Particles of the Standard Model:

Gauge Bosons

1. Gauge Theory
2. screening in QED
   - Vacuum polarization
   - running coupling constant
3. anti-screening in QCD
   - asymptotic freedom
   - confinement
4. massive vector bosons

Gauge Bosons — Gauge Theories

Electro Magnetism (EM) as a gauge theory

- classic EM is described with $\vec{E} = \vec{\nabla} V$ and $\vec{B} = \vec{\nabla} \times \vec{A}$
  - the change $V \to V' = V + const.$ and $\vec{A} \to \vec{A}' = \vec{A} + \vec{\nabla}\Lambda$ does not change $\vec{E}' = \vec{E}$ and $\vec{B}' = \vec{B}$

- in SR $\vec{E}$ and $\vec{B}$ are unified to $F_{\mu\nu}$ with $E_i = -F_{0i}$ and $B_i = -\frac{1}{2} e_{ijk} F_{jk}$
  - with $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$ and $A^\mu = (V, \vec{A})$

- a change of the type $A_\mu \to A'_\mu = A_\mu + \partial_\mu \Lambda$ does not change anything

  $\Rightarrow$ gauge transformation

a gauge transformation describes the redundant parametrisation of a system

but

nature is described most exactly by gauge theories

Gauge Bosons — Gauge Theories

Making global symmetries local: ”gauge-principle”

- The $U(1)$ symmetry transformation is just the change of a phase.
  - for instance of the normal Dirac spinor, describing a charged fermion:

$$\Psi \to \Psi' = e^{i\alpha}\Psi$$

  - if we make the global phase transformation $e^{i\alpha}$ local:

$$\Psi \to \Psi' = e^{i\alpha(x)}\Psi$$

  - the derivatives spoil the invariance of the theory

- solution:
  - changing the normal derivative to a covariant derivative

$$\partial_\mu \to D_\mu = \partial_\mu - igA_\mu$$

  - that $D_\mu\Psi$ has the same transformation as Ψ:

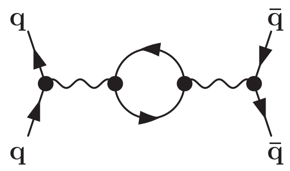
$$D_\mu\psi \to (D_\mu\psi)' = D'_\mu\psi' = e^{i\alpha}D_\mu\psi$$

  - and we get the gauge transformation for A_μ with $\Lambda = (1/g)\alpha$

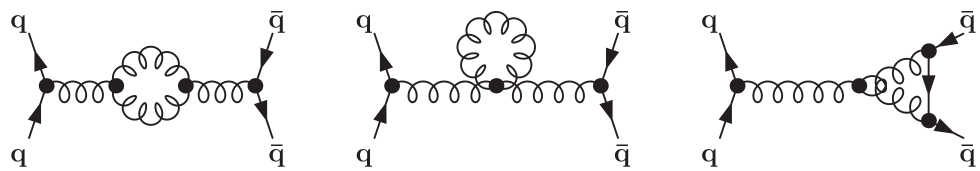
Gauge Bosons — Gauge Theories

General features of gauge fields

- They are real, massless (if the gauge group is unbroken) vector fields
  $\Rightarrow$ they carry 2 (if massive 3) degrees of freedom
- They couple to fields that are charged under the gauge group:
  - electrons are charged under $U(1)$ electro-magnetic
  - quarks are charged under color $SU(3)$ and $U(1)$
- Abelian gauge fields are not charged
  - photons are electrically neutral
  - they do not couple to themselves (at tree level)



- non Abelian gauge fields are charged under their own gauge group
  - gluons carry color themselves
  - they couple to themselves
    - $\Rightarrow$ asymptotic freedom
    - $\Rightarrow$ confinement



Gauge Bosons — Gauge Theories

different gauge groups

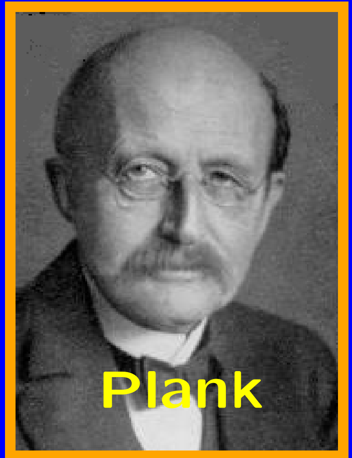
- The simple phase transformation has the group structure of $U(1)$:
  - $U(1)$ is represented by the complex unitary 1×1 matrix $e^{i\alpha}$
  - in nature it appears as the gauge group of QED

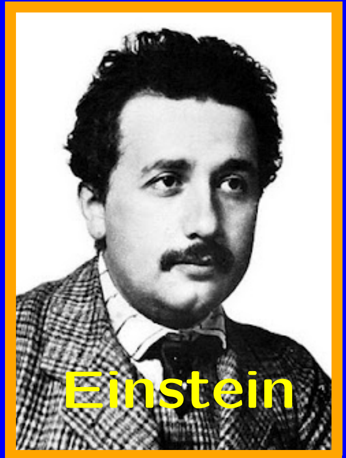
- The simplest non Abelian group is $SU(2)$
  - it's fundamental representation (t_r): complex 2-vector = spinor
  - it's adjoint representation (t_G): the 3 Pauli matrices $\{\frac{1}{2}\sigma^j\}$
  - in nature it appears as part of the electro-weak gauge group
  - note, that (t_r) and $(-t_r^*)$ are equivalent for $SU(2)$

