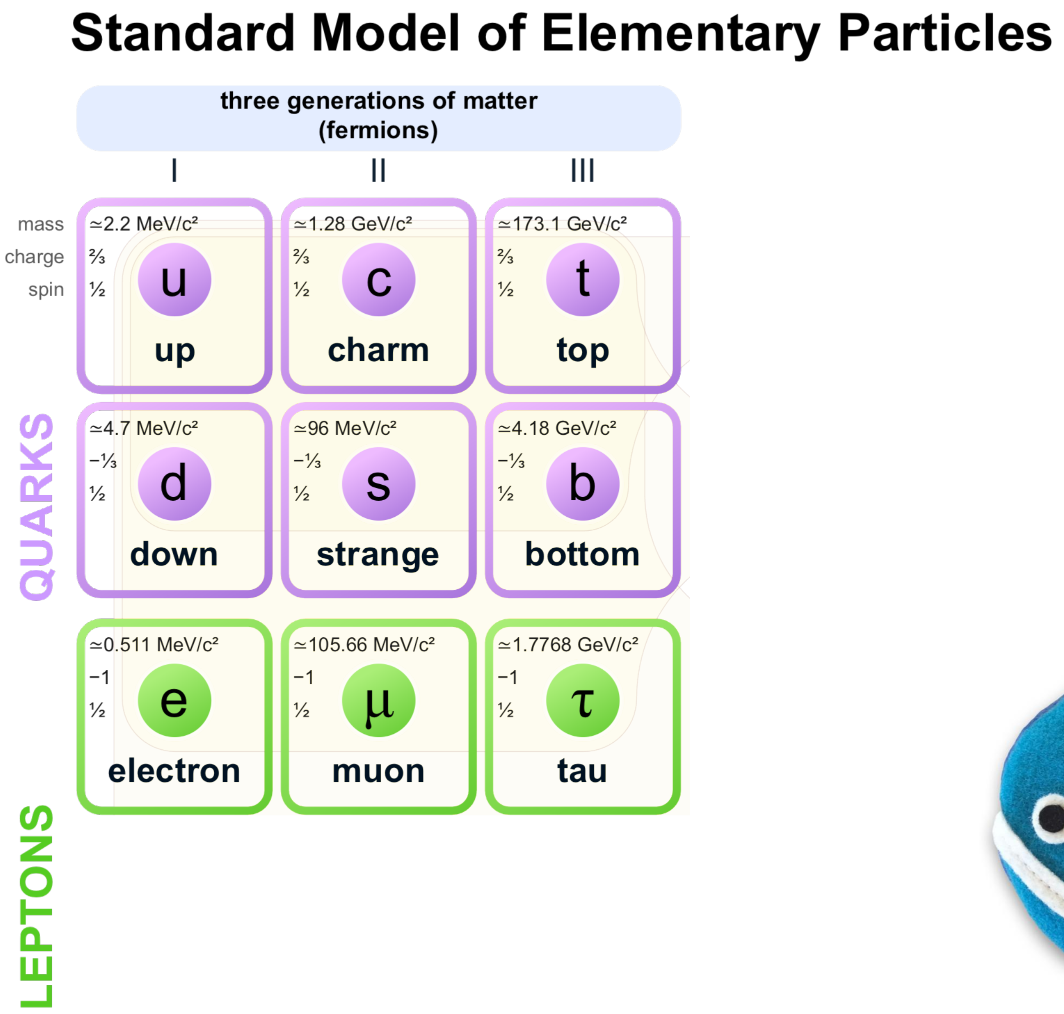
- Overview of the Standard Model
  - Particles in the SM: matter particles and force carriers
  - Feynman diagrams

Earth's building blocks



- All ordinary matter is made from **up quarks**, **down quarks**, and **electrons**

