Experimental Elementary Particle Physics

Cesare Bini

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Aim of these lectures

Experimental Physics:

- define the "question to nature"
- design the experiment
- build the experimental apparatus
- run the experiment
- analyze the data and get the "answer"

Learn in this course:

- How to design an EPP experiment
- How to analyze data in order to extract physics results

Outline of the Lectures

Short introduction: the goal and the main "numbers"

The language of the random variables and of the statistical inference (a recap of things you already know…)

The Logic of an EPP experiment

Quantities to measure in EPP

How to analyze data

How to design an EPP experiment

- The projectiles and the targets: cosmic rays, particle accelerators
- The detectors: examples of detector designs

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.

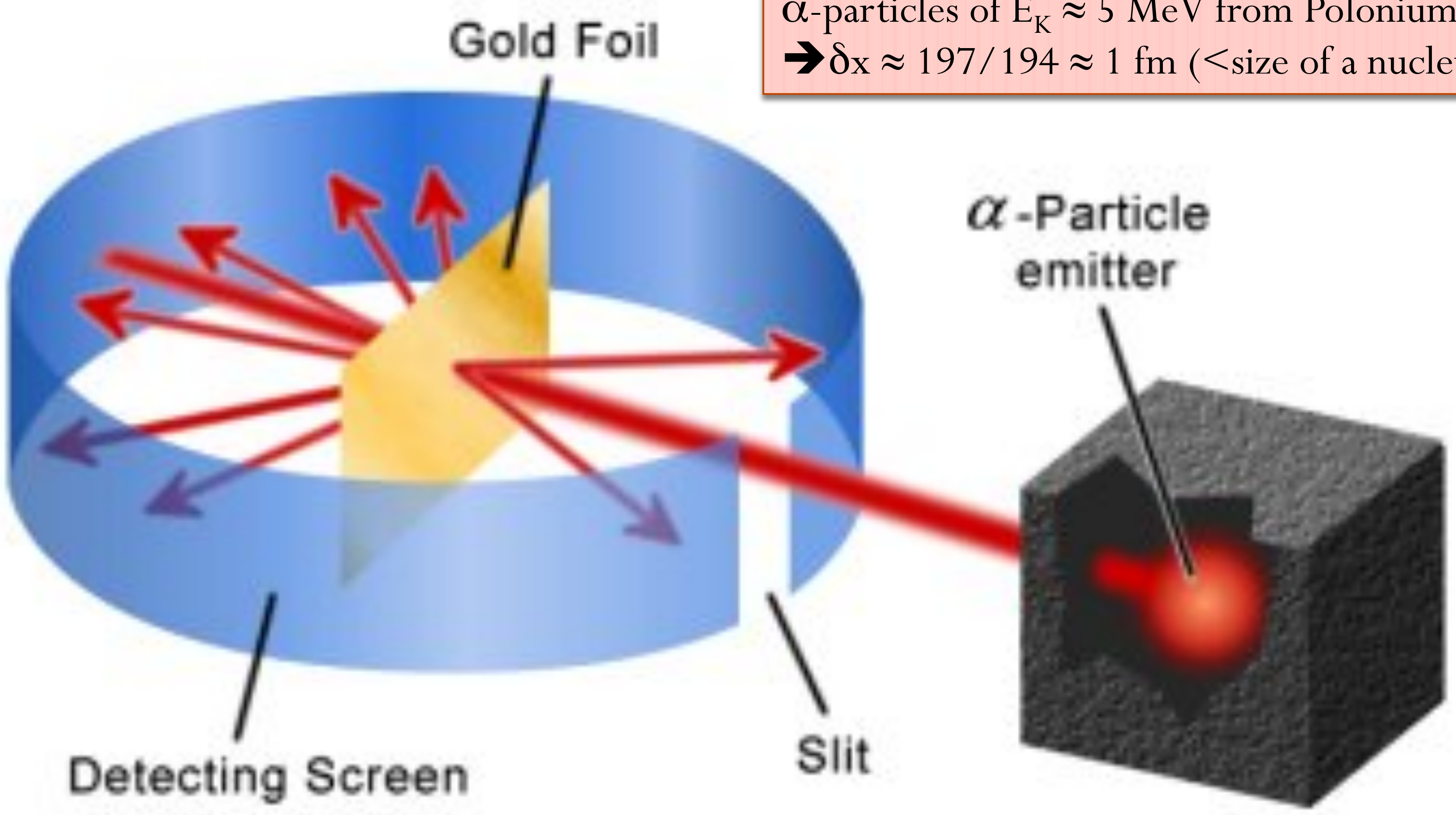
$$\delta x \approx \frac{\hbar c}{pc} \Rightarrow \delta x(fm) \approx \frac{197}{p(MeV/c)}$$

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 - I

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 ?)

