Introduction to Particle Physics

Marie-Hélène Schune and Achille Stocchi
LAL-Orsay   Université Paris-Sud and IN2P3/CNRS

- Introduction to Particle Physics
- The strong interaction
- The weak interaction
- The Standard Model and Higgs
- Few open questions

+ EXCERCISES !

Chapter I

Introduction to Particle Physics

What is particle physics about ?

The particle world

The laws of « this world » are not really intuitive..

e =1.602176462(63) 10^{-19} *C*
m = 9.10938188(72) 10^{-31} kg

Quantum field theory

Relativity

$E = mc^2$
High Energy Physics

Mass/Energy

→ <u>New particles production</u>

Quantum mechanics

$p = h / \lambda$
(physics on extremely small scales)

Particle/Wave

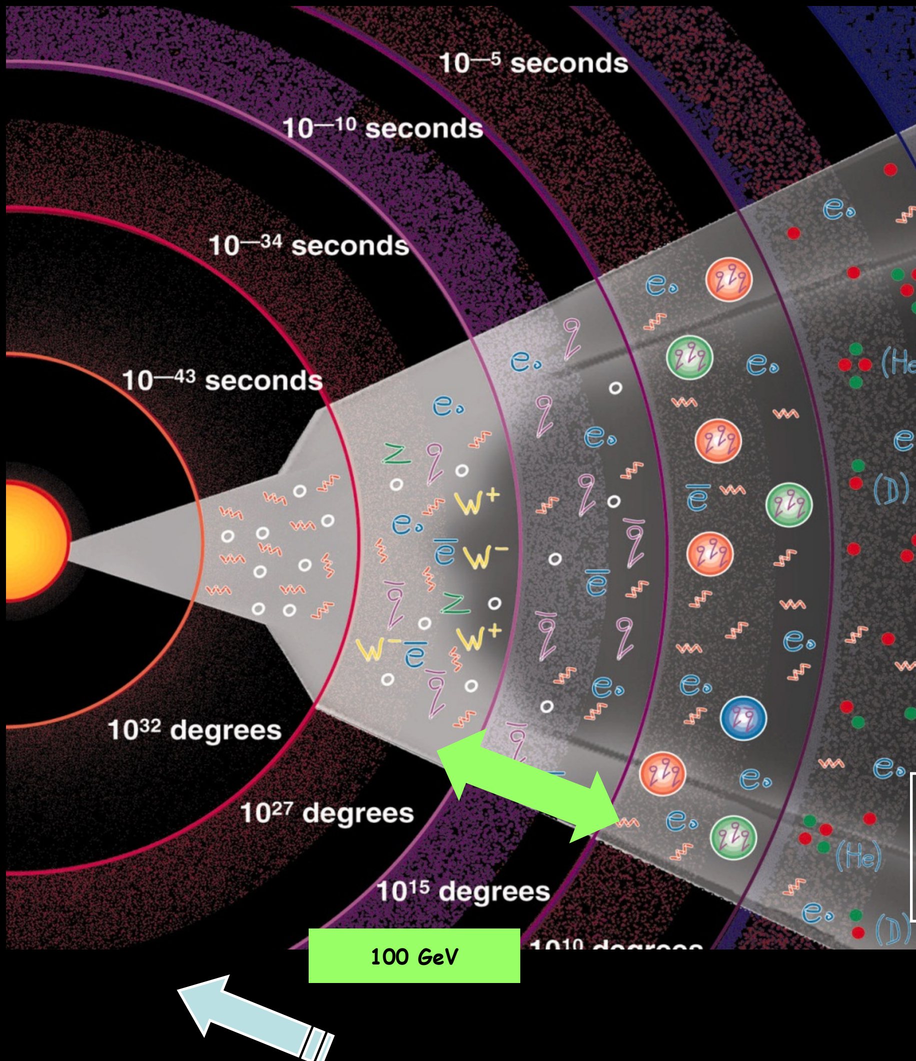
→ <u>Study the matter</u>

<u>Particle world is described by quantum field theory</u>

It is our main working tool for particles physics

It comes from the marriage between <u>quantum mechanics and relativity</u>

The particle world : Physics of the two-infinities



Produce particles at 100GeV ~ 10^{-8} Joule

↓

Temperature ~ 10^{15} degrees

↓

Condition of the Universe after ~10^{-10} sec from Big Bang

Particles (which are very small « objects ») of high energy are instruments to go back in time (very large scales)

The mass

Defined by : $m^2c^4=E^2-p^2c^2$ ← Invariant length of the Energy-momentum 4-vector

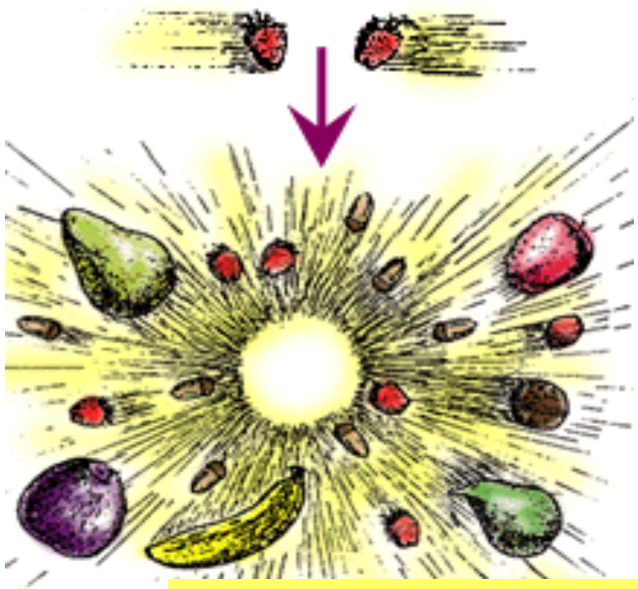
With c=1 E, p and m are expressed using the same unity (GeV/MeV ....)

- When $p=0$ ⇒ $E = mc^2$
- When v increases ⇒ E^2 et p^2c^2 increase but their difference remains constant
- m is a Lorentz invariant

New particles production:

It is not "divisibility" !

Since c is large
small mass
=
Large energy



A particle is a lump of energy

Mass/energy

mass	energy
energy	mass

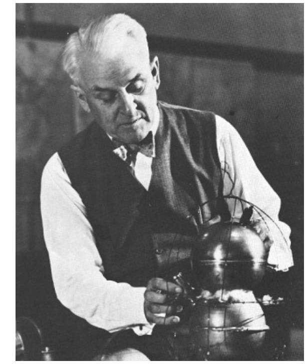
MICROSCOPIC WORLD

Thompson experiment

Determination of m/e for electrons

Determination of the quantum nature and the value of the electric charge for electrons

Millikan experiment



Today

- e =1.602176462(63) 10^{-19} C
- m = 9.10938188(72) 10^{-31} kg

1 Joule =1Coulomb*1 Volt

1eV = Energy for an electron fealing a potential difference of 1 V

1eV = 1.6 10^{-19} Joule

$mc^2 = 9.1\ 10^{-31}\ kg \times (3\ 10^8)^2\ m^2/sec^2 = 50\ 10^4\ eV$

$1eV/c^2 = 1.78\ 10^{-36}$ kg

m_e = 0.5 MeV/c^2 = 0.5 MeV (c=1)

m_p = 938 MeV $\approx$ 1 GeV

KeV (10^3 eV)

MeV (10^6 eV)

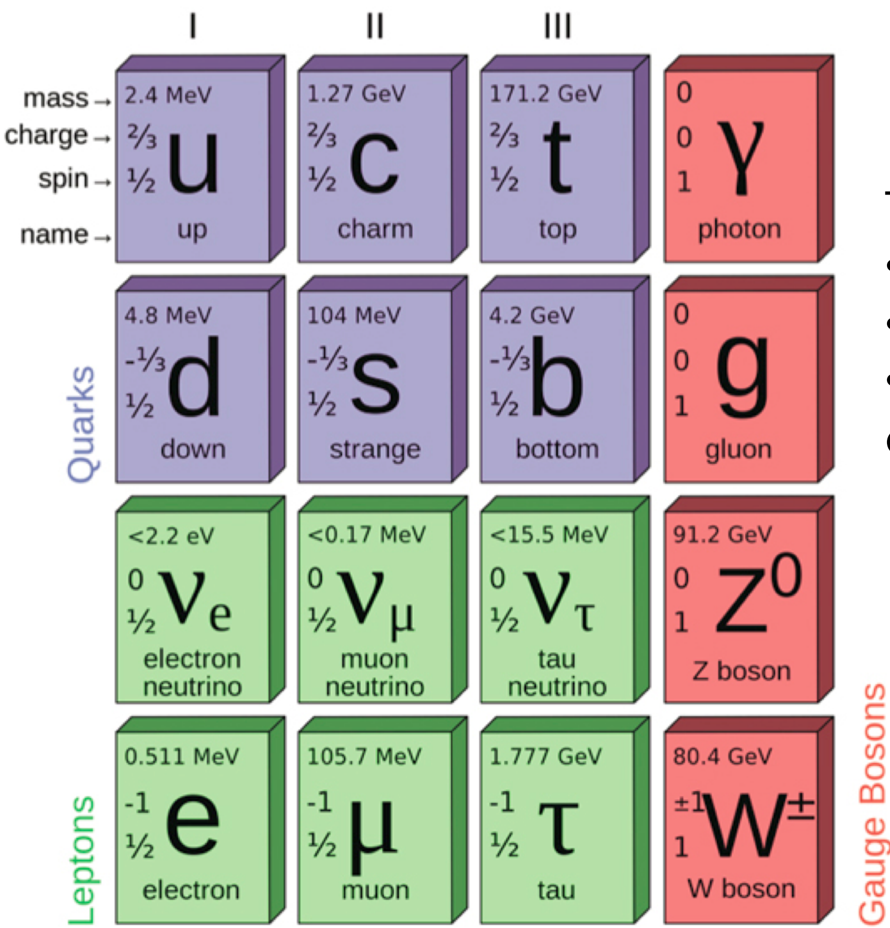
GeV(10^9 eV)

TeV (10^{12} eV)

