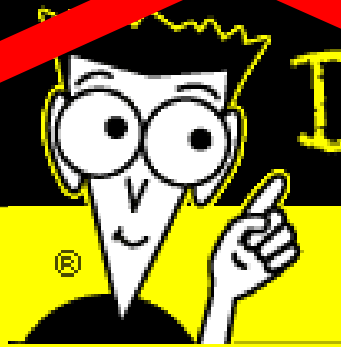


# Particle Physics

FOR



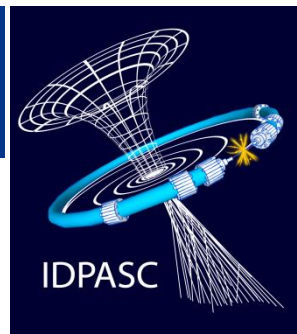
DUMMIES

## *Introducing* Particle Physics

Pablo del Amo Sánchez



**IN2P3**  
Les deux infinis



# Aim of this lecture:

Particles and Forces of the Standard Model

The particle zoo

Qualitative Feynman diagrams

# The Standard Model: elementary particles and their interactions

## Fermions matter particles

### Quarks



### Leptons



## Gauge bosons force carriers



photon



gluon

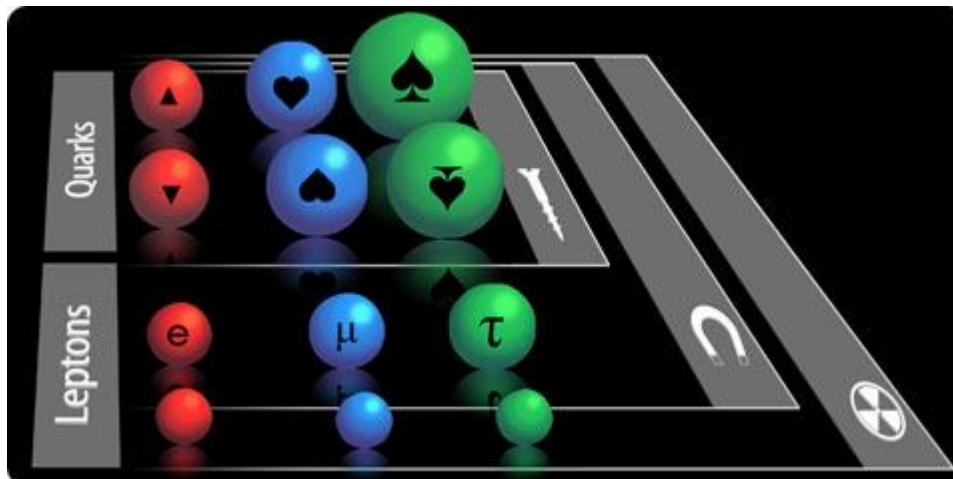
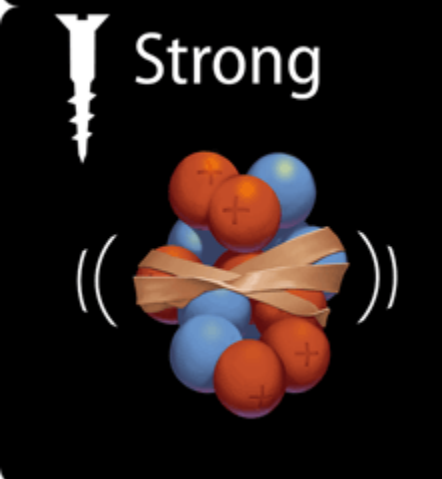
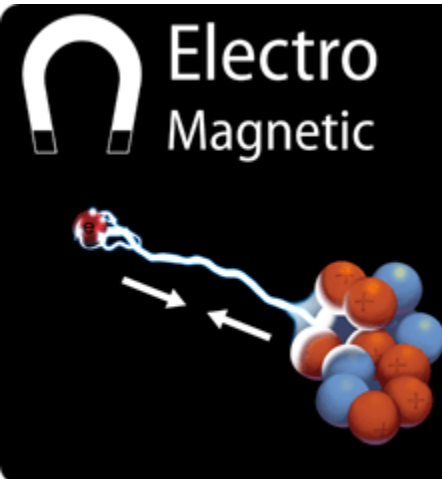


Z boson



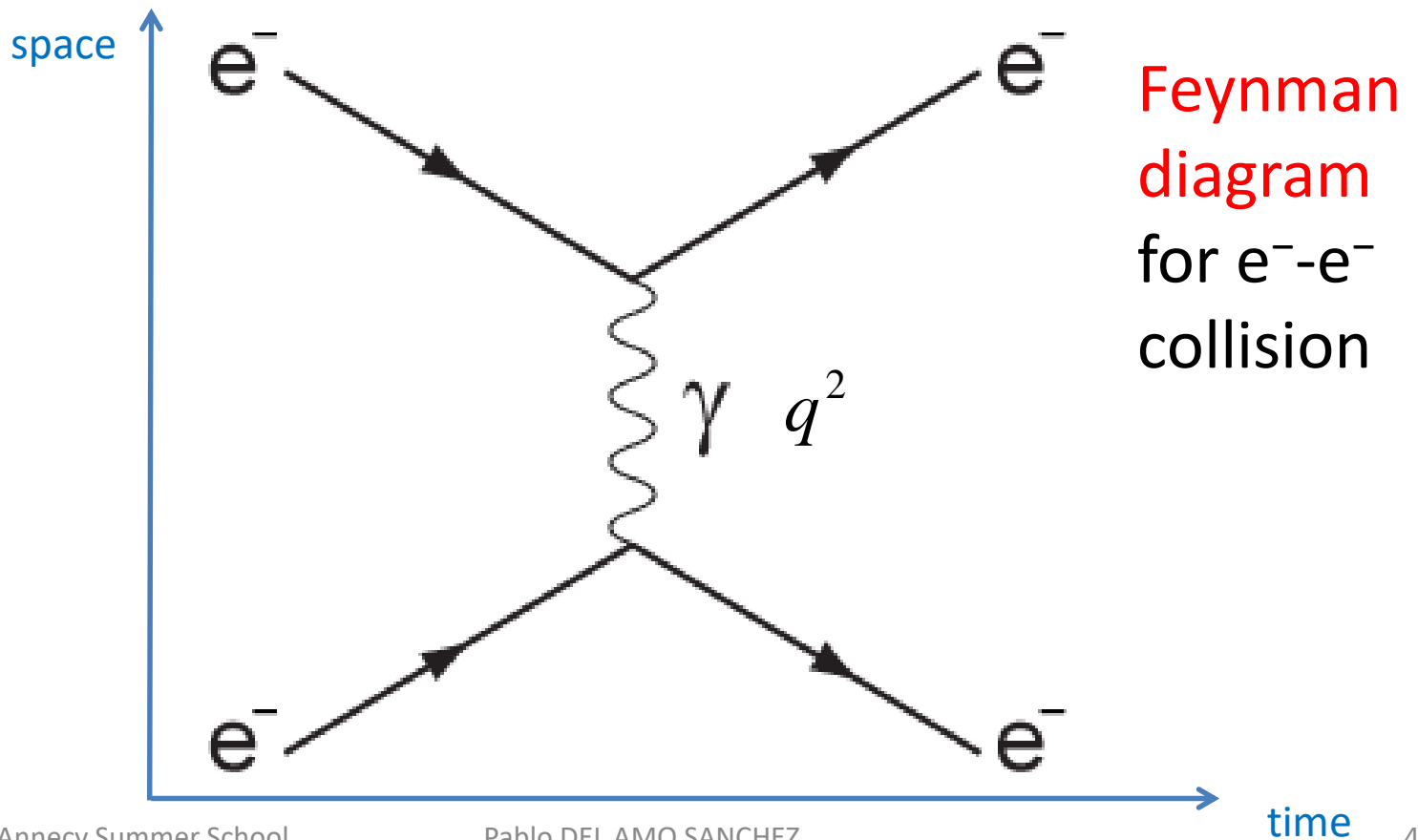
W boson

## Higgs boson origin of mass



# Example of EM interaction

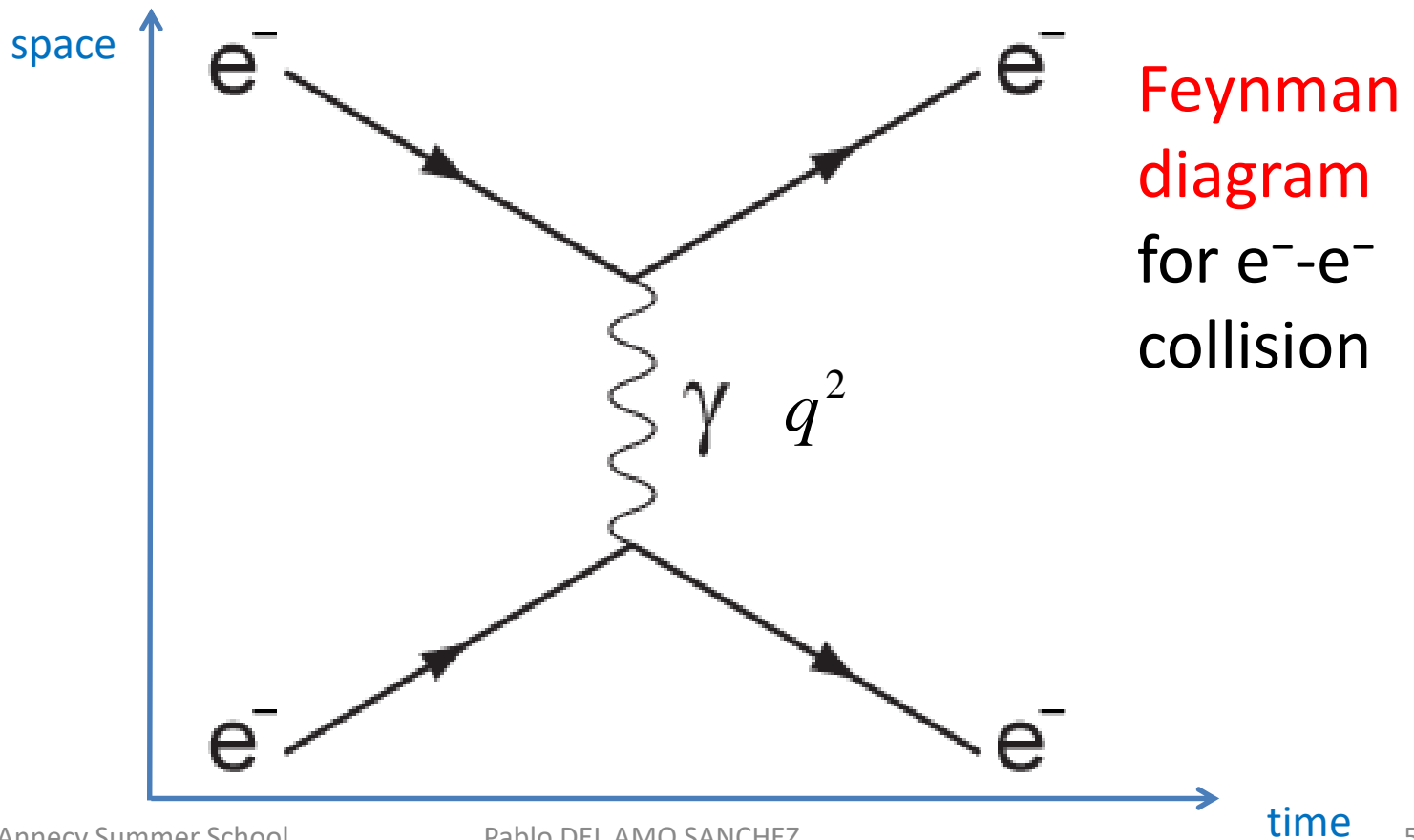
$e^- - e^-$  collision, transferring momentum  $q$  by exchange of photon, quanta of EM field



# Example of EM interaction

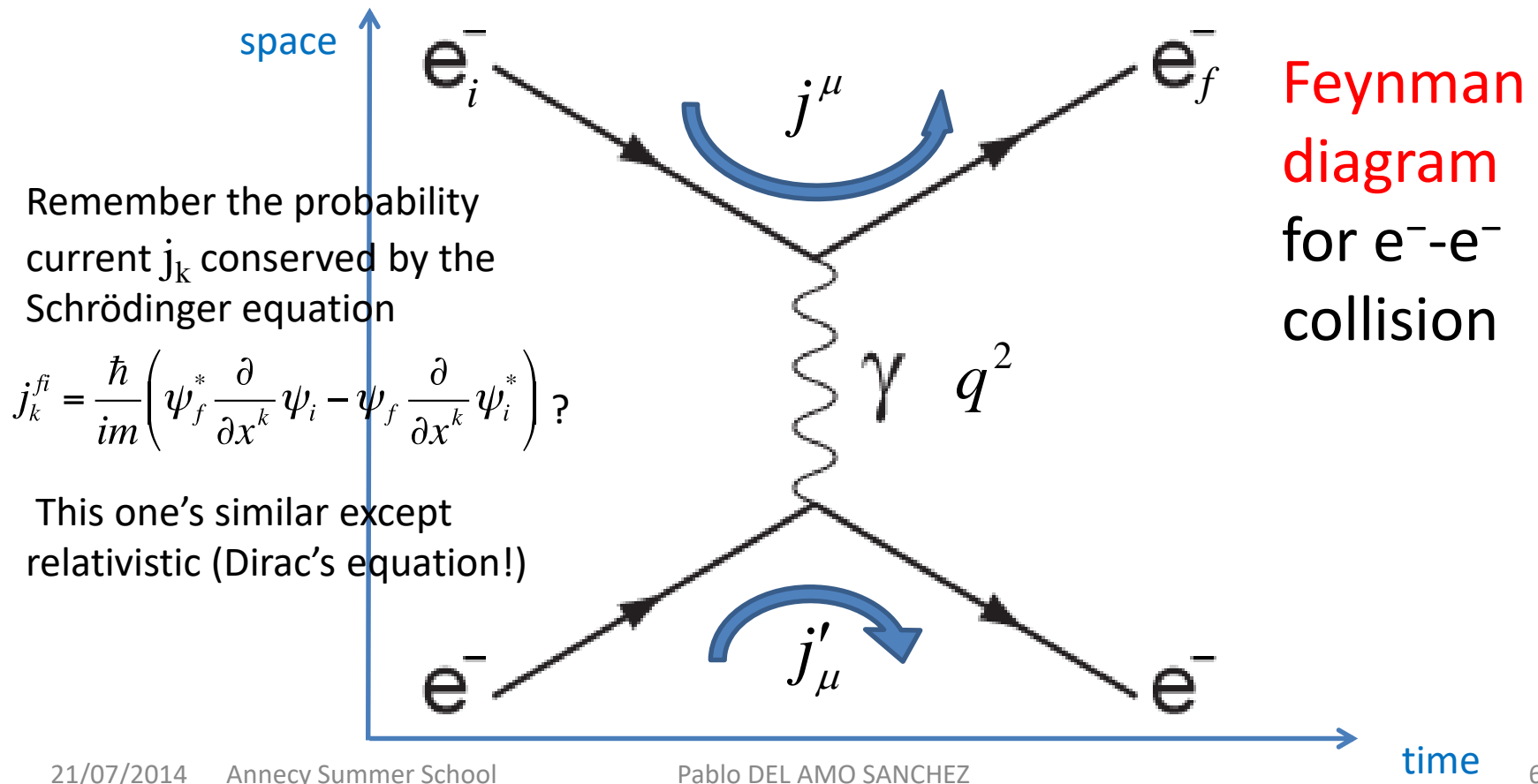
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Feynman diagrams are calculational tools: will sketch computation of QM amplitude



