MODULE-5

- Introduction to Elementary Particles
- Discovery and properties of Elementary Particles
- Baryon octet and decuplet and Meson octet
- Conservation laws

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PARTICLE PHYSICS(L1&L2)

1. What are we made up of ?
2. What are Elementary particles?
3. Why are they called so?
4. How are they produced?
5. How are they identified?
6. Do they all have masses?
7. How do they acquire their masses?
8. How do they interact with each other?
9. What are the Fundamental interactions of the nature?
10. What underlying theory governs their interaction?

Macroscopic Objects

↓

Molecules

↓

Atoms

↓

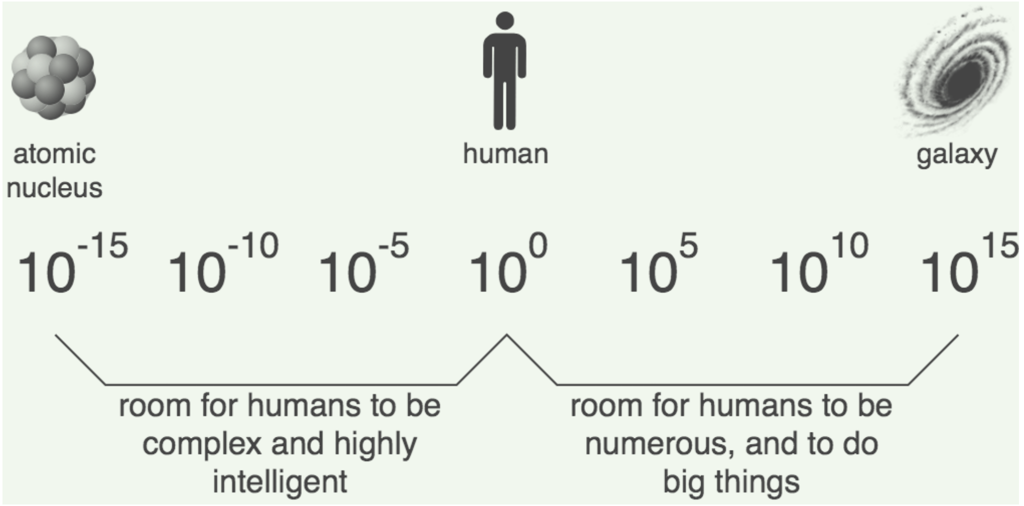
Nucleus + Electrons

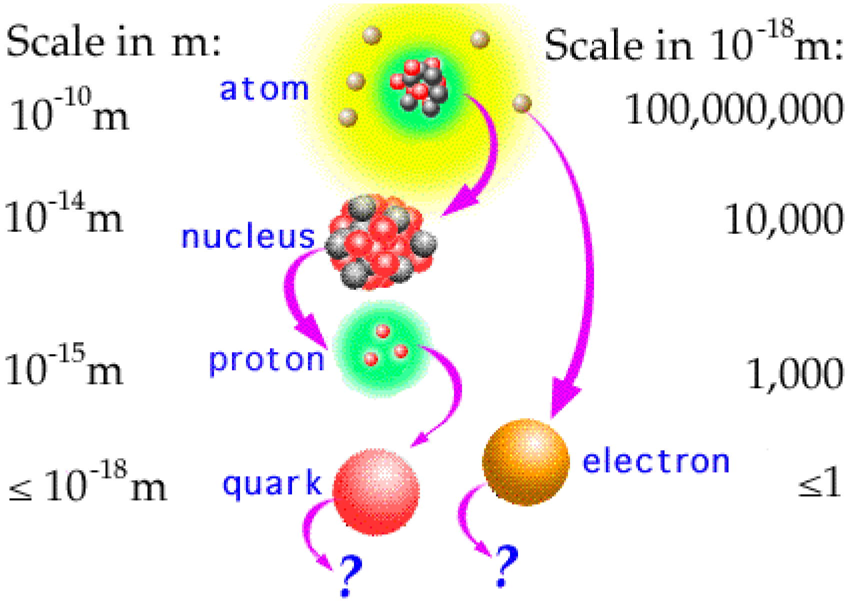
↓

Protons & Neutrons

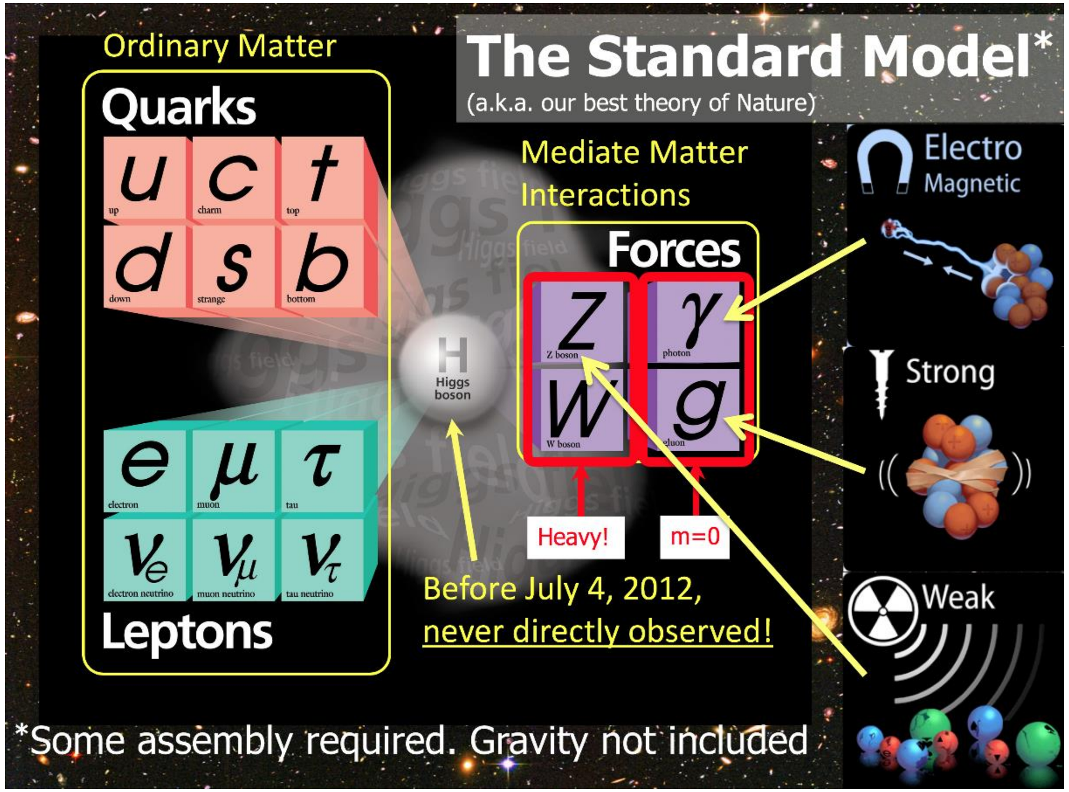
↓

Quarks

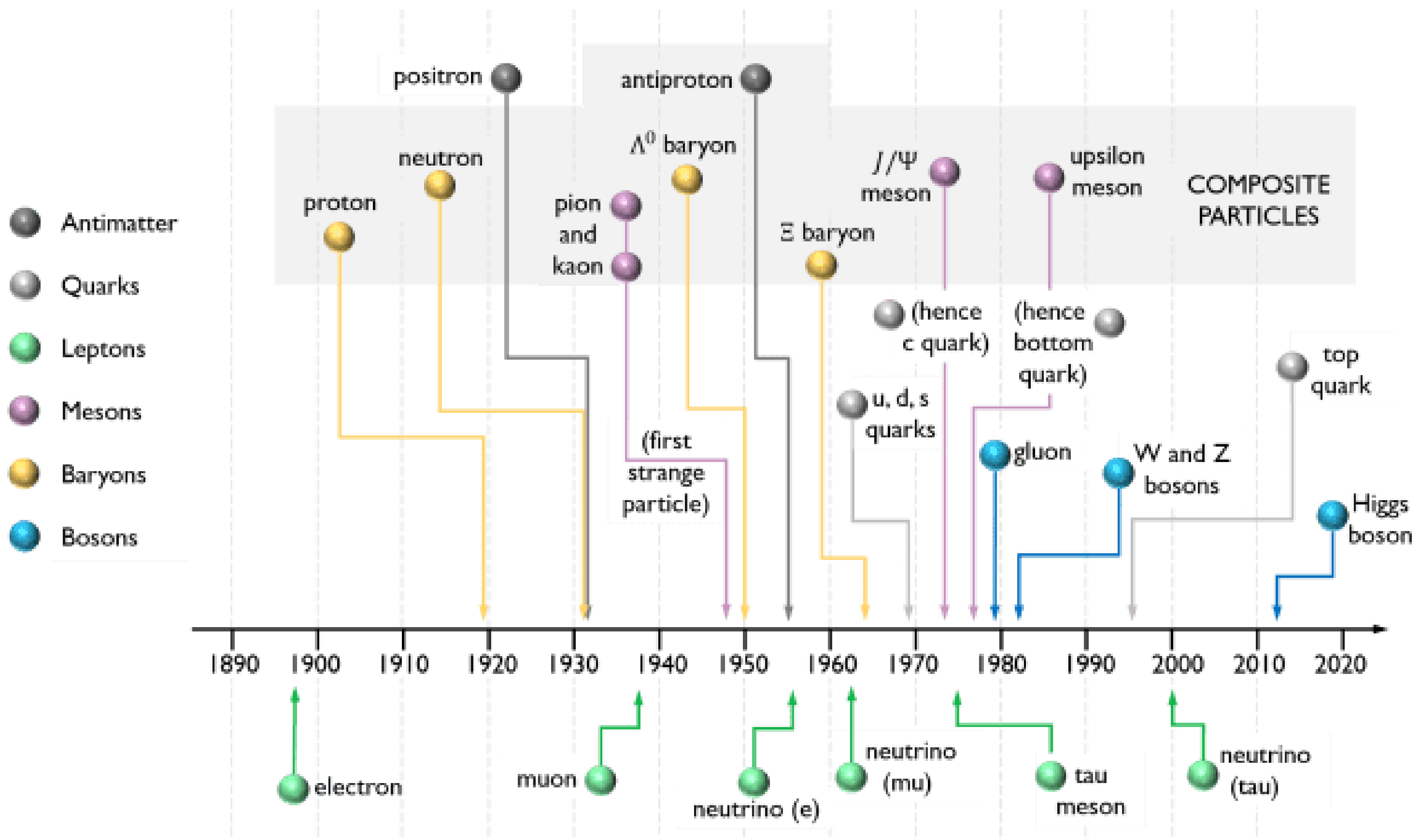




Elementary particles are the building block of our universe.



