NPAC
Particle Physics
Course 1 – Introduction and basics

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A few words about us and the course

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- We are both experimentalists, and will present particle physics from this point of view.
- We will have 20 sessions mainly on Mondays (Orsay) and Wednesdays (SU), some on Friday (UPC) at the end. Check the "planning" on the web site!
- We will accompany the lectures with some exercises (some of them to complement the course and others for self training).
- You are expected to work with references.

- Please remember to **send an email to Catherine Bourge** with your choice of modules **before October 9th (next Monday).**

Program of the course

- **Introduction and basics**
  Standard model in a nutshell
  Short history
- **Symmetries**
  Discrete symmetries, spin, isospin
- **Collisions and decays**
  Reminders of special relativity
  Cross sections, widths
- **Quantum Electrodynamics (QED)**
  Fields and Feynman rules
  Radiative corrections, running coupling
- **Quantum Chromodynamics (QCD)**
  Historical and pheno. introduction
  Theoretical basics of QCD
  Deep Inelastic Scattering
  Structure functions
  Hadronic collisions
- **Charged weak interaction**
  Couplings and applications
  Theoretical basics and parity violation
  Properties of the W boson
  CP violation and flavor physics
- **The Standard Model (SM)**
  Neutral currents, electroweak unification
  Higgs boson: discovery and properties
  Complete Lagrangian of the SM
- **Neutrinos – (usually skipped)**
  Neutrino Oscillations
  Observables and their measurement
- **Open questions; beyond the SM**
  The limitations of the SM
  Short introduction to searches for physics beyond the SM

This program may be slightly modified as we progress

Bibliography (in an almost arbitrary order)

- **D. Griffiths, Introduction to elementary particles, Wiley-Vch**
- **M. Peskin, D.V. Schroeder, An introduction to Quantum Field Theory, CRC Press**
- D. H. Perkins, Introduction to high energy physics, Cambridge Univ. Press
- A. Seiden, Particle physics - a comprehensive introduction, Addison-Wesley
- F. Halzen and A. D. Martin, Quarks and leptons: an introductory course in modern particle physics, John Wiley & Sons
- B. R. Martin and G. Shaw, Particle physics, John Wiley & Sons
- Fayyazudin and Riazuddin, A modern introduction to particle physics, World Scientic
- F. Scheck, Electroweak and strong interactions - an introduction to theoretical particle physics, Springer-Verlag
- Q. Ho-Kim and X.-Y. Pham, Elementary particles and their interactions: concepts and phenomena, Springer-Verlag
- H. Murayama, Standard Model, Introductory lecture, http://videolectures.net/site/normal_dl/tag=65671/cernstudentsummerschool09_murayama_sm_01.pdf
- C. Cohen-Tannoudji, B. Diu and F. Laloe, Quantum mechanics, Wiley-Vch
- W. Rindler, Introduction to special relativity, Oxford University Press

Exams and grades

- 2 exams of 3 hours each
  → [1] mid-term exam – November 14^{th} 14:00, SU (including all we do by then)
  → [2] final exam – February 5^{th}
- grade = max(¼ x [1] + ¾ x [2] ; [2])
- In case your grade after the final exam is below 50% you will pass an oral exam (30 min) with a maximum grade of 50%

The mid-term exam is very important for many reasons. Take it very seriously!

We will progress rapidly. It is strongly recommended to revise your courses continuously and not leave pending issues until the exams.

Today's lecture: Introduction and basics

- Standard Model: particles and interactions in a nutshell
  - Elementary particles (fermions)
  - Interactions
    - A word on QFT
    - The four interactions
    - Feynman diagrams
    - Diagrams of the different interactions
    - Lifetimes and widths
    - Additive quantum numbers (charges): conservation laws
- History of particle physics in brief

The elementary particles (fermions)

	LEPTONS		QUARKS	
	neutrinos $Q = 0$	charged leptons $Q = -e$	up type quarks $Q = +\frac{2}{3}\,e$	down type quarks $Q = -\frac{1}{3}\,e$
1^{st} generation (family) Constituents of all ordinary matter (atoms…)	ν_e electron neutrino $(\tau = \infty)$ $m \lesssim 2$ eV	e^- electron $\tau = \infty$ $m = 0.511$ MeV	u up $(\tau = \infty)$ $m \approx 2$ - 3 MeV	d down $(\tau = \infty)$ $m \approx 4$ - 5 MeV
2^{nd} family More massive "replica" of the 1^{st} generation	ν_μ μ neutrino $(\tau = \infty)$ m ~ probably few eV	μ^- muon $\tau = 2.2\times10^{-6}$ s $m = 105.7$ MeV	c charm $(\tau \sim 10^{-12}$ s$)$ $m \simeq 1.3$ GeV	s strange $(\tau \sim 10^{-10}$ s$)$ $m \simeq 0.1$ GeV
3^{rd} family Even more massive "replica" of the 1^{st} and 2^{nd} generations	ν_τ τ neutrino $(\tau = \infty)$ m ~ probably few eV	τ^- tau lepton $\tau = 0.29\times10^{-12}$ s $m = 1777$ MeV	t top quark $(\tau \sim 10^{-25}$ s$)$ $m = 173.21 \pm \ldots$ GeV	b bottom/beauty $(\tau \sim 10^{-12}$ s$)$ $m \simeq 4.5$ GeV

+ Antiparticles with the exact same mass and lifetime and opposite charges

- All of the elementary fermions have S (= J) = 1/2
- Elementary: have no internal structure (as presently supposed…); fundamental objects.
- Masses in eV (commonly used convention for eV/c^2)
- "Flavors" of quarks and leptons
- Quarks are never observed as free particles (apart from the top! See next slide)

Particles made of quarks: <u>hadrons</u>

- Two types of hadrons:
  - **baryons**: $q_1q_2q_3$
    (the proton and neutron are called **neucleons**)
  - **mesons**: $q_1\bar{q}_2$
    ($q_{1,}$ q_2 etc. may be the same or not, from the same generation or not)
  - Other "exotic" hadrons discovered in recent years: tetraquarks ($q_1\bar{q}_2q_3\bar{q}_4$) and pentaquarks ($q_1q_2q_3q_4\bar{q}_5$)

