Particle Physics FOR DUMMIES®

Introducing
Particle Physics

Pablo del Amo Sánchez

UNIVERSITE DE SAVOIE CHAMBERY ANNECY

lapp Laboratoire d'Annecy-le-Vieux de Physique des Particules

Enigmass

IDPASC

Aim of this lecture:

Particles and Forces of the Standard Model

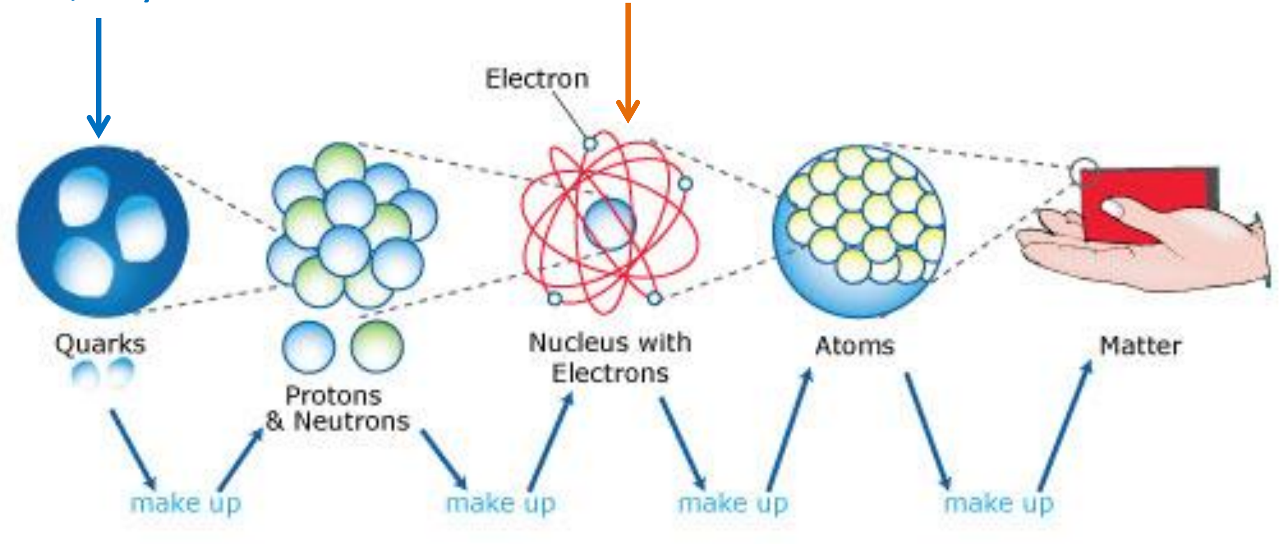
The particle zoo

Qualitative Feynman diagrams

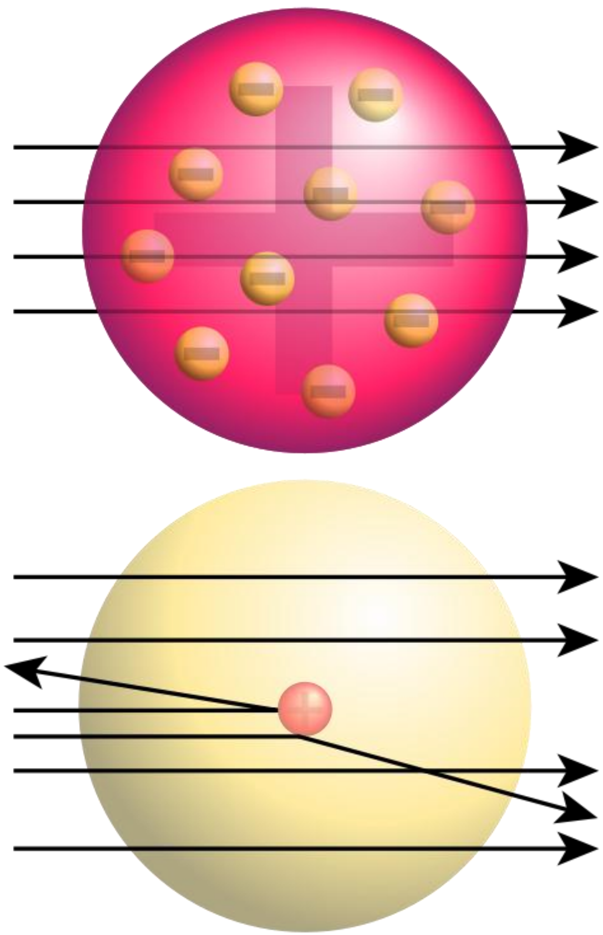
A VERY brief history of particles

1968-69 SLAC, Bjorken, Feynman

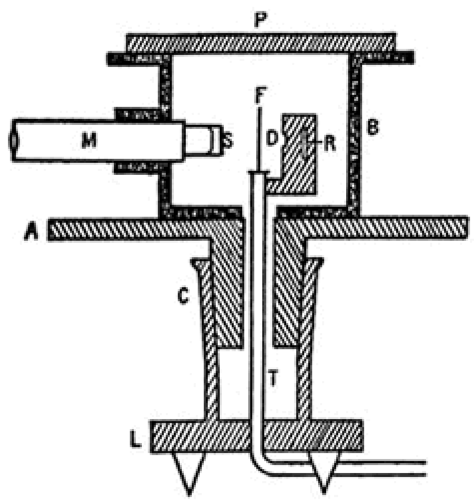
1911 Rutherford, Geiger, Marsden

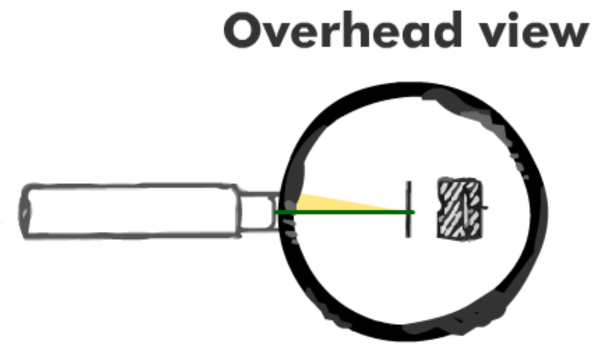


The nucleus: Rutherford scattering



- 1906, J.J. Thomson: plum pudding model of the atom
- Rutherford set to test it by firing α particles into a thin foil



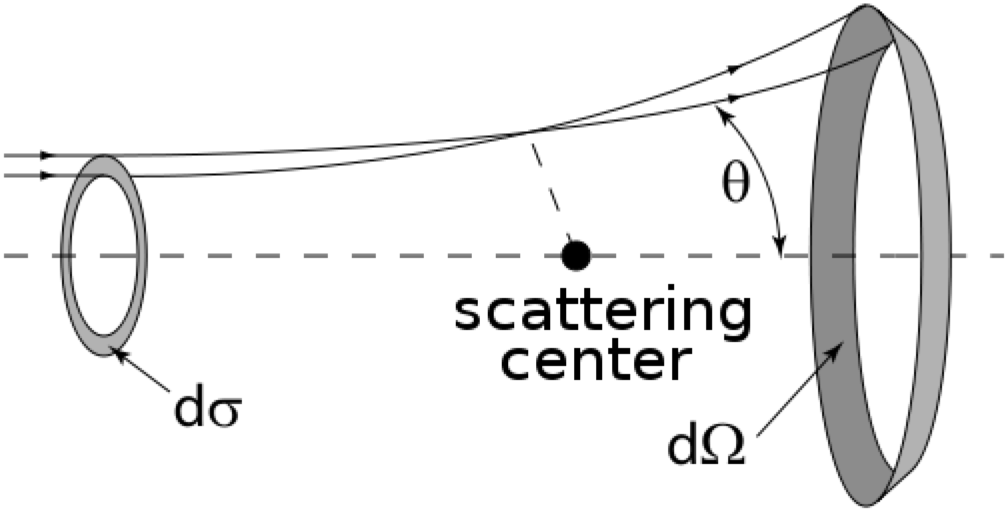


- 1909, Geiger & Marsden: ~1/8000 alpha particles bounce off!
- 1911, Rutherford: nucleus small within atom, surrounded by e^- cloud

$$E_\alpha^{kin} = \frac{1}{4\pi\varepsilon_0}\frac{q_{\text{bullet}}Q_{\text{target}}}{R_{\text{target}}} \Rightarrow R_{\text{target}} \approx 10^{-14}\,m << 10^{-10}\,m \approx R_{\text{atom}}$$

The nucleus: Rutherford scattering

- Notion of Cross Section $d\sigma/d\Omega$: particles crossing transverse area $d\sigma$ are scattered into a solid angle $d\Omega$ at an angle θ with the beam direction
- Can find out about force between target and bullet by looking at xsection, e.g. stronger forces → bigger xsections; range of force ↔ dependence on θ

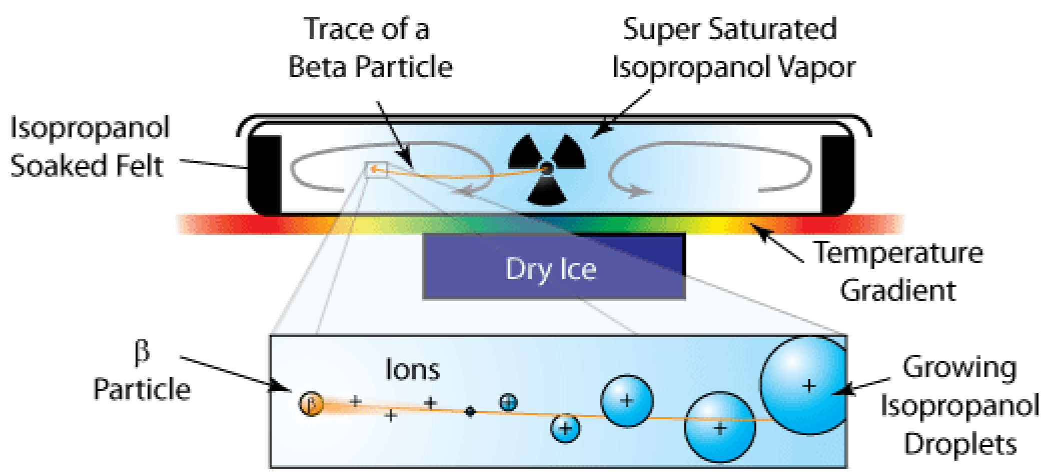


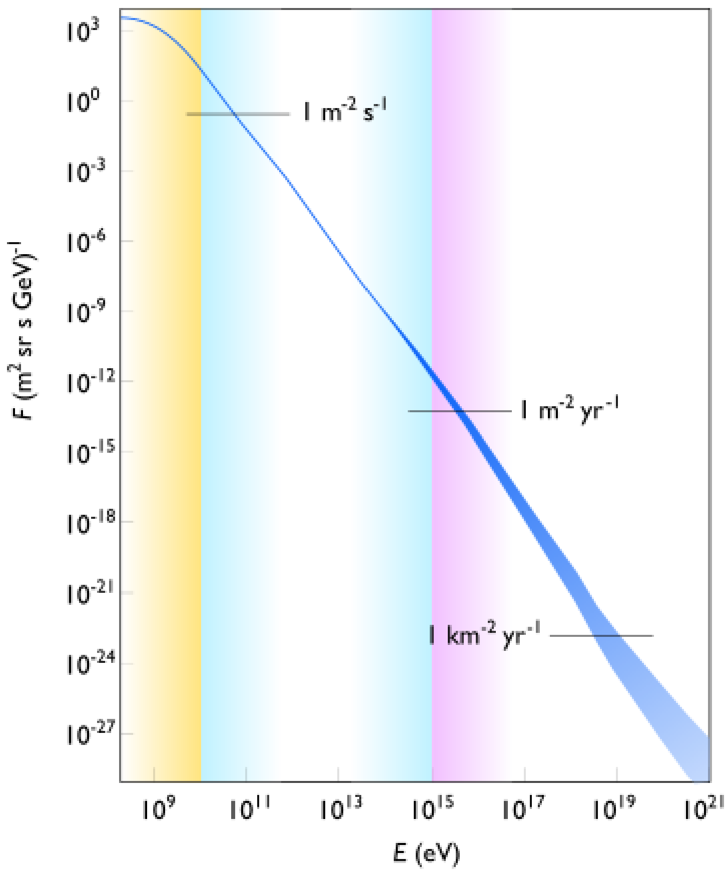
- Ex, scattering of spinless charged particles off a spinless charged target (Rutherford):

$$\frac{d\sigma}{d\Omega} = \frac{Z_1 Z_2 e^2}{4\pi\varepsilon_0 E_{kin}} \frac{1}{\sin^4(\theta/2)}$$

Cosmic rays

- Particles from outer space constantly in collision with upper atmosphere
- Source of exotic (unstable) particles from early times (pre WWII)
- Cloud chambers (or Wilson chambers): supersaturated vapor, passage of charged particles slightly ionizes medium, condensation occurs track
- Photographic emulsions also used

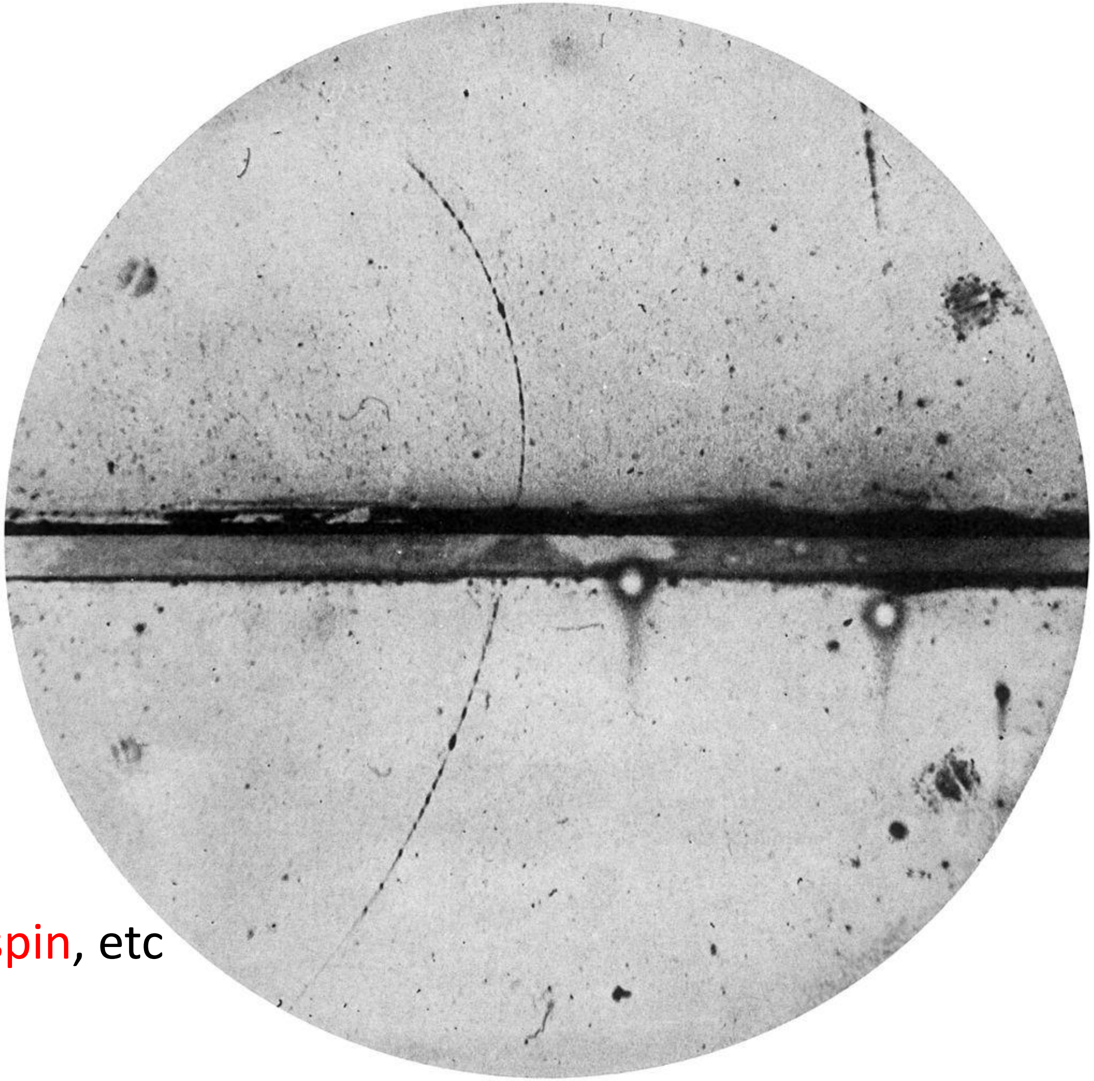




Antiparticles: the positron

- 1932, Anderson: picture of cloud chamber in magnetic field
- Track crosses lead plate, looses energy, going upwards
- Positive charge (curvature), mass < 20 m_e

