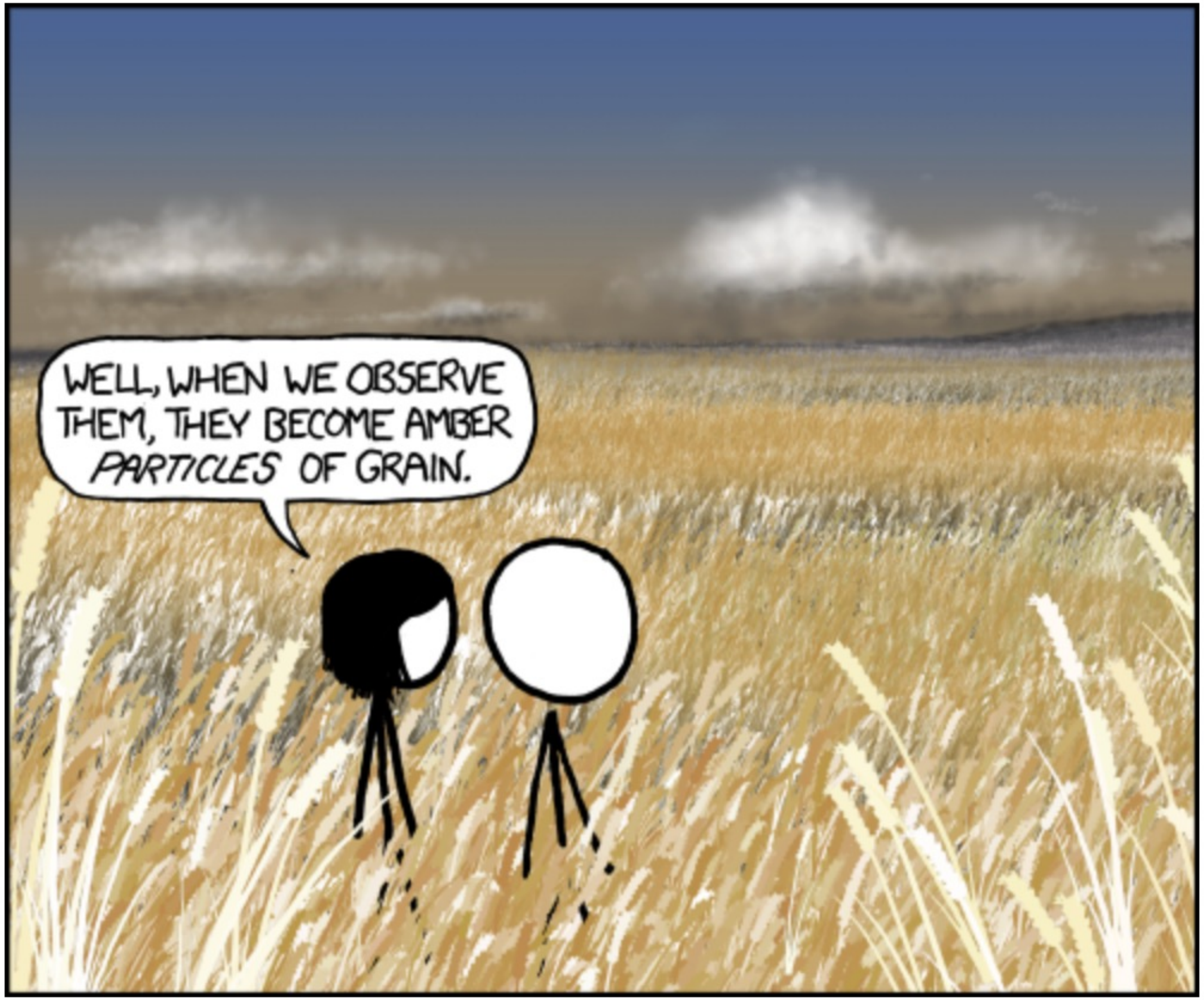
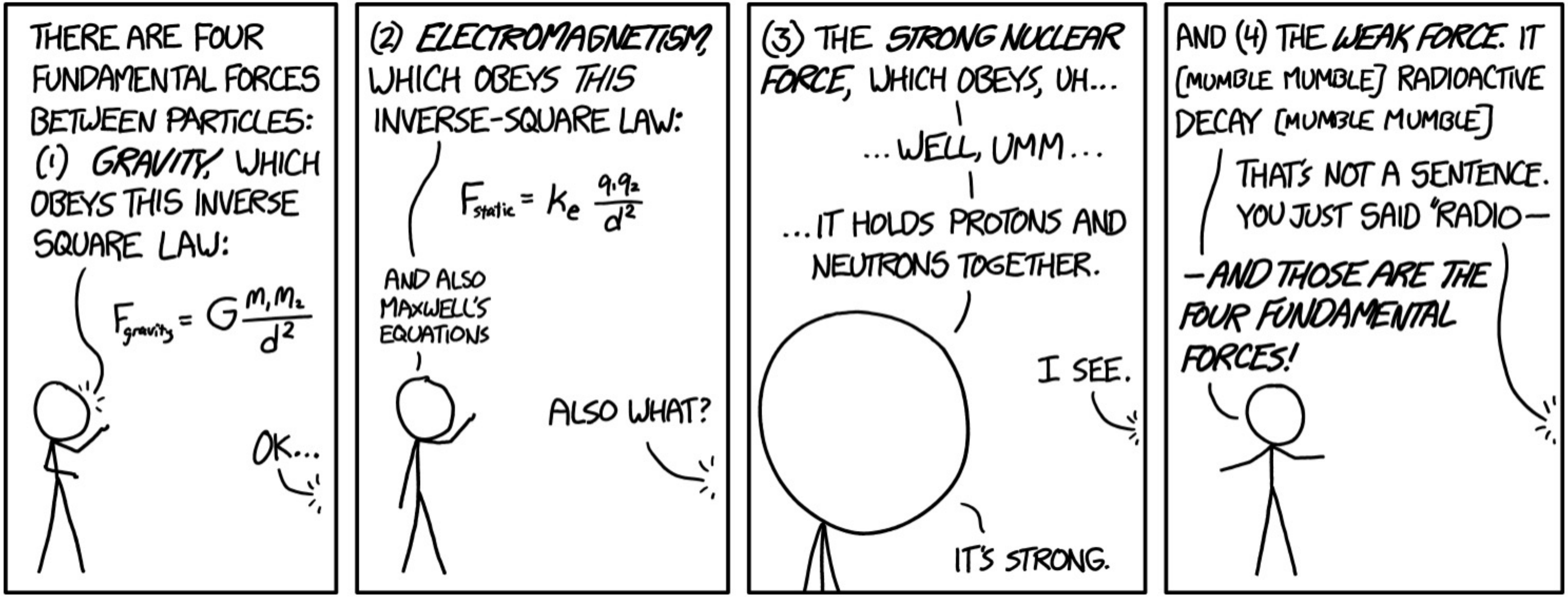
Wave-particle duality

https://xkcd.com/967



Fundamental Forces

https://xkcd.com/1489



QuarkNet Summer Session for Teachers:
The Standard Model and Beyond

Allie Reinsvold Hall

Summer 2024

Course overview

What are the fundamental building blocks that make up our universe?

Mission: overview of the past, present, and future of particle physics

1. History of the Standard Model, Part 1: Chemistry to Quantum Mechanics
2. **History of the Standard Model, Part 2: Particle zoo and the Standard Model**
3. Particle physics at the Large Hadron Collider (LHC)
4. Beyond the Standard Model at the LHC
5. Neutrino physics
6. Dark matter and cosmology

Goal: Bring you to whatever *your* next level of understanding is and provide resources for when you teach. Not everyone is at the same level and that's okay.

Plan for today

- Loose ends from Session 1

- Lecture: protons, neutrons, neutrinos
- Homework discussion in breakout rooms – D0 activity

- 10 minute break

- Lecture: particle zoo, quark model
- Homework discussion in breakout rooms – November Revolution

- Final logistics, plan for next week

Follow up – Heisenberg uncertainty activity

"I would love to hear from someone who has done this in a class and how it went."

Let's discuss!

Many of the other follow up questions about this activity can be answered by looking at the resources in the teacher's guide from the QuarkNet data activities portfolio

Additional resources

Also added to the bottom of the session 1 page:

- Nagaoka's Saturnian model of the atom
- Copenhagen interpretation and alternatives
- Definitive experimental paper by Geiger and Marsden, showing that the scattering results agreed with Rutherford's new atomic model

- Note about particle physics and special relativity: Whenever we refer to mass in particle physics, I always mean the **rest mass.** We also call this the particle's **invariant mass**

$$E^2 = p^2c^2 + m^2\,c^4$$

  - Here E is the **total energy** of the system

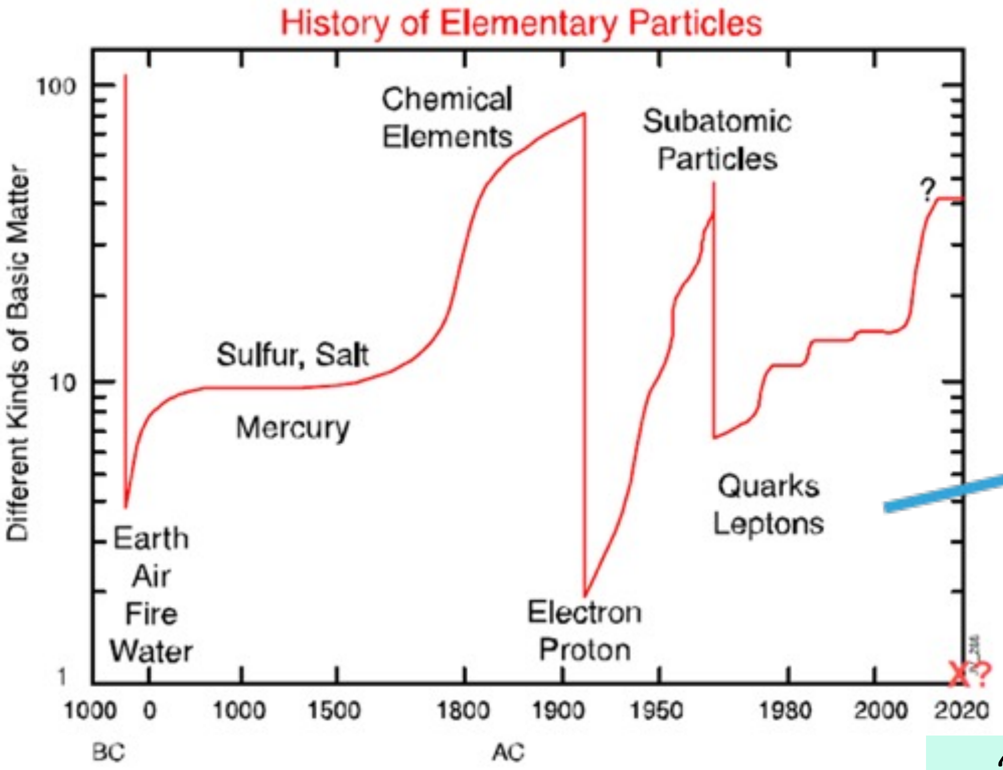
History of the Standard Model: Part 2

Who ordered that?

