The Standard Model of Particles and Interactions
I- Introduction

Elsayed Ibrahim Lashin
Ain Shams University, Cairo Egypt
7-17 July 2025
The Fifth Summer School at CTP (Centre for Theoretical Physics), The British University in Egypt

Aims of Particle Physics

1. To understand nature at it's most fundamental level.

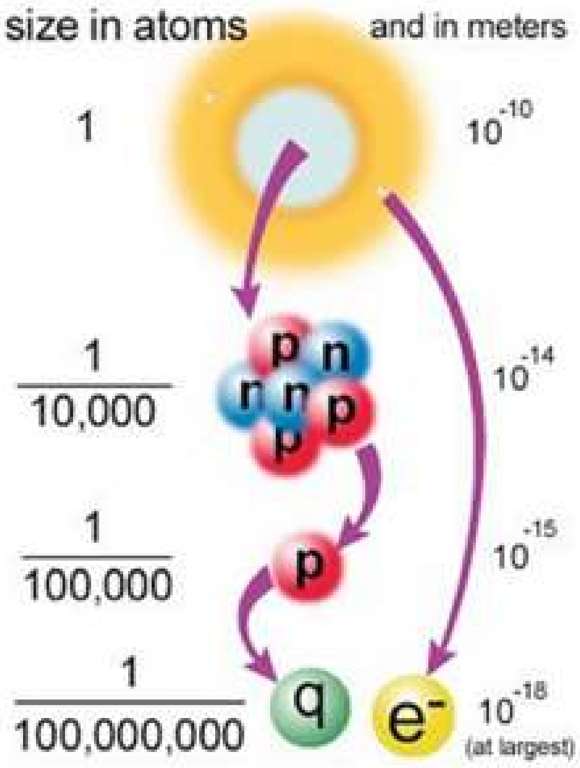
2. What are the smallest pieces of matter, and how do they make up the large scale structures that we see today ?

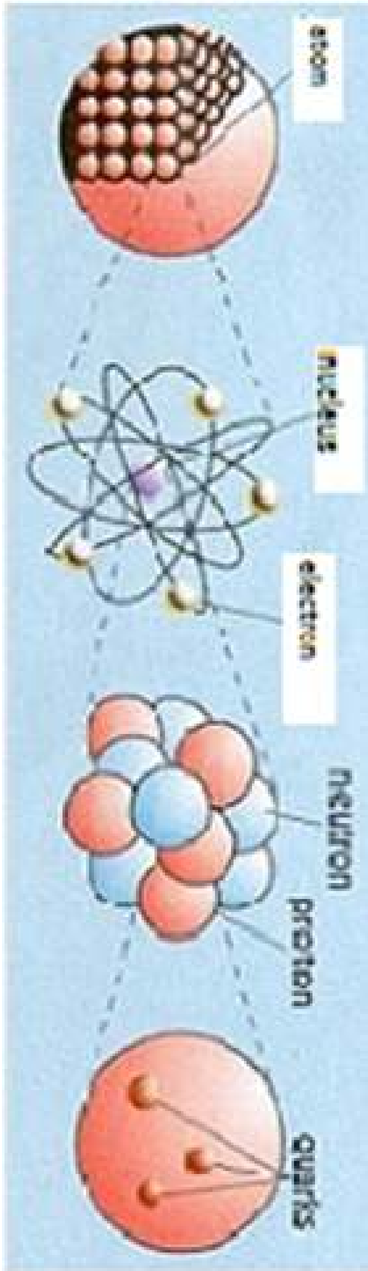
3. How and why do these 'fundamental particles' interact the way that they do?

4. Understand the fundamental forces in nature.

The Elementary Blocks of Matter

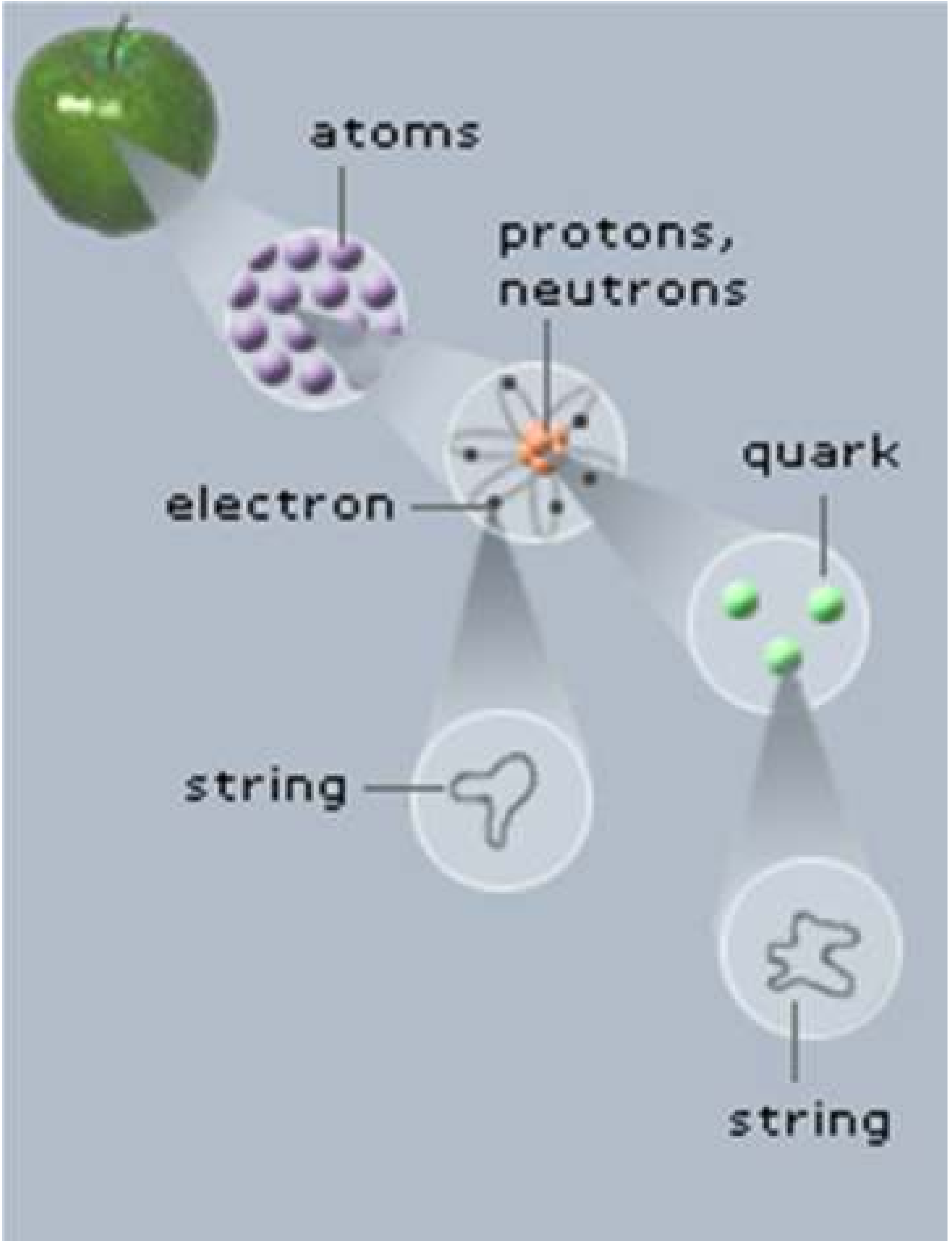
- ❑Matter is made of molecules
- ❑Molecules are built out of atoms
- ❑Atoms are made of nuclei and electrons
- ❑Nuclei are assemblies of protons and neutrons
- ❑Protons and neutrons are quarks bound together





