

Particle Physics

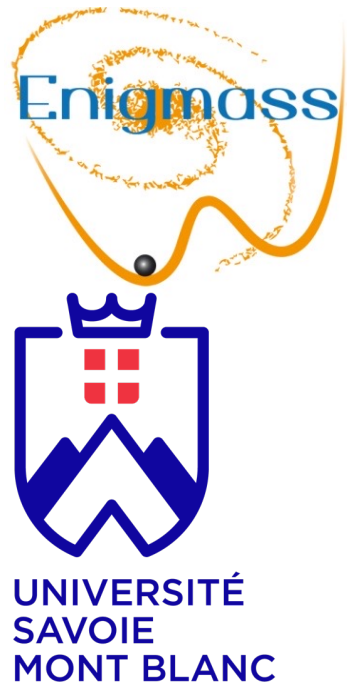
FOR



DUMMIES

Introducing Particle Physics

Pablo del Amo Sánchez

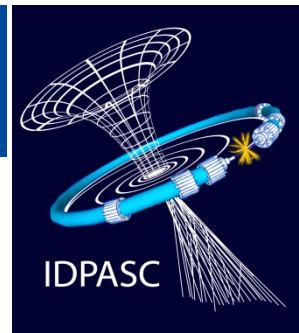


IN2P3
Les deux infinis



Communauté

UNIVERSITÉ Grenoble Alpes



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

Fermions matter particles

Quarks



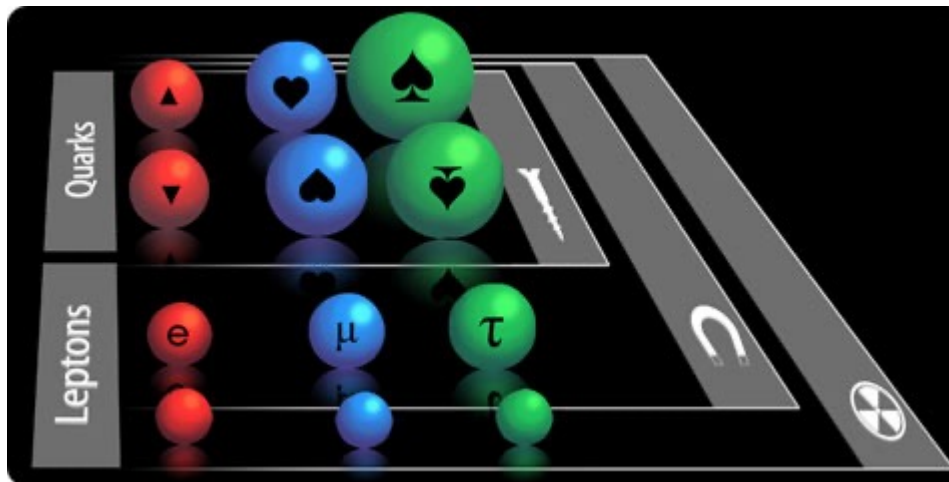
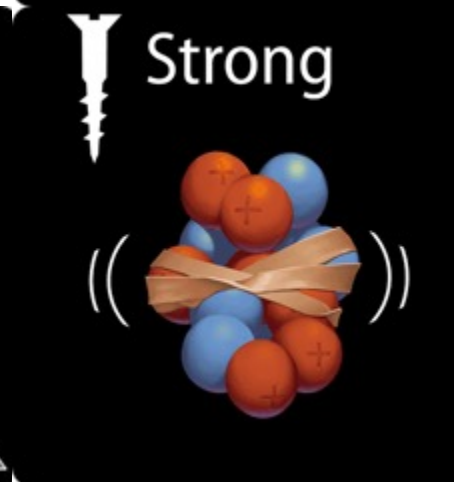
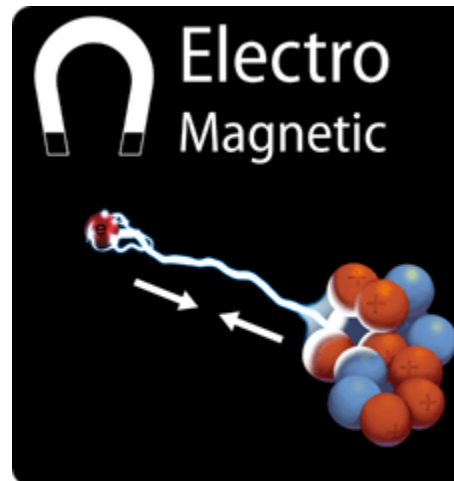
Leptons



Gauge bosons force carriers

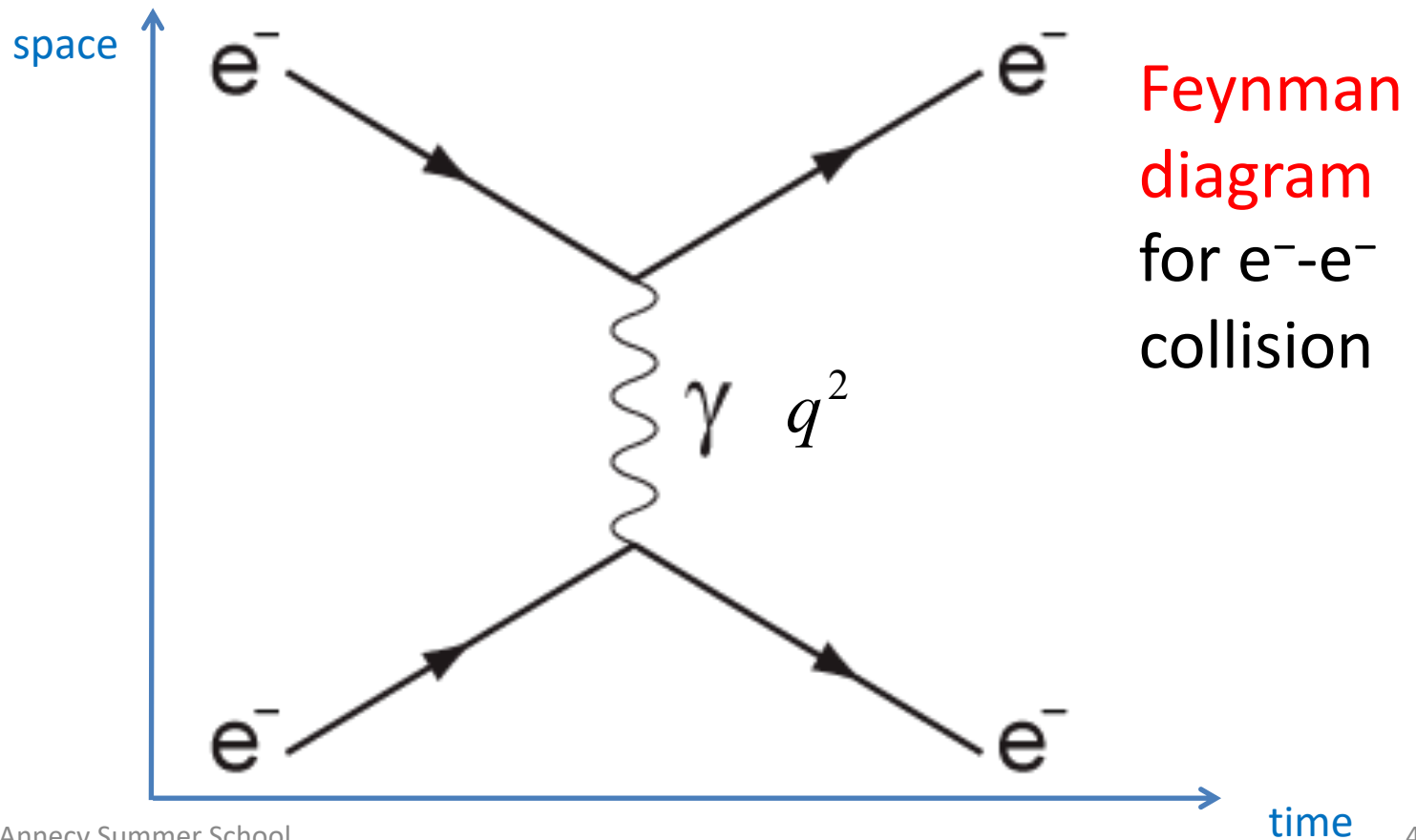


Higgs boson origin of mass



Example of EM interaction

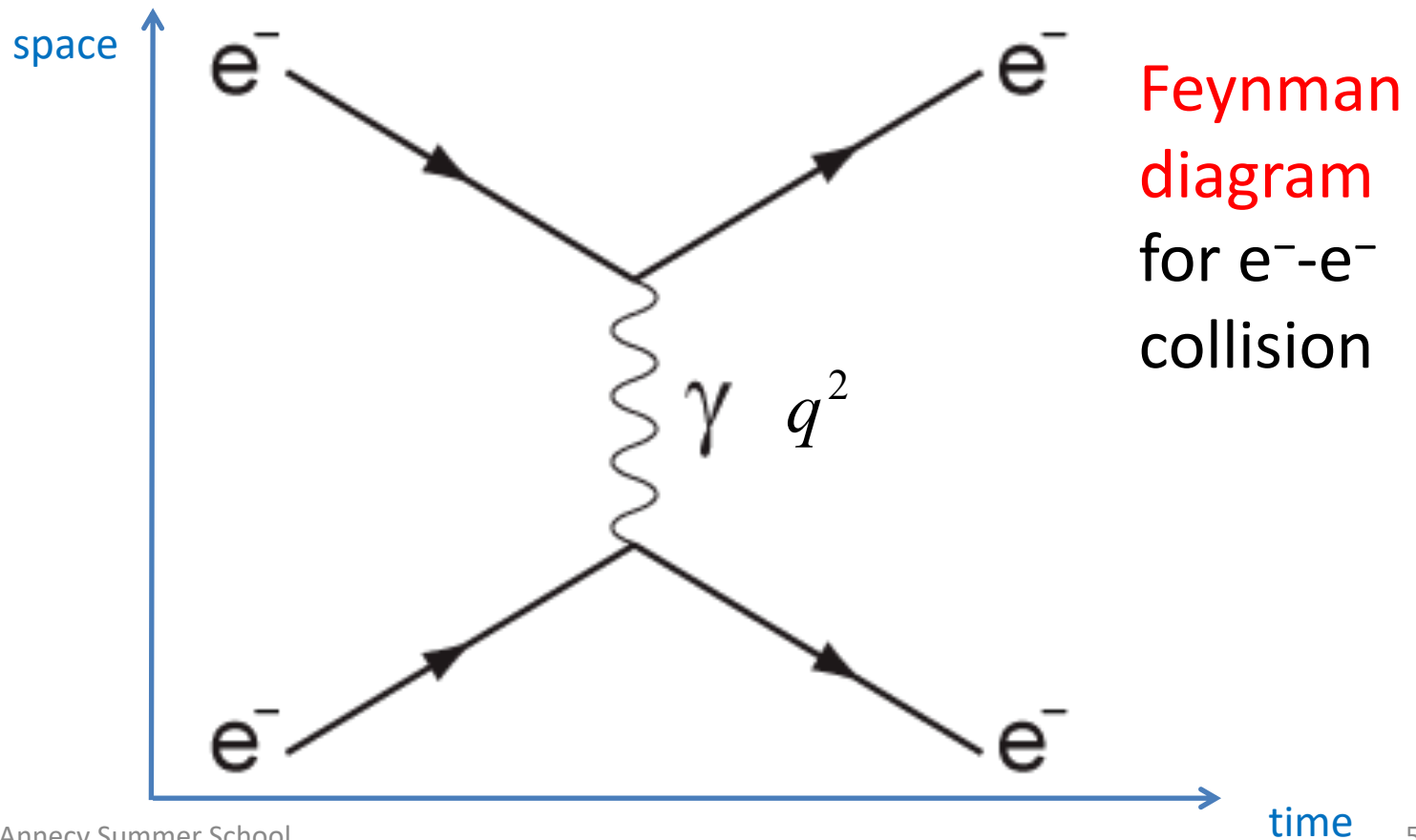
e^- - e^- collision, transferring momentum q by exchange of photon, quanta of EM field



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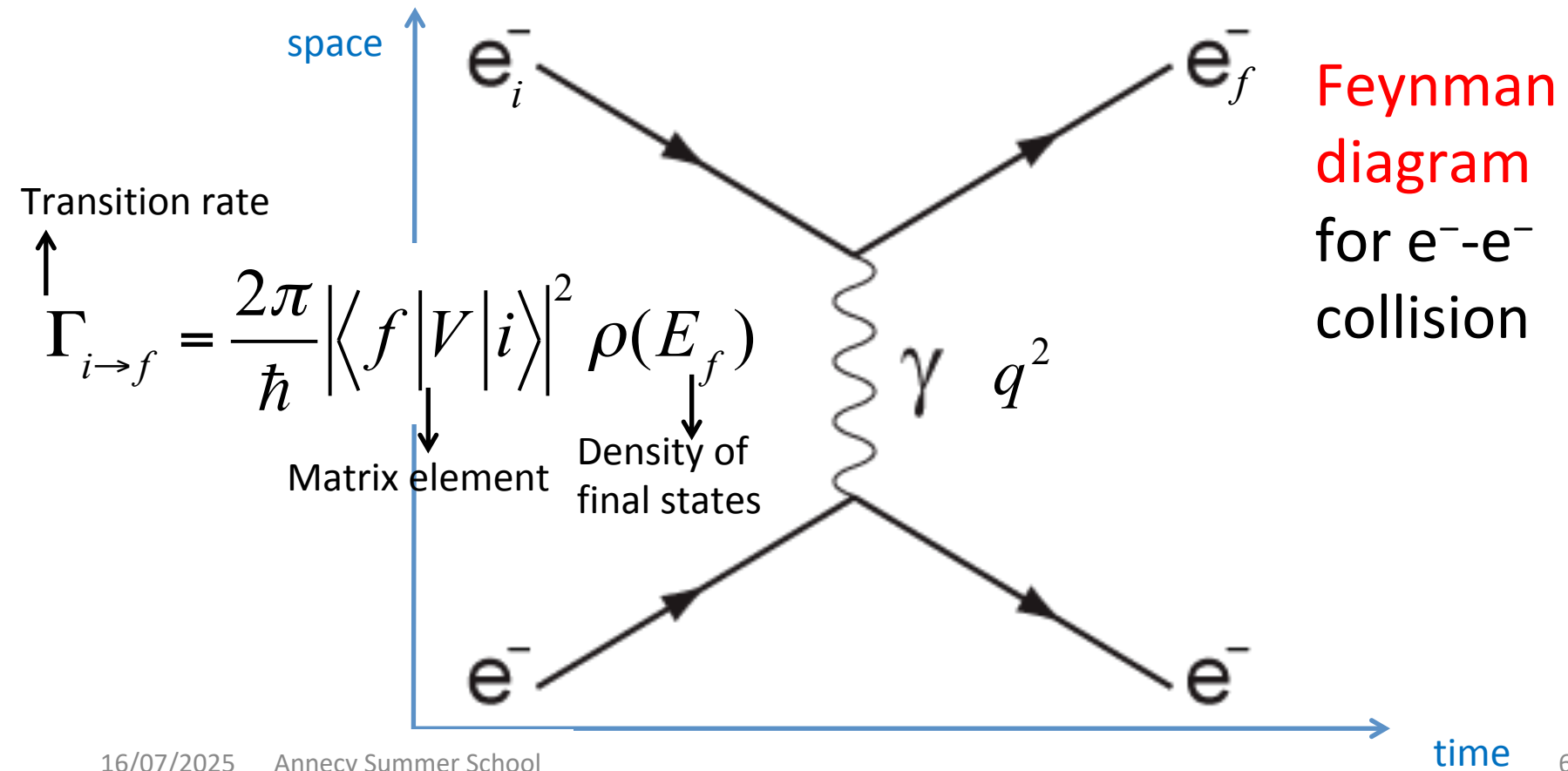
Feynman diagrams are calculational tools: will sketch computation of QM amplitude



