Methods in Experimental Particle Physics

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II semester a.y. 2018-2019

(also I semester only this year)

Aim of these lectures*

* Many thanks to Prof. C. Bini for the provided material.

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)

COMMUNICATIONS ON PURE AND APPLIED MATHEMATICS, VOL. XIII, 001–14 (1960)

The Unreasonable Effectiveness of Mathematics in the Natural Sciences

Richard Courant Lecture in Mathematical Sciences delivered at New York University, May 11, 1959

EUGENE P. WIGNER
Princeton University

"and it is probable that there is some secret here which remains to be discovered." (*C. S. Peirce*)

There is a story about two friends, who were classmates in high school, talking about their jobs. One of them became a statistician and was working on population trends. He showed a reprint to his former classmate. The

<<..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.>>

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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.

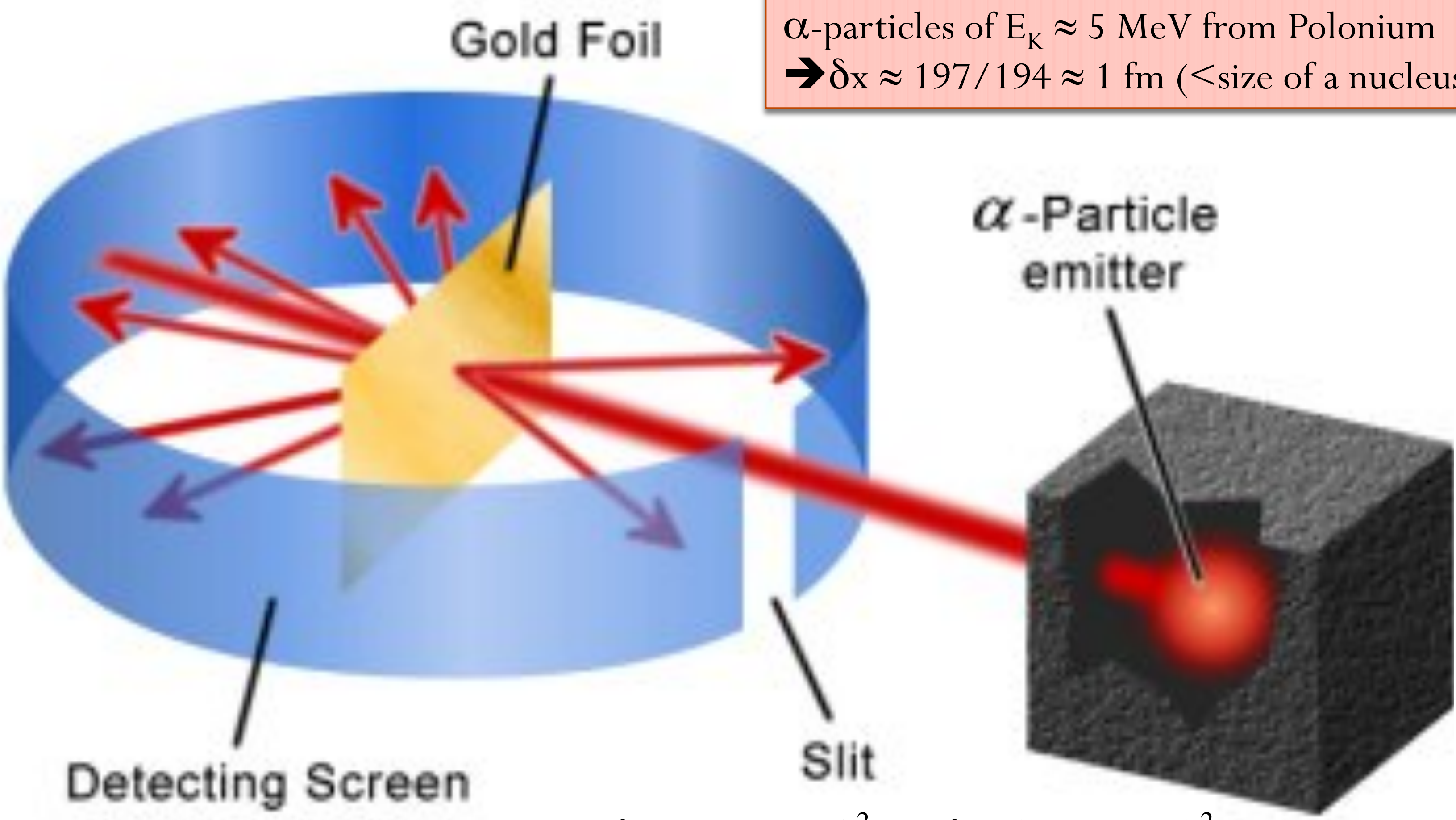
$$\delta x \approx \frac{\hbar c}{pc} \Rightarrow \delta x(fm) \approx \frac{197}{p(MeV/c)}$$

