Lecture on

PARTICLE PHYSICS

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Lecture contents

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- **Section-2: Fundamental interactions/forces**
- **Section-3: Conservation laws & Symmetries**
- **Section-4: Building blocks of matter**
- **Section-5: Conclusion with the Fundamental Model of particles**

Section-1: Basics of elementary particle physics

Some open questions for students:

- What is Particle Physics and why do we study it?
- What are the Elementary particles?
- What are the basic building blocks of matter in the Universe?
- What are fundamental forces and how are they transmitted?
- What is the world made of?
- What is the origin of mass?
- What do the theories underlying particle physics look like?
- How much matter present in the universe?
- What does this tell us about the origins of the Universe?

Elementary Particle Physics:

- ✓ Elementary particle physics studies the fundamental building blocks of nature. But what fundamental does mean? By fundamental we mean objects that are simple and structureless, not made of anything smaller.
- ✓ During the past century the word "fundamental" was addressed firstly to the atom. The word "atom" was introduced by Democritus (400 BC) who described the matter as composed by small and indivisible particles ("atom" comes from greek *a-temno*, which can not be divided).
- ✓ The internal structure of the atom was discovered and protons, neutrons and electrons became the building blocks of matter.
- ✓ After 1960, scattering experiments of high energy particles on nucleons lead to the discovery of the quarks, which are thought now as the fundamental consituents of matter.

Sub-atomic dimensions

Everyday Objects are made of Molecules.

Molecules are made of Atoms.

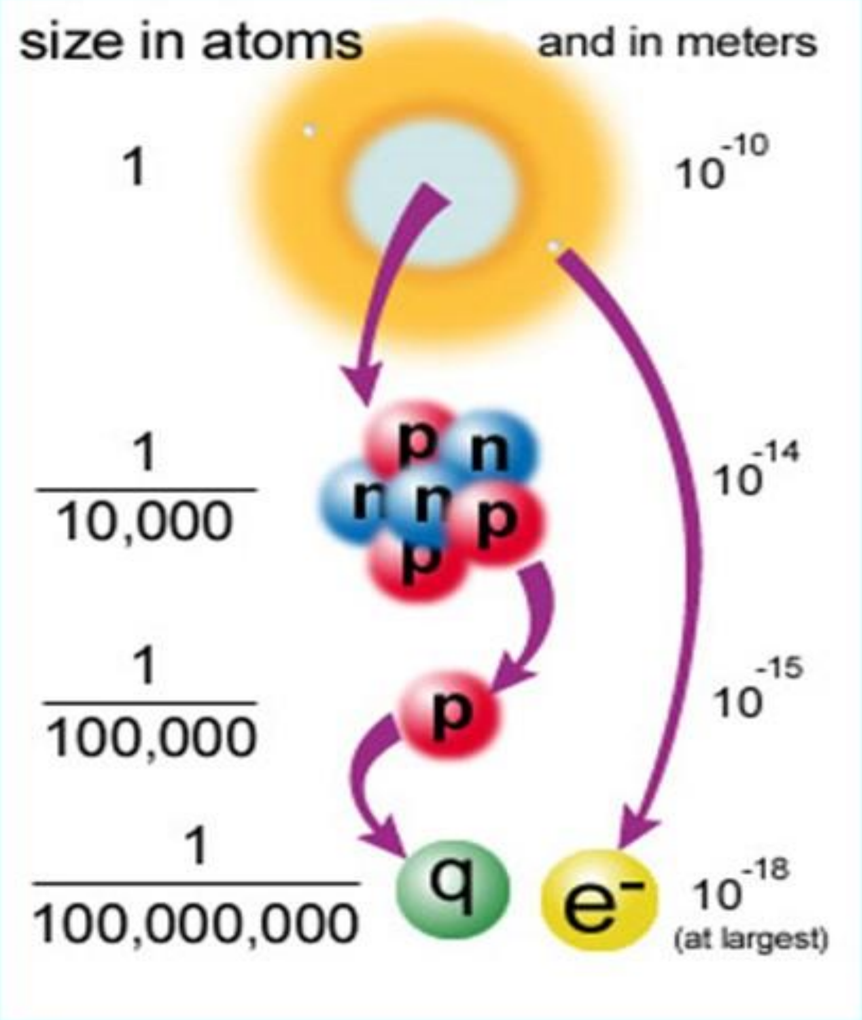
Atoms are made of Nuclei and Electrons.

Nuclei are made of Protons and Neutrons.

Protons and Neutrons are made of Quarks.

Quarks and Electrons are made of ???

Quarks and Electrons are "Elementary Particles"



How small is small?

10^{-7} m virus

10^{-9} m molecule

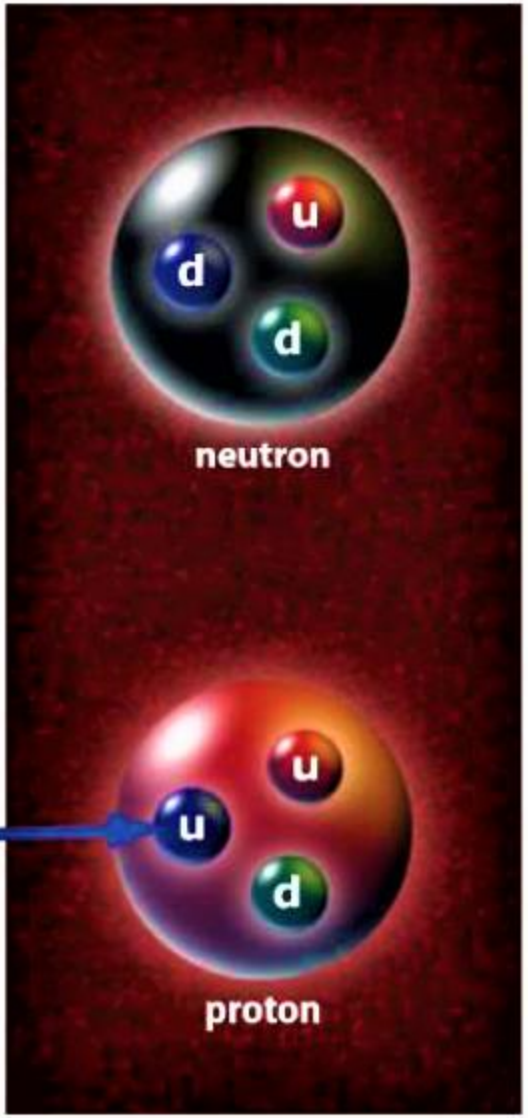
10^{-10} m atom

10^{-14} m nucleus

10^{-15} m proton/neutron

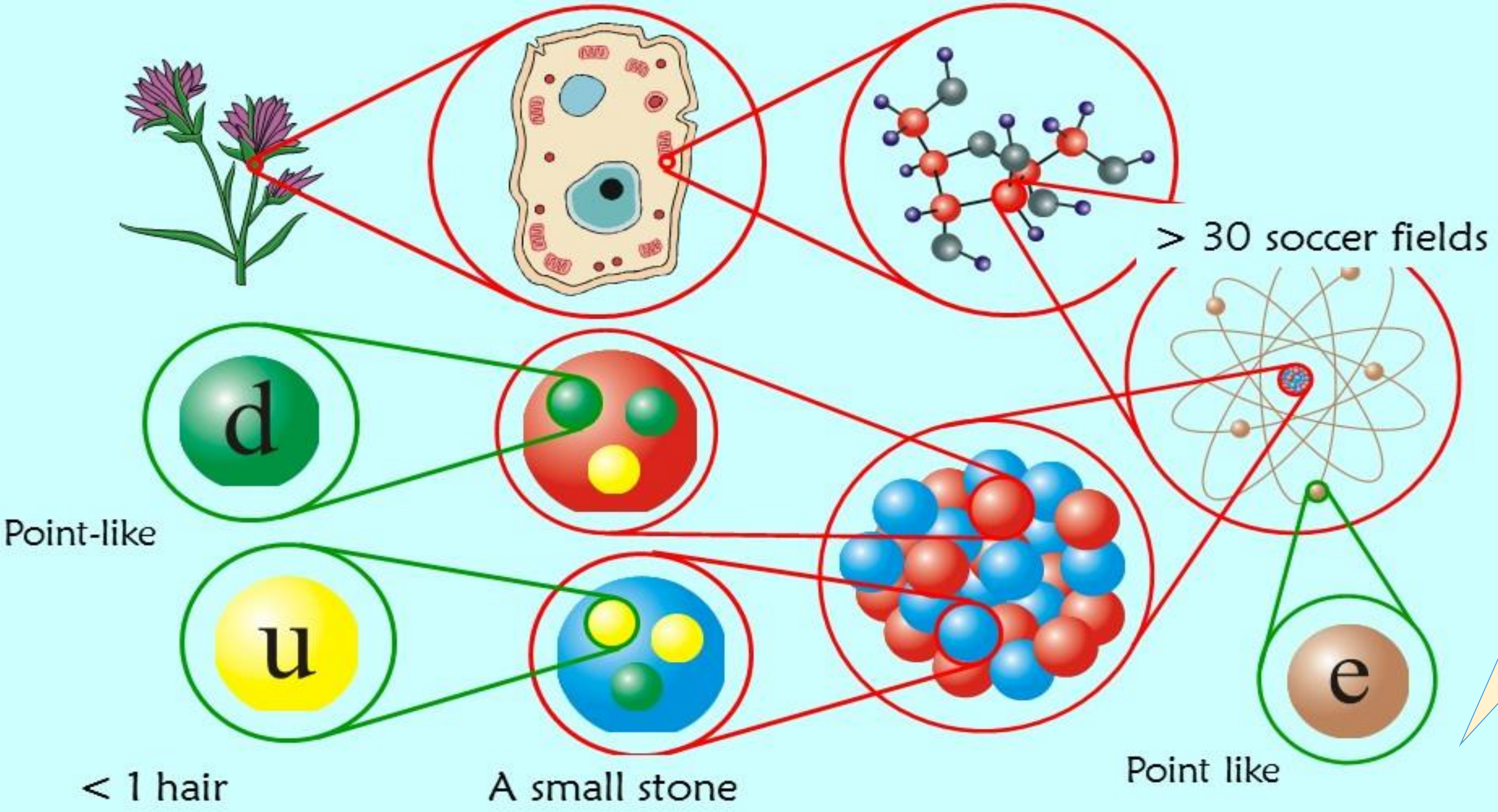
$<10^{-18}$ m quarks

?



Particle Physics

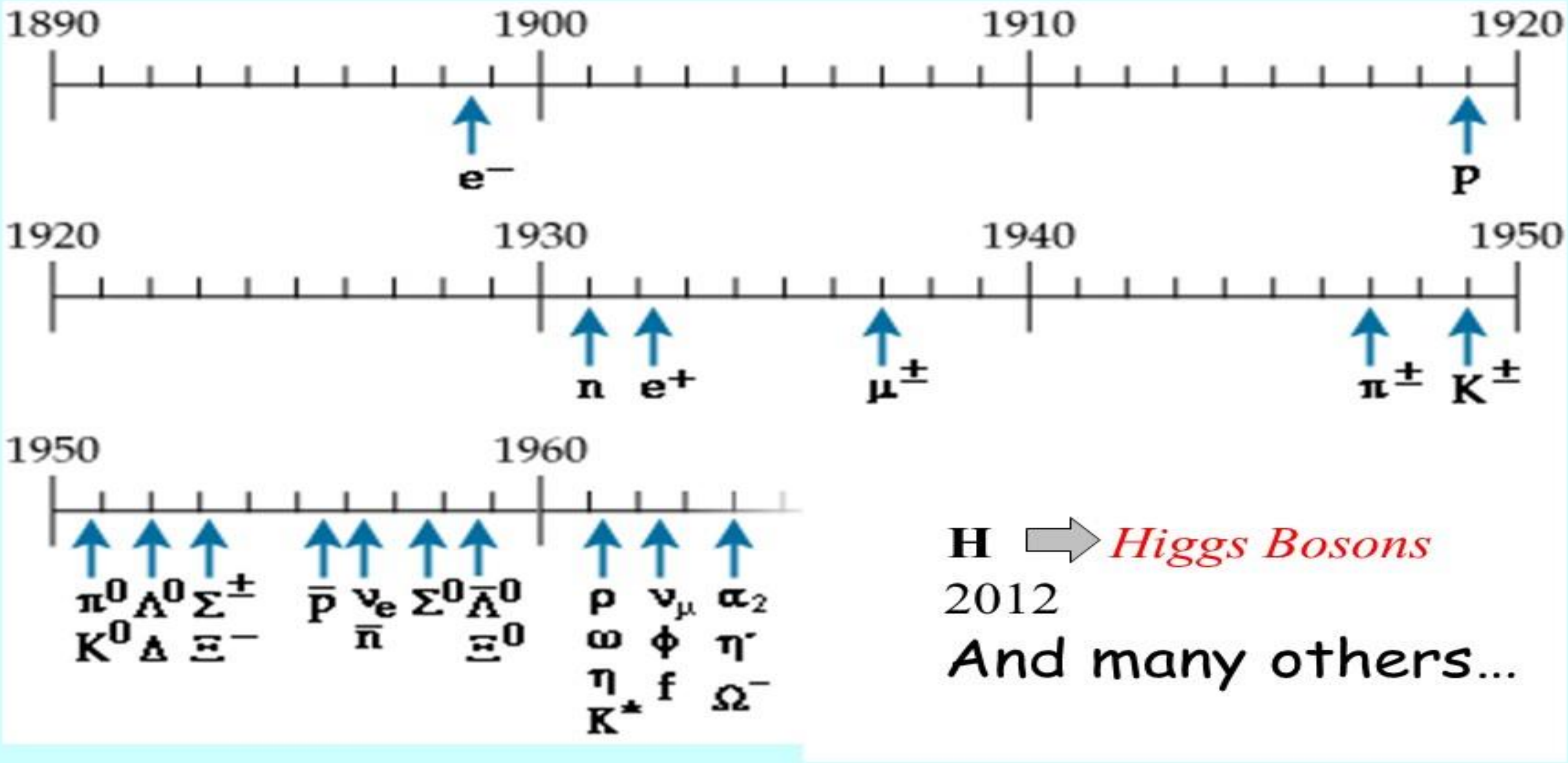
...small, smaller...extremely small physics!...