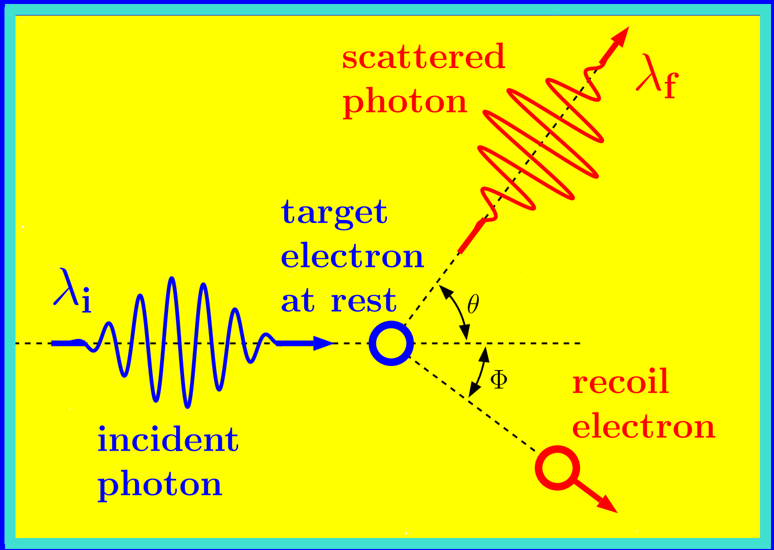
- The next simple non Abelian group is $SU(3)$
  - it's fundamental representation (t_r): complex 3-vector
  - it's adjoint representation (t_G): the 8 Gellman matrices $\{\frac{1}{2}\lambda^j\}$
  - in nature it appears as the gauge group of QCD
  - note, that (t_r) and $(-t_r^*)$ are not equivalent for $SU(3)$

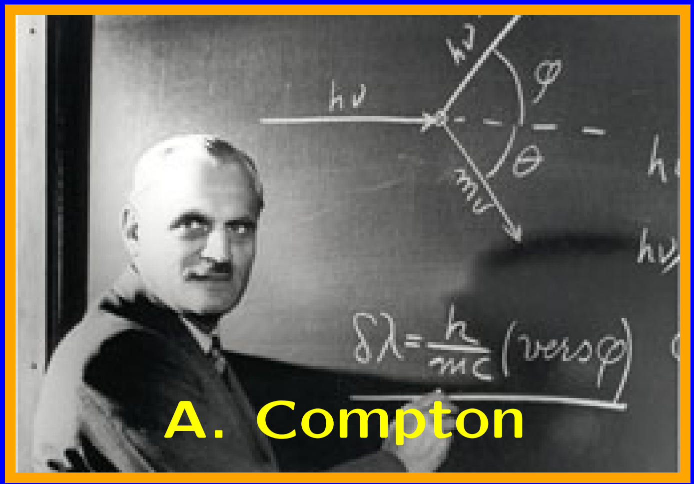
γ the photon

e^-







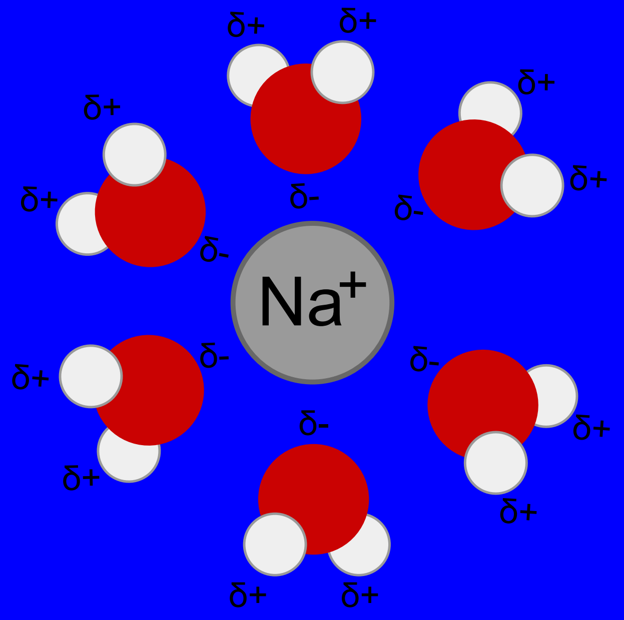


1897

1900 – 1924

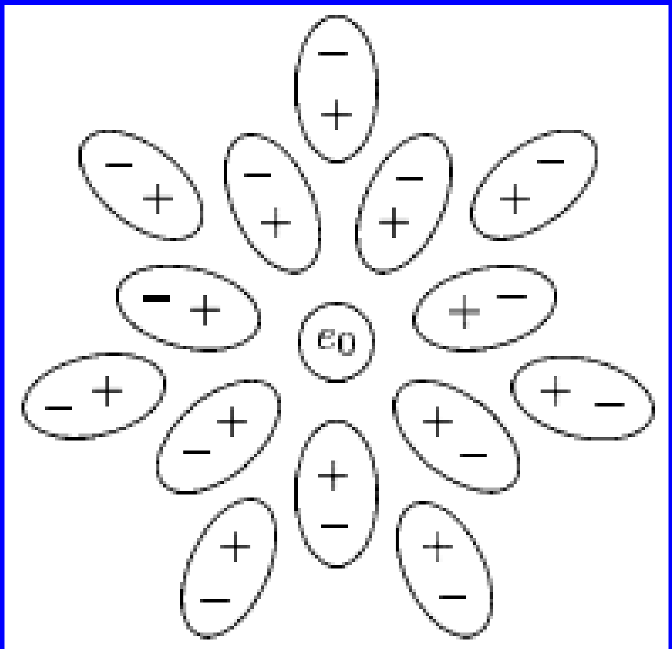
screening

- the effective charge of an ion in a dielectric medium is reduced by the dielectric molecules surrounding the charge



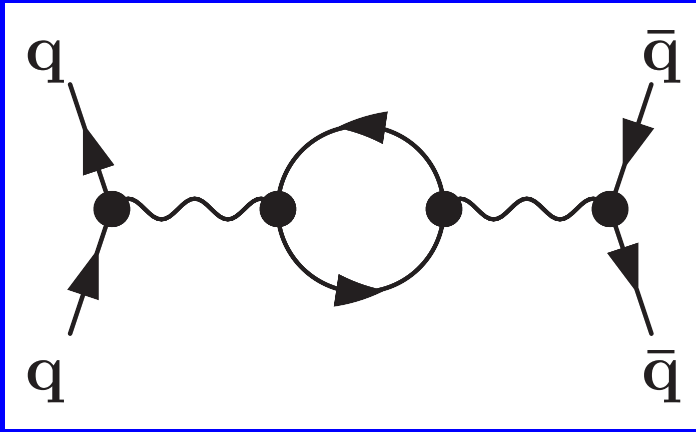
- the same happens in the vacuum:
  - if one looks at the charge with sufficient energy to see virtual electron-positron pairs

