Hystorical introduction

Introduction

- “Program” of the EPP: 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 ?
  - **(1)** ***how to design an experiment***
  - **(2)** ***how to understand its data***.
  - We concentrate on subnuclear physics.
  - A selection of experiments is needed.

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".
- "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.

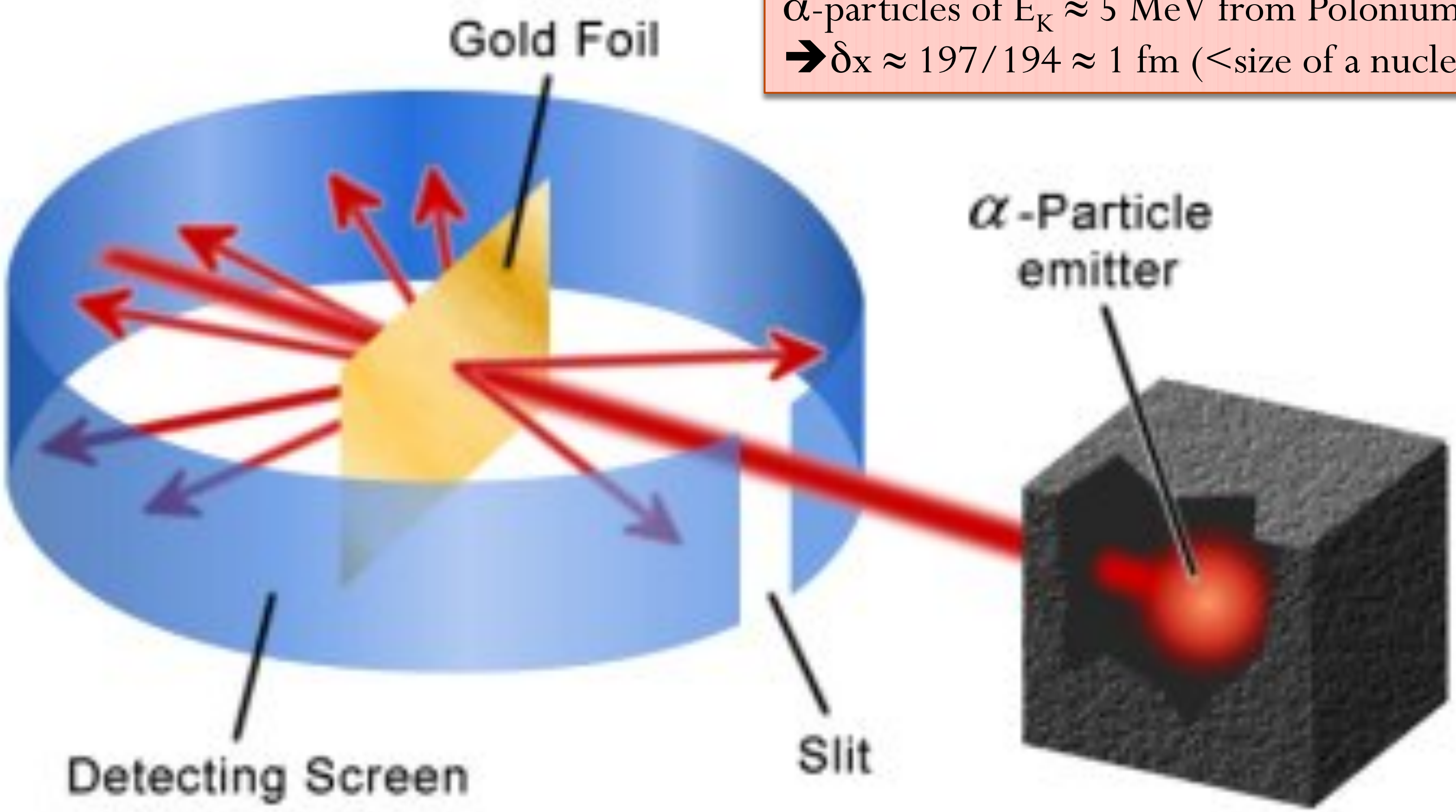
$$\delta x \approx \frac{\hbar c}{pc} \Rightarrow \delta x(fm) \approx \frac{197}{p(MeV/c)}$$

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)



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

Unit system

- We have seen that by posing $c = 1$ energy, momentum and mass get the same dimensions and units. All are expressed in eV.
- 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

$$\hbar = c = 1$$

- It implies the following dimensional equations:
  - $[L] = [T]$
  - $[E] = [L]^{-1} = [T]^{-1}$
- Only one fundamental quantity is required: e.g. energy ➔ time and length are $(\text{energy})^{-1}$
  - cross-section is a $(\text{length})^{2}$ so an $(\text{energy})^{-2}$.
  - decay width is a $(\text{time})^{-1}$ so an (energy)
- Numerically we need few conversion factors:
  - $1\ \text{MeV} == 0.00506\ \text{fm}^{-1}$
  - $1\ \text{MeV} == 1.519\ \text{ns}^{-1}$

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 ***mc²*** of the charges

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

Scales in the ∞ly small - II

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

$$\lambdabar_e = \frac{\hbar}{m_e c} = \frac{r_e}{\alpha}$$

3. Bohr radius: radius of the hydrogen atom orbit

G

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

- Weak Interaction scale: determined by the Fermi constant G_F

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

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

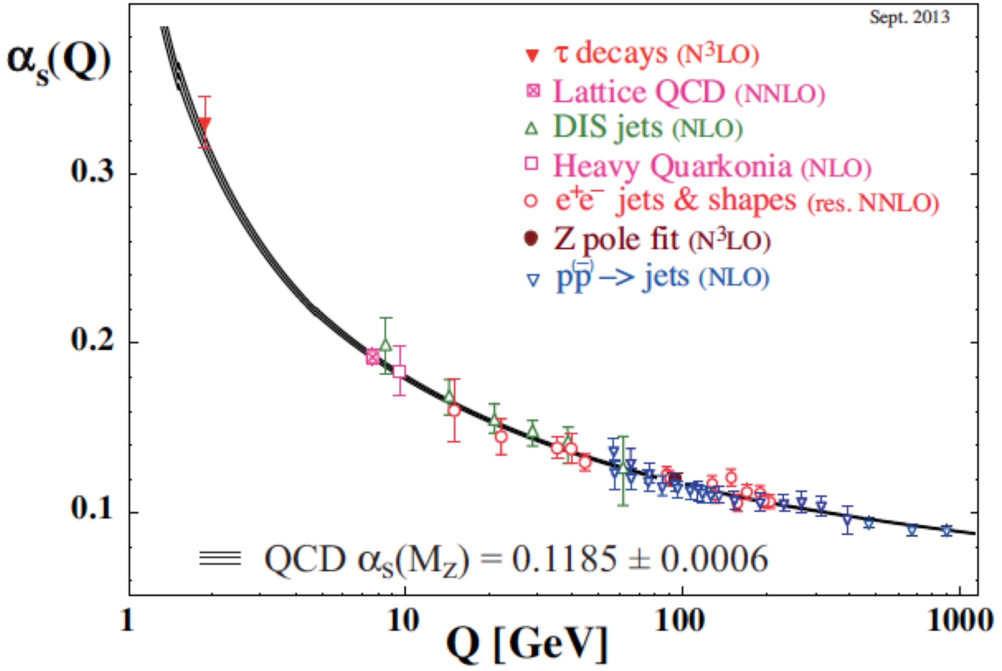
We know that G_F is NOT a "fundamental" constant, but an "effective" one:

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

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.

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



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

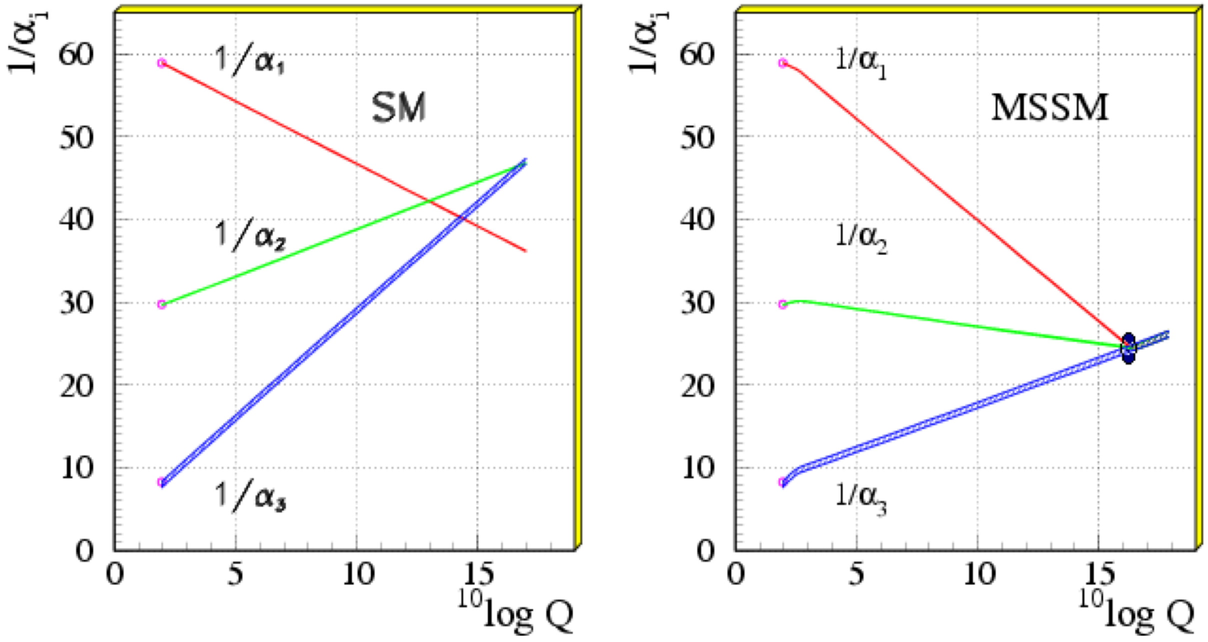
$$\frac{Gm^2}{\hbar c}$$

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 $\boldsymbol{M_{Planck}}$)

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

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 ??

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.

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

- The Higgs mass $\boldsymbol{m_H}$ is UV sensitive
- $\boldsymbol{\Lambda}$ is the scale above 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,…

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

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
Electro-weak scale	8.00×10^{-19} m (Λ_{EW}=246 GeV)	246 GeV
"New Physics" scale		1 TeV
GUT Scale		10^{16} GeV
Planck scale	1.62×10^{-35} m	1.2×10^{19} GeV

How to increase alpha-particles kinetic energies ?
Which is the best projectile ? Electrons allow to probe the e.m. structure and are also easy to obtain and accelerate.

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.

