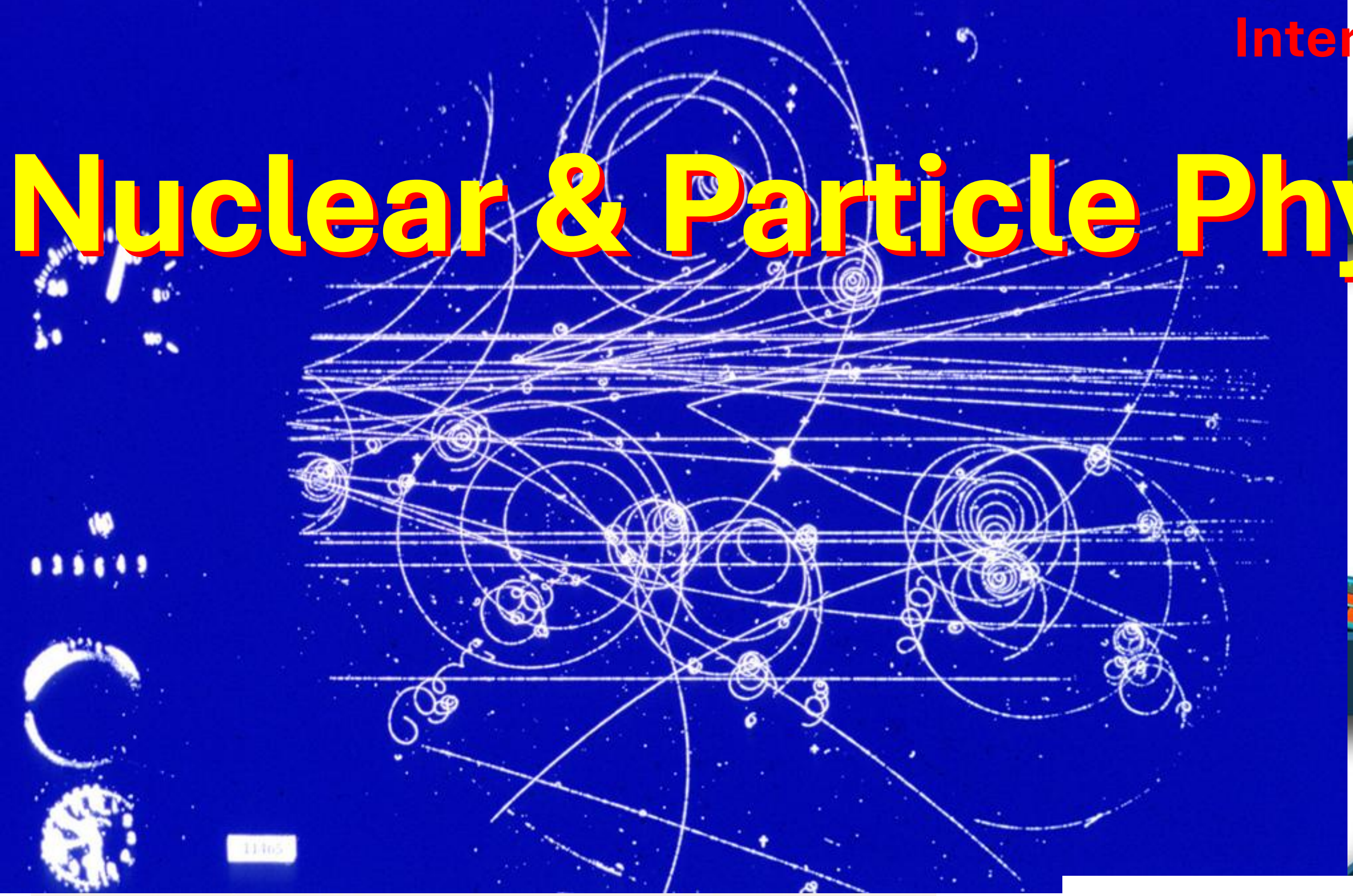
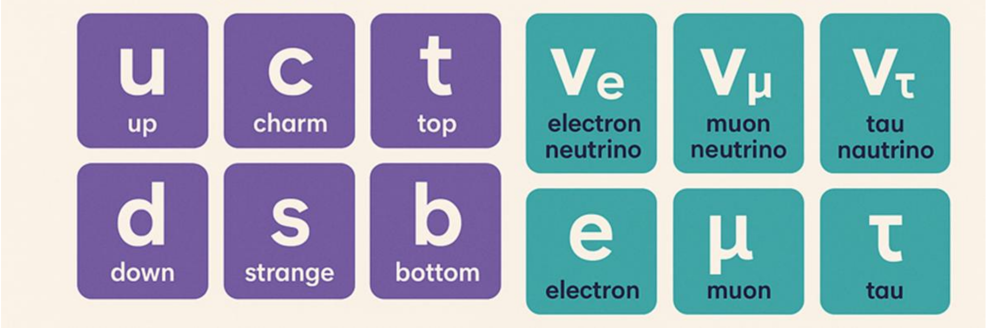
International Advanced Level A2-Physics

