Landscape of the Standard Model

Lecture 1: Development of the SM

Amol Dighe, TIFR

XVth ICFA School
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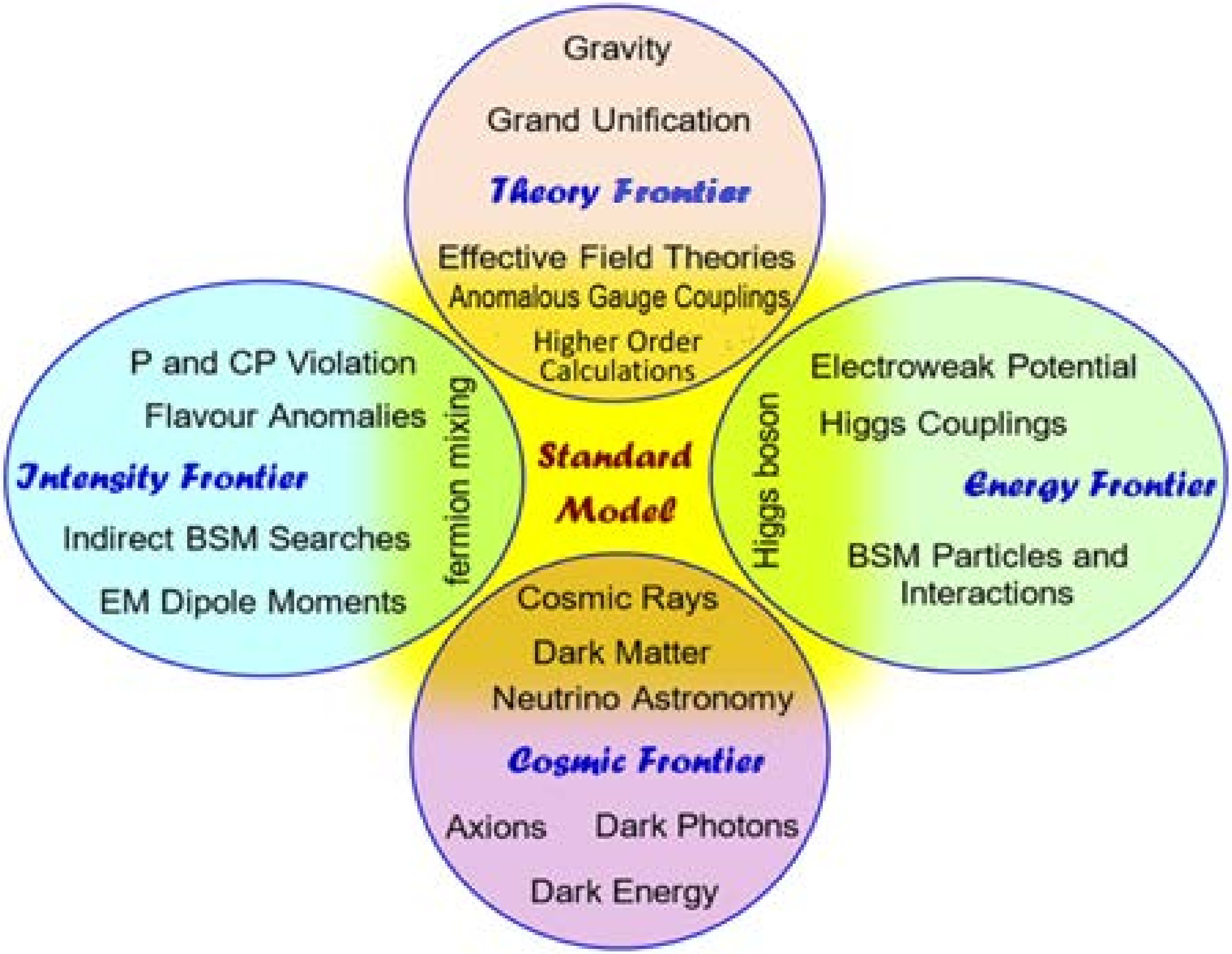
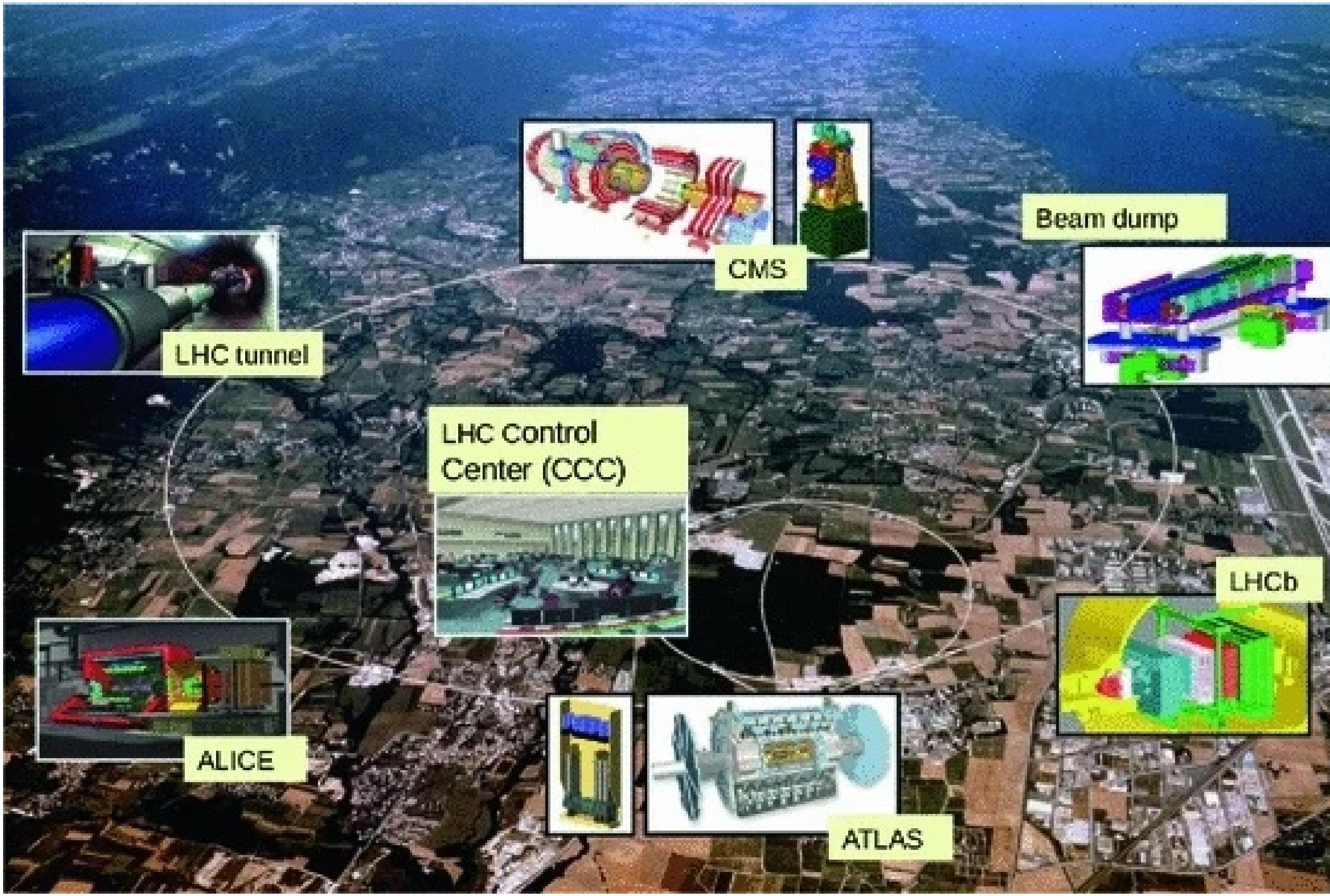
The Quest and the frontiers

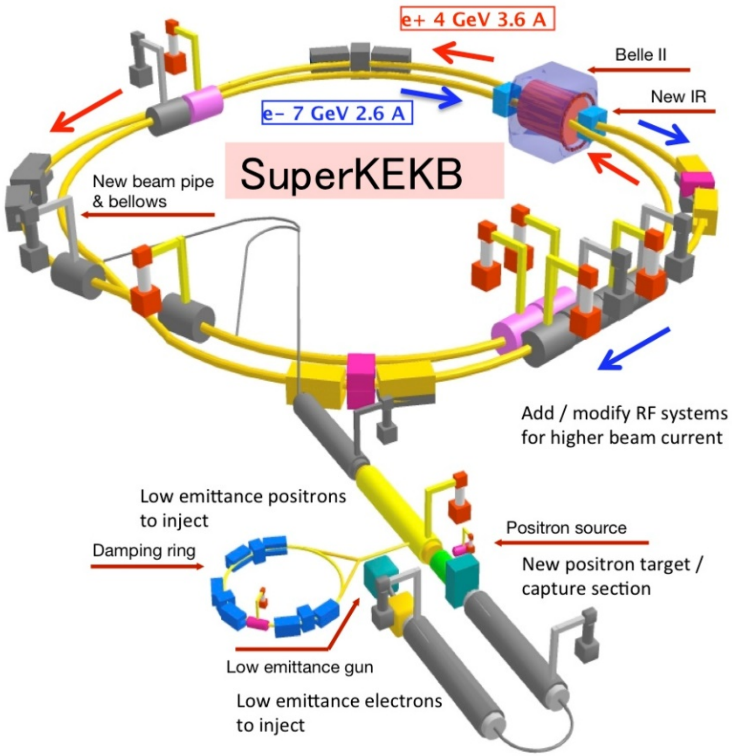


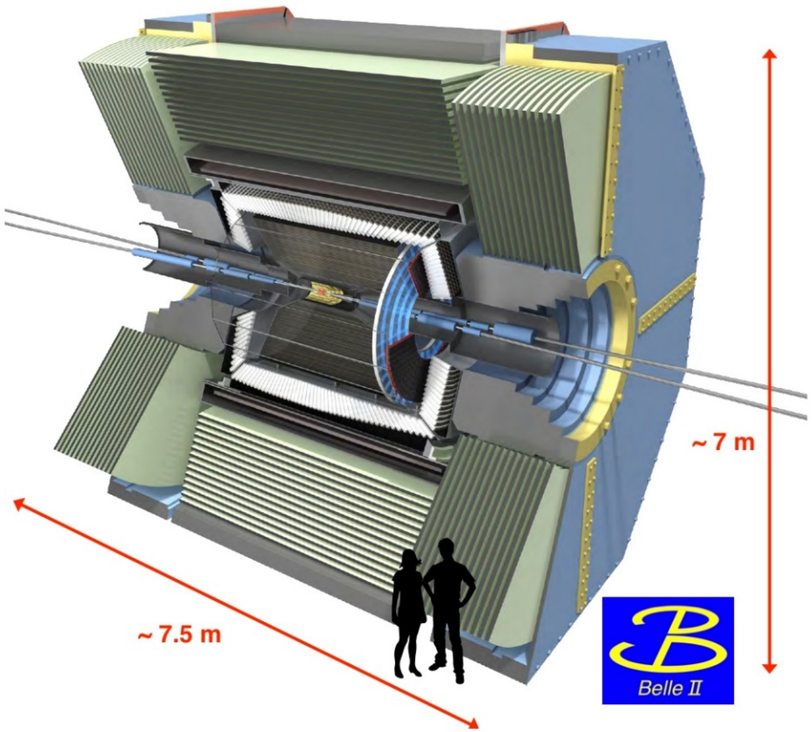
Current (accelerator-based) tools @ LHC



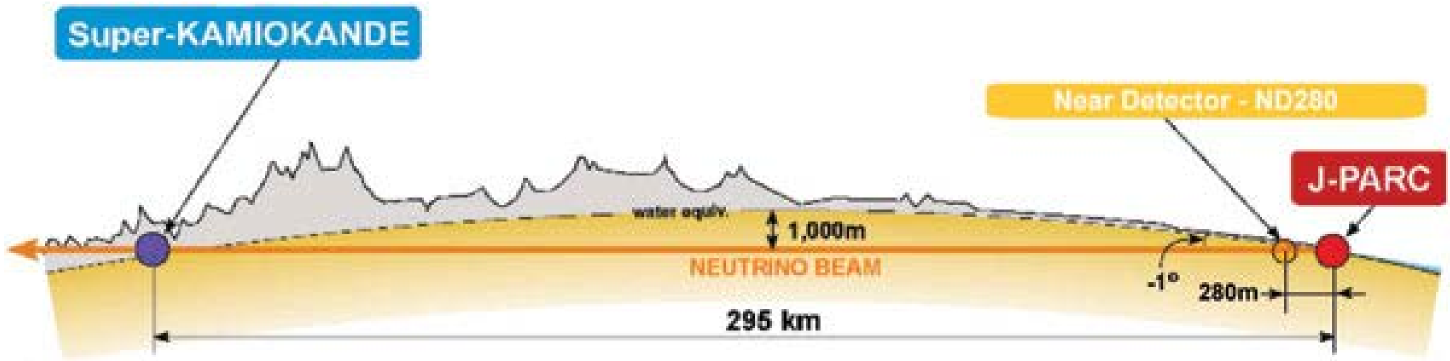
From the thesis of Olena Karacheban

Current (accelerator-based) tools @SuperKEKB





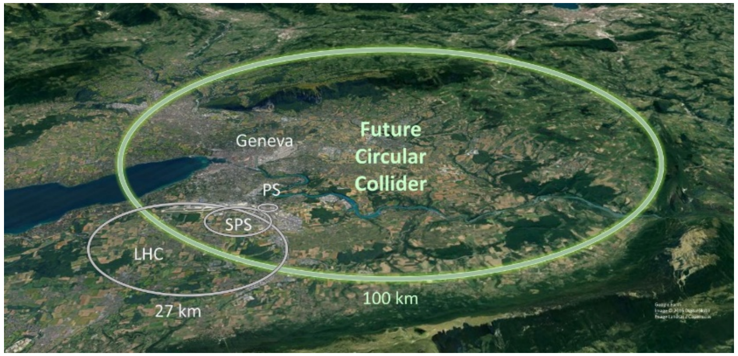
Current (accelerator-based) tools with neutrino