Elementary particles

3 families of fermions : matter **+ anti-matter !**

3 forces : electromagnetism, weak interaction, strong interaction

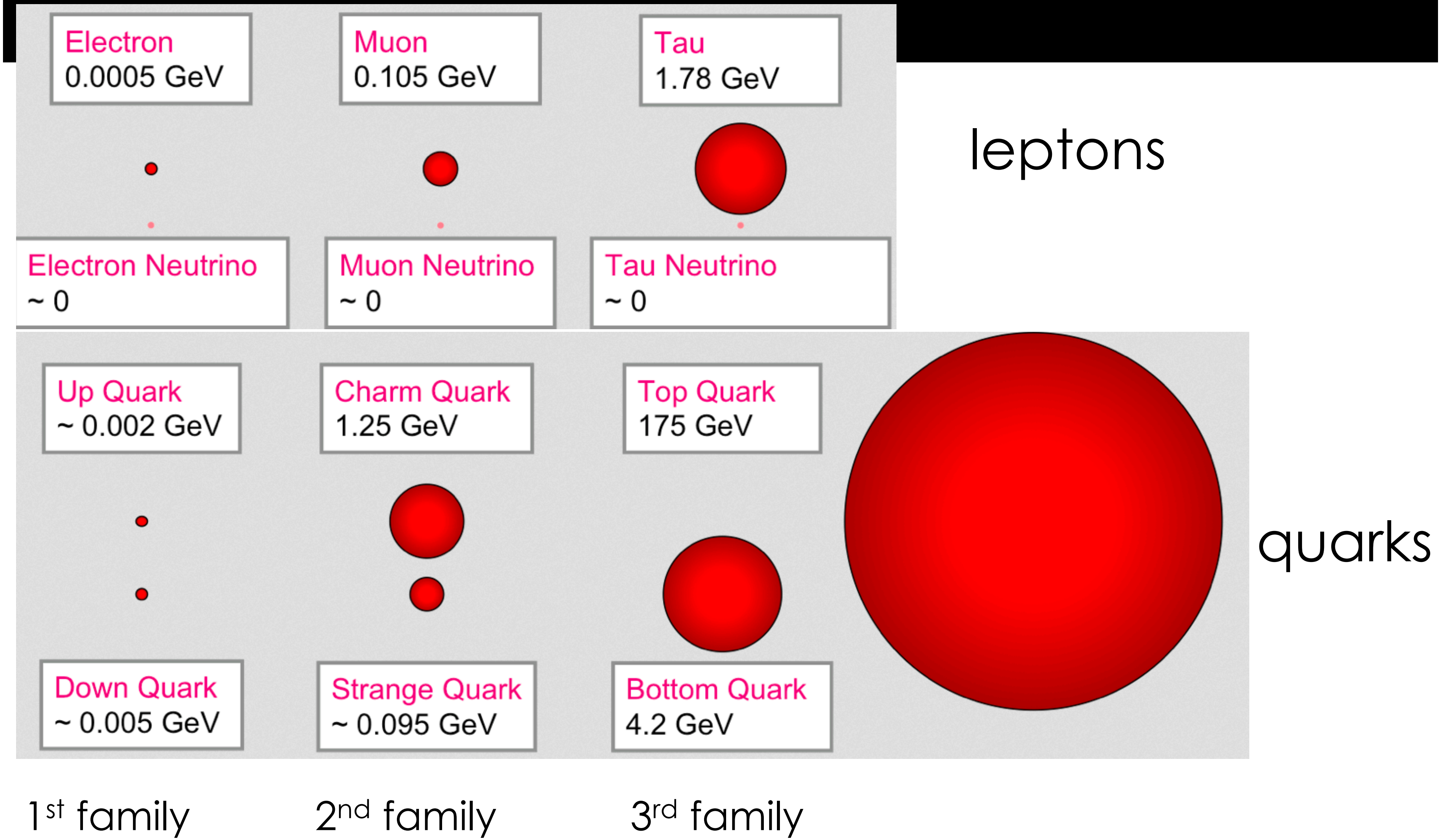


And the Higgs boson !

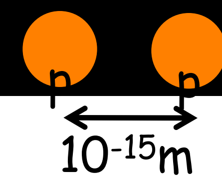
The particles are characterized by :
- their spin
- their mass
- the quantum numbers (charges) determining their interactions

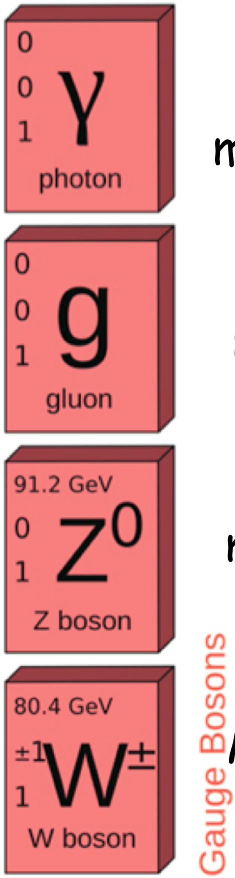
All our knowledge is today « codified » in the **Standard Model** :
Matter, Interaction, Unification Interaction, Unification

The fermions and their masses



The interactions and their mediators





m=0	Electromagnetism	10^{-2}
m=0	Strong interaction	1
m=91.2 GeV	Weak interaction	10^{-8}
M=80.4 GeV		

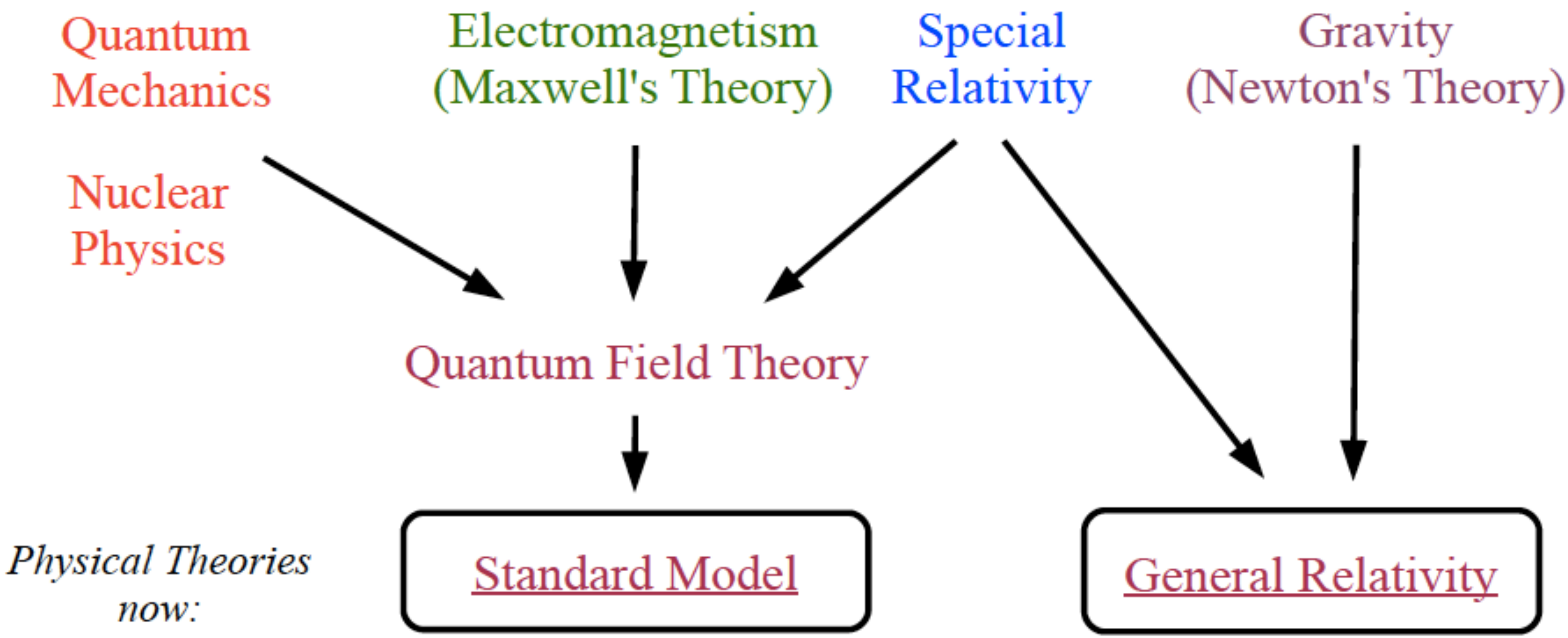
Gravity :
negligible at the scale of elementary particles
We do not know today how to quantify it

Probe the underlying structure of matter

Production of new particles

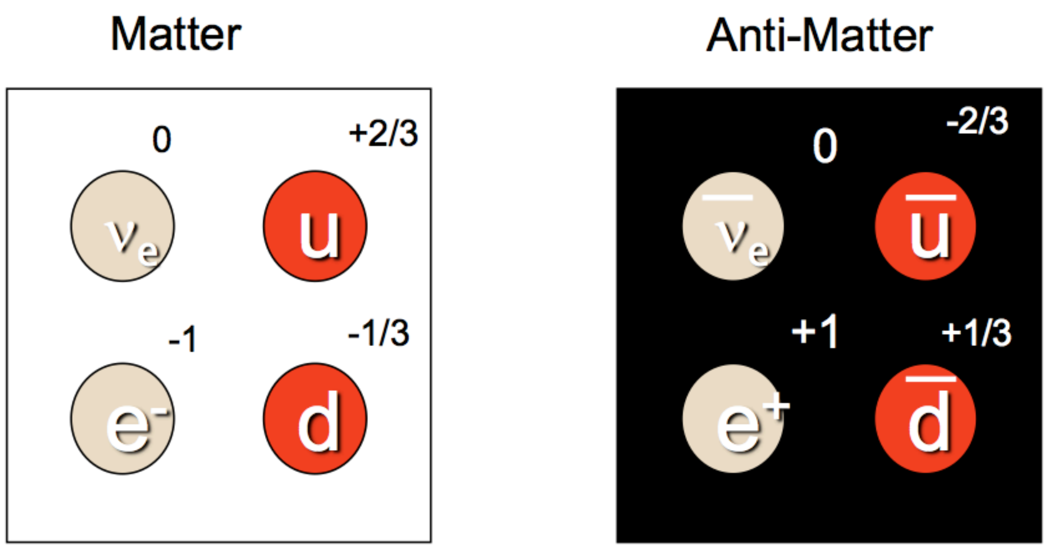
$p = h/\lambda$
(towards the smallest scales)

$E = Mc^2$
(High energy physics



Anti-matter ?

