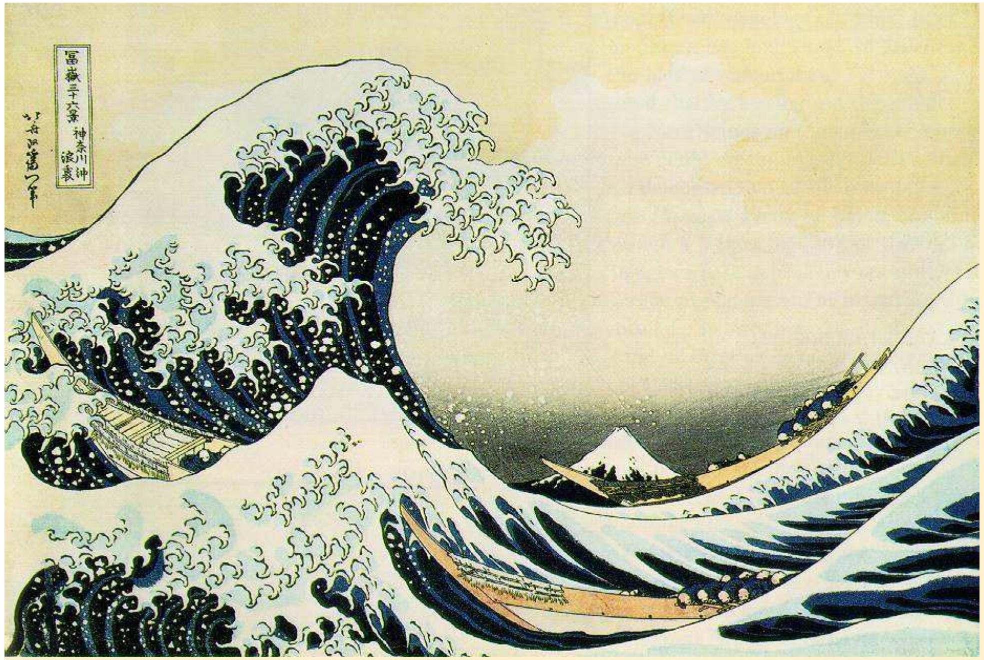
Electroweak interaction

Vanina Ruhlmann-Kleider
CEA-Saclay/Irfu/SPP

1. Basics and history
2. The Standard Model
3. Tests of the Standard Model



Lecture 1

Basics and history

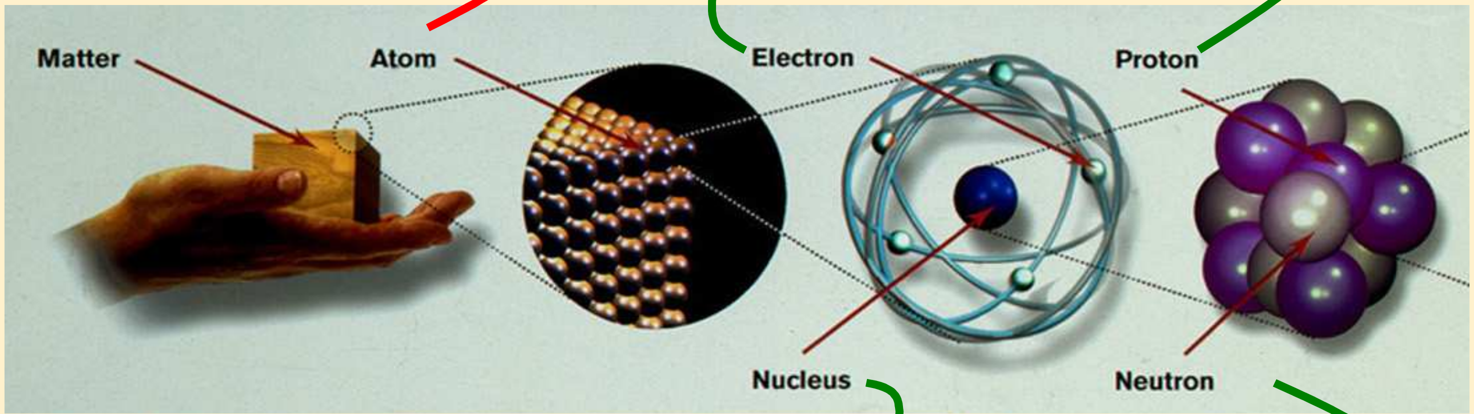
1. History 1: the birth of particle physics
2. Basics: particle features, importance of symmetries
3. History 2: towards the Standard Model of the electroweak interaction

The starting point: atomic structure

1913: N.Bohr,
quantum theory
of atoms

1919, E.Rutherford

1897, J.J.Thomson



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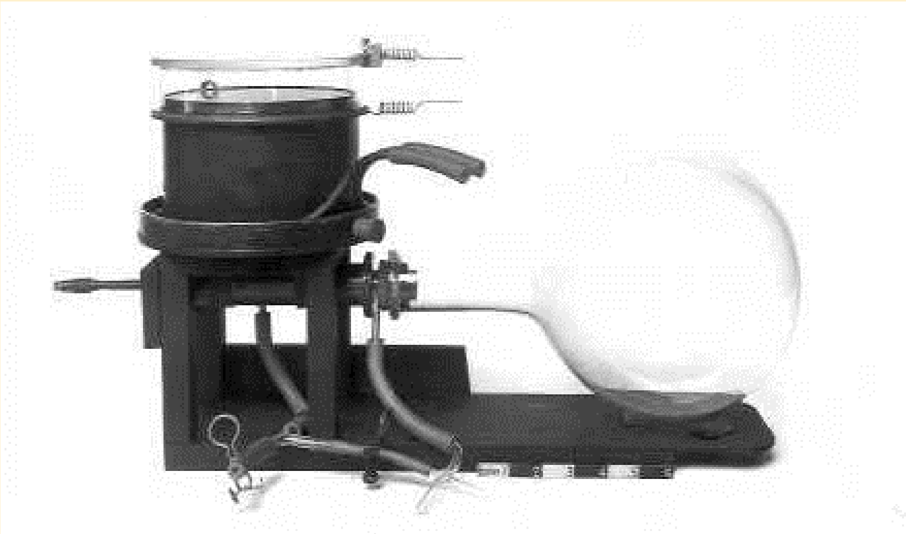
1911, E.Rutherford, H.Geiger & E.Marsden

1932, J.Chadwick

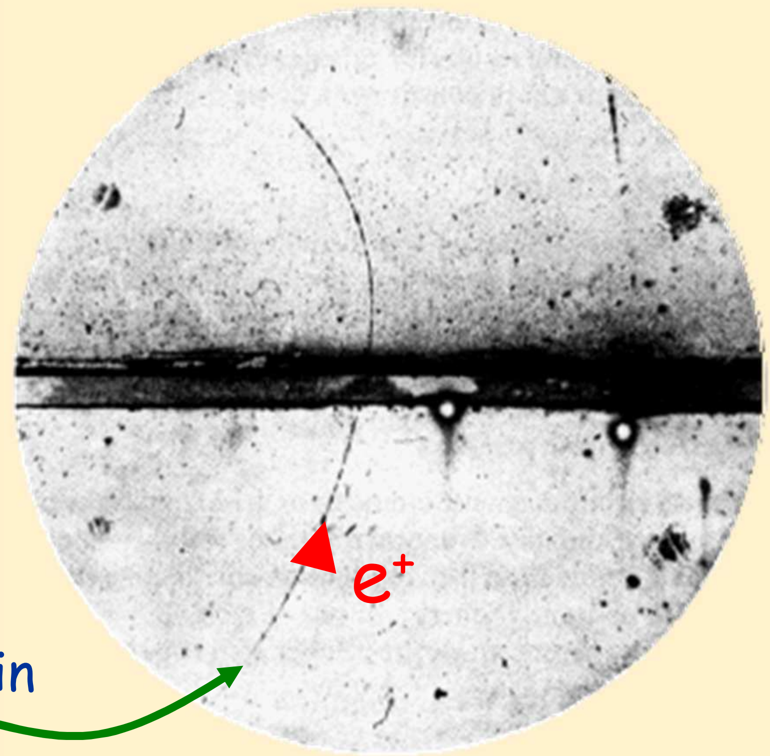
1931, P. Dirac : e^+ is predicted

Antimatter exists !



