Lecture 11
Strong and weak interactions

THE MODERN THEORY OF STRONG INTERACTIONS:

the interactions between quarks based on "Colour Symmetry" Quantum ChromoDynamics (QCD) formulated in the early 1970's

- **Each quark exists in three states of a new quantum number named "color"**
- **Particles with color interact strongly through the exchange of spin 1 particles named "gluons", in analogy with electrically charged particles interacting electromagnetically through the exchange of spin 1 photons**

A MAJOR DIFFERENCE WITH THE ELECTROMAGNETIC INTERACTION

Electric charge: positive or negative

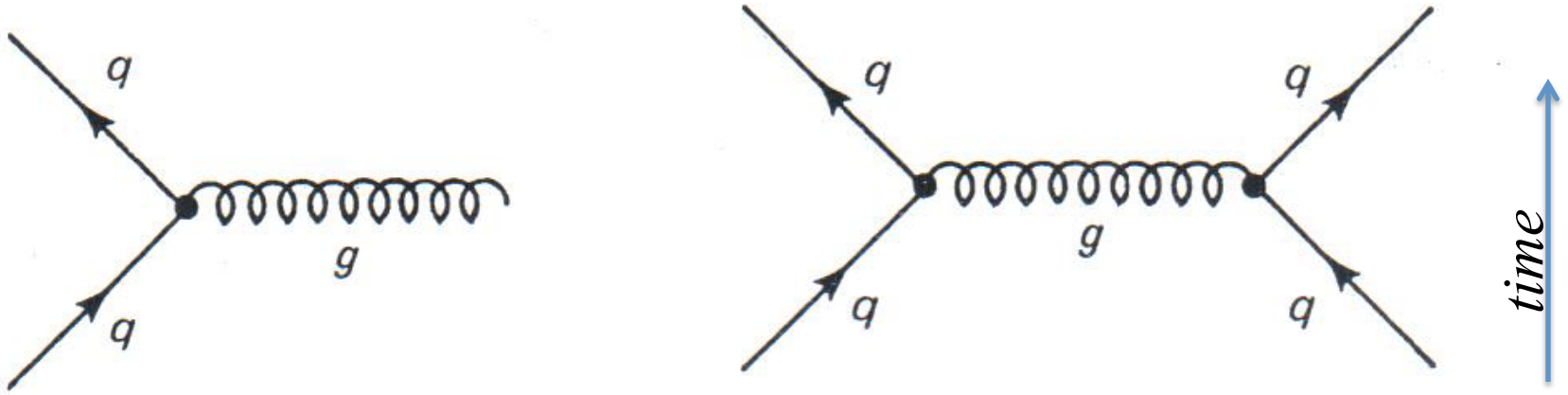
Photons have no electric charge and there is no direct photon-photon interaction

Colour: three varieties

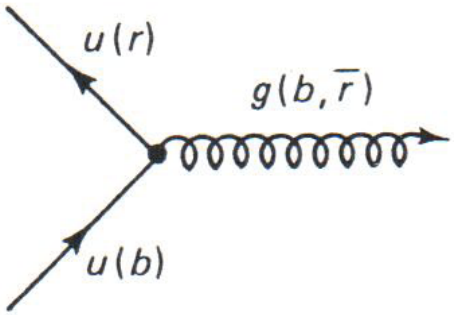
Mathematical consequence of color symmetry: the existence of eight gluons with eight variety of colors, with direct gluon – gluon interaction

- **The observed hadrons (baryons, mesons) are colorless combinations of colored quarks and gluons**
- **The strong interactions between baryons, mesons is an "apparent" interaction between colorless objects, in analogy with the apparent electromagnetic interaction between electrically neutral atoms**

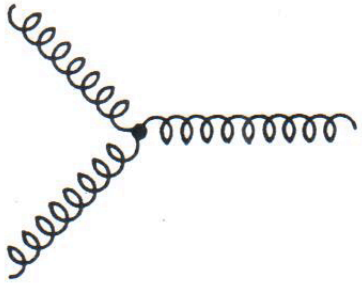
Carrier of the strong force - gluon

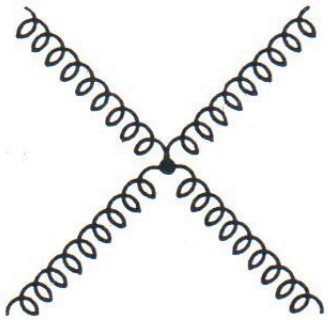


Gluon carries color-anti-color combination



Since gluons carry color, they can also couple to themselves
Recall, photon does not carry the charge and cannot couple to itself.





