Elementary Particles: An Introduction

By

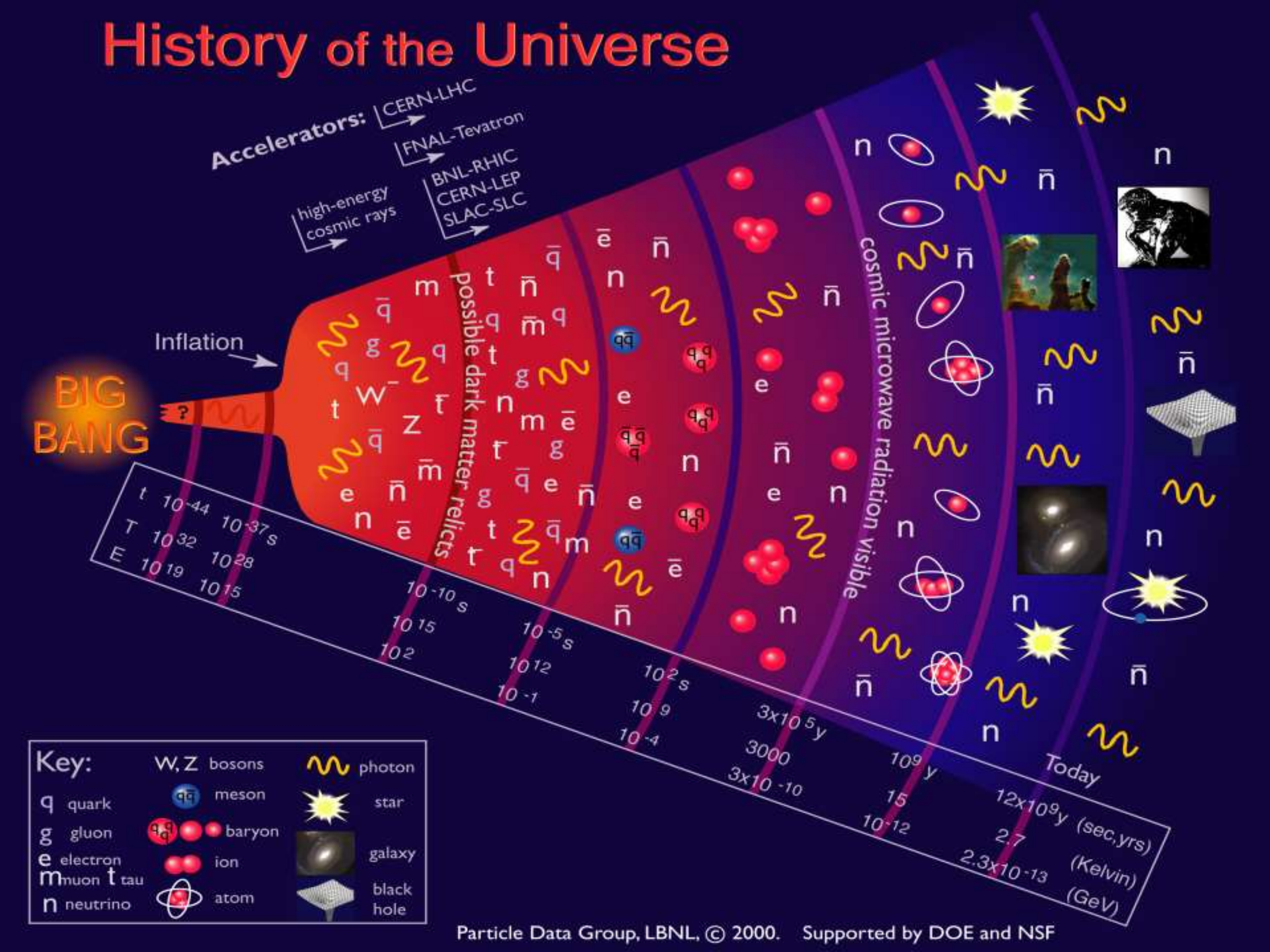
Dr. Mahendra Singh

Deptt. of Physics

Brahmanand College, Kanpur

What is Particle Physics?

