~~Particle Physics~~

~~FOR DUMMIES~~

Introducing
Particle Physics

Pablo del Amo Sánchez

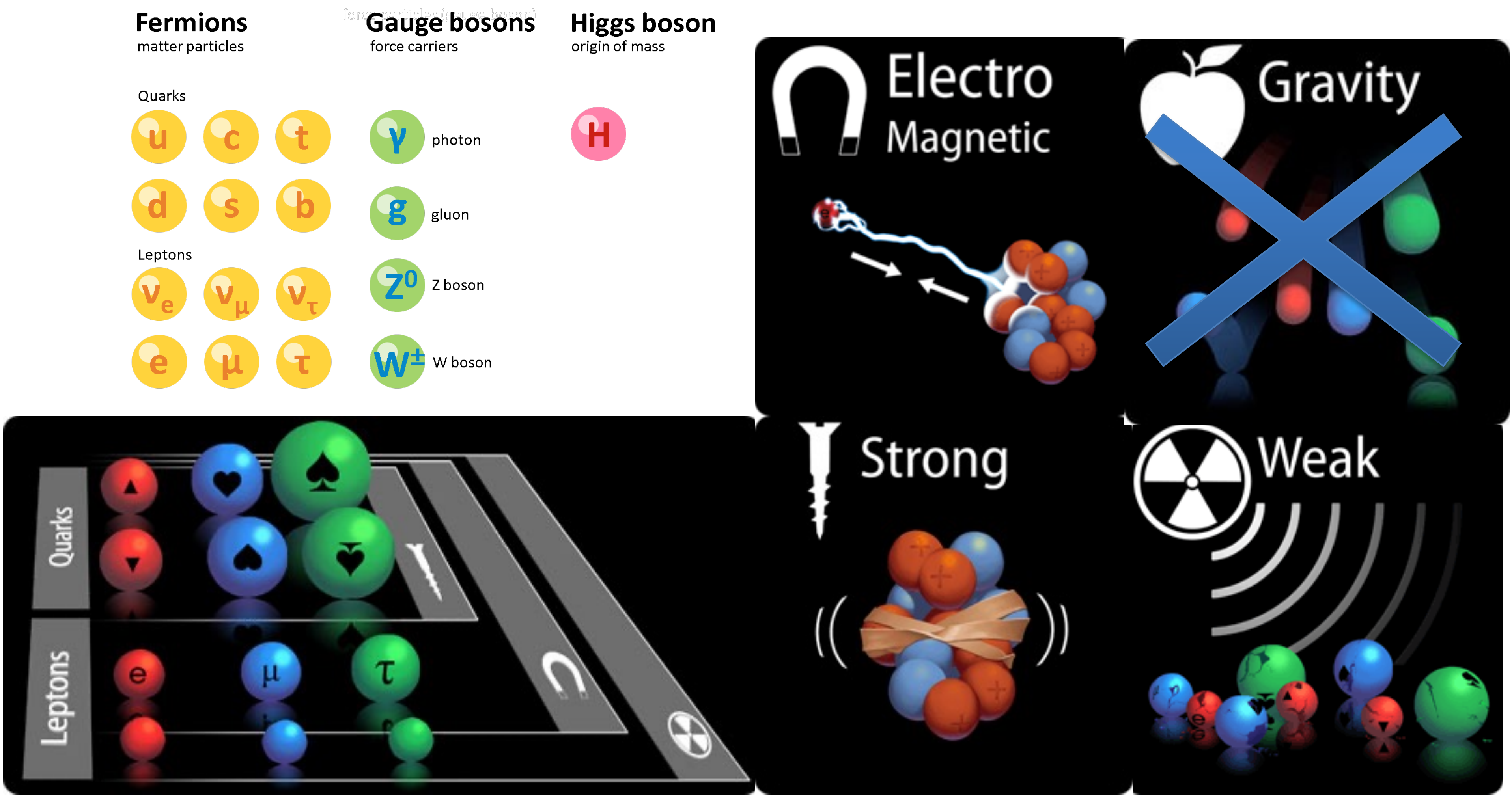
Aim of this lecture:

Particles and Forces of the Standard Model

First contact with Feynman diagrams

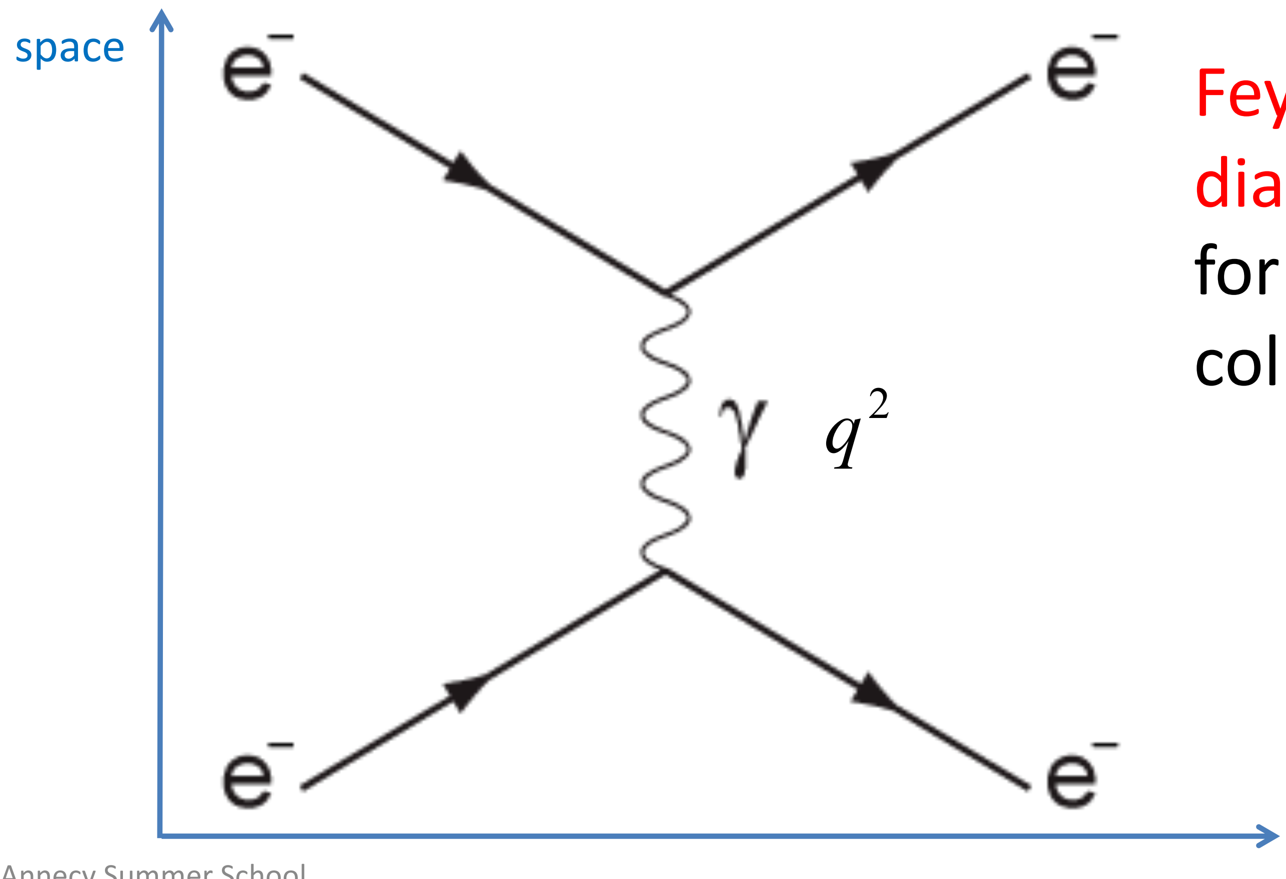
The (composite) particle zoo

The Standard Model: elementary particles and their interactions



Example of EM interaction

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

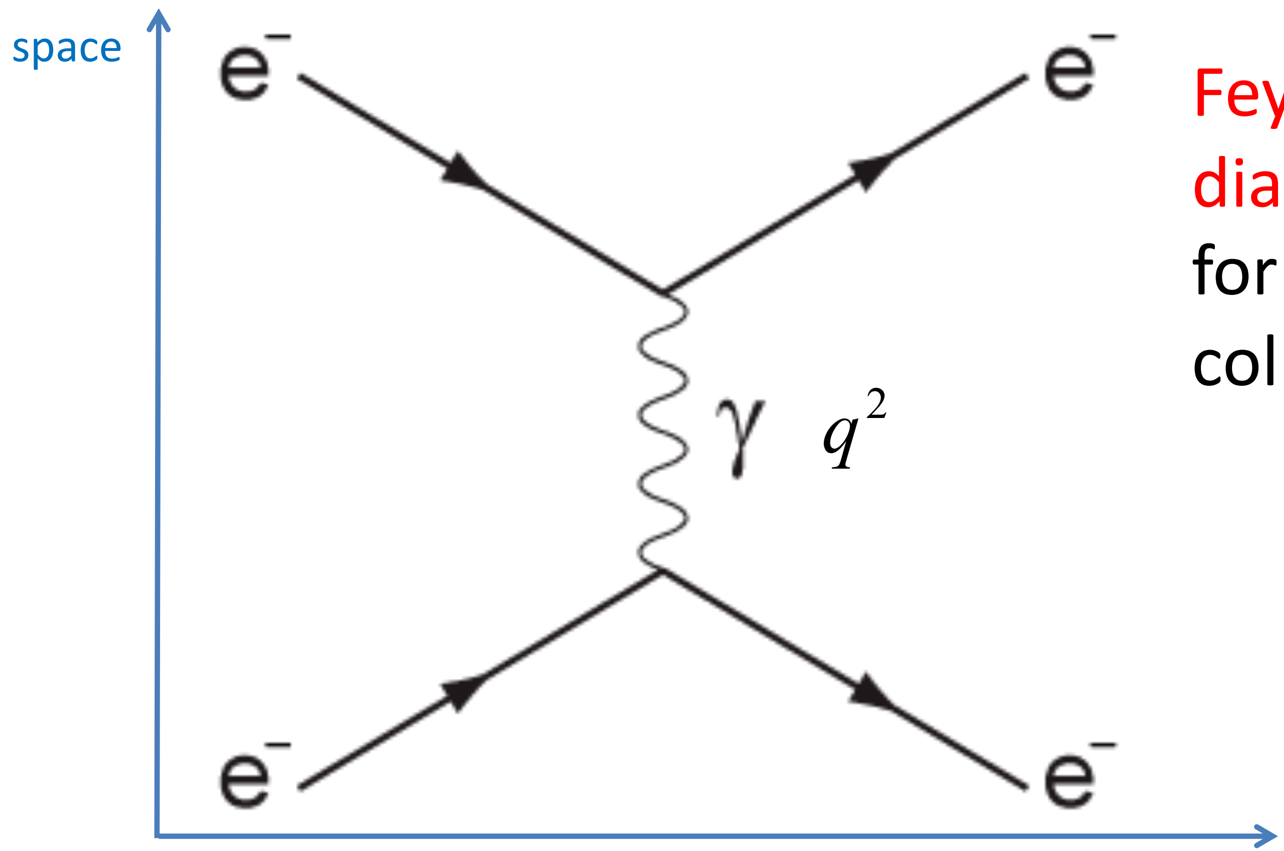


Feynman diagram for e^--e^- collision

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



Feynman diagram for e^{-}-e^{-} collision

Reminder: Fermi's Golden Rule

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

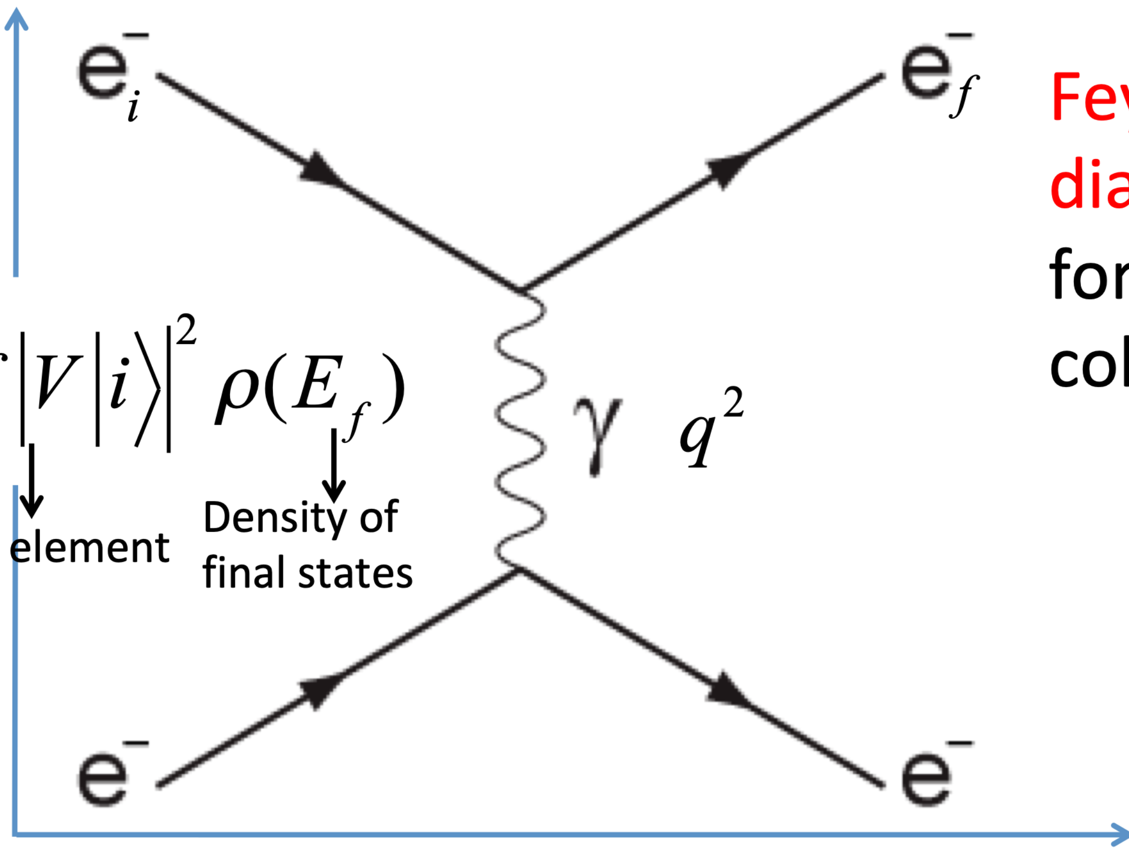
Feynman diagrams are calculational tools: will sketch computation of QM amplitude

Transition rate

$$\Gamma_{i\to f} = \frac{2\pi}{\hbar}\left|\langle f|V|i\rangle\right|^2 \rho(E_f)$$

Matrix element

Density of final states



Feynman diagram for e^--e^- collision

Reminder: Fermi's Golden Rule

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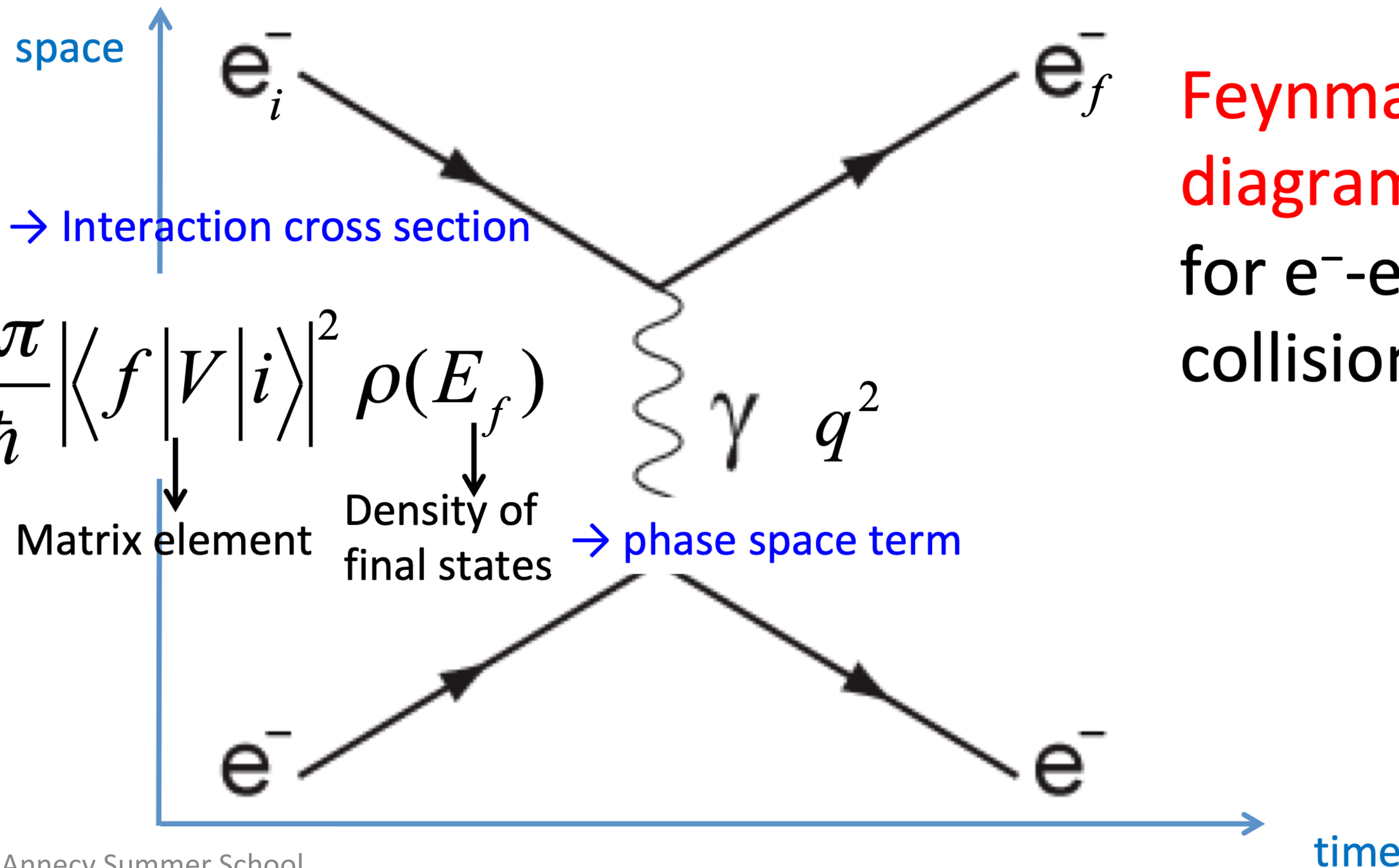
Feynman diagrams are calculational tools: will sketch computation of QM amplitude

Transition rate → Interaction cross section

$$\Gamma_{i\to f} = \frac{2\pi}{\hbar}\left|\left\langle f\left|V\right|i\right\rangle\right|^2 \rho(E_f)$$

