Short introduction

In short which is the main purpose of the EEPP and few numbers that every experimental particle physicist should have in his/her hands.

Introduction

- The "Question to Nature" in EPP: it is the quest for the "fundamental" aspects of the Nature: not single phenomena but the common grounds of all physics phenomena.
- Historical directions of the EPP:
  - Atomic physics → Nuclear Physics → Subnuclear Physics: the ∞ly small; Nature = point-like particles interacting through forces..
  - Look at the ∞ly large: connections with cosmology, cosmic rays, etc..
  - Paradigm: unification of forces, theory of everything.
- What shall we do in this course ?
  - We concentrate on subnuclear physics and will select few experiments
  - We review some "basic statistics" and then will extend it to more "advanced" methods for data analysis EPP experiments

The EPP experiment

- Something present through all the 20° century and continuing in 21° : the best way to understand the elementary particles and how do they interact, is to send ***projectiles*** on ***targets***, or, more generally, "to make things collide". And look at the ***final state***: a+b→ X
- "Mother-experiment" (Rutherford): 3 main elements:
  - a projectile
  - a target
  - a detector
- Main rule: the higher the momentum *p* of the projectile, the smaller the size δx I am able to resolve.

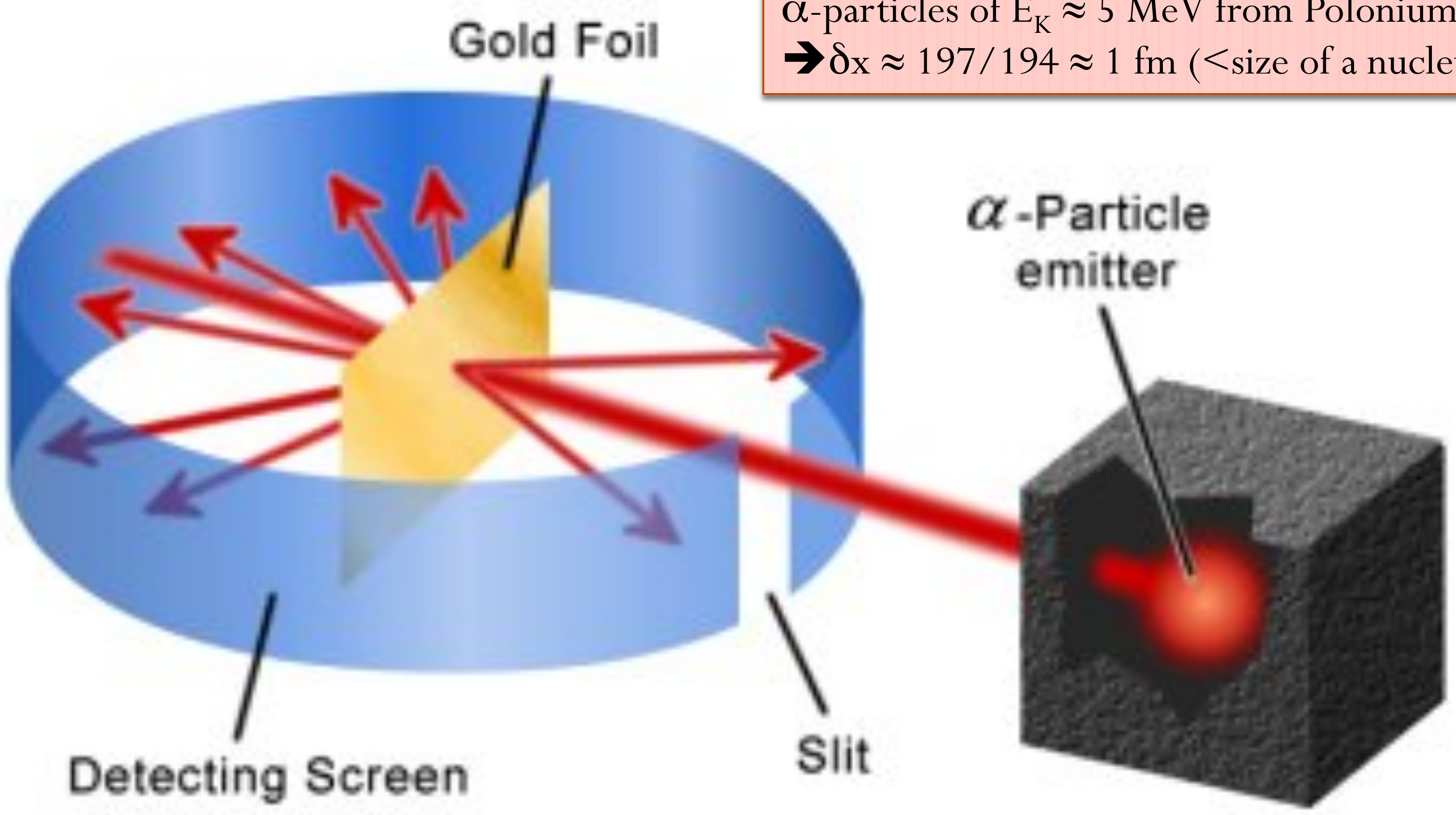
$$\delta x \approx \frac{\hbar c}{pc} \Rightarrow \delta x(fm) \approx \frac{197}{p(MeV/c)}$$