To each particle one can associate an anti-particle : same mass but all quantum numbers opposite



In 1931 Dirac predicts the existence of a particle similar to the electron but of charge +e

Two important observables :

Lifetime/Width : τ / Γ

Cross Section : σ

Lifetime : τ

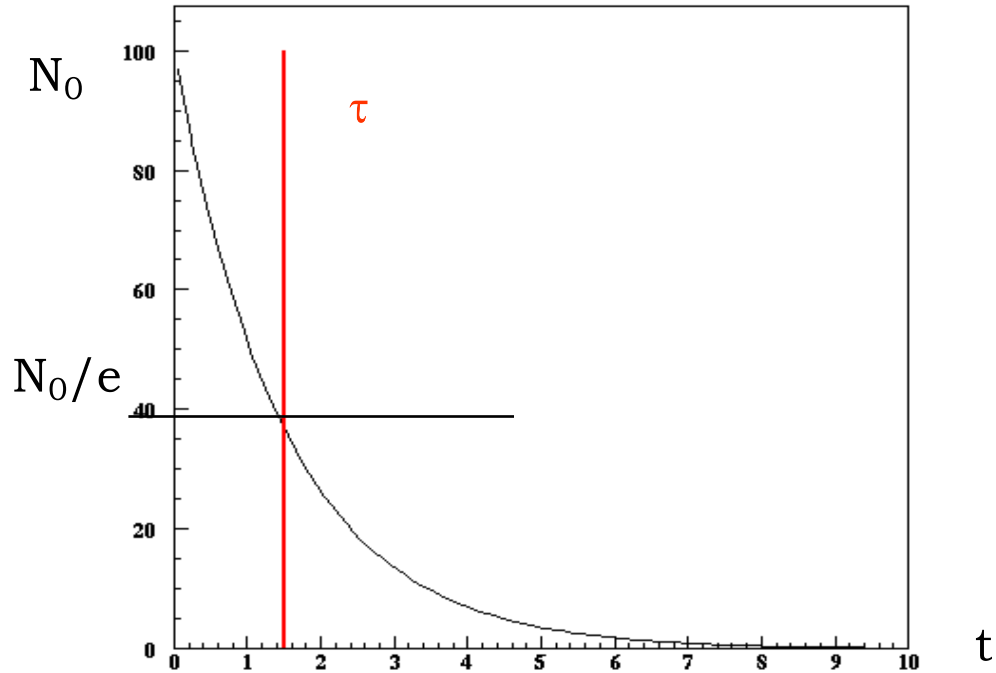
Lifetime : the exponential law

Instable particles and nuclei : number of decays per unit of time ($\Delta N/\Delta T$) proportional to the number of particles/nuclei (N)

$\Delta N = cte \times N \times \Delta t \Rightarrow$ exponential law

$N(t) = N_0 e^{-t/\tau}$

Mean lifetime (defined in the particle rest frame)



The majority of the particles are instable

τ from 10^{-23} sec (resonances)

to $\sim 10^{+3}$ sec (neutron)

The probability for a radioactive nucleus to decay during a time interval *t*, does not depend on the fact that the nucleus has just been produced or exists since a time T :

$$\begin{bmatrix}\textbf{Survival probability}\\ \textbf{after the time T + t}\end{bmatrix} = \begin{bmatrix}\textbf{Survival probability}\\ \textbf{after the time T}\end{bmatrix} \times \begin{bmatrix}\textbf{Survival probability}\\ \textbf{after the time t}\end{bmatrix}$$

$$e^{a+b} = e^a \times e^b$$

Few important examples of different lifetimes

- Stable particles : γ,e,p,ν → the only ones !

proton stability $\tau(p) > \sim 10^{32}$ ans

- particles with long lifetimes :

$n \rightarrow p + e^- + \bar{\nu}_e$ $\tau = 6.13\ 10^{+2}$ sec, β decay

$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$ $\tau = 2.2\ 10^{-6}$ sec, cosmic rays

$\pi^+ \rightarrow \mu^+ \nu_\mu$ (mainly) $\tau = 2.6\ 10^{-8}$ sec

K^+ $\tau = 1.2\ 10^{-8}$ sec

- particle with short lifetimes :

D^+ $\tau = 1.04\ 10^{-12}$ sec

B^+ $\tau = 1.6\ 10^{-12}$ sec

$\Delta^{++} \rightarrow N\,\pi$ $\tau \sim 10^{-23}$ sec

particles which can be directly detected

- The lifetimes are given in the particle rest frame
- What we see is the lifetime in the laboratory rest frame

  → one should take into account the relativistic time dilation

  → In real life one measures lengths in the detector

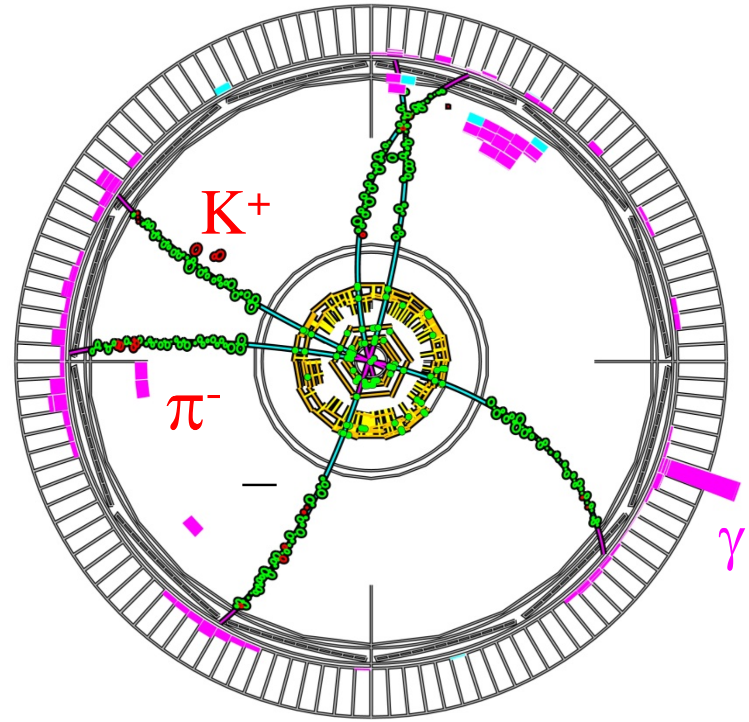
L =	$\beta\gamma$	$\times$	$c\tau$
	Boost	$\times$	lifetime

- Some particles are seen as stable in the detectors.
- Example a pion ($c\tau$ = 7.8m) :

  if E_π = 20 GeV → $\gamma = 20/m_\pi = 142.9$; $\beta = 0.999975$

→ L = 1114.3m

« Event display » of the BELLE experiment
($e^+e^- \to B\bar{B}$, E_{CM}=10.58 GeV)



$B^0 \to K^{*0}\gamma$
$\quad \hookrightarrow K^+\pi^-$

particles which can be directly detected in the detector : n, γ ,e, p, μ, $\pi^\pm$, $K^\pm$

Width : Γ

- The uncertainty principle from Heisenberg for an unstable particle is :

Heisenberg : $\Delta E \, \Delta t \sim \hbar$

$\Delta mc^2 = \Gamma c^2$ → ΔE ; τ → Δt

Uncertainty on the mass (width Γ) due to τ

By definition : $\Gamma c^2 \equiv \frac{\hbar}{\tau}$ ⇒

The faster the decay, the larger the uncertainty on *m*

Stable particle ↔ well defined mass state

$\hbar c = 197 \text{ MeV} \times 1\text{fm}$; $\hbar = \frac{197 \times 10^{-15}}{3.10^{8}} = 6.582\ 10^{-22} \text{MeV.s}$

Measuring widths, one is able to have information on very small lifetimes. This is the way one can have information on a phenomenon extremely fast (the fastest in Nature?...) : a particle with a lifetime of 10^{-23} sec)

Decay	mc²	τ	Γc^2
$K^{*0} \rightarrow K^- \pi^+$	892 MeV	$1.3\ 10^{-23}$ s	51 MeV ← Measurable width
$\pi^0 \rightarrow \gamma\ \gamma$	135 MeV	$8.4\ 10^{-17}$ s	8 eV
$D_s \rightarrow \phi \pi^+$	1969 MeV	$0.5\ 10^{-12}$ s	10^{-3} eV

Measurable lifetimes

Breit-Wigner

(approximate computations)

- Schrödinger equation (free particle with energy E_0):

$$i\hbar\frac{\partial\psi}{\partial t} = H\psi = E_0\psi$$

$$\Rightarrow \psi = ae^{-\frac{i}{\hbar}E_0 t}$$

$$\Rightarrow \psi = ae^{-i\frac{c^2}{\hbar}m_0 t}$$ (particle rest frame $E_0=m_0c^2$)

Message a particle with a given mass and witdh is a resonannce with a Breit-Wigner