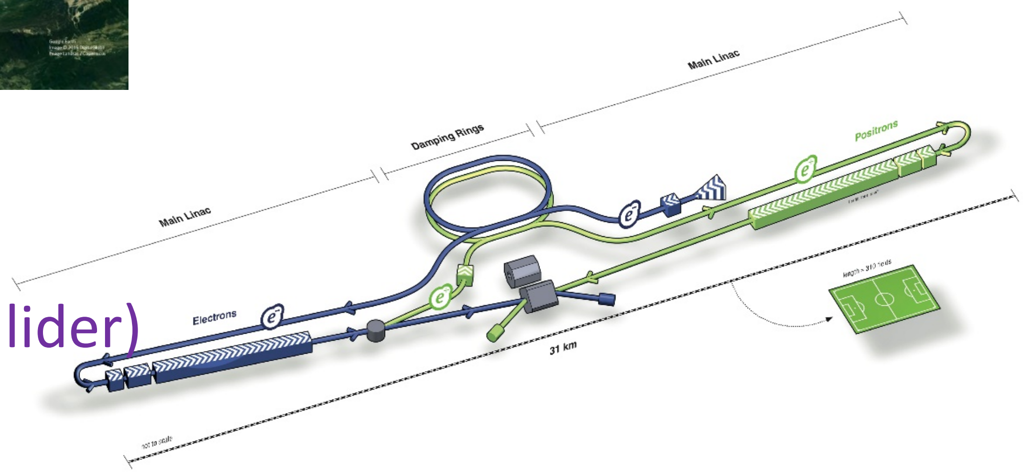
T2K

Nova

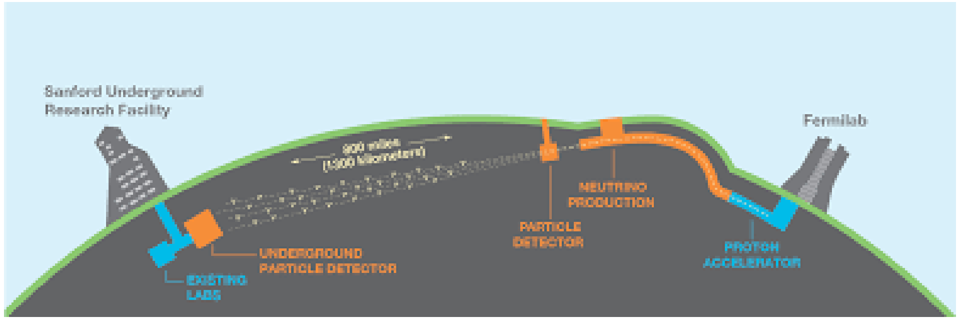
The future (accelerator) tools ??



FCC @ CERN
(Future Circular Collider)



ILC @ Japan
(International Linear Collider)



DUNE @ USA
Deep Underground
Neutrino Experiment

Let’s start at the very beginning
A very good way to start …

Landscape of the Standard Model

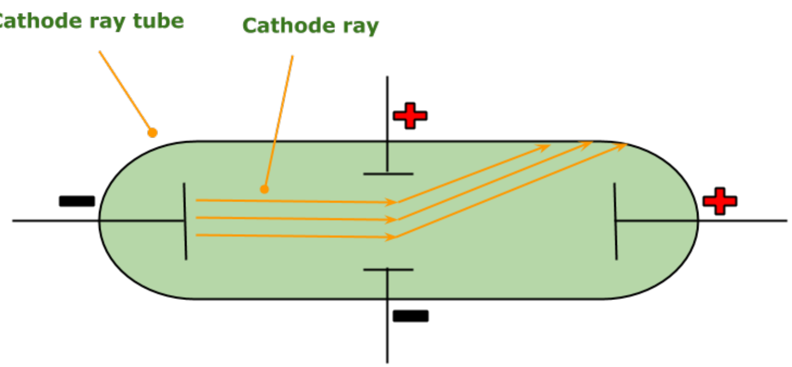
- Lecture 1:
  Historical development of the SM
  (Changing tools: experimental and theoretical)

- Lecture 2:
  Theoretical foundations of SM
  (Gauge symmetries and electroweak symmetry breaking)

- Lecture 3:
  Flavor structure of the SM

The discovery of an electron

- Discovery of electron : J. J. Thompson (1897)



1906

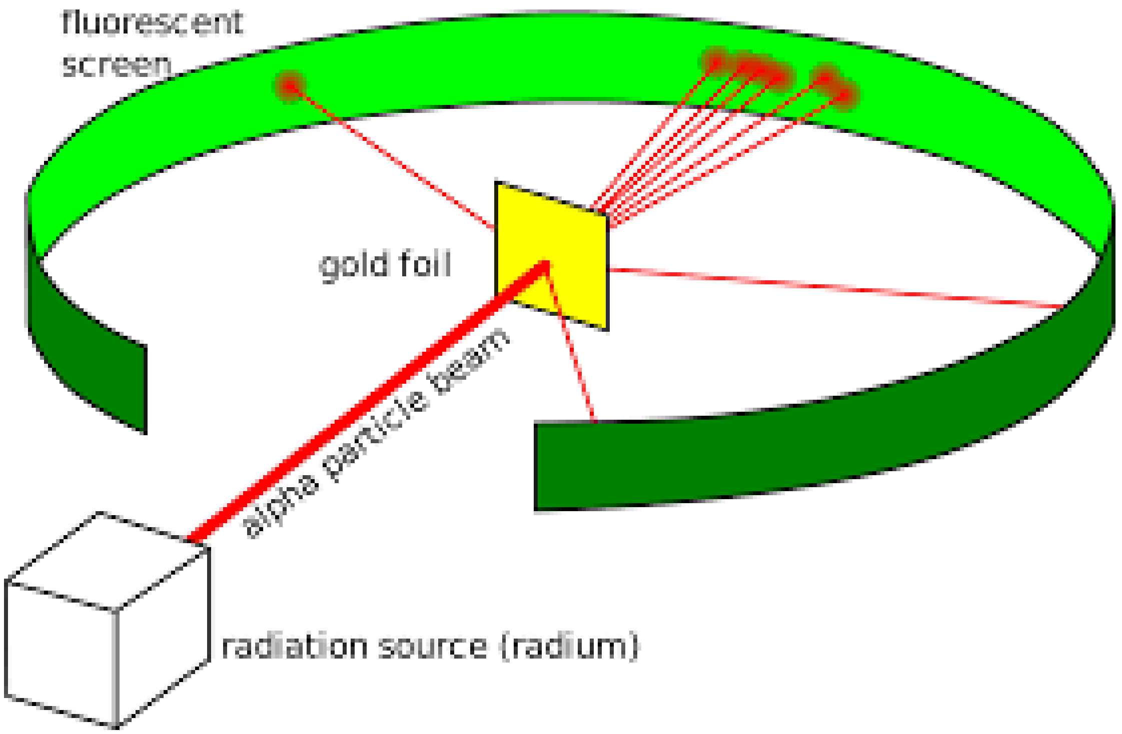
$$\frac{e}{m} = -1.76 \times 10^{8} \text{ Coulomb per gram}$$

- Millikan's oil drop experiment (1910):
  $e = -1.60 \times 10^{-19}$ Coulomb

1923

Discovery of the nucleus

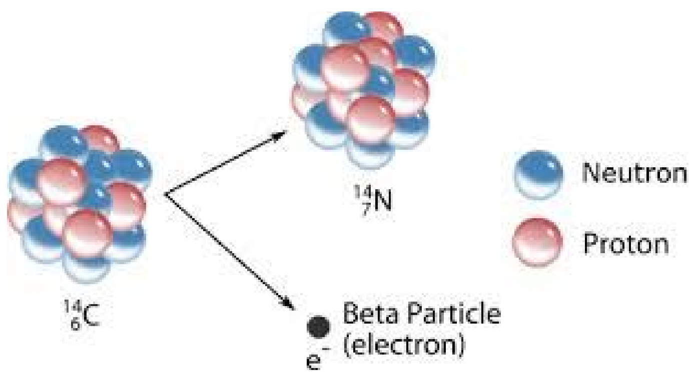
- Rutherford experiment (1911)

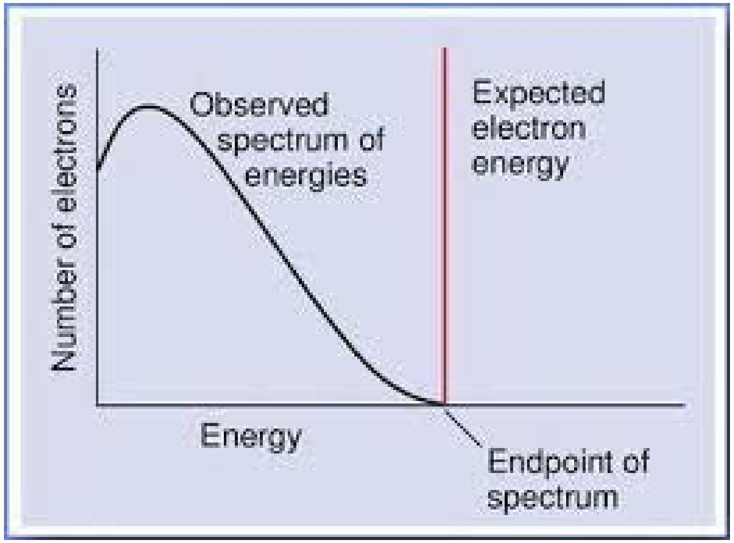


1908

Hypothesis of the neutrino

- Nuclear beta decay:



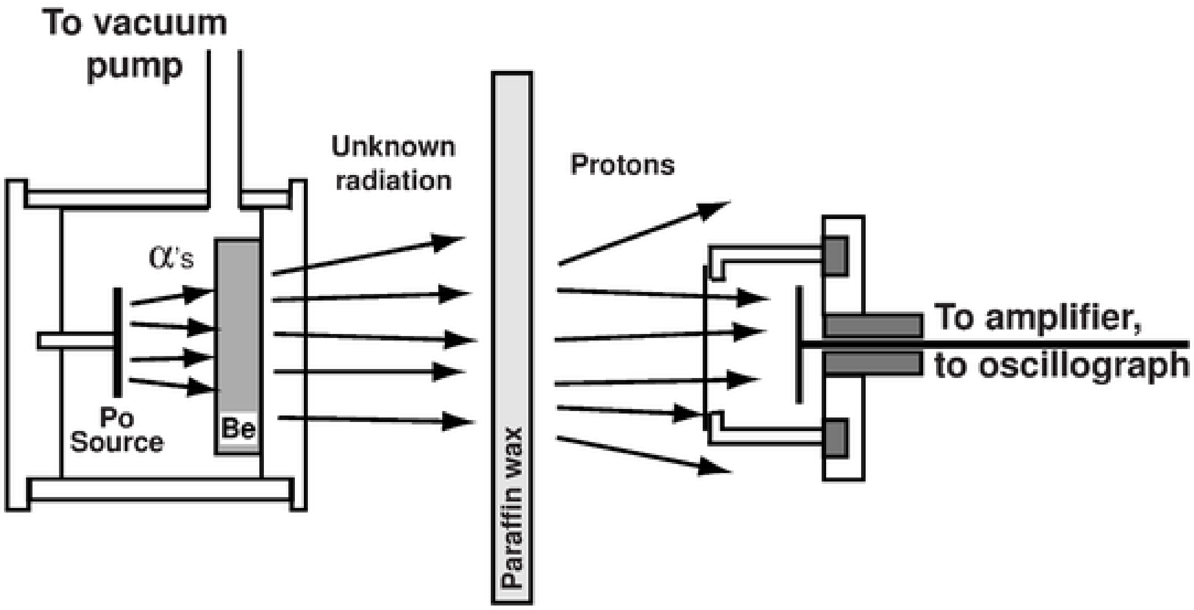


- Pauli hypothesis: 1930

  (Does not count as discovery)