- I.I. Rabi, 1936

Review

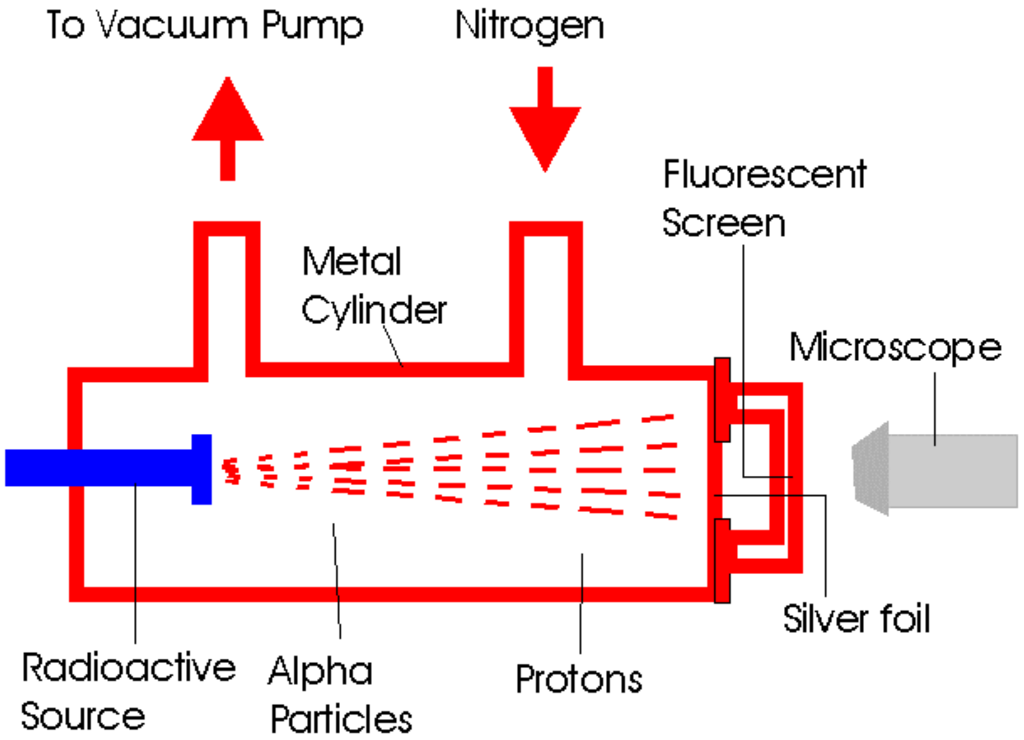
- Particle physics is the search for fundamental building blocks of nature
- Motivated by **reductionism,** guided by conservation laws and symmetry



“Particle Physics and Cosmology”, P. Pralavorio
https://arxiv.org/abs/1311.1769

Observation of the proton

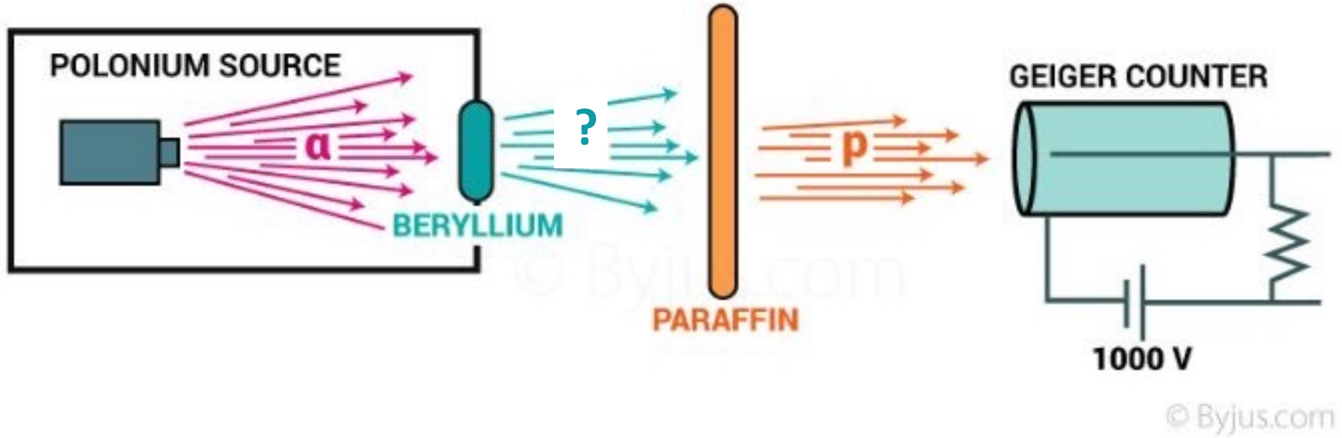
- First proposed by **William Prout** in 1815
  - Asserted that all atoms are made of hydrogens
- **Rutherford** proved in 1917 that nitrogen contains hydrogen nuclei using the reaction $^{14}N + \alpha \rightarrow {}^{17}O + p^{+}$



Observation of the neutron

- Already known that the nucleus contained more than just protons
  - Mass of helium was 4, but it had an atomic number of 2
  - **Rutherford**: extra mass comes from combining extra protons and electrons in the nucleus
- **Irene Joliet-Curie** and **Frederic Joliet** in 1930 produced high energy protons from unknown Be radiation on paraffin wax
  - Hypothesis: radiation from Be was high energy photons
- **James Chadwick** (1891 – 1974) in 1932: radiation was a **new neutral particle, the neutron**
  - Mass just above that of the proton

1935 Nobel Prize

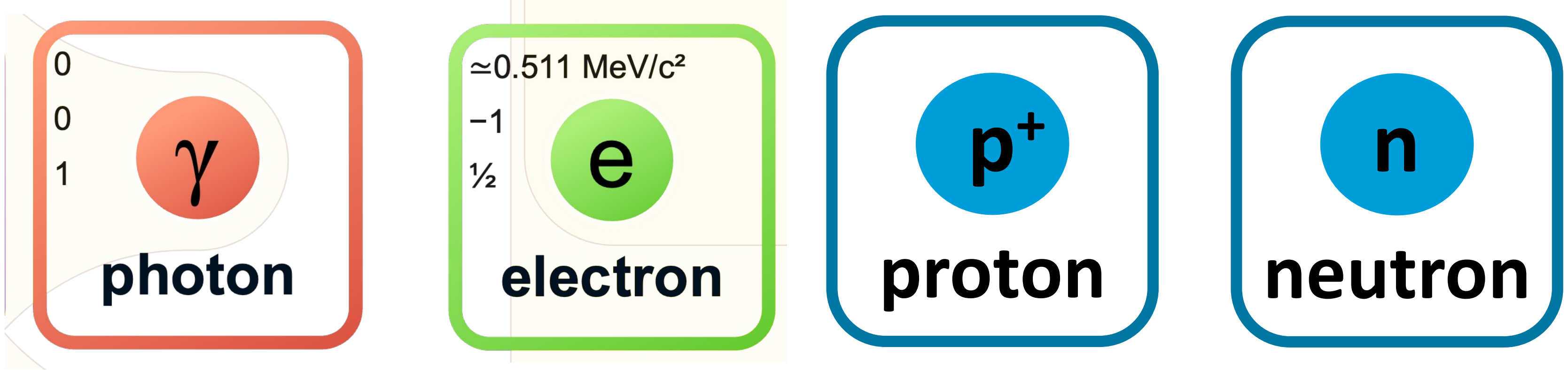


Check point: Standard Model of early 1930’s:

Standard Model of early 1930’s:

- Theory: Schrödinger equation, Dirac equation, Maxwell’s equation, and Einstein’s theory of relativity
- Standard Model: photon, electron/positron, proton, neutron

- Life was (relatively) simple!



Quantum field theory

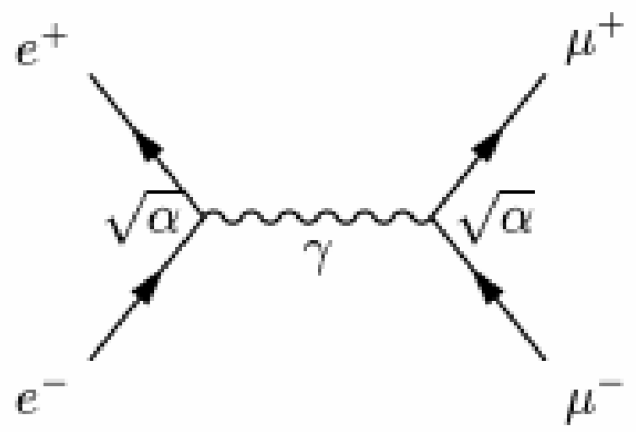
- **Dirac**'s goal: find a new theory that can describe particles that are **both** relativistic (fast) and quantum mechanical (small)
- **Result:** Quantum field theory (QFT)

	Big	**Small**
Slow	Newtonian mechanics	Quantum mechanics
Fast	Special relativity	**Quantum field theory**

Quantum Electrodynamics (QED)

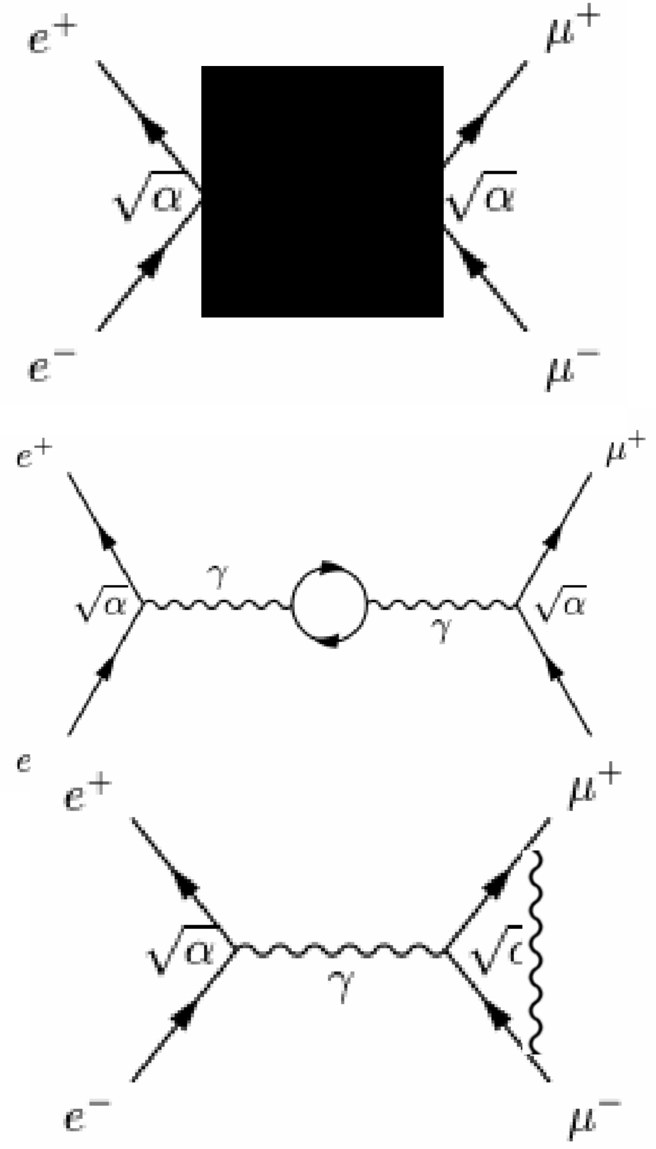
- QFT theory for describing charged particles and electromagnetic fields
- Developed in 1930s - 1950s, building off **Dirac**'s equation
- Makes incredibly precise theoretical predictions that have been verified by incredibly precise experiments
- Key development: *renormalization*
  - Fixing the infinities that appear when you do calculations
  - 1947 - 1949: **Kramer, Feynman, Schwinger, Bethe, Tomonaga, Dyson**