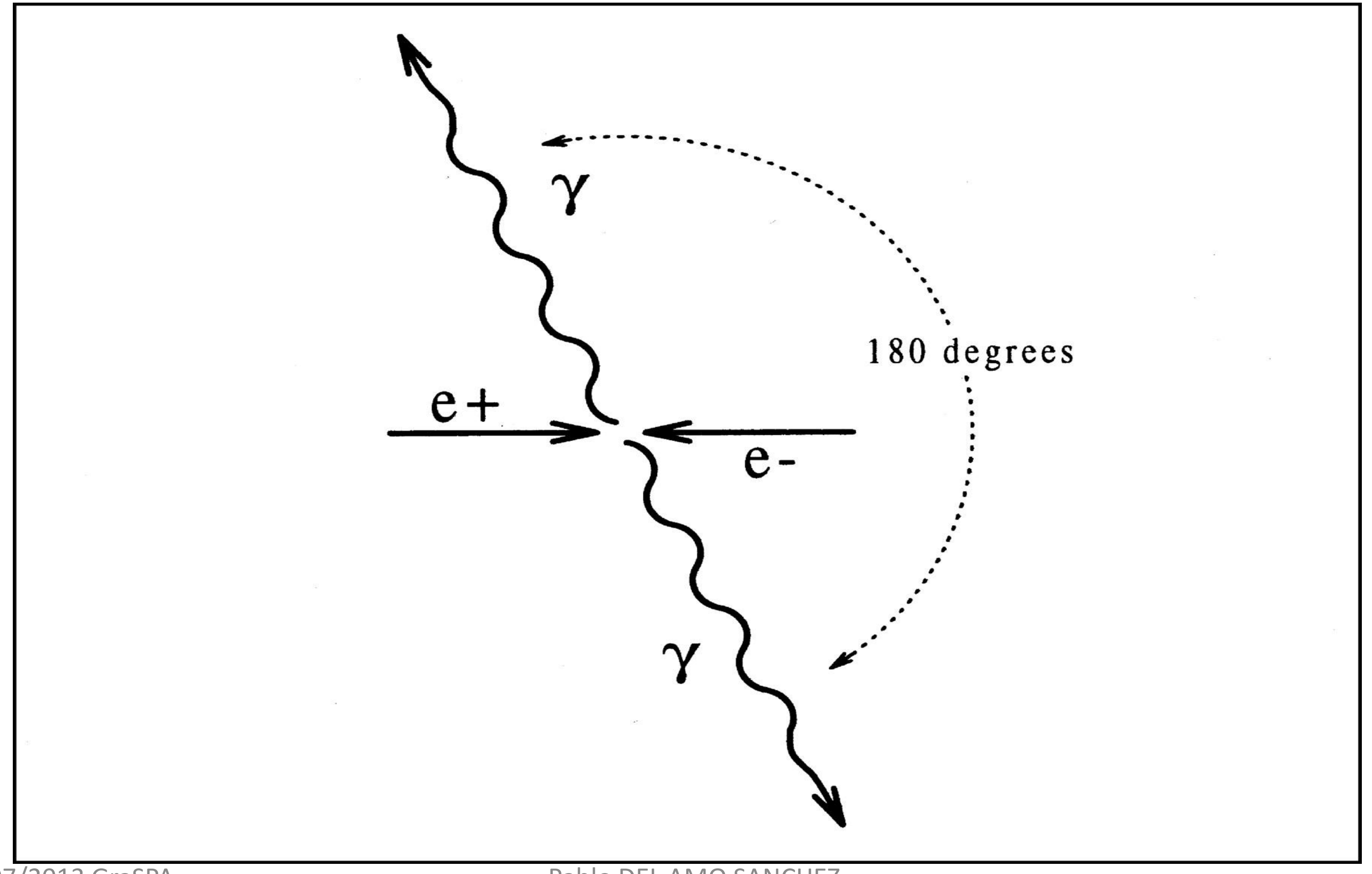
… A POSITIVE ELECTRON!



- Actually predicted by Dirac's equation (Oppenheimer 1930)!
- Antiparticle has same mass, spin, etc but opposite charge

Matter-antimatter annihilation

- Particle + antiparticle = radiation ($E=mc^2$!)

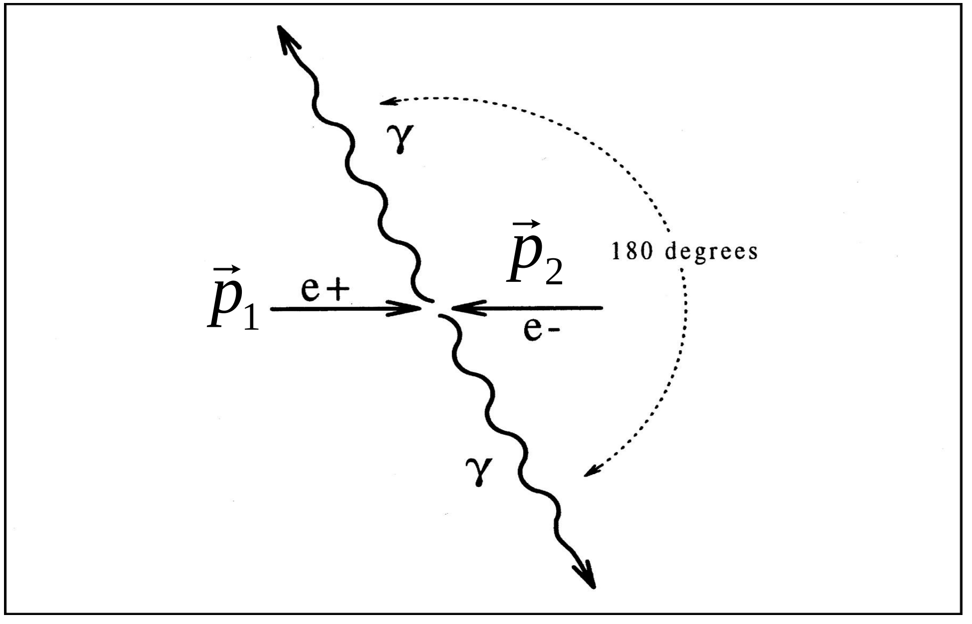


Matter-antimatter annihilation

- Particle + antiparticle = radiation (E=mc²!)

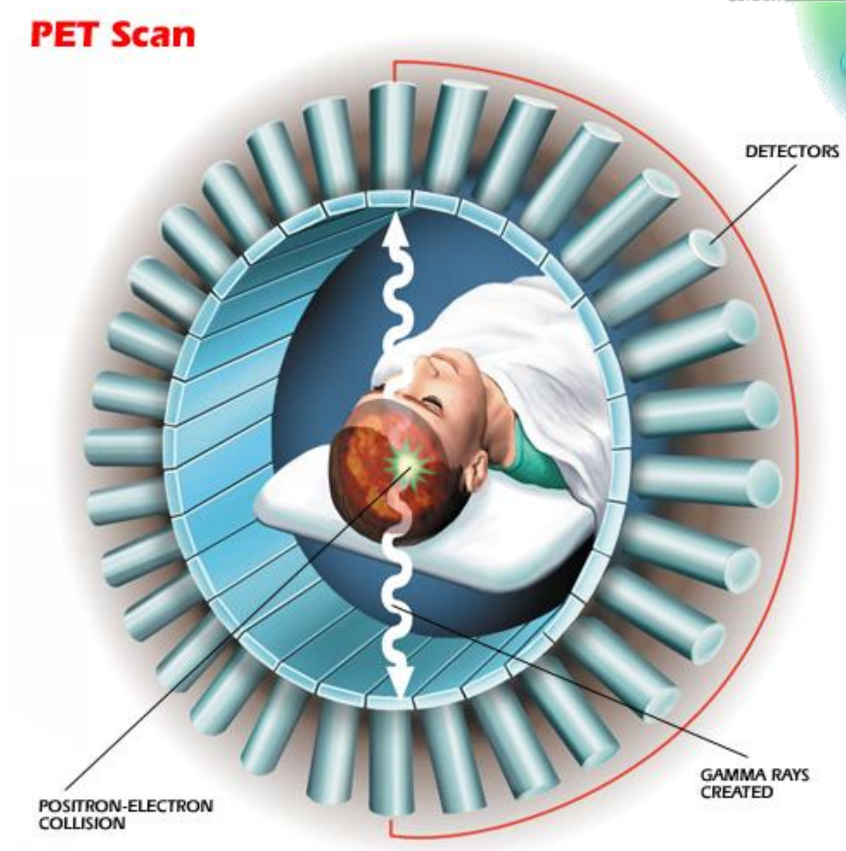
where m is “relatisvistic invariant mass” of system:

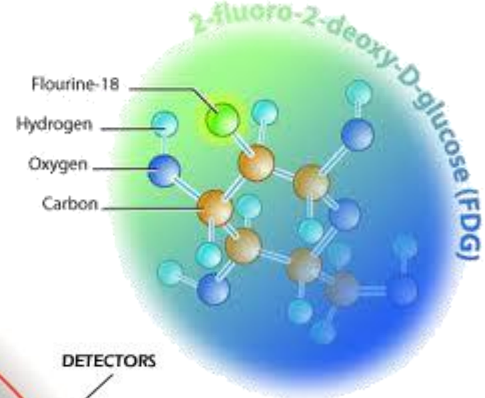
$$m_{12}^2 = (E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2 \equiv (p_1^\mu + p_2^\mu)^2$$

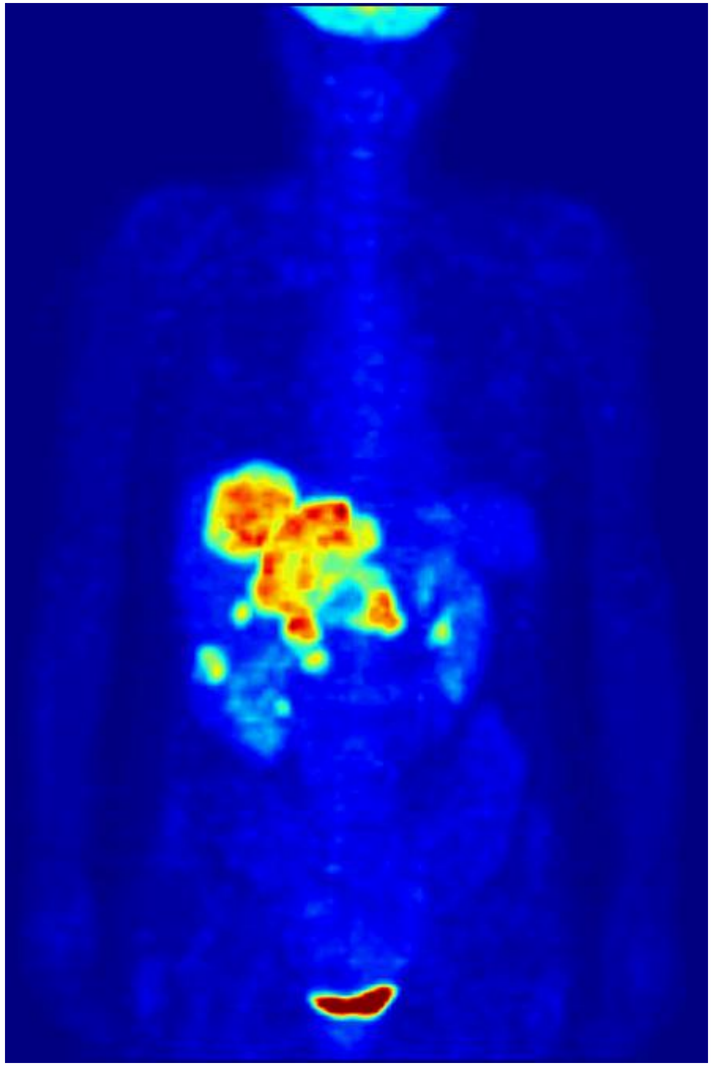


Applications

Positron emission tomography (PET)







More cosmic rays: the muon

1936 Neddermeyer, Anderson:

- unit charge particle, spin 1/2
- heavier than electron, lighter than proton
- like electrons, does not induce nuclear reactions
- unstable but long-lived (10^{-6} s)