Discovery of the neutron

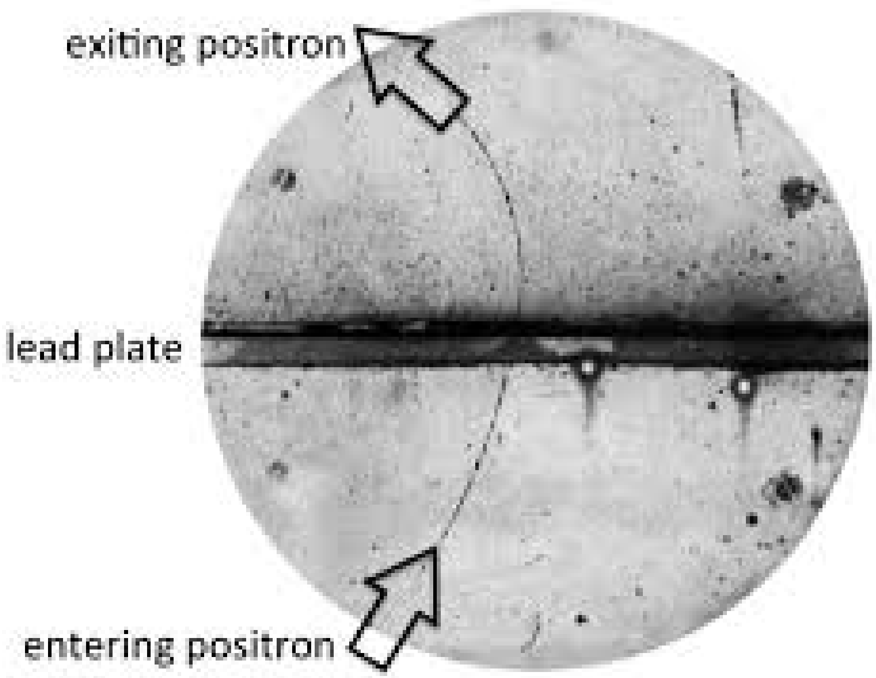
- Chadwick (1932)



1935

The first antiparticle: positron

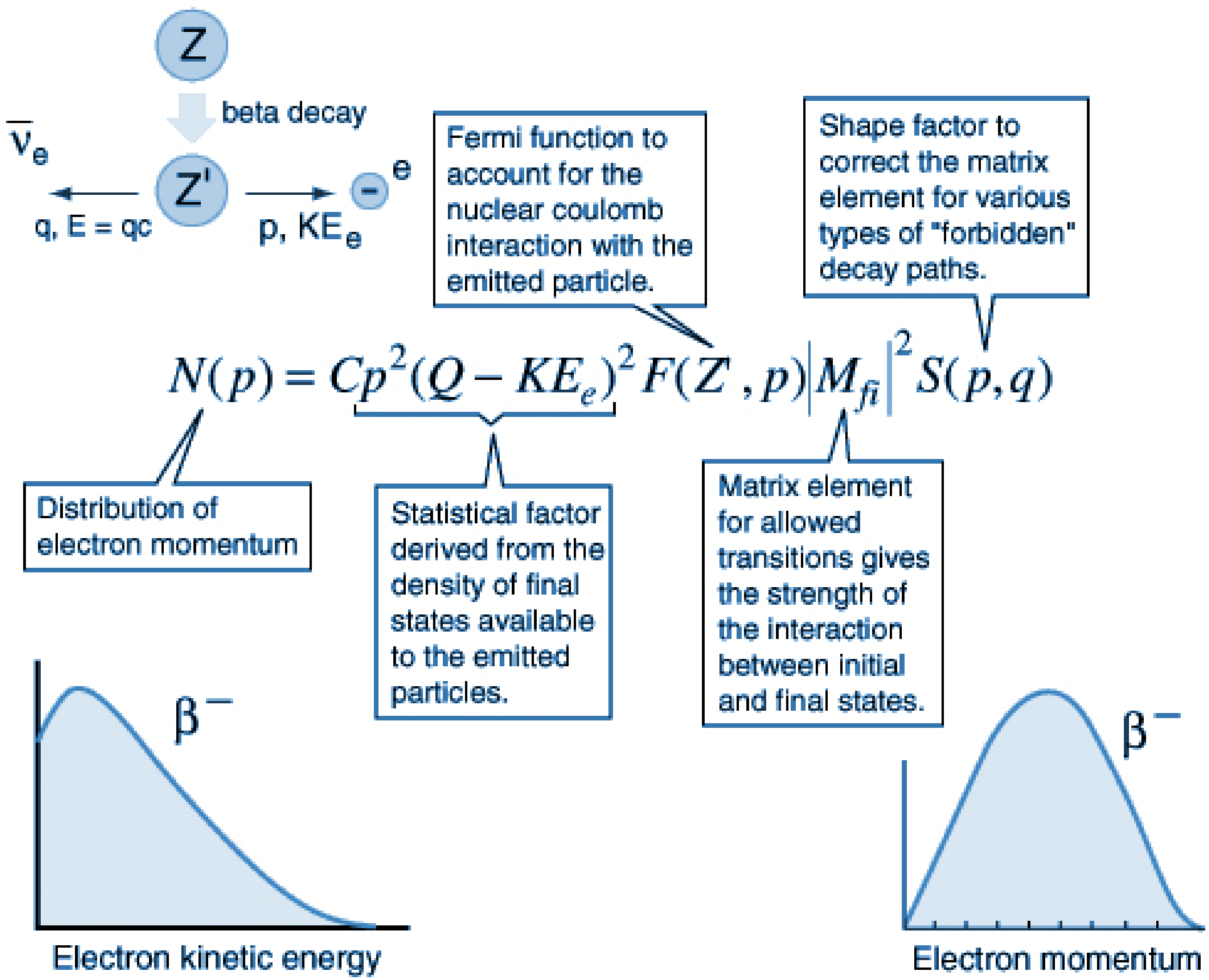
- Anderson (1932)



Cloud chamber

1936

Fermi theory of beta decay (1933)



Particles in 1935

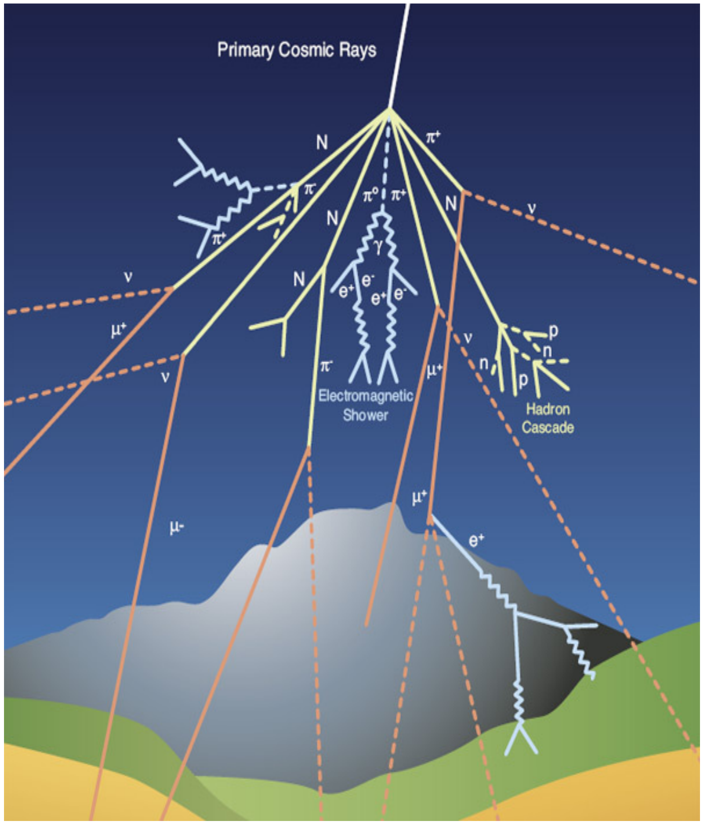
- Electron - positron
- Proton
- Neutron
- Nuclei

Who ordered the muon ?

- Yukawa: meson hypothesis for short-range force carriers

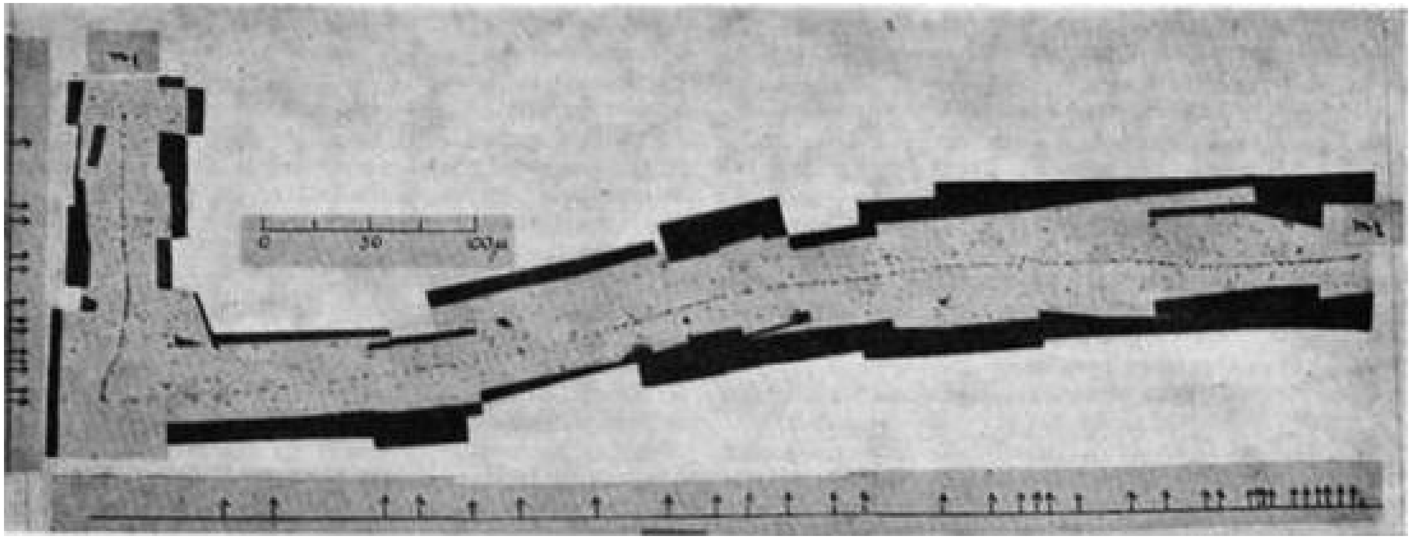
- Muon: highly penetrating cosmic rays. When discovered (Anderson, Neddermeyer, 1936), thought of as "mu meson"

- Bhabha: ``heavy electron''



Pion: the first meson

- Cecil Powell (1946)

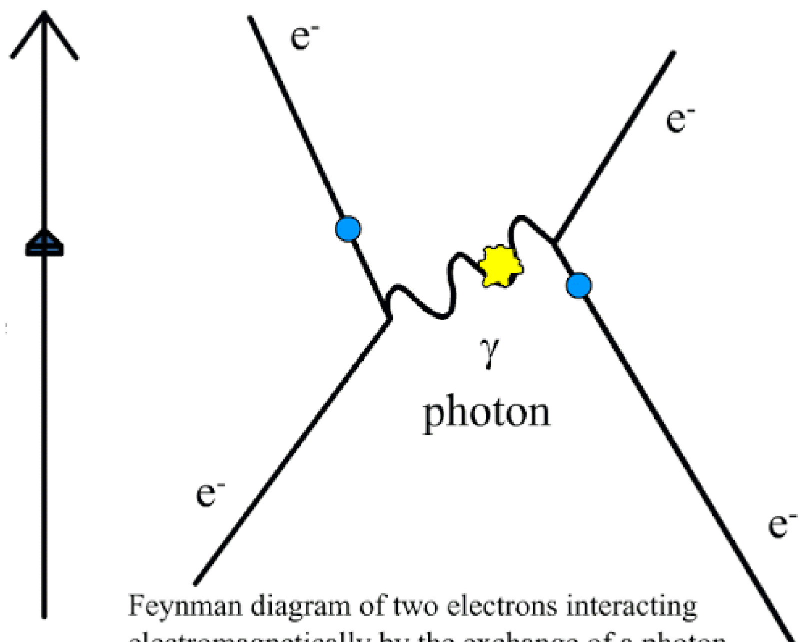


- Tracks in nuclear emulsion

1950

Quantum theory of electromagnetism

- Feynman, Schwinger, Tomonaga (~ 1950)
- Charged particles interact via exchange of photons (QED)