The scale: $\hbar c = 197 MeV \times fm$

- From Rutherford, a major line of approach to nuclear and nucleon structure using electrons as projectiles and different nuclei as targets.

The Rutherford experiment

α-particles of $E_K \approx 5$ MeV from Polonium
➔ $\delta x \approx 197/194 \approx 1$ fm (<size of a nucleus)

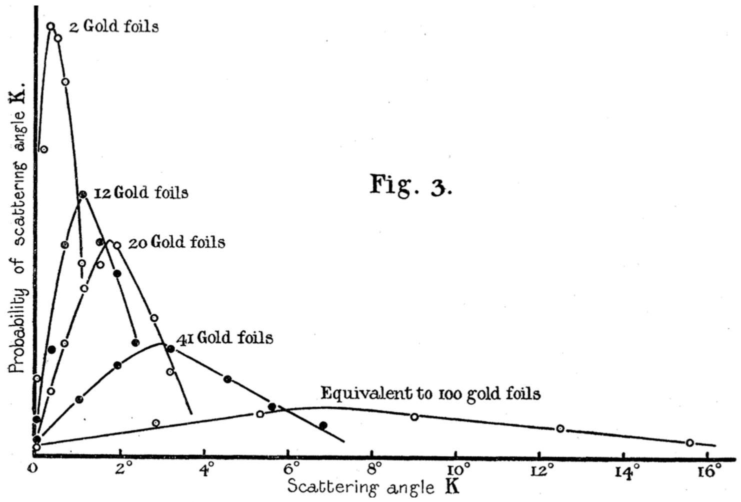


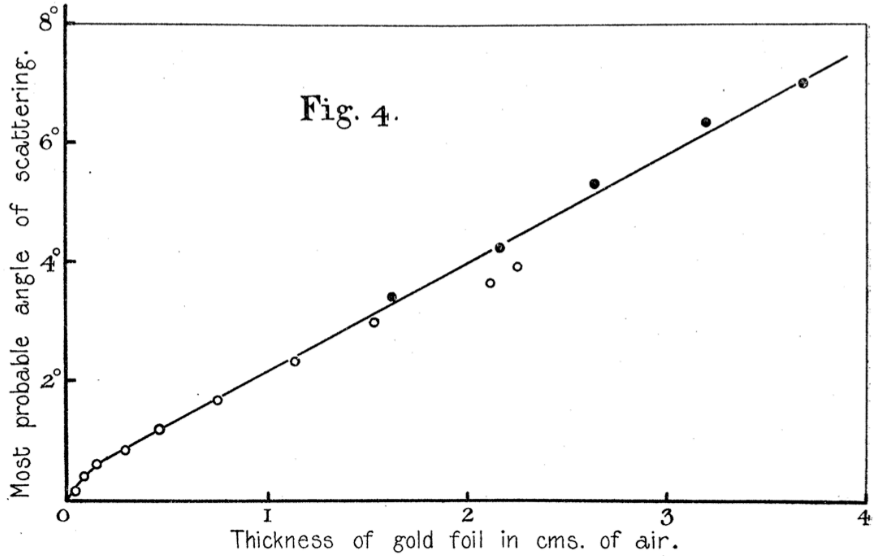
$$p^2 = (m_\alpha + E_K)^2 - m_\alpha^2 = 194\,MeV$$