Reminder: Fermi's Golden Rule

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

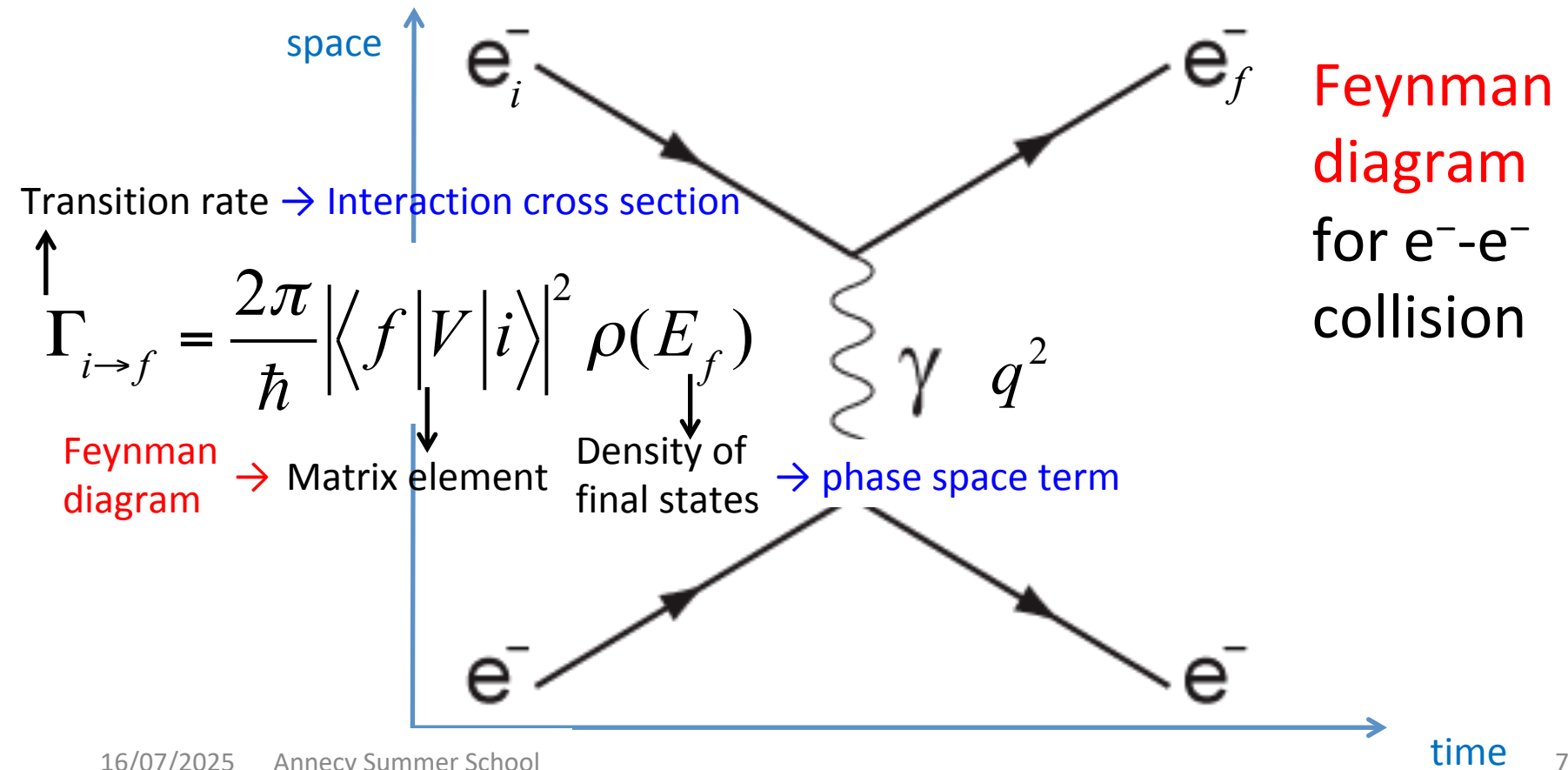
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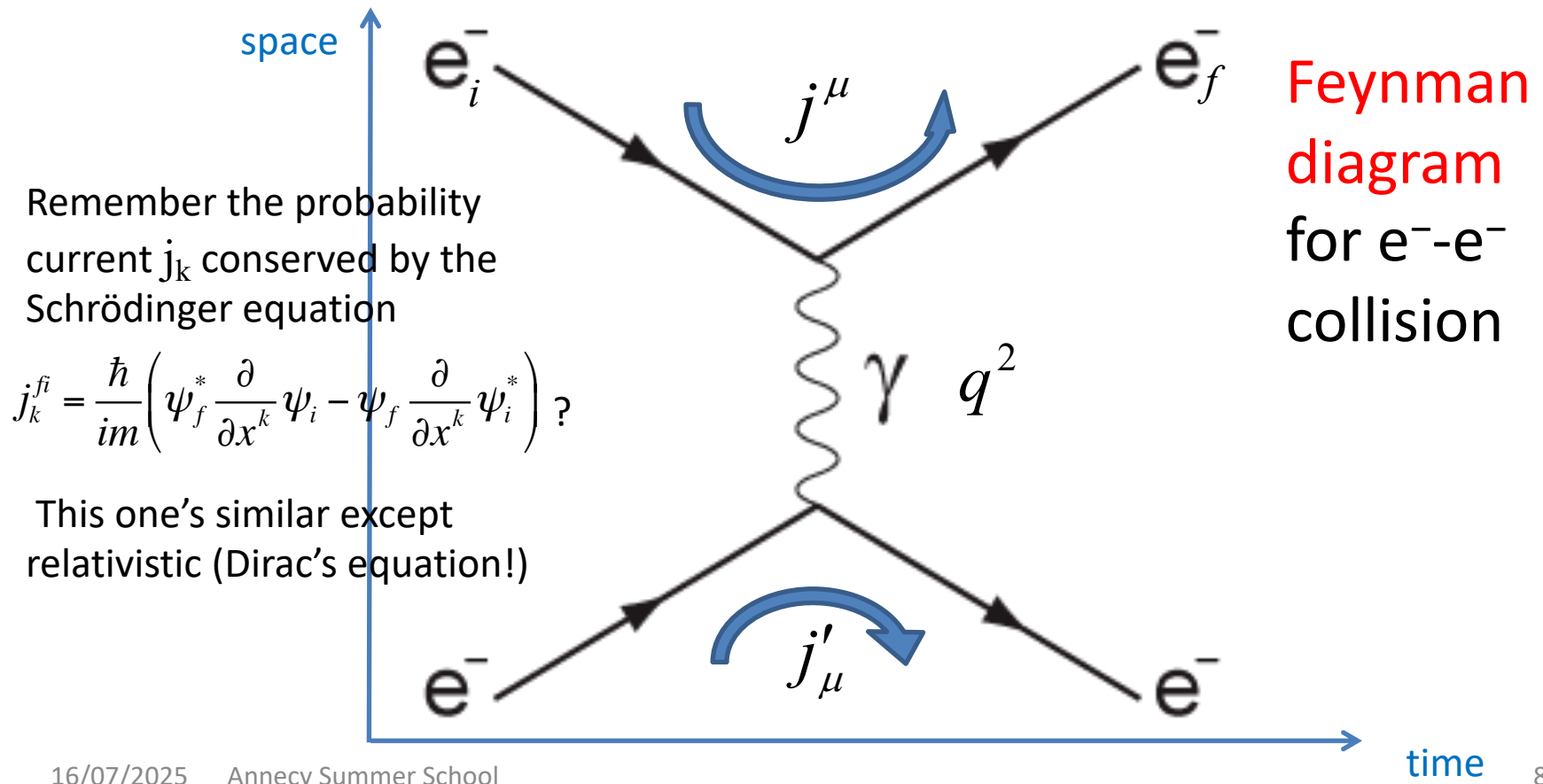
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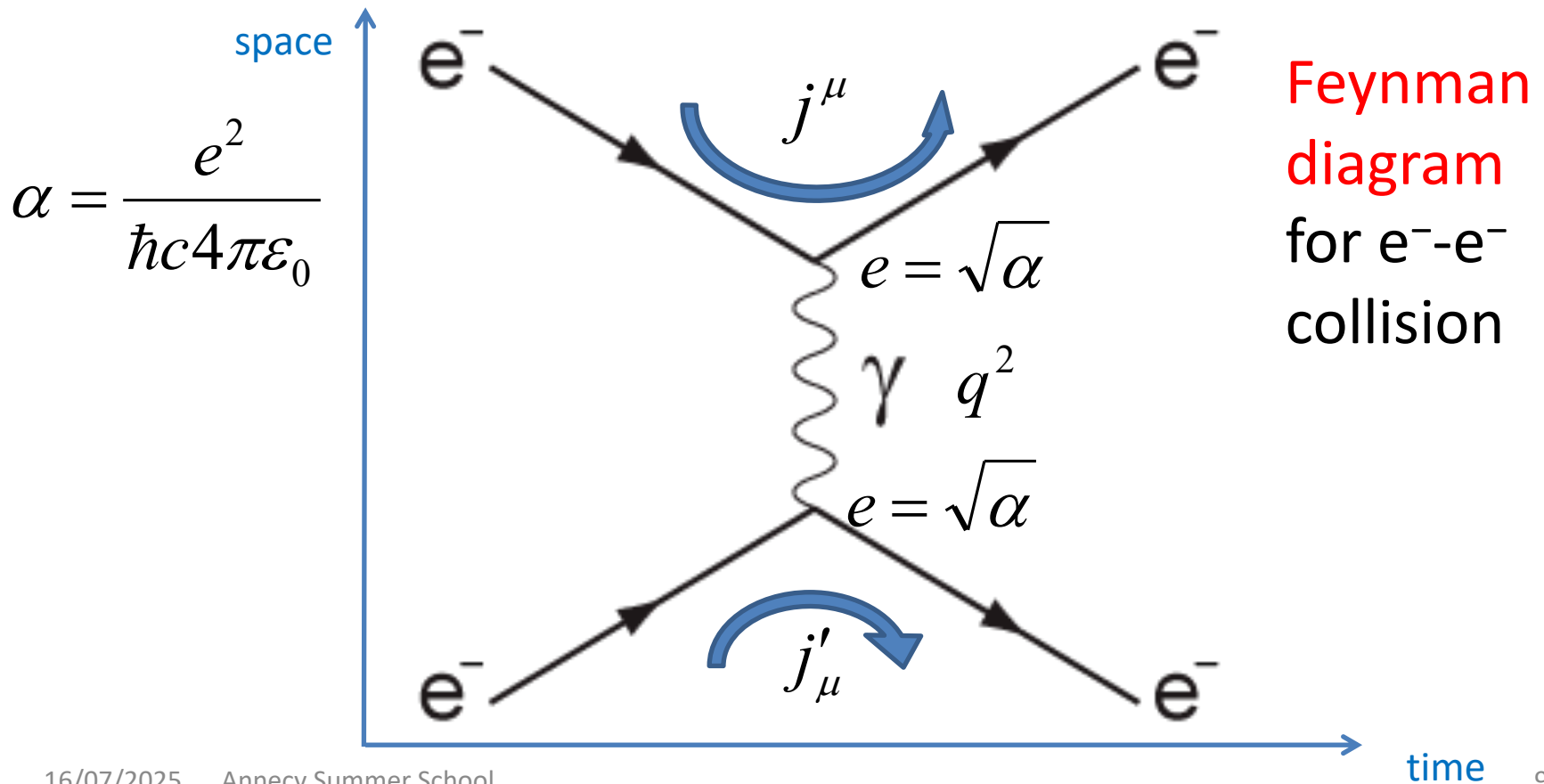
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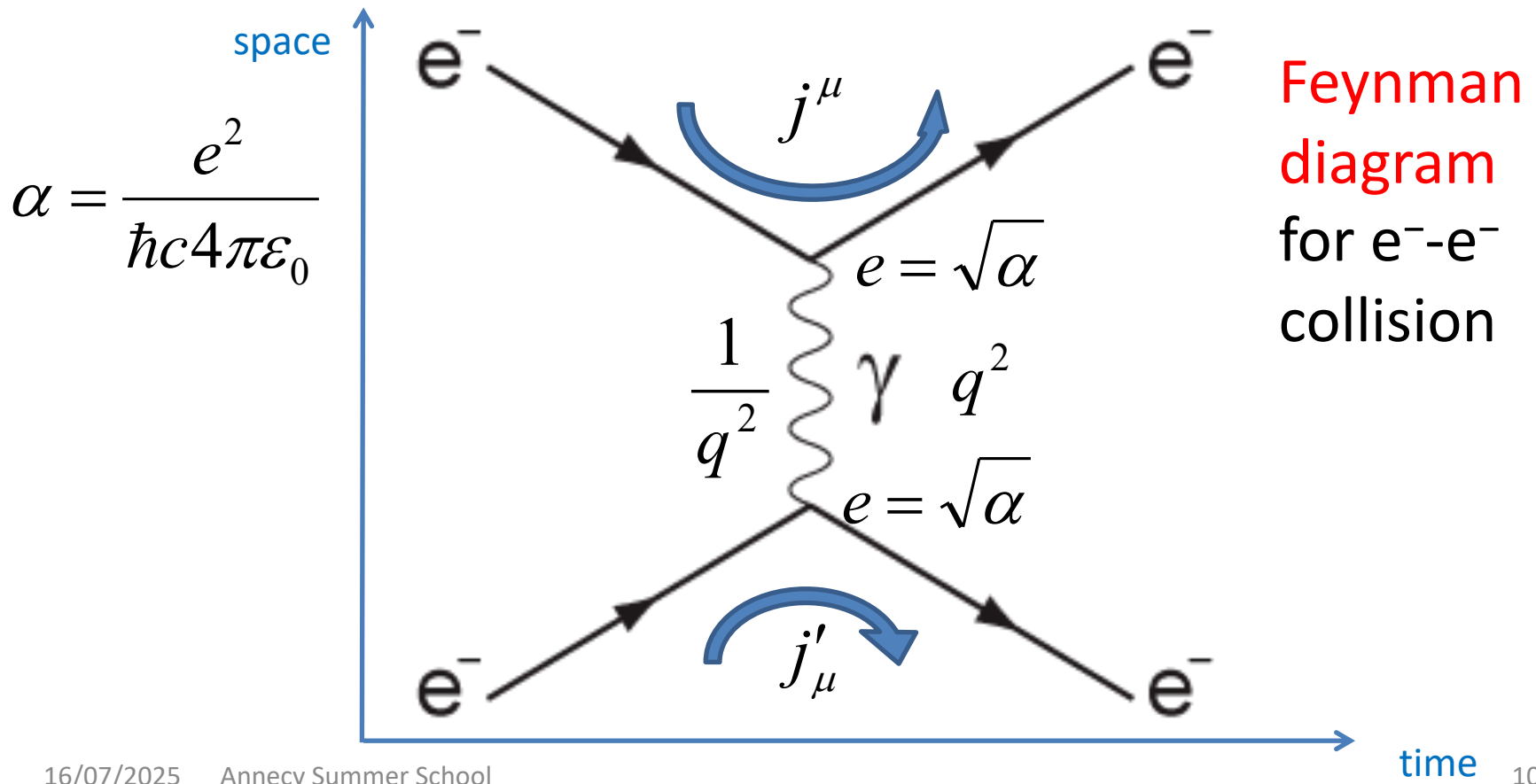
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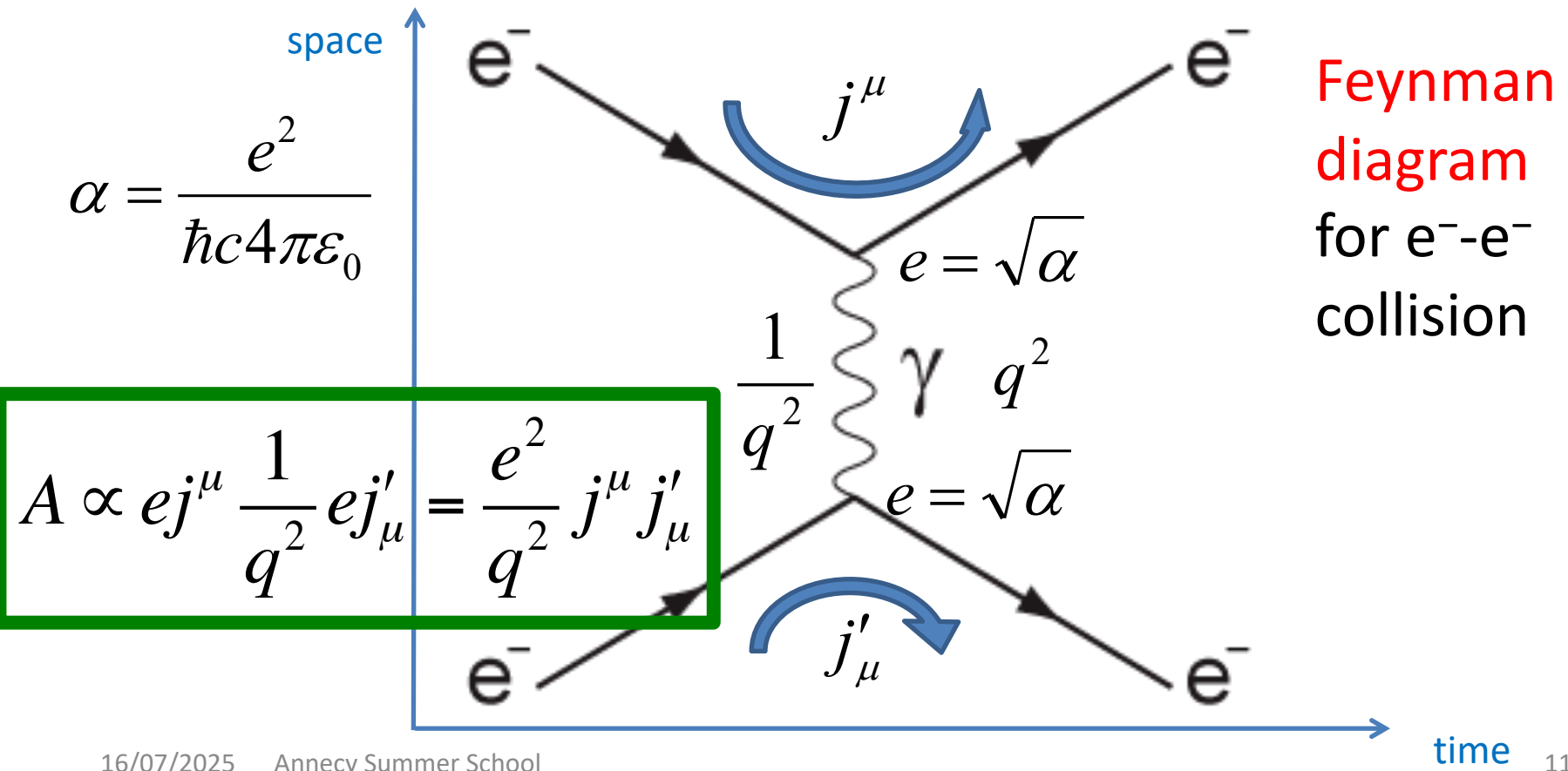
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Example of EM interaction

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

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



Photon propagator

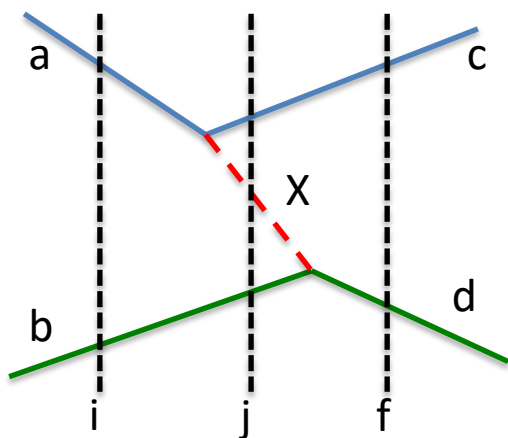
- Can derive it from standard QM time-indep. perturbation theory:

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

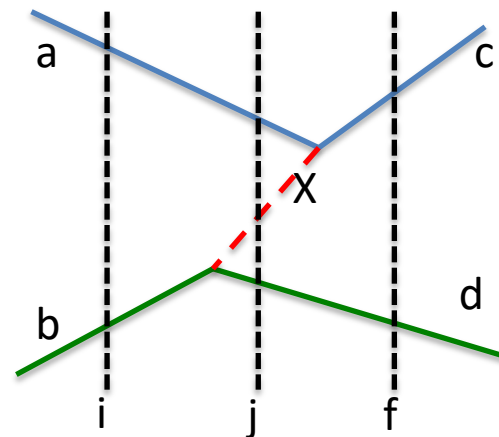
(See e.g. Halzen & Martin for a more detailed discussion)

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



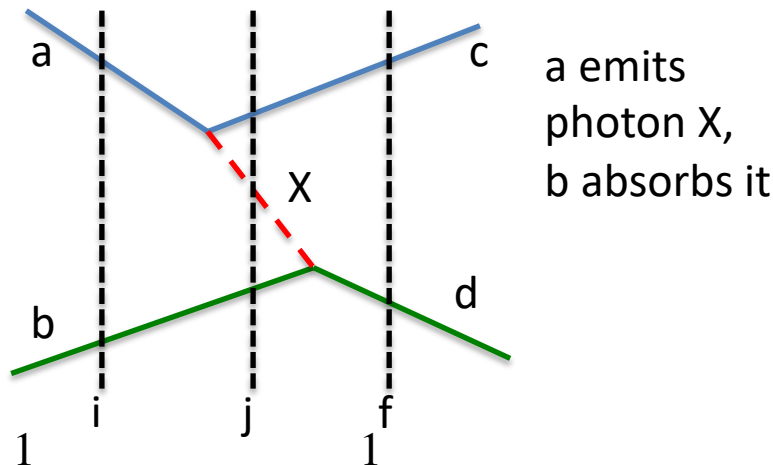
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Photon propagator