The Rutherford experiment - II

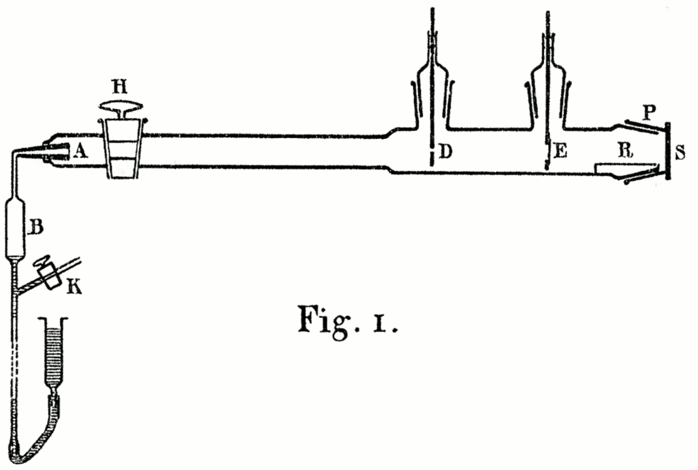


Fig. 1.

- Experimental set-up

(1910 experiment)

- The projectile: α-particles of $E_K = 4.5 \div 5.5$ MeV (from Radon, Radium, Bismuth)
- The target: gold foils of ≈1 mm air equivalent:
  - Gold thickness = 1 mm $\rho(\text{air})/\rho(\text{gold}) = 1.2\times10^{-3}/19$ mm ≈ 10^{-4} mm = 1000 Å
- The detector:fluorescent zinc sulfide screen + microscope (magnification = × 50): count hit/unit time at different distances

The Rutherford experiment - III

- E. Rutherford, **The scattering of alpha and beta particles by matter and the structure of the atom**, *Philosophical Magazine*, volume **21** (1911), pages 669-688.
  - Develope a theory of scattering from a "Rutherford-like" atom;
  - Predict scattering angle distribution (in particular fraction of "large angle" scatterings);
  - Compare with predictions from "Thompson-like" atom;
  - Compare with data from Geiger-Marsden experiment and also from other experiments involving β particles
- Example of "modern" methodology: data vs. "MC" (theory)

The Rutherford experiment - IV

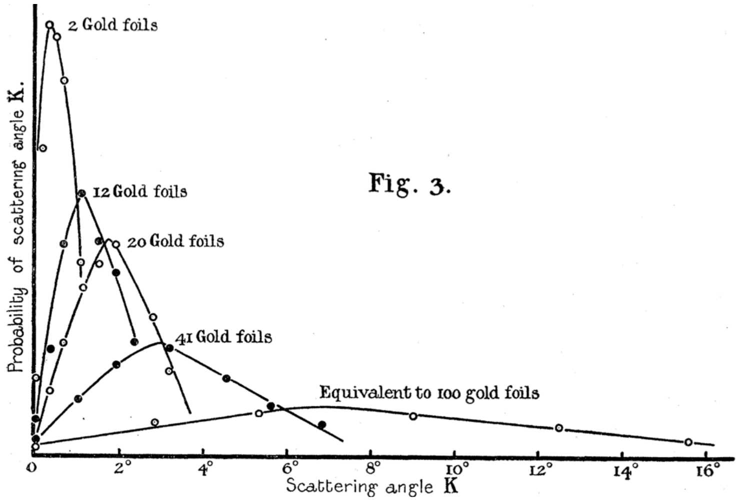


Fig. 3.

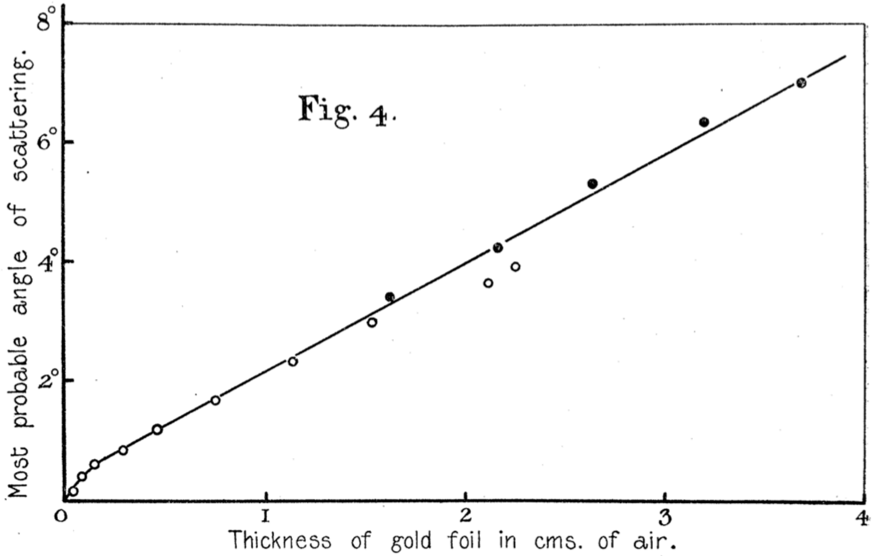


Fig. 4.

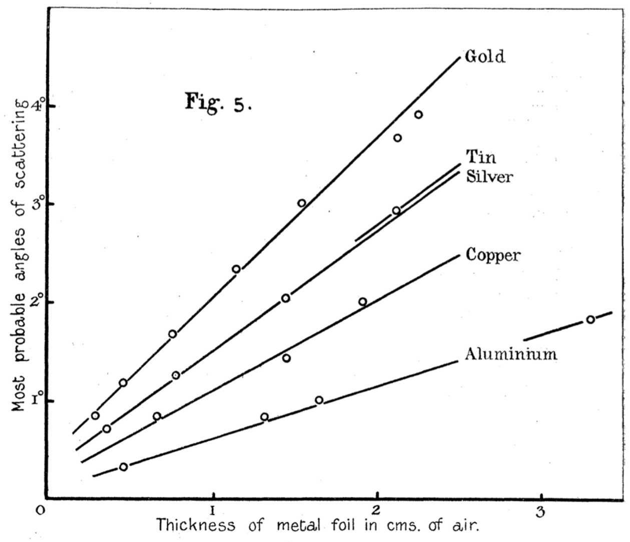


Fig. 5.

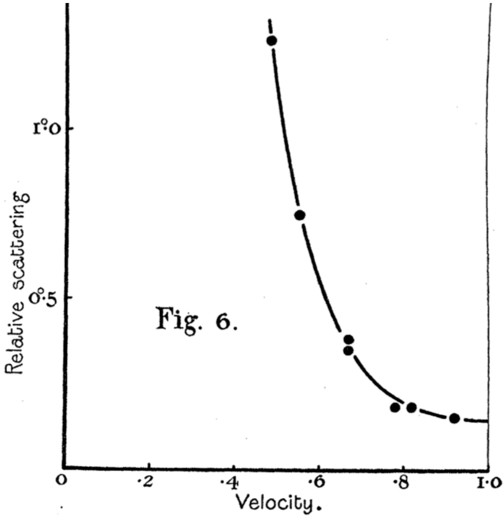


Fig. 6.

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..

An important step: electronics..

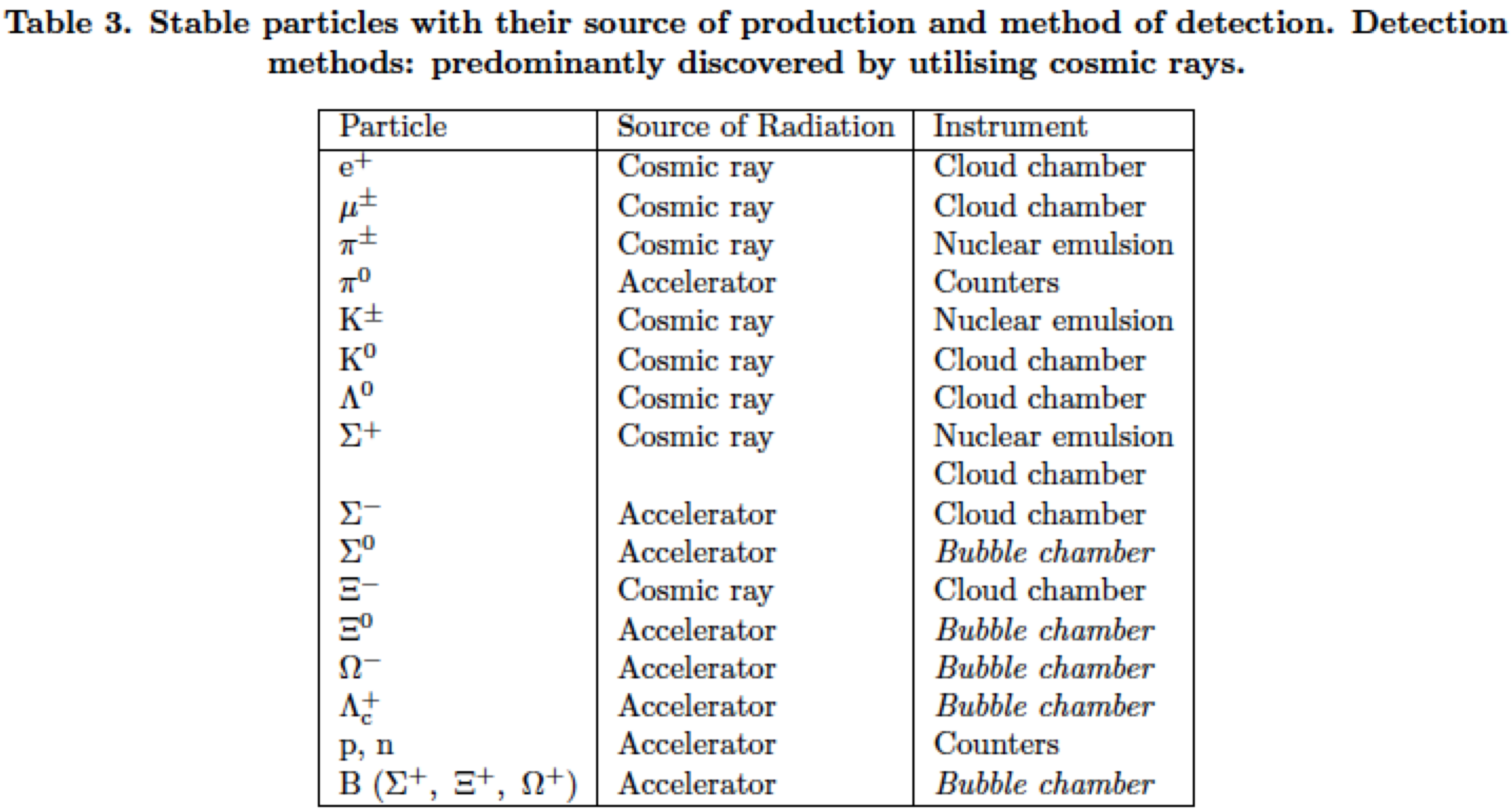


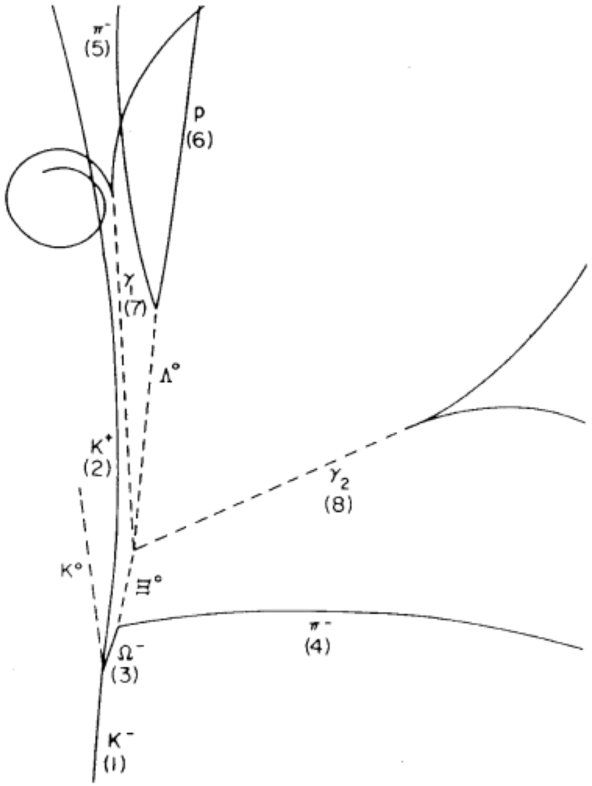
Table 3. Stable particles with their source of production and method of detection. Detection methods: predominantly discovered by utilising cosmic rays.

