Particle Physics

I. Particles

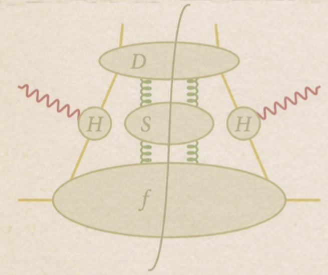


Figure 8.11: Factorisation in SIDIS: the bull diagram. All IR divergences are absorbed in the soft factor S, that hence only interacts with the TMD and FF. Note that there is no real radiation coming from the hard

Figure 5.8: All types of first order corrections to the DIS process. Real corrections are on the upper line; virtual on the lower line.

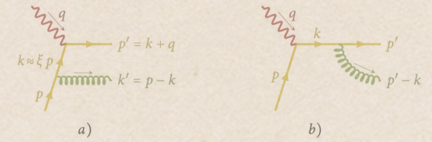
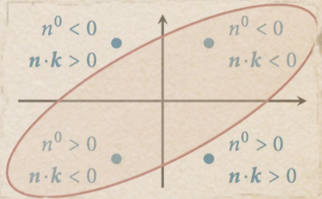


Figure 5.9: a) Initial state gluon radiation. b) Final state gluon radiation.

Figure 2.1: As a parallel transporter transforms in function of its path endpoints only, all paths shown will give rise to equivalent $\mathcal{U}_{(y;x)}$'s, shifting a field at x to a field at y.



The Mikowskian loop integrals are then the same as the Euclidian ones, up to a possible sign difference:

$$\int \frac{d^\omega k}{(2\pi)^\omega} \frac{1}{(k^2-\Delta)^n} = i \frac{(-)^n}{(4\pi)^{\frac{\omega}{2}}} \frac{\Gamma\left(n-\frac{\omega}{2}\right)}{\Gamma(n)} \Delta^{\frac{\omega}{2}-n}, \tag{B.25a}$$

$$\left(\begin{matrix} d \geq 2n \\ d \text{ even} \end{matrix}\right) = i \frac{\Delta^{\frac{d}{2}-n}}{(4\pi)^{\frac{d}{2}}} \frac{(-)^{\frac{d}{2}}}{(n-1)!\left(\frac{d}{2}-n\right)!} \left(\frac{1}{\epsilon} - \gamma_E + \sum^{\frac{d}{2}-n} \frac{1}{j} \right),$$

$$\int \frac{d^\omega k}{(2\pi)^\omega} \frac{k^2}{(k^2-\Delta)^n} = i \frac{(-)^{n+1}}{(4\pi)^{\frac{\omega}{2}}} \frac{\omega}{2} \frac{\Gamma\left(n-\frac{\omega}{2}-1\right)}{\Gamma(n)} \Delta^{\frac{\omega}{2}+1-n}, \tag{B.25b}$$

$$\left(\begin{matrix} d \geq 2n-2 \\ d \text{ even} \end{matrix}\right) = i \frac{\Delta^{\frac{d}{2}+1-n}}{(4\pi)^{\frac{d}{2}}} \frac{\omega}{2} \frac{(-)^{\frac{d}{2}}}{(n-1)!\left(\frac{d}{2}+1-n\right)!} \left(\frac{1}{\epsilon} - \gamma_E + \sum^{\frac{d}{2}+1-n} \frac{1}{j} + \ln 4\pi - \ln \Delta \right)$$

$$\int \frac{d^\omega k}{(2\pi)^\omega} \frac{k^4}{(k^2-\Delta)^n} = i \frac{(-)^n}{(4\pi)^{\frac{\omega}{2}}} \frac{\omega(\omega+2)}{4} \frac{\Gamma\left(n-\frac{\omega}{2}-2\right)}{\Gamma(n)} \Delta^{\frac{\omega}{2}+2-n}, \tag{B.25c}$$

$$\left(\begin{matrix} d \geq 2n-4 \\ d \text{ even} \end{matrix}\right) = i \frac{\Delta^{\frac{d}{2}+2-n}}{(4\pi)^{\frac{d}{2}}} \frac{\omega(\omega+2)}{4} \frac{(-)^{\frac{d}{2}}}{(n-1)!\left(\frac{d}{2}+2-n\right)!} \left(\frac{1}{\epsilon} - \gamma_E + \sum^{\frac{d}{2}+2-n} \frac{1}{j} + \ln 4\pi - \ln$$

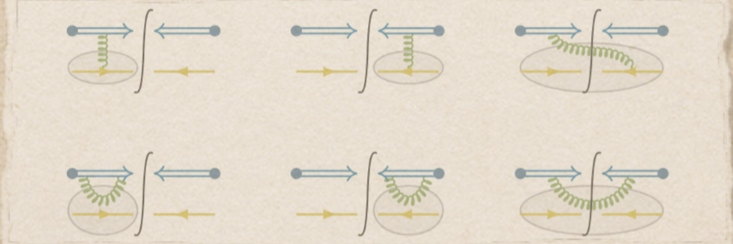
We list some other common Minkowskian integrals:

$$\int \frac{d^\omega k}{(2\pi)^\omega} \ln(k^2-a) = -\frac{i}{(4\pi)^{\frac{\omega}{2}}} \Gamma\left(-\frac{\omega}{2}\right) a^{\frac{\omega}{2}}, \tag{B.26a}$$

$$\int \frac{d^\omega k}{(2\pi)^\omega} e^{ak^2 - i b \cdot k} = \frac{i}{(4\pi)^{\frac{\omega}{2}}} a^{-\frac{\omega}{2}} e^{\frac{b^2}{4a}}, \tag{B.26b}$$

$$\int \frac{d^\omega k}{(2\pi)^\omega} \frac{1}{(-k^2)^\alpha} e^{-i b \cdot k} = \frac{i}{4^\alpha \pi^{\frac{\omega}{2}}} \frac{\Gamma\left(\frac{\omega}{2}-\alpha\right)}{\Gamma(\alpha)} \frac{1}{(-b^2)^{\frac{\omega}{2}-\alpha}}. \tag{B.26c}$$

$$\oint_C dx \cdot A = \int_\Sigma d\sigma \cdot (\partial \wedge A)$$



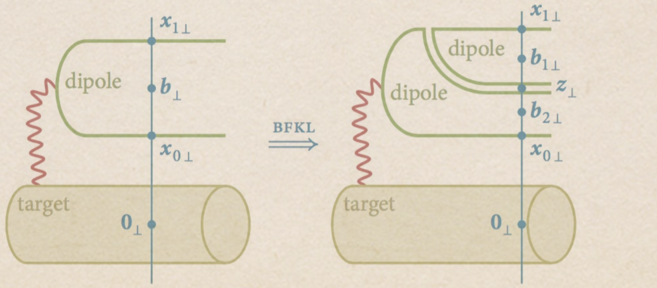


Figure 9.6: In the dipole picture, the BFKL evolution is an evolution in dipoles, i.e. new dipoles are created during the evolution. A gluon that is radiated from the dipole can be represented as two fundamental lines (see Equation 10.13). This essentially splits the dipole in two at the point $z_\perp$, as is illustrated in the second diagram.

$$\text{tr}\left(t^a t^x t^b t^x\right) = -\frac{1}{4N_c}\delta^{ab},$$

$$\text{tr}\left(t^b t^x t^y\right) f^{ayx} = -i\frac{N_c}{4}\delta^{ab},$$

$$\text{tr}\left(t^y t^z\right) f^{axy} f^{bzx} = -\frac{N_c}{2}\delta^{ab},$$

$$f^{xay} f^{ycz} f^{zbw} f^{wcx} = \frac{N_c^2}{2}\delta^{ab},$$

$$f^{avw} f^{xby} f^{ywz} f^{zvx} = \frac{N_c^2}{2}\delta^{ab},$$

$$f^{awv} f^{bzw} f^{xzy} f^{yvx} = N_c^2 \delta^{ab},$$

$$f^{xay} f^{ycz} f^{zbw} f^{wcx} = \frac{N_c^2}{2}\delta^{ab},$$

$$f^{vaw} f^{wbz} f^{xzy} f^{yvx} = N_c^2 \delta^{ab},$$

and similarly for the seven remaining diagrams.

Goals

¿ Subatomic Particles ?

¿ Forces ?

¿ Spin ?

¿ Baryons & Mesons & Hadrons ?

