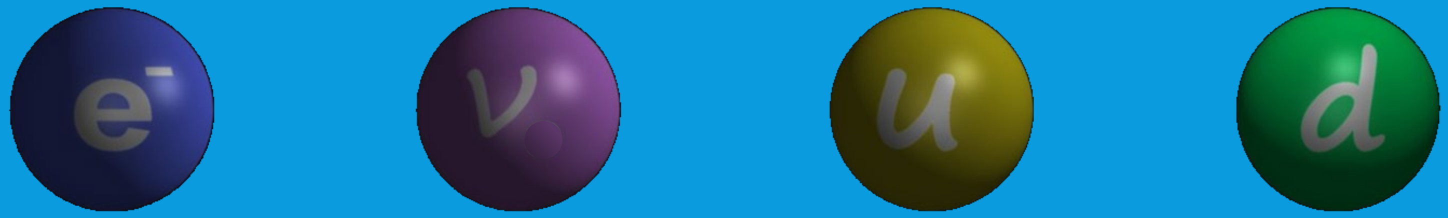
WHAT'S ANTIMATTER?

VISIBLE MATTER IN THE UNIVERSE*…



electron neutrino up quark down quark

But, the Universe does have other particles ….
For one thing, each of the matter particles has a twin.

ANTIMATTER TWIN.

It is traditional to use a little bar in the symbol for an antimatter particle to distinguish it from the symbol for its matter twin (the exception is the positron, where we use a '+' instead of the '-' of the electron).

Matter, Antimatter: What’s the difference?

MATTER, ANTIMATTER: WHAT'S THE DIFFERENCE?

There is one essential and obvious difference:

A particle of matter that has an ELECTRIC CHARGE

has an antiparticle twin with the exact opposite charge.

For example, if the electron has a charge of -1,

then its antiparticle, the positron, has a charge of +1.

Electron
Charge: -1

−1

Positron
Charge: +1

+1

Remember that

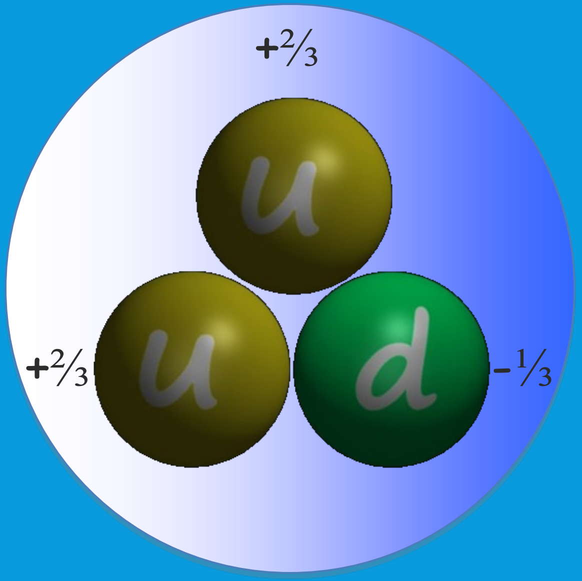
protons and neutrons

are made up of particular combinations

of the up and down quarks,

and that these quarks have a fractional charge…

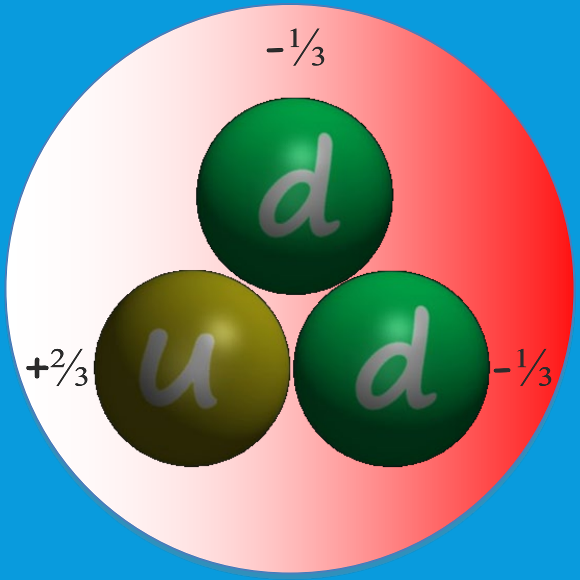
PROTON
(p)