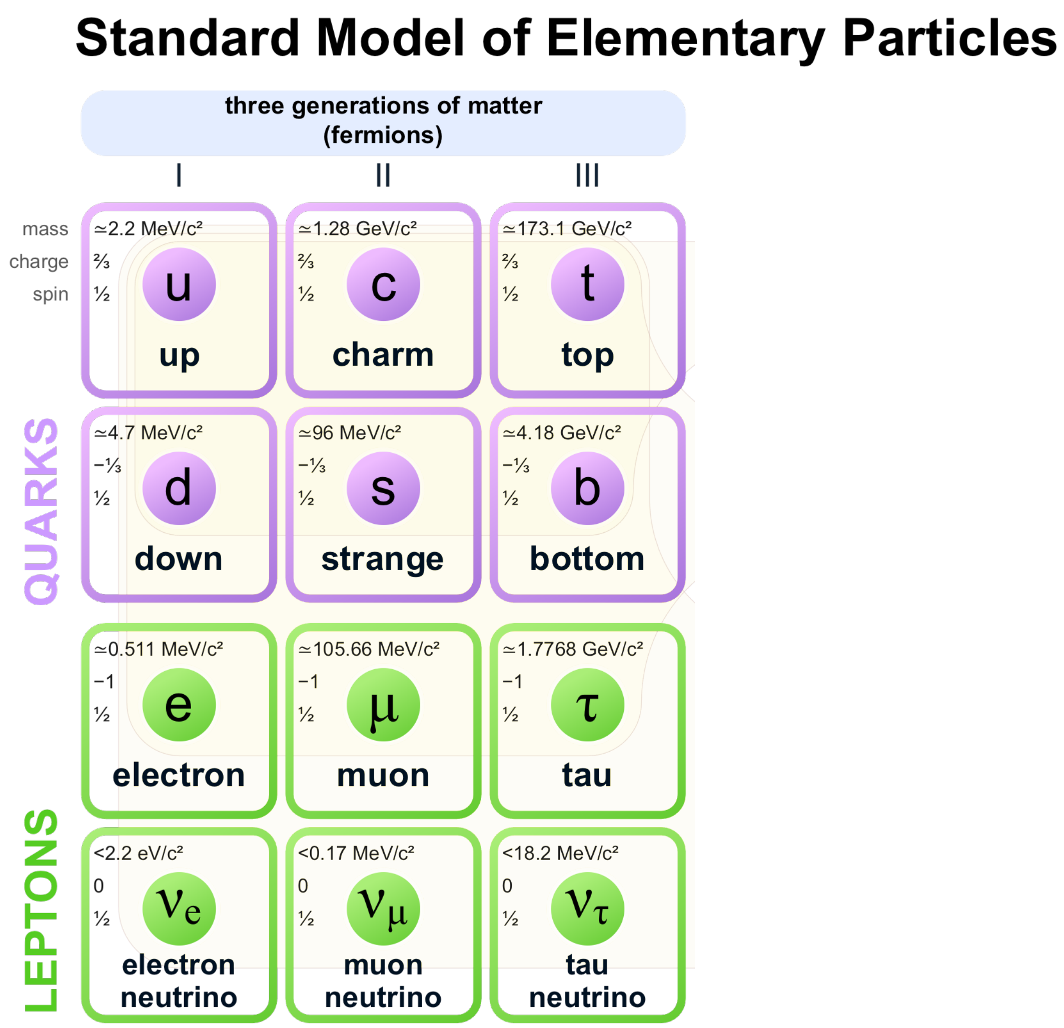
Three generations



- All ordinary matter is made from up quarks, down quarks, and electrons
- There are three copies, or *generations*, of quarks and leptons
  - Same properties, only heavier

- Muons discovered in cosmic rays in 1937
  - "Who ordered that?" -I.I. Rabi

Neutrinos

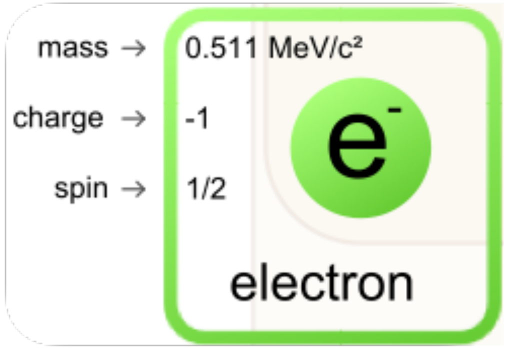


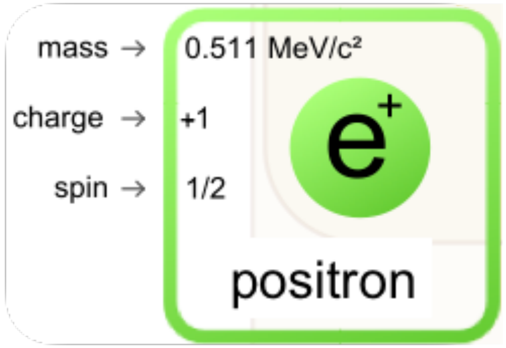
- All ordinary matter is made from **up quarks**, **down quarks**, and **electrons**
- There are three copies, or *generations*, of quarks and leptons
  - Same properties, only heavier
- Leptons also include **neutrinos**, one for each generation

All of these *matter* particles are **fermions:** they have **half integer spin**

