High energy physics for pedestrians

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Orsay

1. Forces and interactions
2. Standard Model
3. Experimental aspects
4. Open questions and future

- Apologies for high energy physicists
- Compilation of some ideas/problems, but not in chronological order
- In principle, transparencies are self-consistent
- Will not speak of neutrino physics
- Assume electromagnetism is known. I will use a little special relativity and quantum mechanics

Some orders of magnitude

- Energies are measured in eV (1 eV ≡ 1,6 10^{-19} J),
  - keV (10^3 eV), MeV (10^6 eV), GeV (10^9 eV), TeV (10^{12} eV)

- Maximum energy artificially given to particules is
  - electrons: around 100 GeV (LEP II)
  - protons: 3.5 TeV at LHC (ultimately 7 TeV)

- Higher energy particles exist in Universe, but we do not know their acceleration mechanism (see for instance Auger experiment)

« High energy » collisions

- At macroscopic scale, « high energy » is very low:
  - Ultimate LHC : 7 TeV
    - $\Rightarrow E_{LHC} = 14\ 10^{12}$ eV
  - High speed bee (1 g = 5,8 10^{32} eV/c^2 et v = 1 m/s)
    - $\Rightarrow E_{Bee} = 10^{-3}$ J = 6,25 10^{15} eV
  - However, energy density is very high

- Total beam energy is huge:
  - Nominal LHC : 10^{14} protons
    - $\Rightarrow E_{Beam} = 10^{14} \times 14\ 10^{12} \approx 10^{8}$ J
    - Kinetic energy of a 100 t truck running at 120 km/h

High energy and special relativity

- Main property: the speed of light (photon) is *c* in any reference frame

- Particules in high energy physics are ultra-relativistic:
  - Special relativity
  - Moving frame is the particule one's
  - Rest frame is the lab one's

- No influence of gravitation in HEP

$$\begin{cases} F^{EM} \propto \dfrac{1}{r^2} \\ F^{G} \propto \dfrac{1}{r^2} \end{cases} \qquad \frac{F^{EM}}{F^{G}} \approx 10^{39} - 10^{42}$$

- Energy and momentum verifies :

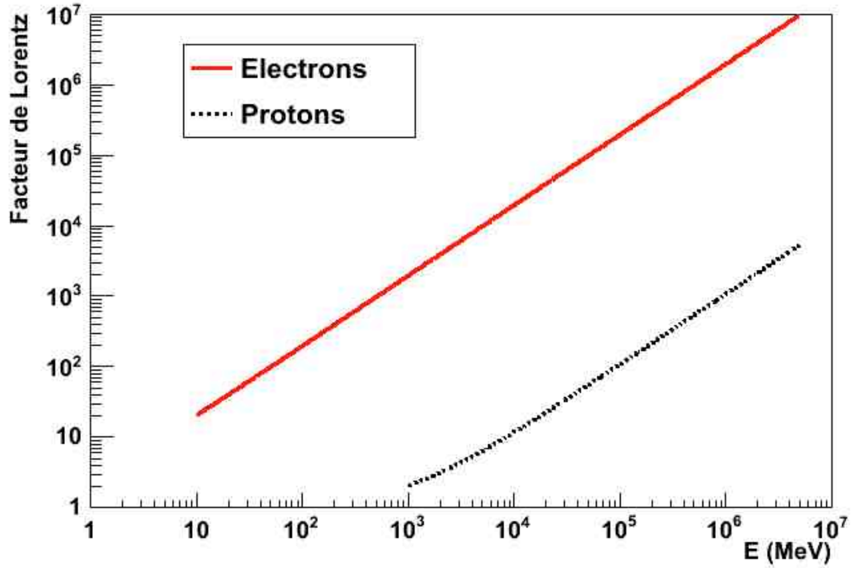
$$\begin{cases} E = \gamma m c^2 \\ p = m \gamma \beta c \approx m \gamma c \end{cases} \qquad \begin{cases} \beta = \frac{v}{c} = \frac{p c}{E} \\ \gamma = \frac{1}{\sqrt{1-\beta^2}} \end{cases}$$

  - Very useful: $E^2 = p^2 c^2 + m^2 c^4$

- For 7 TeV p or 50 GeV e^-:

$$\gamma_p = \frac{7000}{0.938} \approx 7460$$

$$\gamma_e = \frac{50000}{0.511} \approx 98000$$



- The relevant quantity is no longer speed but energy:

	PS (28 GeV)	SPS (450 GeV)	LHC (7000 GeV)
Speed	0.9989 c	0.99996 c	0,99999998 c

- In special relativity, only momentum and total energy are conserved (not the mass)

- Special relativity: $E^2 = p^2 c^2 + m^2 c^4$
  - Momentum are measured in MeV/c ou GeV/c
  - Masses are measured in MeV/c^2 ou GeV/c^2
  - We sometimes forget « /c » ou « /c^2 », ie « proton mass is 938,27 MeV »
  - In fact, real proton mass is:

$$m_p = \frac{(938{,}27 \times 10^{6}) \times (1{,}6 \times 10^{-19})}{(3 \times 10^{8})^{2}} = 1{,}66 \times 10^{-27}\ \text{kg}$$