QCD postulates quark confinement – all hadrons (baryons and mesons) are formed as color singlets (no color) out of quarks and gluons.
The process of "hadronization" i.e., formation of individual hadrons or jets of hadrons out of a single quark is not addressed by the theory.
Phenomenological models are based on data obtained in e+e- collisions, electron – proton interactions and neutrino – proton/neutron collisions.
These are usually based on a picture of breaking of a color string where a new hadron is produced out of vacuum at each break. This picture is based on a QCD postulate that the strong force increases with distance.
$F \sim -kx$, i.e., quarks cannot get out but are asymptotically free at very short distances.

Free quarks, gluons have never been observed experimentally; only indirect evidence from the study of hadrons – WHY?

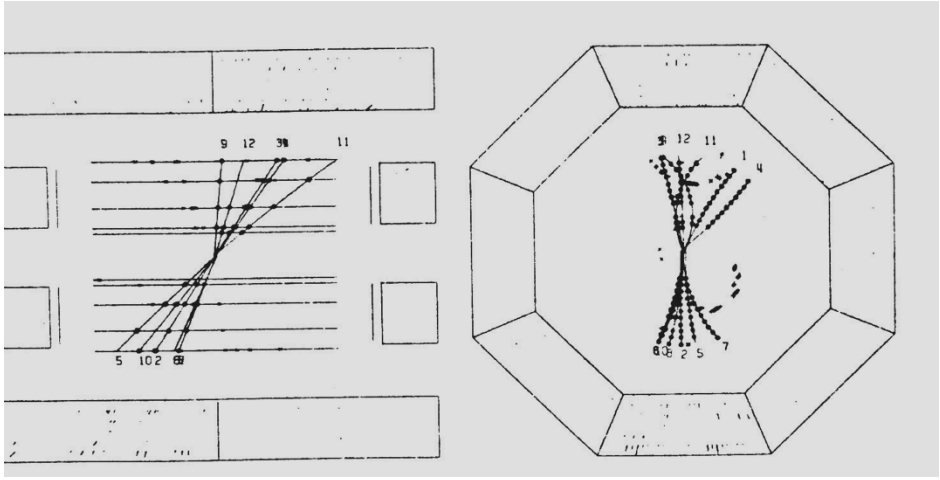
CONFINEMENT: colored particles are confined within colorless hadrons because of the behavior of the color forces at large distances

The attractive force between coloured particles increases with distance → increase of potential energy → production of quark – antiquark pairs which neutralize color → formation of colorless hadrons (hadronization)

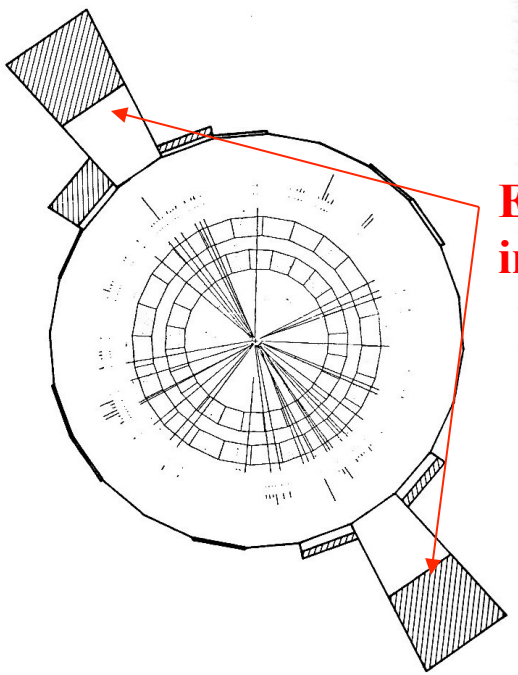
At high energies (e.g., in e^+e^- → $q + \bar{q}$) expect the hadrons to be produced along the initial direction of the $q - \bar{q}$ pair → production of hadronic "jets"

CONFINEMENT, HADRONIZATION: properties deduced from observation. So far, the properties of color forces at large distance have no precise mathematical formulation in QCD.