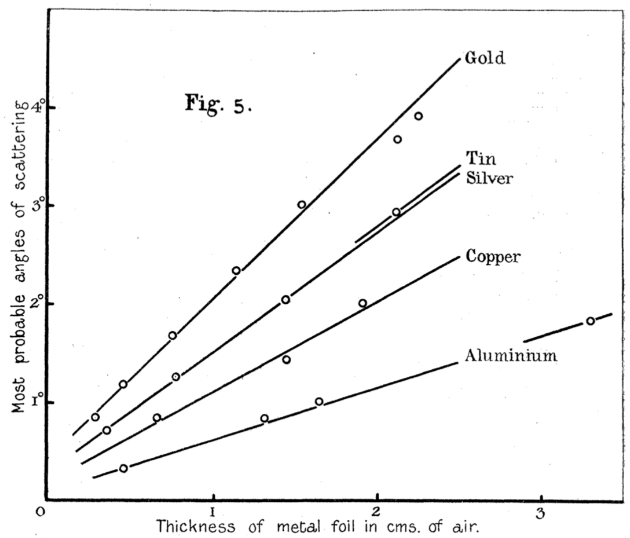
Key elements in the Rutherford experiment – physical quantities

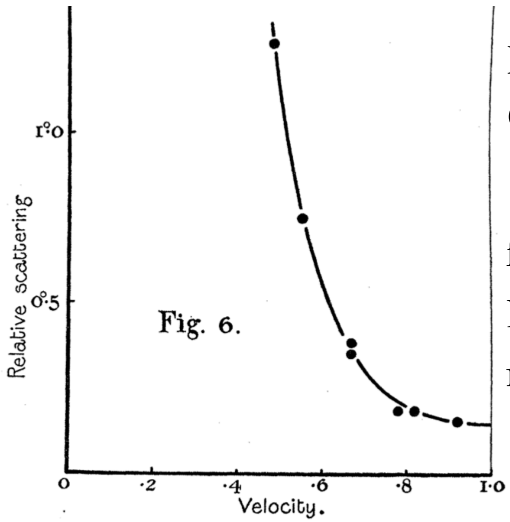
- **Energy of the collision** (driven by the kinetic energy of the α particles) the meaning of $\sqrt{s}$
- **Beam Intensity** (how many α particles /s)
- **Size and density of the target** (how many gold nuclei encountered by the α particles);
- **Deflection angle θ**
- **Probability/frequency of a given final state** (fraction of α particles scattered at an angle θ);
- **Detector efficiency** (do I see all scattered α particles ?)
- **Detector resolution** (how well do I measure θ ?)

The Rutherford experiment – original results









Plots from the original Geiger paper of 1910

➔ MS formula coming out from data: $\theta \approx Z\, \delta X / v$

NB: no mention of measurement uncertainties..

Break: the Rutherford experiment only ?

- Actually more than the Rutherford experiment
- Particle Physics without beams
  - ➔ cosmic ray based experiments
    - In space
    - In Underground Laboratories
    - In DeepSea Detectors
  - ➔ Search for very rare or forbidden decays of ordinary matter
    - Mostly in underground detectors
- Examples during the course
- NOW: let's concentrate on EPP with beams

Energy: what is √s ?

- This is a fundamental quantity to define the "effective energy scale" you are probing your system. It is how much energy is available for each collision in your experiment.
- It is relativistically invariant.
- If the collision is $a+b \rightarrow X$

$$s = (\tilde{p}_a + \tilde{p}_b)^2 = M_a^2 + M_b^2 + 2\tilde{p}_a \bullet \tilde{p}_b$$
$$= M_a^2 + M_b^2 + 2[E_a E_b - \vec{p}_a \bullet \vec{p}_b]$$

- M_X cannot exceed √s.
- What about Rutherford experiment ? $a=\alpha$, $b=$Au, $X=a+b$

$$s = M_\alpha^2 + M_{Au}^2 + 2E_\alpha M_{Au} =$$
$$\sqrt{s} = 188.5 GeV$$

Maybe Rutherford produced a Higgs ??