Composed of:
2 up quarks and
1 down quark

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

NEUTRON
(n)

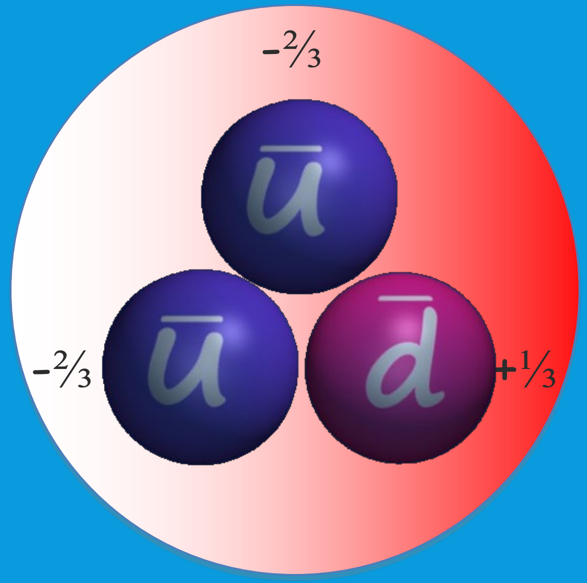


Composed of:
1 up quark and
2 down quarks

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

AND SO THE ANTIMATTER…

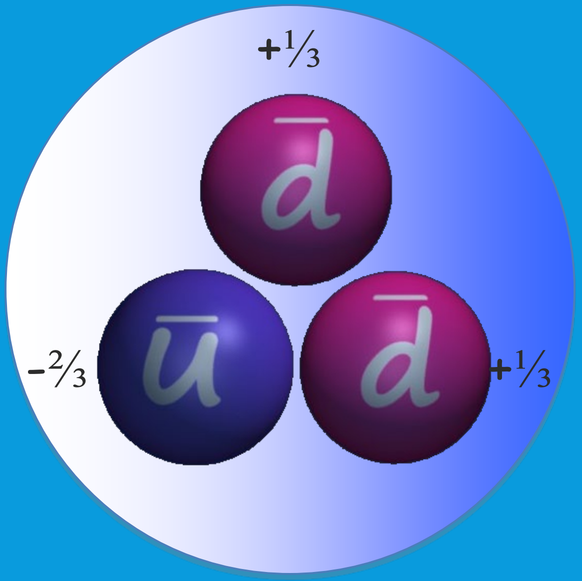
ANTIPROTON ($\bar{p}$):



Composed of:
2 anti-up quarks and
1 anti-down quark

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

ANTINEUTRON ($\bar{n}$):