$e^+ + e^- \rightarrow$ hadrons
A typical event at
$Q = 2E = 35$ GeV:
reconstructed
charged particle tracks



A typical proton-antiproton collision at the CERN $\bar{p}$ p collider (630 GeV) producing high-energy hadrons at large angles to the beam axis (UA2 experiment, 1985)



Energy depositions in calorimeters

Weak interactions

1962-66: Formulation of a Unified Electroweak Theory
(Glashow, Salam, Weinberg)

4 intermediate spin 1 interaction carriers ("bosons"):

- **the photon (γ)**
  responsible for all electromagnetic processes

- **three weak, heavy bosons W^+ W^- Z**
  $W^\pm$ responsible for processes with electric charge transfer = ± 1
  (Charged Current processes)

  Examples:

  $n \rightarrow p\ e^- \bar{\nu}$: $n \rightarrow p + W^-$ followed by $W^- \rightarrow e\ \bar{\nu}$

  $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$: $\mu^+ \rightarrow \bar{\nu}_\mu + W^+$ followed by $W^+ \rightarrow e^+ \nu_e$

Z responsible for weak processes with no electric charge transfer
(Neutral Current processes)
PROCESSES NEVER OBSERVED BEFORE
Require neutrino beams to search for these processes, to remove the much larger electromagnetic effects expected with charged particle beams

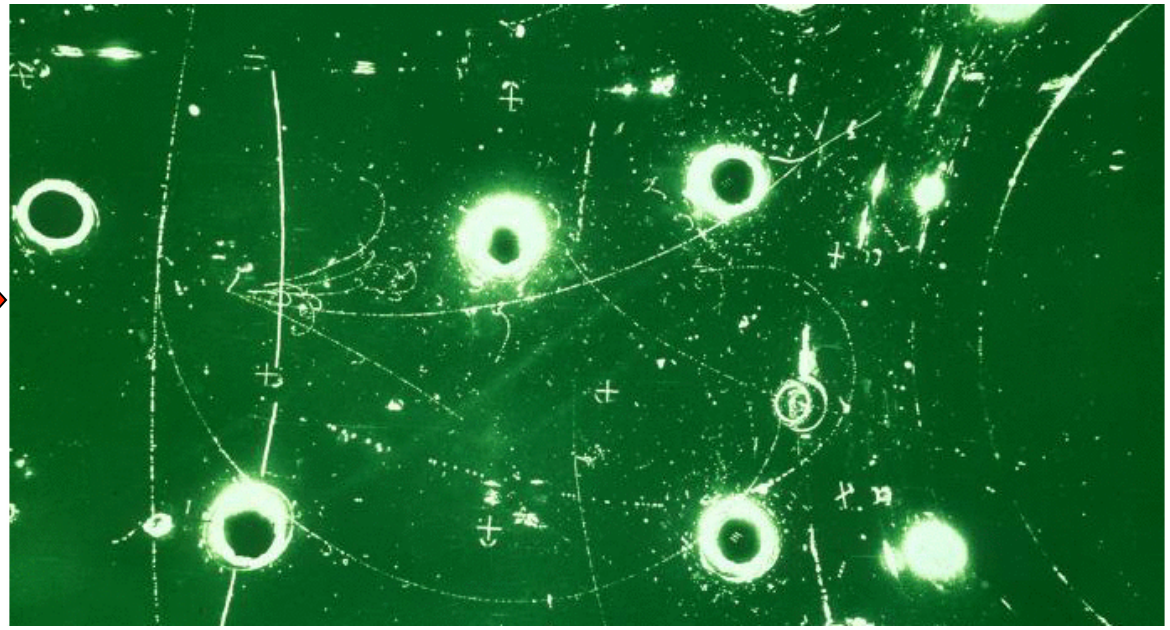
First observation of Neutral Current processes in the heavy liquid bubble chamber Gargamelle at the CERN PS (1973)

Example of
$\bar{\nu}_\mu + e^- \rightarrow \bar{\nu}_\mu + e^-$
(elastic scattering)
Recoil electron energy = 400 MeV

($\bar{\nu}_\mu$ beam from π^- decay in flight)



Example of
$\nu_\mu + p\ (n) \rightarrow \nu_\mu +$ hadrons
(inelastic interaction)
(ν_μ beam from π^+ decay in flight)



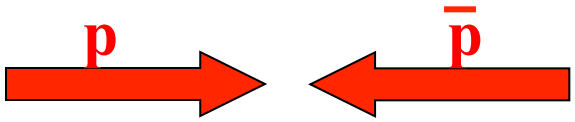


Measured rates of Neutral Current events ➔ estimate of the W and Z masses (not very accurately, because of the small number of events):

$$M_W \approx 70 - 90\ \text{GeV}/c^2 \quad ; \quad M_Z \approx 80 - 100\ \text{GeV}/c^2$$

too high to be produced at any accelerator in operation in the 1970's

1975: Proposal to transform the new 450 GeV CERN proton synchrotron (SPS) into a proton – antiproton collider (C. Rubbia)