Antimatter

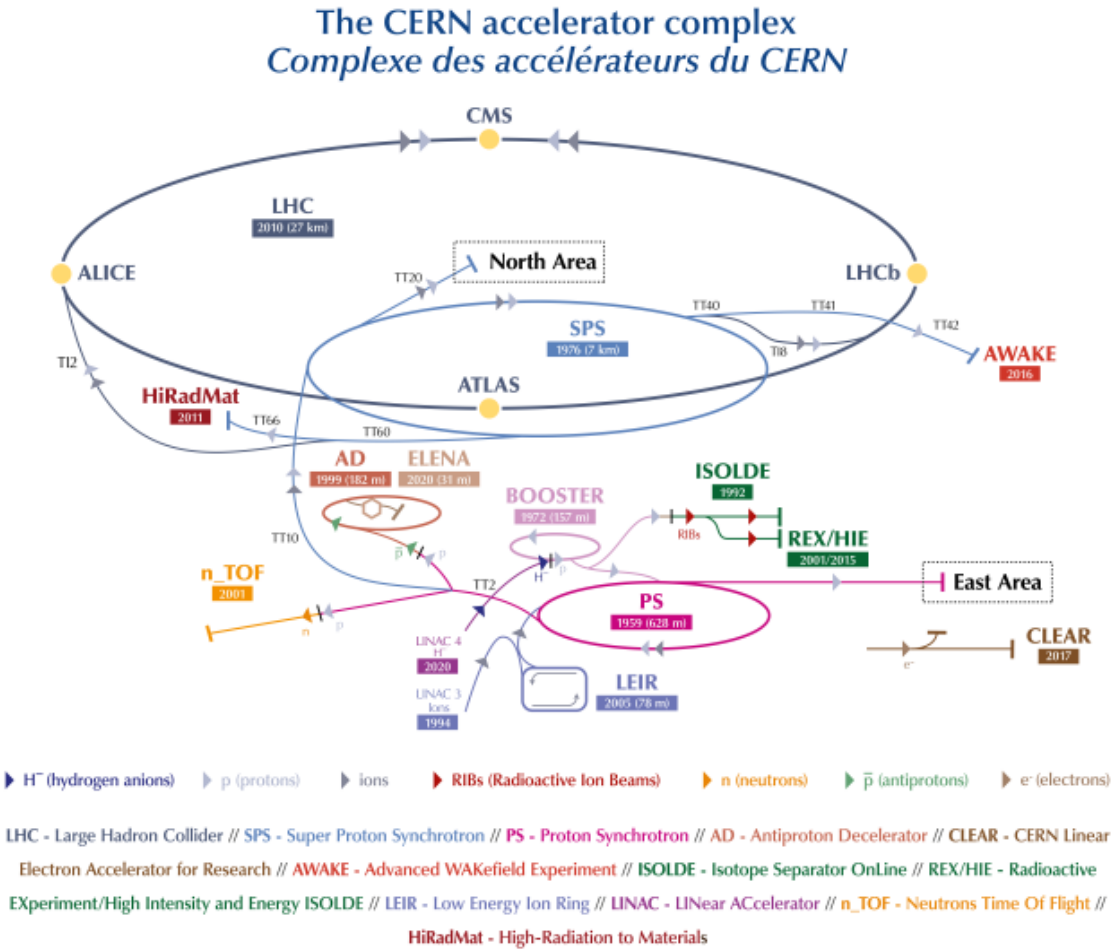
- 1927: Dirac derived an equation to describe relativistic electrons, but there were **two** solutions
  - Just like $x^2 = 4$ has two solutions
  - Corresponded to electrons with +1 or -1 charge
- 1932: Carl Anderson recorded a positron track in a cloud chamber
- Antimatter is exactly the same as matter except one attribute is flipped: the *charge*





How do we make antimatter?

At the antimatter factory of course!

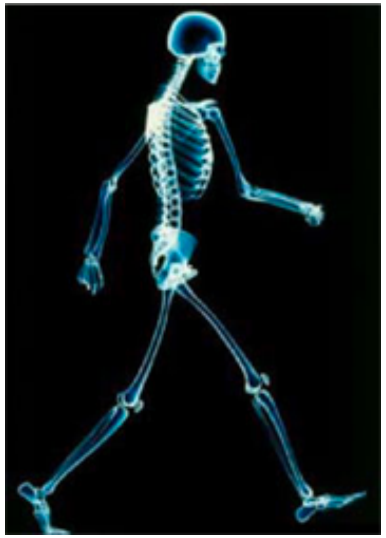


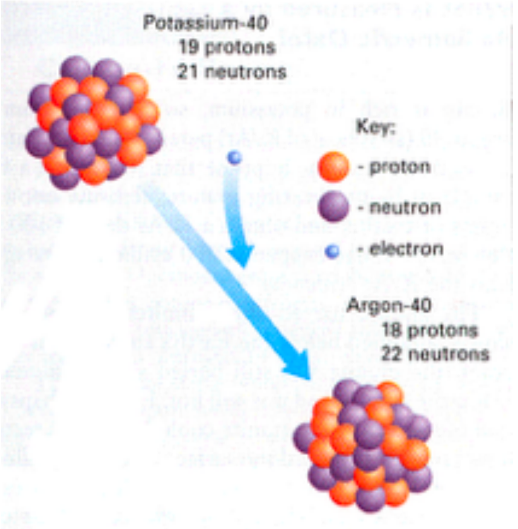
How do we make antimatter?

Some antimatter is easier to produce than others...

Positrons from Potassium-40: your body produces about 180 positrons per hour!

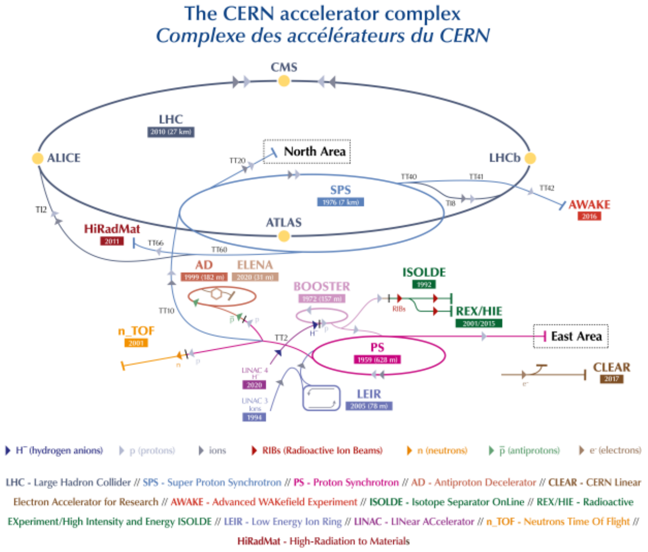
$${}^{40}_{19}\mathrm{K} \rightarrow {}^{40}_{18}\mathrm{Ar} + e^{+} + \nu_e$$