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)



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

Some numbers

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?)

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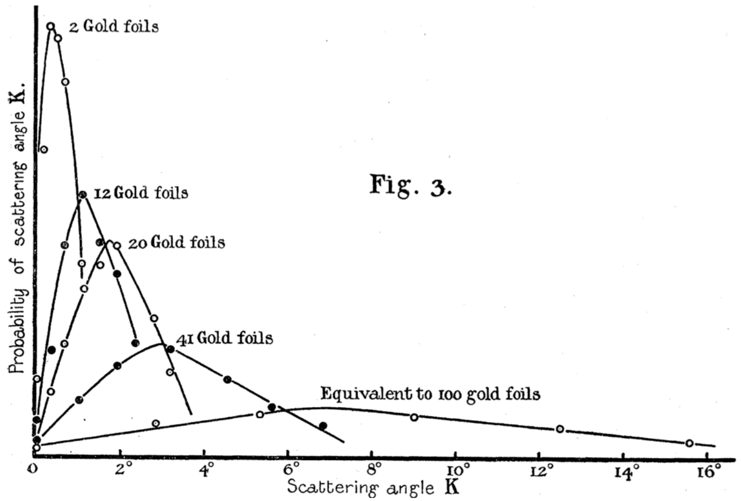
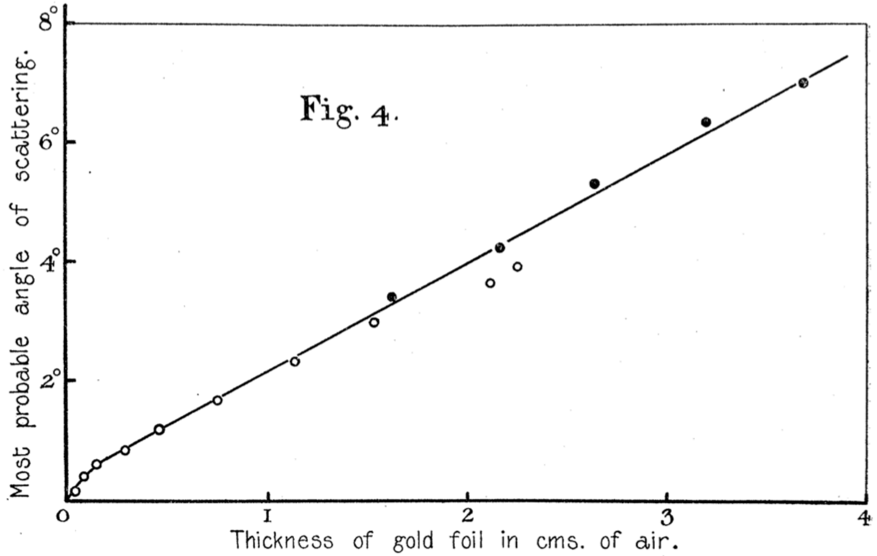
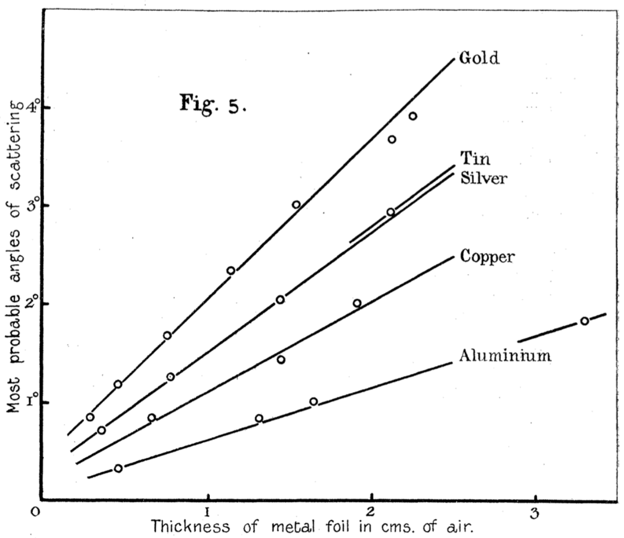
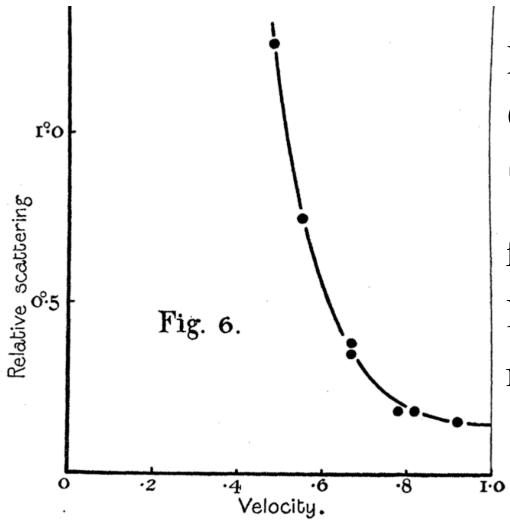
The Rutherford experiment – original results