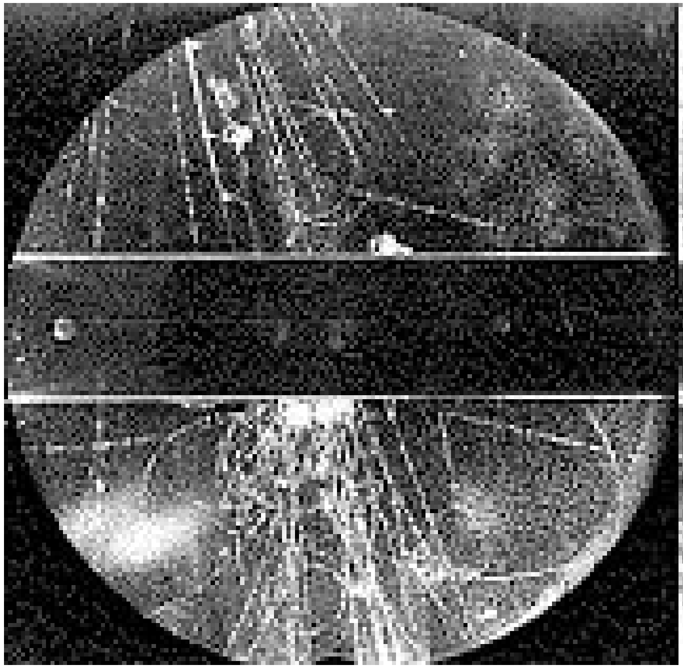


Feynman diagram of two electrons interacting electromagnetically by the exchange of a photon.

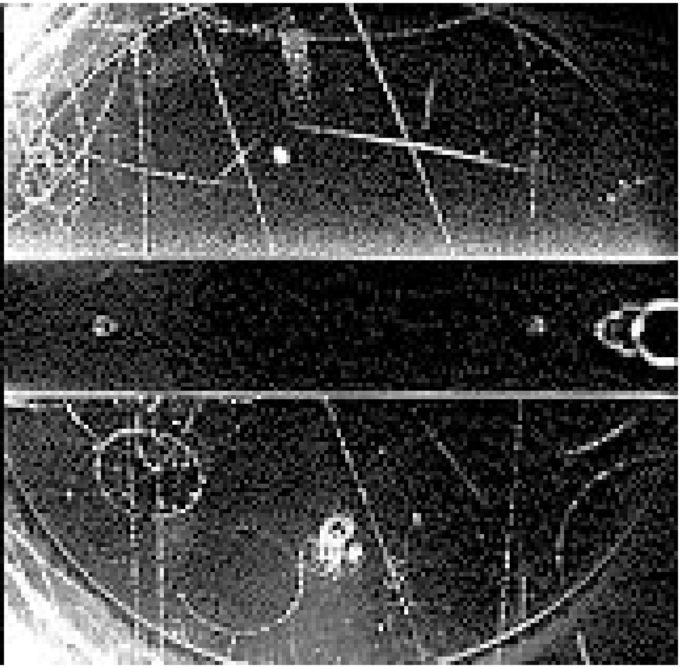
1965

The strange particles

- In cosmic rays: Butler and Rochester (1947)
- In lab: Brookhaven, 1952-53



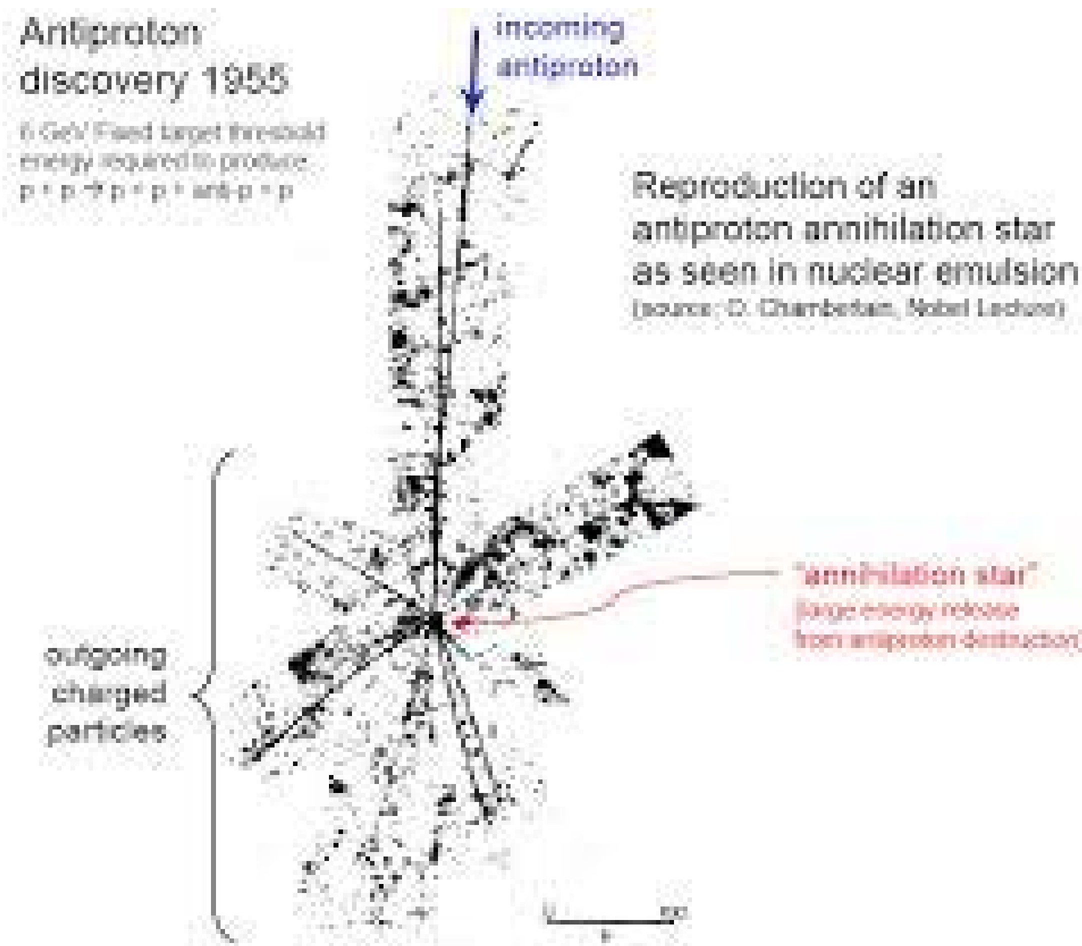
$K^0 \rightarrow \pi^+\pi^-$



$K^+ \rightarrow \mu^+ \nu_\mu$

Antimatter

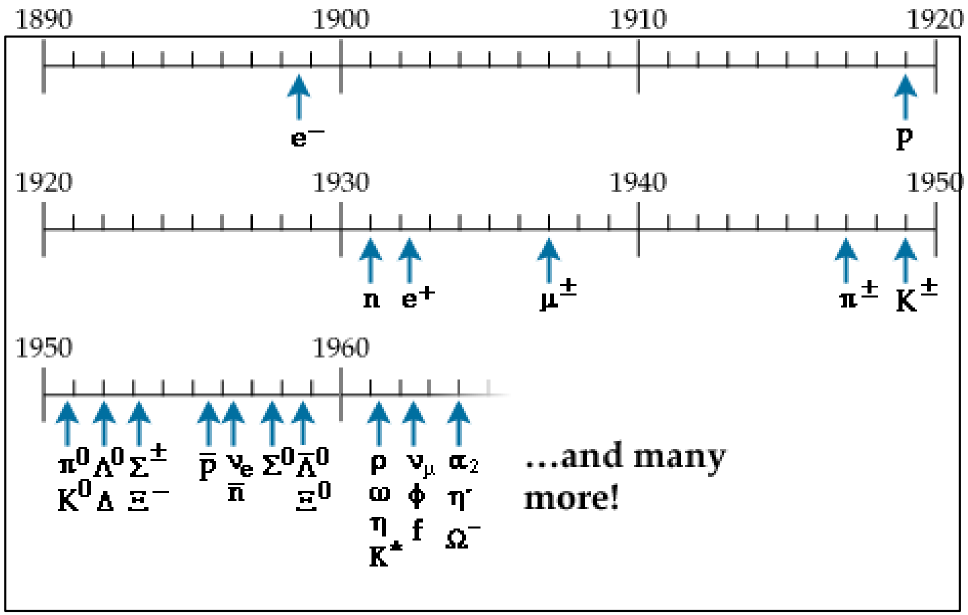
- Antiproton: Chamberlain and Segre (1955)



1959

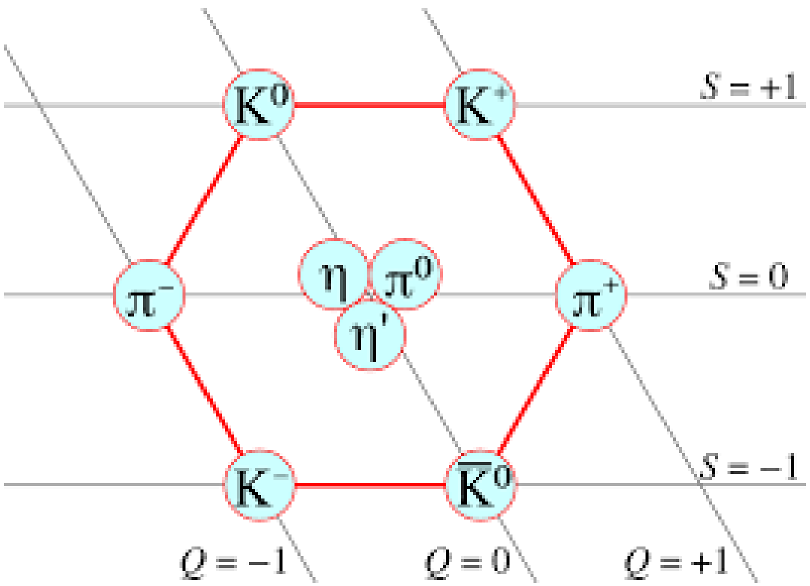
The particle zoo

1960-70 : Tens of new particles discovered !

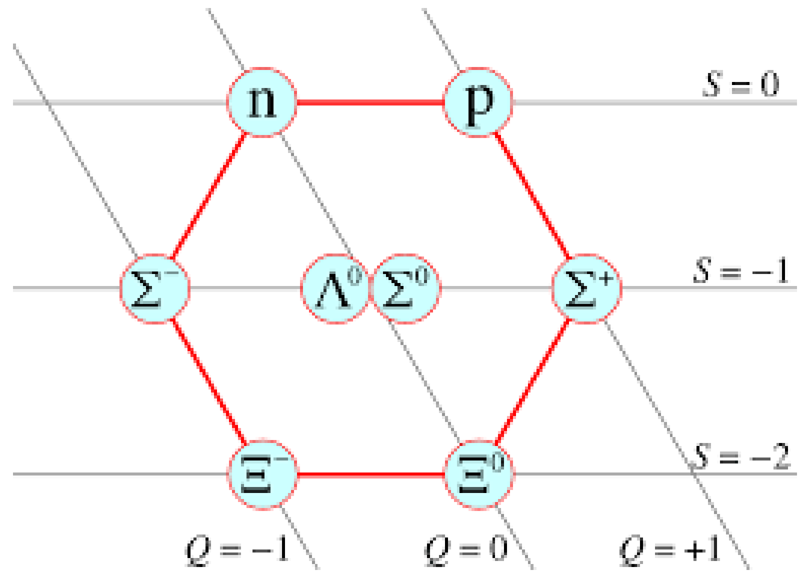


All these particles can be explained by combinations of more fundamental 'quarks', u, d, s and their anti-quarks.