Particle	Source of Radiation	Instrument
e^+	Cosmic ray	Cloud chamber
$\mu^\pm$	Cosmic ray	Cloud chamber
$\pi^\pm$	Cosmic ray	Nuclear emulsion
π^0	Accelerator	Counters
$K^\pm$	Cosmic ray	Nuclear emulsion
K^0	Cosmic ray	Cloud chamber
Λ^0	Cosmic ray	Cloud chamber
Σ^+	Cosmic ray	Nuclear emulsion Cloud chamber
Σ^-	Accelerator	Cloud chamber
Σ^0	Accelerator	*Bubble chamber*
Ξ^-	Cosmic ray	Cloud chamber
Ξ^0	Accelerator	*Bubble chamber*
Ω^-	Accelerator	*Bubble chamber*
Λ_c^+	Accelerator	*Bubble chamber*
p, n	Accelerator	Counters
B (Σ^+, Ξ^+, Ω^+)	Accelerator	*Bubble chamber*

$$\begin{array}{l} K^- p \to \Omega^- K^+ (K^0) \\ \qquad\quad \lfloor \Xi^0 \pi^- \\ \qquad\qquad \lfloor \Lambda^0 \pi^0 \\ \qquad\qquad | \quad \lfloor \gamma \qquad \gamma \\ \qquad\qquad | \qquad \lfloor e^+e^- \lfloor e^+e^- \\ \qquad\qquad \lfloor \quad p\pi^- \end{array}$$

“Old” detectors

-Cloud Chamber (C.Wilson, 1911)
- Nuclear Emulsions (1937-1947)
- Bubble Chambers (D.Glaser, 1952)



High spatial resolution devices, very good for single event analysis
BUT: slow and difficult to trigger. Not useful for high statistics applications

“New” detectors

In the ‘40s (**B.Rossi**, F.Rasetti, M.Conversi,…)
“electronics” enters in the game
1930: B.Rossi invents the electronic coincidence:
→ electric signals from counters (Geiger counters and/or scintillators coupled to PMTs) are sent to “electronic circuits” that give in output a “trigger” signal. It is a revolution!

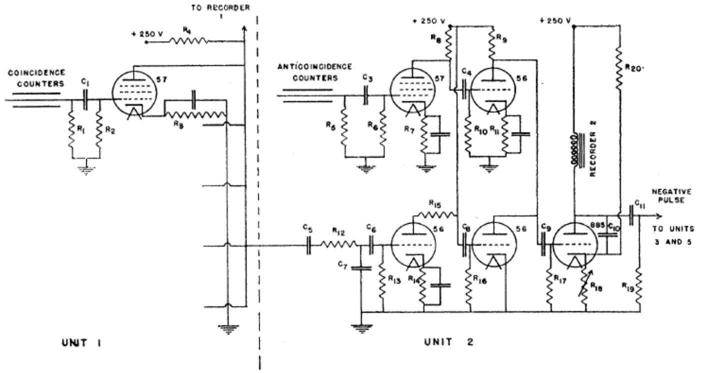


FIG. 2. Fivefold coincidence circuit (unit 1) and anticoincidence circuit (unit 2). Only one of the five Rossi tubes is shown. $R_1=R_5=10^8$; $R_2=R_6=R_8=500{,}000$; $R_3=5000$; $R_4=1$ Meg; $R_7=3000$; $R_9=7500$; $R_{10}=R_{13}=R_{16}=2$ Meg; $R_{11}=R_{19}=50{,}000$; $R_{12}=200{,}000$; $R_{14}=30{,}000$; $R_{15}=15{,}000$; $R_{17}=300{,}000$; $R_{18}=10{,}000$ adjustable; $R_{20}=25{,}000$; $C_1=0.00001$; $C_3=0.00005$; $C_4=0.03$; $C_5=0.0001$; $C_6=0.001$; $C_7=0.00003$; $C_8=C_9=0.001$; $C_{10}=0.1$; $C_{11}=0.0001$. Resistance in ohms, capacity in μf.

F.Rasetti: disintegration of slow mesotrons
Phys.Rev. 60 198 (1941)

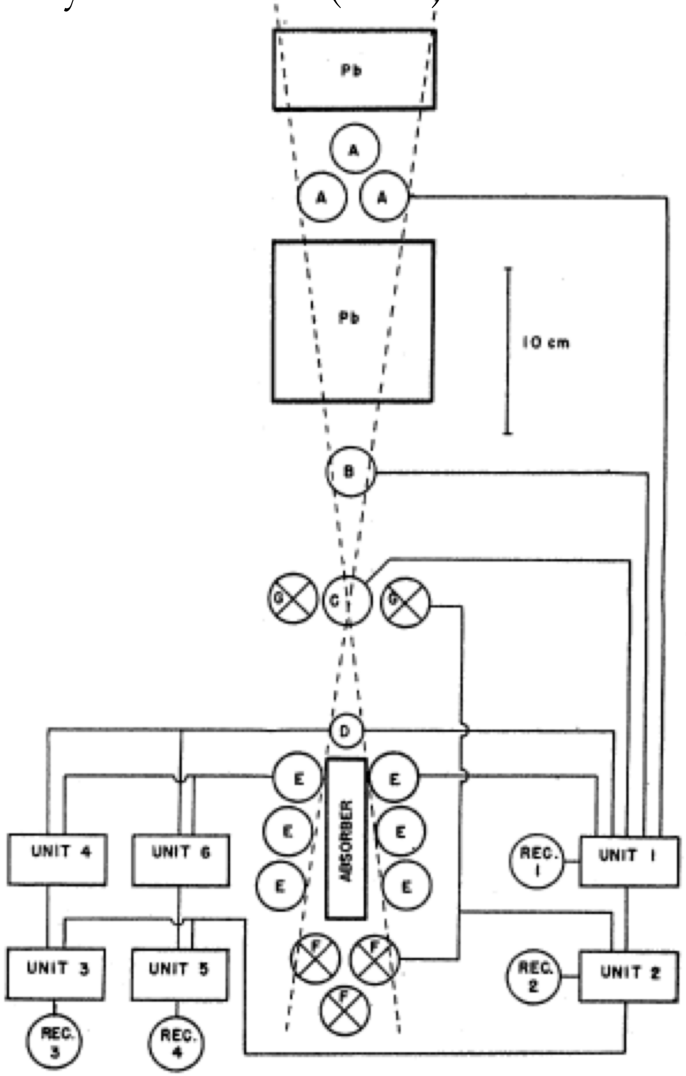
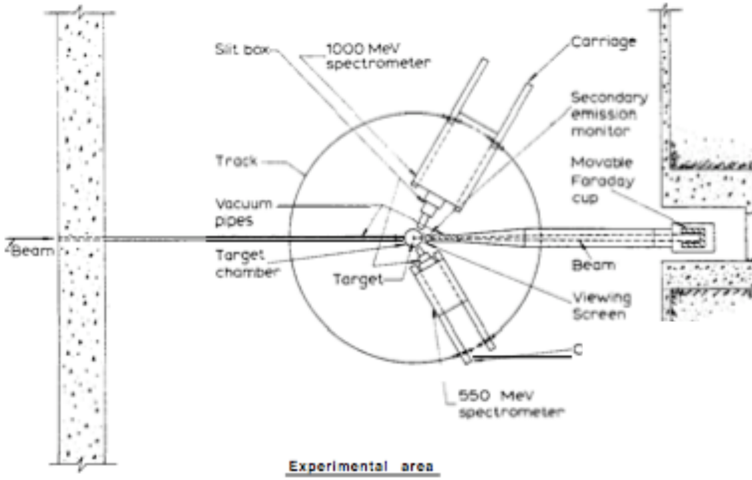


FIG. 1. Arrangement of counters, illustrating connections to amplifier units.

After Rutherford - I

- On the same line of a-la-Rutherford experiments: experiments in the '50s at SLAC (Hofstadter et al.)
- Results: "Hofstadter's experiments with nuclei such as gold and carbon showed clear differences from scattering from a point charge, as expected. However, when targets of high pressure hydrogen gas became available in 1954, he could study scattering from single protons (hydrogen nuclei) and found that the proton also was not a point-like object, but had a size that was "surprisingly large", about 0.75×10^{-13}cm. "
- New probe: electrons (up to 400 MeV) rather than α-particles
  - "point-like" probe more useful to understand nuclear structure
  - Only electromagnetic effects, not nuclear effects
- Different kinds of targets: high pressure hydrogen targets
- Completely new detector: kinematic study of final states to select "elastic scattering": spectrometer to meaure momentum of outcoming charged particles.

After Rutherford - II



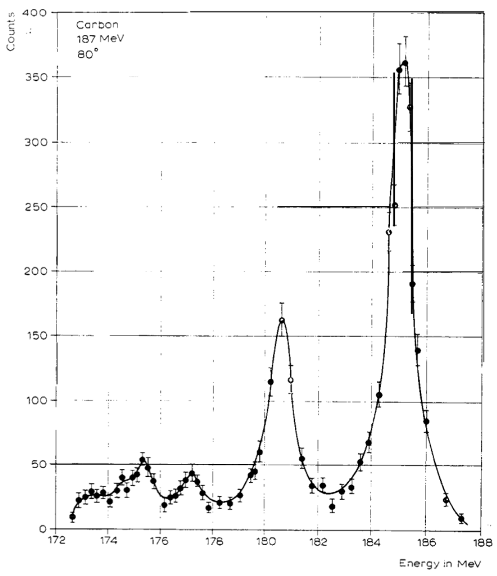


Fig. 4. This figure[8] shows the elastic-scattering peak from carbon at an abscissa near 185 MeV, and the inelastic-scattering peaks from the excited states of ^{12}C. The peak

MeV is associated with the 4.43-MeV level.