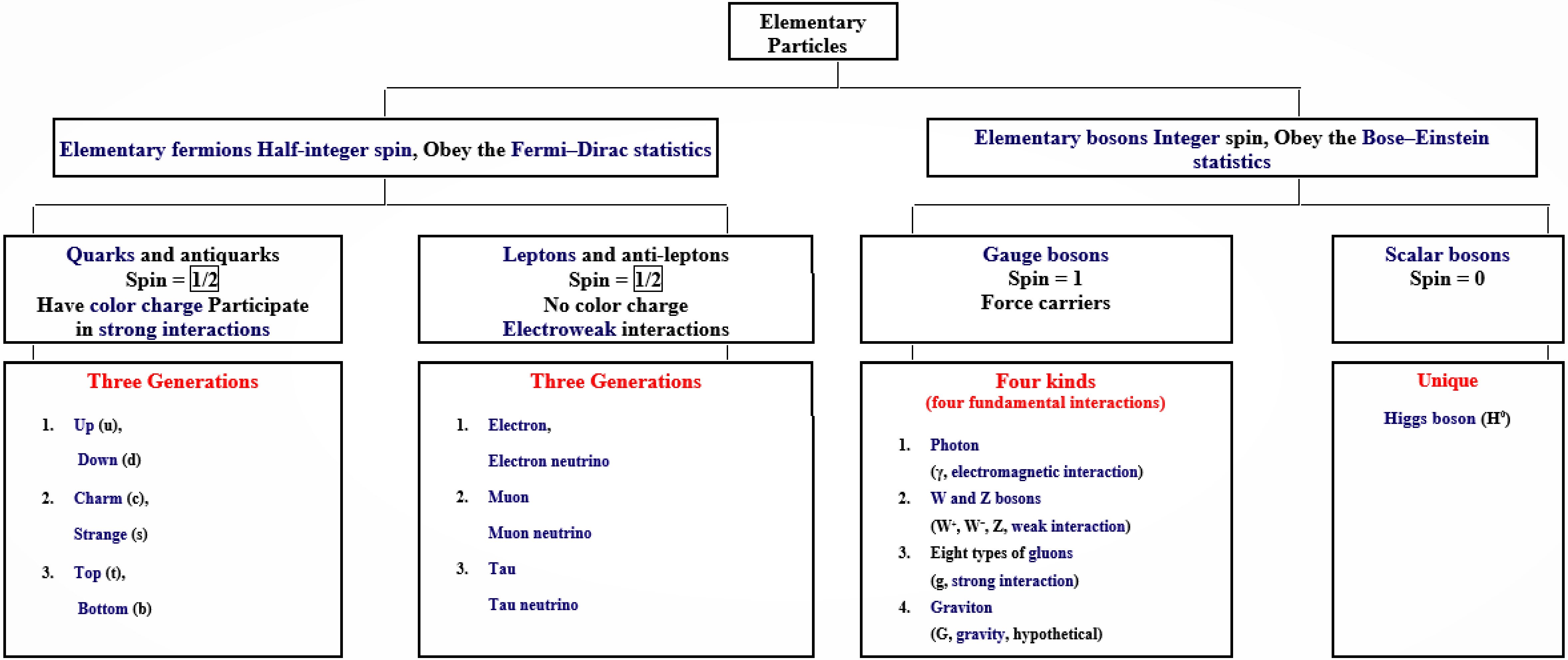
Is it deal with Quantum Physics?

At the beginning just a few…

A Journey of Particles:



Question: **How can we classify all fundamental particles ?**



Elementary Particles

Elementary fermions Half-integer spin, Obey the Fermi–Dirac statistics

Quarks and antiquarks
Spin = $\boxed{1/2}$
Have color charge Participate in strong interactions

Three Generations

1. Up (u),
   Down (d)
2. Charm (c),
   Strange (s)
3. Top (t),
   Bottom (b)

Leptons and anti-leptons
Spin = $\boxed{1/2}$
No color charge
Electroweak interactions

Three Generations

1. Electron,
   Electron neutrino
2. Muon
   Muon neutrino
3. Tau
   Tau neutrino

Elementary bosons Integer spin, Obey the Bose–Einstein statistics

Gauge bosons
Spin = 1
Force carriers

Four kinds
(four fundamental interactions)

1. Photon
   (γ, electromagnetic interaction)
2. W and Z bosons
   (W^+, W^-, Z, weak interaction)
3. Eight types of gluons
   (g, strong interaction)
4. Graviton
   (G, gravity, hypothetical)

Scalar bosons
Spin = 0

Unique

Higgs boson (H^0)

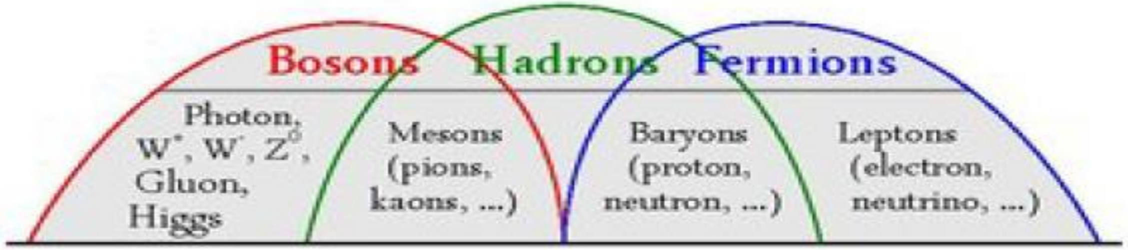
Baryons: Proton, neutron, hyperons

Mesons: Pi-meson, K-meson, eta-meson

Particle classification according to acting interactions :

- ✓ **Leptons** – interact weakly and charged also electromagnetically, they do not interact strongly (e, μ, τ, ν_e, ν_μ, ν_τ) – in the present experiments they are point like

- ✓ **Hadrons** – interact in addition also strongly – they have structure and size ≈1 fm



How hadrons fit with the two other classes of sub atomic particles, bosons and fermions

Particle classification according to statistics:

- ✓ **Bosons:** Bose-Einstein statistic → arbitrary number of particles in given state – integral spin Wave function – symmetric:

$$\Psi_B(x_1,x_2,x_3, \ldots,x_n) = \Psi_B(x_2,x_1,x_3, \ldots,x_n)$$

- ✓ **Fermions:** Fermi-Dirac statistic → Pauli exclusion principle → only one identical particle in given state – half-integral spin. Wave function is antisymmetric:

$$\Psi_F(x_1,x_2,x_3, \ldots,x_n) = -\Psi_F(x_2,x_1,x_3, \ldots,x_n)$$

Strange Particles:

- ✓ Produce through the strong interaction and decay through the weak interaction.
- ✓ None of the product particle i.e. neutrino or anti-neutrino in weak interaction (unlike as beta decay)
- ✓ Production time is very fast and decay time is very slow

  (it is very interacting property).
- ✓ Tp = less than 1 sec. Td = 3000 years (approx.)
- ✓ K −mesons, $\Lambda, \Sigma, \Xi, \Omega$ −hyperons are called strange particles.
- ✓ These particles have additional quantum number called **“Strangeness”.**

Section-2: Fundamental interactions/forces

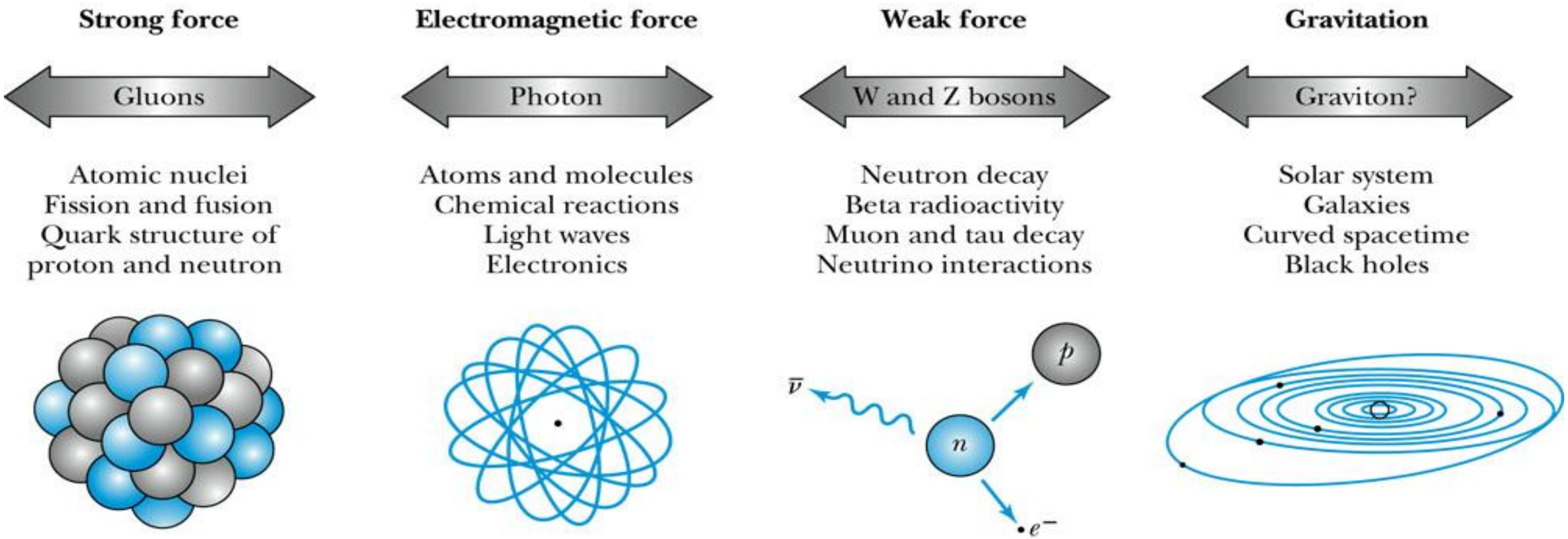
What is the difference between a force and an interaction?

- ✓ This is a hard distinction to make. Strictly speaking, a force is the effect on a particle due to the presence of other particles. The interactions of a particle include all the forces that affect it, but also include decays and annihilations that the particle might go through.

- ✓ The reason this gets confusing is that most people, even most physicists, usually use "force" and "interaction" interchangeably, **although "interaction" is more correct**.

- ✓ You will usually be okay using the terms interchangeably, but you should know that they are different.

Fundamental interactions/forces



- ✓ One of the main goals of particle physics is **to unify these forces** (to show that they’re all just different aspects of the same force), just as **Maxwell did** for the electric and magnetic forces many years earlier.

Summary of fundamental forces in nature:

Name	Acts on:	Carrier	Range	Strength	Stable systems	Induced reaction
Gravity	all particles	graviton	long $F \propto 1/r^2$	$\sim 10^{-39}$	Solar system	Object falling
Weak force	fermions	bosons W and Z	$< 10^{-17}$ m	10^{-5}	None	β-decay
Electromagnetism	particles with electric charge	photon	long $F \propto 1/r^2$	$1/137$	Atoms, stones	Chemical reactions
Strong force	quarks and gluons	gluons	10^{-15} m	1	Hadrons, nuclei	Nuclear reactions

Question: **How can we calculate the 'Range' of forces?**

Only four fundamental forces?