Feynman diagram → Matrix element

Density of final states → phase space term



Feynman diagram for e^--e^- collision

Example of EM interaction

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

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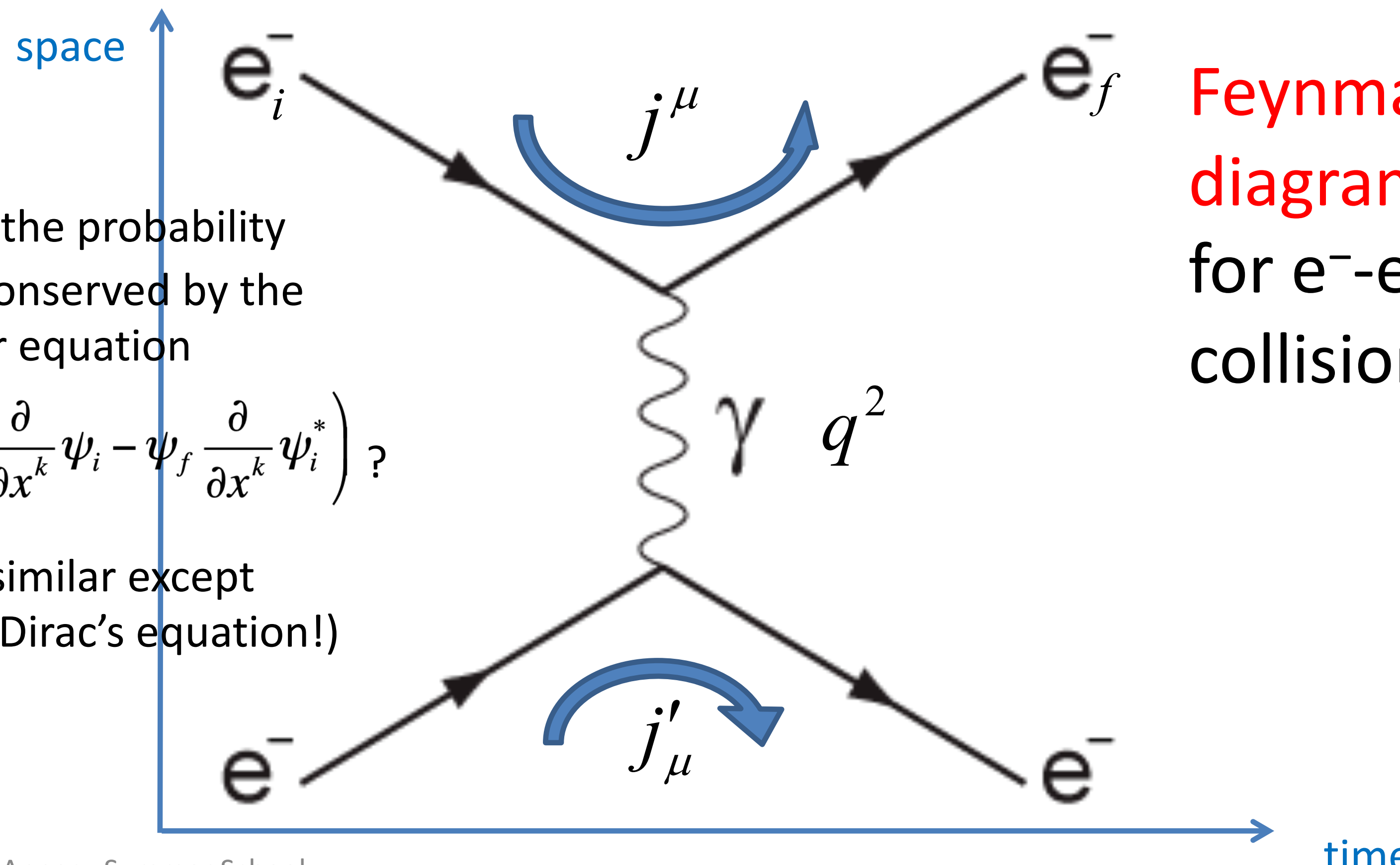


Feynman diagram for e⁻-e⁻ collision

Remember the probability current j_k conserved by the Schrödinger equation

$$j_k^{fi} = \frac{\hbar}{im}\left(\psi_f^* \frac{\partial}{\partial x^k}\psi_i - \psi_f \frac{\partial}{\partial x^k}\psi_i^*\right) \;?$$

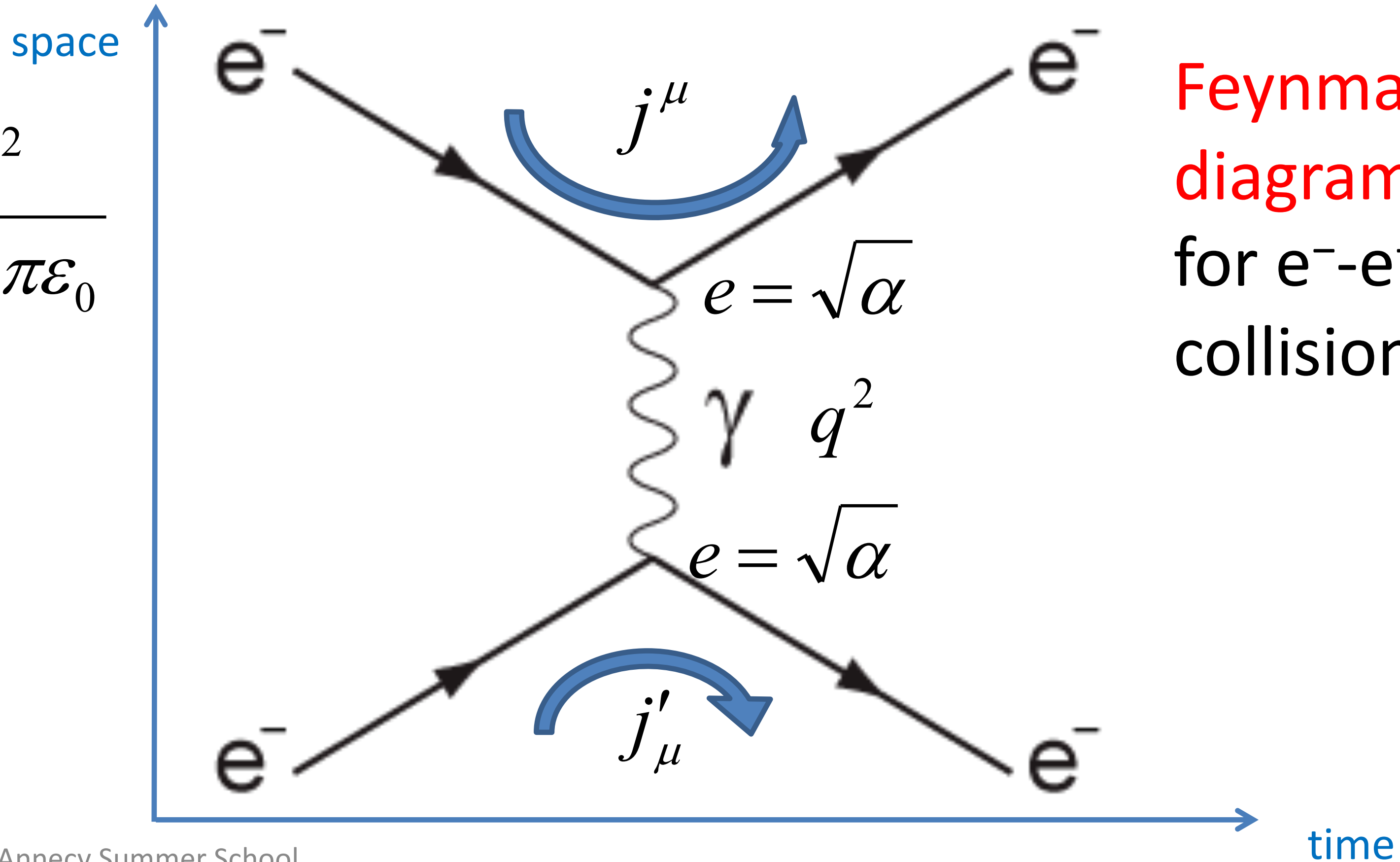
This one's similar except relativistic (Dirac's equation!)

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

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



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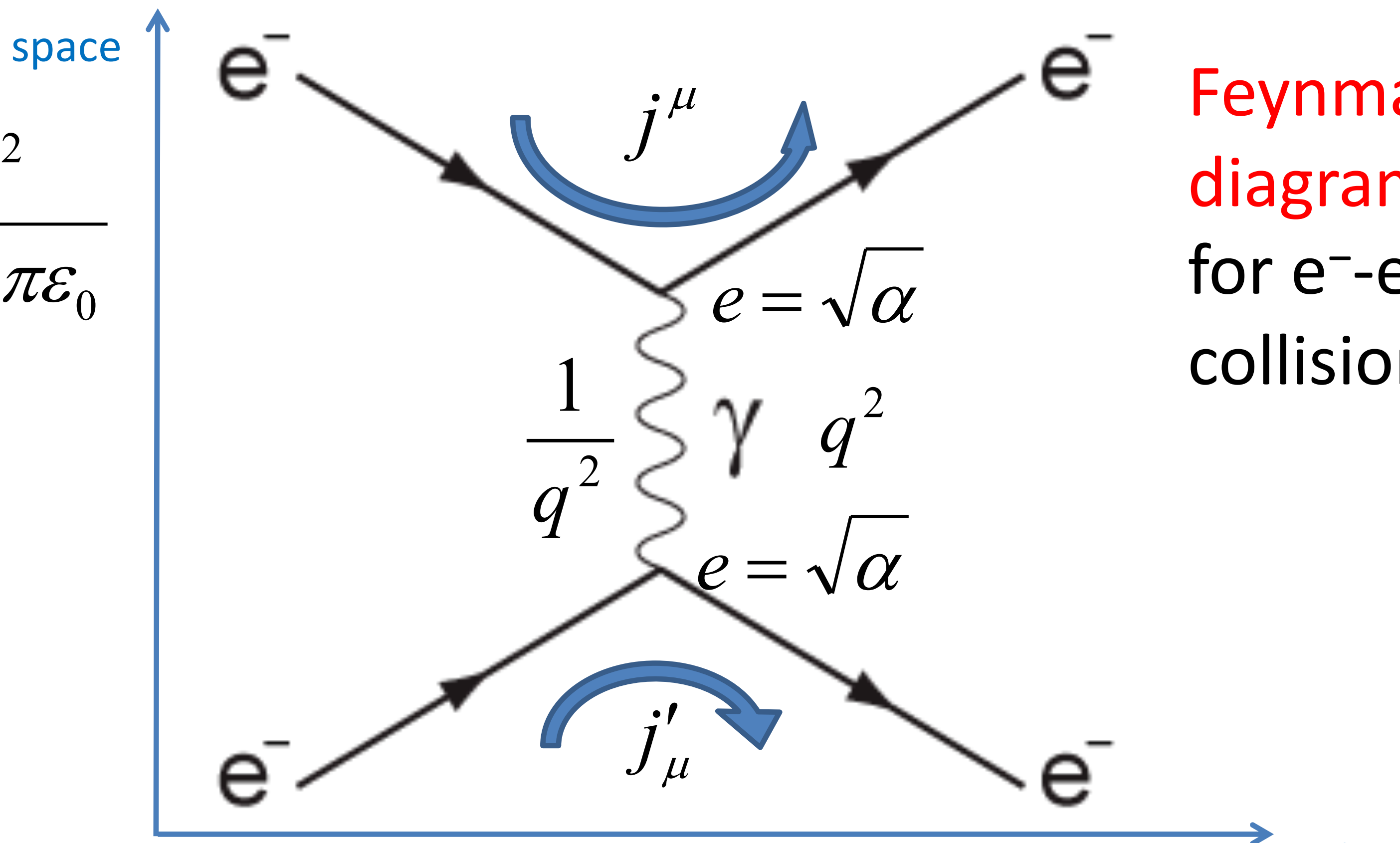

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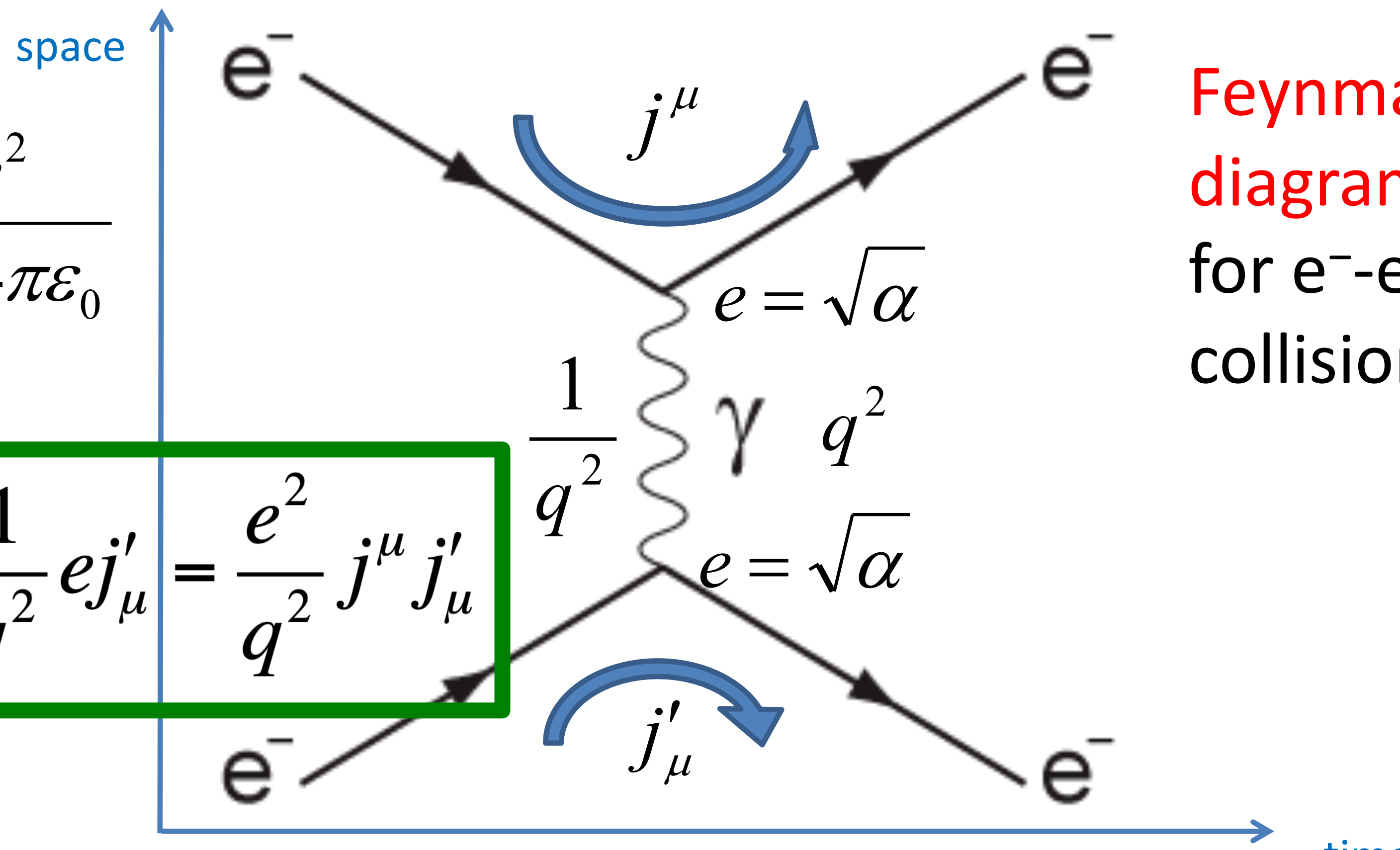


$$A \propto e j^\mu \frac{1}{q^2} e j'_\mu = \frac{e^2}{q^2} j^\mu j'_\mu$$

Feynman diagram for e⁻-e⁻ collision

Photon propagator

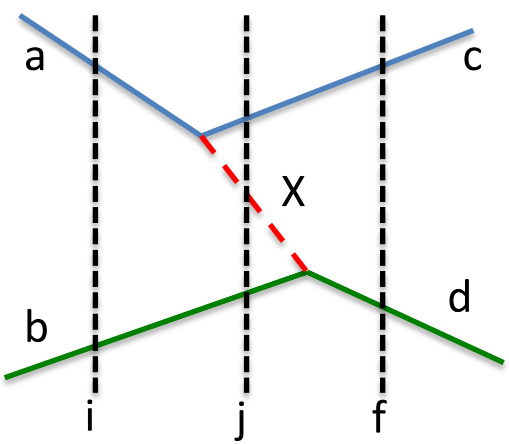
- Can derive it from standard QM time-indep. perturbation theory:

$$T_{fi} = \langle f|V|i\rangle + \sum_{j\neq n}\frac{\langle f|V|j\rangle\langle j|V|i\rangle}{E_i - E_j} + \ldots$$

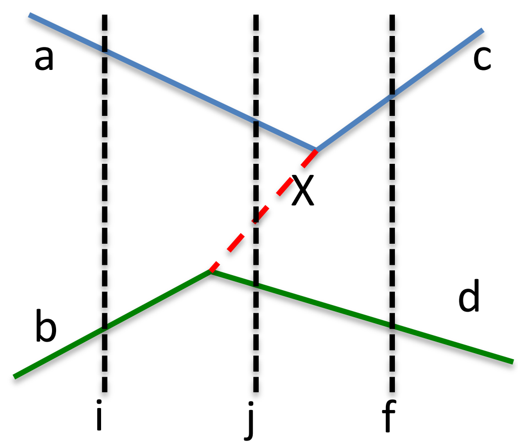
(See e.g. Halzen & Martin for a more detailed discussion)

This is the term that concerns us: scattering via an intermediate state (the photon)