- In high energy physics, we always have $p\,c \gg m\,c^2$.
  - *pc* et *E* are not distinguished: speaking of « 50 GeV electrons » or « 7 TeV protons », we do not precise if this is their momentunm or their energy

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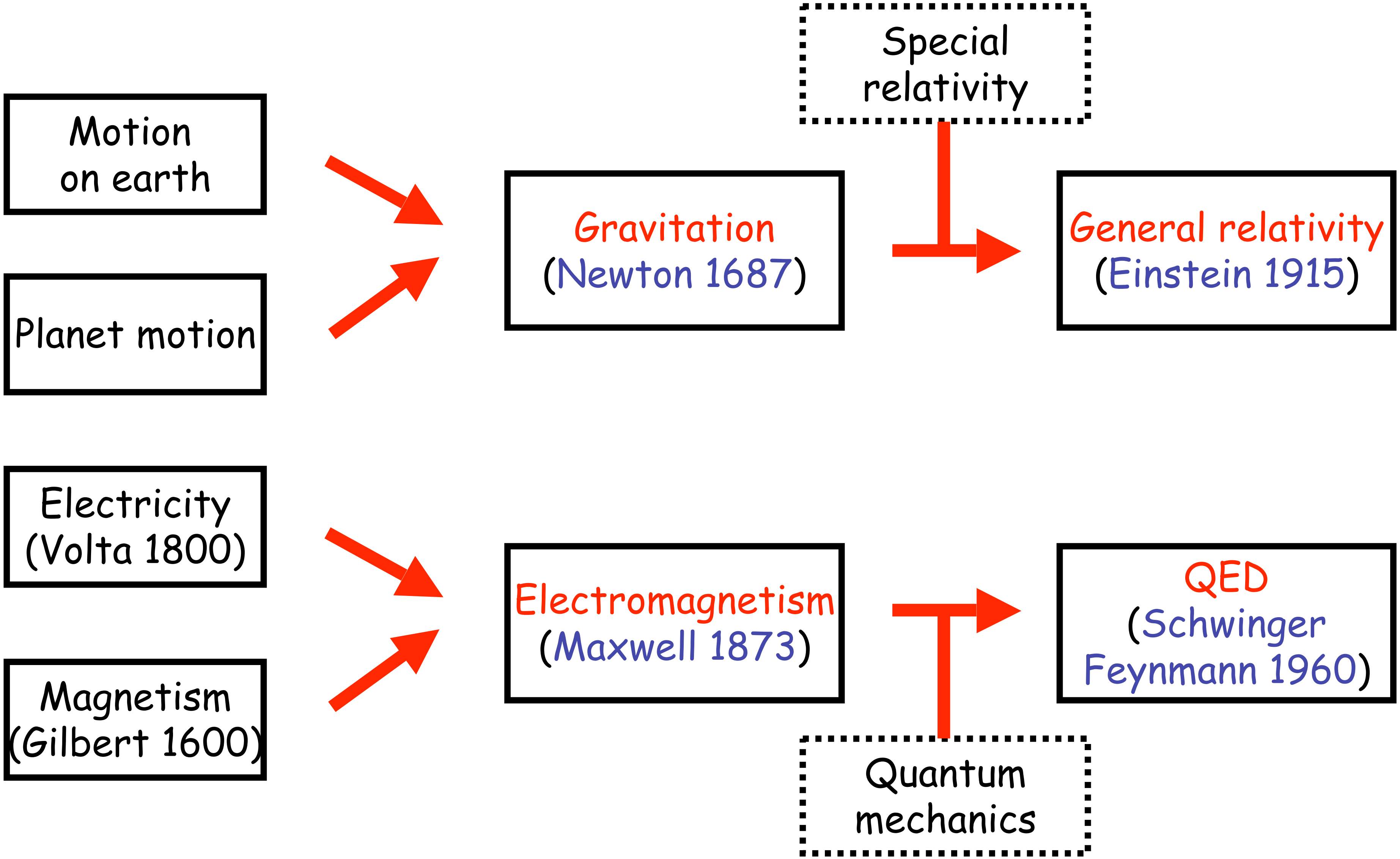
First unifications