  – stable particle : $|\psi(t)|^2 = |\psi(0)|^2 = |a_0|^2$

$$\Gamma c^2 \equiv \frac{\hbar}{\tau}$$

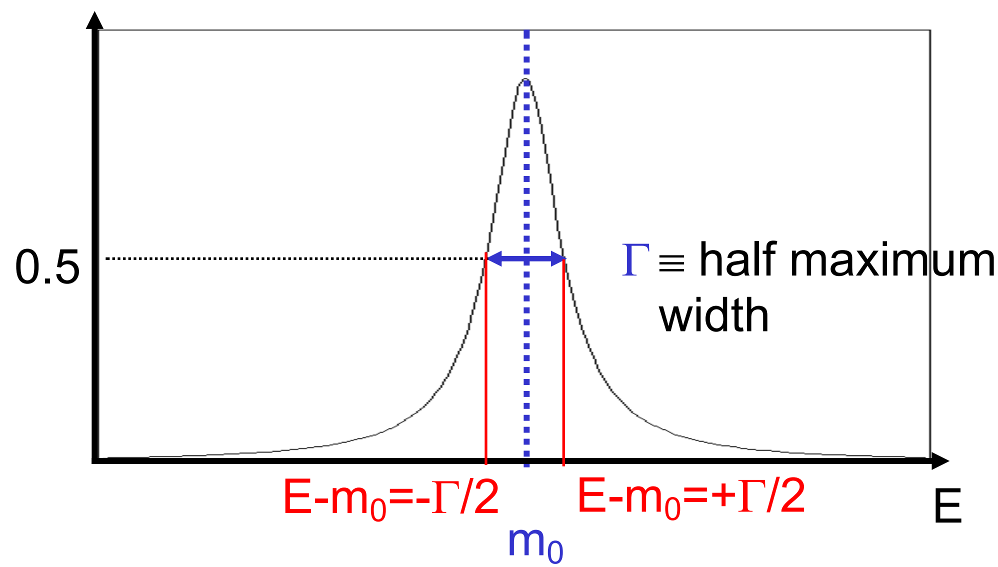
  – unstable particle : $\Rightarrow \psi(t) = a_0 e^{-i\frac{c^2}{\hbar}\left(m_0 - i\frac{\Gamma}{2}\right)t}$ $\Rightarrow a = a_0 e^{-\frac{t}{2\tau}}$ $\Rightarrow |\psi(t)|^2 = |\psi(0)|^2\, e^{-t/\tau}$

We want the probability to find a state of energy E

$$A(E) = \frac{1}{\sqrt{2\pi}}\int_0^{+\infty}\psi(t)e^{\frac{i}{\hbar}Et}dt \propto \frac{1}{\left(E - m_0c^2\right) + i\frac{\Gamma c^2}{2}}$$

Probability = $|A|^2$

$$\Rightarrow |A|^2 \propto \frac{1}{\left(E - m_0c^2\right)^2 + \Gamma^2 c^4/4}$$



Several possible final states (decay modes/channels) :

$\Rightarrow$ branching ratios (BR_i) : probability to obtain a final state i ($\Sigma_i BR_i = 1$)
partial width Γ_i (definition) : $BR_i = \Gamma_i / \Gamma$

Relation between lifetime, partial widths and branching ratios :

$$\tau = \frac{\hbar}{c^2}\frac{1}{\Gamma} = \frac{\hbar}{c^2}\frac{BR_i}{\Gamma_i}$$

Example:

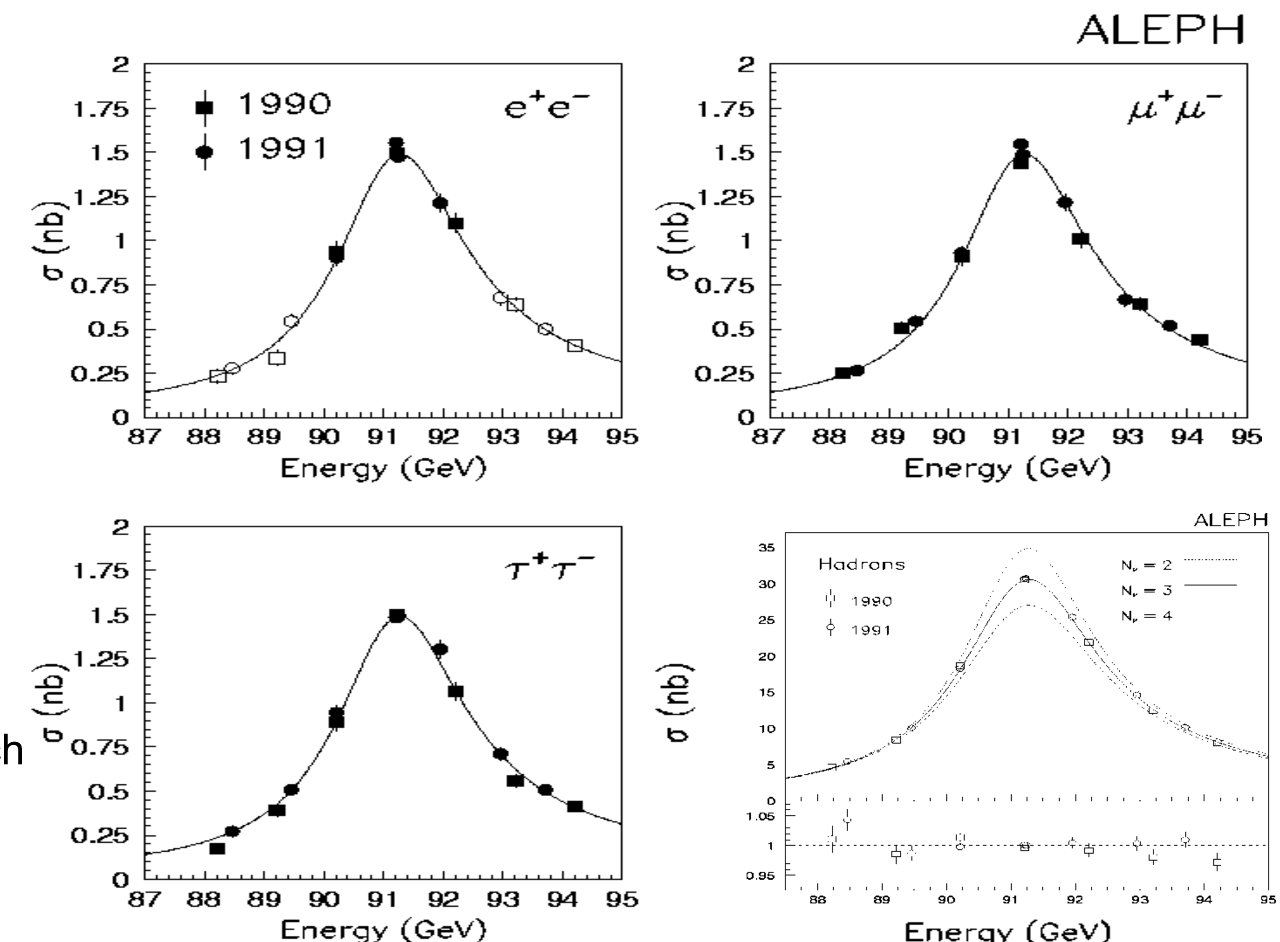
$\Lambda \to p\pi$ in 64 % of the cases

$\Lambda \to n\pi^0$ in 36 % of the cases

Example : Z^0 partial widths

$J = 1$

Charge = 0
Mass $m = 91.1882 \pm 0.0022$ GeV [d]
Full width $\Gamma = 2.4952 \pm 0.0026$ GeV
$\Gamma(\ell^+ \ell^-) = 84.057 \pm 0.099$ MeV [b]
$\Gamma(\text{invisible}) = 499.4 \pm 1.7$ MeV [e]
$\Gamma(\text{hadrons}) = 1743.8 \pm 2.2$ MeV
$\Gamma(\mu^+ \mu^-)/\Gamma(e^+ e^-) = 0.9999 \pm 0.0032$
$\Gamma(\tau^+ \tau^-)/\Gamma(e^+ e^-) = 1.0012 \pm 0.0036$ [f]

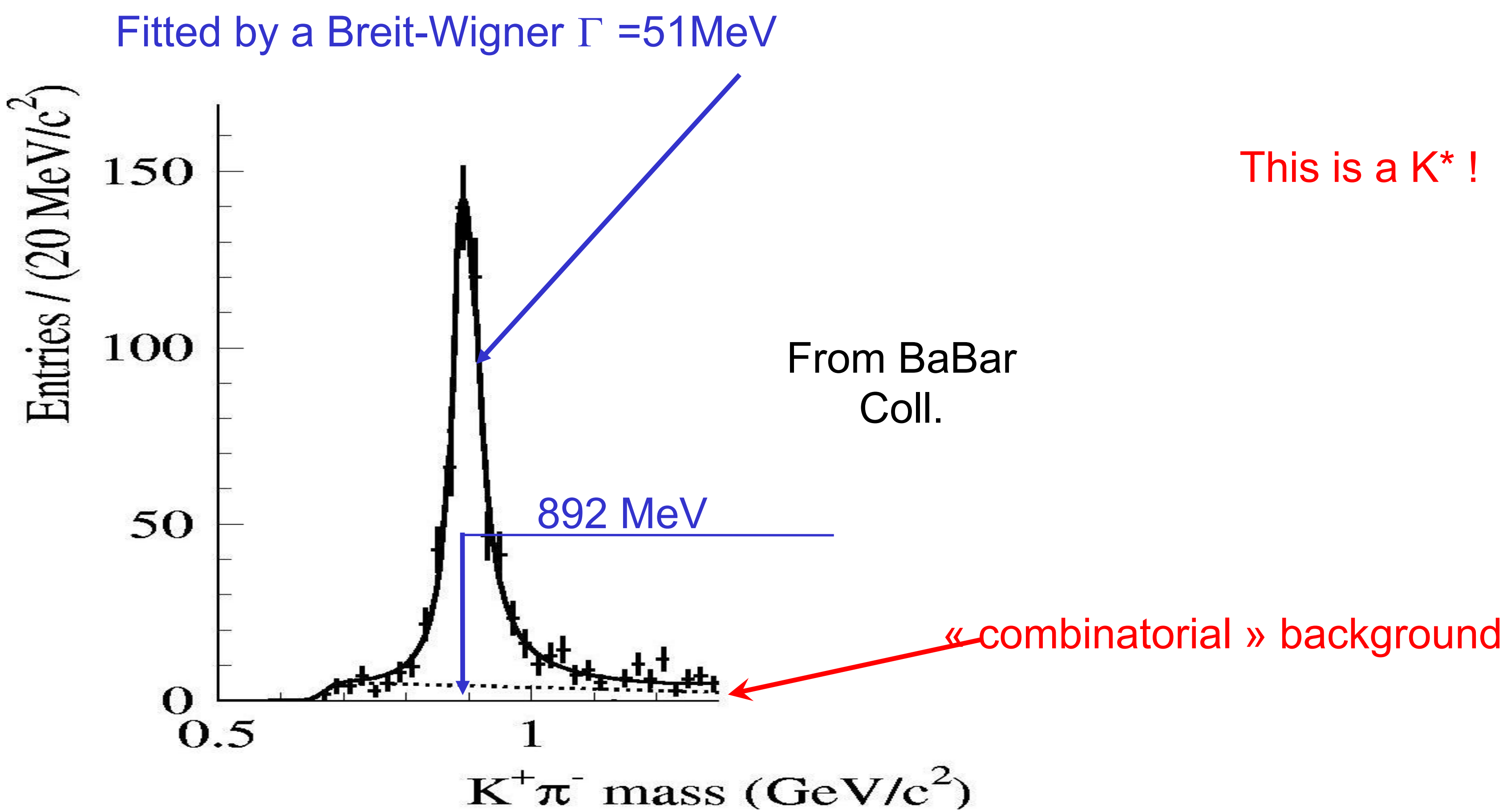


You can see that Z^0 in different decay modes has always the same width which is related to his lifetime

Experimental spectra

<u>experimental spectrum $K^-\pi^+$</u> :

- Search for a K^- and a π^+ in the detector and computation of the invariant mass



π^0 experimental spectrum :

2 γ reconstruction and computation of the invariant mass.