Nuclear & Particle Physics





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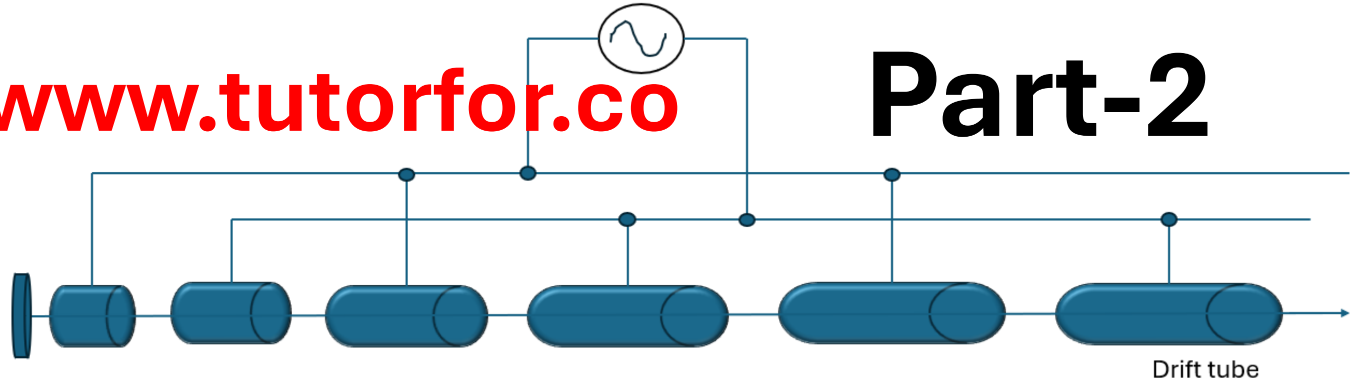
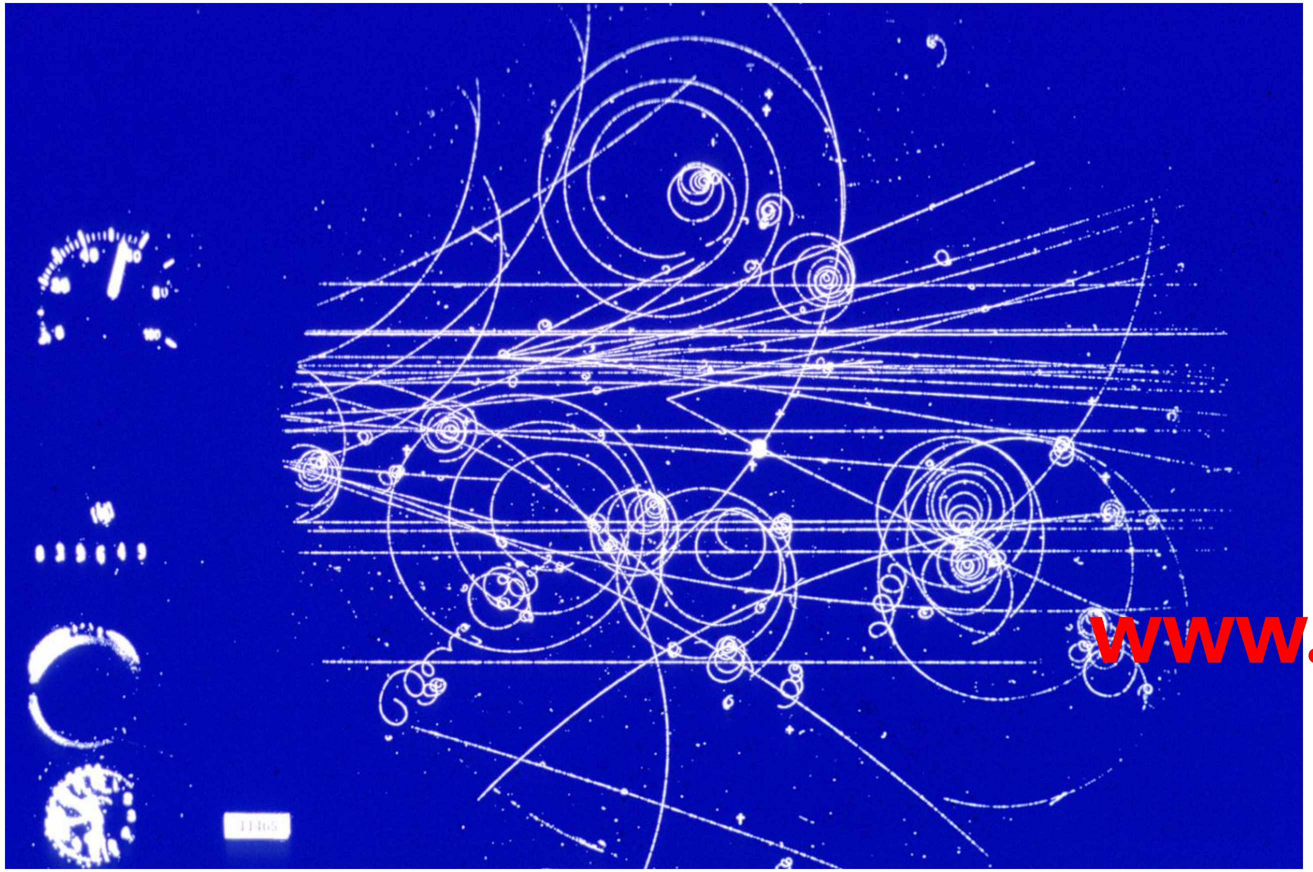
Part-2



