Lecture 9.
Bump hunting - kinematics

Resonances have life time ~ 10^{-23}s, i.e., partial decay width of few hundred MeV. For our current best technology of detection of few μm, they decay practically at the point of production . As a result the observed final state consisting of "long lived particles" can be a result several different processes with different resonces in the intermediate final state,

$e^+ + e^- \rightarrow \varpi\, 2\pi^0 \rightarrow \pi^+ \pi^- 3\pi^0 \qquad \varpi \rightarrow \pi^+ \pi^- \pi^0$

$e^+ + e^- \rightarrow \eta\, \pi^+ \pi^- \rightarrow \pi^+ \pi^- 3\pi^0 \qquad \eta \rightarrow 3\pi^0$

$e^+ + e^- \rightarrow \pi^+ \pi^- 3\pi^0$

Each if these three processes has different kinematical distribution of the momenta vectors of the observable particles. Quantum Mechanics tells us that the amplitudes of these processes can interfere (same initial and same final states)

Lecture 9

Why strange ?

CP violation and K decays

1955 Gell-Mann and Pais: Second order weak interactions can turn K^0 with strangeness +1 into its antiparticle $\overline{K}^0$ with strangeness -1.

$$P|K^0> = -|K^0>$$

$$P|\overline{K}^0> = -|\overline{K}^0>$$

$$C|K^0> = |\overline{K}^0>$$

$$C|\overline{K}^0> = |K^0>$$

$$CP|K^0> = -|\overline{K}^0>$$

$$CP|\overline{K}^0> = -|K^0>$$

Observed neutral kaons are not single particles but linear combination of the two.

$$K_1 = \left(1/\sqrt{2}\right)\left(K^0 - \overline{K}^0\right)$$

$$K_2 = \left(1/\sqrt{2}\right)\left(K^0 + \overline{K}^0\right)$$

K_1 decays into states with CP=+1, K_2 decays into states with CP=-1

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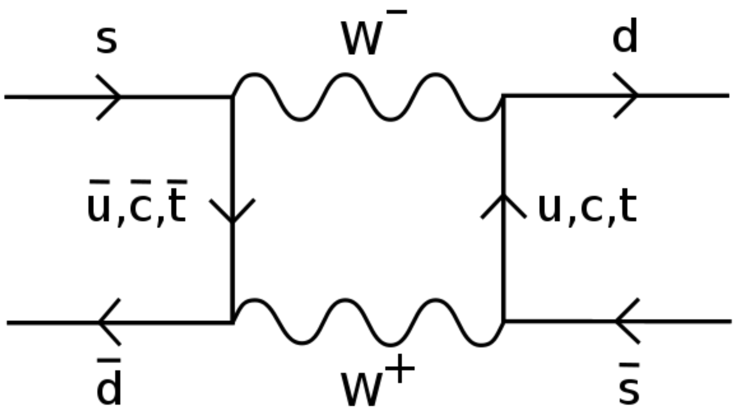
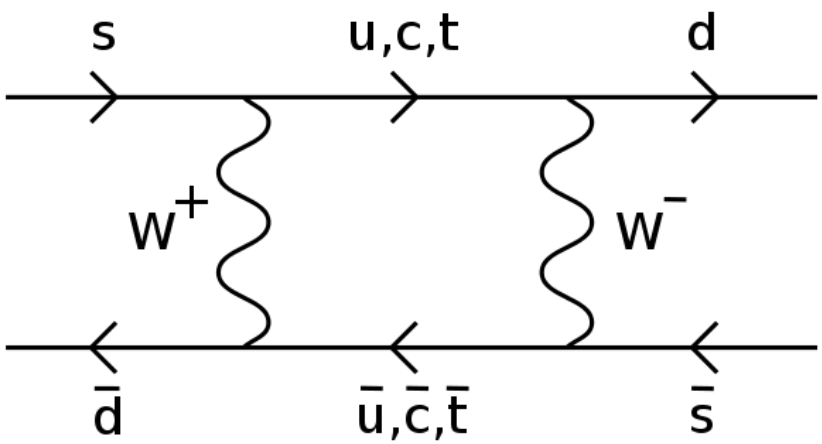
Feynman diagrams for K^0 oscillations





The neutral kaon

K_1 decays into two pions (P = +1, C = +1)
K_2 decays into three pions (P = - 1, C = +1)

$$K^0 = \left(1/\sqrt{2}\right)\left(K_1 + K_2\right)$$

Beam of neutral kaons will start with equal number of K_1 and K_2.
K_1 will oscillate into K_2 and vice versa.
K_1 decays faster because the energy released is greater so the composition of the beam is time dependent.