→ **Vacuum polarization !**



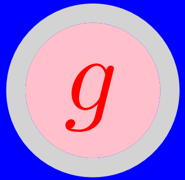
screening

- the energy dependence of the effective charge in the vacuum due to the Vacuum polarization is described by the

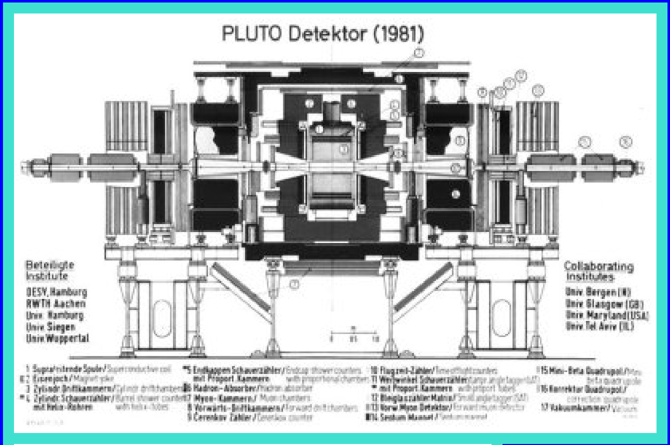


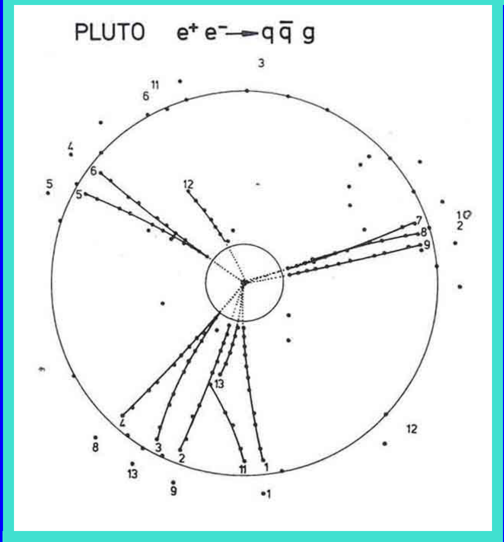
★ running coupling

$$\alpha_{\mathrm{em}}(Q^2) = \frac{\alpha_0}{1 - \frac{\alpha_0}{3\pi}\ln[\frac{Q^2}{m_e^2}]}$$

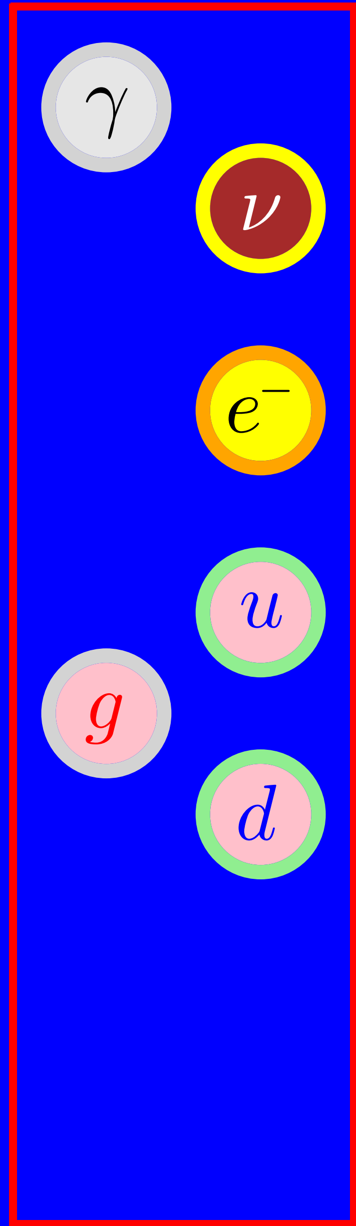


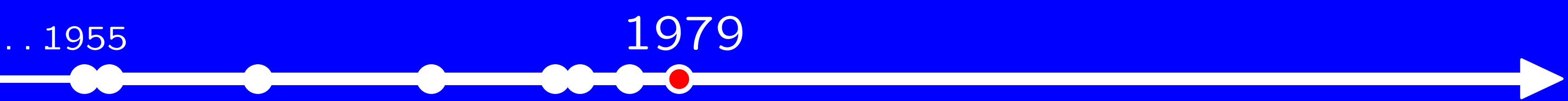
gluon





the consistent interpretation of **3-jet events** as **gluon bremsstrahlung** in the framework of QCD, done in PLUTO, TASSO, MARK-J, and JADE (experiments at PETRA, DESY), marks the discovery of the gluon **1979**