Fifth fundamental forces: A scientific approach

- ✓ Some speculative theories have proposed a fifth fundamental force to explain various anomalous observations that do not fix existing theories.
- ✓ It is hypothetical force, not observed yet
- ✓ Most Scientists believe that this force helps us to explain that most of the universe is accounted for by an unknown form of matter called dark matter.
- ✓ It require extra dimensions to formulate.

Range of forces:

- ✓ The range of forces is related to the **mass of exchange particle M**.
- ✓ An amount of energy ΔE=Mc^2 borrowed for a time Δt is governed by the Heisenberg's Uncertainty Principle:

$$\Delta E \times \Delta t \sim \hbar$$

- ✓ The maximum distance the particle can travel is Δx = c Δt, where c is speed of light.

$$\Delta x = \hbar c / \Delta E$$

$$\boxed{\Delta x = \hbar c / Mc^2}$$

- ✓ **Exp: The photon has** M=0 ---- → **infinite range of EM force**

W boson has a mass of *80 GeV/C^2* → **Range of weak force is about 2x10^{-3} fm**

Which forces act on which particles?

- ✓ The weak force acts between all quarks and leptons
- ✓ The electromagnetic force acts between all charged particles
- ✓ The strong force acts between all quarks (i.e. objects that have color charge)
- ✓ Gravity does not play any role in particle physics

	Weak	**EM**	**Strong**
Quarks	+	+	+
Charged leptons	+	+	–
Neutral leptons	+	–	–

Section-3: Conservation laws & Symmetries

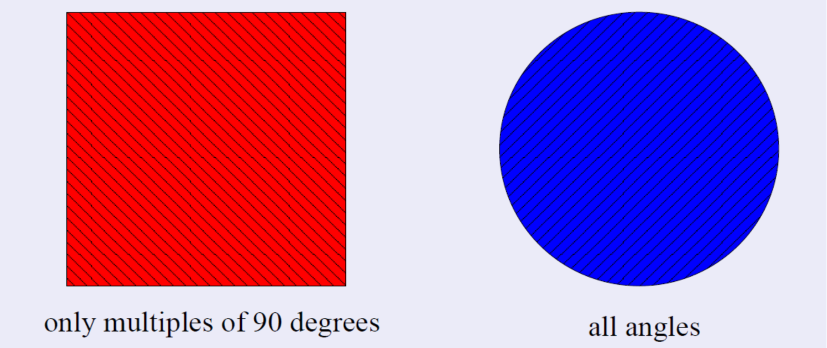
- ✓ Conservation laws are fundamental to our understanding of the physical world, in that they describe which processes can or cannot occur in nature.
- ✓ **Exact conservation laws** include conservation of energy, conservation of linear momentum, conservation of angular momentum, and conservation of electric charge.
- ✓ There are also many **approximate conservation laws** in particle physics, which apply to such quantities as parity, charge conjugation, time reversal, lepton number, baryon number, strangeness, hypercharge, isospin etc.
- ✓ **One particularly important result concerning conservation laws is Noether's theorem, which states that there is a one-to-one correspondence between each one of them and a differentiable symmetry of nature.**

What actually the Noether's theorem means?

Conservation Law	Respective Noether’s symmetry invariance		Meaning of invariance
Conservation of energy	Time invariance	Lorentz invariance symmetry	translation about time axis
Conservation of linear momentum	Translation symmetry		translation about x,y,z position
Conservation of angular momentum	Rotation invariance		rotation about x,y,z axes
CPT symmetry (combining charge conjugation, parity and time reversal)	Lorentz invariance		(charge inversion $q \rightarrow -q$) + (position inversion $r \rightarrow -r$) + (time inversion $t \rightarrow -t$)
Conservation of electric charge	Gauge invariance		scalar field (1D) in 4D spacetime (x,y,z + time evolution)
Conservation of color charge	SU(3) Gauge invariance		r,g,b
Conservation of weak isospin	$SU(2)_L$ Gauge invariance		weak charge
Conservation of probability	Probability invariance		total probability always = 1 in whole x,y,z space, during time evolution

Symmetries:

- ✓ A symmetry is a physical or mathematical feature of the system that remains unchanged under some transformation.
- ✓ **Global or Local Symmetries (broadly classified):** A *global symmetry* is one that holds at all points of spacetime, whereas a *local symmetry* is one that has a different symmetry transformation at different points of spacetime.
- ✓ **Discrete and Continuous Symmetries:** The quadratic one has a discrete symmetry w.r.t. rotation along its axis, while the round one enjoys a continuous symmetry.



Class	Invariance	Conserved quantity
Lorentz symmetry	translation in time (homogeneity)	energy
	translation in space (homogeneity)	linear momentum
	rotation in space (isotropy)	angular momentum
Discrete symmetry	P, coordinate inversion	spatial parity
	C, charge conjugation	charge parity
	T, time reversal	time parity
	CPT	product of parities
Internal symmetry (independent of spacetime coordinates)	U(1) gauge transformation	electric charge
	U(1) gauge transformation	hypercharge
	$U(1)_Y$ gauge transformation	weak hypercharge
	SU(2) gauge transformation	isospin
	$SU(2)_L$ gauge transformation	weak isospin
	SU(3) gauge transformation	quark color
	SU(3) (approximate)	quark flavor
	[U(1) × SU(2) × SU(3)]	Standard Model

CPT-Theorem:

- ✓ **Parity (P):** The conservation of parity *P* describes the inversion symmetry of space,

$$\vec{x} \longrightarrow -x;\ \vec{y} \longrightarrow -y,\ \text{and}\ \vec{z} \longrightarrow -z$$

- ✓**Charge conjugation (C):** It has the effect of interchanging every particle with its antiparticle.

- ✓ **Time Reversal (T):** Here time *t* is replaced with –*t*.

- ✓**CPT Theorem:** **Georg Ludens, Wolfgang Pauli and Julian Schwinger** independently showed that invariance under Lorentz transformations implies CPT invariance.

It states that if a quantum field theory is invariant under Lorentz transformation, then ***C P T*** is an exact symmetry !!

(Note that if, for example, CP is violated, then T must be violated)

Some conservation numbers:

- ✓ **Baryon Conservation:** The conservation of baryon number requires the same total baryon number before and after the reaction. The value B = +1 for baryons and −1 for antibaryons, and 0 for all other particles. **(See: Neutron & anti-neutron?)**

- ✓ **Lepton Conservation:** The number of leptons from each family is the same both before and after a reaction. We let $L_e = +1$ for the electron and the electron neutrino; $L_e = -1$ for their antiparticles; and $L_e = 0$ for all other particles. We assign the quantum numbers L_μ for the muon and its neutrino and L_τ for the tau and its neutrino similarly. See beta decay: $n \rightarrow p + e + \bar{\nu}_e$ **(Why anti-electron neutrino here?)**

- ✓ **Strangeness Conservation:** The kaons have $S = +1$, lambda and sigmas have $S = -1$, the xi has $S = -2$, and the omega has $S = -3$.

- ✓ **Isospin Conservation:** The isotropic spin, makes out that proton and neutron are two charge states of a single particle nucleon. $I = 1/2$ for nucleon and $I_3 = +1/2$ for proton and $I_3 = -1/2$ for neutron.

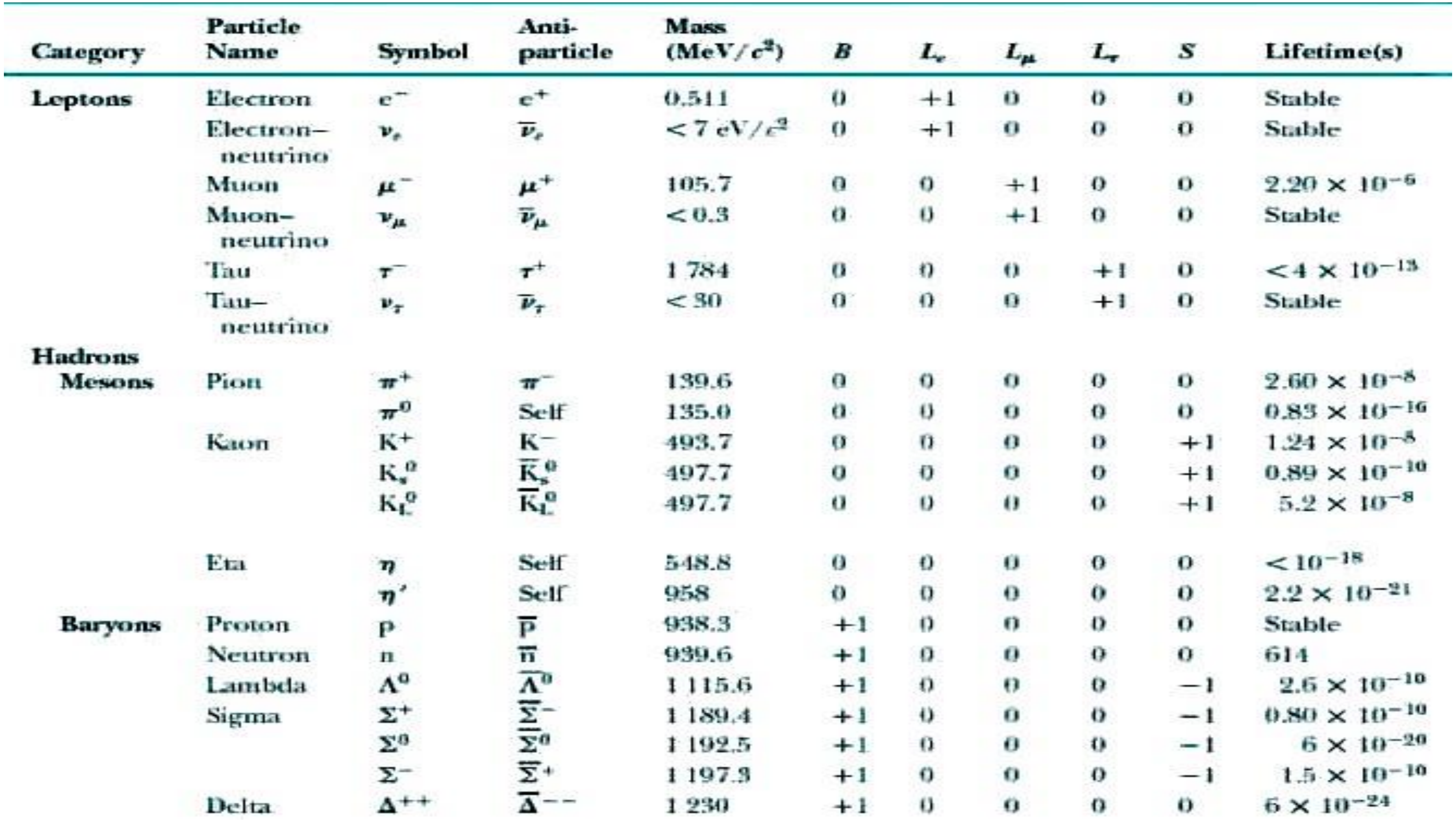
Conservation Laws

	Strong	E.M.	Weak
Energy/Momentum	✓	✓	✓
Electric Charge	✓	✓	✓
Baryon Number	✓	✓	✓
Lepton Number	✓	✓	✓
Isospin (I)	✓	✗	✗
Strangeness (S)	✓	✓	✗
Charm (C)	✓	✓	✗
Parity (P)	✓	✓	✗
Charge Conjugation (C)	✓	✓	✗
CP (or T)	✓	✓	✗
CPT	✓	✓	✓

Physical quantities for particle and antiparticle:

Quantity	particle	antiparticle
Mass m	same	same
Spin (magnitude)	same	same
Lifetime τ	same	same
Isospin (magnitude)	same	same
Electric charge	Q	-Q
Magnetic moment	μ	-μ
Baryon number	B	-B
Lepton number	L	-L
Strangeness	S	-S
z component of isospin I_z	I_z	$-I_z$
Intrinsic parity P	Same for bosons	Opposite - fermions