K_1 is called K^0_S (short)
K_2 is called K^0_L(long)

Similar CP violation has been also observed in neutral charm and bottom mesons D^0 and B^0.

The CP is not conserved in weak interactions.

*There is also an evidence for the CP violation in strong interactions The theory of strong interactions in the Standard Model formulation permits such violation due to complex structure of the vacuum. The CP violating interactions in QCD would induce large electric moment for the the neutron that is contrary to observation. (Neutron is electrically neutral, but nothing prevents it from having internal spatial distribution of charge generating dipole moment.) One proposed possible solution requires an existence of a new particle called **axion** that would have to be light and could also be a candidate for dark matter.*

Another neutrino

A puzzle of the late 1950's: the absence of $\mu \rightarrow e\,\gamma$ decays

Experimental limit: < 1 in 10^6 $\mu^+ \rightarrow e^+ \nu \bar{\nu}$ decays

A possible solution: existence of a new, conserved "muonic" quantum number distinguishing muons from "electronic" quantum numbeer

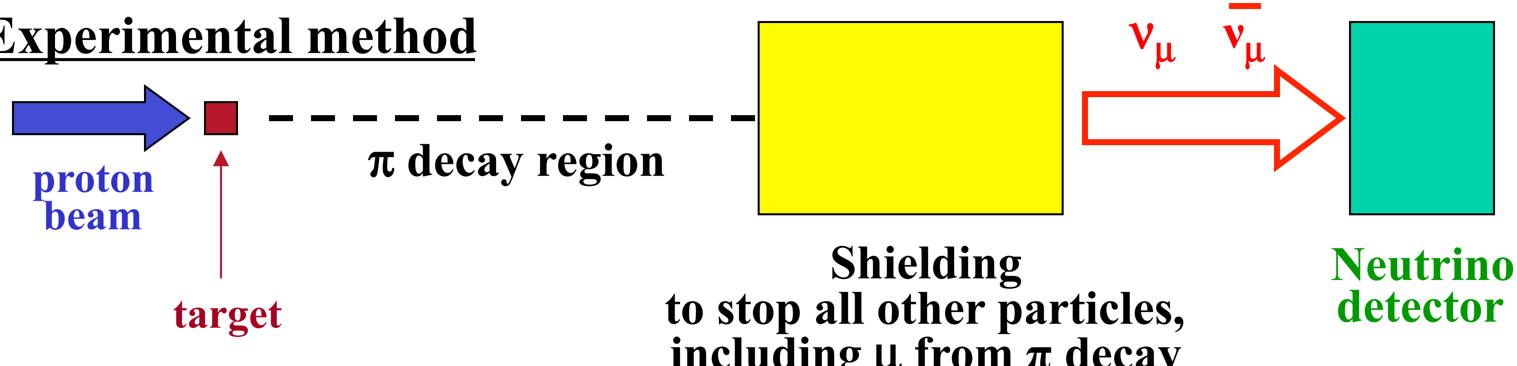
To allow $\mu^+ \rightarrow e^+ \nu \bar{\nu}$ decays, $\bar{\nu}$ must have "muonic" quantum number but not ν $\rightarrow$ in μ^+ decay the $\bar{\nu}$ is not the antiparticle of ν

$\rightarrow$ **two distinct neutrinos (ν_e, ν_μ) in the decay $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$**

Consequence for π – meson decays: $\pi^+ \rightarrow \mu^+ \nu_\mu$; $\pi^- \rightarrow \mu^- \bar{\nu}_\mu$ to conserve the "muonic" quantum number