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 $a+b \rightarrow X$

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

- 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 ??

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

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

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

Examples

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.

$$E^2 = (pc)^2 + (mc^2)^2 --> E^2 = p^2 + m^2$$

  - 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:

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

- α sets the scale of the ***intensity*** of the electromagnetic interactions. In natural units ($\hbar = c = \varepsilon_0 = \mu_0 = 1$) ***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 ***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, O(100 GeV). By convention it is given by $\boldsymbol{v}$, the Higgs vacuum expectation value:

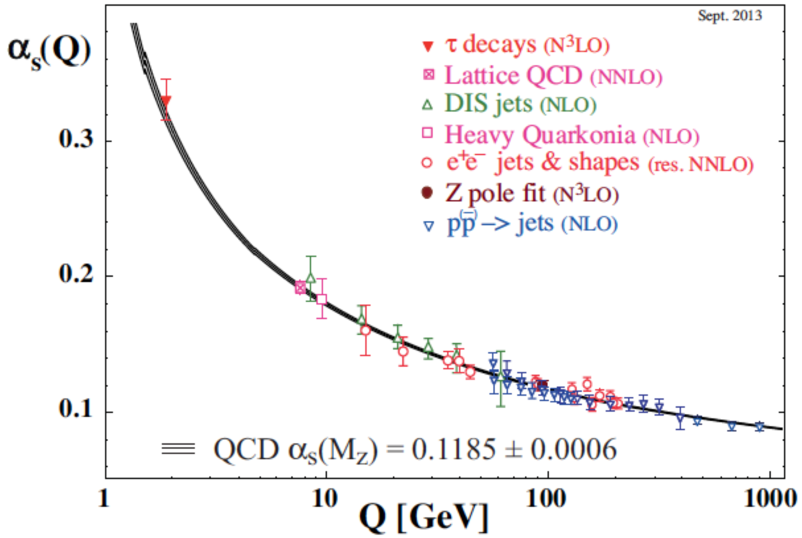
$$v = \frac{1}{\sqrt{\sqrt{2}G_F}} = 246 GeV \qquad r_{EW} \approx \sqrt{\sqrt{2}G_F}\,(\hbar c)$$