- Study the fundamental interactions and constituents of matter?
- The Big Questions:
  - Where does mass come from?
  - Why is the universe made mostly of matter?
  - What is the missing mass in the Universe?
  - How did the Universe begin?


History of the Universe
Acceleerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
t 10^-44 10^-37 s
T 10^32 10^28
E 10^19 10^15
10^-10 s
10^15
10^2
10^-5 s
10^12
10^-1
10^2 s
10^9
10^-4
3x10^5 y
3000
3x10^-10
10^9 y
15
10^-12
Today
12x10^9 y (sec,yrs)
2.7 (Kelvin)
2.3x10^-13 (GeV)
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
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Fundamental building blocks of which all matter is composed:

Elementary Particles

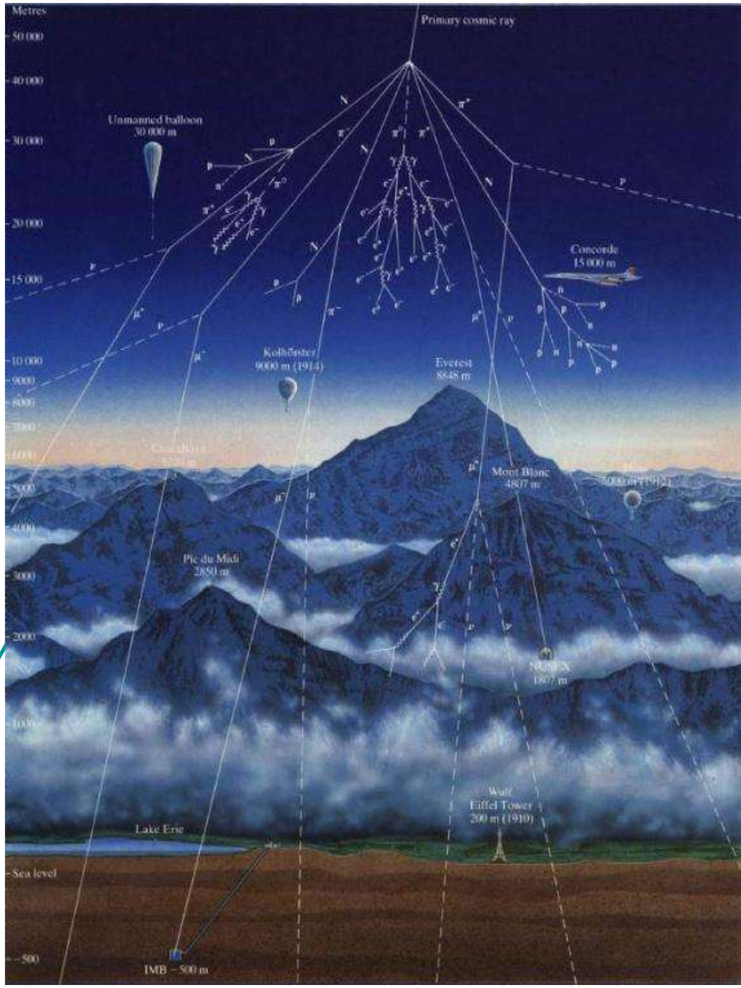
*Pre-1930s it was thought there were just four elementary particles