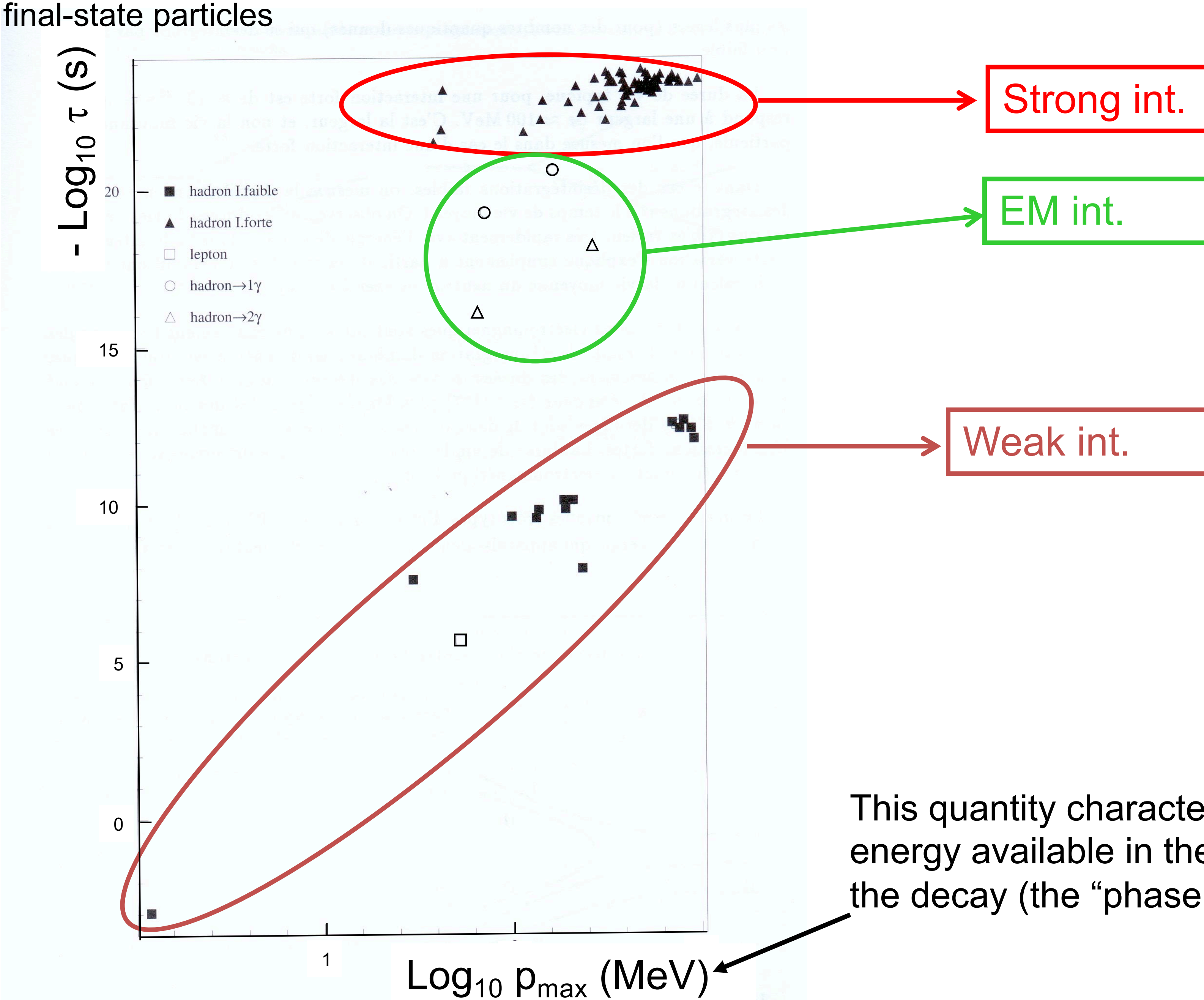
No hadrons with top quarks!

Typical time to create hadrons (hadronisation process) $\sim 10^{-23}$ s
The top quark is so heavy that it decays after $\sim 10^{-25}$ s

The interactions

	Mediating bosons	Order of relative intensity	Typical distance of action	Sensitive particles
Strong (SI)	gluons (8) m = 0 ; Q = 0 "colored"	1	10^{-15} m	"color" charged particles: quarks and gluons
Electromagnetic (EM)	Photon (γ) m = 0 ; Q = 0	~10^{-2}	∞	electrically charged particles
Weak (WI)	$W^{\pm}$, Z $m_W \simeq 80.4$ GeV $m_Z \simeq 91.2$ GeV $Q_W = \pm 1e$ $Q_Z = 0$	~10^{-6} At low energy! Strongly depends on energy regime; in some conditions larger than EM	10^{-17} m "pointlike"	All particles
Gravitation	graviton	~10^{-40}	∞	Massive particles

Liftime of hadrons decaying by the three interaction as a function of the momentum of one of the final-state particles



This quantity characterizes the energy available in the CM of the decay (the "phase space")

A list of a few things to memorize (for the time being…)

Masses in MeV (unless stated otherwise)
Learn approximate values or OM

leptons	e	0.511
	μ	$\simeq 106$
	τ	$\simeq 1777$
	ν	negligible
hadrons	p / n	938.3 / 939.6
	$\pi^0 / \pi^\pm$	$\simeq$ 135 / 140
	$K^0 / K^\pm$	$\simeq$ 498 / 494 (~500)
	J/ψ	$\approx$ 3100
	$D^\pm$	$\simeq$ 1870
	$B^\pm$	$\simeq$ 5280
quarks	u, d	~ few MeV
	s	~ 100
	c	~ 1.3 GeV
	b	~ 4.2 GeV
	t	173 GeV
int. bosons	$W^\pm$	$\simeq$ 80 GeV
	Z	$\simeq$ 91 GeV

Lifetimes

n	$\sim 10^3$ s
$\mu^\pm$	$\simeq 2.2\times10^{-6}$
K	$\sim 10^{-10}$ - 10^{-7}
$\pi^0 / \pi^\pm$	$\sim 10^{-17}$ / 10^{-8}
B, D, τ	$\sim 10^{-12}$
+ typical lifetimes of the three interactions	

Particles that may be detected directly

	stable	unstable
charged (tracks)	$e^\pm$, p	$\mu^\pm$, $\pi^\pm$, $K^\pm$ (d)
neutral	γ	n

All the other particles are detected as bumps in the spectra of invariant masses of their decay products.

$\hbar c \cong 197.3$ MeV fm

History of particle physics in brief

Young science: ~100 years of research

- **1897** (*Thompson*) Discovery of the electron (shortly after that of the atom)
- **1909** (*Rutherford*) Discovery of the atomic nucleus
- Demonstration of the existence of the photon (photoelectric effect, *Einstein*, **1915** Nobel prize)
- **1918** (*Rutherford*) Discovery of the proton (by the same kind of experiment)
- **~1930** (*Pauli*) hypothesis about the existence of the neutrino ν_e
  1956 (*Reines-Cowan*): its discovery
- **1932** (*Chadwick*) Discovery of the neutron
- **1932** (*Anderson*) Discovery of the positron (e^+) 1st particle of antimatter

Known particles at the beginning of 1930: e^- e^+ p n, EM force, γ

Attempts to explain nuclear forces between p and n $\Rightarrow$ strong int. (SI)

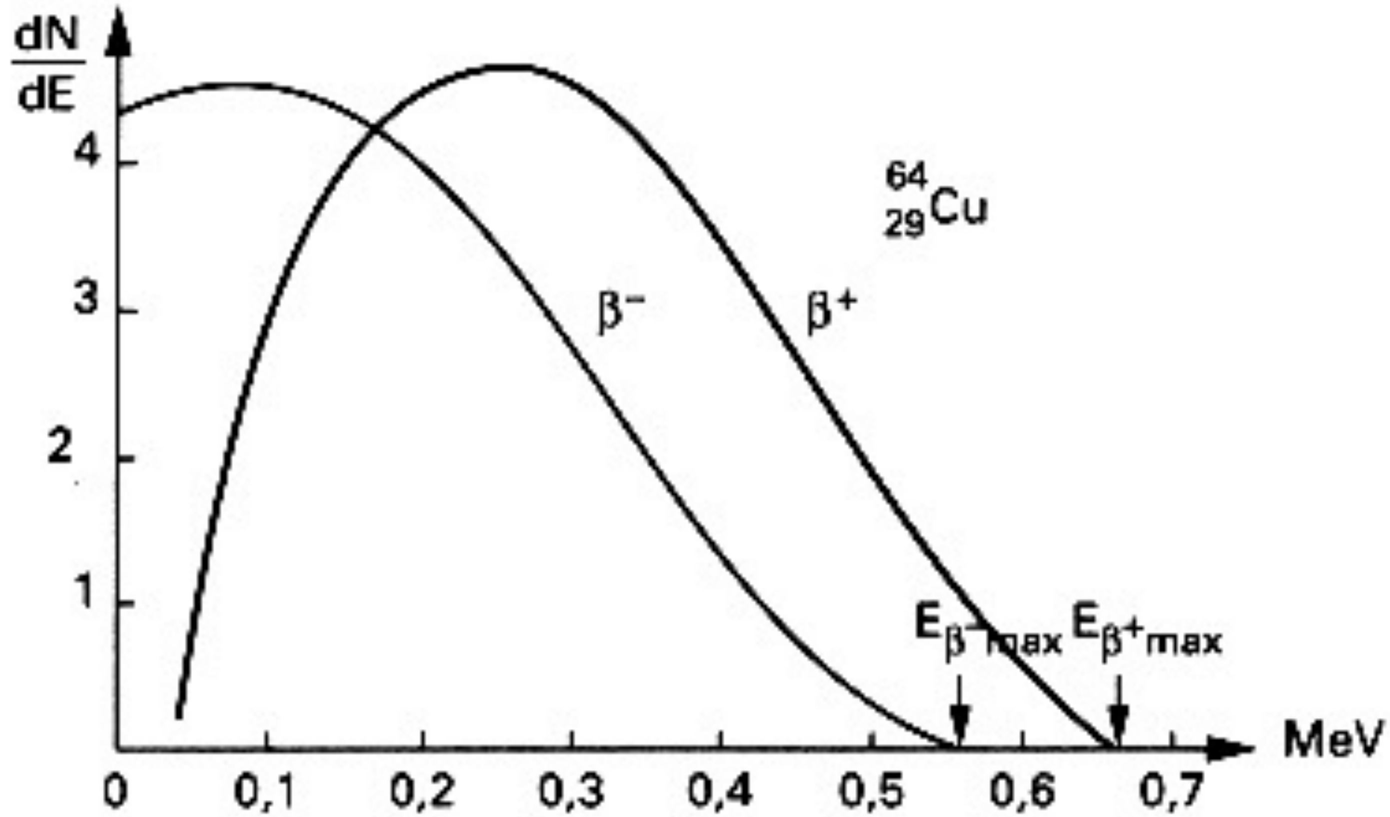
Instable particles in the cosmic rays + β decays $\Rightarrow$ weak int. (WI)