Some particles and their properties

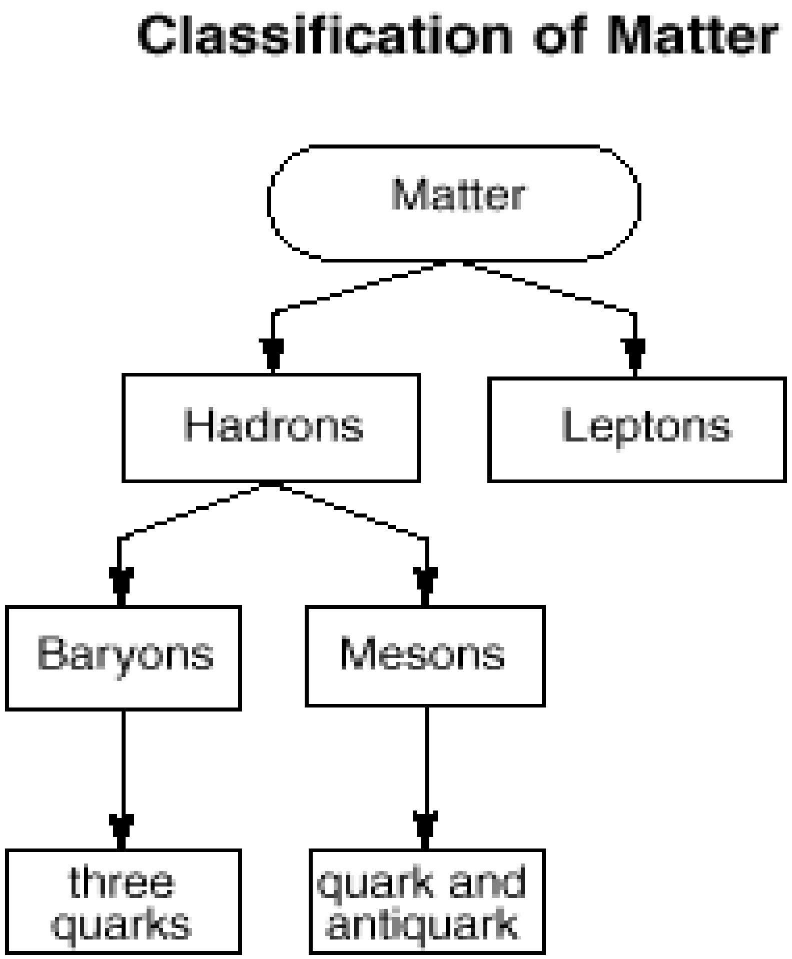


Category	Particle Name	Symbol	Anti-particle	Mass (MeV/c^2)	B	L_e	L_μ	L_τ	S	Lifetime(s)
Leptons	Electron	e^-	e^+	0.511	0	+1	0	0	0	Stable
	Electron–neutrino	ν_e	$\bar{\nu}_e$	$< 7\ \text{eV}/c^2$	0	+1	0	0	0	Stable
	Muon	μ^-	μ^+	105.7	0	0	+1	0	0	2.20×10^{-6}
	Muon–neutrino	ν_μ	$\bar{\nu}_\mu$	< 0.3	0	0	+1	0	0	Stable
	Tau	τ^-	τ^+	1 784	0	0	0	+1	0	$< 4 \times 10^{-13}$
	Tau–neutrino	ν_τ	$\bar{\nu}_\tau$	< 30	0	0	0	+1	0	Stable
Hadrons										
Mesons	Pion	π^+	π^-	139.6	0	0	0	0	0	2.60×10^{-8}
		π^0	Self	135.0	0	0	0	0	0	0.83×10^{-16}
	Kaon	K^+	K^-	493.7	0	0	0	0	+1	1.24×10^{-8}
		K_S^0	$\bar{K}_S^0$	497.7	0	0	0	0	+1	0.89×10^{-10}
		K_L^0	$\bar{K}_L^0$	497.7	0	0	0	0	+1	5.2×10^{-8}
	Eta	η	Self	548.8	0	0	0	0	0	$< 10^{-18}$
		η'	Self	958	0	0	0	0	0	2.2×10^{-21}
Baryons	Proton	p	$\bar{p}$	938.3	+1	0	0	0	0	Stable
	Neutron	n	$\bar{n}$	939.6	+1	0	0	0	0	614
	Lambda	Λ^0	$\bar{\Lambda}^0$	1 115.6	+1	0	0	0	−1	2.6×10^{-10}
	Sigma	Σ^+	$\bar{\Sigma}^-$	1 189.4	+1	0	0	0	−1	0.80×10^{-10}
		Σ^0	$\bar{\Sigma}^0$	1 192.5	+1	0	0	0	−1	6×10^{-20}
		Σ^-	$\bar{\Sigma}^+$	1 197.3	+1	0	0	0	−1	1.5×10^{-10}
	Delta	Δ^{++}	$\bar{\Delta}^{--}$	1 230	+1	0	0	0	0	6×10^{-24}

Example: In the following pairs of proposed reactions, determine which ones are allowed and the relevant force at work

	$\pi^- + p \to \Sigma^0 + \eta^0$	$\pi^- + p \to \Sigma^0 + K^0$	$\Sigma^- \to \pi^- + n$	$\Sigma^- \to \pi^- + p$
Interaction:	strong		weak	
charge:	$-1 + 1 = 0 + 0$	$-1 + 1 = 0 + 0$	$-1 = -1 + 0$	~~$-1 = -1 + 1$~~
lepton number:	$0 + 0 = 0 + 0$	$0 + 0 = 0 + 0$	$0 = 0 + 0$	$0 = 0 + 0$
baryon number:	$0 + 1 = 1 + 0$	$0 + 1 = 1 + 0$	$1 = 0 + 1$	$1 = 0 + 1$
strangeness:	~~$0 + 0 = -1 + 0$~~	$0 + 0 = -1 + 1$	?	?
Isospin (I_3) :	~~$-1 + 1/2 = 0 + 0$~~	$-1 + 1/2 = 0 - 1/2$		

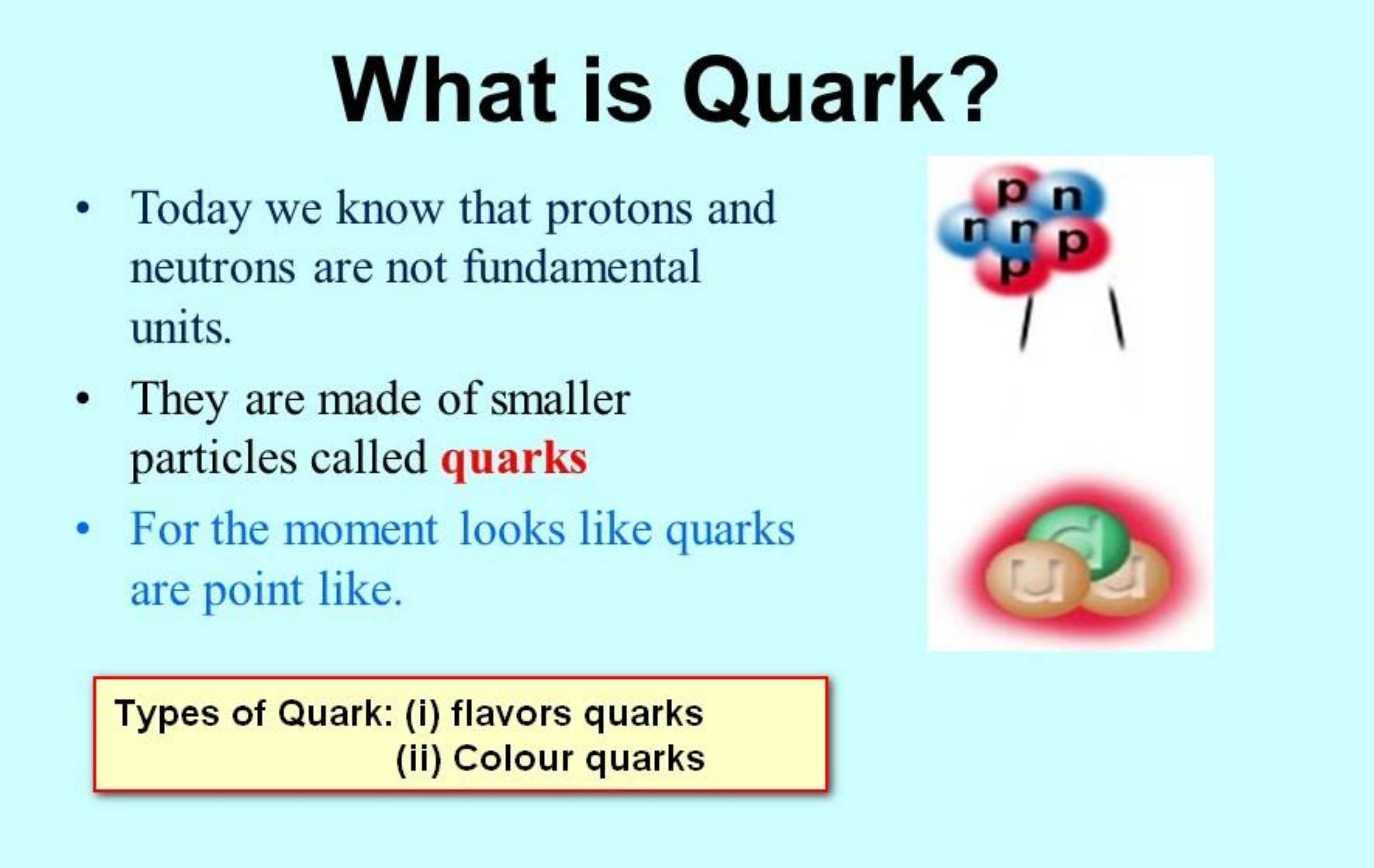
Section-4: Building blocks of matter



Classification of Matter

What is the world made of?

- Real world is not done by single quarks
- Quarks exist only in groups, to form the so-called hadrons (protons and neutrons are hadrons)
- Example: a proton is made of two quarks of up type and one quark of type down.
- The matter around, and even each of us, is made of quarks and of leptons.



What is Quark?

- Today we know that protons and neutrons are not fundamental units.
- They are made of smaller particles called **quarks**
- For the moment looks like quarks are point like.

Types of Quark: (i) flavors quarks
(ii) Colour quarks

Quark model

1929

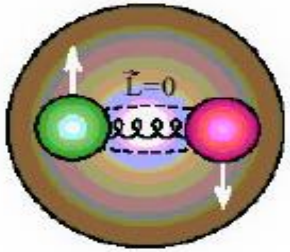
The quark model is a classification scheme for hadrons in terms of their valence quarks — the quarks and antiquarks which give rise to the quantum numbers of the hadrons.

The quark model in its modern form was developed by Murray Gell-Mann - american physicist who received the 1969 Nobel Prize in physics for his work on the theory of elementary particles.
*** QM - independently proposed by George Zweig**

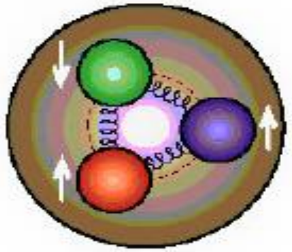
- **Hadrons are not ‚fundamental‘, but they are built from ‚valence quarks‘, i.e. quarks and antiquarks, which give the quantum numbers of the hadrons**

$$|\text{Baryon}\rangle = |qqq\rangle \qquad |\text{Meson}\rangle = |q\bar{q}\rangle$$

q= quarks, $\bar{q}$ – antiquarks



Meson ($q\bar{q}$)



Baryon (qqq)

Quark quantum numbers

The quark quantum numbers:

- flavor (6): u (up-), d (down-), s (strange-), c (charm-), t (top-), b(bottom-) quarks

  anti-flavor for anti-quarks $\bar{q}$: $\bar{u},\ \bar{d},\ \bar{s},\ \bar{c},\ \bar{t},\ \bar{b}$

- charge: Q = -1/3, +2/3 (u: 2/3, d: -1/3, s: -1/3, c: 2/3, t: 2/3, b: -1/3)
- baryon number: B=1/3 - as baryons are made out of three quarks
- spin: s=1/2 - quarks are the fermions!
- strangeness: $S_s = -1, \quad S_{\bar{s}} = 1, \quad S_q = 0$ for $q = u, d, c, t, b$ (and $\bar{q}$)
- charm: $C_c = 1, \quad C_{\bar{c}} = -1, \quad C_q = 0$ for $q = u, d, s, t, b$ (and $\bar{q}$)
- bottomness: $B_b = -1, \quad B_{\bar{b}} = 1, \quad B_q = 0$ for $q = u, d, s, c, t$ (and $\bar{q}$)
- topness: $T_t = 1, \quad T_{\bar{t}} = -1, \quad T_q = 0$ for $q = u, d, s, c, b$ (and $\bar{q}$)

Quark quantum numbers

The quark quantum numbers:

hypercharge: $Y = B + S + C + \mathcal{B} + T$ (1)

(= baryon charge + strangeness + charm + bottomness +topness)

