Collider Particle Physics
- Chapter 0 -

A brief historical overview of particle physics

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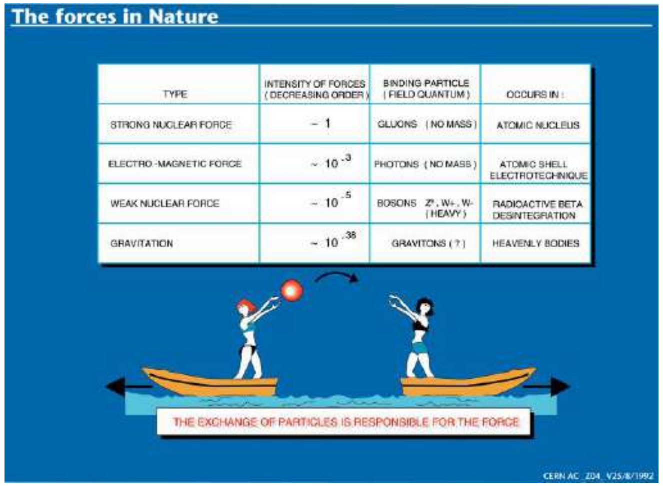
Chapter Summary

- 1937 status and cosmic rays
- Accelerators
- The birth of CERN
- Quarks
- ADA
- The Standard Model
- The discovery of W and Z
- LEP
- LHC

What we knew in … 1935

- ❑ **Atoms are composed by three particles: electron, proton and neutron**
- ❑ **neutrino hypothesis (1930 by Pauli, discovered later in 1956)**
- ❑ **there are four fundamental forces:**
  - ➢ **Strong force: it acts only on nucleons (hadrons), range ~ 10^{-15} m**
  - ➢ **e.m. force: it acts on all charged particles, infinit range**
  - ➢ **Weak force: it acts on all particles, range ~ 10^{-15} m**
  - ➢ **Gravitational force: it acts on all particles, infinit range**



TYPE	INTENSITY OF FORCES (DECREASING ORDER)	BINDING PARTICLE (FIELD QUANTUM)	OCCURS IN :
STRONG NUCLEAR FORCE	~ 1	GLUONS (NO MASS)	ATOMIC NUCLEUS
ELECTRO-MAGNETIC FORCE	~ 10^{-3}	PHOTONS (NO MASS)	ATOMIC SHELL ELECTROTECHNIQUE
WEAK NUCLEAR FORCE	~ 10^{-5}	BOSONS Z^0, W+, W- (HEAVY)	RADIOACTIVE BETA DESINTEGRATION
GRAVITATION	~ 10^{-38}	GRAVITONS (?)	HEAVENLY BODIES

- ❑ **Positron discovery (anti-electron) in 1932, predicted by Dirac in 1928**
- ❑ **Mesotron discovery, predicted by Yukawa as mediator of the strong force**

We understood everything (almost!)

… and then?

- **… and then many bad things happened.**
- **The racial laws in Italy (1938).**
- **Beginning of the Second World War (1939)**

⇨ **many European scientists fled to the United States**

- **Nuclear fission (1938).**

$$\text{Ex}: \ {}^{238}_{92}\text{U} \rightarrow {}^{145}_{57}\text{La} + {}^{90}_{35}\text{Br} + 3\text{n}$$

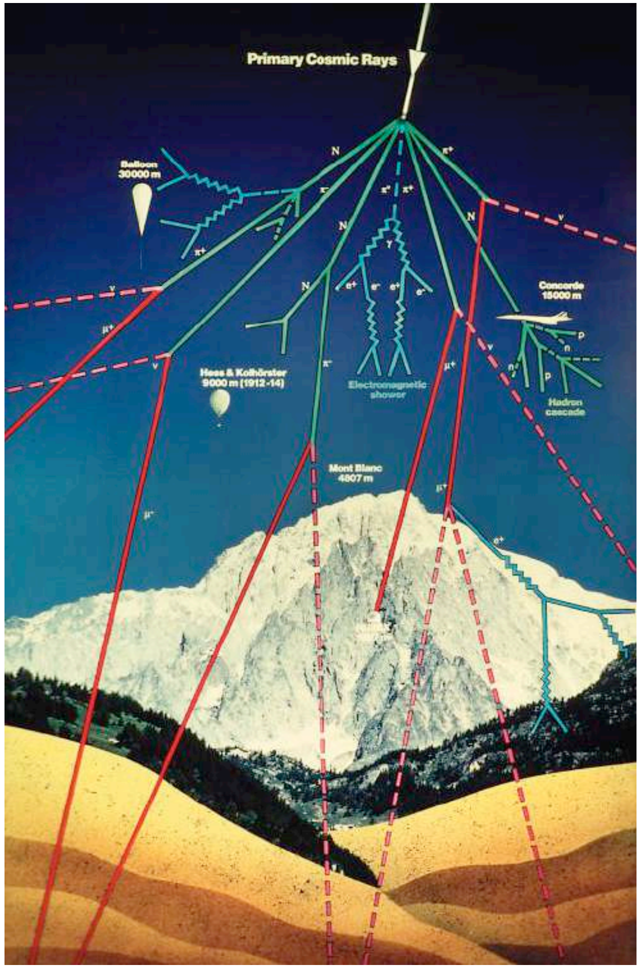
- **In 1942 Fermi created the first controlled chain reaction (atomic pile) in Chicago**
- **And finally, in 1945:**

- **After the war, most European scientists remained in the United States.**

- **We returned to fundamental research, abandoning the nucleus.**

Cosmic rays

- ❑Discovered by V.Hess in 1912. They are composed by proton (86%), alpha (12%) and other nuclei.
- ❑ Positron discovery (1932)
- ❑ Mesotron discovery (1937), later identified (1947) by Conversi, Pancini and Piccioni as the “muon”, an heavier replica of the electron, unstable.
- ❑Pion discovered in 1947 followed by the discovery of ’’strange’’ particles, some one heavier than proton