# Example of EM interaction

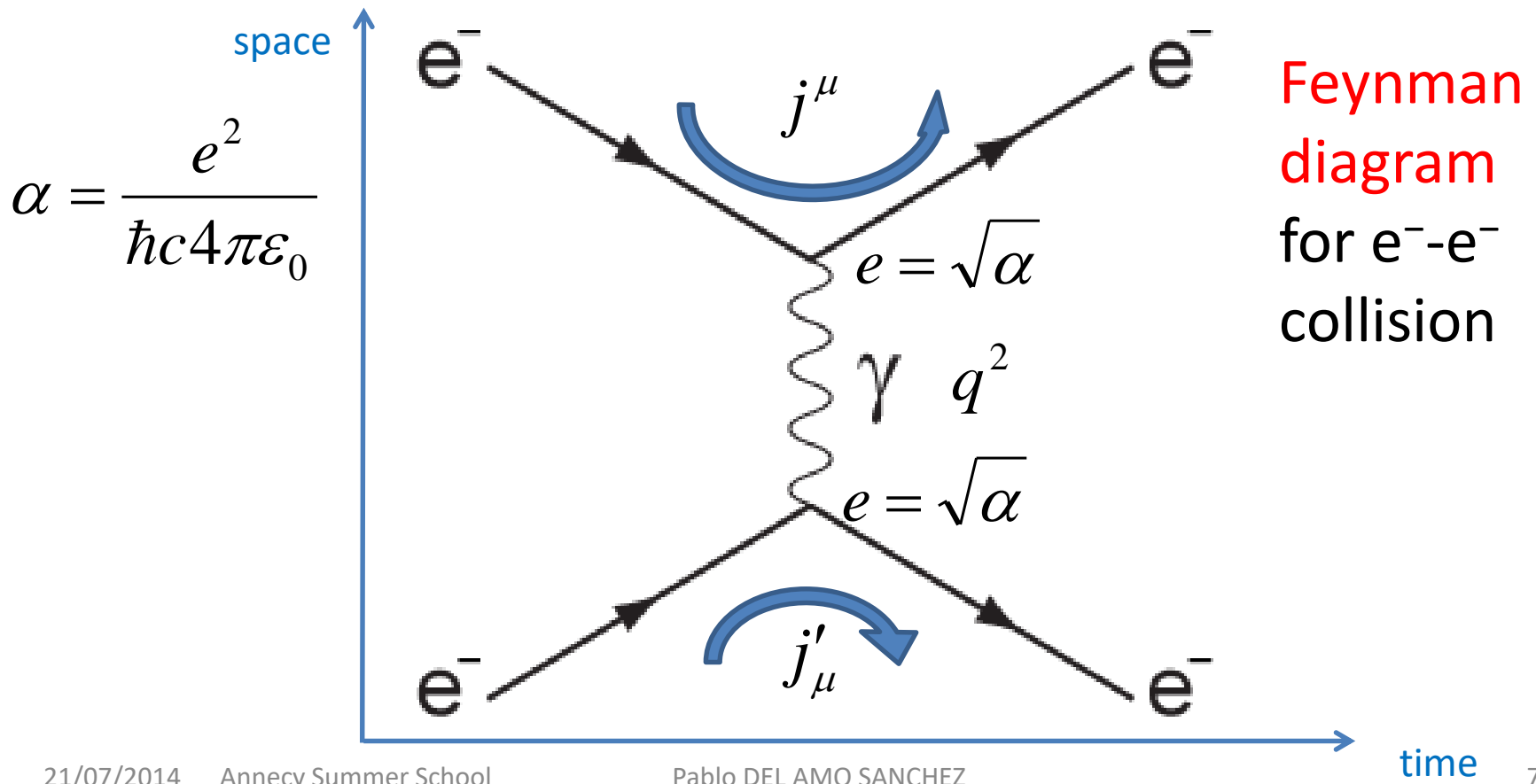
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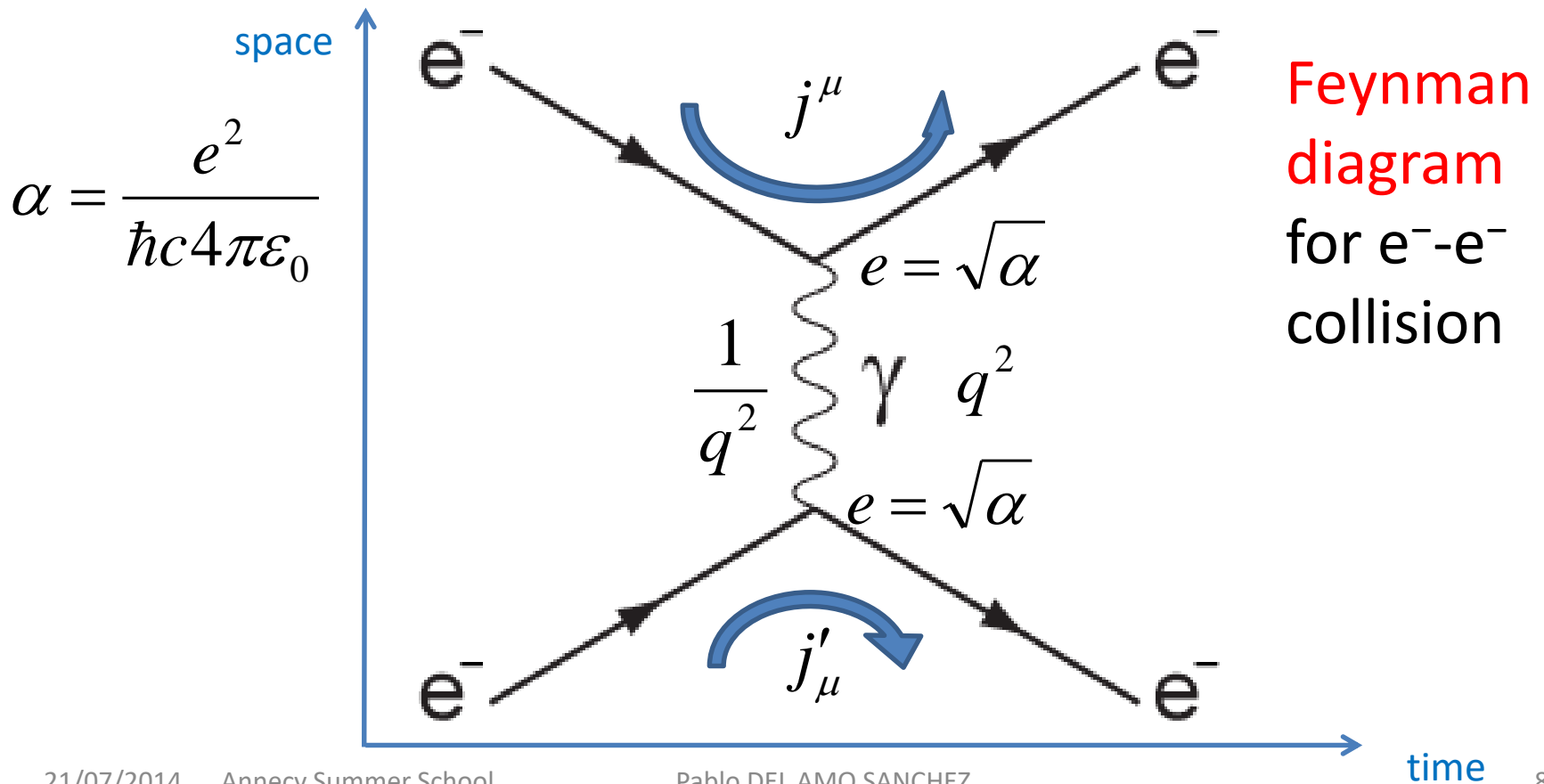
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# Example of EM interaction

$e^- - e^-$  collision, transferring momentum  $q$  by exchange of photon, quanta of EM field

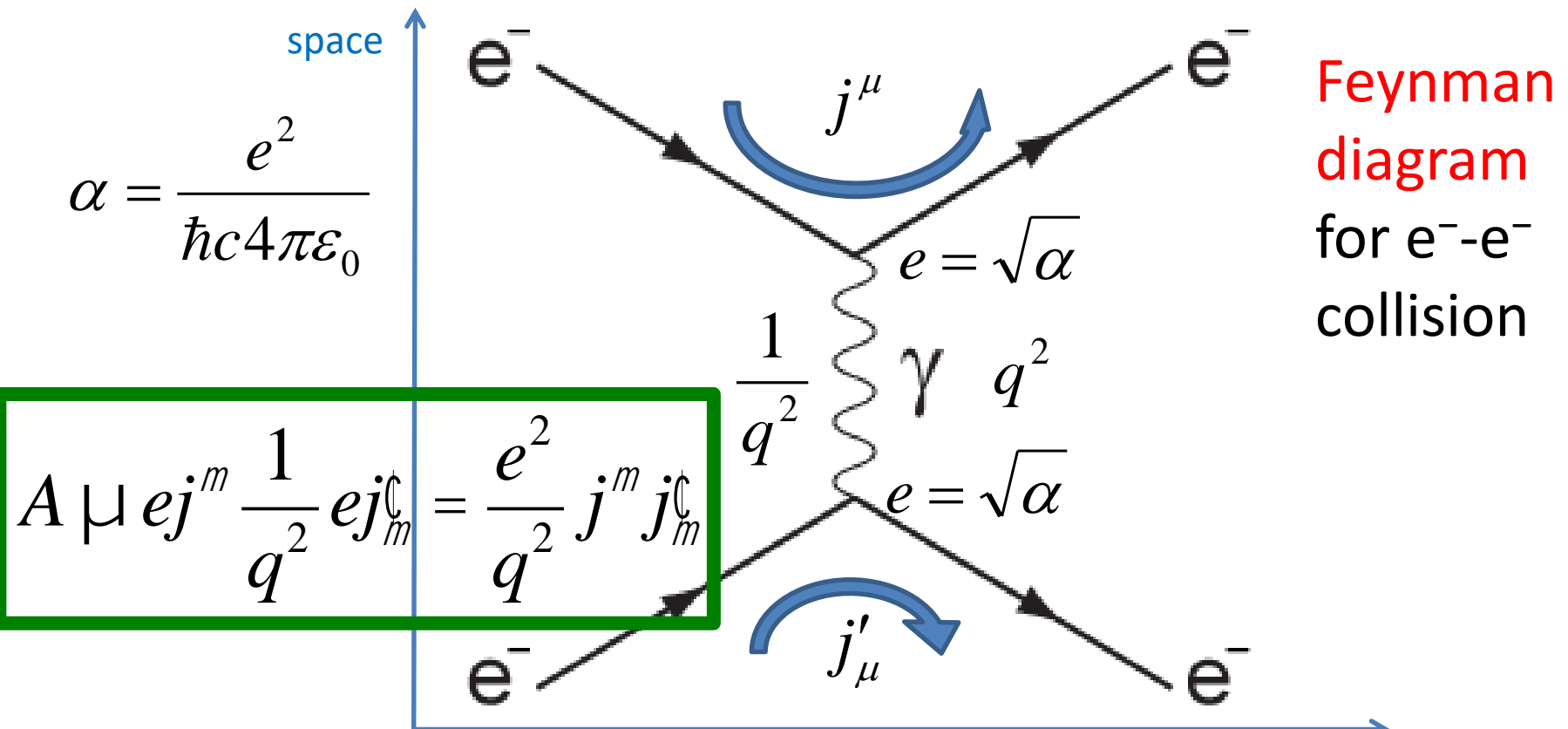
Feynman diagrams are calculational tools: will sketch computation of QM amplitude



# Example of EM interaction

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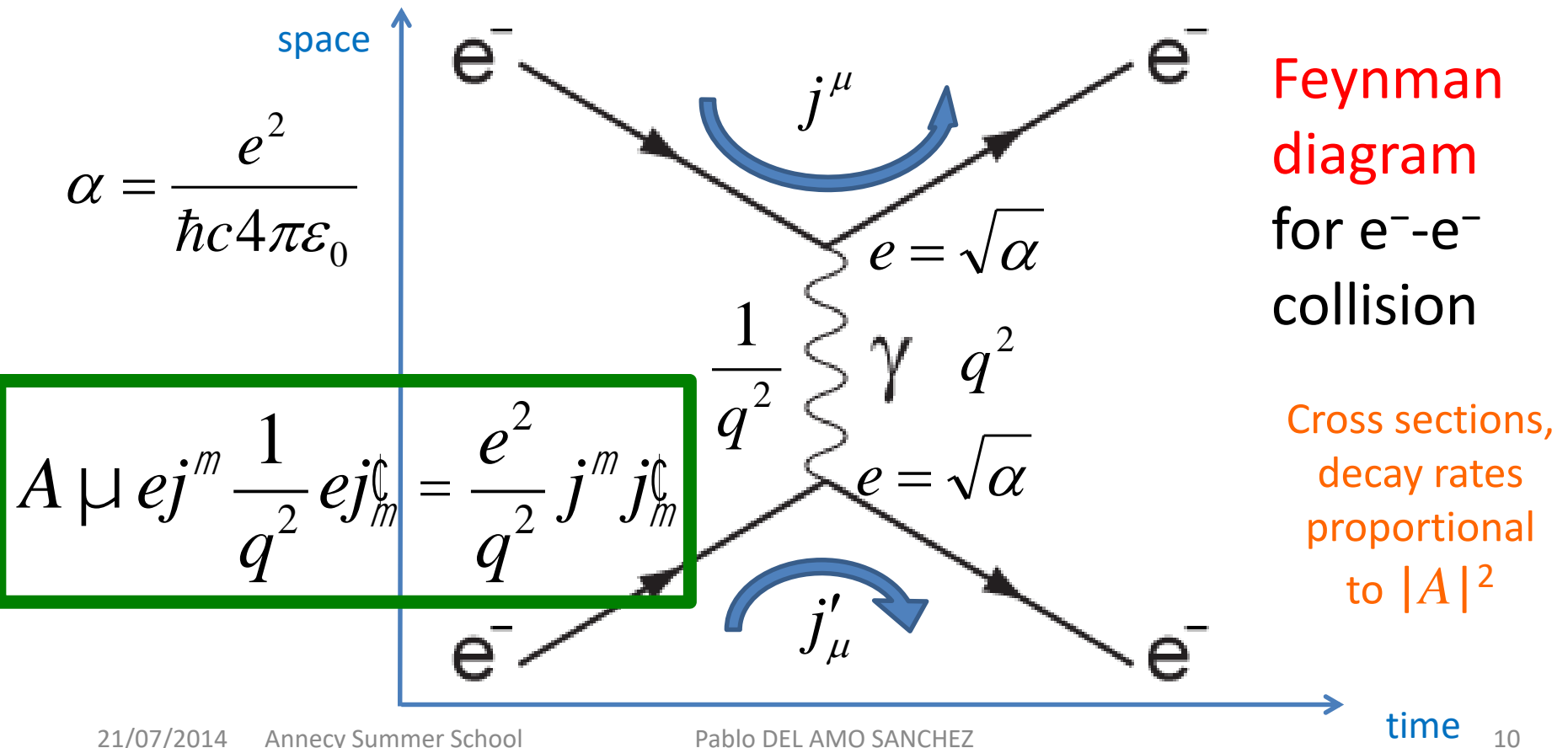
Feynman diagrams are calculational tools: will sketch computation of QM amplitude