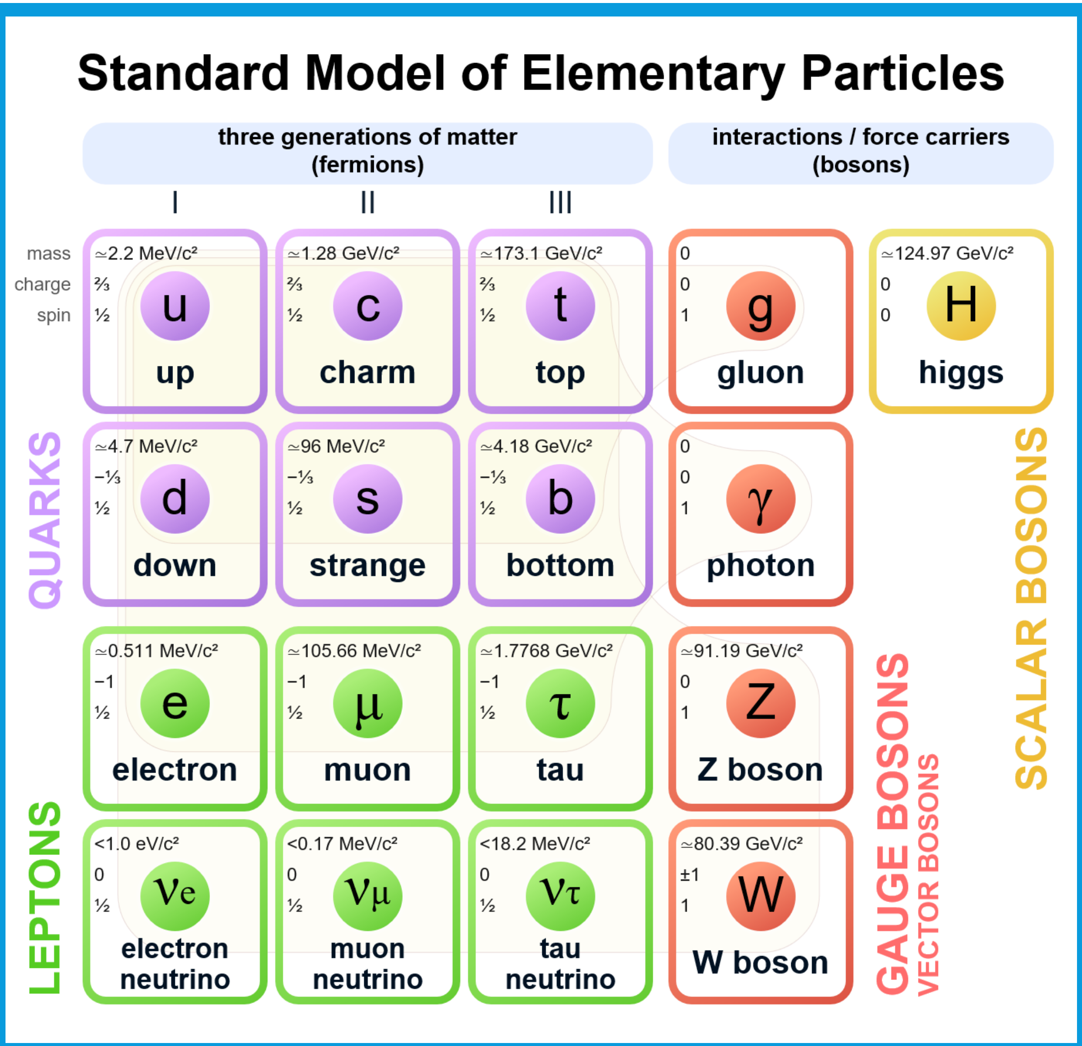


Composed of:
1 anti-up quark and
2 anti-down quarks

Total charge:
$-\frac{2}{3} + \frac{1}{3} + \frac{1}{3} = 0$

Notice that the antineutron also has zero charge. If a particle has no charge, then its antiparticle has no charge.

......FUNDAMENTAL BRICKS



FROM WHERE IT COMES FROM?

PROBLEM: LORENTZ INVARIANT SCHRÖDINGER EQN.

With the quantum mechanical energy & momentum operators:

$$E = i\frac{\partial}{\partial t}$$

$$\vec{p} = -i\vec{\nabla}$$

recall: $p^{\mu} = (E, \vec{p})$ *and* $\partial^{\mu} = \left(\frac{\partial}{\partial t}, -\frac{\partial}{\partial x}, -\frac{\partial}{\partial y}, -\frac{\partial}{\partial z}\right) = \left(\frac{\partial}{\partial t}, -\vec{\nabla}\right)$

You simply 'derive' the Schrödinger equation from classical mechanics:

$$E = \frac{p^2}{2m} \rightarrow i\frac{\partial}{\partial t}\phi = -\frac{1}{2m}\nabla^2\phi$$

Schrödinger equation

With the relativistic relation between E, p & m you get:

$$E^2 = p^2 + m^2 \rightarrow \frac{\partial^2}{\partial t^2}\phi = \nabla^2\phi - m^2\phi$$

Klein-Gordon equation

SOLUTIONS

$E^2 = p^2c^2 + m^2c^4 \quad \Rightarrow$

$$\frac{1}{c^2}\frac{\partial^2\Psi}{\partial t^2} = \nabla^2\Psi - \frac{m^2c^2}{\hbar^2}\Psi$$