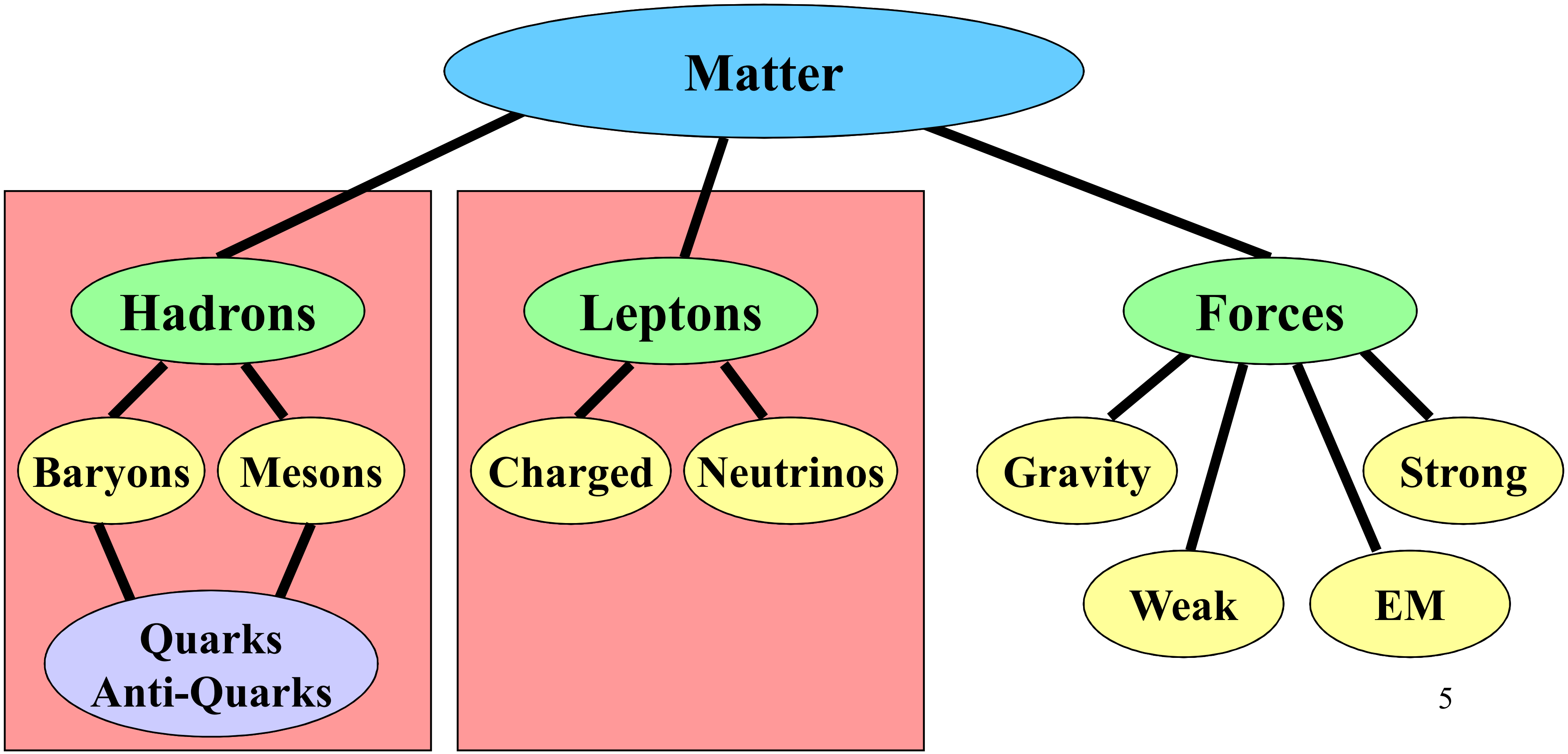
The volume of an atom corresponds to 10^24 times the volume of an electron.
Classically, matter contains a lot of void
Quantum mechanically, this void is populated by pairs of virtual pairs
Of particles