# Example of EM interaction

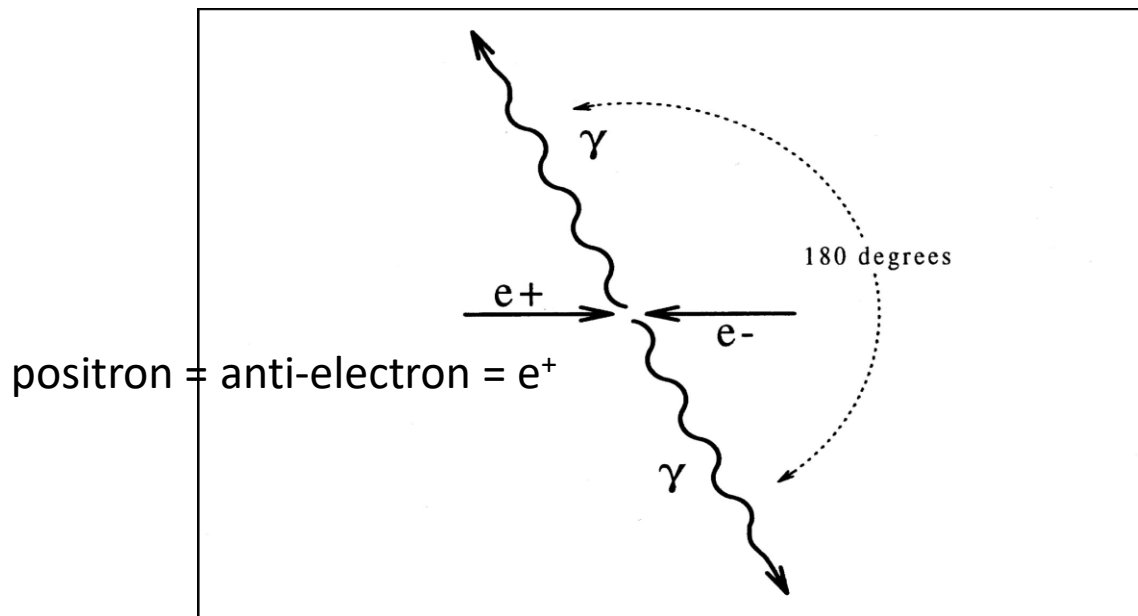
$e^- - e^-$  collision, transferring momentum  $q$  by exchange of photon, quanta of EM field

Feynman diagrams are calculational tools: will sketch computation of QM amplitude



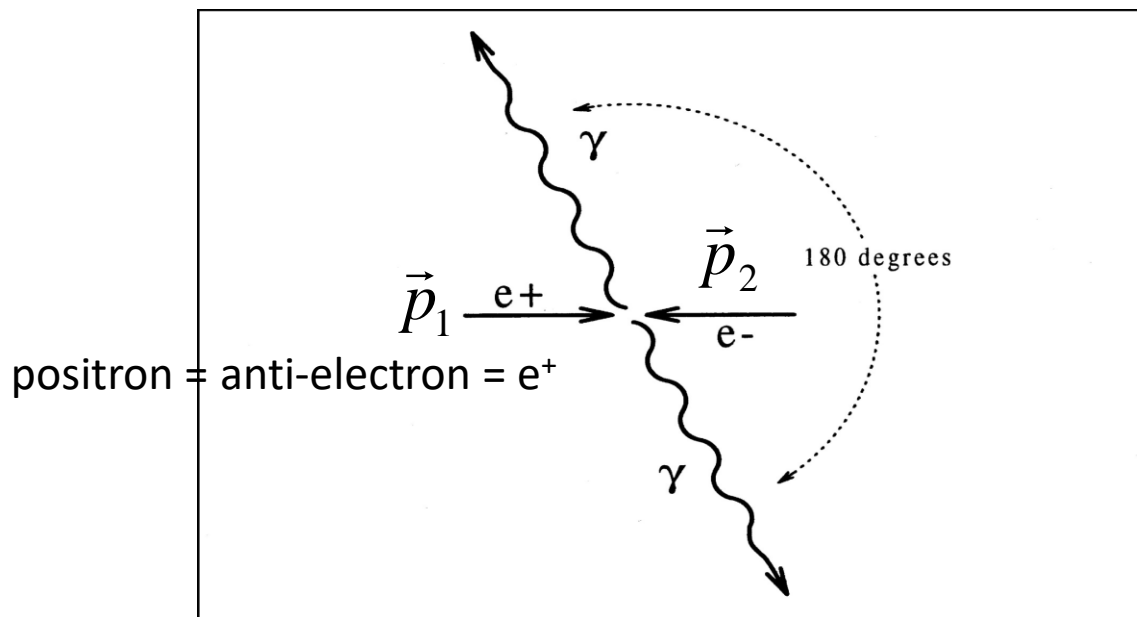
# Example of EM interaction: matter-antimatter annihilation

- Antiparticle: same properties (mass, spin) as particle, but all “charges” reversed (electric, weak force, strong force)
- Particle + antiparticle = radiation ( $E=mc^2$ !)



# Example of EM interaction: matter-antimatter annihilation

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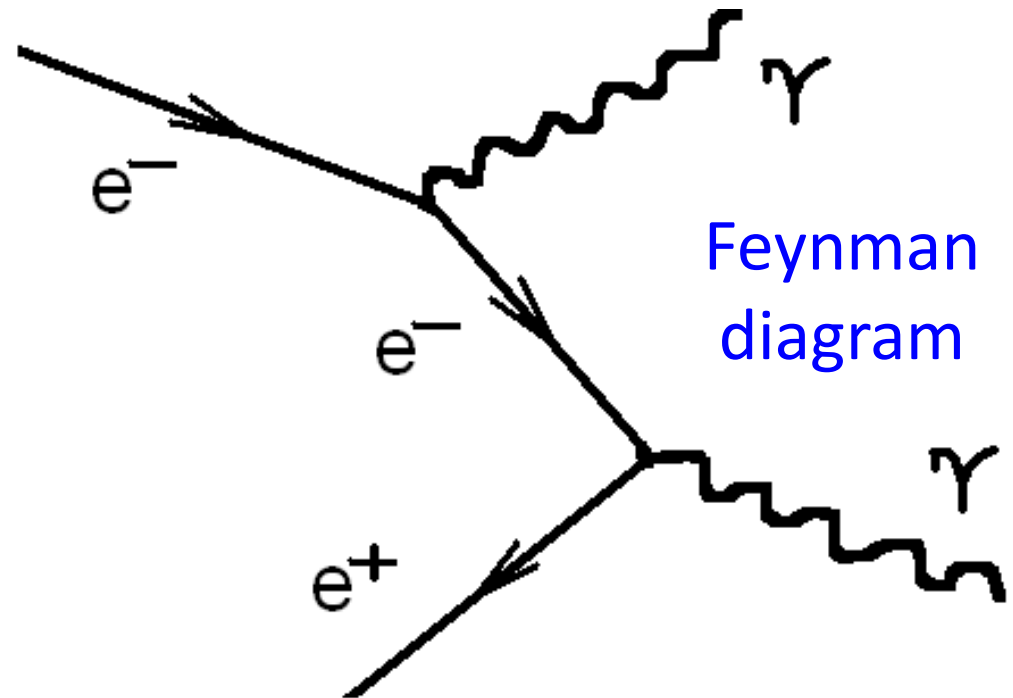
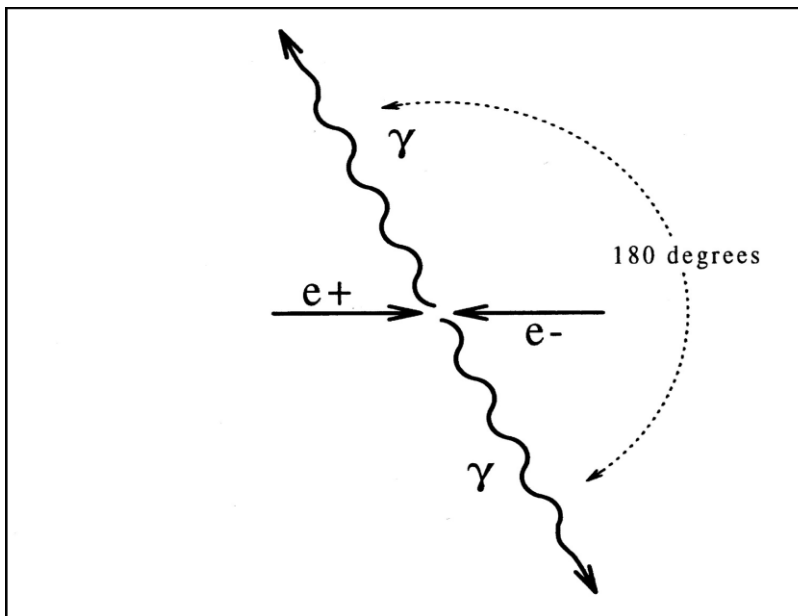
where  $m$  is “relativistic invariant mass” of system:

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

$c = 1$ !

# Example of EM interaction: matter-antimatter annihilation

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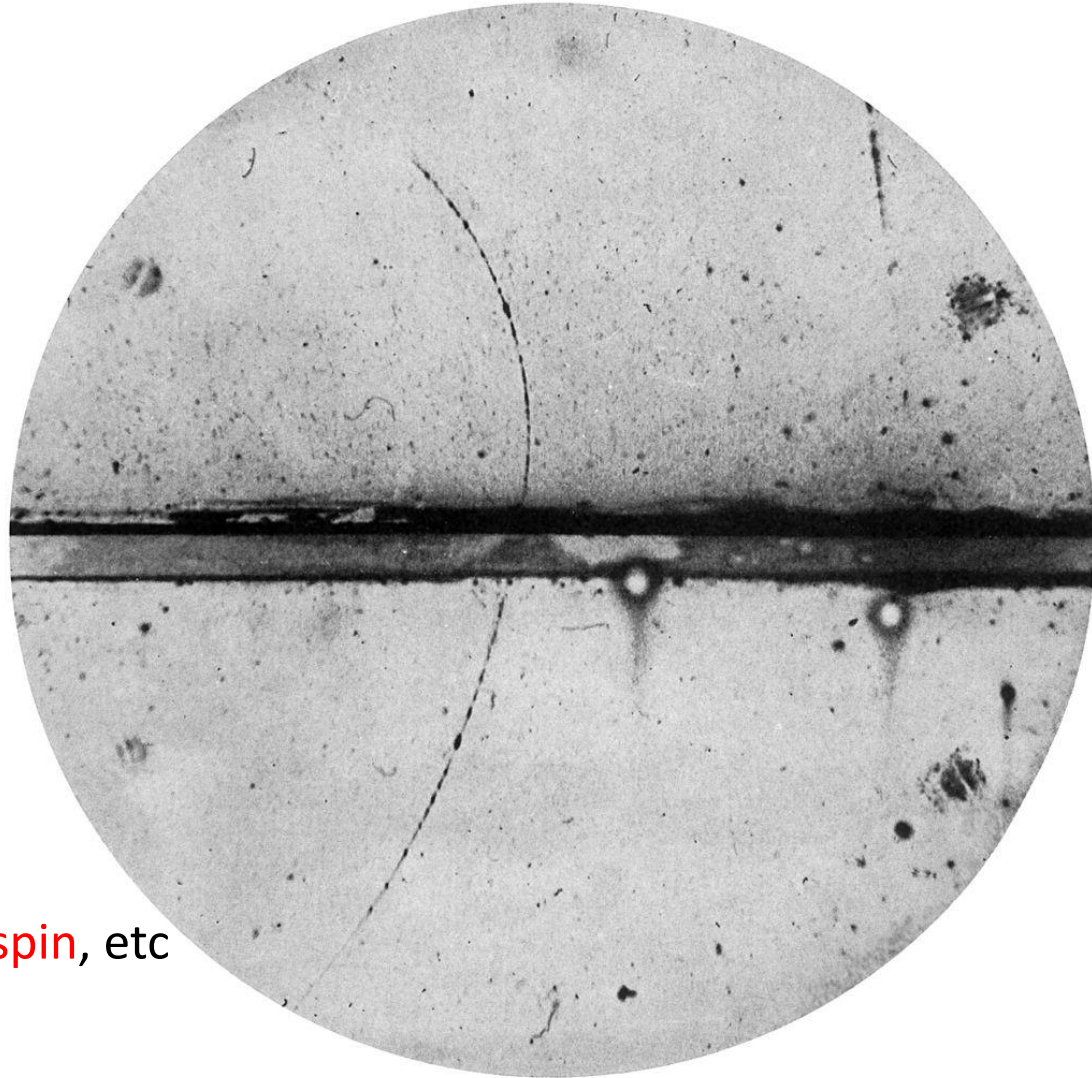


# Antiparticles: the positron

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

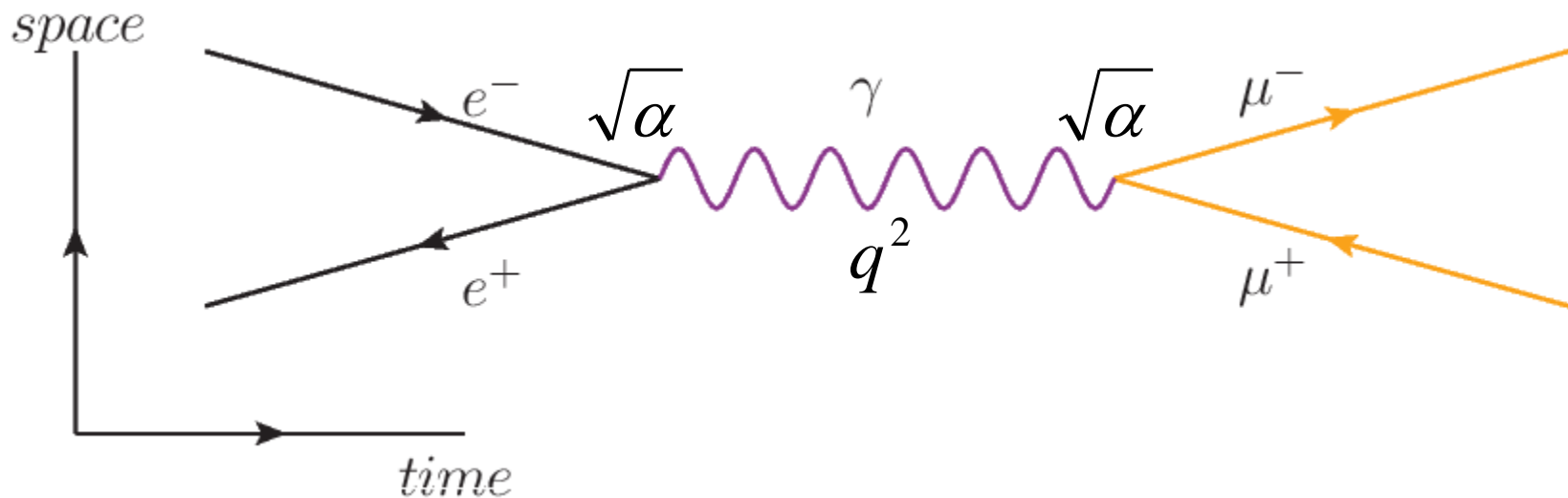
... A POSITIVE ELECTRON!