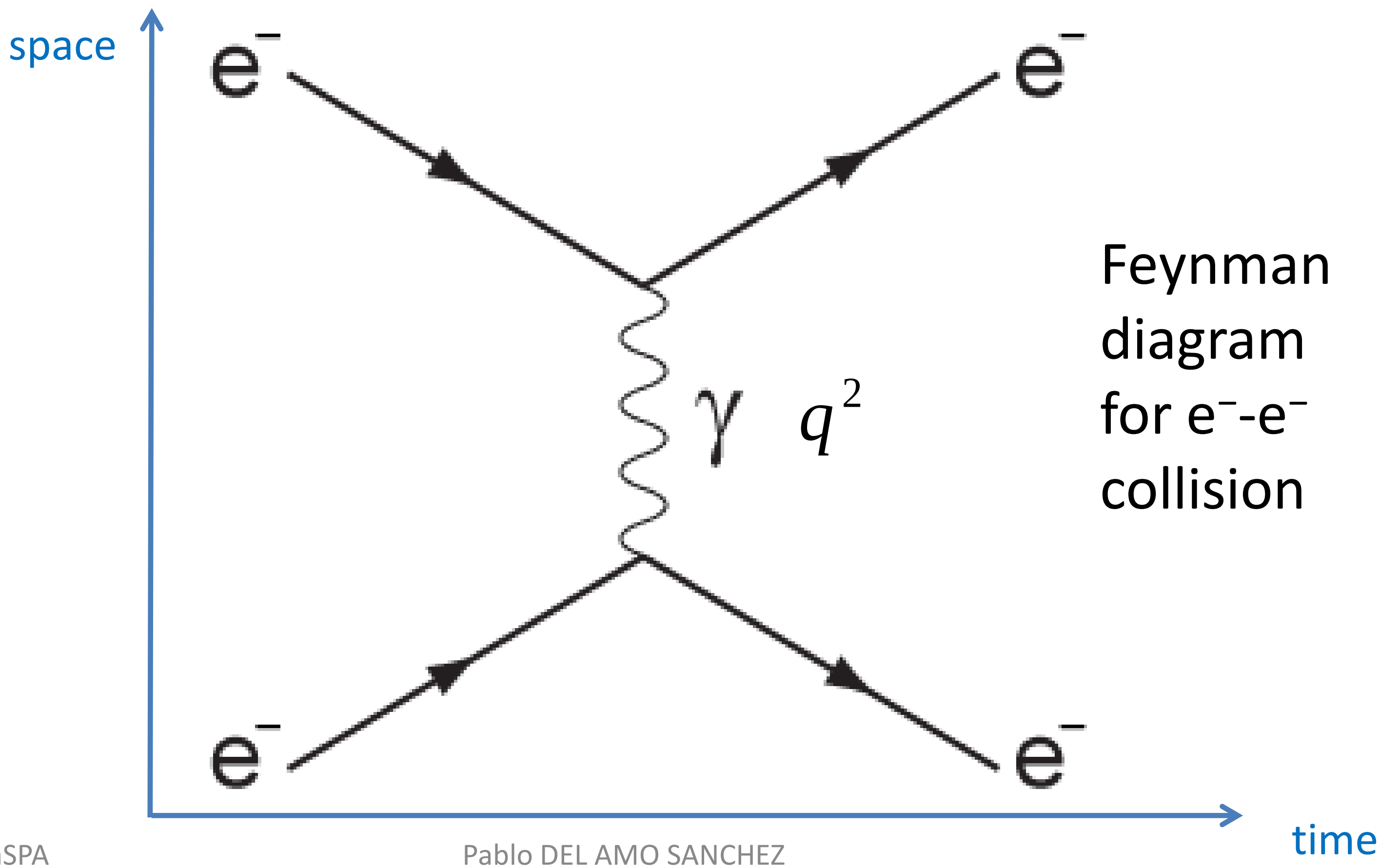
Just like electron but heavy and unstable

"Who ordered that?" (I.I. Rabi)

Quantum ElectroDynamics (QED)

- Tomonaga (1946), Scwhinger (1948) and Feynman (1948) based on Dirac (1928)

Charged particles transfer momentum q, energy by exchange of photons, quanta of EM field



Feynman diagram for e⁻-e⁻ collision

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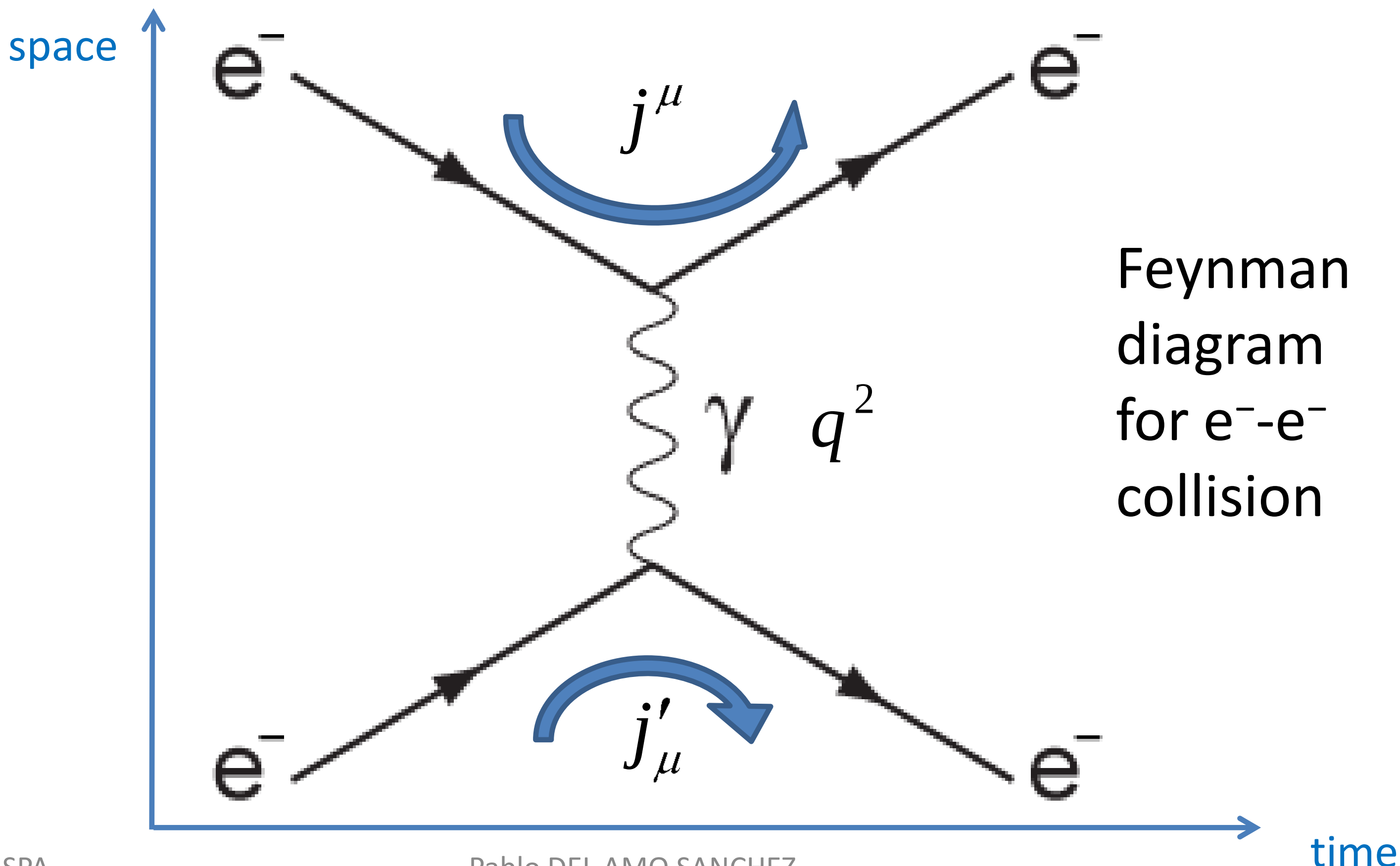

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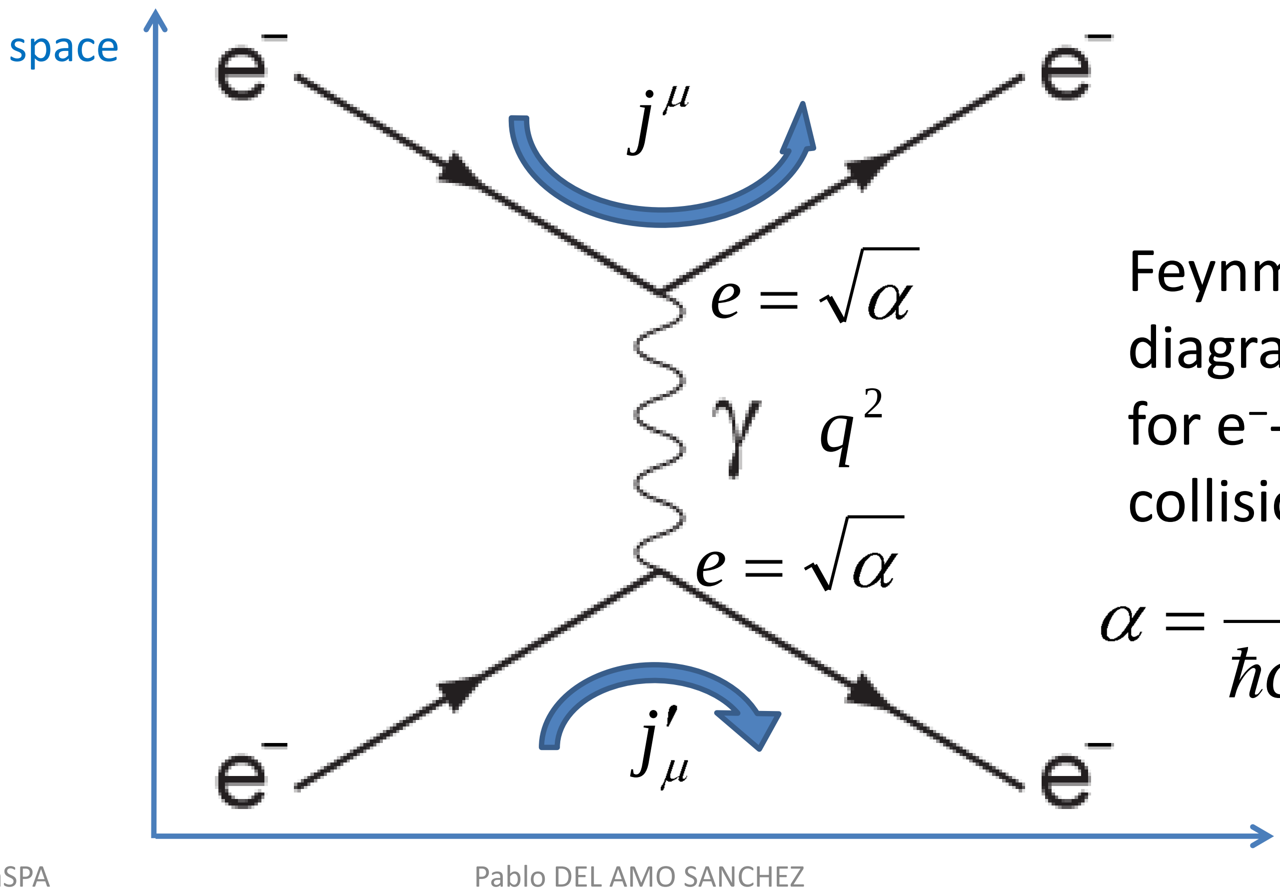

Feynman diagram for e⁻-e⁻ collision

$$\alpha = \frac{e^2}{\hbar c 4\pi\varepsilon_0}$$

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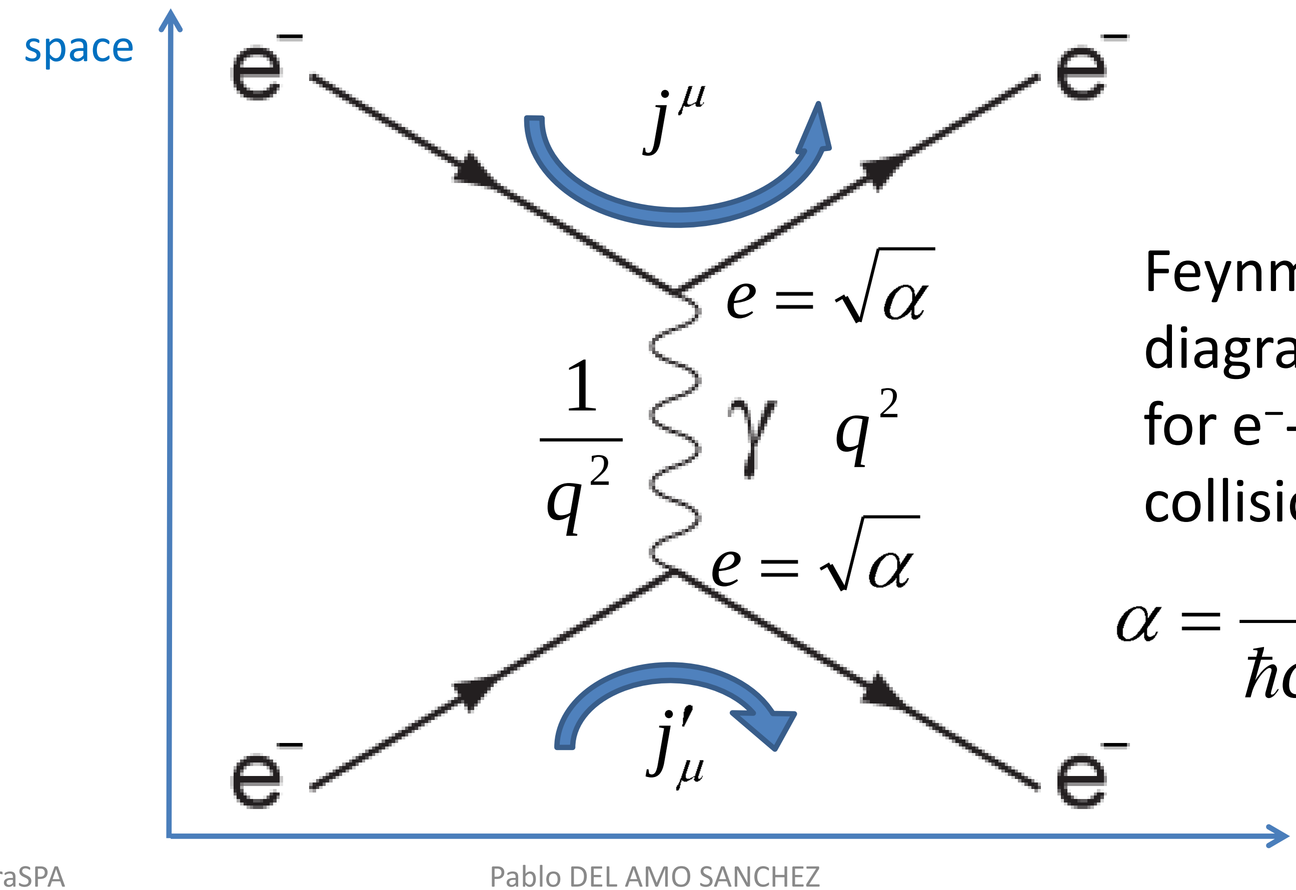
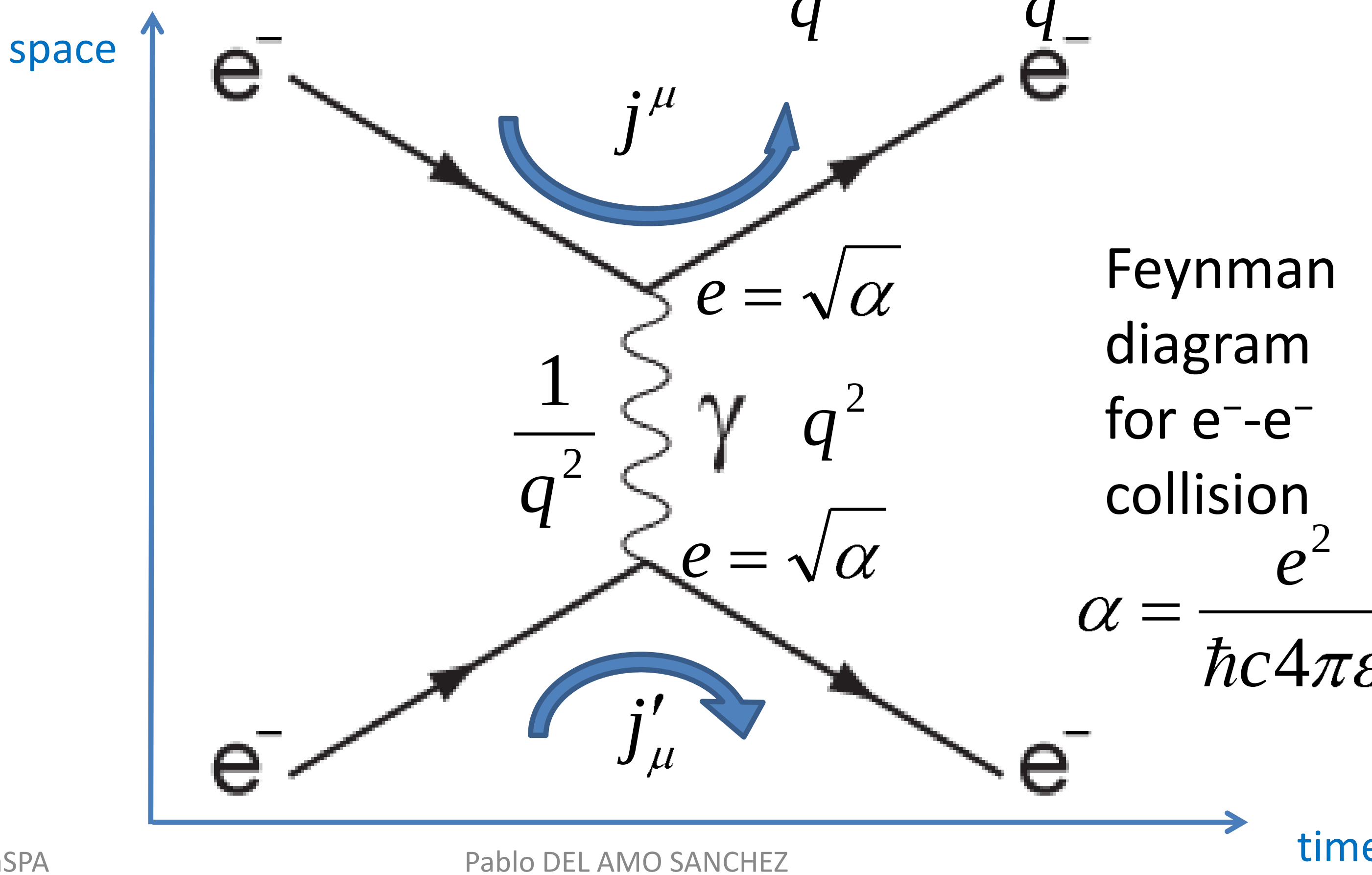