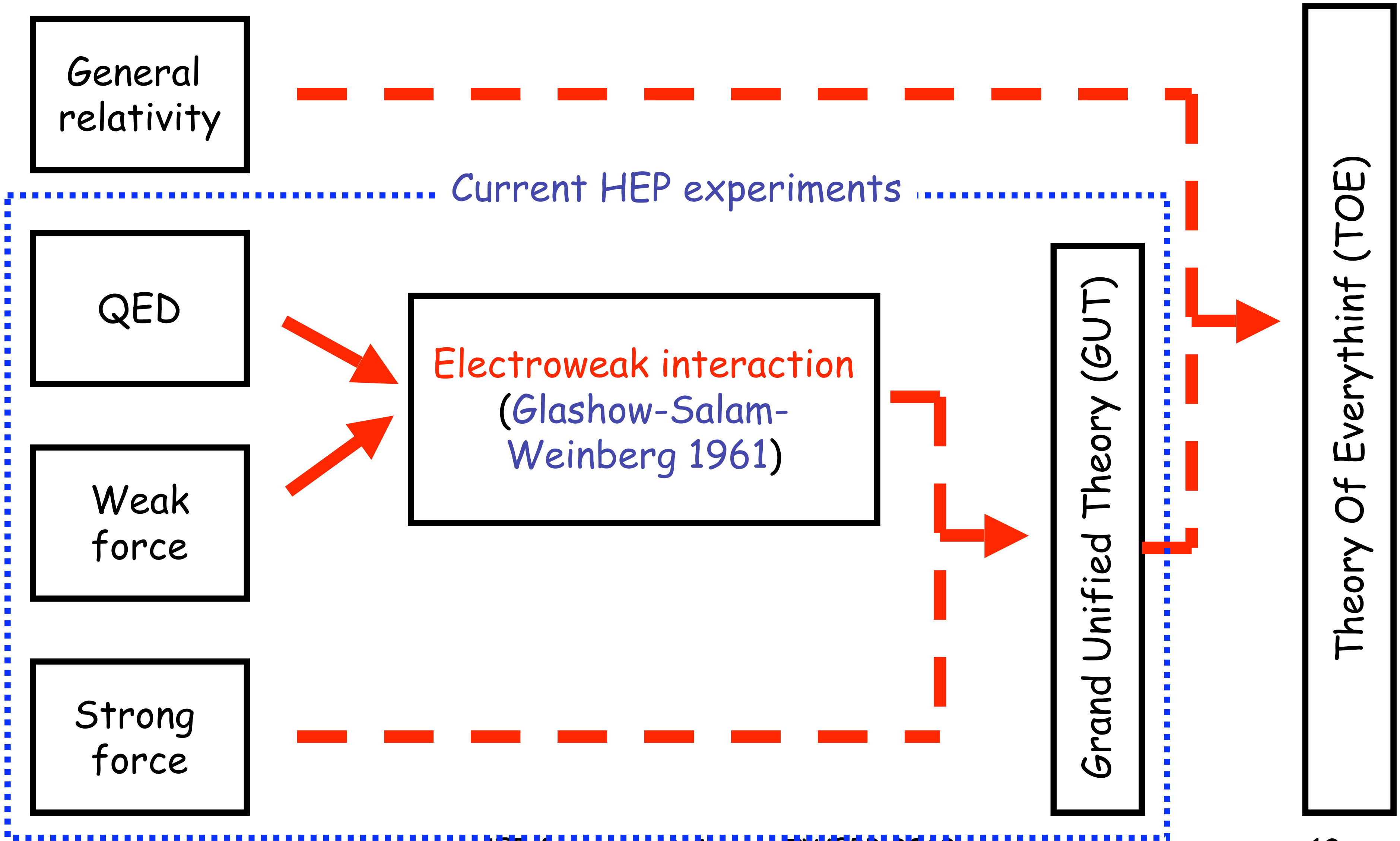
« Modern physics » interactions

- Strong force
  - Once protons have been discovered, we knew someting was needed to keep the nucleus stable
  - In fact, strong force acts:
    - between quarks inside a proton (main effect)
    - between protons inside a nucleus (residual effect)

- Weak force
  - Explain β decay (continuous energy spectrum for e^-):