- Two possibilities (two different time orderings):



a emits photon X, b absorbs it



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Photon propagator

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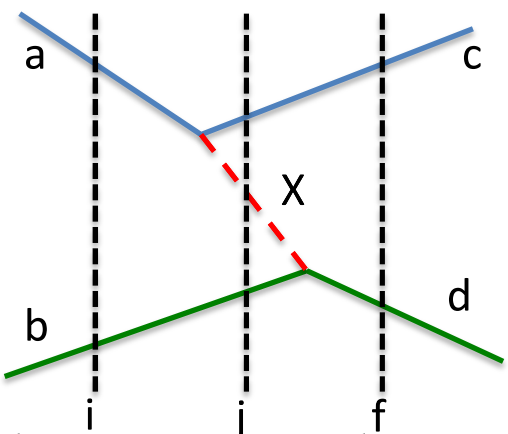
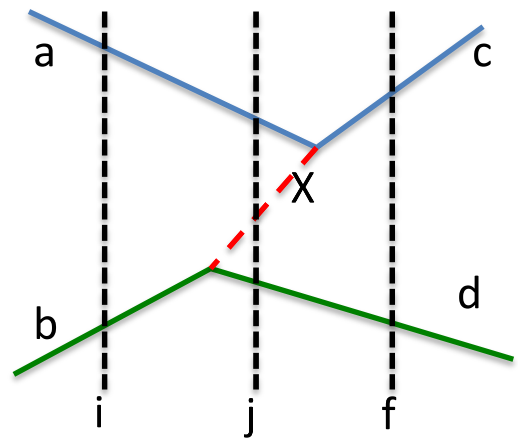
- Two different time orderings:



a emits photon X, b absorbs it

$$\frac{1}{E_i - E_j} = \frac{1}{(E_a + E_b) - (E_c + E_X + E_b)} =$$

$$= \frac{1}{(E_a - E_c) - E_X}$$



b emits photon X, a absorbs it

Use energy conservation: $E_a + E_b = E_c + E_d$

$$\frac{1}{E_i - E_j} = \frac{1}{(E_a + E_b) - (E_a + E_X + E_d)} =$$

$$= \frac{1}{(E_b - E_d) - E_X} = \frac{-1}{(E_a - E_c) + E_X}$$

Photon propagator

- Special relativity doesn't preserve simultaneity, have to sum over two time orderings:

$$T_{fi} = \sum_{j \neq i} \frac{\langle f|V|j\rangle\langle j|V|i\rangle}{E_i - E_j} \propto \frac{1}{(E_a - E_c) - E_X} + \frac{-1}{(E_a - E_c) + E_X}$$

$$\propto \frac{1}{(E_a - E_c)^2 - E_X^2} = \frac{1}{(E_a - E_c)^2 - (\vec{p}_a - \vec{p}_c)^2 - m_X^2} =$$

$$= \frac{1}{(p_a - p_c)^2 - m_X^2} = \frac{1}{q^2 - m_X^2}$$

where $q = p_a - p_c$ is the transferred 4-momentum

and we've used $E_X^2 = \vec{p}_X^2 + m_X^2 = (\vec{p}_a - \vec{p}_c)^2 + m_X^2$

Photons are massless, ${m^2}_X = 0$ and their propagator is $1/q^2$

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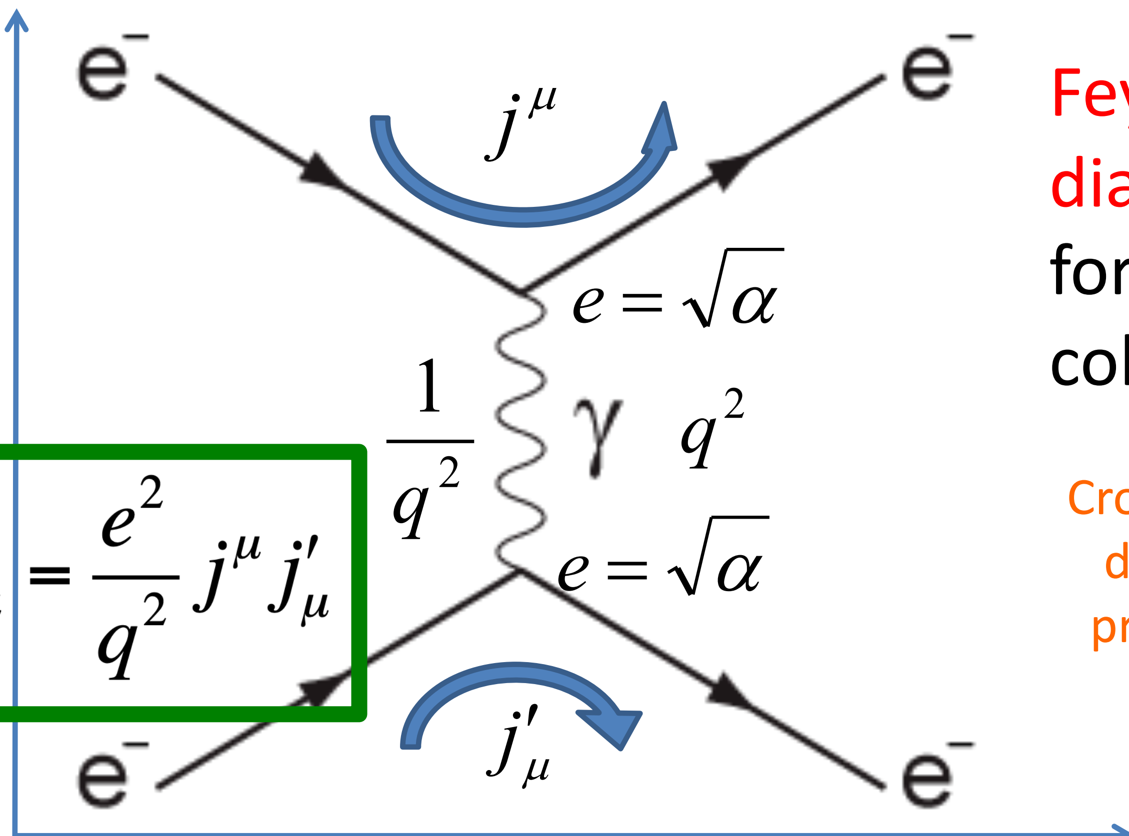
$$\alpha = \frac{e^2}{\hbar c 4\pi\varepsilon_0}$$



$$A \propto e j^\mu \frac{1}{q^2} e j'_\mu = \frac{e^2}{q^2} j^\mu j'_\mu$$

Feynman diagram for e^--e^- collision

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

Antimatter

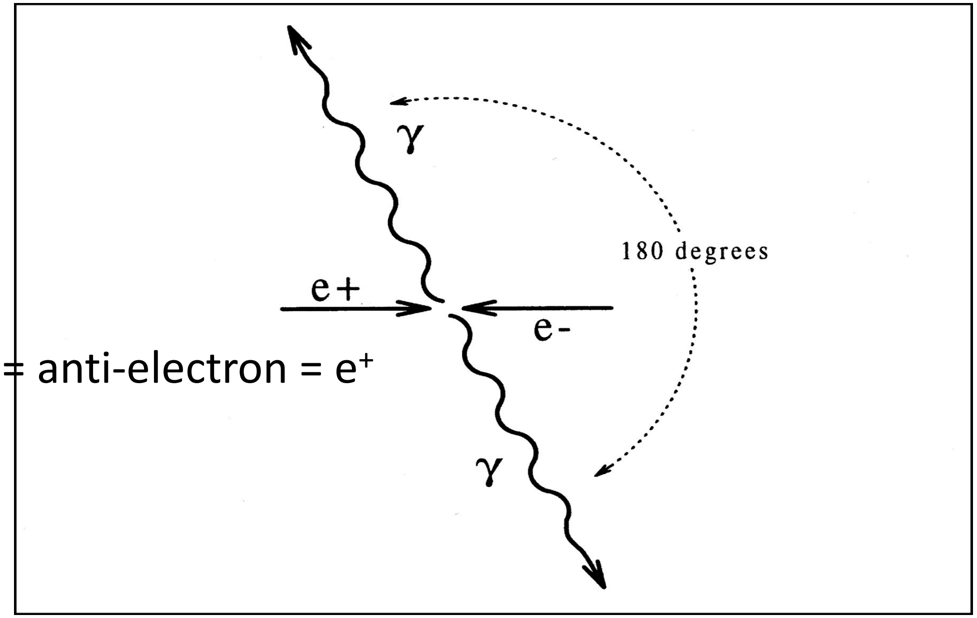
Example of EM interaction: matter-antimatter annihilation

- Antiparticle: same properties (mass, spin) as particle, but all "charges" reversed (electric, weak force, strong force)

positron = anti-electron = e^+

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 ($E=mc^2$!)



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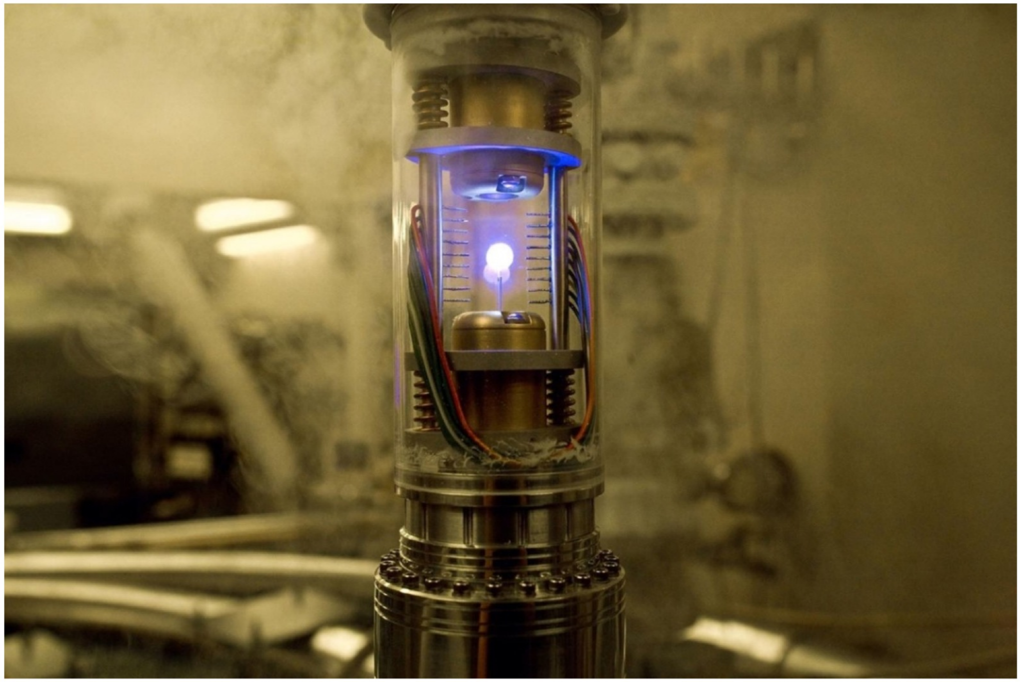
ANGELS AND DEMONS
Antimatter bomb



Exercice:

1) how many kilotons for a bomb of 0.5 g of antimatter?
   (1 kiloton = 4.2×10^{12} J)
2) which cost? (1 kWh = 0.1 €)

Example of EM interaction: matter-antimatter annihilation

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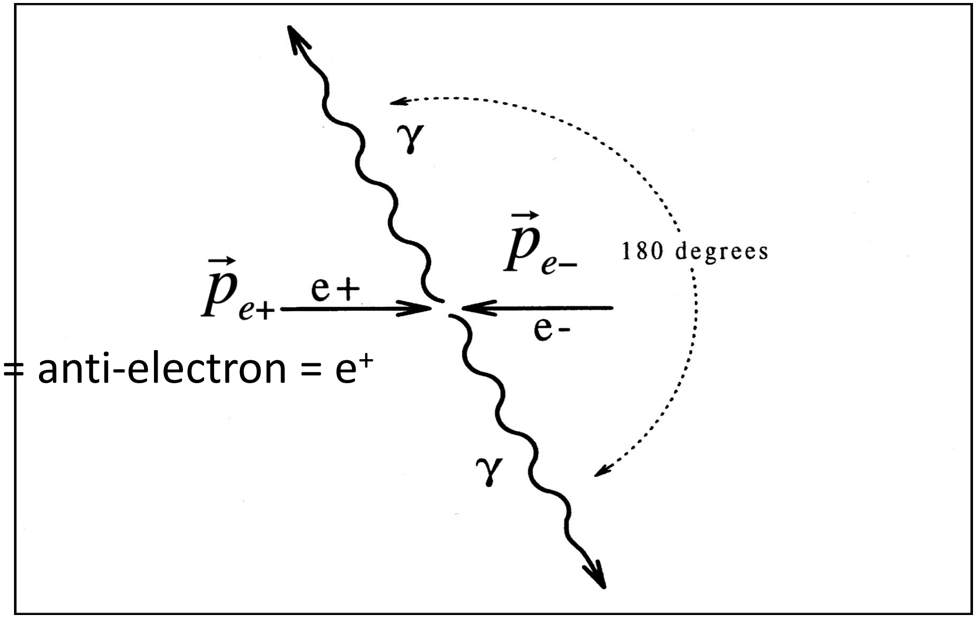

positron = anti-electron = e^+

c = 1!

where m is "relativistic invariant mass" of system:

$$m^2_{e+e-} = (E_{e+} + E_{e-})^2 - (\vec{p}_{e+} + \vec{p}_{e-})^2 \equiv (p^\mu_{e+} + p^\mu_{e-})^2$$

Example of EM interaction: matter-antimatter annihilation

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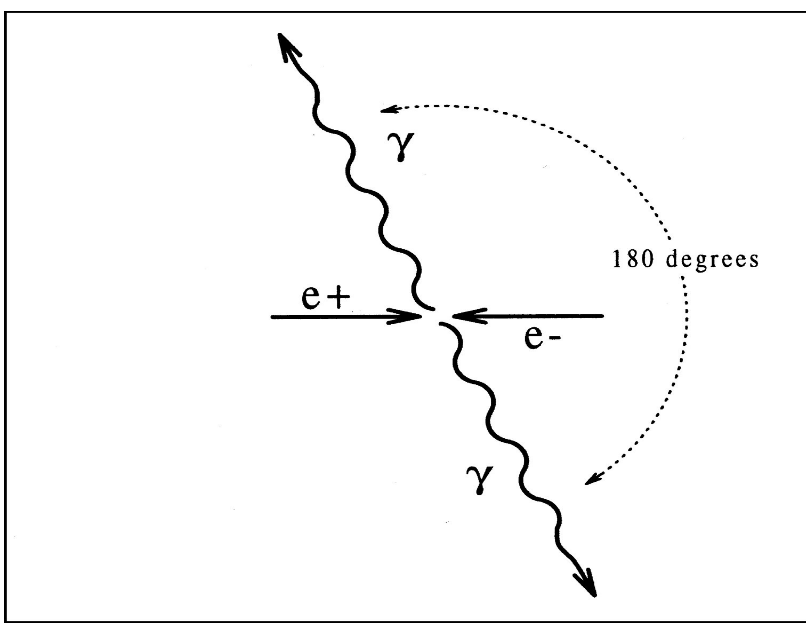
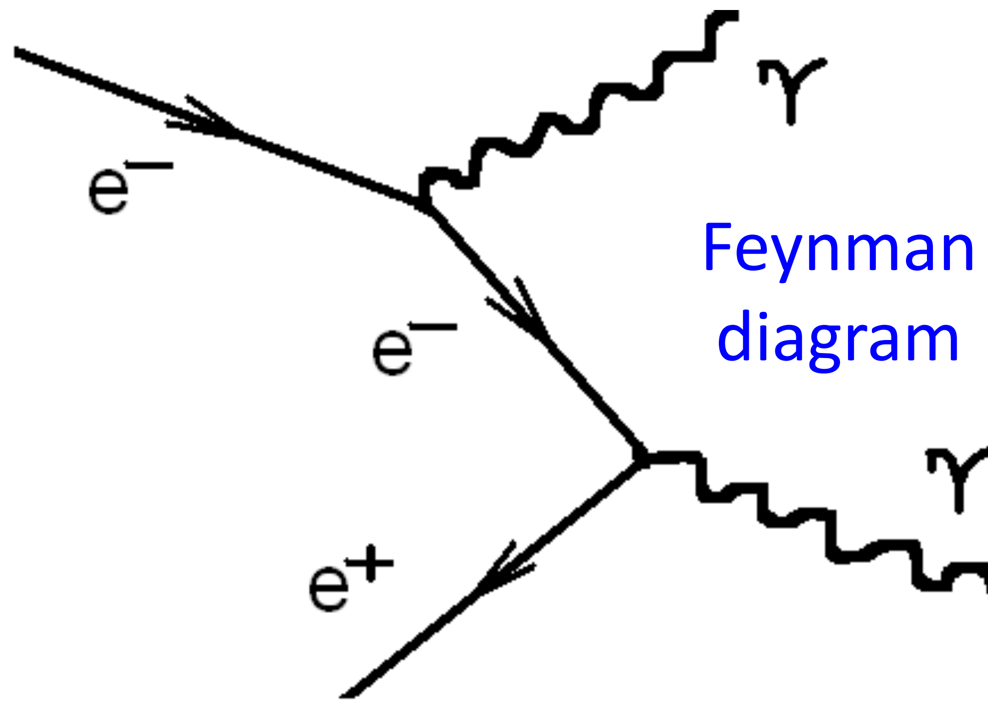
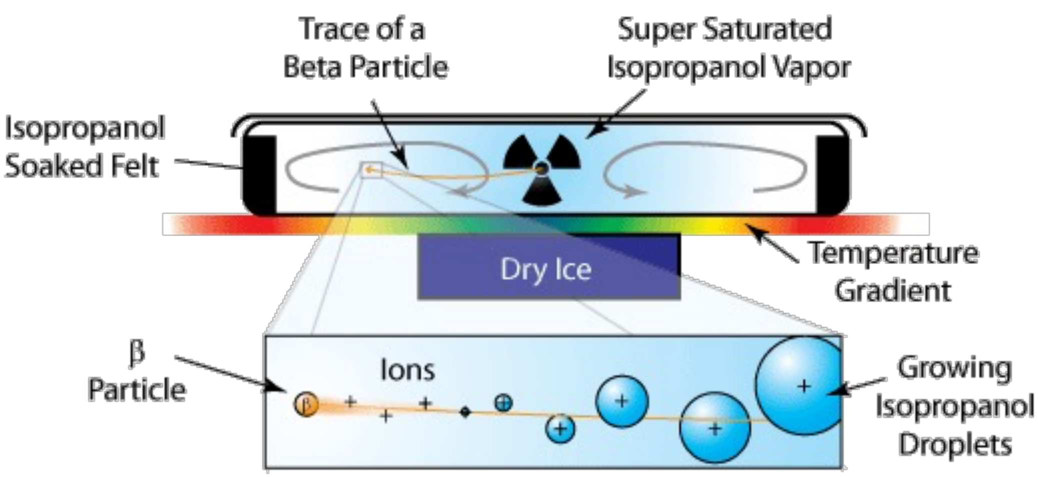


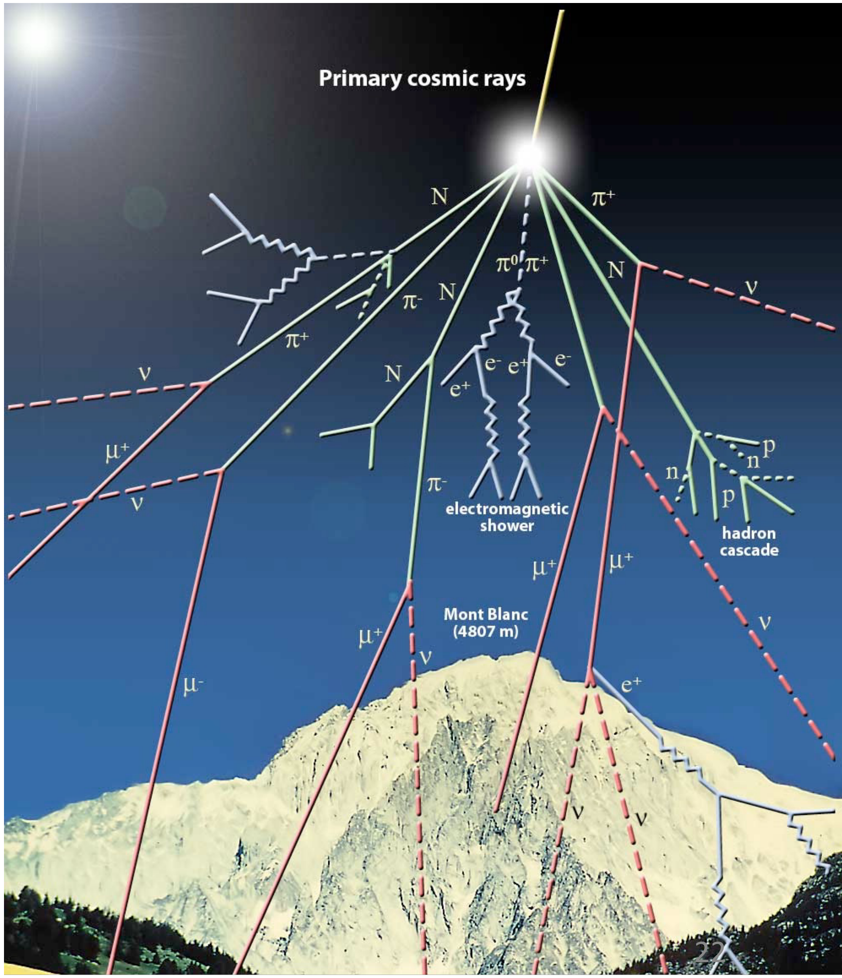


Feynman diagram

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 along track
- Photographic emulsions also used





