Methods in Experimental Particle Physics

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(also I semester only this year)

Aim of these lectures*

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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 a PP experiment
- Quantities to measure in PP
- How to analyze data
- How to design a PP experiment
    - The projectiles and the targets: cosmic rays, particle accelerators
    - The detectors: examples of detector designs

The unreasonable effectiveness of Mathematics in the Natural Sciences

Eugene P. Wigner , “The unreasonable effectiveness of Mathematics in the Natural Sciences”, Communications in Pure and Applied Mathematics, Vol. 13, No. I (February 1960)

<<..it is not at all natural that "laws of nature" exist, much less that man is able to discover them.>>

<<…The exploration of the conditions which do, and which do not, influence a phenomenon is part of the early experimental exploration of a field. It is the skill and ingenuity of the experimenter which show him phenomena which depend on a relatively narrow set of relatively easily realizable and reproducible conditions.>>

EPP= Elementary Particle Physics
alternatively used
HEP=High Energy Physics

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, presently at the forefront of "fundamental" 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 (assuming existence of asymptotic states)
- "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 one is able to resolve.

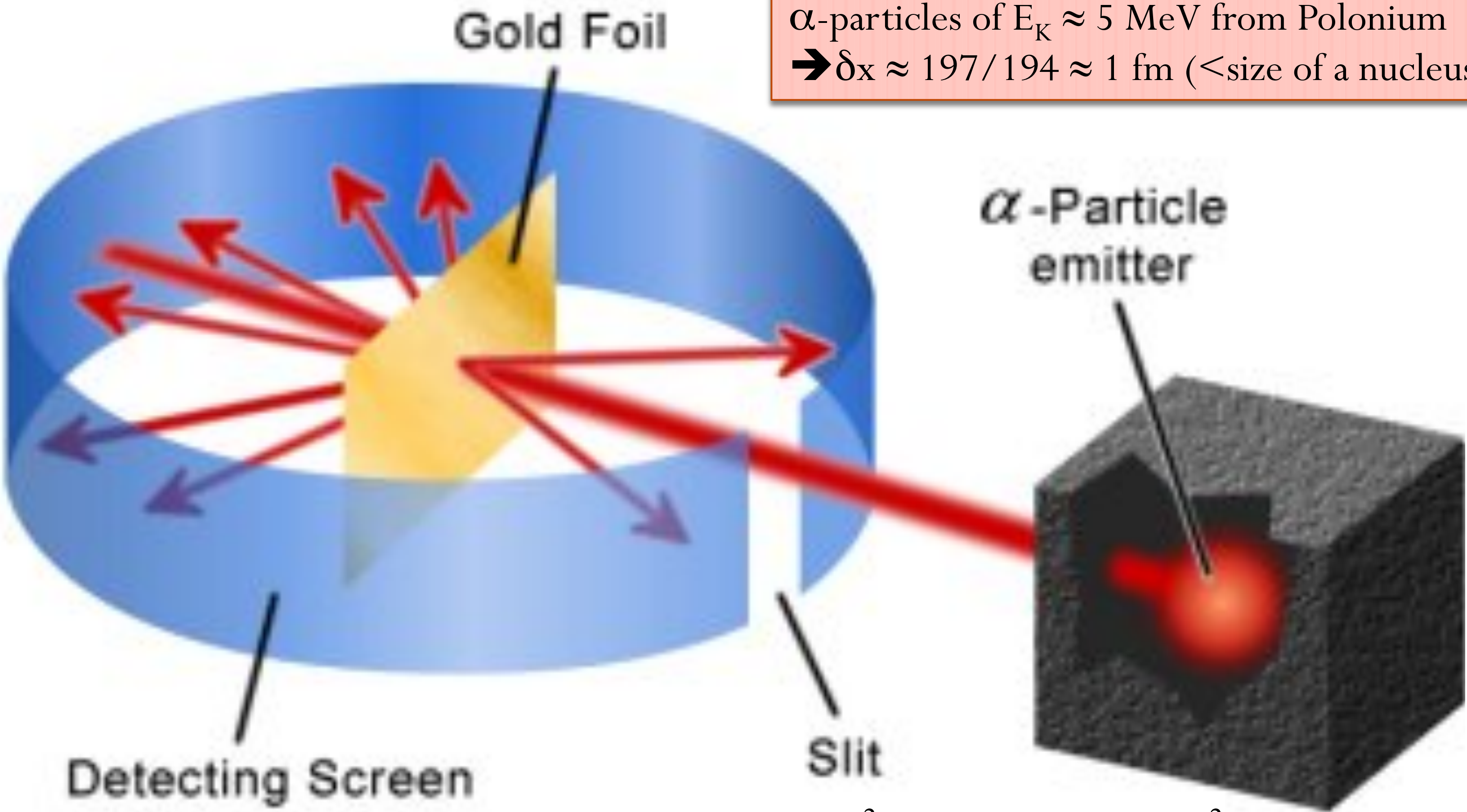
$$\delta x \approx \frac{\hbar c}{pc} \Rightarrow \delta x(fm) \approx \frac{197}{p(MeV/c)}$$

