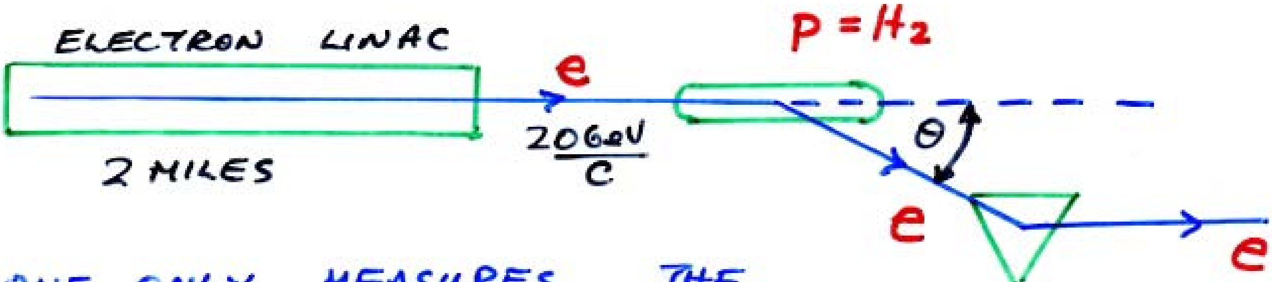
DEEP INELASTIC SCATTERING + DISCOVERY OF QUARKS

FIRST EXPERIMENTS – DICK TAYLOR et al
NOBEL PRIZE (1989)

BORN IN MEDICINE HAT.

THEORETICAL INTERPRETATION – RICHARD FEYNMAN
(QUARK – PARTON MODEL)

REMEMBER THE EXPERIMENTAL LAYOUT



ONE ONLY MEASURES THE ANGLE + MOMENTUM OF THE RECOILING ELECTRON → REMEMBER THAT THIS IS INELASTIC SCATTERING

ANALYZE MOMENTUM OF SCATTERED ELECTRON

ONE IS INTERESTED IN WHAT IS HAPPENING AT THE PROTON → HADRONIC SYSTEM

$$E_{h'} = \nu + m_p c^2$$
$$\bar{p}'_h = \bar{p}_e - \bar{p}'_e$$

PROPERTIES OF RECOILING HADRON SYSTEM, INFERED FROM ELECTRON

INVARIANT MASS OF HADRONIC SYSTEM.

$$W_h^2 = E_h'^2 - p_h'^2 c^2$$

$$= m^2c^4 + q^2c^2 + 2\nu m c^2$$

ALL LORENTZ SCALARS

$\therefore$

ALSO A LORENTZ SCALAR

$$W_h^2 = E_h'^2 - p_h'^2 c^2$$

$$= (\nu + m_p c^2)^2 - p_h' c^2$$

$$= \nu^2 + 2 m_p c^2 \nu + m_p^2 c^4 - p_h' c^2$$

BY DEFINITION! $q^2 = \nu^2 - p_h'^2$ $(c=1)$

$$\boxed{W_h^2 = q^2 c^2 + m_p^2 c^4 + 2 m_p \nu c^2}$$

HAVE PUT c IN EXPLICITLY

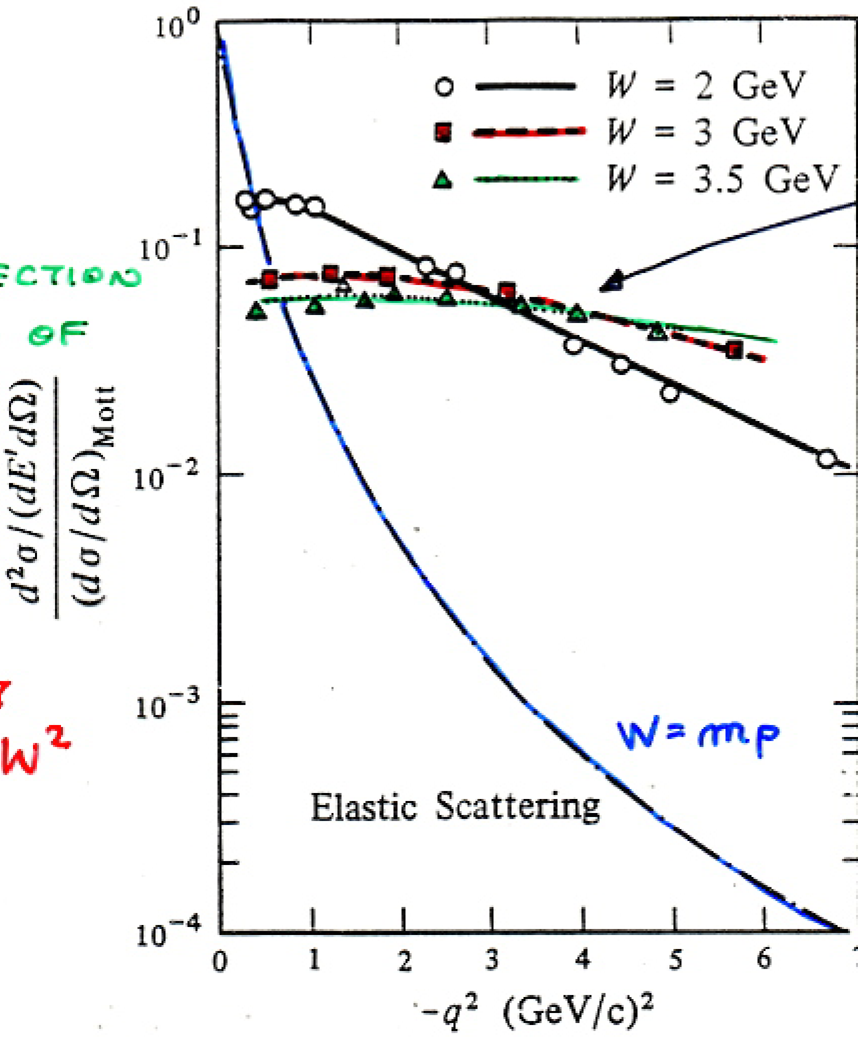
$$m^2 c^2 = \left(\frac{E}{c}, \bar{p}\right)\left(\frac{E}{c}, \bar{p}\right)$$

DISCOVERY OF PARTONS – SCALING

BREIDENBACH et al 1968 @ SLAC

$ep \to eX$

CROSS SECTION AS RATIO OF SCATTERING FROM POINT CROSS SECTION



INDEPENDENT OF q^2 AND W

NO FORM FACTOR

POINT SCATTERING TARGET

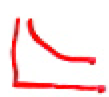
• RUN AT FIXED W^2

LOOK AT $\frac{d\sigma}{dq^2}$

FORM FACTOR $F(q^2)$

ONE FINDS A DRAMATIC DIFFERENCE BETWEEN

ELASTIC

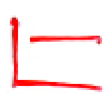


q^2

FORM FACTOR

EXTENDED TARGET

DEEP INELASTIC



q^2

NO FORM FACTOR

POINT TARGET

JUST RUTHERFORD SCATTERING !