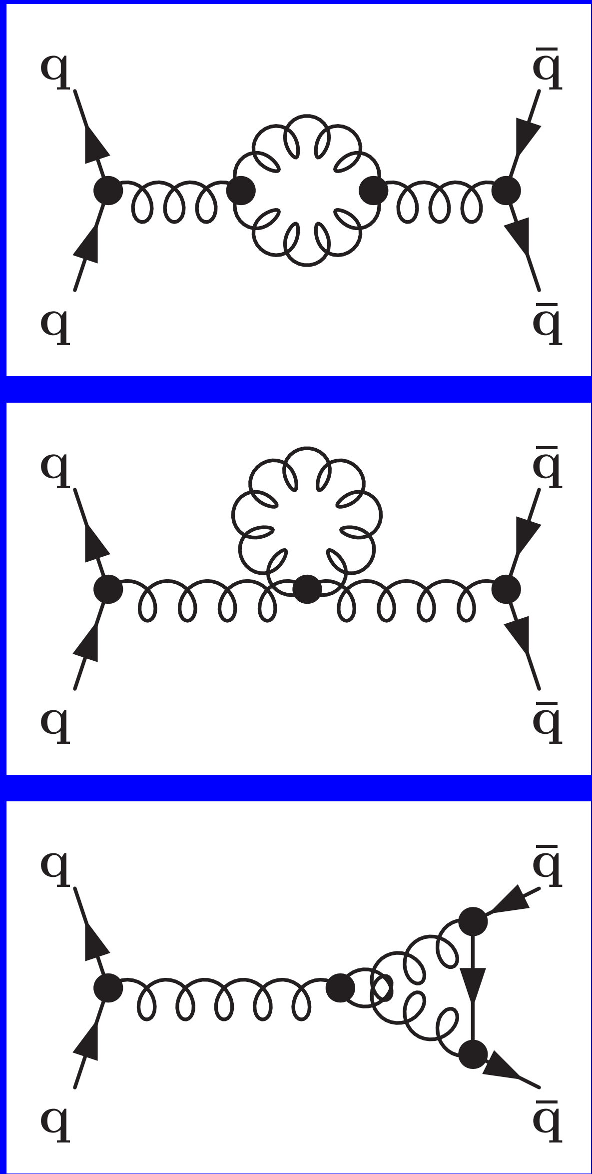




anti-screening

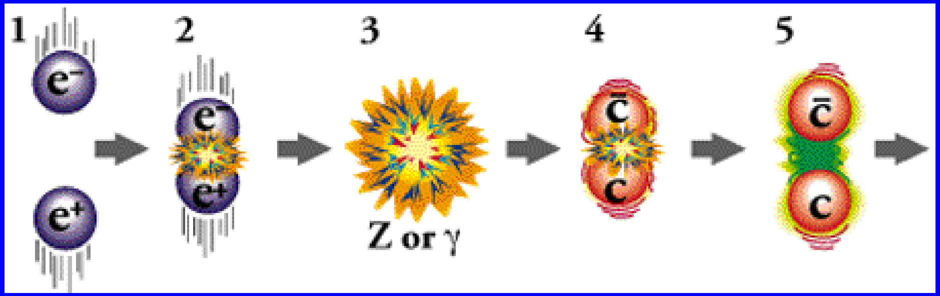
- the self couplings in QCD have the opposite effect for the color charges
  - the closer one looks, the weaker the charges seem to become

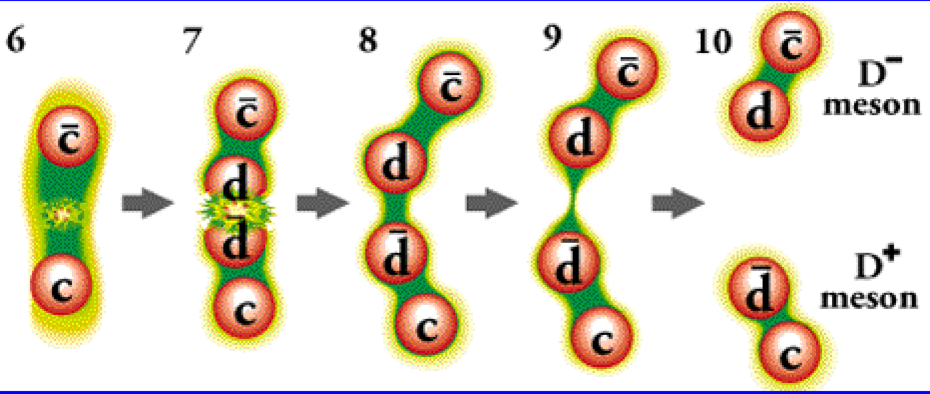
➡ asymptotic freedom !



anti-screening

- at high energies (colliders)
  - we have no problem to separate color charges
- at lower energies
  - the force connecting the charges seems to become stronger





➔ strong enough that the potential (= force * distance) creates a quark-antiquark pair, that restores color neutrality

➔ color confinement !

color confinement

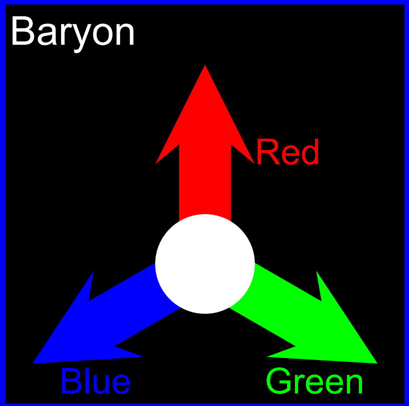
- low energy states have to be color neutral

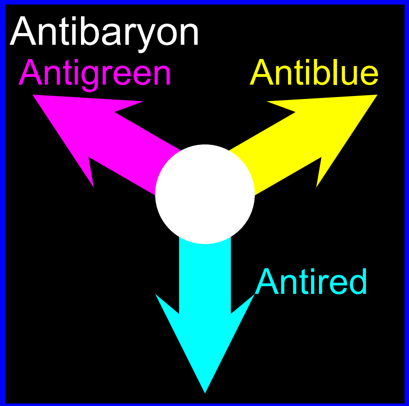
➡ we can only observe color neutral particles

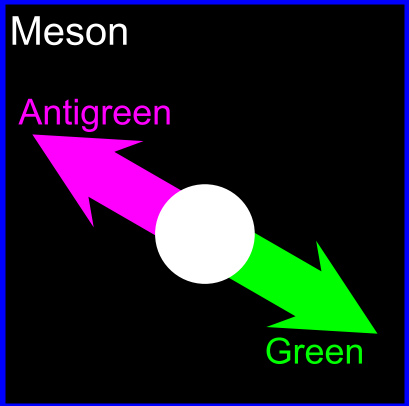
- the strong force hides inside the nucleons