Then, more and more new particles discovered in cosmic rays

Increasing mass

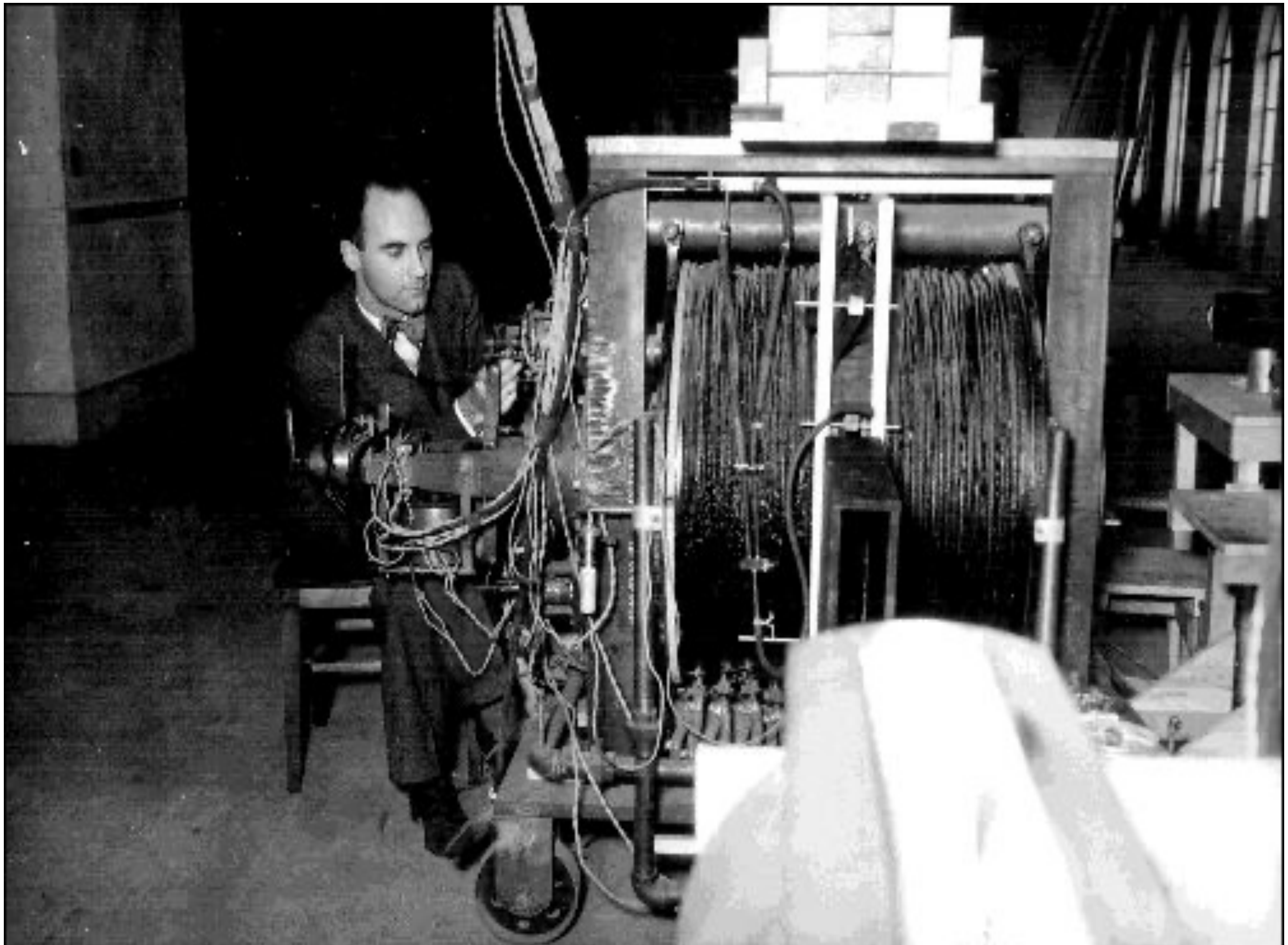
- 1937 $\mu \rightarrow e \nu_e \nu_\mu$
- 1947 $\pi \rightarrow \mu \nu_\mu$
- 1947 strange particles: K, Λ

Discovered in 1962



Spectre d'émission $\beta^- - \beta^+$, *cas du* $^{64}_{29}Cu$

C.D. Anderson, "The Positive Electron", Phys. Rev. **43**, 491 (1933)



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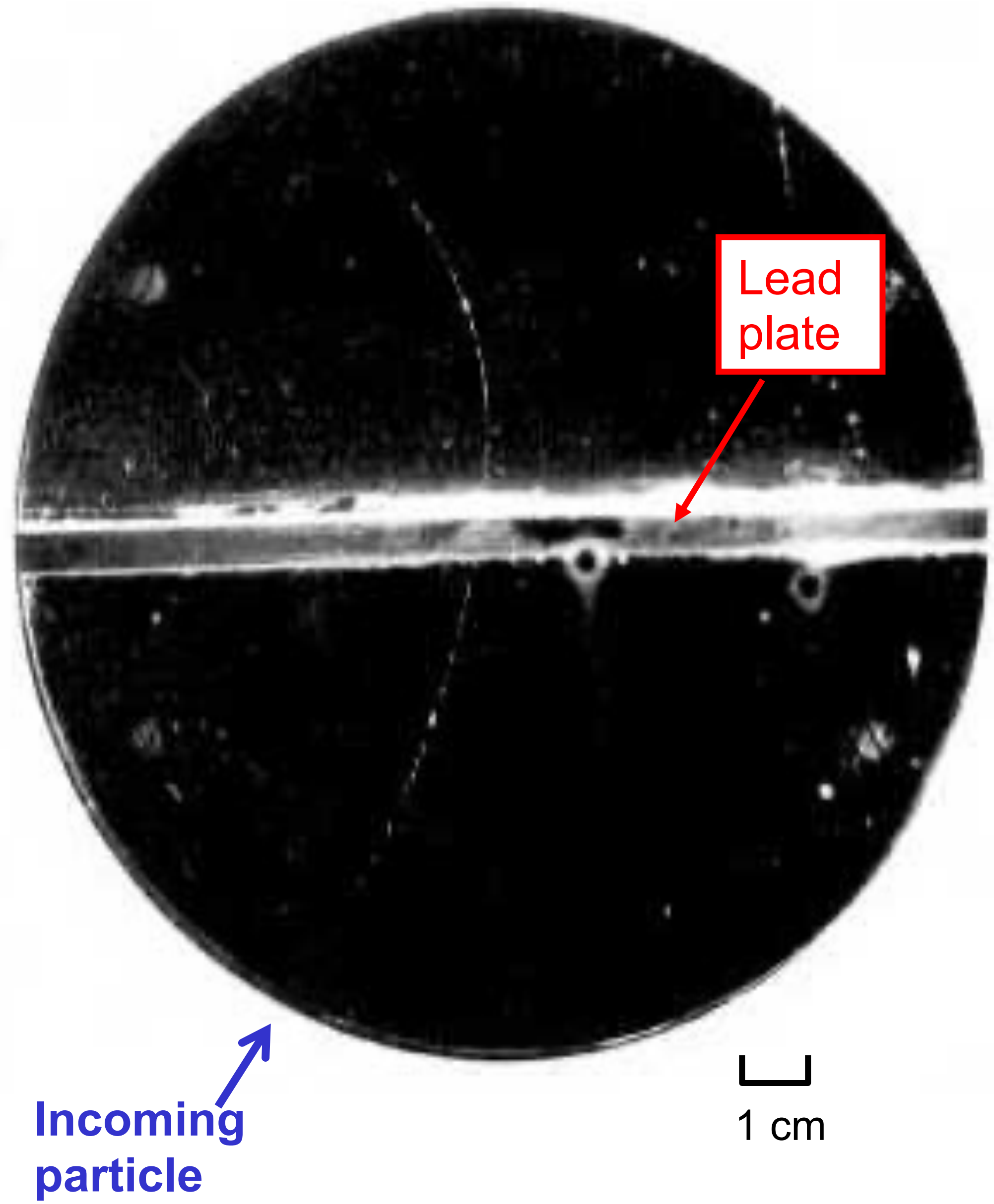
Carl David Anderson : Nobel Prize for Physics in 1936