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)



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

$A(He)=4$

$Z(Au)=79$

$A(Au)=197$

$Mp=938\ MeV/c^2$

$p(\alpha)=\sqrt{(4*938 + 5)^2-4*938^2} =194\ MeV/c$

$E(\alpha)=4*938 + 5=3757\ MeV$

$M(\alpha)=4*938=3752\ MeV/c^2$

$M(Au)=197*938=184786\ MeV/c^2$

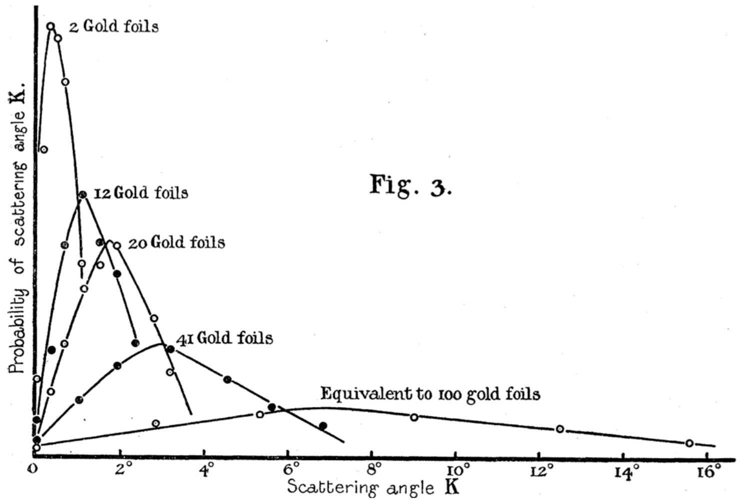
$\sqrt{s}=\sqrt{M(\alpha)^2 + M(Au)^2 +2\ E(\alpha)M(Au)} =$

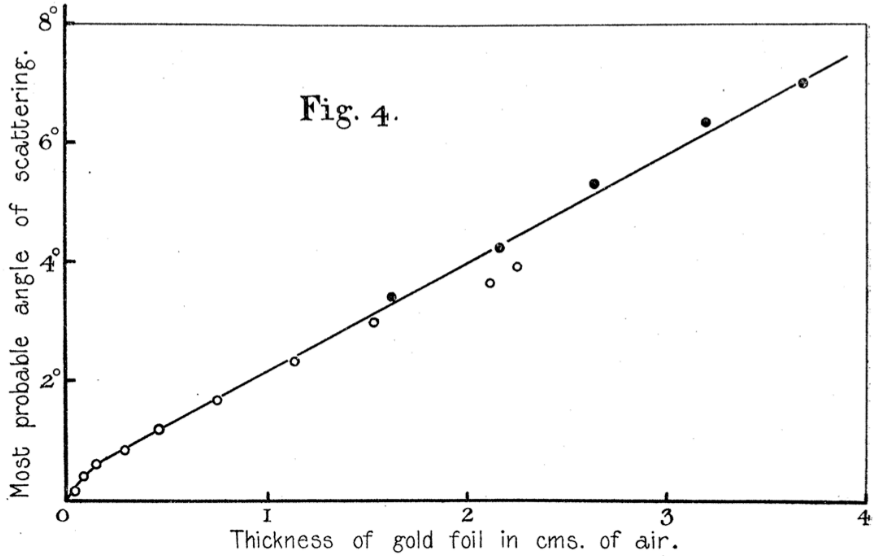
$=\sqrt{3752^2+184786^2+2*184786*3757}=188543\ MeV=188.5\ GeV$

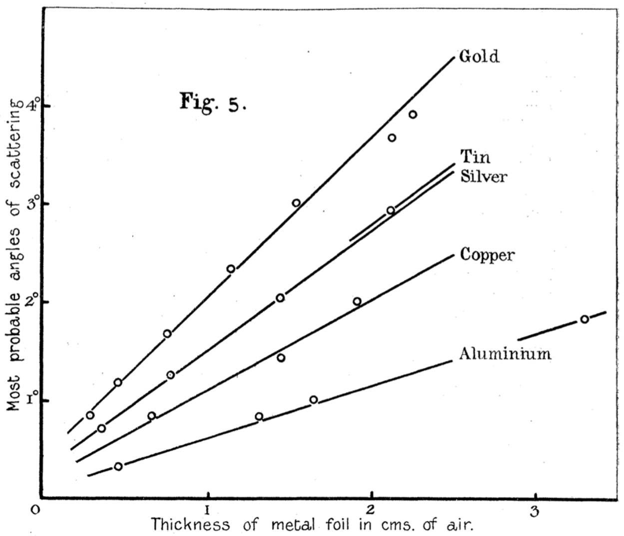
Key elements in the Rutherford experiment – physical quantities