Development along the years

- WARNING: Not only Rutherford: in the meantime EPP developed several other lines of approaches.
- More was found: It was seen that going up with the projectile momentum something unexpected happened: more particles and also new kinds of particles were "**created**".
- ➔ high energy collisions allow to create and study a sort of "**Super-World**". The properties and the spectrum of these new particles can be compared to the theory of fundamental interactions (the Standard Model).
- Relation between projectile momentum and "creation" capability:
- ➔ Colliding beams are more effective in this "creation" program.
  - ep colliders (like HERA)
  - e^+e^- storage rings
  - p-pbar or pp colliders

$$\sqrt{s} = \sqrt{M_1^2 + M_2^2 + 2E_1M_2} \approx \sqrt{2E_1M_2}$$

$$\sqrt{s} = 2\sqrt{E_1E_2}$$

Units - I

- $\Delta E_k = q\Delta V$
- Joule "=" C×V in MKS
- Suppose we have an electron $q = e = 1.602\times10^{-19}$ C and a ΔV=1 V: ➔ $\Delta E_k=1.6\times10^{-19}$ J == 1 eV
- Particularly useful for a linear accelerator
  - Electrons are generated through cathodes by thermoionic effect;
  - Protons and ions are generated through ionization of atoms;
  - Role of "electric field": how many V/m can be provided ?
  - Present limit ≈30÷50 MV/m (100 MV/m CLIC)

    ➔ 1 km for 30÷50 GeV electrons !

Units - II

- Unit system
  - By posing **c = 1**, **energy**, **momentum** and **mass** can all be expressed in terms of a single fundamental unit. All can be expressed using the eV.

$$E^2 = (pc)^2 + (mc^2)^2 \dashrightarrow E^2 = p^2 + m^2$$

  - c=1 implies also the following dimensional equation:
    - [L] = [T]

    Lengths and times have the same units
  - Then we also pose **ħ=1**, this have implications on energy vs. l and t
    - $[E] = [L]^{-1} = [T]^{-1}$

    → time and length are $(\text{energy})^{-1}$
  - Numerically we need few conversion factors:
    - 1 MeV == 0.00506 fm^{-1} == 1.519 ns^{-1}

Energy scales

- In the following we try to see which scales of energy correspond to different phenomenologies. We consider equivalently space and energy scales (since we know it is somehow the same..)
- This quantity is one of the driving element to design HEP experiments: you need to know first of all at which energy you have to go.

Energy scales in the ∞ly small - I

- Electromagnetic interactions have not a length scale

$$V = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{r}$$

- [V×r]=[E][L]=[ħc] ➔ we can define an adimensional quantity α:

$$\frac{e^2}{4\pi\varepsilon_0\hbar c} = \alpha = \frac{(1.610^{-19}C)^2}{4\pi 8.8510^{-19}F/m1.0510^{-34}Js310^8 m/s} = \frac{1}{137} = 0.0073$$

- α sets the scale of the ***intensity*** of the electromagnetic interactions. In natural units (***ħ = c = ε₀ = μ₀ = 1***) ***e*** is also adimensional: $e = \sqrt{4\pi\alpha}$

Energy scales in the ∞ly small - II

- Electromagnetic scales:
  - **1. Classical electron radius:** The distance ***r*** of two equal test charges ***e*** such that the electrostatic energy is equal to the rest mass ***mc***^{2} of the charges

$$r_e = \frac{e^2}{4\pi\varepsilon_0 m_e c^2} = \frac{\alpha}{m_e}\frac{\hbar}{c} \rightarrow \frac{\alpha}{m}$$

In natural units

  - **Electron Compton wavelength:** which wavelength has a photon whose energy is equal to the electron rest mass.

$$\lambda\!\!\!^{-}_e = \frac{\hbar}{m_e c} = \frac{r_e}{\alpha} \rightarrow \frac{1}{m_e}$$

  - **Bohr radius**: radius of the hydrogen atom orbit

$$a_\infty = \frac{4\pi\varepsilon_0\hbar^2}{m_e e^2} = \frac{r_e}{\alpha^2} \rightarrow \frac{1}{\alpha m_e}$$

Energy scales in the ∞ly small - III

- Weak interactions: Fermi theory introduces the constant $\boldsymbol{G_F}$ with dimensions $[E]^{-2}$ (making the theory non-renormalizable). In the electroweak theory $\boldsymbol{G_F}$ is:

$$\frac{G_F}{\sqrt{2}} = \frac{g_W^2}{8m_W^2}$$

- Where $\boldsymbol{g_W}$ is the "fundamental" adimensional coupling directly related to $\boldsymbol{e}$ through the Weinberg angle: $\boldsymbol{e}=\boldsymbol{g_W}\sin\boldsymbol{\theta_W}$
- The "Electroweak scale" is the scale at which the electroweak unification is at work. By convention it is given by $\boldsymbol{v}$, the Higgs vacuum expectation value:

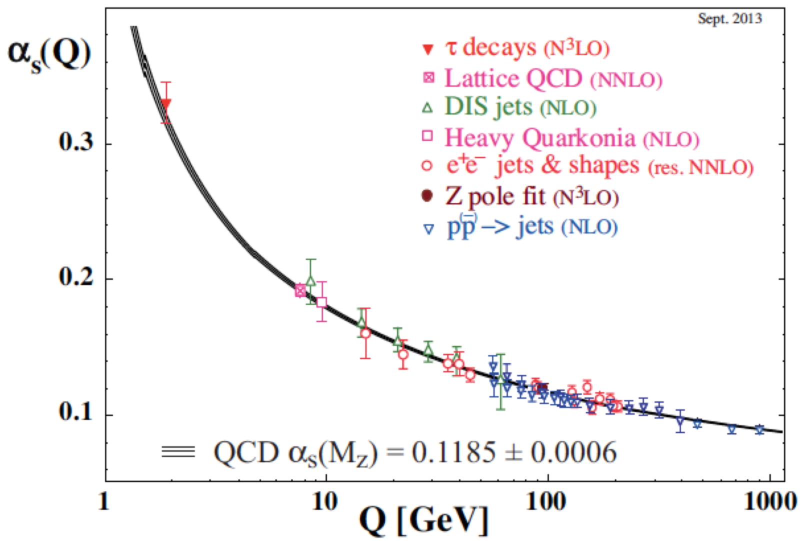
$$v = \frac{1}{\sqrt{\sqrt{2}G_F}} = 246GeV \qquad r_{EW} \approx \sqrt{\sqrt{2}G_F}\,(\hbar c)$$

Energy scales in the ∞ly small - IV

Strong interaction: Yukawa potential

$$V(r) = \frac{g^2}{4\pi}\frac{1}{r}\exp(-\frac{r}{\lambda})$$

λ is 1/m(pion)



- Strong Interaction scale:

α_S depends on q^2. There is a natural scale given by the "confinement" scale, below which QCD predictions are not reliable anymore.

$$r_{QCD} = \frac{1}{\Lambda_{QCD}} \approx \langle r_{proton} \rangle$$

Energy scales in the ∞ly small - V

- Gravitational Interaction scale: the "problem" of the gravity is that the coupling constant is not adimensional, to make it adimensional you have to multiply by $\boldsymbol{m^2}$. The adimensional quantity here is

$$\frac{Gm^2}{\hbar c}$$

depending on the mass. For typical particle masses it is << 1. The mass for which it is equal to 1 is the "Planck Mass" $\boldsymbol{M_{Planck}}$. $\boldsymbol{\lambda_{Planck}}$ is the "Planck scale" (Compton wavelength of a mass $\boldsymbol{M_{Planck}}$)

$$M_{Planck} = \sqrt{\frac{\hbar c}{G}} \qquad \lambda_{Planck} = \sqrt{\frac{\hbar G}{c^3}}$$

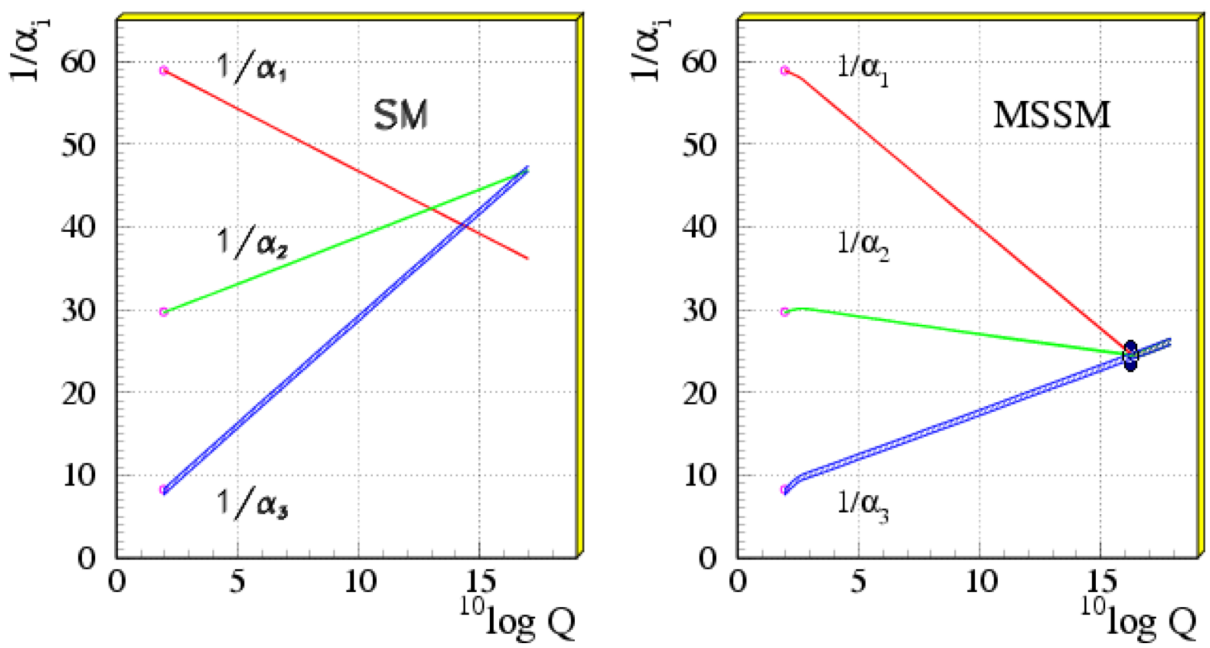
$\boldsymbol{M_{planck}}$ is $\approx$ 20 μg, a "macroscopic" quantity.