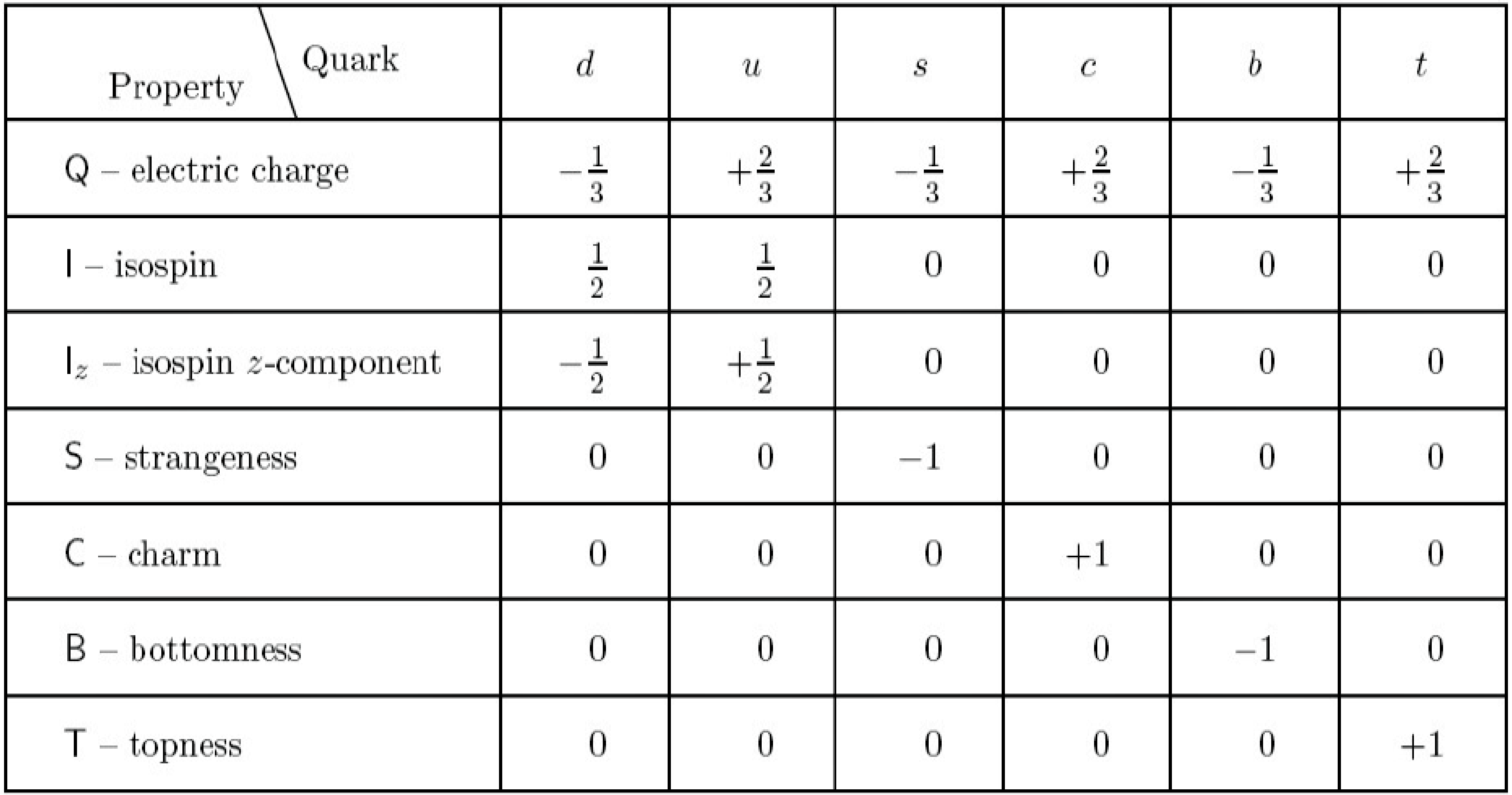
- I_3 (or I_z or T_3) - 3‘d component of isospin

charge (Gell-Mann–Nishijima formula):

$$Q = I_3 + Y/2 \qquad (2)$$

(= 3‘d component of isospin + hypercharge/2)

Quark quantum numbers



Property \ Quark	d	u	s	c	b	t
Q – electric charge	$-\frac{1}{3}$	$+\frac{2}{3}$	$-\frac{1}{3}$	$+\frac{2}{3}$	$-\frac{1}{3}$	$+\frac{2}{3}$
I – isospin	$\frac{1}{2}$	$\frac{1}{2}$	0	0	0	0
I_z – isospin z-component	$-\frac{1}{2}$	$+\frac{1}{2}$	0	0	0	0
S – strangeness	0	0	-1	0	0	0
C – charm	0	0	0	$+1$	0	0
B – bottomness	0	0	0	0	-1	0
T – topness	0	0	0	0	0	$+1$

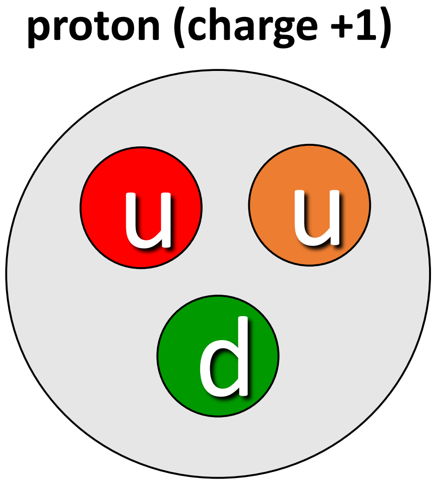
Protons and neutrons in the quark model

Question: **Why proton has positive and neutron has neutral charge?**

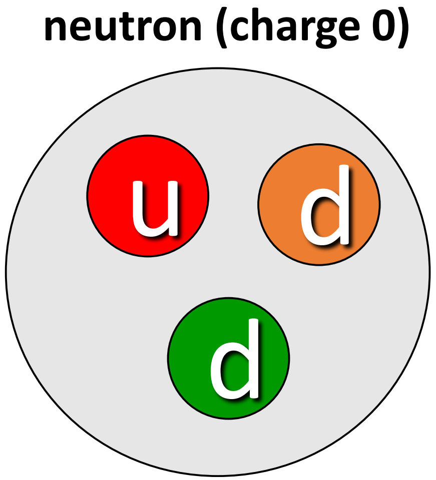
Quarks have fractional electric charge!

u electric charge + 2/3

d electric charge $-1/3$



proton (charge +1)



neutron (charge 0)

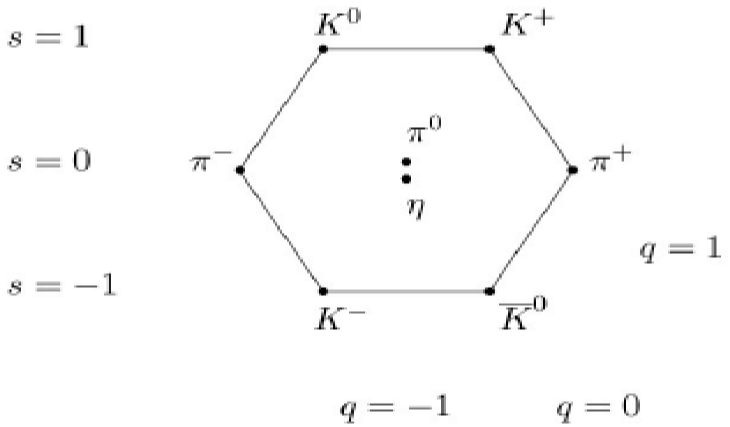
$$u\left(+\frac{2}{3}\right)u\left(+\frac{2}{3}\right)d\left(-\frac{1}{3}\right)=p(+1)$$

$$u\left(+\frac{2}{3}\right)d\left(-\frac{1}{3}\right)d\left(-\frac{1}{3}\right)=n(0)$$

Eightfold Way

The quark model is the follow-up to the Eightfold Way classification scheme (proposed by Murray Gell-Mann and Yuval Ne'eman)

The Eightfold Way may be understood as a consequence of flavor symmetries between various kinds of quarks. Since the strong nuclear force affects quarks the same way regardless of their flavor, replacing one flavor of a quark with another in a hadron should not change its mass very much. Mathematically, this replacement may be described by elements of the SU(3) group.



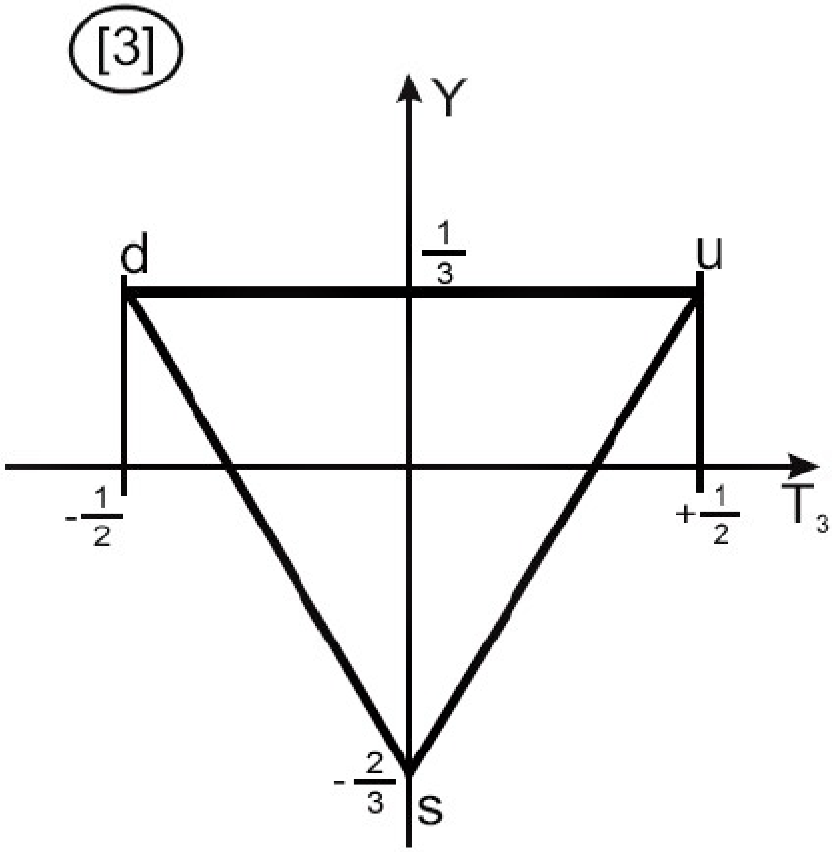
Consider u, d, s quarks :

➔ then the quarks lie in the fundamental representation, 3 (called the triplet) of the flavour group SU(3) : [3]

The antiquarks lie in the complex conjugate representation 3 : $[\bar{3}]$

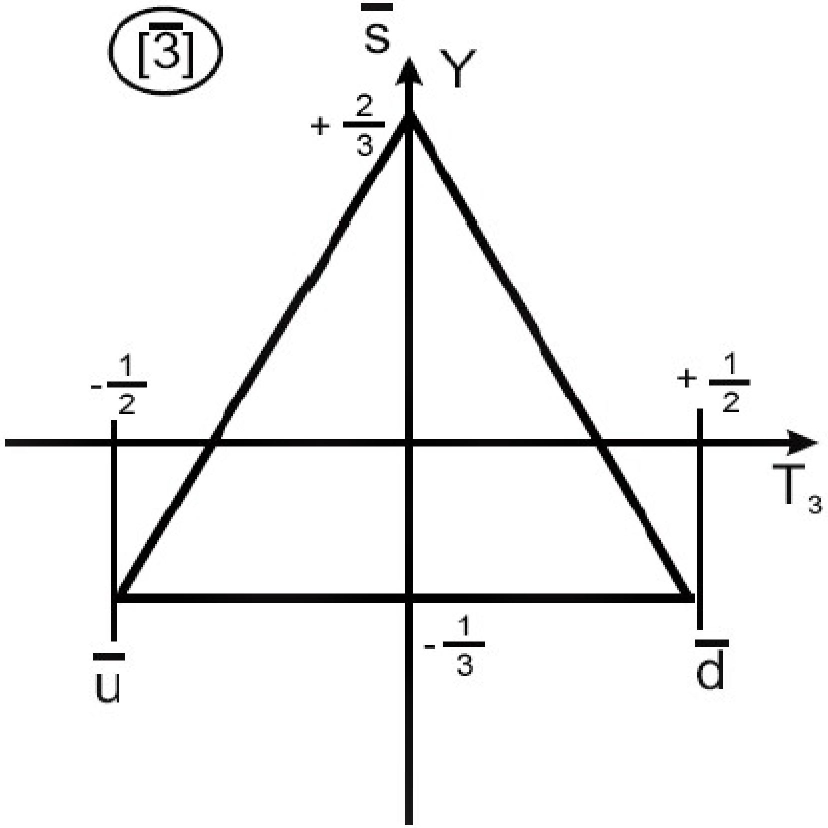
Representation of SU(3) flavor of quarks

triplet in $SU(3)_{flavor}$ group: [3]