The eight-fold way

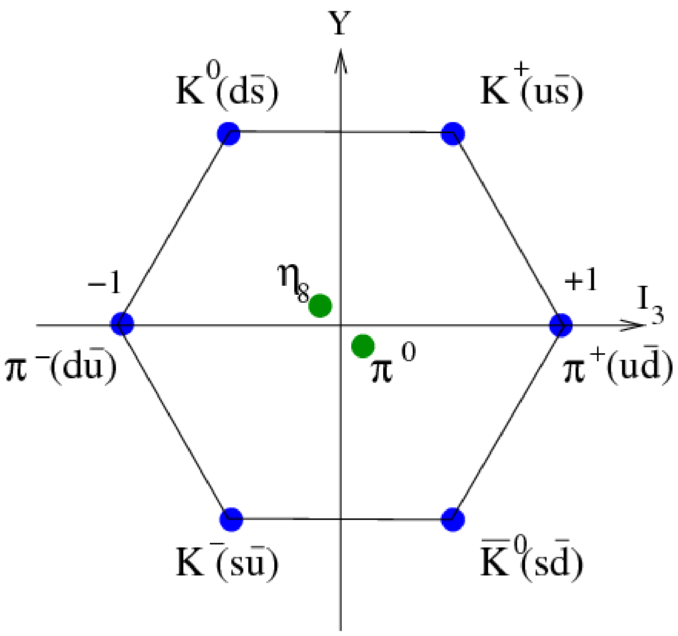


Meson octet
(+1)

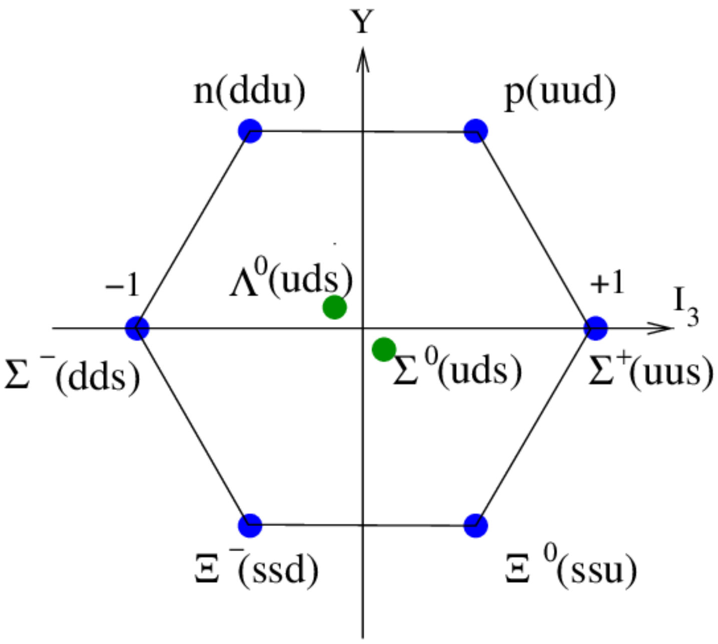


Baryon octet

Octets in terms of quarks

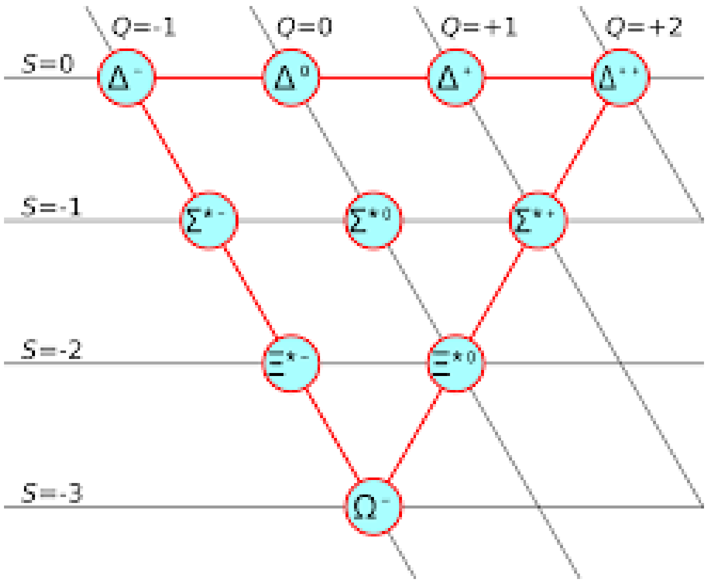


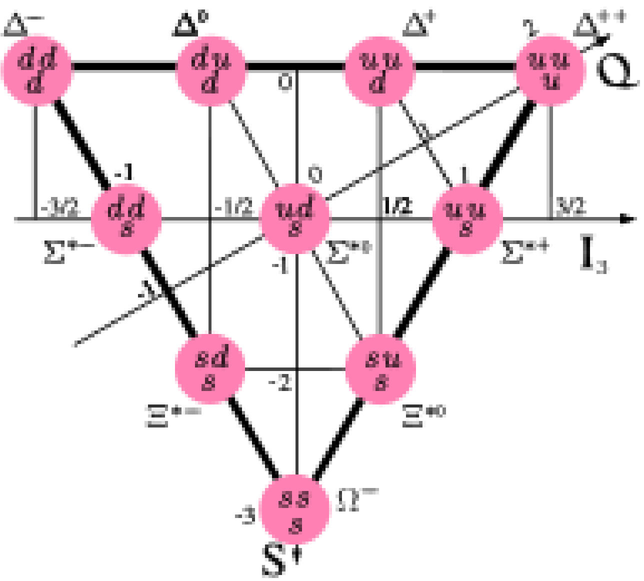
Meson octet



Baryon octet

The need for three colours





Baryon decuplet

Δ^{++} : uuu

Δ^{-} : ddd

Ω^{-} : sss

Pauli exclusion ??

Antisymmetry in "colour":

uuu

ddd

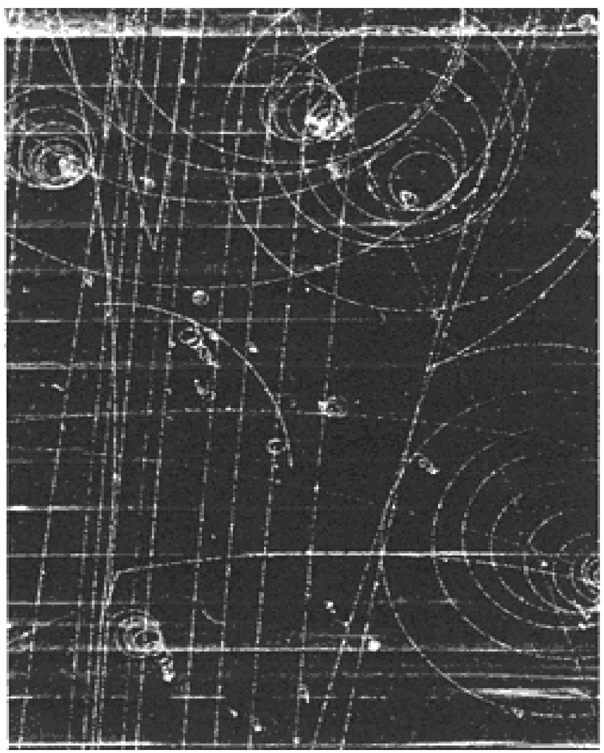
sss

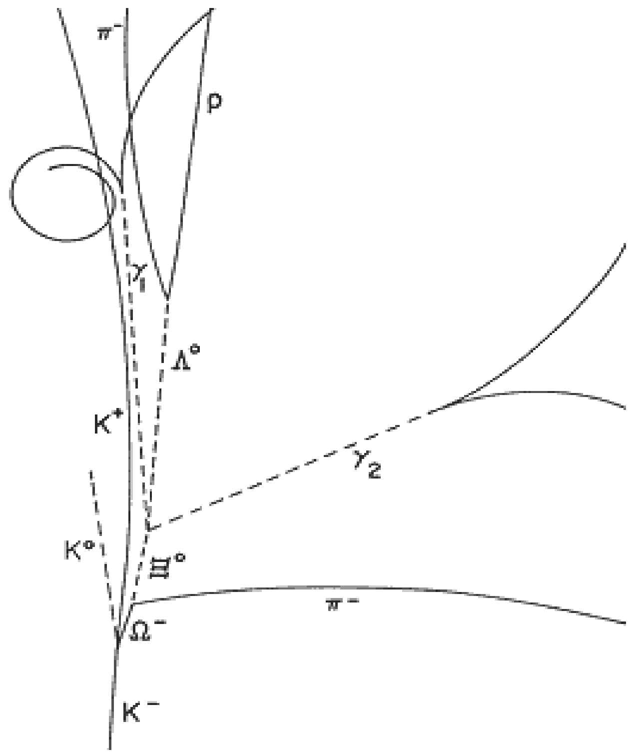
Gell-Mann

1969

Prediction of decuplet: $\Omega^- \equiv sss$

- Ω^- discovered : Brookhaven (1964)





$$K^- p \to \Omega^- K^+ K^0$$

$$\Omega^- \to \Xi^0 \pi^-$$

$$\Xi^0 \to \Lambda^0 \, \pi^0$$

$$\pi^0 \to \gamma\gamma$$

$$\gamma \to e^+ e^-$$

$$\Lambda^0 \to p \, \pi^-$$

Strong and electroweak interactions

- Theory of strong interactions: QCD
- Quarks interact via interchange of gluons

- Parity violation: prediction (1956)

  Observation (1957)

1957

- Charge-parity violation (1964)

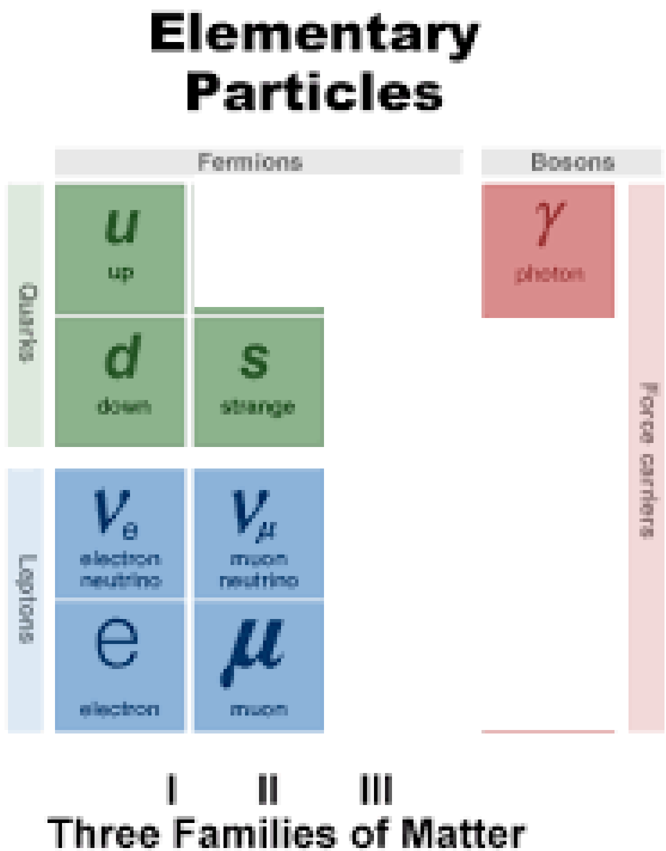
1980

- Theory of electroweak interactions

  (Glashow-Salam-Weinberg)

1979

Particles in 1970



- Force carriers of strong and weak nuclear force just theoretically postulated, not experimentally observed

Prediction and discovery of charm

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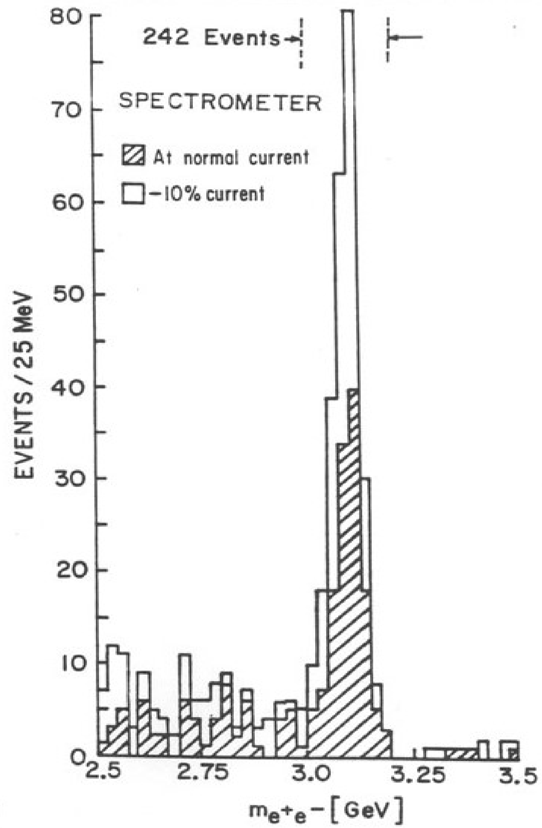


FIG. 2. Mass spectrum showing the existence of J. sults from two spectrometer settings are plotted owing that the peak is independent of spectrometer rrents. The run at reduced current was taken two nths later than the normal run.