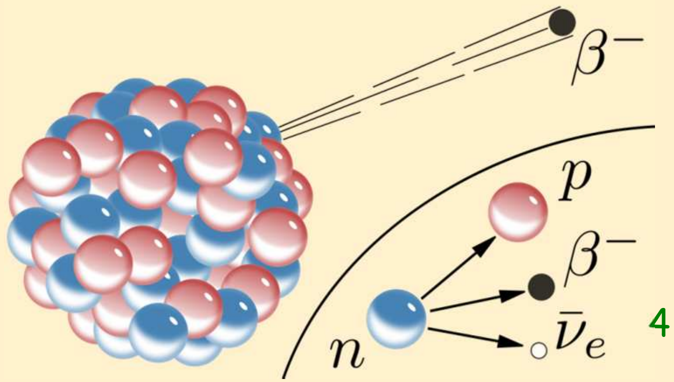
cloud chamber

1932, C. Anderson : positron discovery in cosmic rays



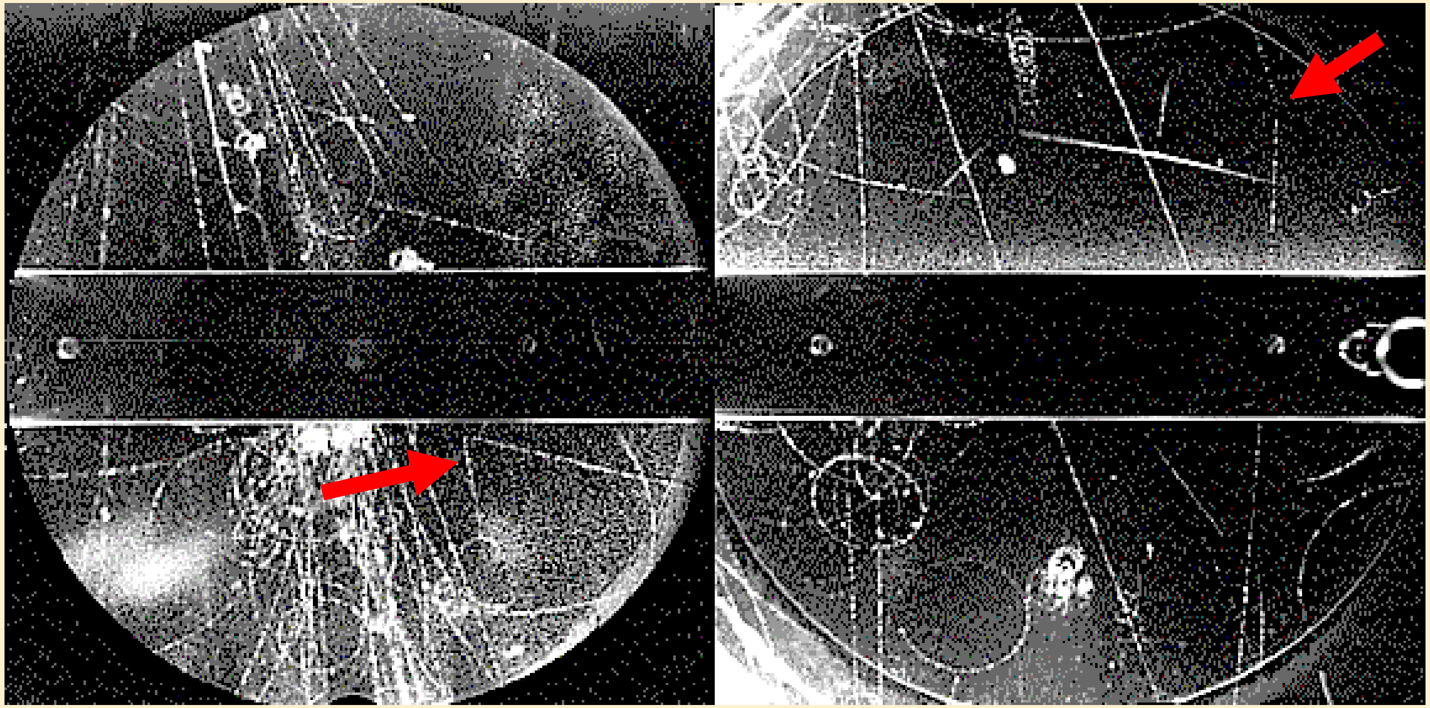
Neutrinos are predicted

1930, W.Pauli : ν is postulated to preserve energy conservation in β decays



Beyond ordinary matter …

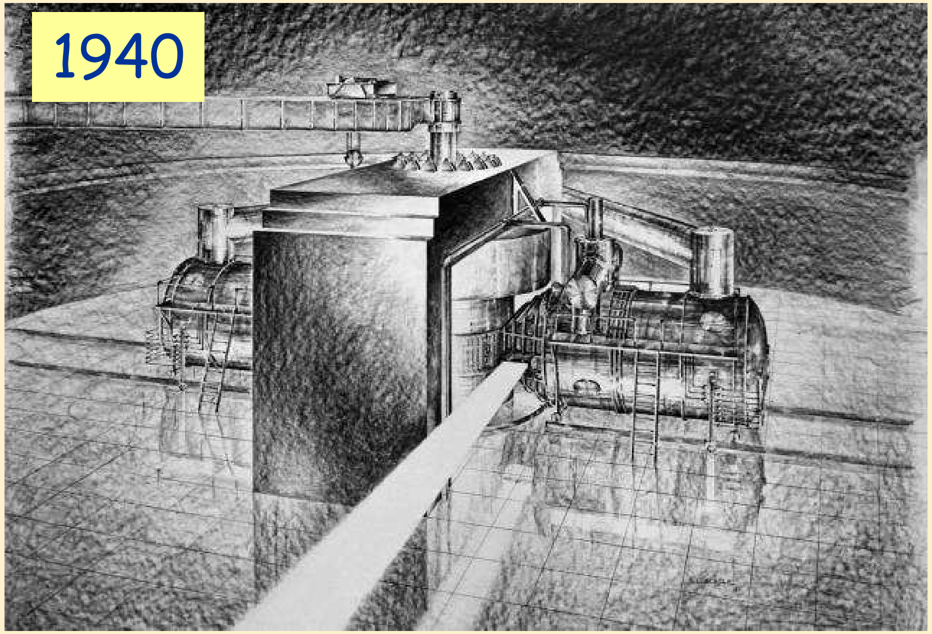
1937, muon discovery (C. Anderson & S. Neddermeyer)
1947, pion discovery (C. Powell)
1947 discovery of neutral and charged kaons (G. Rochester & C. Butler)