Beam energy = 315 GeV ➔ total energy in the centre-of-mass = 630 GeV

Beam energy necessary to achieve the same collision energy on a proton at rest :

$$(E + m_p c^2)^2 - p^2 c^2 = (630\,\text{GeV})^2 \Rightarrow E = 210\ \text{TeV}$$

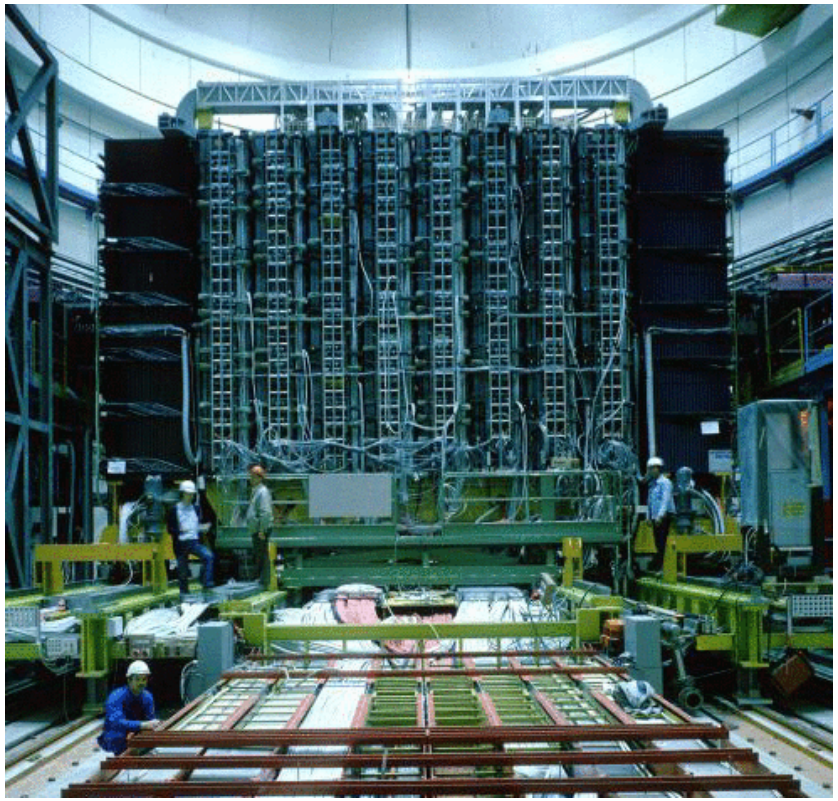
Production of W and Z by quark – antiquark annihilation:

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

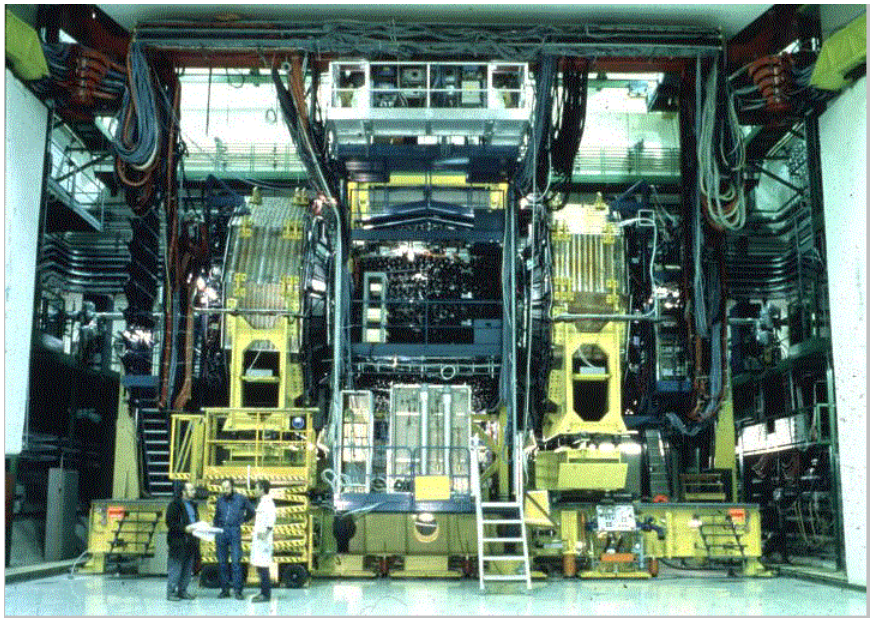
$$u + \bar{u} \rightarrow Z \qquad d + \bar{d} \rightarrow Z$$