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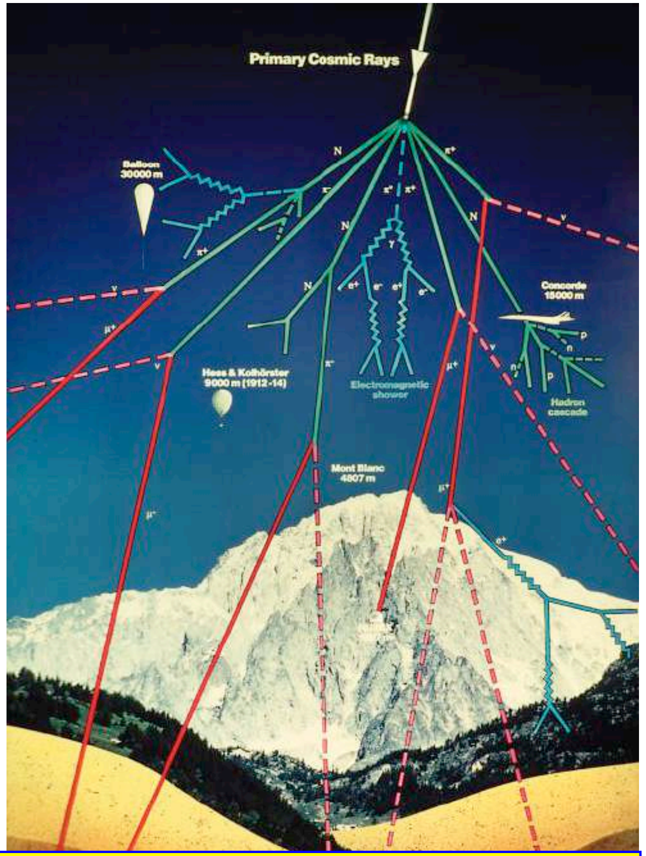
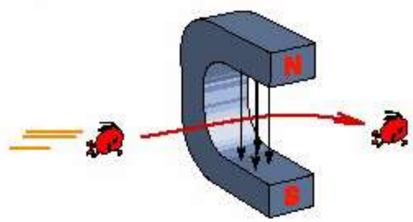


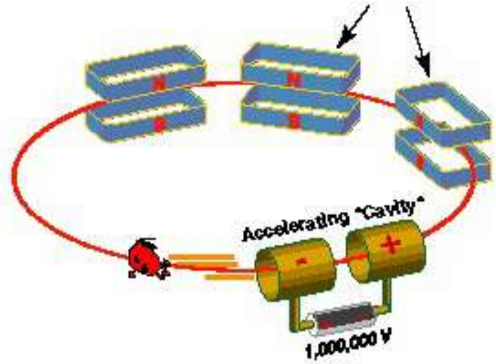
Cosmic rays studies were difficult: experiments up in the mountains or in baloons; flux and energy not under control. People wanted to reproduce the primary interaction in the Lab by accelerating protons (or electrons) and make them colliding with fixed targets.

Accelerators: operating principles

Electric field: acceleration



Magnetic field: bending



$$R = \frac{m \cdot v}{q \cdot B}$$

Cyclotron radius

$$f = \frac{1}{2\pi} \frac{qB}{m}$$

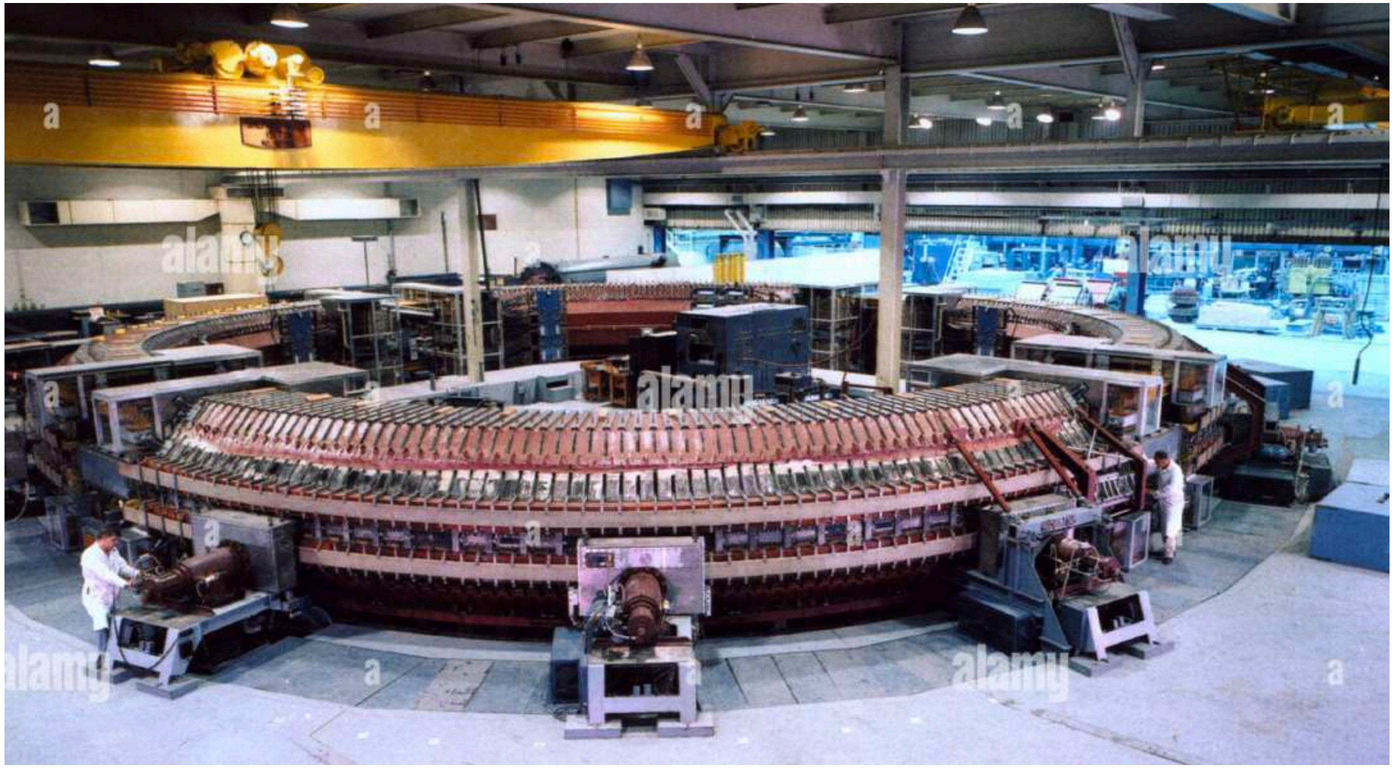
First cyclotron built by
E.Lawrence at Berkeley in 1930