The Planck scale

- When you increase a mass
  - ➔ you are reducing its Compton wavelength (that is the scale at which quantum effects are relevant)
  - ➔ you increase the Schwarzschild radius (that is the radius of the event horizon of the black hole with that mass)
- The mass for which Compton wavelength = Schwarzschild radius is the Planck Mass ➔ is the domain of the quantum gravity

Energy scales in the ∞ly small - VI

- Grand Unification Scale. From the observation that weak, em and strong coupling constants are "running" coupling constants, if we plot them vs. q^2 we get:



Around 10^{16} GeV meeting point ??

Energy scales in the ∞ly small - Summary

quantity	value	Energy
Bohr radius	0.53×10^{-10} m (0.5 Å)	3.7 keV
Electron Compton wavelength	3.86×10^{-13} m (386 fm)	0.51 MeV
Electron classical radius	2.82×10^{-15} m (2.8 fm)	70 MeV
Proton radius – QCD confinement scale	0.82×10^{-15} m (0.8 fm)	240 MeV
Fermi scale	7×10^{-19} m	250 GeV
"New Physics" scale		1 TeV
GUT Scale		10^{16} GeV
Planck scale	1.62×10^{-35} m	1.2×10^{19} GeV

The TeV scale is the maximum reachable with the present accelerator technology

Energy scales in the ∞ly small - VII

- Why LHC is concentrate on the O(TeV) scale ?
- There is an intermediate scale around the TeV. It is motivated by the "naturalness" – "fine tuning" – "hierarchy" problem connected to the properties of the Higgs Mass.

$$m_H^2 \sim -2\mu^2 + \frac{g^2}{(4\pi)^2} M^2$$

Mass parameter in the SM lagrangian

Quantum corrections

- The Higgs mass $\boldsymbol{m_H}$ is UV sensitive (its value depends on quantum corrections)
- $\boldsymbol{M}$ is the scale up to which we have the UV theory.
- If no other scale is there btw Higgs and Planck, $\boldsymbol{M}=\boldsymbol{M_{Planck}}$, so that strong cancellations are needed between $-2\boldsymbol{\mu}^2$ and $\boldsymbol{g}^2\boldsymbol{M}^2/(4\pi)^2$ to give the observed Higgs Mass
- This is un-natural..
- If $\boldsymbol{M} \approx$ O(TeV) all becomes natural, e.g. MSSM, Technicolor,…

$$\Delta \gtrsim \left(\frac{m_{\rm NP}}{0.5\ {\rm TeV}}\right)^2$$

More in detail

- m_H is the Higgs mass; μ is the Higgs "bare" mass (the parameter in the lagrangian). $m_H=\mu+$"RC" (radiative corrections due to fermion and boson loops). If "RC">> m_H it means that also $|\mu|>>m_H$ and a cancellation btw RC and μ is needed.
- Structure of "RC". For every particle p in the loop it is $= g_p^2(\Lambda^2+m_p^2)$. Λ is the "cut-off" of the integration, it is the next scale that nature gives to us.
- Supersymmetric solution. In "RC" N particle-antiparticle pairs with opposite sign couplings enter $= N_p g_p^2(\Lambda^2+m_p^2) - N_{antip} g_{antip}^2(\Lambda^2+m_{antip}^2) = N_p g_p^2(m_p^2-m_{antip}^2)$; Λ is cancelled