Importance of the high-density hydrogen target for proton form factor studies: pressures up to 50 atm and very thin and resistent windows

- → high-pressure gas targets
- → liquified gas targets
- → "jet targets" (to avoid windows)

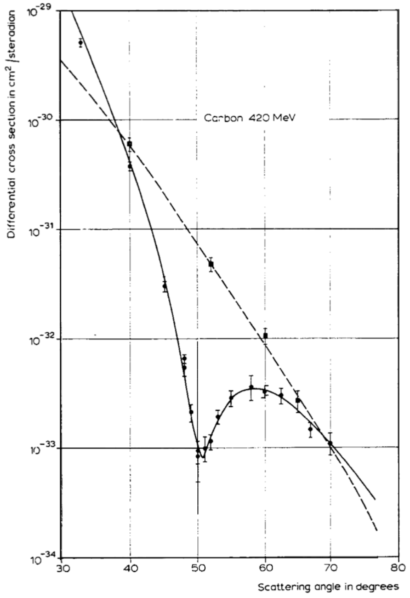
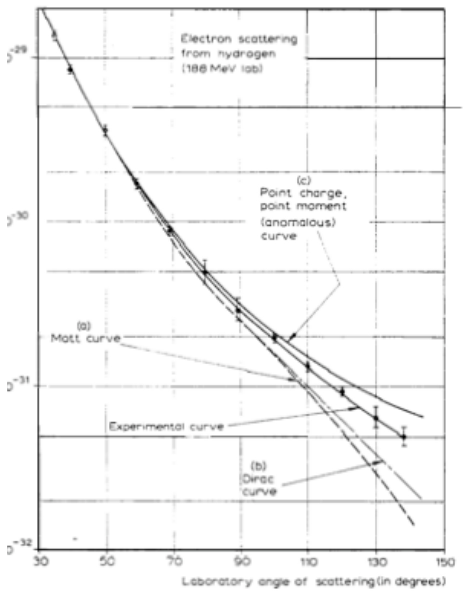


Fig. 5. This figure shows the elastic and inelastic curves corresponding to the scattering of 420-MeV electrons by ^{12}C. The *solid circles*, representing experimental points, show the elastic-scattering behavior while the *solid squares* show the inelastic-scattering curve for the 4.43-MeV level in carbon. The *solid line* through the elastic data shows the type of fit that can be calculated by phase-shift theory for the model of carbon shown in Fig. 8.



What is an ElectronVolt (eV) ?

- $\Delta E_k = q\Delta V$
- 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 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)

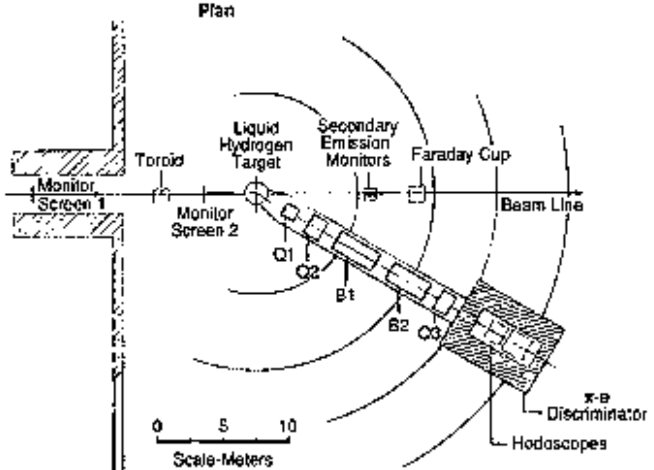
    ➔ 1 km for 30÷50 GeV electrons !

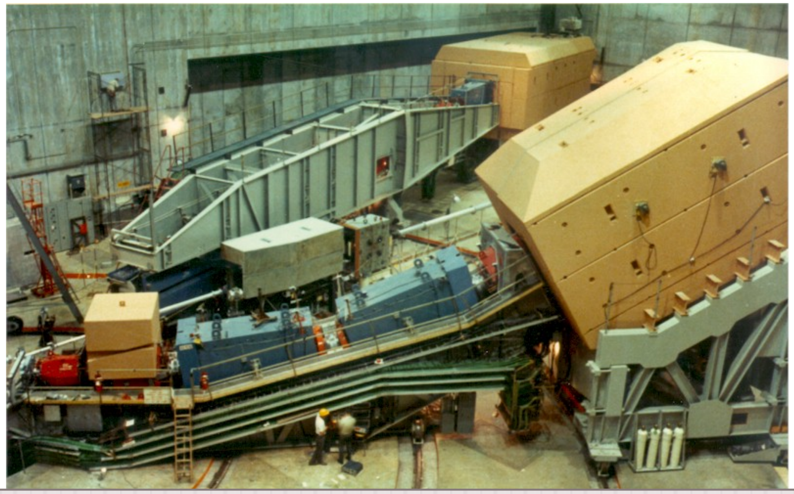
  plasma acceleration is a possibility
- At the time of the first SLAC experiments (400 MeV electrons) the gradients were smaller and it was a technological challenge anyhow.

After Rutherford - III

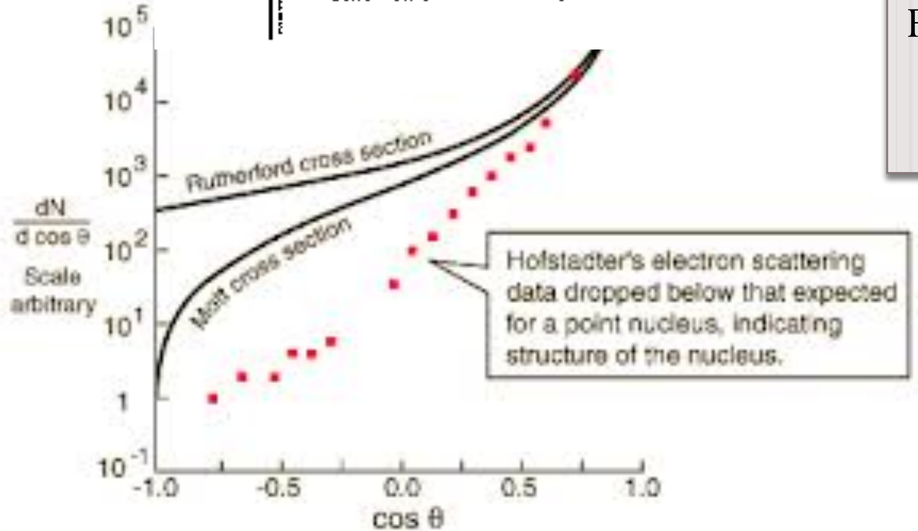
- In the '70s, the experiments of Friedman, Taylor and Kendall at SLAC were mostly devoted to study the inelastic scattering to understand proton structure.
- Main experimental innovations:
  - Higher energy electron beams (up to 20 GeV from the 2-mile linear accelerator)
  - Liquid hydrogen target (the one providing the higher density)
  - A detector including particle identification (Cerenkov et al…) and a more refined kinematic analysis to select inelastic scatterings.

After Rutherford – IV: the '70s

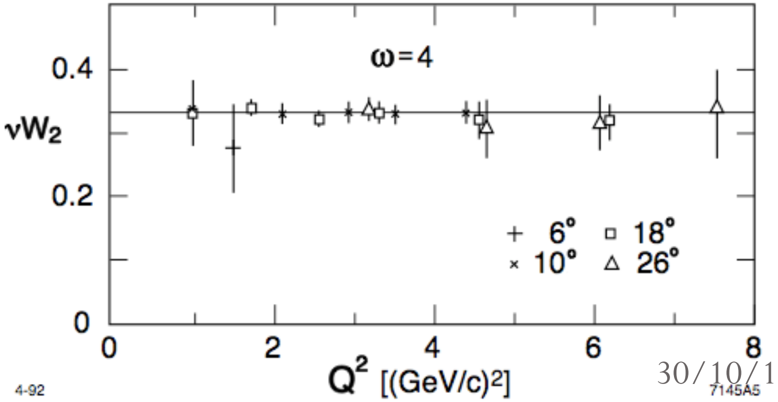




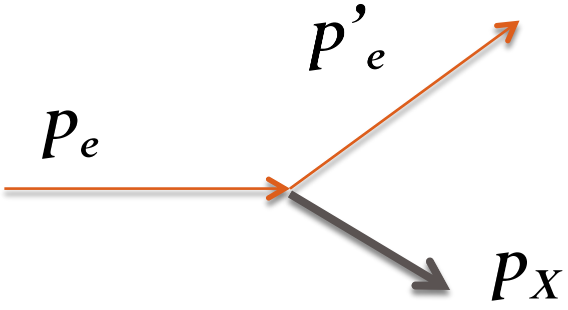
Friedman-Kendall-Taylor experiments:
- -- up to 20 GeV electron beam
- -- evidence of partonic structure of the proton



Hofstadter's electron scattering data dropped below that expected for a point nucleus, indicating structure of the nucleus.



The proton contains “partons”.



$$x = -\frac{q^2}{2\tilde{p}\tilde{q}}$$

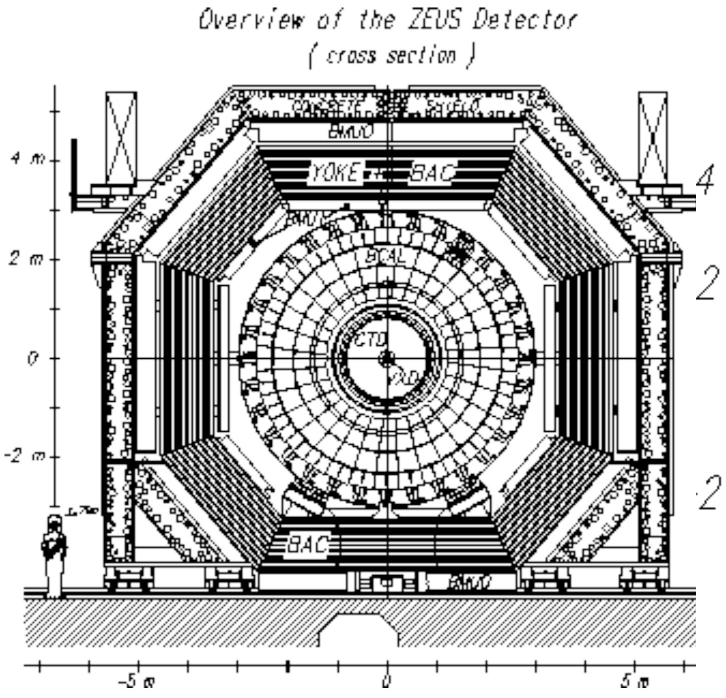
$$q^2 = \left(\tilde{p}_e - \tilde{p}'_e\right)^2 = -4EE'\sin^2\left(\theta/2\right)$$