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



# Example of EM interaction: pair production

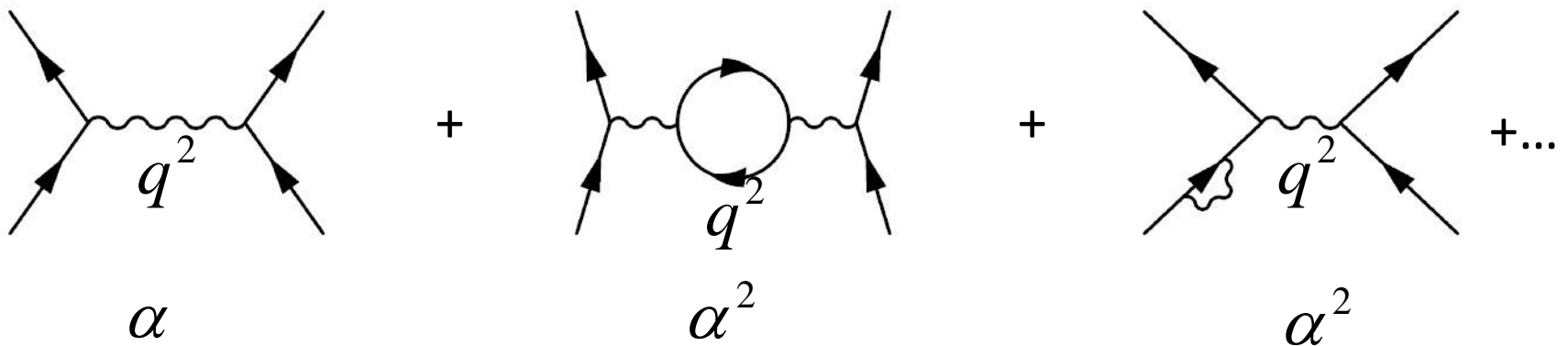
- The inverse of matter-antimatter annihilation: particle-antiparticle pair production
- For instance:  $\mu^+ \mu^-$  production:



- Antiparticles pictured as arrows opposite to flow of time
- Emission of  $e^-$  = absorption of  $e^+$
- Possible only if invariant mass  $m_{e^+e^-}^2 = q^2 > (2m_\mu)^2$
- Internal particles are called “virtual particles”. Note:  $m_v^2 = q^2 \neq 0 !!!$

# Quantum ElectroDynamics (QED)

- Many higher order diagrams possible for  $\mu^+ \mu^-$  production:

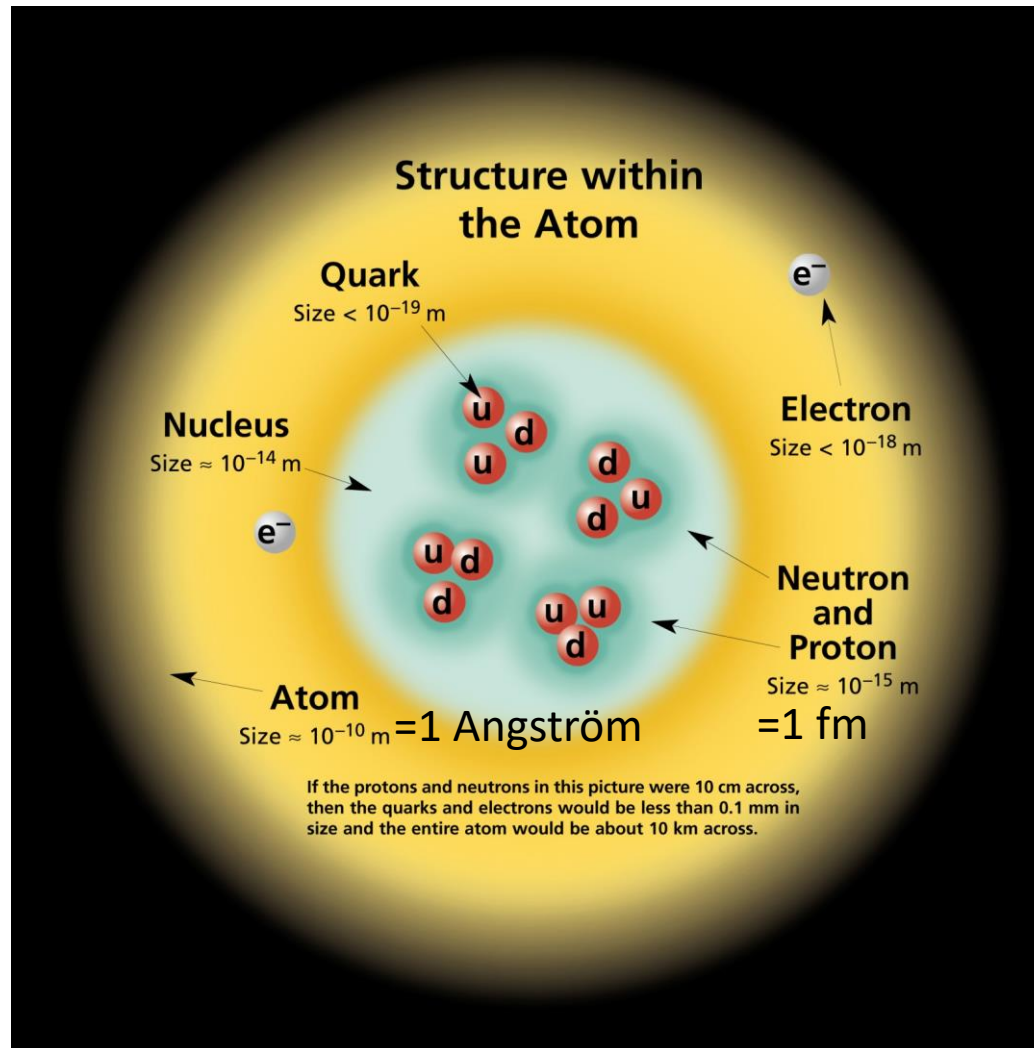


- Feynman diagrams part of a perturbation series in powers of coupling constant  $\alpha$

All this, and much more, described by Quantum ElectroDynamics (QED),  
a consistent Quantum Field Theory

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

# Protons are composite



Nucleons  
composed of  
3 point-like  
particles:  
quarks

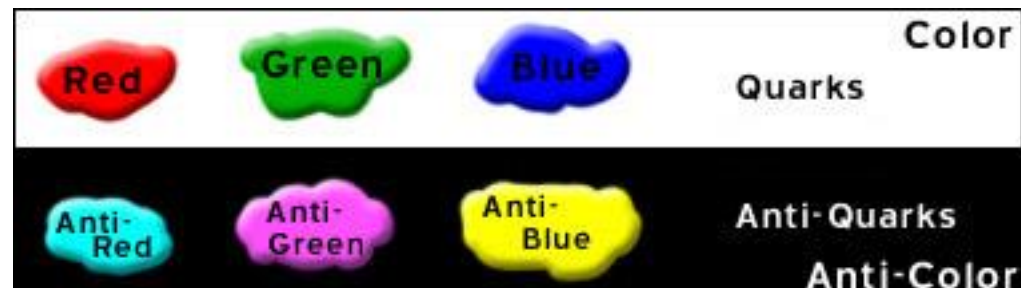
# Quarks and the Strong Force

- Strong force like EM but with *three* different types of charge instead of just one
- Let's call them *red*, *green*, *blue*, just for fun... \* “Positive” charge is then *red* whereas “negative” is *anti-red* (cyan, in this analogy).
- This kind of charge called “color”
  - ➔ theory called Quantum Chromodynamics (QCD)
- Call “quark” a particle with color charge. Leptons don't have color.

EM



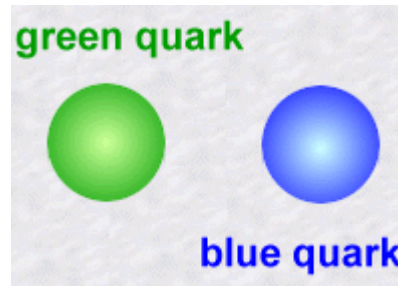
Strong Force



\* Particles with color not responsible for colours of light!

# Quantum ChromoDynamics (QCD)

- Charges repel(attract) if same(different), e.g. **red** and **red** repel, **red** and **anti-red** attract, **red** and **blue** attract.
- Force carriers are called gluons
- Gluons must carry color charge → far-reaching consequences, very different from QED!

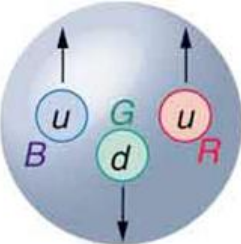
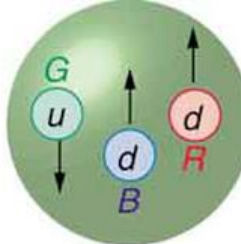
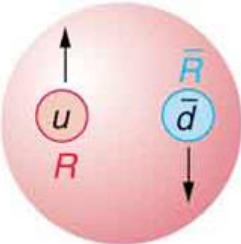
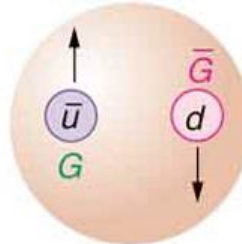


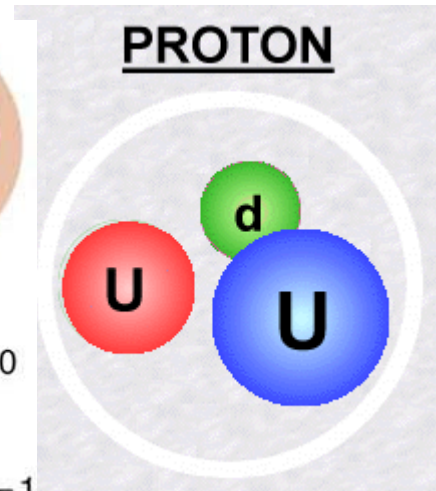
- Consequences:
  - Very short range force
  - Force gets stronger when quarks pulled apart
  - Only see color-neutral free particles in Nature (quark confinement)

# Quarks make up hadrons

- Can get color-neutrality (neither excess nor defect) with following combinations:
  - color+anti-color
  - red+green+blue since anti-red=cyan=green+blue
- So the quarks arrangements found in Nature are:
  - quark+antiquark' (meson)
  - quark+quark'+quark'' or 3 antiquarks (baryon)

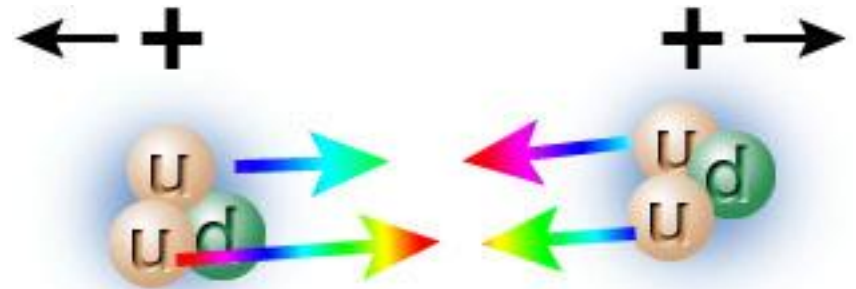
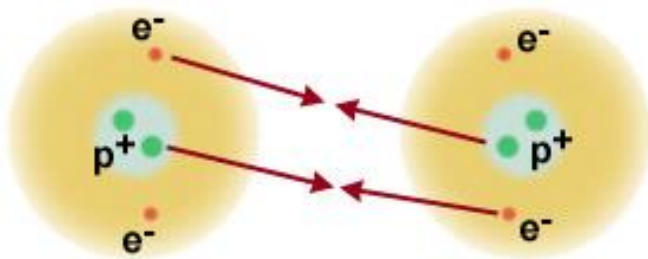
} Hadrons

				
	Proton	Neutron	$\pi^+$	$\pi^-$
Spin	$\frac{1}{2} + \frac{1}{2} - \frac{1}{2} = \frac{1}{2}$	$-\frac{1}{2} + \frac{1}{2} + \frac{1}{2} = \frac{1}{2}$	$+\frac{1}{2} - \frac{1}{2} = 0$	$+\frac{1}{2} - \frac{1}{2} = 0$
Charge	$+\frac{2}{3} + \frac{2}{3} - \frac{1}{3} = 1$	$+\frac{2}{3} - \frac{1}{3} - \frac{1}{3} = 0$	$+\frac{2}{3} + \frac{1}{3} = +1$	$-\frac{2}{3} - \frac{1}{3} = -1$



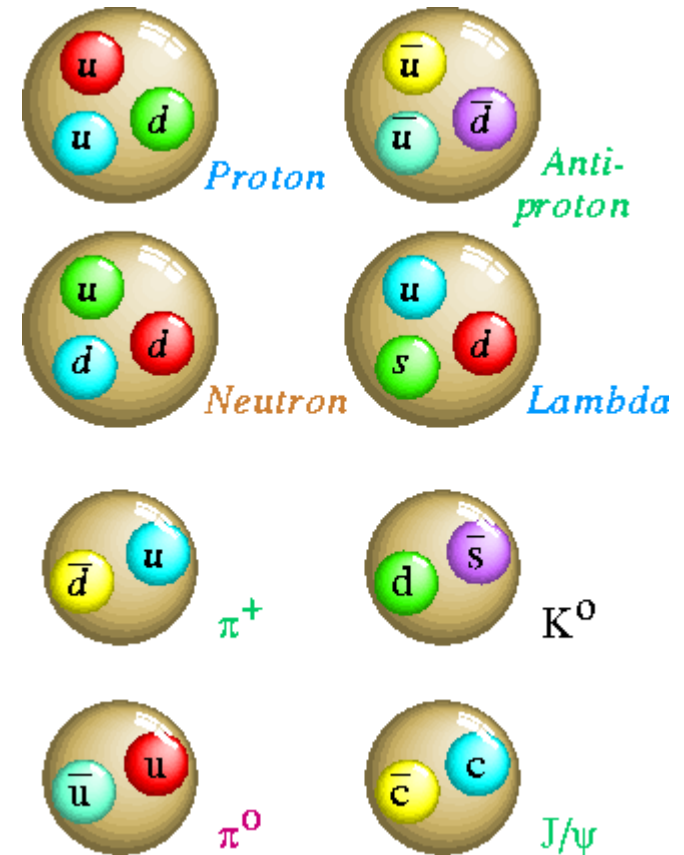
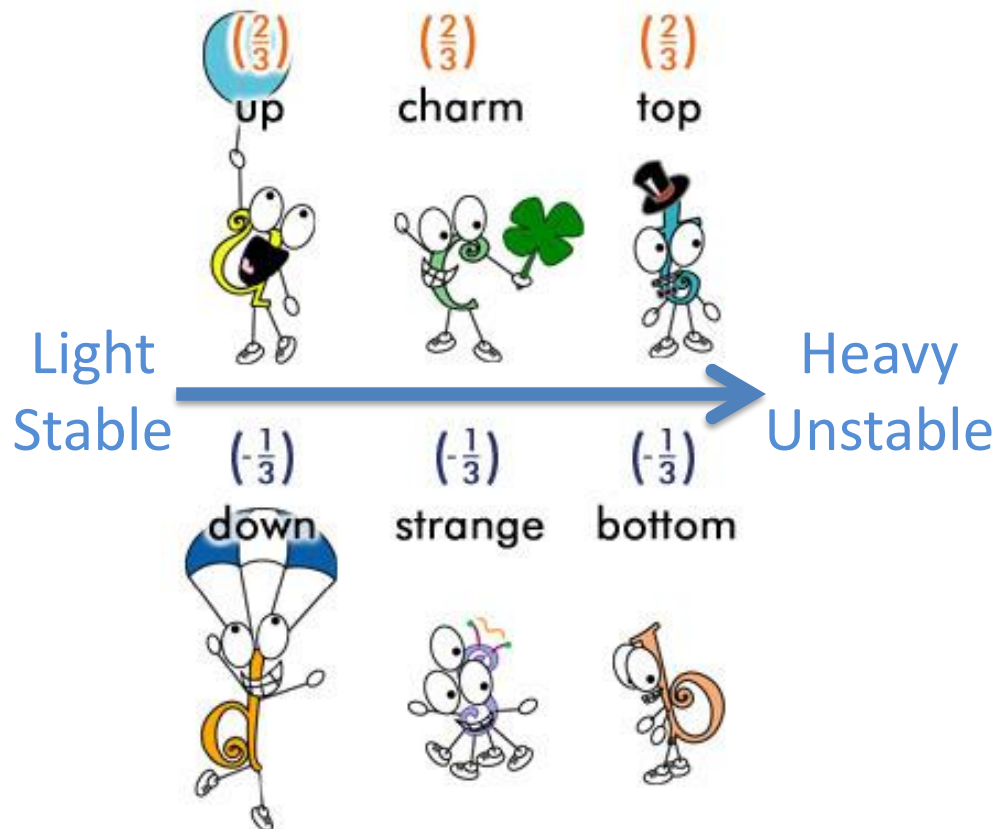
# QCD $\rightarrow$ Strong nuclear force