$K^0 \rightarrow \pi^+ \pi^-$ $K^\pm \rightarrow \mu^\pm \nu$

Photographs of cloud chamber exposed to cosmic rays

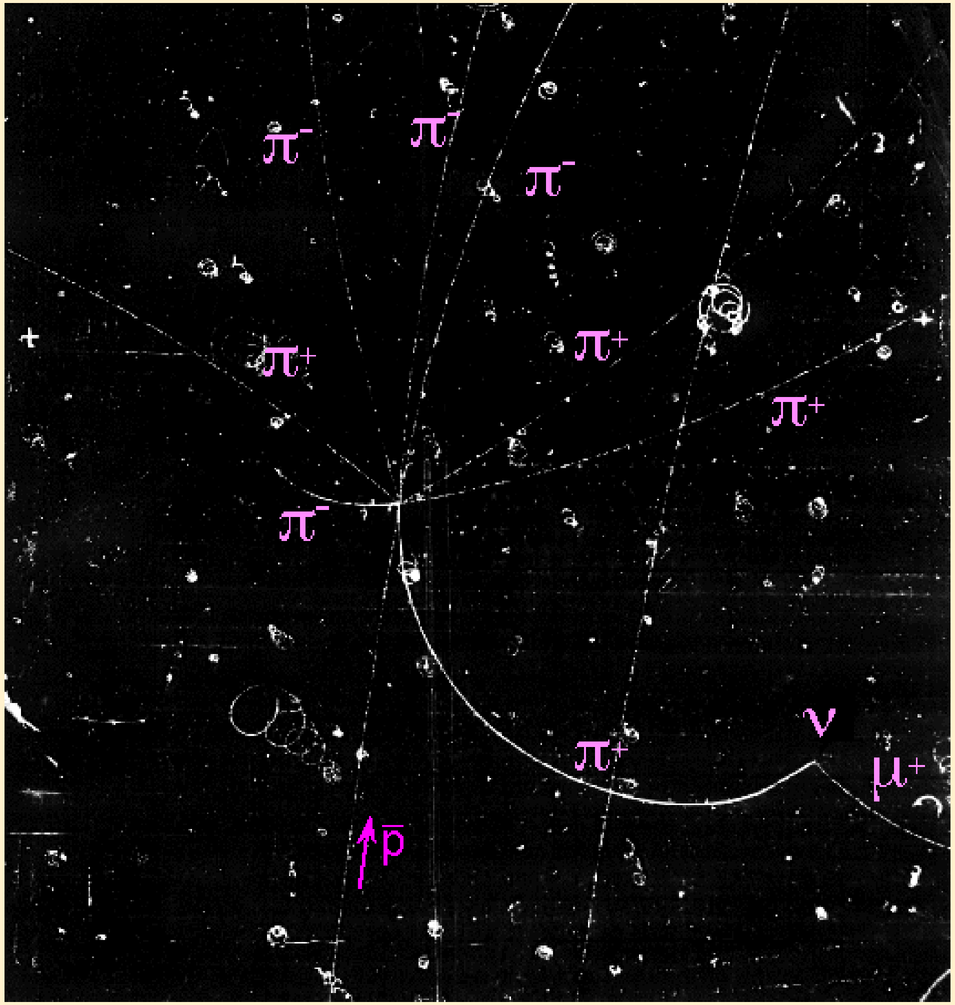
Accelerators come on stage



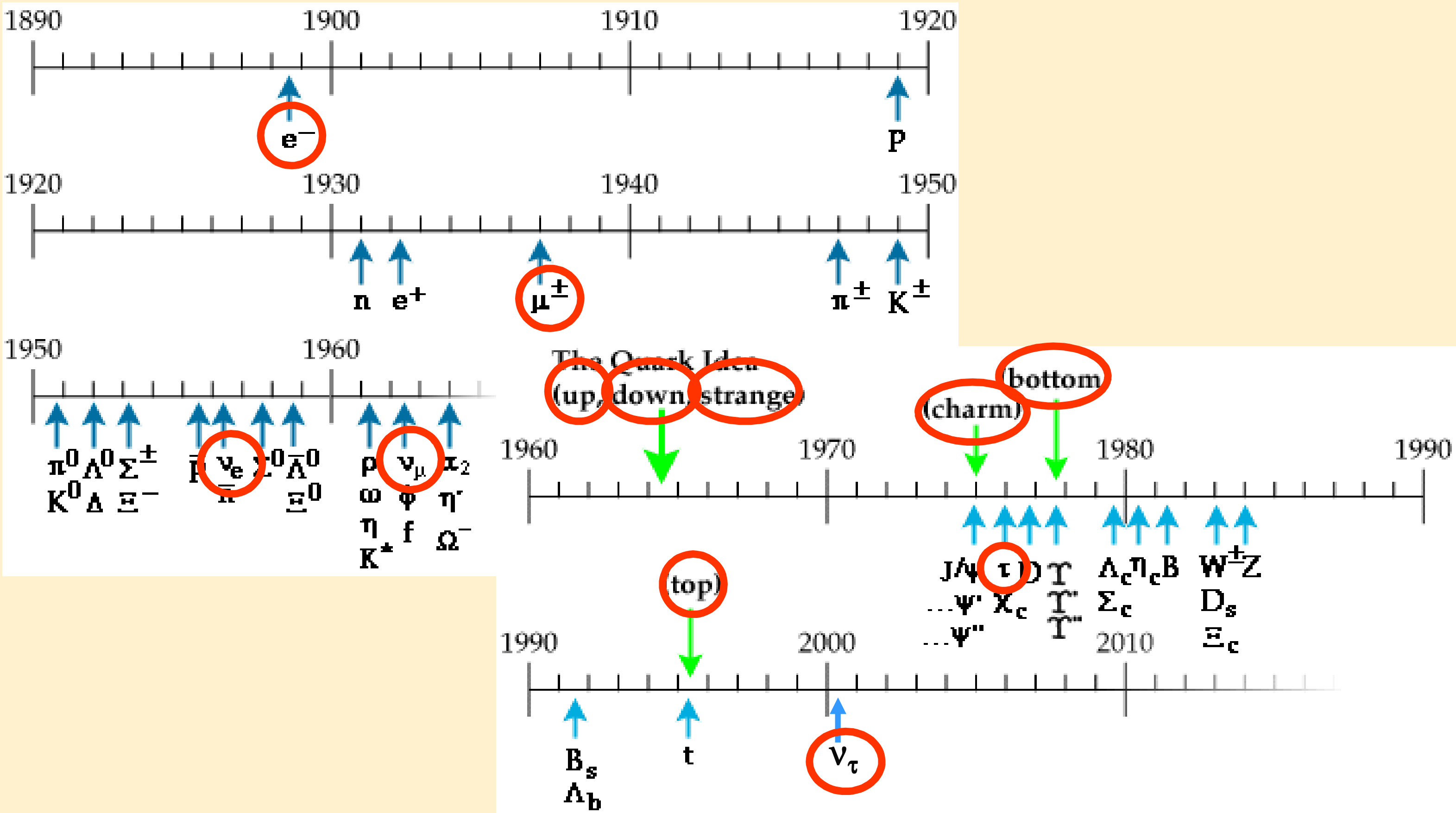
1948, Berkeley cyclotron at 95MeV/nucleon: first π production in laboratory (E.Gardner, G.Lattes)