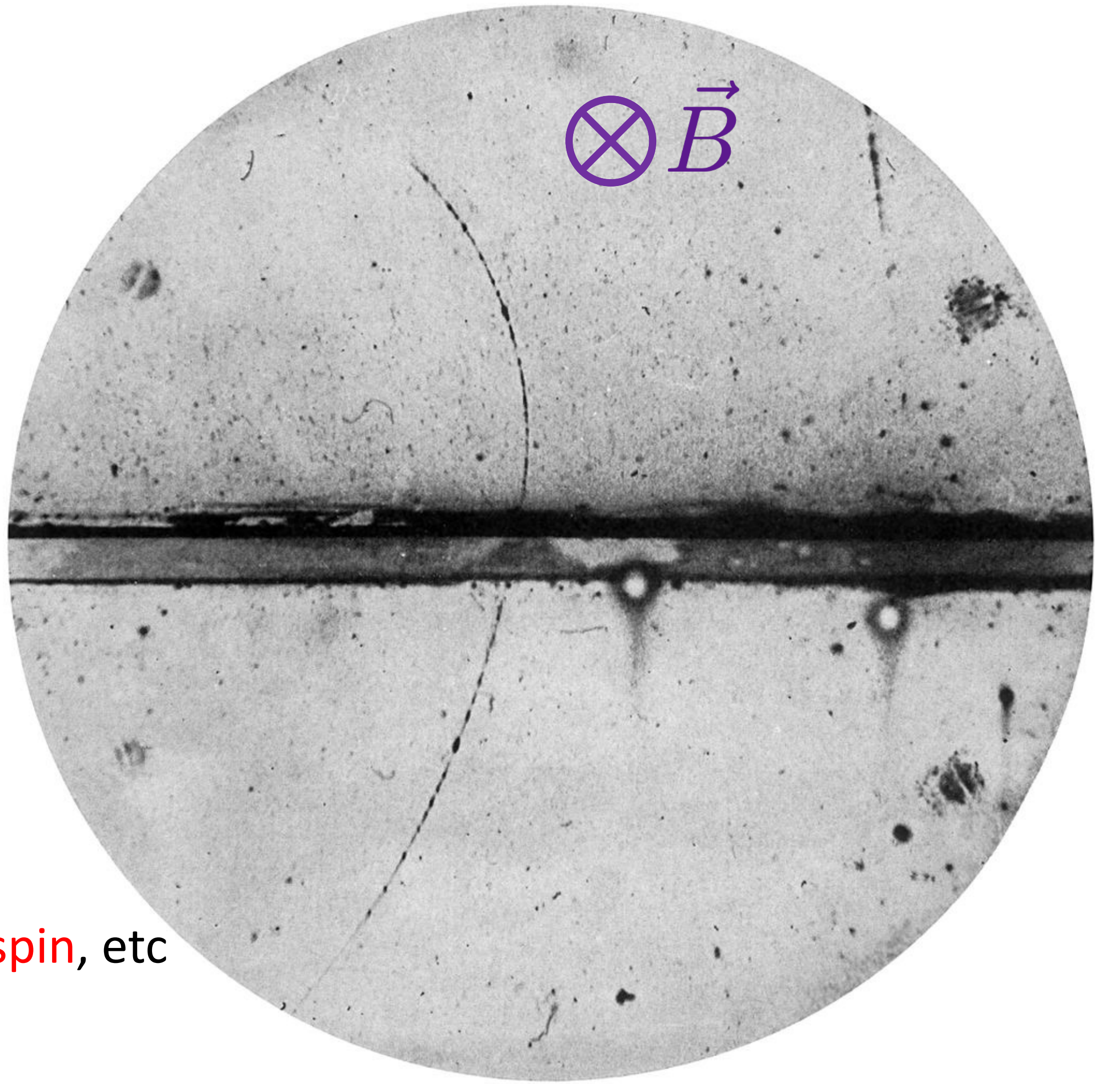
Antiparticles: the positron

- 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



Aside: C, P, T and CP symmetries

- C (charge conjugation) operator: $C|e^-\rangle = |e^+\rangle$ (up to some arbitrary phase)
- P (parity) reverses space: $\mathrm{P}\psi(\vec{r}) = \psi(-\vec{r})$
- T (time reversal): $T\psi(\vec{r}, t) = \psi(\vec{r}, -t)$

(Theorem: the combined CPT transformation is a symmetry of all QFTs)

- Antimatter seems to obey the same equations as matter, except |antimatter> = CP |matter> (rather than antimatter = C |matter>)
- If CP were a symmetry of all interactions (Hamiltonian/Lagrangian), the Universe would be matter/antimatter symmetric
- The whole visible Universe seems to be matter-dominated

⇒ CP not a symmetry? E.g. matter-antimatter asymmetry?

Look for CP violation in fundamental interactions in quarks (e.g. LHCb exp) and in neutrinos (e.g. DUNE exp)

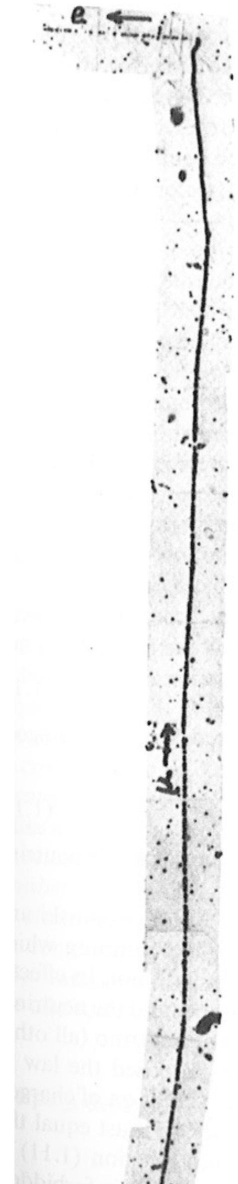
More cosmic rays: the muon

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)

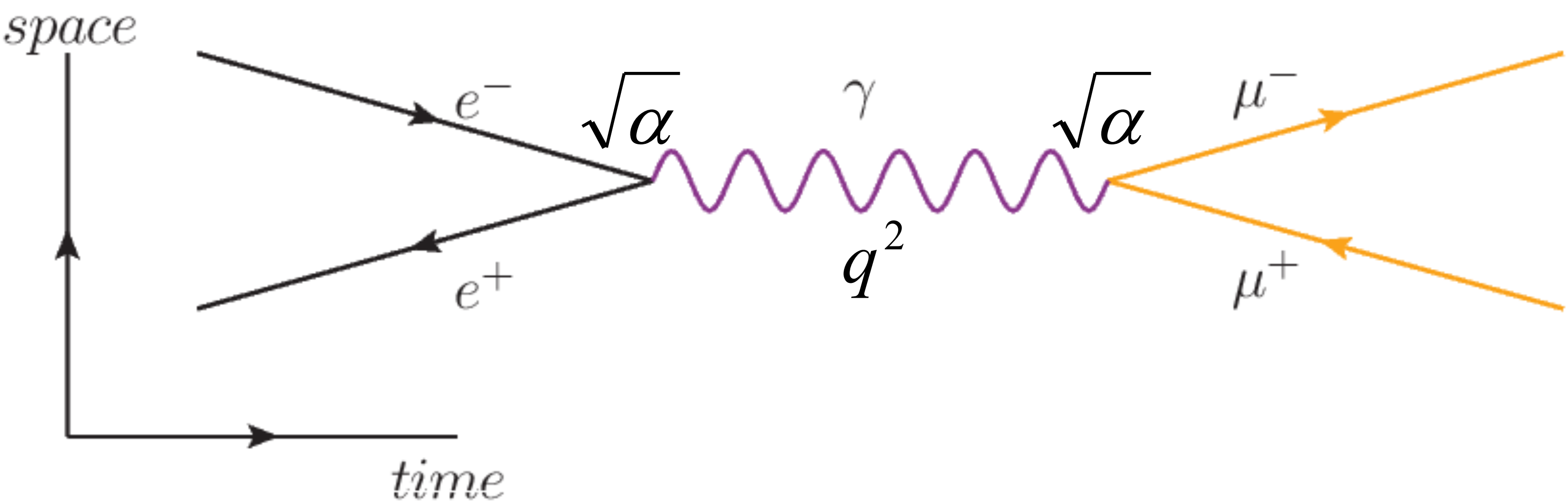
Just like electron but heavy and unstable

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



Example of EM interaction: pair production

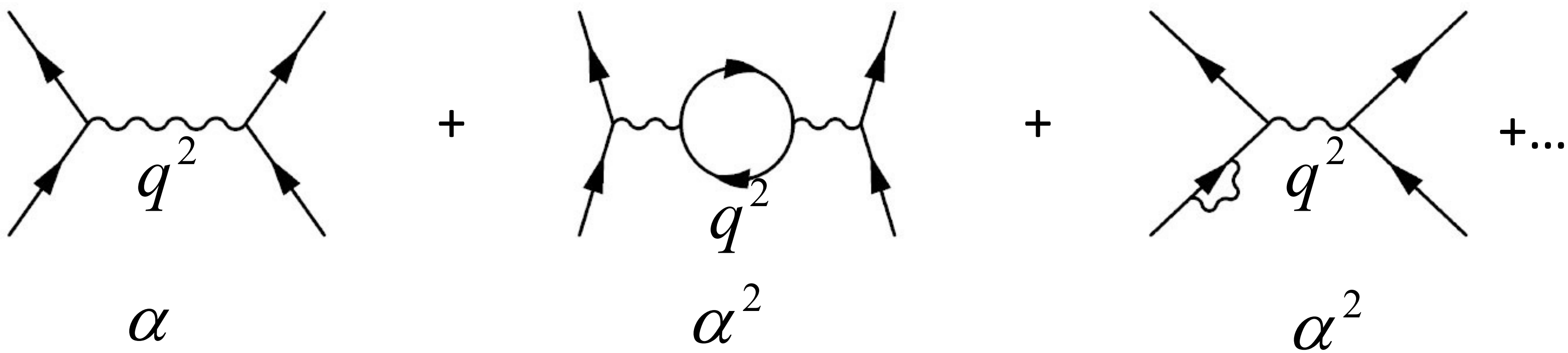
- The inverse of matter-antimatter annihilation: particle-antiparticle pair production
- For instance: $\mu^+ \mu^-$ production:



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

Quantum ElectroDynamics (QED)

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



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

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)

First look at Dirac's equation

- Schrödinger's eq: $\mathrm{E} = \frac{p^2}{2m} + V, \quad E \to i\hbar\, {}^{\partial}\!/_{\partial t}\,,\ \vec{p} \to -i\hbar\vec{\nabla}$

$$\Rightarrow \left(\mathrm{i}\hbar\frac{\partial}{\partial t} + \frac{\hbar^2}{2m}\nabla^2 - V(\vec{r})\right)\psi(\vec{r},t) = 0,$$ where $\psi \sim e^{i(px-Et)/\hbar}$ (free particle)

- Manifestly not relativistically invariant: 1 $(\partial/\partial \mathrm{t}) \neq 2$ $(\partial^2/\partial \mathrm{x}^2)$
- Dirac (1928): time and space on equal footing ⇒ 1st order diff eq

$$0 = p_\mu p^\mu - m^2c^2 = (\beta^\kappa p_\kappa + mc)\left(\gamma_\lambda p^\lambda - mc\right)$$ (see Griffiths section 7.1)

$$\Rightarrow \beta^\kappa = \gamma^\kappa;\ \ (\gamma^0)^2 = 1\,, \left(\gamma^i\right)^2 = -1\ \ (i = 1,2,3),\ \ \gamma^\mu\gamma^\nu + \gamma^\nu\gamma^\mu = 0$$

⇒ γ^κ are 4×4 matrices, not just (complex) numbers!

(Dirac representation) $\gamma^0 = \begin{pmatrix} \mathbb{1} & 0 \\ 0 & -\mathbb{1} \end{pmatrix},\ \ \gamma^i = \begin{pmatrix} 0 & \sigma_i \\ -\sigma_i & 0 \end{pmatrix};\ \ \psi = \begin{pmatrix} \psi_1 \\ \psi_2 \\ \psi_3 \\ \psi_4 \end{pmatrix}$

σ_i, Pauli's matrices

ψ_1, ψ_2: E>0 part spin↑,↓

ψ_3, ψ_4: ? E<0

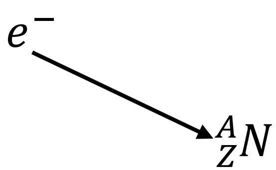
- 4 degrees of freedom:

2 for a spin-1/2 particle E>0, E<0 other 2?

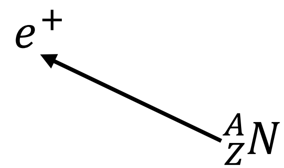
First look at Dirac's equation

- Feynman-Stückelberg interpretation:

absorption of particle = emission of antiparticle



charge: $-1 + Z = Z - 1$
energy: $E_{e-} + E_N$



charge: $Z - 1 = Z - (+1)$
energy: $E_N - E_{e+} = E_N + E_{e-}$

antiparticle = "particle going backwards in time"

- Dirac's eq: $\left(i\hbar\gamma^\mu\partial_\mu - mc\right)\psi = 0$ or $(i\hbar\not\partial - mc)\psi = 0$

$$(\gamma^0)^2 = 1, \left(\gamma^i\right)^2 = -1 \rightarrow \gamma^\mu\gamma^\nu + \gamma^\nu\gamma^\mu = 2g^{\mu\nu} \rightarrow \{\gamma^\mu, \gamma^\nu\} = 2g^{\mu\nu}$$

(Dirac representation) $\gamma^0 = \begin{pmatrix} \mathbb{1} & 0 \\ 0 & -\mathbb{1} \end{pmatrix}, \ \gamma^i = \begin{pmatrix} 0 & \sigma_i \\ -\sigma_i & 0 \end{pmatrix};$

- 4 degrees of freedom:

2 for a spin-1/2 particle, 2 for the spin-1/2 antiparticle

$$\psi = \begin{pmatrix} \psi_1 \\ \psi_2 \\ \psi_3 \\ \psi_4 \end{pmatrix}$$

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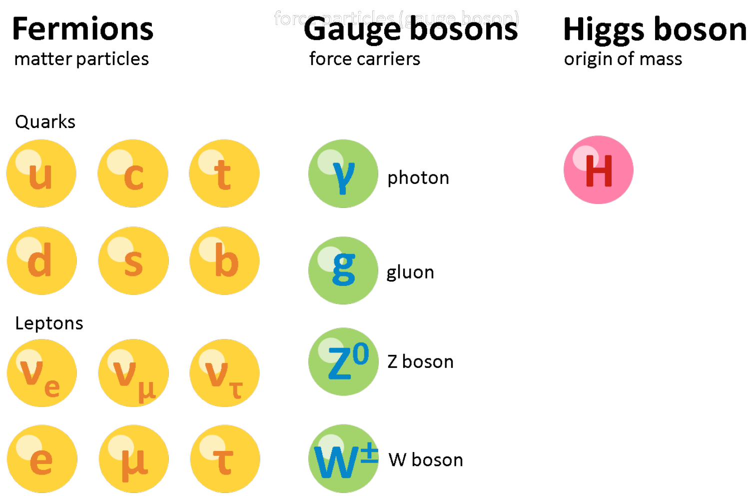
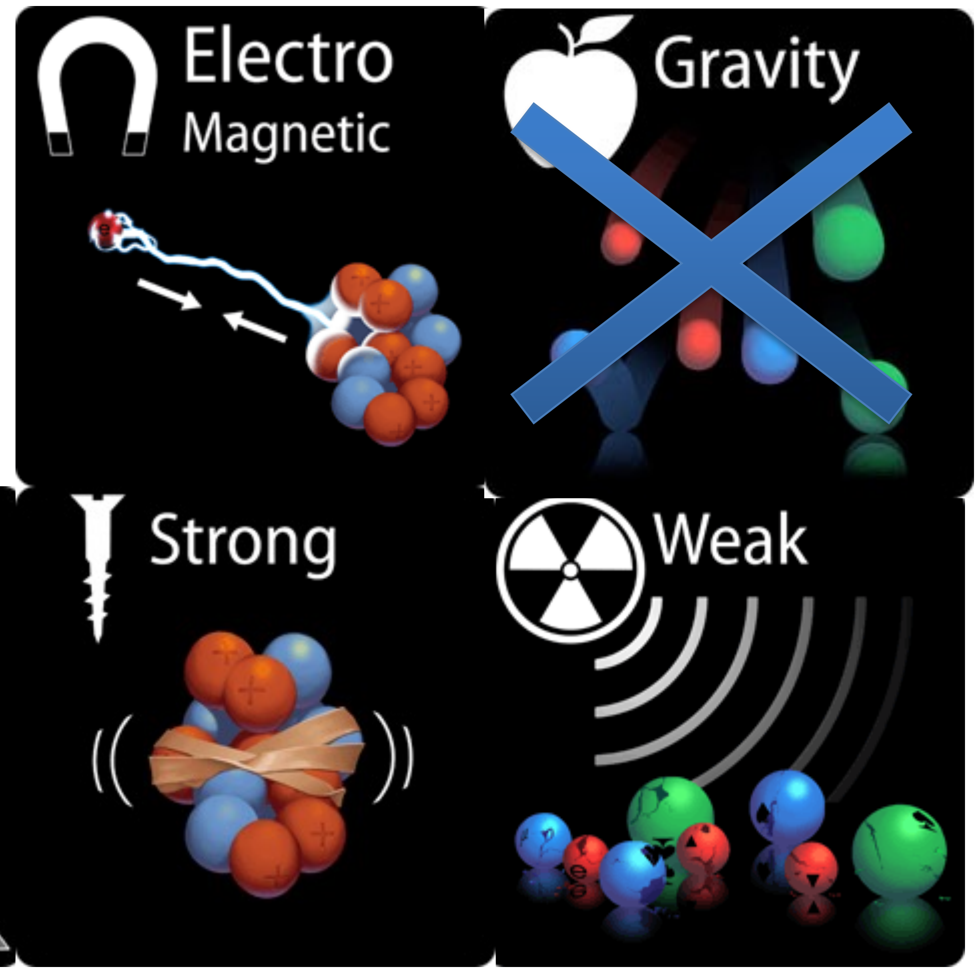
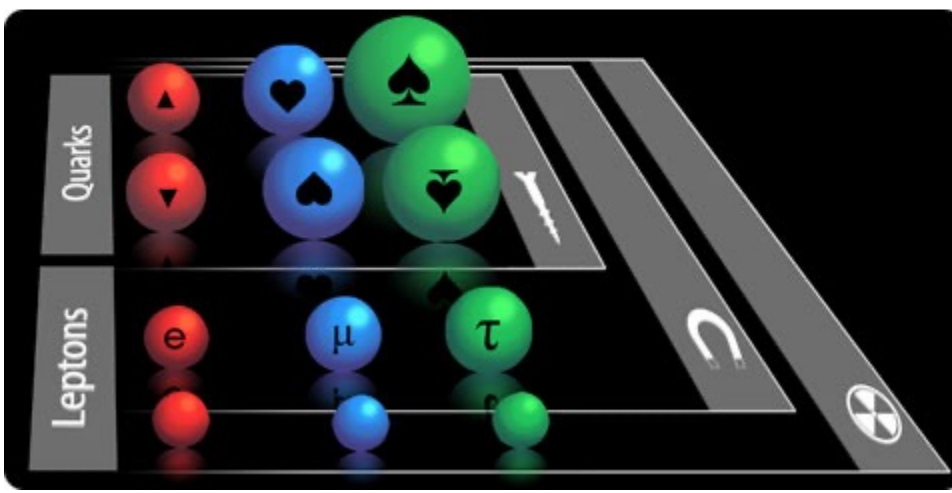
The Standard Model: elementary particles and their interactions