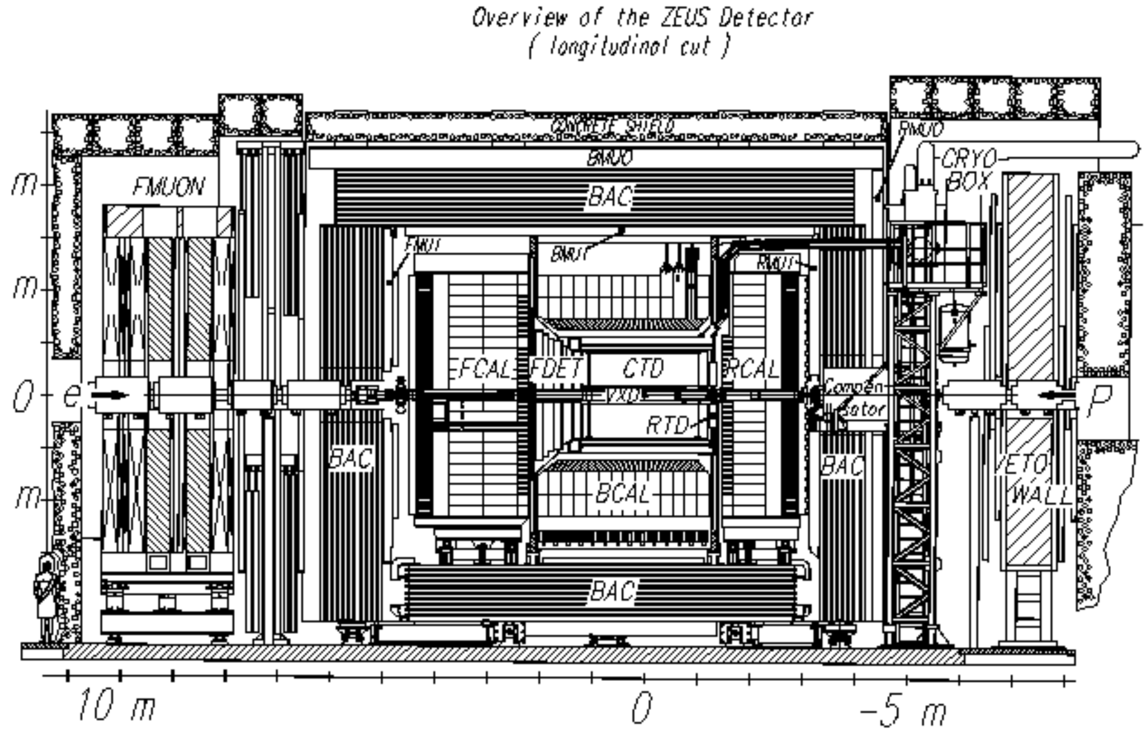
$$\tilde{p}\tilde{q} = M(E-E')$$

Bjorken theory: the hit parton has a fraction ***x*** of the proton momentum. By measuring the energy ***E’*** and the deflection angle $\boldsymbol{\theta}$ of the scattered electron (inclusive measurement, no need to measure p_X) ***x*** can be easily evaluated.

Emerging picture: the proton is a “bunch” of partons each transporting a fraction of the total momentum. The measurement of the ***f(x)***, the so called **PDF** = Parton Density Function, is still a major line of the EPP.

After Rutherford – V: HERA





Here a completely new concept comes out: collisions between electron and proton beams. Higher center of mass energy ➔ higher q^2 lower x

→proton beam = 820 GeV, electron beam = 27.5 GeV, center of mass energy = 300 GeV

→notice the completely new detector concept: full solid angle and cylindrical shape.

From inclusive to exclusive studies: aim to detect and identify all particles in the final states

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 relatively 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.
- Question: Why protons have larger energies than electrons at HERA ?
- Exercise-1: HERA c.m. energy given p_p and p_e.
- Exercise-2: Which p_e if protons at rest to get the same √s ?

Exercises

1.

$$\tilde{p}_e = (27.5,0,0,27.5)$$

$$\tilde{p}_p = (820,0,0,-820)$$

$$s = (\tilde{p}_e + \tilde{p}_p)^2 = m_e^2 + m_p^2 + 2\tilde{p}_e\tilde{p}_p \approx 4E_eE_p$$

$$\sqrt{s} = \sqrt{4 \cdot 820 \cdot 27.5} = 300GeV$$

2.

$$\sqrt{s} = 300GeV$$

$$s = (\tilde{p}_e + \tilde{p}_p)^2 = m_e^2 + m_p^2 + 2\tilde{p}_e\tilde{p}_p \approx 2E_em_p$$

$$E_e = \frac{s}{2m_p} = \frac{(300GeV)^2}{2 \cdot 0.938GeV} \approx 45TeV$$

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

e$^+$e$^-$: multihadronic production and J/psi

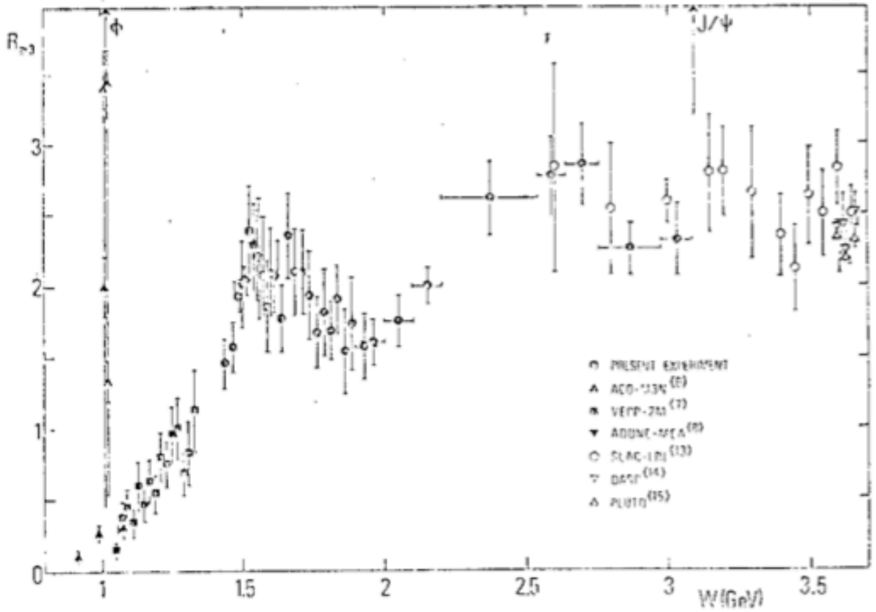
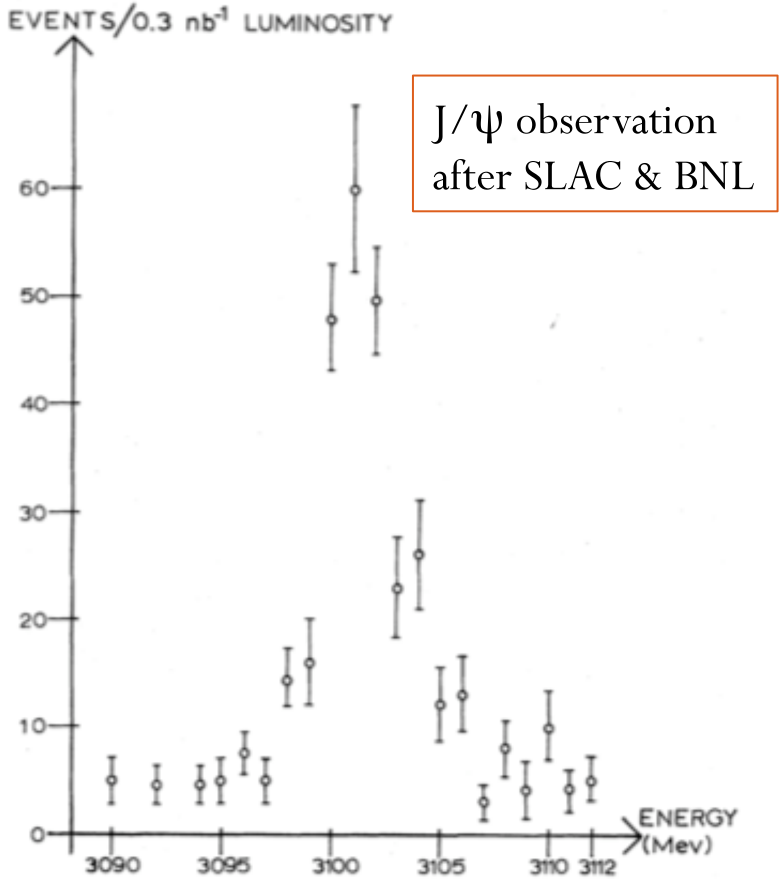


FIG. 3 - Present results and previous ones on $R_{\geq 3}$ vs. total c. m. energy.

N.B. In the first '70s Frascati was the first to run an e$^+$e$^-$ accelerator (AdA then Adone) at GeV energies reporting the multi-hadronic production