- Electrons are considered to be elementary particles as they can not further be broken up.
- Protons and neutrons known as nucleons are found to be made up of quarks which are considered as EPs.



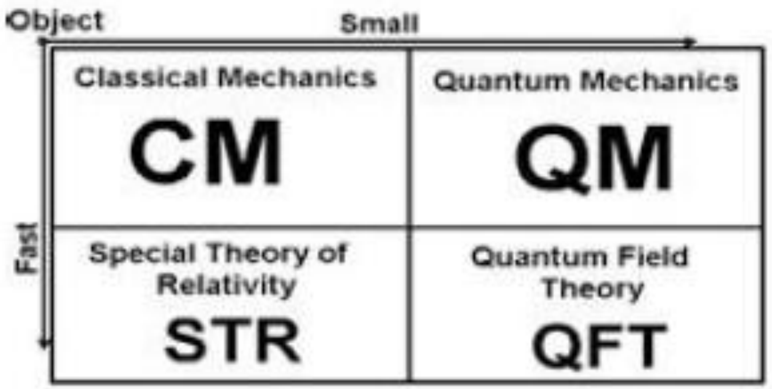
Antimatter
Quarks
Leptons
Mesons
Baryons
Bosons
positron
antiproton
proton
neutron
pion
and
kaon
Λ^0 baryon
Ξ baryon
J/Ψ
meson
upsilon
meson
COMPOSITE
PARTICLES
(hence
c quark)
(hence
bottom
quark)
(first
strange
particle)
u, d, s
quarks
top
quark
gluon
W and Z
bosons
Higgs
boson
1890
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
2020
electron
muon
neutrino (e)
neutrino
(mu)
tau
meson
neutrino
(tau)

High Energy Particle Physics:

Why??

de'Broglie wave length : $\lambda = \frac{h}{\sqrt{2mE}}$

In order to probe smaller dimension, λ has to be smaller, hence E should be larger, i.e., the high energy is required. High Energy Particle Physics



Quantum Field Theory (QFT) describes the interaction among elementary particles. It is union of STR with QM.

Standard Model of Particle Physics unifies EM theory with Weak Interactions. Hence called Electroweak theory.

Grand Unified Theory (GUT) is the framework in which Strong, Weak and EM interactions unify. The energy scale is $M_{Gut} = 10^{16}\ GeV$.

Planck Scale is defined as $M_{Pl} = 10^{19}\ GeV$ where Gravitation unified with other three interactions.

String Theory unified all four Fundamental Interactions namely, Gravitational, Weak, Strong and EM in a very elegant way. Dimension: $(9 + 1)$

At each point extra dimensions are compactified.

Each mode of vibration of the string corresponds to an elementary particle.

In STR mass and energy are equivalent to each other. Each mode of vibration corresponds to a particle.

EM Interaction : Charge

Strong Interaction : Color

Suppose a particle is made up of uuu. According to Pauli's exclusion principle it is not possible. If color quantum numbers are introduced ($R - B - G$) (Not as usual colors!!!), one can evade the problem of Pauli's exclusion principle. $u_R u_B u_G$ state is manifestly color singlet or *'colorless'*.

uuu √

$\bar{u}u$ √

$uuuu$ ×

$\bar{u}u\bar{u}u$ √

$uuuu\bar{u}$ √

How large is 1 TeV amount of energy?

$1\ TeV = 10^{12}\ eV = 1.6 \times 10^{-19} \times 10^{12}\ Joule$

$Mgh = 0.1 \times 10 \times h = 1.6 \times 10^{-19} \times 10^{12}$ (Assume a mass of 0.1 Kg)

$h = 1.6 \times 10^{-7} m$

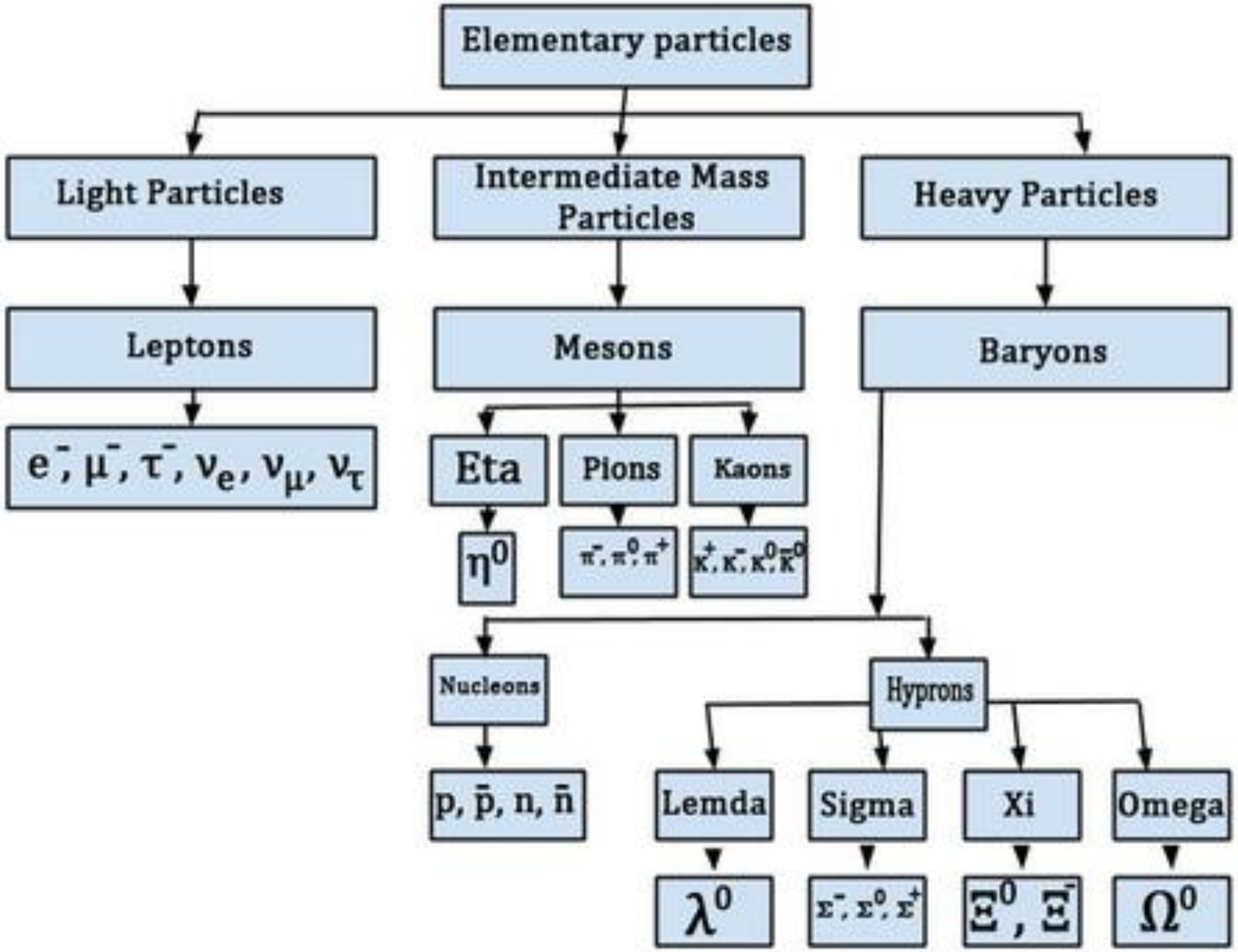
Quarks:

- Quarks are fractionally charged particles
- Spin ½ fermions obeying FD statistics
- Do not exist in free state.
- Interact via gluons as SI exchange particle.
- Can form bound states like baryons or mesons
- Have baryon number 1/3

Three Families of Quarks

	Generations Increasing mass		
	I	**II**	**III**
Charge = **-1/3**	**d** (down)	**s** (strange)	**b** (bottom)
Charge = **+2/3**	**u** (up)	**c** (charm)	**t** (top)

Also, each quark has a corresponding antiquark.
The **antiquarks** have **opposite charge** to the quarks


Elementary particles
Light Particles
Intermediate Mass Particles
Heavy Particles
Leptons
Mesons
Baryons
$e^-, \mu^-, \tau^-, \nu_e, \nu_\mu, \nu_\tau$
Eta
Pions
Kaons
η^0
π^-, π^0, π^+
$K^+, K^-, K^0, \bar{K}^0$
Nucleons
Hyprons
$p, \bar{p}, n, \bar{n}$
Lemda
Sigma
Xi
Omega
λ^0
$\Sigma^-, \Sigma^0, \Sigma^+$
Ξ^0, Ξ^-
Ω^0

Hadrons (heavy) are made up of quarks.