- the nuclear force is more like a van der Waals force:
  - mediated by mesons (quark – antiquark pairs)

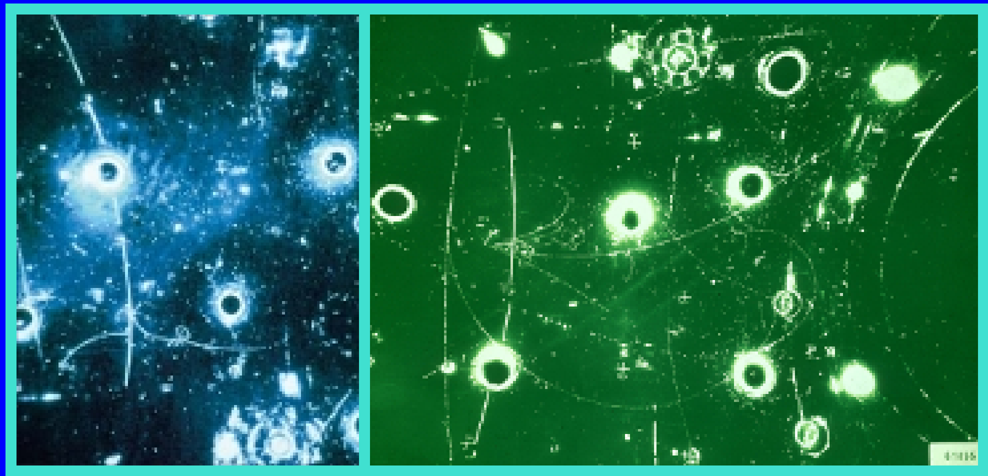
➡ Baryons and Mesons are color singlets





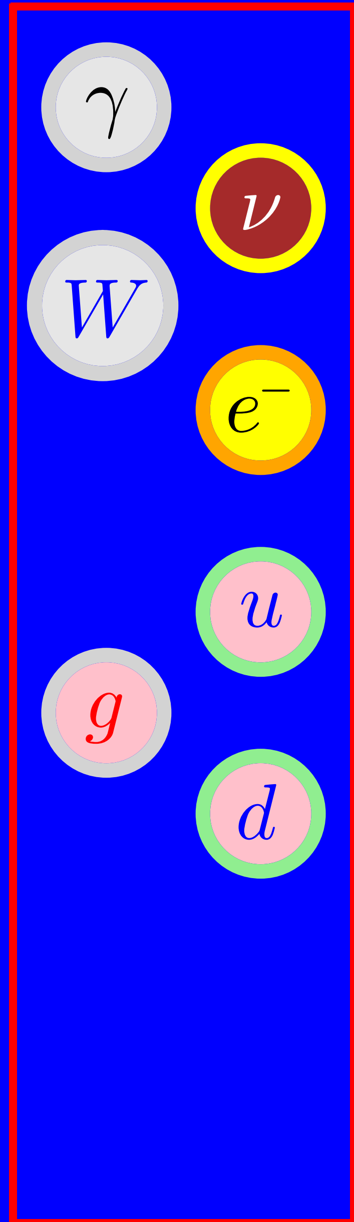


W Z hints for $W^{\pm}$- and Z-boson



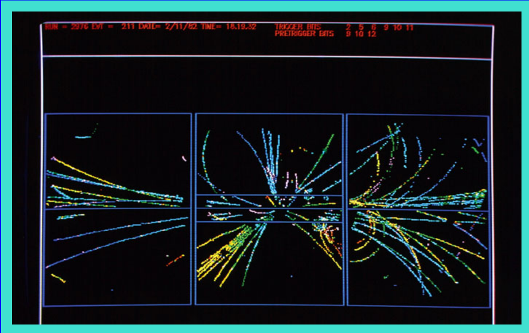
Weak charged currents were known from neutrino detection.

CERN announced the experimental observation of **weak neutral currents**, shortly after they were predicted by the electroweak theory of Abdus Salam, Sheldon Glashow and Steven Weinberg.