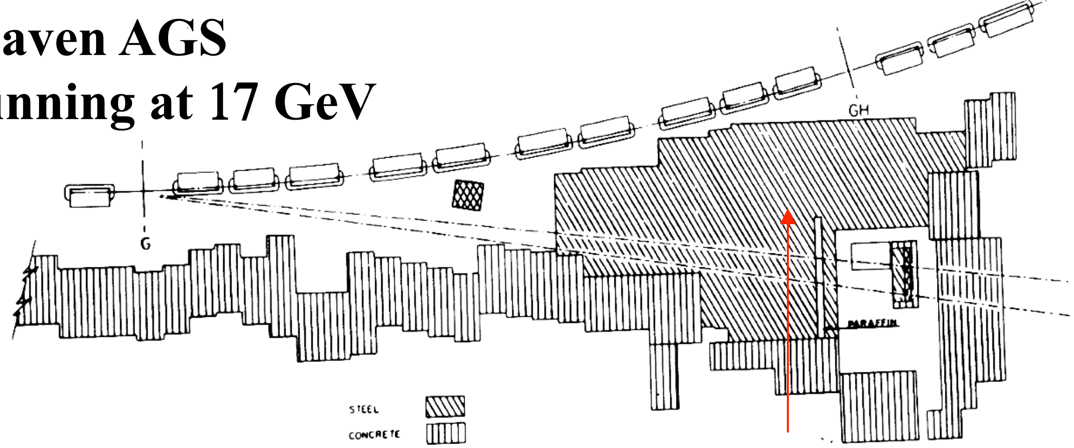
High energy proton accelerators: intense sources of $\pi^\pm$ – mesons $\rightarrow$ ν_μ, $\bar{\nu}_\mu$

Experimental method



If $\nu_\mu \rightarrow \nu_e$, then expect ν_μ interactions produce μ^- and not e^- (example: $\nu_\mu + n \rightarrow \mu^- + p$)

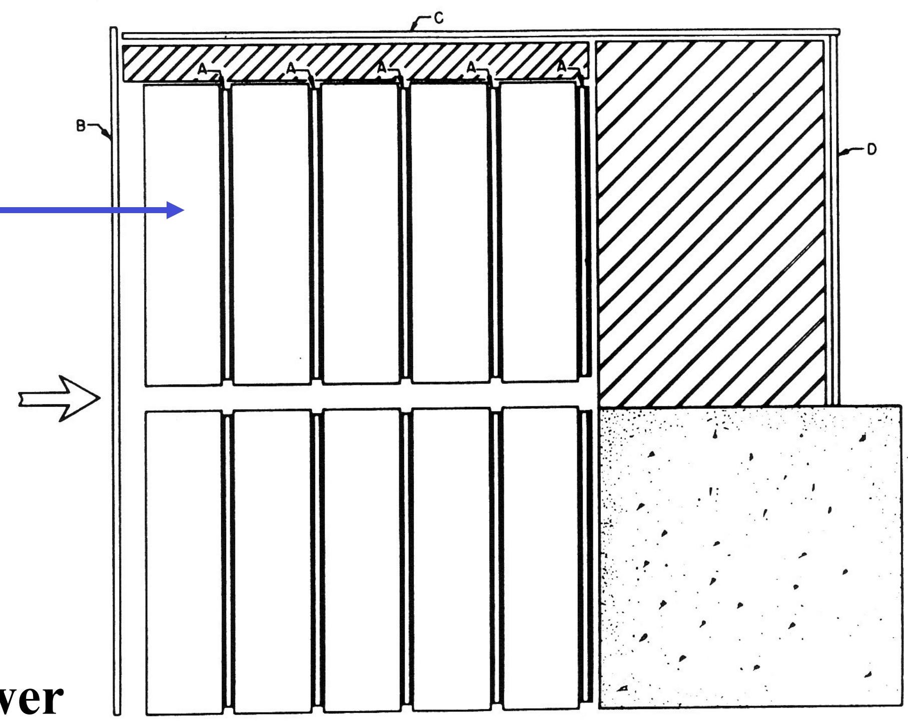
1962: ν_μ discovery at the Brookhaven AGS
(a 30 GeV proton synchrotron running at 17 GeV
for the neutrino experiment)



13. 5 m iron shielding
(enough to stop 17 GeV muons)

Neutrino energy spectrum
known from π, K production
and $\pi \rightarrow \mu$, K $\rightarrow \mu$ decay kinematics