→ feel free to interrupt
& ask questions

Subatomic Particles

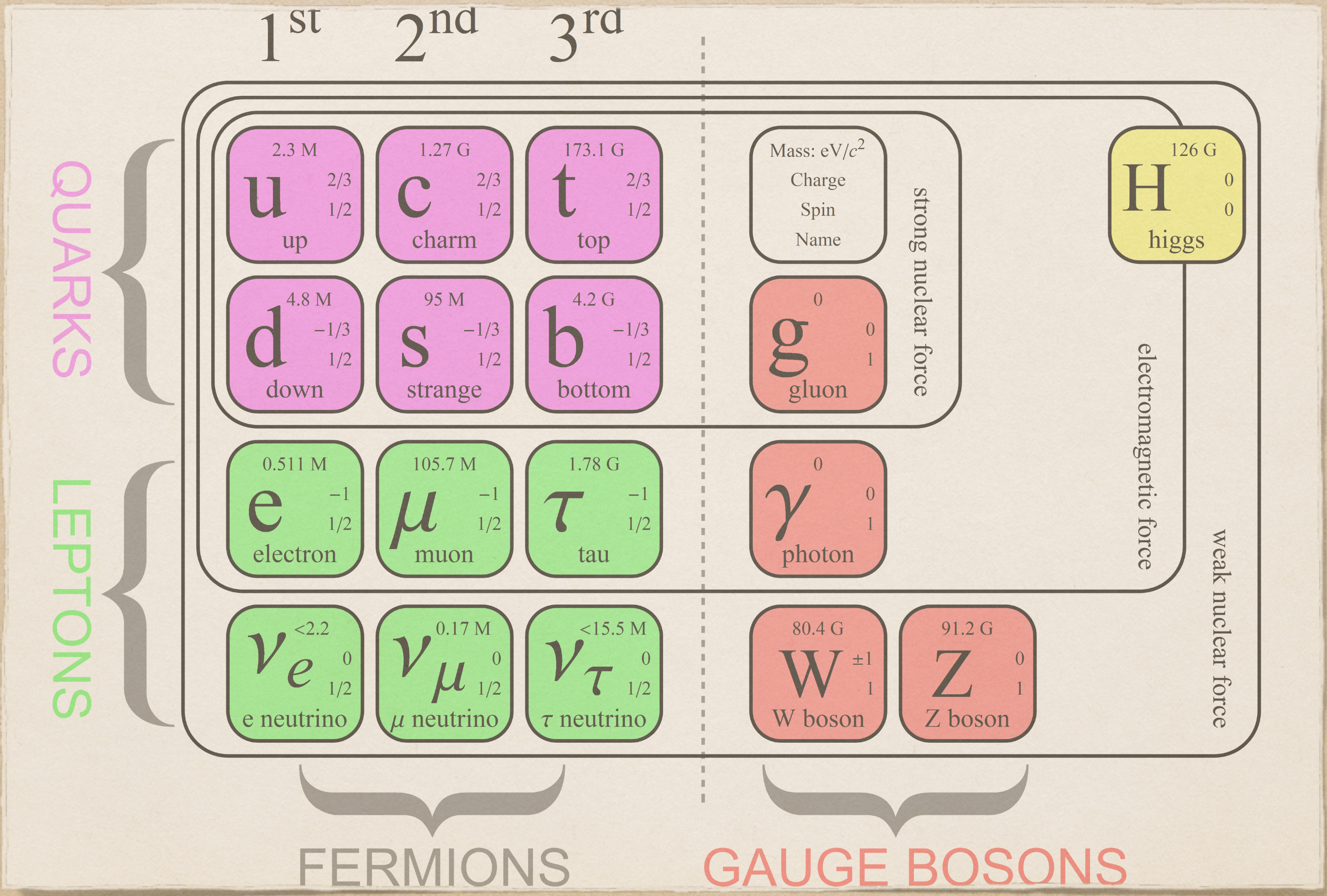
- Hundreds of subatomic particles exist, and new ones keep on being discovered (with the latest one being the Ξ_{cc}^{++} , found at LHCb).

- An important distinction exists between elementary particles (that are indivisible) and composite particles (that are built from other particles, i.e. quarks).