1965 Nobel Prize



Feynman diagrams

- Essential tool in QFT
- Available vertices can be combined in any way to tell you what interactions are allowed
- Feynman diagrams are representations of the underlying math
  - Each line and vertex represents part of the integral that you have to calculate
- Have to add up all possible diagrams based on initial and final state particles
  - Cannot know what happened inside the black box; only see initial and final particles
  - Suppressed by α (approximately 1/137) per vertex



Side note: Fermions vs bosons

Fermions:

- Named for Enrico Fermi (1901 – 1954)
- Half-integer spin
- "Matter" particles (quarks, leptons, neutrinos)
- Wave functions **anticommute**
- Obey Fermi-Dirac statistics
- Exclusion principle: Identical fermions cannot occupy the same quantum state
  - Proposed in 1925 by Wolfgang Pauli (1900 – 1958)

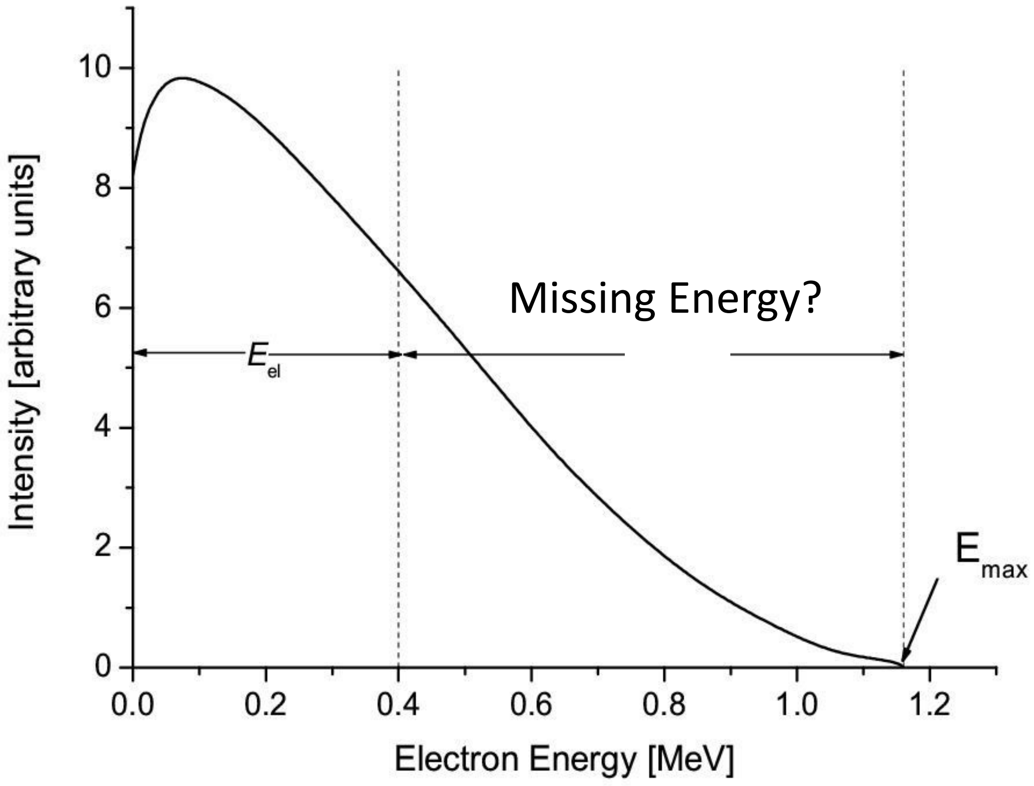
1945 Nobel Prize

Bosons:

- Named for Satyendra Nath Bose (1894 – 1974)
- Integer spin
- "Force-carrying" particles (photons, gluons, W/Z bosons)
- Wave functions **commute**
- Obey Bose-Einstein statistics
- Can all be in the same quantum state – for example, lasers

β decay mystery

- In alpha and gamma decay, particles are mono-energetic: $E = E_f - E_i$
- But in β decay, we see a continuous spectrum
  - First observed by **Lise Meitner, Jean Danysz** in 1913
  - **Is energy conserved??**
- 1930: "desperate remedy" by **Wolfgang Pauli**
  - Maybe there is an undetectable third particle involved in the decay – the **neutrino**
- 1933: **Enrico Fermi** published his theory of beta decay
  - Neutrino & electron are created in the decay
- Experimentally confirmed 23 years later (1956) by **Clyde Cowan, Frederick Reines**



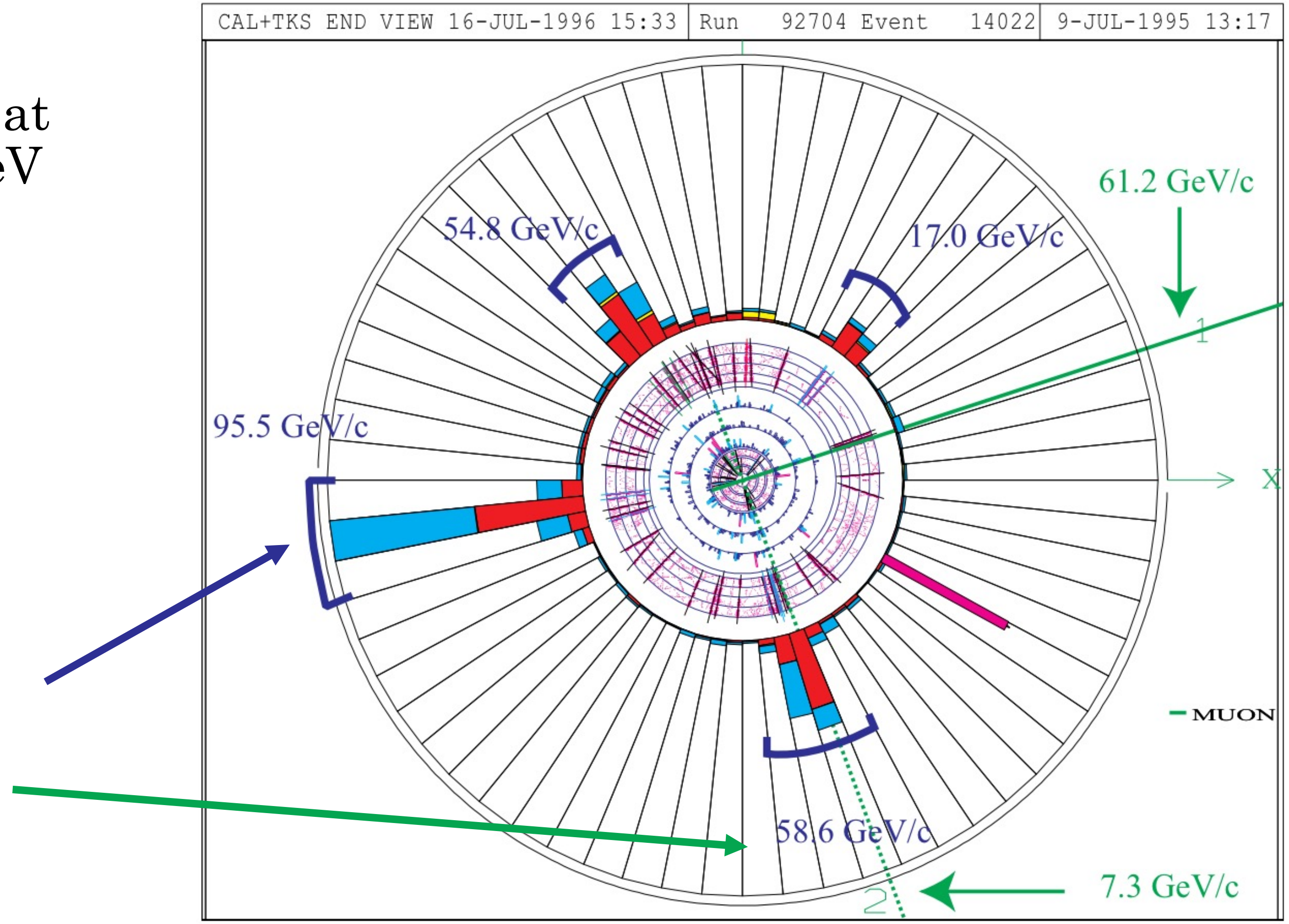
1995 Nobel Prize

Homework discussion – D0 activity

- Fermilab Tevatron collider
  - Operated from 1983 – 2011
  - Collided protons and anti-protons at a center-of-mass energy up to 2 TeV

- Jargon:
  - Event: one collision between "bunches" of particles
  - Transverse plane: plane perpendicular to the beam
  - Jets: collimated spray of particles from the decay of quarks.
  - Muons: Heavier version of the electron