Building blocks of matter



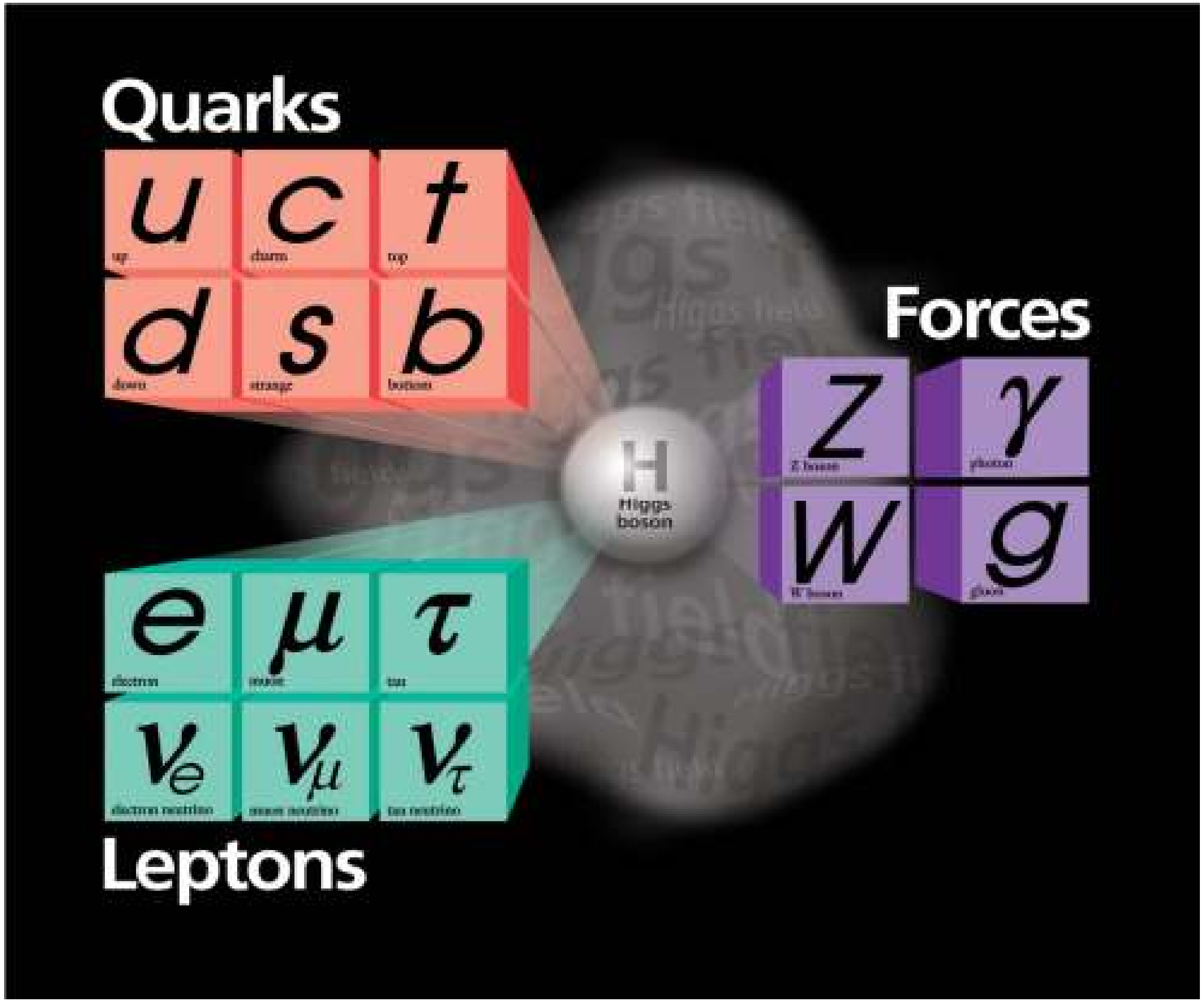
What IS Matter ?

- Matter is all the “stuff” around you!



Particles and Forces

Matter particles



Force particles

The Higgs

One of the most challenging questions physicists have been asking for ~50 years is:

Why do the quarks & leptons have the masses that they do?

Within the Standard Model of Particle Physics, there is a mechanism by which particles acquire their masses.

A prediction of this "mechanism", called **the Higgs mechanism**, is that there should exist a new particle, called the **Higgs particle, H^0**. This is not a quark, or lepton; **it's very different than any other particle we've talked about**…

If the Standard Model of Particle Physics is correct, we believe that this particle must exist….experiments have confirmed its existence!! 4 July 2012 , CMS collaboration announced the discovery of a boson

The mass of Higgs particle = 125 [GeV/c^2]