- Protons and neutrons bound in nucleus by residual force between quarks, same as atoms in molecules



# How many different quarks?

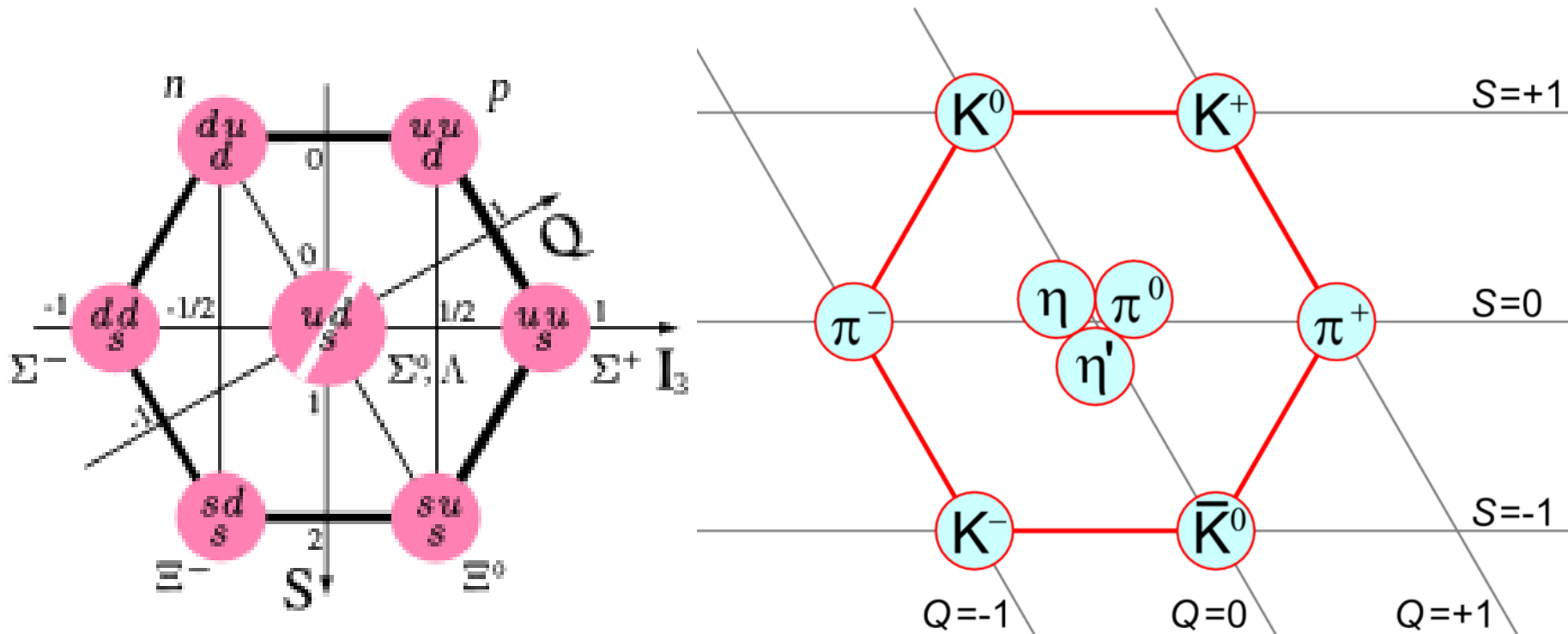
- Experimentally find 6 quarks (*flavours*) , 3 up-type and 3 down-type quarks
- All the same in QCD, except different masses



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

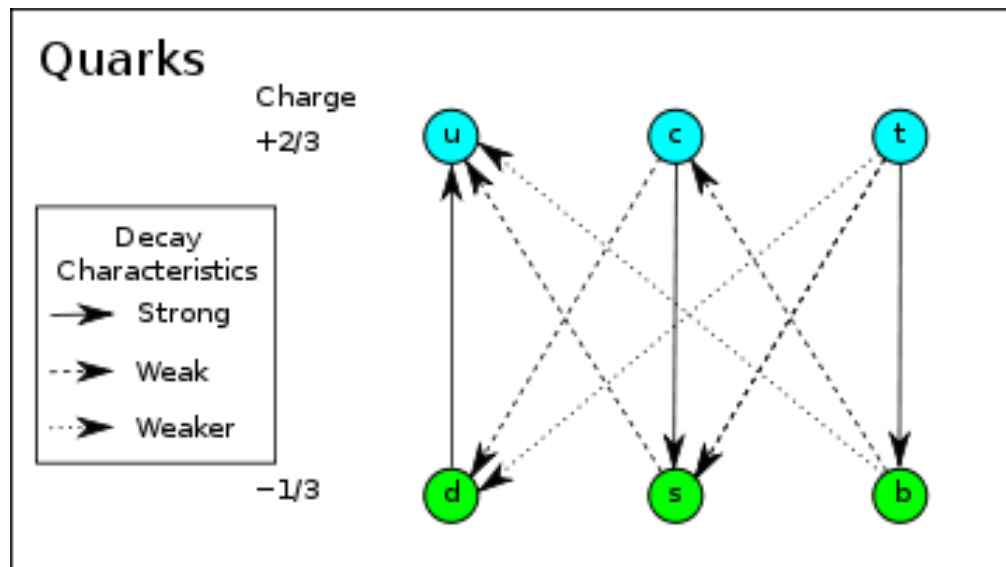
# Symmetries

- Classification and description of hadrons thanks to symmetries (group theory)



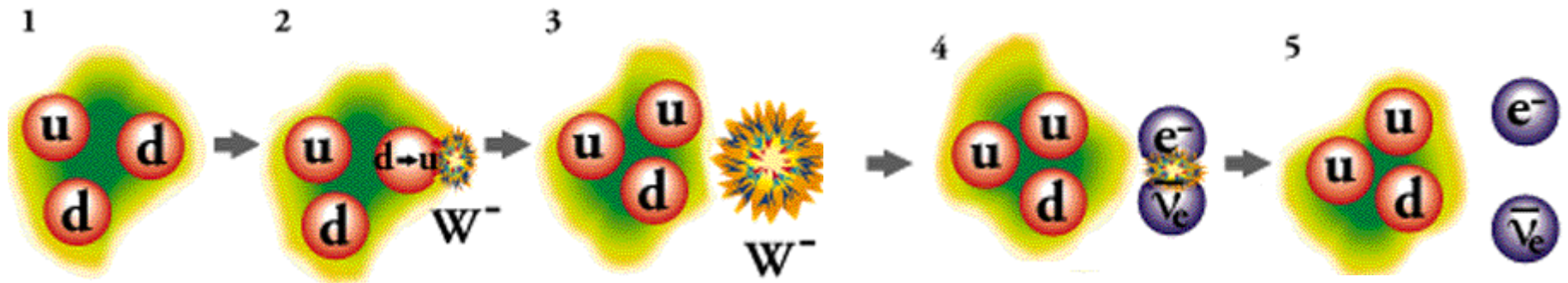
# Heavy flavours

- Heavy quarks unstable... How? Up to now, always creating/annihilating pairs of particle-antiparticle of same type
- *Weak force:*  
*induces decays of unstable elementary particles*

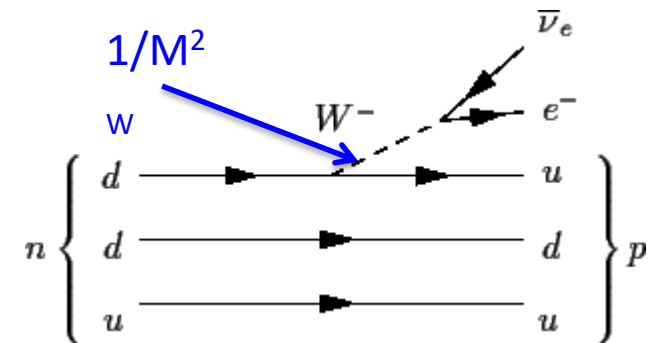


# Weak Force

- Neutron beta decay:  $n \rightarrow p + e^- + \bar{\nu}_e$



- Weak force responsible for decays of unstable elementary particles
- Mediated by  $Z^0$  and  $W^\pm$  bosons
- Contrary to photons and gluons,  $Z^0$  and  $W^\pm$  have non-zero masses
- Propagators proportional to  $1/M_Z^2$ ,  $1/M_W^2$   
 $\rightarrow$  Weak Force very weak!



# Why are Z and W so heavy?

- Z and W are 100 and 85 times heavier than proton
- But photons and gluons massless!



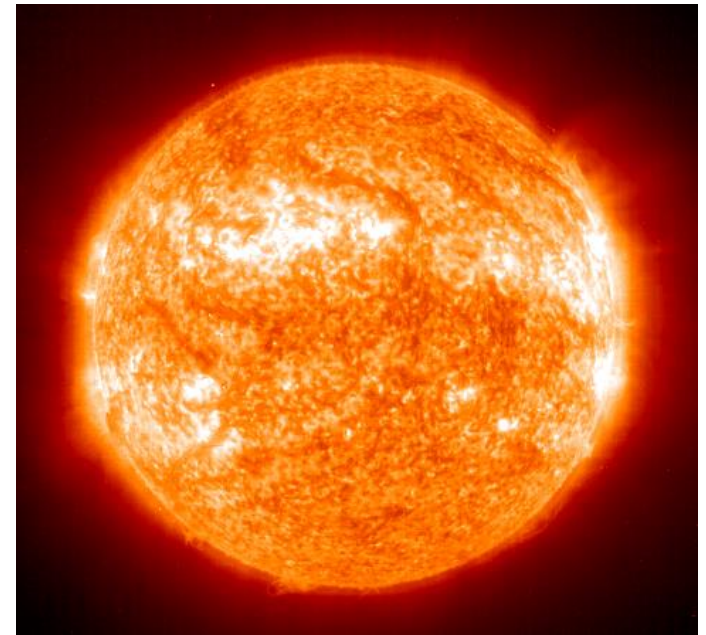
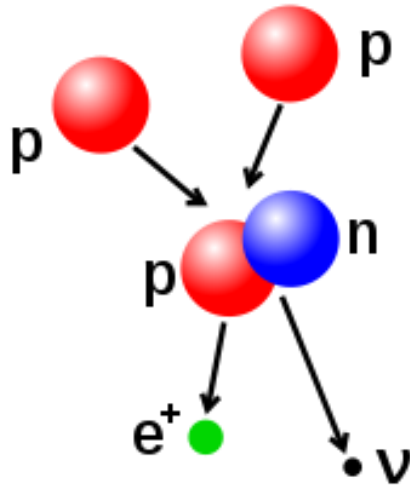
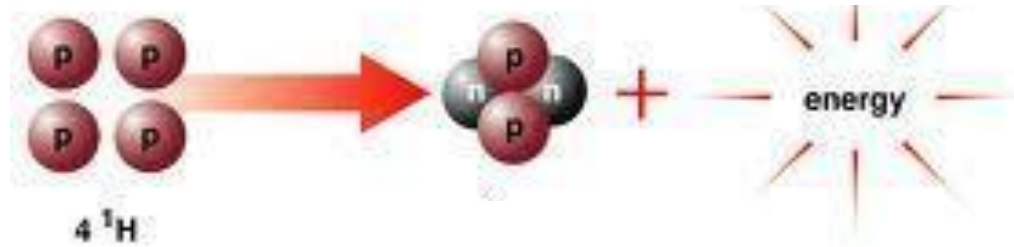
- It's the Higgs boson's fault!