D-Zero Detector at Fermi National Accelerator Laboratory



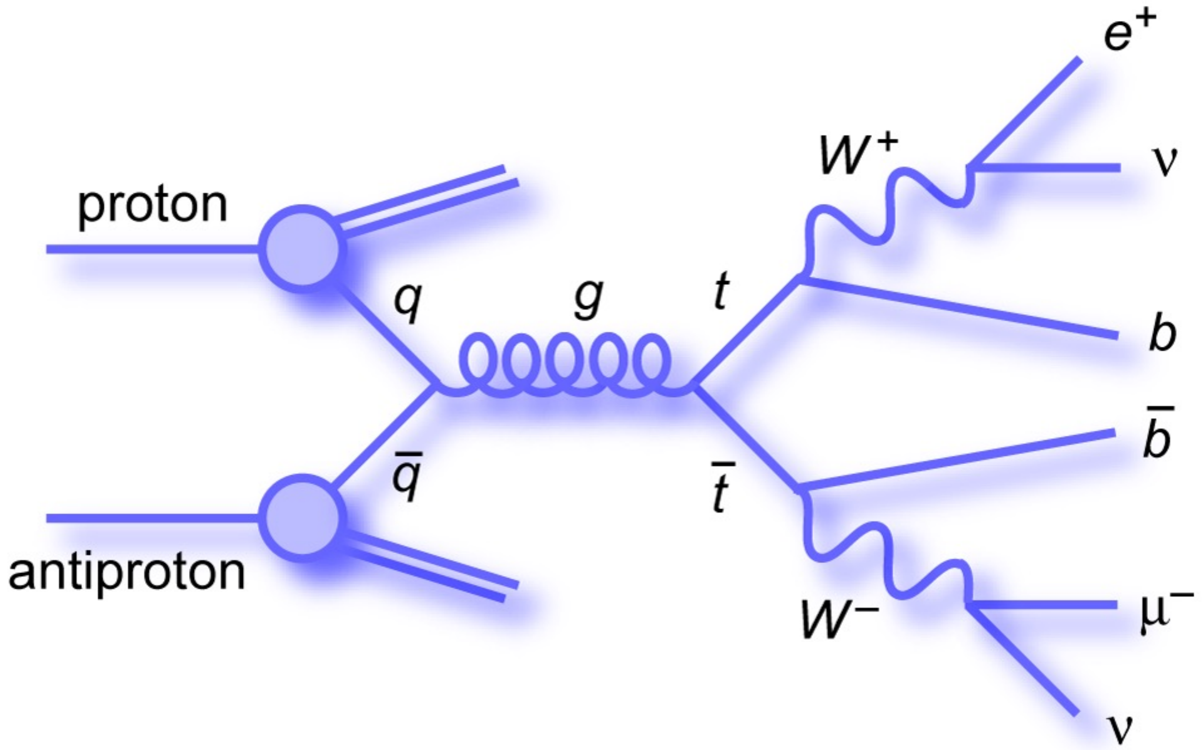
Homework discussion – D0 activity

Share your results, including what events you chose to analyze

- In particle collisions inside the D0 detector, what is the **initial momentum** p_0 in the transverse plane?
- Was the **final observed momentum** equal to the initial momentum?
- Did you observe evidence for **neutrino production** in the D0 events?
- How would this activity work in the classroom?

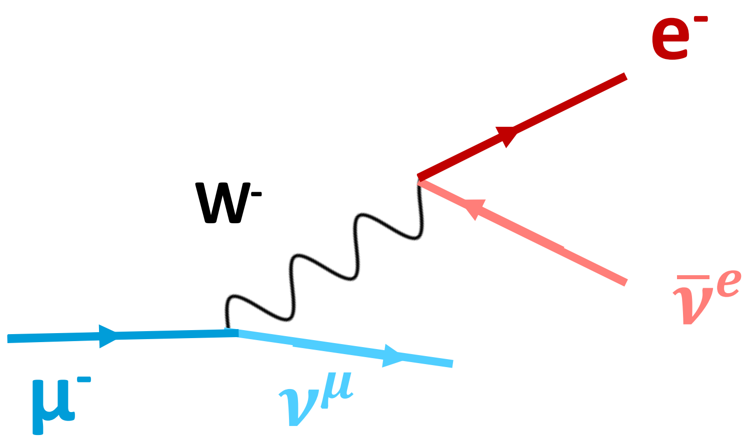
ttbar production

- Production of two top quarks ($t\bar{t}$)
- Analyzing $t\bar{t}$ at the LHC helps provide a quantitative test of Standard Model predictions
- Background to many LHC analyses



1937: Discovery of the muon

- Discovered in 1937 by **Carl Anderson** and **Seth Neddermeyer** in cosmic rays
- Extremely penetrating
- Heavier version of the electron
  - Mass of 105.6 MeV, compared to 0.5 MeV for electron's mass
  - Does not interact via the strong force
- Decays in 2.2 μs:

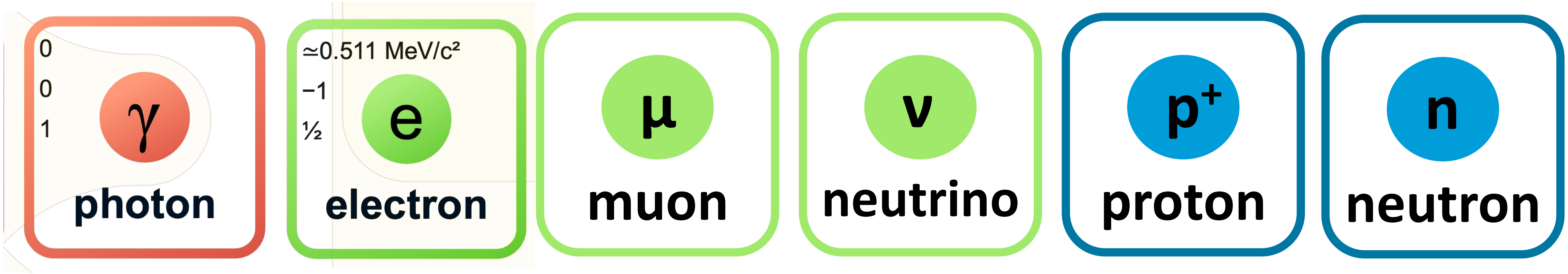


Who ordered that?

Checkpoint: Standard Model in 1937

Observations:

- electron: 1897 by Thomson
- proton: 1919 by Rutherford
- neutron: 1932 by Chadwick
- muon: 1937 by Anderson & Neddermeyer
- neutrino: 1956 by Cowan & Reines



Particle zoo

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

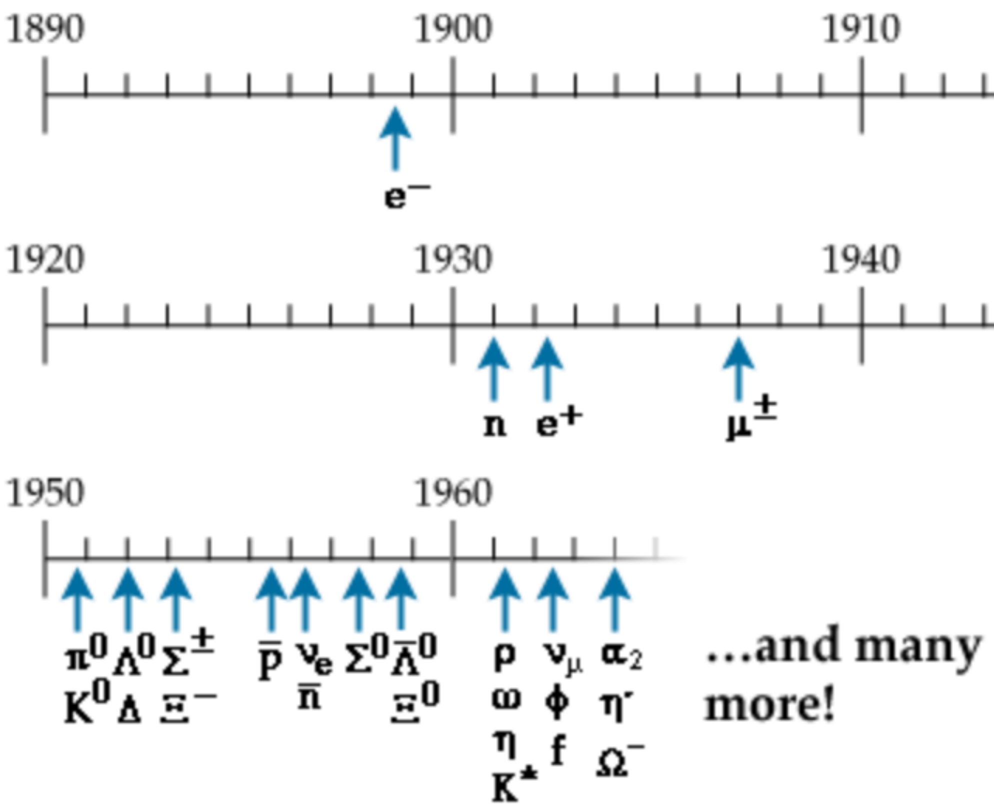


Image from the particle adventure

"The finder of a new elementary particle used to be rewarded by a Nobel Prize, but such a discovery now ought to be punished by a $10,000 fine"
- Willis Lamb, 1955 Nobel Prize acceptance speech

Particle zoo

- Charged Pion (1947)
- Charged Kaon (1947)
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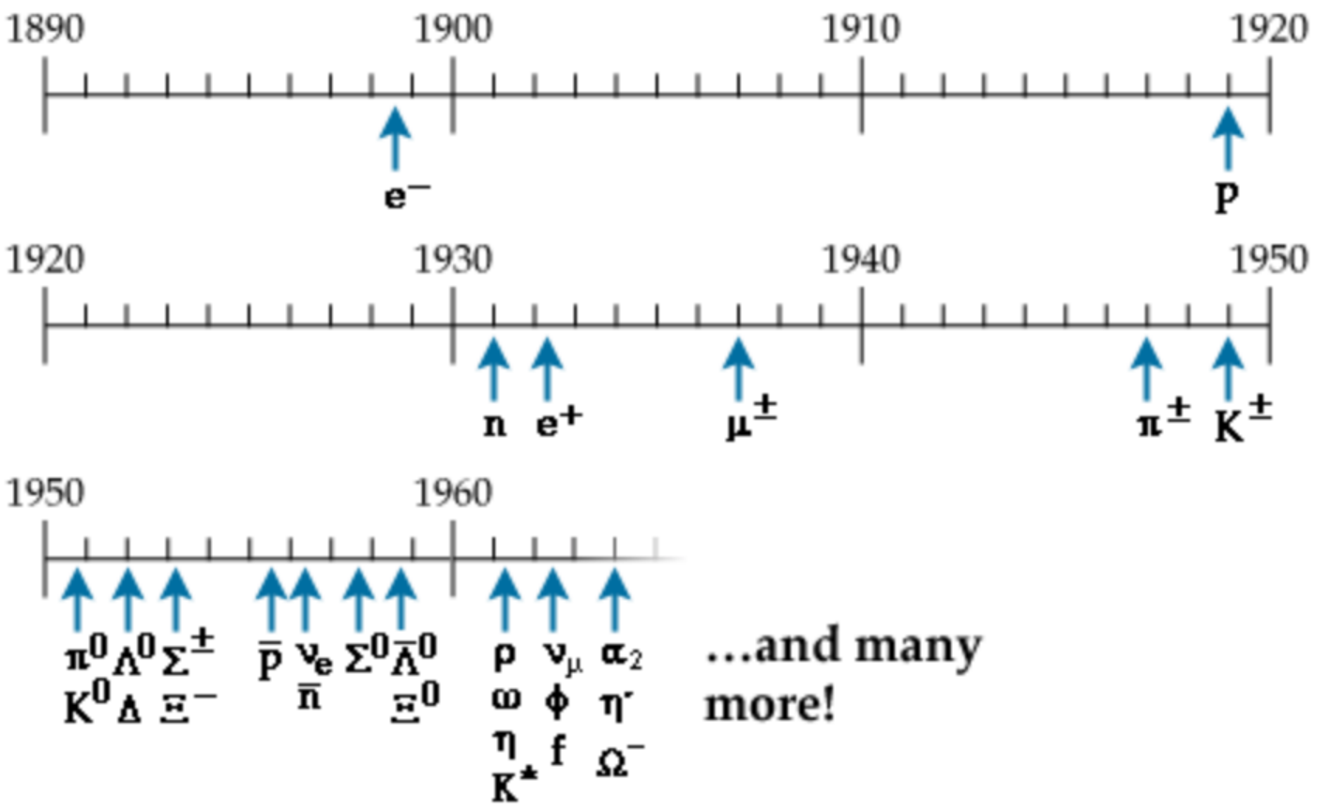