$Y=2(Q-T_3)$

anti-triplet in $SU(3)_{flavor}$ group: $[\bar{3}]$



Mesons in the Quark model

$$|\,\text{Meson}\,\rangle = |\,q\bar{q}\,\rangle$$

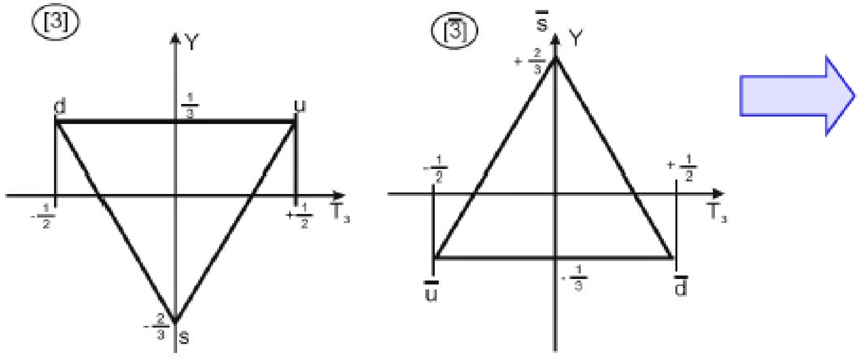
Quark
triplet in $SU(3)_{flavor}$ group: [3]

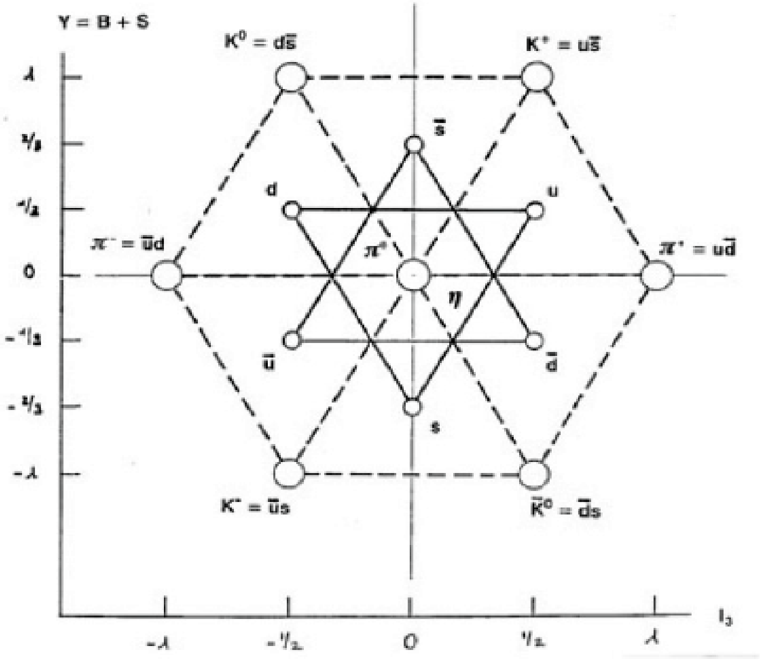
Anti-quark
anti-triplet in $SU(3)_{flavor}$ group: $[\bar{3}]$

From group theory: the nine states (nonet) made out of a pair can be decomposed into the trivial representation, 1 (called the singlet), and the adjoint representation, 8 (called the octet).

$$[3] \otimes [\bar{3}] = [8] \oplus [1]$$

octet + singlet





Baryons in the Quark model

$$|\text{Baryon}\rangle = |qqq\rangle$$

Quark

triplet in SU(3)$_{\text{flavor}}$ group: [3]

Eqs. (4-8): state function for baryons – antisymmetric under interchange of two quarks:

$$\Psi_A \equiv |qqq\rangle_A = [|\text{color}\rangle \otimes |\text{space}\rangle \otimes |\text{spin}\rangle \otimes |\text{flavor}\rangle]_A$$

where |flavor> state can be symmetric (S), antisymmetric (A) or mixed symmetry (M)

From group theory: with three flavours, the decomposition in flavour is

$$[3] \otimes [3] \otimes [3] = ([6]_S \oplus [\bar{3}]_A) \otimes [3] =$$

$$= ([6]_S \otimes [3]) \oplus ([\bar{3}] \otimes [3]) =$$

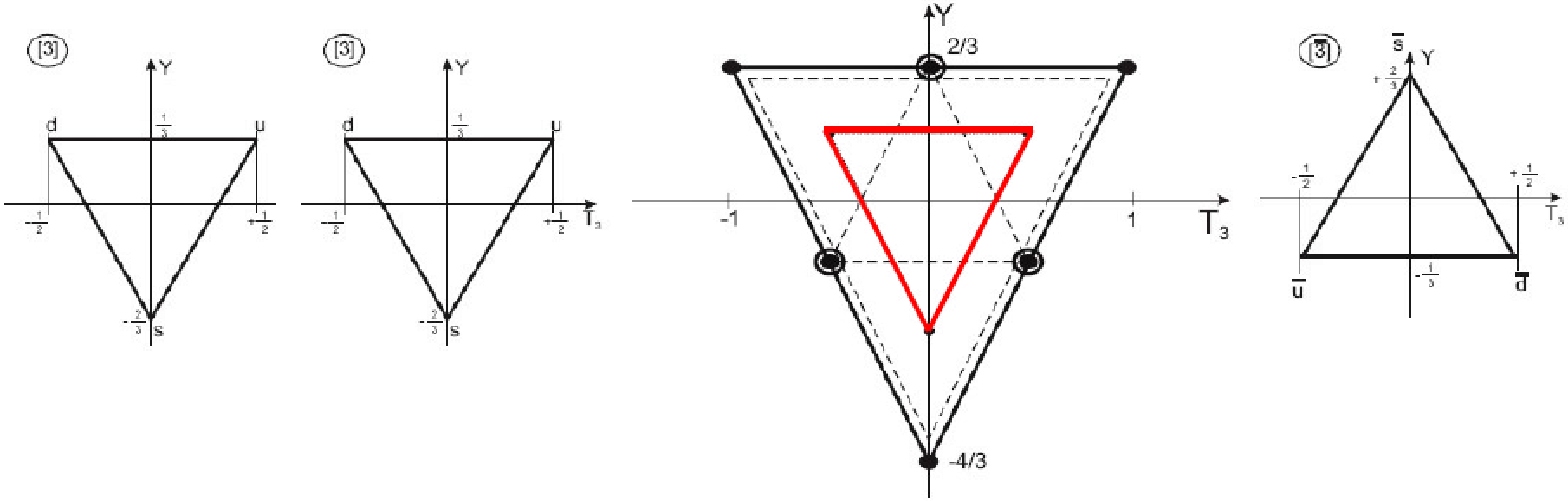
$$= \underset{\uparrow}{[10]_S} \oplus [8]_M \oplus [8]_M \oplus \underset{\uparrow}{[1]_A}$$

The decuplet is symmetric in flavour, the singlet antisymmetric and the two octets have mixed symmetry (they are connected by a unitary transformation and thus describe the same states).

Baryons in the Quark model

1) Combine first 2 quark triplets:

$$[3] \otimes [3] = [6]_S \oplus [\bar{3}]_A$$



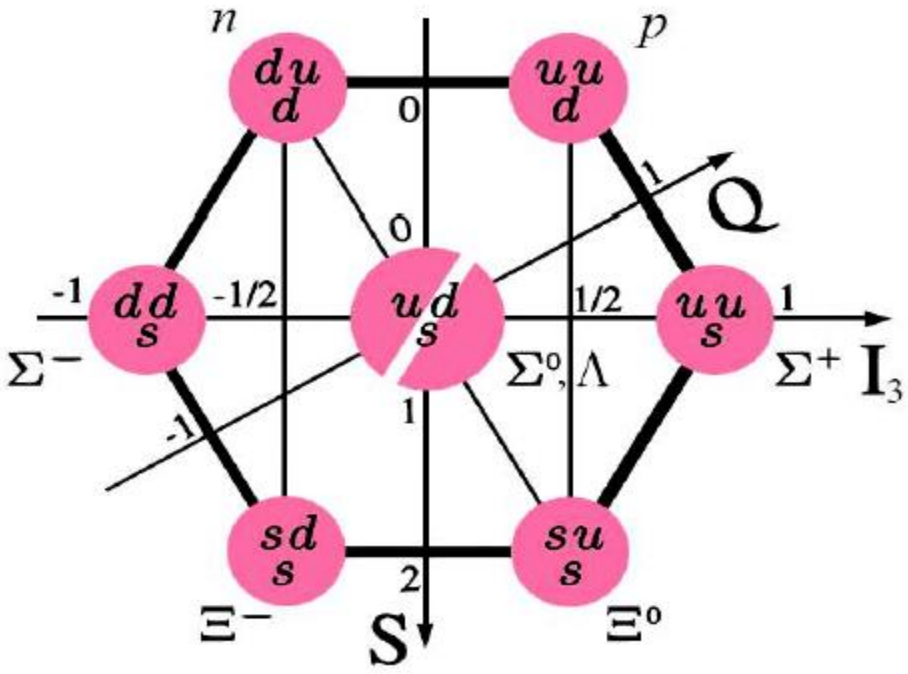
2) Add a 3'd quark:

$$[3] \otimes [3] \otimes [3] = ([6]_S \oplus [\bar{3}]_A) \otimes [3] =$$

$$= [10]_S \oplus \boxed{[8]_M \oplus [8]_M} \oplus [1]_A$$

Baryonic Octet and Decuplet

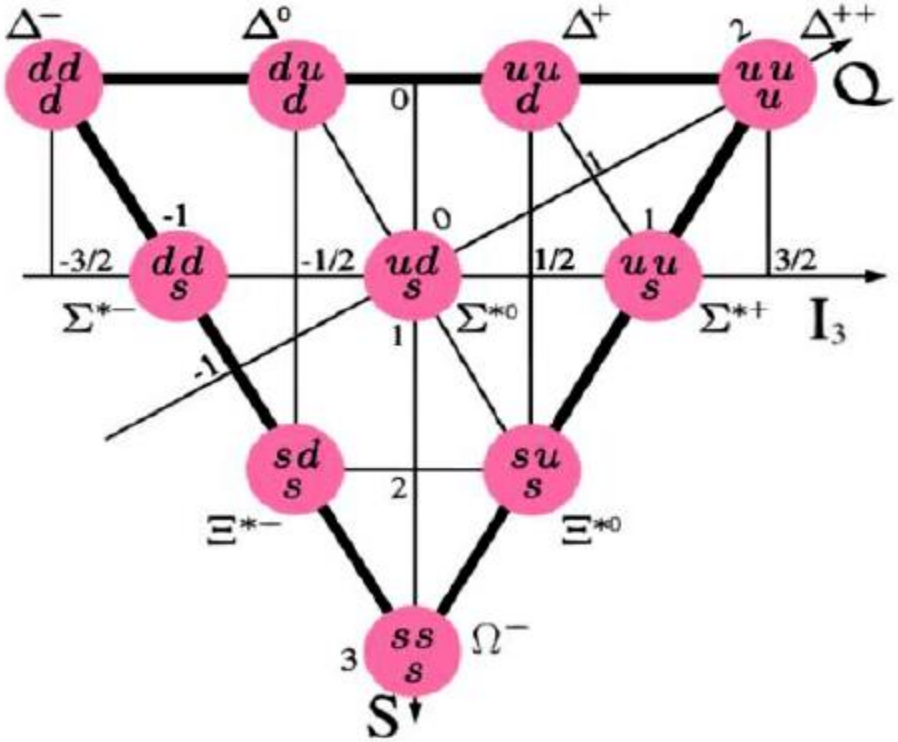
Octet [8]



Spin:
J=S
L=0

$$J^P = \frac{1}{2}^+$$

Decuplet [10]



J=S+L
L=1

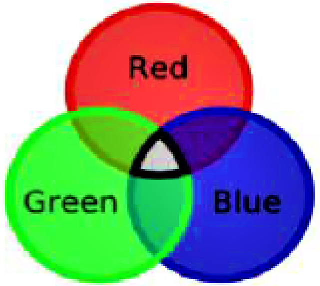
$$J^P = \frac{3}{2}^+$$

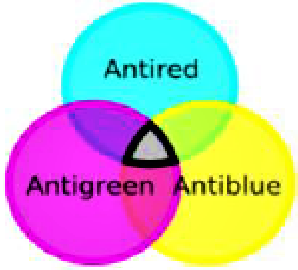
Color Quarks

The quark quantum numbers:

- **Collor 3: red, green and blue ➔ triplet in SU(3)$_{\text{collor}}$ group: [3]**

Anticollor 3: antired, antigreen and antiblue ➔ anti-triplet in SU(3)$_{\text{collor}}$ group [$\bar{3}$]





- **The quark colors (red, green, blue) combine to be colorless**
- **The quark anticolors (antired, antigreen, antiblue) also combine to be colorless**

All hadrons ➔ color neutral = color singlet in the SU(3)$_{\text{collor}}$ group

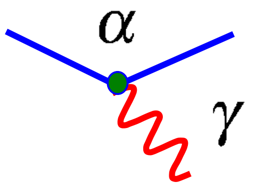
History: The quantum number ‚color‘ has been introduced (idea from Greenberg, 1964) to describe the state Δ^{++}(uuu) (Q=+2, J=3/2) , discovered by Fermi in 1951 as π^+p resonance: $\Delta^{++}(uuu) \to p(uud) + \pi^{+}(\bar{d}u)$
The state $\Delta^{++}(u\uparrow u\uparrow u\uparrow)$ **with all parallel spins (to achieve J=3/2) is forbidden according to the Fermi statistics (without color) !**

Colour in QCD

The theory of the strong interaction, Quantum Chromodynamics (QCD), is very similar to QED but with 3 conserved "colour" charges

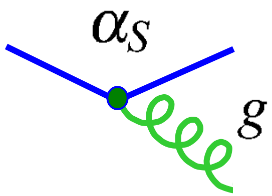
In QED:

- the electron carries one unit of charge $-e$
- the anti-electron carries one unit of anti-charge $+e$
- the force is mediated by a massless "gauge boson" – the photon



In QCD:

- quarks carry colour charge: r, g, b
- anti-quarks carry anti-charge: $\bar{r}, \bar{g}, \bar{b}$
- The force is mediated by massless gluons



In QCD, the strong interaction is invariant under rotations in colour space

$$r \leftrightarrow b;\ r \leftrightarrow g;\ b \leftrightarrow g$$

i.e. the same for all three colours

→ SU(3) colour symmetry

This is an exact symmetry, unlike the approximate uds flavour symmetry discussed previously.