- To explain decays of K mesons, Glashow-Iliopoulos-Maiani (GIM) proposed the existence of a fourth ``charmed'' quark (1970)
- Discovery by Richter and Ting independently (1974)

$$e^+e^- \to J/\psi \equiv c\,\bar{c}$$

Peak at $E_{CM} = 2\,m_c$

1976

Prediction of third generation

- Kobayashi and Maskawa: In order to explain the charge-parity violation, a simple solution is to have a third generation of quarks (1972)

- This simple solution explains hundreds of different observations !

2008

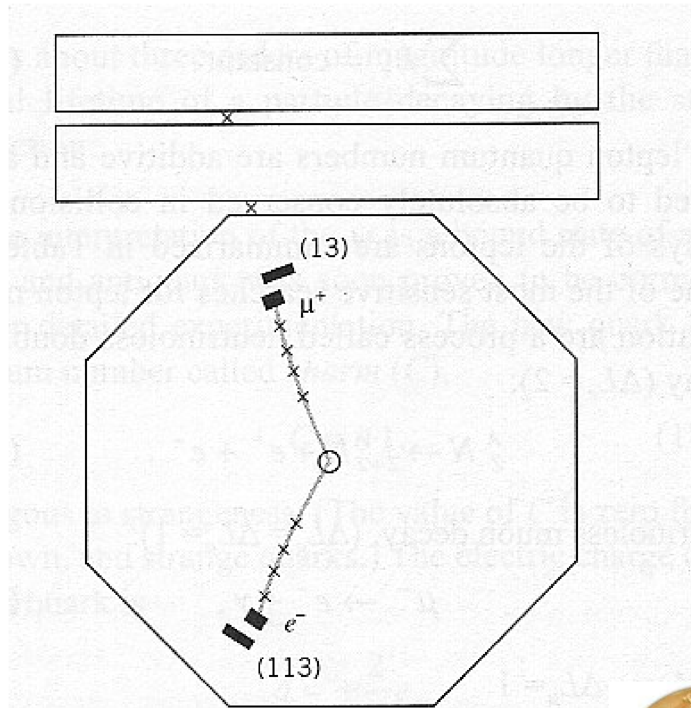
The first 3G particle: tau lepton

- Martin Perl 1975

$$e^+ \; e^- \rightarrow \tau^+ \; \tau^-$$

$$\tau^- \rightarrow e^- \; \overline{\nu}_e \; \nu_\tau$$

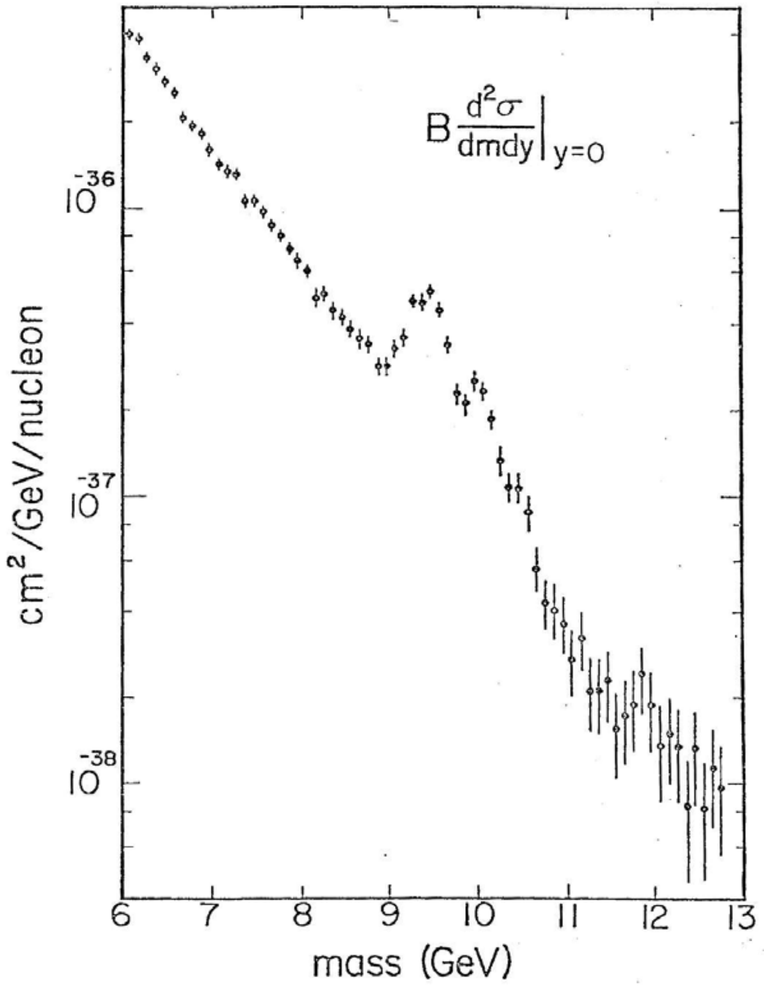
$$\tau^+ \rightarrow \mu^+ \; \nu_\mu \; \overline{\nu}_\tau$$



1995

The first 3G quark: bottom / beauty

- Lederman 1978
- $e^+e^- \to \Upsilon \equiv b\,\bar{b}$
- Peak at $E_{CM} = 2\,m_b$



Strong force carrier: gluon

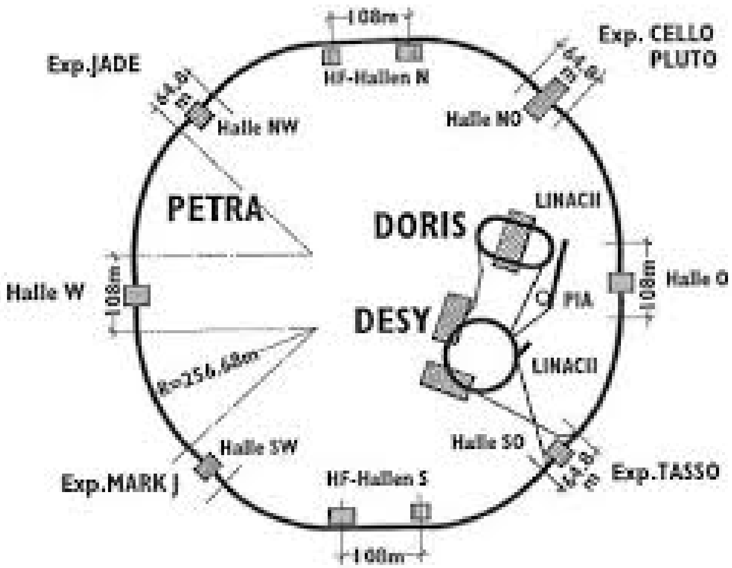
Located at DESY

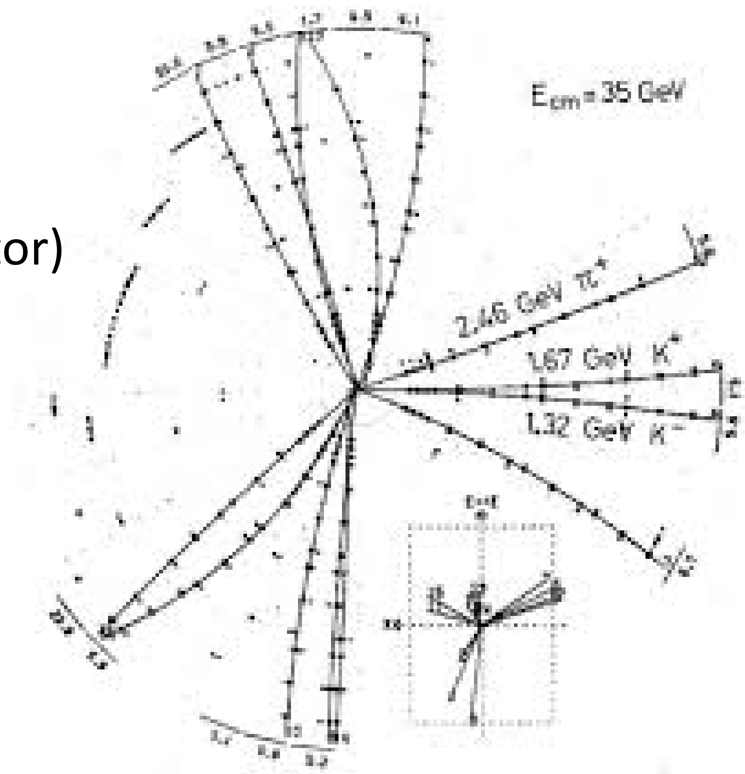
PETRA accelerator ring

(Positron-Electron Tandom Ring Accelerator)

TASSO experiment

(Two-Arm Spectrometer SOlenoid)

