Lecture 4:

- Last time we talked about deep-inelastic scattering and the evidence of quarks
- Next time we will talk about hard-scattering in QCD (pp collisions)
- Today I want to spend a little more time on elementary interactions, since we need to know about them before we move to a more complicated system : AA collisions

Goal of the Lecture

- (Re)introduce the fundamental particles of the Standard Model
- Describe simple conservation laws
- Make the connection between observables (decay rates) and coupling constants that we learn from the Standard model

Leptons

- There are three lepton families

e electron	μ muon	τ tau	L
$m_e = 0.511\ MeV$	$m_\mu = 105.7\ MeV$	$m_\tau = 1777\ MeV$	1
ν_e	ν_μ	ν_τ	

- Neutrinos are nearly massless (at least they were until 1998)
  - All of them are left handed!
- Each lepton number is conserved separately (except in neutrino mixing)
  - L_e, L_μ, L_τ must be the same coming into and leaving a reaction

$$n \rightarrow p + e^- + \bar{\nu}_e \qquad \pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$L_e \quad 0 \rightarrow 0 + 1 + (-1) \qquad L_\mu \quad 0 \rightarrow (-1) + 1$$

Quarks

			Charge
u up ~0 MeV	c charm 1600 MeV	t top 180 GeV	+2/3
d down ~5 MeV	s strange 150 MeV	b bottom 4.5 GeV	-1/3

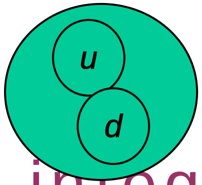
- Quarks are the building blocks of protons and neutrons, the stable non-leptonic matter in the universe.
- Although we assign them identities and charge states, no free quarks have ever been seen!

Quark Quantum Numbers

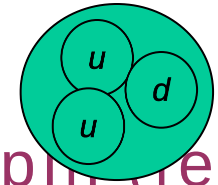
- Quark numbers are conserved separately by the strong & electromagnetic interactions
  - Up-ness, Down-ness, Strange-ness, Charm, Bottom, Top
- Strong Isospin : I=1/2 for u,d and I=0 for s,c,b,t. As a results hadrons come as isospin singlets (I=0), doublets (I=1/2 , (p,n)) and vectors (I=1, $\pi^{+/-}$, π^0). Strong isospin is conserved in the strong interactions.
- Other "flavor" QN's have a simple rule:
  - If quark has q=2/3 (e.g. c,t) then positive
  - If quark has q=-1/3 (e.g. s,b) then negative
- So s→S=-1, c→C=1, b→B=-1, t→T=1

Hadrons

- In nature, quarks are hidden.
- Instead, they appear in pairs and triplets:
  - Mesons – QQ (π, K, ρ, ω)



    - quark-antiquark pairs with integral spin (bosons)
  - Baryons – QQQ (p, n, Λ, Δ)



    - 3 quarks with half-integral spin (fermions)
- Baryon number is conserved in nature
  - Some baryons are stable (nuclei exist!)
  - No mesons are stable – they decay rather quickly (~10^{-9} s for weak decays)

Examples of Hadrons

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$

Baryons are fermionic hadrons.
There are about 120 types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	–1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	–1	1.672	3/2

Mesons $q\bar{q}$

Mesons are bosonic hadrons.
There are about 140 types of mesons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2 .980	0

- In particle physics "stable" hadrons means: do not decay via strong interaction.
- Unstable states (or strongly decaying states) are called "resonances"