19
29

OBSERVED BEHAVIOR OF HIGHLY INELASTIC ELECTRON-PROTON SCATTERING

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(Received 22 August 1969)

Results of electron-proton inelastic scattering at 6° and 10° are discussed, and values of the structure function W_2 are estimated. If the interaction is dominated by transverse virtual photons, νW_2 can be expressed as a function of $\omega = 2M\nu/q^2$ within experimental errors for $q^2 > 1$ (GeV/c)^2 and $\omega > 4$, where ν is the invariant energy transfer and q^2 is the invariant momentum transfer of the electron. Various theoretical models and sum rules are briefly discussed.

In a previous Letter,[1] we have reported experimental results from a Stanford Linear Accelerator Center–Massachusetts Institute of Technology study of high-energy inelastic electron-proton scattering. Measurements of inelastic spectra, in which only the scattered electrons were detected, were made at scattering angles of 6° and 10° and with incident energies between 7 and 17 GeV. In this communication, we discuss some of the salient features of inelastic spectra in the deep continuum region.

One of the interesting features of the measurements is the weak momentum-transfer dependence of the inelastic cross sections for excitations well beyond the resonance region. This weak dependence is illustrated in Fig. 1. Here we have plotted the differential cross section divided by the Mott cross section, $(d^2\sigma/d\Omega dE')/(d\sigma/d\Omega)_{\rm Mott}$, as a function of the square of the four-momentum transfer, $q^2 = 2EE'(1-\cos\theta)$, for constant values of the invariant mass of the recoiling target system, W, where $W^2 = 2M(E-E') + M^2 - q^2$. E is the energy of the incident electron, E' is the energy of the final electron, and θ is the scattering angle, all defined in the laboratory system; M is the mass of the proton. The cross section is divided by the Mott cross section

$$\left(\frac{d\sigma}{d\Omega}\right)_{\rm Mott} = \frac{e^4}{4E^2}\frac{\cos^2\frac{1}{2}\theta}{\sin^4\frac{1}{2}\theta}$$

in order to remove the major part of the well-known four-momentum transfer dependence arising from the photon propagator. Results from both 6° and 10° are included in the figure for each value of W. As W increases, the q^2 dependence appears to decrease. The striking difference between the behavior of the inelastic and elastic cross sections is also illustrated in Fig. 1, where the elastic cross section, divided by the Mott cross section for $\theta = 10°$, is included. The q^2 dependence of the deep continuum is also consider-

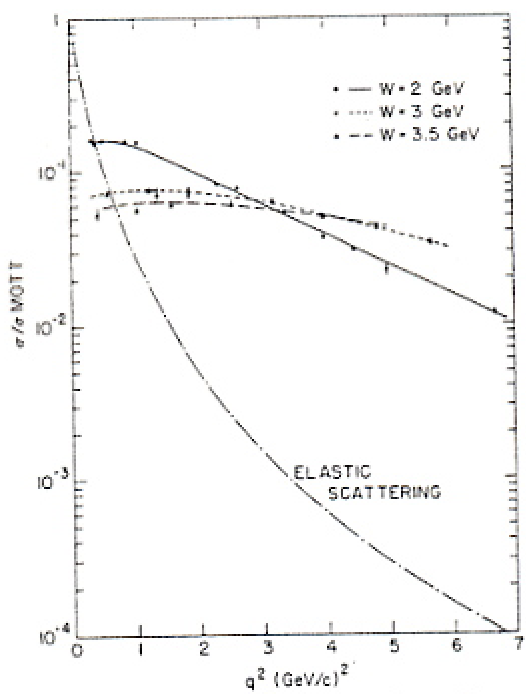


FIG. 1. $(d^2\sigma/d\Omega dE')/\sigma_{\rm Mott}$, in GeV^{-1}, vs q^2 for W = 2, 3, and 3.5 GeV. The lines drawn through the data are meant to guide the eye. Also shown is the cross section for elastic e-p scattering divided by $\sigma_{\rm Mott}$, $(d\sigma/d\Omega)/\sigma_{\rm Mott}$, calculated for $\theta = 10°$, using the dipole form factor. The relatively slow variation with q^2 of the inelastic cross section compared with the elastic cross section is clearly shown.

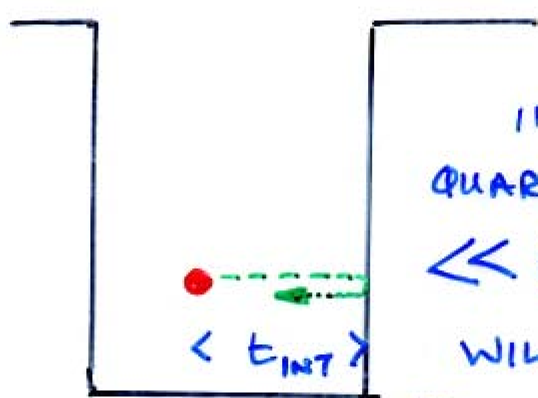
PARTON MODEL OF DEEP INELASTIC SCATTERING

THE DEEP INELASTIC SCATTERING RESULTS LOOK LIKE SCATTERING FROM FREE POINT CHARGES IN PROTON. BUT THEY MUST BE STRONGLY BOUND (= NOT FREE) SINCE THEY ARE CONFINED.