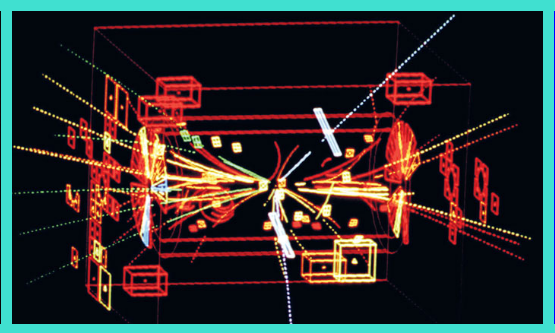


$W^{\pm}$- and Z-boson

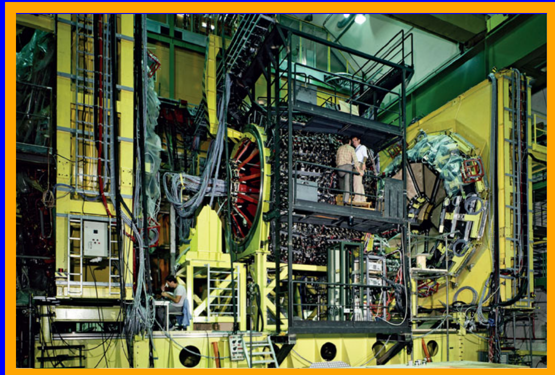
event in the UA1 detector

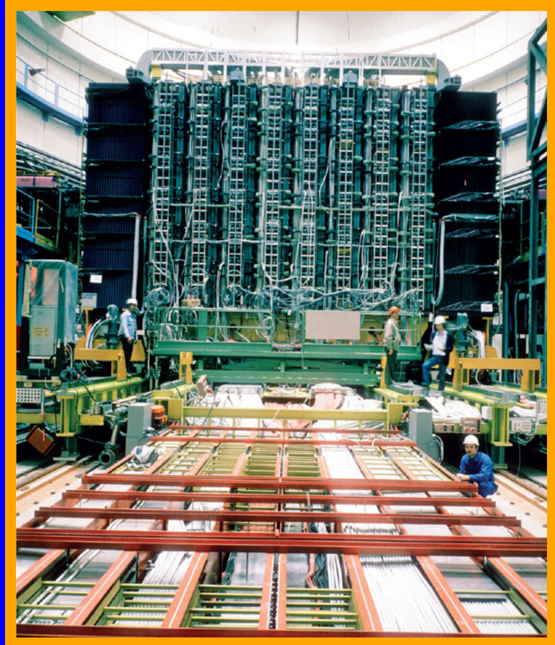


Z-event in UA1



UA2 detector



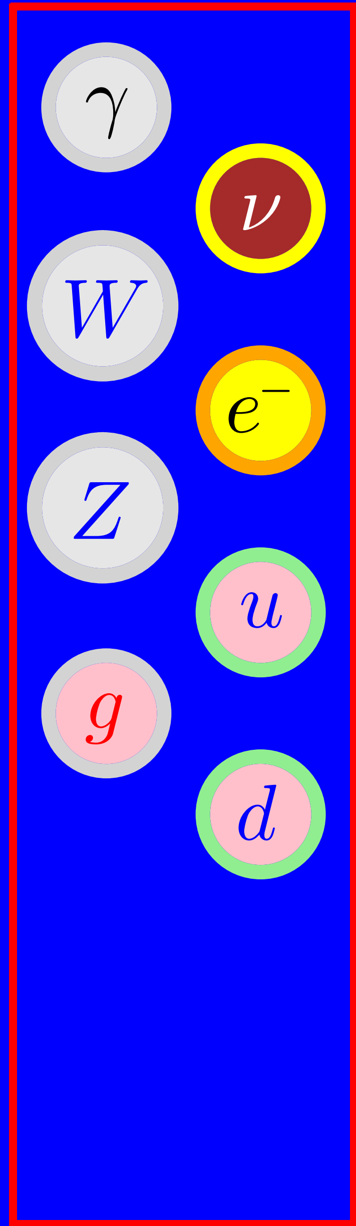


UA1 detector (parking)

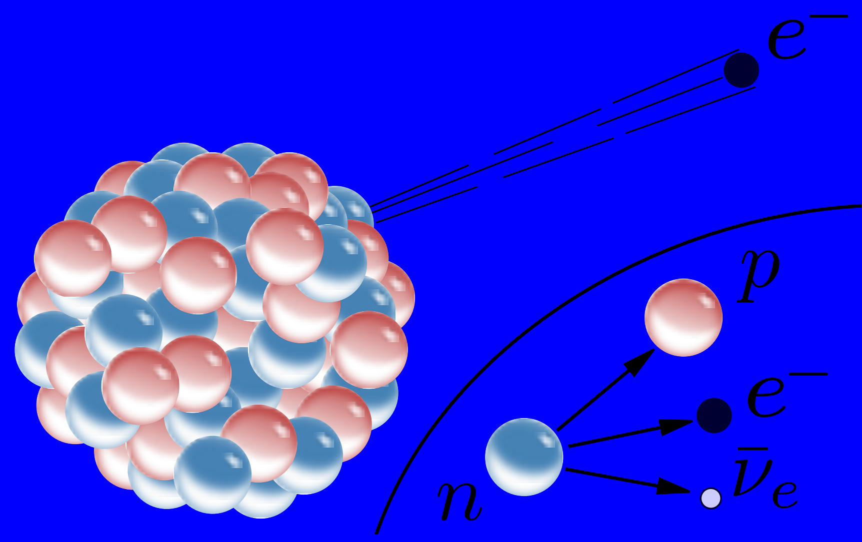
January 1983:

Rubbia: "They look like Ws, they feel like Ws, they smell like Ws, they must be Ws".

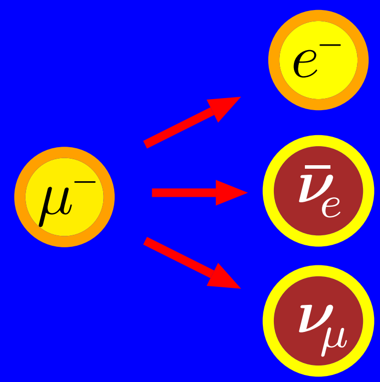
4 Z-events by end of June 1983

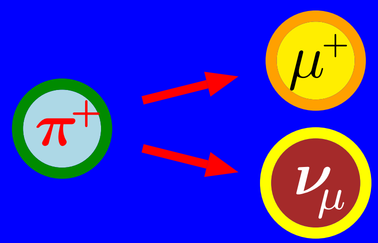


Weak Interactions



- 1933 Enrico Fermi explained the radioactive beta decay
  - by coupling four fermions
- the same coupling constant $G_F = \frac{1.16637 \times 10^{-5}}{\mathrm{GeV}^2}$ describes
  - radioactive beta-decay
  - muon decay
  - charged pion decay
  - neutrino interactions