- α particles in radioactive decays: 1÷5 MeV
- 1939: cyclotron 1.5 m diameter: 19 MeV.
- Maximum cyclotron energy: 25 MeV
- next steps: syncrocyclotron and then syncrotron

Pay attention: cyclotrons are still largely used in hospitals and for other purposes other than research

And man created cosmic rays

- 1952: BNL (Brookhaven National Laboratory, Long Island), COSMOTRON
  - 3 GeV protons; 2000 Tons of iron. 20 m diameter.
  - it confirms associated production of strange particles: $\pi + p \rightarrow \Lambda + K$



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  - 3 GeV protons; 2000 Tons of iron. 20 m diameter.
  - it confirms associated production of strange particles: $\pi + p \rightarrow \Lambda + K$
- 1954: LBL (Lawrence-Berkeley Laboratory, California), BEVATRON
  - 6 GeV protons; 10000 Tons of iron.
  - E. Segré discovers the antiproton (Nobel prize in 1959). $p + p \rightarrow p + p + p + \overline{p}$
- 1957: Dubna; SYNCROPHASATRON. 10 GeV protons , 36000 Tons of iron!

In order to go at higher energy it was needed a smart idea to reduce the amount of iron needed to build the magnets.
Livingston discovered/invented/found/designed the strong focusing in 1952.

[*In the same year (1952) D.Glaser invents the bubble chamber*]

The birth of CERN

- After the war, Europe was in ruins. The physicists had been missing. Scientific knowledge and technical skills had moved to the USA.
- In December 1949, Louis de Broglie recommended an international research laboratory at a UN cultural conference.
- In 1950 UNESCO approved a resolution by I.Rabi and in 1952, 11 European countries participated in CERN (European Council for Nuclear Research).
  P. Auger and E. Amaldi were the spiritual fathers of CERN.
- It was chosen as the site of the laboratory Meyrin, a town near Geneva, close to the French border.

Sur le terrain du futur institut nucléaire

Sous la conduite de M. A. Picot, les membres du Conseil européen pour la recherche nucléaire se sont rendus hier à Meyrin pour reconnaître le terrain où s'élèvera le Centre nucléaire (voir en Dernière heure)

(Photo Freddy Bertrand, Genève)

La Suisse du 30 octobre 1953

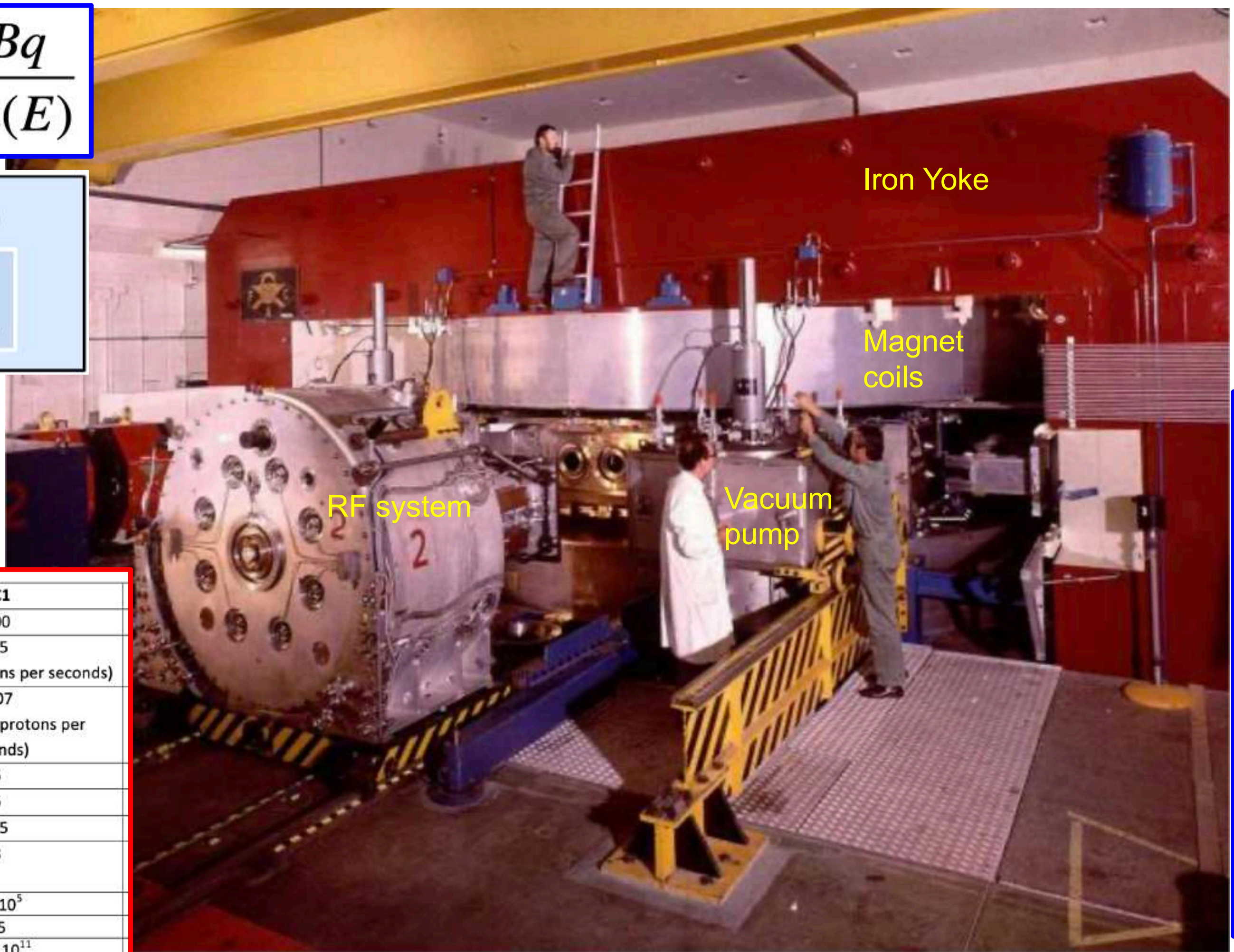
- On 29 September 1954 the European Organization for Nuclear Research (CERN) was born
- August 8, 1951: the National Institute of Nuclear Physics (INFN) was established with decree number 599 of the CNR president Gustavo Colonnetti.

