Particles

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Particles

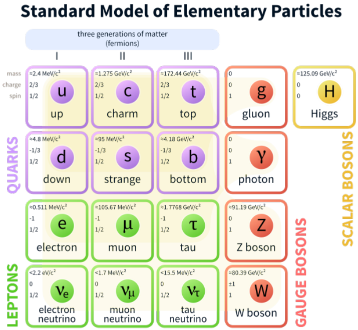
- High Energy Physics = Particle Physics
- HEP addresses fundamental questions, just to name a few:
  - what is the origin of mass?
  - what is dark matter?
  - why there is an imbalance of matter and antimatter in the Universe?
  - hierarchy problem (why gravity is so weak)?
  - where are magnetic monopoles?
  - is the proton stable?
- The way it tries to solve these problems is by looking at fundamental particles and their interactions
  - "fundamental" = can't be made by a combination of other particles

Particles and fields

- We can't look at particles directly – they are "too small"
  - we study properties of particles through their interactions which are carried out by fields
- There is no real boundary between particles and fields:
  - particles are localized in space and fields exist everywhere – but this distinction is moot because of uncertainty principle
  - particles exhibit wave properties, and fields are quantized
- Most of the particles we are interested in are extremely short-lived and quickly convert to other particles
  - these conversions are also carried out by interactions

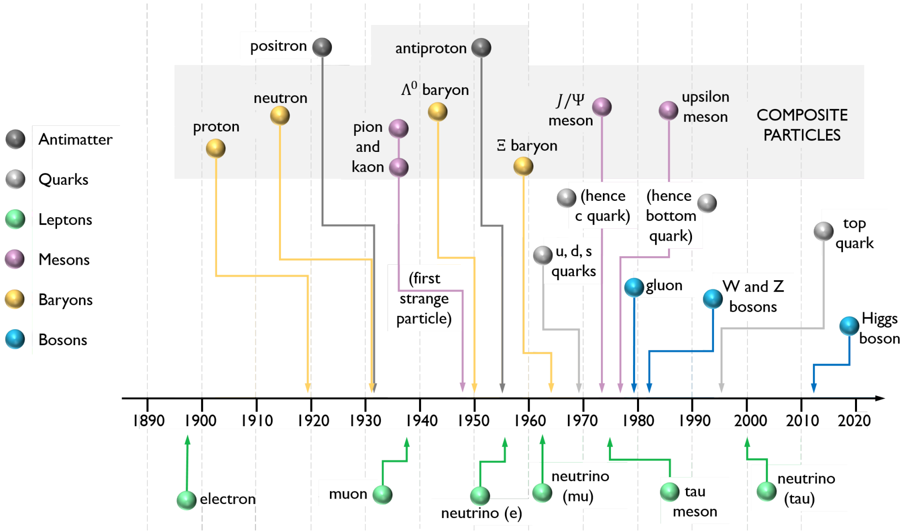
Standard Model

- A little "periodic table" that includes all known fundamental particles and carriers of all fundamental interactions
  - gravity is not included (and we have no clue about it)



- e,μ,τ,ν are leptons, u, d, c, s, b, t are quarks
- leptons and quarks are fermions, field carriers are bosons
- ν, Z, γ do not have a charge, e,μ,τ have "integer" charge, and quarks have "fractional" charge
- γ, g, and ν (in SM!) don't have a mass

Particle physics timeline



Composite particles

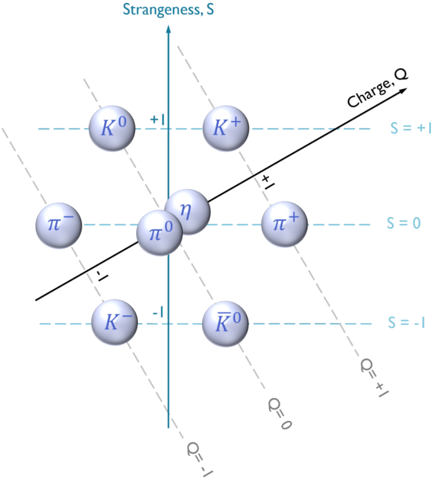
- Quarks and gluons are not observed as isolated particles due to color confinment
  - what we see are colorless composite particles
- Two main ways to make a colorless object out of colored quarks:
  - mesons: quark-antiquark bound states with symmetric color wavefunction $\chi_s = \frac{1}{\sqrt{3}}(r\bar{r} + g\bar{g} + b\bar{b})$
  - baryons: three quark bound states with asymmetric color wavefunction $\chi_c = \frac{1}{\sqrt{6}}(rgb - rbg + gbr - grb + brg - bgr)$
- They don't interact by exchanging single gluons (need to stay color neutral), typical interaction is through pions
  - pions are massive ($\sim$140 GeV), so strong interaction has a finite range (Yukawa, 1935)
- Baryons and mesons are collectively known as hadrons (Okun, 1962)