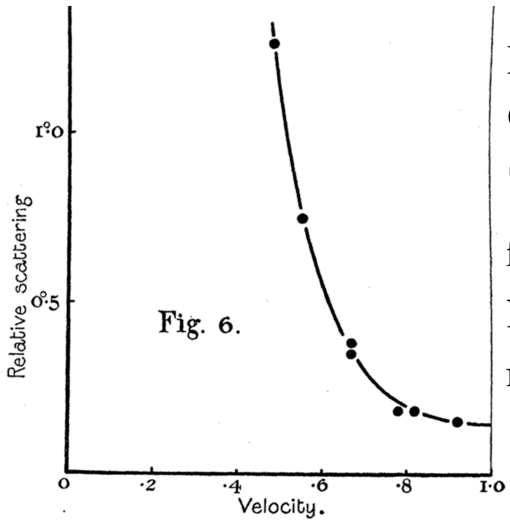
- **Energy of the collision** (driven by the kinetic energy of the α particles) the meaning of $\sqrt{s}$
- **Beam Intensity** (how many α particles /s)
- **Size and density of the target** (how many gold nuclei encountered by the α particles);
- **Deflection angle θ**
- **Probability/frequency of a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

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, $X=a+b$

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

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 (developed in Frascati from an idea of Bruno Touschek).
  - ep colliders (like HERA)
  - e^+e^- storage rings
  - p-pbar or pp colliders

$$\sqrt{s} = \sqrt{M_1^2 + M_2^2 + 2E_1M_2} \approx \sqrt{2E_1M_2} \quad \text{(fixed target)}$$

$$\sqrt{s} = 2\sqrt{E_1E_2} \quad \text{(colliding beams)}$$

Electron beam E=100 GeV on Hydrogen target

$\sqrt{s} \approx 13.7$ GeV

Electron/positron colliding beams E=100 GeV

$\sqrt{s} \approx 200$ GeV

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.

$$E^2 = (pc)^2 + (mc^2)^2 \text{ --> } E^2 = p^2 + m^2$$

  - 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 (ħc=1)
    - $[E] = [L]^{-1} = [T]^{-1}$

    ➔ 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:

$$\frac{e^2}{4\pi\varepsilon_0\hbar c} = \alpha = \frac{(1.610^{-19}C)^2}{4\pi 8.8510^{-19}F/m 1.0510^{-34}Js 310^8 m/s} = \frac{1}{137} = 0.0073$$

- α sets the scale of the ***intensity*** of the electromagnetic interactions. In natural units ($\hbar = c = \varepsilon_0 = \mu_0 = 1$) ***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 $\boldsymbol{mc^2}$ of the charges

$$r_e = \frac{e^2}{4\pi\varepsilon_0 m_e c^2} = \frac{\alpha}{m_e}\frac{\hbar}{c} \rightarrow \frac{\alpha}{m} \qquad \text{In natural units}$$

  - **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: $\boldsymbol{e = g_W \sin\theta_W}$
- The "Electroweak scale" is the scale at which the electroweak unification is at work, $O(100\ \mathrm{GeV})$. By convention it is given by $\boldsymbol{v}$, the Higgs vacuum expectation value:

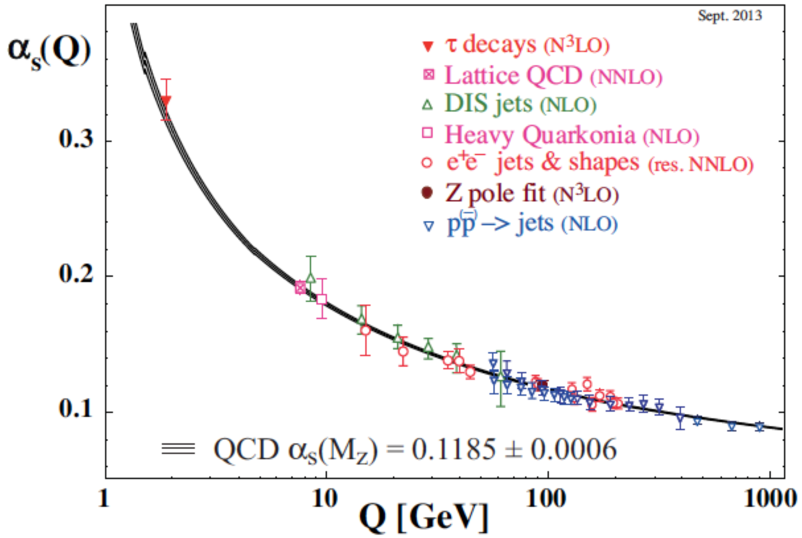
$$v = \frac{1}{\sqrt{\sqrt{2}G_F}} = 246GeV \qquad r_{EW} \approx \sqrt{\sqrt{2}G_F}\,(\hbar c)$$

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

$$\frac{Gm^2}{\hbar c} \qquad \text{(equivalent to } \frac{e^2}{4\pi\varepsilon_0 \hbar c} = \alpha \text{)}$$

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.

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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 $r=2MG/c^2$ (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 supposed to be the domain of the "quantum gravity".
- N.B. The theory of general relativity (i.e. the classical theory of gravitation) and Quantum Mechanics are highly incompatible. Does a Quantum theory of gravitation exist?
  Hints (by S.Hawking): black hole evaporation, information loss paradox etc..