Probability/Frequency of a final state: the cross-section and the decay width

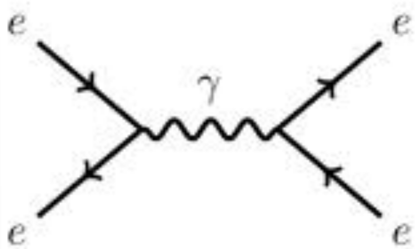
- The **cross-section** measures the "probability" of a given final state in a collision (actual definition will be in a later lecture). It is a $[L]^2$.
- The **decay width** and the **branching ratio** measure the "probability" of a given final state in a deca. The decay width is the inverse of the lifetime so that it is a $[T]^{-1}$. The branching ratio is an adimensional quantity
- If we include **cross-sections** and **decay widths**, we enter in the quantum field theories where the normalized Planck constant enters in the game.
- In the "natural system" the units are

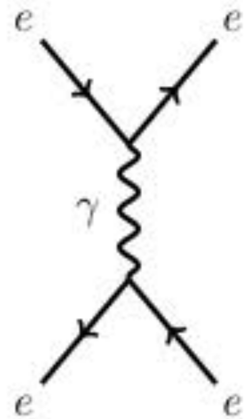
$$\hbar = c = 1$$

  - **cross-section** is a $(\text{length})^2$ so an $(\text{energy})^{-2}$.
  - **decay width** is a $(\text{time})^{-1}$ so an (energy)
  - $1\ \text{GeV}^{-2} = 3.88\text{x}10^{-4}$ barn

Cross-section scales

- Relation between an experimental cross-section and the theory (same applies for branching ratios)

$\sigma = \int \Big|$ 

$+$ 

$\Big|^2 d\varphi$

Two ingredients in the theory calculations:

→ dynamics (amplitude from lagrangian, Feynman diagrams… mainly the coupling constants);

→ phase space $d\phi$

NB: the integration on the phase space DEPENDS in general on the experiment details (accessible kinematic region) → **Montecarlo**

Cross-section order of magnitude estimates

- Based on dimensional arguments and few numbers (neglects phase-space and more…)
  - Electromagnetic processes: $e^+e^- \rightarrow \mu^+\mu^-, \gamma\gamma$
  - Weak processes: νN scattering
  - Hadron strong interaction scattering: pp scattering

α	**1/137**
G_F	**10^{-5} GeV^{-2}**
r_p	**1 fm**
1 GeV^{-2}	**3.88×10^{-4} b**

$$\sigma\left(e^+e^- \rightarrow \mu^+\mu^-, \gamma\gamma\right) \approx \frac{\alpha^2}{s}$$

$$\sigma\left(\nu e \rightarrow \nu e\right) \approx G_F^2 2 m_e E_\nu$$

$$\sigma\left(pp\right) \approx \pi r_p^2$$

S=(1 GeV)^2	S=(100 GeV)^2
20 nb	2 pb
40 fb	4 pb
30 mb	30 mb

LifeTime (or Width) of a particle vs. theory

- As for the cross-section the value depends on two ingredients:
  - Decay type (weak, em, strong) through decay matrix element
  - Volume of the available phase space
- The Width Γ is an additive quantity: you have to add the ***partial widths*** of the single decays to get the ***total width***
- Useful formulas: two-body decay phase-space (rest system)

$$\Gamma = \frac{1}{8\pi}\frac{p}{M^2}|\mathfrak{M}|^2.$$

NB Dimensions: If Γ is [E] → |M| is also [E]

$$|\vec{p}_1| = |\vec{p}_2| = \frac{[(M^2-(m_1+m_2)^2)(M^2-(m_1-m_2)^2)]^{1/2}}{2M},$$

Width (LifeTime) order of magnitude estimates

- The amplitude square has the dimensions of E^2.
  - Weak → $|\text{Ampl}|^2 \approx G_F^2 \times M^6$
  - E.m. → $|\text{Ampl}|^2 \approx \alpha^2 \times M^2$
  - Strong → $|\text{Ampl}|^2 \approx \alpha_s(M)^2 \times M^2$
- Examples of estimates (wrong by factor ≈10 maximum):