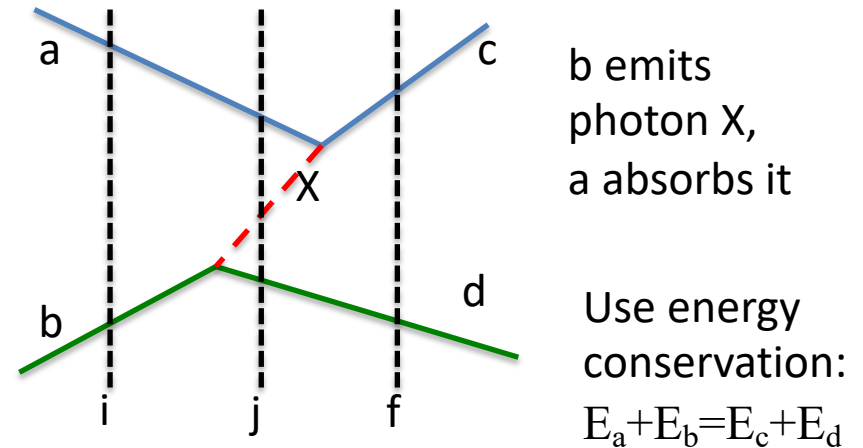
- Can derive it from standard QM time-indep. perturbation theory:

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

- Two different time orderings:



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



$$\begin{aligned} \frac{1}{E_i - E_j} &= \frac{1}{(E_a + E_b) - (E_a + E_X + E_d)} \\ &= \frac{1}{(E_b - E_d) - E_X} = \frac{-1}{(E_a - E_c) + E_X} \end{aligned}$$

Photon propagator

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

$$\begin{aligned}
 T_{fi} &= \sum_{j \neq i} \frac{\langle f|V|j\rangle \langle j|V|i\rangle}{E_i - E_j} \propto \frac{1}{(E_a - E_c) - E_X} + \frac{-1}{(E_a - E_c) + E_X} \\
 &\propto \frac{1}{(E_a - E_c)^2 - E_X^2} = \frac{1}{(E_a - E_c)^2 - (\vec{p}_a - \vec{p}_c)^2 - m_X^2} = \\
 &= \frac{1}{(p_a - p_c)^2 - m_X^2} = \frac{1}{q^2 - m_X^2} \quad \text{where } q = p_a - p_c \text{ is the} \\
 &\quad \text{transferred 4-momentum}
 \end{aligned}$$

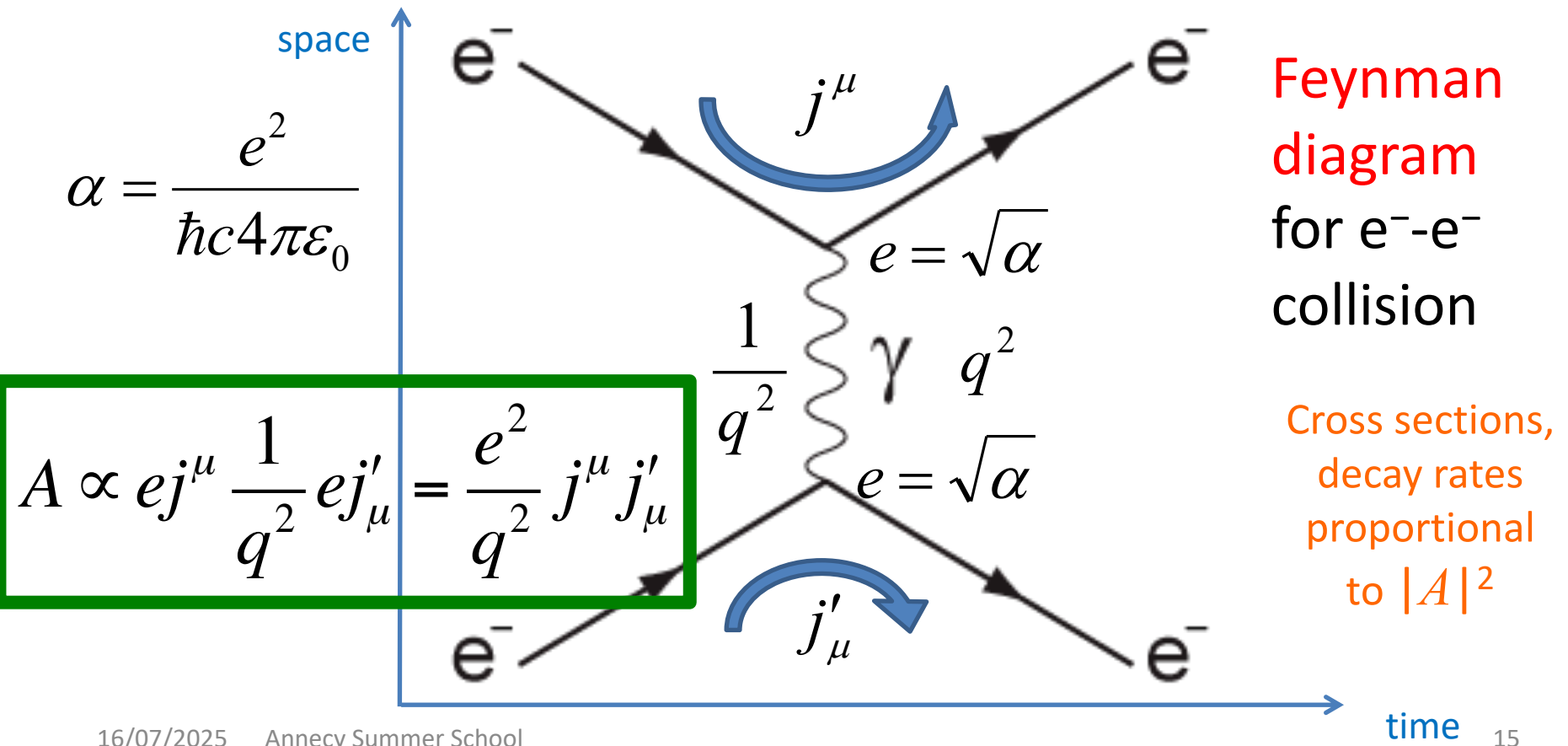
and we've used $E_X^2 = \vec{p}_X^2 + m_X^2 = (\vec{p}_a - \vec{p}_c)^2 + m_X^2$

Photons are massless, $m_X^2 = 0$ and their propagator is $1/q^2$

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



Antimatter

Star Trek's "antimatter warp drive"



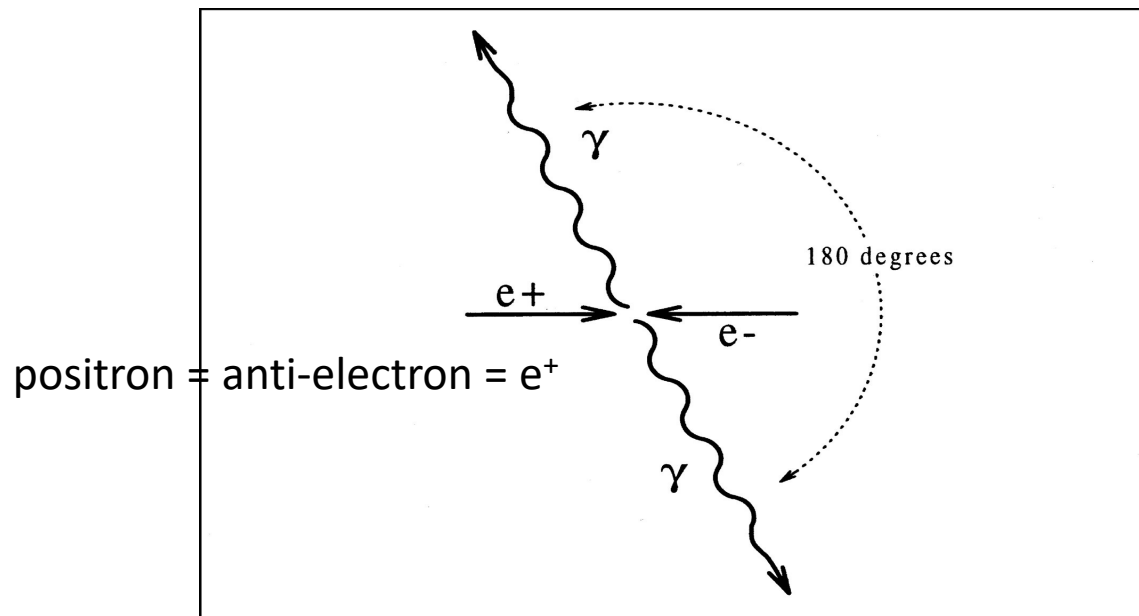
Example of EM interaction: matter-antimatter annihilation

- 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 ($E=mc^2$!)



Example of EM interaction: matter-antimatter annihilation

- **Antiparticle: same** properties (**mass, spin**) as particle, but all “**charges**” **reversed** (electric, weak force, strong force)
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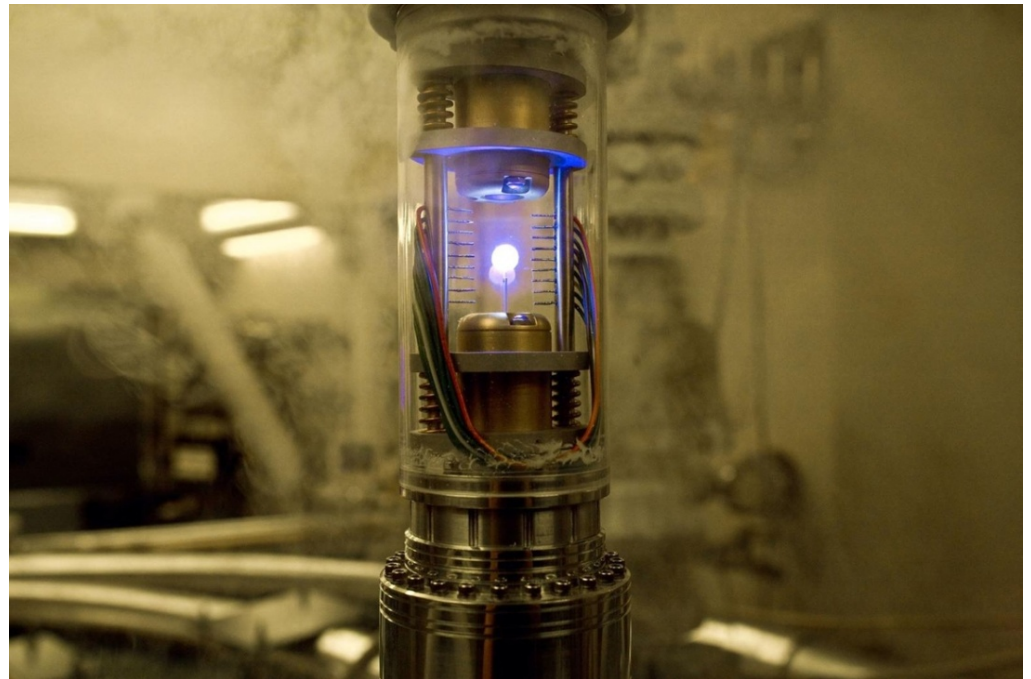
ANGELS AND DEMONS Antimatter bomb

Exercise:

1) how many kilotons for a bomb of 0.5 g of antimatter?

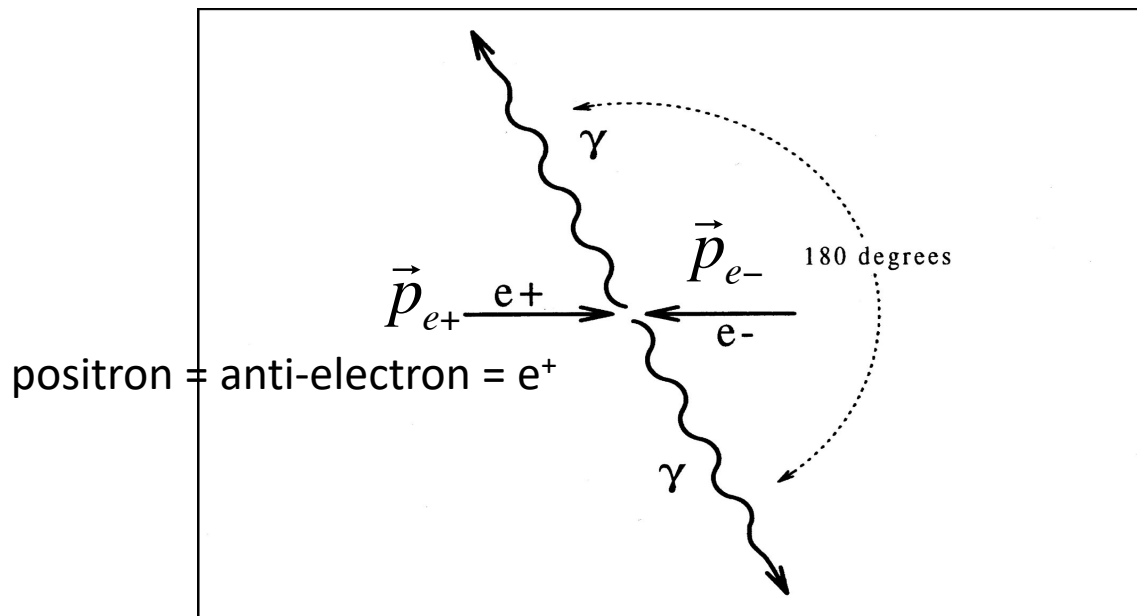
(1 kiloton = 4.2×10^{12} J)

2) which cost? (1 kWh = 0.1 €)



Example of EM interaction: matter-antimatter annihilation

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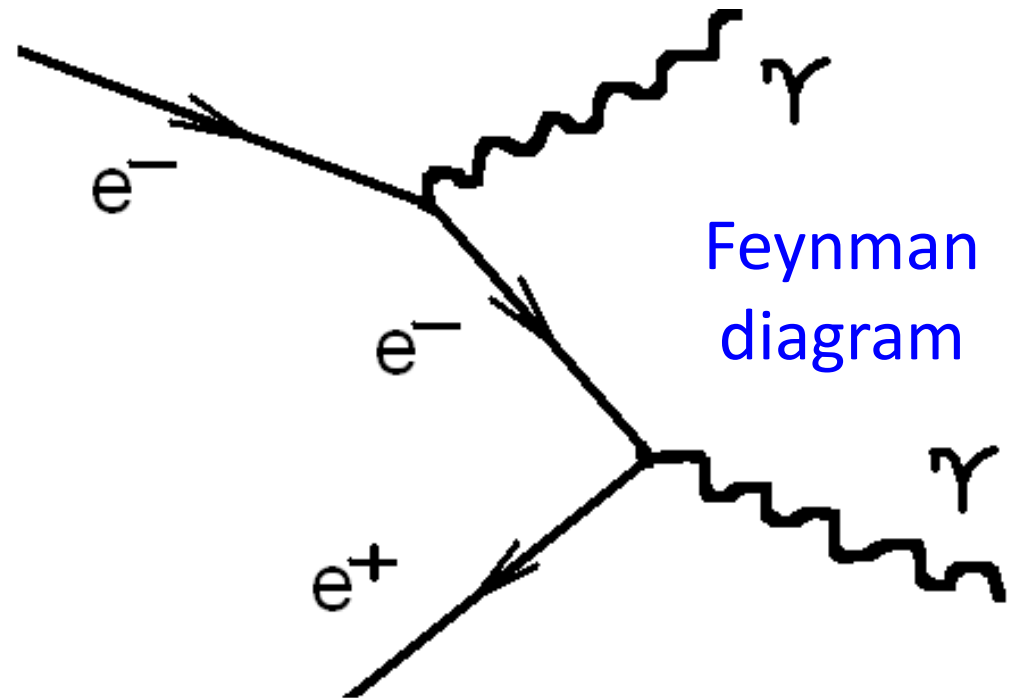
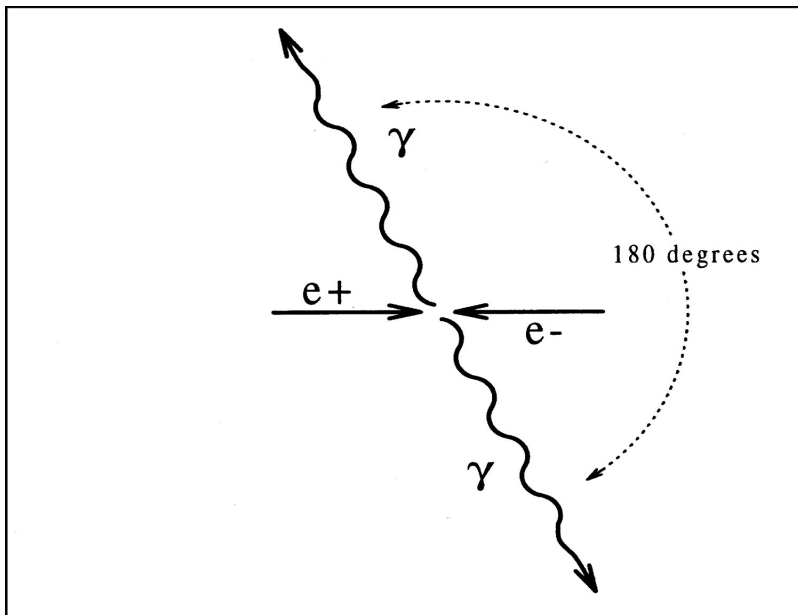
where m is “relativistic invariant mass” of system:

$$m_{e^+e^-}^2 = (E_{e^+} + E_{e^-})^2 - (\vec{p}_{e^+} + \vec{p}_{e^-})^2 \equiv (p_{e^+}^\mu + p_{e^-}^\mu)^2$$

$c = 1$!