Image from the particle adventure

- “Strangeness” quantum # proposed by Gell-Man, Tadao Nakano and Kazuhiko Nishijima in 1953
  - Strange particles took longer to decay
  - Now understood to be because they decay via the **weak force** and not the **strong force**

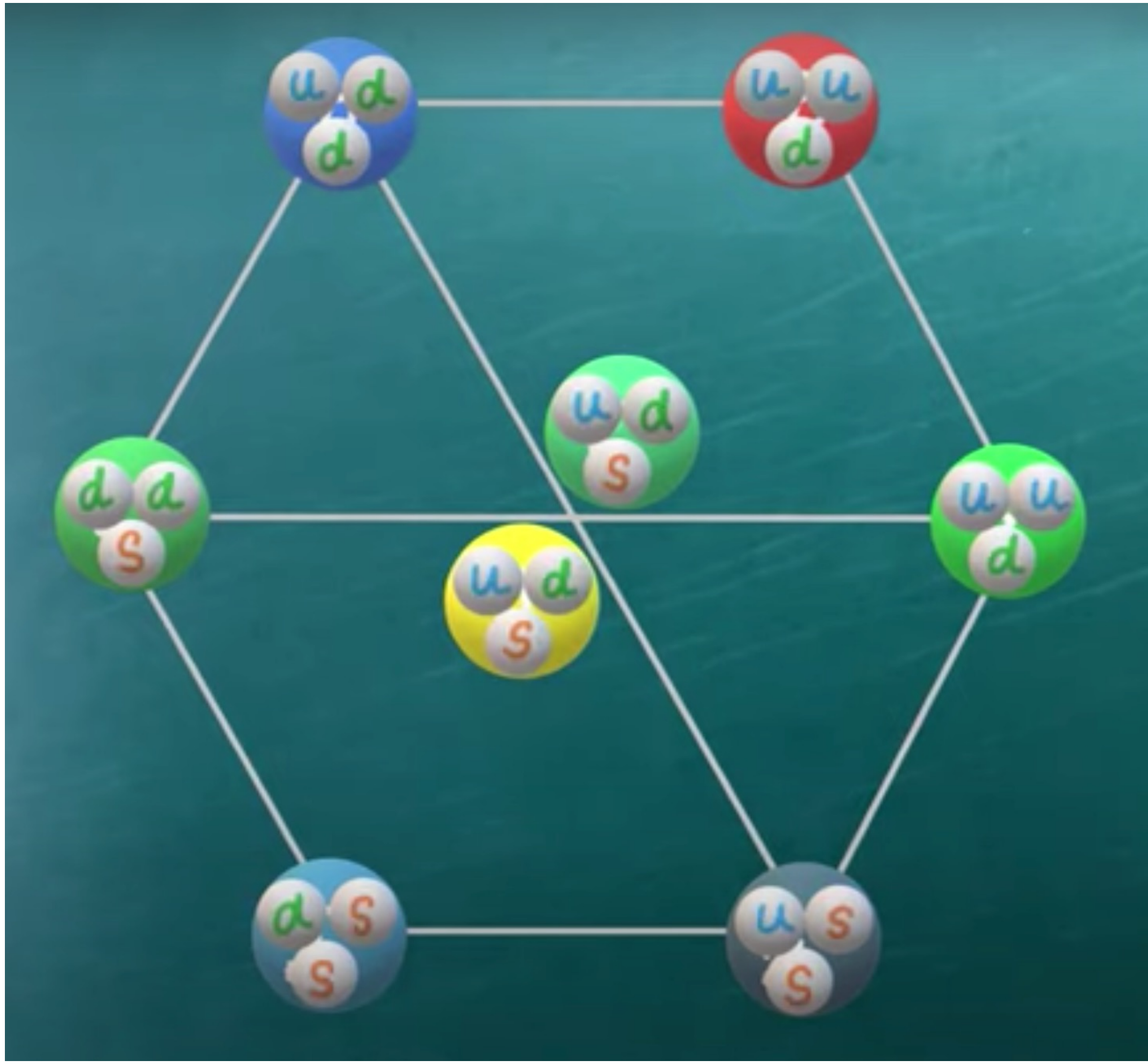
Back to simplicity

- Scheme proposed by Gell-Mann and Ne'eman in 1961
  - Organize baryons and mesons by charge and strangeness
- Predicted Ω^- particle that was later discovered in 1964
- Cries out for internal structure

- **Quarks:** proposed by Gell-Mann and Zweig in 1964

1969 Nobel Prize

- Mathematical framework or the way the world actually works?
  - Are there real quarks? If so, why haven't we seen them?



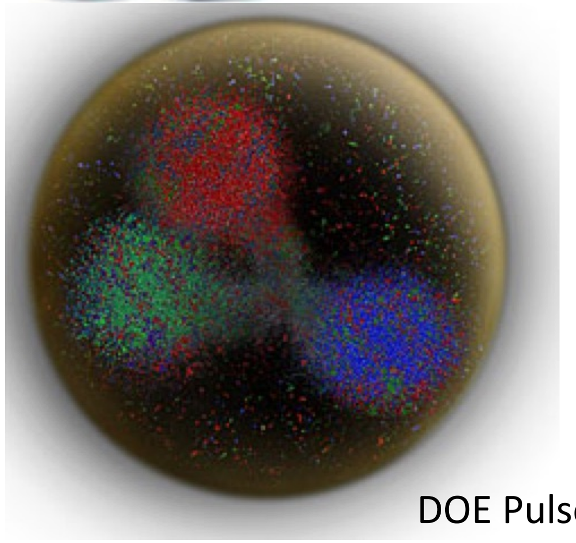
Quantum Chromodynamics (QCD): strong force

- Quarks and gluons are **color-charged particles**.
- **Confinement**: force increases at increasing distance
  - Color-charged particles cannot be found individually.
  - Must form **color neutral** bound states: mesons or baryons
  - “Jets” are created in the decay of individual quarks
- **Asymptotic freedom:** force decreases at small distances
  - Enables us to use perturbative calculations at high energies
  - Discovered by Wilczek, Gross, Politzer in 1973

2004 Nobel Prize

- Direct evidence for quarks within proton came from deep inelastic scattering experiments at SLAC in 1968

1990 Nobel Prize



DOE Pulse

Electroweak interaction

- 1959: Glashow, Salam, Ward developed field theory for **weak force**
  - Only works if you include electromagnetism
  - 4 massless gauge bosons (force messenger particles)

1979 Nobel Prize

- 1967: Weinberg incorporated the Higgs mechanism
  - 3 bosons "gain mass", photon stays massless
- Shown to be renormalizable in 1971 by 't Hooft and Veltman
  - Predictions for the W, Z boson masses

1999 Nobel Prize

Low energy (below 246 GeV)

- Electromagnetic and weak forces are separate
- 3 massive gauge bosons + photon

High energy (above 246 GeV)

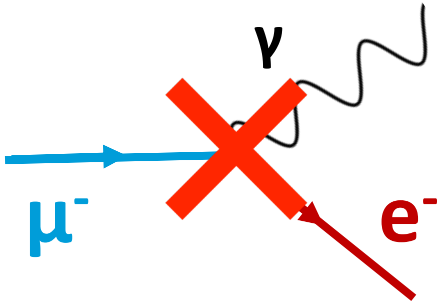
- Unified electroweak force
- 4 massless bosons

Broken symmetry

- Designed by Robert Wilson, first director of Fermilab
- Installed June 1978 at the West entrance to the lab

Image: Reider Hahn, Fermilab

1962: Two neutrino experiment



"Anything that isn't forbidden is compulsory" –Murray Gell-Mann

- Unobserved muon decay indicates a deeper theoretical truth

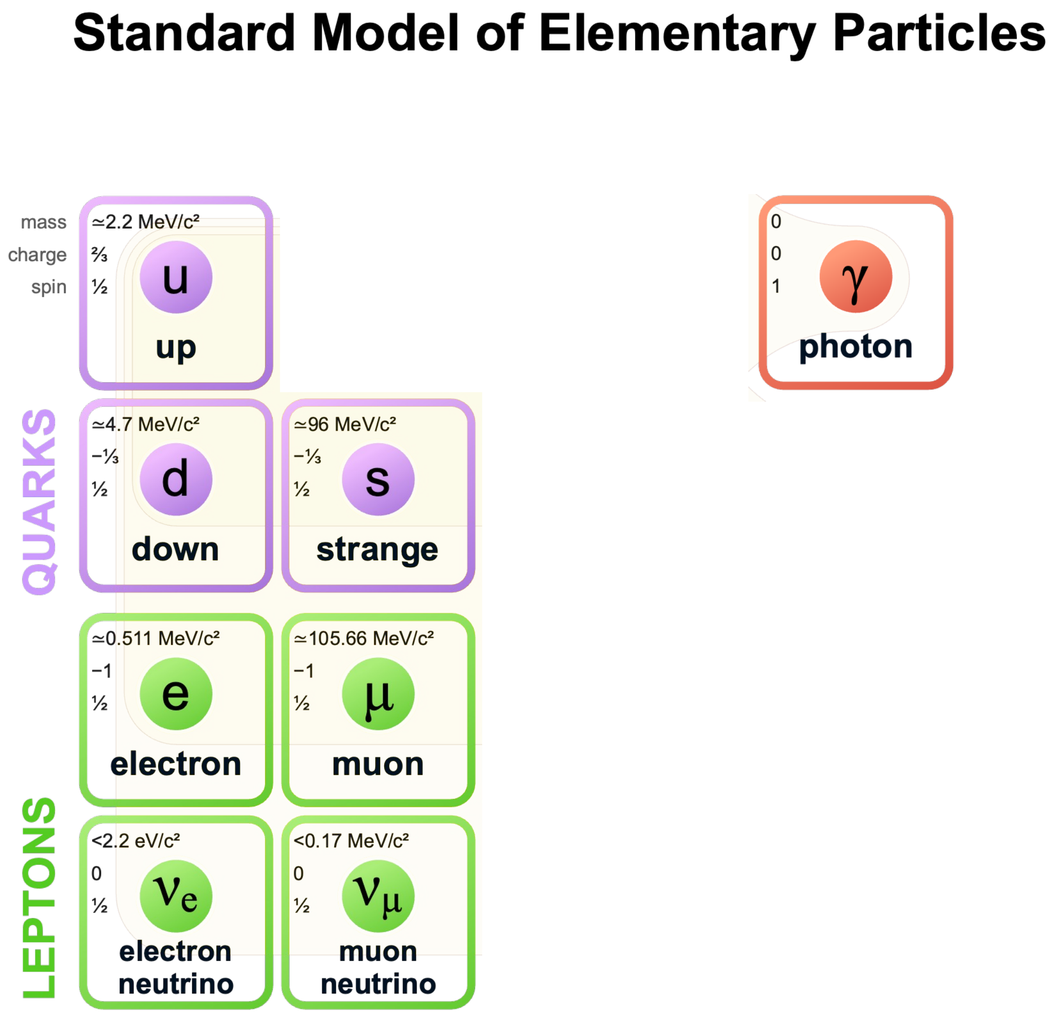
- Jack Steinberger, Melvin Schwartz, Leon Lederman: experiment at Alternating Gradient Synchroton (AGS) at Brookhaven: 30 GeV protons
  - 40ft steel wall to block all particles except neutrinos from entering detector
  - Neutrinos interact with nucleus and produce muon or electron plus a neutrino
- Expected muon and electrons in equal numbers: saw only muons!