$$n \rightarrow p + e^- + \bar{\nu}_e$$

Current status of unification



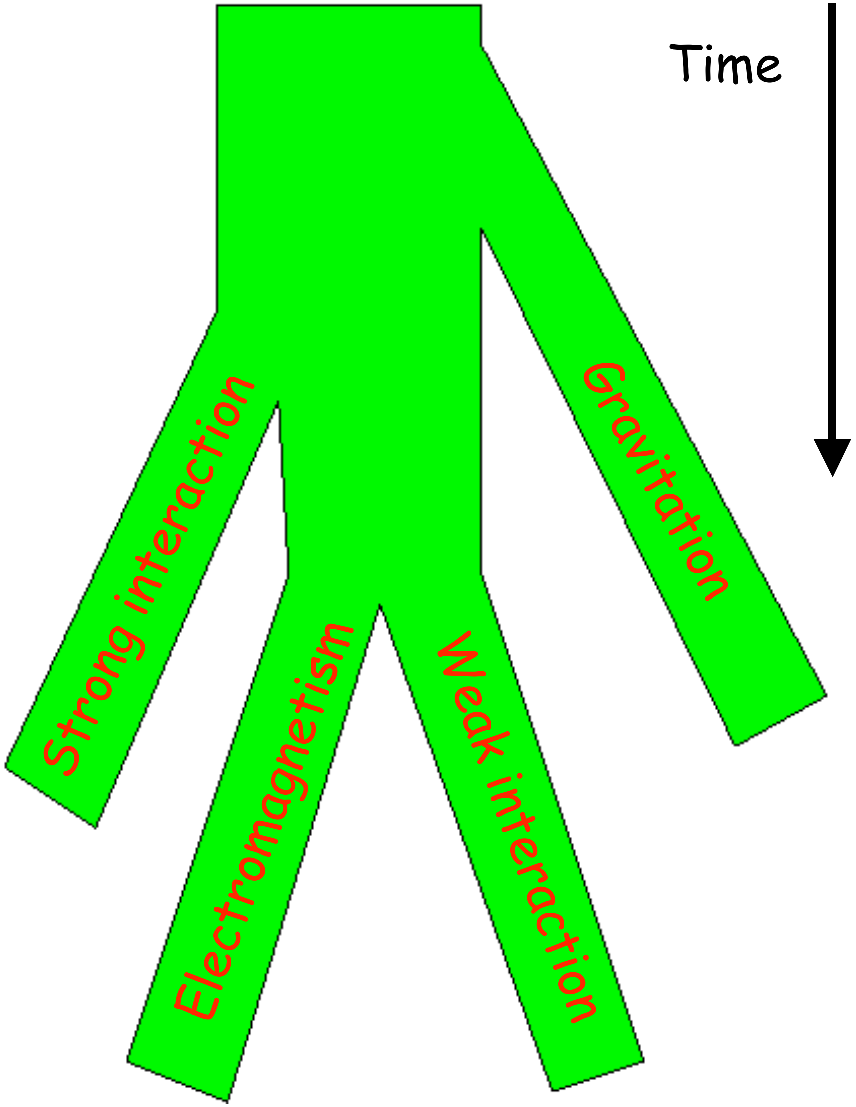
4 fundamental interactions

	Gravity	Weak	Electromagnetism	Strong
Relative intensity	$\approx 10^{-40}$	$\approx 10^{-5}$	$\approx 10^{-2}$	1

- The strong force is the strongest (and the least known)
- All known phenomena can be explained by these 4 forces

Interactions splitting: link with cosmology

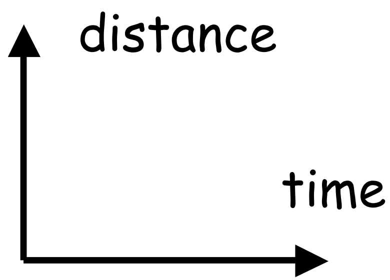
- t = 0 (Big Bang)
  - One single interaction
- $t = 10^{-43}$ s, $T = 10^{32}$ K
  - Gravitation splits
- $t = 10^{-35}$ s, $T = 10^{27}$ K
  - Strong interaction splits
- $t = 10^{-11}$ s, $T = 10^{15}$ K
  - Electroweak interaction splits
- $t = 1.4\ 10^{10}$ years, T = 2.7 K
  - 4 interactions



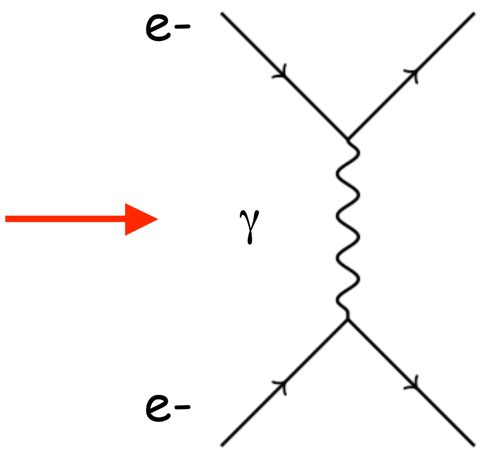
What occurs during an « interaction » ?

- When 2 particules interact, they exchange a third one
  - which carries properties between both particules (E, P_T, ..)

- Modelisation through Feynman diagrams:
  - Only rule: *Conservation laws* have to be checked in each *vertex*



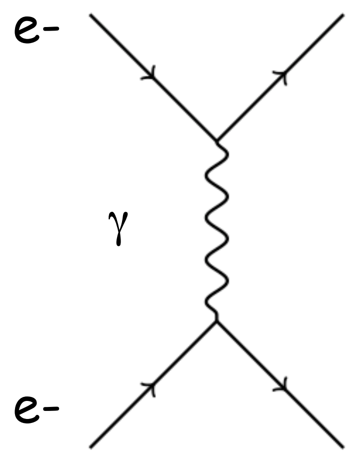
Rutherford scattering



- QED allows to violate energy conservation, if it is very fast :

$$\Delta E \, \Delta t \approx \hbar$$

  - During Δt, virtual particules are exchanged (energy is taken from the field)
  - After Δt, energy conservation is valid again



- Qualitatively:

$$\Delta E \geq m\, c^2 \qquad \Longleftrightarrow \qquad \Delta t \leq \frac{\hbar}{m\, c^2}$$

  - The interaction range is at most $\frac{\hbar}{m\, c}$

Exchange particules

	Gravity	Electromagnetism	Weak	Strong
Exchange particule	Graviton (?)	Photon γ	Z^0, $W^\pm$	gluons
Range	Infinity	Infinity	$\approx 10^{-17}$ m	$\approx 10^{-15}$ m

- Strong interaction:
  - Nuclear radius (1.4 fm) $\Rightarrow mc^2 = 140$ MeV (OK with π)
- Weak interaction
  - $m_{W\pm} \approx 80$ GeV/$c^2 \Rightarrow \Delta x \approx 2.5\ 10^{-17}$ m
- Photon is massless: infinite range for electromagnetism

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Elementary particules

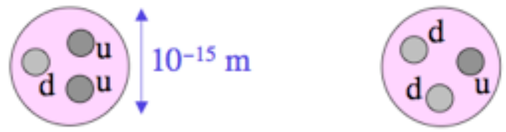
- All known matter is made of 6 leptons and 6 quarks