- Cloud chamber (Wilson chamber)
- Charged particles leave tracks
- Magnetic field (“entering” the plane): curvature + direction → charge
- Direction from curvature on both sides of the lead plate
- Density of the track → ionization power of the particle (information on its mass)



Result: existence of a particle that carries a positive charge, with mass less than 20 m_e

Discovery of the π^+ (1947)

Nuclear emulsion exposed to cosmic rays on high-altitude mountains and developed (less sensitive than the image shown here)

$\pi^+ \to \mu^+ \nu_\mu$ (~26 ns)

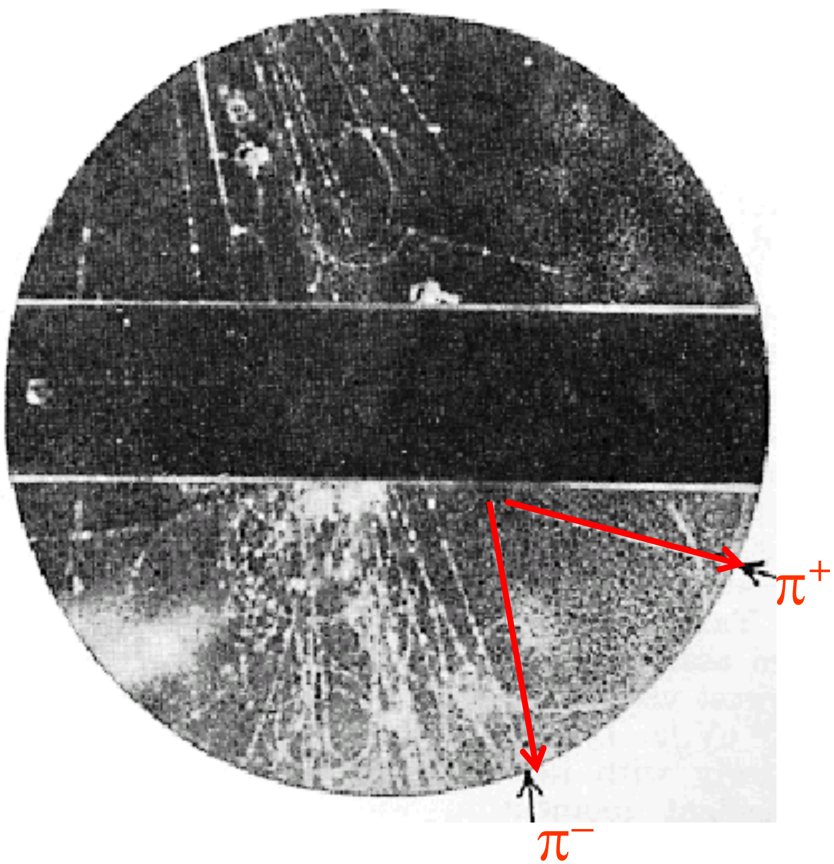
Muon tracks in all similar images indicate that all the muons have the same energy (two body decay)

This is not the case in the muon decay

$\mu^+ \to e^+ \nu_e \nu_\mu$ (~2.2 μs)

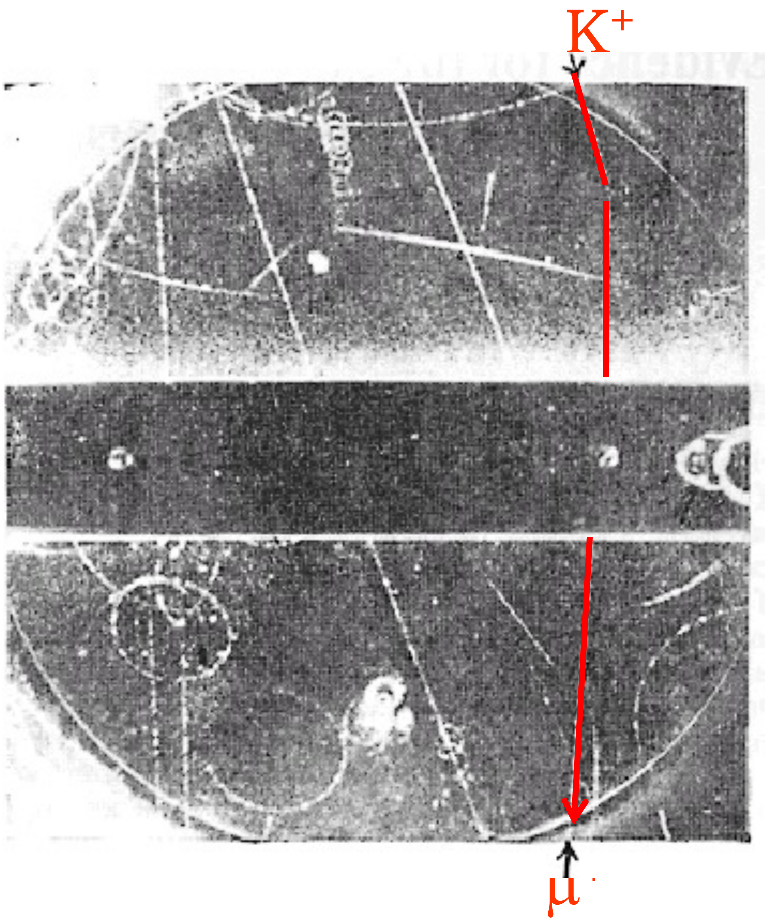
First experimental signatures of strange particles: Kaons