★ but it cannot work for energies bigger than ~100 GeV

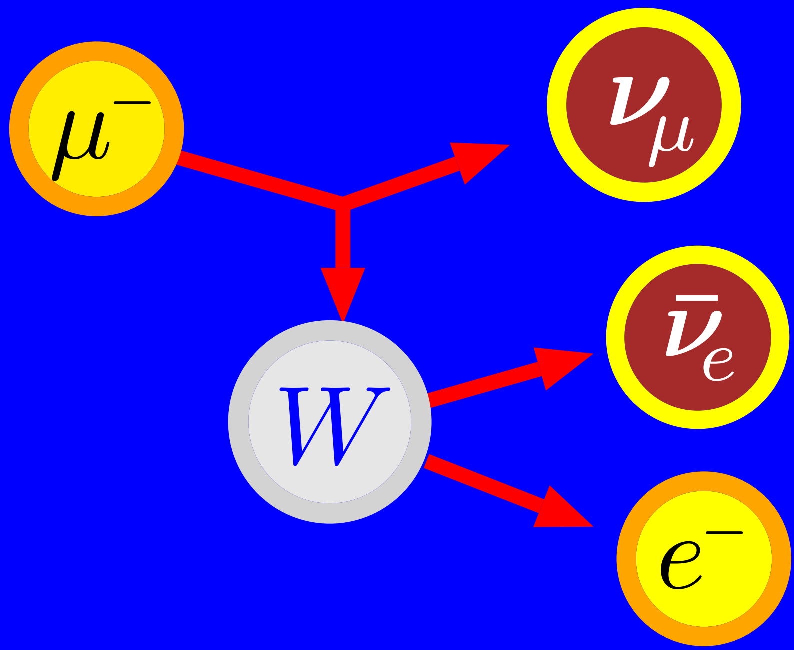
Weak Interactions: modern explanation

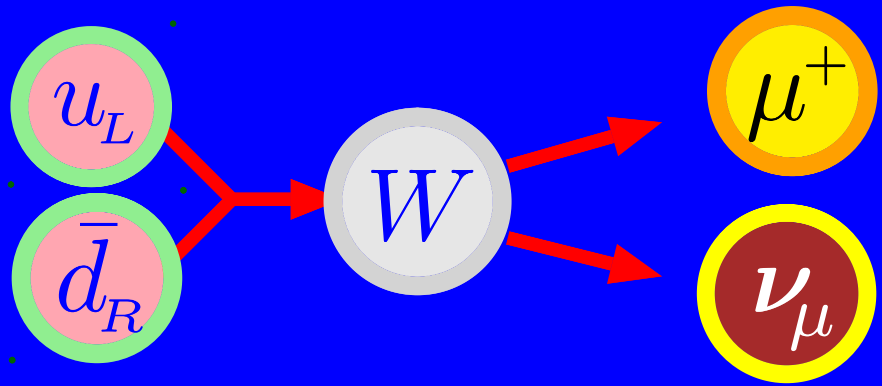
- weak interactions couple a pair of fermions with another pair
  – via vector bosons
- the Fermi coupling constant

$$G_F = \frac{\sqrt{2}}{8}\frac{g^2}{m_W^2}$$

is independent of energy

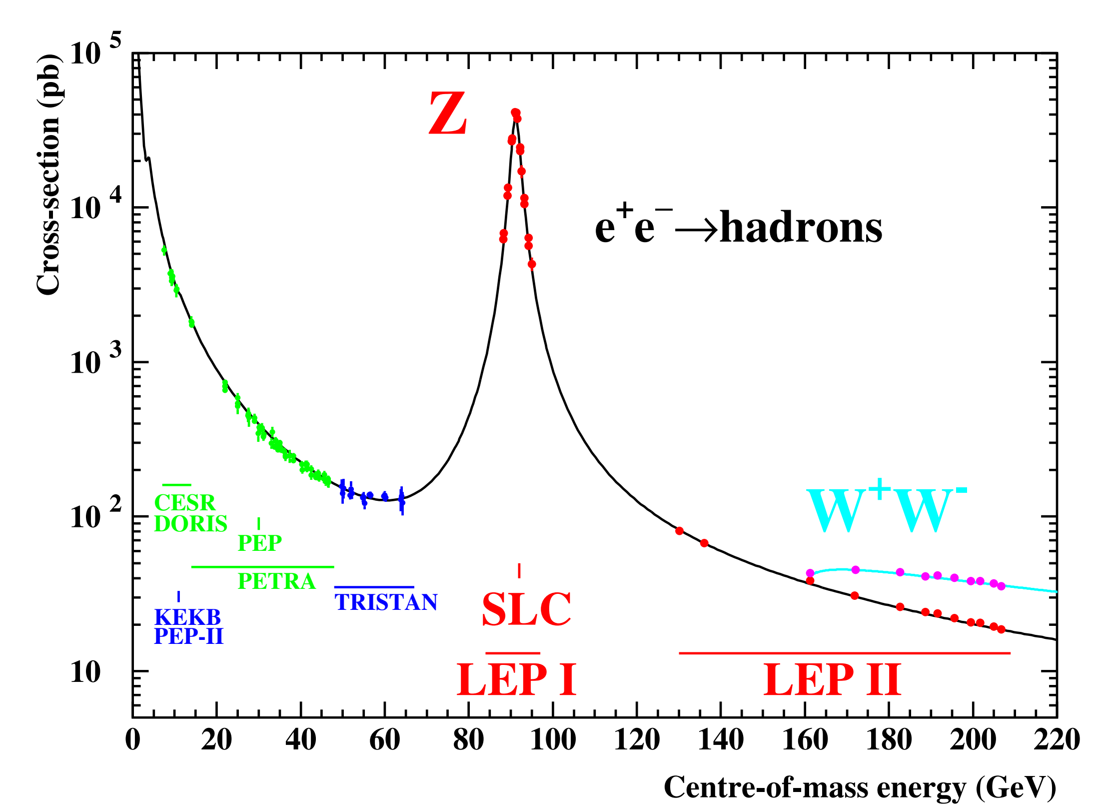
★ only if the energy is (much) smaller than the mass of the W-boson (80 GeV)