Colour Confinement

- ✓ It is believed (although not yet proven) that all observed free particles are "colourless"
  - i.e. never observe a free quark (which would carry colour charge)
  - consequently quarks are always found in bound states colourless hadrons

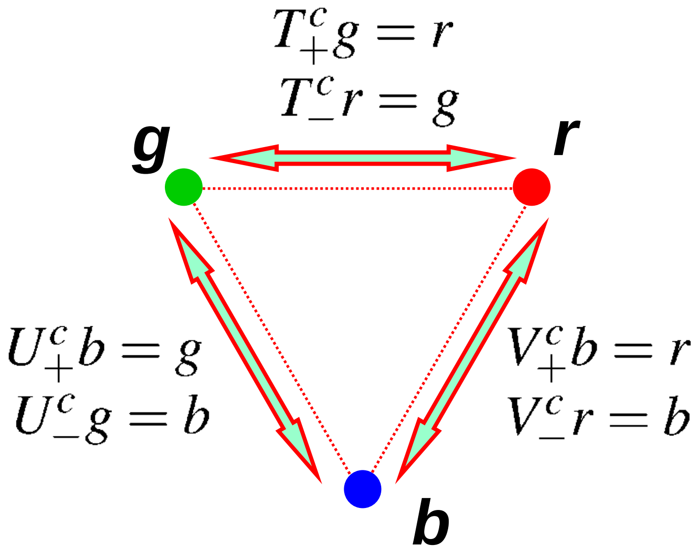
❑ **<u>Colour Confinement Hypothesis:</u>**

only <u>colour</u> <u>singlet</u> states can exist as free particles

- ✓ **All hadrons must be "colourless" i.e. colour singlets**
- ✓ **To construct colour wave-functions for hadrons, replace SU(3) flavour symmetry into SU(3) colour symmetry**

$$\boxed{\begin{array}{c} u \longrightarrow r \\ d \longrightarrow g \\ s \longrightarrow b \end{array}}$$

- ✓ **Just as for uds flavour symmetry can define colour ladder operators**



Section-5: Conclusion with the fundamental model of particles

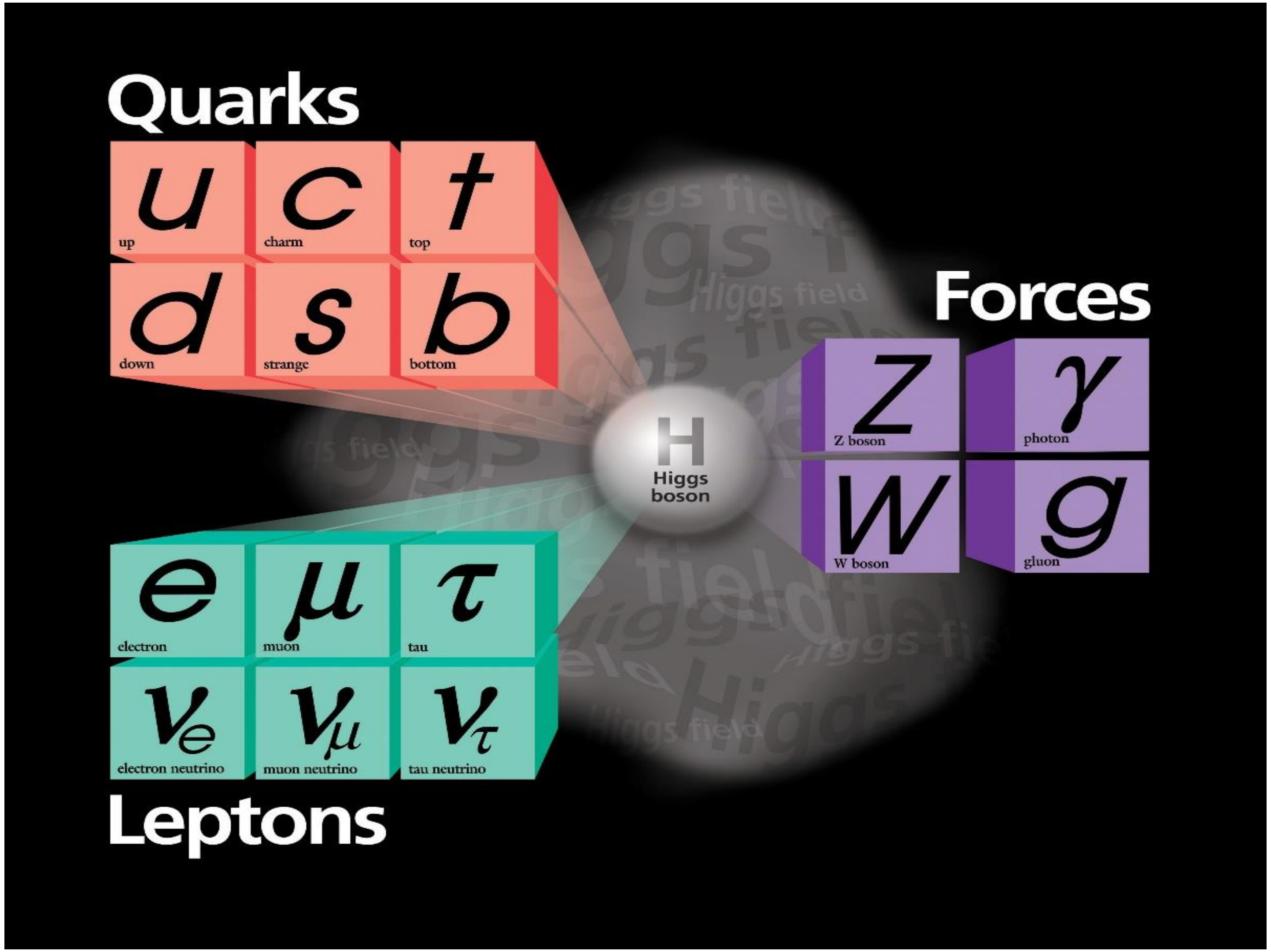
- Physicists have found hundreds of new particles.
- Today we know that most of them are not fundamental.

Now, question arises :

What is the Fundamental Model in particle physics?

A theory has been developed that seems to explain quite well what we do observe in nature: the theory is called Standard Model (SM).

The Standard Model



Framework which includes:

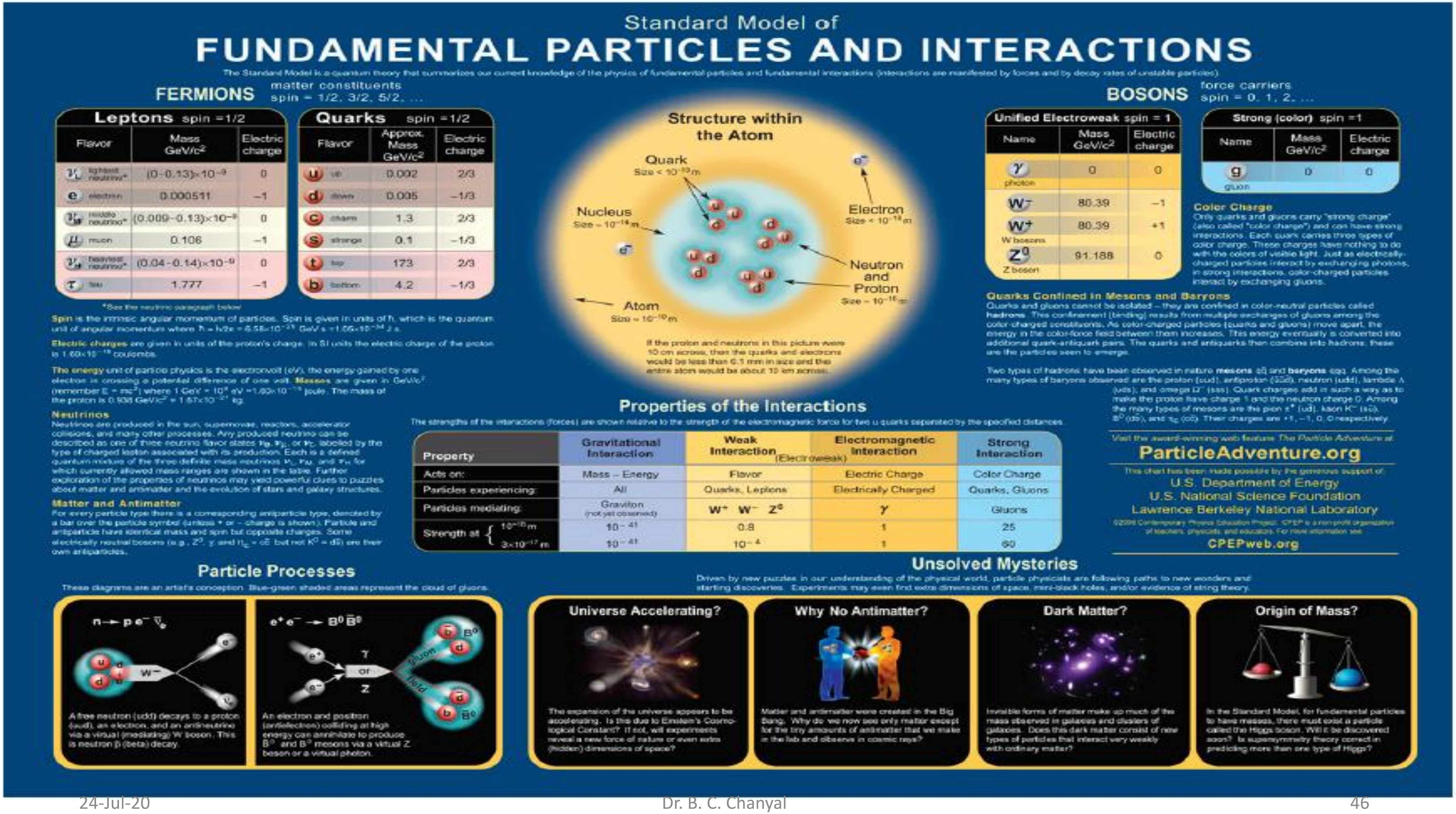
Matter:
- 6 quarks
- 6 leptons

Grouped in three generations

Forces:
- Electroweak:
  - g (photon)
  - Z^0, $W^\pm$
- Strong
  - g (gluon)

Not gravity! No quantum field theory of gravity.

The best theoretical framework we have for particle physics today



Standard Model of

FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model is a quantum theory that summarizes our current knowledge of the physics of fundamental particles and fundamental interactions (interactions are manifested by forces and by decay rates of unstable particles)

FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin =1/2

Flavor	Mass GeV/c²	Electric charge
ν_L lightest neutrino*	$(0-0.13)\times10^{-9}$	0
e electron	0.000511	–1
ν_M middle neutrino*	$(0.009-0.13)\times10^{-9}$	0
μ muon	0.106	–1
ν_H heaviest neutrino*	$(0.04-0.14)\times10^{-9}$	0
τ tau	1.777	–1

*See the neutrino paragraph below.