electron

proton

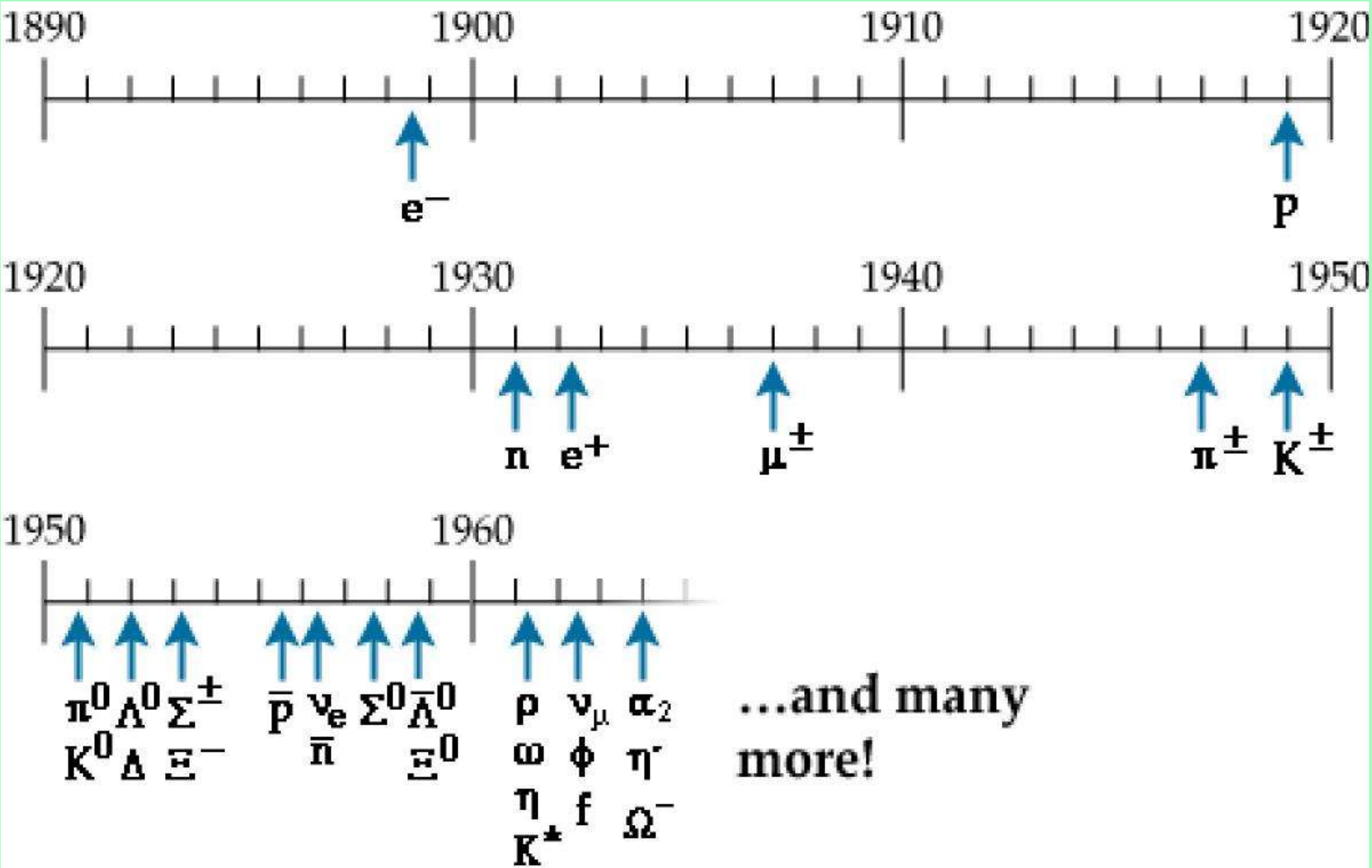
neutron

photon

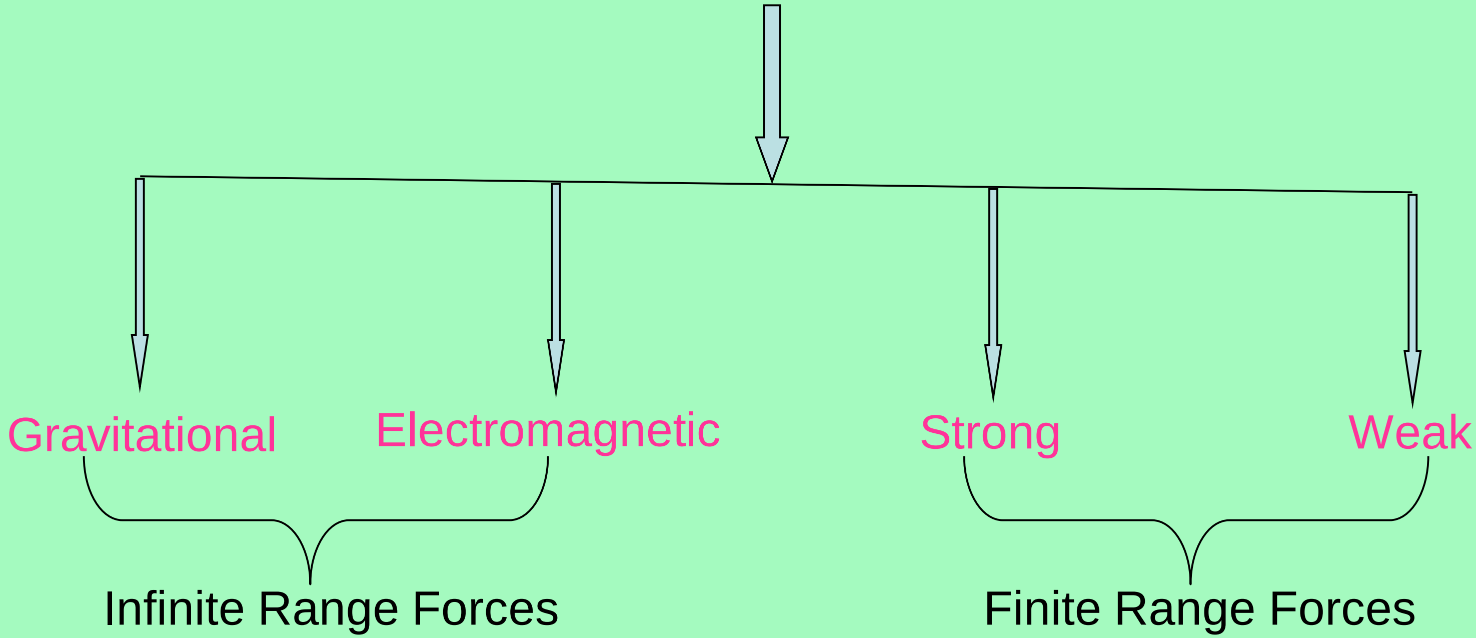


1932 positron or anti-electron discovered, followed by many other particles (muon, pion etc)

We will discover that the electron and photon are indeed fundamental, elementary particles, but protons and neutrons are made of even smaller elementary particles called quarks


1890
1900
1910
1920
e^-
p
1920
1930
1940
1950
n
e^+
$\mu^\pm$
$\pi^\pm$
$K^\pm$
1950
1960
π^0 Λ^0 $\Sigma^\pm$
K^0 Δ Ξ^-
$\bar{p}$ ν_e Σ^0 $\bar{\Lambda}^0$
$\bar{n}$ Ξ^0
ρ ν_μ a_2
ω ϕ η'
η f Ω^-
K^*
…and many more!

Four Fundamental Interactions



- Exchange theory of forces suggests that to every force there will be a mediating particle(or exchange particle)

Force	Exchange Particle
Gravitational	Graviton → **Not detected so for**
EM	Photon
Strong	Pi mesons
Weak	Intermediate vector bosons

Range of a Force

$R = c\,\Delta t$

c: velocity of light

Δt: life time of mediating particle

Uncertainity relation: $\Delta E\,\Delta t = h/2\pi$

$mc^2\,\Delta t = h/2\pi$

$R = h/2\pi mc$

So $R \propto 1/m$

If $m = 0$, $R \to \infty$

- As masses of graviton and photon are zero, range is infinite for gravitational and EM interactions
- Since pions and vector bosons have finite mass, strong and weak forces have finite range.