Feynman diagram for e⁻-e⁻ collision

$$\alpha = \frac{e^2}{\hbar c 4\pi\varepsilon_0}$$

Quantum ElectroDynamics (QED)

- Tomonaga (1946), Scwhinger (1948) and Feynman (1948) based on Dirac (1928)
- Amplitude for e⁻-e⁻ scattering: $A \propto ej^{\mu} \frac{1}{q^2} ej'_{\mu} = \frac{e^2}{q^2} j^{\mu} j'_{\mu} \propto \alpha$



Feynman diagram for e⁻-e⁻ collision

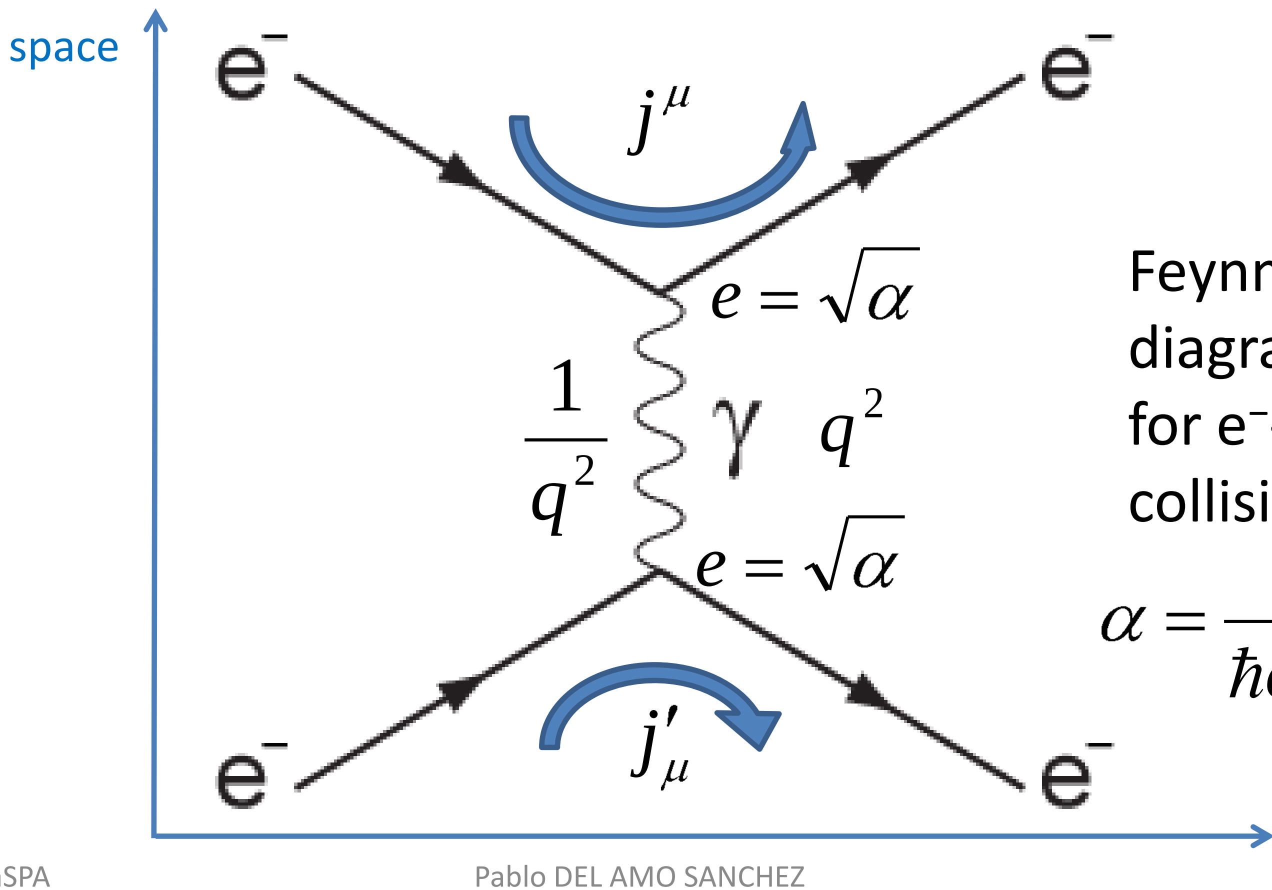
$$\alpha = \frac{e^2}{\hbar c 4\pi\varepsilon_0}$$

Quantum ElectroDynamics (QED)

- Tomonaga (1946), Scwhinger (1948) and Feynman (1948) based on Dirac (1928)
- |Amplitude|^2 for e$^-$-e$^-$ scattering:

$$A \propto \alpha \Rightarrow |A|^2 \propto \alpha^2$$

Cross sections, decay rates proportional to |A|^2

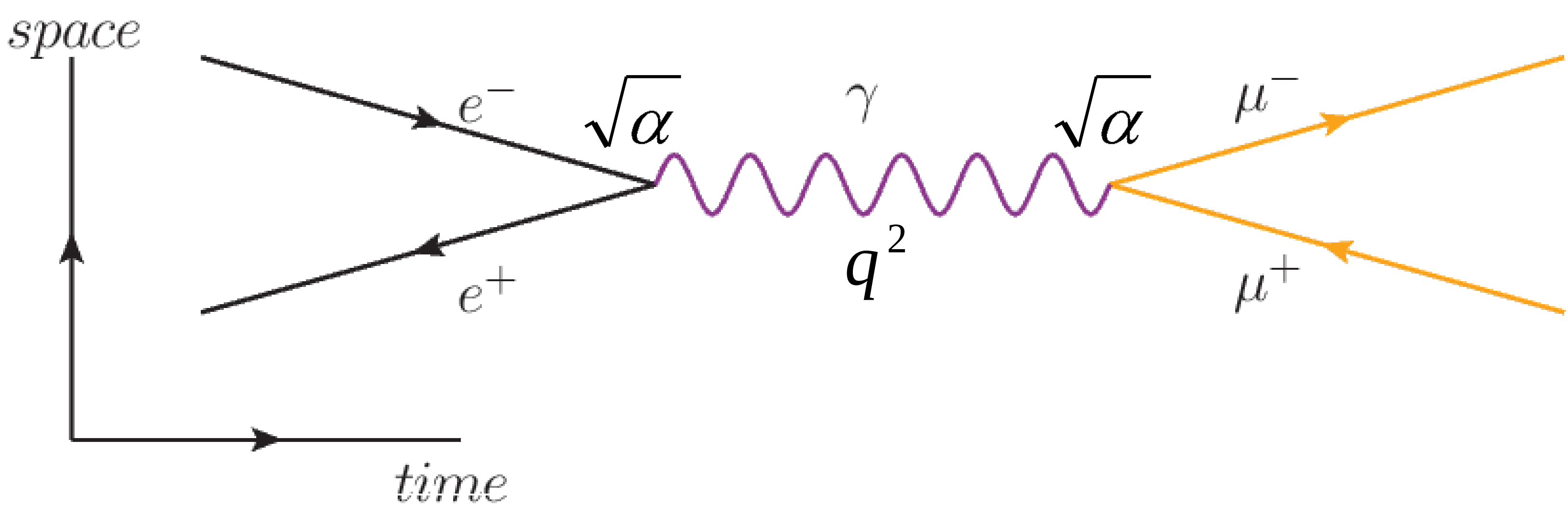


Feynman diagram for e$^-$-e$^-$ collision

$$\alpha = \frac{e^2}{\hbar c 4\pi\varepsilon_0}$$

Quantum ElectroDynamics (QED)

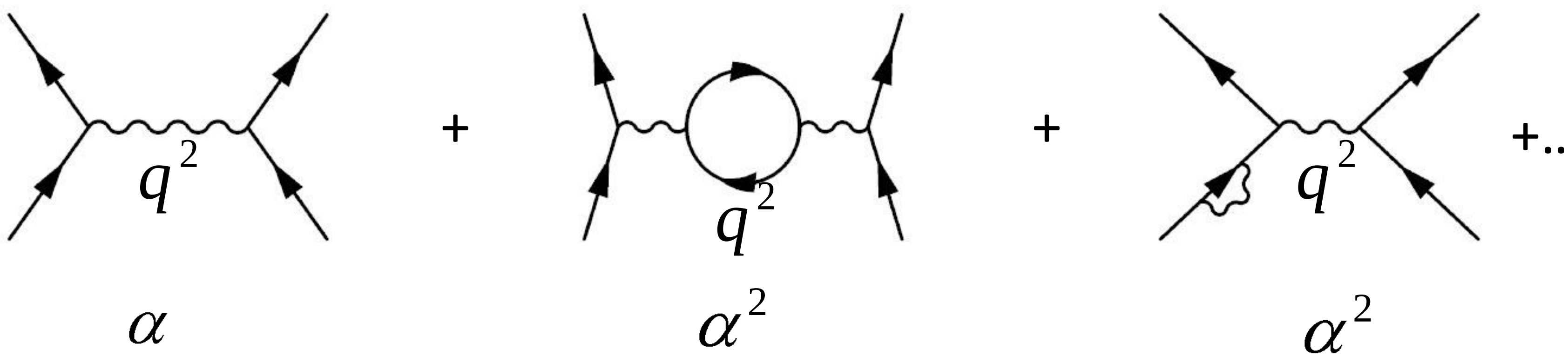
- Tomonaga (1946), Scwhinger (1948) and Feynman (1948) based on Dirac (1928)
- Another example $\mu^+ \mu^-$ production:



- Antiparticules pictured as arrows opposite to flow of time
- Emission of e^- = absorption of e^+
- Internal particles are called “virtual particles”
- Possible if invariant mass $m_{e+e-}=q^2>2m_\mu$

Quantum ElectroDynamics (QED)

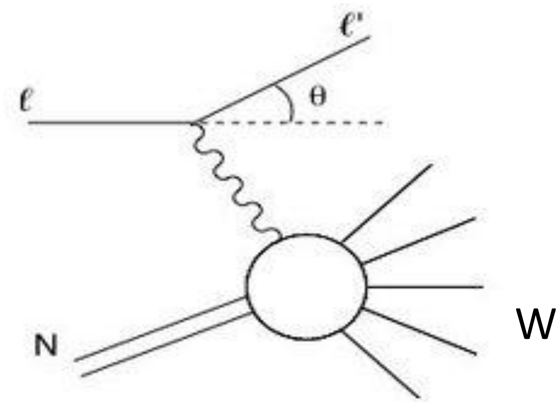
- Tomonaga (1946), Schwinger (1948) and Feynman (1948) based on Dirac (1928)
- Another example $\mu^+ \mu^-$ production:

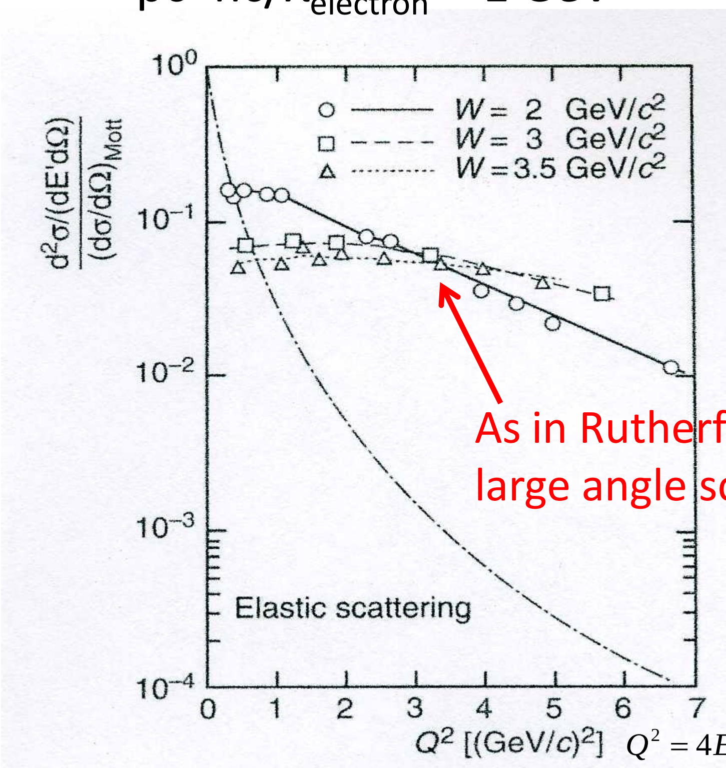


- Feyman diagrams part of a perturbation series in powers of coupling constant α

Back to history: protons are composite

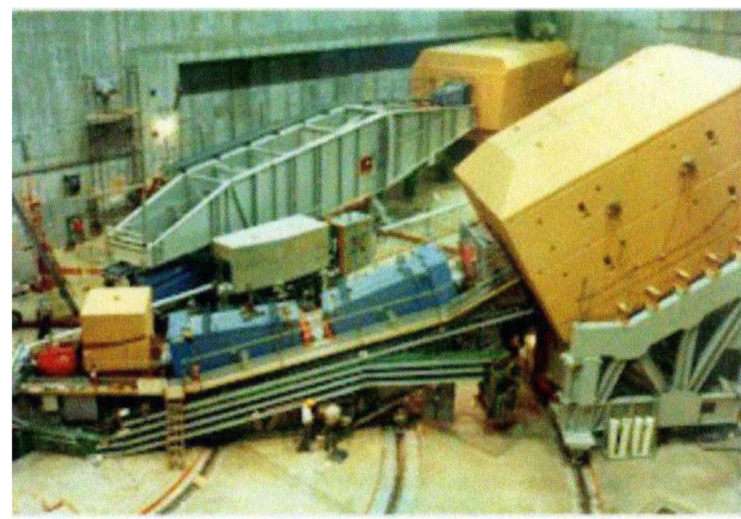
- Post WWII: accelerator era
- 1968 SLAC: shoot e^- to proton target
- High energies: $\lambda_{electron} << R_{proton}$
  $pc = hc/\lambda_{electron} >> 1$ GeV