IF WE EXAMINE THE QUARKS DURING A SHORT SPACE TIME INTERVAL, CAN FREEZE QUARK FERMI MOTION DUE TO BINDING FORCE

THIS IS IMPULSE APPROXIMATION

IMAGINE A QUARK INSIDE THE PROTON POTENTIAL WELL :-



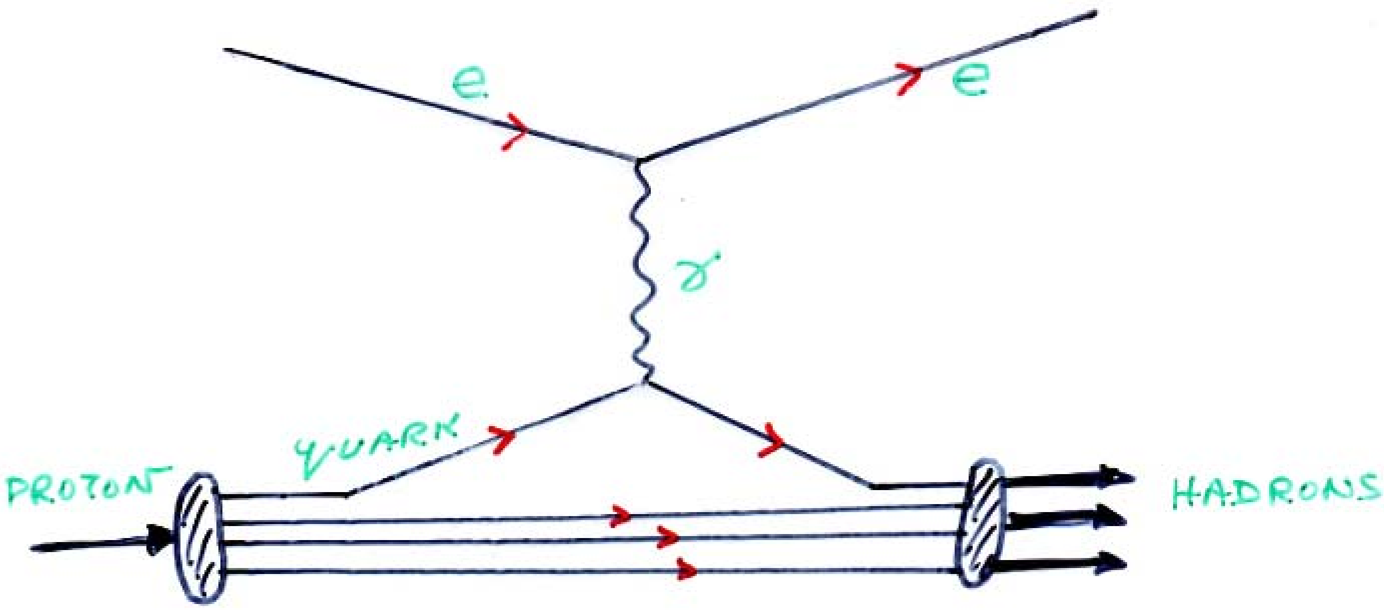
IF YOU CAN EXAMINE QUARK IN A TIME $\ll t_{INT}$ THEN IT WILL APPEAR FREE EVEN THO' TIGHTLY BOUND.

$$\Delta t \sim \frac{\hbar}{\Delta E}$$

$$\Delta x \sim \frac{\hbar}{\Delta p}$$

TO INVESTIGATE A SMALL SPACE-TIME INTERVAL $E, \bar{p}$ MUST BOTH BE LARGE $\rightarrow$ SHORT WAVE LENGTH PROBE

LARGE $|q|^2$



$$\left(\frac{d\sigma}{d\Omega}\right)_{RUTH} = \frac{4m^2 \left(Z_1 Z e^2\right)^2}{q^4}$$

→ NOW HAVE ELASTIC SCATTERING FROM QUARKS. Ze IS ANALOGOUS TO QUARK CHARGE

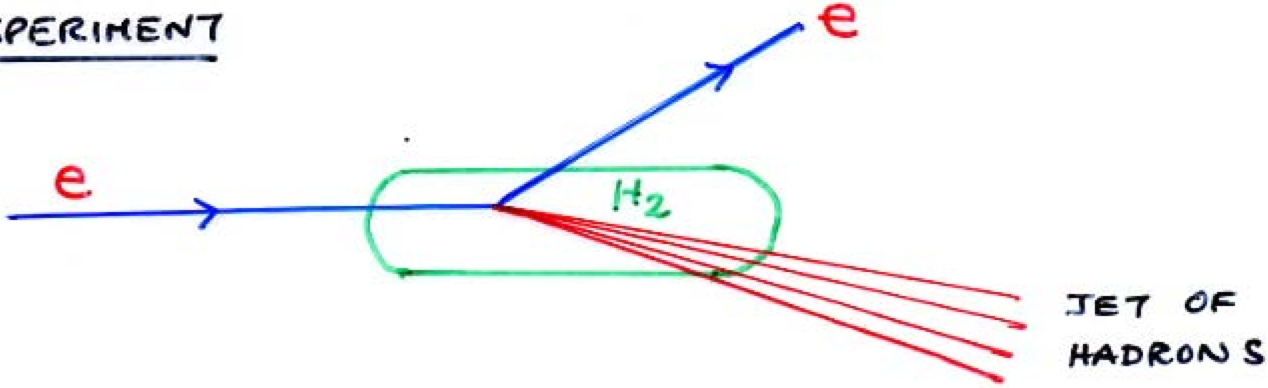
⇒ TAKE RMS AVERAGE OF QUARK CHARGES

$$\sigma_{DIS} \sim \frac{1}{3}\left[\left(\frac{2}{3}\right)^2 + \left(\frac{2}{3}\right)^2 + \left(\frac{1}{3}\right)^2\right] e^2$$

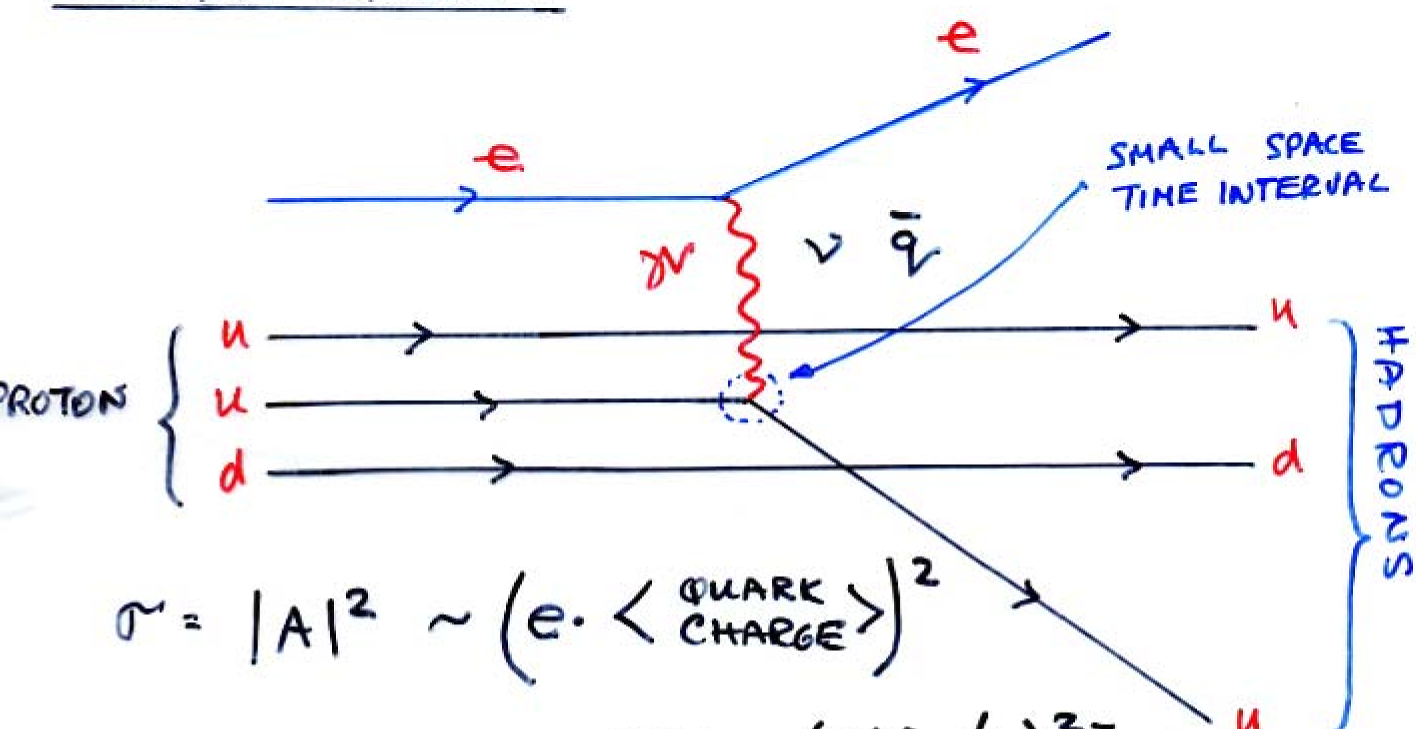
$$\sigma_{DIS} \sim \frac{1}{3}\,\sigma_{\substack{\text{ELECTRON}\\ \text{TARGET}}}$$