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

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

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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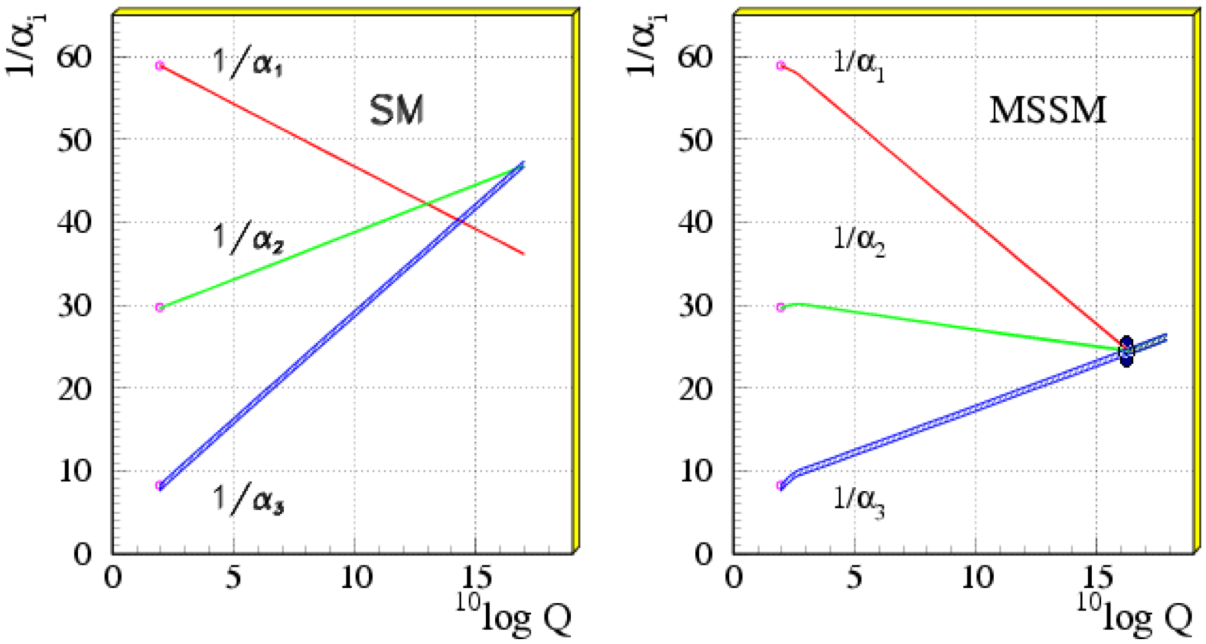
The Planck scale

- 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..

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

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

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 (electroweak 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

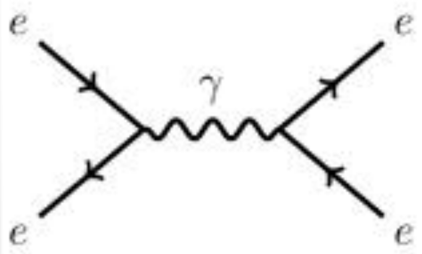
The TeV scale is the maximum reachable with the present accelerator technology

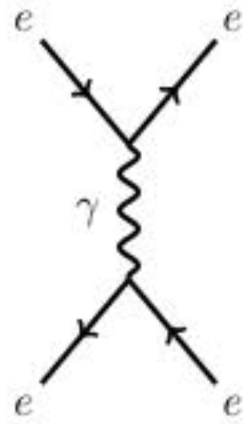
Probability/Frequency of a final state:
the cross-section and the decay width

- 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 decay. 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 (1 b = 10^{-24} cm^2 =100 fm^2)