note: 1 MeV = 10^6 eV, 1 GeV=10^9 eV

Bubble chamber photograph: proton proton interaction

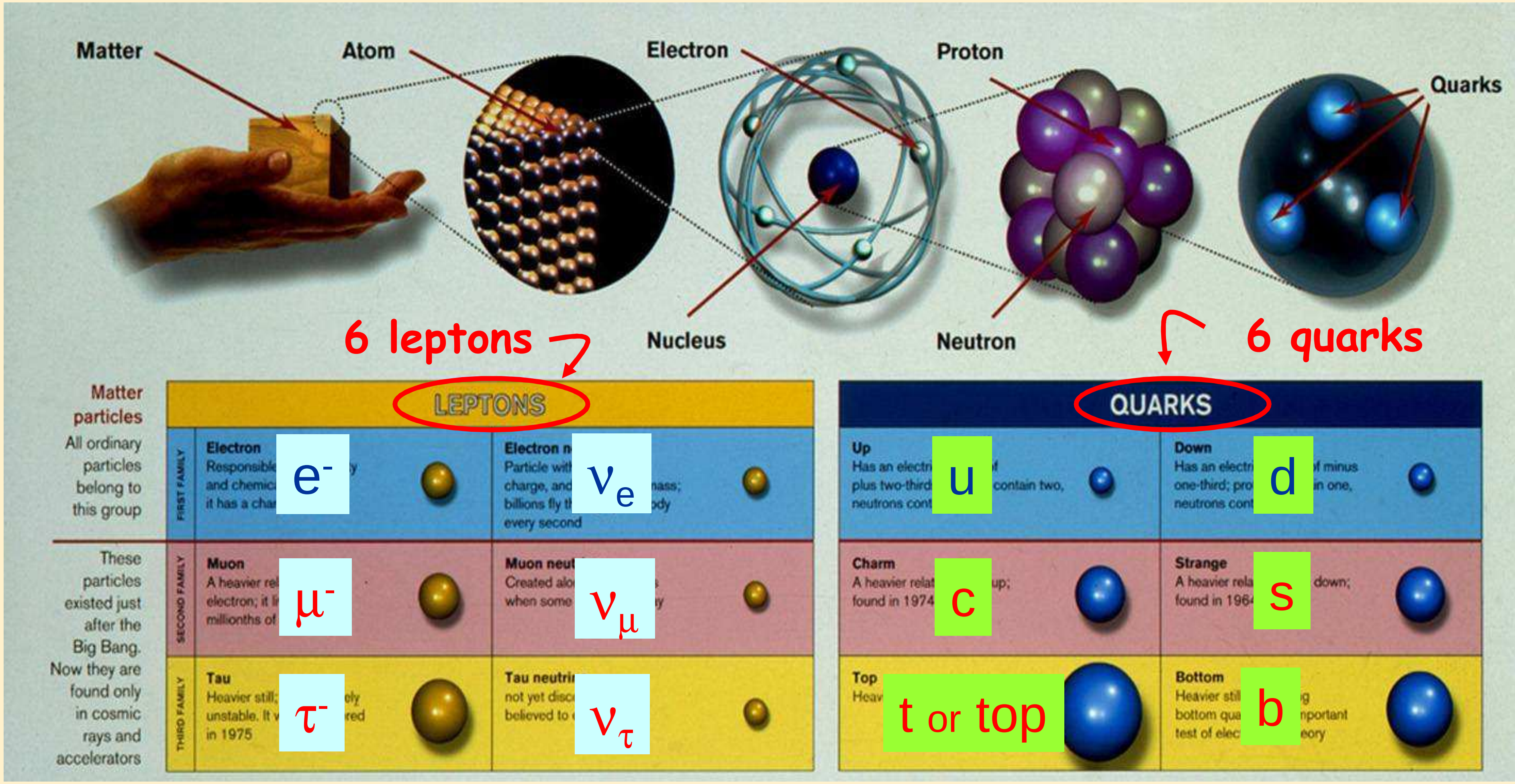


More and more particles !



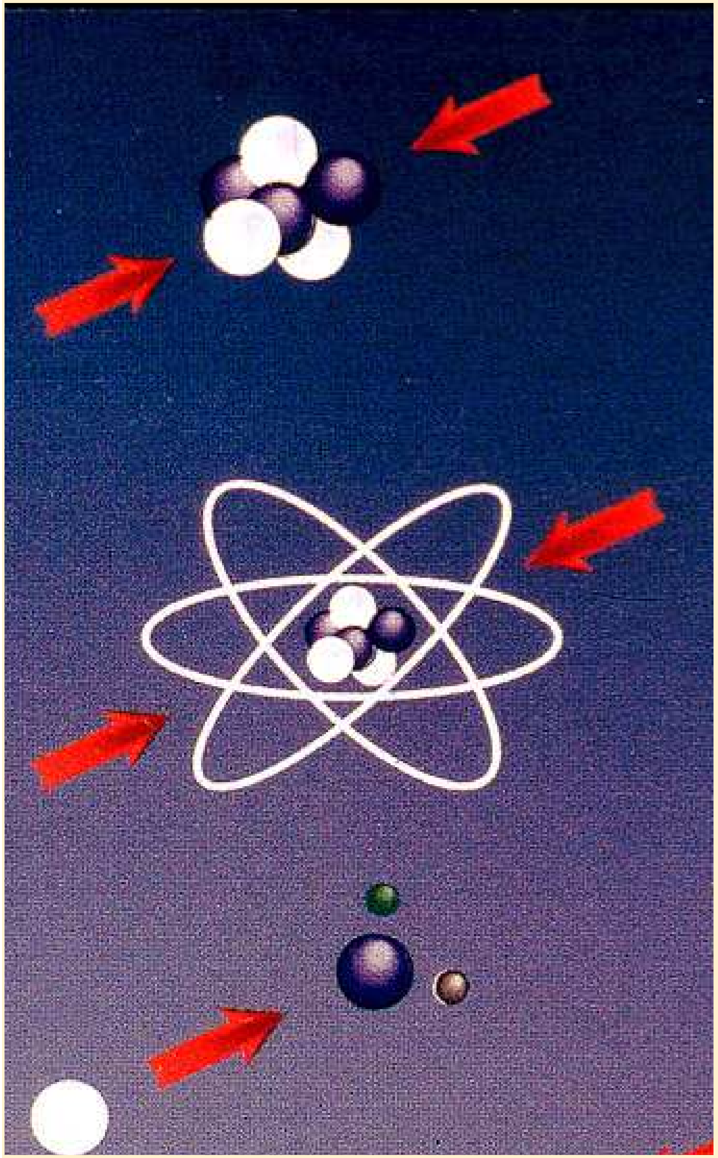
… but only 12 elementary constituants
governed by 3 fundamental interactions
in a quantic, relativistic and unified framework:
the Standard Model of particle physics

The 12 elementary constituants



All constituants observed experimentally: from e^- (1897) to top quark (1995) and ν_τ(2000). So far, no internal structure detected.