S'Cool LAB

Elementary

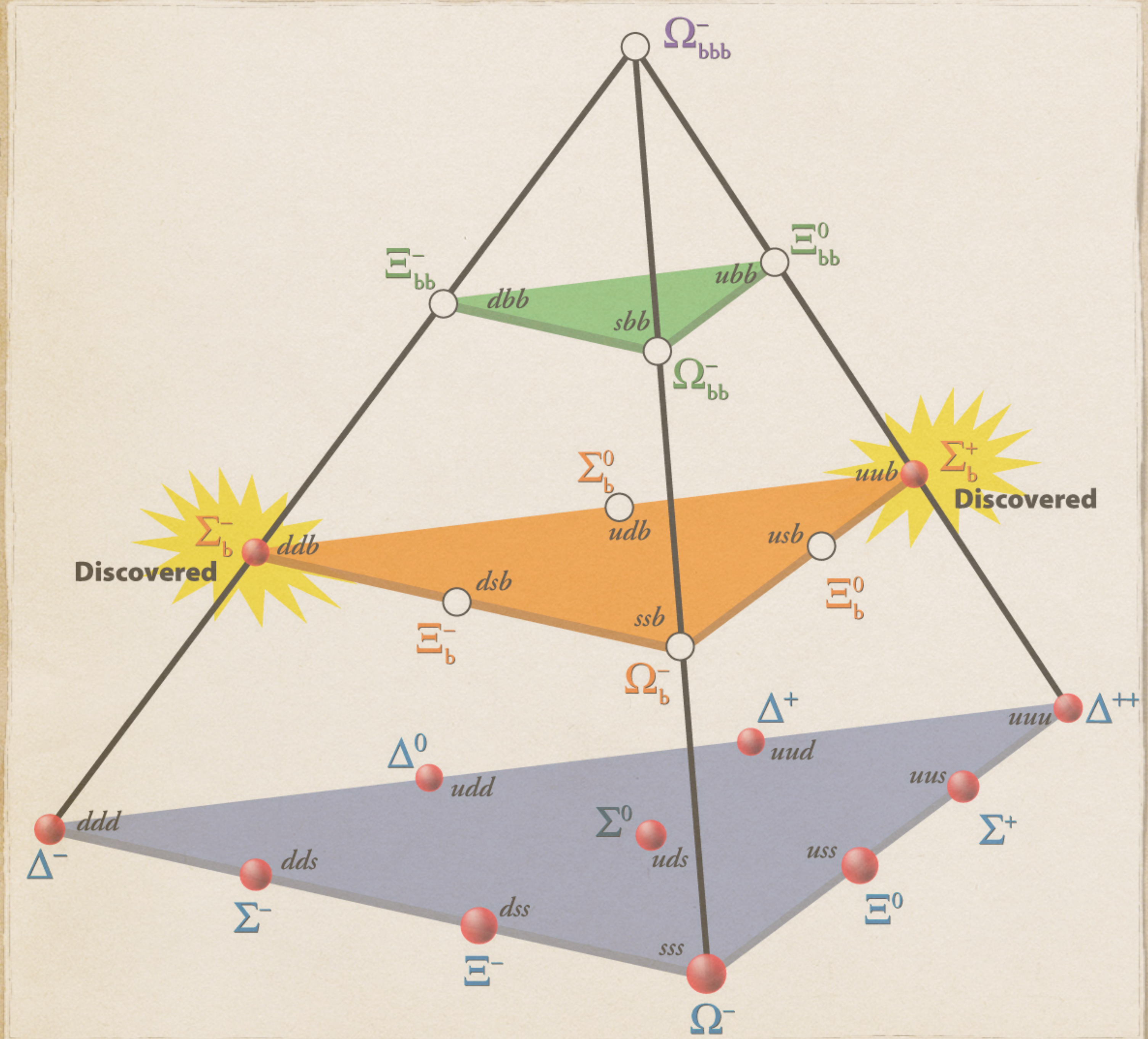
CERN

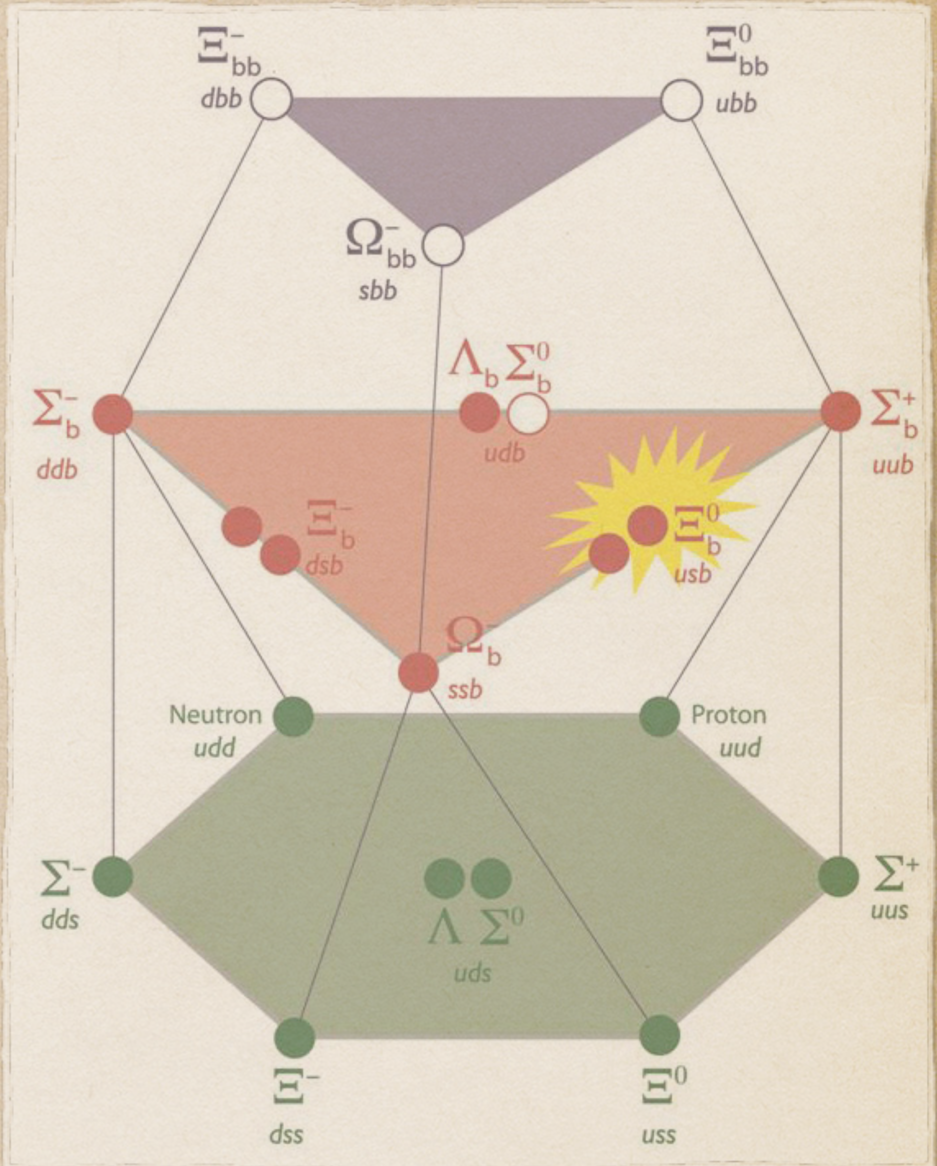


	1st	2nd	3rd			
QUARKS	2.3 M u 2/3 1/2 up	1.27 G c 2/3 1/2 charm	173.1 G t 2/3 1/2 top	Mass: eV/c^2 Charge Spin Name		126 G H 0 0 higgs
QUARKS	4.8 M d −1/3 1/2 down	95 M s −1/3 1/2 strange	4.2 G b −1/3 1/2 bottom	0 g 0 1 gluon		
LEPTONS	0.511 M e −1 1/2 electron	105.7 M μ −1 1/2 muon	1.78 G τ −1 1/2 tau	0 γ 0 1 photon		
LEPTONS	<2.2 ν_e 0 1/2 e neutrino	0.17 M ν_μ 0 1/2 μ neutrino	<15.5 M ν_τ 0 1/2 τ neutrino	80.4 G W ±1 1 W boson	91.2 G Z 0 1 Z boson	

source: http://www.physik.uzh.ch/groups/serra/StandardModel.html

Composite





source: http://www.fnal.gov/pub/inquiring/physics/discoveries/images/BaryonChart_MR.jpg
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Elementary Particles

- Three types:
    - **Fermions:** matter particles
    - **Bosons:** force carriers (“exchange particles”)
    - **Higgs:** special guy

- Difference lies in spin, but..

Elementary Particles

- Three types:
  - **Fermions:** matter particles
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- Difference lies in **spin**, but..

What is spin ??

Spin

Wikipedia:

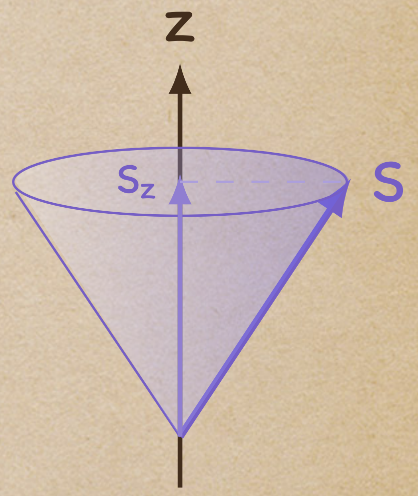
"In quantum mechanics and particle physics, spin is an intrinsic form of angular momentum carried by elementary particles, composite particles (hadrons), and atomic nuclei.

In some ways, spin is like a vector quantity; it has a definite magnitude, and it has a 'direction' (but quantisation makes this 'direction' different from the direction of an ordinary vector).

All elementary particles of a given kind have the same magnitude of spin angular momentum, which is indicated by assigning the particle a spin quantum number."

Spin

- Spin is a vector, however, due to uncertainty in quantum mechanics, we cannot know all three components S_x, S_y, and S_z at the same time



- But we can know the length S and the z-component S_z simultaneously
- But spin is a quantum vector, which puts some restrictions on its possible values, as they are quantised (which means values go in steps)..

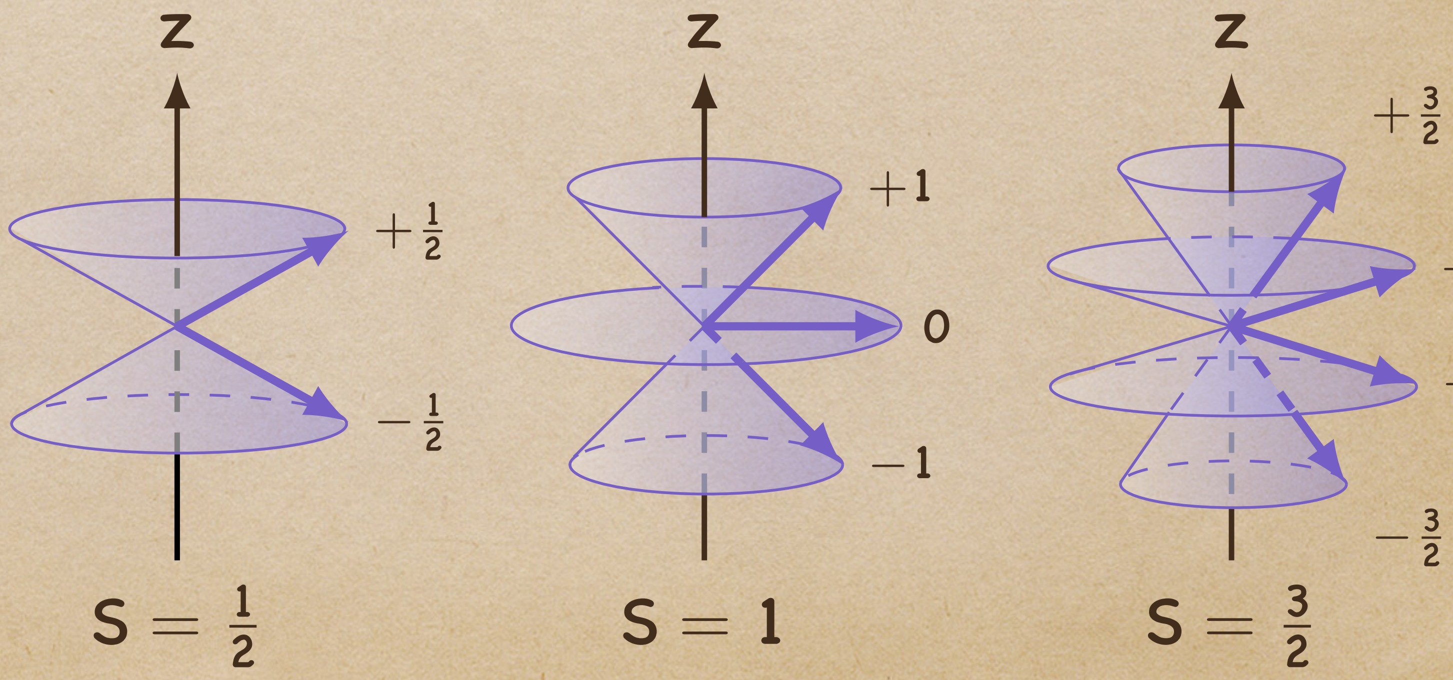
Spin

- The length needs to be a positive multiple of 1/2, so $S = 0, 1/2, 1, 3/2, \ldots$
- S_z can be anything between $-S, -S+1, \ldots, S-1, S$
  This means that spin states come in multiplets.