$K^0 \rightarrow \pi^+ \pi^-$



V - Particle

$K^+ \rightarrow \mu^+ \nu$



"Kink" in the detector

Cloud chamber ~1947

1950

Era of Accelerators and bubble chambers

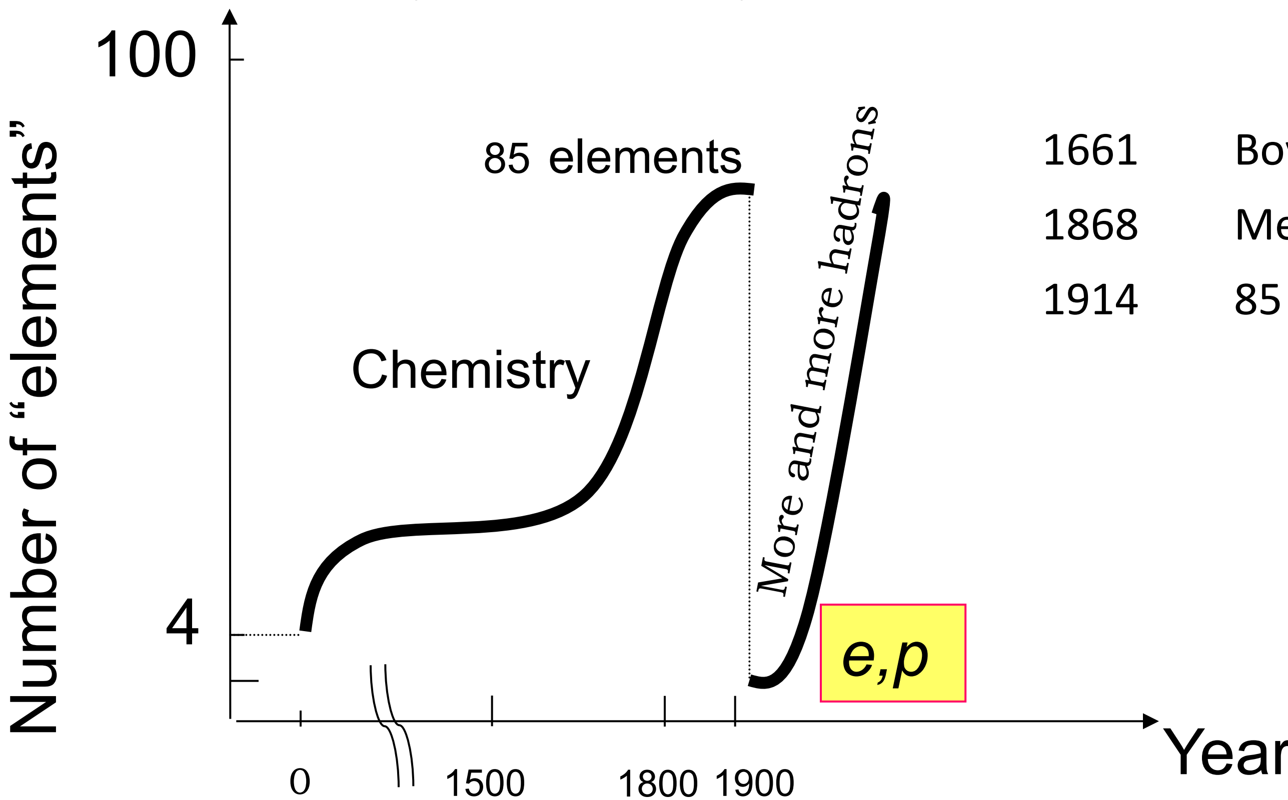
More statistics
Control of the experiment

More and more hadrons

- 1948 first π meson created (Berkley Cyclotron)
- 1950 discovery of π^0 (Berkley Cyclotron)
- 1954 production of strange particles K^+ K^0 , Σ
- 1955 discovery of the antiproton (pp → ppp$\bar{p}$) *Chamberlain, Segrè, Wiegand, Ypsilantis*

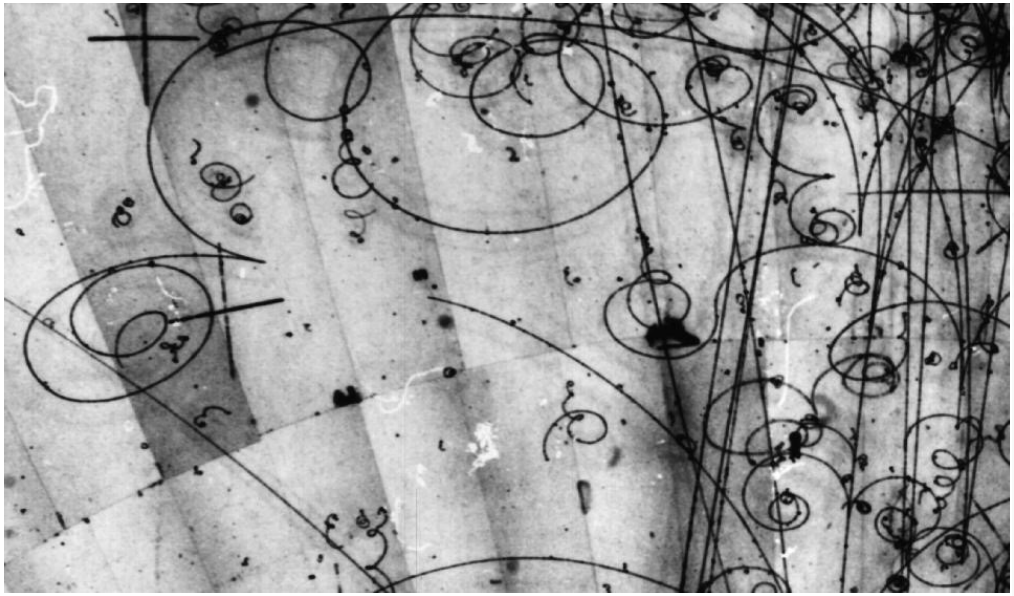
…

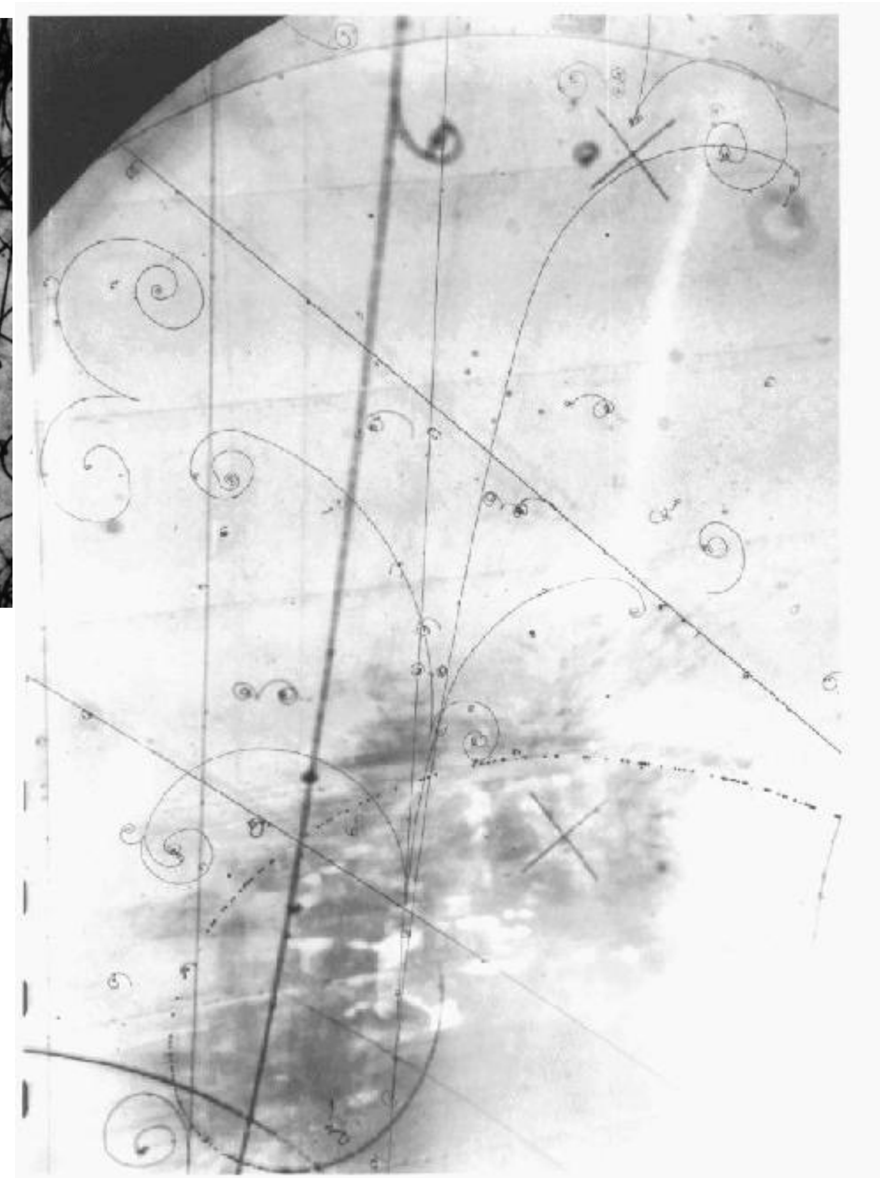
- 1964 discovery of the sss baryon Ω



1661	Boyle defines chemistry
1868	Mendeleïev…
1914	85 elements are known

Clichees from bubble chambres





We can identify

- Tracks of charged particles
- Positrons that annihilate
- Photons converted to $e^{+}e^{-}$ pairs
- Accelerated charged particles irradiating photons