PHYSICAL INTERPRETATION OF DEEP INELASTIC SCATTERING AMPLITUDE

EXPERIMENT



FEYNMAN DIAGRAM

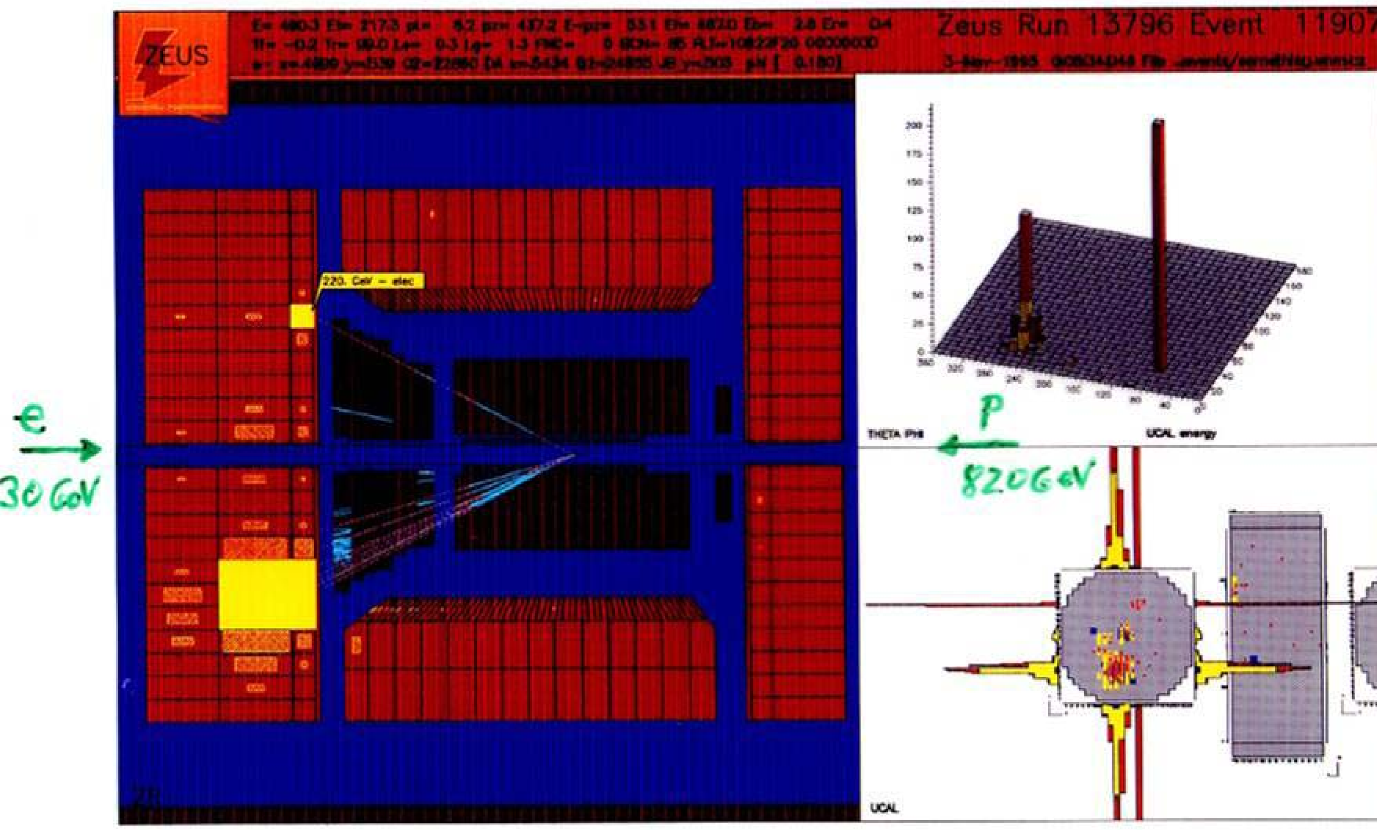


$$\sigma = |A|^2 \sim \left(e \cdot \langle \text{QUARK CHARGE} \rangle\right)^2$$

$$\sim \frac{1}{3}\Big[\underset{u}{\left(\tfrac{2}{3}\right)^2} + \underset{u}{\left(\tfrac{2}{3}\right)^2} + \underset{d}{\left(\tfrac{1}{3}\right)^2}\Big] e^2$$

$$\sigma \simeq \frac{1}{3} e^2 \sim \frac{1}{3} \left(\begin{array}{c}\text{POINT SCATTERER} \\ \text{OF CHARGE } e\end{array}\right)$$

ELECTRON - PROTON SCATTERING @ HERA



CAN EASILY CALC RATIO OF

$$\frac{\sigma_p}{\sigma_d} = \frac{\text{LIQUID } H_2}{\text{LIQUID } D_2} \leftarrow \text{ISOSCALAR}$$

$$\sigma_p \sim \frac{e^2}{3}$$

FOR A NEUTRON HAVE ddu

$$\sigma_n \sim \frac{e^2}{3}\left\{\left(\frac{1}{3}\right)^2 + \left(\frac{1}{3}\right)^2 + \left(\frac{2}{3}\right)^2\right\} = \frac{2e^2}{9}$$

$$\frac{\sigma_{ep}}{\sigma_{en}} = \frac{e^2}{3} \cdot \frac{9}{2e^2} = \frac{3}{2}$$