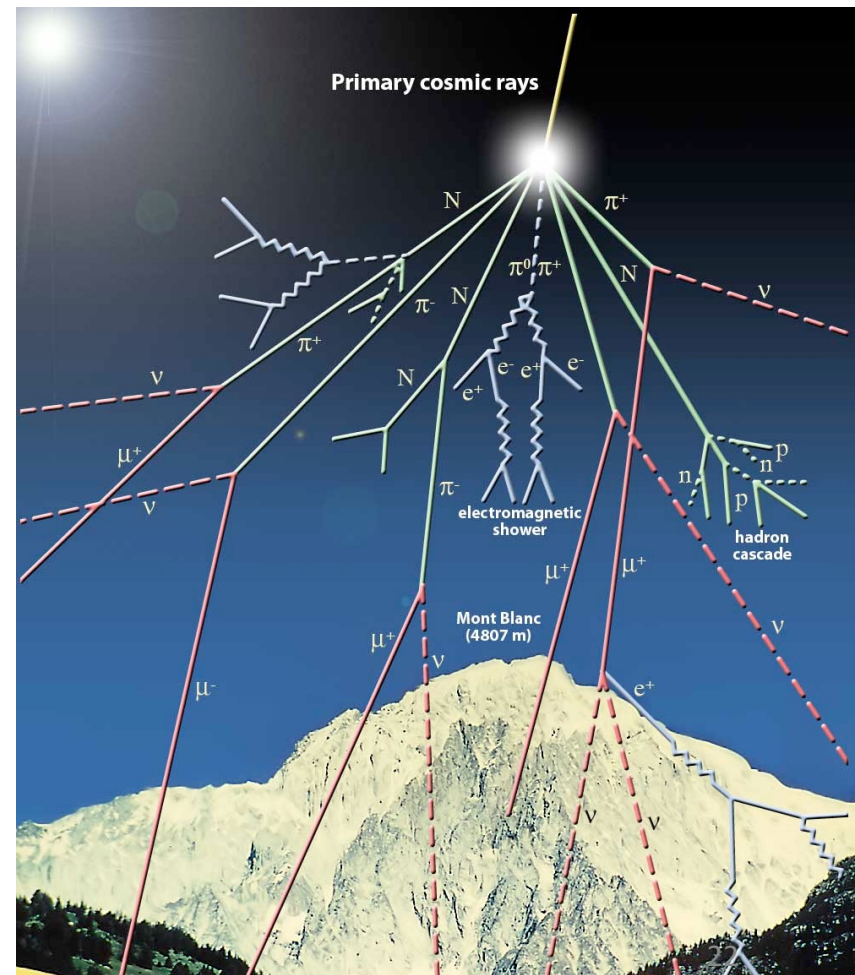
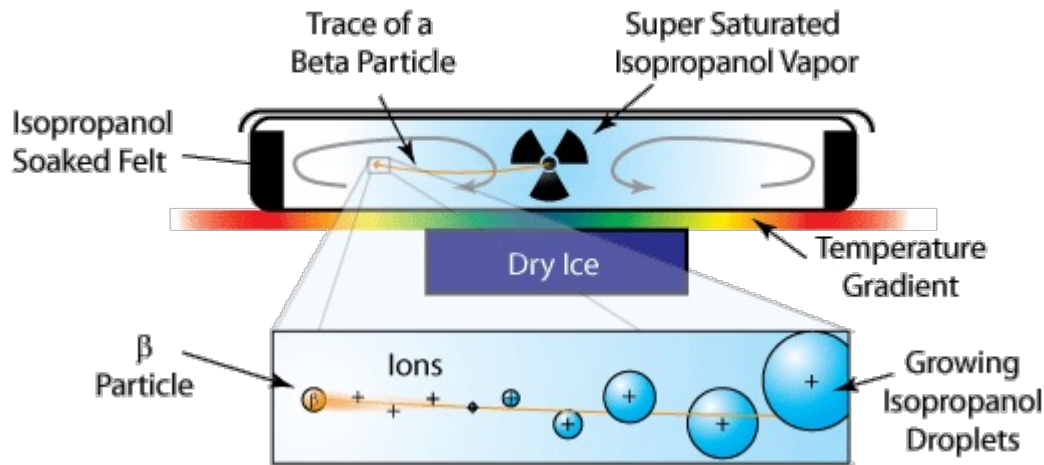
Example of EM interaction: matter-antimatter annihilation

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



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 along track
- Photographic emulsions also used

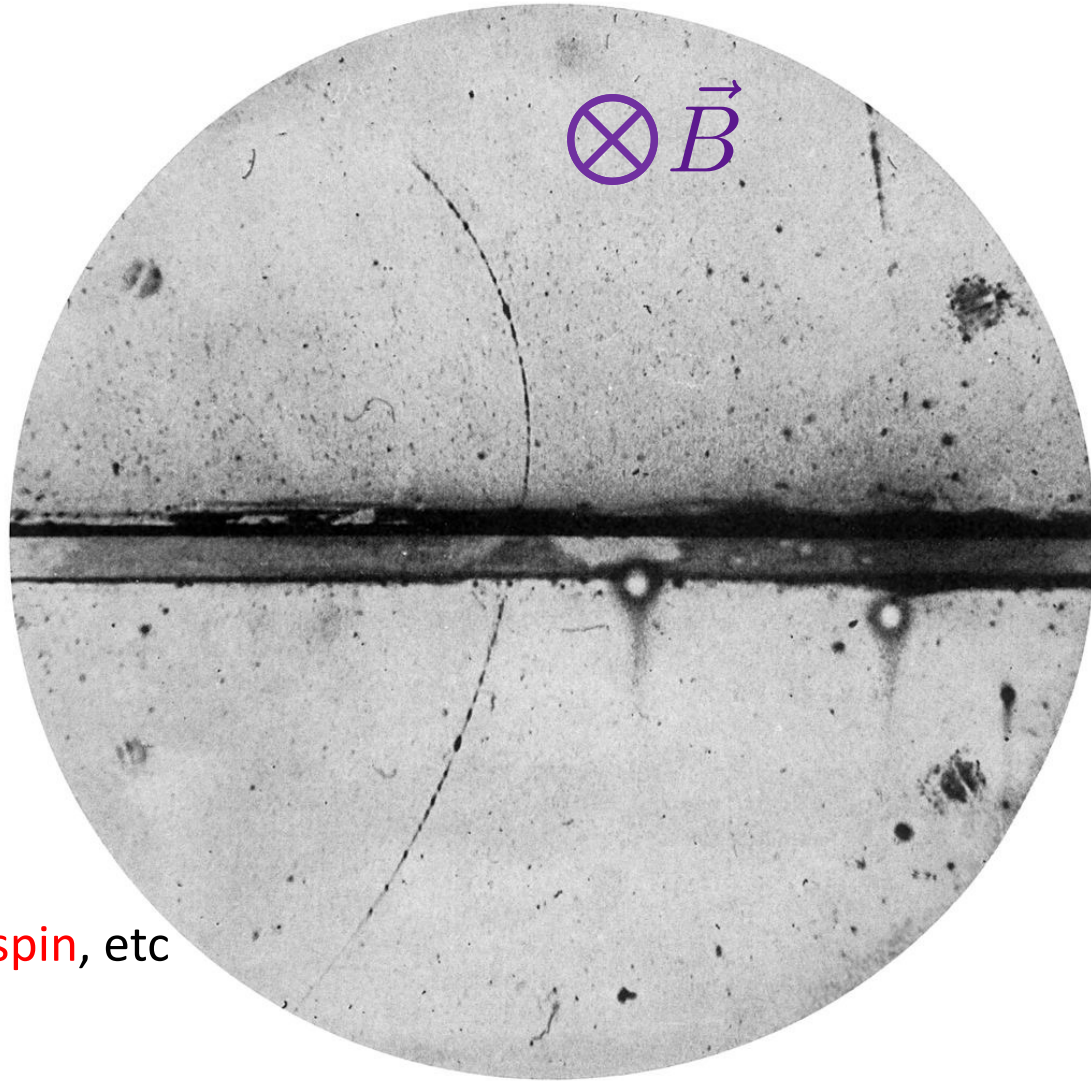


Antiparticles: the positron

- 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



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: $P\psi(\vec{r}) = \psi(-\vec{r})$
- 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
 $|\text{antimatter}\rangle = CP |\text{matter}\rangle$ (rather than $\text{antimatter} = C |\text{matter}\rangle$)
- 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
 $\Rightarrow$ 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)

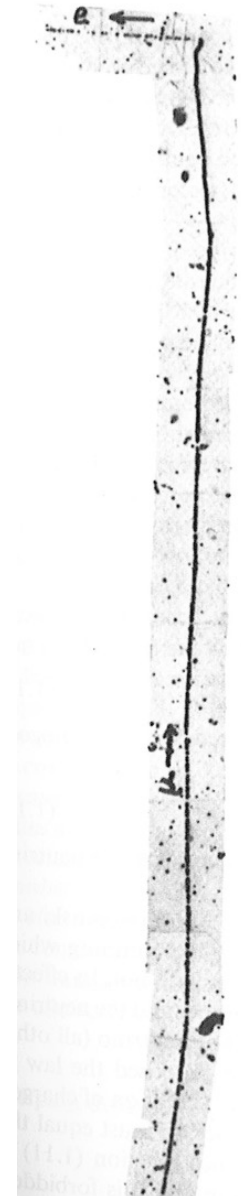
More cosmic rays: the muon

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)

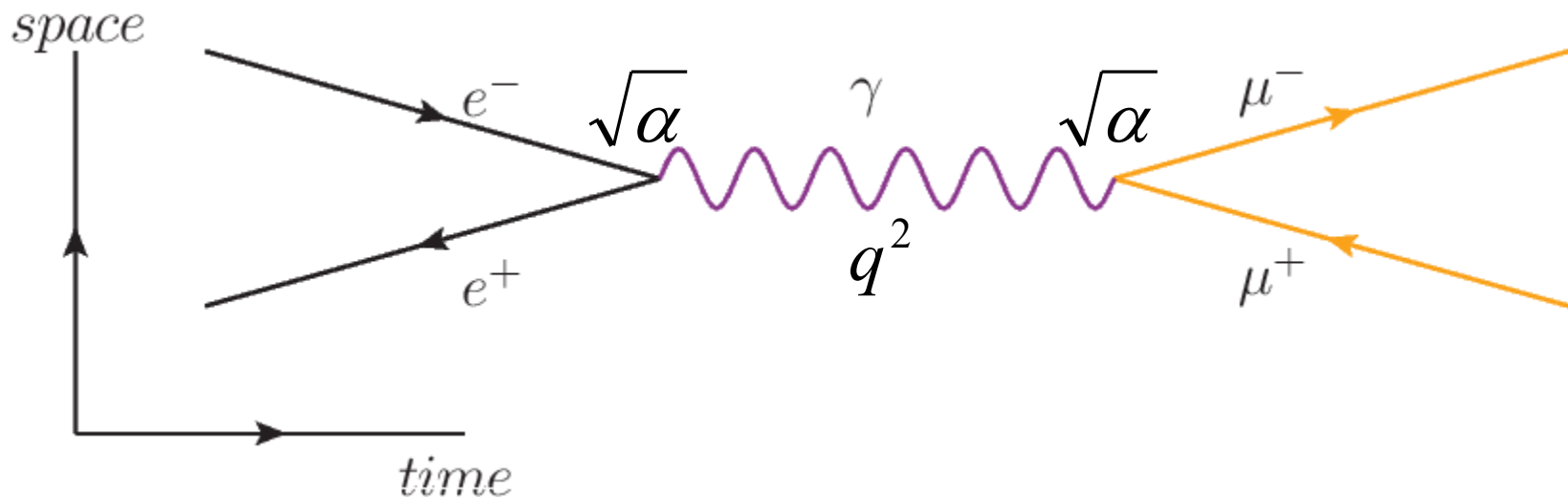
Just like electron but heavy and unstable

“Who ordered that?” (I.I. Rabi)



Example of EM interaction: pair production

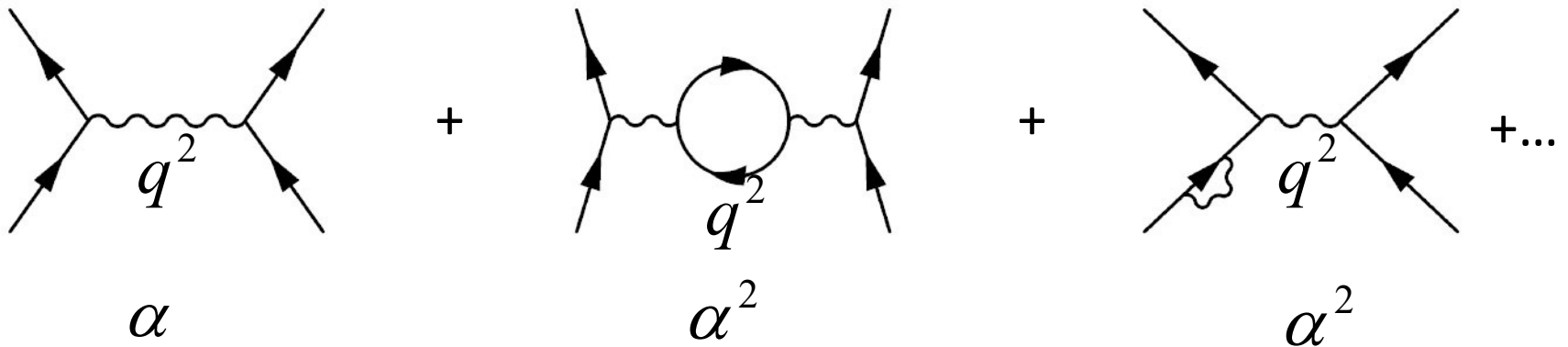
- The inverse of matter-antimatter annihilation: particle-antiparticle pair production
- For instance: $\mu^+ \mu^-$ production:



- 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: $m_\gamma^2 = q^2 \neq 0 !!!$

Quantum ElectroDynamics (QED)

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



- Feynman diagrams part of a perturbation series in powers of coupling constant 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)

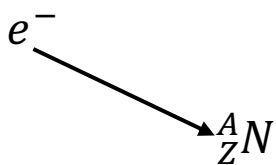
First look at Dirac's equation

- Schrödinger's eq: $E = \frac{p^2}{2m} + V, \quad E \rightarrow i\hbar \partial/\partial t, \quad \vec{p} \rightarrow -i\hbar \vec{\nabla}$
 $\Rightarrow \left(i\hbar \frac{\partial}{\partial t} + \frac{\hbar^2}{2m} \nabla^2 - V(\vec{r}) \right) \psi(\vec{r}, t) = 0$, where $\psi \sim e^{i(px-Et)/\hbar}$ (free particle)
- Manifestly not relativistically invariant: $1 (\partial/\partial t) \neq 2 (\partial^2/\partial x^2)$
- Dirac (1928): time and space on equal footing $\Rightarrow$ 1st order diff eq
 $0 = p_\mu p^\mu - m^2 c^2 = (\beta^\kappa p_\kappa + mc)(\gamma_\lambda p^\lambda - mc)$ (see Griffiths section 7.1)
 $\Rightarrow \beta^\kappa = \gamma^\kappa; \quad (\gamma^0)^2 = 1, \quad (\gamma^i)^2 = -1 \quad (i = 1, 2, 3), \quad \gamma^\mu \gamma^\nu + \gamma^\nu \gamma^\mu = 0$
 $\Rightarrow \gamma^\kappa$ are 4×4 matrices, not just (complex) numbers!
- (Dirac representation) $\gamma^0 = \begin{pmatrix} \mathbb{1} & 0 \\ 0 & -\mathbb{1} \end{pmatrix}, \quad \gamma^i = \begin{pmatrix} 0 & \sigma_i \\ -\sigma_i & 0 \end{pmatrix}; \quad \psi = \begin{pmatrix} \psi_1 \\ \psi_2 \\ \psi_3 \\ \psi_4 \end{pmatrix}$
 σ_i , Pauli's matrices
 $\left. \begin{array}{l} \psi_1 \\ \psi_2 \end{array} \right\} \begin{array}{l} E > 0 \\ \text{part} \\ \text{spin } \uparrow, \downarrow \end{array}$
 $\left. \begin{array}{l} \psi_3 \\ \psi_4 \end{array} \right\} \begin{array}{l} ? \\ E < 0 \end{array}$
- 4 degrees of freedom:
 2 for a spin-1/2 particle $E > 0$, $E < 0$ other 2?

First look at Dirac's equation

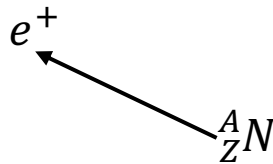
- Feynman-Stückelberg interpretation:

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: $(i\hbar\gamma^\mu\partial_\mu - mc)\psi = 0$ or $(i\hbar\not{D} - mc)\psi = 0$

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

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

- 4 degrees of freedom:

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

$$\psi = \begin{pmatrix} \psi_1 \\ \psi_2 \\ \psi_3 \\ \psi_4 \end{pmatrix} \left\{ \begin{array}{l} \text{E>0} \\ \text{part} \\ \text{spin } \uparrow, \downarrow \\ \text{antipart} \\ \text{spin } \uparrow, \downarrow \\ \text{E<0} \end{array} \right.$$

The Standard Model: elementary particles and their interactions

Fermions matter particles

Quarks



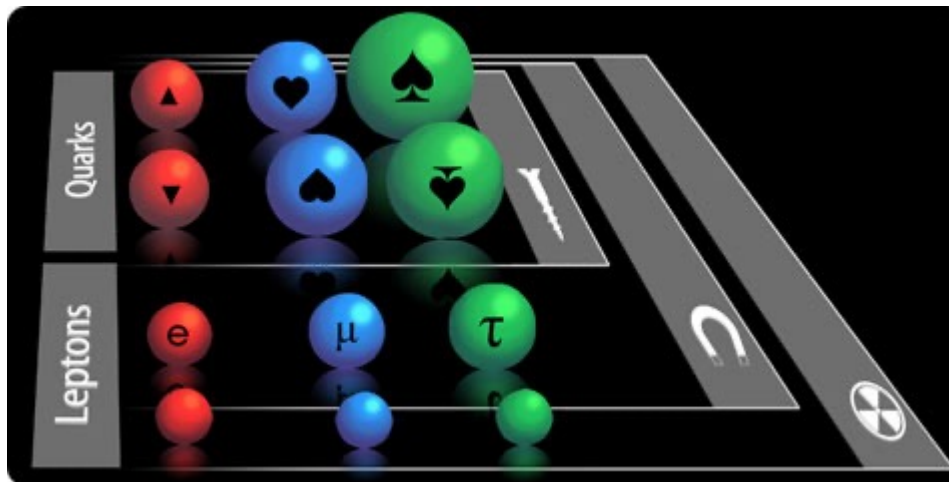
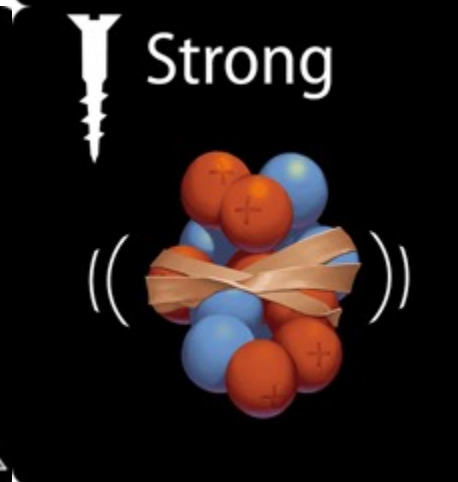
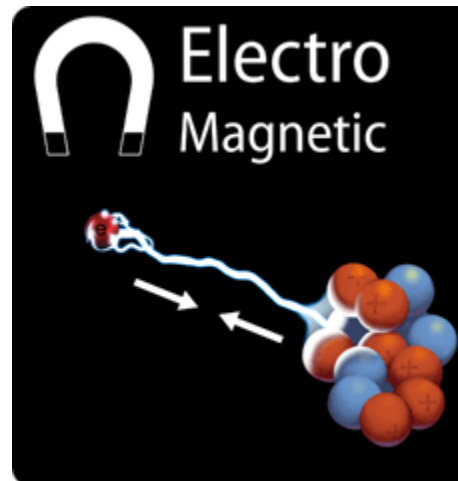
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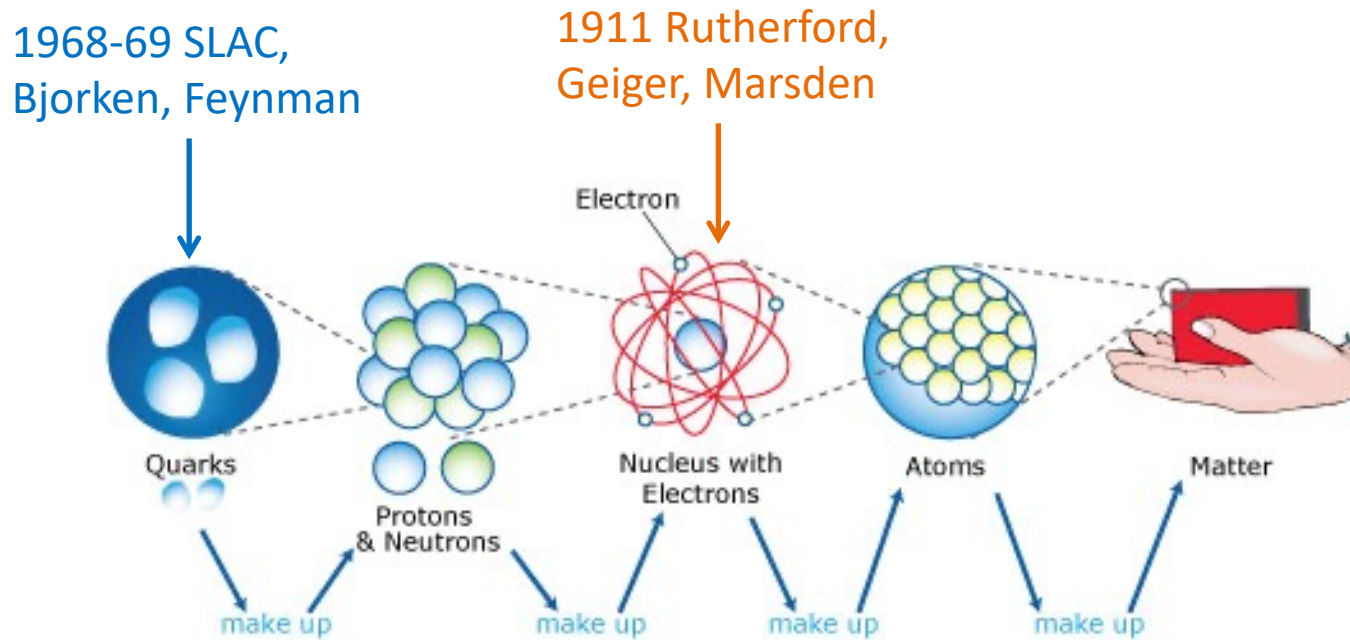
Gauge bosons force carriers