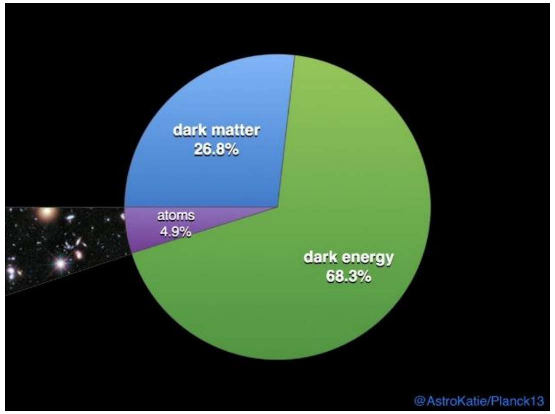
Baryons are bound state of three quarks. Fermions

Mesons (mid-weight) are bound states of quark-antiquark pairs. Scalars/vector bosons

Leptons are light particles like e, μ, τ etc. Neutrinos are leptons which have tiny masses although SM does not allow them to be massive. Fermions

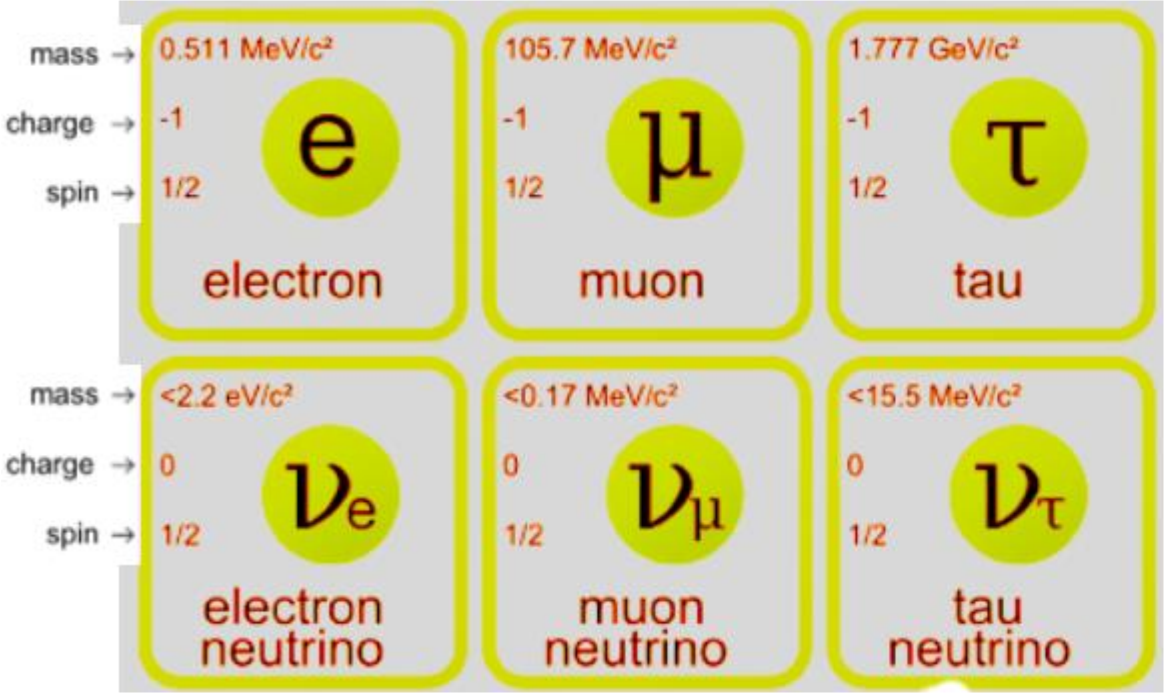
Lightest Baryon is Proton which is stable because if Baryon number is violated, proton would have decayed and consequently stable structure formation would not have been possible. The estimated lifetime of proton is greater than the age of the universe (10^{32} $years$).

Only about 4% of the universe is made ordinary matter. About 27% is made of Dark Matter which does not sense EM interactions. Rest are Dark Energy having negative pressure.



Leptons:

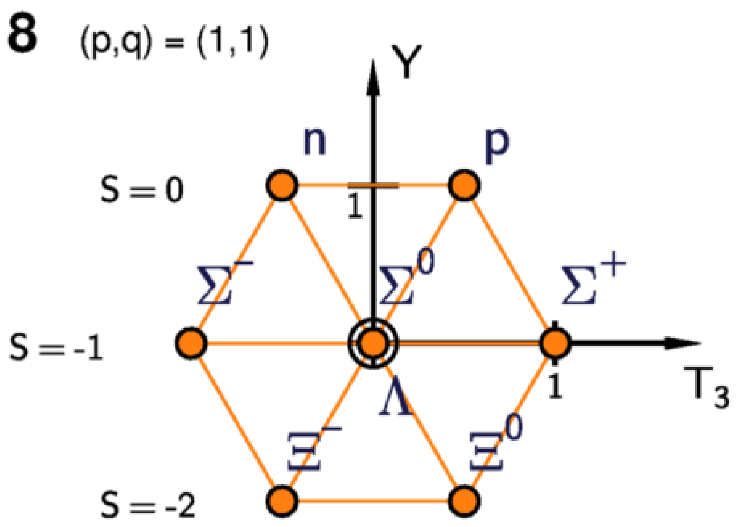
- They are light spin ½ particles
- Obeys FD statistics
- There exists three families of leptons namely $e - \mu - \tau$
- Can be charged (e, μ, τ) or neutral $(\nu_e\ , \nu_\mu, \nu_\tau)$
- They all have their antiparticles called antileptons.
- Can sense EMI and WI but does not sense SI.
- In SM neutrinos are assumed massless.
- Neutrinos have tiny masses – experimentally verified.

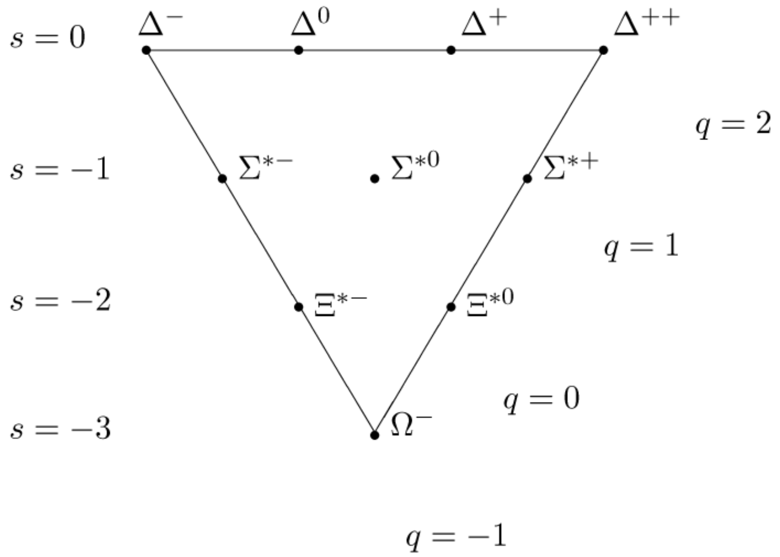


- Lepton number is conserved in all interactions.
- Lepton number for leptons is 1 but that for antileptons is -1.
- There are 6-leptons and 6-antileptons.
- For electron type leptons $L_e = +1$ for e^- and ν_e; $L_e = -1$ for e^+ and $\overline{\nu_e}$ but zero for other leptons.

Baryons:

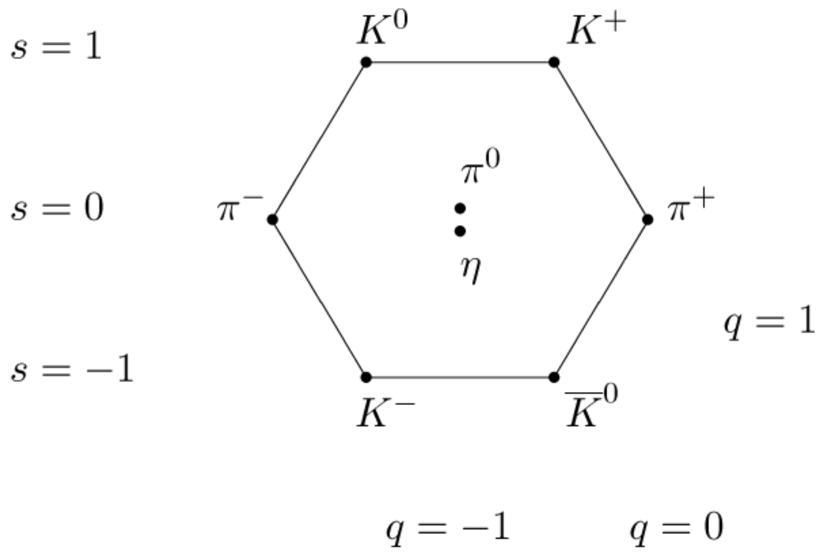
- Bound state of three quarks
- Constituent quarks are u, d, s
- Obeys FD statistics
- Spin ½ or 3/2 fermions
- Can take part in SI in addition to EMI and WI
- Color hypothesis was introduced to make the theory consistent with Pauli's Exclusion Principle.
- Proton is the lightest baryon.
- Baryons have baryon number +1 and -1 for the antibaryons.
- Baryon number is conserved in all interactions .
- There are 27 baryons.





Mesons:

- Middle weight hadrons
- Constituents quarks are u, d, s
- Made up of quark-antiquark pairs
- Can take part in EMI, SI and WI
- Scalar or Vector bosons
- Mesons have baryon number as well as lepton number to be zero.



How do we produce Elementary Particles?

Electrons and Protons are stable constituents of ordinary matter and they can easily be produced.

Electrons: Heating up a piece of metal produces electrons and by placing a positively charged plate nearby, to attract them over, and cuts a small hole in it; the electrons coming out of the hole form a beam of electrons. Such an electron gun is used in television tube, oscilloscope and electron accelerator.