Understanding building blocks

I think I finally understand atoms

Plan to Introduce Particle Physics

Lecture 1: Introduction to QFT, Relativity, Kinematics and Symmetries

Lecture 2: Towards Gauge Theories

Lectures 3: Towards the Standard Model

Why High Energies

The Large Hadron Collider

➜ The LHC: the most gigantic microscope ever built

Going to higher energies ⇒ allows to study finer details

Particle Physics:
study of short distances

resolution limited by the de Broglie wavelength $\lambda = h/p$

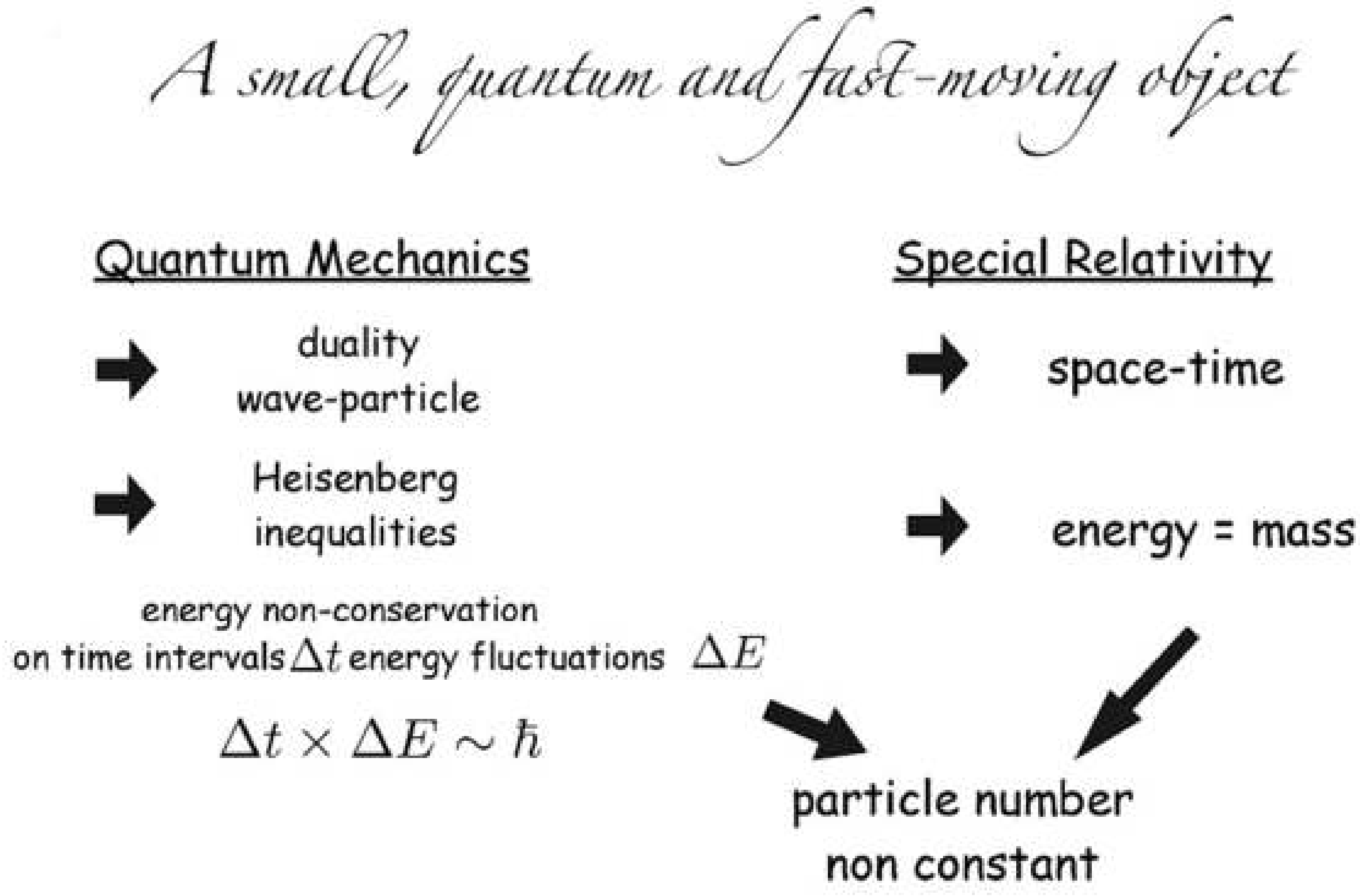
➜

High energy physics

high resolution necessitates large p

p>>m:
relativistic regime

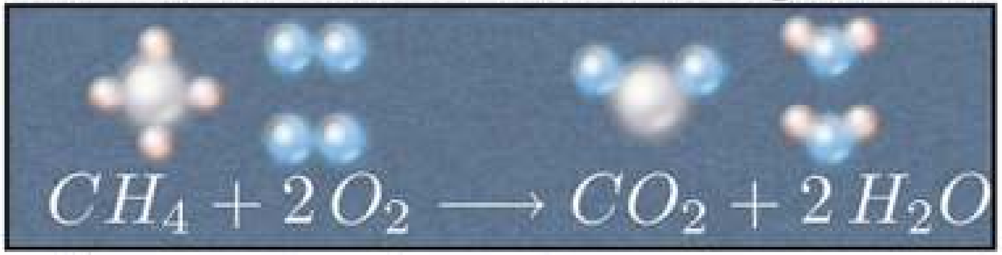
What is Particle ?



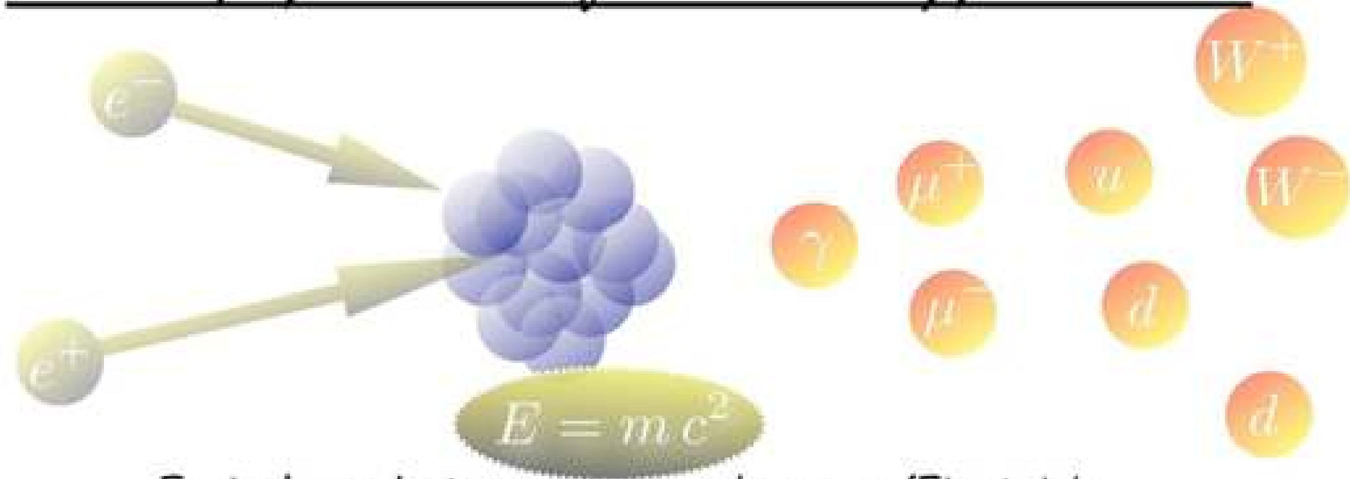
Creation of Matter from Energy

- ***Chemistry : rearrangement of matter***

  the different constituents of matter reorganize themselves



- ***Particle physics : transformation energy ↔ matter***



Equivalence between mass and energy (Einstein's idea) plays a very fundamental role in particle physics

Natural Units in High Energy Physics

The fundamental units have dimension of length (L), mass (M) and time (T).
All other units are derived from these.