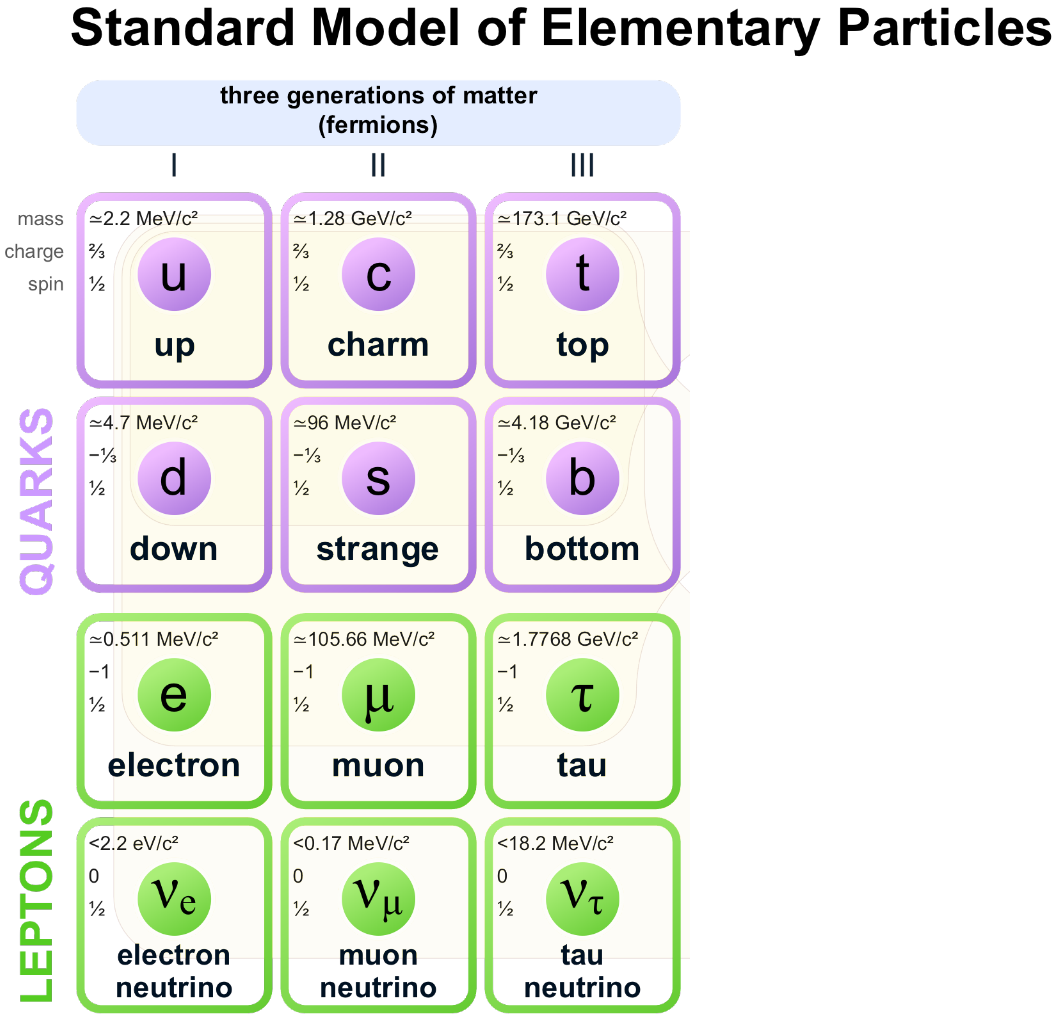


Antiprotons from high energy collisions of a proton beam on a fixed target of metal

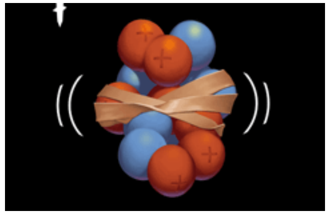
$$p + p \rightarrow \bar{p} + p + p + p$$



Force carriers

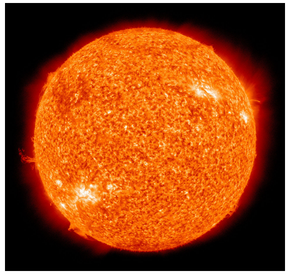


- The other group of particles in the Standard Model are bosons: particles with **integer spin**
- These are the force carriers