Interaction	**Decay**	**Phase space (MeV^{-1})**	**$\|\text{Ampl}\|^2$ (MeV^2)**	**Γ (MeV)**	**τ (s)**
Weak	$\pi^\pm \to \mu^\pm \nu$	6.0×10^{-5}	6.0×10^{-10}	3.6×10^{-14}	1.8×10^{-8} **(2.6×10^{-8})**
e.m.	$\pi^0 \to \gamma\gamma$	1.5×10^{-4}	0.97	1.4×10^{-4}	4.6×10^{-18} **(8.5×10^{-17})**
strong	$\rho^0 \to \pi^+\pi^-$	2.4×10^{-5}	6.0×10^{5}	13 **(150)**	5.0×10^{-23}

	Lifetime τ	Width Γ
Weak decays		
K_S, K_L	0.89564×10^{-10} s, 5.116×10^{-8} s	
$K^{\pm}$	1.2380×10^{-8} s	
Λ	2.632×10^{-10} s	
B-hadrons	$\approx 10^{-12}$ s	
Muon	2.2×10^{-6} s	
Tau-lepton	2.9×10^{-13} s	
Top-quark	$\approx 5 \times 10^{-25}$ s	2 GeV
e.m. decays		
π^0	8.52×10^{-17} s	8 eV
η	$\approx 10^{-19}$ s	1.30 keV
Strong decays		
J/ψ		92.9 keV
Υ		54.02 keV
ρ		149.1 MeV
ω		8.49 MeV
ϕ		4.26 MeV
Δ		114 ÷ 120 MeV

Recap - fundamental interactions

- Electromagnetic interaction:
  - Can be studied at all energies with "moderate" cross-sections;
  - Above O(100 GeV) becomes electro-weak
- Weak interactions:
  - At low energies it can be studied using decays of "stable" particles – large lifetimes and small cross-sections;
  - Above O(100 GeV) becomes electro-weak
- Strong interactions:
  - At low energy (below 1 GeV) "hadronic physics" based on confinement: no fundamental theory available by now
  - At high energies (above 1 GeV) QCD is a good theory: however since partons are not directly accessible, only "inclusive" quantities can be measured and compared to theory. Importance of simulations to relate partonic quantities to observables.

Comparison between beam possibilities

- Electrons:
  - Clean, point-like, fixed (almost) energy, but large irradiation due to the low mass. "Exclusive" studies are possible (all final state particles are reconstructed and a complete kinematic analysis can be done)
  - ➔ e^+e^- colliders less for energy frontier,mostly for precision measurements
- Protons:
  - Bunch of partons with momentum spectrum, but low irradiation. "Inclusive" studies are possible. A complete kinematic analysis is in general not possible (only in the transverse plane it is to first approximation possible)
  - ➔ highest energies are "easily" reachable, high luminosity are reachable but problems in the interpretation of the results; very "demanding" detectors and trigger systems.
- Anti-protons:
  - Difficult to obtain high intensities and high luminosity but no problems with energies, same problems of protons (bunch of partons)
- ➔ p-antip limited by luminosity, e^+e^- limited by energy BUT perfect for precision studies, pp good choice for energy frontier

Implications for experiments:

- You need high energy for
  - Probe electro-weak scales, get closer to higher scales
  - Enlarge the achieveble mass spectrum (particle discoveries)
- You need high beam intensity and large/dense targets or high efficiency detectors
  - To access low probability phenomena
- You need high resolution detectors
  - To improve particle discrimination especially for rare events.

Where do we stand now.

- The EW + QCD Standard Model allows to describe reasonably well most of the "high energy" > O(10 GeV) phenomena
- However:
  - The model is unsatisfactory under several points of view
    - Hierarchy / naturalness problem
    - Large number of unpredictable parameters
  - Left behind "ununderstood areas"
    - Strong interaction phenomena below O(1 GeV)
    - Hadron spectroscopy
    - No description / no space left for dark matter
    - Still not clear picture of neutrino dynamics
    - Of course gravitation is out…

End of the Introduction

- Present prospects of Elementary Particle experiments:
  - ENERGY frontier → LHC, HL-LHC, ILC, TLEP,….
  - INTENSITY frontier → flavour-factories, fixed target,…
  - SENSITIVITY frontier → detectors for dark matter, neutrinos,..
- The general idea is to measure quantities for which you have a clear prediction from the Standard Model, and a hint that a sizeable correction would be present in case of "New Physics".