1964 *GellMann-Neeman-Zweig*: quarks theory

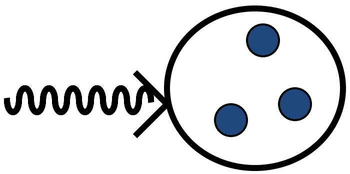
'70 SLAC — Deep Inelastic Scattering experiments

Experimental evidence of quarks

p≡(uud) n ≡(udd)

Strange particles (Λ,K…): s quark

'90 HERA



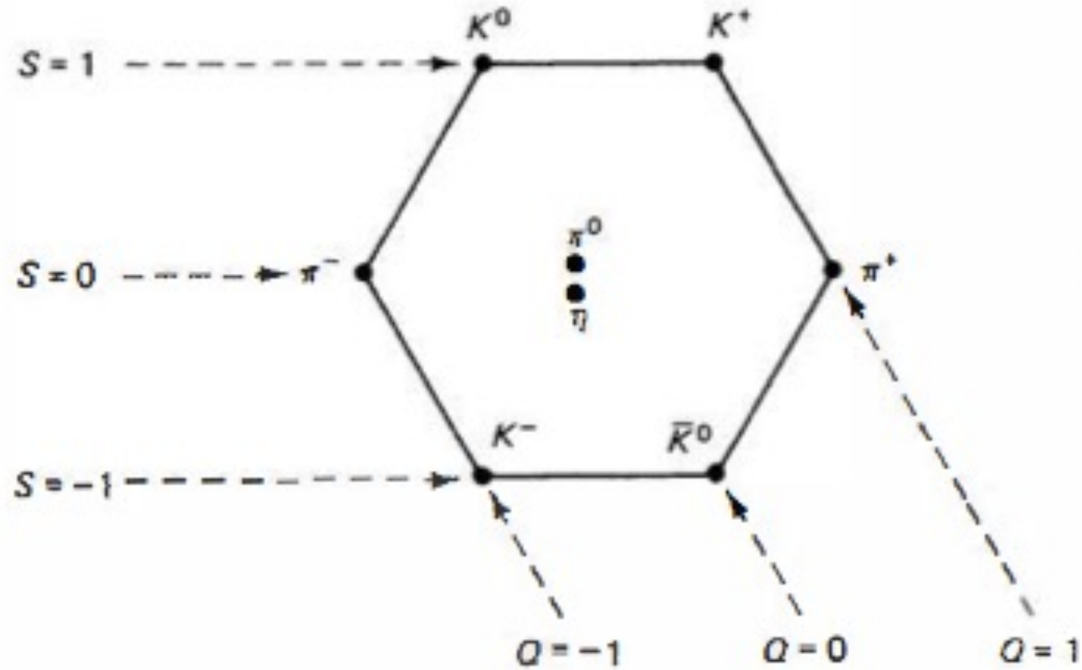
…. Discovery of new particles

- 1962 (Brookhaven accelerator) ν_μ
- 1974 (*Richter/Ting*) J/ψ ($c\bar{c}$ bound state): c quark

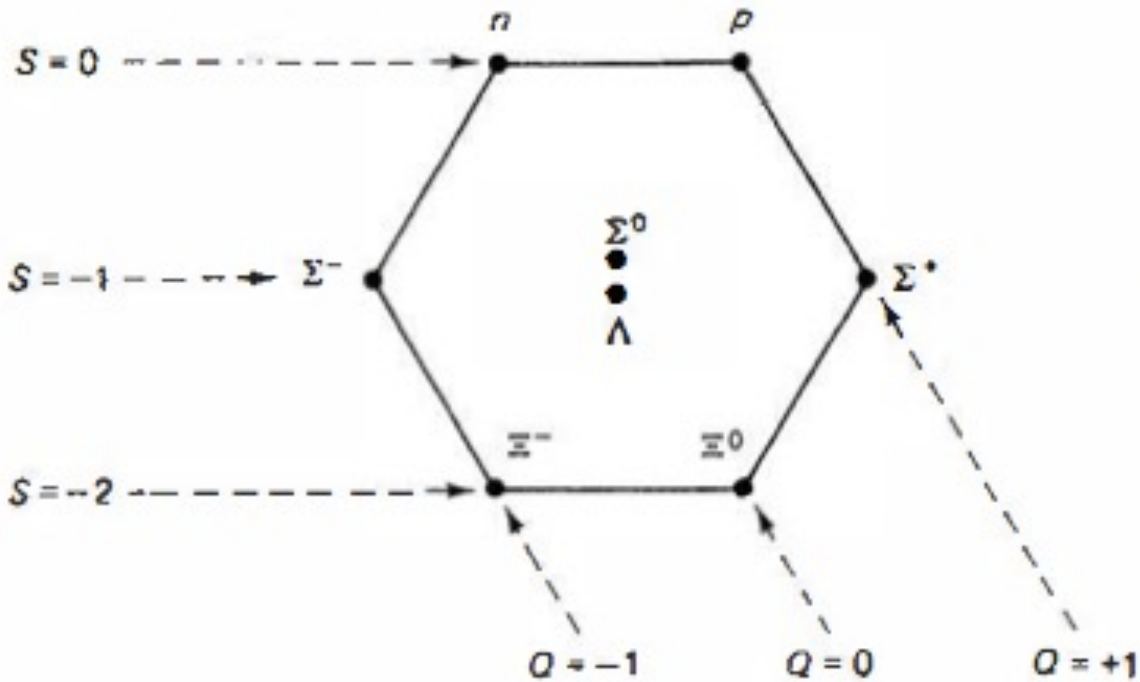
} 2nd gen.

- 1975 (*Perl*) τ lepton
- 1977 (*Ledermann*) Υ ($b\bar{b}$ bound state): b quark
- 1995 (*CDF/DØ @ Fermilab*) discovery of t quark
- 2000 (Donut experiment) ν_τ

} 3rd gen.