UA1 and UA2 experiments (1981 – 1990)

Search for $W^{\pm} \rightarrow e^{\pm} + \nu$ (UA1, UA2) ; $W^{\pm} \rightarrow \mu^{\pm} + \nu$ (UA1)
$Z \rightarrow e^{+}e^{-}$ (UA1, UA2) ; $Z \rightarrow \mu^{+}\mu^{-}$ (UA1)

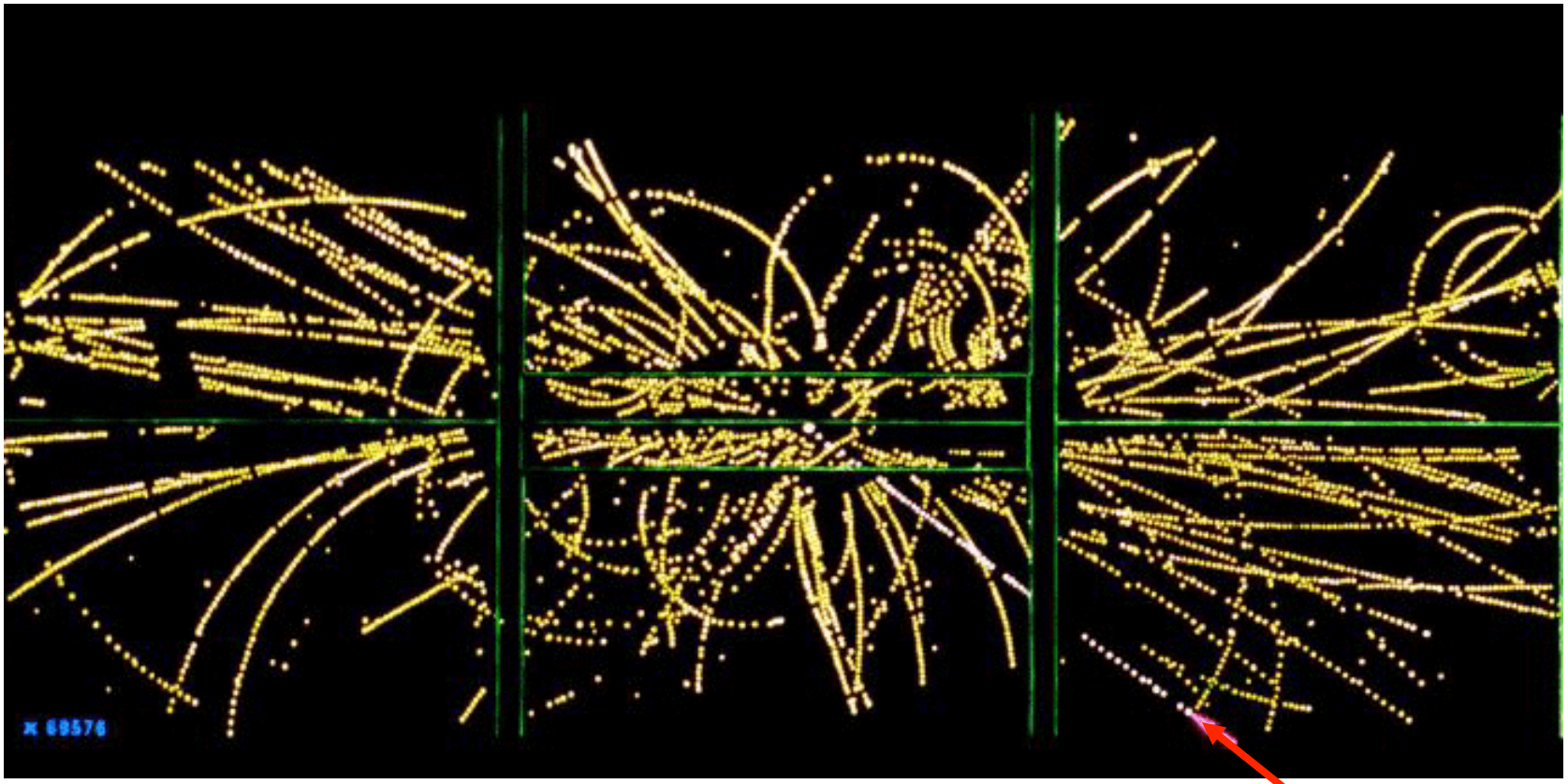


UA1: magnetic volume with trackers, surrounded by "hermetic" calorimeter and muon detectors