$S = 0 \rightarrow S_z = 0$

$S = 1/2 \rightarrow S_z = -1/2, +1/2$

$S = 1 \rightarrow S_z = -1, 0, +1$



Spin

- Typical example is the electron: it has spin 1/2, which means it has two possible states:

  -1/2 or +1/2

  also known as ‘up’ or ‘down’

- Now back to elementary particles..

Elementary Particles

- Three types:
    - **Fermions:** matter particles => spin 1/2
    - **Bosons:** force carriers => spin 1
    - **Higgs:** special guy => spin 0

Elementary Particles

- Two types of matter particles:
  - **Leptons:** electrons, muons, taus, and neutrinos
  - **Quarks:** don't exist alone, but combine to form hadrons (composite particles)

- Four fundamental forces:
  - **Electromagnetic:** exchanged by photon
  - **Weak:** exchanged by W^+, W^-, Z^0
  - **Strong:** exchanged by gluons
  - **Gravity:** exchanged by graviton

Elementary Particles

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Three very cool and quantisable and not 'totally ignorable'

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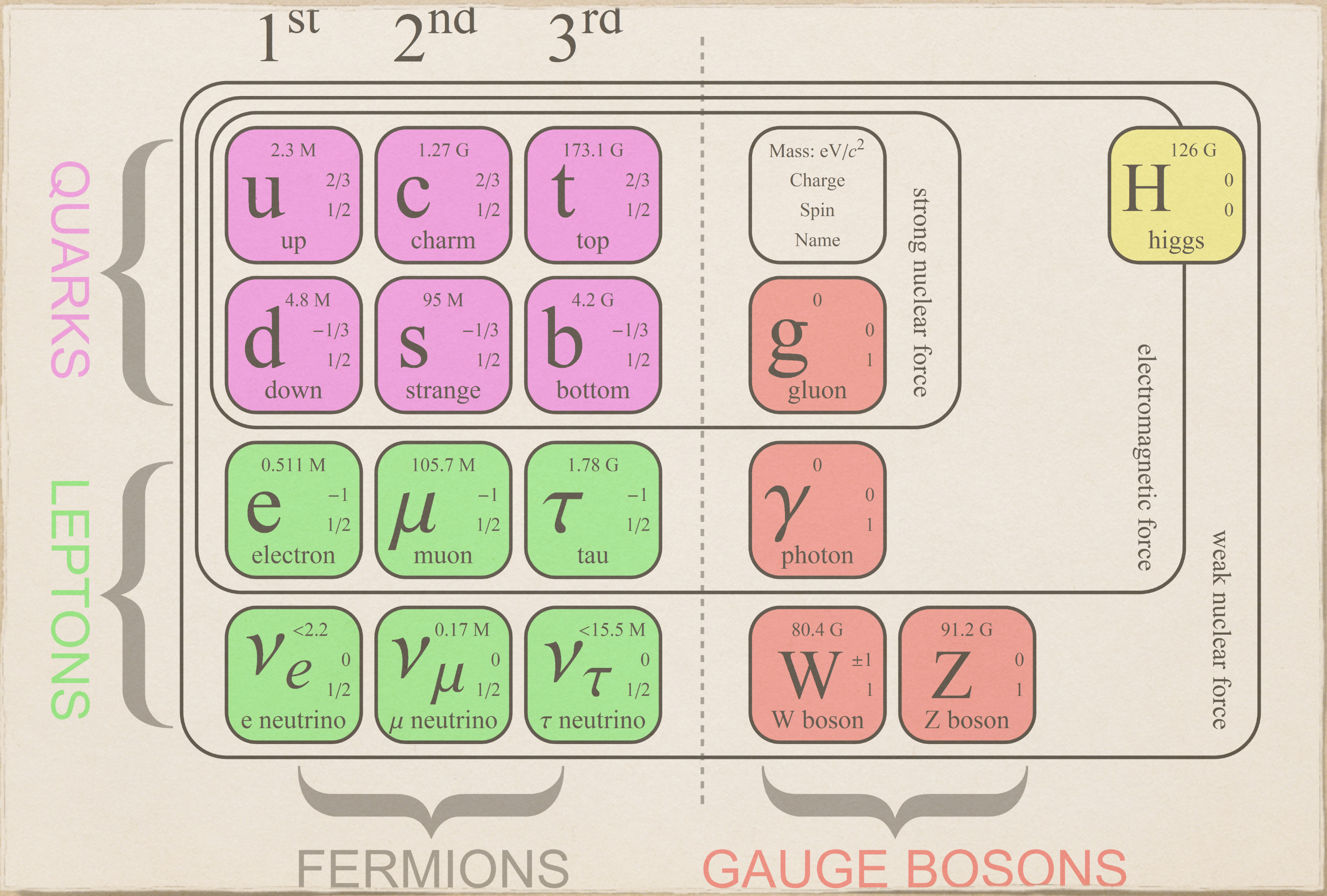
  - **Weak:** exchanged by W^+, W^-, Z^0
  - **Strong:** exchanged by gluons
  - ~~**Gravity:** exchanged by graviton~~

Particle Properties

- Every force comes with an associated charge. If a certain particle does not have this charge, it will not interact with this force.
    - Electromagnetic charge
    - Weak hypercharge
    - Colour (strong force)

- Fermions come in 3 families, the difference between the families being the mass.