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 $a+b \rightarrow X$

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

- 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 ??

Units

- $\Delta E_k = q\Delta V$
- Joule "=" C×V in MKS
- Suppose we have an electron q = e = 1.602×10^{-19} C and a ΔV=1 V: ➔ $\Delta E_k = 1.6\times10^{-19}$ J == 1 eV
- Particularly useful for 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 !
- 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.
  - It implies the following dimensional equations:
    - [L] = [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 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

- Electromagntic interaction: the meaning of α :
  - [Vr]=[E][L]=[*hc*] ➔[α] adimensional and << 1

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

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

- 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

$$r_e = \frac{e^2}{4\pi\varepsilon_0 m_e c^2}$$

Energy scales in the ∞ly small - II

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

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

3. Bohr radius: radius of the hydrogen atom orbit

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

- Weak Interaction scale: determined by the Fermi constant G_F

  $[G_F] = [E]^{-2}$

$$r_{EW} \approx \sqrt{G_F}(\hbar c)$$

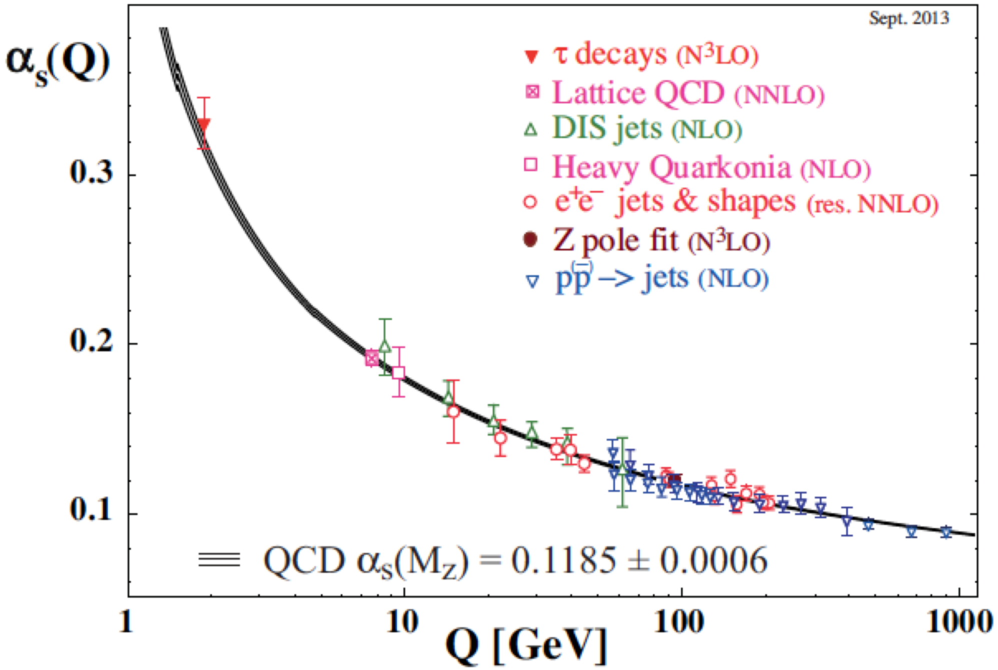
We know that G_F is NOT a "fundamental" constant, but an "effective" one:

$$G_F \approx g / M_W{}^2$$

Energy scales in the ∞ly small - III

- 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 - IV

- 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 $\boldsymbol{m^2}$. An adimensional quantity is