Spark chamber
each with 9 Al plates
(112 x 112 x 2.5 cm)
mass 1 Ton



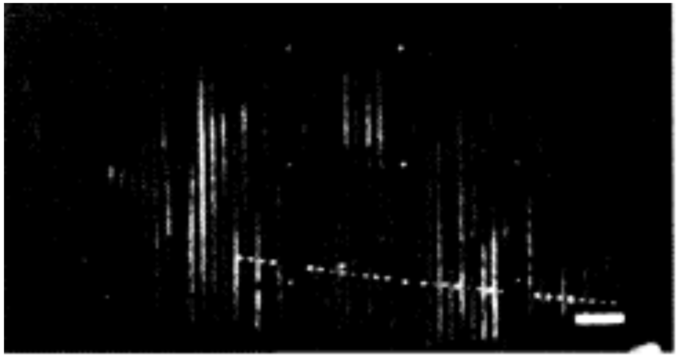
Neutrino detector

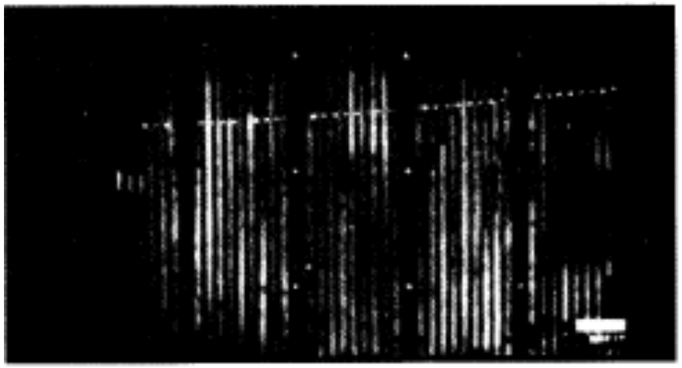
<u>Muon – electron separation</u>
Muon: long track
Electron: short, multi-spark event
from electromagnetic shower

64 "events" from a 300 hour run:

- **34 single track events, consistent with μ track**
- **2 events consistent with electron shower**
  (from small, calculable ν_e contamination in beam)

Clear demonstration that $\nu_\mu \neq \nu_e$





Three typical single-track events in the BNL neutrino experiment

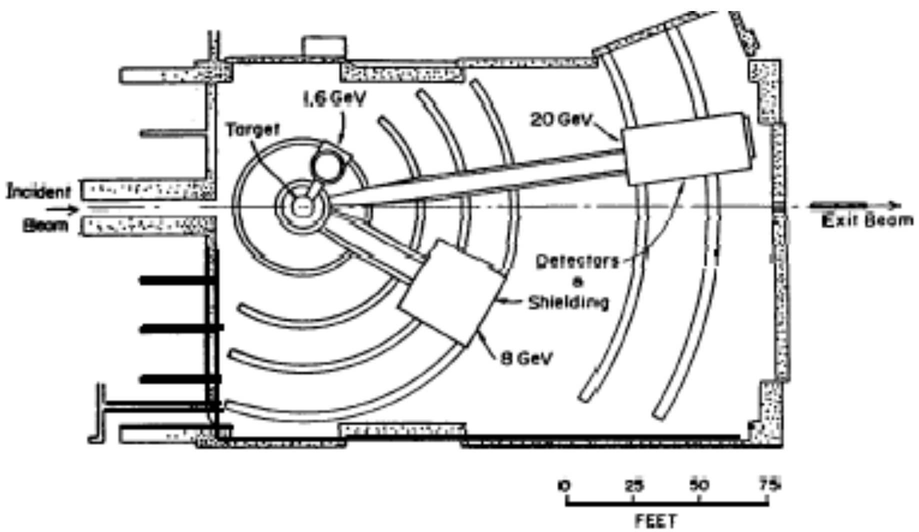
"DYNAMIC" EVIDENCE FOR QUARKS

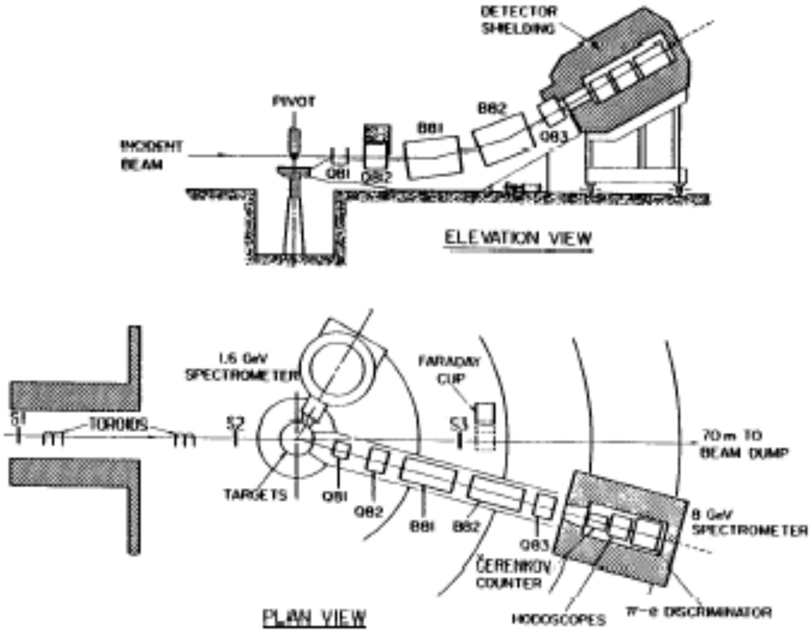
Electron – proton scattering using a 20 GeV electron beam from the Stanford two – mile Linear Accelerator.