UA2: non-magnetic, calorimetric detector with inner tracker

One of the first W → e + ν events in UA1



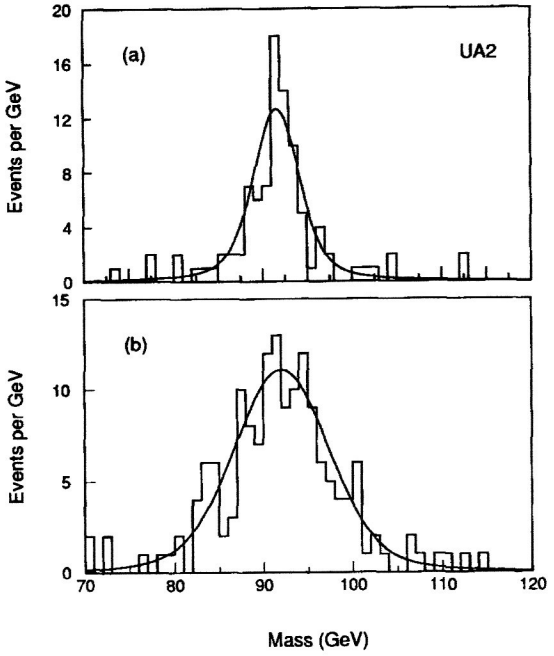
48 GeV electron identified by surrounding calorimeters

UA2 final results

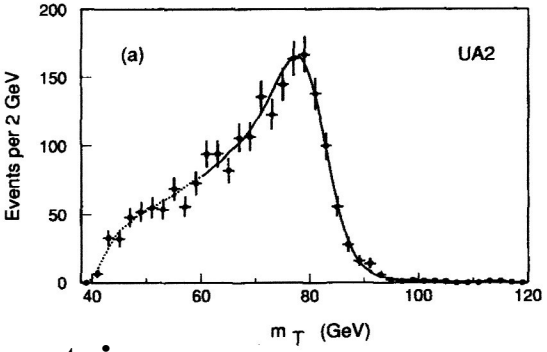
Events containing two high-energy electrons:
Distributions of the "invariant mass" M_{ee}

$$(M_{ee}c^2)^2 = (E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2 c^2$$

(for Z → e^+e^- $M_{ee} = M_Z$)