Klein-Gordon Equation

For every plane-wave solution of the form $\Psi = A\exp(-\frac{i}{\hbar}Et)$

(positive E)

There is another solution of the form $\Psi' = A\exp(\frac{i}{\hbar}Et)$

(*negative* E)

LINEARIZATION - > DIRAC

The negative energy solutions led Dirac to try an equation with first order derivatives in time (like Schrödinger) as well as in space

$$i\frac{\partial}{\partial t}\phi = -i\,\vec{\alpha}\cdot\vec{\nabla}\phi + \beta m\phi$$

Dirac equation

SOLUTIONS

$$i\hbar \frac{\partial}{\partial t}\Psi = -i\hbar \sum_{n=1}^{3} c\,\alpha_n \frac{\partial}{\partial x_n}\Psi + \beta m c^2 \Psi$$

Dirac Equation

Where α_n and β are determined by requiring that solutions of this equation also satisfy the Klein-Gordon equation

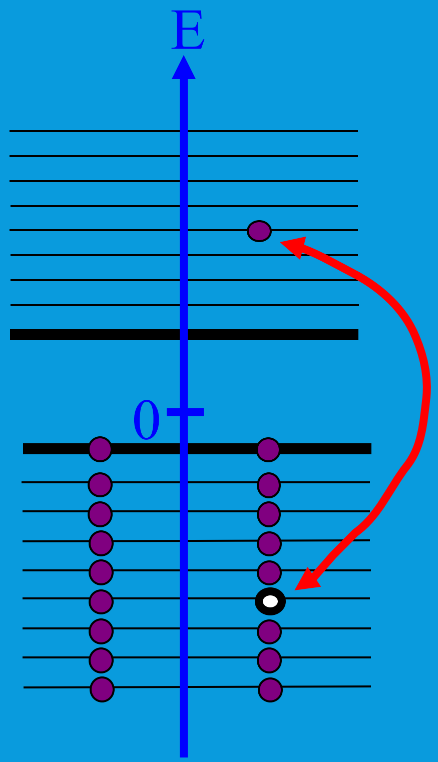
$\Rightarrow$ α and β need to be 4x4 matrices and

$$\Psi = \begin{pmatrix} \Psi_1 \\ \Psi_2 \\ \Psi_3 \\ \Psi_4 \end{pmatrix}$$

still have positive and negative energy states but now also have spin!

NEGATIVE ENERGY..INTERPRETATION?