Youtube: TutorFor ExamPhysics

Particle detectors.

Hydrogen Bubble Chamber



What is a Bubble Chamber?

Important!

- A bubble chamber is a vessel filled with a superheated liquid, usually liquid hydrogen in this case.
- When a charged particle passes through this liquid, it ionizes the atoms along its path.

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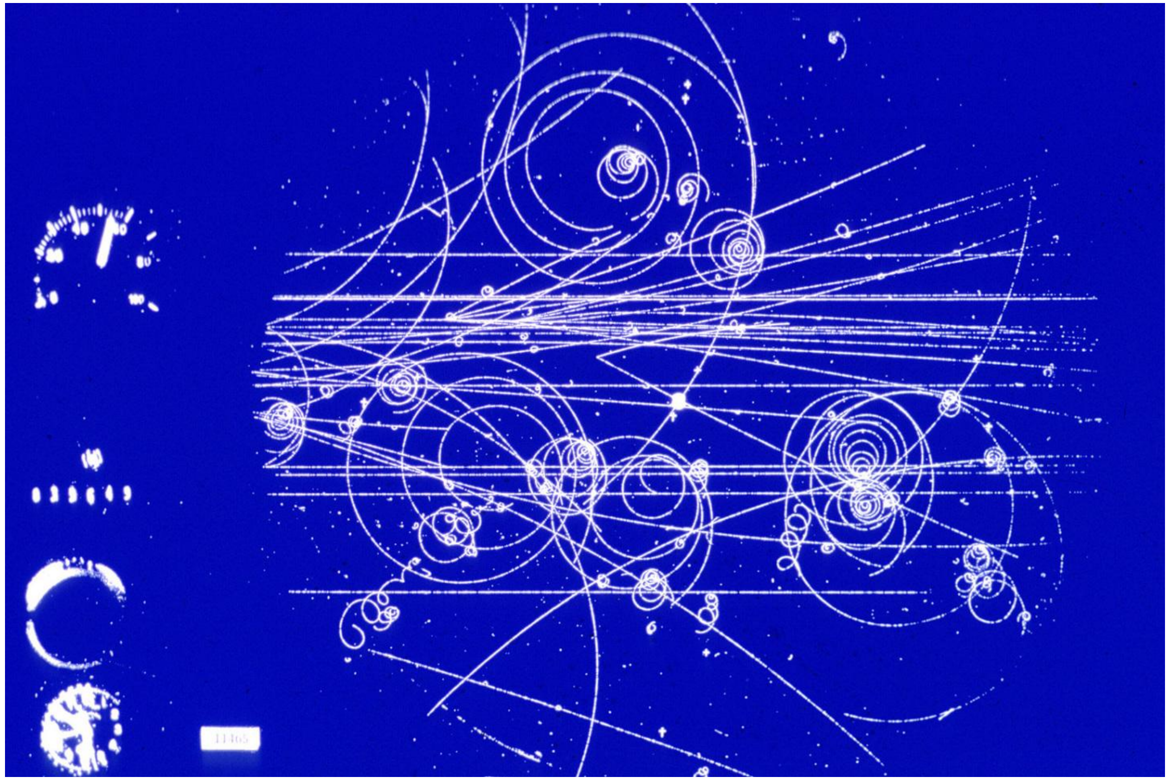