				Electric charge	Strong charge
Leptons	Electron (e^-)	Muon (μ^-)	Tau (τ^-)	-1	no
	Neutrino (ν_e)	Neutrino (ν_μ)	Neutrino (ν_τ)	0	no
Quarks	Up (u)	Charm (c)	Top (t)	+2/3	yes
	Down (d)	Strange (s)	Bottom (b)	-1/3	yes

- For each of these, it exists an antiparticle with opposite electrical charge
- A good theory is predictive: τ, *b* and *t* found after being thought
- No internal structure is known

Stable vs unstable particules

- Usual matter (stable) is only made of electrons, *u* and *d* quarks
  - Electron, proton, photon and neutrinos (?) are the only stable particules



proton neutron

- All other particules are unstable :
  - Decay following: $N(t) = N_0 \exp\left(-\frac{t}{\tau}\right)$

	n	μ^-	π^+	J/Ψ	Z
τ (s)	887	$\approx 10^{-6}$	$\approx 10^{-8}$	$\approx 10^{-20}$	$\approx 10^{-25}$

  - Note that in the lab frame: $\tau_{lab} = \gamma\, \tau$

Neutrino

- Can be produced by neutron decay:

$$n \rightarrow p + e^- + \bar{\nu}_e$$

- Electron and neutrino are two kind of the same « particule ». We always have :

$$\nu \leftrightarrow e^- \qquad \bar{\nu} \leftrightarrow e^+$$

- They all carry an electronic leptonic number which is preserved (+1 for e^- and neutrino, -1 for e^+ and antineutrino)

- We have the same behaviour with μ and τ

- Any neutrino oscillation would violate these rules …

- Weak interaction
  - Z^0: elastic scattering of neutrino and anti neutrino
  - $W^{\pm}$: inelastic scattering between leptons

- The three radiation types are linked to three interactions: α (strong), β (weak) and γ (electromagnetic)

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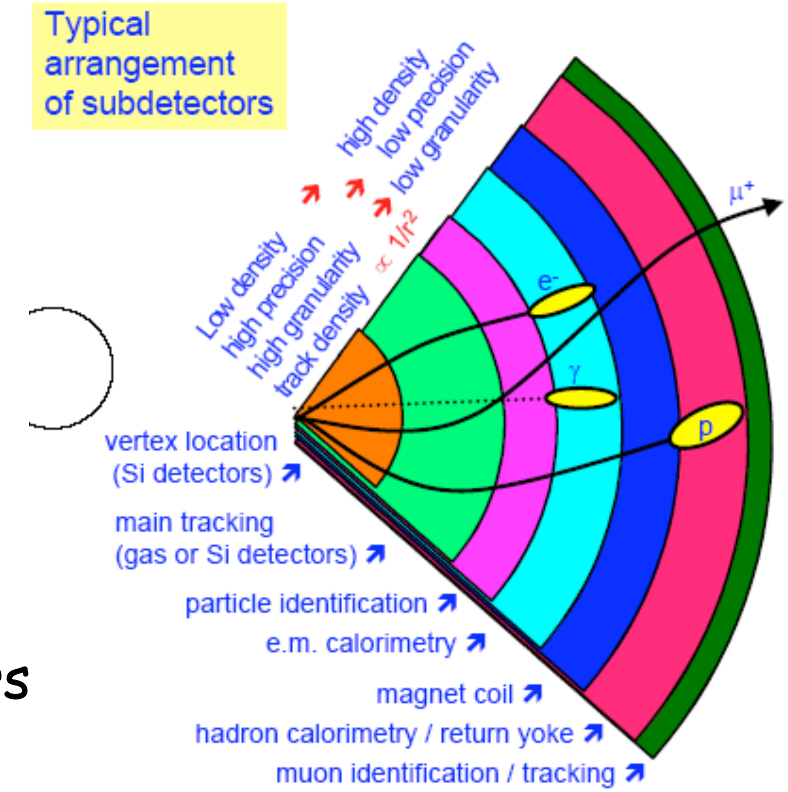
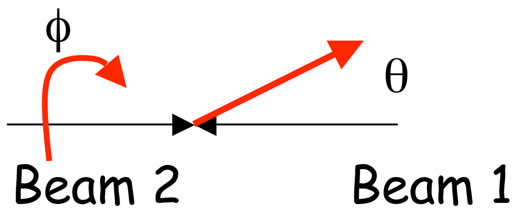
- Detectors shall give particules properties :
  - Masse, energy, charge, ..
- All detectors on colliders have the same onion skin structure
- Only options :
  - Solenoid location wrt calorimeters
  - Shape (octogonal, cylindric, …)



- On event to event basis, we use *transverse energy* or *transverse momentun*



$$E_T = \sum E_i \sin(\theta_i) \qquad P_T = \sqrt{P_x^2 + P_y^2}$$

$$P_x = \sum E_i \sin(\theta_i) \cos(\phi_i) \qquad P_y = \sum E_i \sin(\theta_i) \sin(\phi_i)$$

  - These quantities are constrained by initial conditions (E_T = 0 and P_T = 0)

- Of interest is also *missing transverse energy* or (missing P_T)

- A very efficient way of creating missing E_T is a wrong calibration…

What do we measure ?