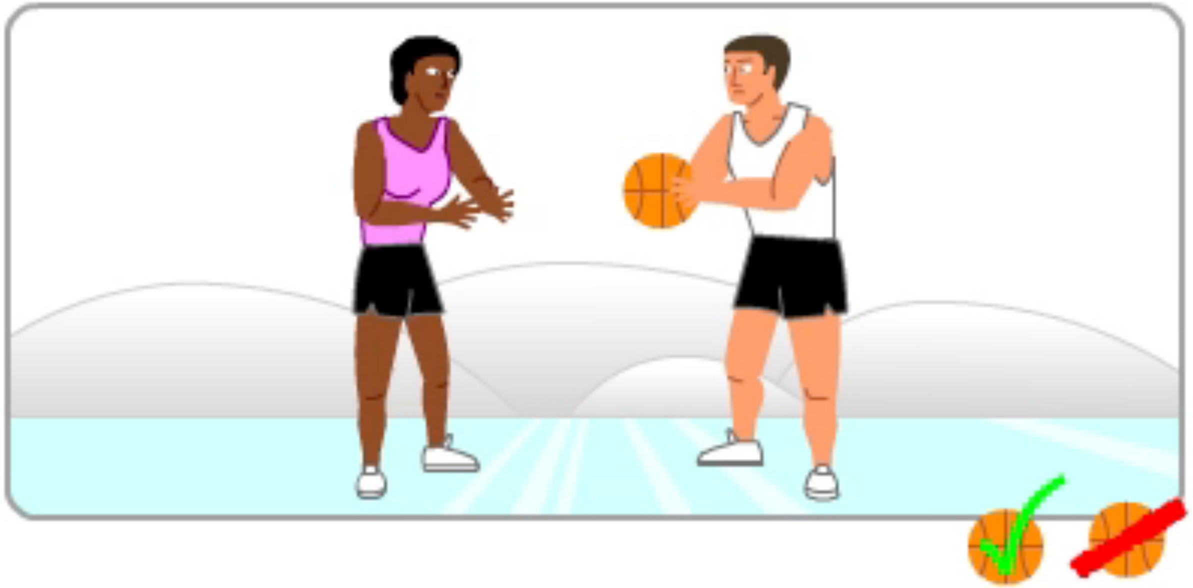
Strong force

Electromagnetic force



Weak force

The Unseen Effect



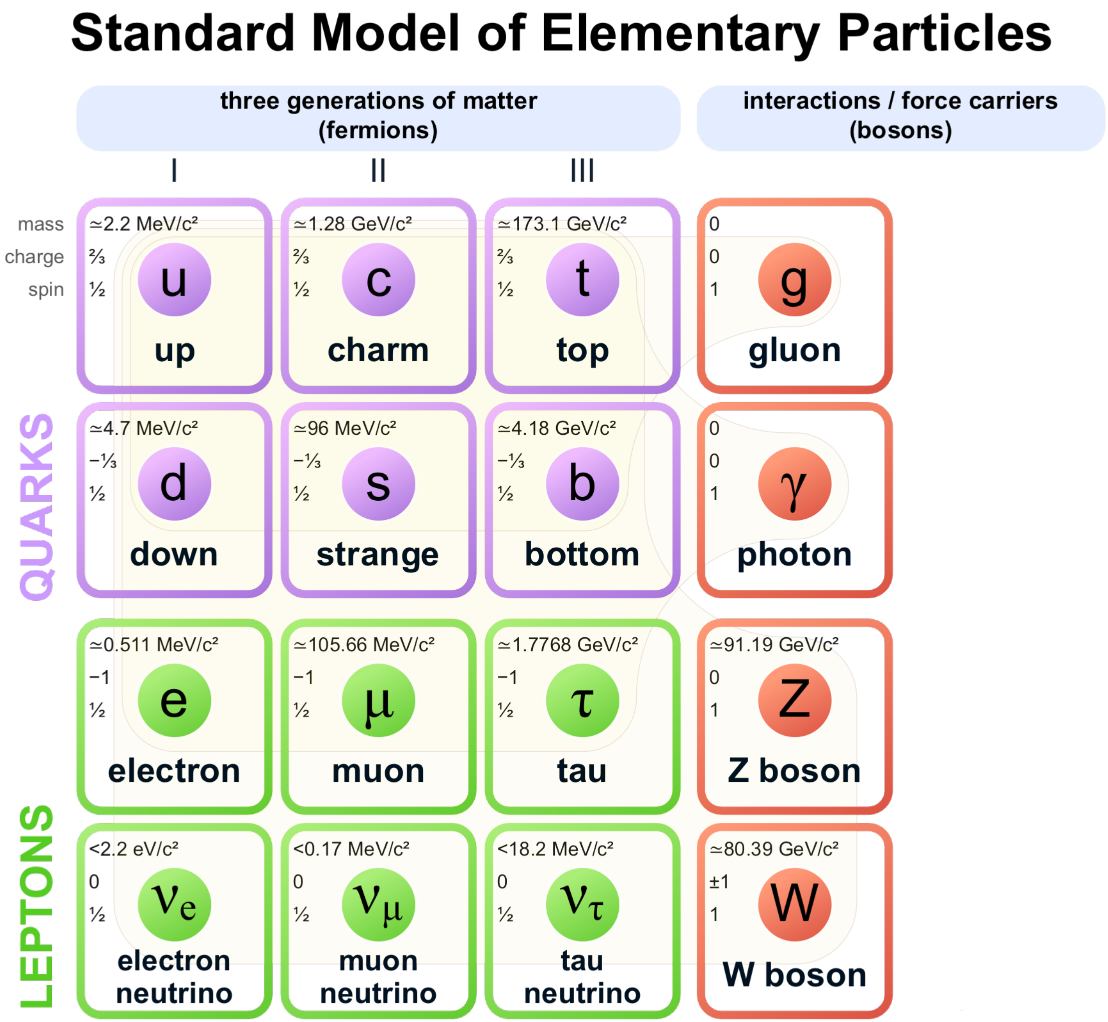
- Even though we cannot see the basketball, we see the effect throwing it has on the two people.
- All interactions which affect matter particles are due to the exchange of force carrier particles
- Forces are the effects of the force carrier particles (bosons) on matter particles (fermions)