Higgs boson origin of mass

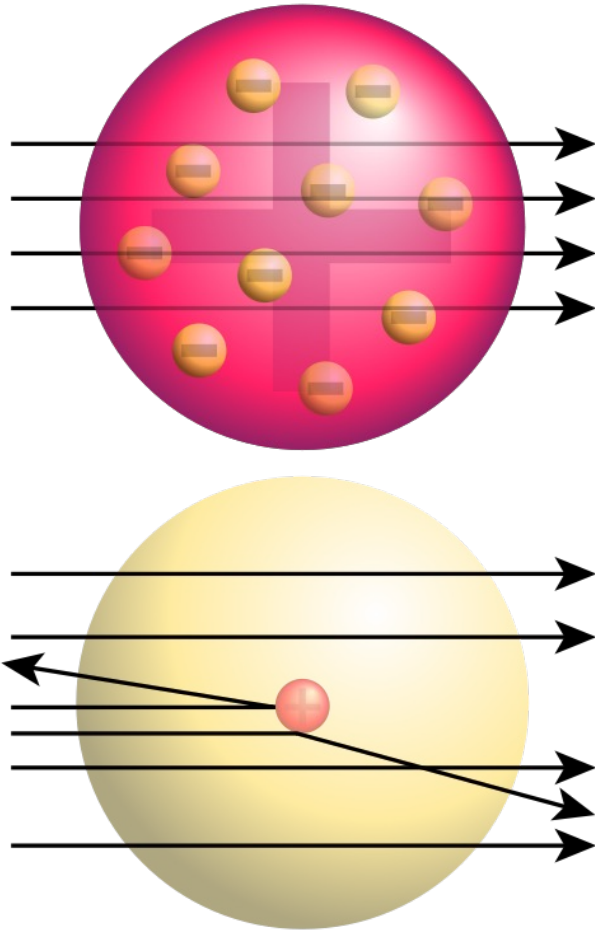


A VERY brief history of particles

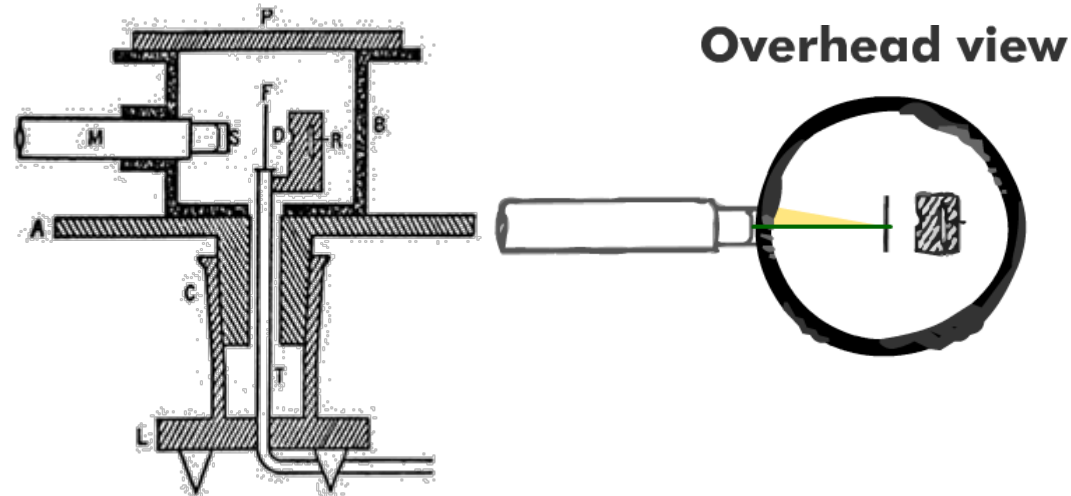


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The nucleus: Rutherford scattering



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

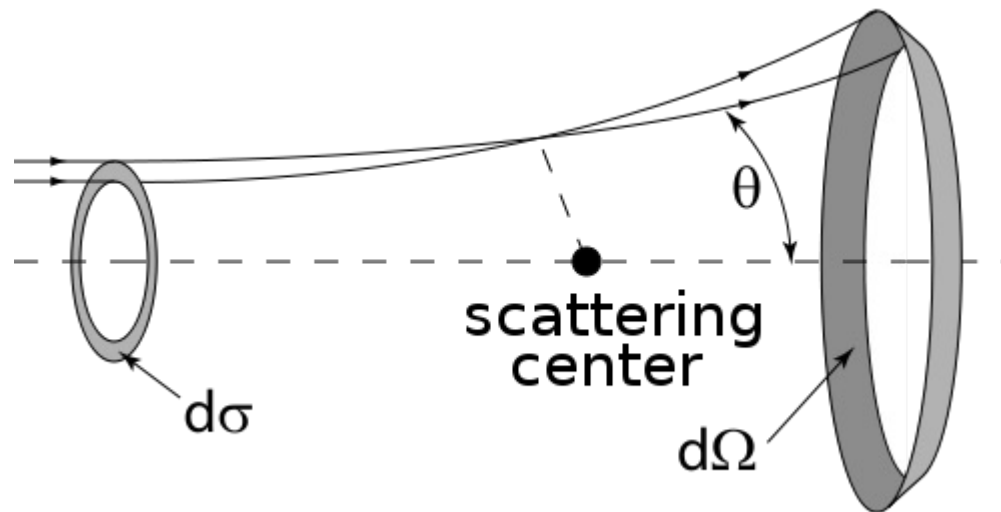


- 1909, Geiger & Marsden: $\sim 1/8000$ alpha particles bounce off!
- 1911, Rutherford: nucleus small within atom, surrounded by e^- cloud

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

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 θ** 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 θ



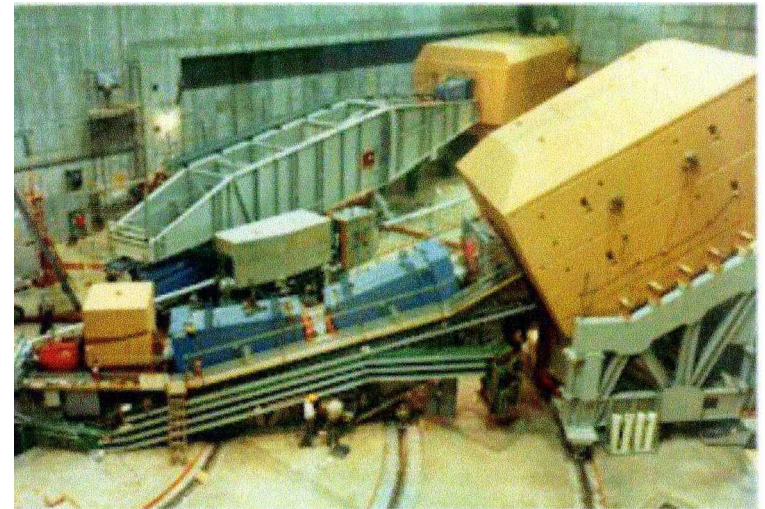
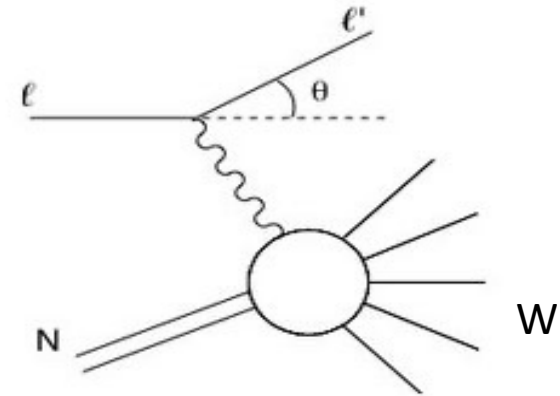
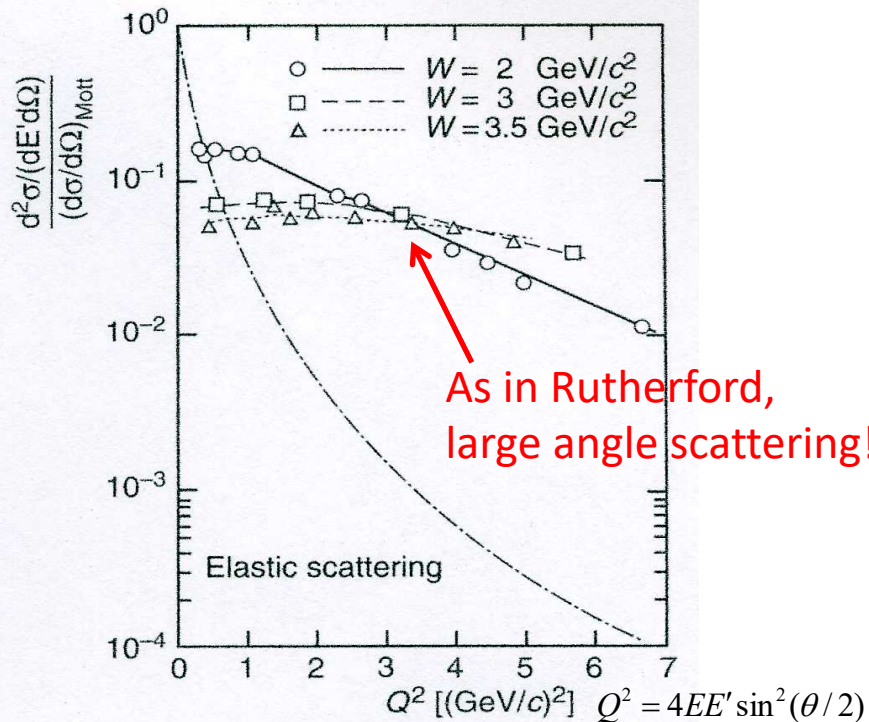
- Ex, scattering of spinless charged particles off a spinless charged target (Rutherford):

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

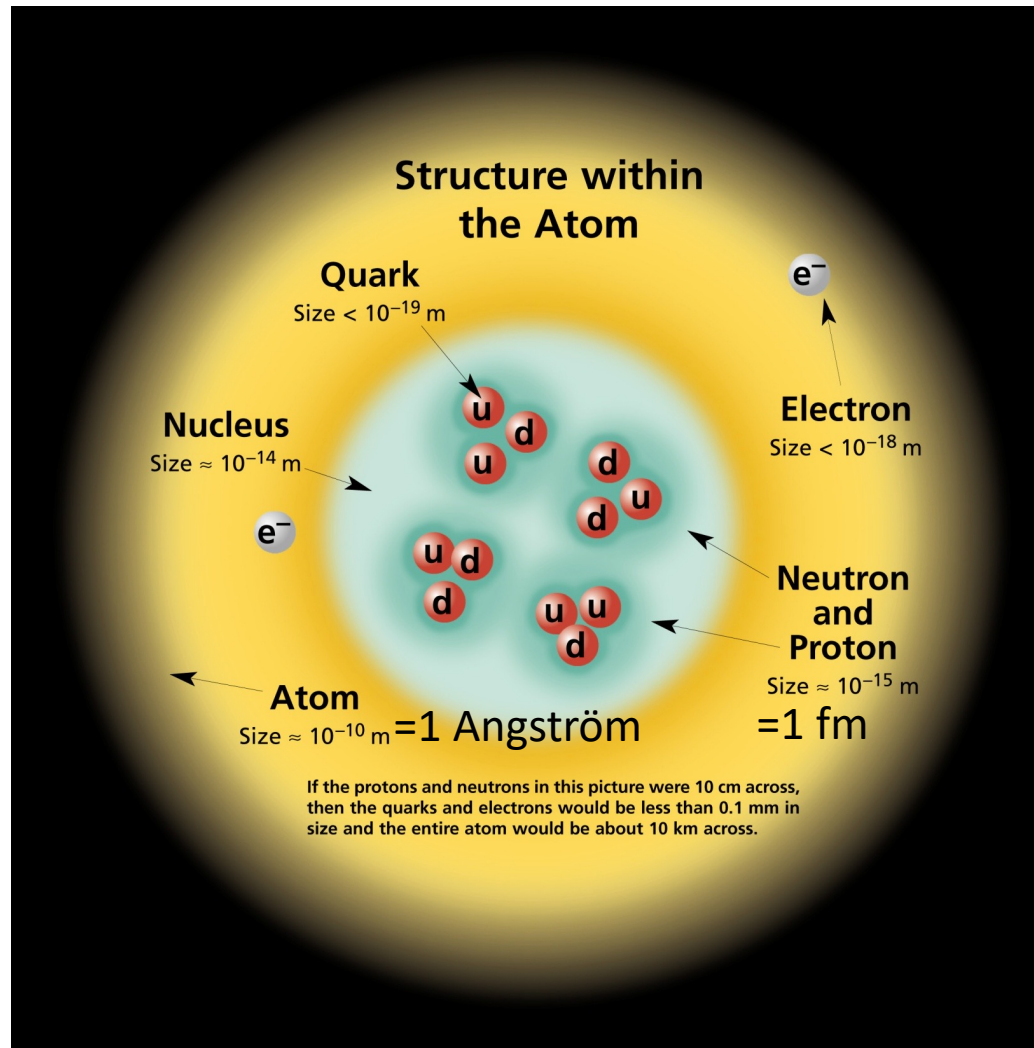
Back to history: protons are composite

- Post WWII: accelerator era
- 1968 SLAC: shoot e^- to proton target
- High energies: $\lambda_{\text{electron}} \ll R_{\text{proton}}$

$$pc = hc/\lambda_{\text{electron}} \gg 1 \text{ GeV}$$

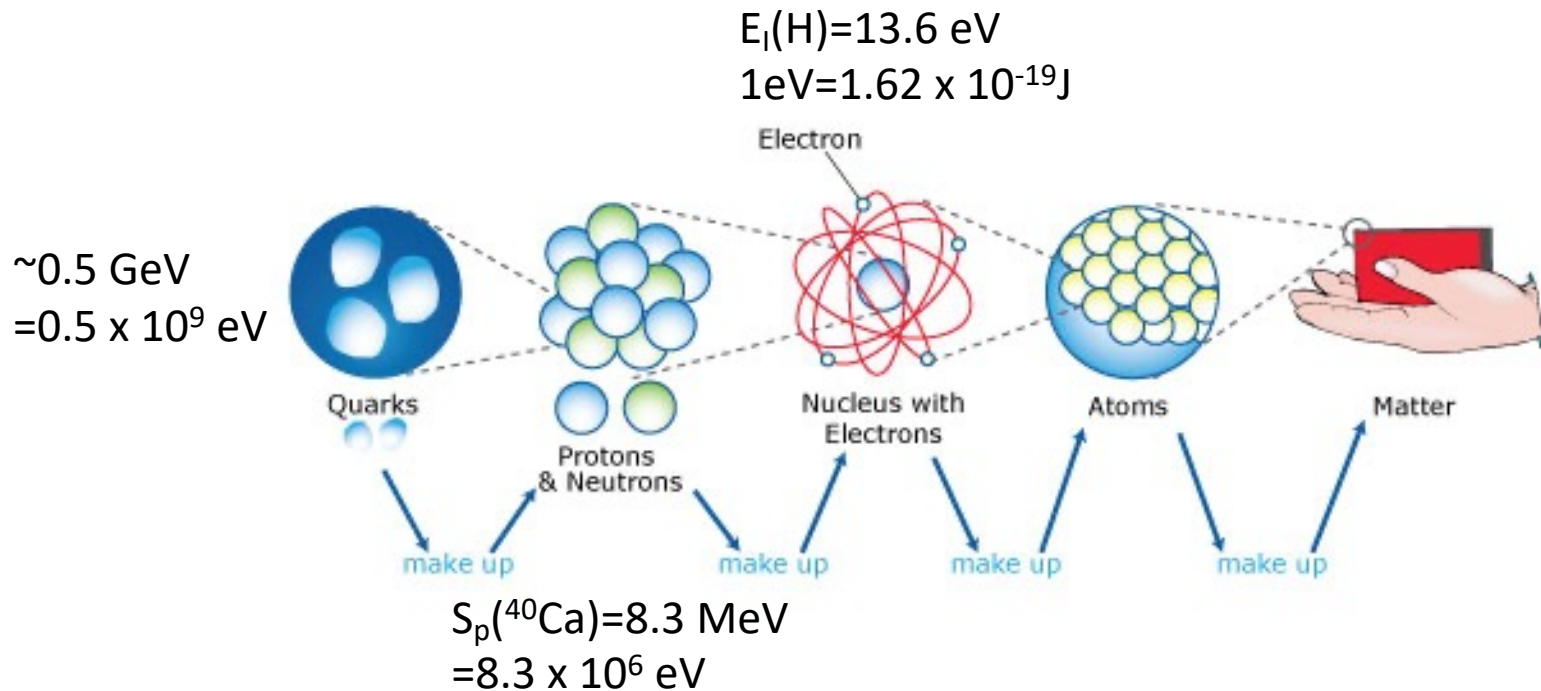


Protons are composite



Nucleons
composed of
3 point-like
particles:
quarks

Orders of magnitude, units



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

e.g. $m(\text{proton}) = 938 \text{ MeV}$, $m(\text{electron}) = 0.511 \text{ MeV}$

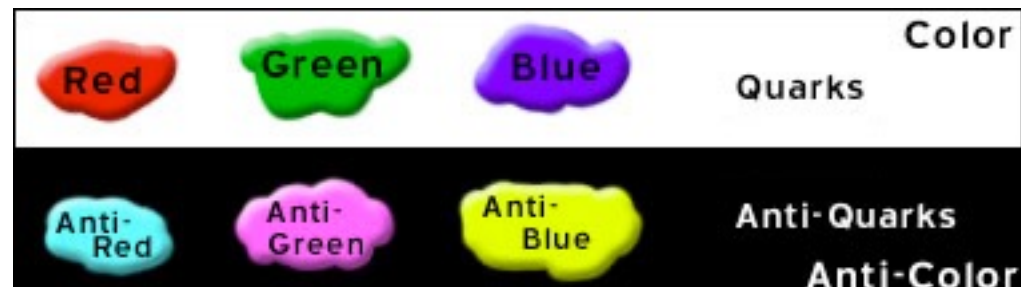
Quarks and the Strong Force

- 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



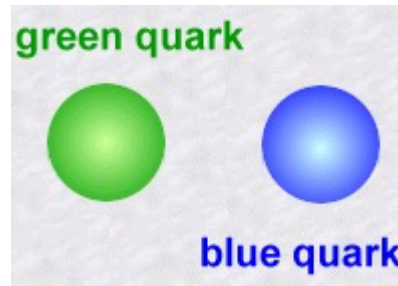
Strong Force



* 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!