Dirac
''Hole'' Theory

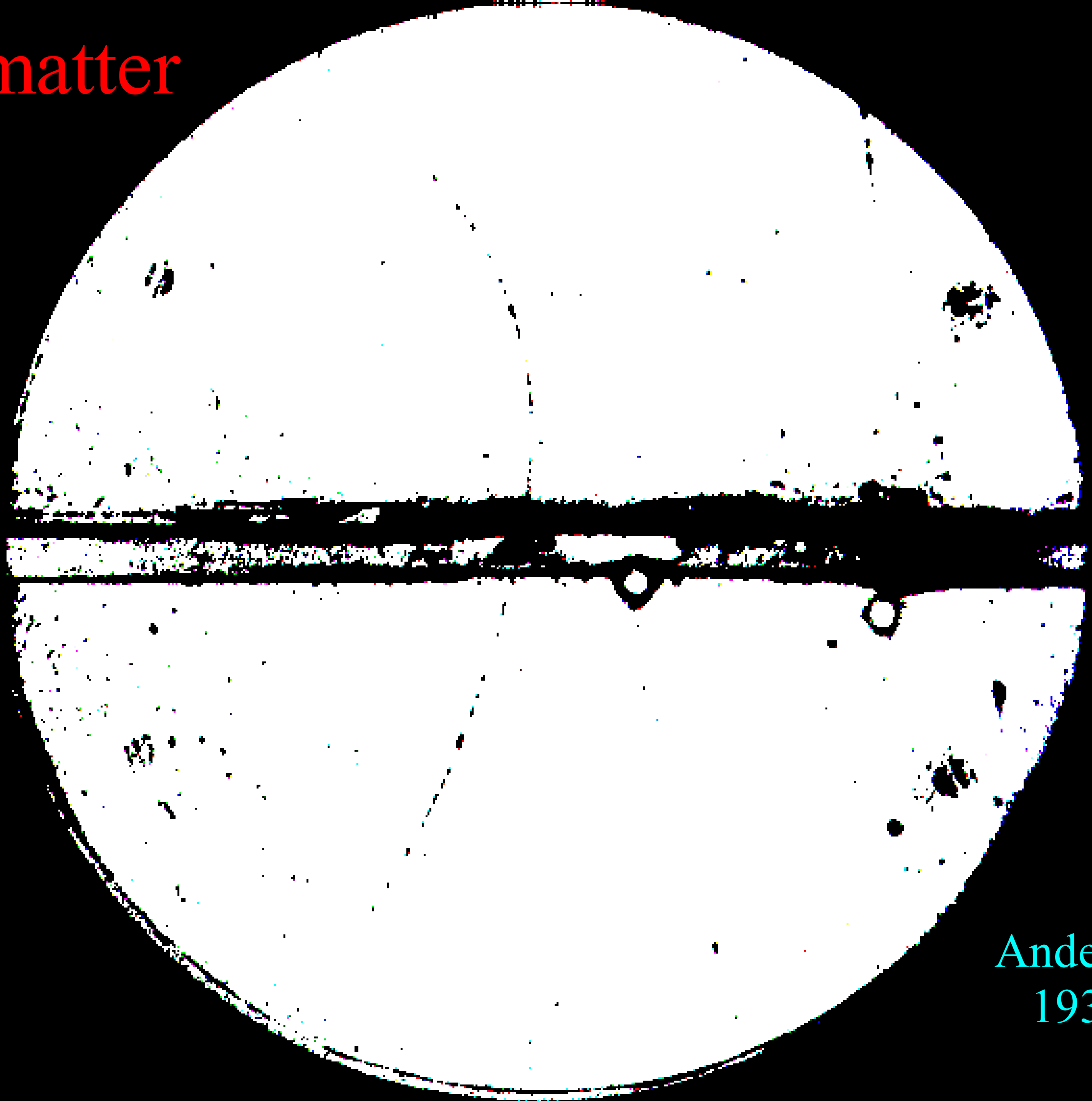


''sea'' of negative energy states

Nowdays we don't think of it this way!

Instead we can say that energy always remains positive, but solutions exist with **time** reversed (Feynman-Stukelberg)

Antimatter



Anderson
1933

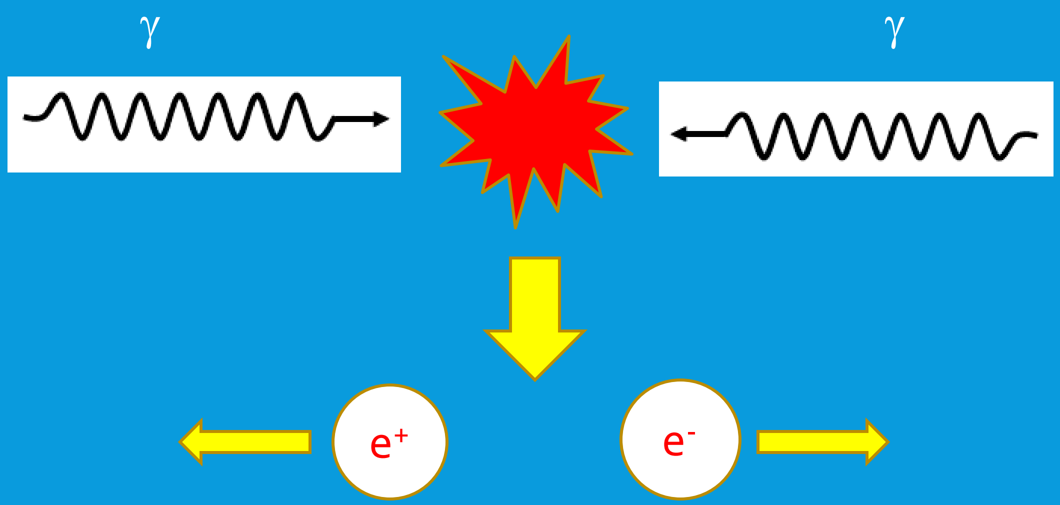
HOW TO PRODUCE ANTIMATTER?