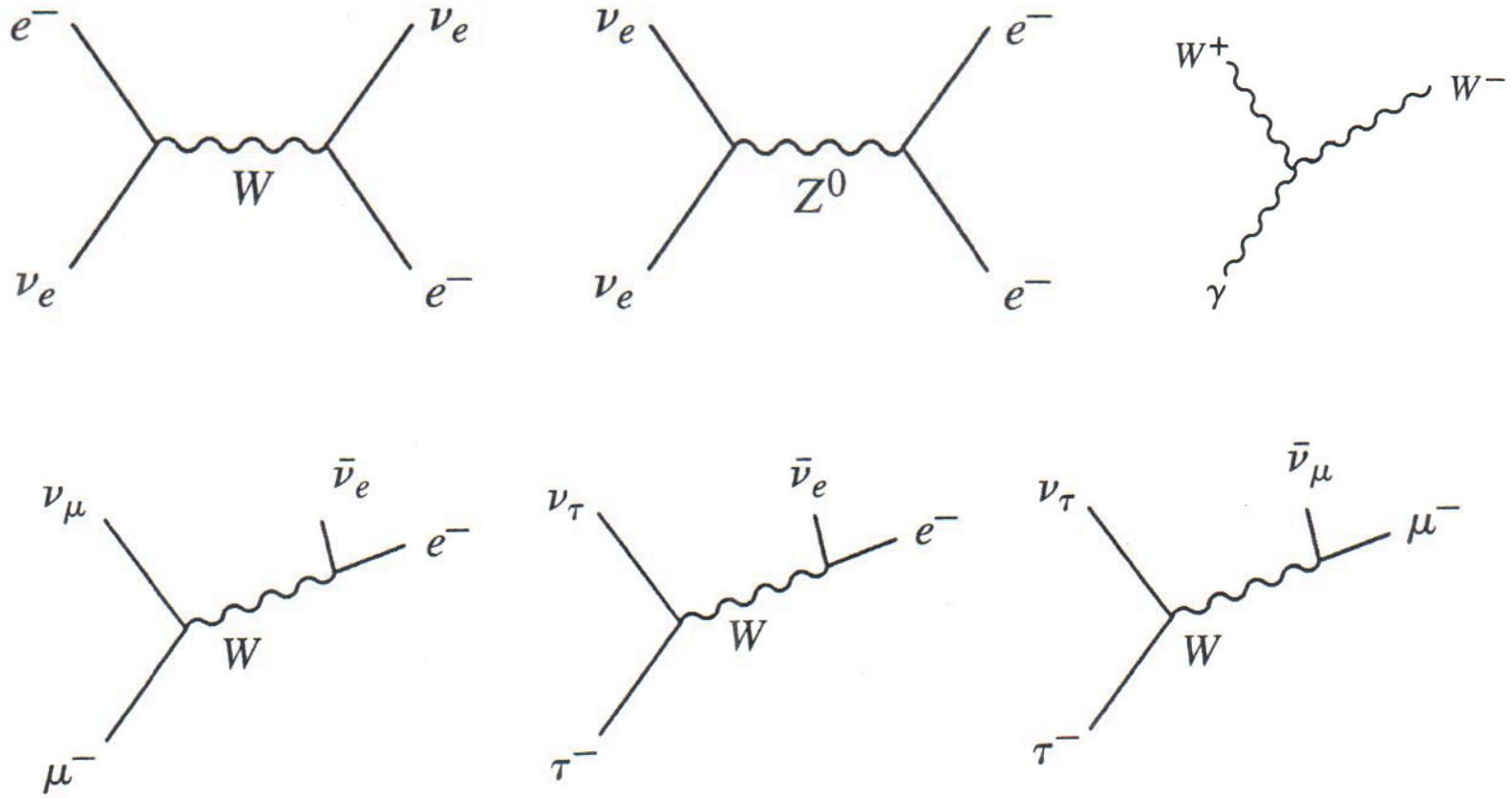
Events containing a single electron with large transverse momentum (momentum component perpendicular to the beam axis) and large missing transverse momentum (apparent violation of momentum conservation due to the escaping neutrino from W → e ν decay)



m_T ("transverse mass"): invariant mass of the electron – neutrino pair calculated from the transverse components only

M_W is determined from a fit to the m_T distribution: $M_W = 80.35 \pm 0.37$ GeV/c^2

Weak interactions: 3 carriers of the weak force: W^+, W^-, Z^0
Heavy - mass(W) =80.4 GeV, mass(Z) = 91.2 GeV



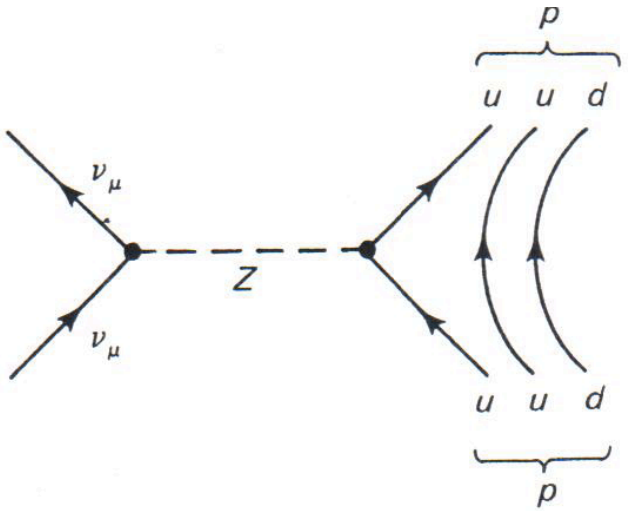
All observed W mediated processes indicate left-handed spin polarization of $W^{\pm}$. So far there is no evidence for right-handed W current. That leads to the uncomfortable list of quarks and leptons from the perspective of their spins: left-handed doublets, right-handed singlets and no info whether right-handed neutrino exist.