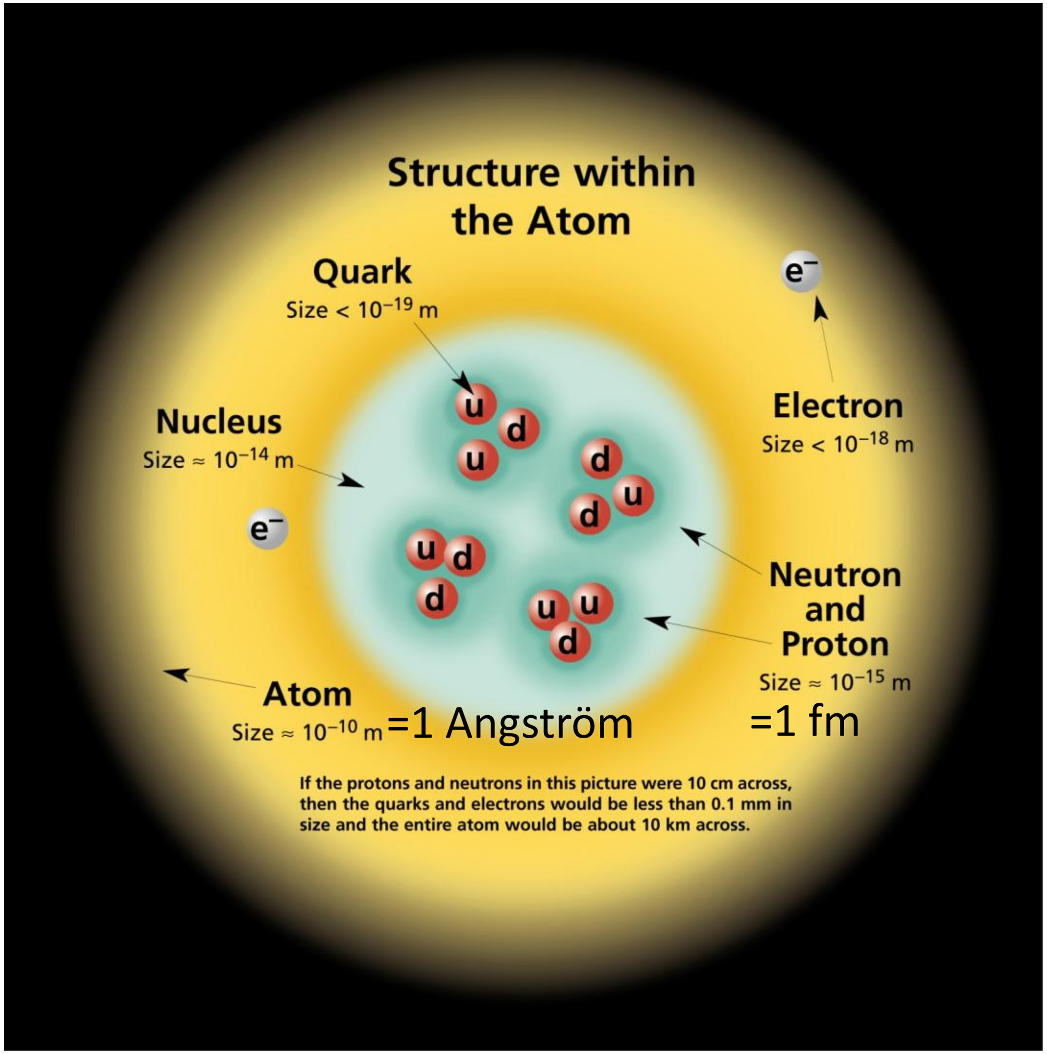


As in Rutherford, large angle scattering!

$Q^2 = 4EE' \sin^2(\theta/2)$



Protons are composite

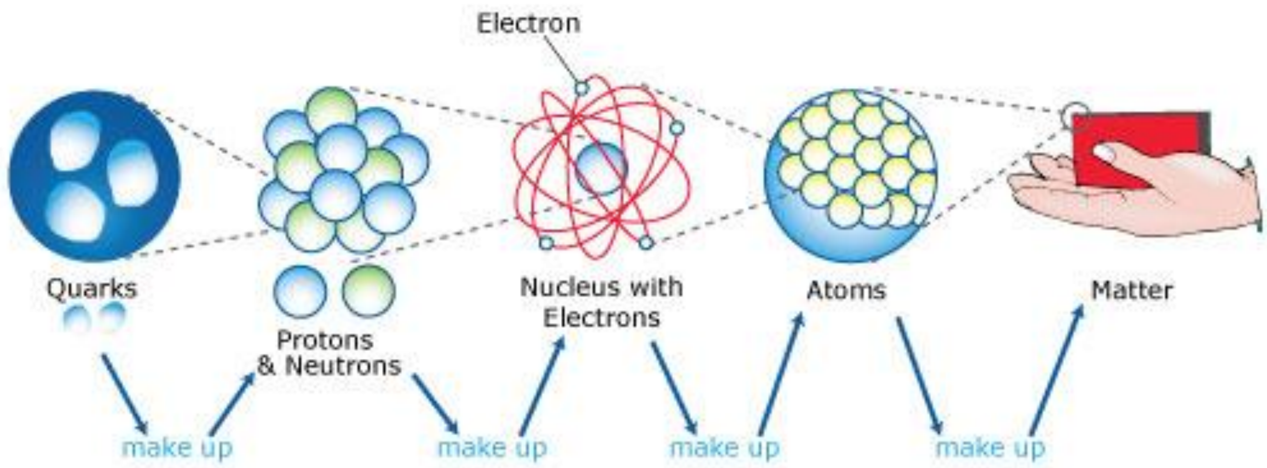


Nucleons composed of 3 point-like particles: quarks

Orders of magnitude, units

$E_I(H)$=13,6 eV
1eV=1,62 x 10^{-19}J

~0,5 GeV
=0,5 x 10^9 eV



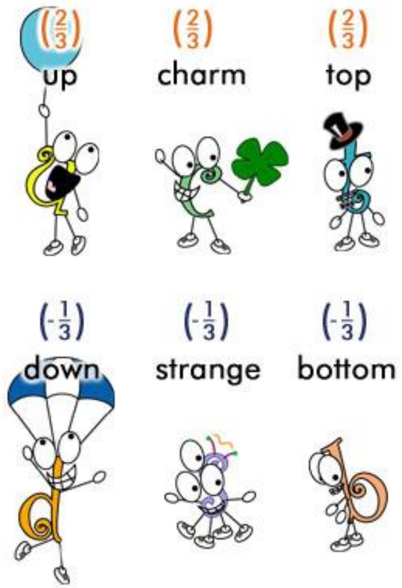
$S_p(^{40}Ca)$=8,3 MeV
=8,3 x 10^6 eV

Masses in energy units ($E=mc^2$!)

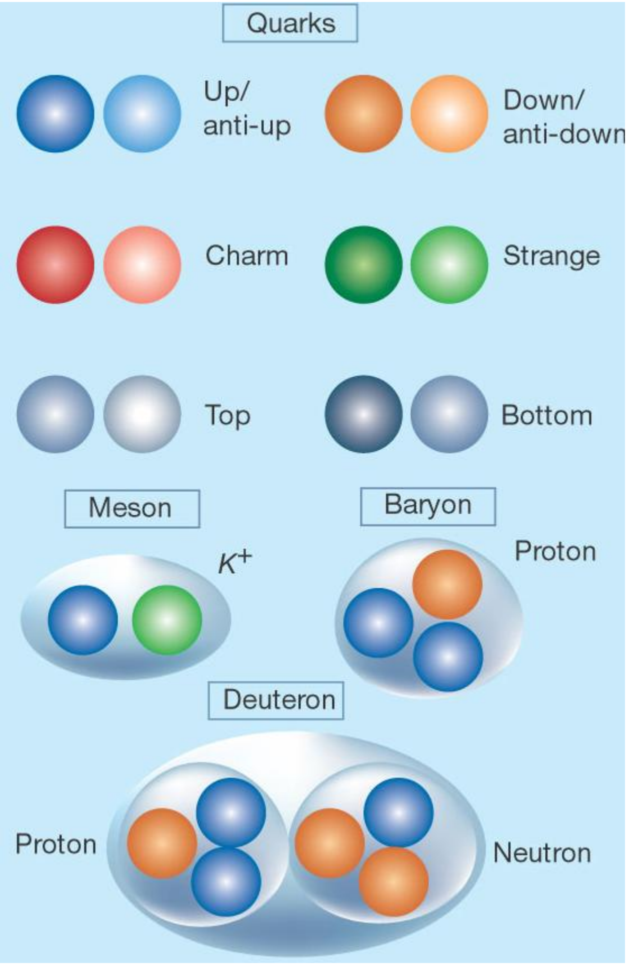
e.g. m(proton) = 938 MeV, m(electron) = 0,511 MeV

Quarks make up hadrons

- Repeat of the muon story: many different quarks, each time heavier and more unstable,
  3 “families” or “generations”, 6 “flavours”



- Arranged in:
  - 3 quarks, 3 antiquarks *(baryons)*
  - quark+antiquark *(mesons)*



Why?

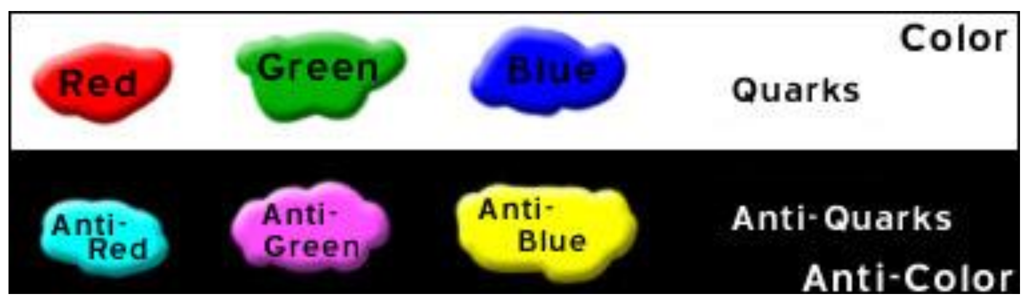
- EM with *three* different types of charge
- Let's call them red, green, blue, just for fun…*
  "Positive" charge is then red whereas "negative" is anti-red (cyan, in this analogy).
- Call "quark" a particle with color charge

E&M

+

−

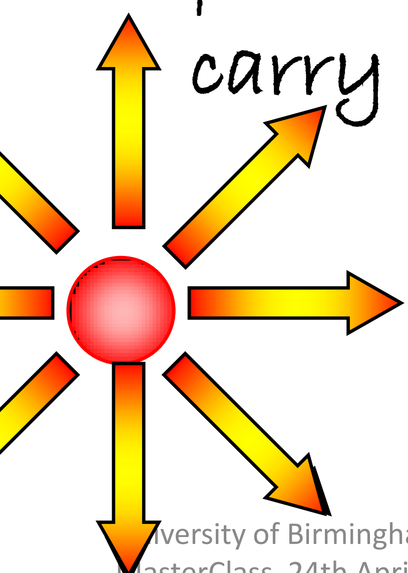
3 charges

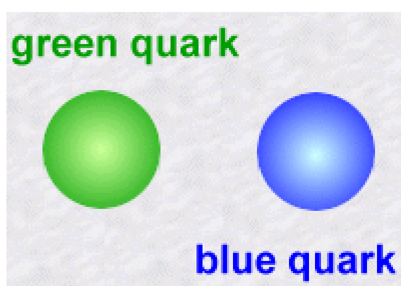


* Particles with color not responsible for colours of light!

Quantum ChromoDynamics (QCD)

- Charges attract (repel) if opposite (same), e.g. red and red repel, red and anti-red attract.
- Also through exchange of particles (gluons)
- But red and green (blue) attract as well. More possibilities: the exchanged particles must carry charge (color) themselves!



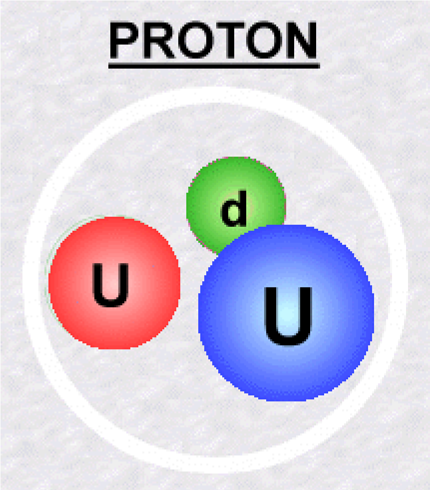


So quarks change color after emitting gluons!