The two universal constants in SI units

$\hbar = 1.055\times10^{-34}$ J s = 1.055×10^{-34} kg m^2/s and $c = 3\ 10^8$ m/s

In particle physics we work with units $\hbar = c = 1$

Thus, velocity of particle is measured in units of the speed of light, very natural in particle physics where $0 \le v < 1$ for massive particles and $v = 1$ for massless particles

In the c=1 unit:
[velocity]=pure number
[energy]=[momentum]=[mass]

notation: dimension of quantity P is [P]

Natural Units in High Energy Physics

$\hbar$ has dimension of [Energy]×[time].

$\hbar$/mc~length (from uncertainty principle $\Delta p \Delta x \geq \hbar/2$)
or de Broglie's formula $\lambda = h/p$

$\hbar = 1$ ---> [length]=[mass]$^{-1}$

Thus all physical quantities can be expressed as powers of mass or of length.

e.g. energy density, $E/L^3 \sim M^4$

$$\alpha = \frac{e^2}{4\pi\hbar c}$$ pure number

We specify one more unit taken as that of the energy, the GeV.

mass unit: $M\,c^2/c^2 = 1$ GeV

length unit: $\hbar c/M\,c^2 = 1\ \mathrm{GeV}^{-1} = 0.1975$ fm

time unit: $\hbar c/M\,c^3 = 1\ \mathrm{GeV}^{-1} = 6.59\ 10^{-25}$ s.

Natural Units in High Energy Physics

1 eV = 1.6 10^{-19} J

--> $\hbar$ c = 1.055×10^{-34} J s × 3 10^{8} m/s= 1.978×10^{-7} eV m

Using 1 fm = 10^{-15} m and 1 MeV = 10^{6} eV: $\hbar$ c = 197.8 MeV fm

So in natural units: $1 \text{ fm} \approx 1/(200 \text{ MeV})$

also, c=1 --> 1 fm ~ 3×10^{-24} s^{-1} --> $GeV^{-1} \sim 6 \times 10^{-25}\, s^{-1}$

$\hbar$= 1.055×10^{-34} kg m^2/s ----> GeV ~ 1.8×10^{-27} kg

1 TeV = 10^{12} eV

1 electron volt (eV) = *The energy of an electron accelerated by an electric potential difference of 1 volt. One* eV *is thus equal to …* $1.6\,10^{-19}\,\mathrm{J}$

1 kg of sugar = 4000 kCalories= 17 millions of Joules ≈ 10^{14} TeV

but 1 kg sugar ≈ 10^{27} protons --> 0.1 eV / protons

To accelerate each proton contained in 1 kg of matter at 14 TeV, we would need the energy of of 10^{14} kg of sugar* i.e. 1% of the world energy production

*world annual production of sugar=150 millions of tons≈10^{11} kg

How impressive is this?

energies involved at CERN: 1 TeV = 1000 billions of eV=$10^{-24}\mathrm{kg}$

compared with the kinetic energy of a mosquito $10^{-3}\,J \sim 10^{16}\,\mathrm{eV} \sim 10^{4}\mathrm{TeV}$

…however, in terms of energy density… this corresponds to the mass of the Earth concentrated in a 1 mm³ cube !

Why Relativity

Particle physics is all about creating and annihilating particles.
This can only occur if we can convert mass to energy and vice-versa, which requires relativistic kinematics

A bit of history

Contemplating the unusual invariance of Maxwell's equations under Lorentz transformation, Einstein stated that Lorentz invariance must be the invariance of our space and time.

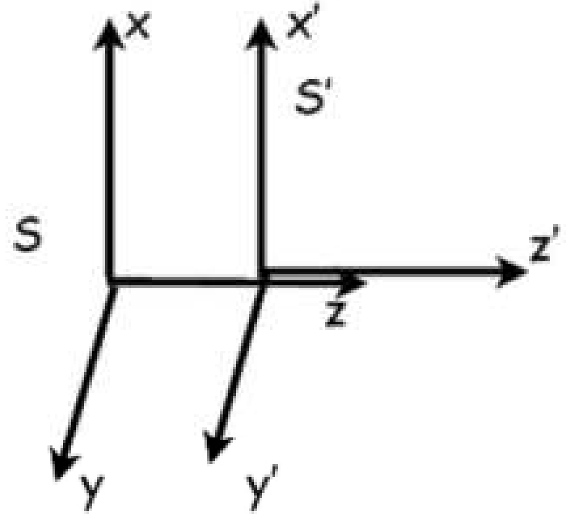
-> completely changed our view of space and time, so intertwined that it is now called spacetime, leading to exotic phenomena such as

- time dilation
- length contraction
- prediction of antimatter when special relativity is married with quantum mechanics

Relativistic Transformations

The two postulates of Special relativity

- Speed of light is the same in all reference frames
- Laws of physics are unchanged under a galilean transformation, i.e. in all reference frames moving at constant velocity with respect to each other



Look for coordinate transformations that satisfy these requirements

Unique choice: Lorentz transformations

$$\begin{pmatrix} ct' \\ z' \end{pmatrix} = \begin{pmatrix} \gamma & -\gamma\beta \\ -\gamma\beta & \gamma \end{pmatrix} \begin{pmatrix} ct \\ z \end{pmatrix}$$

$$\beta = \frac{v}{c}$$

$$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$$

Implication of Lorentz Transformations

$$\begin{pmatrix} ct' \\ z' \end{pmatrix} = \begin{pmatrix} \gamma & -\gamma\beta \\ -\gamma\beta & \gamma \end{pmatrix} \begin{pmatrix} ct \\ z \end{pmatrix} \qquad \beta = \frac{v}{c} \qquad \gamma = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}}$$