Color Charge

- Quarks and gluons are color-charged particles.
- Color-charged particles cannot be found individually; Quarks are confined in groups with other quarks. These composites are color neutral.
  - Baryons: 3 quarks (red+green+blue = color neutral)
  - Meson: 2 quarks (red + anti-red = color neutral)
- Referred to as Quantum Chromodynamics (QCD)

"Color charge" has nothing to do with the visible colors, it is just a convenient naming convention for a mathematical system

Last piece of the puzzle



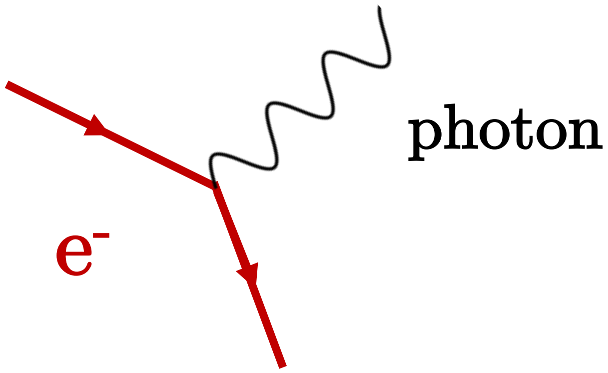
- Last missing piece = Higgs boson
- Higgs mechanism was developed in the 1960's to explain how particles get their mass

1. **Higgs field** permeates the universe
   - Massive particles interact a lot with the field
2. New particle predicted: **Higgs boson**
   - Discovered at the LHC in 2012
   - Only fundamental spin-0 particle (so far)

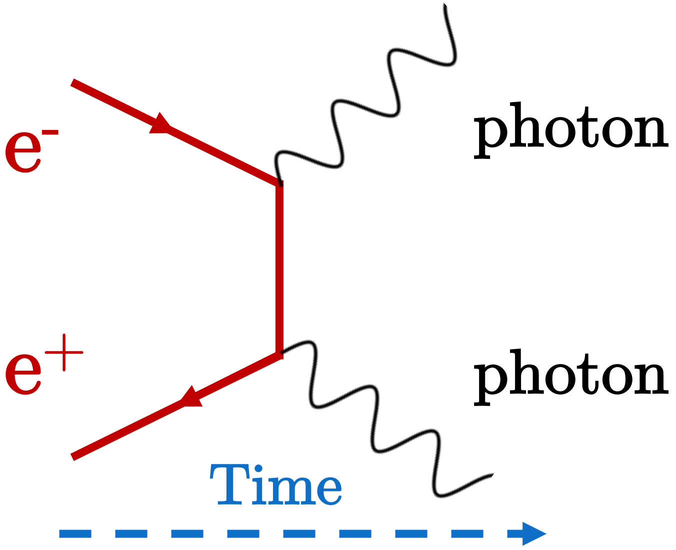
Feynman diagrams

- Essential tool in Quantum Field Theory (QFT), the math behind the Standard Model
- Feynman diagrams are representations of the underlying math
  - Each line and vertex represents part of the integral that you have to calculate
- Available vertices can be combined to produce allowed interactions
  - **Example 1:** electron-positron annihilation
  - Antimatter is shown with arrows moving backwards in time

Allowed vertex:



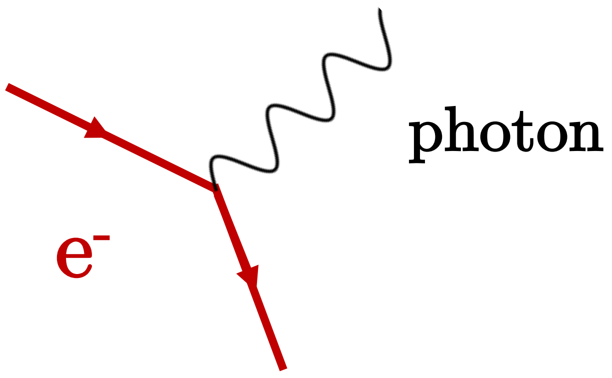
Allowed interaction

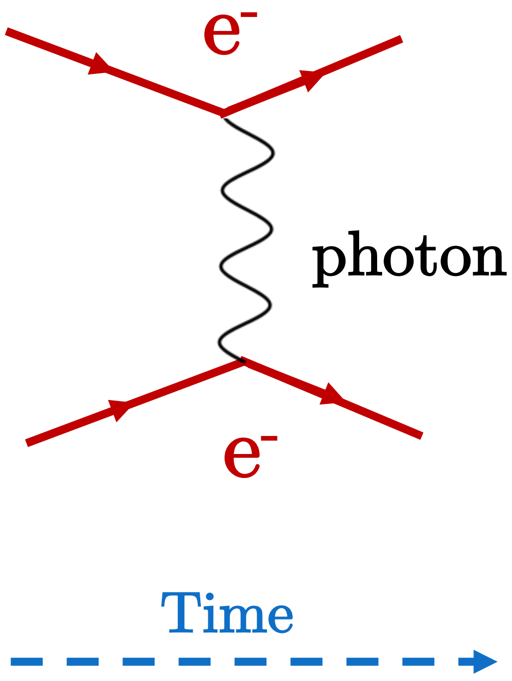


Feynman diagrams

- **Example 2:** Electron scattering (start with two electrons, end with two electrons)

Allowed vertex:





Feynman diagram exercise

Go to https://feynman.aivazis.com and try to draw the following diagrams.