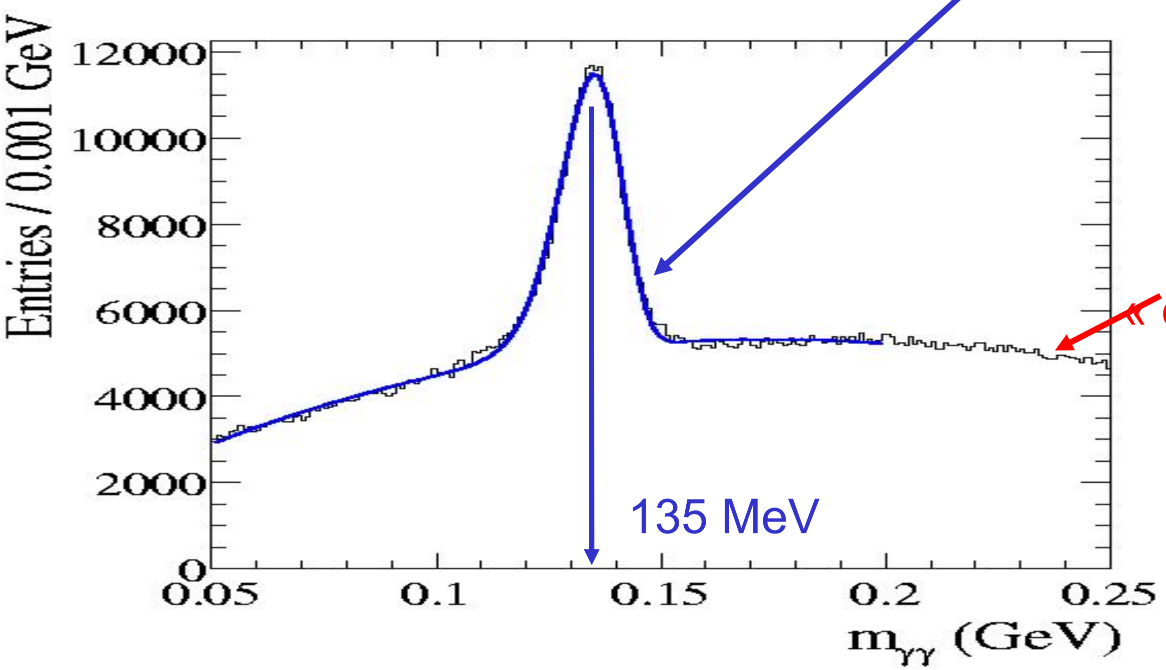
PDG → τ = 8.4 x10^{-17} s ⟷ Γ= 8 eV

Fit by a gaussian

σ ~ 7MeV

?

Detector resolution effect



« combinatorial » background

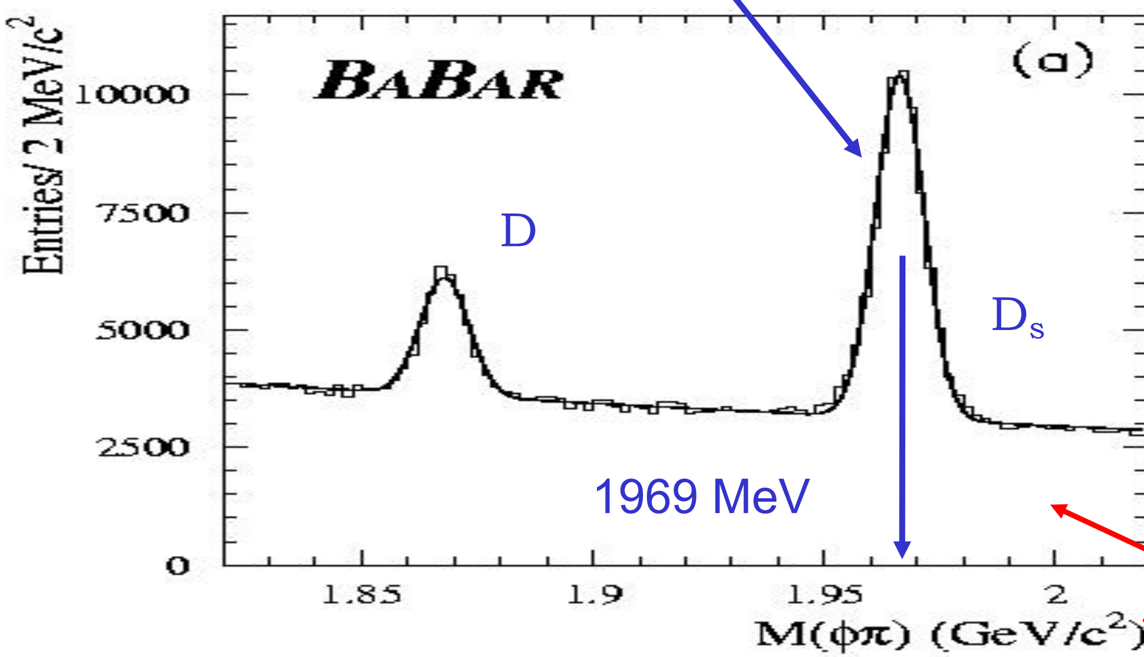
D_s experimental spectrum : ($D_s \to \phi\pi^+$ and $\phi \to \pi^+\pi^-$)

PDG → τ = 500 x10^{-15} s ⟷ $\Gamma \sim 10^{-3}$ eV

But one sees >> 10^{-3} eV

Fit by a gaussian $\sigma \sim$ 10MeV

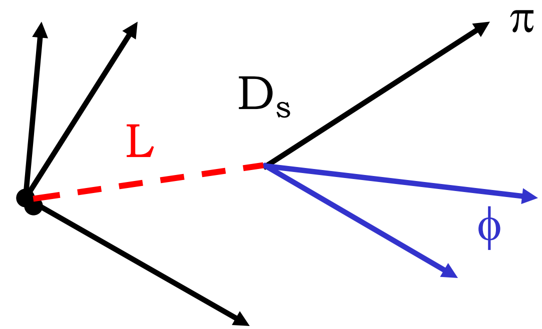
Detector resolution effect



« combinatorial » background

⇒ One measures directly «long » lifetimes not through widths

$\tau(D_s)$:

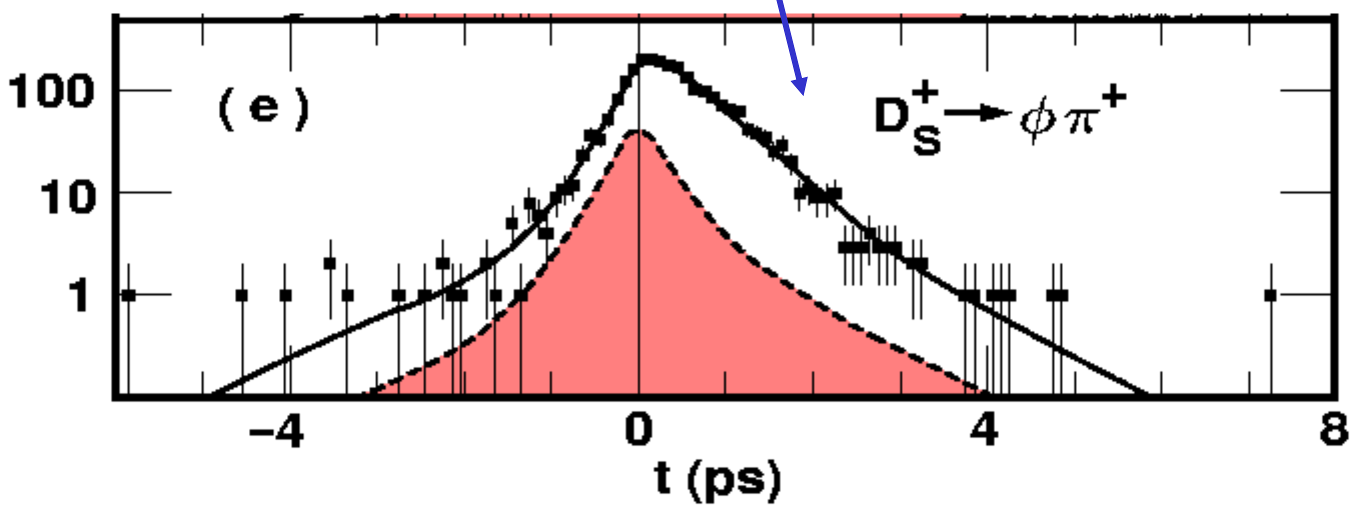


Measurement of the D_s lifetime

$$t = \frac{L \cdot m}{p}$$

t : proper time

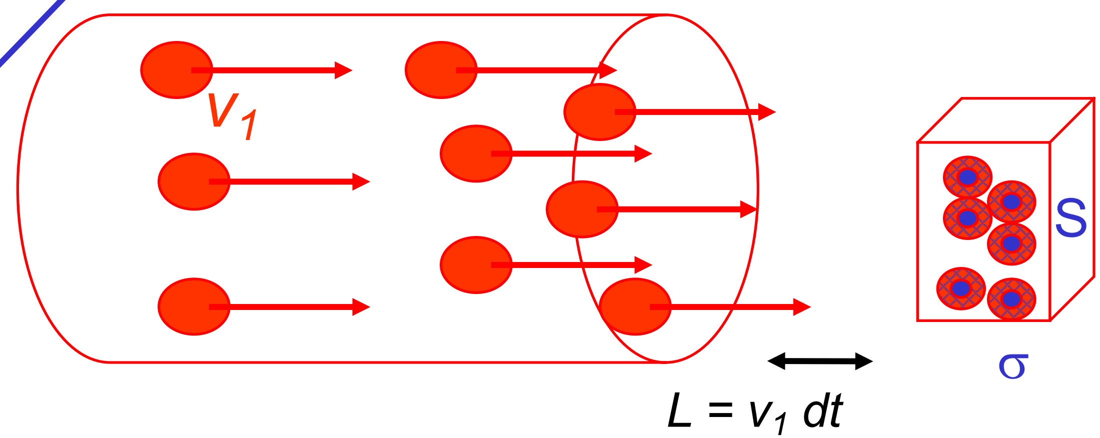
Experiment CLEO : $\tau(D_s) = 486.3 \pm 15.0 \pm 5.0$ fs



Cross Section : σ

Volume of target ($dV=Sdx$)

$$\frac{dN_{int}}{dt} = \quad = F\sigma n_2 dV$$



Flux F=number of particle crossing, in dt, the unity surface ⊥ to $v1$

$F=n_1\ (L/dt) = n_1 v_1$

$$\frac{dN_{int}}{dt\,dV} = n_1 v_1 n_2 \sigma$$

The number of interactions per unit of volume and time is thus defined by

- **The physics processes σ** are « hidden » in this term
- The number of particles per unit of volume in the beam (n_1)
- The number of particles per unit of volume in the target (n_2)

- σ : $[L]^2$
- *1 barn* = 10^{-24} cm^2

Parentheis : From cross section → number of produced event : the luminosity

nstantaneous luminosity

$$\frac{dN}{dt} = L \cdot \sigma$$

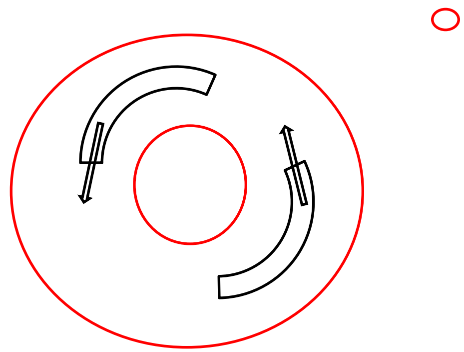
Number of interactions /s

luminosity

$cm^{-2}\ sec^{-1}$

Cross section

$$\frac{dN_{int}}{dtdV} = n_1 v_1 n_2 \sigma$$



Colliding mode

$$\frac{dN}{dt\,dV} = \frac{n1}{V}\frac{d}{c}\frac{n2}{V}\sigma dV = \frac{n1}{2\pi R sxsy}\frac{2\pi R}{c} n2\ \sigma = \frac{n1}{sxsy} f\ n2\sigma$$

$$L = \frac{kfN_+N_-}{\cdot s_x s_y}$$

k bunches

f (=c/circumference) frequency

N_+ : number of electrons in a bunch

N_- : number of positrons in a bunch

An example : PEP-2 (where BaBar detector was installed)

$$I(e) = \left[\frac{C}{s}\right]$$

charge (C), time (s)

$$I(e) = N(e) \times q_e \times N^{e}_{bunches} \times \frac{c}{L_{circ}}$$

Circumference	2200 m
$I(e^-)$	0.75 A
$I(e^+)$	2.16 A
$N_{paquets}$	2 x 1658
$N(e^-)$/bunch	$2.1\ 10^{10}$
$N(e^+)$/bunch	$6.0\ 10^{10}$
Beams size	s_x=150 μm, s_y=5 μm

$$L = \frac{kfN_+N_-}{\cdot s_x s_y}$$

$\Rightarrow$ $L=3\ 10^{33}\ cm^{-2}\ s^{-1}$

Macroscopic quantity → relates the microscopic world (σ) to a number of events

$$\frac{dN}{dt} = L \cdot \sigma$$

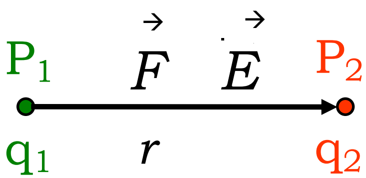
Introduction to the interactions

Interactions : introduction

Classical physics :

The particle P_1 creates around it a force field. If one introduces the particle P_2 in this field it undergoes the force.

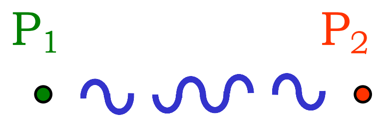
Electrostatic example :



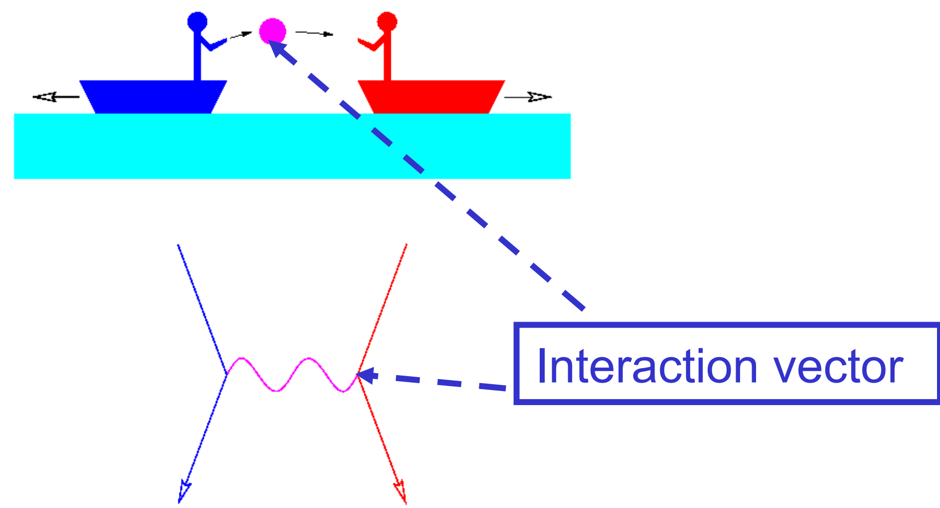
$$\vec{F} = q_2 \vec{E}(r) = q_2 \frac{k q_1}{r^2} \vec{u}_r$$

«modern» physics:

P_1 and P_2 exchange a field quantum; the interaction boson



The **heavier** the ball, the more difficult it will be to throw it **far away**



Range of the interaction $\propto$ 1/mass of the vector

Range of an interaction

Not exact. Heuristic

- Creation and exchange of an interaction particle
  $\Rightarrow$ violation of the energy conservation principle during a limited time

$$\Delta t \approx \frac{\hbar}{\Delta E} = \frac{\hbar}{mc^2}$$

Heisenberg principle

- During Δt the particle can travel $R = c\,\Delta t$

$$R = \frac{\hbar c}{mc^2}$$

Range → « reduced » wave length (Compton)

with $\hbar c \cong 197.3\ MeV\ fm$

Example : an interaction particle with $m = 200\ MeV \Leftrightarrow R = 1\ fm$

Force	Relative intensity (order of magnitude)	Vector	Lifetime (order of magnitude)
Strong	1	Gluons	10^{-24} s
electromagnetic	10^{-2}	Photon	10^{-19} - 10^{-20} s
Weak	10^{-5}	W and Z^0	10^{-16} - 10^{+3} s
Gravitation	10^{-40}	Graviton	???

For the strong, electromagnetic and gravitational interactions these orders of magnitudes can be obtained comparing the binding energy of 2 protons separated by ~1fm

The intensity of the interactions dictates the particles lifetimes and their interaction cross sections.

Shape of the interaction potential

Klein-Gordon equation for a spin 0 particle :

$$E^2 = p^2c^2 + m^2c^4$$

operators: $E = i\hbar \frac{\partial}{\partial t}$, $p = -i\hbar\nabla$

$$(i\hbar)^2 \frac{\partial^2 \psi}{\partial t^2} = (i\hbar)^2 c^2 \nabla^2 \psi + m^2c^4\psi$$

$$-\frac{\partial^2 \psi}{\partial t^2} = -c^2\nabla^2\psi + \frac{m^2c^4}{\hbar^2}\psi$$

$$\Rightarrow \nabla^2\psi - \frac{m^2c^2}{\hbar^2}\psi - \frac{1}{c^2}\frac{\partial^2\psi}{\partial t^2} = 0$$

(one only deals with stationary states)

$$\nabla^2\psi - \frac{m^2c^2}{\hbar^2}\psi = 0$$

In spherical symmetry : $\psi = U(r)$ and $\Delta U(r) = \nabla^2 U(r) = \frac{1}{r^2}\frac{d}{dr}\left(r^2 \frac{dU(r)}{dr}\right) = \frac{m^2c^2}{\hbar^2}U(r)$

if $m \neq 0$:

$$U(r) = -\frac{g^2}{r}e^{-r/R}$$

$r>0$

Yukawa potential

g coupling constant

$$R = \frac{\hbar}{mc}$$

Range

if $m=0$:

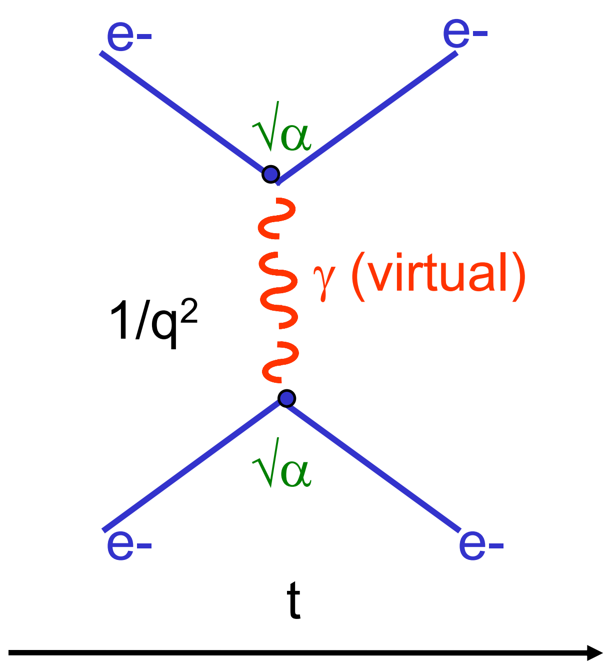
$r>0$

q_i = charge

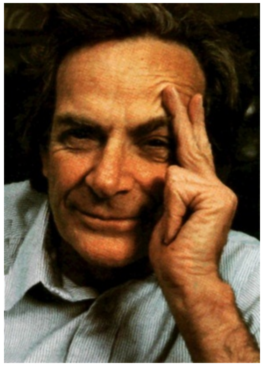
In this case the Yukawa potential is equivalent to the Coulomb one

Electromagnetism (QED)

- Between charged particles
- Vector of the interaction : the photon (γ)
- One Feynman graph for QED:



R. Feynman



electrons exchanging a photon

or

An e^- which emits a γ and moves back. The γ is absorbed by an other e^- whose direction is modified

Feynman graph

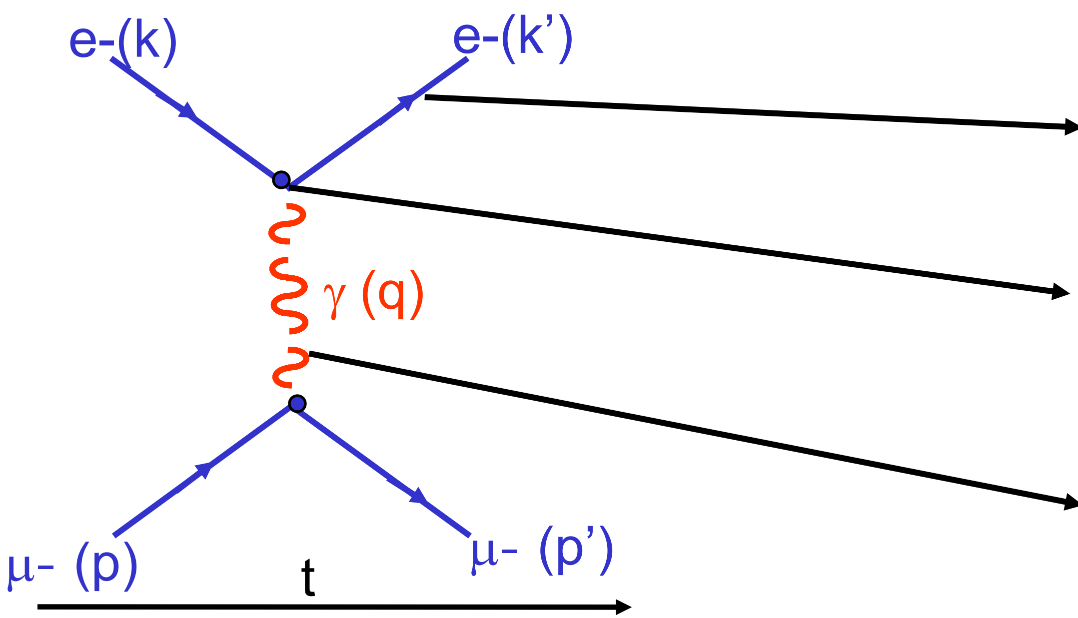
- A powerful « graphical » method to display the interaction in perturbations theory (each diagram is a term in the perturbation series)
- Each graph is equivalent to « a number »

$\forall$ $\rightarrow$ computation of the matrix elements and of the transition probabilities

particle

Vector boson of the interaction

- Horizontal axis : the time
- Lines are particles which propagate in space-time
- The ● represent the vertices «location» of the interaction (where there is quantum number conservation)



Feynman rules :

External lines: fields (spinors, vectors, …)

Vertex: $\sqrt{\alpha}$ factor in the matrix element « interaction intensity »

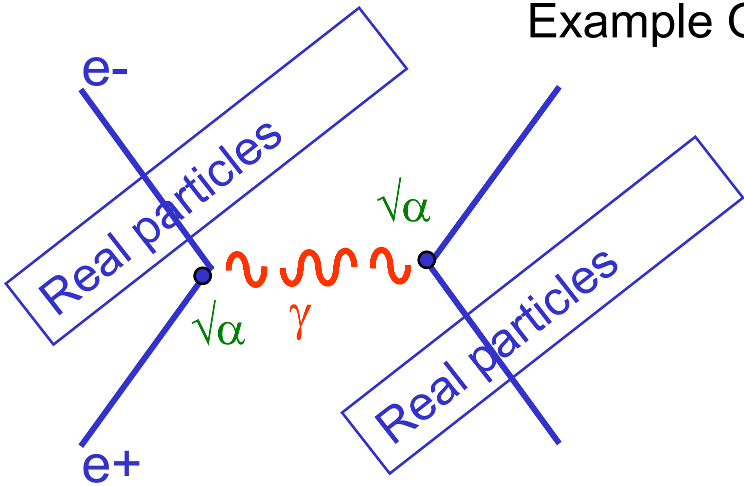
Propagator:

factor $ig_{\upsilon\nu}/(q^2-m^2)$ (depends also on spin …)

$$\alpha = \frac{e^2}{4\pi\varepsilon_0 \hbar c} = \frac{1}{137}$$

Virtual particles

Example QED : e^+e^- symmetric collision in the rest frame



$$E_{e+} + E_{e-} = E_\gamma$$

$$\vec{p}_+ + \vec{p}_- = \vec{p}_\gamma$$

$$m_\gamma^2 = 2m_e^2 + 2E_{e+}E_{e-} - 2p_+p_-\cos\theta$$

In the rest frame : $\vec{p}_+ + \vec{p}_- = \vec{p}_\gamma = \vec{0}$

$$\theta = \pi \Rightarrow m_\gamma^2 = 2m_e^2 + 2E_{e+}E_{e-} + 2p_+p_-$$

incompatible with $m_\gamma = 0$

The γ is « off-shell »

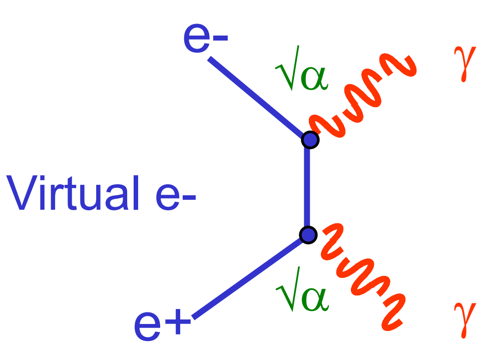
It can be interpreted as :

Violation of the energy-momentum conservation law

Or

Creation of a massive virtual photon during a « short » time

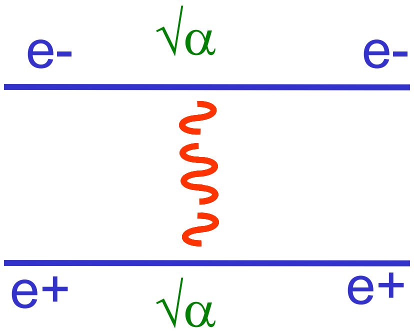
the γ can only exist virtually thanks to $\Delta E . \Delta t \approx \hbar$