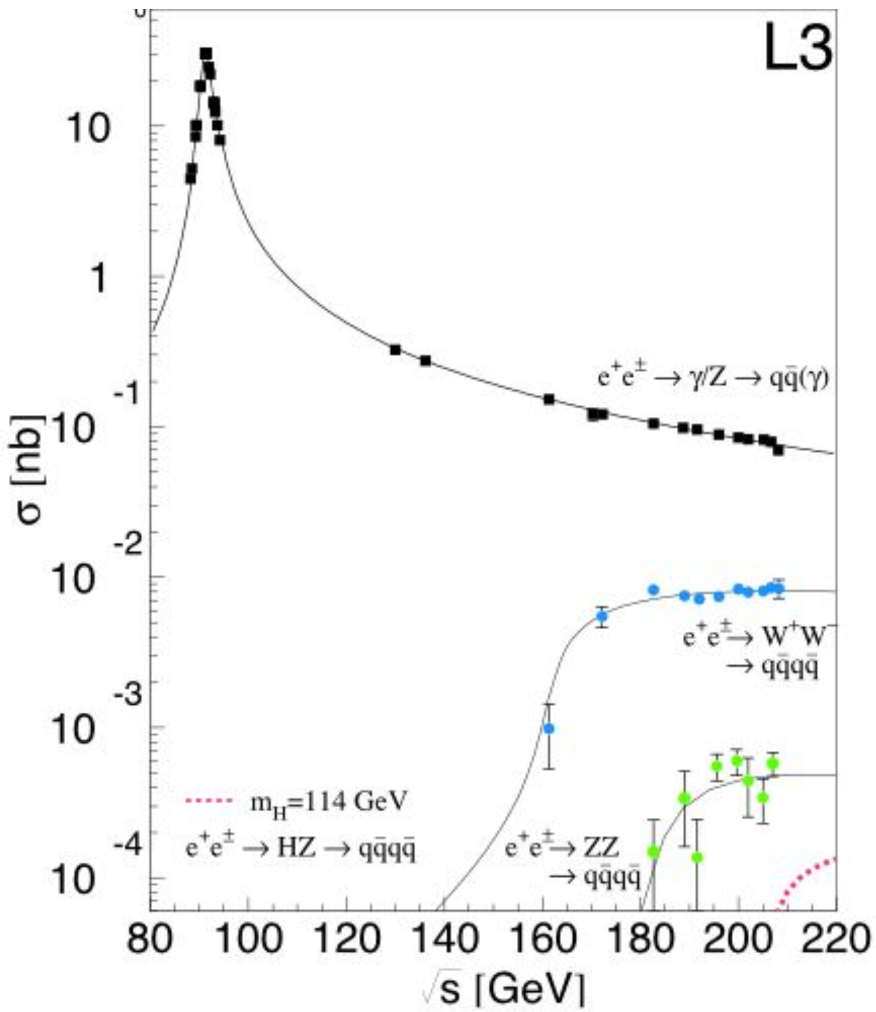


J/ψ observation after SLAC & BNL

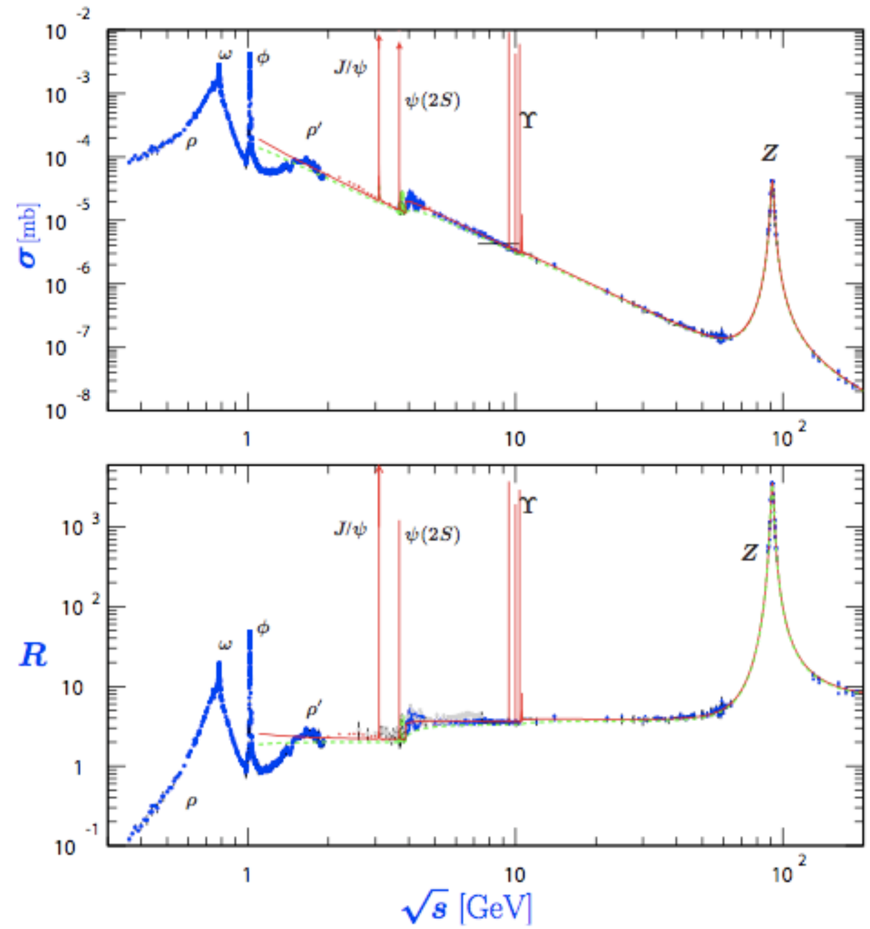
FIG. 1. Result from the Gamma-Gamma Group, total of 446 events. The number of events per 0.3 nb^{-1} luminosity is plotted versus the total c.m. energy of the machine.

e^+e^-: energy scan

- In pp and p-anti-p there is no reason to do an energy scan, the center of mass energy being “undefined”. On the other hand in e^+e^- the scan is a fundamental tool:
  - Thresholds appear: e.g. $e^+e^- \rightarrow W^+W^-$
  - Peaks appear: e.g. Z peak at LEP $e^+e^- \rightarrow Z \rightarrow \ldots$



$e^+e^- \rightarrow$hadrons cross-section in the full explored range

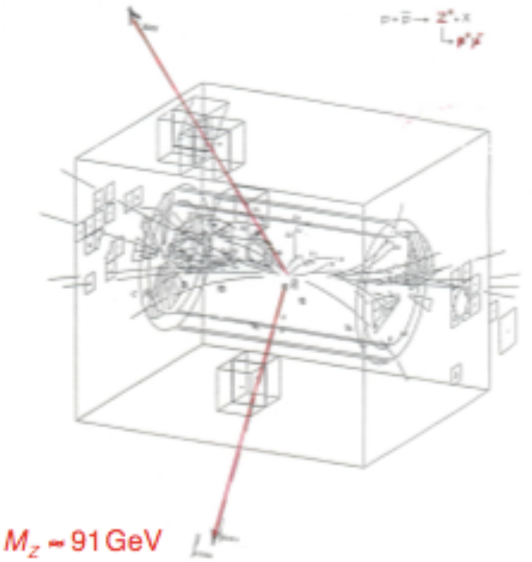


Collection of present e^+e^- data:
many structures (resonances) superimposed to a smooth behaviour.
Much physics in these plots:
→how quarks are linked together;
→appearance of an intermediate vector boson (the Z)
→how the virtual photon does work..

p-pbar: Z discovery - 1983

How can a discovery be done in a pp or p-pbar collider ?
The idea is to study the "mass distributions" using data at a unique center of mass energy of super-selected data samples → "Inclusive" searches based on "lepton" probes.

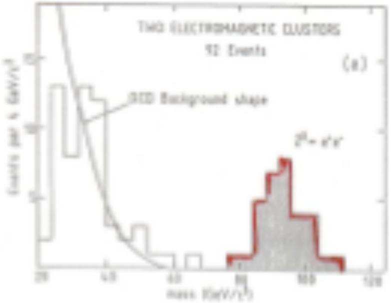
(1) Z discovery:
Conceptually the simplest case:
p-pbar → Z + X
Look for Z→ 2 leptons decay
independently of what is X
M(ll) is the relevant quantity



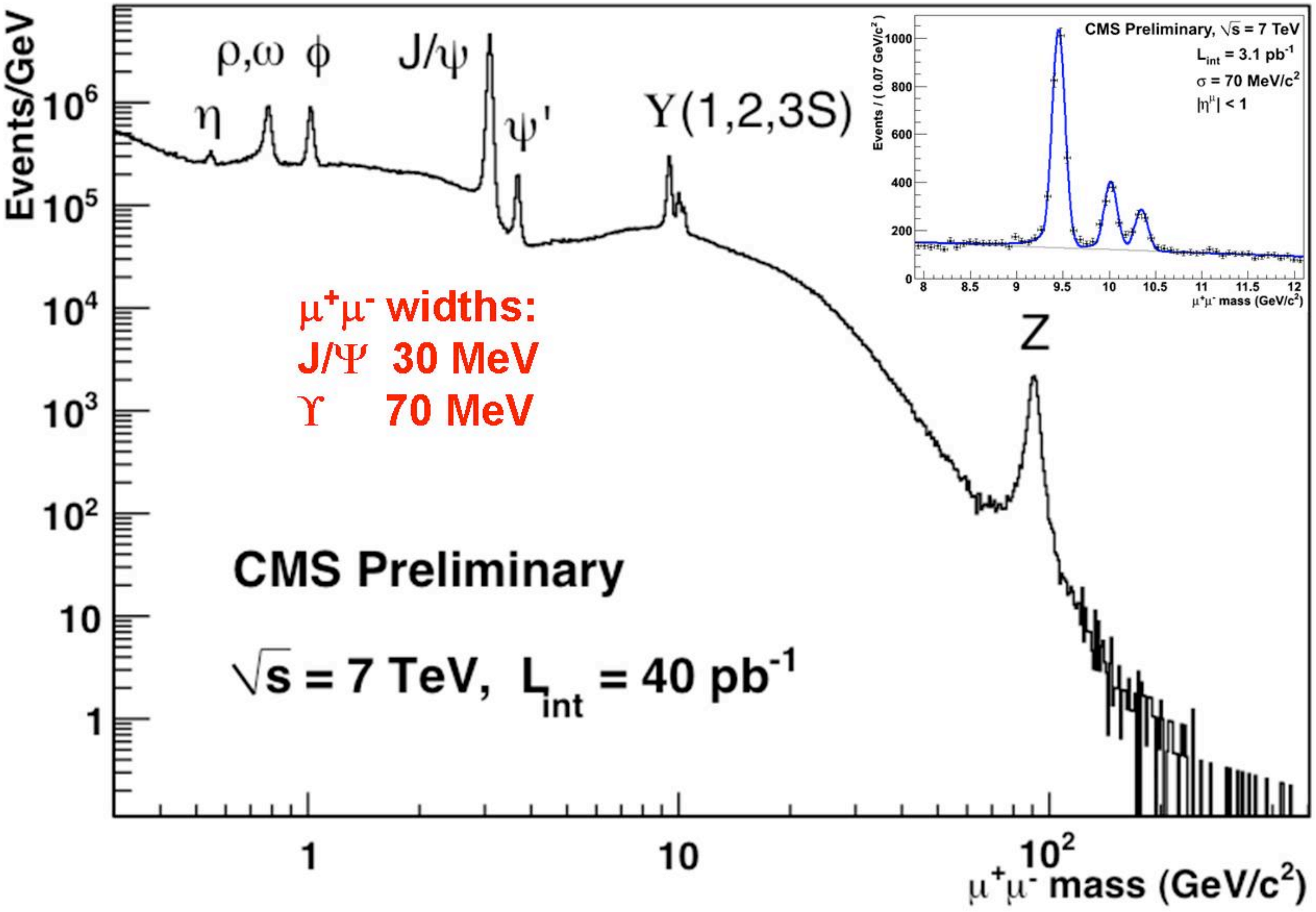
$M_Z \sim 91$ GeV

High-energy lepton pair:

$m_{\ell\ell}^2 = (p_{\ell^-} + p_{\ell^+})^2 = M_Z^2$



Di-muon production, LHC



$\mu^+\mu^-$ widths:
J/Ψ 30 MeV
Υ 70 MeV

p-pbar: W discovery - 1983

(2) W discovery: conceptually more "complicated:
p-pbar → W + X but W→ lepton + neutrino and the neutrino cannot be detected. (actually W mostly → qqbar but hard to see…)

3-step logic:
→ In pp (ppbar) collisions balancing of momenta only in the transverse plane;
→ W is produced through qqbar → W → W has only longitudinal boost;
→ In the transverse plane we have a ***lepton*** and a ***neutrino*** "back to back"