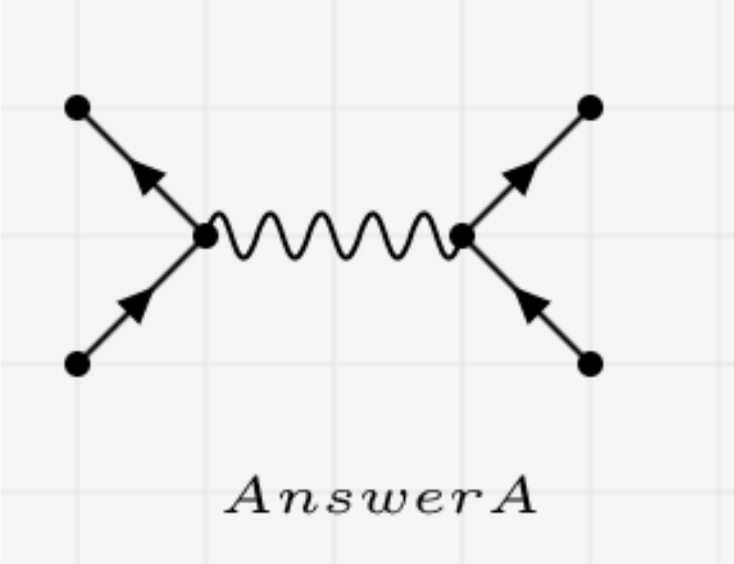
A. Start with one electron and one positron; end with one electron and one positron
B. Start with one electron and one photon; end with one electron and one photon
C. Start with two photons; end with one electron and one positron

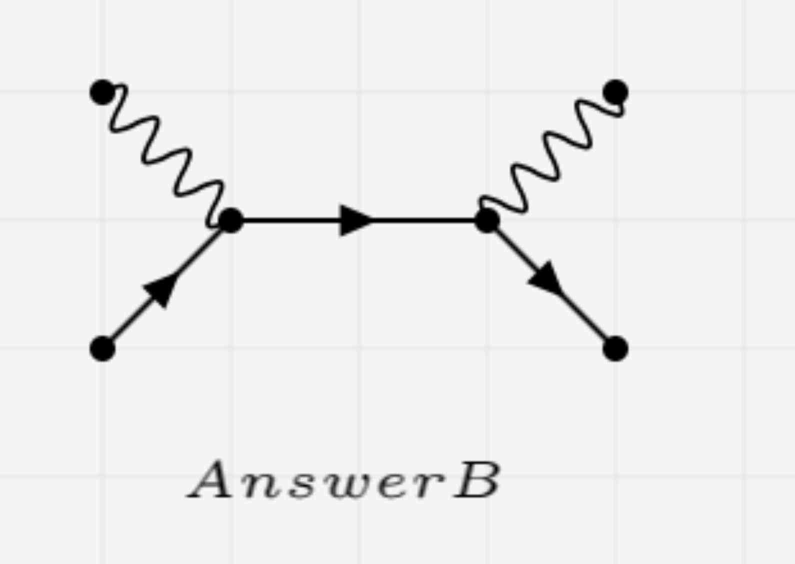
Hint: Try rotating one of the two diagrams I've already shown!

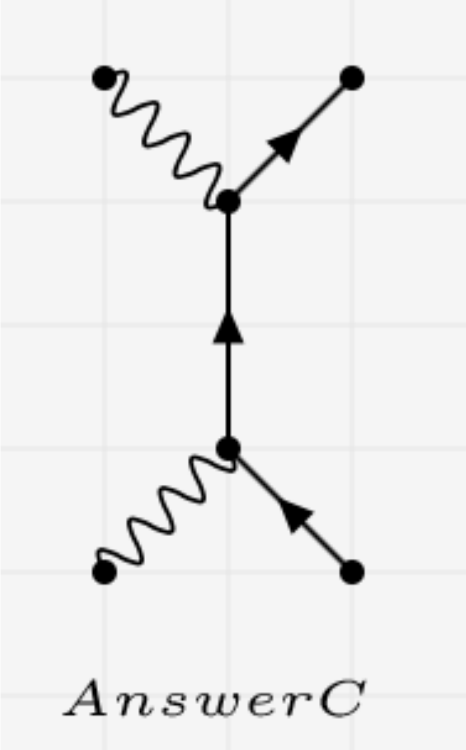
Sanity checks:

- Does each vertex have one arrow going in, one going out, and a squiggly line for the photon?
- Is charge conserved?
- Are all lines in your diagram connected?