The 3 fundamental interactions



Strong interaction:

- Binding force in nucleons and atomic nuclei; nuclear reactions in stars
- range: 1fm = 10^{-15}m
- mediated by **gluons**

→ *See lectures of Pr. K.Nagano*

Electromagnetic interaction:

- Binding force in atoms, molecules and cristals; electricity, magnetism
- range: infinite
- mediated by the **photon**

Electroweak interaction

Weak interaction:

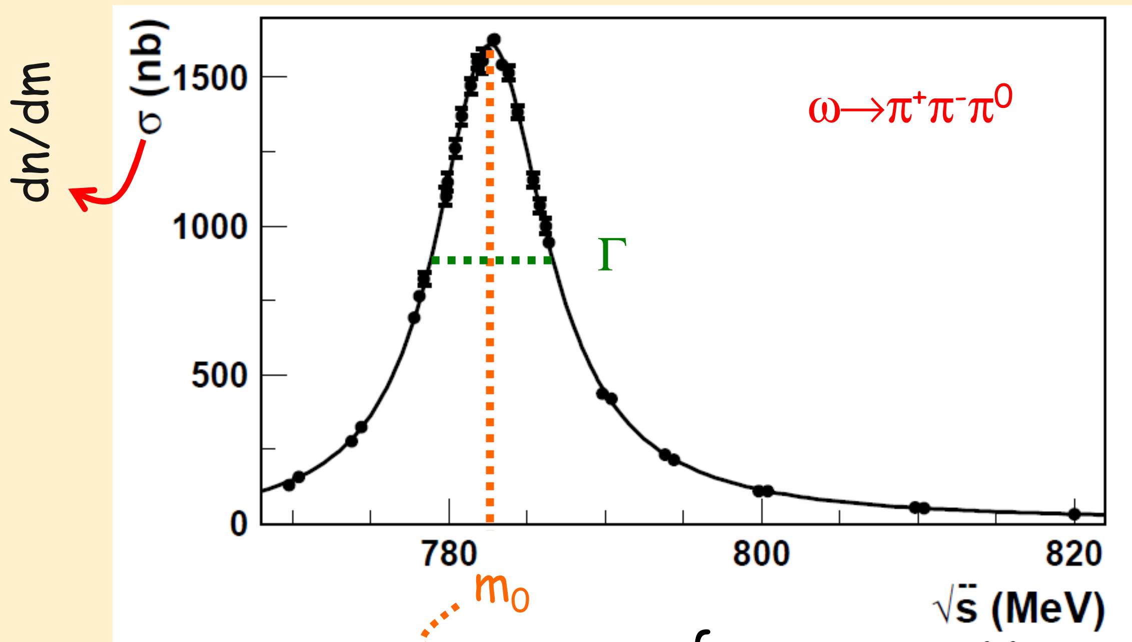
- Radioactive decays; nuclear reactions in stars
- range: 10^{-18} m
- mediated by the **W and Z bosons**

Particle features

- Particle = mass eigenstate:
  mass, spin (S), quantum numbers (P, C…)

- Unstable particle: mass distribution

$$\Delta E.\Delta t \approx \hbar \overset{rest-frame}{\Rightarrow} \Delta mc^2.\tau \approx \hbar \Rightarrow \Gamma c^2.\tau \approx \hbar \Rightarrow \Gamma c^2 = \frac{\hbar}{\tau}$$



m_0 reference mass

Γ : particle total width

τ : particle mean lifetime

mass distribution:

$$\frac{dn}{dm} \propto \frac{1}{(m-m_0)^2 + \frac{\Gamma^2}{4}}$$

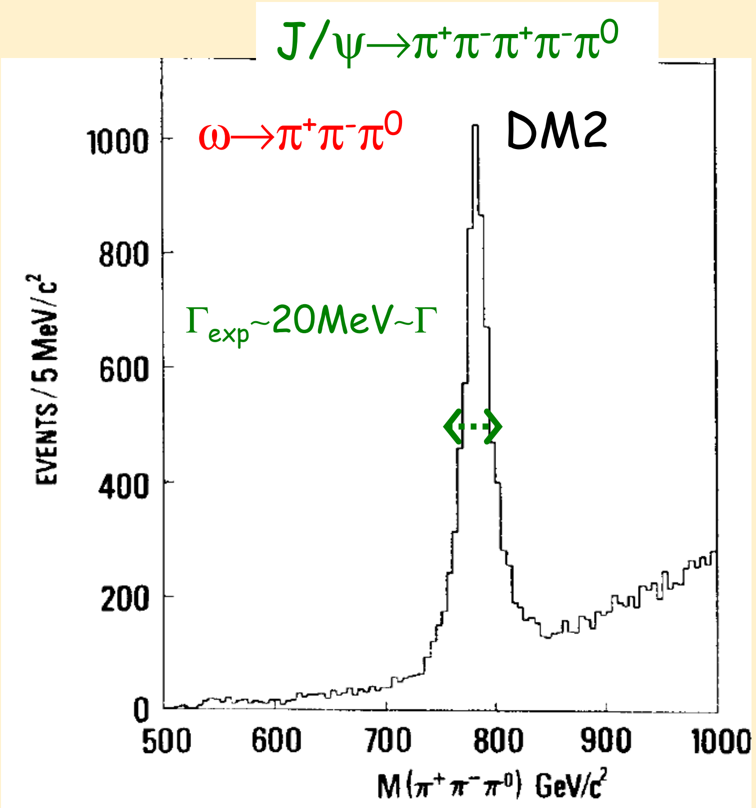
Breit-Wigner shape (here non relativistic)

Particle features

- Particle width and interaction strength:

strength ↑

interaction	example	τ (s)	Γc^2	mc^2(MeV)
strong	$\omega \to \pi^+\pi^-\pi^0$	6.6 10^{-23}	10 MeV	783
electromagnetic	$\pi^0 \to \gamma\gamma$	0.8 10^{-16}	8 eV	135
weak	$\pi^+ \to \mu^+\nu$	2.6 10^{-8}	2.5 10^{-8} eV	140



- strong interaction: Γ
  electromagnetic interaction: Γ or path
  weak interaction: mean path

- several decay channels:

$$\Gamma_{tot} = \sum_{channels} \Gamma_{channel}$$

with:

$$\tau = \frac{\hbar}{\Gamma_{tot} c^2} \quad \text{and} \quad Br_{channel} = \frac{\Gamma_{channel}}{\Gamma_{tot}}$$

Importance of symmetries

- For any physical object (e.g. a system of particles in interaction)

  Non observable property

  ⇔ Invariance under symmetry transformation

  ⇔ Conservation law (for charges & currents)

- Examples:

non observable property	symmetry transformation	conserved charge
absolute time	time translation	energy
absolute coordinates	spatial translation	momentum
absolute reference frame	rotations	angular momentum
left/right directions	space reflection	parity
absolute phase	global phase change	global charge

- QM approach: symmetry operator ([A,H]=0) eigenstates are stationary states, and their eigenvalues are conserved charges

Examples of symmetries, 1

Discrete symmetry: space reflection or parity

- Definition: $\Pi|\vec{r}\rangle \equiv |-\vec{r}\rangle$ with $\Pi^2 = Id$ $\quad \Pi\Pi^+ = \Pi^+\Pi = Id$
- Effect on quantum states: $\langle \vec{r}|\Pi|\psi\rangle = \psi(-\vec{r})$
- Eigenvalues:

  $\Pi|\psi\rangle = \lambda|\psi\rangle$ and $\Pi^2 = Id \Rightarrow \lambda^2 = 1 \Rightarrow \lambda = \pm 1$

  $\Rightarrow$ eigenstates of even or odd parity
- More definitions:

  Vector : λ=-1 $\qquad \vec{r} \xrightarrow{\Pi} -\vec{r}$

  Pseudovector (or axial vector): λ=+1 $\qquad \vec{r}\wedge\vec{p} \xrightarrow{\Pi} \vec{r}\wedge\vec{p}$