So:
→ Lepton p_T equal in CM and Lab frame:

$$p_T = \frac{M_W}{2}\sin\theta^*$$

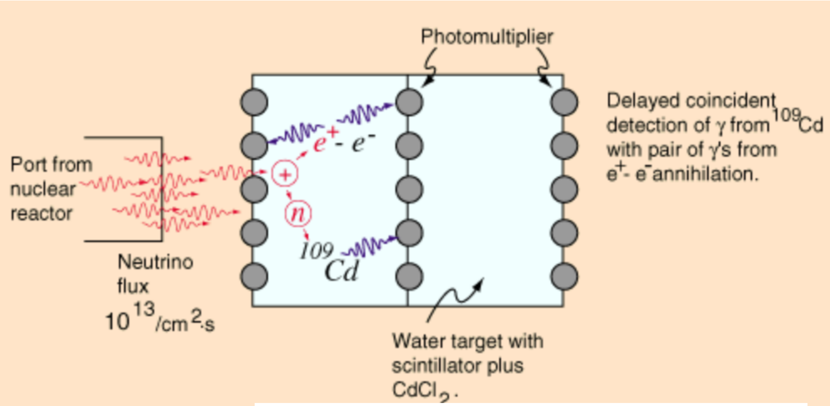
→ Expected p_T spectrum: Jacobian peak "singularity" for $p_T = M_W/2$

$$\frac{dN}{dp_T} = \frac{dN}{d\theta^*}\frac{d\theta^*}{dp_T} = \frac{1}{\sqrt{(M_W/2)^2 - p_T^2}}\frac{dN}{d\theta^*}$$

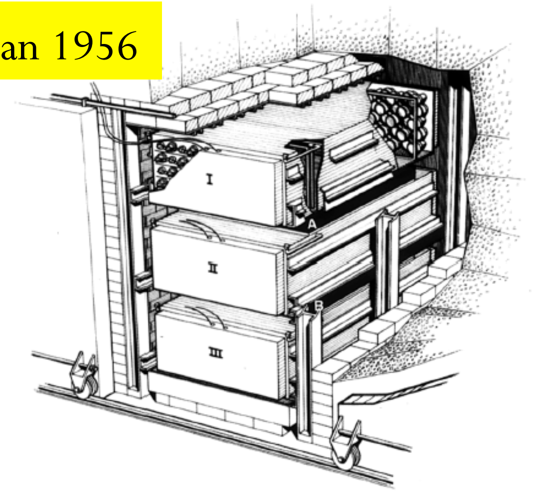
Observation of W from lepton p_T spectrum in evts with large missing p_T

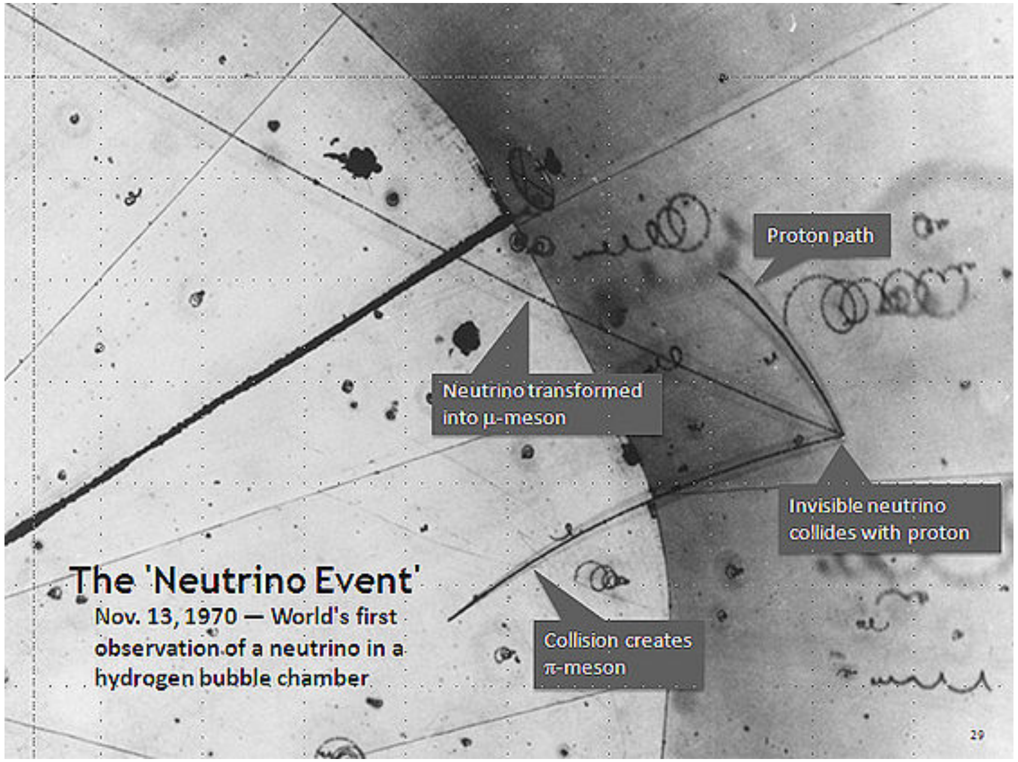
Neutrino beam experiments - I

- Due to the low cross-section of neutrino interactions, the real point is to have a target with a large number of nuclei !



Reines – Cowan 1956





Proton path

Neutrino transformed into μ-meson

Invisible neutrino collides with proton

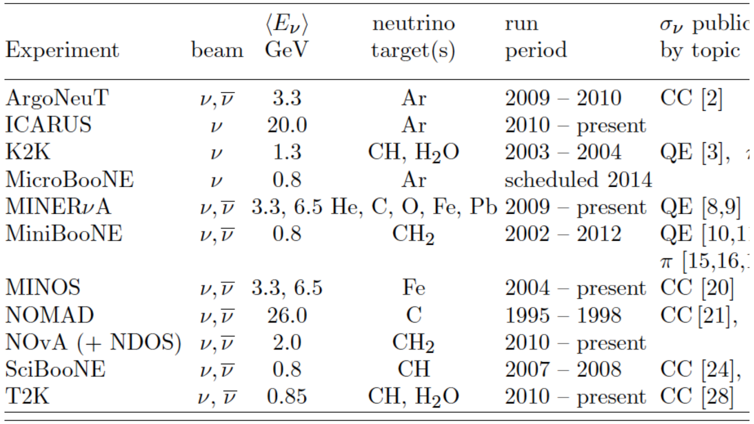
Collision creates π-meson

The 'Neutrino Event'

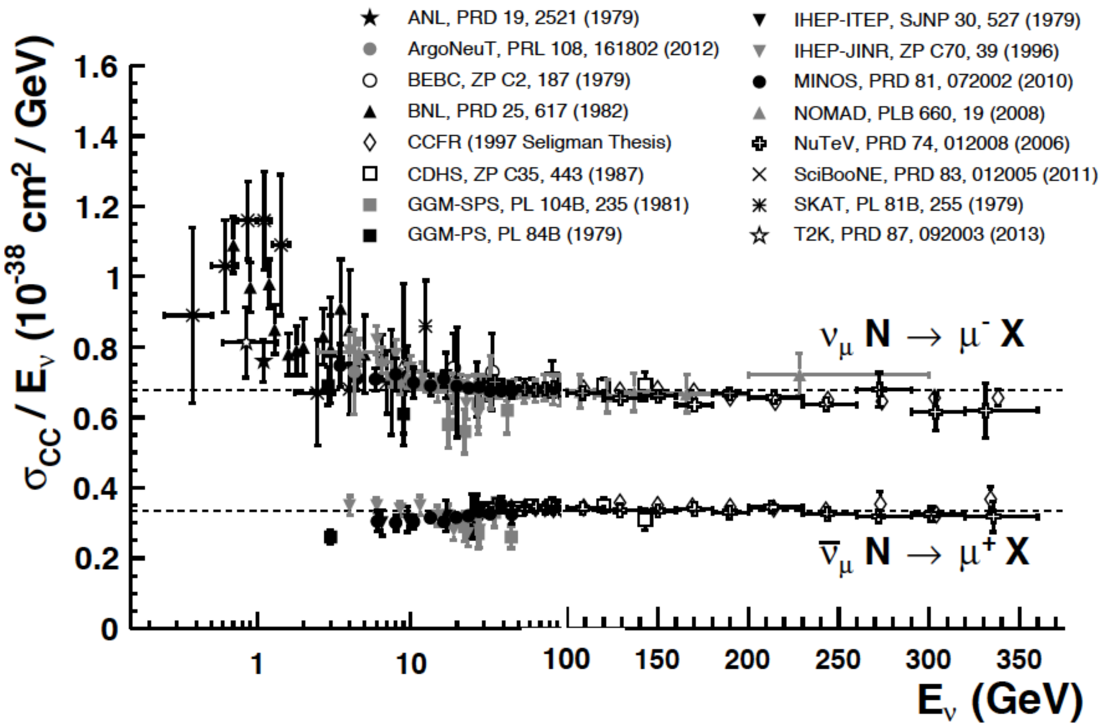
Nov. 13, 1970 — World's first observation of a neutrino in a hydrogen bubble chamber

Neutrino beam experiments - II

- Neutrino sources can be: reactors, accelerators and cosmic rays. Large experiments working for several years.