The hadrons

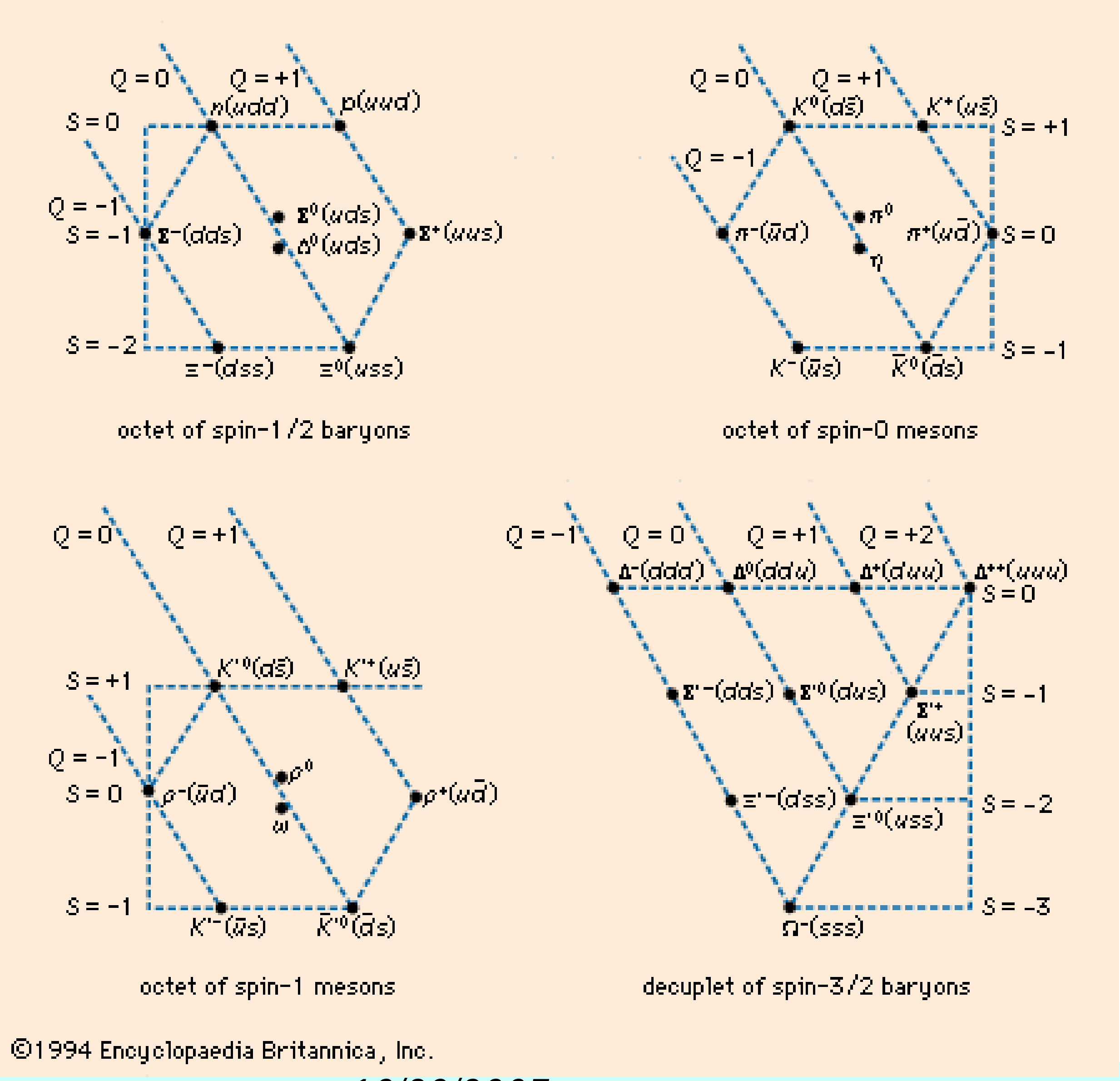
See http://pdg.lbl.gov

For an index of reviews of particle physics see:

http://pdg.lbl.gov/2007/reviews/content_sports.html

The hadrons have been classified into groups (sort of periodic table of sub-atomic particles) based of their symmetrical properties. The system was proposed in 1961 by the American physicist Murray Gell-Mann and the Israeli physicist Yuval Ne'eman.

The SU(3) – 3 quarks hadron classification



Conservation laws

1. Energy and momentum conservation

(implies that in decays $M_0 > \Sigma m_i$)

2. Angular momentum conservation
3. Charge
4. Baryon number
5. Lepton number (each individual L# is conserved, except in neutrino mixing)

1-5 are are conserved by any interaction

In addition:

6. Hadronic flavor is conserved by EM & strong interactions (but not in weak)
7. Parity is conserved in EM& strong, but not in weak

Example of lepton # conservation (Lepton Decay Madness ☺)

$$\tau^- \to \mu^- + \bar{\nu}_\mu + \nu_\tau$$

$$\mu^- \to e^- + \bar{\nu}_e + \nu_\mu$$

- So we start with 1 tau lepton
- We end with 1 tau neutrino, 2 muon neutrinos (particle & anti-particle), 1 electron, and one anti-electron neutrino!
- Nothing is violated!