Protons: Ionizing H-atom by stripping off the outer shell electron would result in protons only. A tank of hydrogen is essentially a tank of protons as the energetic particle incident on the proton targets easily knock out the outer electron.

For more ***exotic particles*** there are three main sources.

- Cosmic Rays: The earth is constantly bombarded with high-energy particles (mostly protons) coming from outer space. When they hit atoms in the upper atmosphere they produce showers of secondary particles (mostly muons).

  Advantages: 1. Free particles

  2. High energy particles

  Disadvantages: 1. The rate at which they strike any detector of reasonable size is low.

  2. Uncontrollable

Patience and Luck!!!

- Nuclear Reactors: When a radioactive nucleus disintegrates, it may emit a variety of particles – neutrons, neutrinos, $\alpha -$ rays, $\beta -$ rays and $\gamma -$ rays.
- Particle Accelerators:

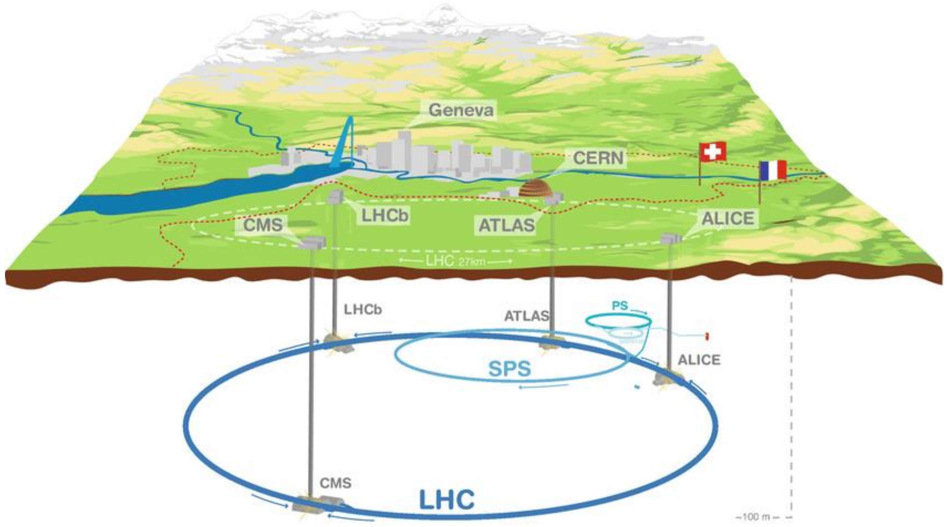
1. In accelerators, electrons, protons are accelerated to high energy, and smash them into a target.
2. Magnets etc. are placed to collect newly produced particles.
3. Intense beams of positrons, muons, pions, antiprotons are produced in accelerators.
4. The stable particles – electrons, protons, positrons and antiprotons are further fed into giant storage rings.
5. They are made to circulate at high speed for hours at a time.

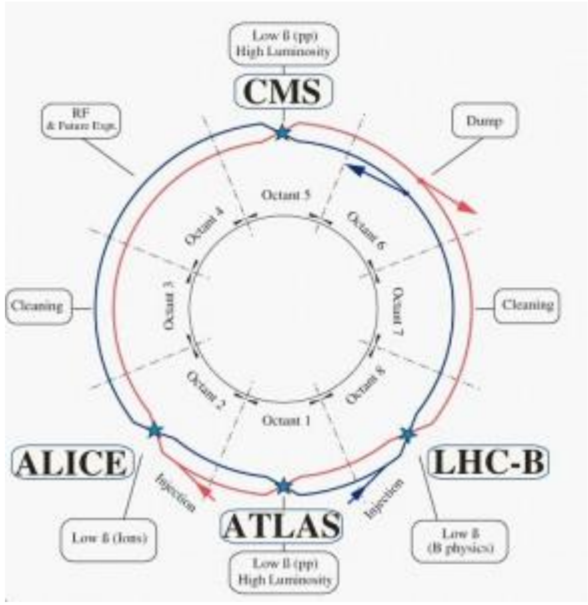
High energy collisions are required:

a) For the discovery of heavier particles (so far top quark! 173 GeV)

b) To study interaction at very short range. According to de Broglie formula ($\lambda = \frac{h}{\sqrt{2mE}}$) at large wavelength one can resolve relatively large structures. In order to explore small dimension, comparably short wavelength is needed, hence high momenta.

Large Hadron Collider: (Biggest Experiment on our Planet!!)

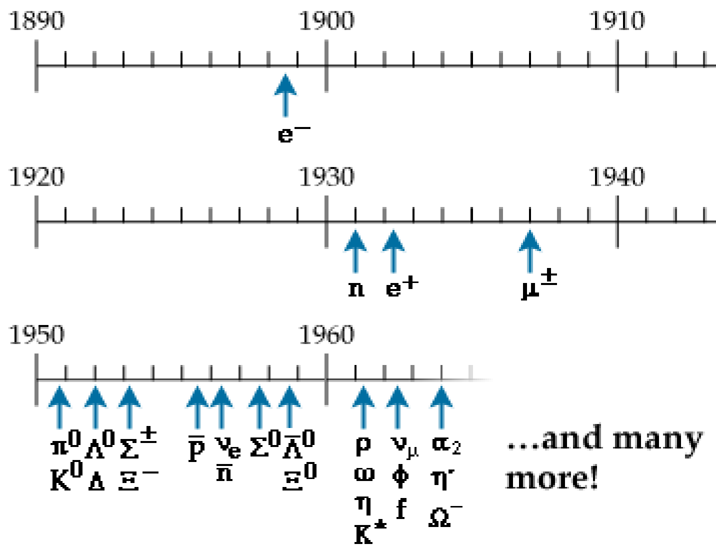


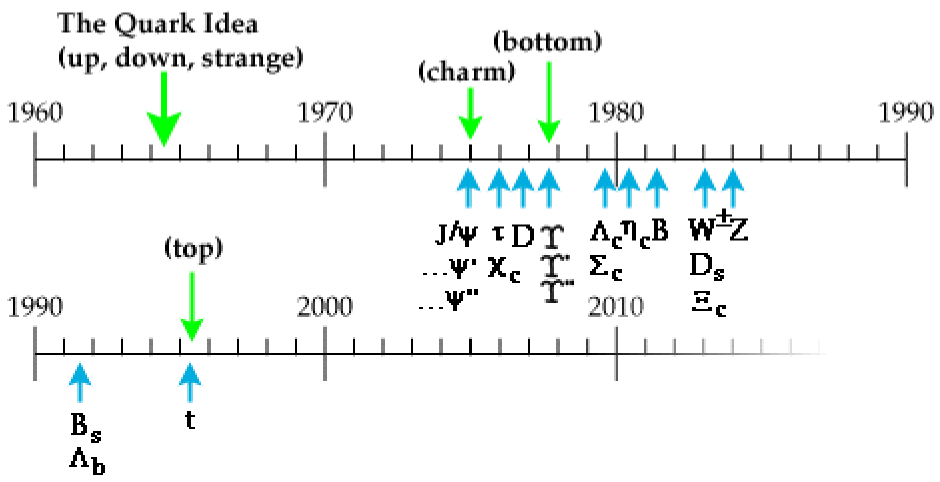


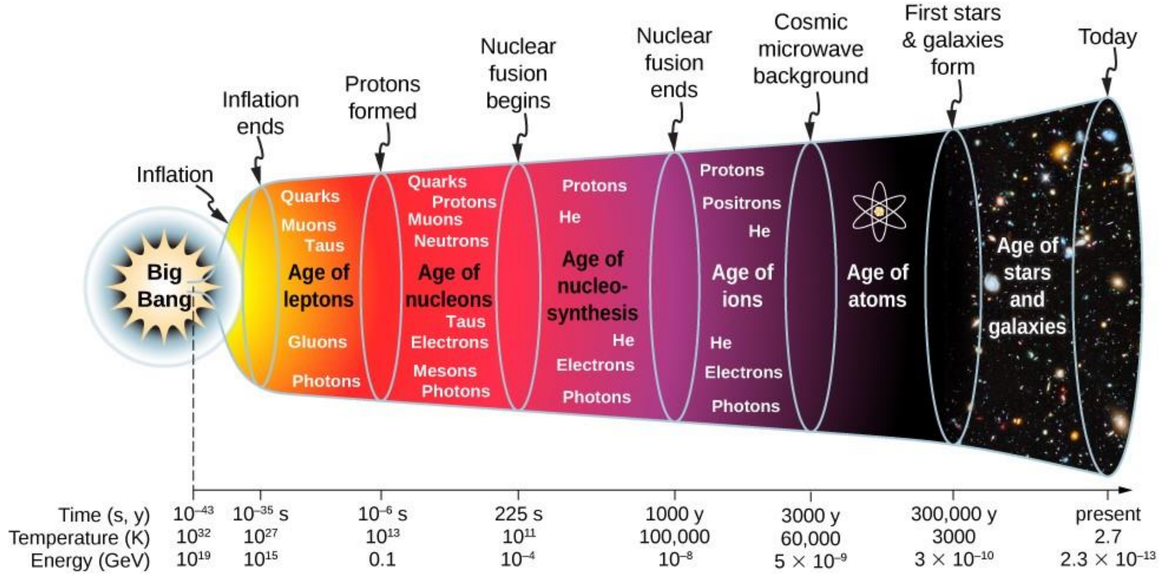
How do we detect Elementary particles?