Implications:

- Muon neutrino and electron neutrinos are distinct
- "Electron number" and "muon number" have to be conserved

1988 Nobel Prize

Checkpoint: Standard Model in 1970



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

Million-dollar question:

Wouldn't it be "charming" if there was a fourth quark to fill the hole?

Bump hunting

- Look for events with $\mu^+\mu^-$ pair
- Assume muons came from the decay of one massive, neutral particle X with mass M
- To calculate the invariant mass, start with mass energy equivalence:

$$E_X^2 = p_X^2 + M_X^2$$

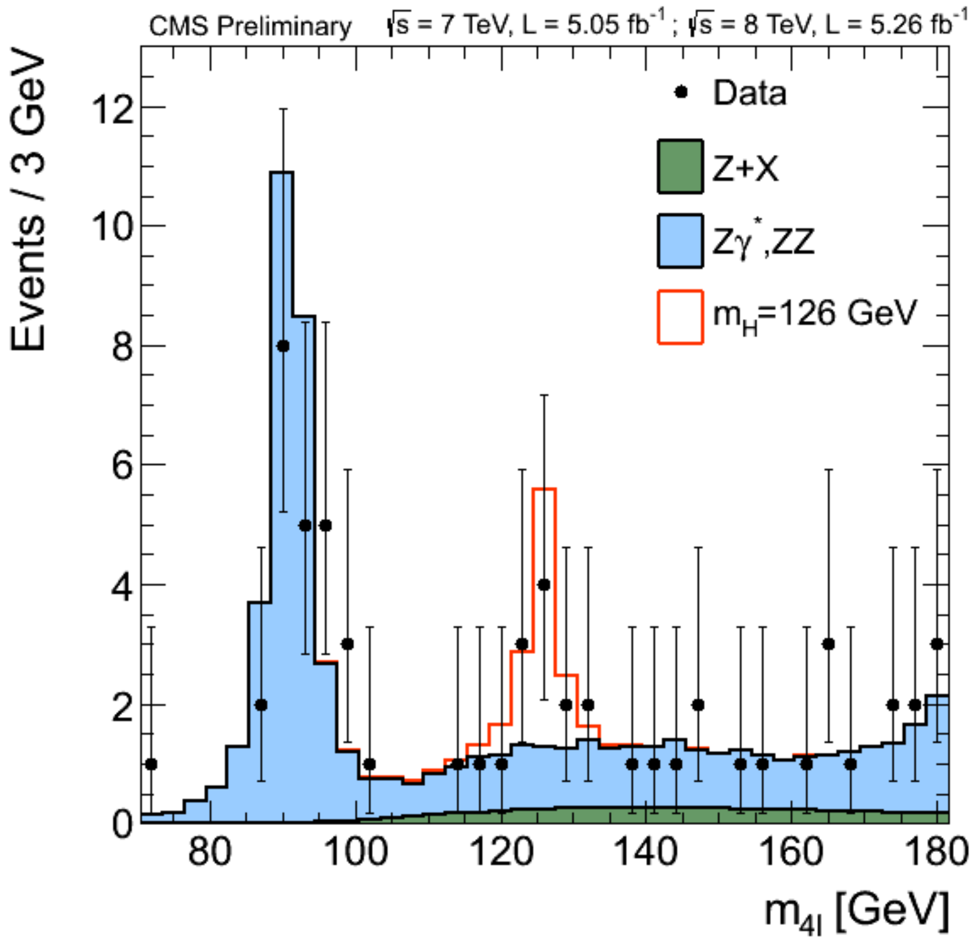
  - Rearrange equation:

$$M_X^2 = E_X^2 - p_X^2$$

  - Apply conservation of Energy and conservation of momentum:

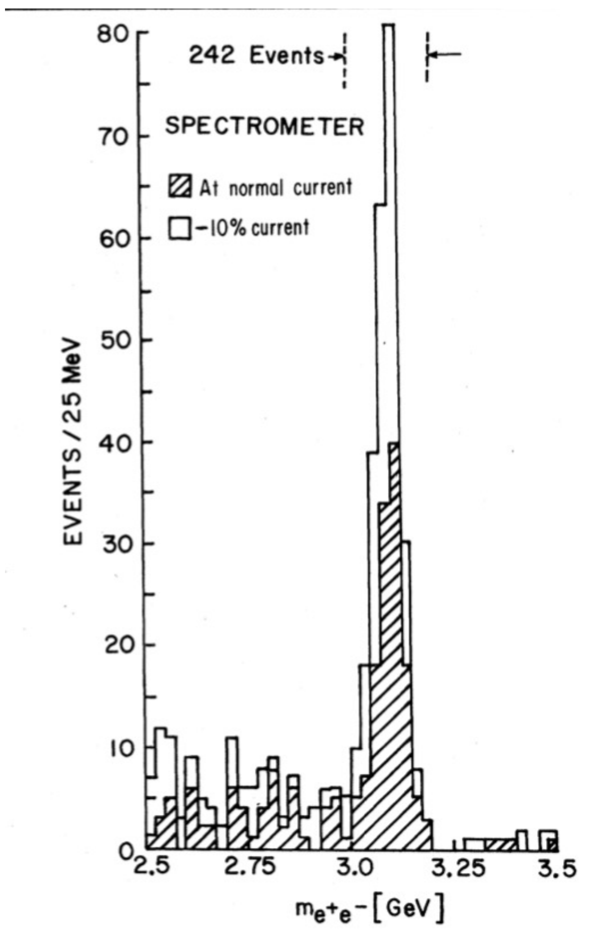
$$M_X^2 = (E_1 + E_2)^2 - |p_1 + p_2|^2$$

  - Plot invariant mass for many events
    - Bump = new particle!



Breakout discussion – 1974 Nov. Revolution

- Why was the discovery of the J/ψ particle in November 1974 so revolutionary? Many hadrons had been discovered by then – why was this one special?
- What does the extremely narrow width of the J/ψ particle's mass "bump" tell you about its lifetime? (recall last week's homework assignment)
- How did the results of Nov. 1974 and subsequent discoveries provide evidence for the quark model?

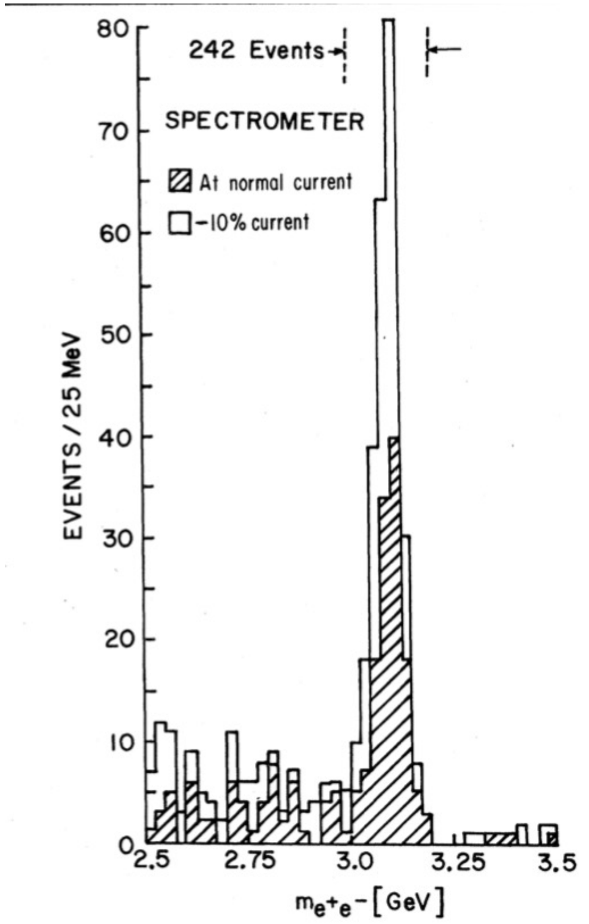


1976 Nobel Prize

"Experimental Observation of a Heavy Particle J". *Physical Review Letters*. **33** (23): 1404–1406

November revolution

- Normally high mass = unstable = short lifetime, but this particle has a large mass and a long lifetime!
  - Heavier particles have more options for other particles to decay into
- Some new conservation law (new quantum number) must be at work
  - CHARM!
  - J/Psi can't decay into any of the lighter hadrons because it is the lightest hadron containing charm quark
    - Can only decay via the **weak force** and not the **strong force**



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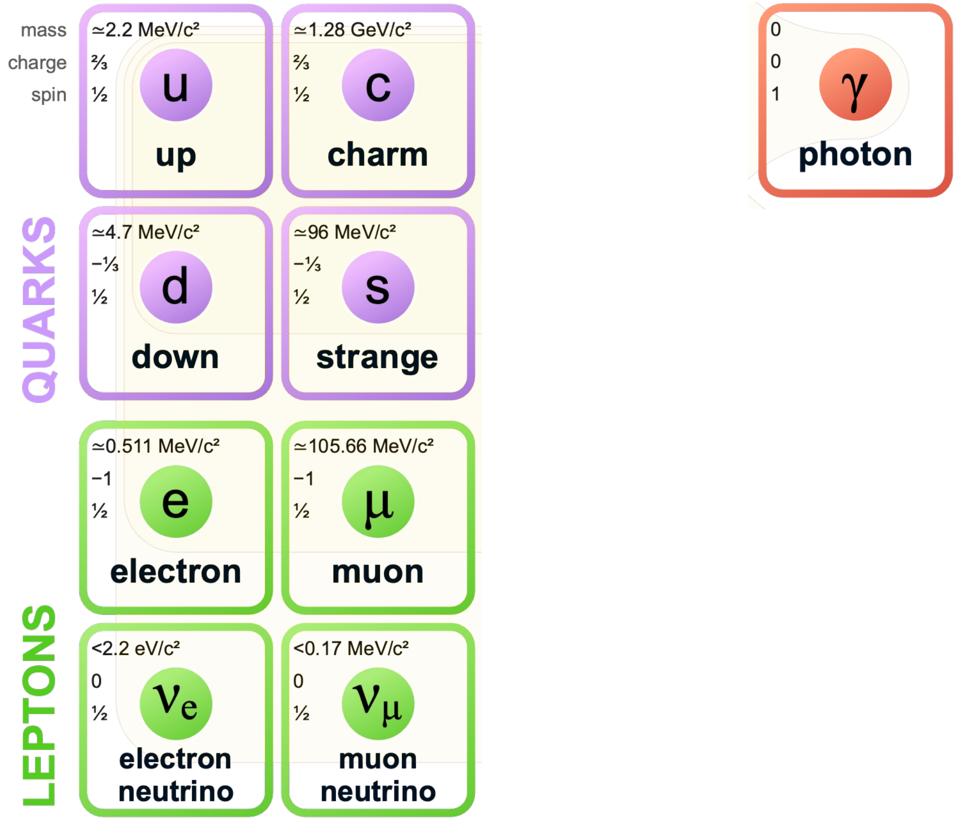
Checkpoint: Standard Model in 1974

Standard Model of Elementary Particles



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- muon neutrino: 1962@BNL
- up, down, strange quark: 1968@SLAC
- charm quark: 1974@SLAC, BNL

Two ***generations*** of quarks and leptons

Million-dollar question:

Are there more quarks or leptons at higher mass?