- In collisions we have a certain probability to produce Dirac states

- We need to respect the conservations rules: ENERGY, MOMENTUM, CHARGE (angular momentum, lepton number) conserved

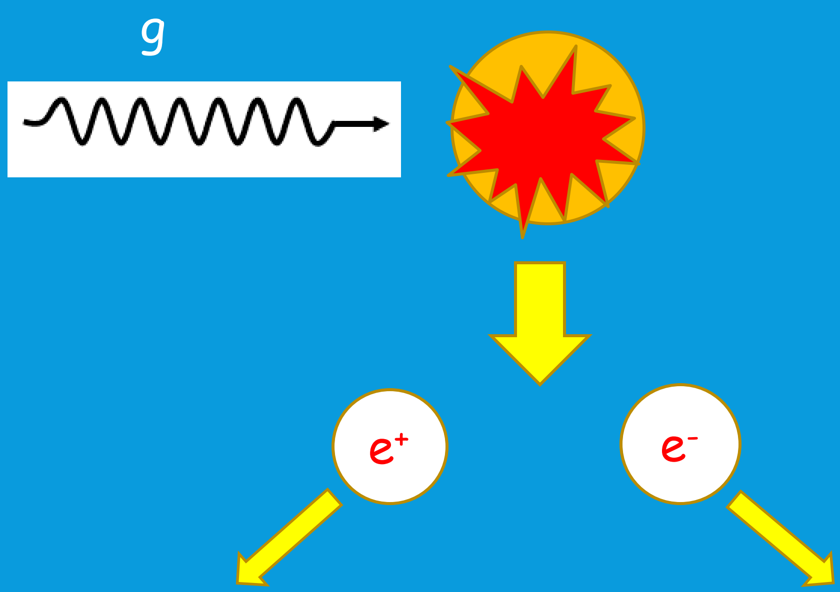
- We need to have the minimum energy available for pairs (electron 2x0,511 MeV)

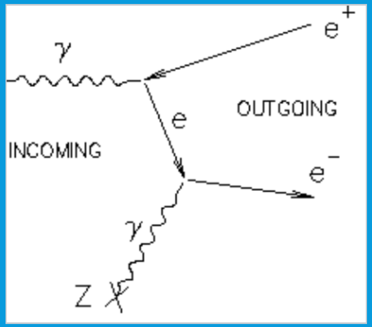
EXAMPLE - PAIR CREATION (VERY RARE)



- ENERGY :
- before collision is the energy of the two photons
- After collision it is the sum of the rest energy and the kinetic energy of the two particles. This fixed a threshold to 2x0,511 MeV for the photon energy
- MOMENTUM
- Before collision, same value and opposite direction. total momentum=0
- After collision, same mass, opposite velocities. Total momentum=0
- CHARGE
- Before -> 0+0=0
- After -> +1-1=0

BUT IT IS POSSIBLE TO INTERACT WITH A ATOM NUCLEUS….





$$p_\gamma = p_{e^-} + p_{e^+} + p_R$$

p_R = nucleus recoil
Nucleus carries away momentum to conserve momentum and energy.
Final state Lorentz boosted.
The mediator is a Nucleus virtual photon (see before..)

Squaring the conservation relation and neglecting the Nucleur recoil in respect to the photon energy it is possible to obtain the relation for the emission angle

$$2(\gamma^2 - 1)m_e^2 c^2 (1 - \cos\theta_e) \approx 0$$

SO……

- The main scheme is to send a primary beam on a **TARGET**
- Positrons – Photons or electrons.
- Muons – Electrons/positrons or protons producing pions and then collecting the decays.
- Antiprotons – Protons

- Hierarchy due to the needed energies, Antiprotons can also be produced by 2 GeV photons, but what source?

THE ANTIMATTER SOURCES ARE BASICALLY DEFINED BY THE PRIMARY BEAM AND THE TARGET