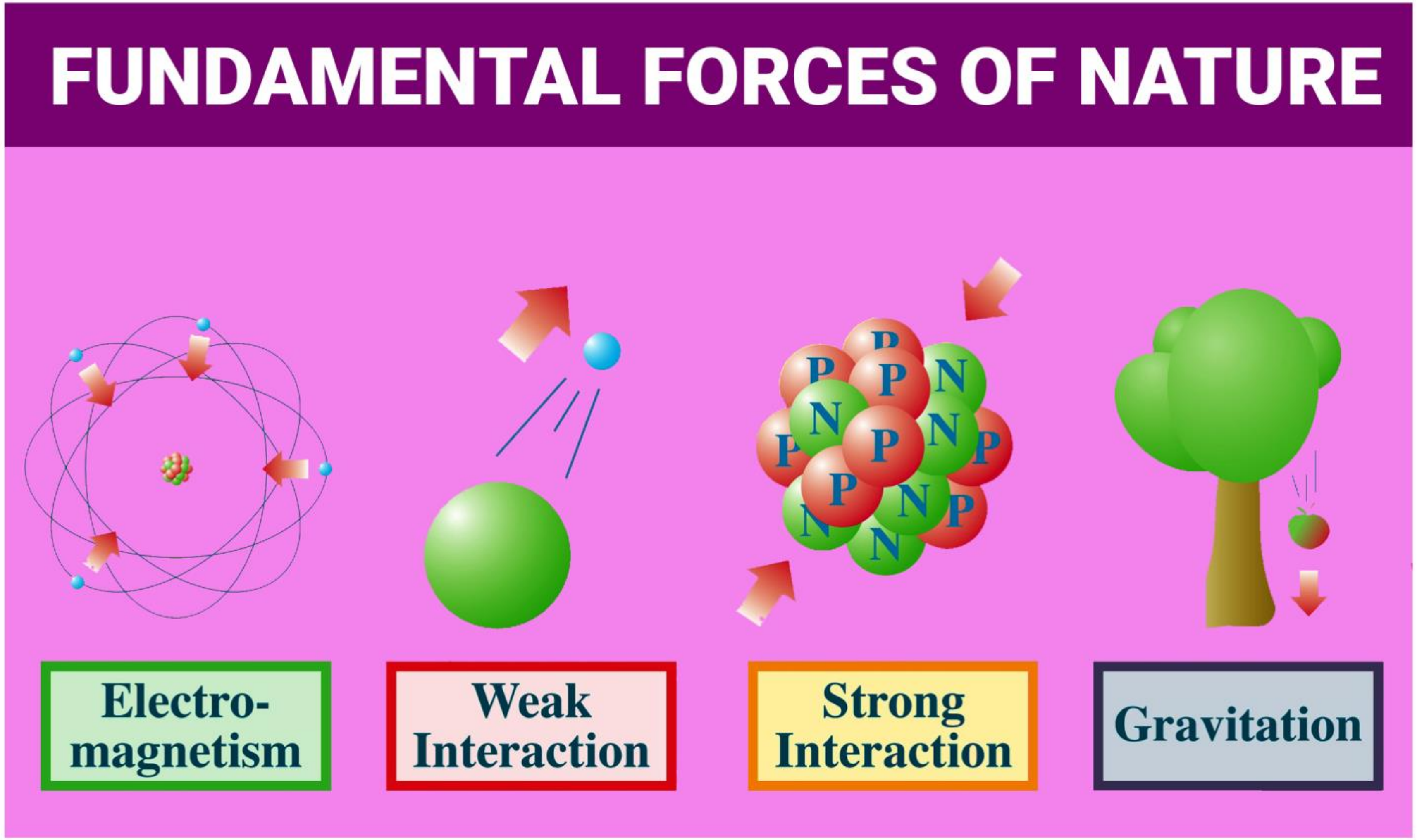
- Depending upon mass, spin, charge etc. elementary particles can be detected.
- Bubble Chambers, GM counters, Cloud Chamber, Photomultiplier tube, Scintillator detectors, Chrenkov counters, Solid state detectors etc.
- In modern detectors combination of all types of detectors are used and the whole set up is wired up to a computer that tracks the particles and displays the trajectories on the television screen.
- When high-energy charged particles pass through matter they ionize atoms of the target along their path. These ions act as ***seeds*** in the formation of *droplets* in Bubble chambers, *bubbles* in Bubble chambers and *sparks* in Spark Chambers as the case may be.
- Neutral particles do not leave any tracks. Their paths are reconstructed by analyzing the tracks of the charged particles in the picture and invoking conservation of energy and momentum in each vertex.
- Deflection of charged particles in magnetic fields determine the sign of charges of those particles.

Timeline of Discovery of Elementary particles








FUNDAMENTAL FORCES OF NATURE
Electro-magnetism
Weak Interaction
Strong Interaction
Gravitation

PARTICLE PHYSICS(L3,L4)

Photon:

- Discovery of Photon ????
- Planck (1900) : Blackbody Radiation

  => Untraviolet Catastrophe

  => EM radiation is *quantized* $(E = h\nu)$

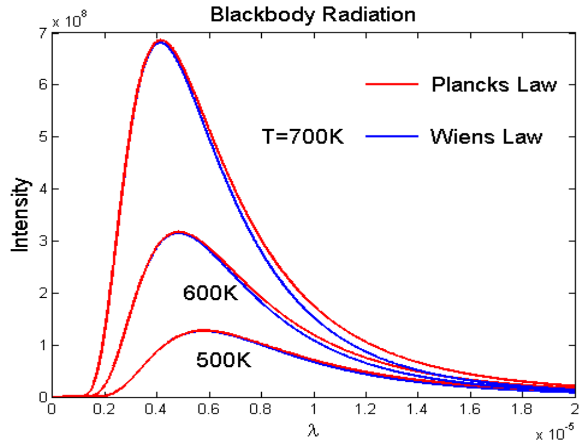
  => *Emission Mechanism*
- Einstein (1905) : Photoelectric effect

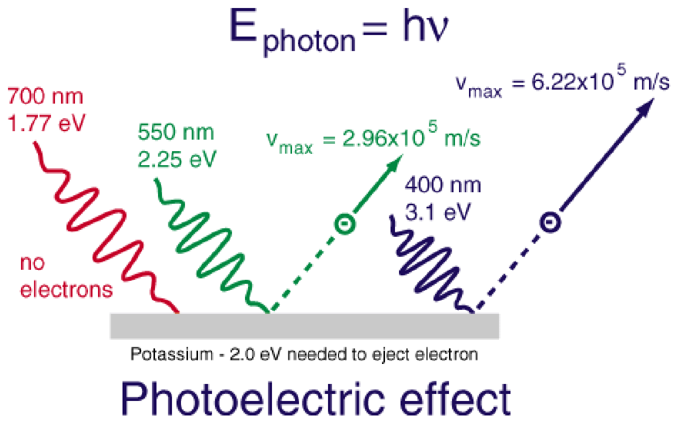
  => Nothing to do with emission mechanism rather quantization was a feature of electromagnetic field itself.
- Einstein's idea of photons reconcile with the Newton's idea of corpuscular nature of light.
- Compton's Effect (1923) :

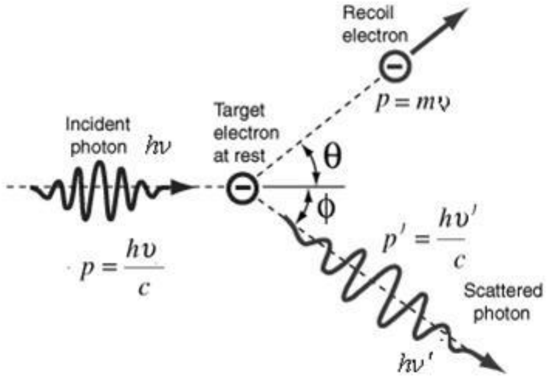
  => Elastic Collision between light wave and target electron

  => Light behaves like particles

  => Photons







- Quantum Field Theory (QFT) : EM Interactions => Photons
- In classical EM theory, repulsion between two electrons which produce electric field and each of them responds to the produced field.
- But in QFT, the electric field is quantized (photons) => Interaction may be viewed as exchange of stream of photons between the two charges => Action at a distance mediated by a field => mediated by an exchange of particles (the quanta of the field)=> Photon
- Binding force => Exchange of photons between the electrons and the protons in the nucleus => Atomic Physics => quantization of em field => produces minute effects = > Lamb shift and anomalous magnetic moment of the electron.
- Coulomb’s law gives approximately correct results => For any bound state numerous photons are continually streaming back and forth => “lumpiness” of the field is effectively smoothed out => Quantization effect may be ignored.
- Elementary particle processes like Photoelectric effect, Compton effect, individual photons take part in the interactions => Quantization of the field can no longer be neglected.

Mesons (1934-1947)

- What holds the nucleus together?
- Positively charged protons must repel each other but tightly bound in a very tiny region => Some other force must exist => Strong Force (Stronger than the Coulomb repulsion)
- Why can't we notice it in everyday life?
- Short range force => Size of the nucleus
- However, Gravitational and Electromagnetic forces are of infinite range.
- Yukawa's theory of meson exchange between nucleons inside the nucleus => Quantum of strong field => Massive because of short range nature => Calculation shows , it is 300 times mass of electron or about 1/6th of proton mass => lies in between electron mass ("light weight" – Lepton) and proton mass ("heavy weight" –Baryon) => "middle weight" => Meson
- The Yukawa's theory was not accepted due to lack of experimental observations.