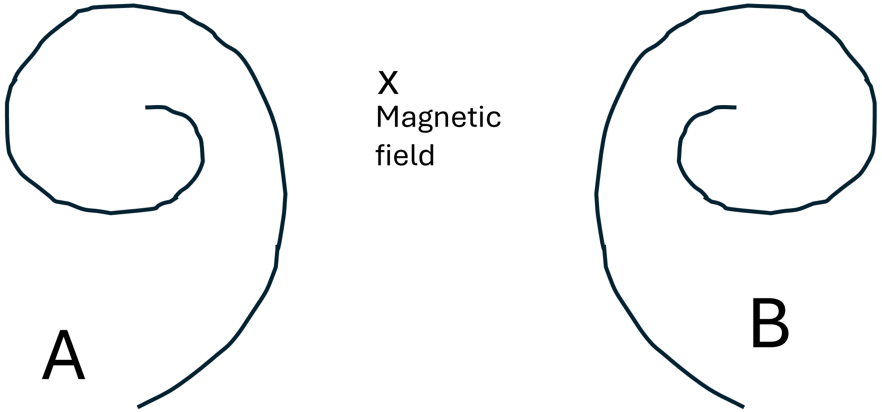
- The ionized path triggers the formation of tiny bubbles, which can be photographed and analyzed to determine the properties of the particle.

Detecting Particles

Important!

Curved tracks indicate particles affected by a magnetic field (often applied perpendicularly), allowing measurement of:

Momentum (from curvature)



$$r = \frac{mv}{Bq}$$

Particle losing kinetic energy on the way. Radius decreases making it spirally inwards.

Charge (positive or negative from direction of curvature)-

Path A and B shows oppositely charged particles. (Use Flemings left hand Rule to find the charge of particles)

Branching points

Important!

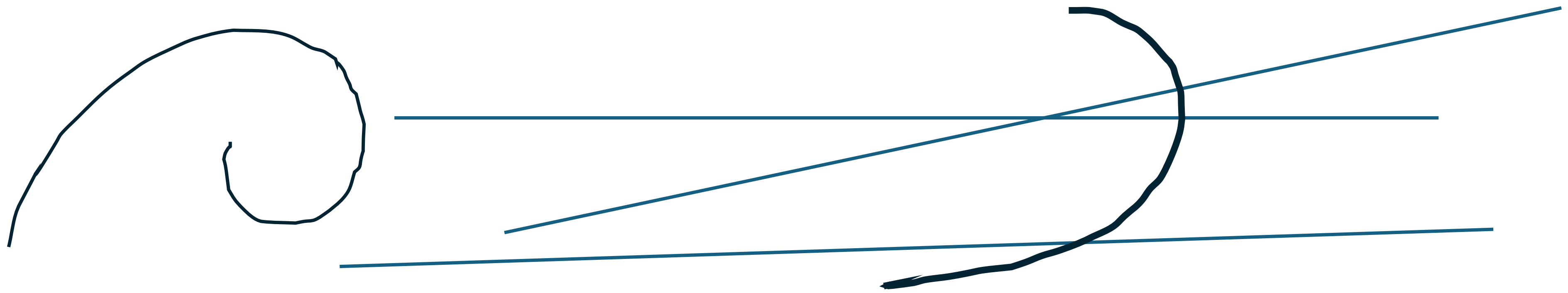
These indicates decay or interacting points where particle transforms into others.

Ex: Neutral particle which leave no track decay into two opposite particles.

Straight tracks and Thickness

Important!

Straight tracks usually correspond to neutral particles that do not interact electromagnetically.



Thicker bubbles corresponds to more ionization meaning heavier or slow-moving particles.