# Neutrinos?

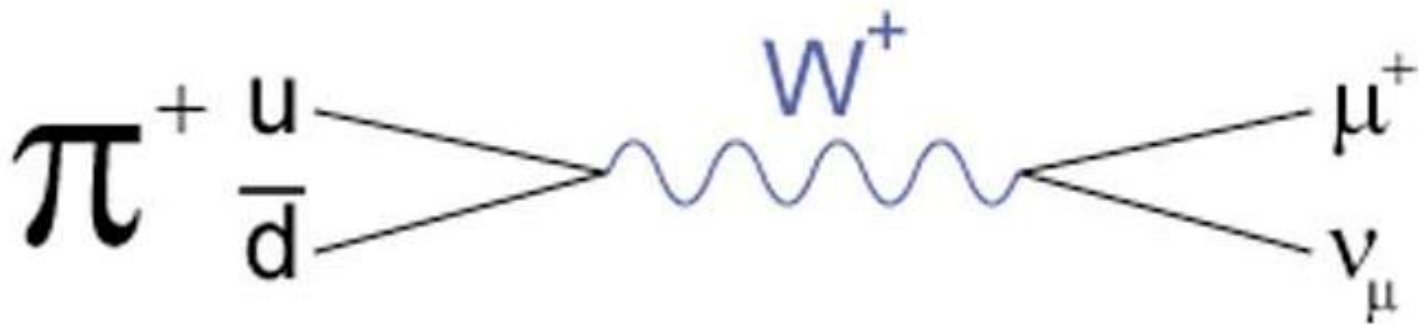
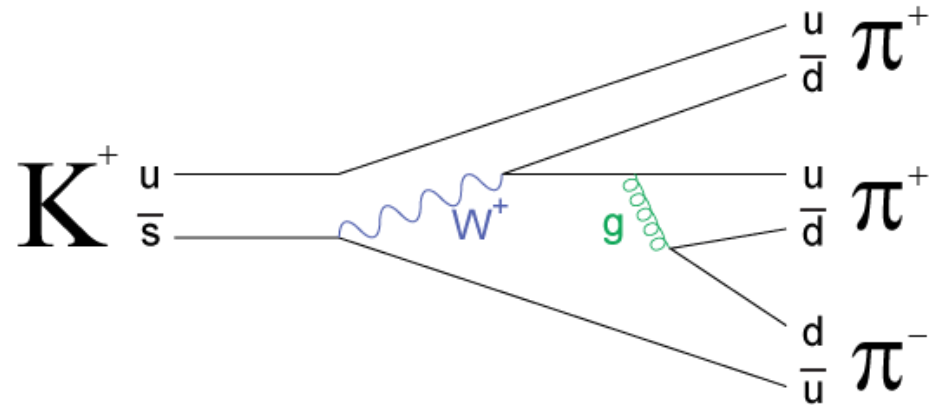
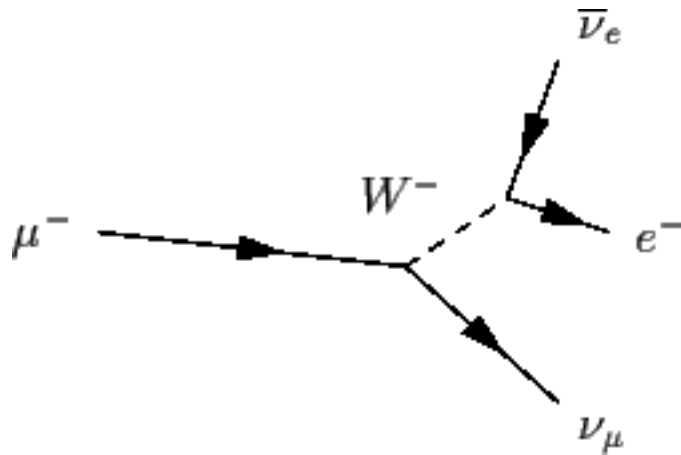
- Nearly zero masses (but not quite!)
- No electric charge, no color charge, **only** interacts through **Z** et **W**s
- So very hard to study...
- Electron also light and without color → leptons
- Plenty of open questions...

# Weak Force

- Governs rate of energy production in the sun (inverse beta decay a step in fusion process)



# Weak Force: other examples



Pion decay: important way of making neutrinos

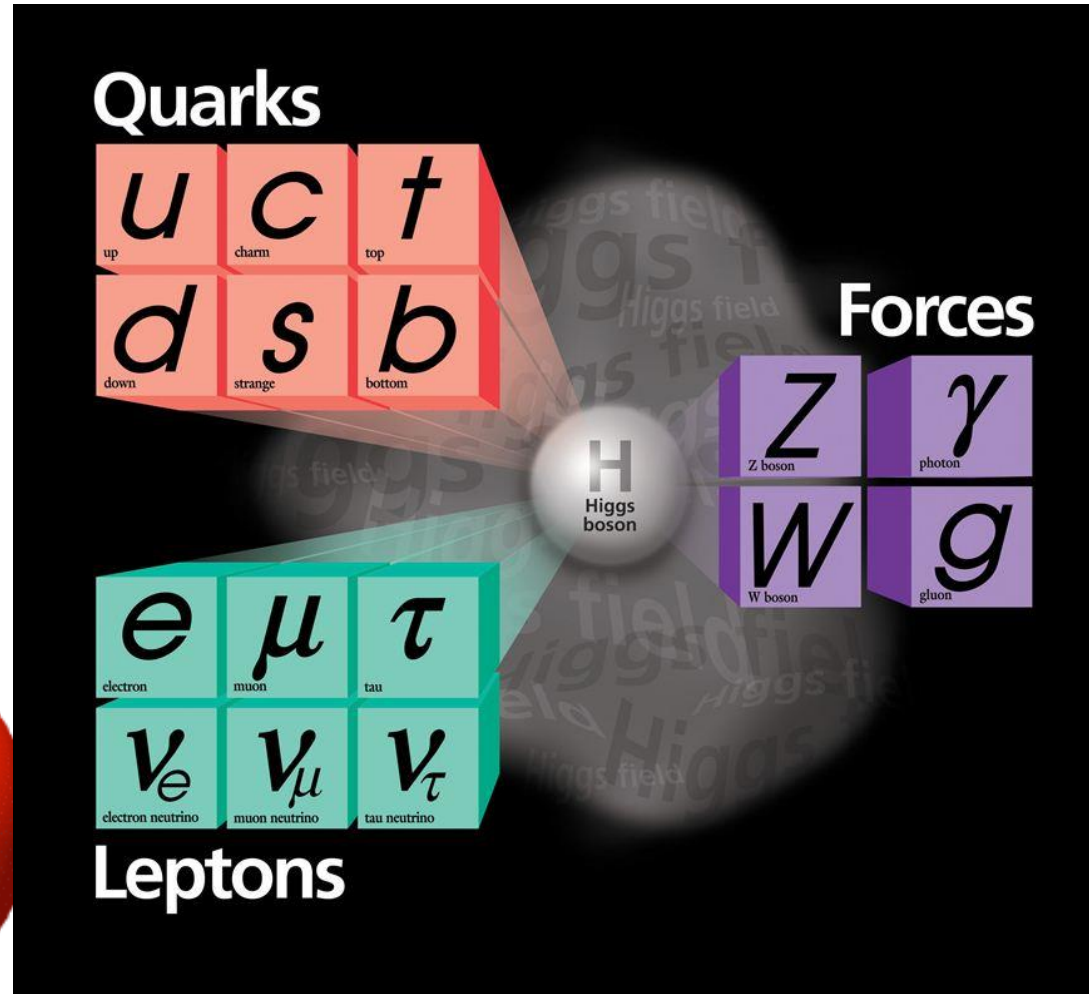
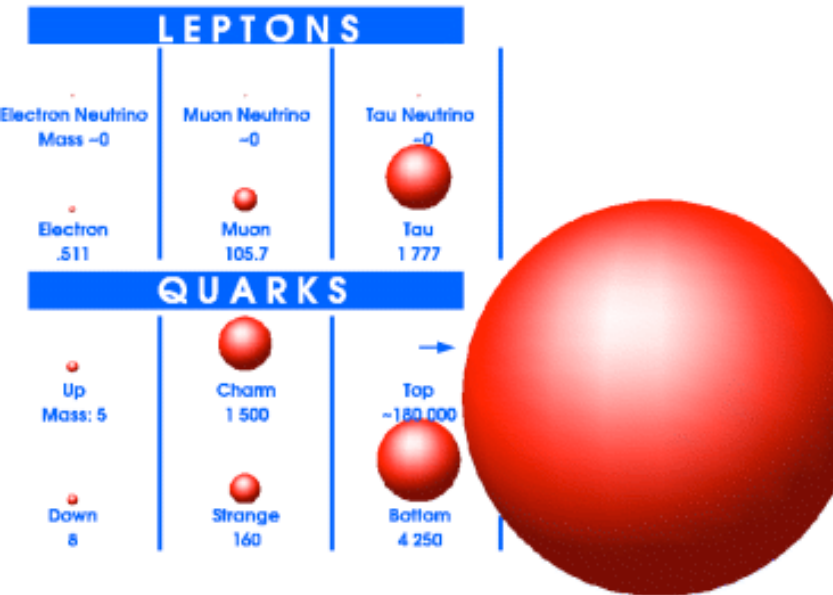
# Three families or generations

- 3 times the u, d quark couple, except heavier and less stable
- Same story about leptons:  
muon is just an unstable, heavy electron
- Columns of table are called *generations*
- Why more than one? Why three?

Quarks	$u$ up I	$c$ charm II	$t$ top III
	$d$ down I	$s$ strange II	$b$ bottom III
Leptons	$\nu_e$ e- Neutrino I	$\nu_\mu$ $\mu$ - Neutrino II	$\nu_\tau$ $\tau$ - Neutrino III
	$e$ electron I	$\mu$ muon II	$\tau$ tau III
The Generations of Matter			

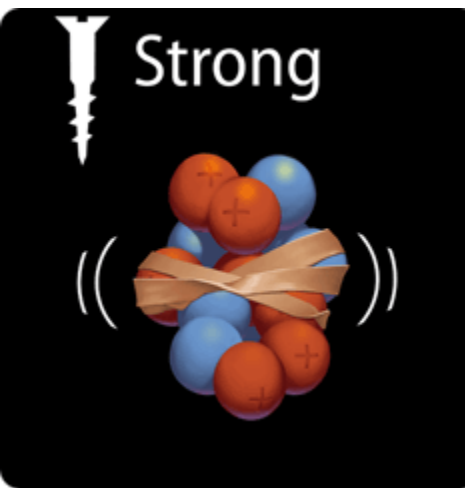
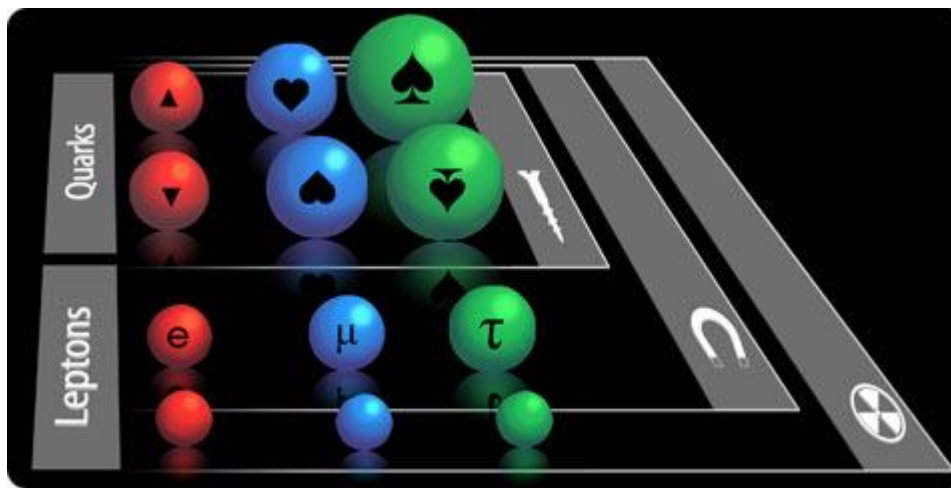
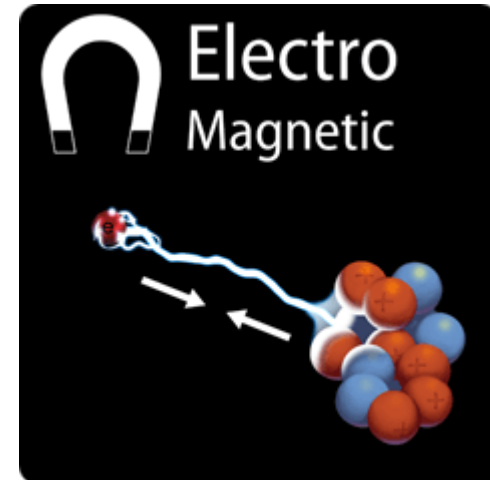
# The Standard Model

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



# Summary

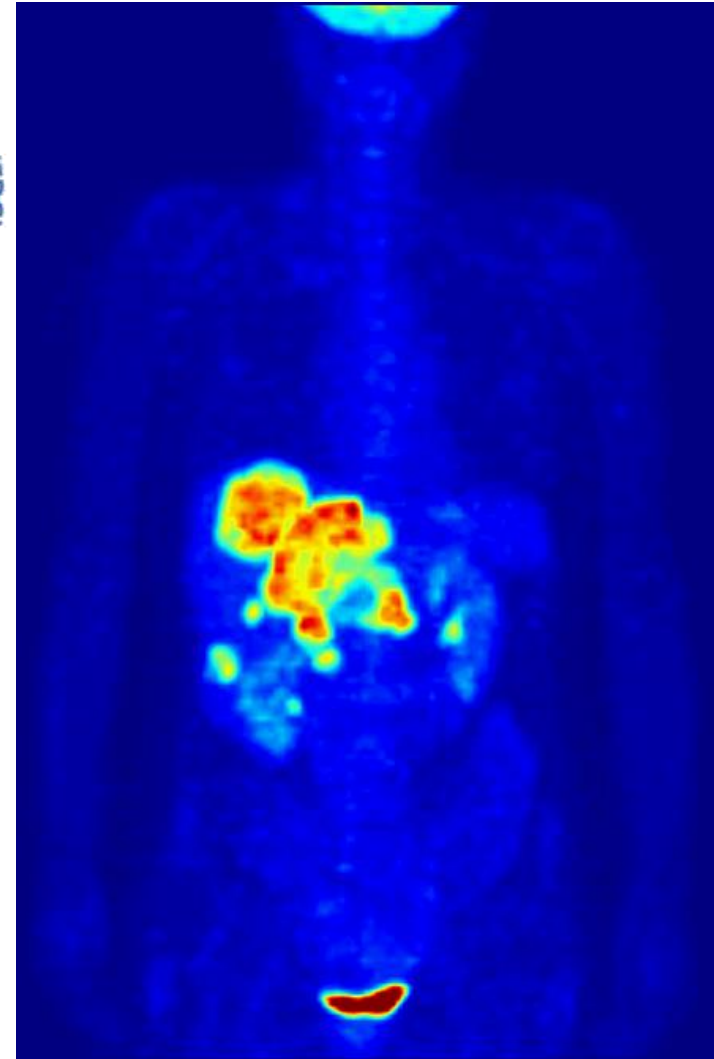
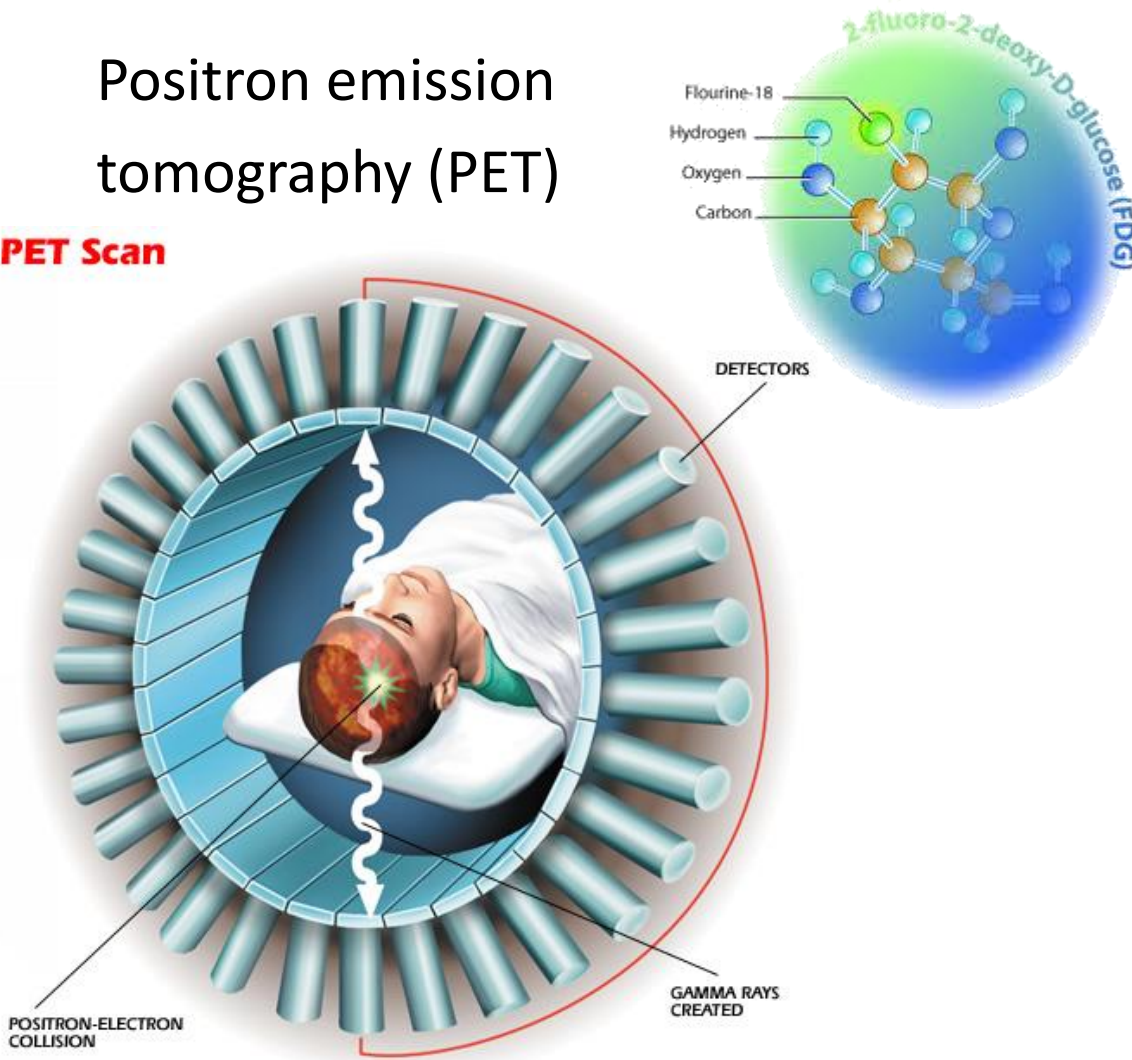
- Plenty of open questions; much learnt!
- Electromagnetisme,  $\gamma$ : all particles except  $\nu$ 's
- Strong force, gluon: only quarks
- Weak force,  $W^\pm$  et  $Z$ : all particles