Quarks spin =1/2

Flavor	Approx. Mass GeV/c²	Electric charge
u up	0.002	2/3
d down	0.005	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	173	2/3
b bottom	4.2	–1/3

Spin is the intrinsic angular momentum of particles. Spin is given in units of ħ, which is the quantum unit of angular momentum where $\hbar = h/2\pi = 6.58\times10^{-25}$ GeV s $=1.05\times10^{-34}$ J s.

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.60×10^{-19} coulombs.

The energy unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/c² (remember $E = mc^2$) where 1 GeV = 10^9 eV $=1.60\times10^{-10}$ joule. The mass of the proton is 0.938 GeV/c² $= 1.67\times10^{-27}$ kg.

Neutrinos

Neutrinos are produced in the sun, supernovae, reactors, accelerator collisions, and many other processes. Any produced neutrino can be described as one of three neutrino flavor states ν_e, ν_μ, or ν_τ, labelled by the type of charged lepton associated with its production. Each is a defined quantum mixture of the three definite mass neutrinos ν_L, ν_M, and ν_H for which currently allowed mass ranges are shown in the table. Further exploration of the properties of neutrinos may yield powerful clues to puzzles about matter and antimatter and the evolution of stars and galaxy structures.

Matter and Antimatter

For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or – charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., Z^0, γ, and $\eta_c = c\bar{c}$ but not $K^0 = d\bar{s}$) are their own antiparticles.

Structure within the Atom

If the proton and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

BOSONS

force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c²	Electric charge
γ photon	0	0
W^-	80.39	–1
W^+ W bosons	80.39	+1
Z^0 Z boson	91.188	0

Strong (color) spin =1

Name	Mass GeV/c²	Electric charge
g gluon	0	0

Color Charge

Only quarks and gluons carry "strong charge" (also called "color charge") and can have strong interactions. Each quark carries three types of color charge. These charges have nothing to do with the colors of visible light. Just as electrically-charged particles interact by exchanging photons, in strong interactions, color-charged particles interact by exchanging gluons.

Quarks Confined in Mesons and Baryons

Quarks and gluons cannot be isolated – they are confined in color-neutral particles called **hadrons**. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs. The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge.

Two types of hadrons have been observed in nature **mesons** $q\bar{q}$ and **baryons** qqq. Among the many types of baryons observed are the proton (uud), antiproton ($\bar{u}\bar{u}\bar{d}$), neutron (udd), lambda Λ (uds), and omega Ω^- (sss). Quark charges add in such a way as to make the proton have charge 1 and the neutron charge 0. Among the many types of mesons are the pion π^+ ($u\bar{d}$), kaon K^- ($s\bar{u}$), B^0 ($d\bar{b}$), and η_c ($c\bar{c}$). Their charges are +1, –1, 0, 0 respectively.

Visit the award-winning web feature *The Particle Adventure* at

ParticleAdventure.org

This chart has been made possible by the generous support of:
U.S. Department of Energy
U.S. National Science Foundation
Lawrence Berkeley National Laboratory

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Properties of the Interactions

The strengths of the interactions (forces) are shown relative to the strength of the electromagnetic force for two u quarks separated by the specified distances.

Property	Gravitational Interaction	Weak Interaction (Electroweak)	Electromagnetic Interaction (Electroweak)	Strong Interaction
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge
Particles experiencing:	All	Quarks, Leptons	Electrically Charged	Quarks, Gluons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons
Strength at 10^{-18} m	10^{-41}	0.8	1	25
Strength at 3×10^{-17} m	10^{-41}	10^{-4}	1	60

Particle Processes

These diagrams are an artist's conception. Blue-green shaded areas represent the cloud of gluons.

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

A free neutron (udd) decays to a proton (uud), an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β (beta) decay.

$e^+ e^- \rightarrow B^0 \bar{B}^0$

An electron and positron (antielectron) colliding at high energy can annihilate to produce B^0 and $\bar{B}^0$ mesons via a virtual Z boson or a virtual photon.

Unsolved Mysteries

Driven by new puzzles in our understanding of the physical world, particle physicists are following paths to new wonders and startling discoveries. Experiments may even find extra dimensions of space, mini-black holes, and/or evidence of string theory.

Universe Accelerating?

The expansion of the universe appears to be accelerating. Is this due to Einstein's Cosmological Constant? If not, will experiments reveal a new force of nature or even extra (hidden) dimensions of space?

Why No Antimatter?

Matter and antimatter were created in the Big Bang. Why do we now see only matter except for the tiny amounts of antimatter that we make in the lab and observe in cosmic rays?

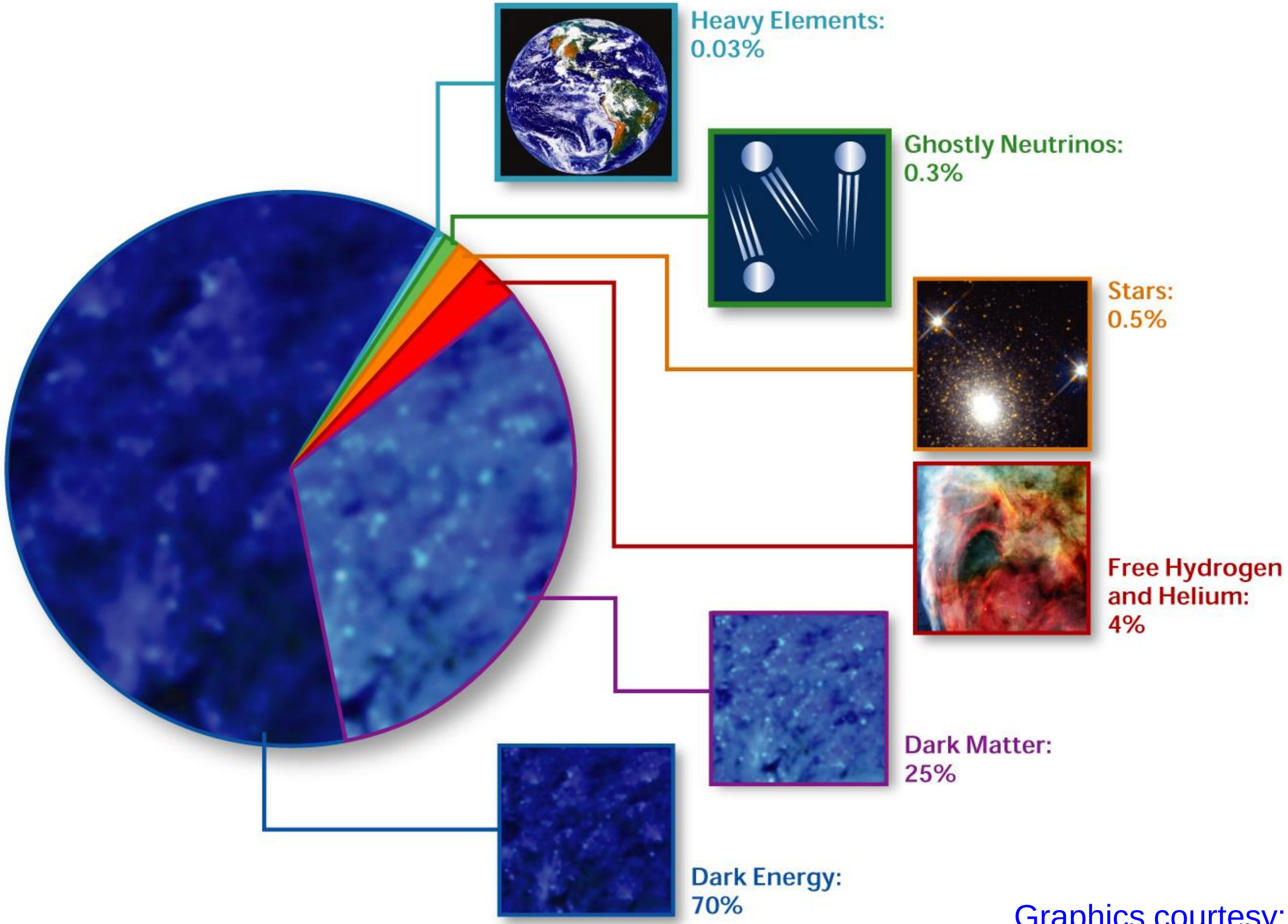
Dark Matter?

Invisible forms of matter make up much of the mass observed in galaxies and clusters of galaxies. Does this dark matter consist of new types of particles that interact very weakly with ordinary matter?

Origin of Mass?

In the Standard Model, for fundamental particles to have masses, there must exist a particle called the Higgs boson. Will it be discovered soon? Is supersymmetry theory correct in predicting more than one type of Higgs?

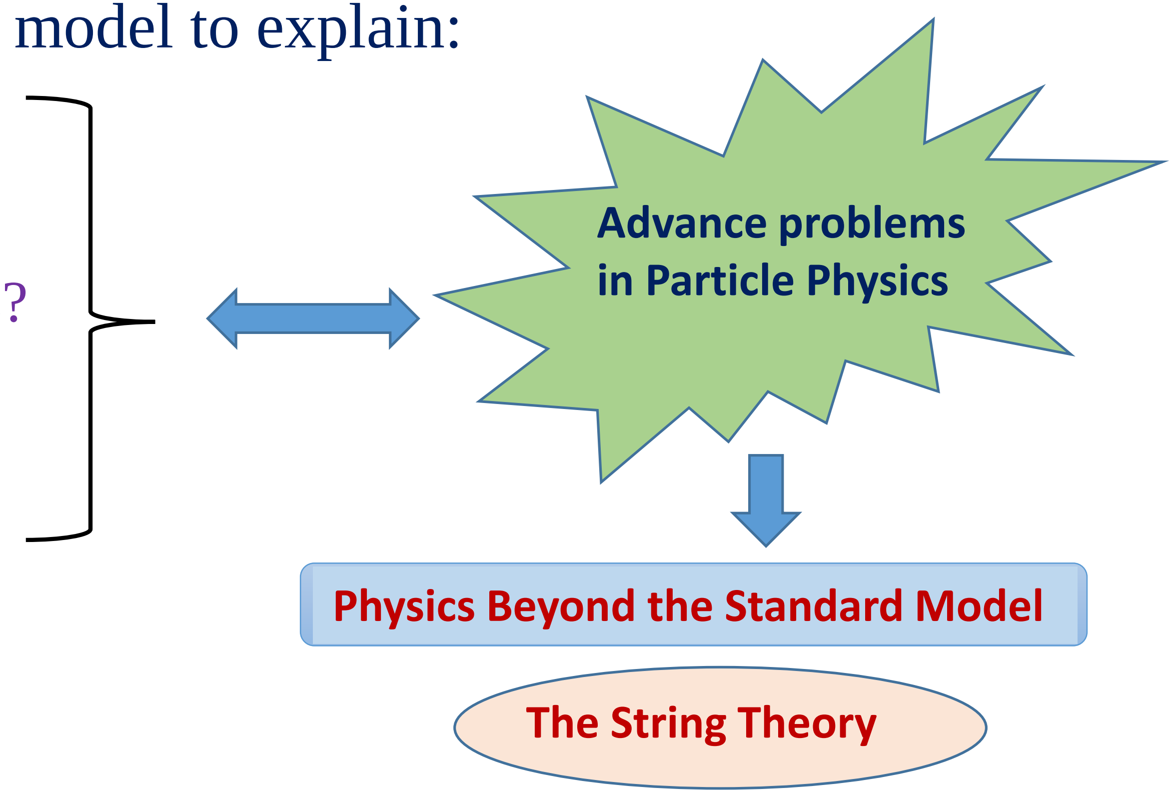
Composition of the Universe



Graphics courtesy: NASA

Mysteries, failures and new approach

- ✓ The SM is a theory of the Universe.
- ✓ It gives a good description of the phenomena which we observe experimentally.
- ✓ But under many respects it is incomplete model to explain:
  - What is the dark matter and dark matter?
  - What about gravity?
  - How can we unify all fundamental forces?
  - Existence of anti-matter in the universe?
  - Origin of Big-Bang? Etc…



Advance problems in Particle Physics

Physics Beyond the Standard Model

The String Theory

Suggested books:

- “Introduction to Elementary Particles”, **By D. Griffiths**
- “Quarks & Leptons”, **By F. Halzen & A. Martin**
- “The Experimental Foundations of Particle Physics”, **By R. Cahn & G. Goldhaber**
- “Gauge Theories in Particle Physics”, **By I.J.R. Aitchison & A.J.G. Hey**
- “Introduction to High Energy Phyics”, **By D.H. Perkins**

Thank you for the attention!

For any queries or questions, students can contact me on the given email id:

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- E-mail Id: bcchanyal@gmail.com