  Scalar: λ=+1 $\qquad \vec{r}.\vec{p} \xrightarrow{\Pi} \vec{r}.\vec{p}$

  Pseudoscalar: λ=-1 $\qquad (\vec{r}\wedge\vec{p}).\vec{r}' \xrightarrow{\Pi} -(\vec{r}\wedge\vec{p}).\vec{p}'$

Discrete symmetry: space reflection or parity

- Examples of particle intrinsic parities:

Scalar :	$f_0(980)$	$J^P=0^+$
Pseudoscalar :	π^0 π^+ π^-	$J^P=0^-$
Vector :	$\omega(782)$	$J^P=1^-$
Pseudovector :	$h_1(1170)$	$J^P=1^+$

- Parity conserved in electromagnetic and strong interactions but violated in weak interactions (many experiments in the 50's)
  - Charged kaon decays into three and two pions (Lee & Yang, 1956)
  - Radioactive decays of polarized nuclei (Wu et al. 1957) ←
  - Charged pion decay into muon-neutrino pair (Lederman et al., 1957)

Parity violation in weak interactions

✗ Radioactive decays of polarized Co^{60} (Wu et al. 1957)

$$Co^{60} \to Ni^{60*} e^- \overline{\nu_e}$$

- β decay: $n \to p e^- \overline{\nu_e}$
- initial state: polarized Co^{60} ($J^P=5^+$)
- If parity conserved:

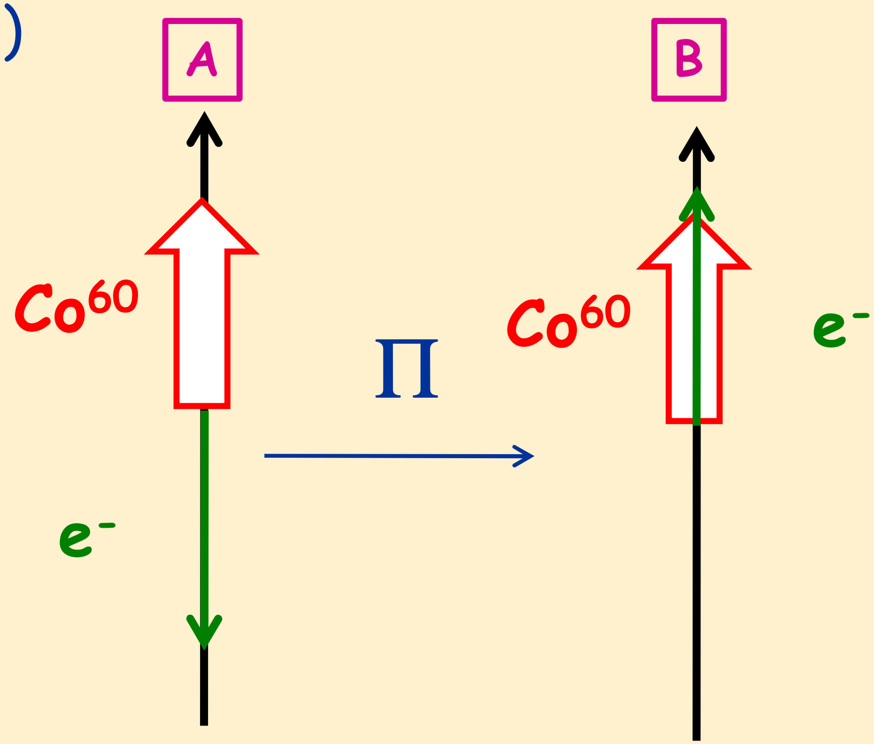
  $n_A = n_B$
- Measurement:

  $n_A >> n_B$

  ⇒ strong asymmetry of the e^- angular distribution :

  $$\frac{dn}{d\cos\theta} \propto \langle \vec{S}_{Co} \rangle . \vec{p}_e$$

  ⇒ parity violation



$\vec{S}_{Co} . \vec{p}_e$ is a pseudoscalar

Examples of symmetries, 2

Continuous symmetry: U(1) global gauge symmetry

- Definition: $\psi(x) \rightarrow \psi'(x) = e^{-i\alpha}\psi(x)$ for the free Dirac field

- Effect on Lagrangian density $L = \overline{\psi}(x)(i\gamma^{\mu}\partial_{\mu} - m)\psi(x)$ ✗

  invariance (⇔no effect of a global phase change)

- Conservation law: Noether's theorem (1918)

  one conserved current : $J^{\mu}(x) = \overline{\psi}(x)\gamma^{\mu}\psi(x)$ $\partial_{\mu}J^{\mu}(x) = 0$

  one conserved charge:

$$Q(t) = \int dx^3 J_0(x) = \int dx^3 \psi^{+}(x)\psi(x) \qquad \frac{dQ(t)}{dt} = 0$$

Continuous symmetry: U(1) global gauge symmetry

- Properties of the conserved charge, Q:

  Q, generator of the symmetry group

  $$|\psi'\rangle = U_\beta|\psi\rangle = e^{-i\beta Q}|\psi\rangle \qquad \text{with} \qquad Q|\psi\rangle = q|\psi\rangle$$

  conservation of Q eigenvalues (q)

- Applications:

  Q : electric charge operator $\Rightarrow$ electric charge conservation

  Q_B: baryon-charge operator $\Rightarrow$ baryon-number conservation

  Q_L: lepton-charge operator $\Rightarrow$ lepton-number conservation

- Note: these conservation laws hold for free Dirac fields but they are preserved in the Standard Model of the electroweak and strong interactions

Examples of symmetries, 3

Continuous symmetry: U(1) local gauge symmetry of QED

- From global to local gauge transformations: $\alpha \to \alpha(x)$

  for the free Dirac field $\psi(x) \xrightarrow{U_\alpha} \psi'(x) = e^{-i\alpha(x)}\psi(x)$

- To preserve Lagrangian density invariance: ✗

  $$L = \overline{\psi}(x)(i\gamma^\mu \partial_\mu - m)\psi(x) \quad \to \quad L = \overline{\psi}(x)(i\gamma^\mu D_\mu - m)\psi(x)$$

  with

  $D_\mu = \partial_\mu + iqA_\mu(x)$ gauge-covariant derivative

  $A_\mu(x)$ new vector field called gauge field

  $A_\mu(x) \xrightarrow{U_\alpha} A'_\mu(x) = A_\mu(x) + \frac{1}{q}\partial_\mu \alpha(x)$ gauge field transformation

Continuous symmetry: U(1) local gauge symmetry of QED

- Full QED Lagrangian:

$$L_{QED} = \bar{\psi} i\gamma^{\mu}(\partial_{\mu} + iqA_{\mu})\psi - m\bar{\psi}\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

with

$$F_{\mu\nu} = \partial_{\mu}A_{\nu} - \partial_{\nu}A_{\mu}$$

A_{μ} : vector field interacting with matter Dirac fields: $L_{QED}^{int} = -q\bar{\psi}\gamma^{\mu}\psi A_{\mu}$

$\Rightarrow$ electromagnetic interaction mediated by photons

Photon: massless gauge boson ($A_{\mu}A^{\mu}$ is not gauge-invariant)

$\Rightarrow$ agrees with the infinite range of the em interaction

QED as an abelian gauge theory is renormalizable

- A vector field describing the em interaction enters naturally if gauge invariance is assumed $\rightarrow$ extends this to other two interactions