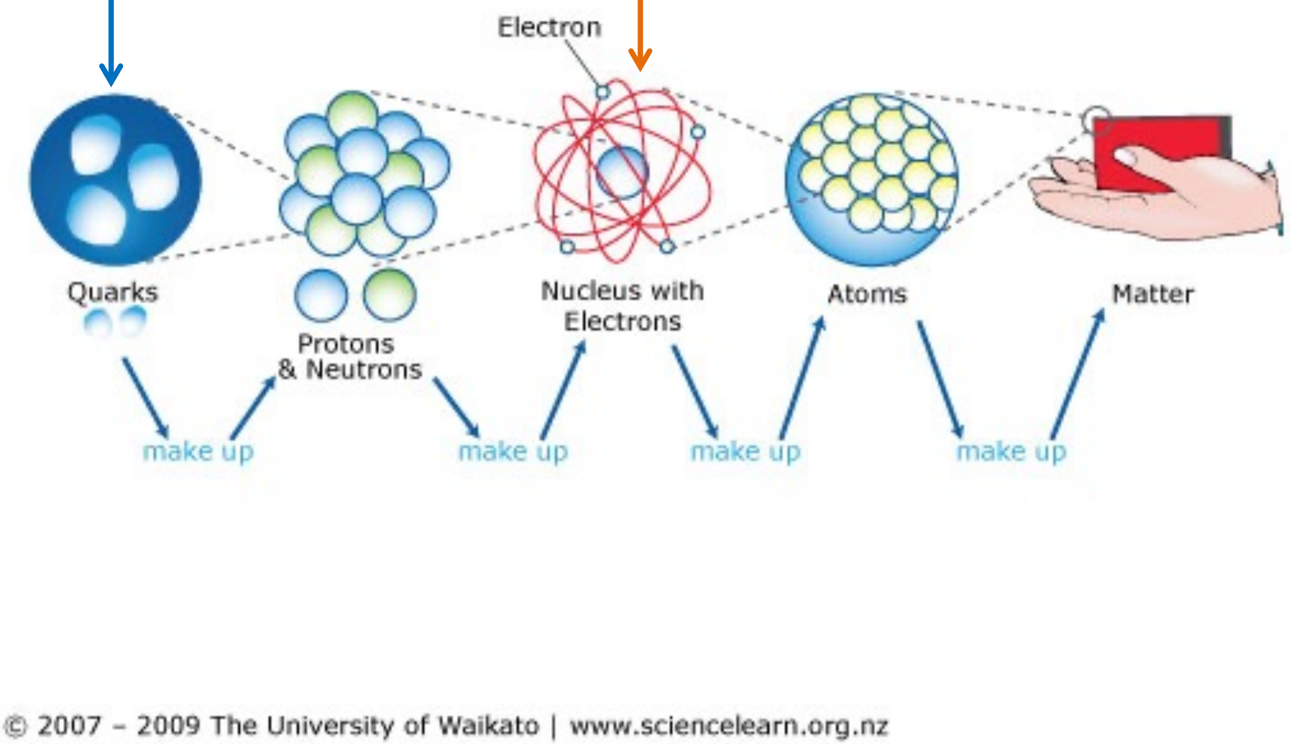




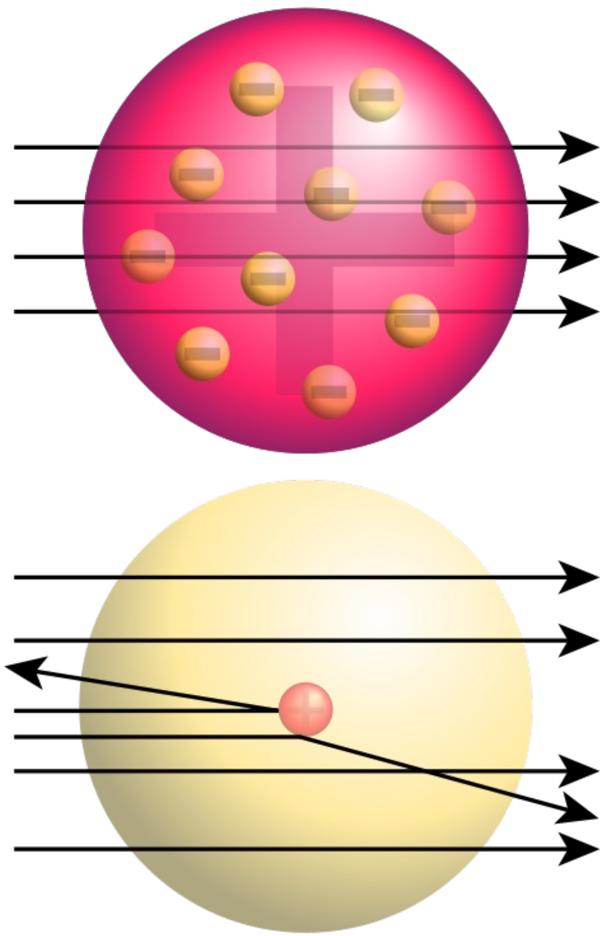
A VERY brief history of particles

1968-69 SLAC,
Bjorken, Feynman

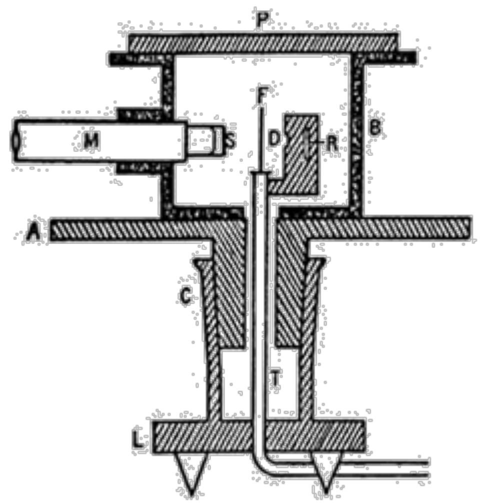
1911 Rutherford,
Geiger, Marsden

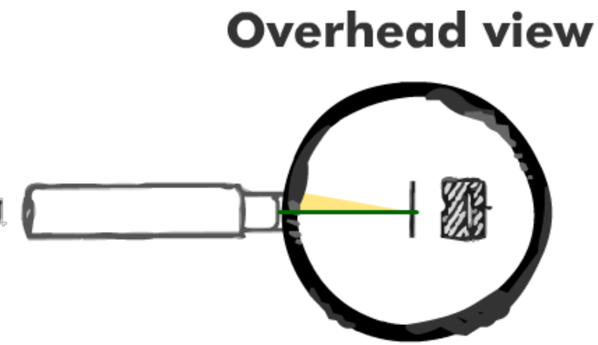


The nucleus: Rutherford scattering



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



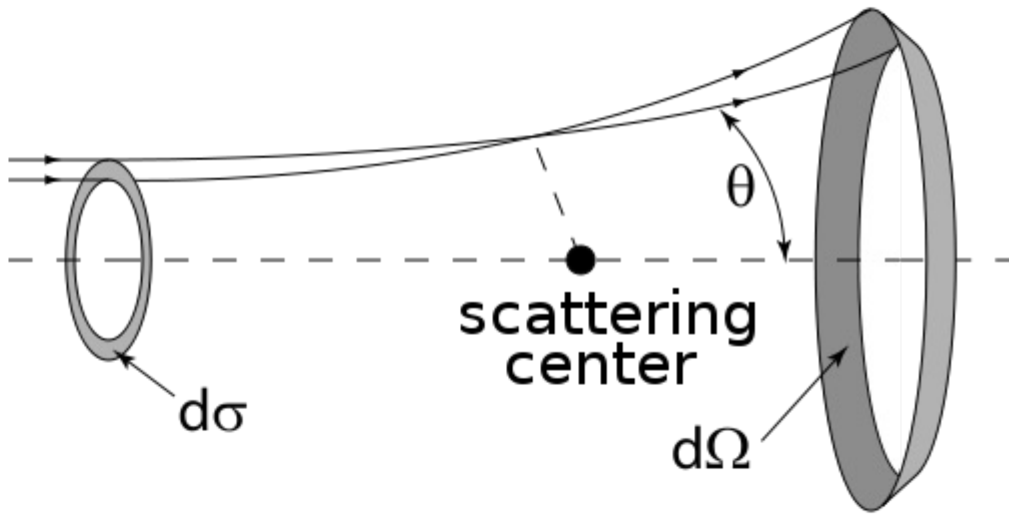


- 1909, Geiger & Marsden: ~1/8000 alpha particles bounce off!
- 1911, Rutherford: nucleus small within atom, surrounded by e⁻ cloud

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

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

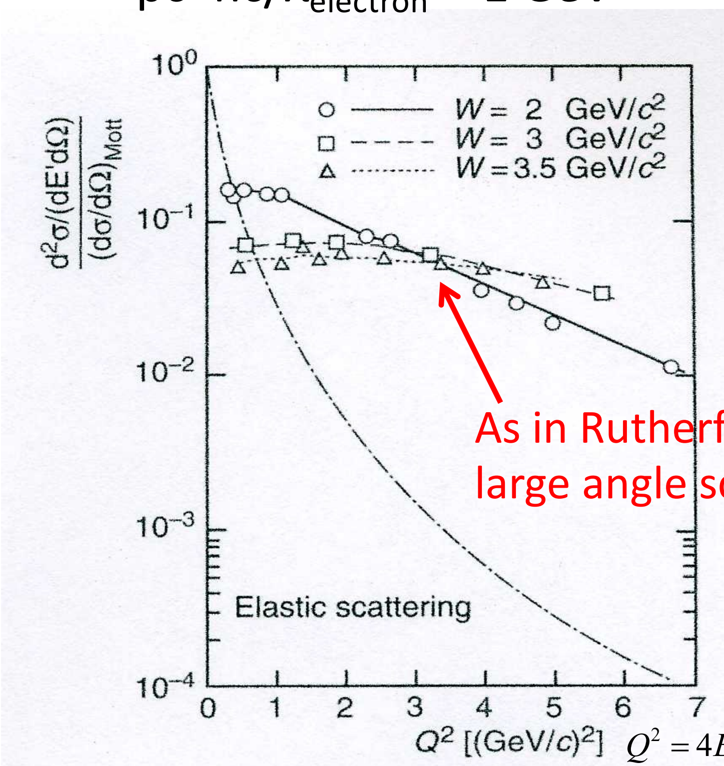


- Ex, scattering of spinless charged particles off a spinless charged target (Rutherford):

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

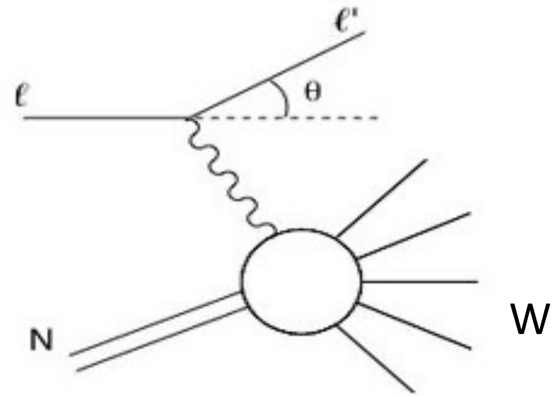
Back to history: protons are composite

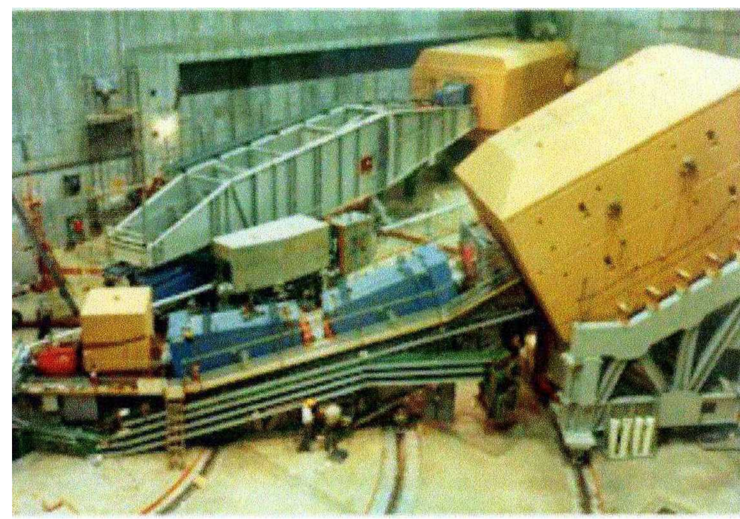
- Post WWII: accelerator era
- 1968 SLAC: shoot e^- to proton target
- High energies: $\lambda_{electron} << R_{proton}$
  $pc = hc/\lambda_{electron} >> 1$ GeV



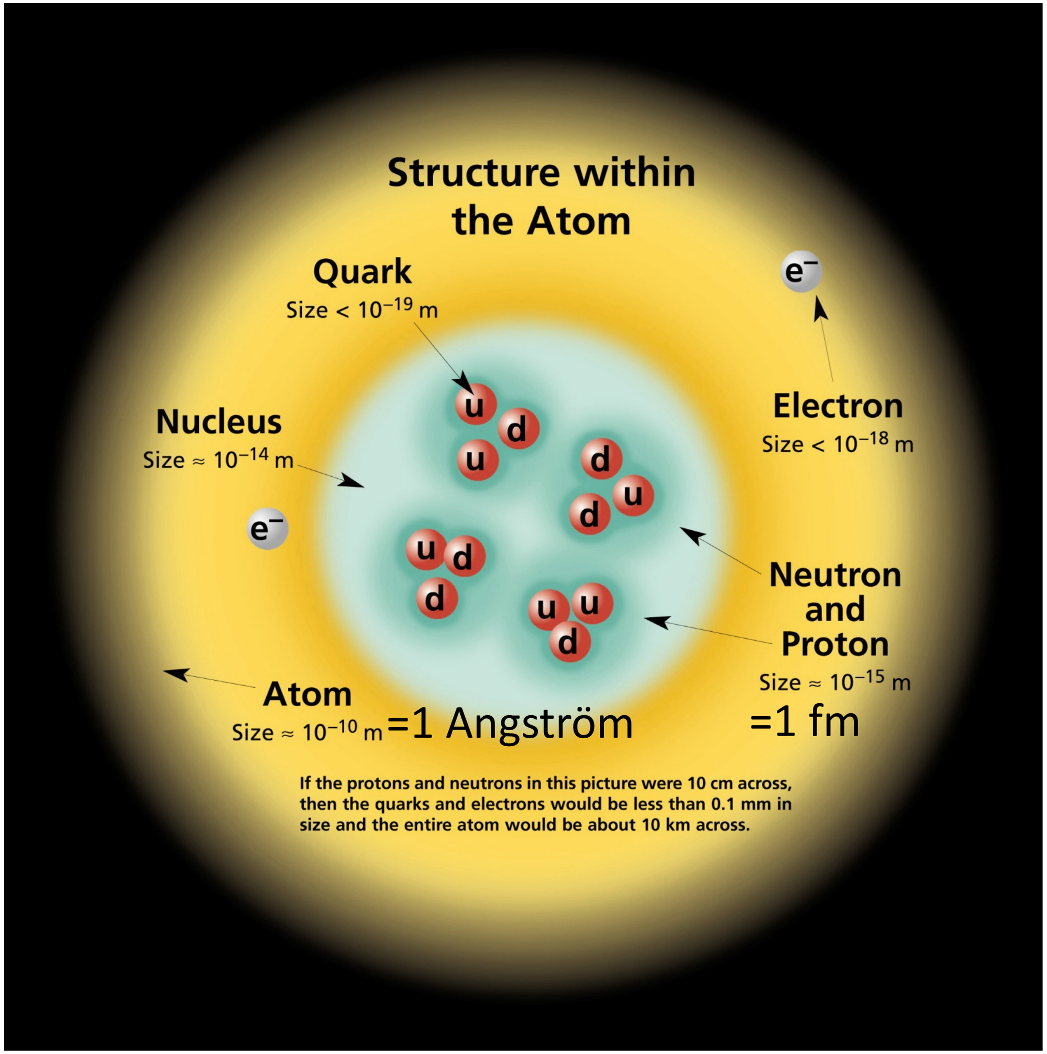
As in Rutherford,
large angle scattering!

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





Protons are composite

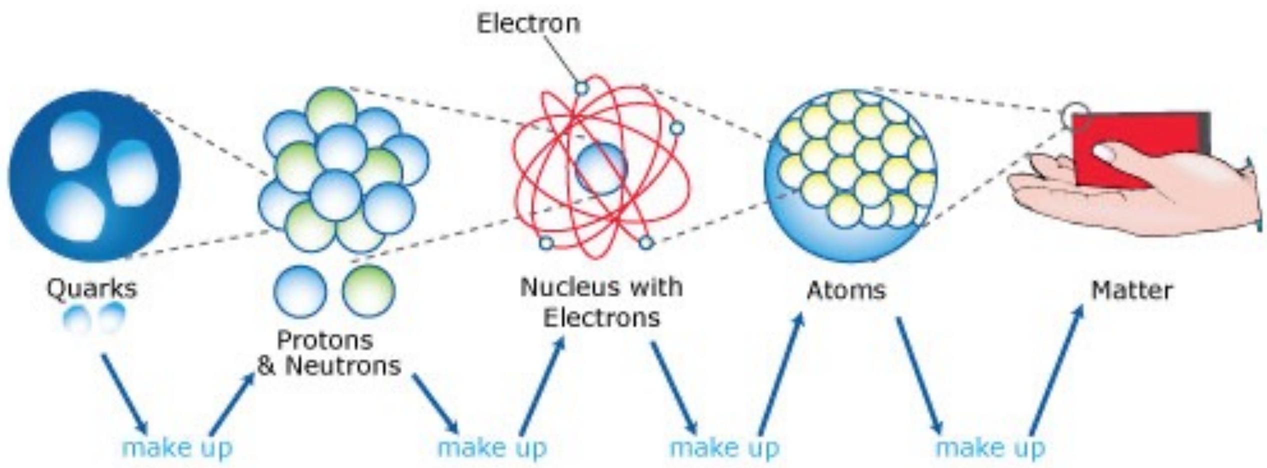


Nucleons composed of 3 point-like particles: quarks

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 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"

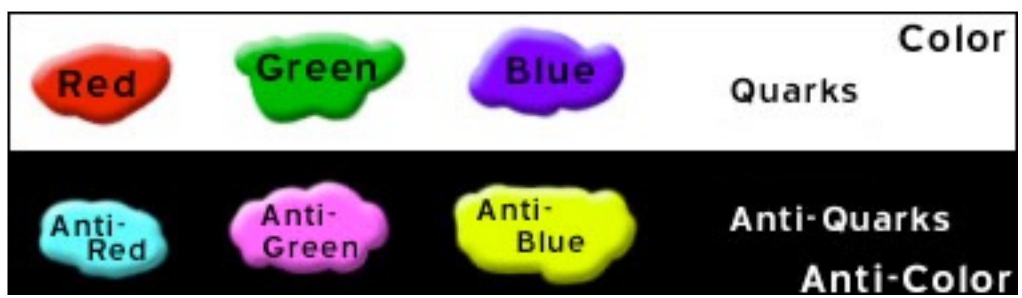
  ➔ theory called Quantum Chromodynamics (QCD)
- Call "quark" a particle with color charge. Leptons don't have color.