Elementary



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FERMIONS

GAUGE BOSONS

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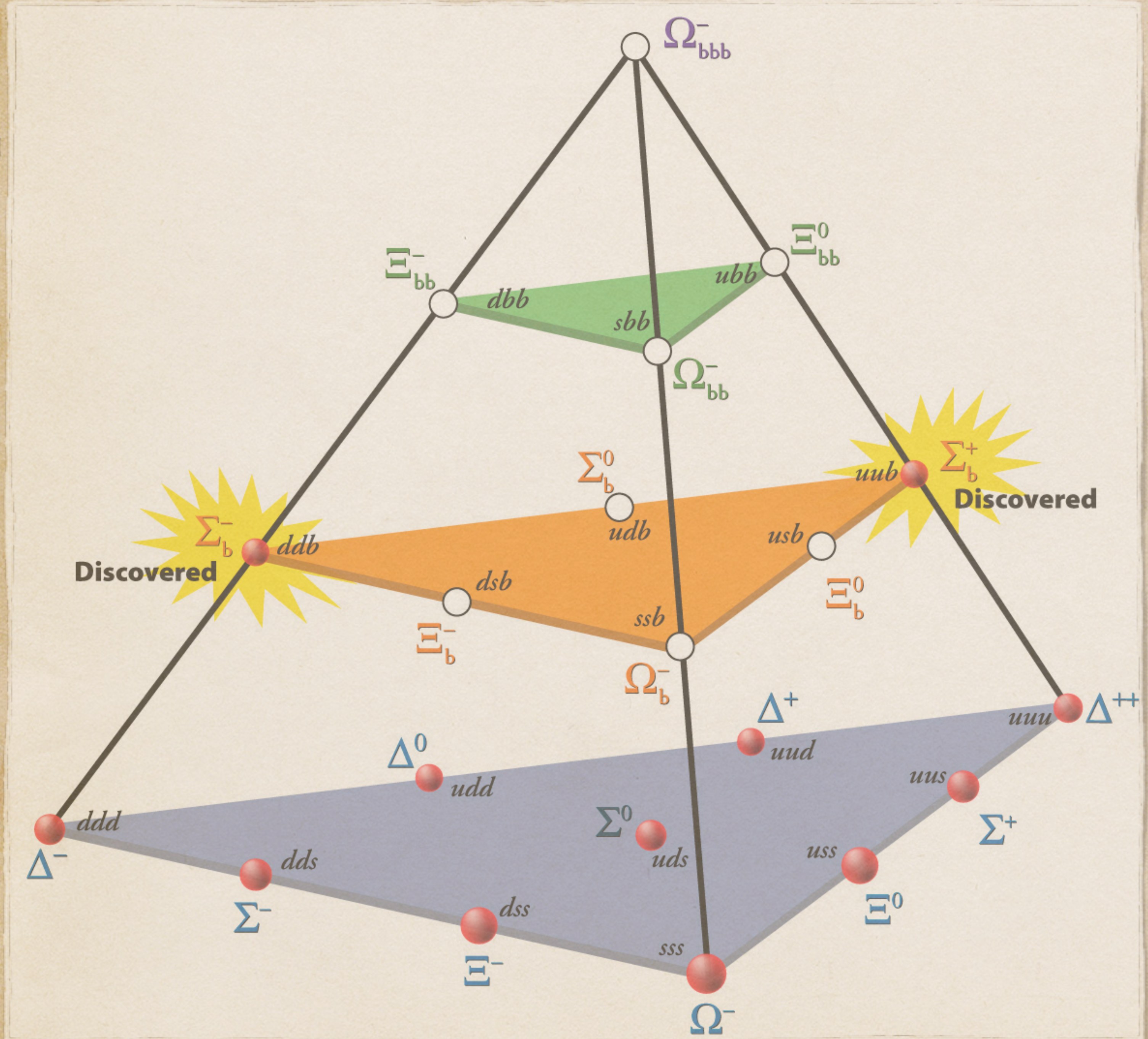
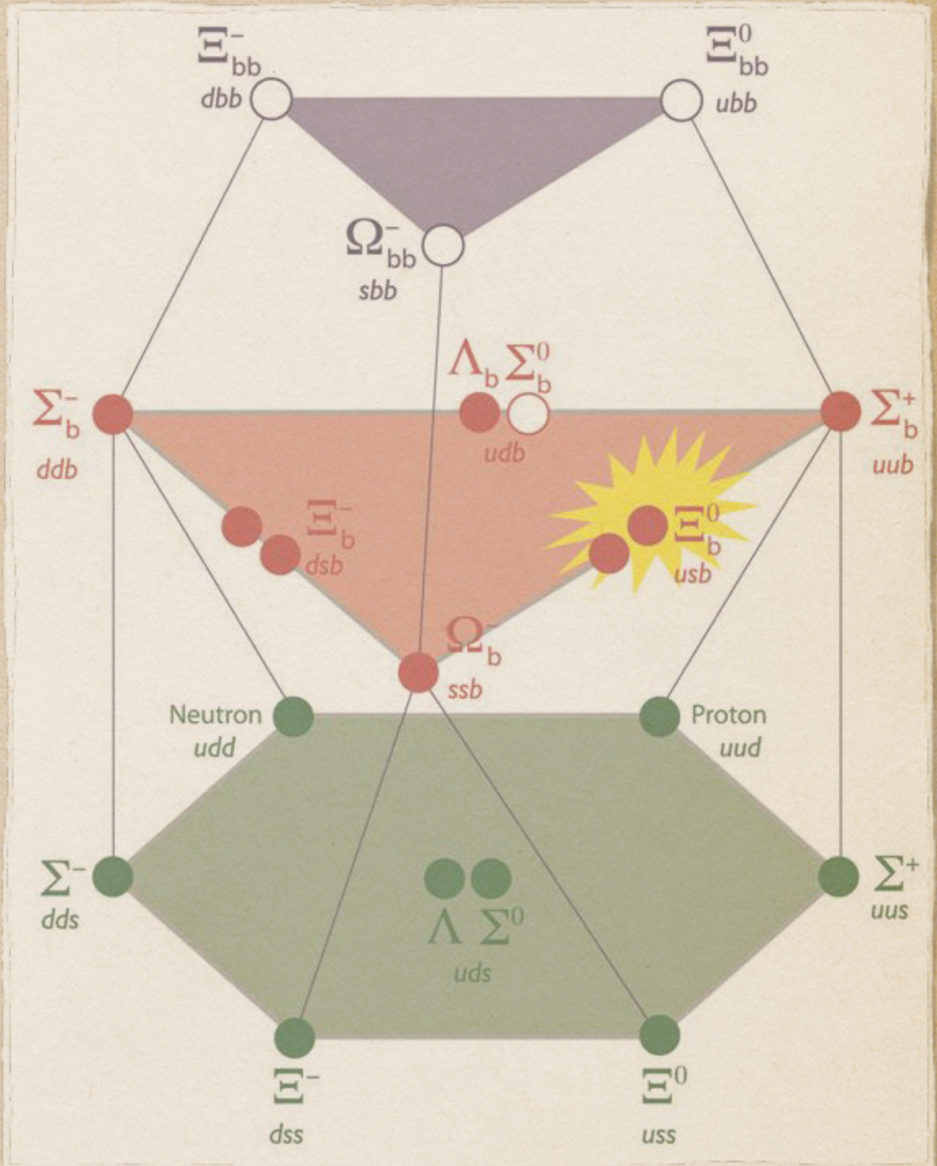
Composite





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Composite Particles

- Are called hadrons and are built from quarks. There are two types:
  - Baryons: built from three quarks
  - Mesons: built from a quark and an antiquark

- Quarks have fractional charge, but resulting hadrons need to have integer charge.

u	c	t	charge +2/3
d	s	b	charge -1/3

Baryons

- Simplest baryons are built from u and d quarks:
  - **Proton:** uud (charge = 2/3 + 2/3 - 1/3 = +1)
  - **Neutron:** udd (charge = 2/3 - 1/3 - 1/3 = 0)

- Anti-baryons are built from antiquarks:
  - **Antiproton:** $\bar{u}\bar{u}\bar{d}$ (charge = -2/3 -2/3 +1/3 = -1)
  - **Antineutron:** $\bar{u}\bar{d}\bar{d}$ (charge = -2/3 +1/3 +1/3 = 0)

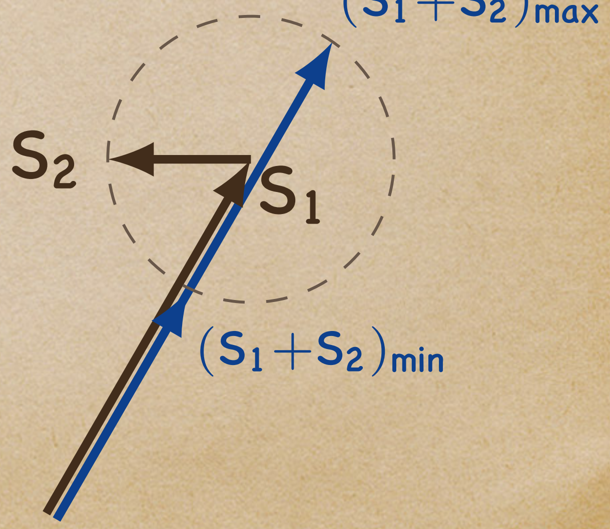
- What about spin? Proton and neutron have spin 1/2, but each quark as well… $1/2+1/2+1/2 \neq 1/2$?

spin = vector => vector sum !

Summing Spins

- Spin is a vector, so should be summed as one. Vectors are not just summed by adding their lengths, because the angle between them matters

- The largest possible result is when both spin vectors are parallel ($|S_{tot}| = |S_1| + |S_2|$), while the smallest possible result is when both are antiparallel ($|S_{tot}| = |S_1| - |S_2|$).