Time dilation

consider time interval $\tau = t'_2 - t'_1$ in S', the rest frame of a particle located at $z'_1 = z'_2 = 0$.

then in frame S where the particle is moving: $t_2 - t_1 = \gamma\tau$

-->The observed lifetime of a particle is $\gamma \times \tau$

so it can travel over a distance $\beta c \gamma \tau$

-->muons which have a lifetime $\tau \sim 2 \times 10^{-6}$ s produced by reaction of cosmic rays with atmosphere at 15-20 km altitude can reach the surface

length contraction

an object at rest in S' has length $L_0 = z'_2 - z'_1$

It measures in S $z_2 - z_1 = L_0/\gamma$

--> densities increase $\rho_0 = \Delta n/(\Delta x' \Delta y' \Delta z')$ $\rho = \Delta n/(\Delta x \Delta y \Delta z) = \gamma \rho_0$

$\Delta x \Delta y \Delta z \Delta t$ is invariant

4-Vectors

Time and space get mixed-up under Lorentz transformations. They are considered as different components of a single object, a four-component spacetime vector:

$$x^\mu = \begin{pmatrix} ct \\ x \\ y \\ z \end{pmatrix} = \begin{pmatrix} x^0 \\ x^1 \\ x^2 \\ x^3 \end{pmatrix} = \begin{pmatrix} x^0 \\ \vec{x} \end{pmatrix}$$

By construction: $x_\mu x^\mu = \mathbf{x}^2 = {x^0}^2 - \vec{x}^2$ is invariant

$d\tau = \sqrt{dt^2 - d\vec{x}^2}$ is invariant

Lorentz invariant action built with the proper time $d\tau$

$$S = -m \int d\tau = \int \mathcal{L} dt$$

$$\mathcal{L} = -m\sqrt{1 - \dot{x}^2}$$

$$\vec{p} = \frac{\partial \mathcal{L}}{\partial \dot{x}} = m\gamma\vec{\beta}$$

$$E = \vec{p}.\dot{x} - \mathcal{L} = m\gamma$$

$$\vec{p} = E\vec{\beta}$$

Energy-momentum four-vector

so we find: $$m^2 = E^2 - \vec{p}^2$$

This suggests to define the four-vector $$p^\mu = (\frac{E}{c}, p_x, p_y, p_z)$$

Relativity allows for mass-less particle but moving with the velocity of light (Examples, Photon, …..)

Conservation of energy-momentum

Consider collision between A and B

Define center of mass (CM) frame as where $\vec{p}_A + \vec{p}_B = 0$

Energy available in center of mass frame is an invariant: sqrt(s)= $E_* = E_A + E_B$

$$\mathbf{p}_{tot}^2 = E_*^2$$

1) Collision on fixed target

B is at rest in lab frame, $E_B = m_B$ and E_A is energy of incident particle

$$E_*^2 = m_A^2 + m_B^2 + 2m_B E_A$$

2) Colliding beams

A and B travel in opposite directions

$$E_*^2 = m_A^2 + m_B^2 + 2(E_A E_B + |p_A||p_B|) \approx 4E_A E_B$$

if $m_A, m_B \ll E_A, E_B$

So for fixed target machine $E_* \sim \sqrt{2m_B E_A}$

while for colliding beam accelerators $E_* \sim 2E$

To obtain 2 TeV in the CM with a fixed proton target accelerator the energy of a proton beam would need to be 2000 TeV!

Next step: marry quantum mechanics and relativity

non relativistic

(Schrodinger's equation cannot account for creation/annihilation of particles)

Schrödinger Equation (1926): $$\left(i\hbar\frac{\partial}{\partial t} + \frac{\hbar^2}{2m}\Delta - V \right)\Phi = 0$$

$$E = \frac{p^2}{2m} + V$$

classical ↔ quantum correspondance

$$E \rightarrow i\hbar\frac{\partial}{\partial t} \quad \& \quad p \rightarrow -i\hbar\frac{\partial}{\partial x}$$

⬇

relativistic

Klein-Gordon Equation (1927): $$\left(\frac{1}{c^2}\frac{\partial^2}{\partial t^2} - \Delta + \frac{m^2c^2}{\hbar^2} \right)\Phi = 0$$

$$\frac{E^2}{c^2} = p^2 + m^2c^2$$

negative energies $E = \pm(p^2 + m^2)^{1/2}$

and

does not admit a positive probability density

and does not describe fermions

Antimatter and Dirac equation

Dirac Equation (1928):

$$\left(i\gamma^\mu \partial_\mu - \frac{mc}{\hbar}\right)\Psi = 0$$

$$E = \begin{cases} +\sqrt{p^2c^2 + m^2c^4} & \text{matter} \\ -\sqrt{p^2c^2 + m^2c^4} & \text{antimatter} \end{cases}$$