- What matters for the physicist is the interaction probability σ or *cross section* :

Event rate in the detector →

$$\frac{dN}{dt} = \sigma \, \mathcal{L} \, A \, \epsilon$$

A: Acceptance
ε : Efficiency

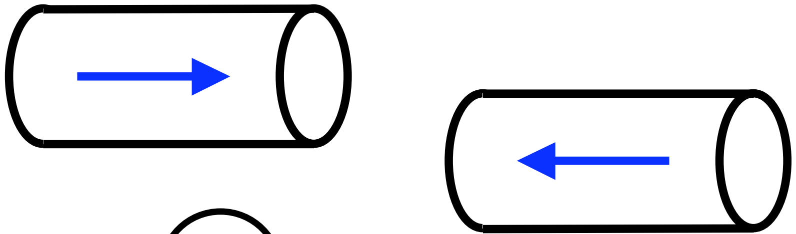
← Luminosity

  - Cross section are measured in barn (1 barn = 10^{-28} m^2 = 10^{-24} cm^2): see the sphere model

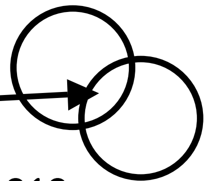
- The luminosity is a quality factor of the collision

f: Frequency
N_1, N_2: Beam currents

$$\mathcal{L} = f \, \frac{N_1 N_2}{\Sigma}$$



Σ: overlap area



$$\frac{dN}{dt} = \sigma \, \mathcal{L} \, A \, \epsilon$$

- Luminosity is expressed in $cm^{-2}\ s^{-1}$

- For instance, if LHC runs at $10^{32}\ cm^{-2}s^{-1}$:

$$100\ 10^{30}\ \mathrm{cm}^{-2}\mathrm{s}^{-1} \ = \ 100\ \mu\mathrm{b}^{-1}\mathrm{s}^{-1}$$

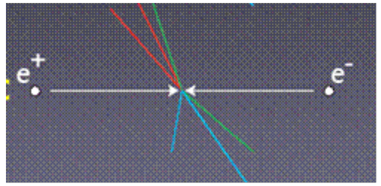
1 b = 10^{-24} cm^2
1 μb = 10^{-30} cm^2

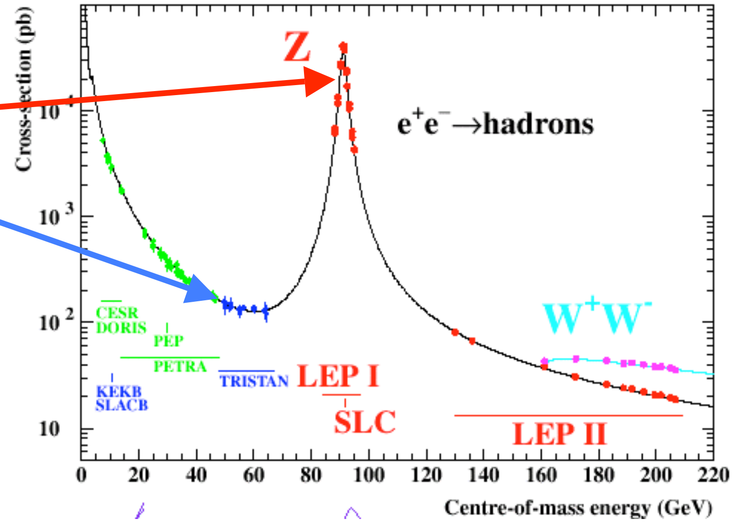
- In one hour, it will integrate

$$3600\ \mathrm{s} \times 100\ \mu\mathrm{b}^{-1}\mathrm{s}^{-1} \ = \ 0.36\ \mathrm{pb}^{-1}$$

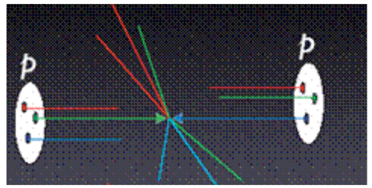
Lepton vs hadron colliders

- Leptons (e^-, e^+, $\mu^\pm$?): Elementary particules
  - Well defined energy
  - Clean final state
  - LEP I/SLC adjusted on the Z
  - TRISTAN was off the Z
  - Suited for precision studies at design energy





- Hadrons: Collision energy unknown but huge dynamical range
  - Discovery machines