According to Heisenberg Uncertainty principle one can borrow an energy ΔE provided he should pay it back in time Δt . $\Delta E = mc^2$ and the nuclear dimension being r_0 and it travel with speed comparable to c , we have

$$\Delta t = \frac{r_0}{c} \quad => \quad \Delta E\ \Delta t \approx \hbar => mc^2 = \frac{\hbar c}{r_0} \approx 160\ \text{MeV}$$

- Cosmic ray experiments (1937) indicated the existence of Yukawa's hypothetical particle => More systematic studies revealed that the mass of the particle was much less than that predicted by Yukawa and the lifetime to be wrong.
- Cosmic ray particles interact very weakly with atomic nuclei => Powell (1937) showed that those two particles were middle weight => Pion and Muon => Yukawa mesons were copiously produced in the upper atmosphere => disintegrates long before reaching the ground => One of the decay products is the lighter one (Muon : long-lived) observed at the sea level (mu-meson at that time later identified as heavier version of electron belonging to lepton family) ($\pi^- \rightarrow \mu^- + \nu$)
- Photographic emulsion plates exposed to cosmic rays at high altitudes were used to identify muons.

Antiparticles (1930-1956):

- Positron (e^+) Anderson (1931)
- Feynman-Stuckelberg formulation => negative-energy solutions are reexpressed as positive energy states of different particle : Antiparticle (positron)
- $\bar{p}, \bar{n}, \mu^+$ etc are antiparticles => purely convension
- Some neutral particles are their own antiparticles. Photon: $\gamma = \bar{\gamma}$
- Neutron is different from antineutron though both are neutral!! Baryon number is different for them. Charge structure and magnetic moments are different.

Crossing Symmetry:

$$A + B \to C + D$$

$$A \to \bar{B} + C + D$$

$$A + \bar{C} = \bar{B} + D$$

$$\bar{C} + \bar{D} = \bar{A} + \bar{B}$$

The above reactions are possible if they are kinematically allowed.

- Compton scattering ($\gamma + e^- \to \gamma + e^-$) and Pair annihilation ($e^- + e^+ \to \gamma + \gamma$) are related by crossing symmetry but describe completely different phenomena.
- Matter and antimatter can not coexist for long time. When particles meet antiparticle, they annihilate.
- Astronomical evidences established the fact that our universe is matter dominated. Why is our universe matter dominated? *UNANSWERED*

Neutrinos: (1930-1962)

Radiactive beta decay: $A \to B + e^{-}$ (Remember in 1930 Neutron was not discovered!!)

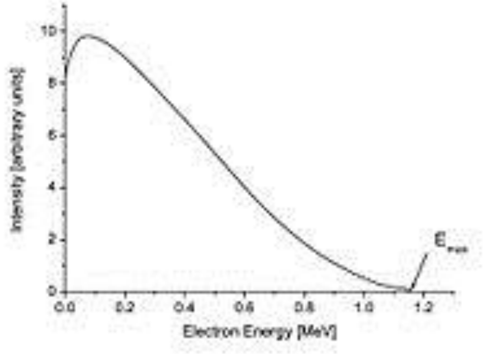
A, B are parent and daughter nuclei respectively.

Energy conservation suggests that the electron energy is (in the rest frame of A) $E = \left(\frac{m_A^2 - m_B^2 + m_e^2}{2m_A}\right) c^2$

Energy of electron should be fixed if the masses of particles are fixed.

Experiments showed that the energy of electron varies and the above expression for energy is satisfied only for maximum electron energy.

Pauli suggested the existence of a new spin ½ neutral massless particle known as *Neutron*



In 1932 Chadwick discovered neutron. In the following year

Fermi proposed the theory of beta-decay taking into account Pauli's suggestion. Fermi named the particle *Neutrino* $n \to p + e^{-} + \bar{\nu}$

Powell's picture of decay of pions showed that muons were emitted at 90° wrt the pion direction. It indicates that another particle was produced, which was neutral and massless leaving no footprints. ($\pi \to \mu + \nu$)

Muon-decay : $\mu \to e + 2\nu$

How do we know that there are two neutrinos?

Measure the energy of electrons, if it varies => there must be at least three particles => By 1949 it was sure that energy of electrons coming from muon decays were not fixed instead it varies +> Emission of neutrinos was the accepted explanation

Detection of neutrinos was a very difficult task as they interacted very weakly with matter. Theoretical evidence was already established.

1954: Cowan-Reines experiment :

- A large tank of water was set up and watched the inverse beta decay reaction $\bar{\nu} + p \rightarrow n + e^{+}$
- At their detector the antineutrino flux was calculated to be 5×10^{13} particles per sq.cm per sec.
- From the detection of positrons the existence of neutrinos was confirmed.
- How could one know that neutrino and antineutrino are different?
- The crossed reaction $\nu + n \rightarrow p + e^{-}$ must occur. Davis and Harmer proved that this reaction did not occur => neutrino and antineutrino are different
- Proposed the law of conservation of lepton number => $L = +1$ for e^{-}, μ^{-}, ν and $L = -1$ for $e^{+}, \mu^{+}, \bar{\nu}$
- Hence, Cowan-Reines reaction is allowed but Davis reaction is forbidden.

In view of conservation of lepton number, the charged pion decays :

$\pi^+ \rightarrow \mu^+ + \nu$ $\quad \pi^+ \rightarrow \mu^+ + \nu_\mu$

$\pi^- \rightarrow \mu^- + \bar{\nu}$ $\quad \pi^- \rightarrow \mu^- + \bar{\nu}_\mu$

And the muon decays :

$\mu^+ \rightarrow e^+ + \nu + \bar{\nu}$ $\quad \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$

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

Lepton number (L) clearly distinguishes the neutrino ($L = +1$) from antineutrino($L = -1$). These numbers are experimentally determinable like electric charge.

Helicity (Projection of spin along the direction of momentum) can distinguish neutrinos from antineutrinos. Neutrinos are always left-handed and antineutrinos are right-handed. Remember, the reverse situation never occurs!!

Consider $\mu^- \rightarrow e^- + \gamma$ $(\times)$

According to above prescription of conservation of lepton number, this reaction should have been allowed. But it does not occur in nature. What new conservation law is to be invoked??

Assign flavor of lepton to each neutrino/antineutrino and enforce the conservation of lepton flavor number in stead of lepton number => L_e/L_μ in stead of L and for the antiparticles also.

Neutron beta decay: $n \rightarrow p + e^- + \gamma$

TABLE 1.1 THE LEPTON FAMILY, 1962–1976

	Lepton number	Electron number	Muon number
Leptons			
e^-	1	1	0
ν_e	1	1	0
μ^-	1	0	1
ν_μ	1	0	1
Antileptons			
e^+	−1	−1	0
$\bar{\nu}_e$	−1	−1	0
μ^+	−1	0	−1
$\bar{\nu}_\mu$	−1	0	−1

The first experimental test of the two-neutrino hypothesis and separate conservation of electron and muon number was conducted at Brookhavenin 1962. Using 10^{14} antineutrinos from π^- decay, the group identified 29 instances of the expected reaction : $\bar{\nu}_\mu + p \rightarrow \mu^+ + n$ but no cases of the forbidden process : $\bar{\nu}_\mu + p \rightarrow e^+ + n$.

With only one kind of neutrino the second reaction would have been as common as the other one is.

By 1962 the lepton family had grown to eight. 4 for particles and 4 for antiparticles.

Leptons do not take part in strong interactions.

Two types of neutrinos :

ν_e associated with electron ($\beta - decay$)

ν_μ associated with muon ($\pi \rightarrow \mu \;\; decay$)

Are these neutrinos different??

$\nu_e + n \rightarrow p + e^-$, $\bar{\nu}_e + p \rightarrow n + e^+$

$\nu_\mu + n \rightarrow p + \mu^-$, $\bar{\nu}_\mu + p \rightarrow n + \mu^+$

- In 1962 an experiment was carried out at Brookhaven.
- Proton beam of energy $> 20 \; GeV$ is bombarded on a target of protons to produce energetic pions and kaons.
- The secondary particles decayed into neutrinos along with other particles.
- A massive shielding block was used to absorb all particles except neutrinos.
- This resultant neutrino beam was used to bombard protons to produce muons or electrons.
- No electron event was confirmed , only muon events were detected.
- Proved that ν_e and ν_μ are different particles.

ν and $\bar{\nu}$ are different particles

- Cross-section for neutrinos in ^{37}Cl.

$$^{37}Ar + e^- \rightarrow {}^{37}Cl + \nu$$

- The reverse process can also occur

$$\nu + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$$

- If $\bar{\boldsymbol{\nu}}$ and ν are the same, the following process must occur

$$\overline{\nu_e} + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$$

- In an experiment by R. Davis and Collaborators placed 4000 liters of CCl_4 next to a nuclear reactor where $\bar{\boldsymbol{\nu}}$ were generated.
- Absorption of the antineutrinos by ^{37}Cl produced ^{37}Ar gas which is separated from CCl_4
- The measured cross-section was far less than the theoretical value $\sigma \approx 10^{-43} cm^2$ expected if $\bar{\nu}$ and ν were the same.

PARTICLE PHYSICS(L5)

Strange Particles (1947 -1960)

By 1947 it was thought that the job of elementary Particle Physics was essentially done.

- Rochester and Butler published a Cloud Chamber photograph in which Cosmic rays produce neutral particles whose presence is revealed when it decays into two charged secondaries. Detailed analysis showed that the charged particles were pi-mesons. $K^0 \to \pi^+ + \pi^-$
- In 1949 Powel published the photograph showing the decay of charged kaon $K^+ \to \pi^+ + \pi^- + \pi^+$
- K^0 was first known as θ^0 and K^+ as τ^+ . These two particles have same mass and almost same life span.
- Until the discovery of parity violations these two particles were thought to be the same particle.
- These particles were always produced via strong interactions with characteristic time of 10^{-23} sec but they decay via weak interactions with characteristic time of 10^{-10}sec.