Summing Spins

- As a quantum vector, not all values are possible for the length of the resulting vector, again only in steps: $S_{tot} = S_1 - S_2, S_1 - S_2 + 1, \ldots, S_1 + S_2 - 1, S_1 + S_2$

- Examples:

  $1/2 + 1 = 1/2$ or $3/2$

  $3/2 + 2 = 1/2$ or $3/2$ or $5/2$ or $7/2$

- And the case of 3 quarks:

  $1/2+1/2+1/2 = (1/2+1/2) + 1/2 = (0 \text{ or } 1) + 1/2$

  $= 1/2$ or $3/2$

Baryons

- So, using only u and d quarks, we can make a proton (uud) or a neutron (udd), but also two other particles which have the same quarks but different spin:
    - Δ^+: uud but spin 3/2
    - Δ^0: udd but spin 3/2

- We can even make two more combinations:
    - Δ^{++}: uuu (spin 3/2)
    - Δ^-: ddd (spin 3/2)

Baryons

- The other quarks are way heavier than u and d:

  $m_s = 20\ m_d = 40\ m_u\ ,\ m_c = 250\ m_d = 500\ m_u$

  which means that the resulting baryons will be much heavier as well

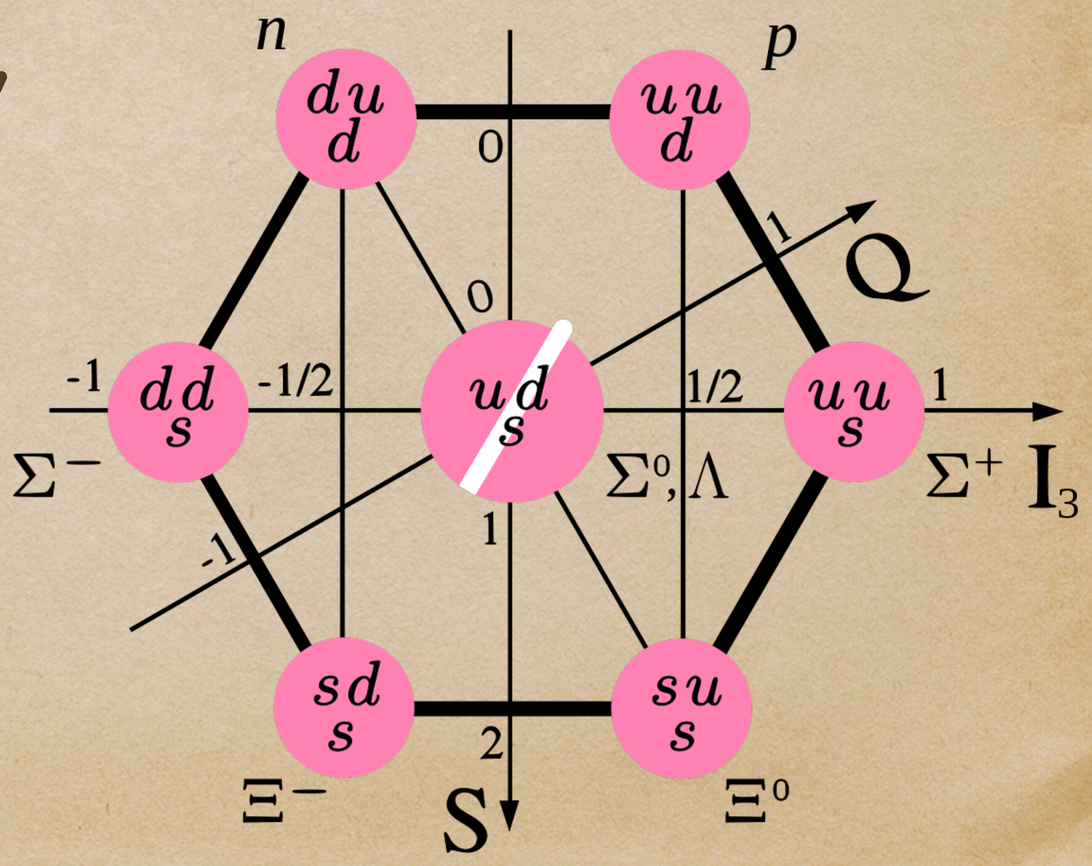
- Before quarks were discovered, only hadrons built from u, d, and s quarks were found. Some were acting ‘normal’, like a proton, but some were acting ‘strange’ (because - we know now - they contain an s quark). They were given a Strangeness

Baryons

- We know today that a hadron with Strangeness -1 contains exactly one s quark (similarly, Strangeness -2 implies two s quarks etc).

- The simplest spin 1/2 baryons can be organised in an octet, called "The eightfold way"

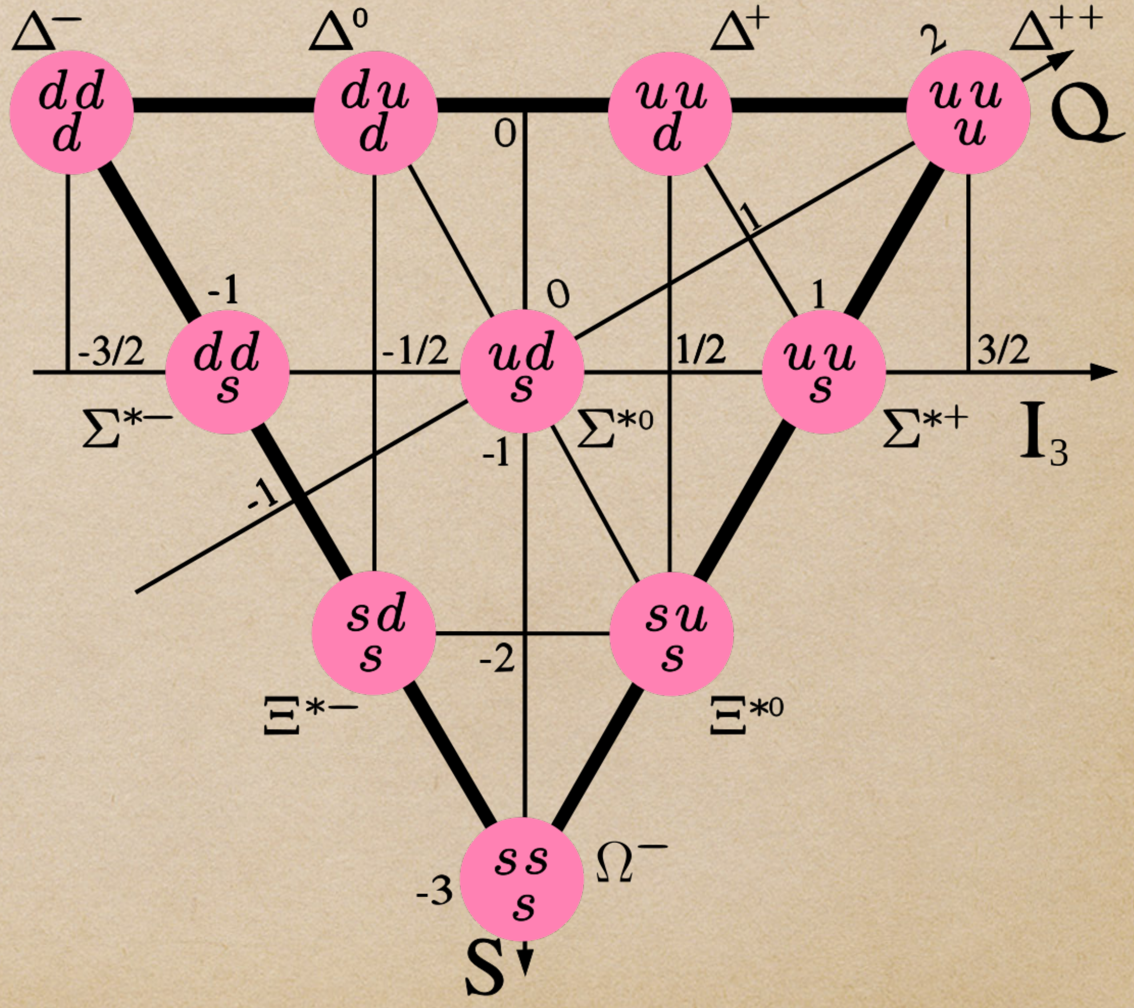
- Strangeness 0: n, p
  Strangeness -1: Σ, Λ
  Strangeness -2: Ξ