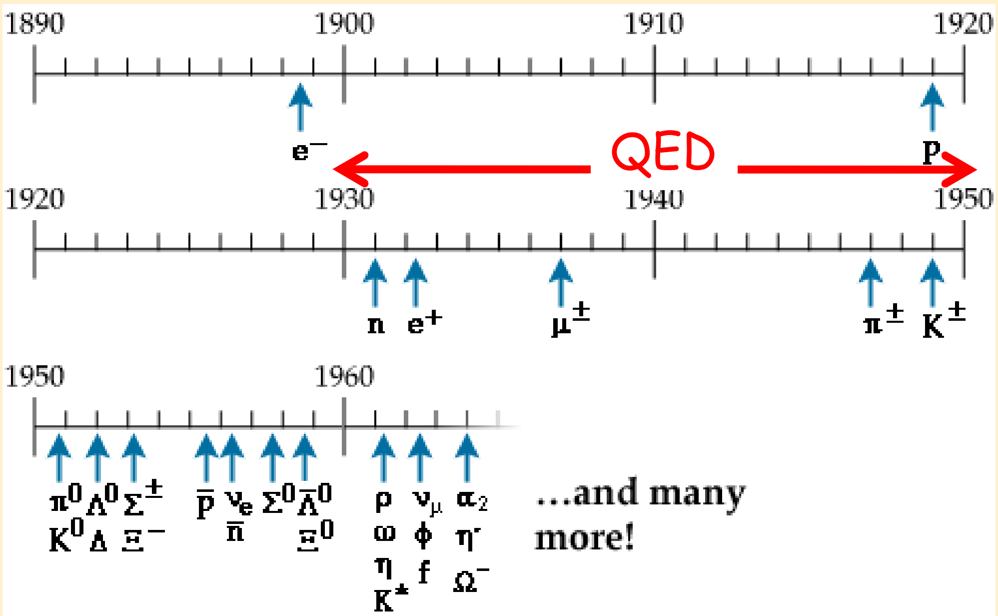
Note: free matter fields do not exist

Electromagnetic interaction

- XIXth cent.: classical electromagnetism (Maxwell equations 1873)
- 1930: relativistic and quantum electron equation of motion (Dirac)
- 1940: quantum field theory of electromagnetism as an abelian gauge theory (Feynman, Dyson, Schwinger,Tomonaga)
- 1951: precision tests of QED (Lamb)

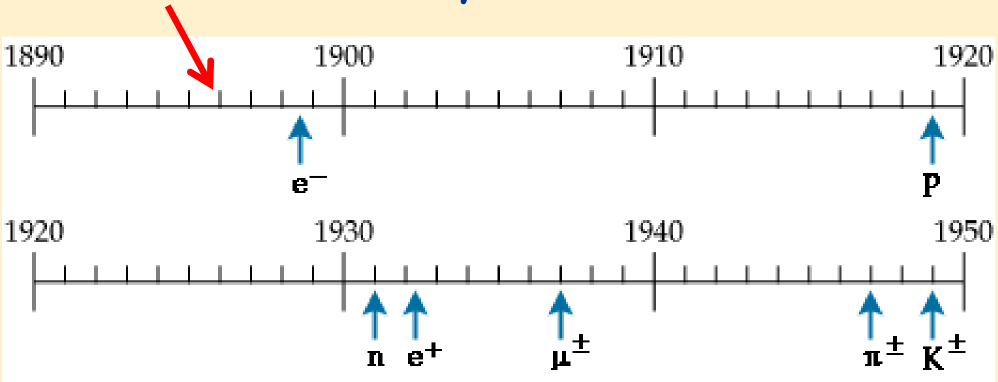
classical

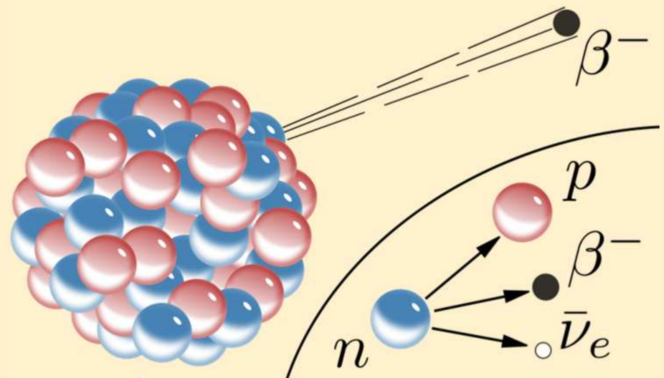
electromagnetism



Radioactive decays

- 1896: discovery of natural radioactivity (Becquerel)



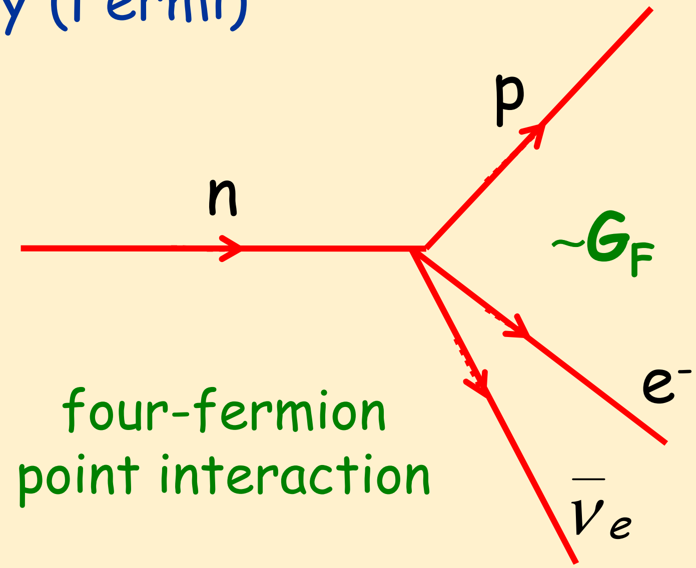


- 1930: neutrino postulate (Pauli)
- 1934: first theory of $n \to pe\bar{\nu}$ β-decay (Fermi)

$$\mathcal{L}_F(x) = -\frac{G_F}{\sqrt{2}} J^{\mu}_{hadr}(x) J^{lept}_{\mu}(x)$$

with

$$G_F \approx \frac{10^{-5}}{m_p^2}$$



Weak interaction

- 1930-1950: discovery of $\pi \rightarrow \mu$ & $\mu \rightarrow e$ decays, long lifetimes

  $\Rightarrow$ weak interactions as a distinctive class of interactions

- 1956: ν confirmed & parity non-conservation in weak interactions

  $\Rightarrow$ 1958: V-A theory of the weak interaction (Feynman & Gell-Mann ; Sudarshan & Marshak ; Sakurai)

  e.g. for leptons:

  γ_μ : vector

  $\gamma_\mu \gamma_5$: axial-vector

$$J_\mu^{lept} = \bar{\nu}_e \gamma_\mu (1 - \gamma_5) e$$

$\Rightarrow$ only left-handed fermions in charged weak currents ("maximal violation parity")

$$J_\mu^{lept} = 2 \bar{\nu}_{e,L} \gamma_\mu e_L \qquad \text{with} \qquad \psi_L = \frac{1}{2}(1 - \gamma_5)\psi$$