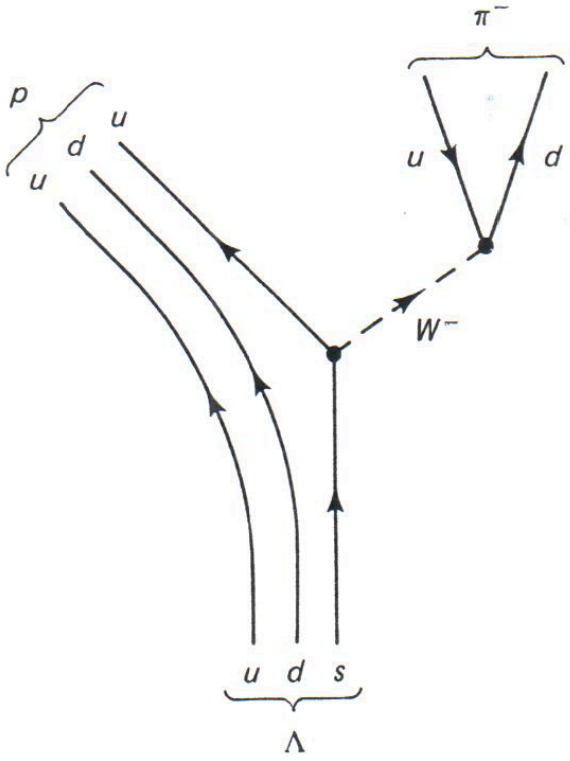
$$\begin{pmatrix} u \\ d \end{pmatrix}_L \quad \begin{pmatrix} c \\ s \end{pmatrix}_L \quad \begin{pmatrix} t \\ b \end{pmatrix}_L \qquad \begin{pmatrix} \nu_e \\ e \end{pmatrix}_L \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L \quad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$$

$$u_R \quad c_R \quad t_R$$

$$d_R \quad s_R \quad b_R \qquad e_R \quad \mu_R \quad \tau_R$$

The problem with the quarks: strange particles, e.g., kaons, decay into non-strange particles. The strange quark disappears. That would mean that weak interactions are not universal. The charged carriers of the force, W±, change the "flavor" of the quark while the flavor is conserved in neutral Z interactions .





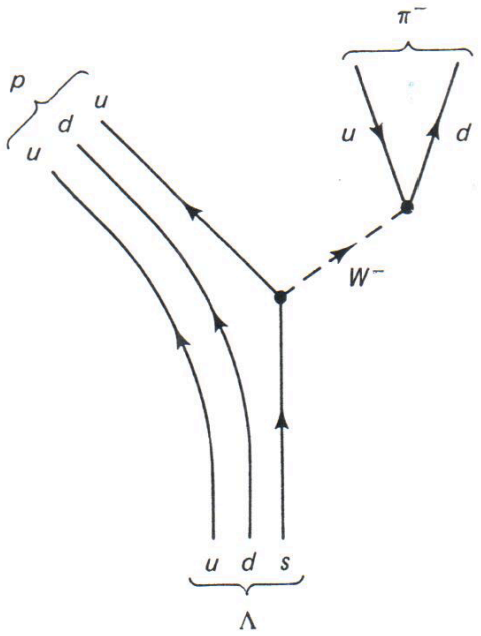
•*The problem with the quarks: strange particles, e.g., kaons, decay into non-strange particles. The strange quark disappears. That would mean that weak interactions are not universal. W can change the "flavor" of the quark. Z does not.*

•*Cabbibo (1963) proposed that the charge -1/3 quark in elementary particles is a* ***superposition*** *of down type quarks*

$$d' = V_{ud}\, d + V_{us}\, s = \cos\theta\, d + \sin\theta\, s$$

V_{ud} and V_{us} are probabilities of down-type quark decaying into the up quark.

•*The extension of that approach to all six quarks is a Cabbibo-Kobayashi-Maskawa (CKM) matrix*



CKM Matrix – Cabibbo-Kobayashi-Maskawa

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

Introducing unitarity – requirement that the total probability of decay is equal to 1 one can rewrite it in terms of sins and cosines and add an arbitrary phase.

$$\begin{bmatrix} c_1 & -s_1 c_3 & -s_1 s_3 \\ s_1 c_2 & c_1 c_2 c_3 - s_2 s_3 e^{i\delta} & c_1 c_2 s_3 + s_2 c_3 e^{i\delta} \\ s_1 s_2 & c_1 s_2 c_3 + c_2 s_3 e^{i\delta} & c_1 s_2 s_3 - c_2 c_3 e^{i\delta} \end{bmatrix}$$

The phase δ is responsible for the asymmetry in the decays of particles versus antiparticles i.e., CP violation.

Rate not sufficient to explain matter-antimatter asymmetry.

Quantities characterizing a particle(or system of particles)

Energy
Momentum
Angular momentum
Parity
Charge
Time reversal
Isospin
Baryon number
Flavor (including lepton flavors)
Color

Strong interactions conserve everything
Weak interaction allow for violations