$$\{\gamma^\mu, \gamma^\nu\} = 2\eta^{\mu\nu}$$

plane wave solution $\Psi(x,t) = u(p)e^{i(p.x - Et)/\hbar}$

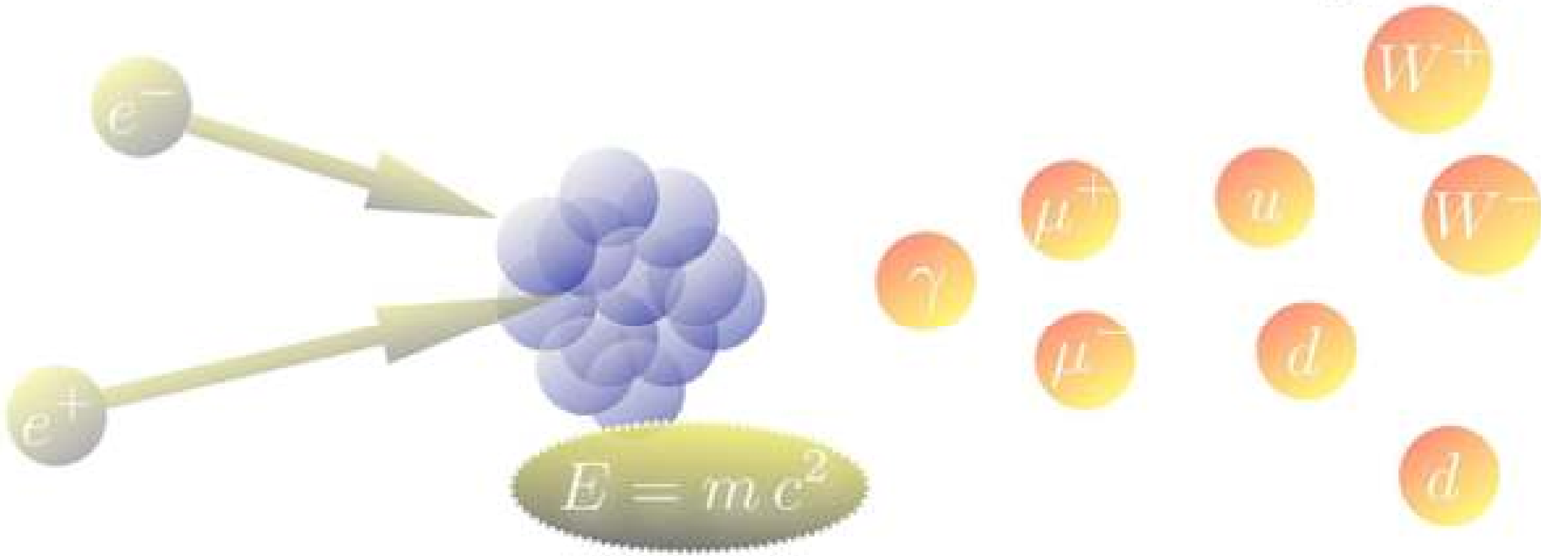
a particle of energy -E travelling backward in time -> antiparticle

positron (e^+) discovered by C. Anderson in 1932

conservation of fermion number: +1 for particles and -1 for antiparticles. fermions can only be created or destroyed in pairs

The necessity to introduce fields for a multiparticle description

Relativistic processes cannot be explained in terms of a single particle.
Even if there is not enough energy for creating several particles, they can still exist for a short amount of time because of uncertainty principle



We need a theory that can account for processes in which the number and type of particles changes like in most nuclear and particle reactions

quantization of a single relativistic particles does not work, we need quantization of fields -> Quantum Field Theory (QFT)

Quantum Field Theory

We want to describe A-> $C_1 + C_2$ or A+B-> $C_1 + C_2 + \ldots$

1) Associate a field to a particle

2) Write action $$S = \int d^4x \mathcal{L}(\phi_i, \partial_\mu \phi_i)$$

3) $\mathcal{L}$ invariant under Poincaré (Lorentz+translations) tranformations and internal symmetries

The symmetries of the lagrangian specify the interactions

4) Quantization of the fields

Symmetries and conservation laws: the backbone of particle physics

Noether's theorem (from classical field theory) :
A continuous symmetry of the system <-> a conserved quantity

I- Continuous global space-time symmetries:

translation invariance in space <-> momentum conservation
translation invariance in time <-> energy conservation
rotational invariance <-> angular momentum conservation

Fields are classified according to their transformation properties under Lorentz group:

$$x^\mu \to x'^\mu = \Lambda^\mu_\nu x^\nu \qquad \phi(x) \to \phi'(x')$$

$$\phi'(x') = \phi(x) \qquad \text{scalar}$$

$$V^\mu \to \Lambda^\mu_\nu V^\nu \qquad \text{vector}$$

$$\psi(x) \to \exp(-\frac{i}{2}\omega_{\mu\nu} J^{\mu\nu})\psi(x) \qquad \text{spinor}$$

The true meaning of spin arises in the context of a fully Lorentz-invariant theory (while it is introduced adhoc in non-relativistic quantum mechanics)

A field transforms under the Lorentz transformations in a particular way.

Picking a particular representation of the
Lorentz transformation specifies the spin.

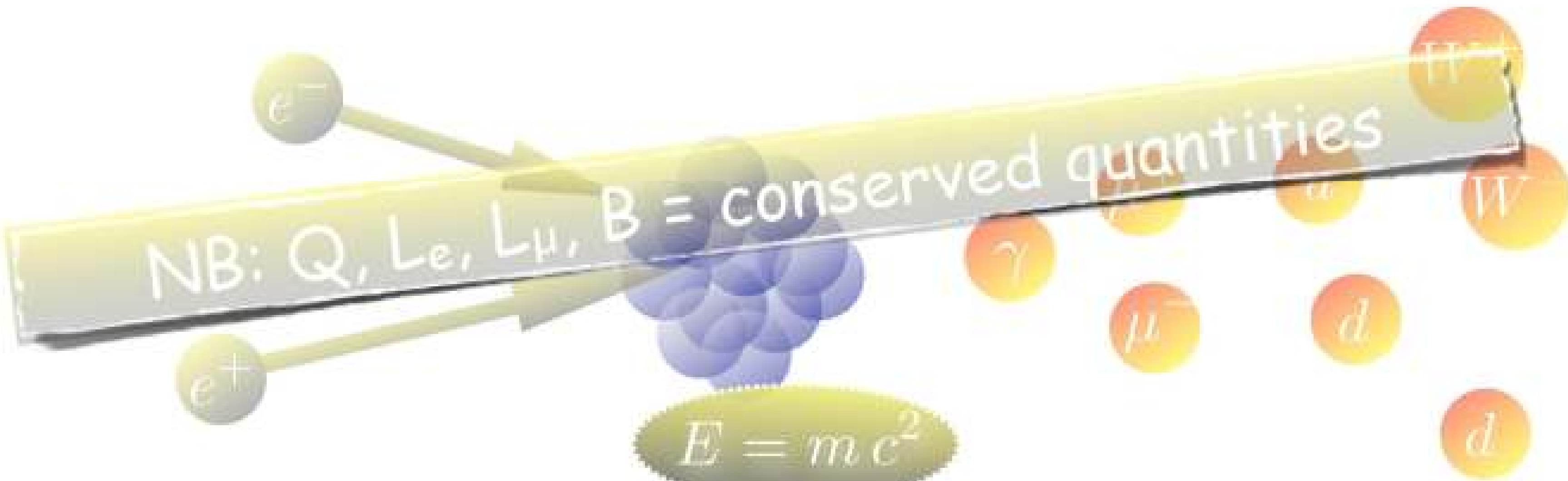
After quantizing the field, you find that the field operator can create or
annihilate a particle of definite spin