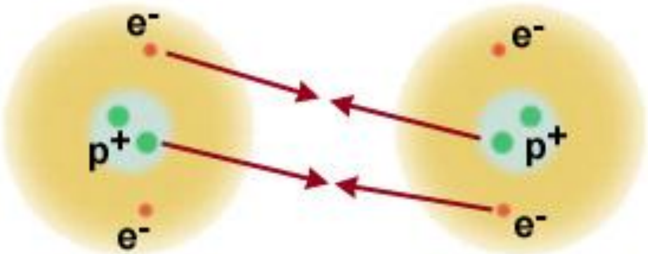
QCD

- Neutrality (neither excess nor defect) of these color charges is got from:
  - color+anti-color
  - red+green+blue since anti-red=cyan=green+blue
- In EM the places where we find particles are in neutral arrangements (atoms). If we find these special charges will be in neutral arrangements too! (*hadrons*: two or three particles with color)

QCD → Strong nuclear force



- Theory of particles with color describe protons, neutrons and nuclei of atoms
- Protons and neutrons bound by residual force between quarks, same as atoms in molecules



Strong but short…

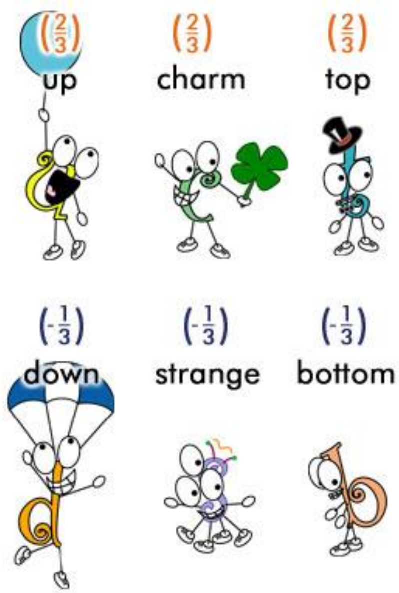
- Since gluons carry color charge, are attracted by quarks and other gluons and concentrate around line between quarks
- Pull quarks apart and there'll be more gluons so force will be stronger! No quark on its own!

- Keep pulling and energy between them will be enough to create a quark and an antiquark:

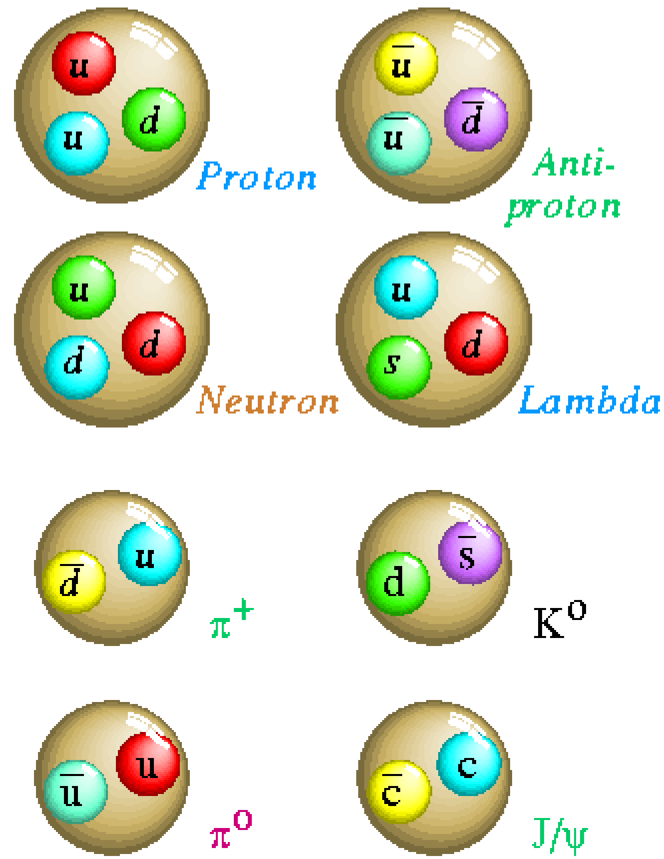
Quark confinement!

Quarks make up hadrons

- Repeat of the muon story: many different quarks, each time heavier and more unstable, 3 “families” or “generations” WHY???

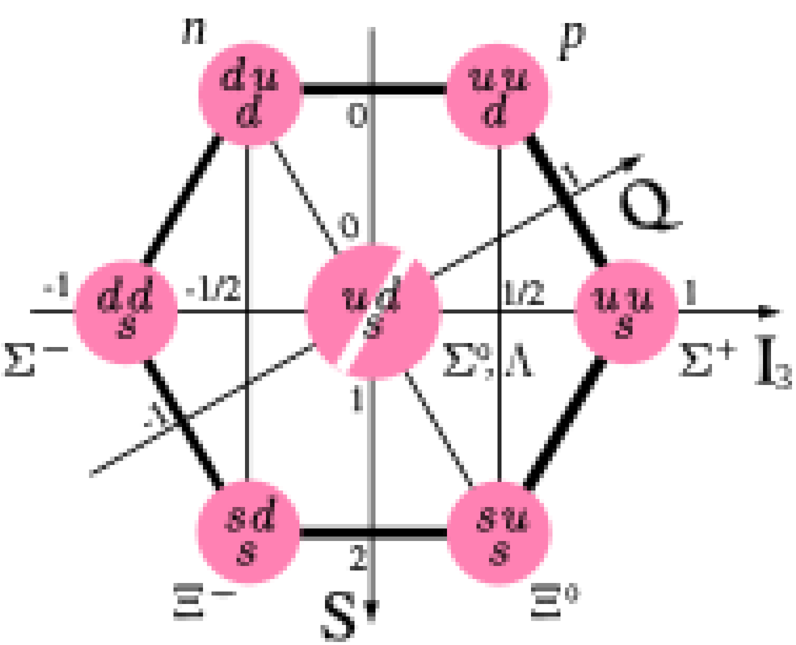


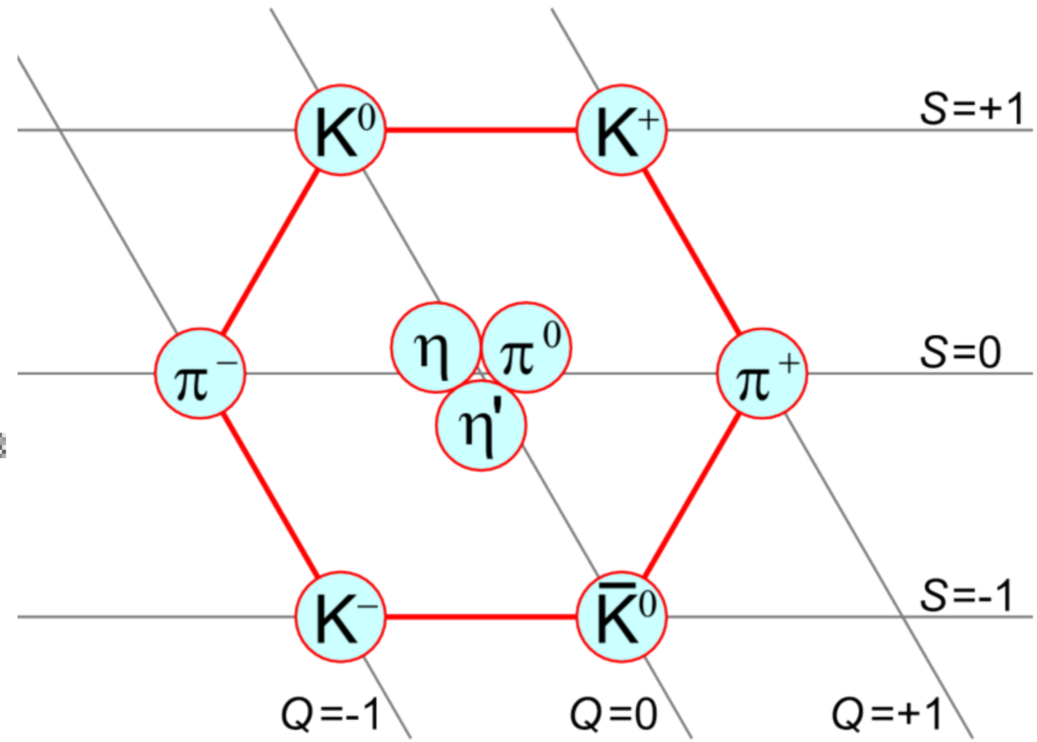
- A few important mesons: pions, kaons (s quark), D (c quark), B(b quark)



Symmetries

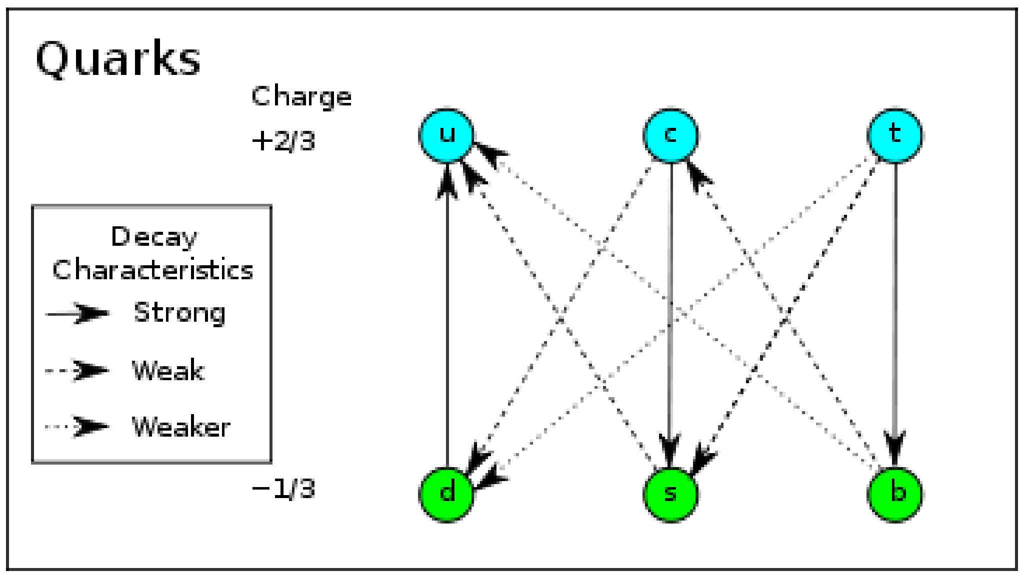
- Classification and description thanks to symmetries (group theory)





Heavy flavours

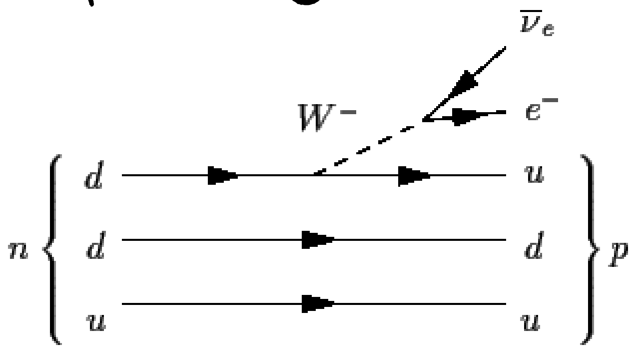
- Heavy quarks unstable… How? Up to now, always creating/annihilating pairs of particle-antiparticle of same type
- *Weak force*



Weak force

- EM with *two* different types of charge and *heavy "photons"*.

  Call them "Z", "W^+", "W^-"



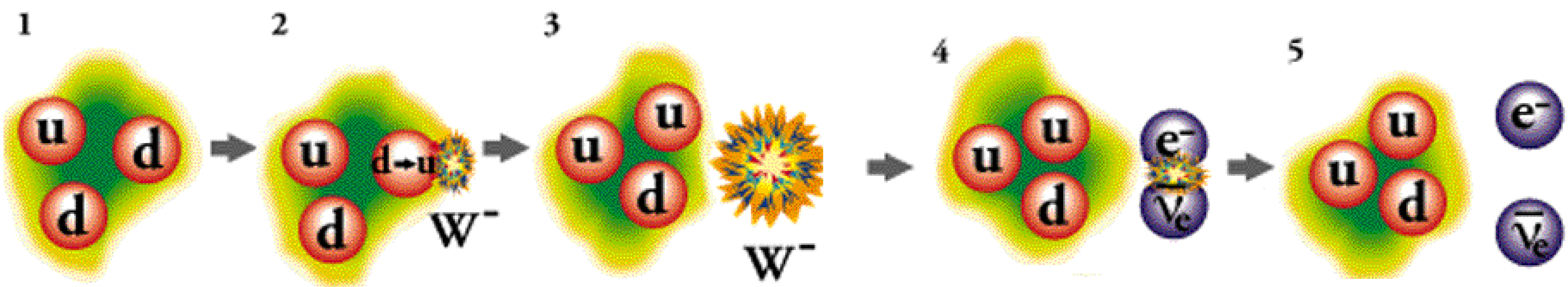
- Propagator prop to $1/M^2_W$

  If masses of Z, W are very high,

  very small rates! → **WEAK force**
- So Z and Ws will only play a role when EM and strong force don't!

Heavy "photons"

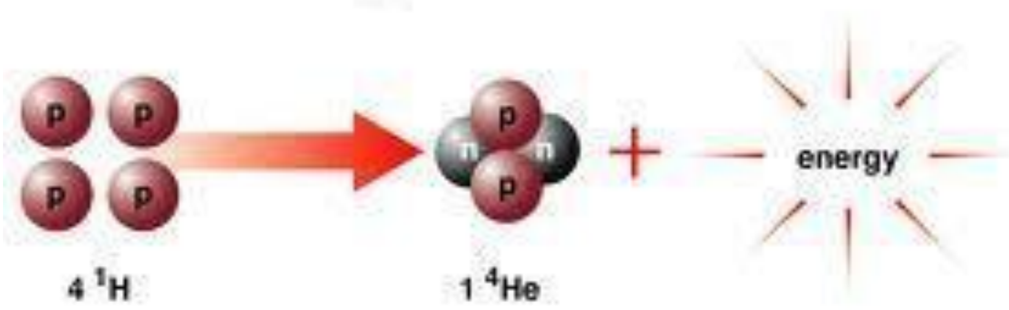
- Some radioactive processes happen like that! E.g. neutron goes to proton and electron

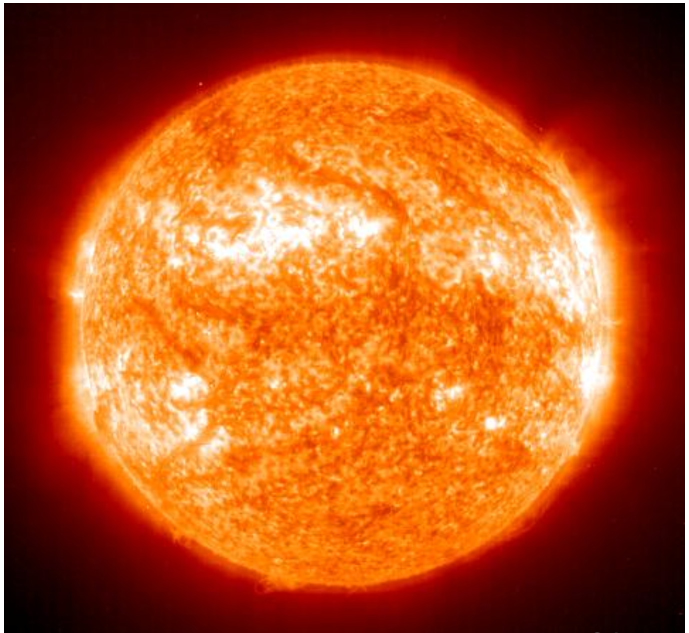


- Same as a quark changes color when emitting a gluon, a particle emitting a W will change! (d→u in this case!)

Weak force

- Responsible for plenty of rare radioactive processes, e.g. neutron becomes proton plus electron (β radiation)
- Speed of energy production in the sun (hydrogene fusion)





Puzzle

- What is a neutrino?
- Very light, only affected by Z and Ws
- Thus hard to see…
- Paired with electron, also light and without color
- Just as happened with the quarks, heavier versions of electrons and neutrinos have turned up in experiments!