Cross-section scales

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

$\sigma = \int \Big|$ 

$+$ 

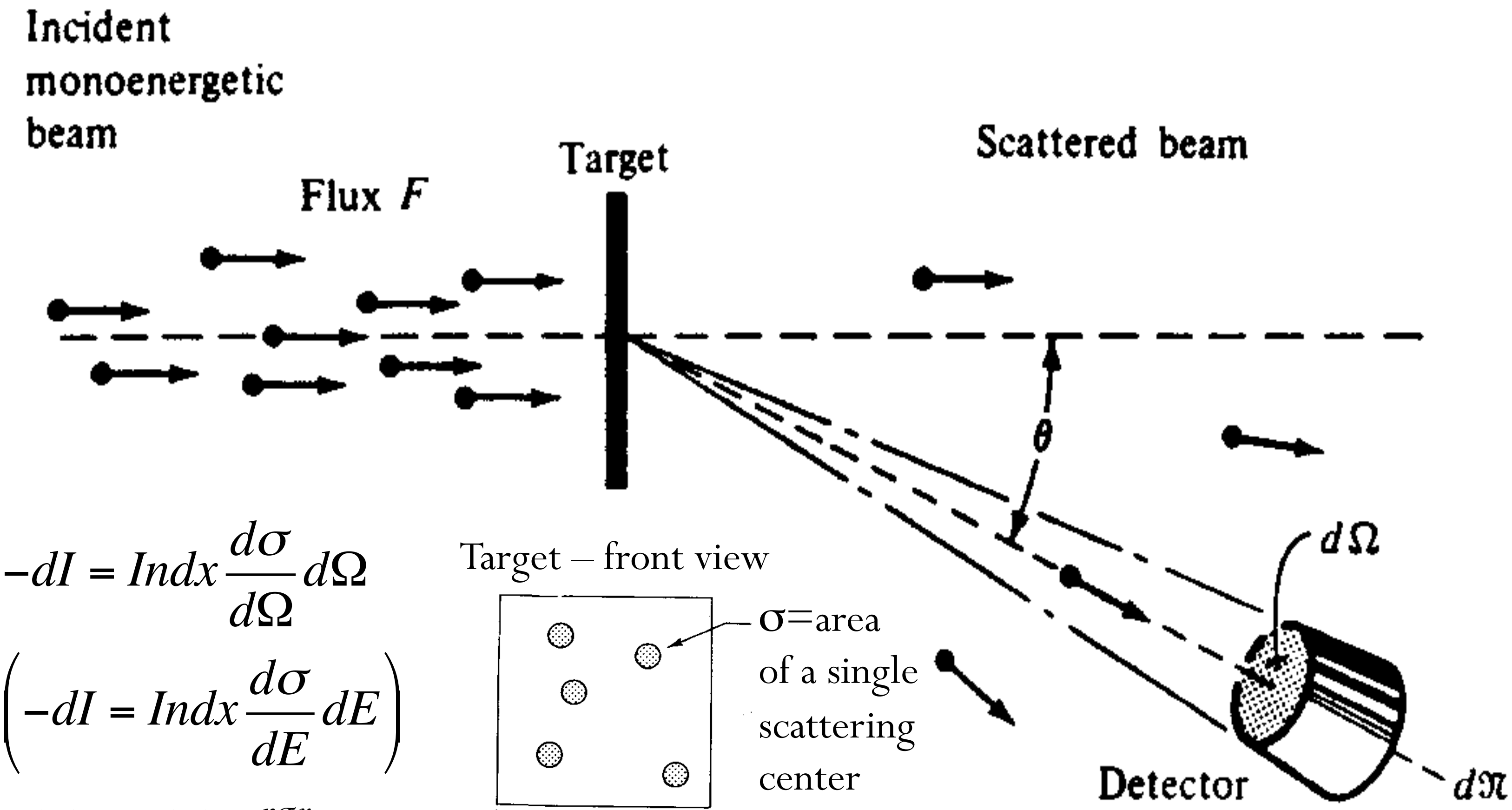
$\Big|^2 d\varphi$

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**



$$-dI = Indx \frac{d\sigma}{d\Omega} d\Omega$$

$$\left(-dI = Indx \frac{d\sigma}{dE} dE \right)$$

$$I(x) = I(0)e^{-n\sigma x}$$

$$\sigma = \int_{4\pi} \frac{d\sigma}{d\Omega} d\Omega$$

$$\left(\sigma = \int_0^{E_{MAX}} \frac{d\sigma}{dE} dE \right)$$

Target – front view

σ=area
of a single
scattering
center

x=target thickness
n = density of scattering centers
I = beam intensity

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

Experimentally:

$\sigma(\nu e\text{-}=>\nu e\text{-})\sim 10^{-41}$ cm^2 x E_ν (GeV) = 0.01 fb x E_ν (GeV)

E_ν neutrino energy in laboatory

$S=2m_eE_\nu = 2*0.000511*E_\nu(\text{GeV})$ GeV^2

$=>E_\nu(\text{GeV})\sim 1000 * s\ (\text{GeV}^2)$

$\sigma(\nu e\text{-}=>\nu e\text{-})(s=1\ \text{GeV}^2)\sim 10$ fb

$\sigma(\nu e\text{-}=>\nu e\text{-})(s=100\ \text{GeV}^2)\sim 1$ pb

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	$\pi^\pm \to \mu^\pm \nu$	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		$114 \div 120$ 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.

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 theory (not only Standard Model), and a hint that a sizeable correction would be present in case of "New Physics".