Quark QNs in Action

- Strange particle production (strong)

$$\underset{uud}{p} + \underset{uud}{p} \rightarrow \underset{uud}{p} + \underset{uds}{\Lambda} + \underset{\bar{s}u}{K^+}$$

$$S = 0 \qquad\qquad S = -1 + 1$$

- Charm particle production (E&M)

$$e^+ + e^- \rightarrow \underset{\bar{d}c}{D^+} + \underset{\bar{c}d}{D^-}$$

$$C = 0 \qquad\qquad C = 1 + (-1)$$

(More) Weak Decay examples

$$\bar{\nu}_e + e^- \xrightarrow{W^-} \bar{\nu}_\mu + \mu^-$$

$$(uus)\Sigma^+ \xrightarrow{s \to u} p + \pi^0 \left(uud + \bar{d}d\right)$$

Note: strangeness is not conserved!

$$\mu^- \xrightarrow{W^-} e^- + \bar{\nu}_e + \nu_\mu$$

$$\bar{\nu}_\mu + e^- \xrightarrow{Z^0} \bar{\nu}_\mu + e^-$$

Consider the following reactions: which are allowed and which not ?

- By which interaction do these process occur (i.e. – if they are possible) ?

$$1)\, p + \overline{p} \rightarrow \pi^{+} + \pi^{0}$$

$$2)\, \eta \rightarrow \gamma + \gamma$$

$$3)\, \Sigma^{0} \rightarrow \Lambda + \pi^{0}$$

$$4)\, \Sigma^{-} \rightarrow N + \pi^{-}$$

$$5)\, e^{+} + e^{-} \rightarrow \mu^{+} + \mu^{-}$$

$$6)\, \mu^{-} \rightarrow e^{-} + \overline{\nu}_{e}$$

$$7)\, \Delta^{+} \rightarrow \pi^{0} + p$$

Examples of hadron decays and lifetimes

- Look at the handout with hadrons lifetimes and major decay modes
- Do you notice patterns ?
  - Lifetimes go in groups
    - $\sim 10^{-10}$ sec
    - $\sim 10^{-19}$ sec
    - $\sim 10^{-23}$ sec
  - Yes, you guessed correctly: weak, EM, strong decays !

How to think about couplings

- The matrix elements relate to lifetime via the "width" $$\Gamma \equiv \hbar / \tau \propto |M|^2 \propto \alpha^2$$
- In addition, there is phase-space (or *dLips* in lecture 2), which indicates how many states are available in the final state and in a way how "easy" it is to decay
- From the matrix element: the ratio of the strengths is

$$\frac{\alpha_1}{\alpha_2} \propto \sqrt{\frac{\tau_2}{\tau_1}}$$

Stronger coupling, shorter life

$$\frac{\alpha_s}{\alpha} \propto \sqrt{\frac{10^{-19}}{10^{-23}}} \sim 100$$

$$\frac{\alpha_w}{\alpha} \propto \sqrt{\frac{10^{-19}}{10^{-10}}} \sim 10^{-5}$$

The weak interaction strength

- Major victory of theoretical physics was finding a structure which could include electromagnetism and weak forces in a single set of fields
- If we assume g=e, and measure G (the strength of the weak interactions) we can extract M

$$\frac{g^2}{q^2 - M^2} \Rightarrow \frac{g^2}{M^2} \equiv G \sim 10^{-5} GeV^{-2}$$

$$\frac{g^2}{M^2} \equiv G \Rightarrow M = \sqrt{\frac{4\pi\alpha}{G}} \sim 90\, GeV$$

- The W & Z bosons were discovered in 1981, exactly where they were predicted to be!
- Note the masses of W and Z are not exactly the same because of the different factors involving the Weinberg angle in the vertices.