Feynman diagram answers







A. Start with one electron and one positron; end with one electron and one positron

B. Start with one electron and one photon; end with one electron and one photon

C. Start with two photons; end with one electron and one positron

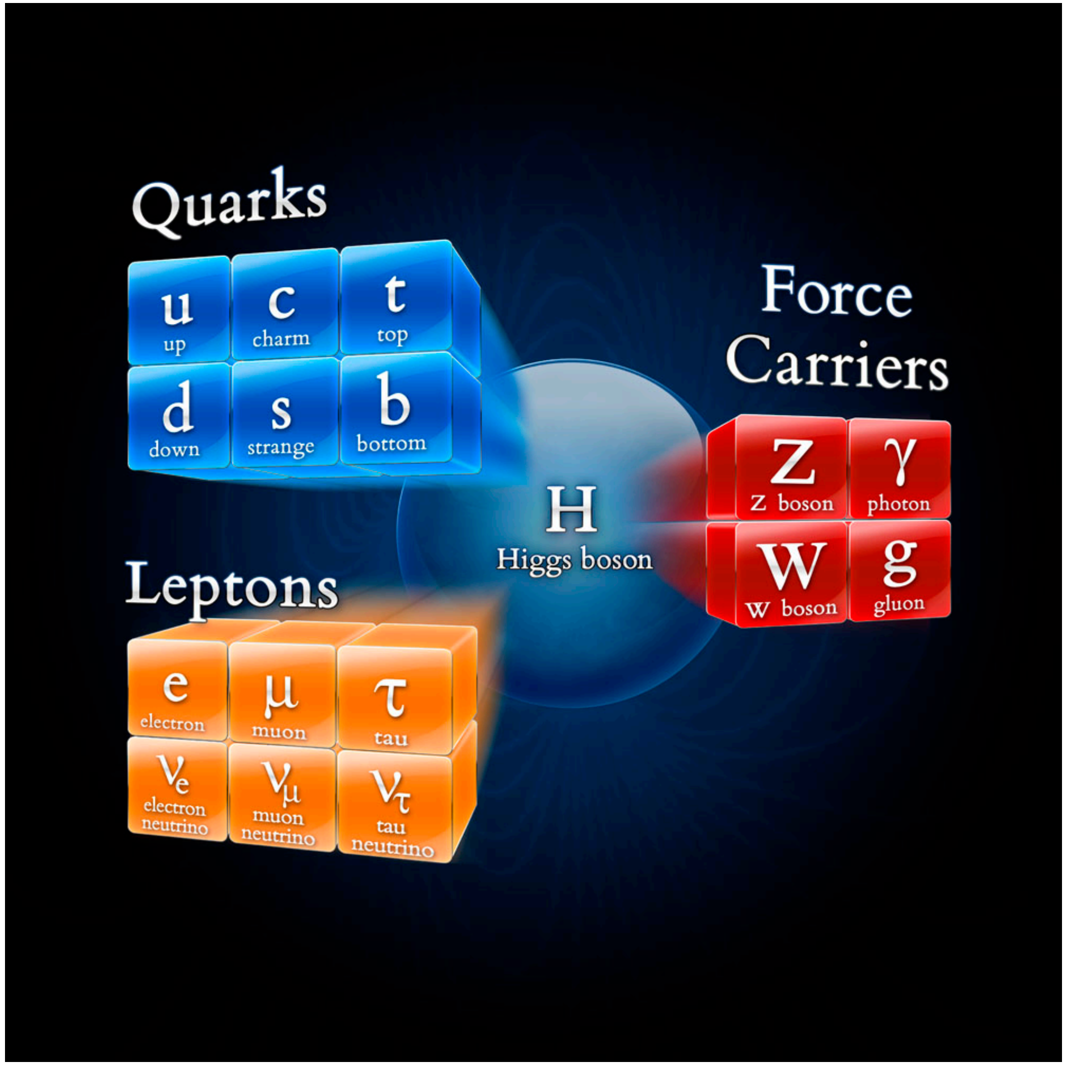
Summary of what we learned

- The Standard Model is the most complete explanation of fundamental particles and their interactions to date

- The building blocks of matter are quarks and leptons

- There are force carrier particles (bosons) associated with each force

- The Higgs mechanism is responsible for the mass of the particles



What next?

Many things left to discover and understand!

- Why is there so much more matter than anti-matter in the universe?
- What is dark matter?
- Is there evidence for supersymmetry?
- Why do the different generations of quarks and leptons have such different masses?
- Why is gravity so much weaker than the other fundamental forces?

We could find the answers to these questions, or discover **something totally unexpected!**

Additional resources

- How-to guide for Feynman diagrams: https://www.quantumdiaries.org/2010/02/14/lets-draw-feynman-diagams/
- Overview of the Standard Model: https://io9.gizmodo.com/the-ultimate-field-guide-to-subatomic-particles-5639192
- Fermilab video by Don Lincoln on the Standard Model: https://www.youtube.com/watch?v=XYcw8nV_GTs
- Fermilab video by Don Lincoln on the Higgs boson: https://www.youtube.com/watch?v=joTKd5j3mzk
  - Check out the Fermilab YouTube channel for many more interesting videos about these topics
- Historical view of hadrons and the "particle zoo": https://www.symmetrymagazine.org/article/hundreds-of-hadrons