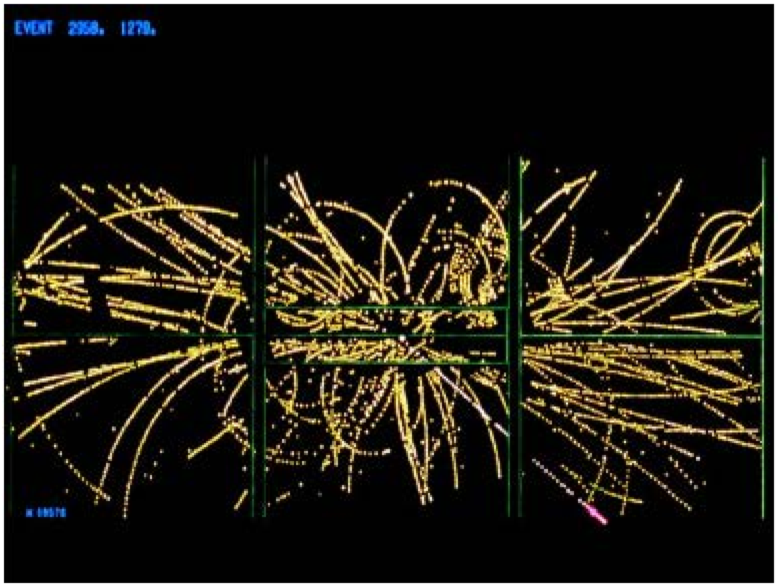




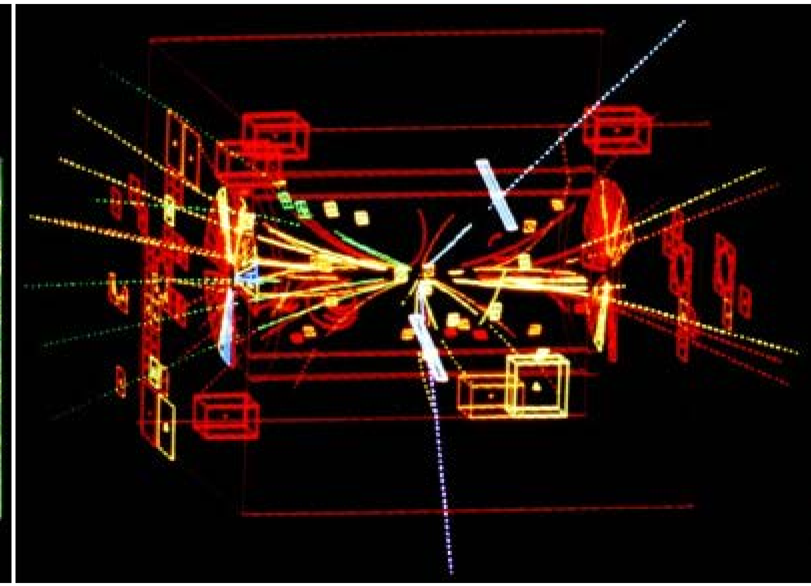
$$e^+ e^- \rightarrow q\,\bar{q}\,g$$

Three-jet event, 1979

Weak force carriers: W and Z bosons



$W \to \mu\nu$

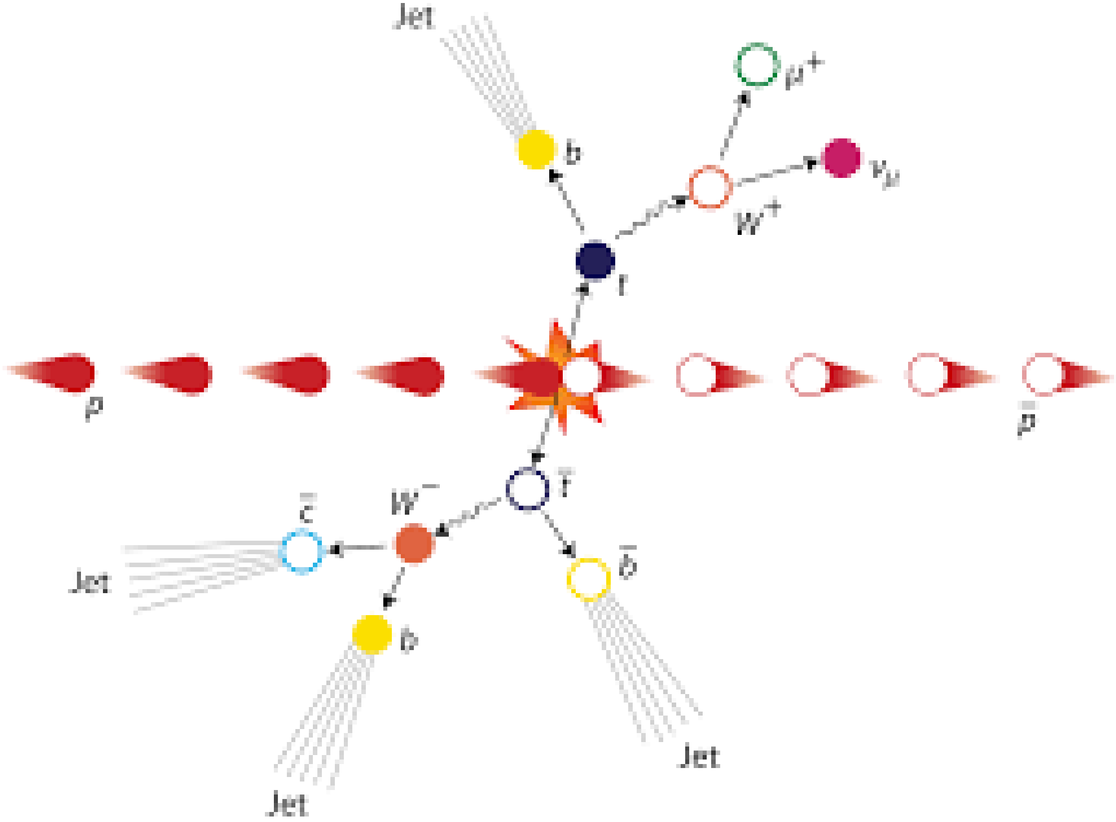


$Z \to \mu^+\mu^-$

- Rubbia, van der Meer (1983)

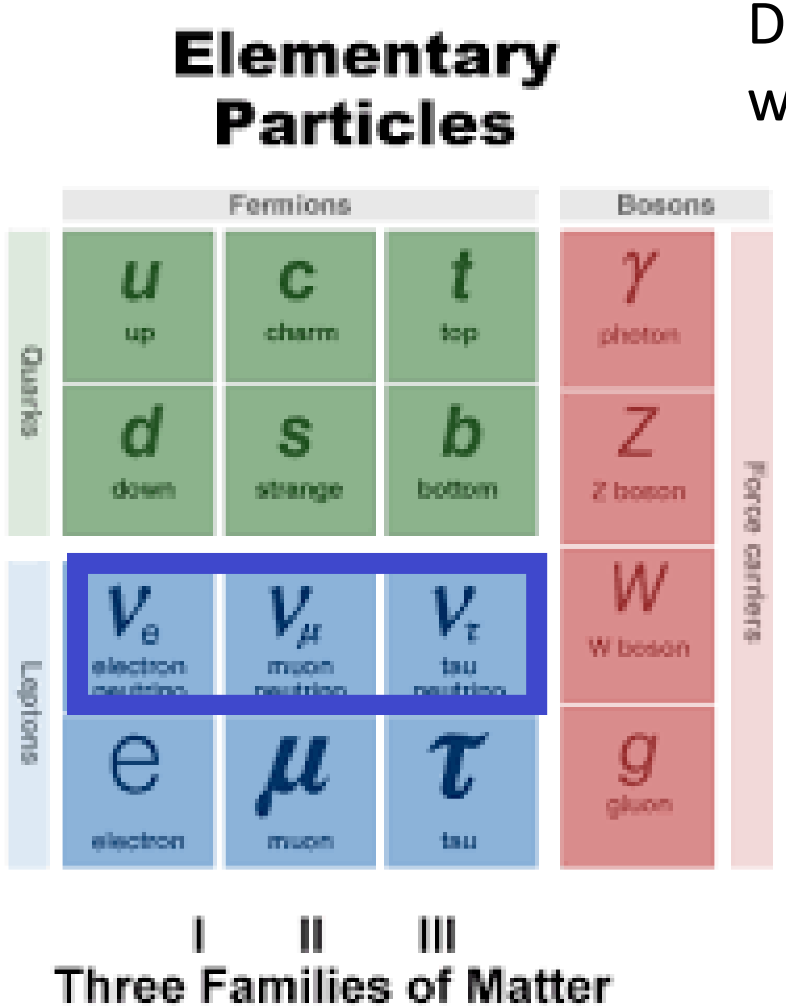
1984

Sixth quark: top

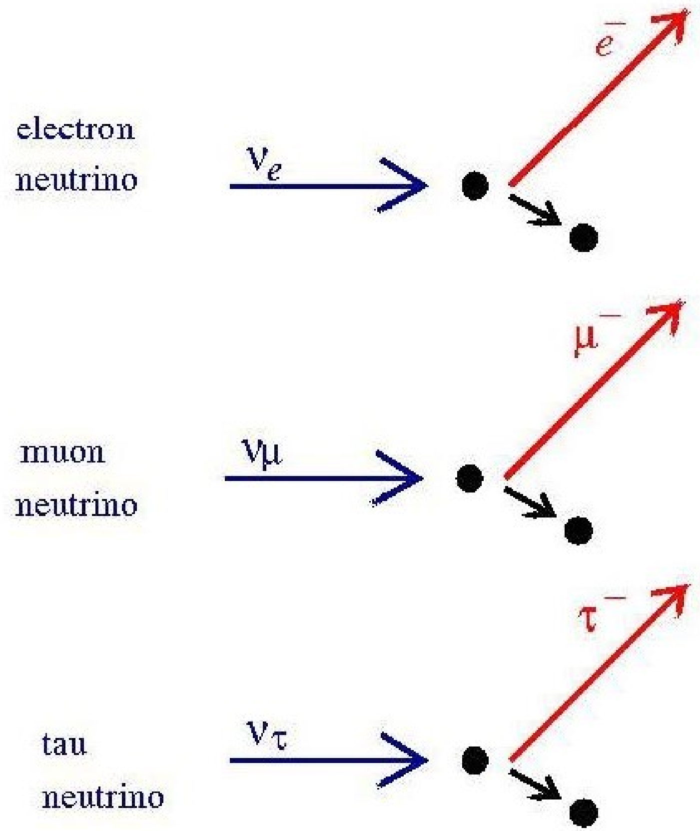


- Fermilab (1995)