EM

+

−

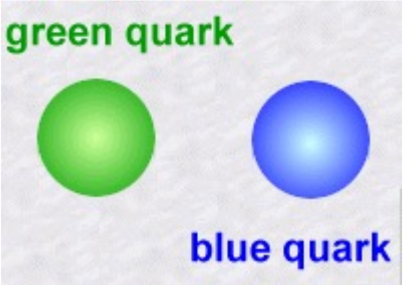
Strong Force



* 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!

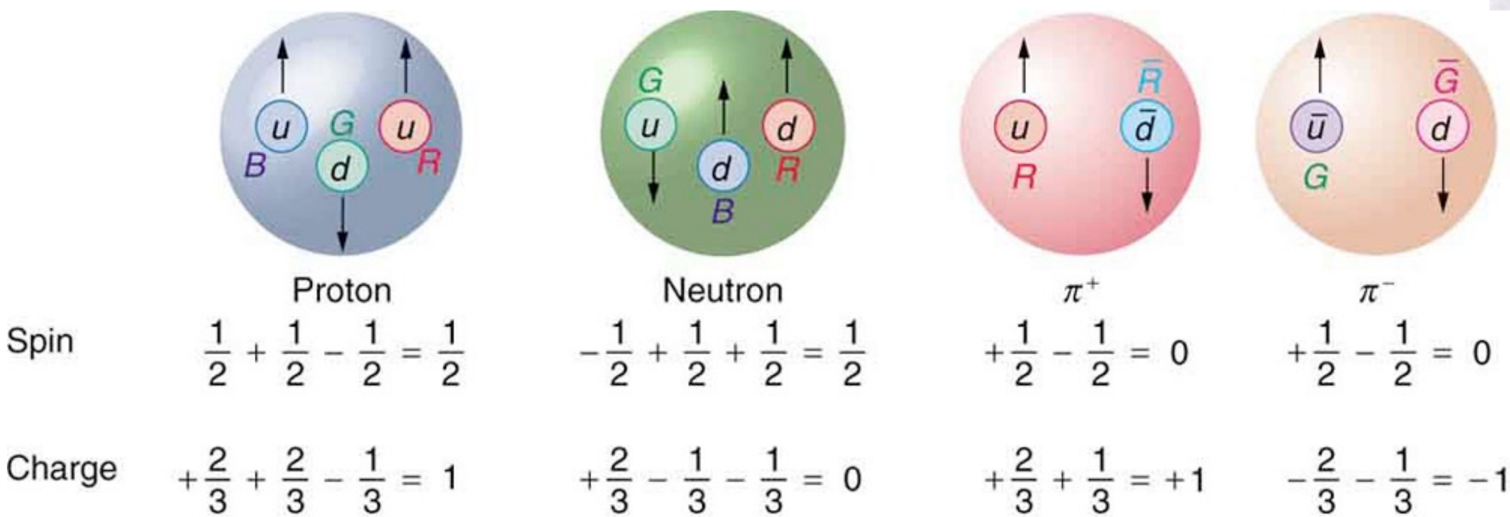


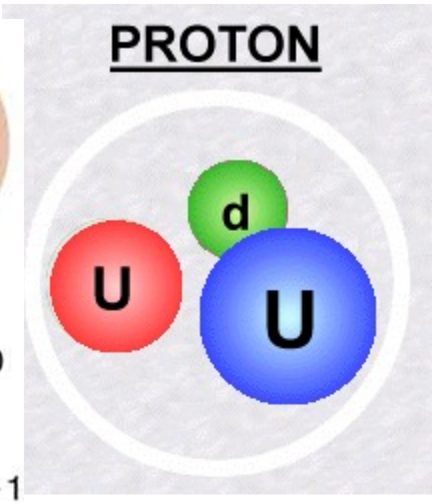
- Consequences:
  - Very short range force
  - Force gets stronger when quarks pulled apart
  - Only see color-neutral free particles in Nature (quark confinement)

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)

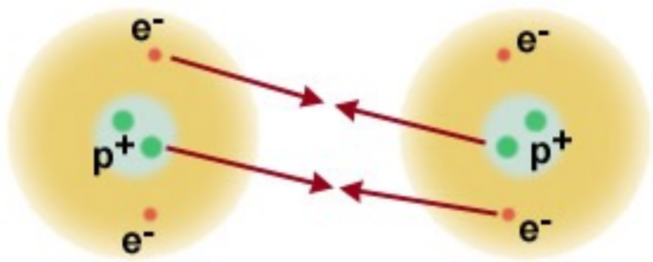
} Hadrons

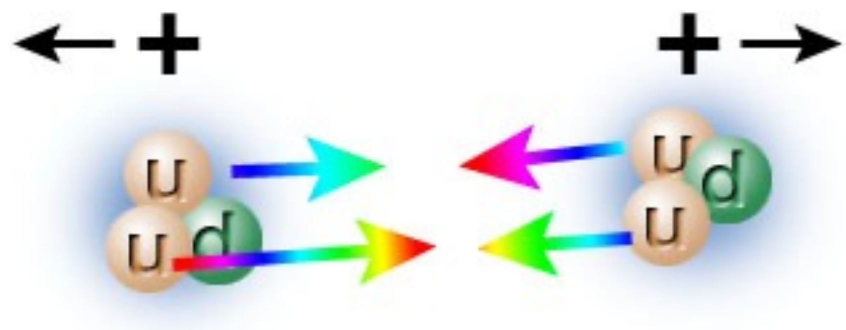




QCD → Strong nuclear force

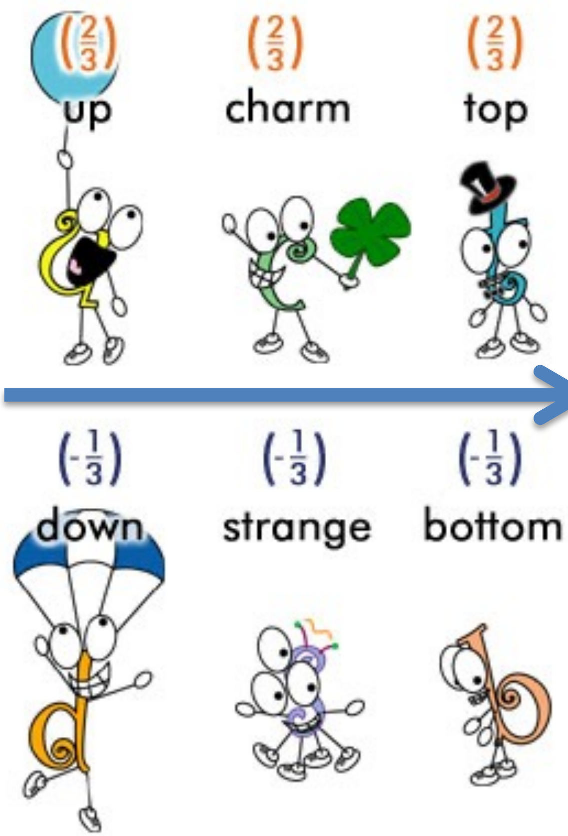
- Protons and neutrons bound in nucleus by residual force between quarks, same as atoms in molecules





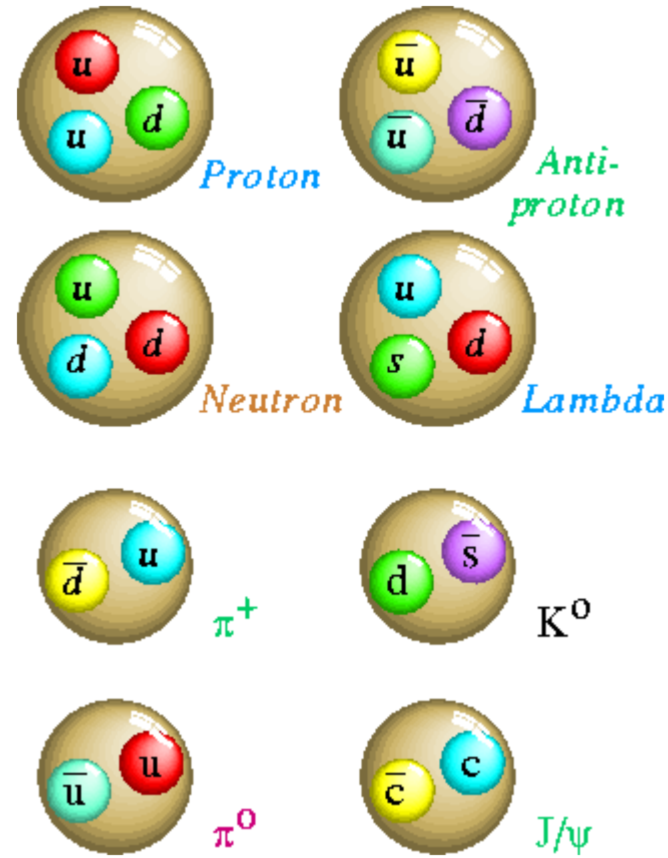
How many different quarks?

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



Light → Heavy

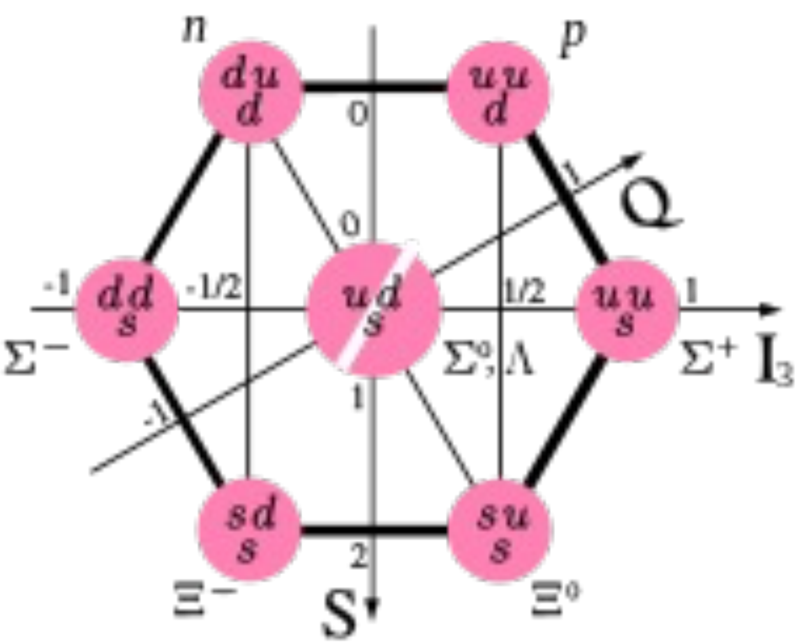
Stable → Unstable

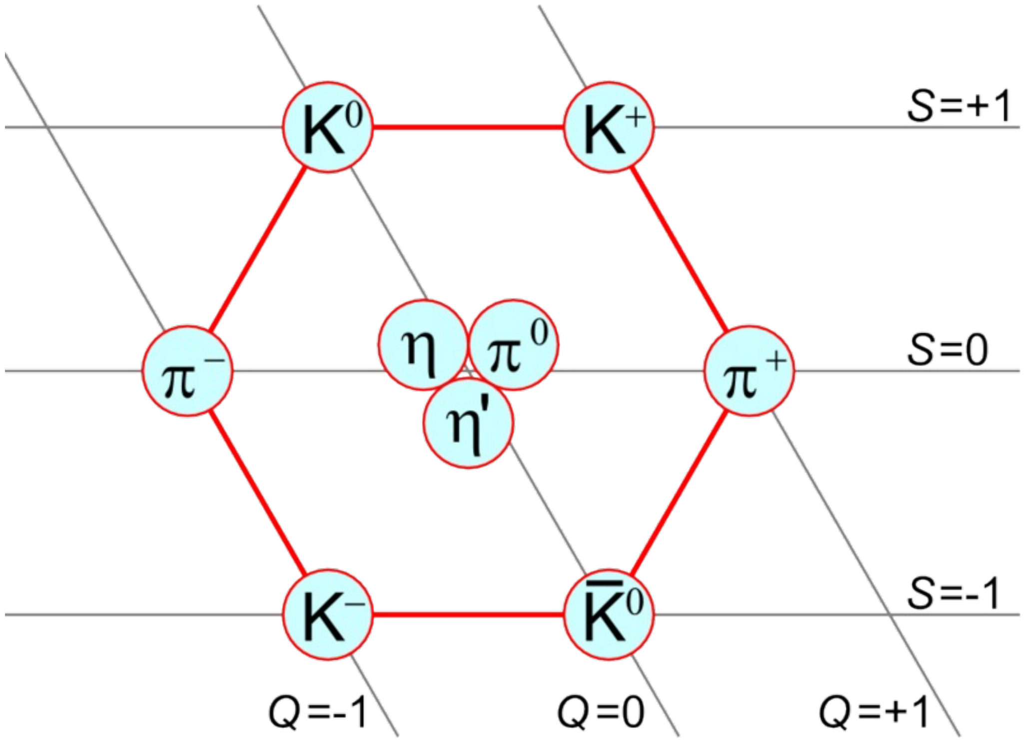


- A few important mesons: pions, kaons (s quark), D (c quark), B(b quark)

Symmetries

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

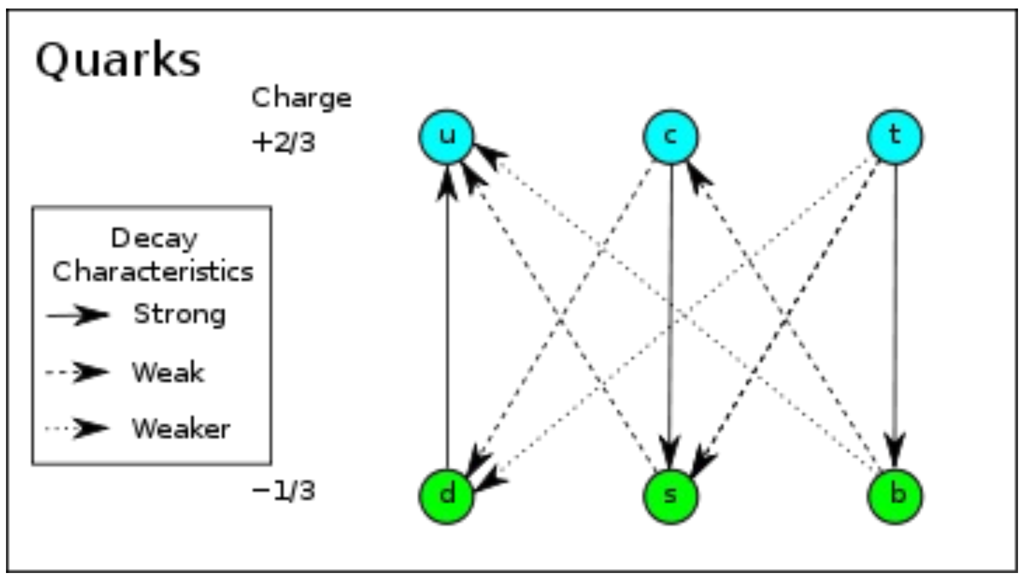




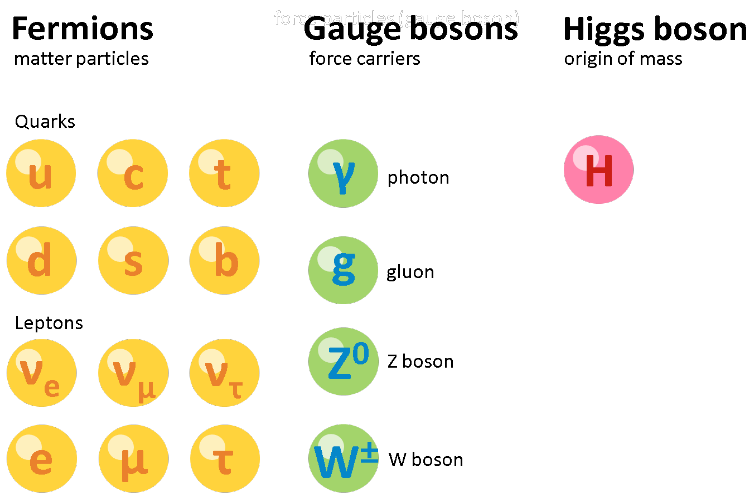
Heavy flavours

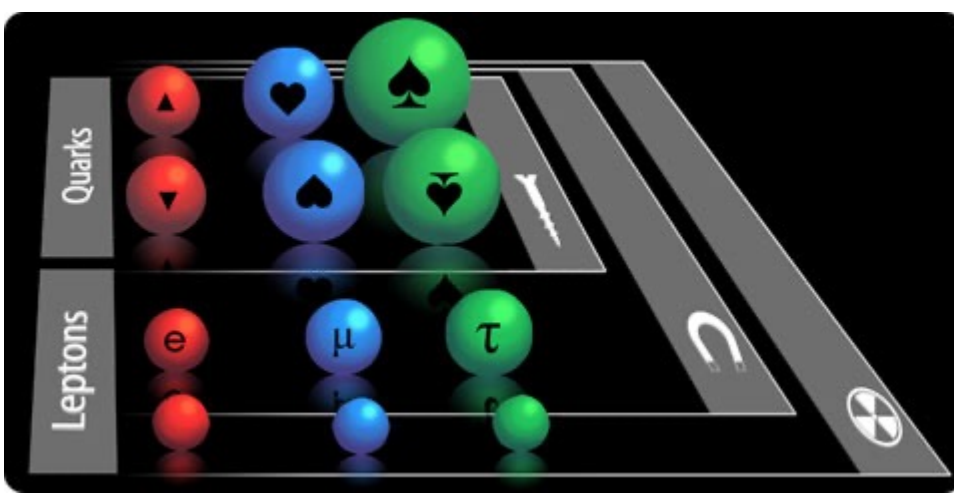
- Heavy quarks unstable… How? Up to now, always creating/annihilating pairs of particle-antiparticle of same type
- *Weak force:*

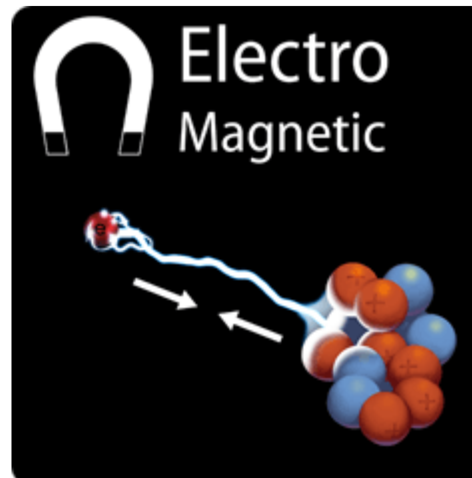
  induces decays of unstable elementary particles