Homework for lecture 3: LHC physics

1. Explore the CMS e-lab: practice your bump-hunting skills

   Details on session 3 page and will be sent via email; choose what to explore based on how familiar you are with the e-lab.

2. Fill out weekly survey

- Additional, optional resources are posted to the course website
- Email me with any concerns or questions

End of Part 2

Instructions

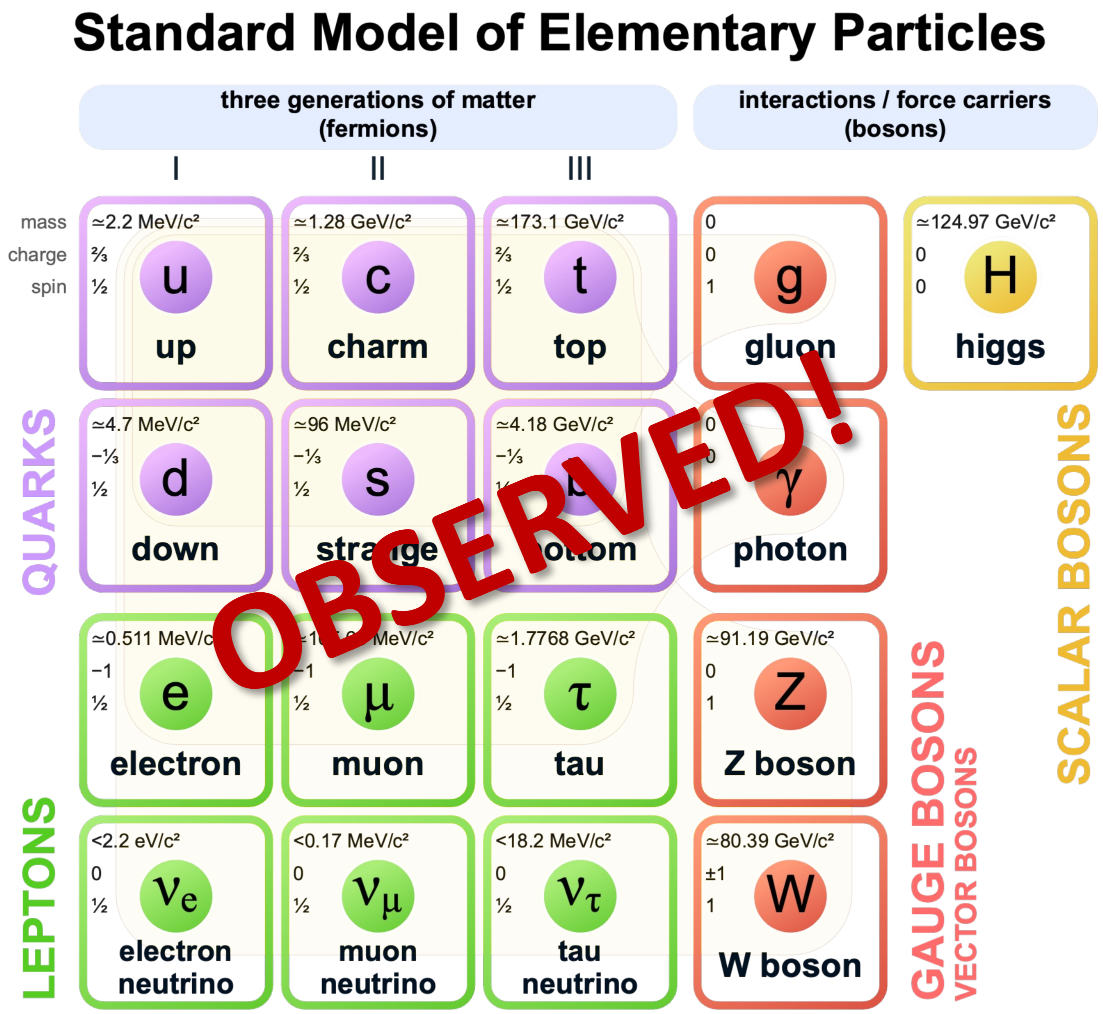
Use the events from the D0 experiment, found here:
https://quarknet.org/sites/default/files/DZero_events.pdf

Note that these events were chosen carefully: all of the decay products moved in the transverse plane, the plane perpendicular to the beam. This means you can analyze the events in two dimensions instead of three.

Repeat the process below for at least 2 of the 4 events.

1. Draw lines through the centers of all jets and muon tracks to the origin of the coordinate system.
2. For each jet and muon track, use a protractor to find the angle θ between the line you drew and the positive x-axis.
3. The magnitude of the momentum p for all of the jets and muons is given on the plot. Find $p_x = p\cos(\theta)$ and $p_y = p\sin(\theta)$ for all jets and muons.
4. Find $p_{x,obs}$ and $p_{y,obs}$. Then find the magnitude and direction of p_{obs}.

Preview: Standard Model



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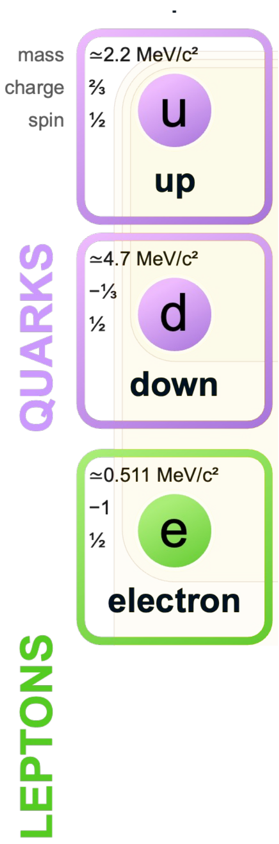
- muon: 1937 by Anderson & Neddermeyer
- electron neutrino: 1956 by Cowan & Reines
- muon neutrino: 1962@BNL
- up, down, strange quark: 1968@SLAC
- charm quark: 1974@SLAC, BNL
- tau lepton: 1975@SLAC
- bottom quark: 1977@FNAL
- gluon: 1979@DESY
- W and Z bosons: 1983@CERN
- top quark: 1995@FNAL
- tau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