The first CERN accelerator: the 600 MeV syncrocyclotron

$$\omega = \frac{v}{r} = \frac{Bq}{m} = \frac{Bq}{m(E)}$$

Synchro-cyclotron

$f_{RF}(E)$
$B(E)$ or B = const.



- 1954: construction started
- 1957: first beam delivered
- 1958: start experimental program
- 1974: new SC2 commissioned
- 1990: end of operation
- 2012(?): it became a visit point

Machine parameters	SC1
Proton kinetic energy (MeV)	600
Internal proton beam (μA)	1.5 (~ 6 x 10^{12} protons per seconds)
Extracted proton beam (μA)	0.07 (~ 4.4 x 10^{11} protons per seconds)
Extraction efficiency (%)	5
Energy spread (FWHM) (MeV)	5
Acceleration time (ms)	8.5
Average energy gain per turn (keV)	3
Number of revolutions	2 × 10^5
Repetition rate (Hz)	55
Protons per pulse	1.2 x 10^{11}
RF frequency swing	30.6 – 16.6 MHz

1958: first important discovery

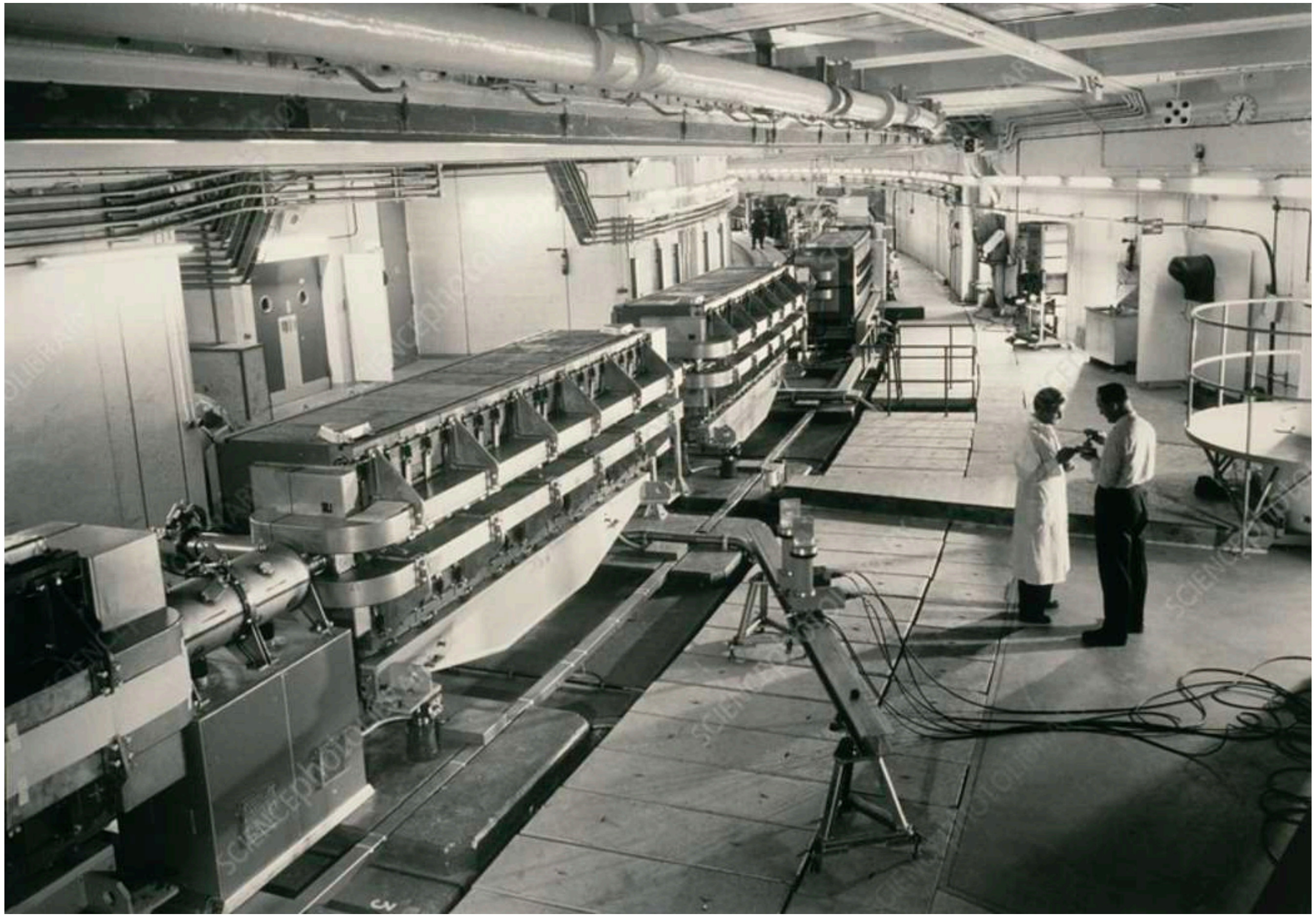
$$\pi^+ \rightarrow e^+ + \nu$$

B.R. $(1.22 \pm 0.30) \cdot 10^{-4}$
in agreement with the V-A theory

today: $(1.230 \pm 0.004) \cdot 10^{-4}$

CERN comes in the game… and strong focusing too!

- 1959: CERN. Protosynchrotron PS, 24 GeV, 3200 Tons, 200 m diameter.



This was the first accelerator to use the strong focusing principle

CERN comes in the game… and strong focusing too!

- **1959: CERN. Protosynchrotron PS, 24 GeV, 3200 Tons, 200 m diameter.**
- **1960: BNL. Alternate Gradient Synchrotron AGS, 33 GeV, 4000 Tons, 257 m diameter.**

It begins the ''economic boom'' for particle physics too. First in cosmic rays and then with the new accelerators a lot of new particles were discovered, too many!
There was a lot of work for theoreticians too.

E.Fermi to one of his student (L.Lederman): "*boy, if I could remember the name of all these particles, I would have been a botanist*".

The first resonance discovered by Fermi at Chicago in 1953, the Δ, suggested that the proton maybe is not a fundamental particle

Hofstadter (1956): proton structure (elasting electron-proton scattering)

Other important discoveries: parity violation in weak interactions (1958); neutrino mu at the AGS in 1962, CP violation in 1964 at the AGS.