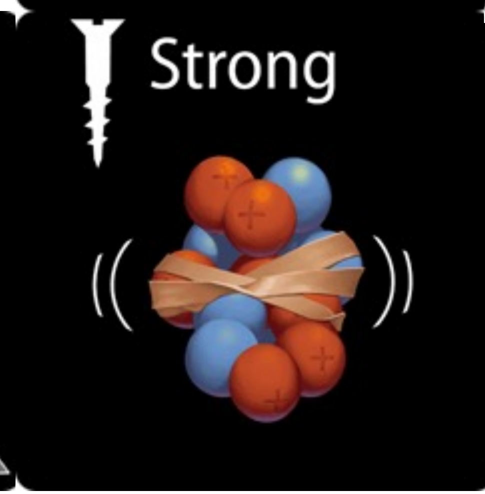


The Standard Model: elementary particles and their interactions



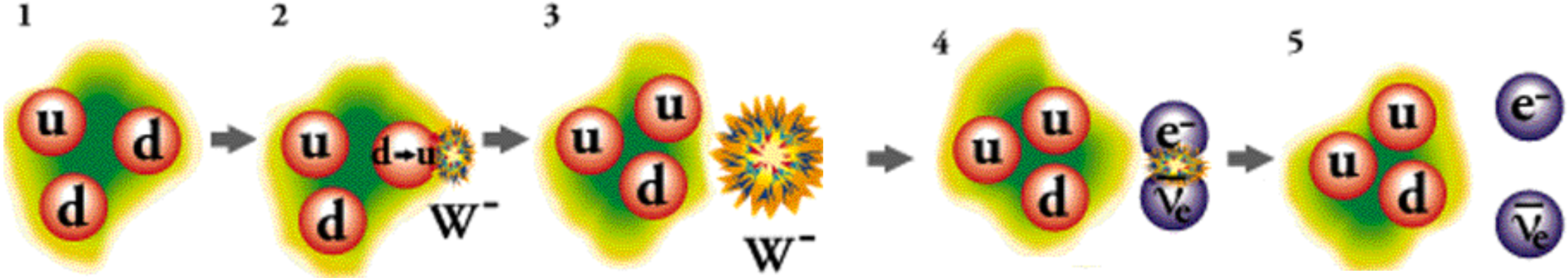






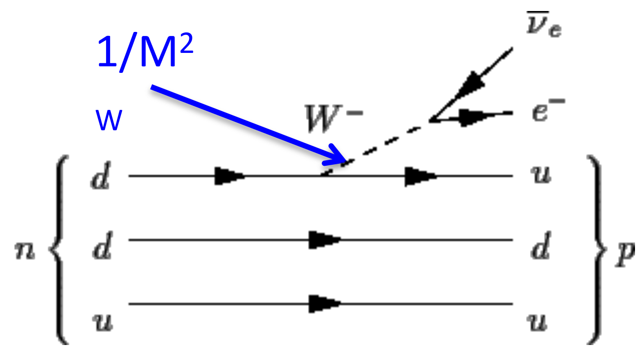
Weak Force

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



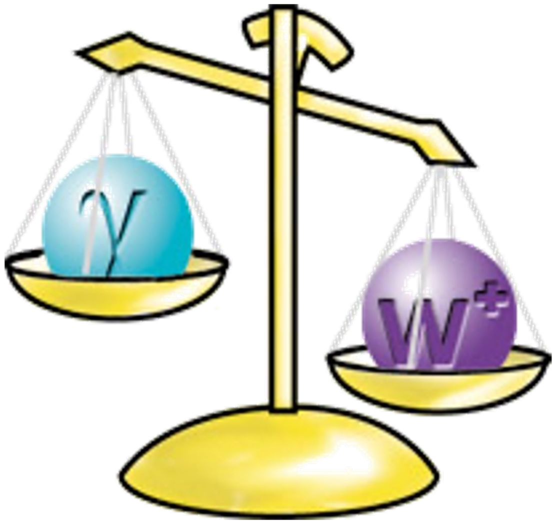
- Weak force responsible for decays of unstable elementary particles
- Mediated by Z^0 and $W^{\pm}$ bosons
- Contrary to photons and gluons, Z^0 and $W^{\pm}$ have non-zero masses
- Propagators proportional to $1/M^2_Z$, $1/M^2_W$

  ➔ Weak Force very weak!



Why are Z and W so heavy?

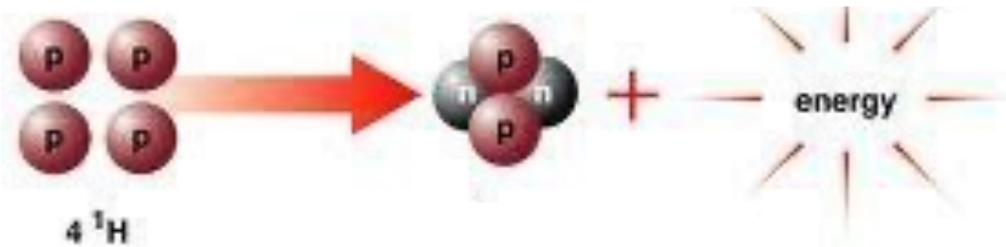
- Z and W are 100 and 85 times heavier than proton
- But photons and gluons massless!

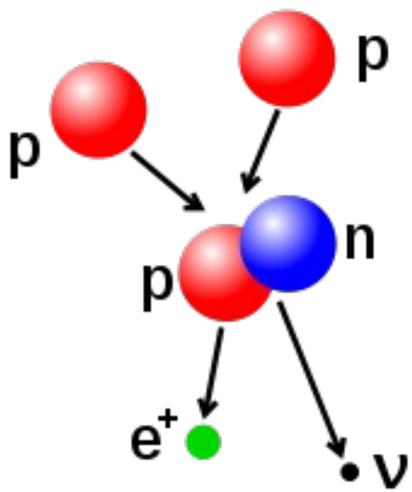


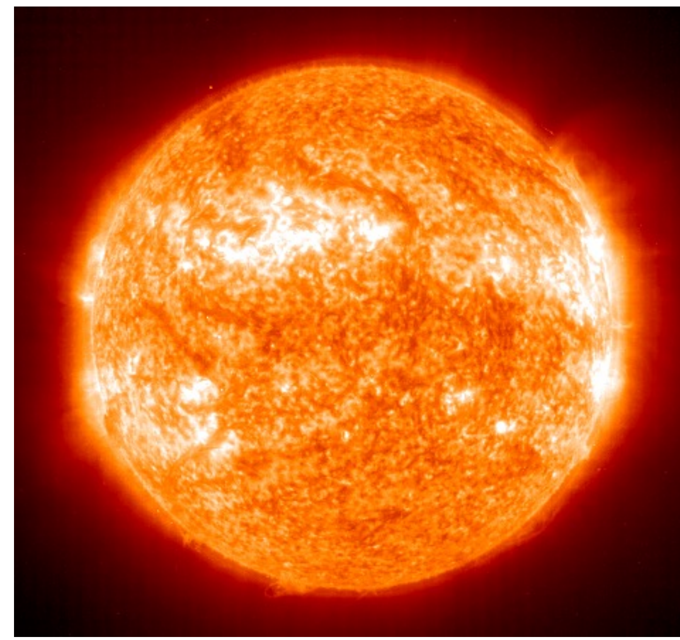
- It's the Higgs boson's fault!

Weak Force

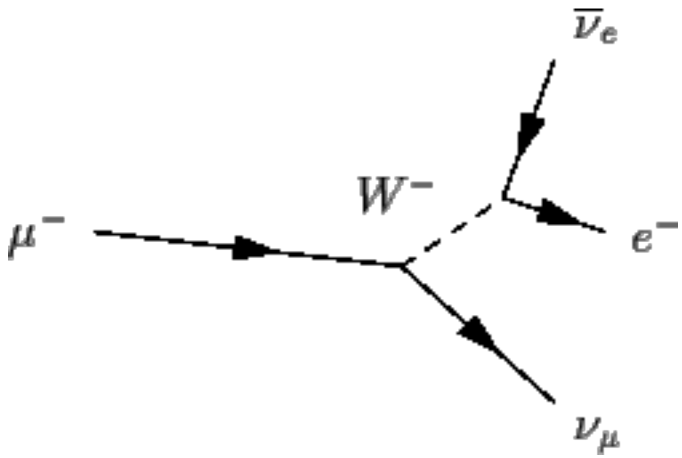
- Governs rate of energy production in the sun (inverse beta decay a step in fusion process)

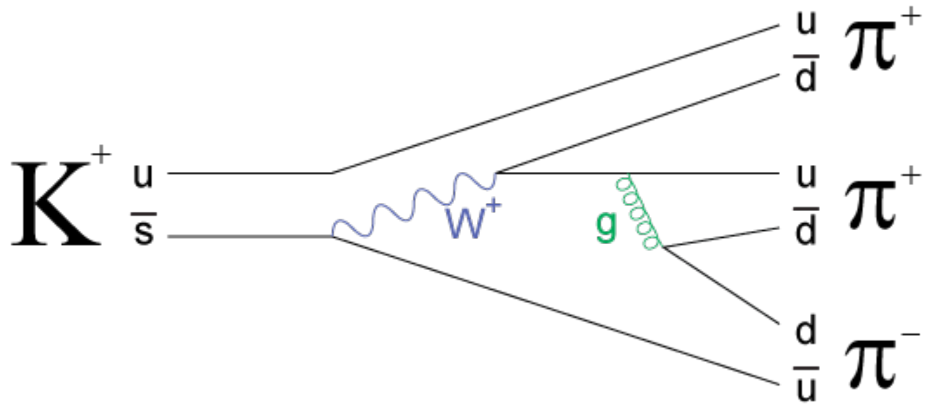


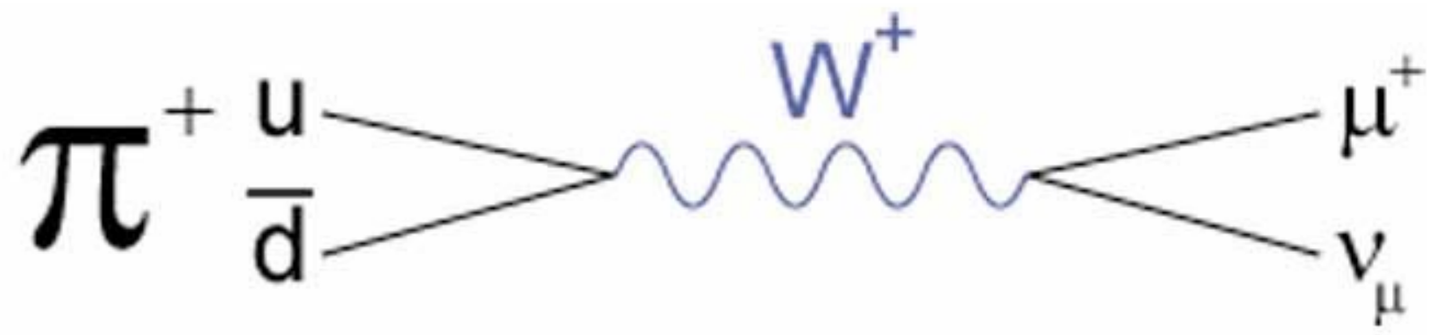




Weak Force: other examples







Pion decay: important way of making neutrinos

Neutrinos?

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

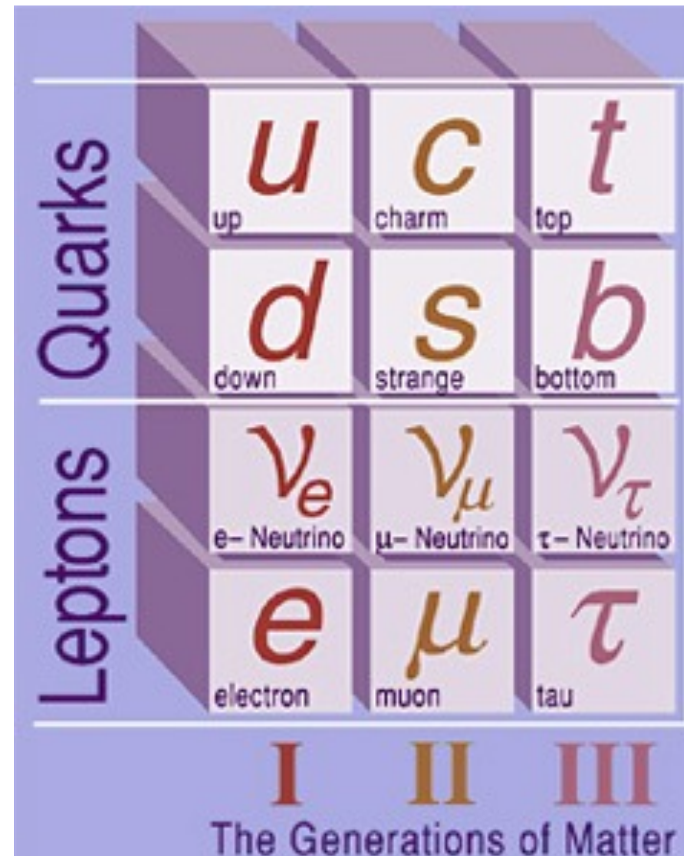
Three families or generations

- 3 times the u, d quark couple, except heavier and less stable
- Same story about leptons:

muon is just an unstable, heavy electron

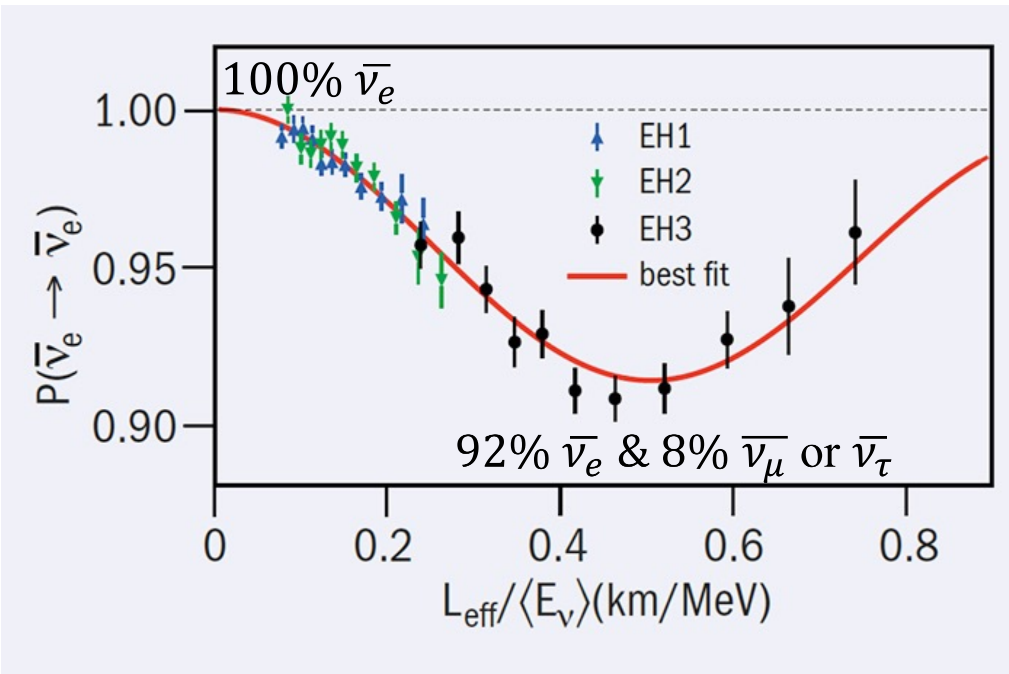
- Columns of table are called *generations (flavour)*

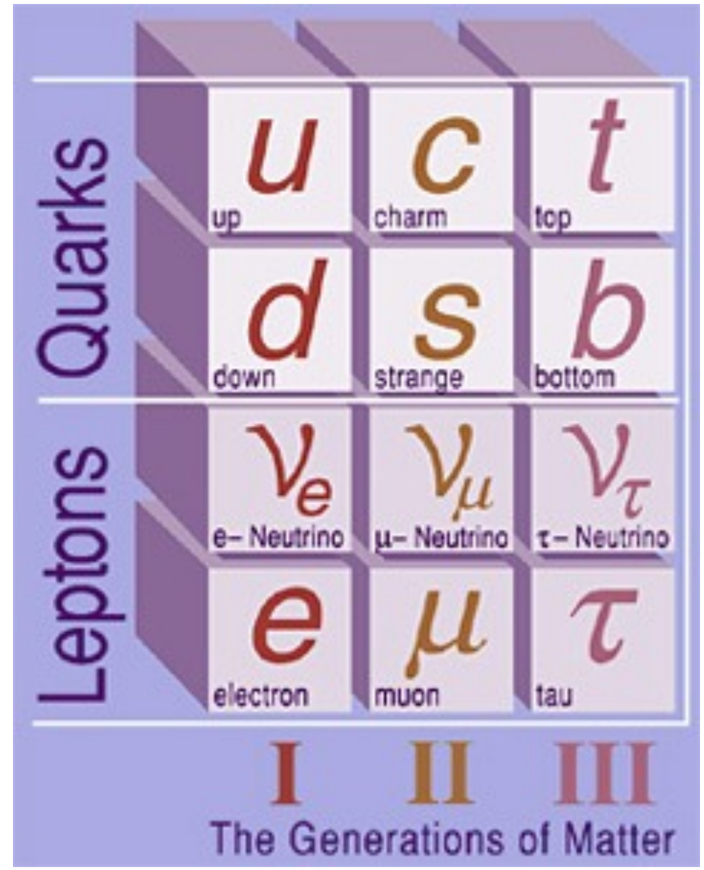
- Why more than one? Why three?



Neutrinos oscillate!