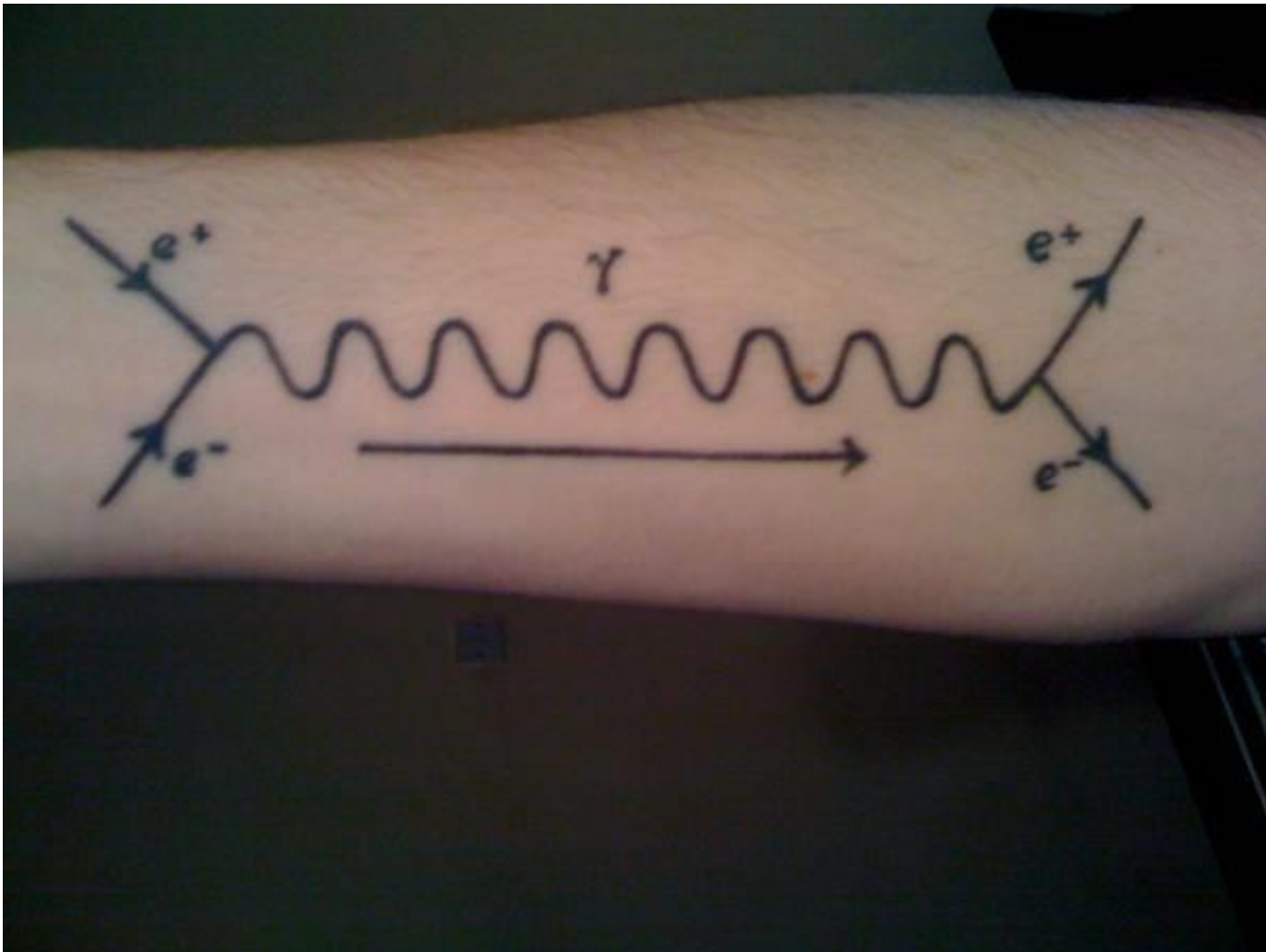


# Applications

## Positron emission tomography (PET)

### PET Scan

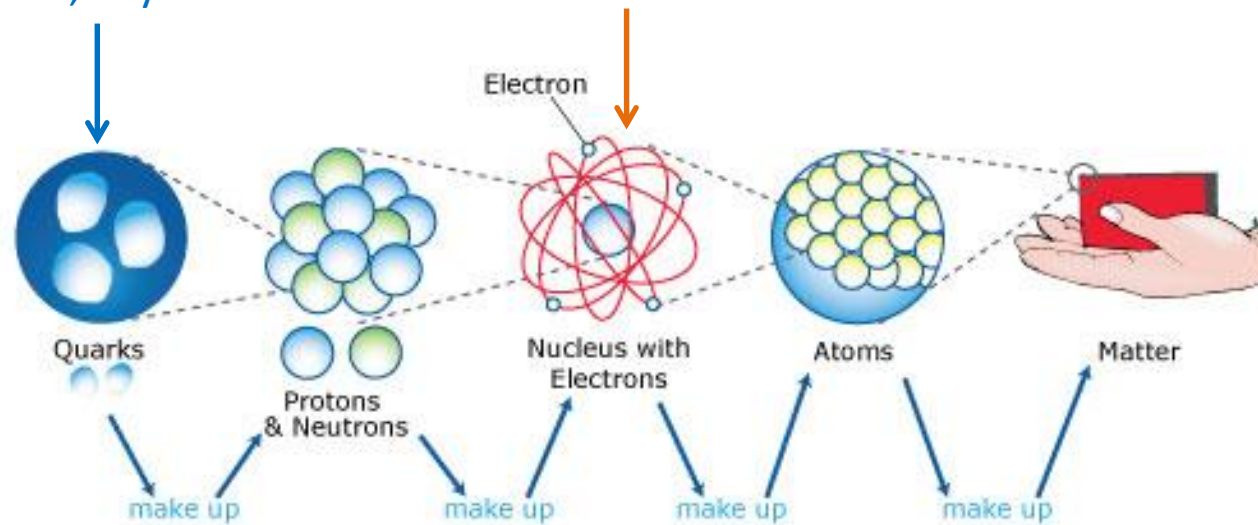




# A VERY brief history of particles

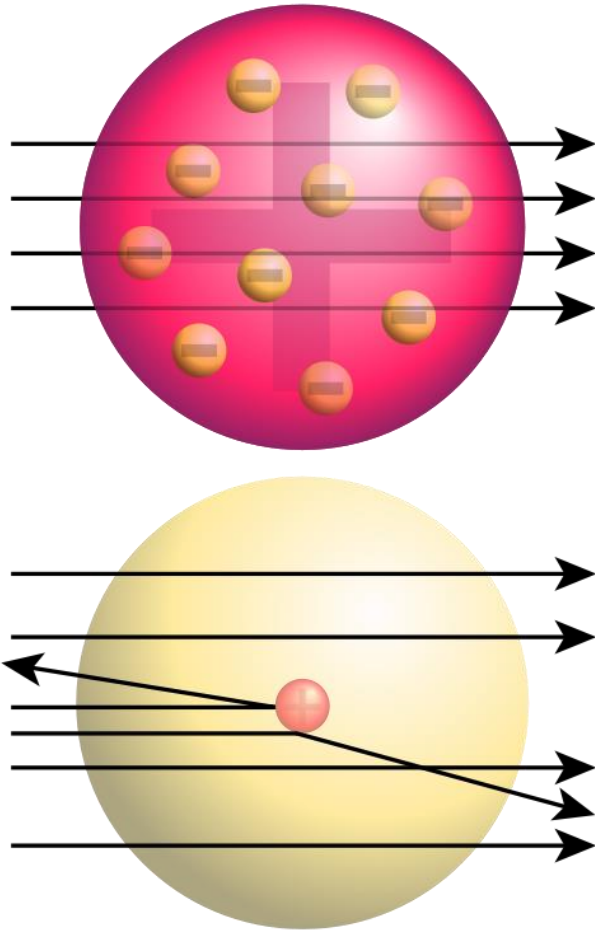
1968-69 SLAC,  
Bjorken, Feynman

1911 Rutherford,  
Geiger, Marsden

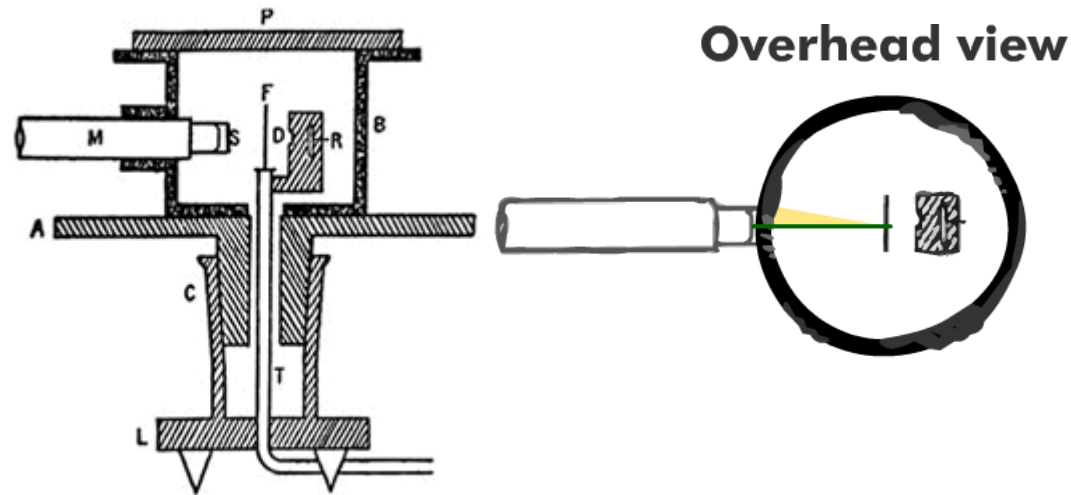


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# The nucleus: Rutherford scattering



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

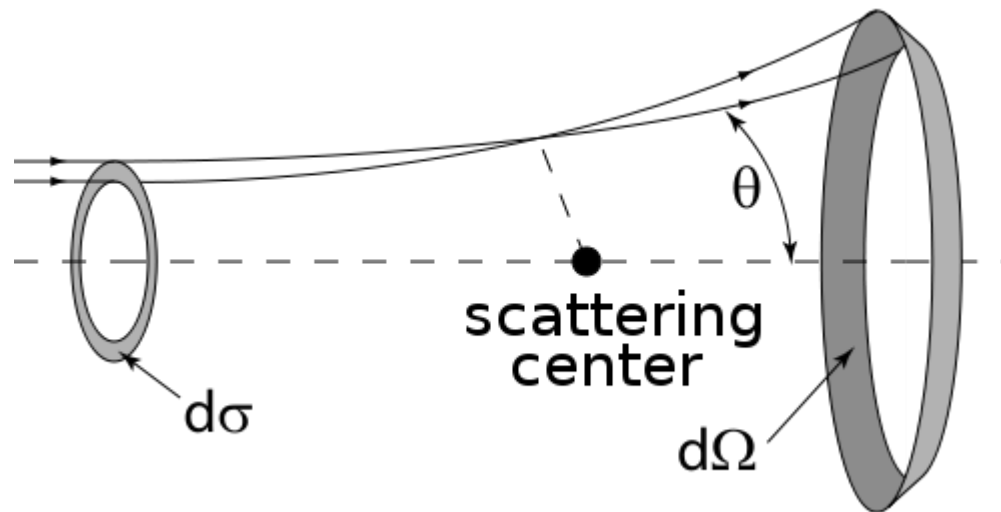


- 1909, Geiger & Marsden:  $\sim 1/8000$  alpha particles bounce off!
- 1911, Rutherford: nucleus small within atom, surrounded by  $e^-$  cloud

$$E_{\alpha}^{kin} = \frac{1}{4\pi\epsilon_0} \frac{q_{bullet} Q_{target}}{R_{target}} \Rightarrow R_{target} \approx 10^{-14} m \ll 10^{-10} m \approx R_{atom}$$

# 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  $\theta$**  with the beam direction
- Can find out about force between target and bullet by looking at xsection, e.g. stronger forces  $\rightarrow$  bigger xsections; range of force  $\leftrightarrow$  dependence on  $\theta$