Properties of Fundamental Interactions

Interaction	Range (m)	Particles Exchanged	Relative Strength	Importance
Gravitational	∞	Gravitons	$\sim 10^{-39}$	Formation of the universe
EM	∞	Photons	$\sim 10^{-2}$	Formation of atoms and molecules and so matter
Strong	$\sim 10^{-15}$	Mesons	1	Holds nucleons together to form nuclei
Weak	$\sim 10^{-17}$	Vector bosons	$\sim 10^{-5}$	Responsible for particle decays

Properties of Elementary Particles

Every elementary particle is characterized by following parameters

- Mass
- Charge
- Spin
- Life Time
- Parity

Spin: Particles may have integral or Half integral spin

Integral

S=0,1,2…..

(Bosons)

Half Integral

S=1/2,3/2,5/2…..

(Fermions)

- S=0 ⟶ $\pi^+, \pi^-, \pi^0;$
- S=1 ⟶ Photon
- S=2 ⟶ Graviton
- S=1/2 ⟶ e, p, n, μ, τ, ν

Life Time: Except electron, proton and neutrinos all other particles are unstable

Particles	Life Time
Neutron	16 min.
Mu Meson	2.2×10^{-6} s
Tao Meson	3.4×10^{-23} s

Parity

- All quantum mechanical particles are characterised by wave function $\psi\ (x,y,z)$
- Parity is an operation that tells about the nature of the wave function

Suppose one reverse the space coordinates i.e. $(x,y,z)\rightarrow(-x,-y,-z)$

Then if $\psi\ (-x,-y,-z)=-\psi\ (x,y,z)\rightarrow$ odd wave function$\rightarrow$Odd parity

$\psi\ (-x,-y,-z)=\psi\ (x,y,z)\rightarrow$ even wave function$\rightarrow$Even Parity

Thus we can say parity operator P has two eigen values viz. +1 & -1

P=+1 $\rightarrow$Even Parity

P=-1 $\rightarrow$Odd Parity

- Total Parity= Orbital Parity$\times$ Intrinsic Parity

Orbital Parity$=(-1)^{l}$

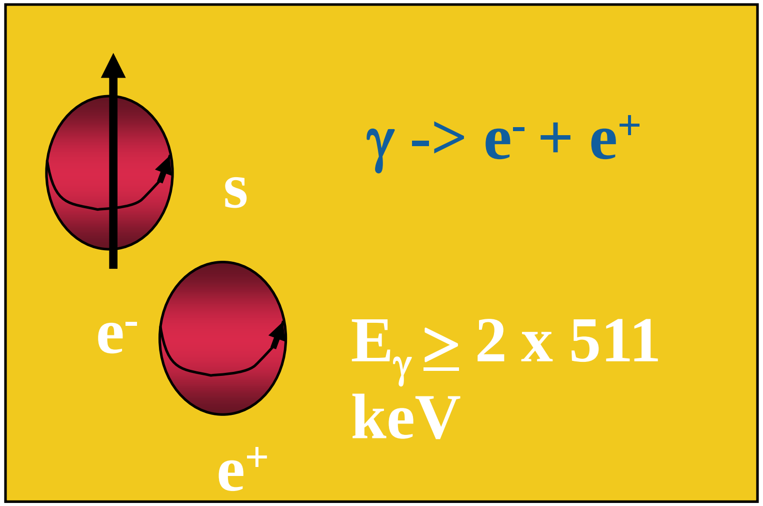
- e, p, n, ν, μ, τ have intrinsic parity=+1
- $\pi+,\pi-,\pi0$ have intrinsic parity$=-1$

Antimatter

For each particle there is an associated *antiparticle*

Anti-particles always created in particle-anti particle pairs

Electron Pair Production



* Antiparticle has the **same mass and magnitude of spin** as the particle

* Antiparticle has the **opposite charge** to the particle

* The positron is stable but has a short-term existence because our Universe has a large supply of electrons

* The fate of a positron is annihilation

CLASSIFICATON OF PARTICLES

An *elementary particle* is a point particle without structure that is not constructed from more elementary entities

With the advent of particle accelerator in the 1950's many new elementary particles were discovered.

The question arose whether perhaps there were too many to all be elementary.

This has led to the need for classification of particles.