$\pi^- + p \to K^+ + \Sigma^- \nrightarrow \pi^+ + \Sigma^-$

$\pi^- + p \to K^0 + \Sigma^0 \nrightarrow \pi^0 + \Lambda$

$\pi^- + p \to K^0 + \Lambda \nrightarrow K^0 + n$

- Here all K's carry strangeness $S = +1$, the Σ's and the Λ have $S = -1$ and the ordinary particles (π, n, p etc.) have $S = 0$
- Strange particles decay via Weak interactions where Strangeness is not conserved. $\Lambda \to p + \pi^-$; $\Sigma^+ \to p + \pi^0$

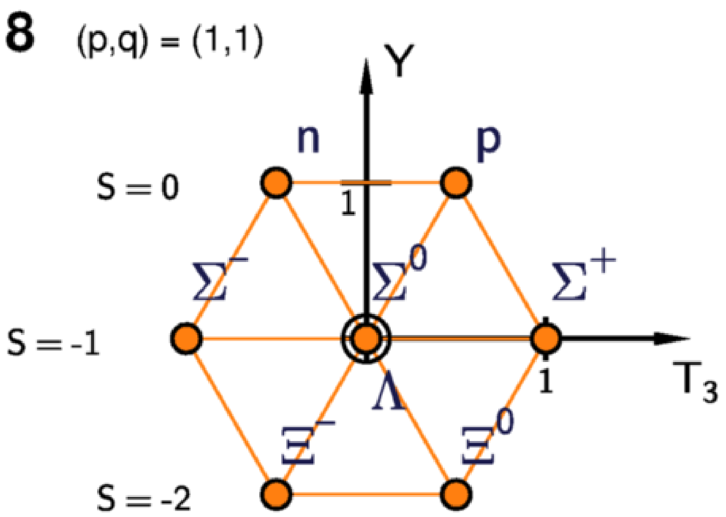
- Kaons behave like heavy pions (mesons) => Meson family gets extended => more mesons like η, ϕ, ω, ρ were discovered in due course.
- In 1950 another heavier one was discovered whose decay products were p and π . That new particle was Λ heavier than proton: $\Lambda \rightarrow p + \pi^-$. It belongs to Baryon family.
- Why proton does not decay into a positron and a photon? (1938) $p \rightarrow e^+ + \gamma$.

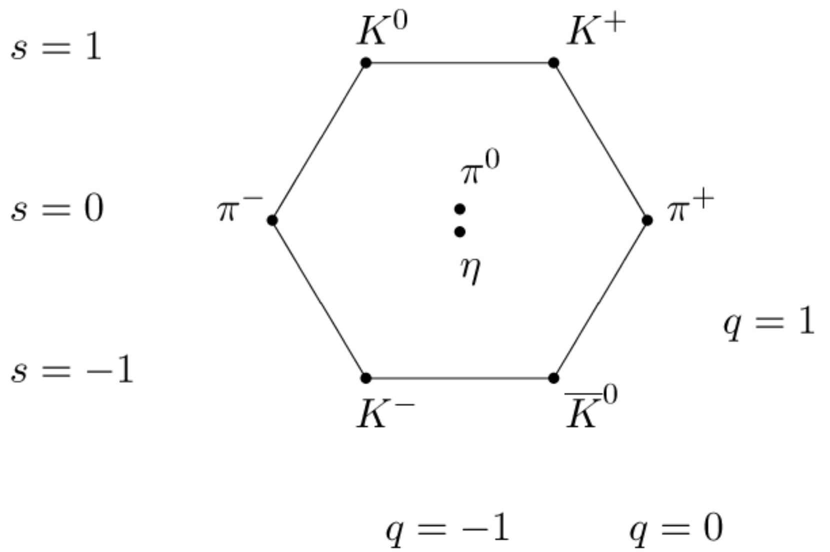
If it would happen, then, all atoms would have disintegrated!! Note that at that lepton number conservation was not known.

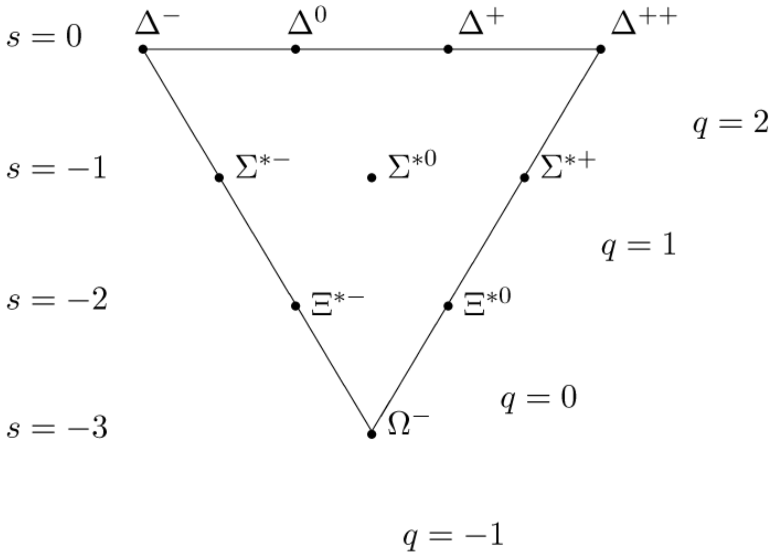
Stuckelberg proposed law of conservation of baryon number to account for stability of proton.

- Baryon number is not yet found to violate in any interaction occurring in nature.
- $p + p \rightarrow p + p + p + \bar{p}$ antiproton was discovered.
- 1952 onwards it was possible to produce Strange particles at laboratories (Brookhaven)
- By 1960 the garden of particle physics turned into a jungle and hadron physics could only explain this chaos.

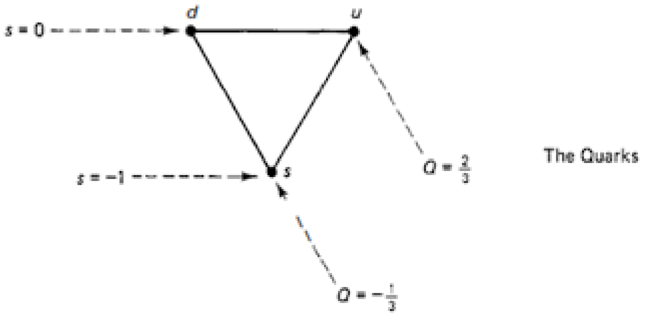
Eightfold Way

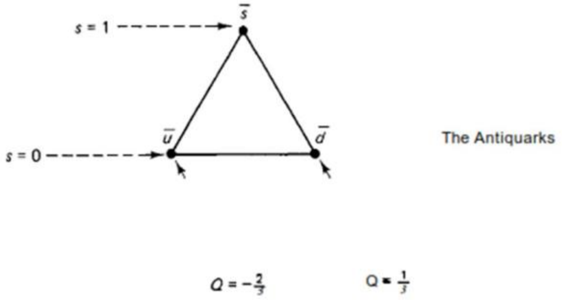






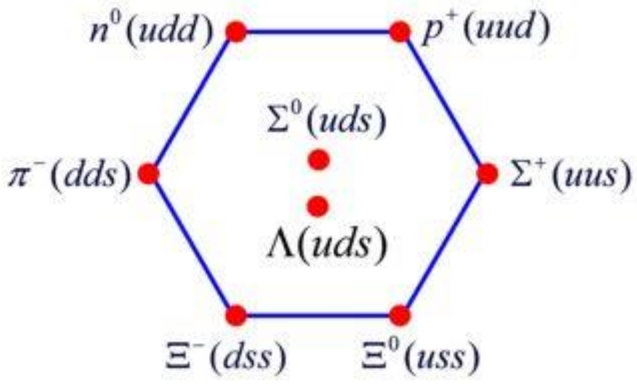
In 1964 the Quark Model was proposed with 3 quarks in hand namely, u, d, s.