Weak force

- Have seen that Ws turn into quark and anti-quark, or leptons (e.g. muon plus neutrino)

- Zs are a bit different: turn into particle plus its antiparticle (eg u and anti-u, electron and anti-electron, neutrino and anti-neutrino).
- Also, a particle doesn't change when emitting a Z

Puzzle

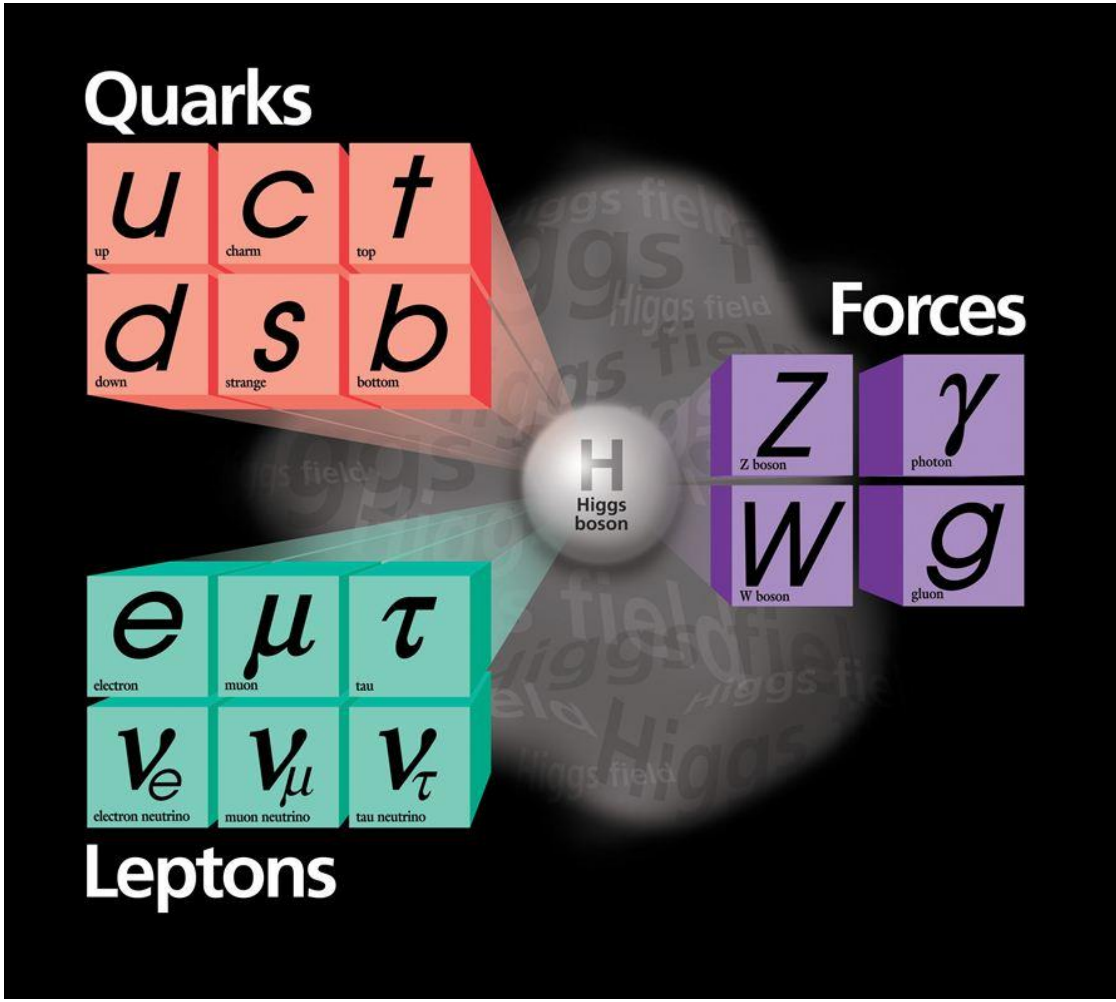
- How heavy are Z and W?
- About 100 and 85 times heavier than proton!
- How can photons and gluons have nearly no mass and Z and W have so much?

- The Higgs boson?

  (see Eric's talk)

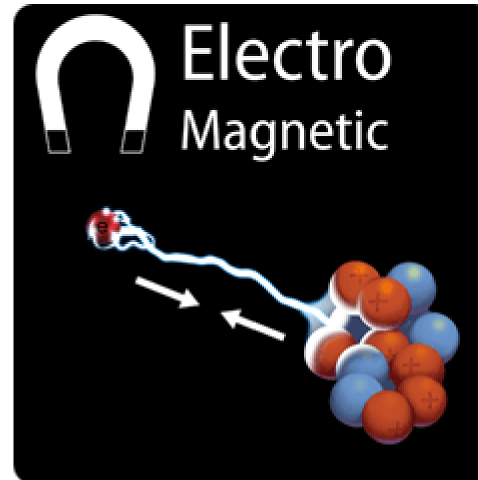
The Standard Model

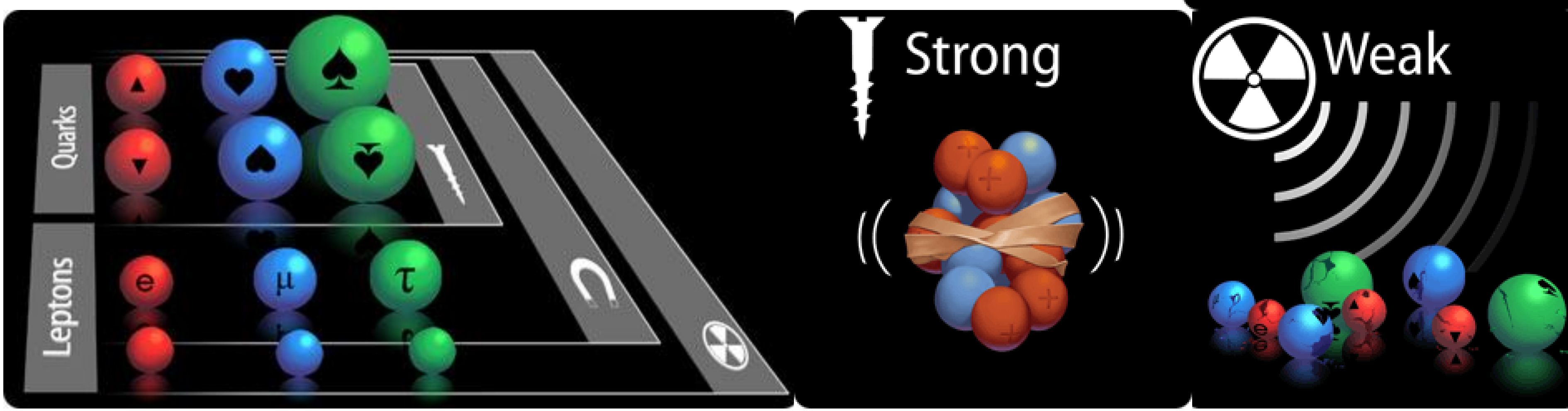
- Are they all elementary?
- Are there any more?
- Why 3 generations?

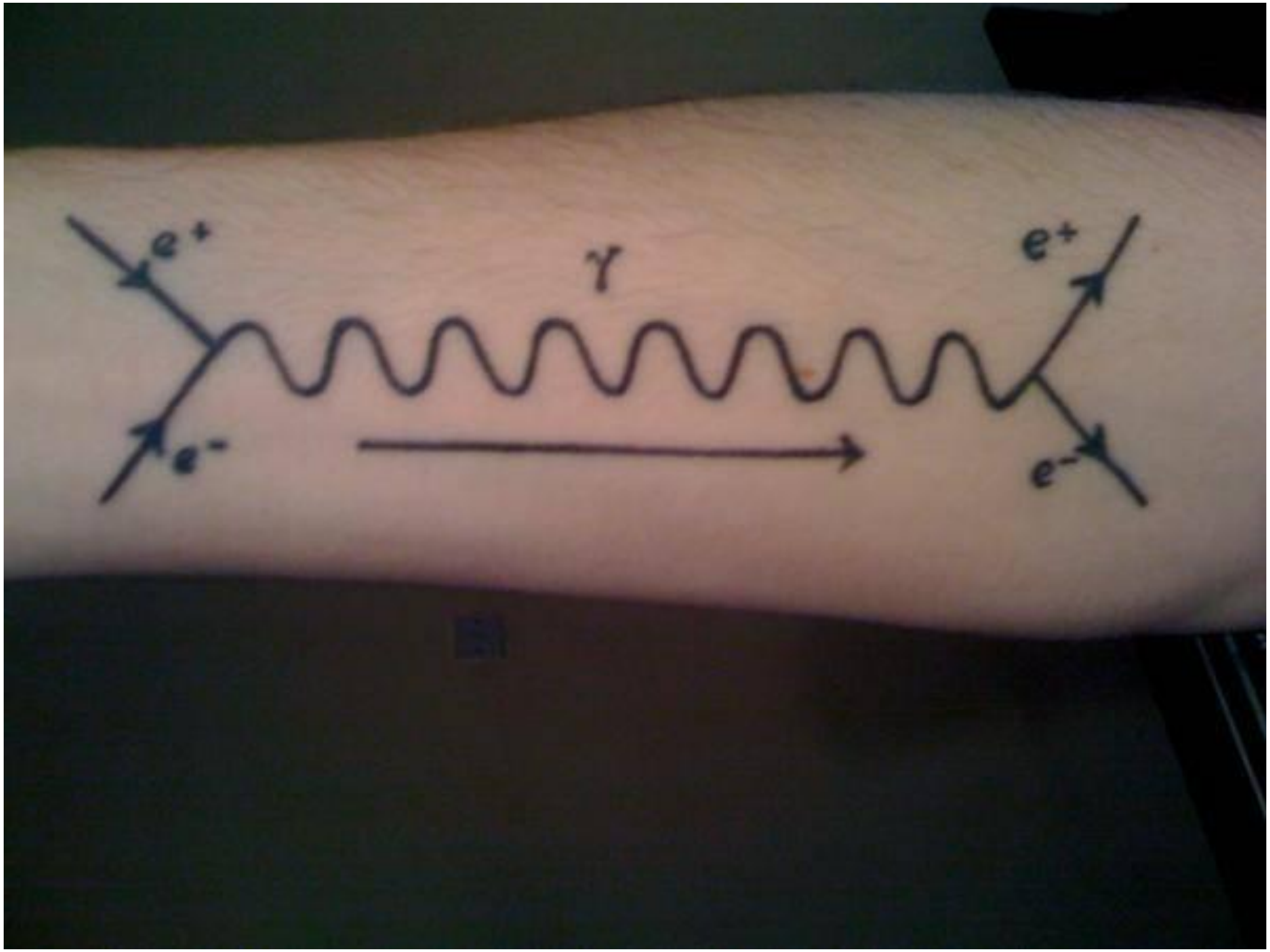


Summary

- Plenty of open questions; much learnt!
- Electromagnetisme, γ : all particles except ν's
- Weak force, $W^{\pm}$ et Z : all particles
- Strong force, gluon : only quarks

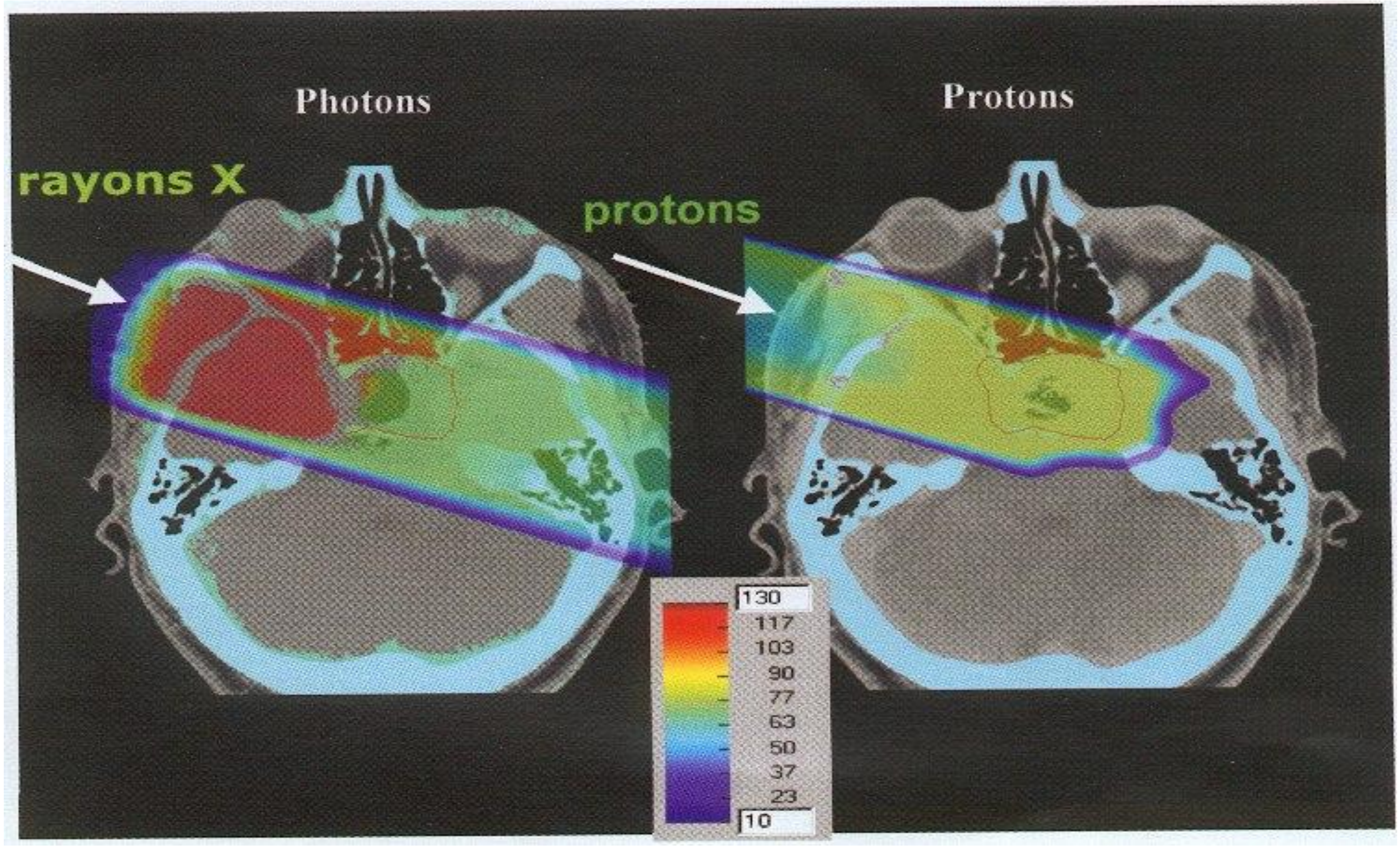





e+
e−
γ
e+
e−

Applications

- Radiothérapie



Applications

- Le World Wide Web a été inventé au CERN ! (1990)
- La grille de calcul

La Physique des Particules

POUR LES NULS

Pablo del Amo Sánchez

Laboratoire d'Annecy-le-Vieux de Physique des Particules

UNIVERSITE DE SAVOIE CHAMBERY ANNECY

En prime : comment fabriquer la bombe de « Anges et démons »

À mettre entre toutes les mains !