Different Bases of Classification

Mass

Spin

Interaction

Not very appropriate and do not fulfil the requirements

These bases were used in initial days when the number of particles was small

This basis is used today and gives answers to related questions

Leptons

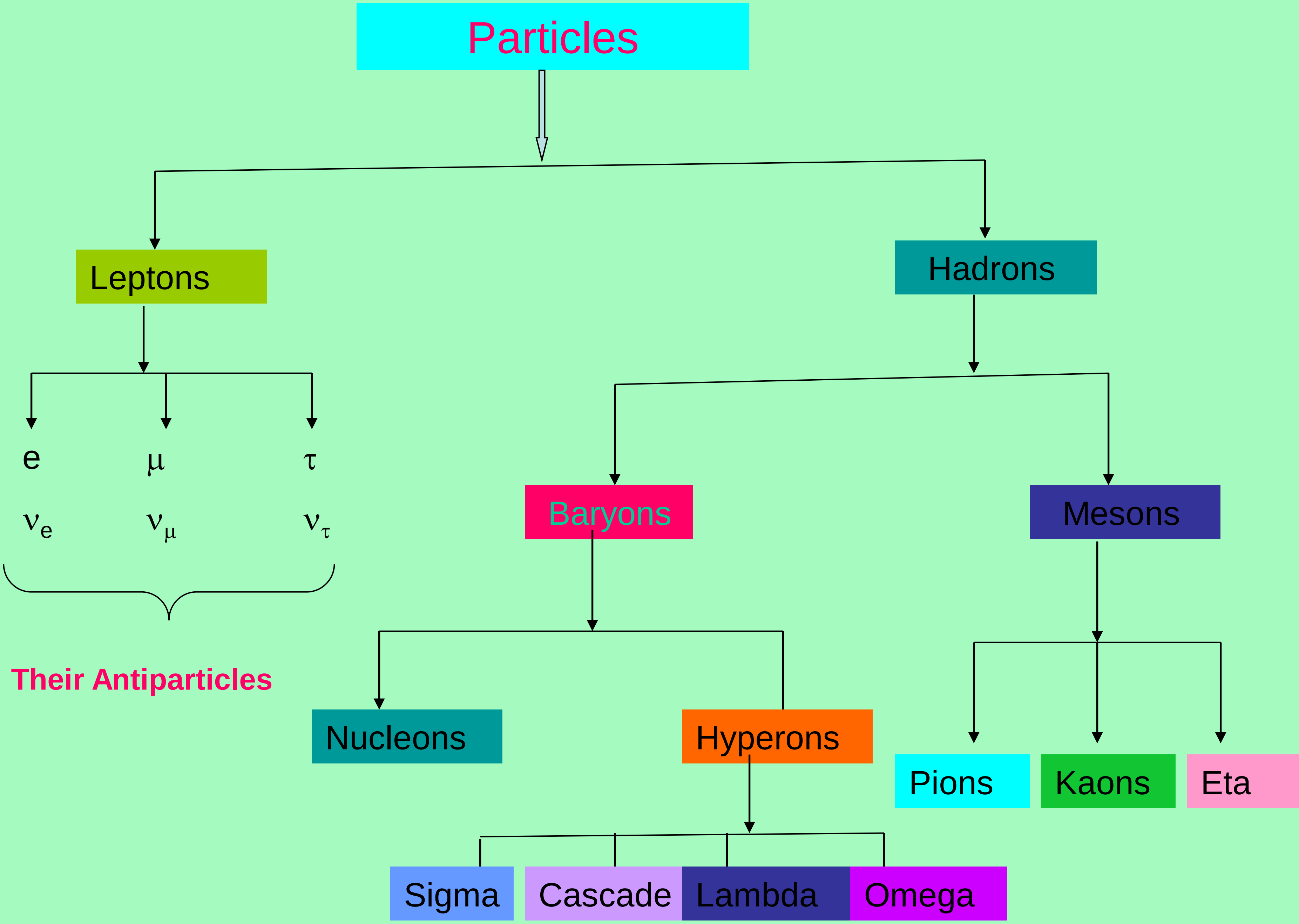
Follow weak interaction but not strong

Follow EM int.