And then there were …quarks

- To put order in the zoo of particles, Gell-Mann and Neeman proposed a classification scheme based on symmetries (SU (3)), which they called: "the eightfold way".
- The eightfold way predicted a new particle (1962), Ω^-, discovered in 1964 by Samios
- To explain the symmetry, Gell-Mann and Zweig made the hypothesis that the particles subject to the strong interaction were composed of elementary particles. Gell-Mann called the new particles "quarks" (Zweig called them aces).

"Three quarks for Muster Mark" – James Joice's Finnegans Wake

quark	charge	strangeness
up	+2/3 e	0
down	-1/3 e	0
strange	-1/3 e	-1

Quarks are very bizarre objects with fractional charge. There was a lot of reluctance to accept them.
Zweig was one of the few people firmly believing that the quarks were real particles.

Barions: 3 quark; Mesons: a quark and an antiquark

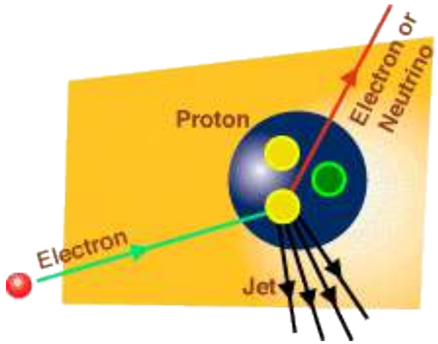
n

p

Greenberg (1964): quarks come in three colours: red, green and blue. Colour charge is the source of strong force

Experimental evidence of the existence of quarks

- At SLAC, a laboratory near San Francisco, the "monster" came into operation in 1967, a linear accelerator of 20 GeV electrons 2 miles long.
- With an experiment similar to that of Rutherford, but using electrons as projectiles, it was experimentally demonstrated that point-like particles must be present inside protons and neutrons (called partons by Feynman).
- This result was then confirmed at CERN with a neutrino beam.



The fundamental particles are (in 1968):
Leptons: e^-, ν_e, μ^-, ν_μ
Quarks: up, down, strange

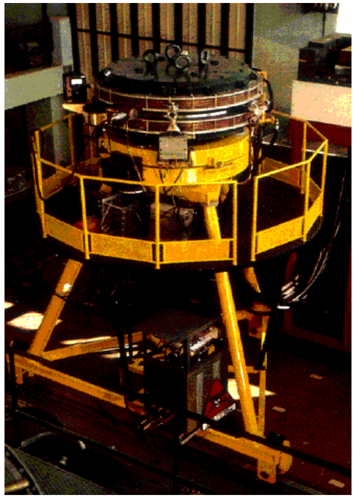
+ their antiparticles

The proton is no longer a fundamental particle but there are many things inside (not only the three valence quarks). PDF (particle density functions) are introduced to describe the proton inner content

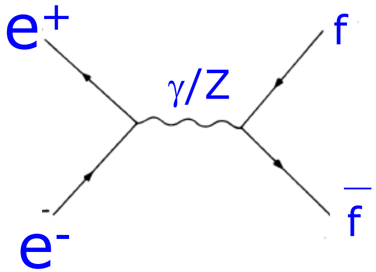
ADA: the first e^+e^- collider

- In 1961, in the Frascati National Laboratories, a small group of young physicists and engineers led by Bruno Touschek conceived and built AdA, the first particle-antiparticle accelerator. In the same ring, electrons and positrons circulated in opposite directions with equal speed, annihilating and transforming all the initial energy into new particles.

ADA – 1961 - LNF



$\sqrt{s}$ = 500 MeV



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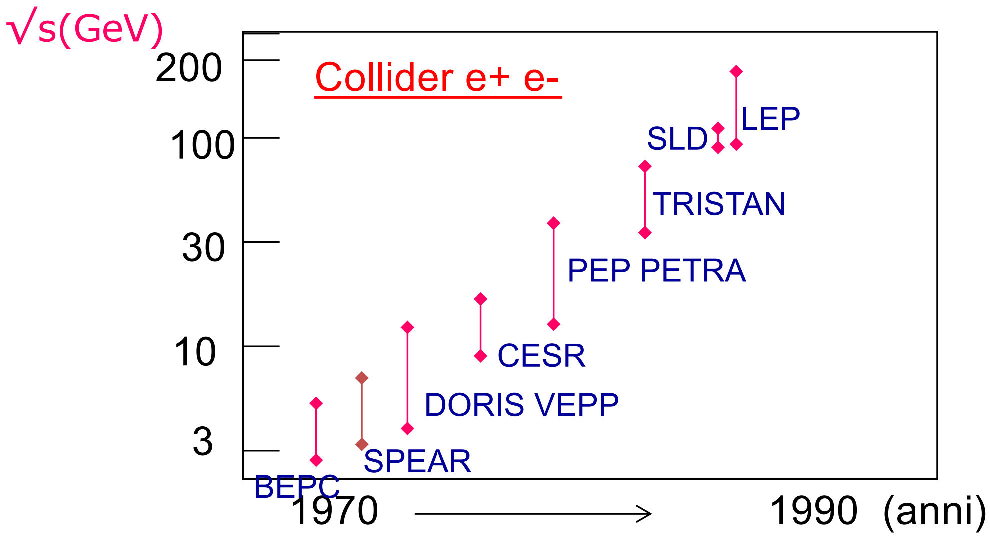
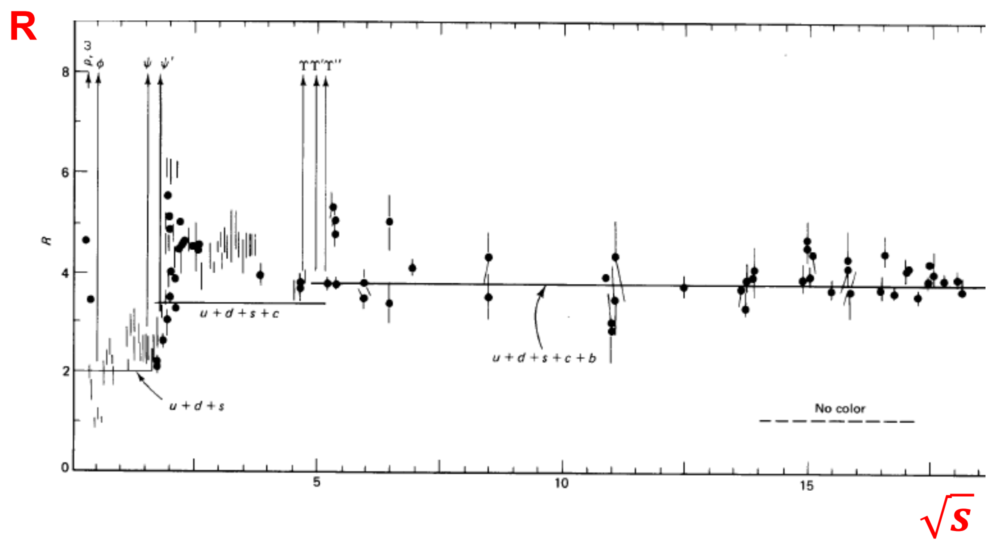
- AdA, despite having had a short scientific life, remains a milestone in the history of science. As a prototype of the many accumulation rings that followed, it showed to the Particle Physics community the concrete feasibility of electron-positron colliders.