Alors… une bombe ?

Le moment tant attendu…

Comment faire une bombe d’antimatière !

Alors… une bombe ?

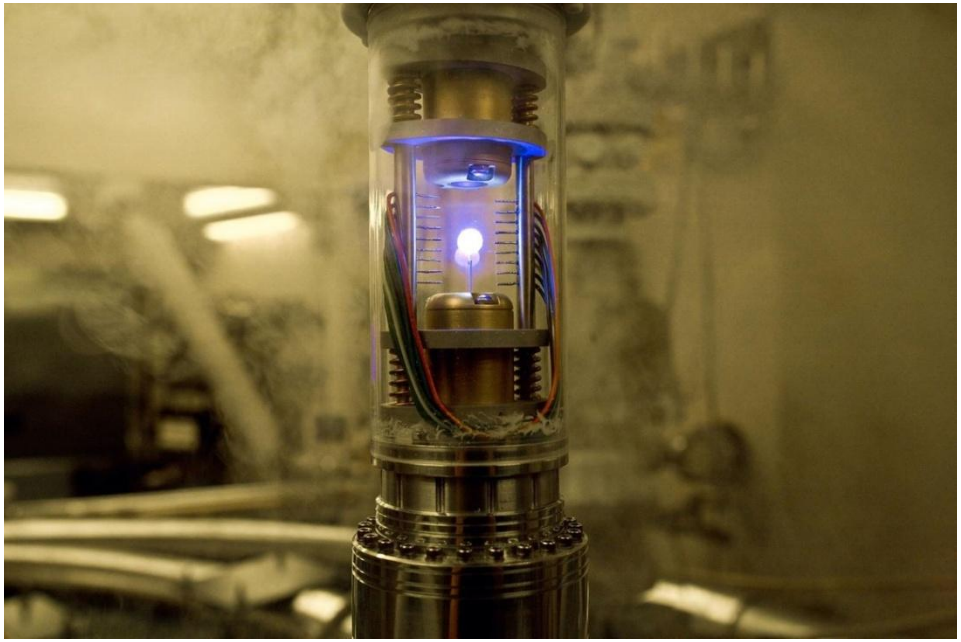
0,5g matière + 0,5g antimatière = 1g

$E = 0{,}001\ kg \times (300\,000\,000\ m/s)^2$

$= 9 \times 10^{13}$ Joules

1 kilotonne = $4{,}2 \times 10^{12}$ Joules

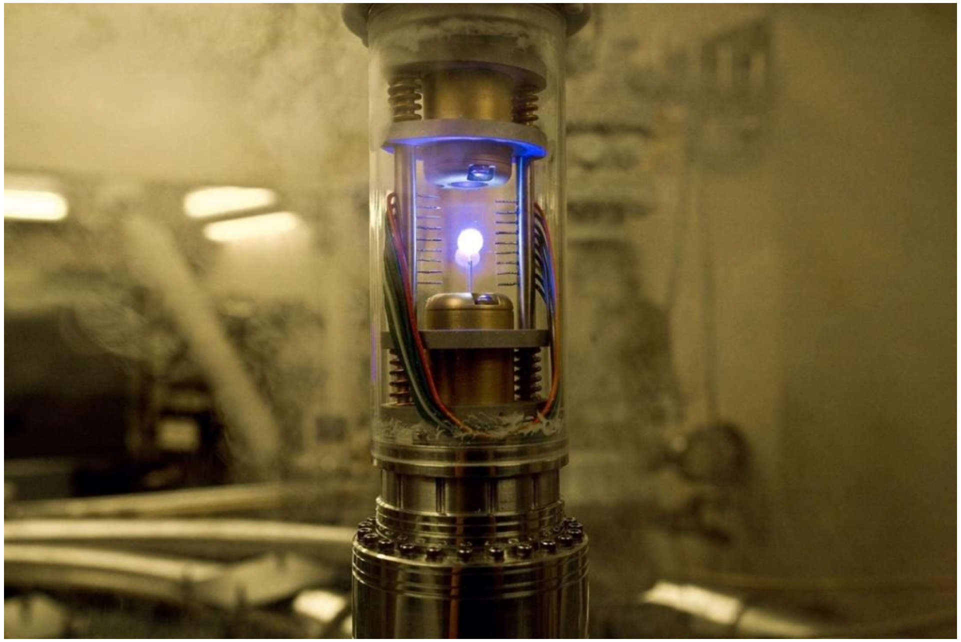
donc **0,5g antimatière → 20 kilotonnes**



Il ne nous reste qu'à fabriquer 0,5 g d'antimatière !

Alors… une bombe ?

0,5g antimatière = $3x10^{23}$ atomes d’antihydrogène



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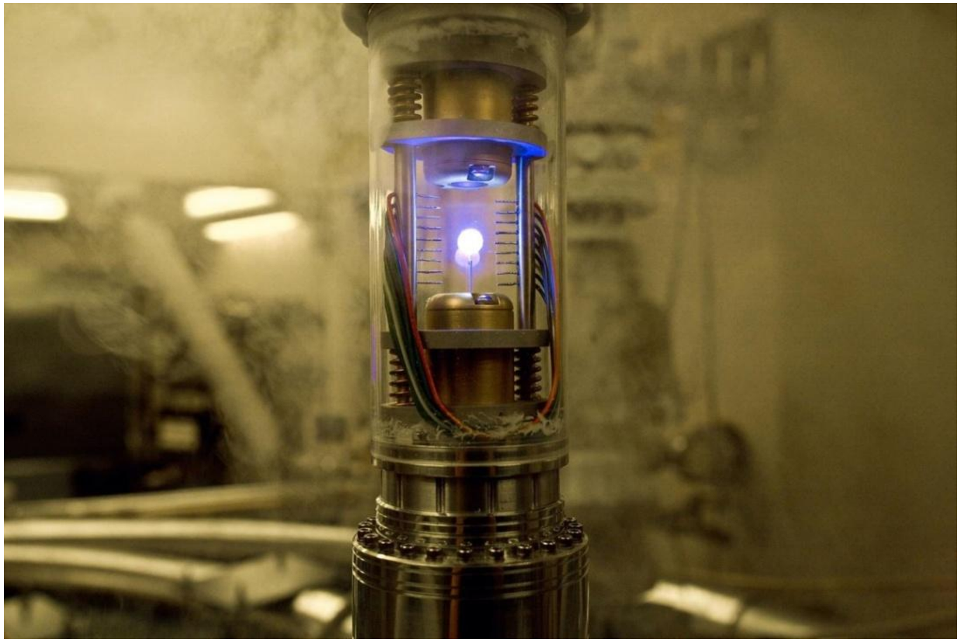
Le CERN arrive à produire tous les 100 secondes 30 000 000 antihydrogènes



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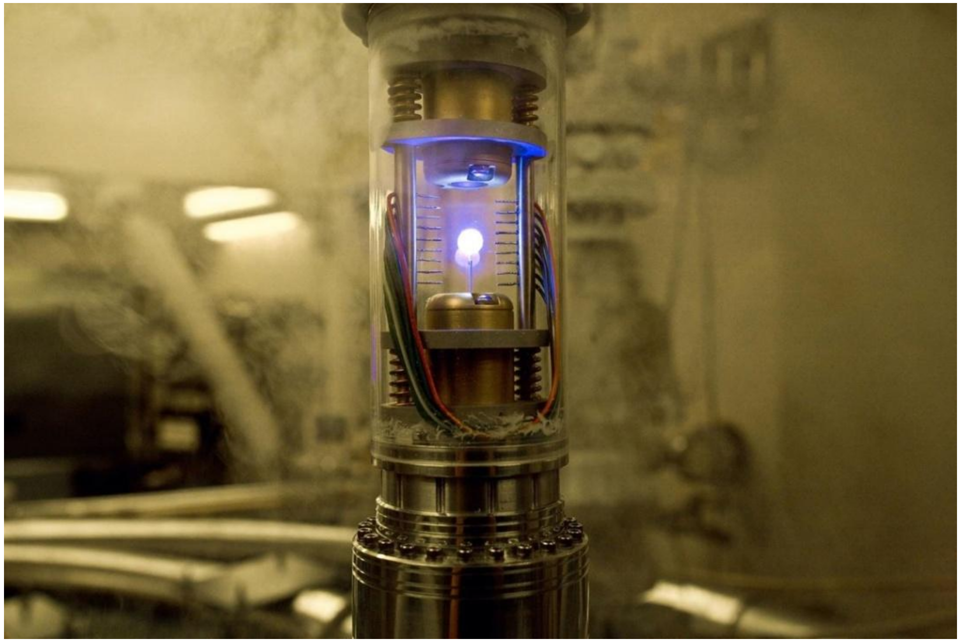

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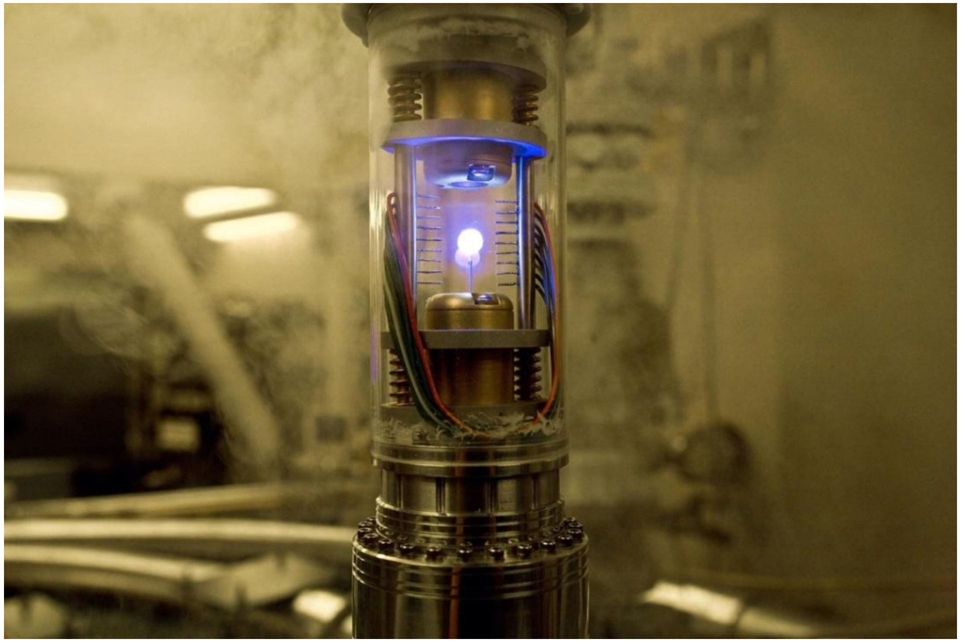

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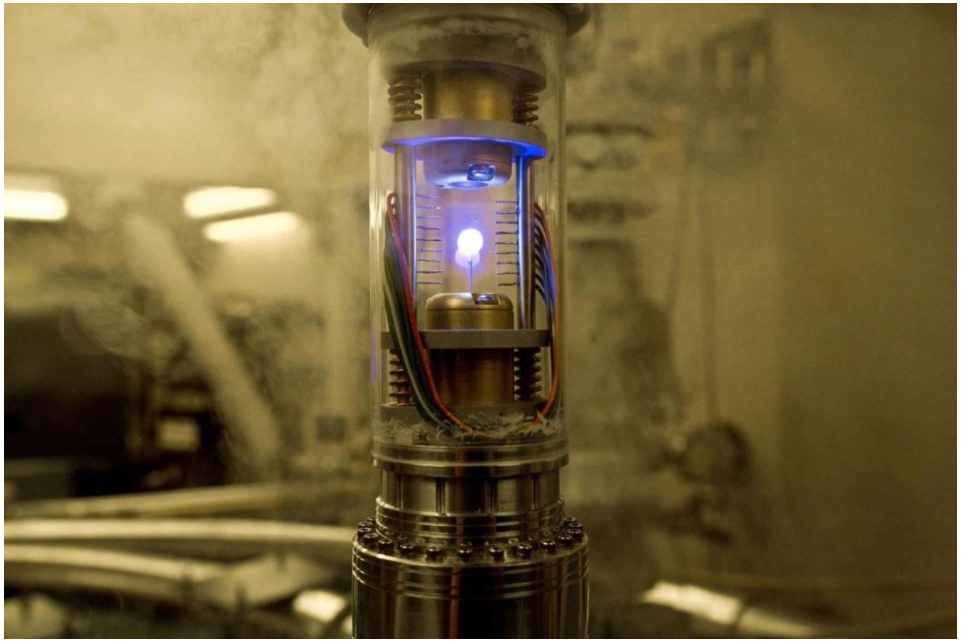

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Et le prix ?

Au prix « discount » payé par le CERN, 1kWh = 0,1€

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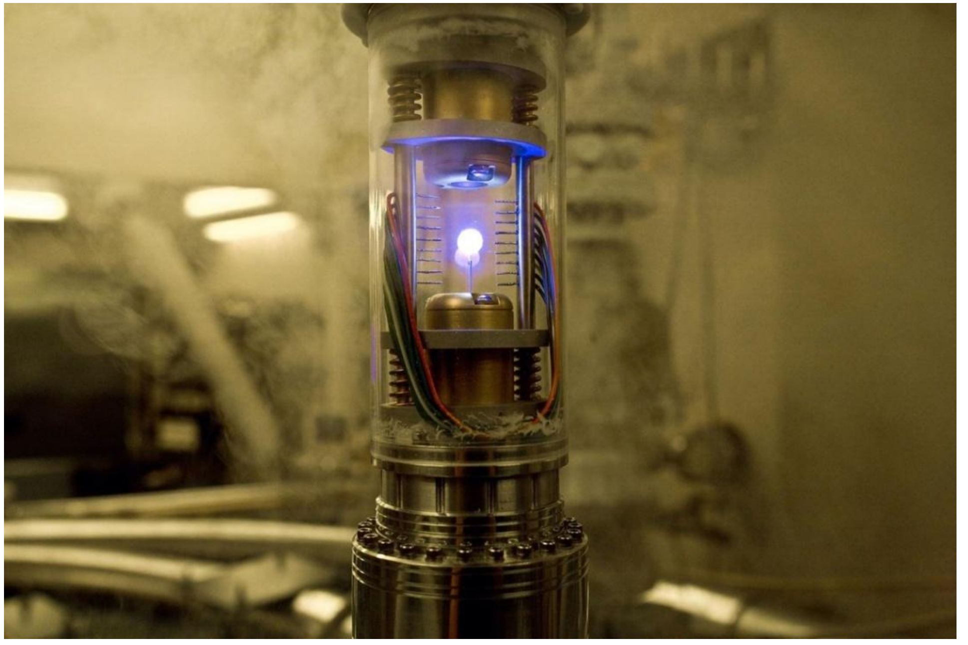

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→ coût = 1 000 000 000 000 000 € = 1 million de milliards d'€ !!