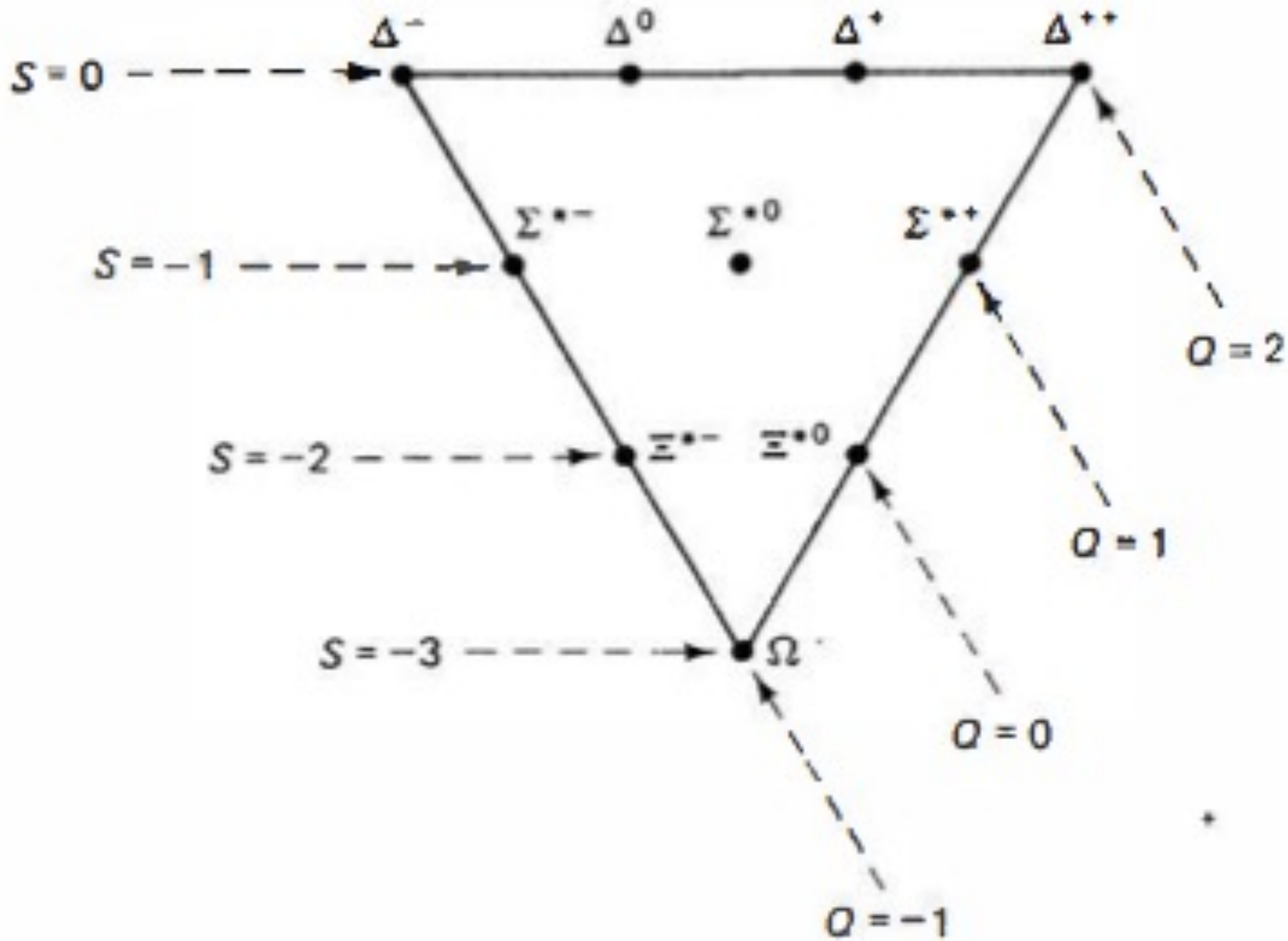


The meson octet



The baryon octet

The baryon decuplet



Discovery of the c quark

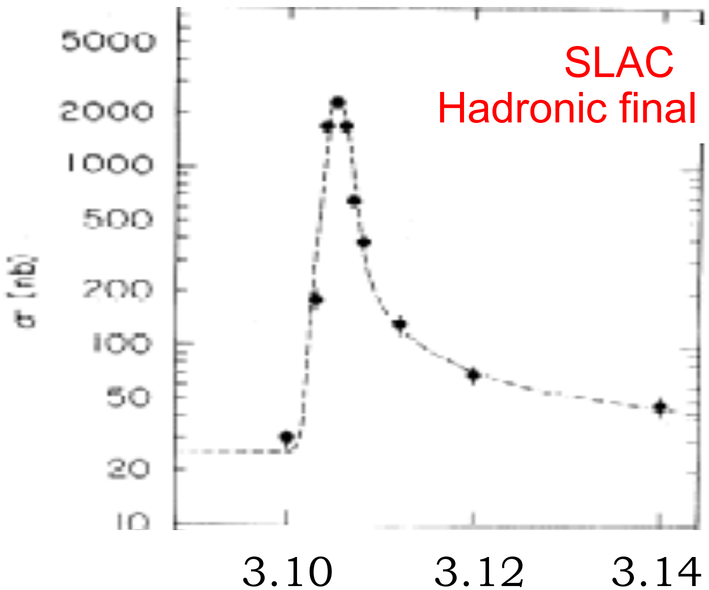
1974 at SLAC (e^+e^-) and at Brookhaven (p on Be target)

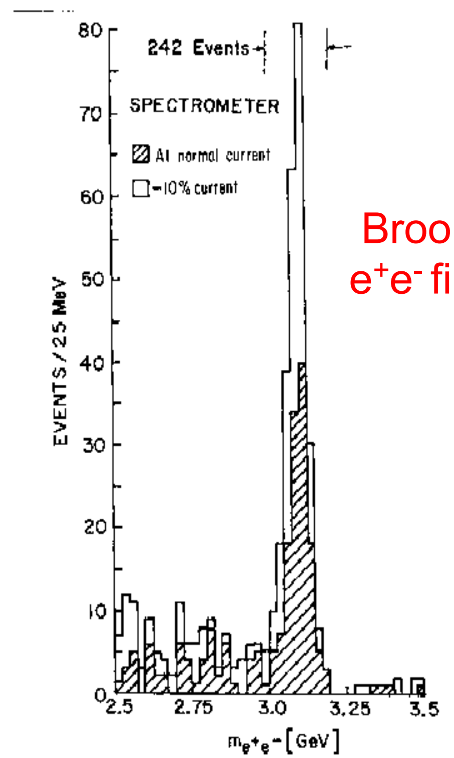
Discovery of a resonance : $m \sim 3.1$ GeV , $\tau \sim 10^{-20}$ s

$\Rightarrow$ decays via EM interaction (suppressed…)

Observed both in the e^+e^- and hadronic decay modes

It is the J/ψ ($c\bar{c}$)