The modern version of Rutherford's original experiment:
resolving power → wavelength associated with 20 GeV electron ≈ 10^{-15} cm

Three magnetic spectrometers to detect the scattered electron:

- **20 GeV spectrometer (to study elastic scattering $e^- + p \rightarrow e^- + p$)**
- **8 GeV spectrometer (to study inelastic scattering $e^- + p \rightarrow e^- +$ hadrons)**
- **1.6 GeV spectrometer (to study extremely inelastic collisions)**





The Stanford two-mile electron linear accelerator (SLAC)

Electron elastic scattering from a point-like charge |*e*| at high energies: differential cross-section in the collision centre-of-mass (Mott's formula)

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2(\hbar c)^2}{8E^2}\frac{\cos^2(\theta/2)}{\sin^4(\theta/2)} \equiv \sigma_M \qquad \left(\alpha = \frac{e^2}{\hbar c} \approx \frac{1}{137}\right)$$

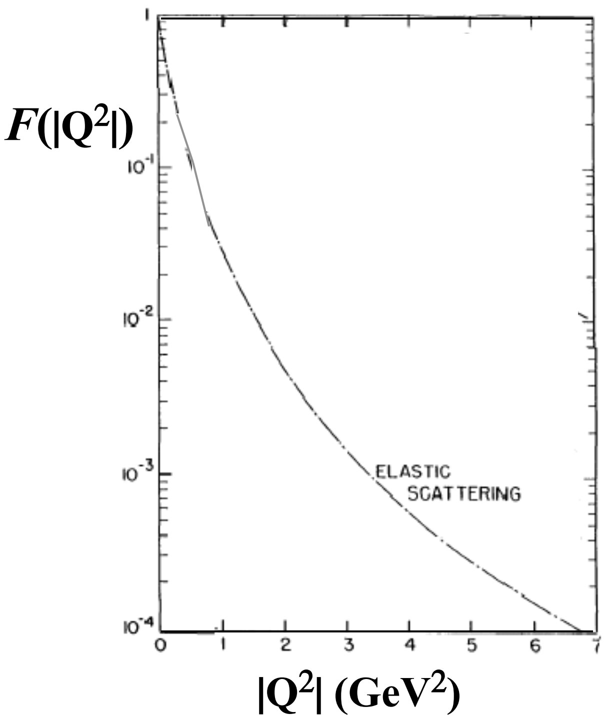
Scattering from an extended charge distribution: multiply σ_M by a "form factor":