1967: ADONE: 3 GeV



The Standard Model

- 1960: Glashow proposed $SU(2)_L \times U(1)_Y$ as the symmetry group for the electroweak theory.
  - Problem: all particles (fermions and bosons) must be massless
- 1964: Higgs, Englert & Brout published two independent papers on spontaneous symmetry breaking of a Lagrangian which is invariant under a local gauge transformation.
- 1967: Weinberg (and later Salam) used the Englert, Brout and Higgs mechanism to give mass to fermions and bosons (actually, electrons/muons … quarks were not yet there).
  - unintended consequence: a massive scalar boson should also be present: the Higgs boson
- 1971: ‘t Hooft and Veltman proved that the Weinberg theory is renormalizable

→ **The hunt for the W, Z and H bosons begins**

1973: first experimental evidence of the Standard Model. Discovery at CERN of "neutral currents" in neutrino-nucleon interactions, which can be explained only by the exchange of a Z.

Weak interaction in the quark sector

- Experimental discrepancy between charged K and charged pion decays violating the weak interaction universality
  - 1963: Cabibbo: week eigenstates are not mass eigenstates → Cabibbo angle
- Experimental discrepancy between neutral K and charged K decays
  - 1970: Glashow, Iliopoulos and Maiani (GIM) introduced the quark charm
    → Flavour changing neutral current are suppressed
- 1964: Fitch and Cronin discovered CP violation in the K_L decays
  - 1973: Kobayashi and Maskawa proposed the existence of three quark families in order to introduce a phase in the quark mixing matrix (CKM)

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

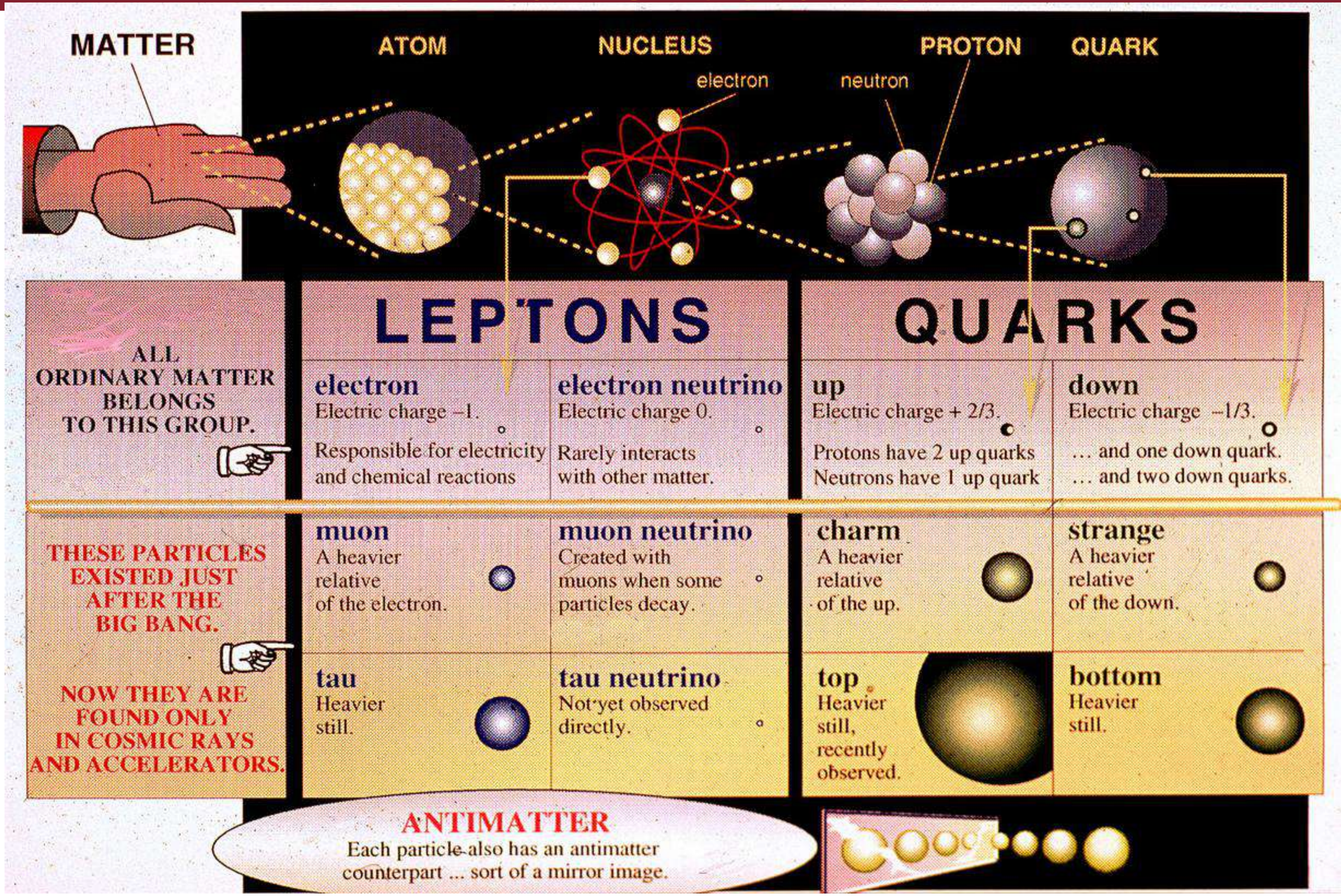
Question: do we have CP violation in other systems besides neutral K?