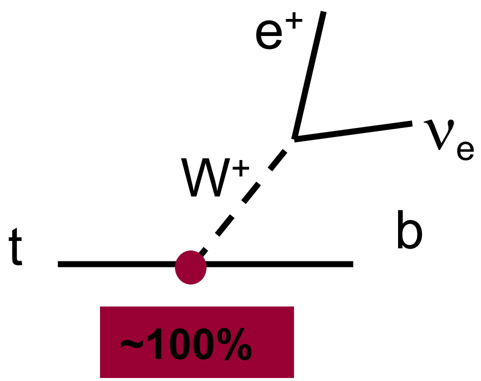


Brookhaven
e^+e^- final state

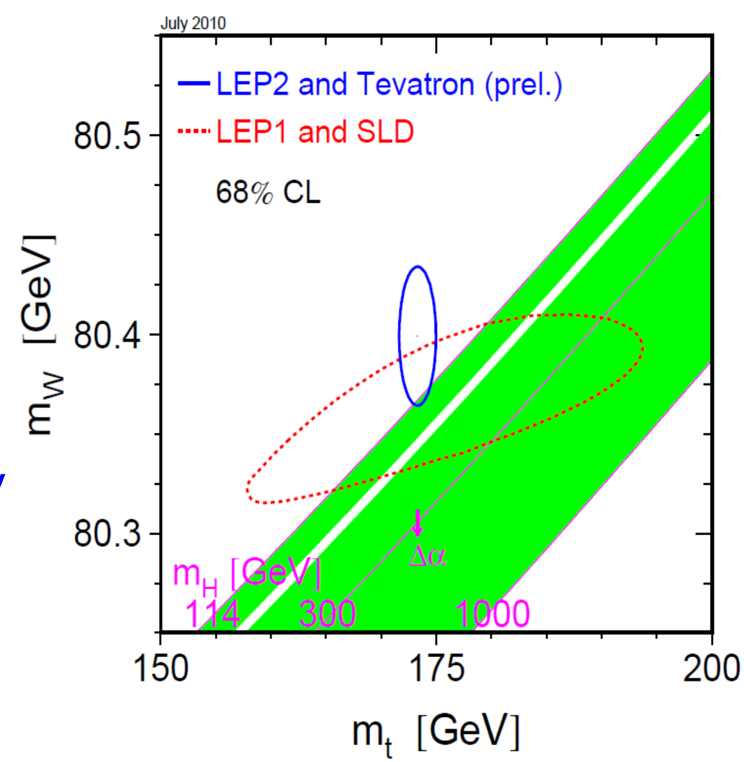
Discovery of the top quark

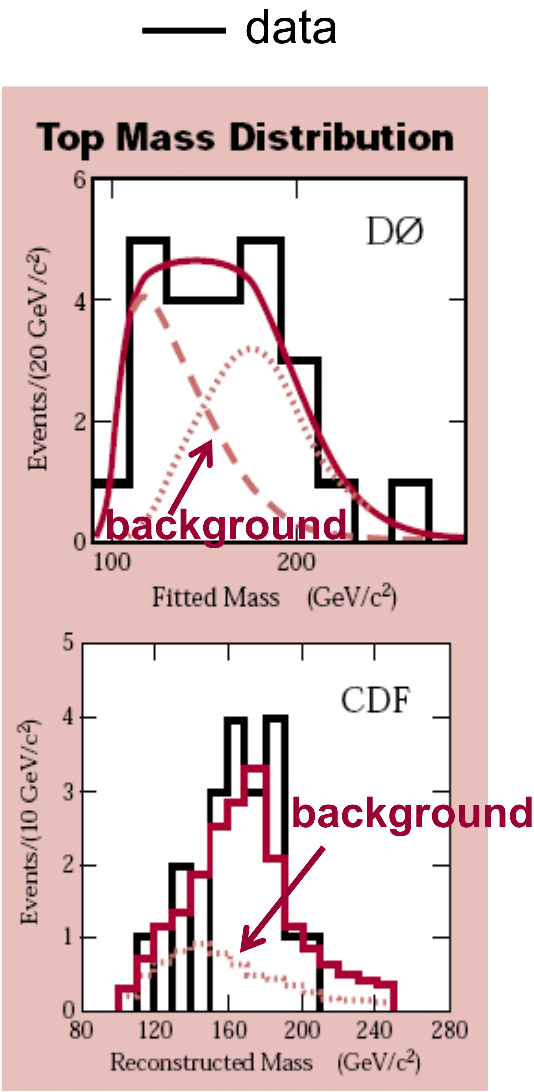
1995 in Fermilab (USA) by the CDF and D0 experiments

Particularity: the top is very massive (~40 x m_b) $\Rightarrow$ it decays before hadronizing (the only isolated quark!)



ICHEP 2010 conference





Top mass: important parameter of the standard model

M(top) = 173.21 $\pm$ 0.87 GeV

(pdg 2016)

Mass hirerchy

Interaction and Higgs bosons

1973 Observation at CERN of weak neutral currents
Interaction of neutrinos → Z ?

1976 Standard Model and electroweak
unification ⇒ γ, Z, $W^{\pm}$
→ Carriers of the weak interaction (masses predicted)

1983 CERN: observation of the Z et $W^{\pm}$ bosons
(Nobel prize 1984: Rubbia and van der Meer)

1989 Production of large quantities of Z at LEP (CERN)

1996 Production of $W^{+}W^{-}$ pairs at LEP (CERN)

2012 Discovery of the Higgs bosons by ATLAS et CMS at LHC (CERN)

Discovery of the $W^{\pm}$ and Z bosons

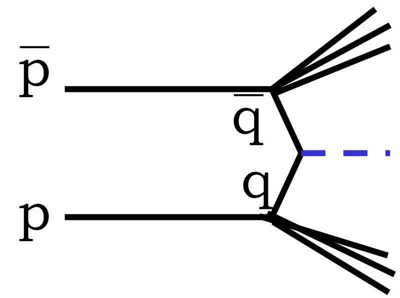
- 1983 at CERN ($p\bar{p}$ collisions)

  Experiments: UA1 and UA2

  Direct production of W and Z:

  $p\bar{p} \rightarrow W^{+} X^{-}$ $\quad W^{+} \rightarrow l^{+} \nu_{l}$

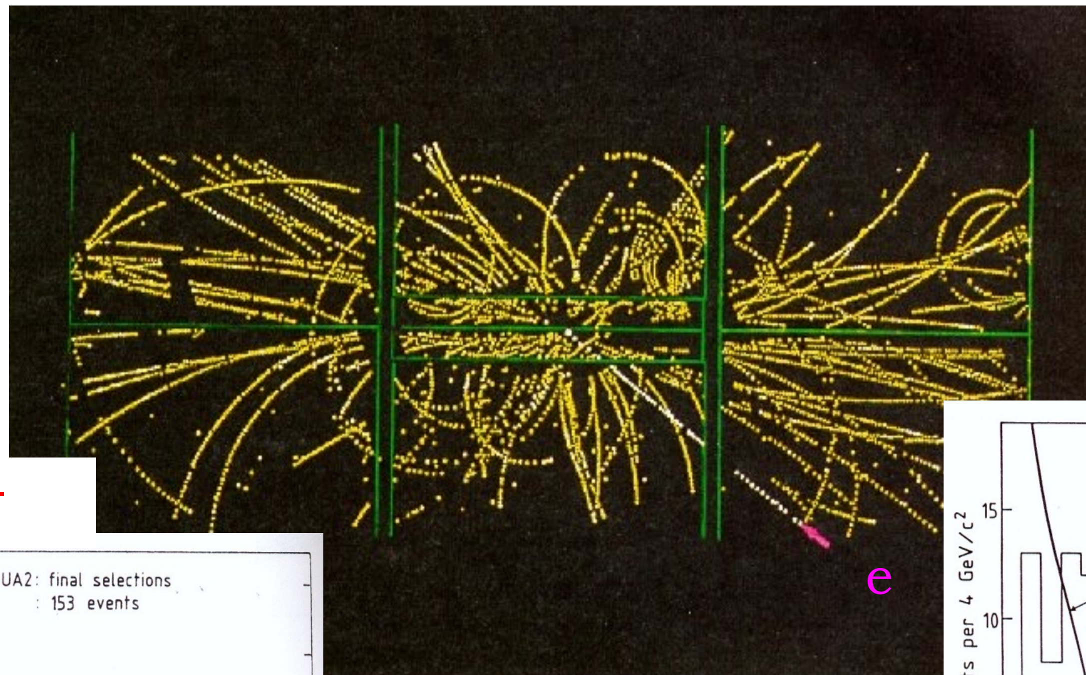
  $p\bar{p} \rightarrow Z X^{0}$ $\quad Z \rightarrow l^{+} l^{-}$



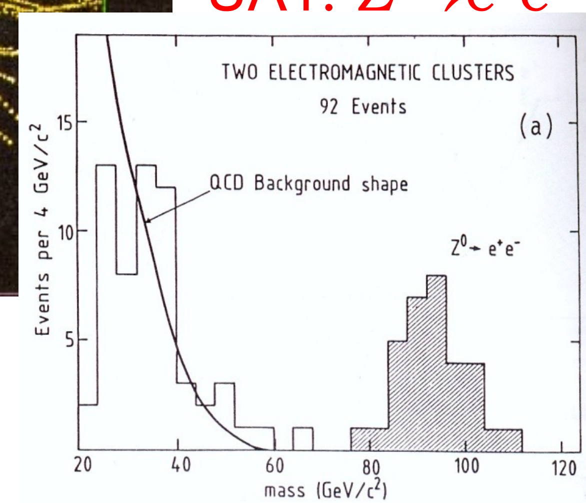
W,Z

$u\bar{d} \rightarrow W^{+}$

$u\bar{u}, d\bar{d} \rightarrow Z$



UA1: $Z \rightarrow e^{+}e^{-}$



UA2: $Z \rightarrow e^{+}e^{-}$