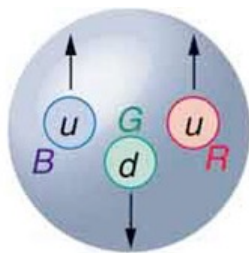


- Consequences:
 - Very short range force
 - Force gets stronger when quarks pulled apart
 - Only see color-neutral free particles in Nature (quark confinement)

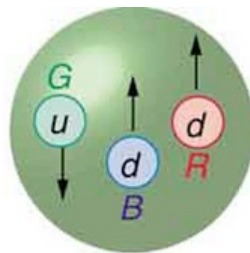
Quarks make up hadrons

- 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)

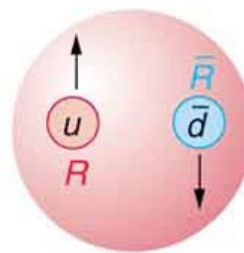
} Hadrons



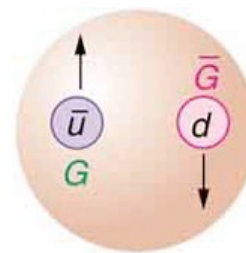
Proton



Neutron



π^+



π^-

Spin

$$\frac{1}{2} + \frac{1}{2} - \frac{1}{2} = \frac{1}{2}$$

$$-\frac{1}{2} + \frac{1}{2} + \frac{1}{2} = \frac{1}{2}$$

$$+\frac{1}{2} - \frac{1}{2} = 0$$

$$+\frac{1}{2} - \frac{1}{2} = 0$$

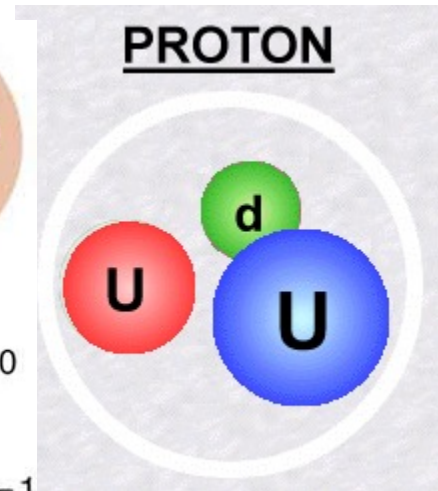
Charge

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

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

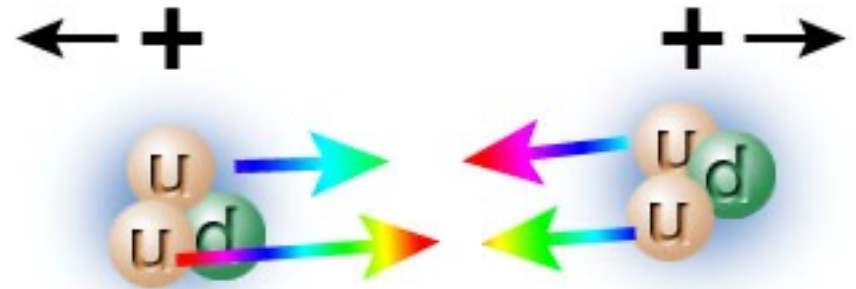
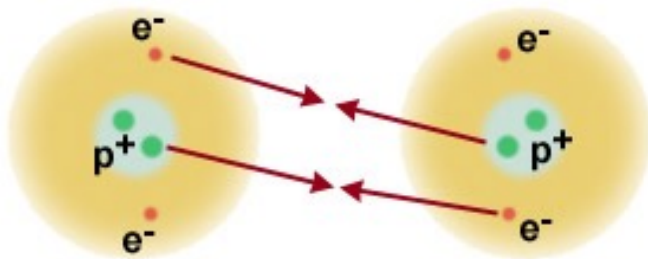
$$+\frac{2}{3} + \frac{1}{3} = +1$$

$$-\frac{2}{3} - \frac{1}{3} = -1$$



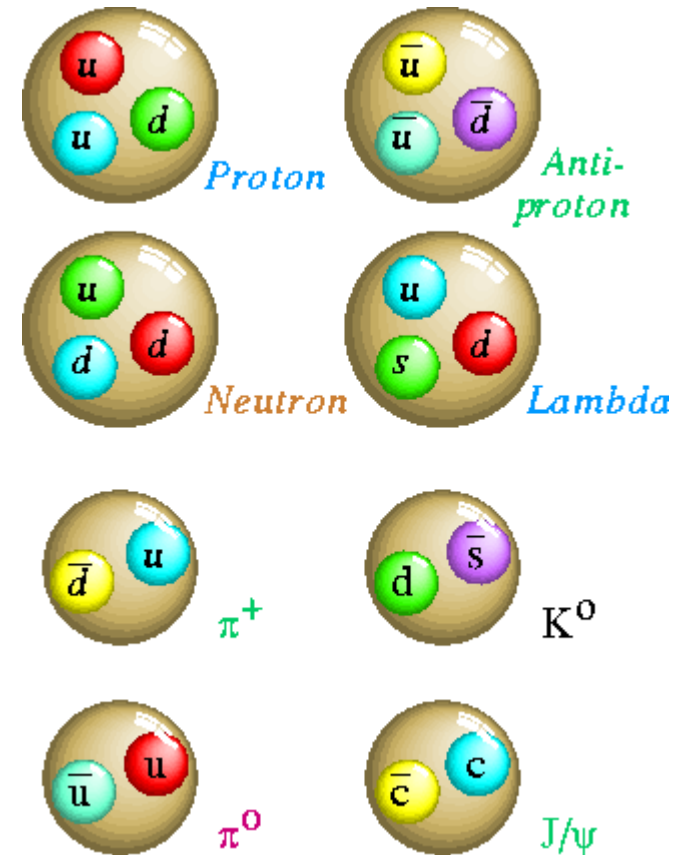
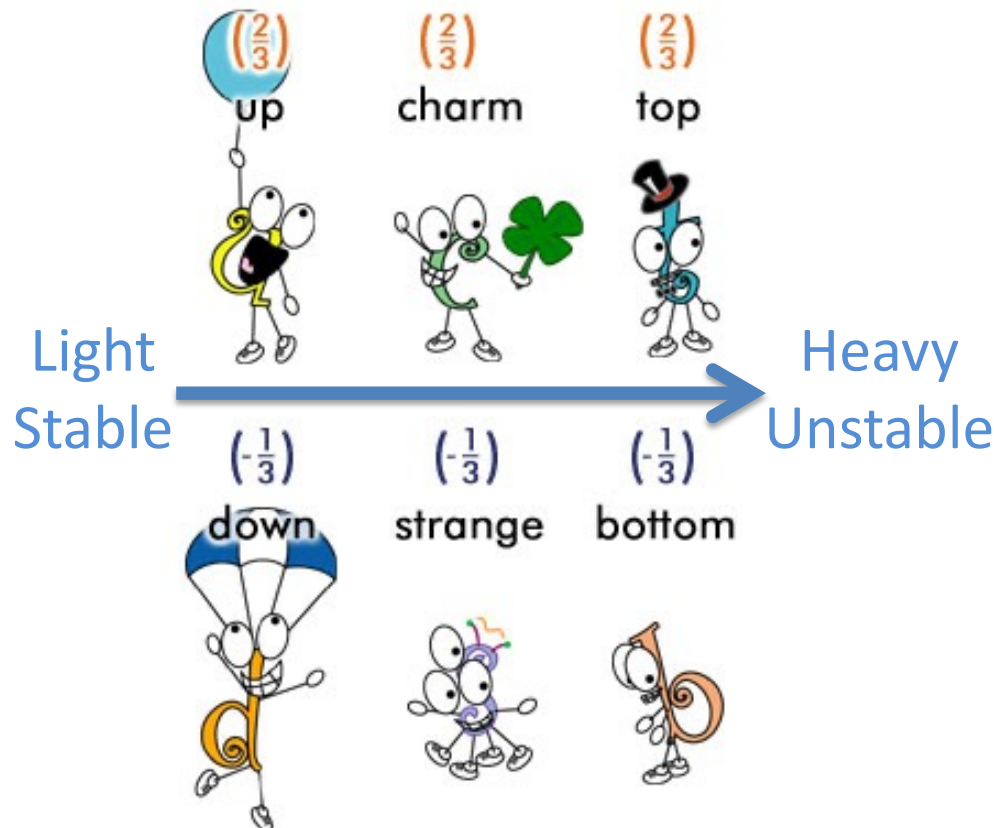
QCD $\rightarrow$ Strong nuclear force

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



How many different quarks?

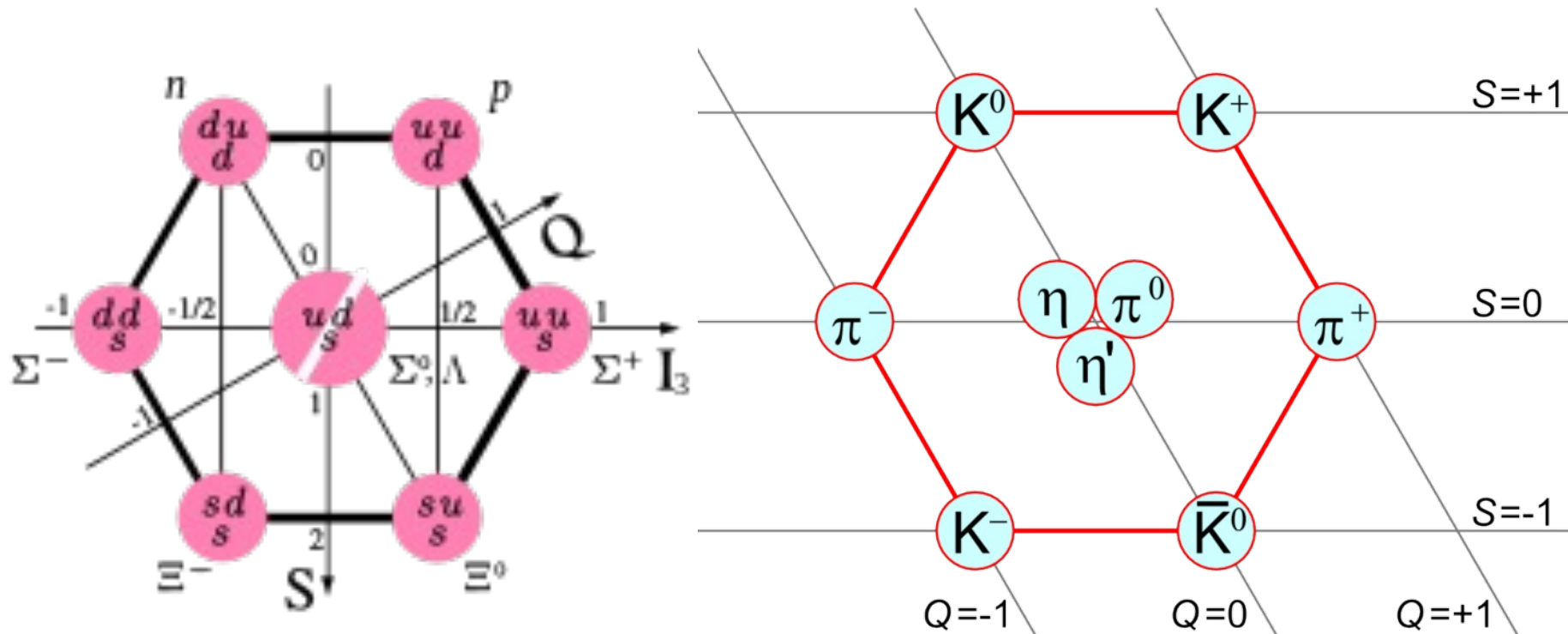
- Experimentally find 6 quarks (*flavours*) , 3 up-type and 3 down-type quarks
- All the same in QCD, except different masses



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

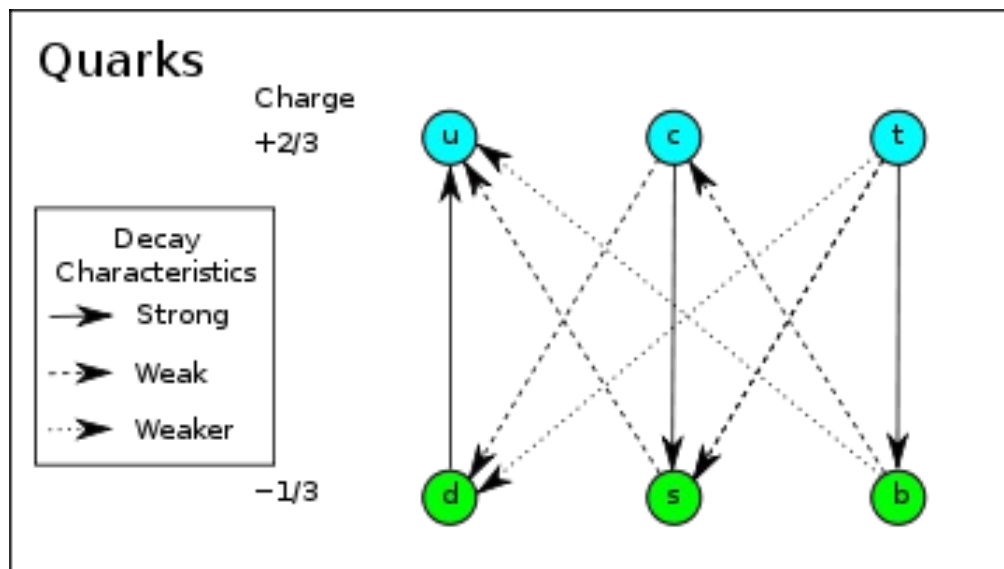
Symmetries

- 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



The Standard Model: elementary particles and their interactions

Fermions matter particles

Quarks



Leptons



Gauge bosons force carriers



photon



gluon

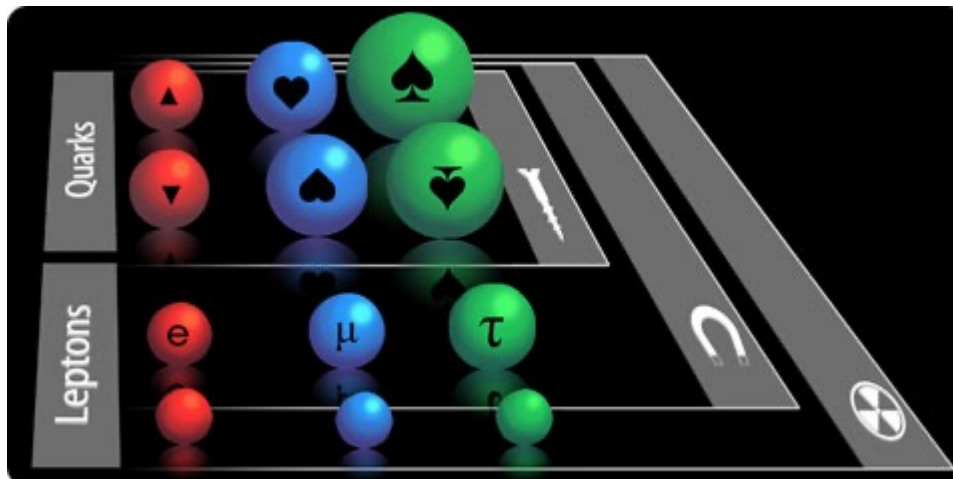
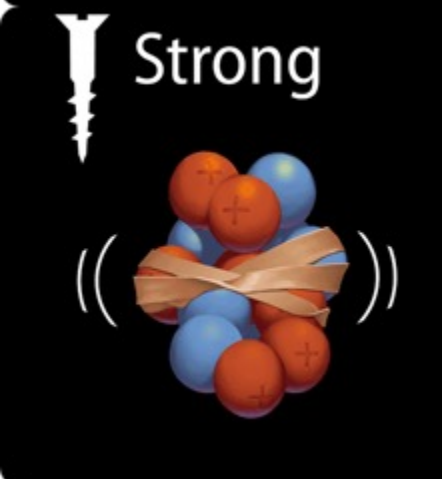
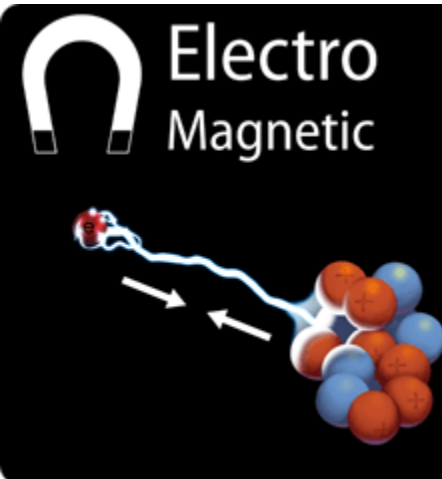