The spin is part of the field

II- Global (continuous) internal symmetries:

acting only on fields

conservation of baryon number and lepton number



Quantum numbers and Conservation laws

When the positron was discovered, it raised a naive question:
why can't a proton decay into a positron and a photon $p \to e^+ \gamma$?

This process would conserve momentum, energy, angular momentum, electric charge and even parity

This can be understood if we impose conservation of baryon number

Similarly, when the muon was discovered, it raised the question:
why doesn't a muon decay as $\mu^- \to e^- \gamma$?

This led to propose another quantum number: lepton family number

The following processes have not been seen.
Explain which conservation law forbids each of them

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

$$\mu^- \rightarrow e^- e^- e^+$$

$$n \rightarrow p\nu_e \bar{\nu}_e$$

$$p \rightarrow e^+ \pi^0$$

$$\tau^- \rightarrow \mu\gamma$$

$$K^0 \rightarrow \mu^+ e^-$$

$$\mu^- \rightarrow \pi^- \nu_\mu$$

The following processes have not been seen.
Explain which conservation law forbids each of them

$n \longrightarrow p\mu^- \bar{\nu}_\mu$	energy
$\mu^- \rightarrow e^- e^- e^+$	muon number or electron number
$n \longrightarrow p\nu_e\bar{\nu}_e$	electric charge
$p \longrightarrow e^+\pi^0$	baryon number or electron number
$\tau^- \longrightarrow \mu\gamma$	tau number or muon number
$K^0 \rightarrow \mu^+ e^-$	muon number or electron number
$\mu^- \rightarrow \pi^- \nu_\mu$	energy

So why does matter appear to be so rigid ?

Forces, forces, forces !!!!

It is primarily the strong and electromagnetic forces which give matter its solid structure.

Strong force ➔ defines nuclear 'size'

Electromagnetic force ➔ defines atomic 'sizes'

So why is this stuff interesting/important?

- **All matter, including us, takes on its shape and structure because of the way that quarks, leptons and force carriers behave.**
- **Our bodies, and the whole universe is almost all empty space !**
- **By studying these particles and forces, we're trying to get at the question which has plagued humans for millenia …**

How did the universe start ?
And how did we emerge from it all ?
Where's has all the antimatter gone ?

Generation 1						
Fermion (left-handed)	Symbol	Electric charge	Weak isospin	Hypercharge	Color charge *	Mass **
Electron	e^-	-1	$-1/2$	$-1/2$	$\mathbf{1}$	511 keV
Positron	e^+	$+1$	0	$+1$	$\mathbf{1}$	511 keV
Electron-neutrino	ν_e	0	$+1/2$	$-1/2$	$\mathbf{1}$	< 2 eV
Up quark	u	$+2/3$	$+1/2$	$+1/6$	$\mathbf{3}$	~ 3 MeV ***
Up antiquark	$\bar{u}$	$-2/3$	0	$-2/3$	$\bar{\mathbf{3}}$	~ 3 MeV ***
Down quark	d	$-1/3$	$-1/2$	$+1/6$	$\mathbf{3}$	~ 6 MeV ***
Down antiquark	$\bar{d}$	$+1/3$	0	$+1/3$	$\bar{\mathbf{3}}$	~ 6 MeV ***

Generation 2						
Fermion (left-handed)	Symbol	Electric charge	Weak isospin	Hypercharge	Color charge *	Mass **
Muon	μ^-	-1	$-1/2$	$-1/2$	$\mathbf{1}$	106 MeV
Antimuon	μ^+	$+1$	0	$+1$	$\mathbf{1}$	106 MeV
Muon-neutrino	ν_μ	0	$+1/2$	$-1/2$	$\mathbf{1}$	< 2 eV
Charm quark	c	$+2/3$	$+1/2$	$+1/6$	$\mathbf{3}$	~ 1.3 GeV
Charm antiquark	$\bar{c}$	$-2/3$	0	$-2/3$	$\bar{\mathbf{3}}$	~ 1.3 GeV
Strange quark	s	$-1/3$	$-1/2$	$+1/6$	$\mathbf{3}$	~ 100 MeV
Strange antiquark	$\bar{s}$	$+1/3$	0	$+1/3$	$\bar{\mathbf{3}}$	~ 100 MeV

Generation 3						
Fermion (left-handed)	Symbol	Electric charge	Weak isospin	Hypercharge	Color charge *	Mass **
Tau lepton	τ^-	-1	$-1/2$	$-1/2$	$\mathbf{1}$	1.78 GeV
Anti-tau lepton	τ^+	$+1$	0	$+1$	$\mathbf{1}$	1.78 GeV
Tau-neutrino	ν_τ	0	$+1/2$	$-1/2$	$\mathbf{1}$	< 2 eV
Top quark	t	$+2/3$	$+1/2$	$+1/6$	$\mathbf{3}$	171 GeV
Top antiquark	$\bar{t}$	$-2/3$	0	$-2/3$	$\bar{\mathbf{3}}$	171 GeV
Bottom quark	b	$-1/3$	$-1/2$	$+1/6$	$\mathbf{3}$	~ 4.2 GeV
Bottom antiquark	$\bar{b}$	$+1/3$	0	$+1/3$	$\bar{\mathbf{3}}$	~ 4.2 GeV