Example: Strength from Time

- Consider 3 decays

$$\Sigma^0(1192) \to \Lambda\gamma \quad Q = 74MeV \quad \tau = 10^{-19}\sec$$

$$\Sigma^+(1189) \to p\pi^0 \quad Q = 189MeV \quad \tau = 10^{-10}\sec$$

$$\Sigma^0(1385) \to \Lambda\pi^0 \quad Q = 208MeV \quad \tau = 10^{-23}\sec$$

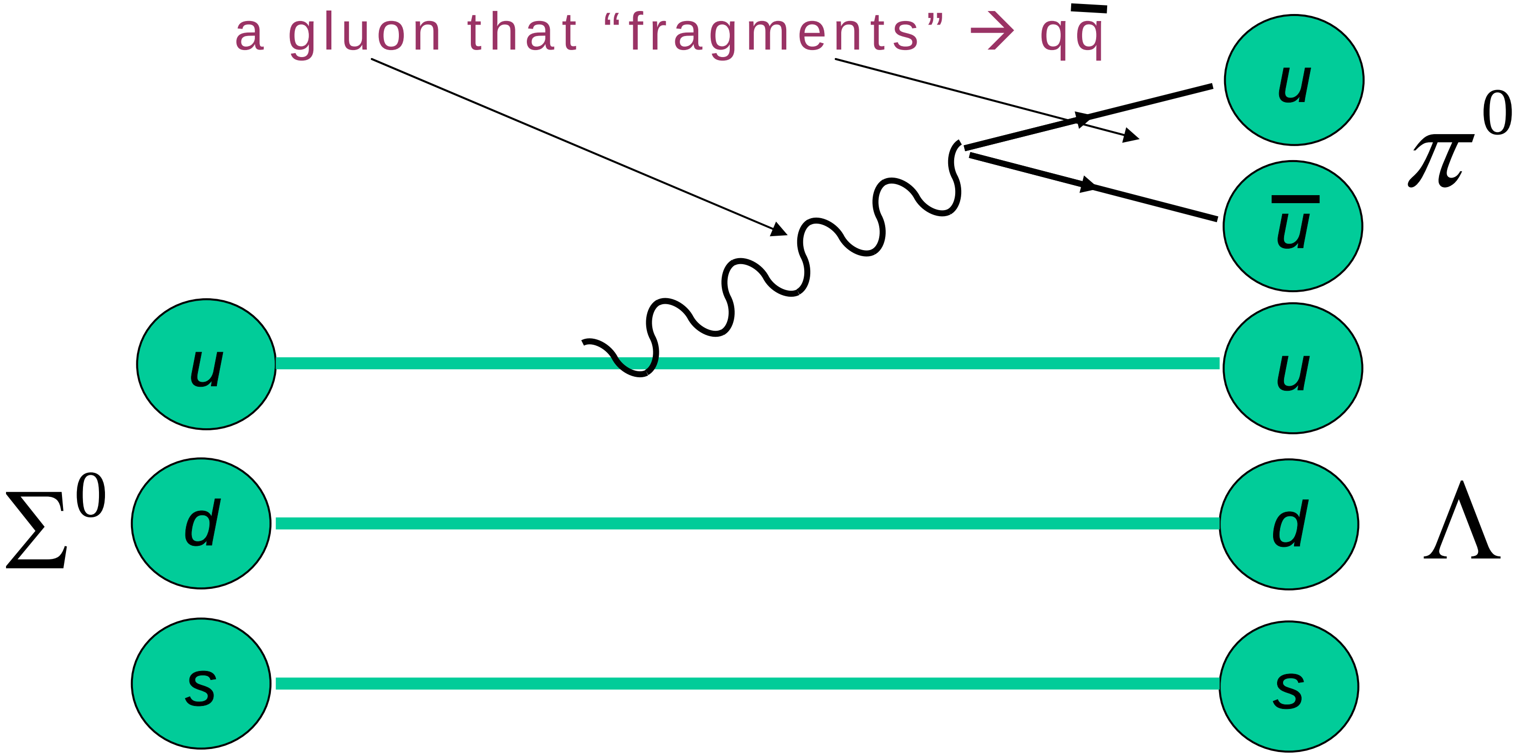
Both Σ^0 have the same quarks (uds) and similar Q values (liberated kinetic energy)

Why the drastically different lifetimes??