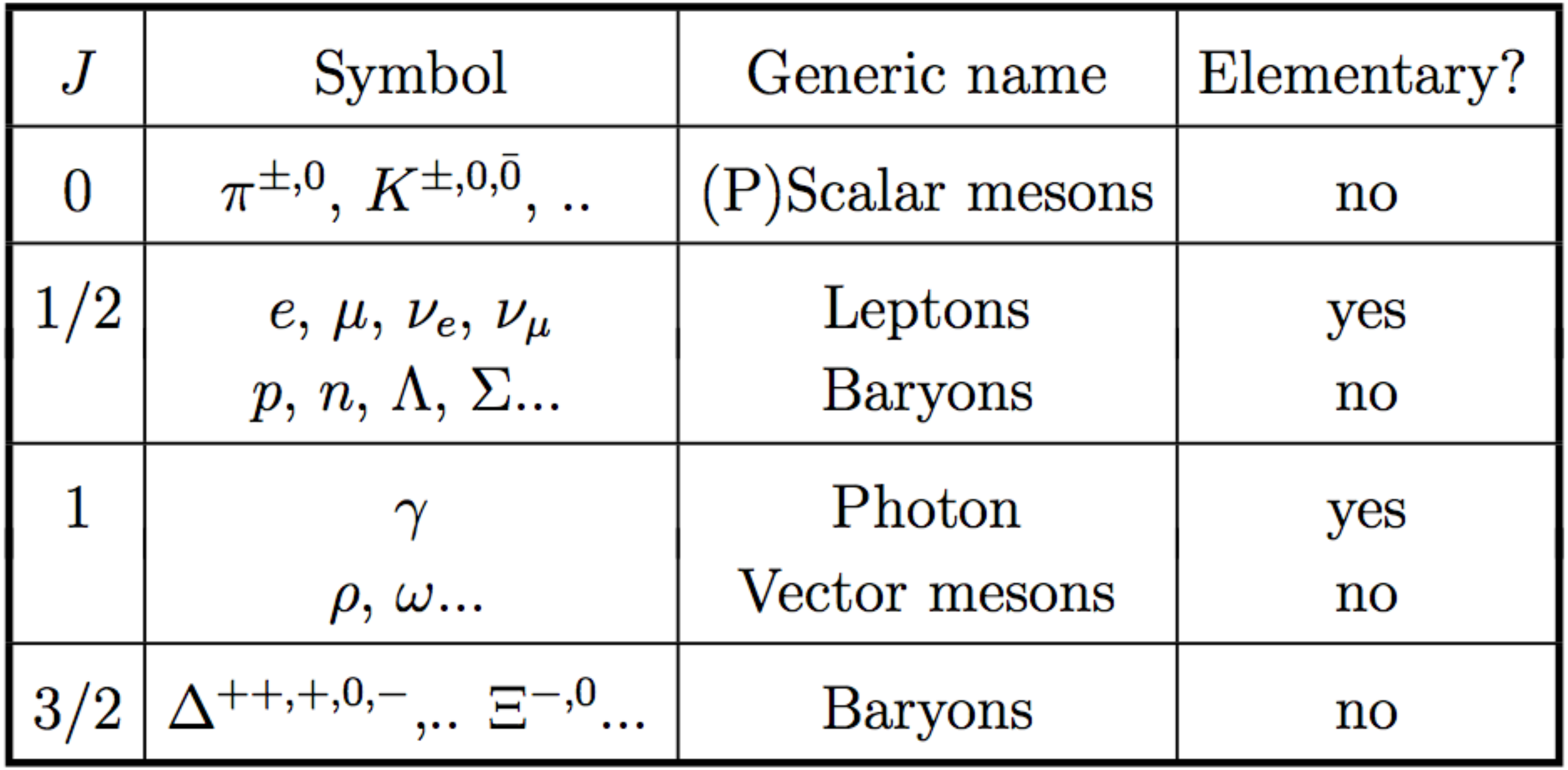
Experiment	beam	$\langle E_\nu \rangle$ GeV	neutrino target(s)	run period	σ_ν public by topic
ArgoNeuT	$\nu, \overline{\nu}$	3.3	Ar	2009 – 2010	CC [2]
ICARUS	ν	20.0	Ar	2010 – present	
K2K	ν	1.3	CH, H_2O	2003 – 2004	QE [3],
MicroBooNE	ν	0.8	Ar	scheduled 2014	
MINERνA	$\nu, \overline{\nu}$	3.3, 6.5	He, C, O, Fe, Pb	2009 – present	QE [8,9]
MiniBooNE	$\nu, \overline{\nu}$	0.8	CH_2	2002 – 2012	QE [10,1 π [15,16,
MINOS	$\nu, \overline{\nu}$	3.3, 6.5	Fe	2004 – present	CC [20]
NOMAD	$\nu, \overline{\nu}$	26.0	C	1995 – 1998	CC [21],
NOvA (+ NDOS)	$\nu, \overline{\nu}$	2.0	CH_2	2010 – present	
SciBooNE	$\nu, \overline{\nu}$	0.8	CH	2007 – 2008	CC [24],
T2K	$\nu, \overline{\nu}$	0.85	CH, H_2O	2010 – present	CC [28]



Developments: the First 50 years…

- In 1919: electron, proton, photon. (Thomson, Rutherford, Einstein)
- 1932: neutron, positron. (Chadwick, Anderson)
- 1937: muon (people think it is the Yukawa particle)
- 1930 – 1950: from Dirac equation to QED – the first description of particle interaction through a QFT (Dirac, Feynman, Schwinger)
- 1934: first attempt of a theory of weak interactions (Fermi)
- 1940 - 1948: pion, muon (Yukawa, Conversi et al., Occhialini et al.)
- 1947: the kaon, the Λ_0 (the "strange" particles)
- 1956: discovery of the neutrino
- 1955-1960: the antiproton and many other hadrons.. (Segrè et al.)
- 1958: discovery of P-violation in weak decays

Elementary particles in 1960

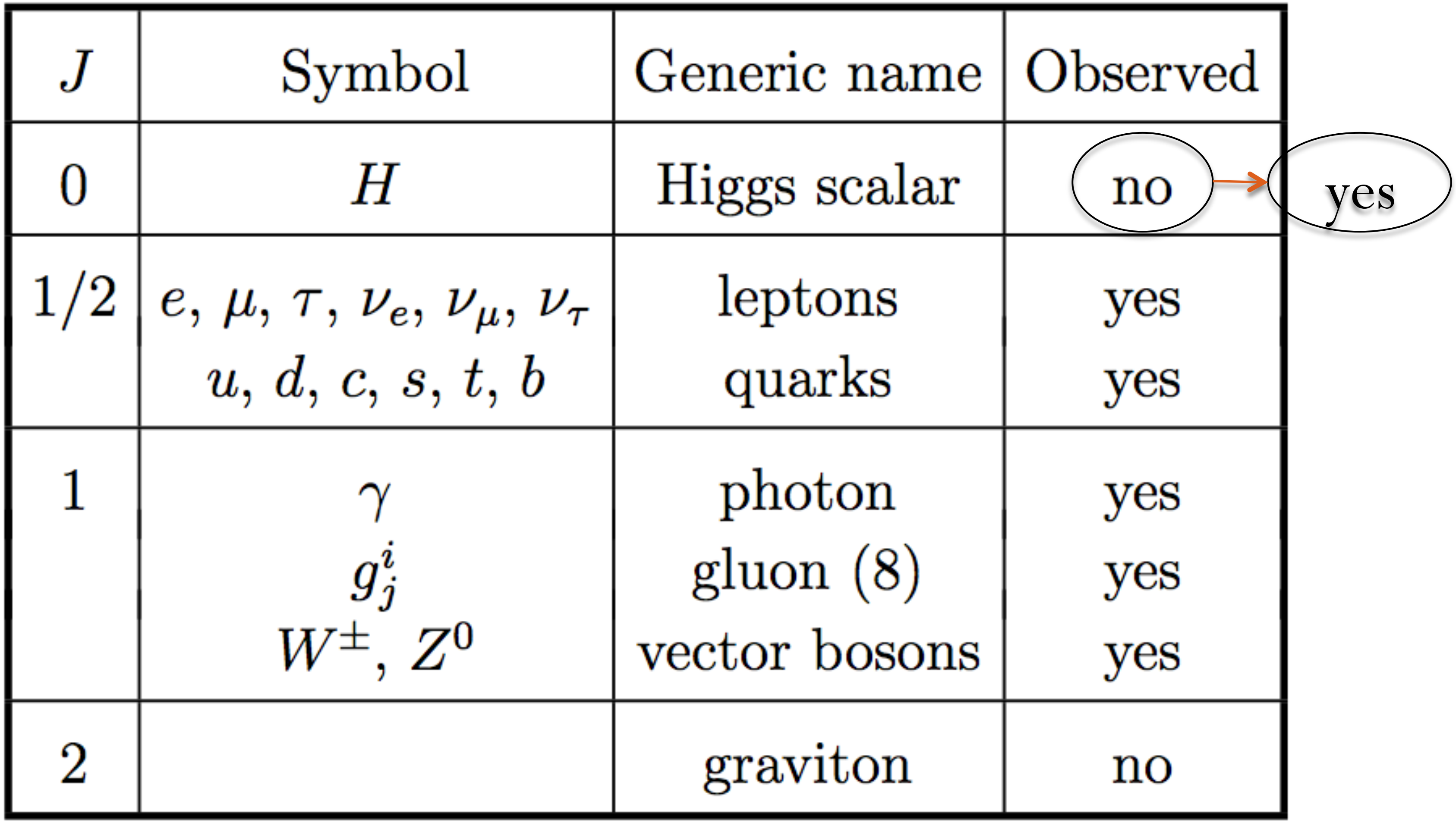


J	Symbol	Generic name	Elementary?
0	$\pi^{\pm,0}$, $K^{\pm,0,\bar{0}}$, ..	(P)Scalar mesons	no
1/2	e, μ, ν_e, ν_μ	Leptons	yes
	p, n, Λ, Σ...	Baryons	no
1	γ	Photon	yes
	ρ, ω...	Vector mesons	no
3/2	$\Delta^{++,+,0,-}$,.. $\Xi^{-,0}$...	Baryons	no

Developments: the Second 50 years …

- 1963 – 1979: the Electro-weak sector of the Standard Model is defined (Glashow, Weinberg, Salam, Higgs, t-Hooft, Cabibbo,…)
- 1964: CP violation discovery
- 1972 - 1974: the QCD sector is defined (Gross, Wilczek, Politzer)
- 1973: discovery of neutral currents in neutrino interactions
- 1974: discovery of the partonic nature of the proton
- 1974 – 1977: quarkonia discoveries: J/ψ and Y
- 1975: discovery of the "heavy-lepton", the τ.
- 1983: discovery of intermediate vector bosons (W, Z)
- 1995: discovery of the top quark
- 1998: discovery of the neutrino oscillations
- 2012: discovery of the Higgs

Elementary particles in 2014



J	Symbol	Generic name	Observed
0	H	Higgs scalar	no → yes
1/2	$e,\ \mu,\ \tau,\ \nu_e,\ \nu_\mu,\ \nu_\tau$	leptons	yes
	$u,\ d,\ c,\ s,\ t,\ b$	quarks	yes
1	γ	photon	yes
	g^i_j	gluon (8)	yes
	$W^\pm,\ Z^0$	vector bosons	yes
2		graviton	no

The projectile

- Natural projectiles: radioactive sources: α, β, γ, neutrons
  - limitation in energy and in type of particles (photons, electrons, α-particles);
- Cosmic rays; essentially muons if at sea-level
  - wide energy spectrum, up to very high energies;
  - BUT wide range of directions, distribution on large surfaces, not very practical… Important today for "specific studies" (***)
- Particle accelerators: the good choice, the projectile-science.
  - all charged particles can be accelerated, neutrals can be produced as well by interactions;
  - control of energy, directions, collimations, etc… The experimentalist can tune his own source, very important.

The target

- It was the object under study (gold plate in Rutherford experiment).
- In many cases today is the object by which we plan to produce what we want to study.
- Fixed target experiments:
  - hydrogen targets (either liquid or gaseuse);
  - nuclear targets;
  - the atmosphere (in cosmic ray experiments);
  - the detector itself (in neutrino experiments).
- Colliding-beam experiments:
  - advantages in terms of c.o.m. energy (***)
  - acceleratorists are able to prepare beams for this.

The detector

- The design and the construction of the detector is one of the main tasks of elementary particle experimentalists.
- Many by-products also:
  - detectors for diagnostics in medicine;
  - detectors for safety, control etc…
  - detectors for archeology.
- Many examples in the following.
- General classification:
  - collider experiments;
  - fixed-target experiments;
  - neutrino experiments
  - cosmic-ray experiments
  - others….

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".