Weak Interactions: LEP

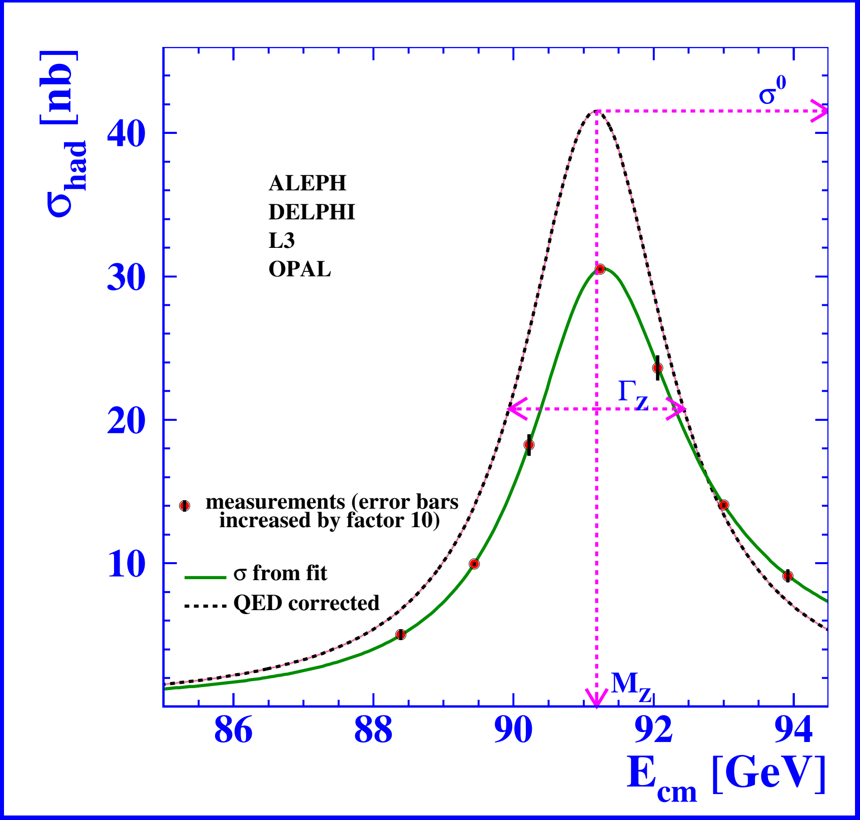
- electron-positron colliders can produce Z-bosons or pairs of W-bosons
  - ★ which decay to hadrons and leptons

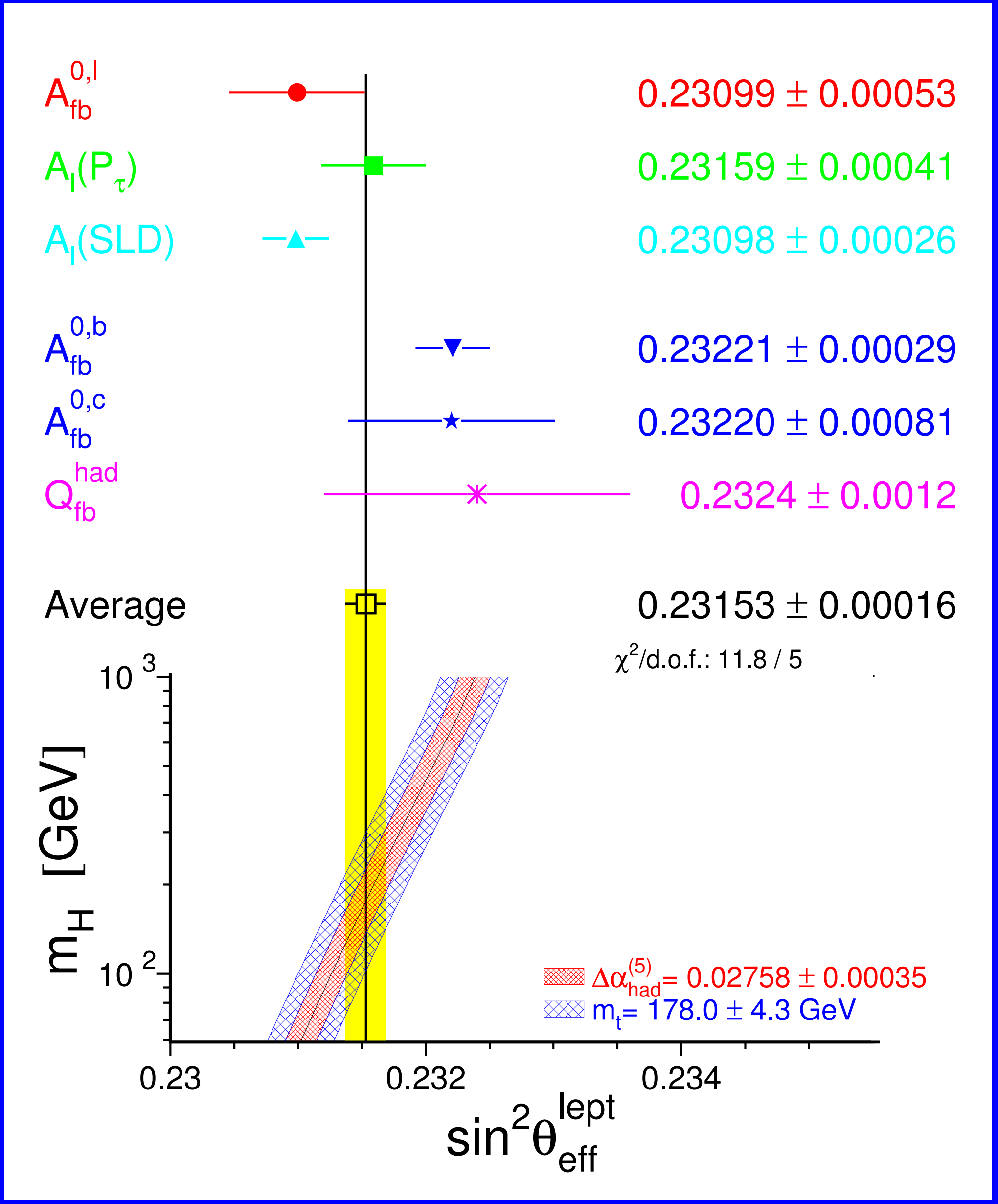


LEP

Weak Interactions: LEP

- electron-positron colliders determine the energy of collisions very accurately
  ➡ precision measurements





Weak Interactions: LEP

- measuring more predictions than there are parameters in a theory

→ consistency check for the Standard Model