Weak interaction

- Strong points of the V-A theory:
  - reproduces a lot of low-energy experimental results
  - led to postulate existence of a new heavy quark

$$J_\mu^{lept} = \bar{\nu}_e \gamma_\mu (1-\gamma_5) e + \bar{\nu}_\mu \gamma_\mu (1-\gamma_5) \mu$$

by symmetry (Bjorken & Glashow, 1964)

new charm quark

$$J_\mu^{hadr} = \bar{u} \gamma_\mu (1-\gamma_5) d_\theta + \bar{c} \gamma_\mu (1-\gamma_5) s_\theta$$

$$d_\theta = \cos\theta_c d + \sin\theta_c s \qquad s_\theta = \cos\theta_c s - \sin\theta_c d$$

compulsory to suppress strangeness-changing neutral currents (Glashow, Iliopoulos & Maiani, 1970)

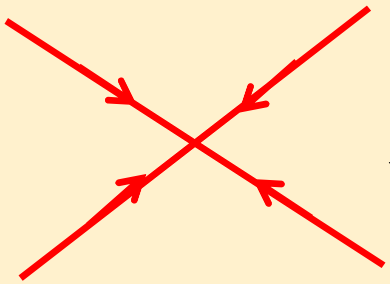
- But:
  - does not explain CP violation by weak interactions, 1964
  - lack of renormalizability and violation of unitarity

Weak interaction

- 1957/59: intermediate vector boson theory of the weak interaction (Schwinger, Bludman & Glashow)

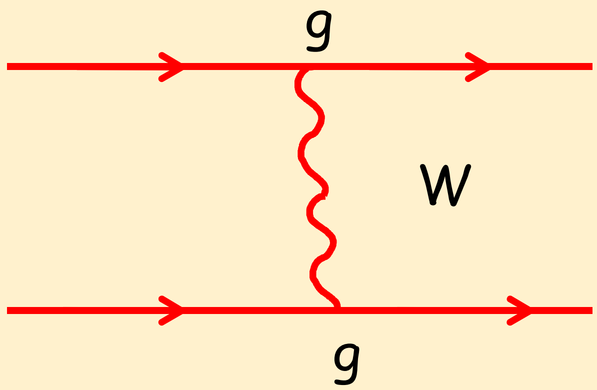
massive vector field ⇔ finite range

$$\mathcal{L}_{IVB}^{int}(x) = g(J^{\mu}W_{\mu} + h.c.) \qquad \lambda_c = \frac{\hbar}{M_W c} << 1fm$$



$$\frac{G_F}{\sqrt{2}}$$

⇔



$$\frac{G_F}{\sqrt{2}} \propto \frac{g^2}{M_W^2}$$

⇒ ~ gauge theory of the weak interaction with massive bosons

- But:
  - lack of renormalizability (IVB mass) and violation of unitarity

Towards the Standard Model

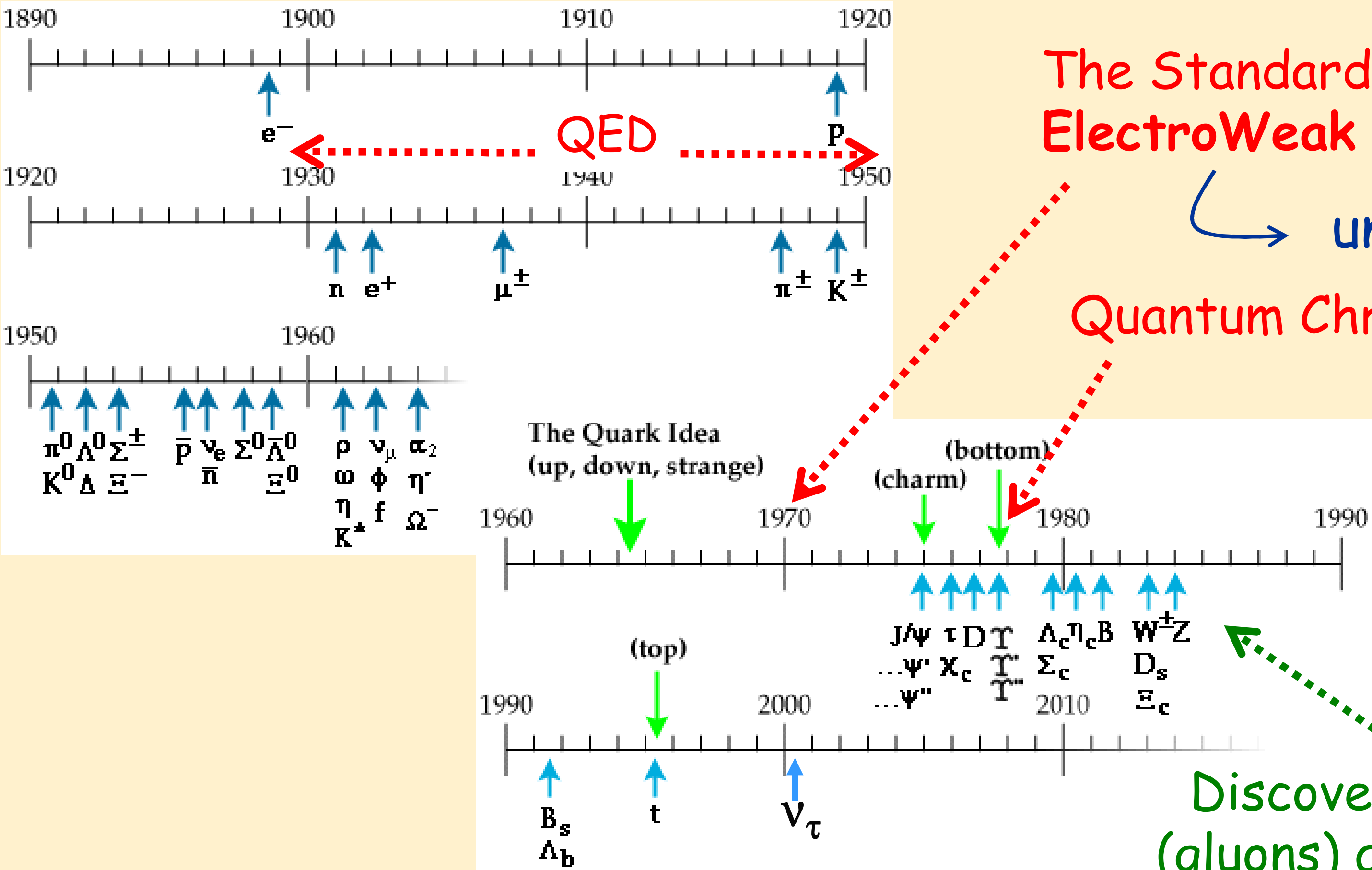
- 1957: idea of weak and electromagnetic unification (Schwinger)
- 1961: SU(2)xU(1) gauge theory of the electroweak interaction (Glashow)
  - Lack of renormalizability (IVB masses put by hand)

- 1967: spontaneously-broken SU(2)xU(1) gauge theory of the electroweak interaction (Weinberg & Salam)
  - Renormalizable theory (IVB masses generated by the Higgs mechanism). Unitarity preserved.
  - Predicts neutral weak currents and one Higgs boson.

- 1971: proof of renormalizability of gauge theories, with or without spontaneous symmetry breaking ('t Hooft)

- 1973: neutral current discovery (Gargamelle experiment, CERN)

The emergence of the Standard Model



The Standard Model of the **ElectroWeak** interaction

unification

Quantum ChromoDynamics

Discovery of strong (gluons) and EW (W,Z) vector bosons

Precise tests of the electroweak theory, tests of QCD