Z boson



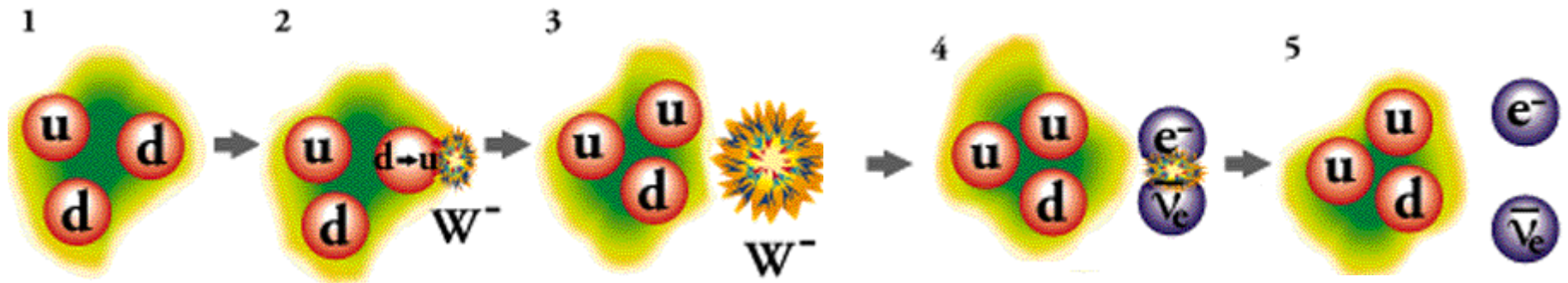
W boson

Higgs boson origin of mass

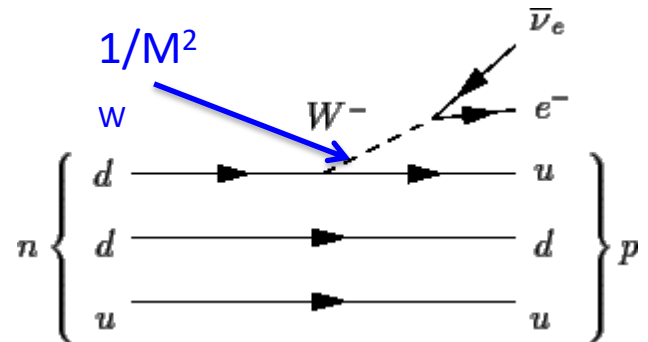


Weak Force

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

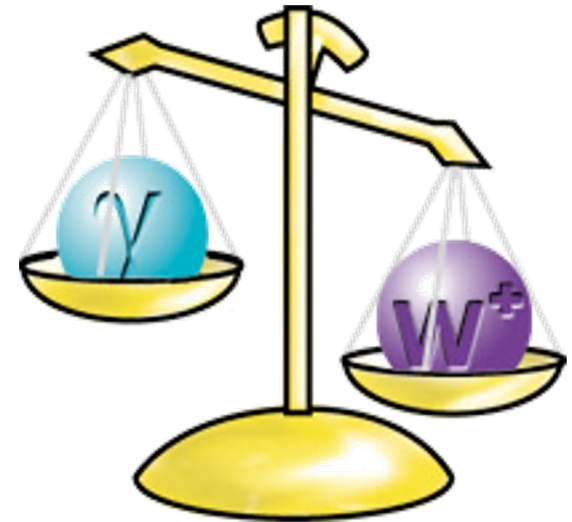


- Weak force responsible for decays of unstable elementary particles
- Mediated by Z^0 and $W^\pm$ bosons
- Contrary to photons and gluons, Z^0 and $W^\pm$ have non-zero masses
- Propagators proportional to $1/M_Z^2$, $1/M_W^2$
 ➔ Weak Force very weak!



Why are Z and W so heavy?

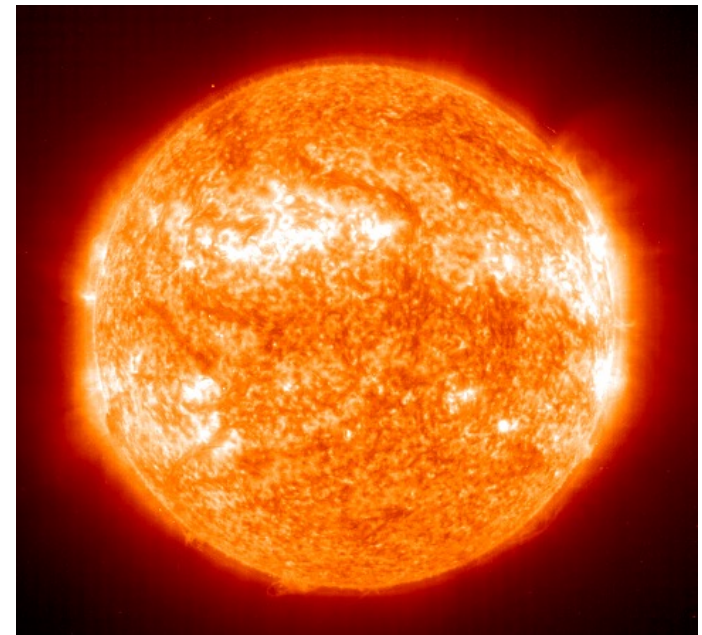
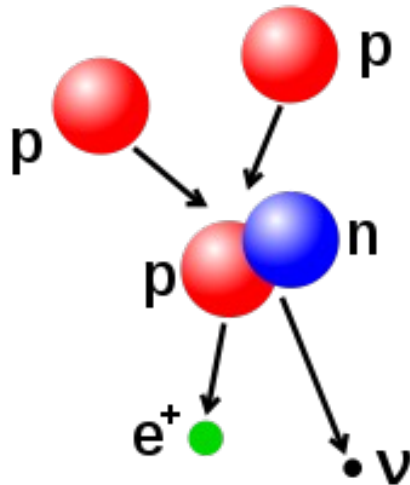
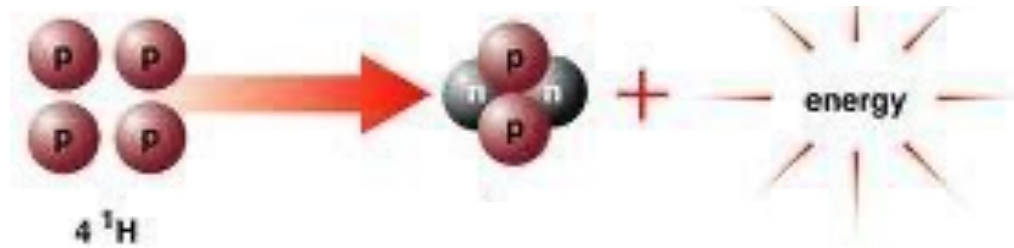
- Z and W are 100 and 85 times heavier than proton
- But photons and gluons massless!



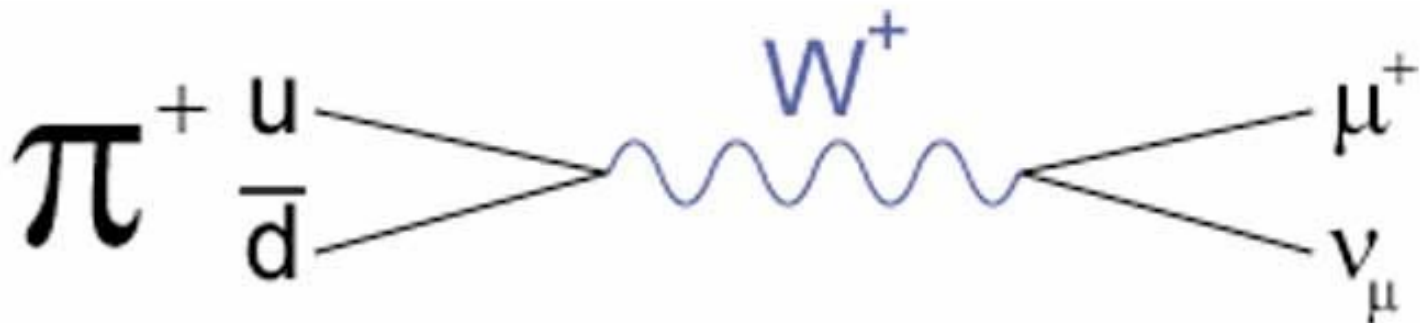
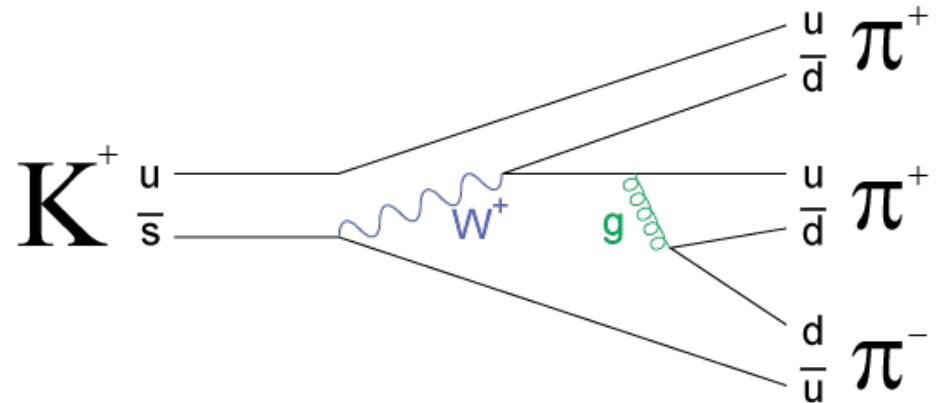
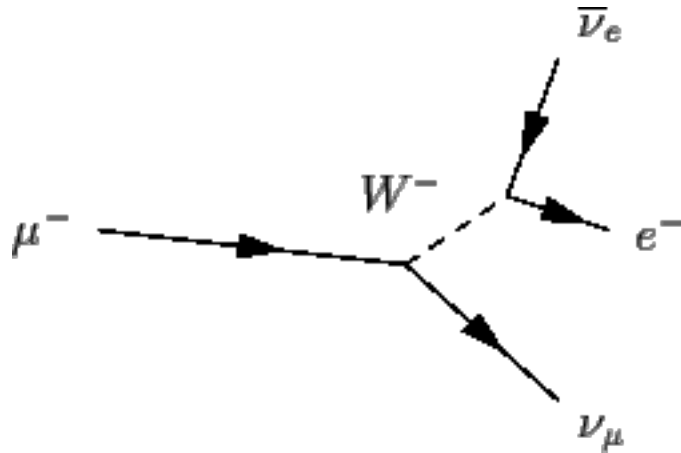
- It's the Higgs boson's fault!

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 **W**s
- So very hard to study...
- Electron also light and without color ➔ leptons
- Plenty of open questions...

Three families or generations

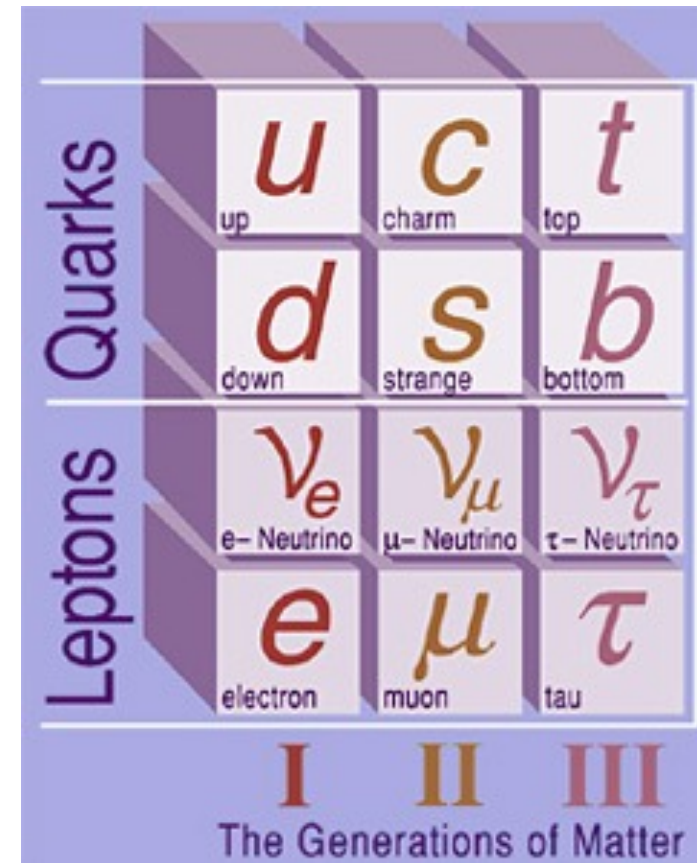
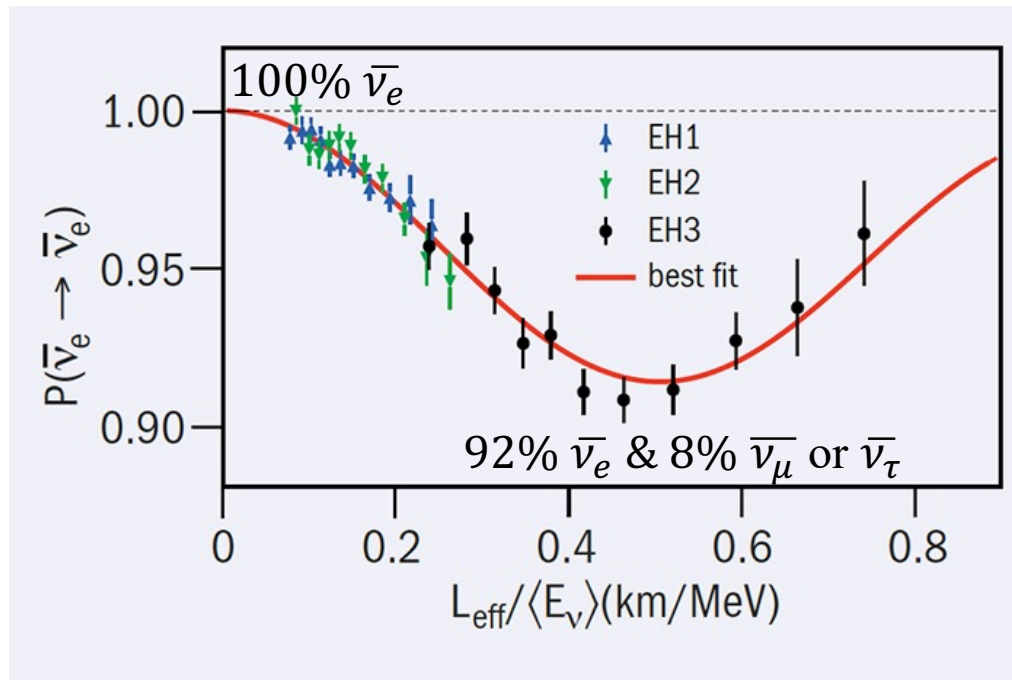
- 3 times the u, d quark couple, except heavier and less stable
- Same story about leptons:
muon is just an unstable, heavy electron
- Columns of table are called *generations* (*flavour*)
- Why more than one? Why three?

Quarks	u up	c charm	t top
	d down	s strange	b bottom
	ν_e e- Neutrino	ν_μ μ - Neutrino	ν_τ τ - Neutrino
	e electron	μ muon	τ tau
	I	II	III
	The Generations of Matter		

Neutrinos oscillate!



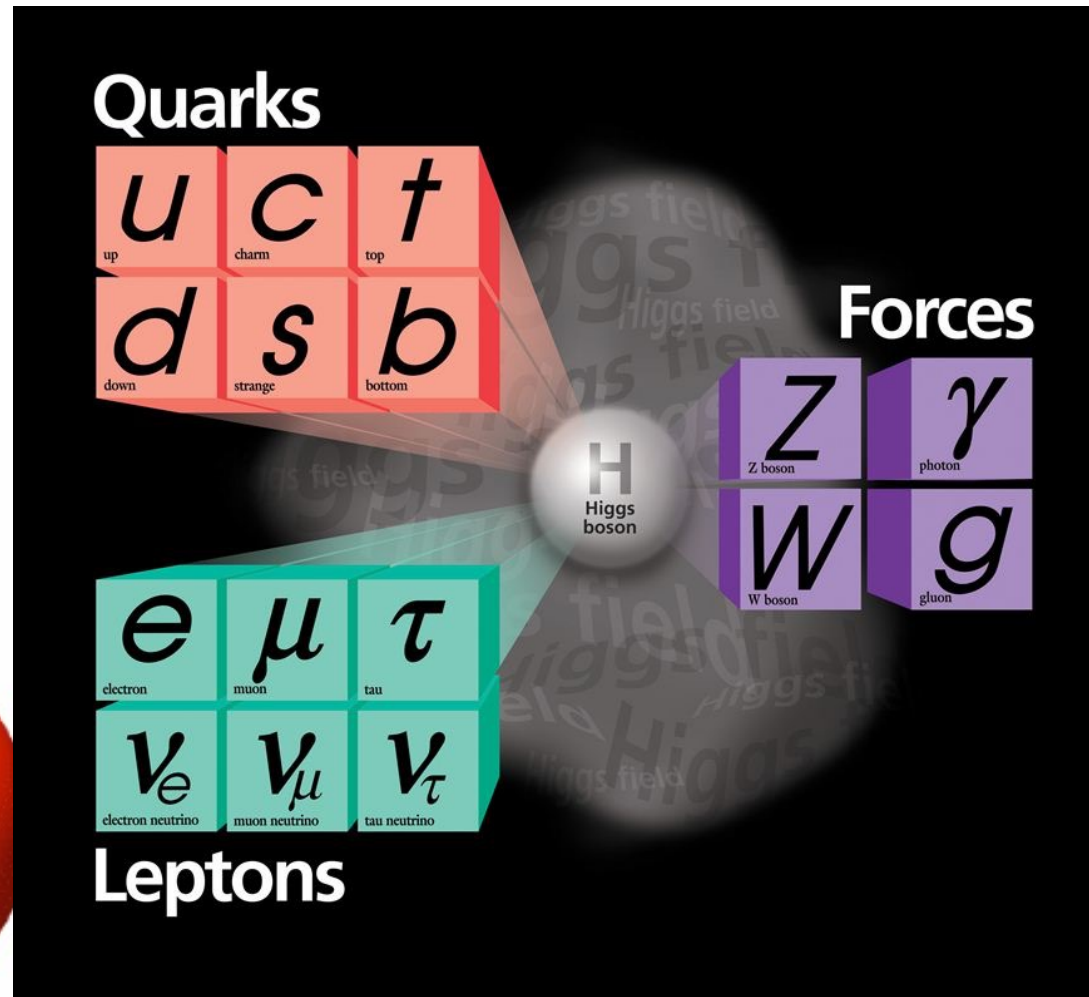
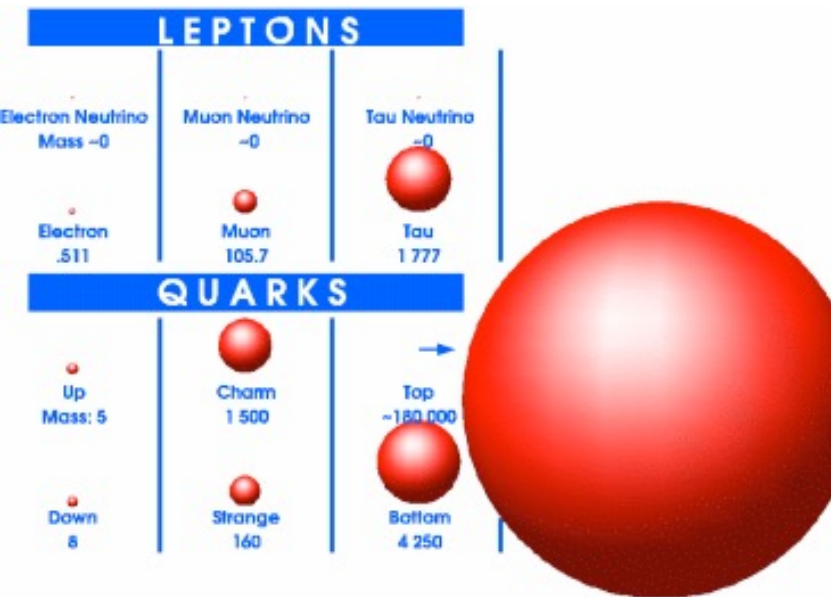
- During propagation, neutrinos can change type. Ex:



- Complex interplay between mass and flavour

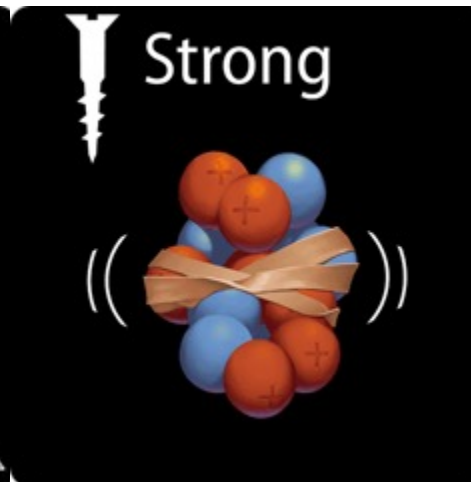
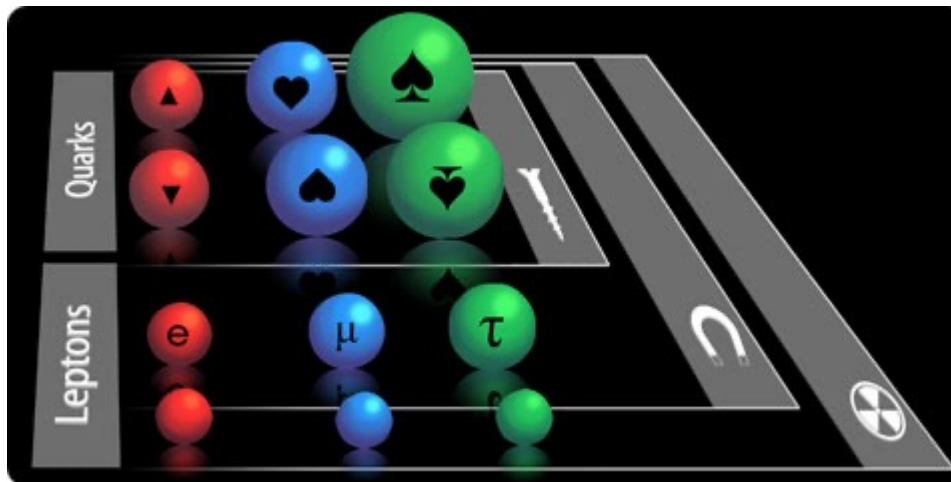
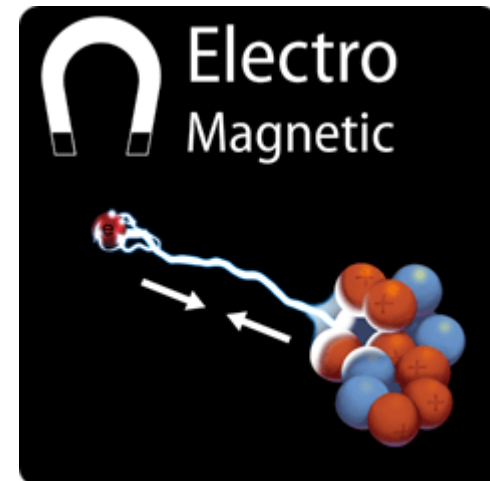
The Standard Model

- 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](#)

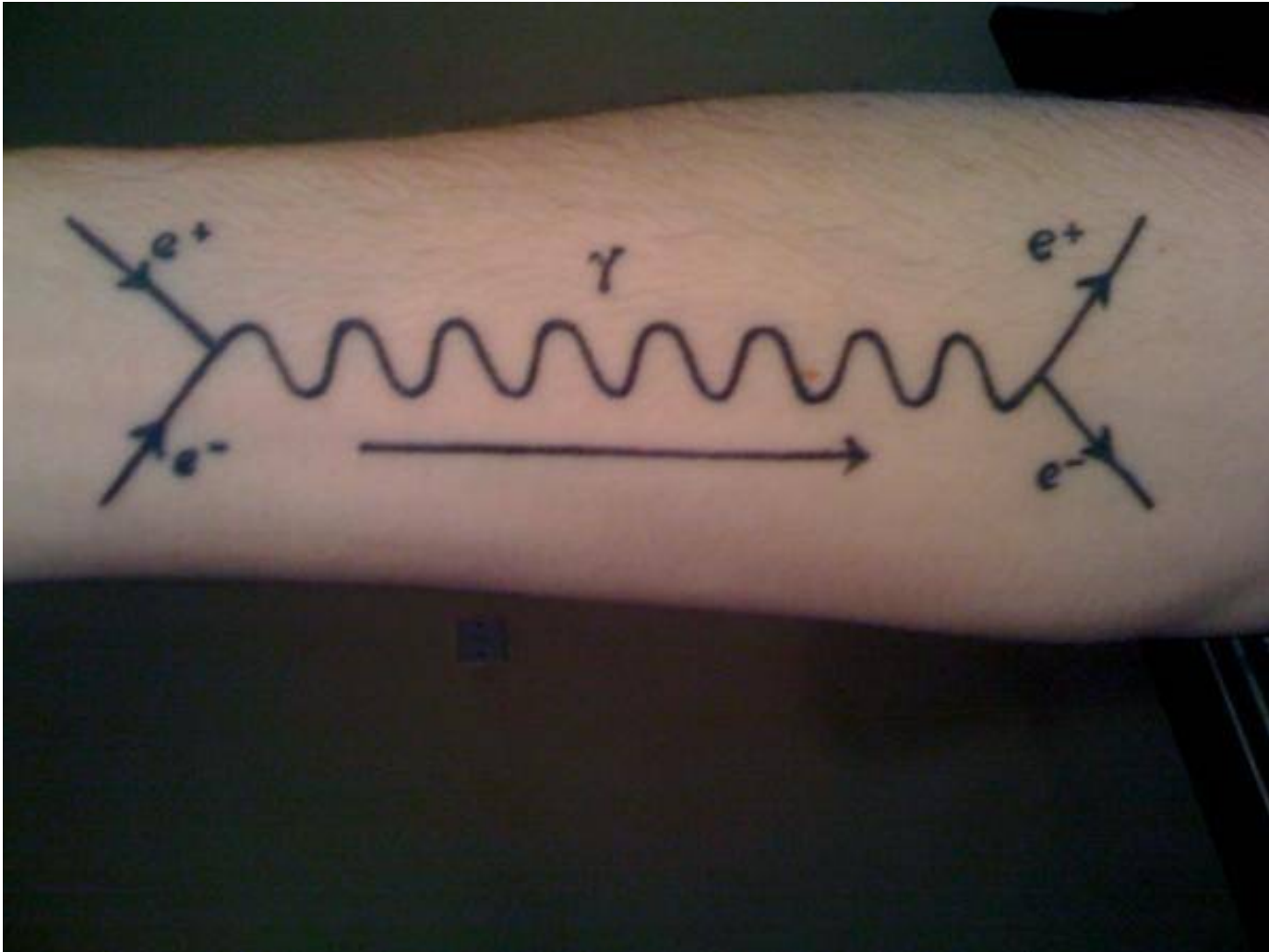


Questions?

Exercise:

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

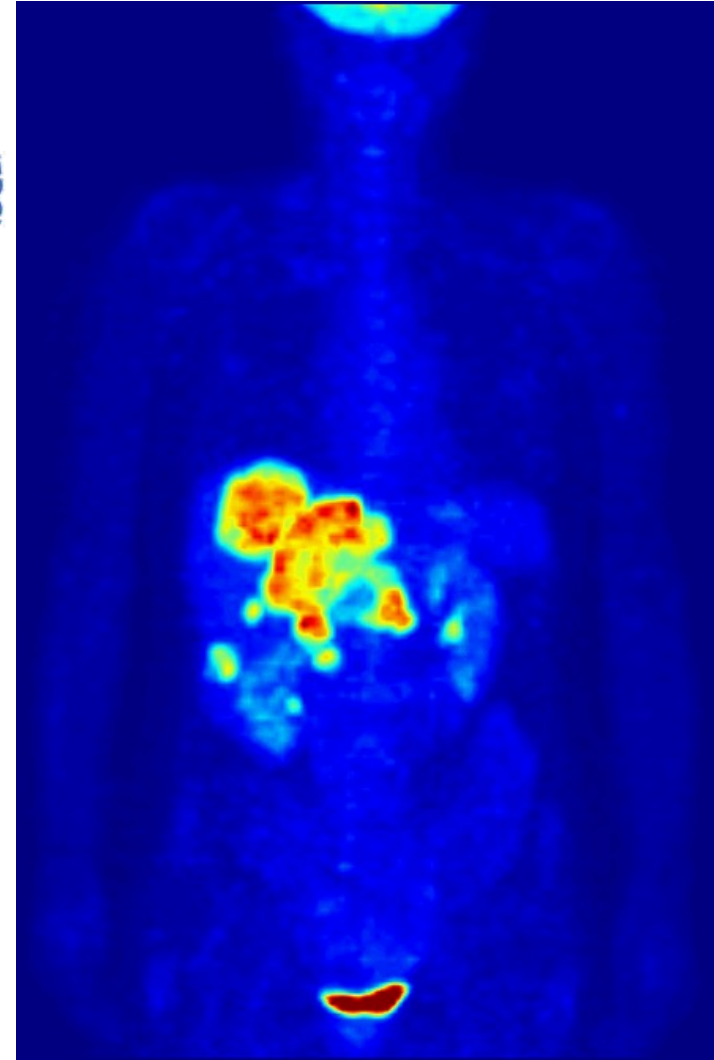
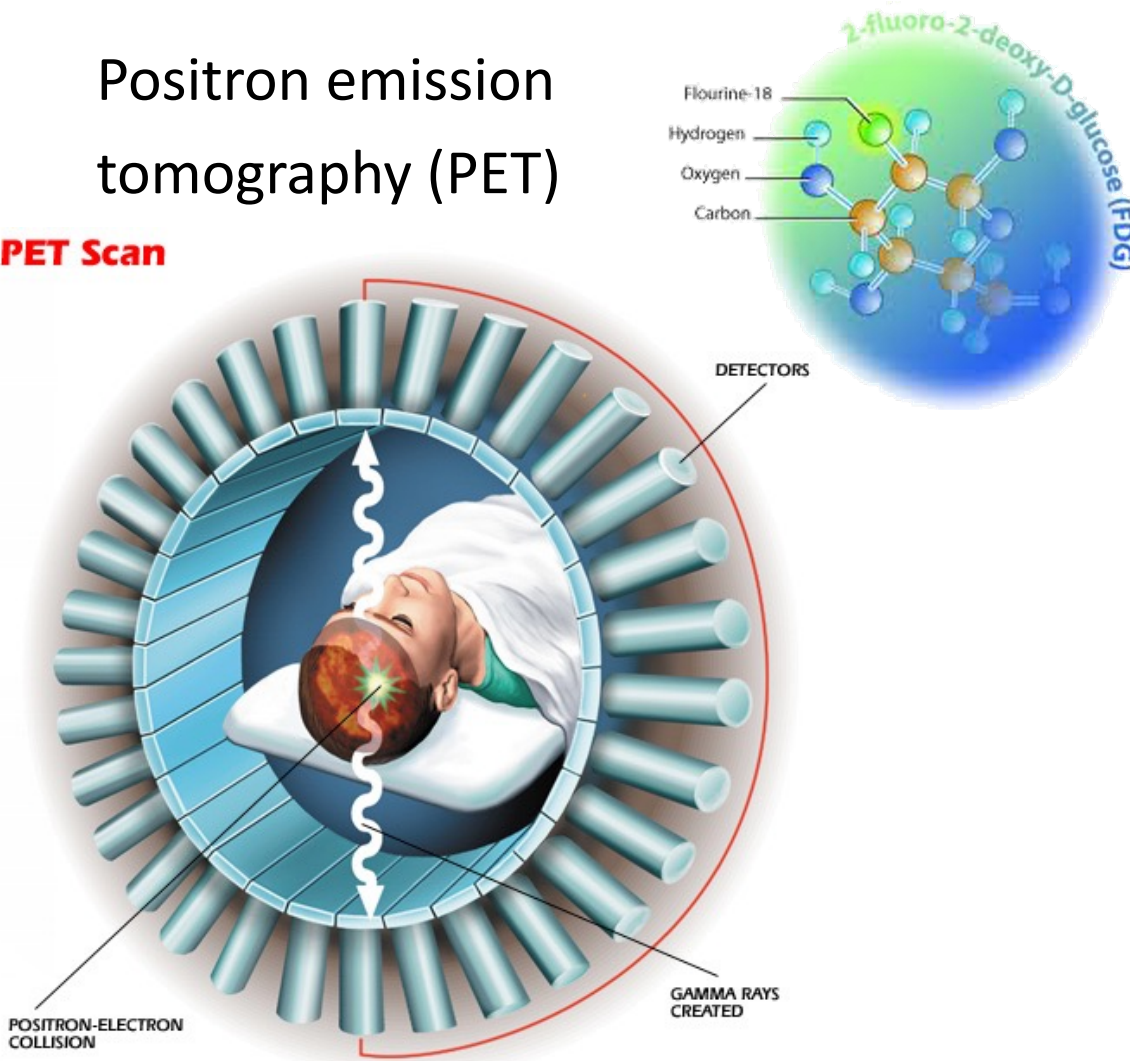
What would be the time difference between two neutrinos of different energies? If the detectors can measure the time with a precision of $\sim 10\text{ns}$, what is the value of L to be sensitive to $m_\nu \sim 0.1\text{ eV}$? Can you think of such a source?



Applications

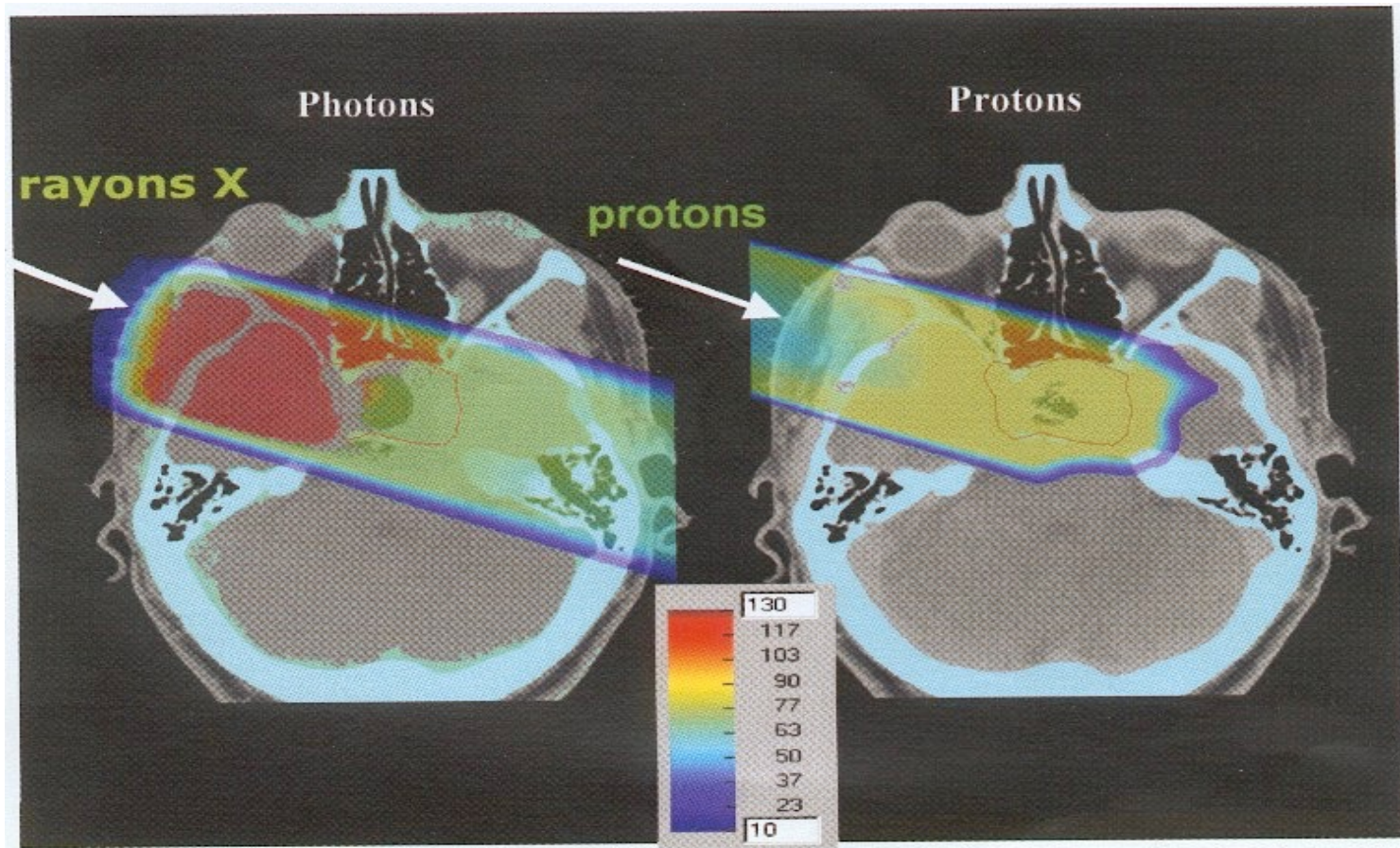
Positron emission tomography (PET)

PET Scan



Applications

- Radiothérapie



Applications

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



Exercise:

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 $\sim 10\text{ns}$, what is the value of L to be sensitive to $m_\nu \sim 0.1\text{ eV}$? Can you think of such a source?

Solution: [arXiv:2203.00024](https://arxiv.org/abs/2203.00024) (F. Pompa et al)

$$t = \text{const} + (L/2c) \times (m_\nu/E_\nu)^2$$