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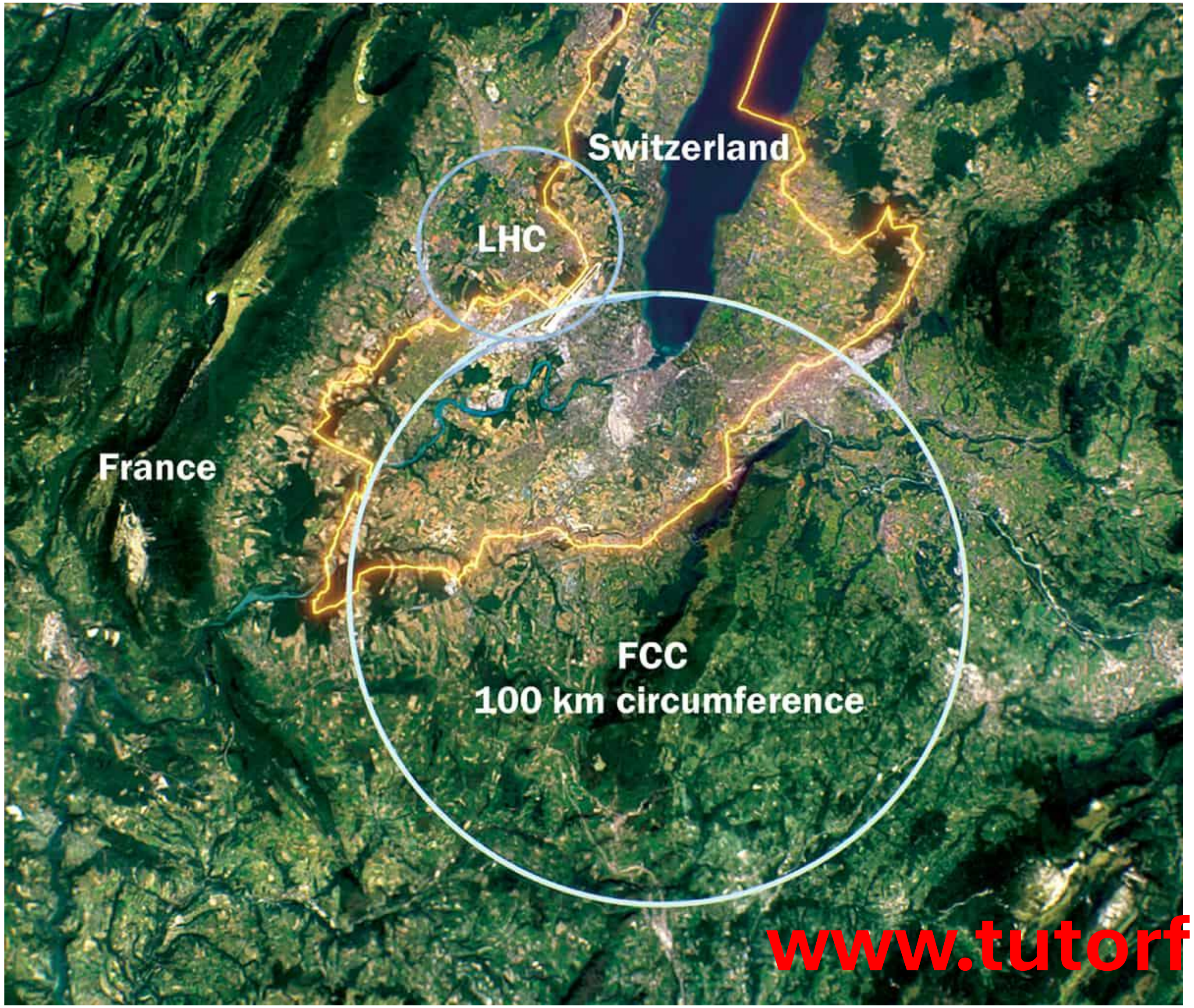
Thiner track suggest lighter or faster moving particles.

The Large Hadron Collider (A Synchrotron)



Reference!

The Large Hadron Collider (LHC) is the world's largest and most powerful particle accelerator, located at CERN (the European Organization for Nuclear Research) near Geneva, on the border between Switzerland and France. It consists of a 27-kilometer circular tunnel buried underground.

The Large Hadron Collider

Reference!

The LHC accelerates protons and heavy ions close to the speed of light and collides them to study fundamental particles and the forces that govern their interactions. These high-energy collisions recreate conditions similar to those just after the Big Bang, helping scientists explore key questions in physics — such as the origin of mass, dark matter, and the structure of the universe. One of its most famous achievements is the discovery of the Higgs boson in 2012, confirming a major part of the Standard Model of particle physics.

Important!

Matter & antimatter

- All matter particles have an antimatter equivalent.

- Anti particles have the same mass, but their properties are opposite.

Ex: electron and positron

Creation & Annihilation

Important!