The amazing years: 1974 ÷1977

- **1970:** Glashow, Iliopoulos and Maiani proposed the existence of a fourth quark, the "charm", charge +2/3 e.
- **1974:** discovery of the quark charm. Ting at BNL and Richter at SLAC. A few weeks later it was also discovered in Frascati pushing Adone beyond its limits (electron-positron collider of 3 GeV) (In life you need luck ☺).
- **1975:** discovery at SLAC of a third charged lepton, the τ, with a mass about 3500 times greater than that of the electron and an average lifetime of 0.3 ps.
- **1977:** discovery at FNAL (Chicago) of a fifth quark, the "bottom" or "beauty", charge –1/3 e. The bottom was discovered at a new proton accelerator of 500 GeV, 2 km in diameter.

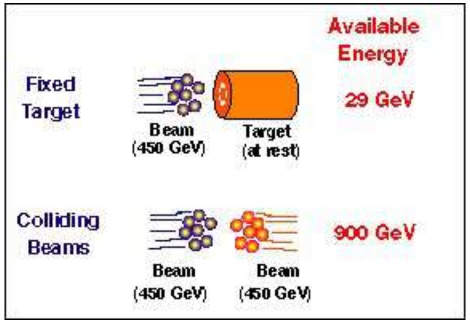
For symmetry reasons, the Standard Model predicts the existence of a third neutrino, the neutrino τ, discovered at FNAL in 2000 and of a sixth quark, the "top" or "truth", discovered at FNAL in 1995, with a mass of about 280 times the proton mass.

The current status



The discovery of W and Z

- In 1976, the SPS, a 400 GeV proton accelerator, 2 km in diameter, came into operation at CERN. However, the energy was not sufficient to produce W and Z, whose estimated mass was 80 ÷ 90 GeV.
- Rubbia's idea was to transform the SPS into a proton-antiproton collider, following what had been done in Frascati with Adone, the collider $e^+ e^-$ where particle and antiparticle rotate in the same ring in the opposite direction.

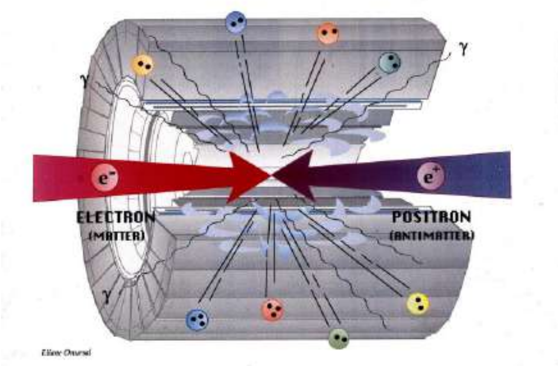


- The problem was to have a sufficient number of suitable antiprotons to collide with the protons (solved by S. Van der Meer with stochastic cooling).
- In 1978 the SppS project (270 + 270 GeV) starts.
- In 1983 the first W and Z were produced, detected in detectors UA1 (Rubbia) and UA2.

1984: Nobel prize to Rubbia and Van der Meer

The LEP Collider

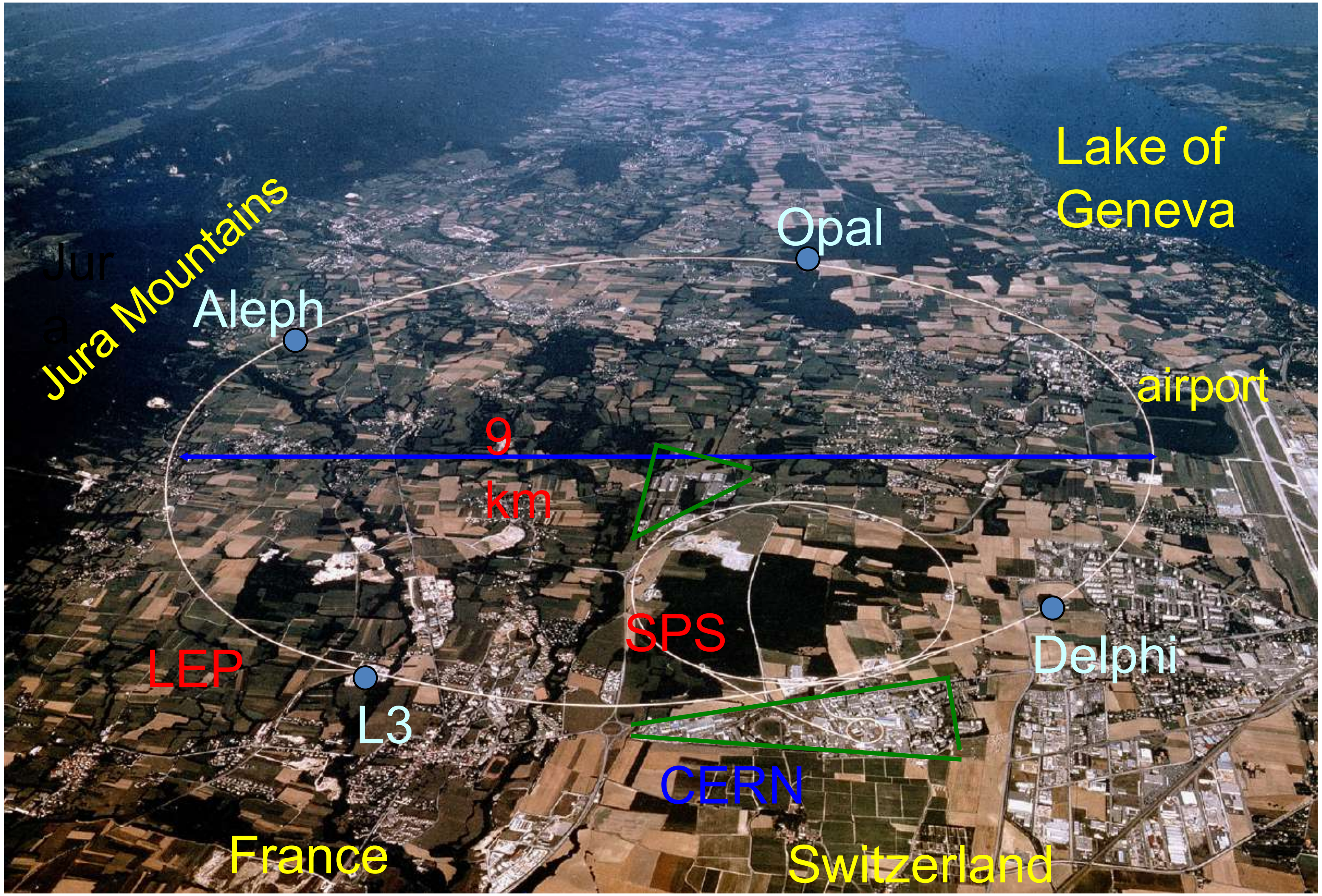
- In 1981, CERN decided to build the largest accelerator in the world: LEP. It is an electron-positron collider of 27 km in circumference. Electrons, unlike protons, are elementary particles, so the electron-positron interaction is much "cleaner" than the proton-antiproton one. The initial state is perfectly known and the theoretical predictions of the Standard Model can be verified with greater accuracy.