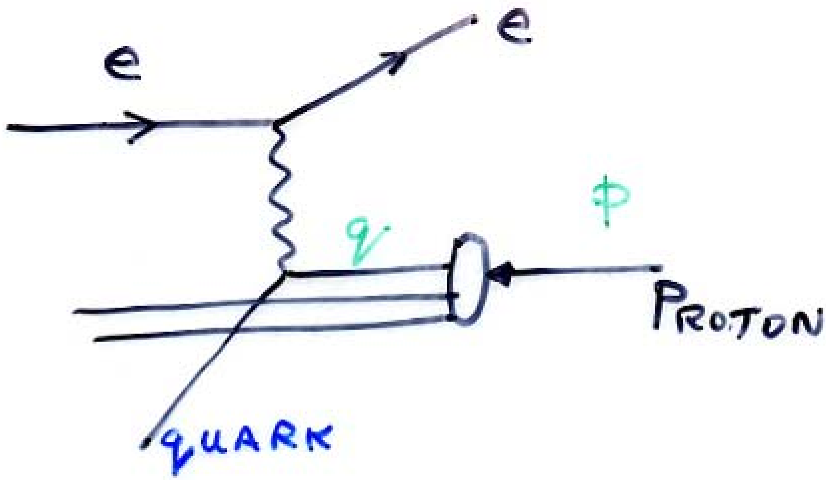
FOR DEUTERIUM ONE HAS $\#d = \#u$

$$\sigma_d \sim e^2 \left\{ \frac{3\left(\frac{1}{3}\right)^2 + 3\left(\frac{2}{3}\right)^2}{6} \right\}$$

$$\sim \frac{e^2}{2} \cdot \frac{5}{9}$$

$$\frac{\sigma_{ed}}{\sigma_{ep}} = \frac{3}{2} \cdot \frac{5}{9}$$

TYPICAL OF SIMPLE BUT AMAZING PARTON MODEL PREDICTIONS



$$x = \frac{\text{QUARK MOMENTUM}}{\text{PROTON MOMENTUM}}$$

$$x = \frac{q}{P} \qquad (0 < x < 1)$$

$$\begin{matrix} W_1(q^2, \nu) \\ W_2(q^2, \nu) \end{matrix} \quad \Rightarrow \quad \begin{matrix} F_1(x) \\ F_2(x) \end{matrix}$$

FOR SPIN $\frac{1}{2}$ PARTONS

$$\boxed{F_2(x) = 2xF_1(x)}$$

MEASUREMENT OF PARTON SPINS

SAY A PROTON HAS 4-MOMENTUM P

EACH PARTON HAS 4-MOMENTUM xP

SUPPOSE PARTON ABSORBS q FROM γ^*

$$(xP + q)^2 = m^2_{PARTON} \sim 0$$

THEY BEHAVE LIKE THIS

$$\cancel{x}P^2 + q^2 + 2xP.q = 0$$

$$x^2 P^2 = x^2 M^2_{PROTON}$$

THIS IS $\ll q^2 \Rightarrow q^2 + 2xPq = 0$

$$\therefore \; x = -\frac{q^2}{2P.q}$$

$$(M_P, 0)(\nu\, \vec{q}^{\,2}) = 2 M_P \nu$$

$$Q^2 = -q^2$$

$$x = \frac{-q^2}{2M_P\nu}$$

DIMENSIONLESS

$$W(q^2, \nu) \rightarrow W(q^2/\nu) \rightarrow F(x)$$

INDEPENDENT OF q^2 — SCALE INVARIANCE

$\rightarrow$ POINT SCATTERING

SUMMARY

- FOR DEEP INELASTIC SCATTERING THERE ARE, IN GENERAL
  - TWO KINEMATIC VARIABLES

$$q \equiv q(\nu, \bar{p})$$

  - TWO PROTON STRUCTURE FUNCTIONS

$$W_1(\underbrace{\nu, q^2}_{\text{TWO VARIABLES}}) \quad W_2(\nu, q^2)$$

- FOR LARGE q^2 THESE STRUCTURE FUNCTIONS DEPEND ON ONE VARIABLE

$$x = \frac{q^2}{2M_p\nu}$$

$$F_1(x) \quad , F_2(x)$$

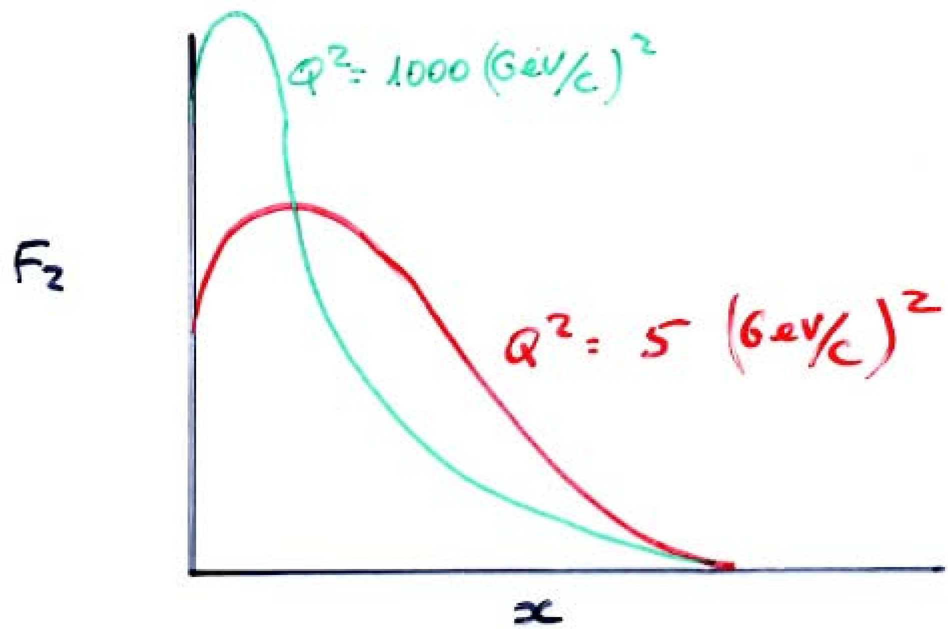
⇨ ELASTIC SCATTERING OFF POINT PARTONS

↳ NO LENGTH SCALE

↳ SCALE INVARIANCE

→ FOR A VERY LARGE RANGE OF q^2, SEE THAT

$$F_2(x) \rightarrow F_2(x, q^2)$$



⇒ SCALE BREAKING IS EFFECT OF QCD.

$$\alpha_s(q^2) = \frac{\alpha_s(q_0^2)}{1 + \ln\left(\frac{q^2}{q_0^2}\right) \cdot B \cdot \alpha_s(q_0^2)}$$