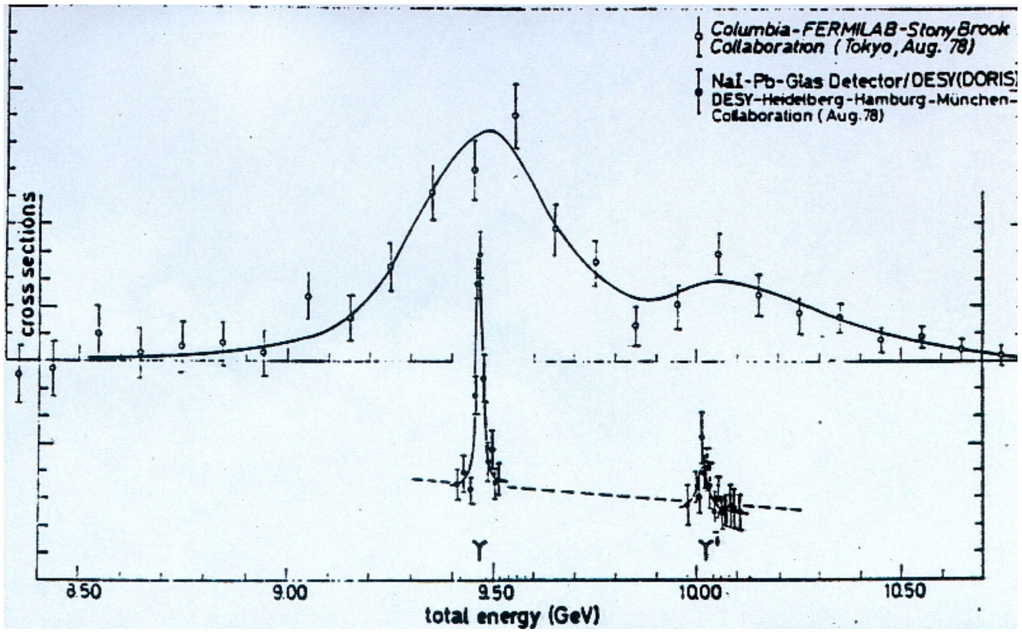


- Leptons : width from an energy scan limited by the beam energy resolution
- Hadrons : width from the detector resolution

Hadrons

Example of Υ particule

Leptons



HEP « tricks »

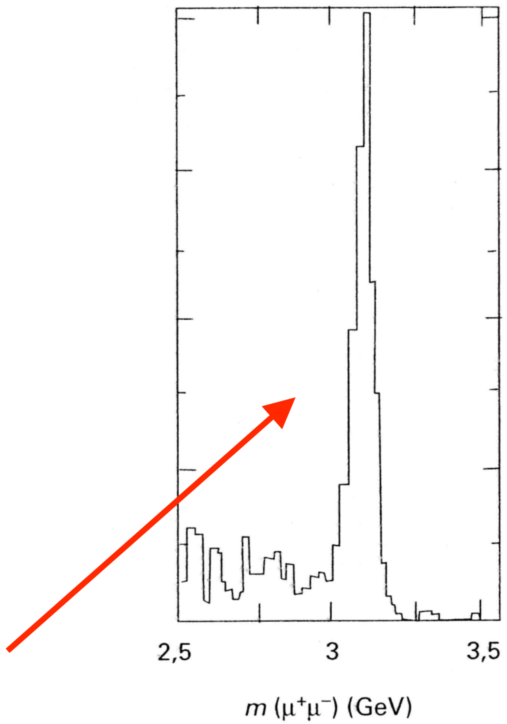
- If decay time < 1 fs, no direct observation possible
  - A 14 GeV π^0 ($\gamma \approx 100$) has in the lab frame $\gamma\tau$ = 0,84 10^{-15} s and only travel d $\approx c\gamma\tau$ = 0,25 μm
  - Indirect reconstruction using $\pi^0 \to \gamma\,\gamma$ using

$$E_\pi = E_{\gamma_1} + E_{\gamma_2} \qquad \vec{p}_\pi = \vec{p}_{\gamma_1} + \vec{p}_{\gamma_2}$$

- Production of « mass plots »:
  - Study of $X \to \mu^+ \mu^-$
  - Special relativity tells us:

$$E_X = E_{\mu^+} + E_{\mu^-} \qquad \vec{p}_X = \vec{p}_{\mu^+} + \vec{p}_{\mu^-}$$

$$E_X^2 - p_X^2\, c^2 = m_X^2\, c^4$$



J/Ψ discovery

Resonances

- For some particules (resonances), mass peak is broad, regardless of detector precision
- From quantum mechanics, we know: $\Delta E \, \Delta t \approx \frac{\hbar}{2}$ Heisenberg relation
  - Measuring *E* with precision *ΔE* requires time *Δt*
  - Only relevant in subatomic world → $\hbar \approx 1.05 \; 10^{-34} \text{ Js}$
- Any instable particule can not have an infinitely precise mass ! It has a mass *m* close to m_0 « nominal »:

$$|m - m_0| \approx \frac{\hbar}{\tau}$$

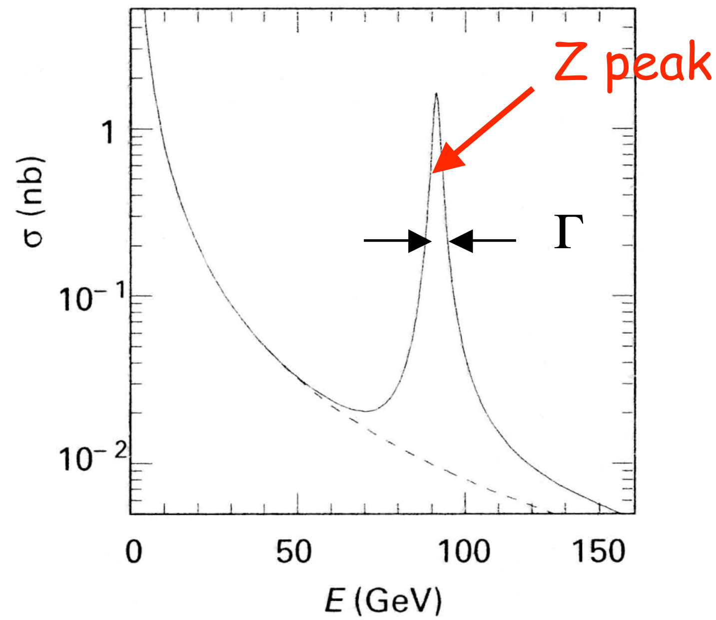
- The mass plot shows a Breit-Wigner shape (or Cauchy or Lorenzt) with intrinsic width:

$$\Gamma \approx \frac{\hbar}{\tau}$$

- For Z:

$m_Z c^2$ = 91,19 GeV Γ_Z = 2,5 GeV

Cross section $e^+e^- \to \mu^+\mu^-$



- For $\tau \ll 10^{-18}$ s, we look for the width $\Gamma \gg 1$ keV

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To be solved by LHC !