$$\frac{d\sigma}{d\Omega} = F\left(\left|Q^2\right|\right)\sigma_M$$

|Q| = ħ / D : mass of the exchanged virtual photon

D: linear size of target region contributing to scattering

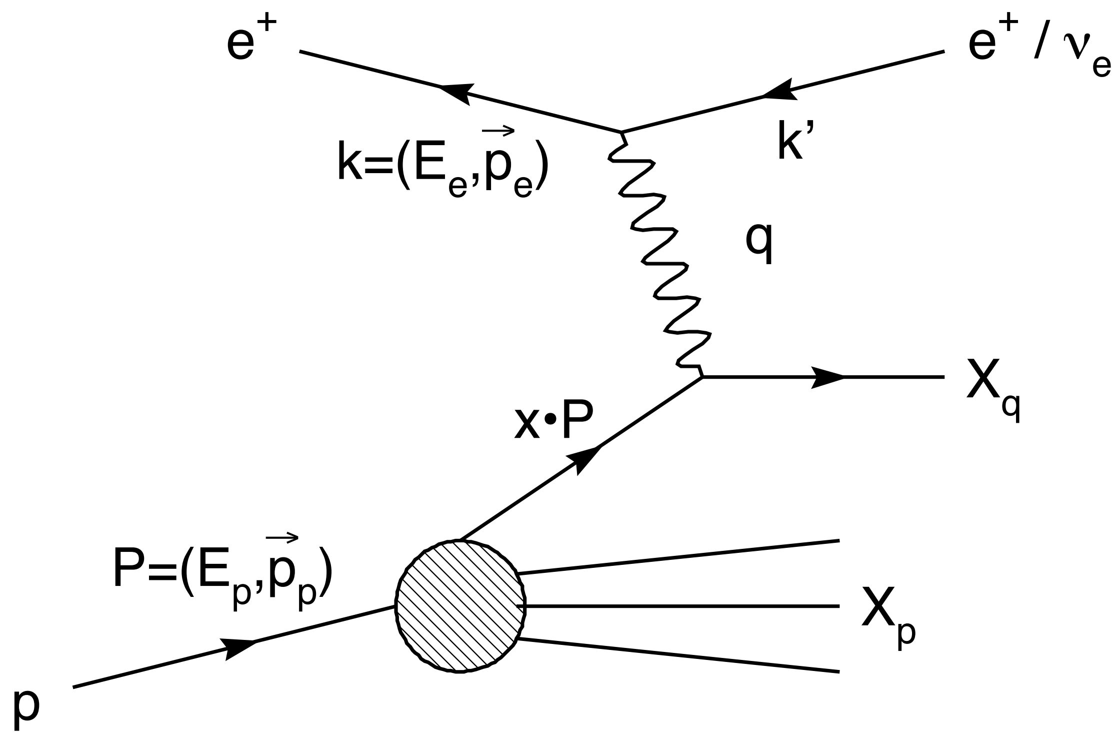
Increasing |Q| —> decreasing target electric charge



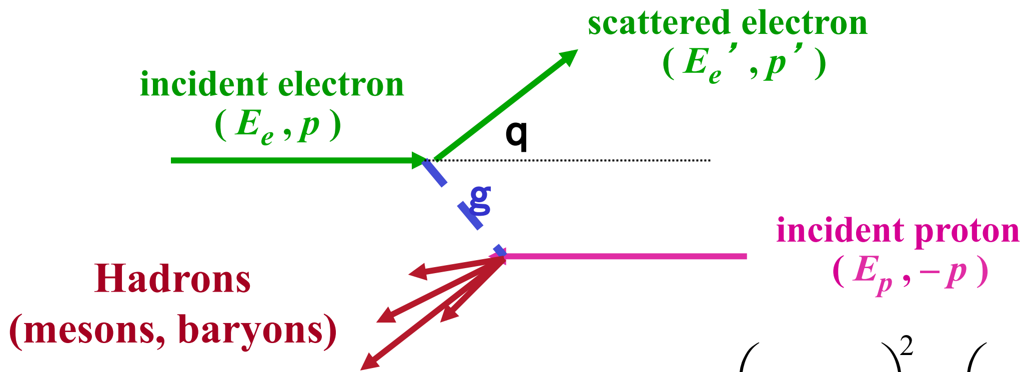
$F(|Q^2|) = 1$ for a point-like particle