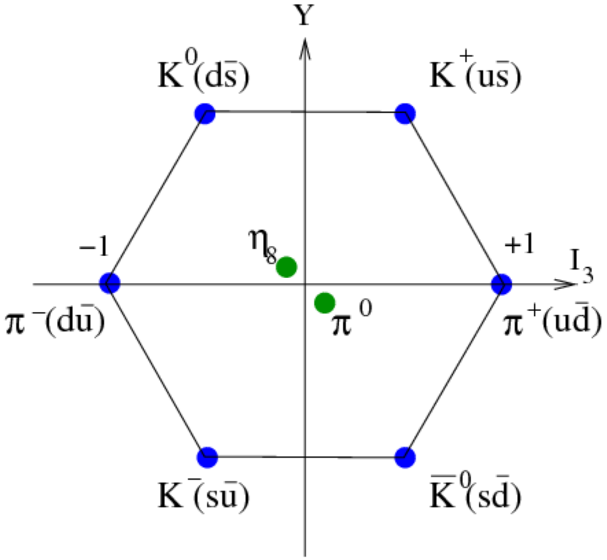


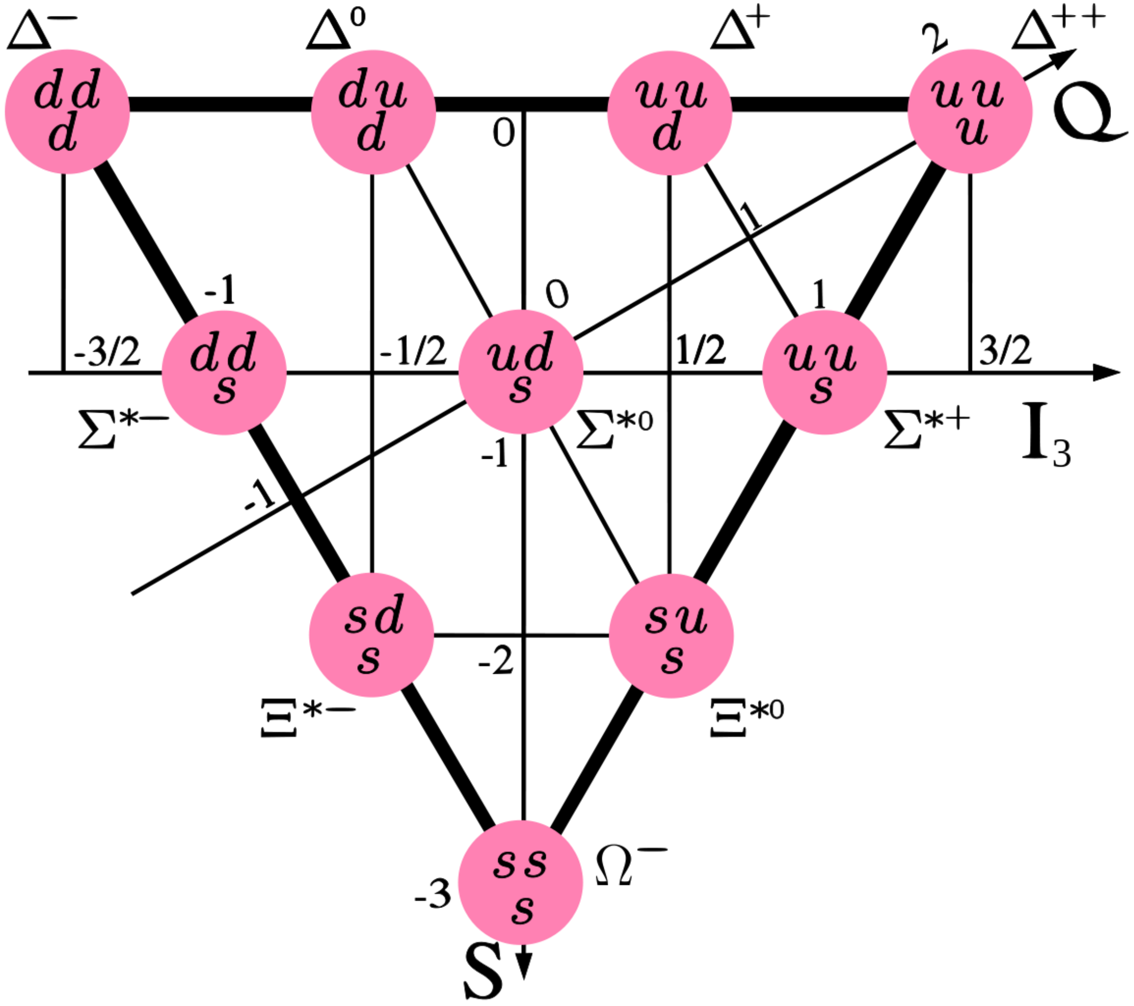


Assertions of Quark Model:

- Every baryon is composed of three quarks and every antibaryon is composed of three antiquarks
- Every meson is composed of a quark and an antiquark.







Δ⁻
Δ⁰
Δ⁺
Δ⁺⁺
ddd
dud
uud
uuu
Q
2
1
0
0
-1
1
-3/2
-1/2
1/2
3/2
dds
uds
uus
I3
Σ*−
Σ*0
Σ*+
-1
-1
sds
sus
-2
Ξ*−
Ξ*0
sss
-3
Ω⁻
S

- Free quarks do not exist in nature!
- Fractionally charged particles have not yet been discovered in laboratories.
- One of the quarks should be absolutely stable, but not a single one with fractional charge has been found out. Quarks are easy to produce, easy to identify, easy to store….
- Introduce the concept of Quark confinement theory which states that it is impossible to pull out one isolated quark from a bound state of baryons or mesons.
- Even if all quarks are stuck inside hadrons, this does not mean they are inaccessible to experimental study.
- Deep Inelastic scattering experiments indirectly proved the existence of quarks inside hadrons.(HEPP Course)
- One serious theoretical objection to Quarks model was Pauli's exclusion principle. (Δ^{++}) (uuu)
- Color concept was introduced. Red, Blue, Green …Nothing to do with ordinary color!!!
- All naturally occurring particles are colorless.
- Why don't we make abound state with two or four quarks??

1974-1983…

- 1964-1974 was barren time for elementary particle physics. The quark model was in back seat and nothing was fruitful.
- Parton model was established from DIS experiments and the coinage of Quarks was not fashionable at that time.
- Quark model could not explain discovery of free quarks, quark confinement or confirmation of the color hypothesis.
- In 1974 , at Brookhaven laboratory a new particle Ψ was discovered… after few months at SLAC a new particle was discovered independently, namely J. The J/Ψ was an electrically neutral, extremely heavy meson (3 times mass of proton) …idea of middle-weight mesons went away!
- Extraordinarily long lifetime (10^{-20}sec). So it has about a thousand times longer lifetime than any comparable particle.
- It was universally accepted that Ψ was a bound state of new particle (fourth) quark, the c (for charm) and its antiquark: $\Psi = (c\bar{c})$
- Parallel between leptons and quarks: Leptons: $e, \nu_e.\ \mu, \nu_\mu$ Quarks: u, d, c, s
- Why four leptons and three quarks?

- Other kinds of new baryons and mesons made up of charm quarks were expected.
- Charmness C=+1 is assigned for charm quark and -1 for anticharm.
- Charmed baryons $\Lambda_c^+ = udc$ was discovered in 1975.
- The story further begins with the discovery of tau lepton.
- Lepton family get extended => six members
- But 1977 upsilon ($\Upsilon = b\bar{b}$) was discovered.
- Search for baryons with bottom quark started => $\Lambda_b = udb$
- Beautiful mesons were discovered in 1983 => $B^0 = b\bar{d}$ $B^- = b\,\bar{u}$
- Search for Top/truth quark began until 1997 when top was discovered.

Intermediate vector bosons:

Fermi's theory of beta decay considered the process as a contact interaction , hence, no mediating particle is required.

As the Weak theory is of short range, the results were well within the range at low energies, however, for high energies the interaction must me mediated by an intermediate vector boson.

In Yukawa's theory of meson exchange, strong bound state was considered but there is no weak bound state.

The mass of pion-the exchange particle may be estimated in terms of range of the force, which is roughly size of the nucleus.

Glashow-Weinberg-Salam proposed the electroweak theory and made predictions regarding vector bosons - $W^{\pm}, Z$

CERN proton-antiproton collider discovered intermediate bosons in 1983.

The masses are, $M_W = 81\ GeV$ & $M_Z = 91\ GeV$.

These were the great achievements of particle physics, crucial aspects of the Standard Model of Particle physics lie on it.

In the SM there are 12 leptons, 36 quarks, 4 gauge bosons , 8 gluons (Mediators of strong force) & the Higgs boson.

Estimation of masses of mediators:

Assuming Yukawa's meson theory, when two protons inside a nucleus exchange a meson (mass m) the must violate conservation of energy by an amount mc^2.

The Heisenberg uncertainty principle says that you may borrow an energy ΔE , provided you pay it back in a time Δt given by $\Delta E \ \Delta t = \hbar$.

In this case we need to borrow $\Delta E = mc^2$ long enough for the meson to make it from one proton to the other.

Assuming the speed of the mediating particle to be c , we get $\Delta t = \frac{r_0}{c}$

Therefore, $\Delta E \ \Delta t = \hbar \Rightarrow \frac{mc^2 r_0}{c} = \hbar \Rightarrow m = \frac{\hbar}{r_0 c}$

Using $r_0 = 10^{-13} cm$, $m \approx 140 \ MeV$

Assuming short range (10^{-18} m)of intermediate vector bosons estimate the mass of corresponding mediating particles.

Try it with an atom and estimate the mass of photon. Comment on your result.

The range of a force is inversely proportionsl to the mass of the mediator, but the size of the bound state is not always good measure of the range.

Examine the following processes, and state for each one whether it is *possible* or *impossible*, according to the Standard Model (which does not include GUTs, with their potential violation of the conservation of lepton number and baryon number). In the former case, state which interaction is responsible—strong, electromagnetic, or weak; in the latter case cite a conservation law that prevents it from occurring. (Following the usual custom, I will not indicate the charge when it is unambiguous, thus γ, Λ, and n are neutral; p is positive, e is negative; etc.)

(a) $p + \bar{p} \to \pi^+ + \pi^0$
(b) $\eta \to \gamma + \gamma$
(c) $\Sigma^0 \to \Lambda + \pi^0$
(d) $\Sigma^- \to n + \pi^-$
(e) $e^+ + e^- \to \mu^+ + \mu^-$
(f) $\mu^- \to e^- + \bar{\nu}_e$
(g) $\Delta^+ \to p + \pi^0$
(h) $\bar{\nu}_e + p \to n + e^+$
(i) $e + p \to \nu_e + \pi^0$
(j) $p + p \to \Sigma^+ + n + K^0 + \pi^+ + \pi^0$
(k) $p \to e^+ + \gamma$
(l) $p + p \to p + p + p + \bar{p}$
(m) $n + \bar{n} \to \pi^+ + \pi^- + \pi^0$
(n) $\pi^+ + n \to \pi^- + p$
(o) $K^- \to \pi^- + \pi^0$
(p) $\Sigma^+ + n \to \Sigma^- + p$
(q) $\Sigma^0 \to \Lambda + \gamma$
(r) $\Xi^- \to \Lambda + \pi^-$
(s) $\Xi^0 \to p + \pi^-$
(t) $\pi^- + p \to \Lambda + K^0$
(u) $\pi^0 \to \gamma + \gamma$
(v) $\Sigma^- \to n + e + \bar{\nu}_e$

(a) $K^+ \to \mu^+ + \nu_\mu + \gamma$
(b) $\Sigma^+ \to p + \gamma$