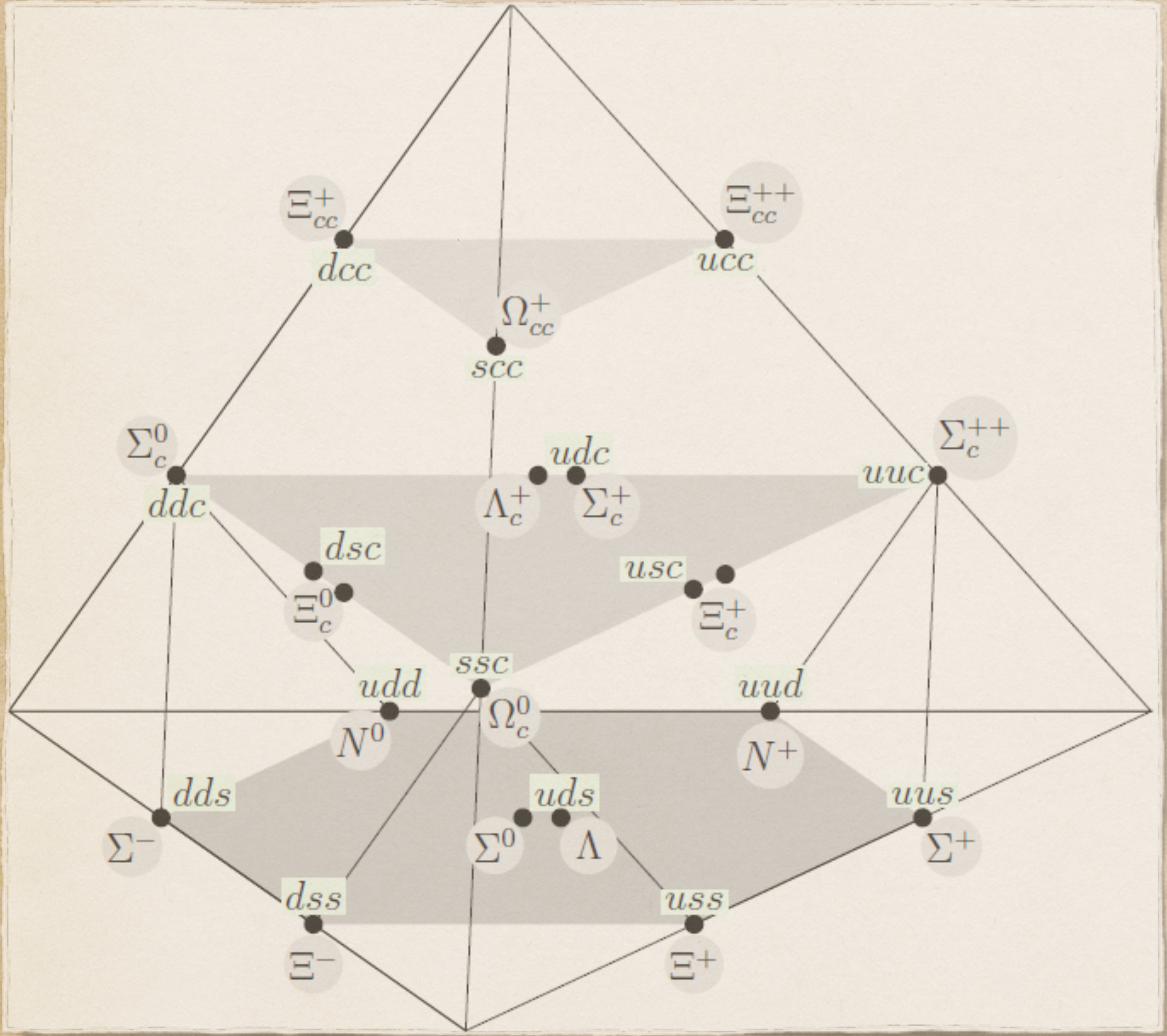
Baryons

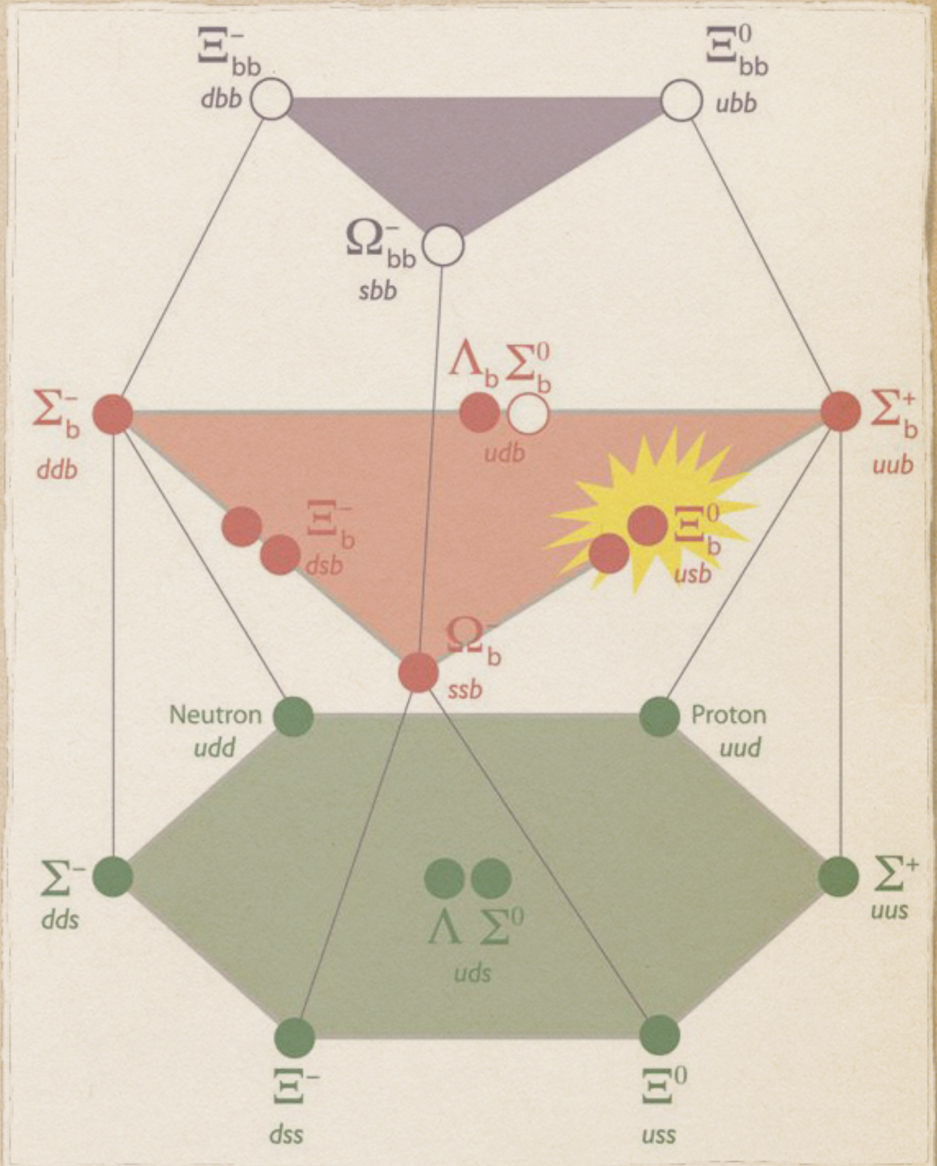
- Similarly, the simplest spin 3/2 baryons can be organised in a **decuplet**

- Strangeness 0: Δ
  Strangeness -1: Σ^*
  Strangeness -2: Ξ^*
  Strangeness -3: Ω



Composite





source: https://en.wikipedia.org/wiki/File:Baryon_Supermultiplet_using_four-quark_models_and_half_spin.png
http://physicsworld.com/blog/Baryons%20Fermilab.jpg