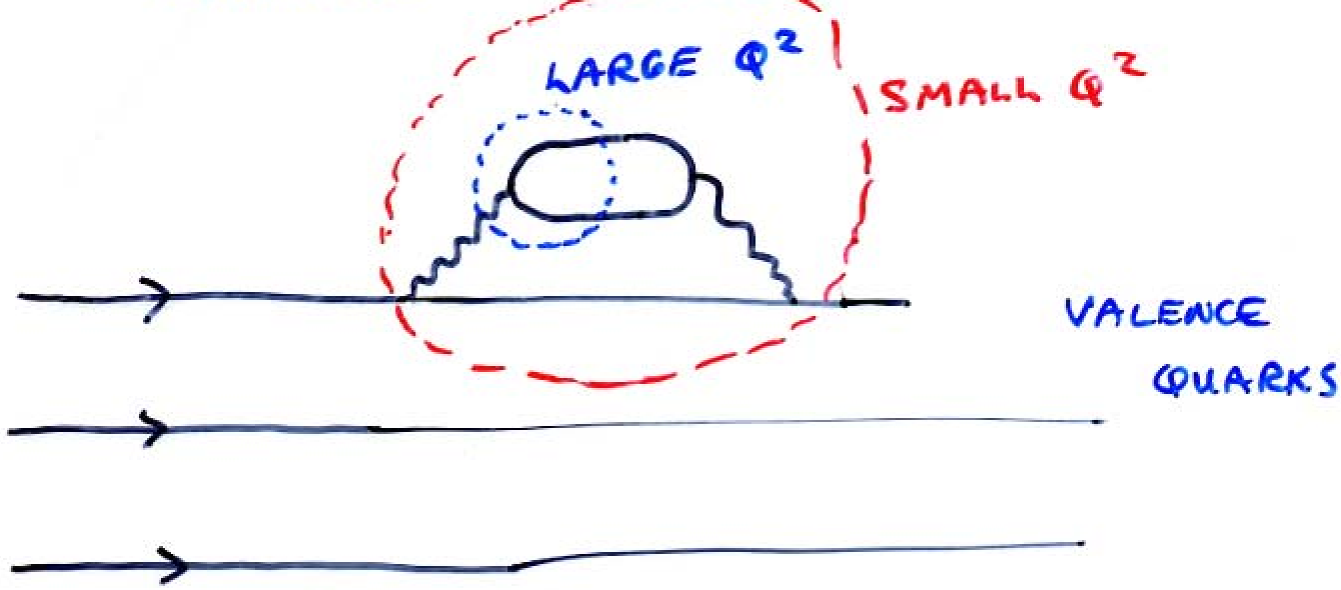
$$= \frac{1}{B \ln \frac{q^2}{\Lambda^2}}$$

QCD SCALE PARAM.

$$\alpha_s(q^2) = \frac{1}{B \ln \frac{q^2}{\Lambda^2}}$$

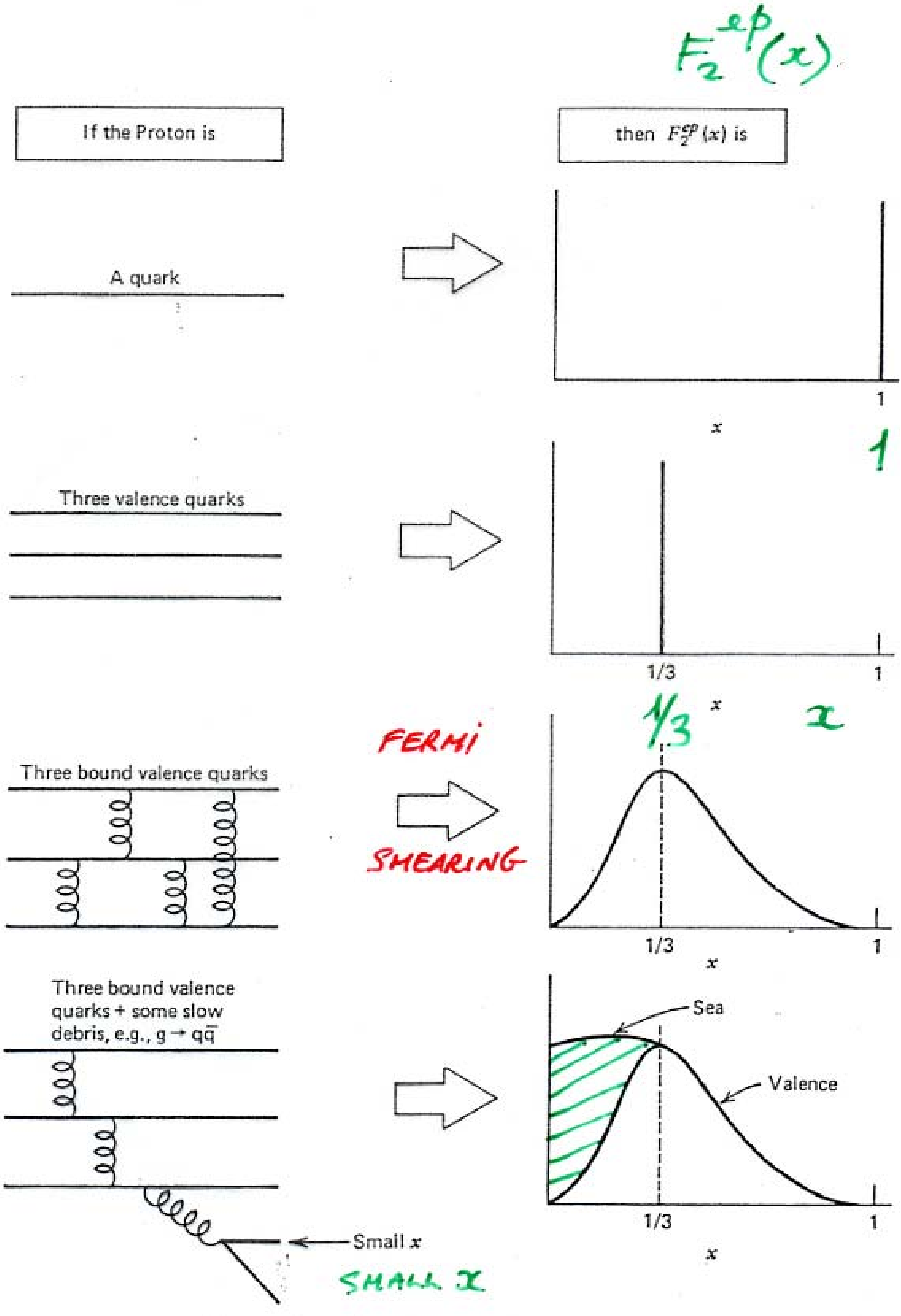
⇒ THE EFFECTIVE NO. OF GLUONS DECREASES AS Q^2 INCREASES

⇒ SAME AS DECREASING PROBED DISTANCE



AT LARGE Q^2 SEE MORE LOW x (= MOMENTUM) QUARKS

DRAMATIC CONFIRMATION OF QCD.