➔ the proton is not a point-like particle

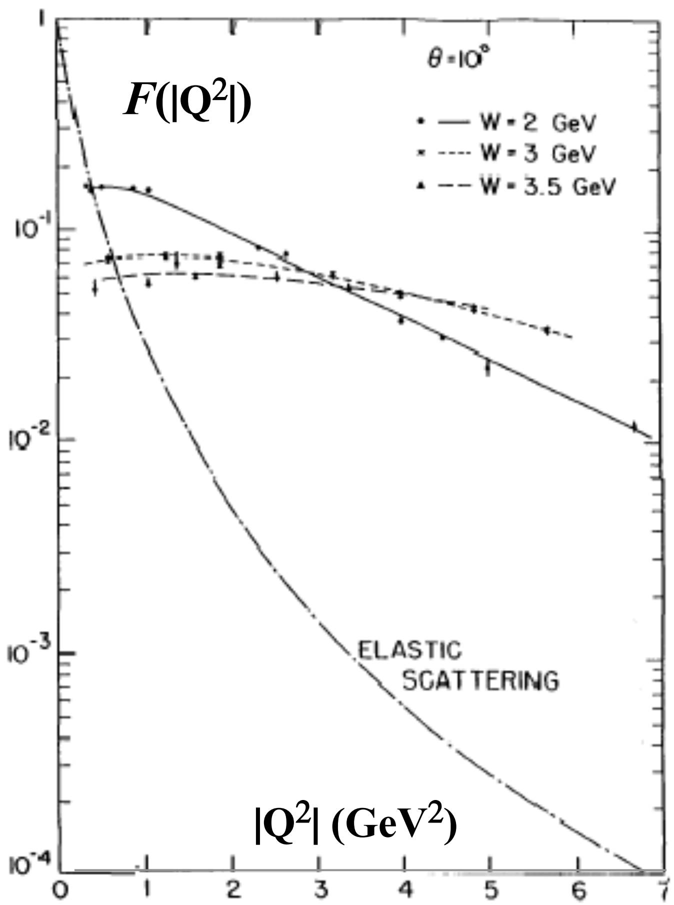
Kinematics of deep inelastic scattering



Inelastic electron – proton collisions 1974



Total hadronic energy : $W^2 = \left(\sum_i E_i\right)^2 - \left(\sum_i \vec{p}_i\right)^2 c^2$



For deeply inelastic collisions, the cross-section depends only weakly on $|Q^2|$, suggesting a collision with a POINT-LIKE object

Interpretation of deep inelastic e - p collisions

Deep inelastic electron – proton collisions are elastic collisions with point-like, electrically charged, spin ½ constituents of the proton carrying a fraction *x* of the incident proton momentum

Each constituent type is described by its electric charge e_i (units of $|e|$) and by its *x* distribution (dN_i/dx) ("structure function")

If these constituents are the *u* and *d* quarks, then deep inelastic e – p collisions provide information on a particular combination of structure functions:

$$\left(\frac{dN}{dx}\right)_{e-p} = e_u^{\ 2}\frac{dN_u}{dx} + e_d^{\ 2}\frac{dN_d}{dx}$$

Comparison with ν_μ – p and $\bar{\nu}_\mu$ – p deep inelastic collisions at high energies under the assumption that these collisions are also elastic scatterings on quarks

$\nu_\mu + p \rightarrow \mu^- +$ **hadrons :** $\nu_\mu + d \rightarrow \mu^- + u$ **(depends on dN_d / dx)**

$\bar{\nu}_\mu + p \rightarrow \mu^+ +$ **hadrons :** $\bar{\nu}_\mu + u \rightarrow \mu^+ + d$ **(depends on dN_u / dx)**

(Neutrino interactions do not depend on electric charge)

All experimental results on deep inelastic e – p , ν_μ – p, $\bar{\nu}_\mu$ – p collisions are consistent with $e_u^{\ 2} = 4/9$ and $e_d^{\ 2} = 1/9$

→ the proton constituents are the quarks

The parton model - Feynman, Yang, Bjorken

- *Quark content of the proton and neutron led to a question how the quarks are distributed inside. Feynman noticed that uncertainty principle allows for appearance of virtual quark-antiquark pairs: "wee" or "sea" quarks. The proton would then have three "valence" quarks providing the global characteristics and a sea of the virtual "wee" quarks.*
- *The proton-proton or meson-proton collisions would consist of a sum of valence-valence , valence-sea and sea-sea quarks collisions.*
- *As a consequence – we should observe "limiting fragmentation" where collisions between valence quarks carry most of the parents energies and the resulting distributions of secondaries depends solely on the distributions of energy carried by valence quarks. Sea quarks collisions should result in low cm energy secondaries and should be produced centrally in the cm rest frame. Since the number of virtual states depends on the energy, this central production of secondaries should increase proportionally to the energy of the parent particles collision.*

•*There is no hint in the theory to explain the origin of a distribution of energy carried by individual types of quarks inside the proton or neutron. Instead the pdf (parton distribution functions) are derived from a series of measurements using e± and neutrino and antineutrino beams. These are then used in Monte Carlo simulation of various physics processes. Fred Olness and Pavel Nadolsky are among leaders of CTEQ Collaboration doing that work.*

•*Aside: Even though we are able to simulate various processes with very high precision there is no understanding of the origin of pdf's and even more disturbing there is no understanding of the origin of the proton spin. Now that Higgs particle has been discovered there is an additional problem – we do not understand how proton gets its mass.*