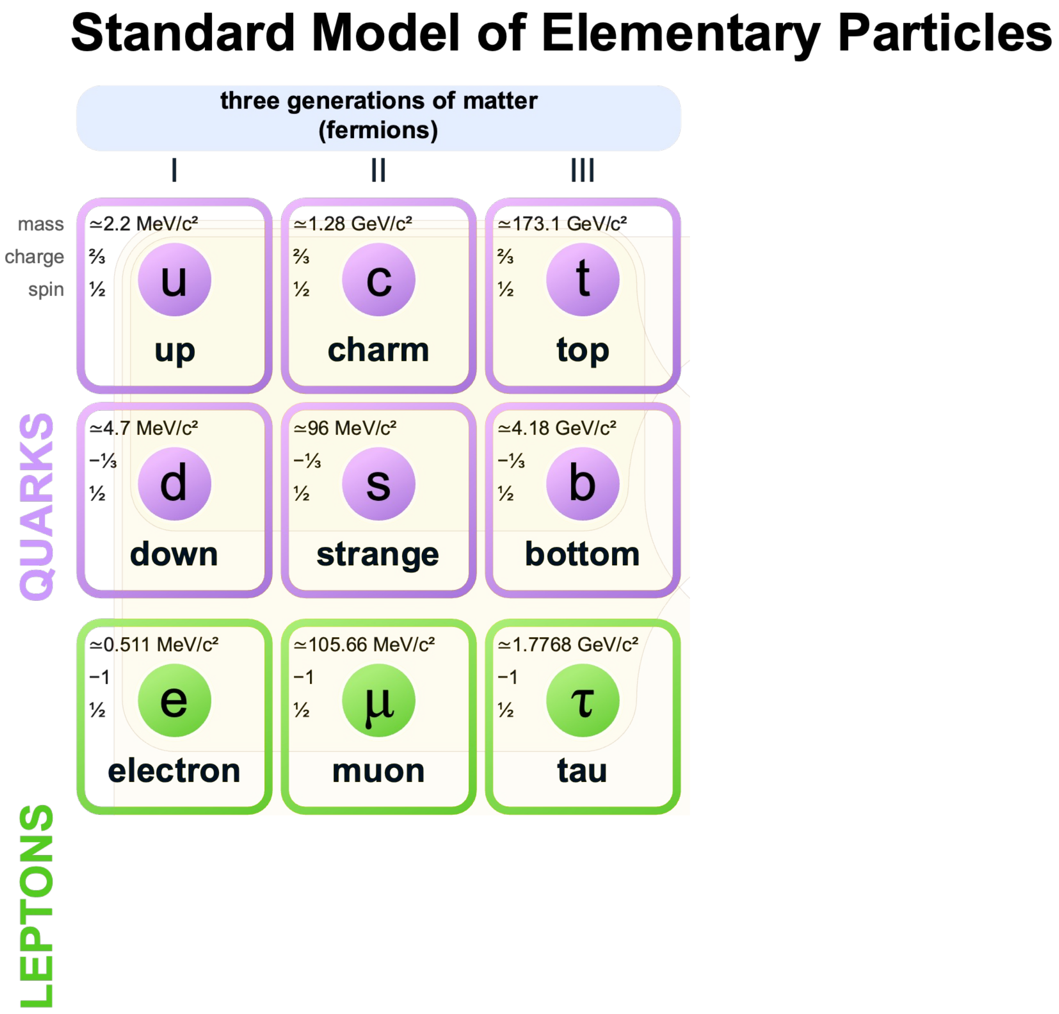
Earth's building blocks

Standard Model of Elementary Particles



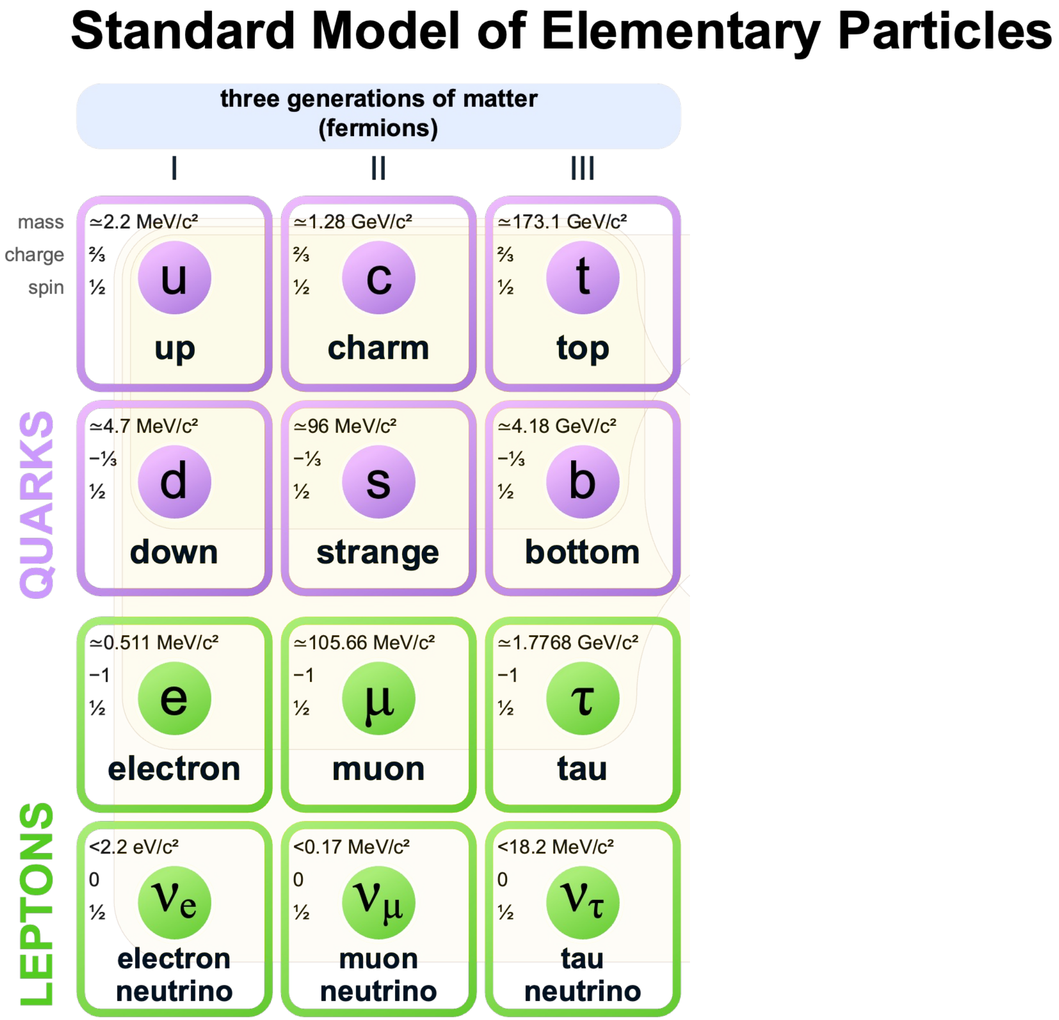
- All ordinary matter is made from **up quarks**, **down quarks**, and **electrons**

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

Neutrinos

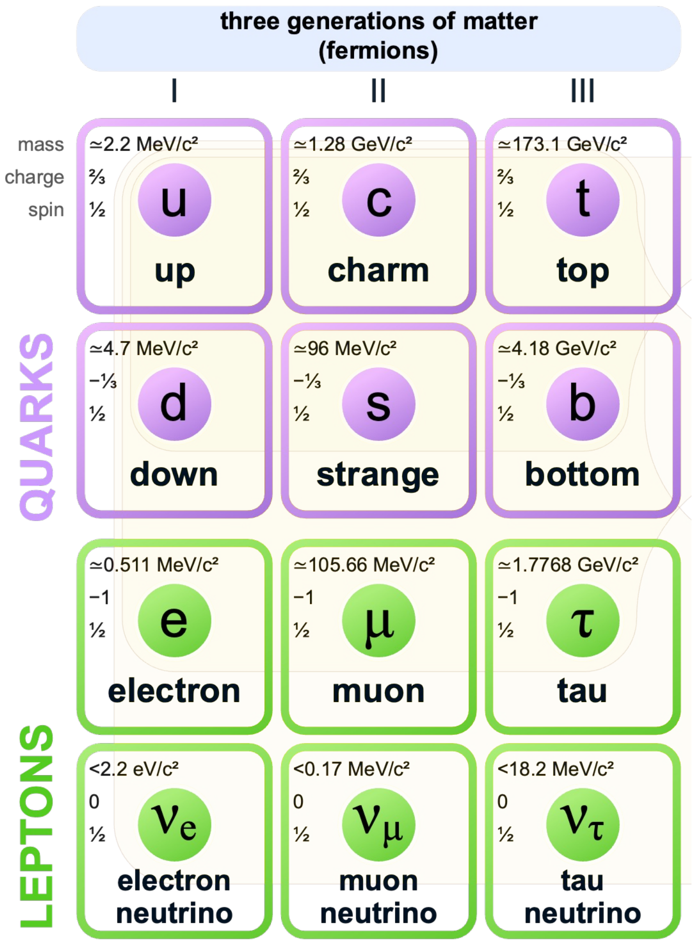


- All ordinary matter is made from **up quarks**, **down quarks**, and **electrons**
- There are three copies, or *generations*, of quarks and leptons
  - Same properties, only heavier
- Leptons also include **neutrinos**, one for each generation
  - Neutrinos have non-zero masses can **oscillate** between flavors–Lecture 5

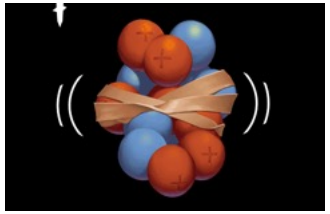
All of these *matter* particles are **fermions:** they have **half integer spin**

Force carriers

Standard Model of Elementary Particles

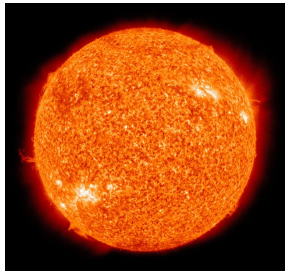


- The other group of particles in the Standard Model are **bosons:** particles with **integer spin**
- These are the force carriers



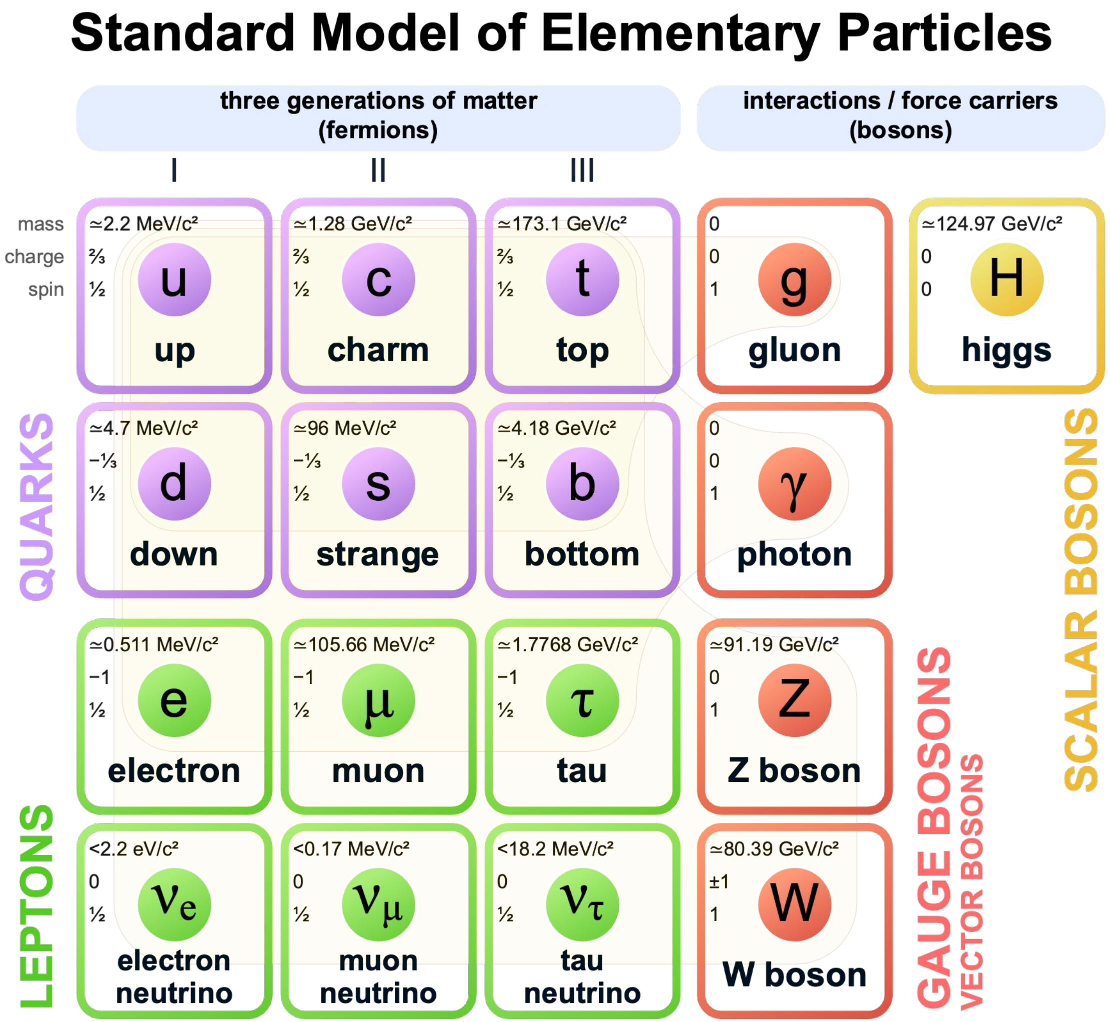
Strong force

Electromagnetic force



Weak force

Higgs boson



Higgs boson

- Spin 0: first fundamental scalar
- Higgs mechanism describes how particles get their mass

Fermions vs bosons

Fermions:

- Named for Enrico Fermi (1901 – 1954)
- Half-integer spin
- "Matter" particles (quarks, leptons, neutrinos)
- Wave functions **anticommute**
- Obey Fermi-Dirac statistics
- Exclusion principle: Identical fermions cannot occupy the same quantum state
  - Proposed in 1925 by Wolfgang Pauli (1900 – 1958)

1945 Nobel Prize

Bosons:

- Named for Satyendra Nath Bose (1894 – 1974)
- Integer spin
- "Force-carrying" particles (photons, gluons, W/Z bosons)
- Wave functions **commute**
- Obey Bose-Einstein statistics
- Can all be in the same quantum state – for example, lasers