$F_2^{ep}(x)$
If the Proton is
then $F_2^{ep}(x)$ is
A quark
1
x
1
Three valence quarks
1/3
1
x
1/3
x
FERMI
SMEARING
Three bound valence quarks
1/3
1
x
Three bound valence quarks + some slow debris, e.g., $g \to q\bar{q}$
Sea
Valence
Small x
1/3
1
x
SMALL x

THE MOMENTUM DISTRIBUTION OF QUARKS INSIDE PROTON, CANNOT BE CALCULATED → MEASURE

$$\frac{d^2\sigma}{dq^2 d\nu} = \frac{4\pi\alpha^2}{q^4}\frac{E'}{EM_p}\left[W_2(q^2,\nu)\cos^2\frac{\theta}{2} + 2W_1(q^2,\nu)\sin^2\frac{\theta}{2}\right]$$

PROTON STRUCTURE FUNCTIONS

⇒ BY MEASURING

$$\frac{d^2\sigma}{dq^2 d\nu}$$

AS A FUNCTION OF E', θ

ONE CAN MEASURE

$W_1(q^2,\nu)$, $W_2(q^2,\nu)$ AS FUNCTIONS OF q^2, ν

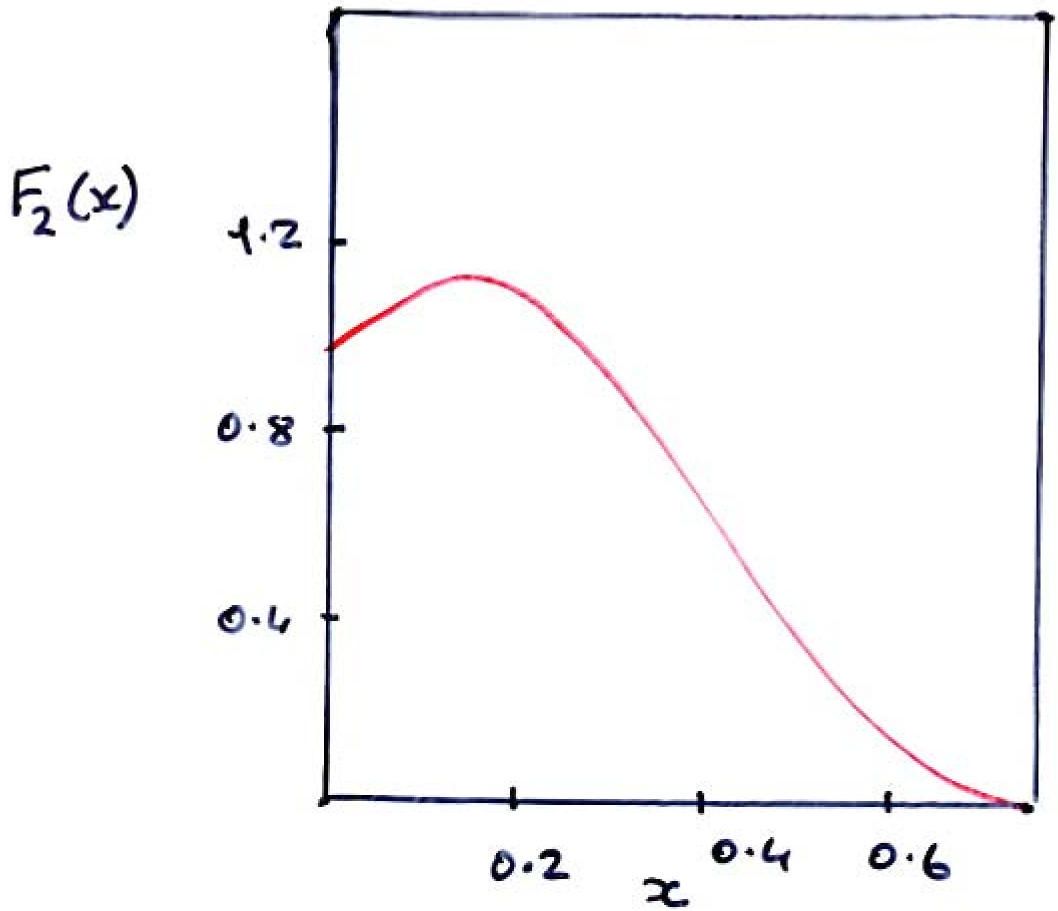
⇒ ONLY FUNCTIONS OF

$$x = q^2/2M_p\nu$$

SCALING

↓

POINT SCATTER



⇒ MOMENTUM DISTRIBUTION OF VALENCE QUARKS

$$\int F_2(x)\, dx \rightarrow \int x \, \vec{p} \, (u(x) + d(x))\, dx$$

FRACTION OF PROTON MOMENTUM CARRIED BY QUARKS $= 50\%$? GLUONS CARRY REST.