2 γ production going in opposite directions

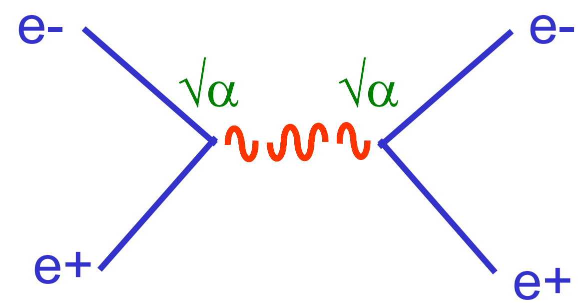
→ energy-momentum conservation

$e^+e^- \rightarrow e^+e^-$ interaction



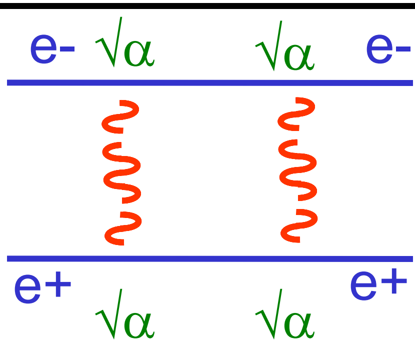
γ exchange between an e+ and an e-

+

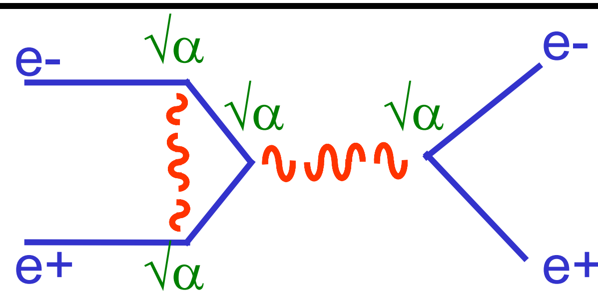


e+e- pair annihilation in γ and γ conversion in an e+ and an e-

$\sim\alpha$



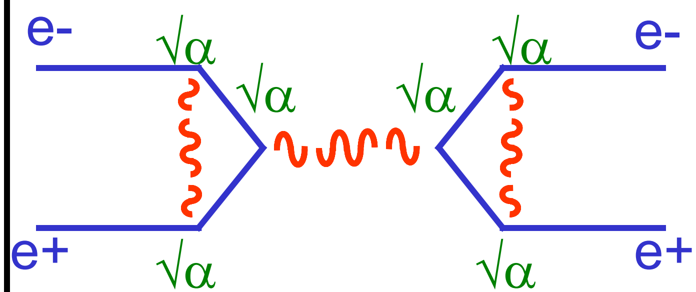
+



+ …

$\sim\alpha^2$

exchange of 2 γ between an e+ and an e-



+ …

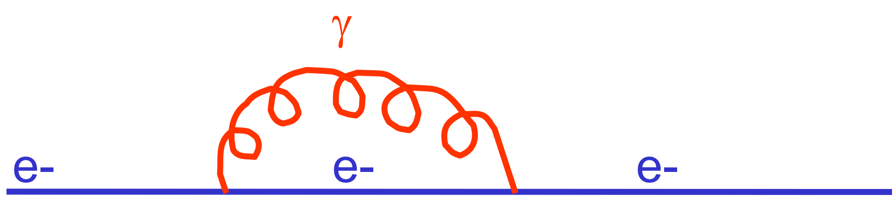
$\sim\alpha^3$

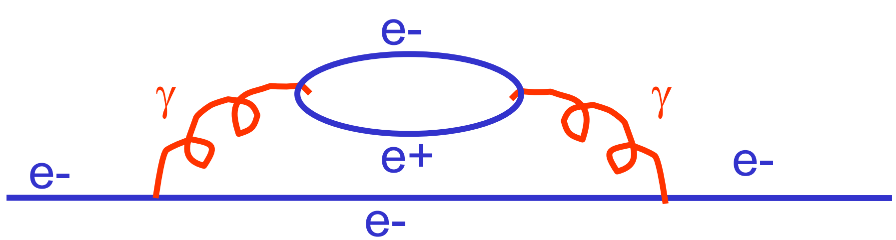
α small (1/137) : one can develop in perturbation series

The way we see the electron and the photon is modified

electron :

The electron emits and absorbs all the time virtual γ, it can be seen as :

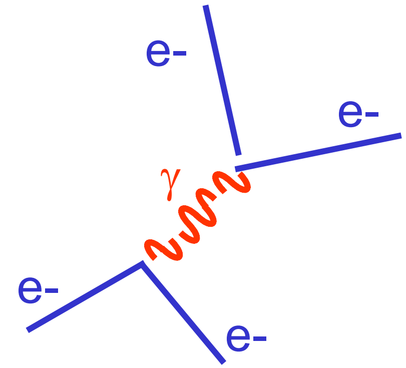


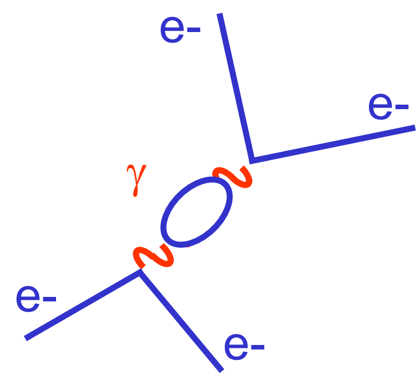


…

=> Theoretical (α « running »), Vacuum polarization and experimental (g-2) consequences

photon :

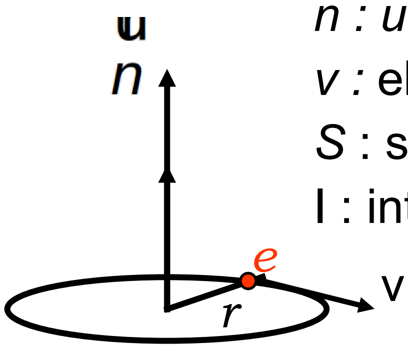




(g-2) : Experimental evidence of the vacuum polarisation

Gyro-magnetic ratio g

- The magnetic moment associated associated to the angular momentum of the electron



n : unity vector
v : electron speed
S : surface
I : intensity = charge / time

$$\vec{\mu} = I\,S\,\vec{n} = \frac{e}{\frac{2\pi r}{v}}\pi r^2\,\vec{n} = \frac{e}{2m}(mvr)\,\vec{n}$$

Angular momentum $\hbar\ell$

$$\mu = \mu_B \ell \quad \text{with} \quad \mu_B = \frac{e\hbar}{2m}$$

Bohr magneton

$$\vec{\mu} = \mu_B \vec{L}$$

- Intrinsic magnetic momentum :

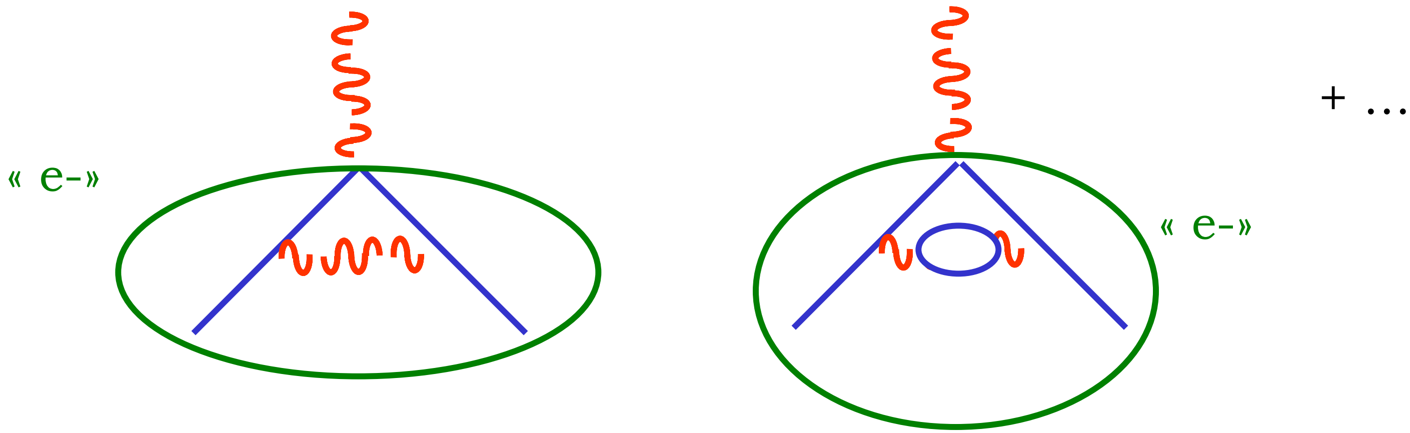
$$\vec{\mu} = g\,\mu_B\,\vec{S}$$

spin

gyro-magnetic spin ratio

Dirac : for spin ½ point-like particles : *g*=2

The value of g is modified by :



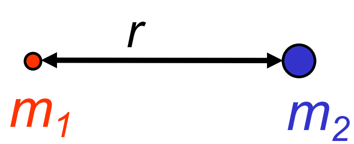
One defines $a = \frac{g-2}{2} = \frac{g}{2} - 1 = \frac{\alpha}{2\pi} + \ldots \approx \frac{1}{800}$

a=0.00115965241 ± 0.00000000020 experiment (10^{-11} precision)

a=0.00115965238 ±0.00000000026 theory (α^3)

Gravitational Force

$$F = \frac{Gm_1m_2}{r^2}$$



$$G = 6.67259(85)10^{-11}\frac{\text{m}^3}{\text{kg sec}^2}$$

Newton constant

To compare with the electromagnetic force for the hydrogen atom

$\dfrac{e^2}{4\pi\varepsilon_0 \hbar c} = \alpha$ � $\dfrac{1}{137}$

$$\frac{Gm_e m_p}{\hbar c} = \alpha_{grav} \approx 3.3\times 10^{-42}$$

The effects of gravitation are very small at the atom scale ➔ neglected..

- Important effects if α_{grav} ~1

$$\frac{Gm^2}{\hbar c} \sim 1 \Rightarrow mc^2 \sim 10^{19}\,GeV$$

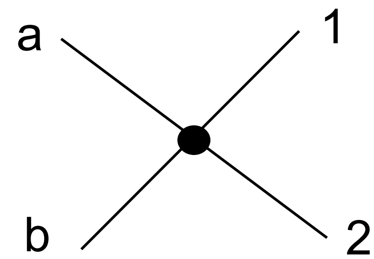
Masse de Planck

- For energies much lower than 10^{19} GeV we can neglect gravitational effects
- Actually there is not satisfactory theory for gravitation

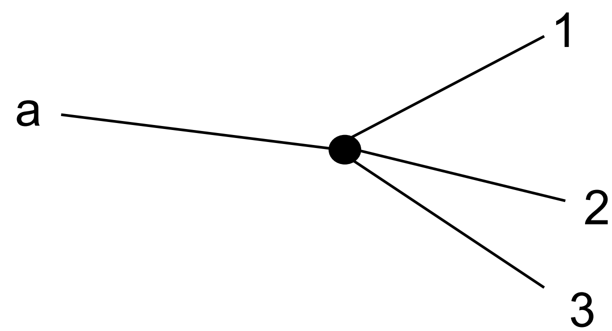
More in details on cross section and width.

The total **cross section** σ for a collision is $a+b \rightarrow 1+2+\ldots$

The **width for a decay** Γ is $a \rightarrow 1+2+\ldots\ n$



Both are described by Feymann diagrams



All traduce the probability that a pheomena occurs.

$$\sigma\,,\Gamma \sim \textbf{Kinematics} \times \textbf{Physics}$$

Why « **Kinematics** » ? Because the probability that a phenomena occurs depends on the number of kinematical configurations « opened » for the process. More configurations opened → larger cross section and larger width (or smaller lifetime).

What we have in « **Physics** » ? For instance we have couplings ! Stronger is the coupling → larger cross section and larger width (or smaller lifetime).

Interactions : summary

- The interactions are mediated by vector bosons
  interaction range $\propto$ 1/mass
- Feynman graph = display of a matrix element of the transition in the perturbations series framework
- Virtual particles (off-shell particles during a short time)

- QED: electric charge, γ, vacuum polarisation, α ↗ with energy

Strong interaction (discussed in devoted lectures)

Weak interaction (discussed in devoted lectures)

- QCD: colour, gluons (self-interaction), α_s ↘ with energy (asymptotic freedom)
- Weak: concerns all fermions, $W^{\pm}$,Z^0