All the energy of the center of mass is available to create new particles: $E = mc^2$

- In 1983 the excavation of the tunnel begins. The tunnel has a diameter of 3.8 m and is located approximately 100 m underground.
- In 1988, the excavation of the tunnel was completed. At the time it was the longest tunnel of Europe, now surpassed by the English Channel tunnel and more recently by the Gottardo railway tunnel

LEP: aerial view



Old picture.
Now there are much more buildings everywhere

LEP: results

- On July 14, 1989, the first electron beam circulated in the LEP. The first collision $e^+ e^-$ took place on 15 August. The energy of the center of mass was equal to m_Z (~ 91 GeV).
- From 1989 to 1995 about 17 million Z were produced in the 4 experiments.

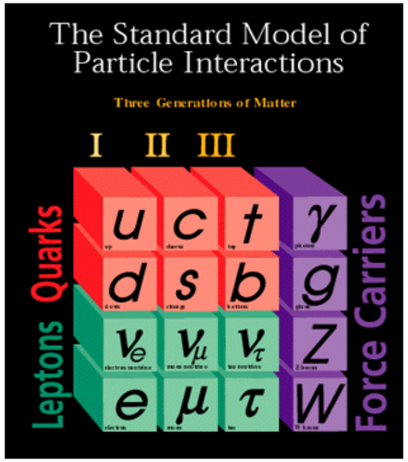
This made it possible to measure the mass of the Z with an accuracy of 0.02 ‰ and to verify the accuracy of the SM predictions better than 1%

Through the effect of the radiative corrections, the top mass of 181 ± 10 GeV was predicted. The value measured at FNAL was 174 ± 5 GeV.

- From 1995 to 2000, the energy of the LEP was increased up to 208 GeV. The search for the Higgs boson and new particles continued. <u>SM was stronger than ever!</u>
- The Higgs, if any, has a mass greater than 115 GeV.

Research continues at LHC.

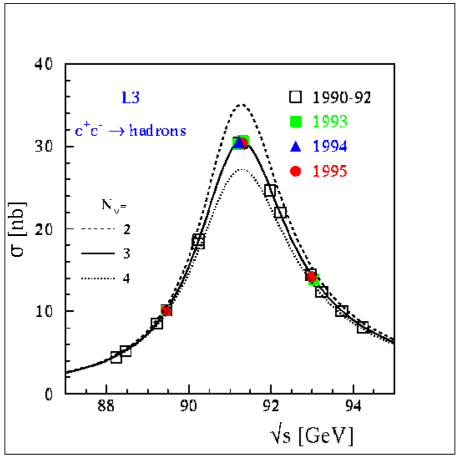
The number of neutrino families



The Standard Model organizes elementary particles in families.

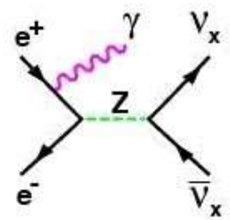
The Model does not predict the number of families and before the advent of the LEP, a fourth family was not excluded.

- **From the width of the Z resonance and the single photon method:**



LEP: N_ν=2.984±0.008

$$e^+e^- \to \nu\bar{\nu}\gamma$$



L3: N_ν=2.98±0.10

There are 3 light neutrino families!

LHC

- In December 1994 CERN officially approved the construction of the LHC (Large Hadron Collider). It is a proton-proton collider with 8 T superconducting magnets, to be installed in the LEP tunnel.
- The proton beams cross with a frequency of 40 MHz (every 25 ns).
- On the collider there are two main experiments (ATLAS and CMS), plus two 'specialized' experiments (LHCb and ALICE) and two other 'small' experiments (TOTEM and LHCf).
- The LHC went into operation in December 2009. In 2010 and 2011 it operated with a center of mass energy of 7 TeV (that of the project is 14 TeV); 8 TeV in 2012
- On July 4th 2012 the discovery of the Higgs boson was announced
- From 2015 to 2018 (Run-2) the CoM energy was 13 TeV
- On July 5th 2022 officially started the Run-3 at 13.6 TeV

A parallel story: neutrinos

Neutrino Physics and oscillation

1930	ν existence postulated	Pauli
1934	ν interaction theory and name	Fermi
1938	Solar ν flux calculation	Bethe
1946	Idea of ν chlorine detector	Pontecorvo
1956	ν interactions observed	Reines & Cowan
1957	Idea of ν oscillation	Pontecorvo
1958	Left-handed ν	Goldhaber
1962	2 ν's, ν_μ, ν_e	Lederman, Schwartz & Steinberger
1968	Solar neutrino deficit	Davis
1973	ν NC interactions observed	Gargamelle
1975	τ and the third ν	Perl
1986	Solar deficit again, atmospheric(?)	Kamiokande
1987	ν from SN1987A	Kamiokande, IMB
1989	3 light neutrino families	LEP Collaborations
1991	Solar deficit again	Gallex, SAGE
1998	Atmospheric ν oscillation	Super-Kamiokande
2002	Solar ν oscillation confirmed	SNO, KamLand
2005	Atmospheric ν oscillation confirmed	K2K

~ 1965 Standard Solar Model : John Bahcall

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End of chapter 0