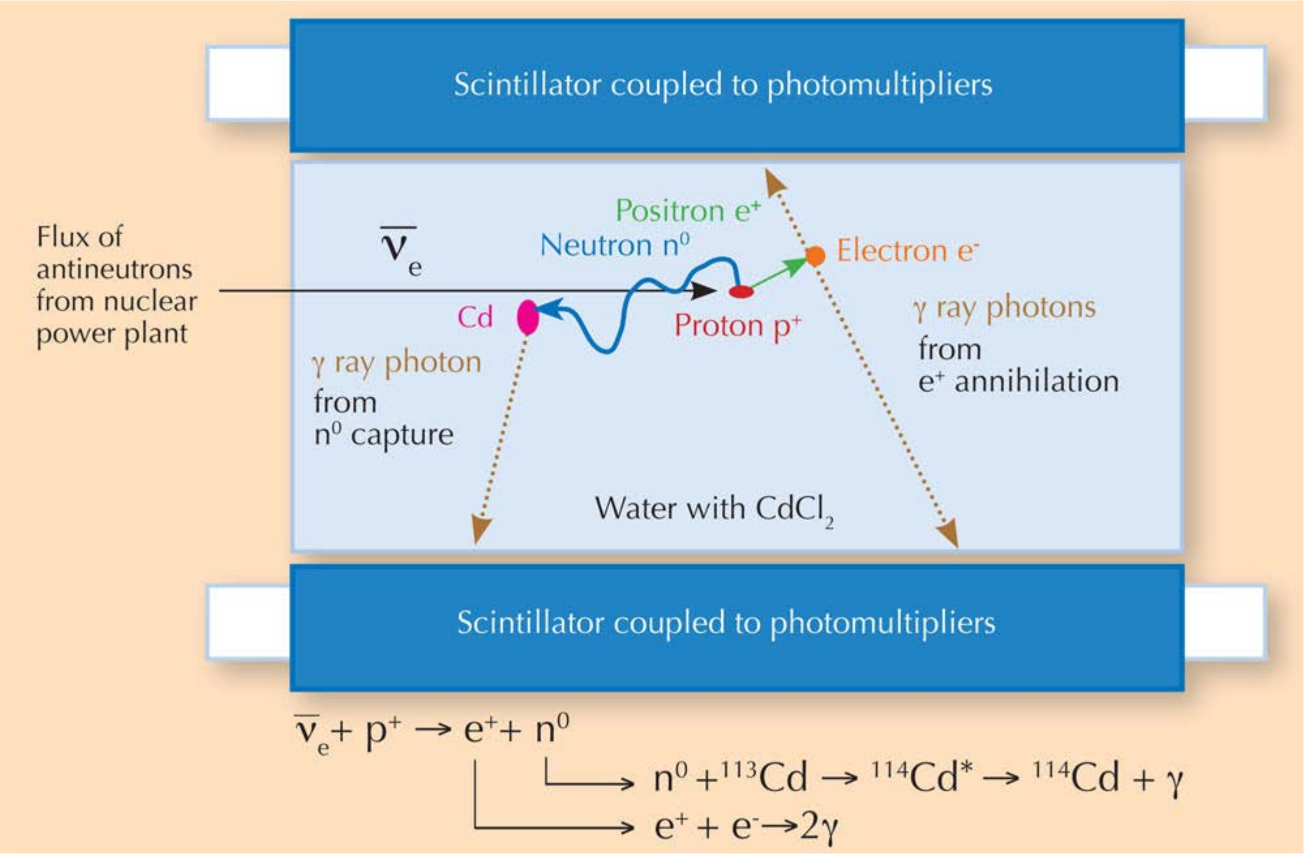
The three neutrinos



Difficult to detect because only weak interactions

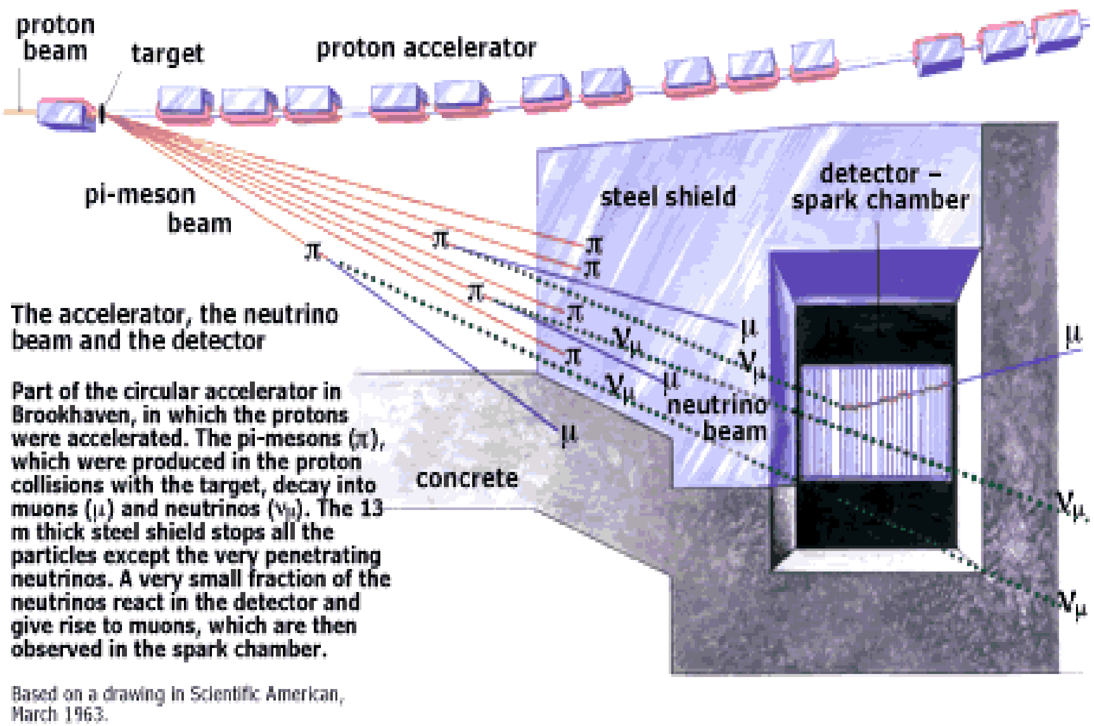


Electron neutrino



1995

Muon neutrino



$$\pi^+ \rightarrow \mu^+ \ \nu$$

$$\nu + n \rightarrow p + e^- \, ??$$

$$\nu + n \rightarrow p + \mu^-$$

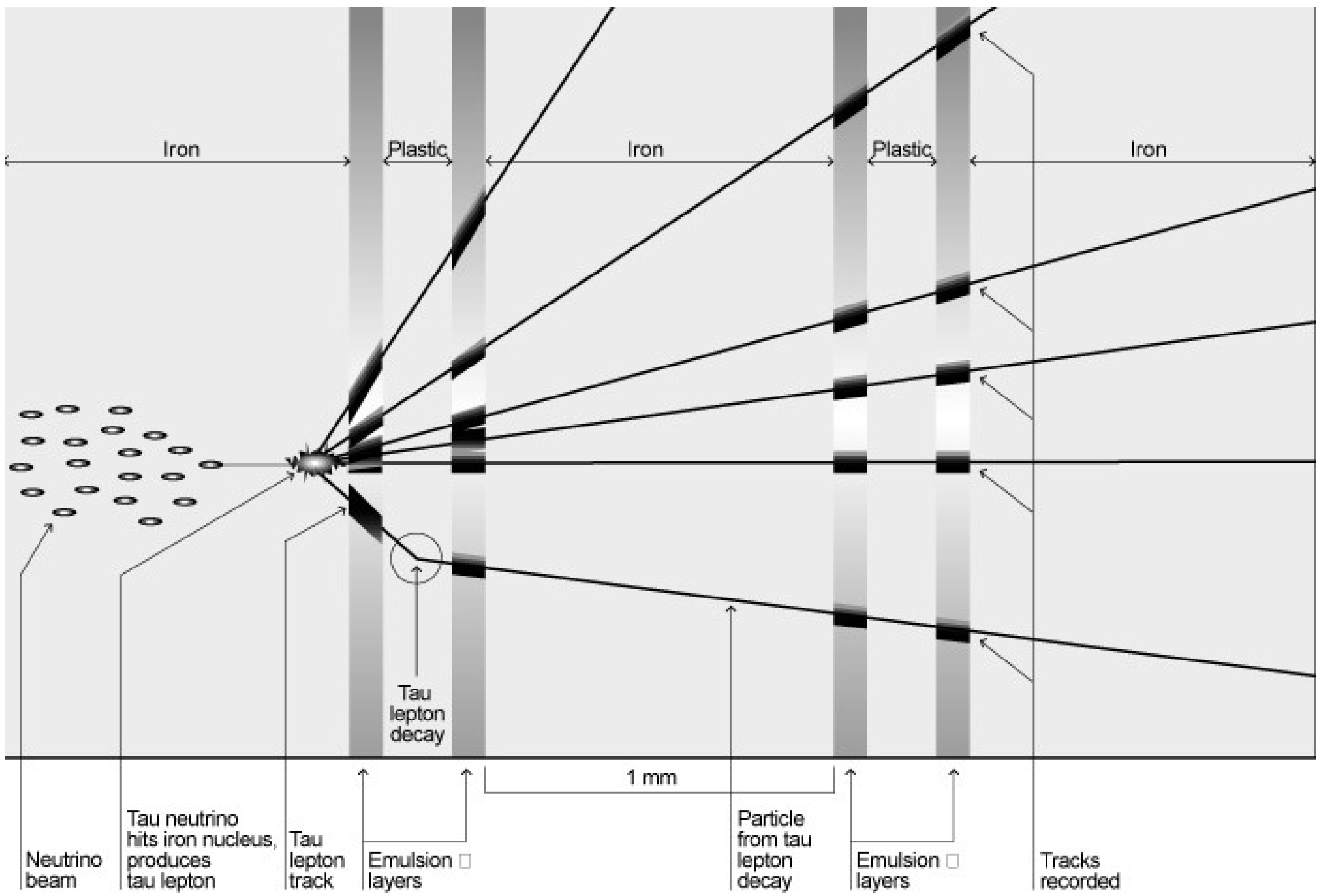
$$\therefore \quad \nu \ \equiv \ \nu_\mu$$

Lederman, Schwartz, Steinberger (1962)

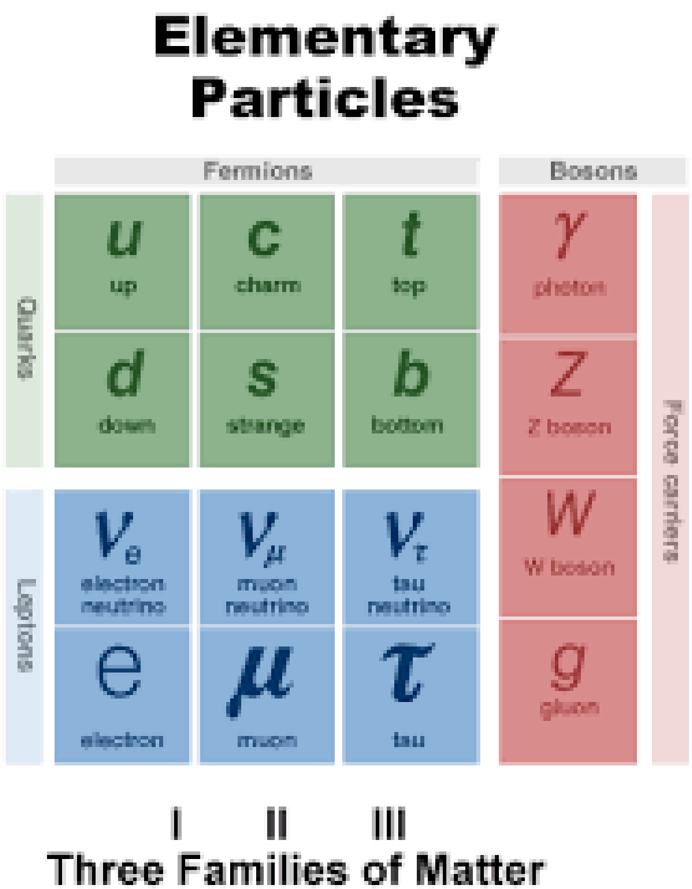
1988

Tau neutrino

- DONUT experiment , Fermilab (2000)

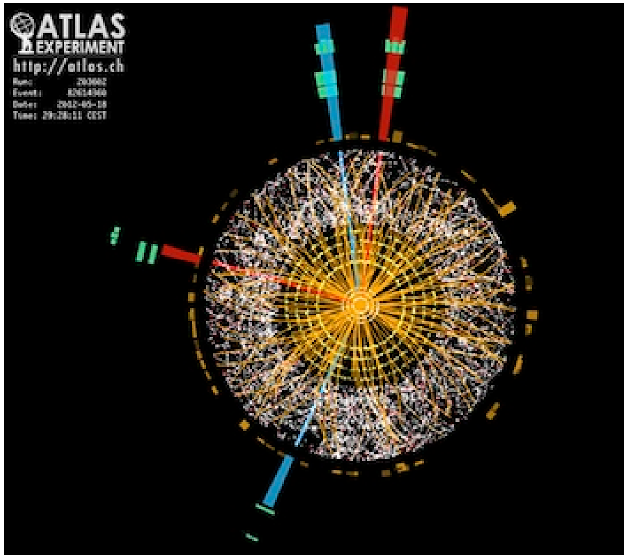


The standard model: complete ?

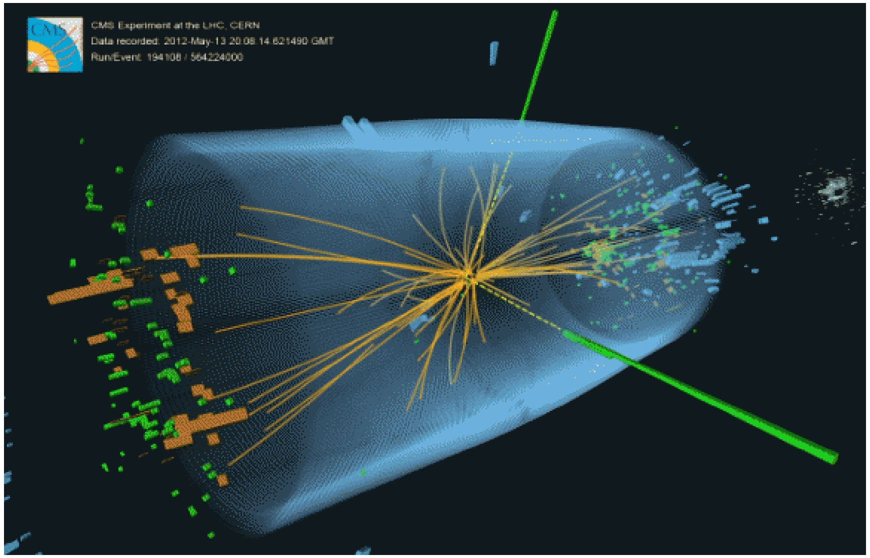


- Higgs boson needed to give masses to
  - W, Z bosons
  - fermions

Higgs boson discovered in 2012



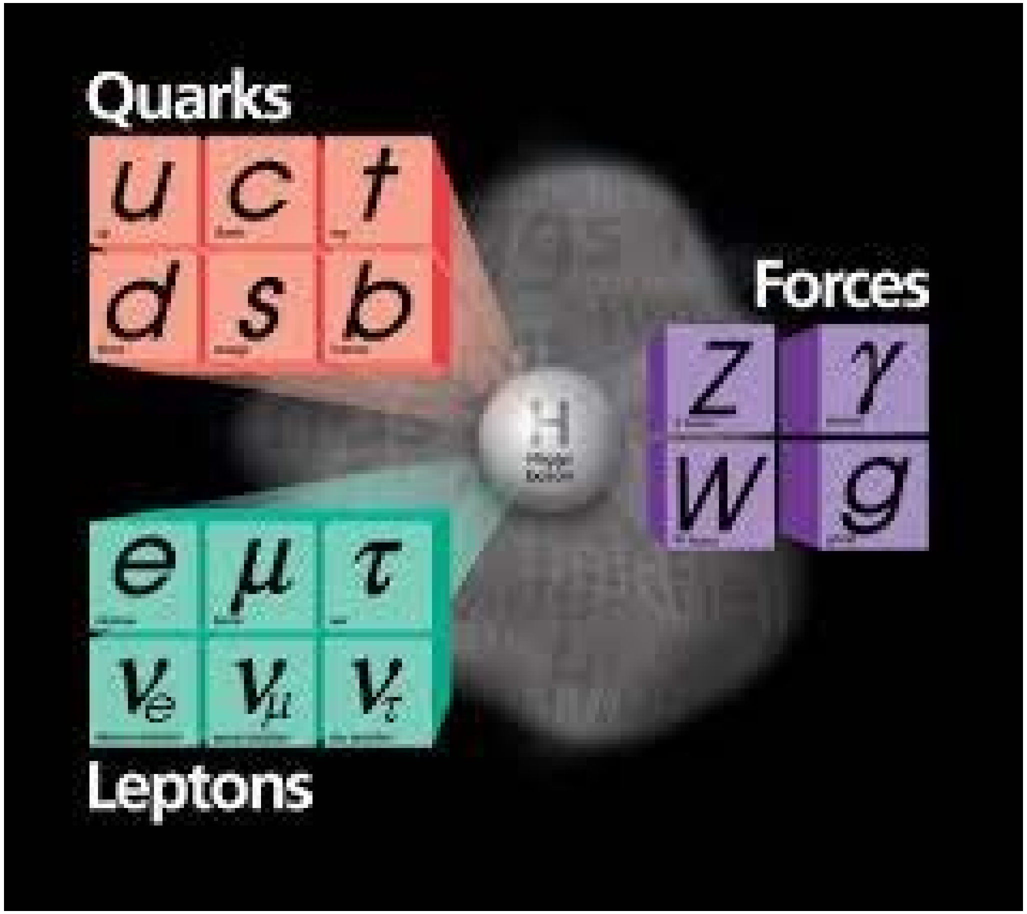
$$H \to Z \ Z^* \to \ell \, \ell \, \ell \, \ell$$



$$H \to \gamma \, \gamma$$

ATLAS and CMS experiments, Large Hadron Collider, CERN

That completes the Standard Model



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