- During propagation, neutrinos can change type. Ex:

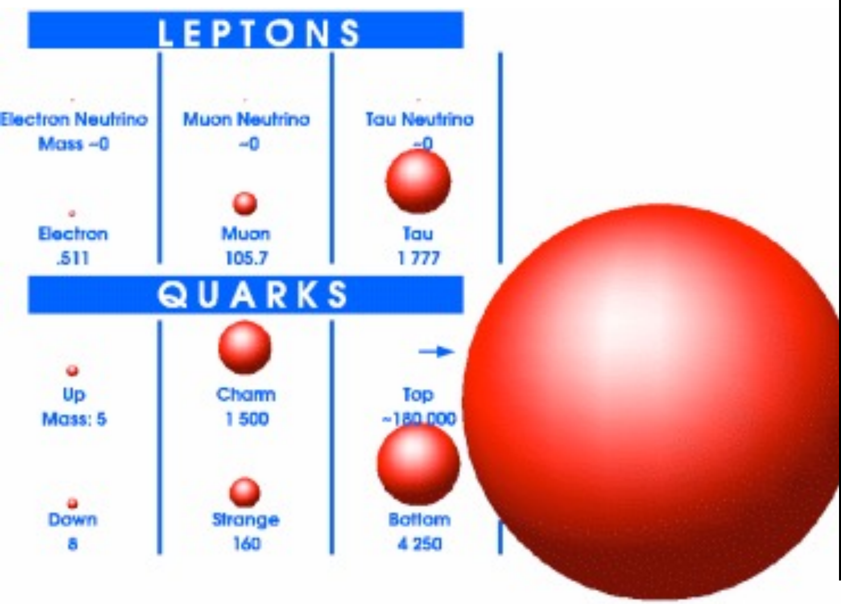


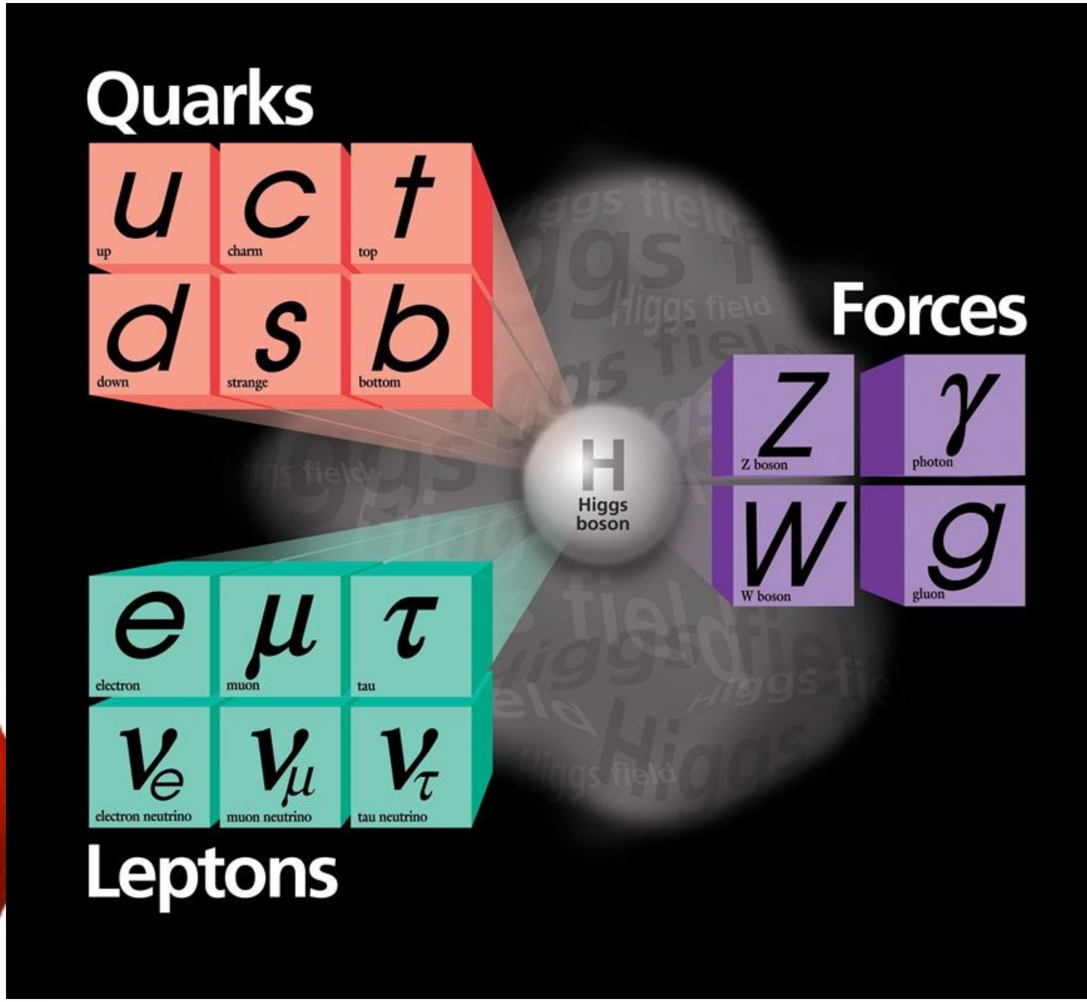


- Complex interplay between mass and flavour

The Standard Model

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

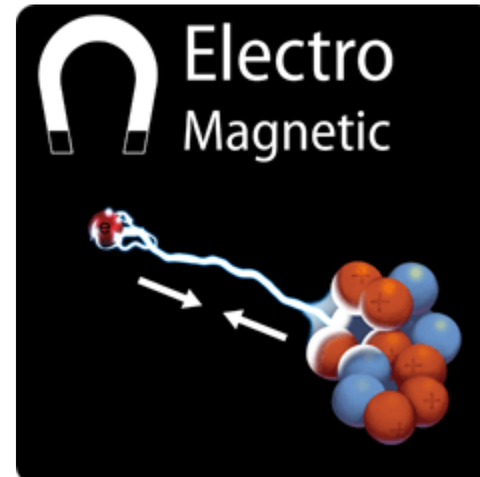


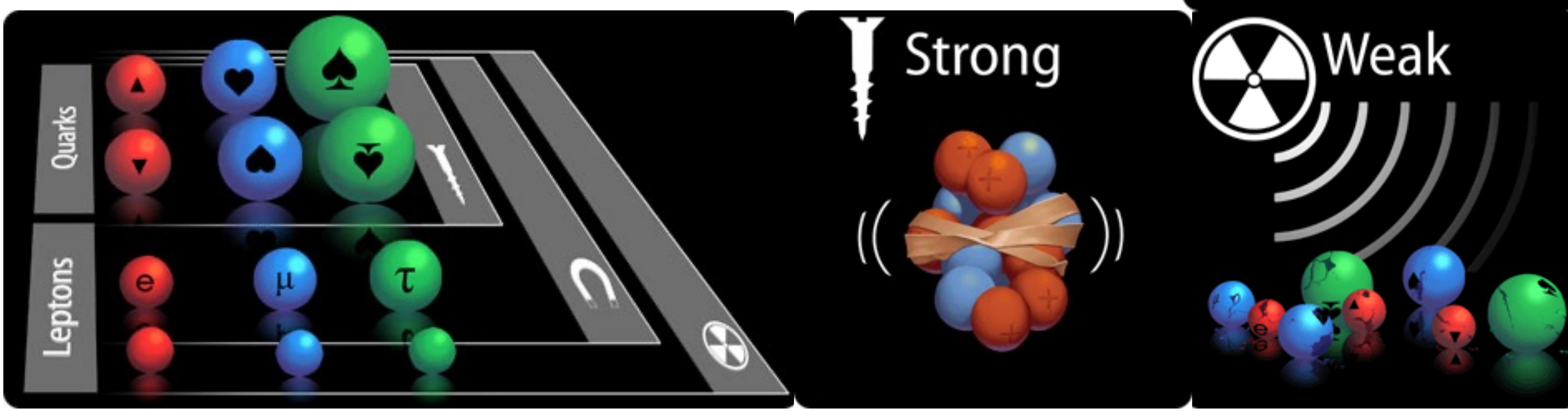


Summary

- Much learnt, but also plenty of open questions!
- Electromagnetism, γ: all particles except ν's
- Strong force, gluon: only quarks
- Weak force, $W^{\pm}$ et Z: all particles
- First look at Feynman diagrams, Dirac's eq,

C & P symmetries, gauge theories…





Optional reading

- If you want to go further, some suggestions:
  - Introduction to Elementary Particles, David Griffiths (chapters 1, 2, 3, 6)
  - Modern Particle Physics, Mark Thomson (chapters 1, 2, 3)
  - Quarks & Leptons, F. Halzen & A. D. Martin (chapters 1, 3, 4)
  - Eric Pilon's 2013 GraSPA lecture writeup

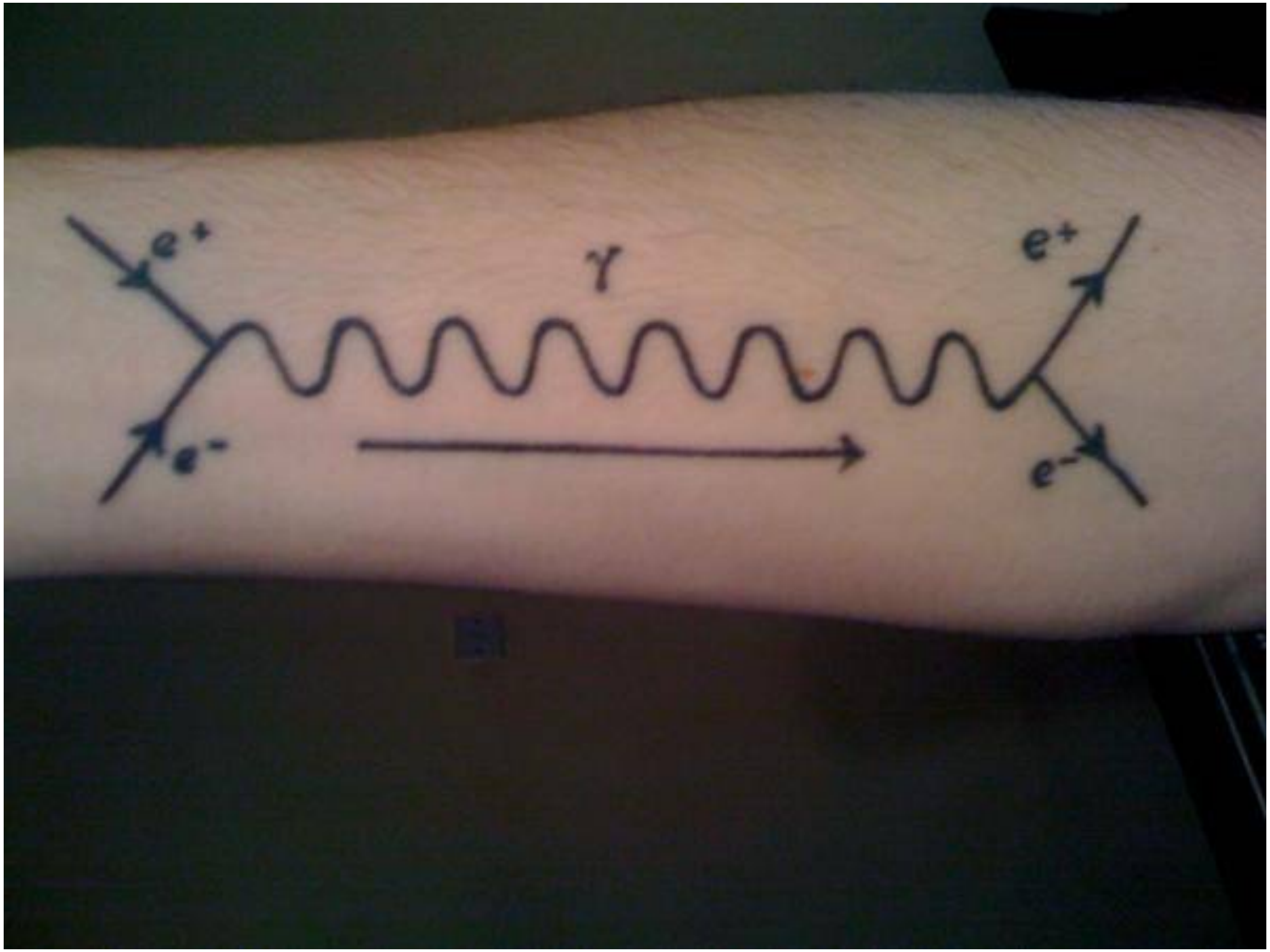

HE PILLADO "INFRAGANTI" A PROTÓN Y ELECTRÓN BESÁNDOSE
VAYA FOTÓN
DaniGove
bababanga

Questions?

Exercice:

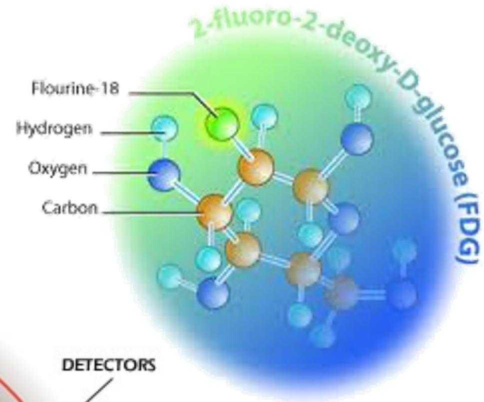
Compute a neutrino's time of flight t over a distance L. Assume the neutrino is relativistic. Taylor expand to first order in $(m_\nu/E_\nu)^2$.

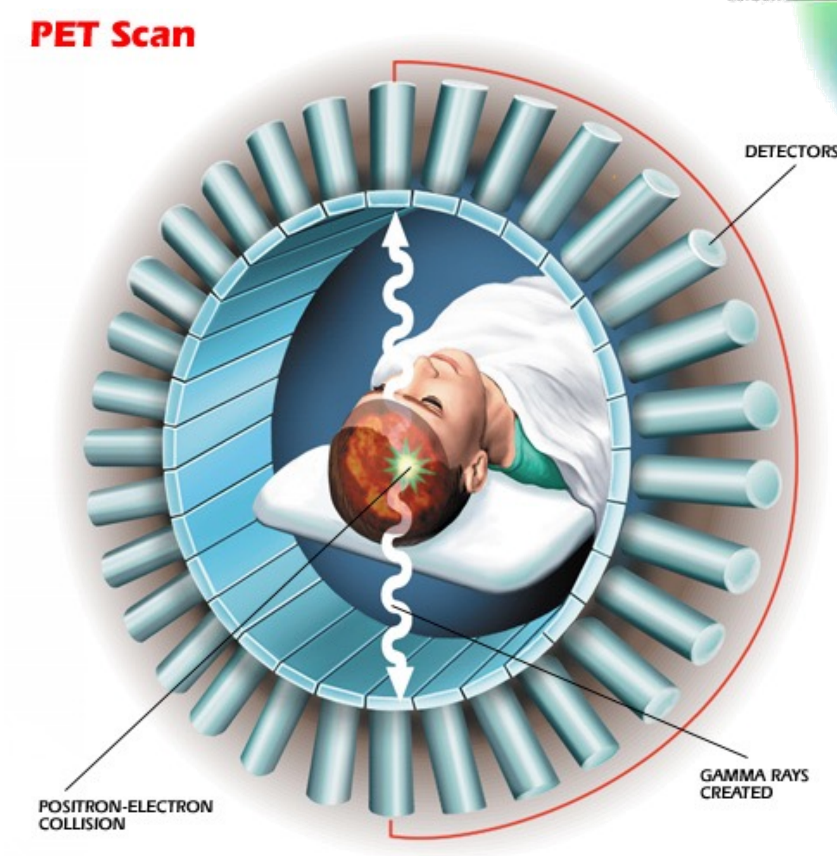
What would be the time difference between two neutrinos of different energies? If the detectors can measure the time with a precision of ∼10ns, what is the value of L to be sensitive to m_ν∼0.1 eV? Can you think of such a source?

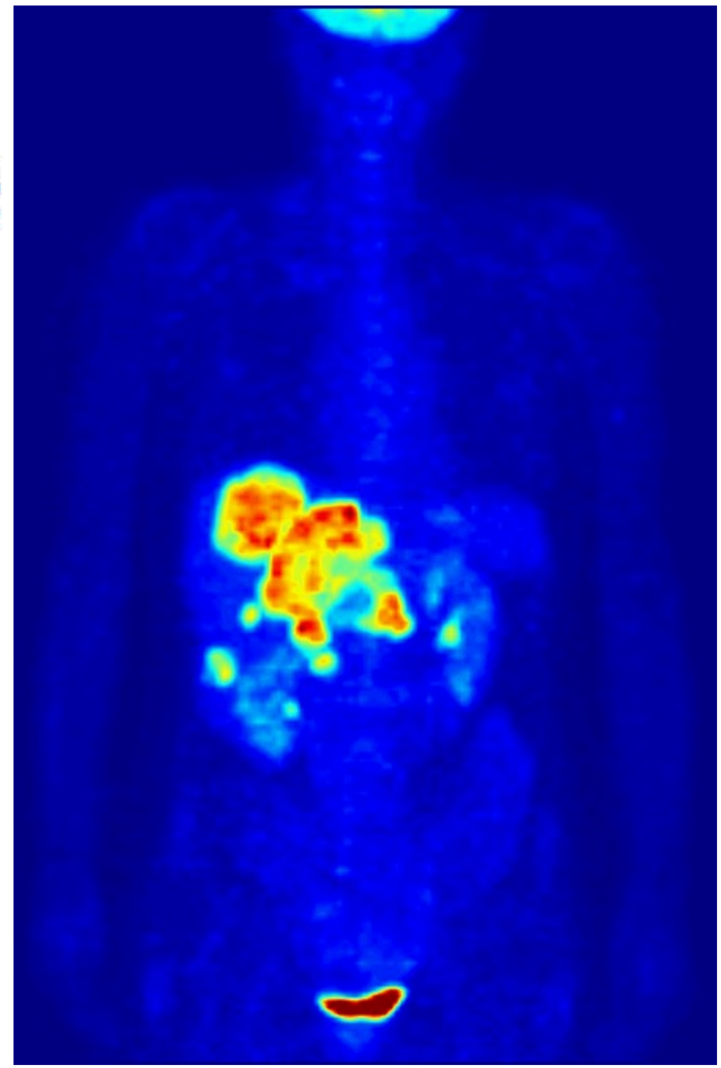

e+
γ
e+
e⁻
e⁻

Applications

Positron emission tomography (PET)

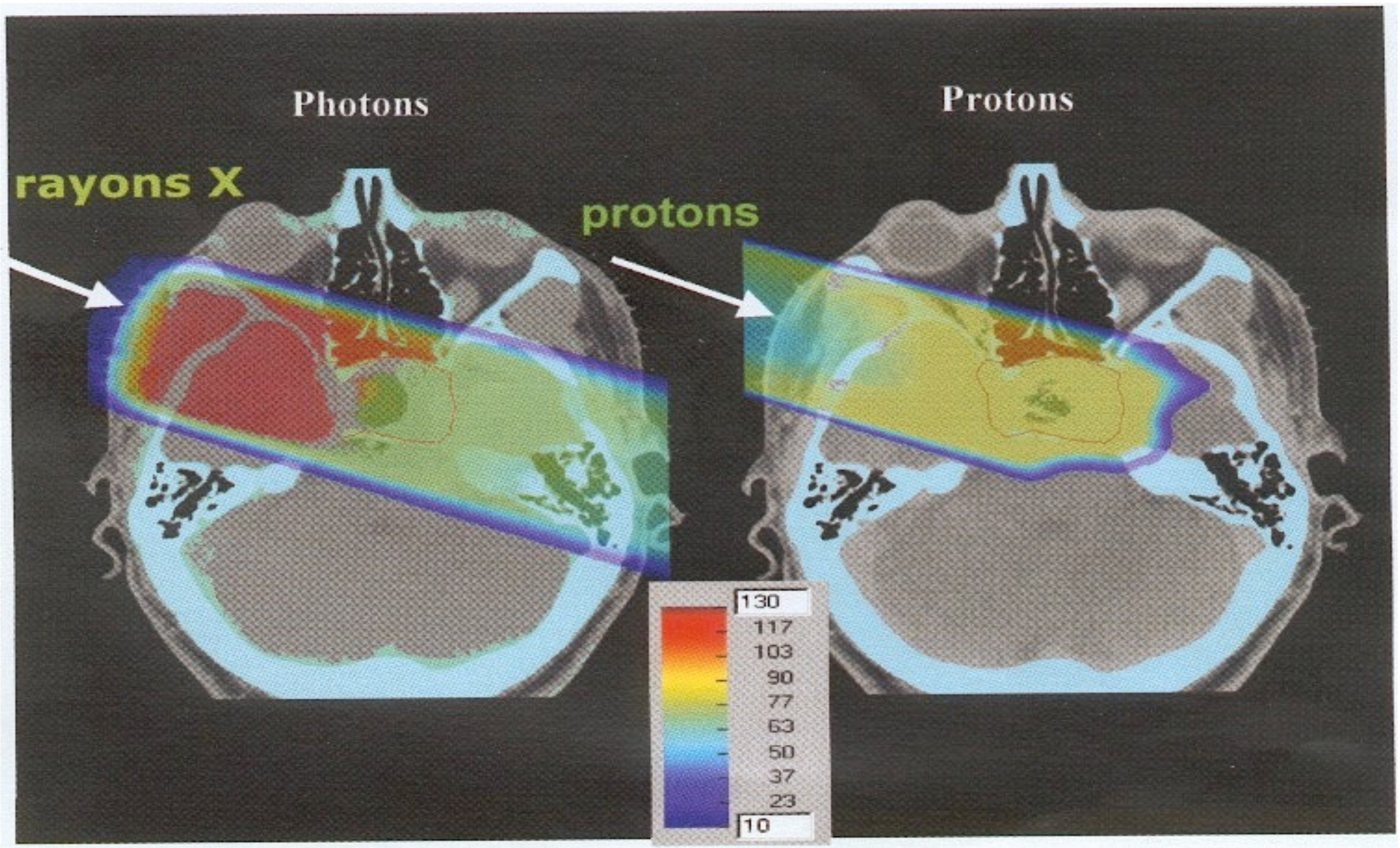






Applications

- Radiothérapie



Applications

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