- **Creation (Pair Production):**

- A **high-energy photon** (usually gamma ray) transforms into a **particle-antiparticle pair** — typically an **electron** and a **positron**.
- This process requires a nearby **nucleus or electron** to conserve momentum.
- Minimum photon energy needed: **1.022 MeV**.

$$\boxed{\Delta E = c^2 \Delta m}$$

$$\gamma \rightarrow e^- + e^+$$

- **Annihilation:**

- When an **electron and positron** meet, they **annihilate** each other.
- Their **mass is converted into energy**, producing **two gamma photons** (usually of 0.511 MeV each) moving in opposite directions.

$$e^- + e^+ \rightarrow \gamma + \gamma$$

Mass Units $\frac{MeV}{c^2}$, $\frac{GeV}{c^2}$

Important!

1 MeV = $1 \times 10^6 \times 1.6 \times 10^{-19} = 1.6 \ \times 10^{-13} J$

$$\boxed{\frac{1MeV}{c^2} = \frac{1.6 \times 10^{-13}}{(3 \times 10^8)^2} = 1.78 \times 10^{-30} kg}$$

Atomic mass unit(u) = $1.66 \times 10^{-27} kg$

$$\Delta m = \frac{\Delta E}{c^2}$$

1 u = 931.5 $\frac{MeV}{c^2}$

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1 GeV = $1 \times 10^9 \times 1.6 \times 10^{-19} = 1.6 \ \times 10^{-10} \ J$

$$\boxed{\frac{1GeV}{c^2} = \frac{1.6 \times 10^{-10}}{(3 \times 10^8)^2} = 1.78 \times 10^{-27} kg}$$

Concept Learning Questions

1) A gamma ray photon converts into an electron and a positron. Calculate the frequency of the gamma photon.

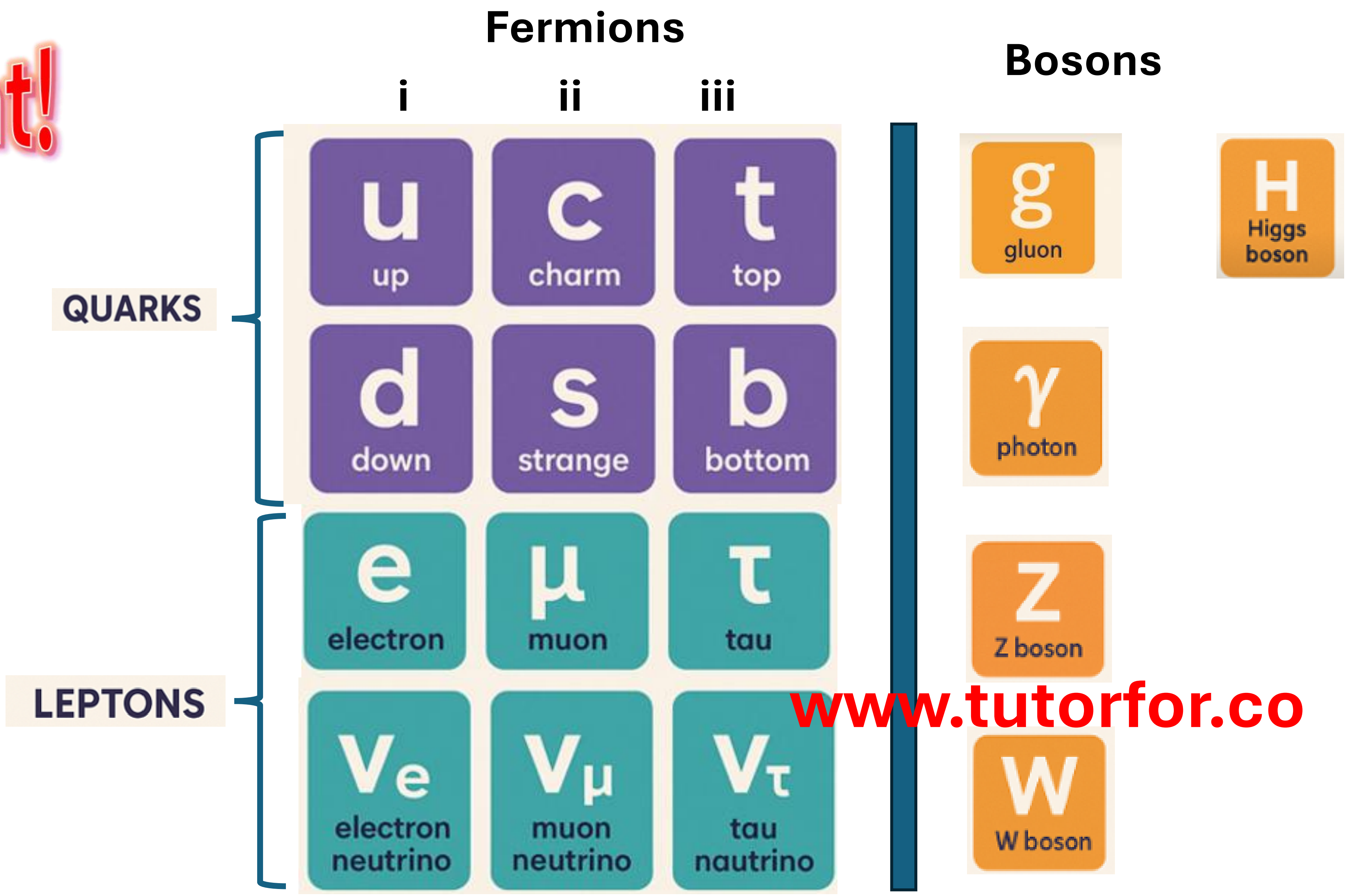
2) A positron with kinetic energy 2.2 MeV collides with an electron at rest, and they annihilate each other.