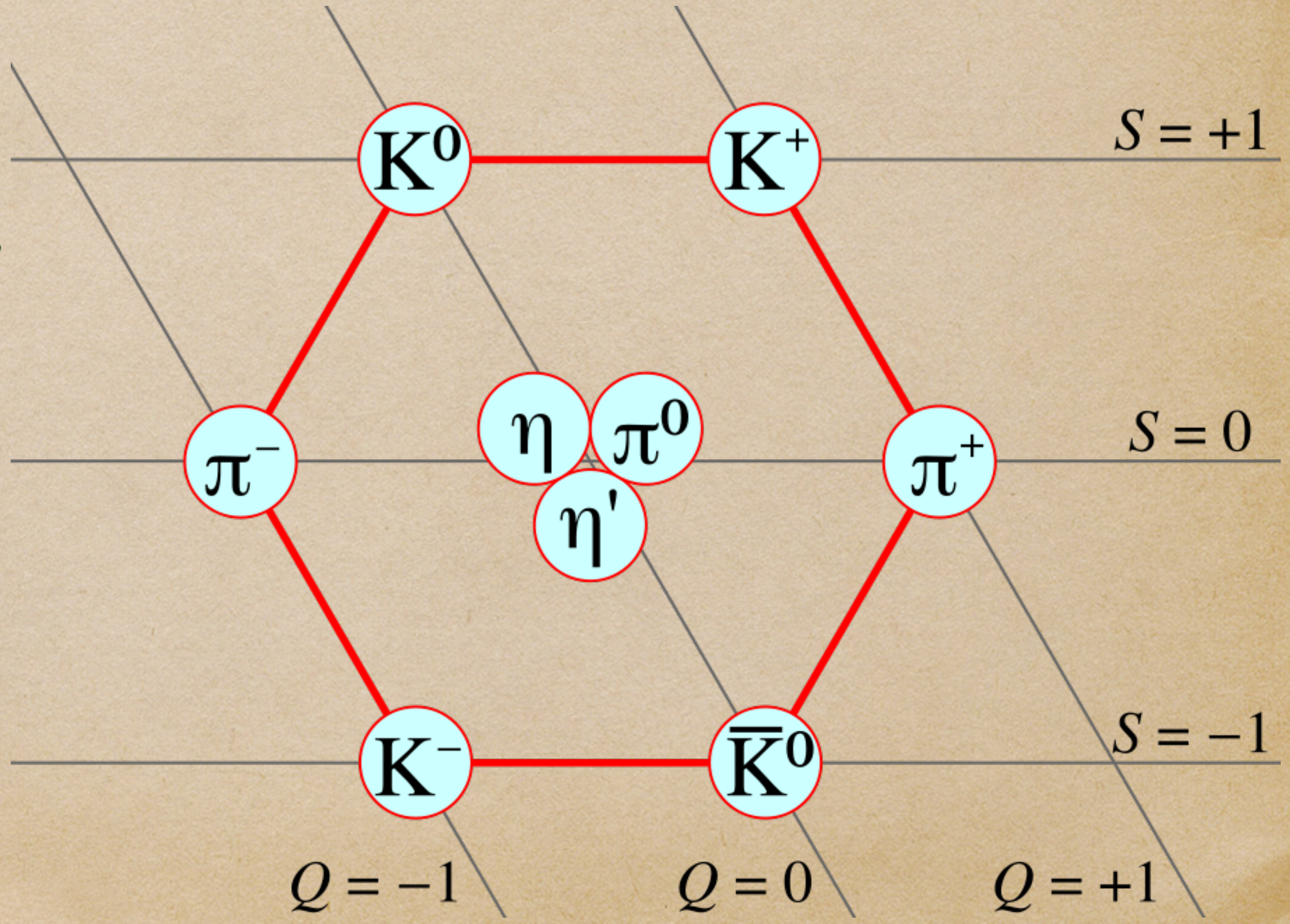
Mesons

- Mesons are built from a quark and an antiquark, and hence lighter dan baryons.
- As they are built from two quarks, their spin is 1/2 + 1/2 = 0 or 1.
- They are classified similarly to baryons, in function of their Strangeness.

Mesons

- The simplest spin 0 mesons can be organised in a **nonet**, originally called "The eightfold way" as well (because η′ wasn't found yet)

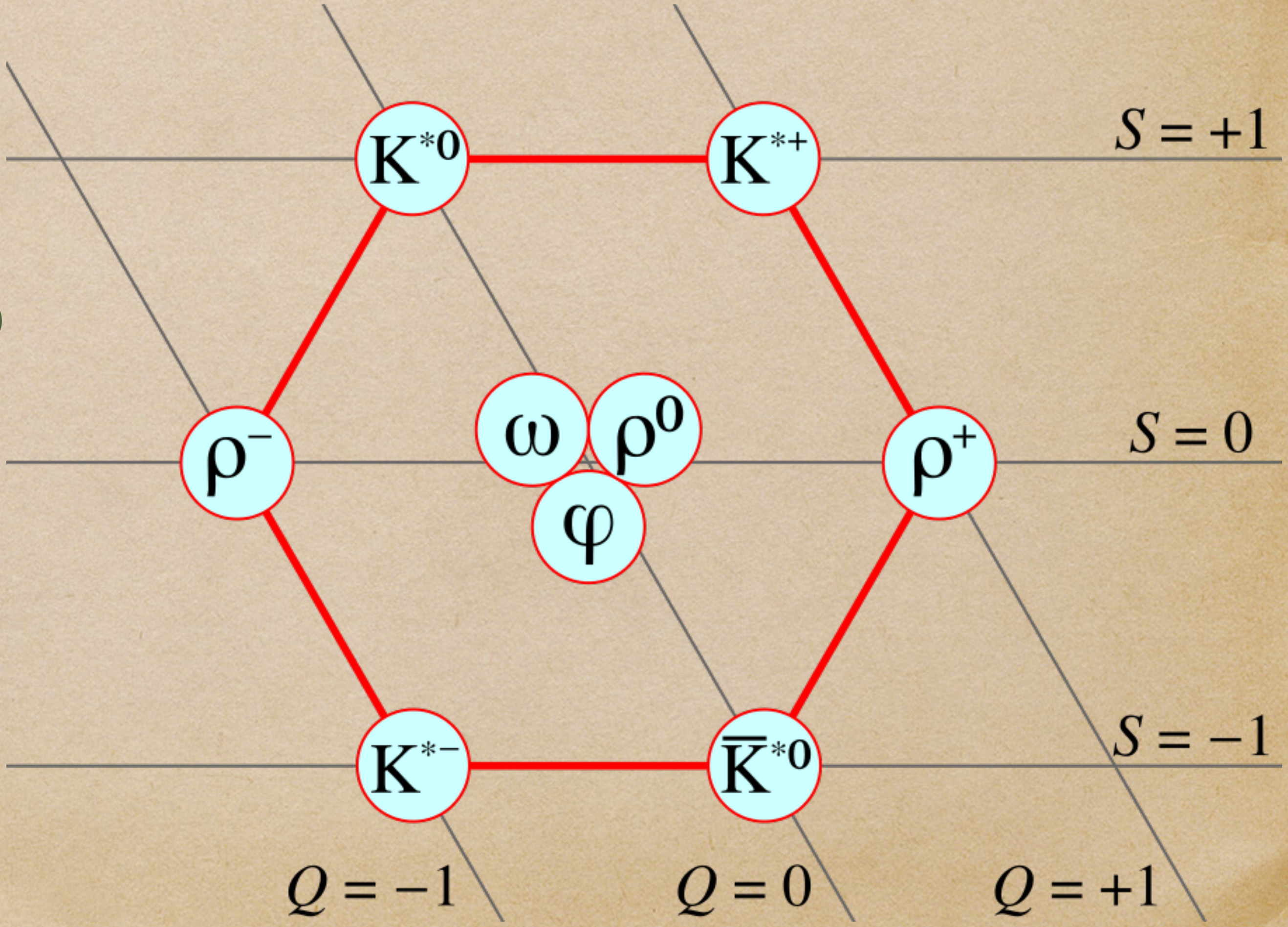
- Strangeness +1: **K**
  Strangeness 0: **π, η, η′**
  Strangeness -1: **K**



Mesons

- And the simplest spin 1 mesons can be organised in another nonet

- Strangeness +1: K^*
  Strangeness 0: ρ, ω, φ
  Strangeness -1: K^*



Summary

- Subatomic particles can be elementary or composite
  - Elementary particles can be fermions or bosons
    - Fermions are matter, and are divided in leptons and quarks
    - Bosons exchange forces
  - Composite particles (hadrons) can be baryons or mesons
    - Baryons are made from 3 quarks and are generally heavy
    - Mesons are made from a quark and an antiquark and are lighter

Exercises

- Can a gluon interact with a photon?
- Can a gluon interact With a W^+?
- Can a photon interact with itself? Why (not)?
- What is the only elementary boson that can interact with neutrinos without changing them?
- Can we have a meson with charge ++?
- What is the quark content of:

Λ^0	(baryon, strangeness -1)
D_s^+	(meson, strangeness 1, charmness 1)
Ω^-	(baryon, strangeness -3)
Ξ_{cc}^{++}	(baryon, charmness 2)