- The goal of LHC is to complete Standard Model with Higgs boson (to complete electroweak theory)
  - Would explain the particules's masses
    - e^- : 511 keV/c^2, n/p (930 MeV/c^2), μ (105 MeV/c^2), τ (1785 MeV/c^2), Z (91 GeV/c^2), W (80 GeV/c^2)
  - Should be light (less than 200 GeV) following LEP/SLD

- Golden mode at LHC is $H \rightarrow \gamma\,\gamma$
  - A lot of expectations in EM calorimeters !
  - Other modes have a lot of background, may be not easily under control (strong force)

- New physics expected at LHC:
  - Higgs boson
  - Supersymetry (SUSY)
    - Allows to treat the same way fermions and bosons (GUT)
    - Today we see fermions and bosons fields
  - Heavy gauge bosons
  - Extra dimensions

} Should be detected by large amount of missing E_T

CP violation

- Experimentaly, we observe $\sigma(s \to u\, W^-) \ll \sigma(d \to u\, W^-)$
- This is due to the fact weak interaction between *ud* and *us* is in fact an interaction between *u* and

$$d' = \cos(\theta_c)\, d + \sin(\theta_c)\, s$$

θ_c : Cabibbo angle

- This idea was extended by Kobayashi and Maskawa to other quarks (CKM matrix):
  - V_{ij} accessible via weak coupling
  - If V_{ij} complex, would explain « CP violation »

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

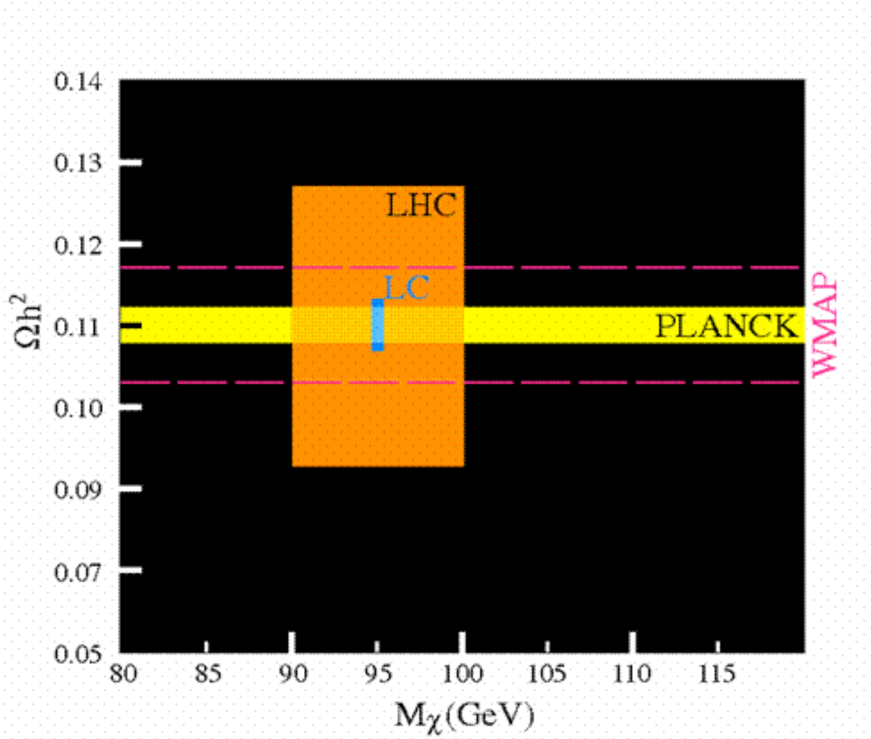
CKM matrix

Neutrinos oscillations

- Quantum mechanics property:
  - A neutrino created with a specific lepton flavour (e, μ or τ) can later be measured with a different flavor
- Neutrino oscillation implies that the neutrino has a non-zero mass, which is left possible by the Standard Model
- Several hints towards neutrino oscillation have been seen since 60's (solar neutrinos). In may 2010, OPERA claimed a τ observation in a ν_μ beam

- Next machine will be e^+e^-, but at which energy ?
  - Current best guess is around 500 GeV
  - Need for the LHC to say this

- This shall give enough accuracy on SUSY and dark matter searches to match cosmological needs



From detector point of view

- Very demanding on:
  - hermiticity to improve E_T measurement
  - detector quality (no dead channels)

- Higher granularity requires lower consumption
  - From ATLAS LAr FEB electronics (1W/ch) to ILC needs (100 μW/ch)

Conclusion

- Hope I did not bother you too much
- What I said is obviously too simplified to be completely correct..
- I heavily used materials from CERN Summer Students Program (2002, 2007, 2010)