   a) Calculate the energy of each of the identical gamma photons produced as a result of the annihilation.

   b) Calculate the frequency of these gamma photons.

The Standard Model

Important!



Charge

each → $+\frac{2}{3}$

each → $-\frac{1}{3}$

each → -1

each → 0

Important!

Ex: Proton → uud

$$\text{charge} = \frac{2}{3} + \frac{2}{3} - \frac{1}{3} = +1$$

Neutron → udd

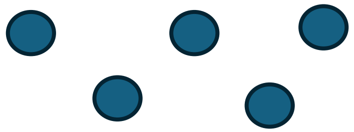
$$\text{charge} = \frac{2}{3} - \frac{1}{3} - \frac{1}{3} = 0$$

A reaction must conserve charge.

Reference!

Fermions(matter particles)

- Fermions obey the Pauli exclusion principal.



- It means fermions can’t share the same quantum state.

Ex: electrons populate in all of the energy shells.

Otherwise, all the electrons collapse into lowest energy shell.

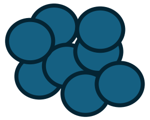
- Quarks interact with all of the fundamental forces.

Force carriers (Bosons)

Reference!

- They allowed to share the same quantum state.

Ex: Superfluidity, super conductivity, Laser



Types of Bosons

- ❑ **Photons –** Electromagnetic force (mediate light, electricity, magnetism)
- ❑ **Gluons-** Strong nuclear force (Binds quarks inside protons and neutrons)
- ❑ **W and Z bosons-** Weak nuclear force (responsible for radioactive decay)
- ❑ **Higgs Boson-** Give mass to particles via the Higgs field.

Four fundamental forces

Reference!

1) Gravity (Exchange boson-graviton?)
2) Electromagnetic forces
3) Strong Nuclear forces
4) Weak nuclear force.

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Baryons & Baryon number

Important!

- ❖ A particle created by combining 3 quarks called a baryon.
  Ex: proton (uud) , neutron (udd)

- ❖ Each quark has a baryon number **B** $=+\frac{1}{3}$
  Ex: protons baryon number = $\frac{1}{3}+\frac{1}{3}+\frac{1}{3}=+1$

- ❖ An anti quark has baryon number **B** $=-\frac{1}{3}$

- ❖ A reaction must conserve baryon number.

Ex: ${}^{235}_{92}U \rightarrow {}^{231}_{90}Th + {}^{4}_{2}\alpha$

$Baryon\ Number: +235 \rightarrow +231 + 4$

$Baryon\ Number\ before = Baryon\ Number\ after$

$Baryon\ Number\ conserved$

Lepton Number

Important!

- ❑ Each lepton has lepton number **L = +1**
- ❑ Anti particle of lepton has lepton number **L = -1**
- ❑ A reaction must conserve lepton number.

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Ex: $$n \rightarrow p + e^{-} + \bar{\nu}_e$$

Lepton Number : 0 → 0 + 1 -1

Lepton number before = Lepton number after
Lepton number conserved.

Hadrons

Important!

Hadrons are particles made of quarks that interact through the strong nuclear force.

Two main types:

1. **Baryons** – made of **3 quarks** (e.g., proton, neutron)
2. **Mesons** – made of **1 quark + 1 antiquark** (e.g., pion, kaon)

- **Examples of Hadrons:**

Type	Examples
Baryons	Proton (p), Neutron (n), Lambda (Λ)
Mesons	Pion (π), Kaon (K), Eta (η)

Mesons

Important!