Hadrons

Follow weak as well as strong interact.

Follow EM int.


Particles
Leptons
Hadrons
e
μ
τ
ν_e
ν_μ
ν_τ
Their Antiparticles
Baryons
Mesons
Nucleons
Hyperons
Pions
Kaons
Eta
Sigma
Cascade
Lambda
Omega

Quark Model

- 1964 The model was proposed independently by Gell-Mann and Zweig
- Three fundamental building blocks 1960's (p,n,λ) $\Rightarrow$ 1970's (u,d,s)
- <u>mesons</u> are bound states of a of quark and anti-quark:

  Can make up "wave functions" by combing quarks:

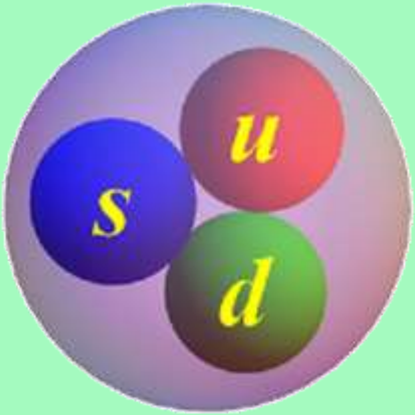
$$\pi^+ = u\bar{d},\quad \pi^- = d\bar{u},\quad \pi^o = \frac{1}{\sqrt{2}}(u\bar{u} - d\,\bar{d}),\quad k^+ = d\bar{s},\quad k^o = d\bar{s}$$

- <u>Baryons</u> are bound state of 3 quarks:

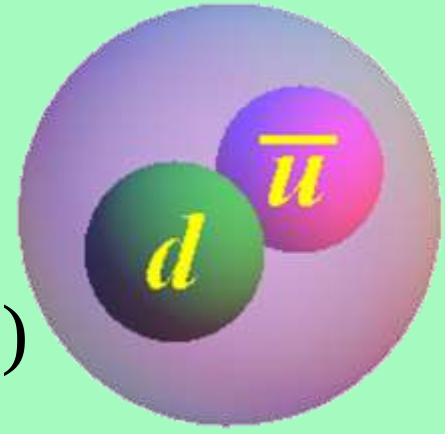
  proton = (uud), neutron = (udd), Λ= (uds)

  <u>anti-baryons</u> are bound states of 3 anti-quarks:

$$\bar{p} = \bar{u}\bar{u}\bar{d} \quad \bar{n} = \bar{u}\bar{d}\bar{d} \quad \bar{\Lambda} = \bar{u}\bar{d}\bar{s}$$



Λ = (uds)



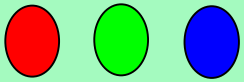
$$\pi^- = (d\bar{u})$$

Quarks

These quark objects are:

- point like
- spin 1/2 fermions
- parity = +1 (-1 for anti-quarks)
- Two quarks are in isospin doublet (u and d), s is an iso-singlet (=0)
- Obey $Q = I_3 + 1/2(S+B) = I_3 + Y/2$
- Group Structure is SU(3)
- For every quark there is an anti-quark
- The anti-quark has opposite charge, baryon number and strangeness
- Quarks feel all interactions (have mass, electric charge, etc)

Colored Quarks

- Another **internal degree of freedom** was needed "**COLOR**"
- Postulates
  - quarks exist in three colors: 
  - hadrons built from quarks have net zero color

  (*otherwise, color would be a measurable property*)

- We overcome the spin-statistics problem by dropping the concept of identical quarks; now distinguished by color

$$\Delta^{++} = u_R\, u_G\, u_B$$

Quantum Chromodynamics (QCD)

- QCD gave a new theory of how quarks interact with each other by means of color charge
- The strong force between quarks is often called the color force
- The strong force between quarks is carried by *gluons*
  - Gluons are massless particles
  - There are 8 gluons, all with color charge
- When a quark emits or absorbs a gluon, its color changes

Thanks