SU(2) hadrons

- Consider u and d quarks as a single particle that has isospin $I = 1/2$, so that u has $I_3 = +1/2$ and d has $I_3 = -1/2$
  - by observation, electric charge $Q = B/2 + I_3$, where B is baryon charge (quarks have $B = 1/3$)
- u and d form a doublet under symmetry group SU(2)
  - **S**pecial ($\det A = 1$) **U**nitary ($A^\dagger A = I$) Lie group of 2×2 matrices
  - $A = \begin{pmatrix} a & -\bar{b} \\ b & \bar{a} \end{pmatrix}$, $|a|^2 + |b|^2 = 1$
- On top of isospin, quarks also have regular (angular) spin 1/2
  - considering lowest orbital angular momentum $L = 0$, mesons can have $J = 0$ or 1, and baryons can have $J = 1/2$ or $3/2$
- Examples:
  - $J = 0$ (pseudoscalar) mesons: $\pi^+ = u\bar{d}$, $\pi^- = d\bar{u}$, $\pi^0 = \frac{1}{\sqrt{2}}(d\bar{d} - u\bar{u})$
  - $J = 1$ (vector) mesons: $\rho^+ = u\bar{d}$, $\rho^- = d\bar{u}$, $\rho^0 = \frac{1}{\sqrt{2}}(d\bar{d} - u\bar{u})$
  - $J = 1/2$ baryons: proton p (uud) and neutron n (ddu)
  - $J = 3/2$ baryons: Δ-resonances

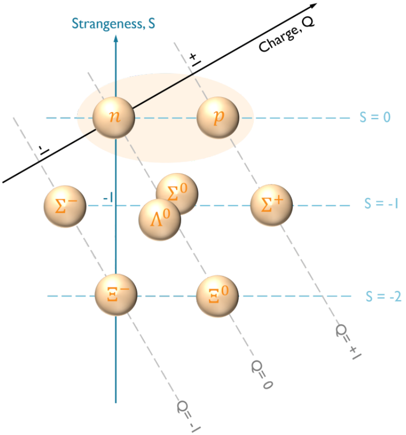
SU(3) mesons

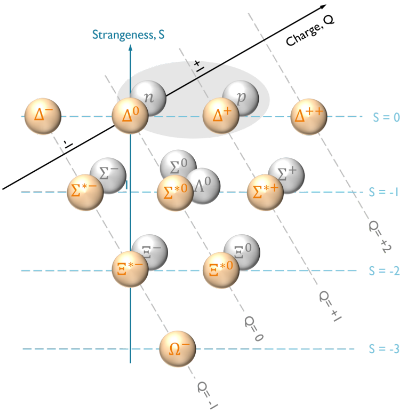
- After strange particles were discovered, particle physics started to look like a zoo (Oppenheimer, 1956)
- SU(2) $\rightarrow$ SU(3) (broken due to massive s-quark)
  - clean SU(3) states are $\eta_8 = \frac{1}{\sqrt{6}}(u\bar{u} + d\bar{d} - 2s\bar{s})$ and $\eta_1 = \frac{1}{\sqrt{3}}(u\bar{u} + d\bar{d} + s\bar{s})$
  - observed state (η, η') are mixed
- Visualization: "the eightfold way" (Gell-Mann, 1961)



SU(3) baryons

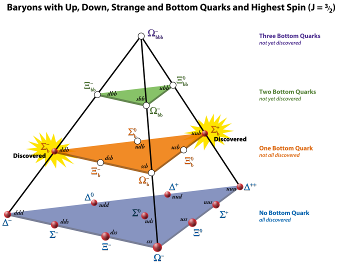
- For baryons, have an octet ($J = 1/2$) and a decuplet ($J = 3/2$)





Charm and beauty

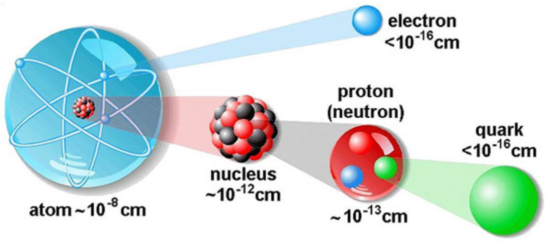
- Discovery of strange particles was followed by discovery of charm and beauty, and things became complicated
- Luckily (?), that has completed the picture – all baryons and mesons we know are made of u, d, s, c, and b quarks
  - the last, top quark does not form bound states



Plot taken from the CDF report on discovery of Σ_b (2006)

Most common particles

- To explain most of matter around us, we just need electrons, protons, and neutrons

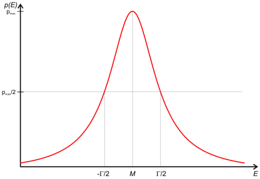


Stable and unstable particles

- There are very few particles which have infinite (or at least very large) lifetime
  - photon – the one we can detect by naked eye
  - protons and electrons (is the proton really stable?)
  - neutrinos (but they oscillate)
  - gluons / light quarks – but they can't be observed directly
- neutron is not stable but its lifetime is macroscopic (15 minutes)
  - it's for a "free" neutron, those inside the nucleus keep turning into protons and vice versa
- muons: 2.2 μs, charged pions: 26 ns (π^0 is only 8.4×10^{-17} s)
  - doesn't look much but think of the path it may travel: $c = 3 \times 10^8$ m/s, 1 ns means 30 cm
- most particles (including W/Z and Higgs) decay so fast there is no way to "catch" them

How unstable is unstable?

- To address this question, need to compare particle's lifetime to its mass
  - mass is energy: $E = mc^2$
  - energy is time: $\Delta E \Delta t \geq \hbar/2$
  - 1 GeV corresponds to 3×10^{-25} s
- measurement of lifetime is intrinsically uncertain
  - having done it many times, we will get a bell-shaped distribution (strictly speaking, a Breit-Wigner one: $\sim \Gamma/((E - E_0)^2 + (\Gamma/2)^2))$
- At some point, the "particle" is no longer a particle!



Other particles

- So far we are not aware of any other particles which might be there
- But there are many reasons to believe that more particles exist
  - Supersymmetric particles
  - More SM generations
  - More Higgs particles
  - Monopoles, gravitons, axions, KK excitations
  - ?