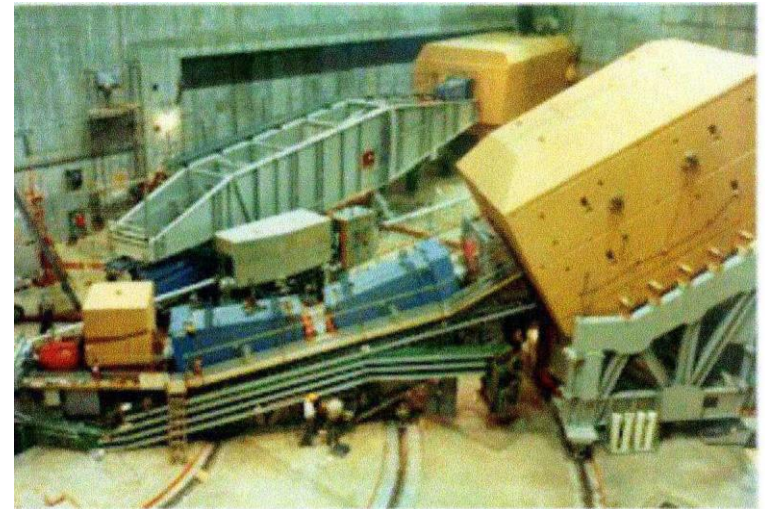
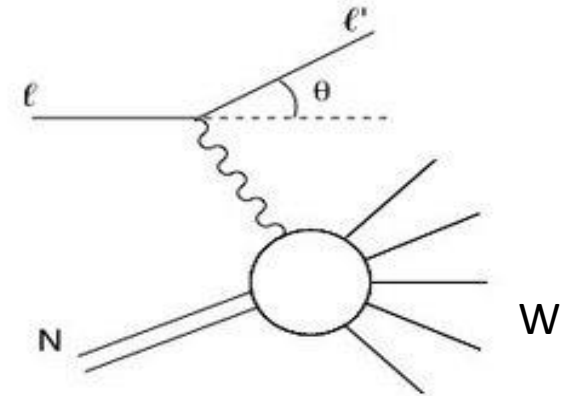
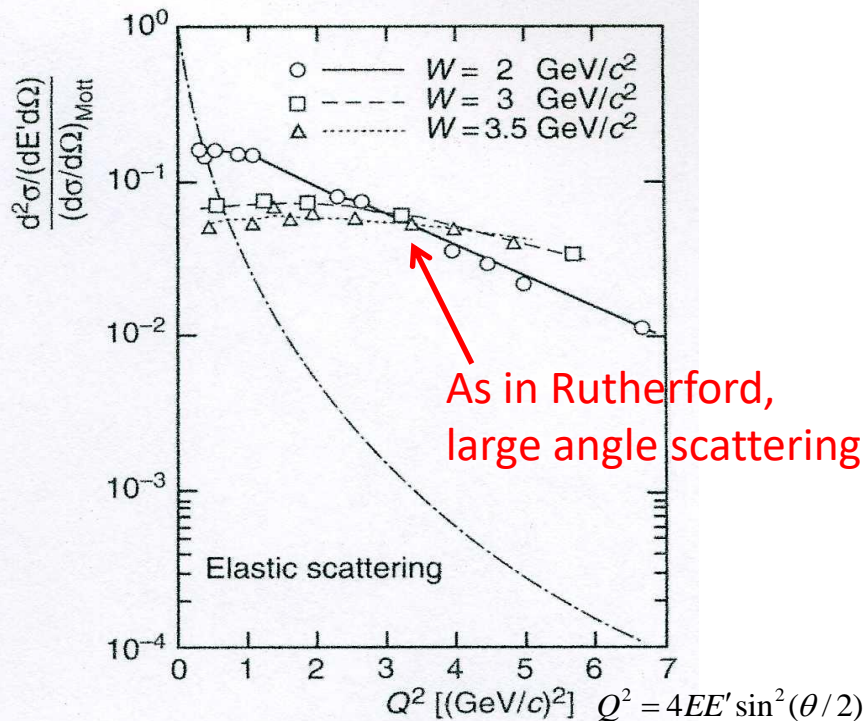


- Ex, scattering of spinless charged particles off a spinless charged target (Rutherford):

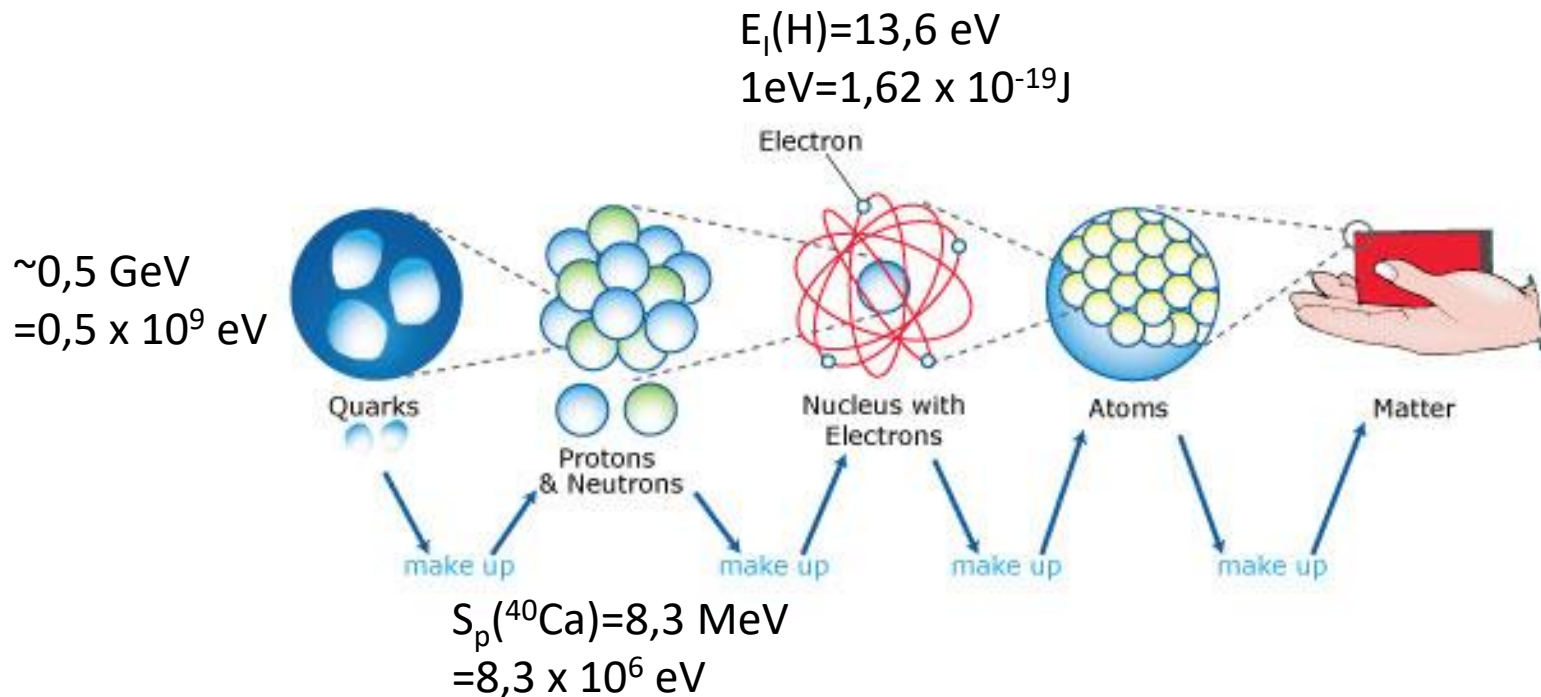
$$\frac{d\sigma}{d\Omega} = \frac{Z_1 Z_2 e^2}{4\pi\epsilon_0 E_{kin}} \frac{1}{\sin^4(\theta/2)}$$

# Back to history: protons are composite

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



# Orders of magnitude, units

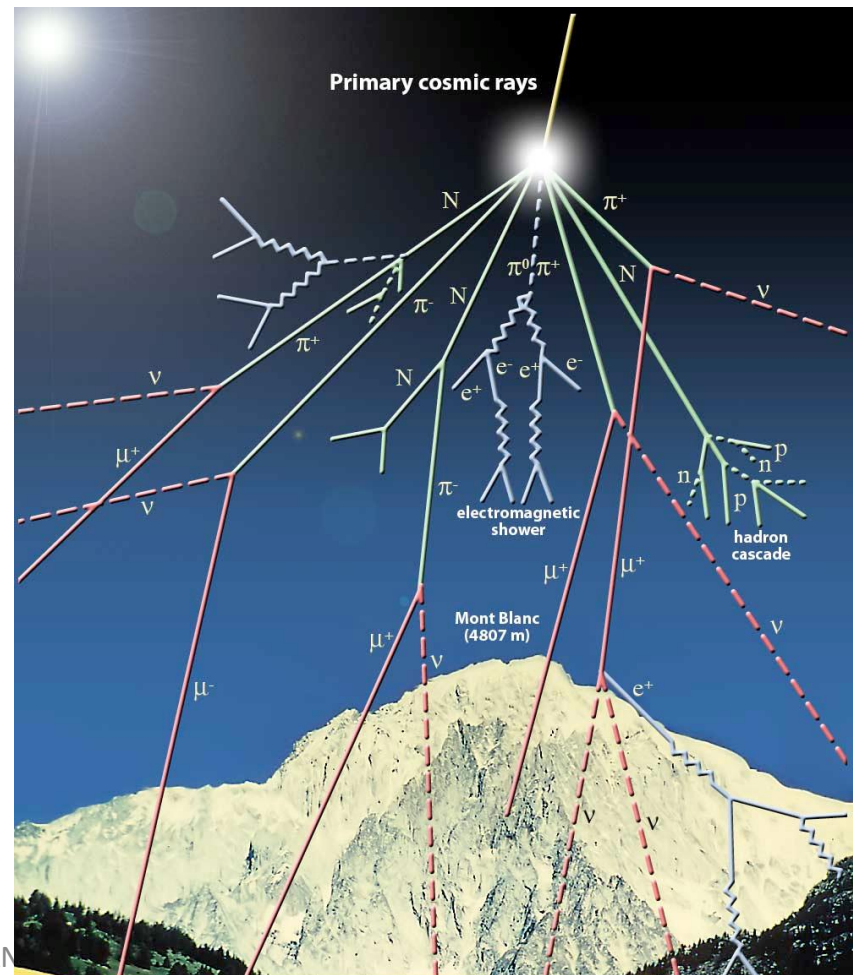
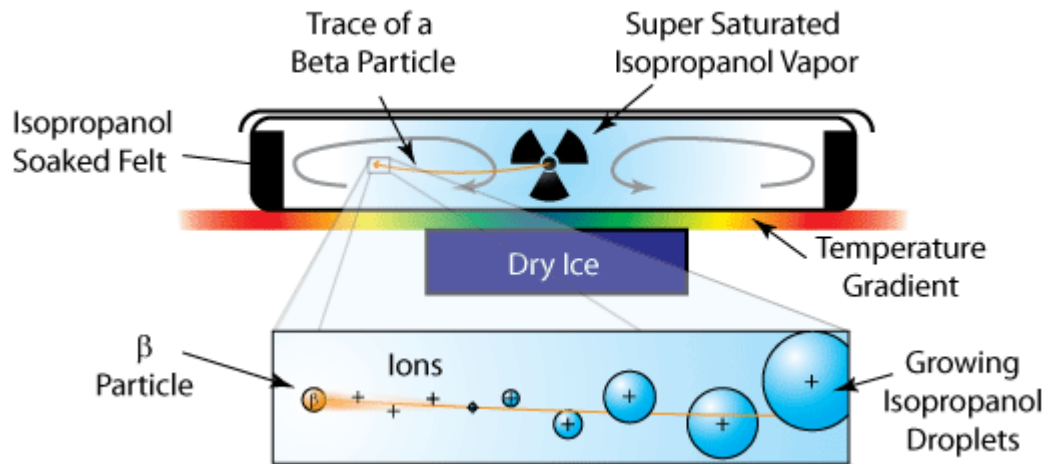


Masses in energy units ( $E=mc^2$  !)

e.g.  $m(\text{proton}) = 938$  MeV,  $m(\text{electron}) = 0,511$  MeV

# 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



# 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)

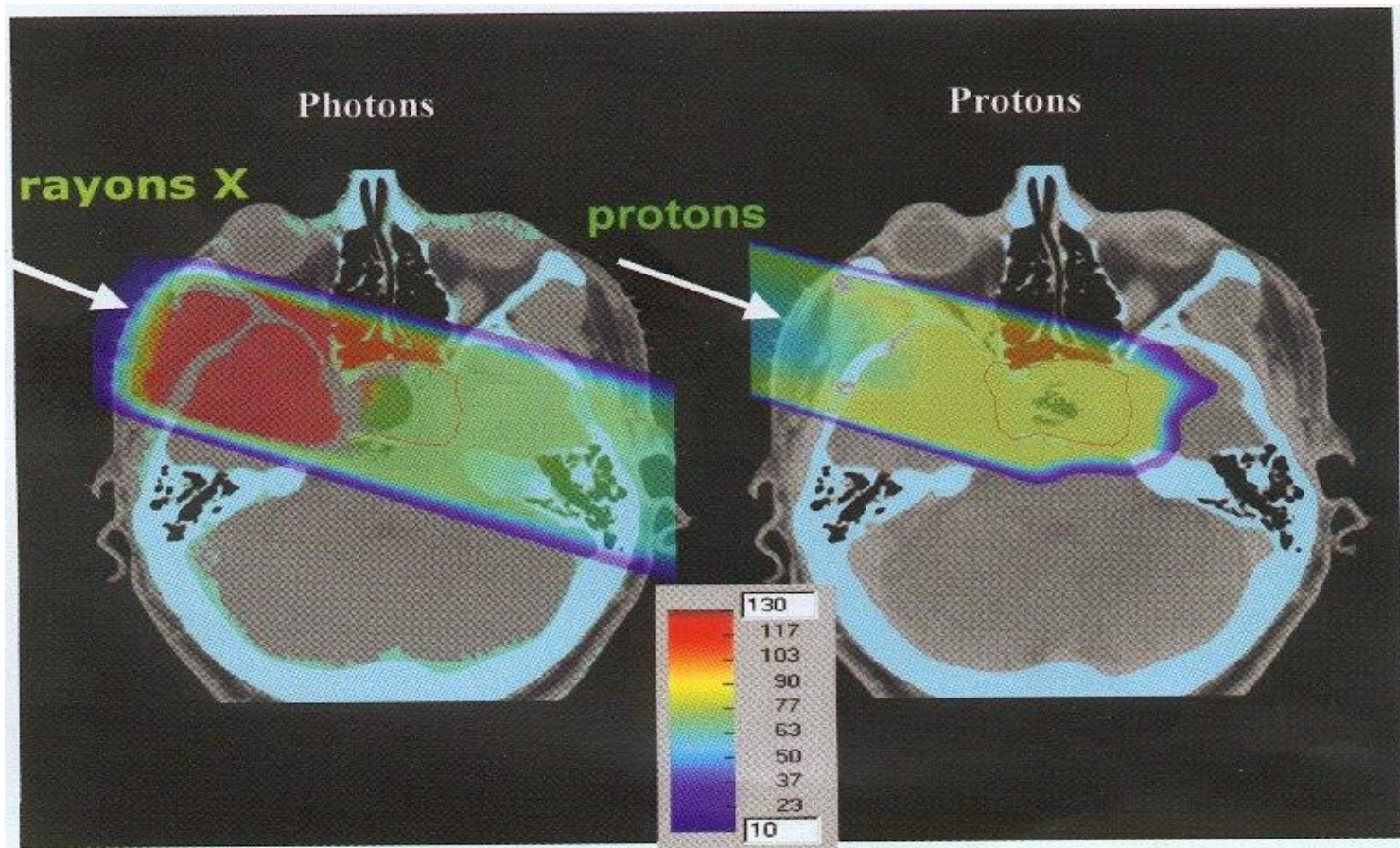
Just like electron but heavy and unstable

“Who ordered that?” (I.I. Rabi)



# Applications

- Radiothérapie



# Applications

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