Mesons are **hadrons** (particles that experience the strong nuclear force) made up of **one quark and one antiquark.**

Examples:

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- Pions (π^+, π^0, π^-)
- Kaons (K^+, K^0, etc.)
- Eta (η), rho (ρ), D, B mesons, etc.

◆ **Meson Composition Table**

Meson	Symbol	Quark Composition
Pion (π^+)	π^+	$u\bar{d}$
Pion (π^-)	π^-	$d\bar{u}$
Pion (π^0)	π^0	$\frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d})$*
Kaon (K^+)	K^+	$u\bar{s}$
Kaon (K^-)	K^-	$s\bar{u}$
Kaon (K^0)	K^0	$d\bar{s}$
Anti-Kaon	$\bar{K}^0$	$s\bar{d}$
Eta (η)	η	mixture of $u\bar{u}, d\bar{d}, s\bar{s}$
Rho (ρ^+)	ρ^+	$u\bar{d}$
D^+ meson	D^+	$c\bar{d}$
B^0 meson	B^0	$d\bar{b}$

Strangeness (S)

Important!

- Strange Quark **S= -1**
- Anti strange quark **S = +1**
- Strong and electromagnetic force interactions must conserve strangeness.

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Ex: $K^- + p \rightarrow \Lambda^0 + \pi^0$

- **Before the Reaction:**
  - Total Strangeness = $-1 + 0 = -1$
- **After the Reaction:**
  - Total Strangeness = $-1 + 0 = -1$

✅ **Strangeness is conserved.**

Particle	Strangeness (S)
K^-	−1
p	0
Λ^0	−1
π^0	0

Concept Learning Questions.

Are **baryon number**, **lepton number**, and **electric charge** conserved in this reaction?

a) $p \rightarrow n + e^{+} + \nu_e$

b) $p + p \rightarrow p + n + \pi^{+}$

c) $\pi^{-} + p \rightarrow n + \gamma$

d) $p + \bar{\nu}_e \rightarrow n + e^{+}$

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

f) $p + p \rightarrow p + \Lambda^{0} + K^{+}$

🧾 What is a Muon?

Reference!

- A **muon (μ⁻)** is an elementary particle similar to the electron, but with about **207 times more mass**.
- It is **unstable**, with a **proper (rest) lifetime** of about:

$$\tau_0 = 2.2\,\mu s$$

- Muons are produced in the upper atmosphere (around 10–15 km above the Earth's surface) when **cosmic rays** collide with atomic nuclei.

❓ The Puzzle

If muons live for only 2.2 microseconds in their own rest frame, and they travel close to the speed of light, say $v \approx 0.998c$, how can they **reach sea level**, which is tens of kilometers away?

Let's do a quick Newtonian estimate:

$$\text{Distance} = v \cdot \tau_0 = (0.998c)(2.2 \times 10^{-6}) \approx 660\,\text{meters}$$

➡️ That's **way too short** compared to the ~10,000 m (or more) from the upper atmosphere to sea level.

Yet, **muons *are* observed at sea level** in large numbers.

🧭 The Relativistic Explanation: **Time Dilation**

Reference!

According to **Einstein's special relativity**, time slows down for fast-moving particles as observed from the Earth frame.

The **dilated lifetime** in the Earth frame is:

$$\tau = \gamma \tau_0$$

where:

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

Let's plug in $v = 0.998c$:

$$\gamma \approx \frac{1}{\sqrt{1 - (0.998)^2}} \approx 15.8$$

So in our frame (on Earth), the muon's lifetime appears to be:

$$\tau = 15.8 \times 2.2\,\mu s \approx 34.8\,\mu s$$

And the **distance** a muon can now travel is:

$$d = v \cdot \tau \approx (0.998c)(34.8 \times 10^{-6}) \approx 10.4\,\text{km}$$

✅ This explains how muons can **survive the journey from the upper atmosphere to sea level**.

In the Muon's Frame (Length Contraction)

From the **muon's point of view**, it's the Earth rushing up at them. The distance to the surface appears **contracted** due to **length contraction**:

$$L = \frac{L_0}{\gamma}$$

So the 10 km appears much shorter to the muon, allowing it to reach the ground **within its 2.2 μs lifetime**.

Important!

Summary:
Muons are unstable particles produced in the upper atmosphere as a result of cosmic ray interactions. Under normal conditions, their short lifetime would not allow them to travel the long distance to sea level. They are moving with relativistic speeds. Due to relativistic effects, specifically time dilation, their lifetime appears longer to an observer on Earth. This relativistic effect enables many muons to survive the journey and be detected at sea level.