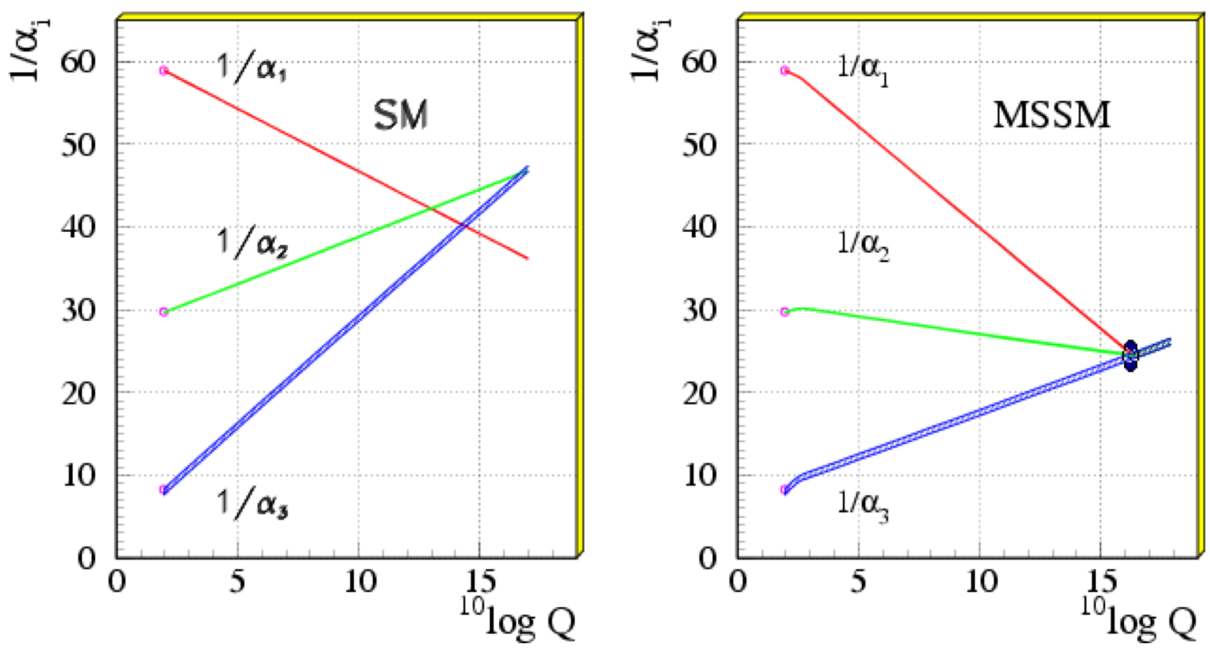
$$\frac{Gm^2}{\hbar c}$$

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 $\boldsymbol{M_{Planck}}$)

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

Energy scales in the ∞ly small - V

- 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 - VI

- 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.

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

- The Higgs mass $\boldsymbol{m_H}$ is UV sensitive (its value depends on quantum corrections)
- $\boldsymbol{\Lambda}$ is the scale up to which we have the UV theory: e.g. $\boldsymbol{\Lambda} = \boldsymbol{M_{Planck}}$?
- If no other scale is there btw Higgs and Planck, $\boldsymbol{M}=\boldsymbol{\Lambda}$, 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 $\boldsymbol{\Lambda}\approx$O(TeV) all becomes natural, e.g. MSSM, Technicolor,…

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

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

Energy scales in the ∞ly small - V

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	280 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

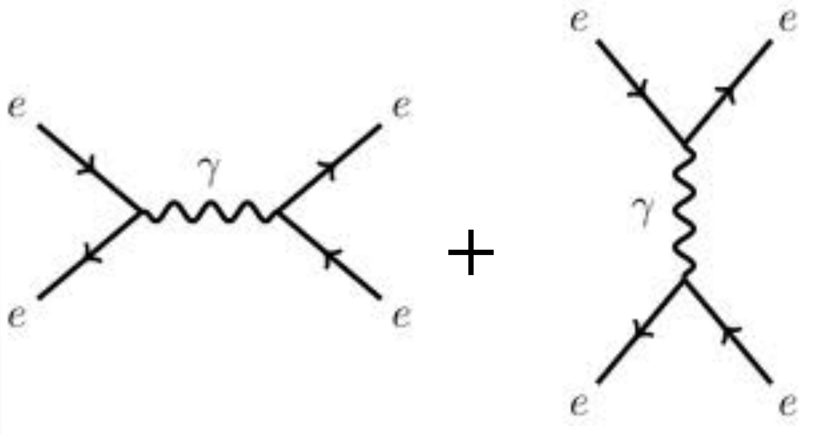
Probability/Frequency of a final state: the cross-section and the decay width

- 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 a new constant enters in the game: the normalized Planck constant.
- We introduce the "natural system" where $\hbar = c = 1$
  - **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)

$$\sigma = \int \Bigg|$$



$$\Bigg|^{2} d\varphi$$

Two ingredients in the theory calculations:

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

→ phase space $d\phi$

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

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

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

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

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

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 → $|Ampl|^2 \approx G_F^2 \times M^6$
  - E.m. → $|Ampl|^2 \approx \alpha^2 \times M^2$
  - Strong → $|Ampl|^2 \approx \alpha_s(M)^2 \times M^2$
- Examples of estimates (wrong by factor ≈10 maximum):

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

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

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

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

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".