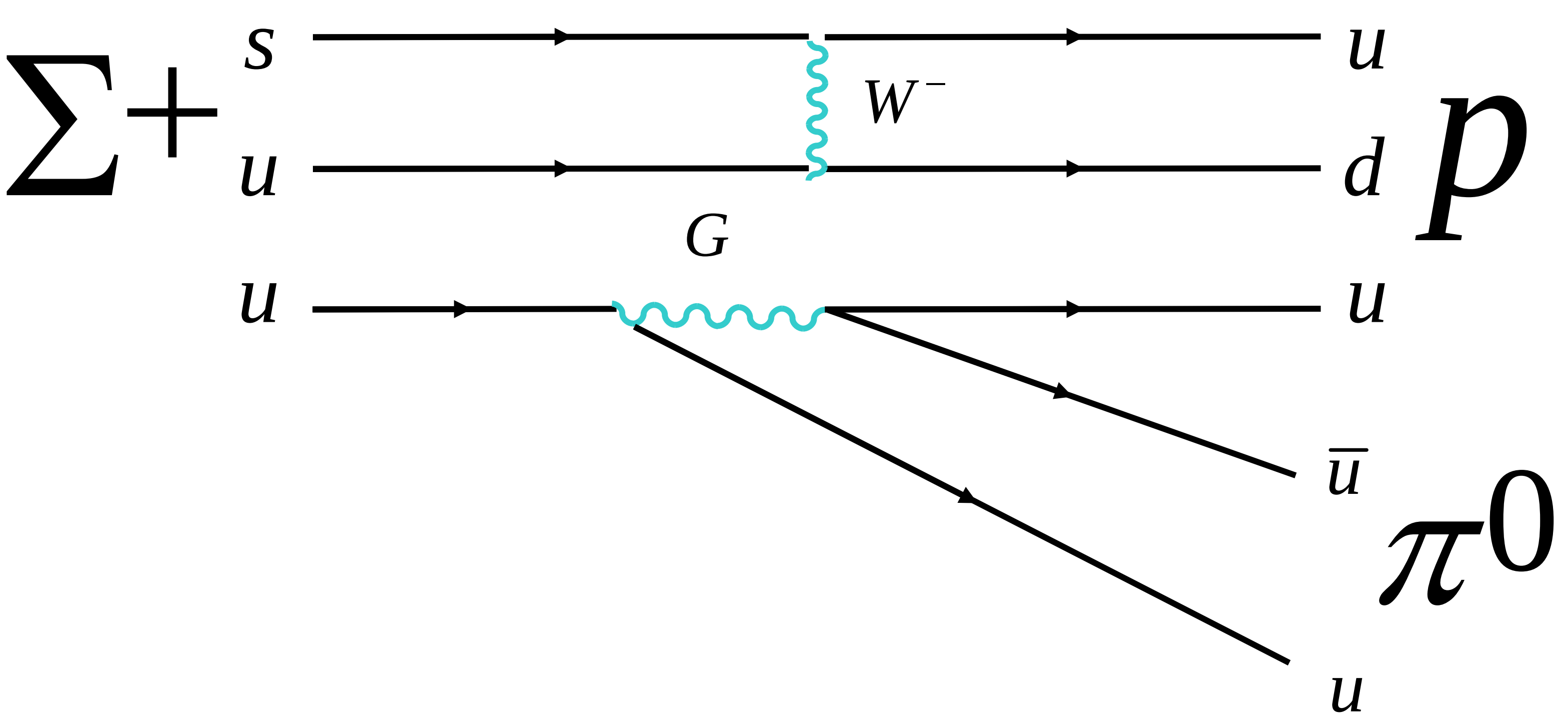
Back to our example: Strong Decays

The basic idea is that

- Initial and final states are “color neutral”
  - Only $Q\bar{Q}$ mesons, and QQQ baryons
- Strong interaction conserves flavor
  - Quark lines can emit quark-antiquark pairs by radiating a gluon that “fragments” → $q\bar{q}$



A Hybrid Example: Weak interaction is involved – long lifetime

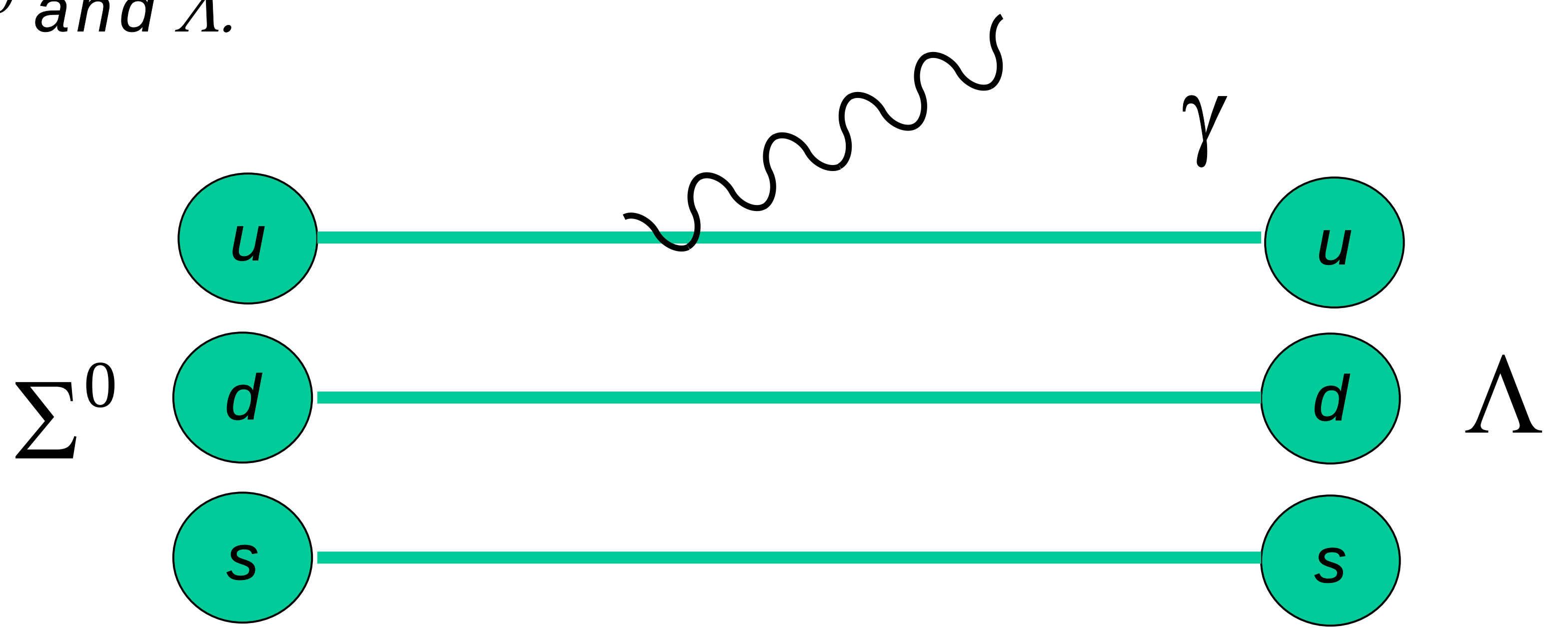


This decay is much slower ($\tau \sim 10^{-10}$ s) than for Σ^0.

Coming back to our example:

This decay can occur because the spectator quarks can exchange gluons such that the overall momentum Is conserved .

Strong decay : Σ^0 (1192) –> $\pi^0 + \Lambda$ is impossible because the mass of Σ^0 is less than the summed masses of π^0 and Λ.



More examples:

- Consider the charged and neutral pions: belong to a strong isospin triplet, but very different lifetimes

$$\pi^{+/-} : \tau \sim 10^{-8} \sec \qquad \text{weak}$$

$$\pi^{0} : \tau \sim 10^{-16} \sec \qquad \text{EM}$$

- Also consider the branching ratios for the different decay modes of π^0: the decay with gets smaller proportionally to the added factors of α at every additional decay vertex

Summary

- Today we reviewed:
  - Quark and lepton quantum numbers
  - Conservation Laws
  - Fermi's golden rule for decays
  - Coupling strength
  - Relation between lifetime and coupling