$\hookrightarrow$ @ $Q^2 \approx 1 - 10 \left(\frac{GeV}{c}\right)^2$

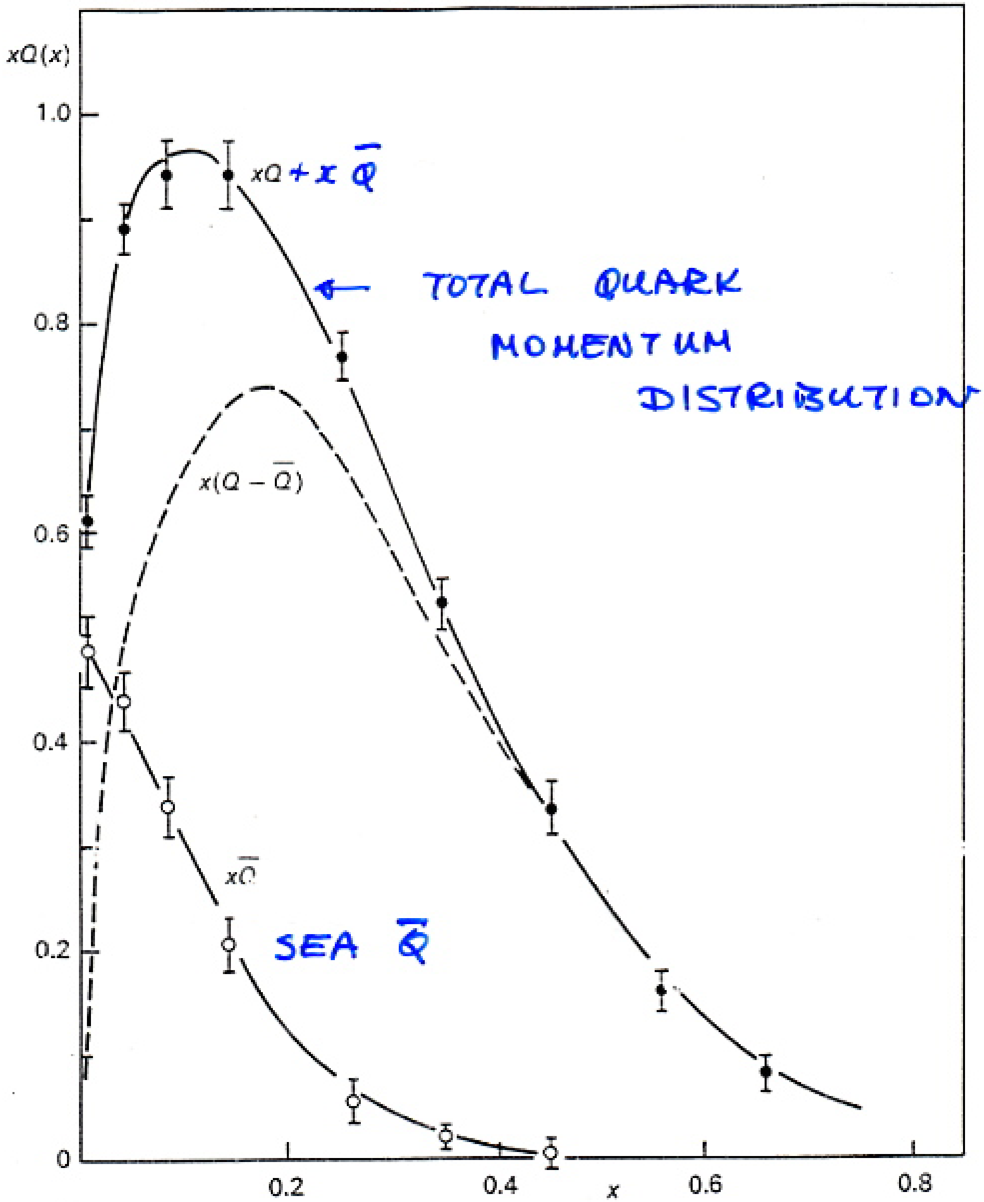
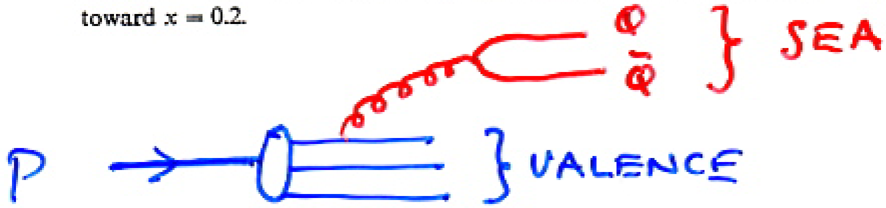
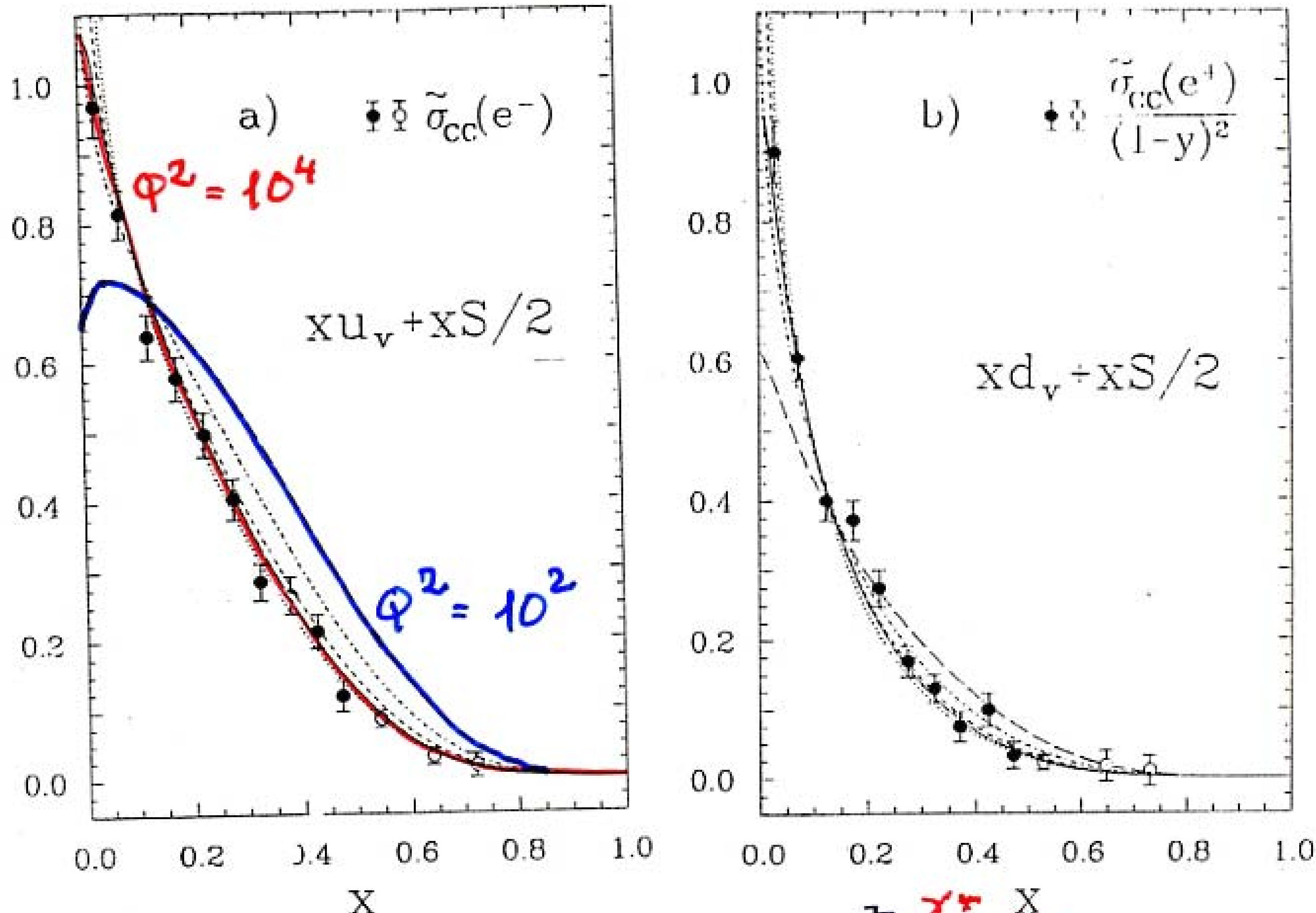
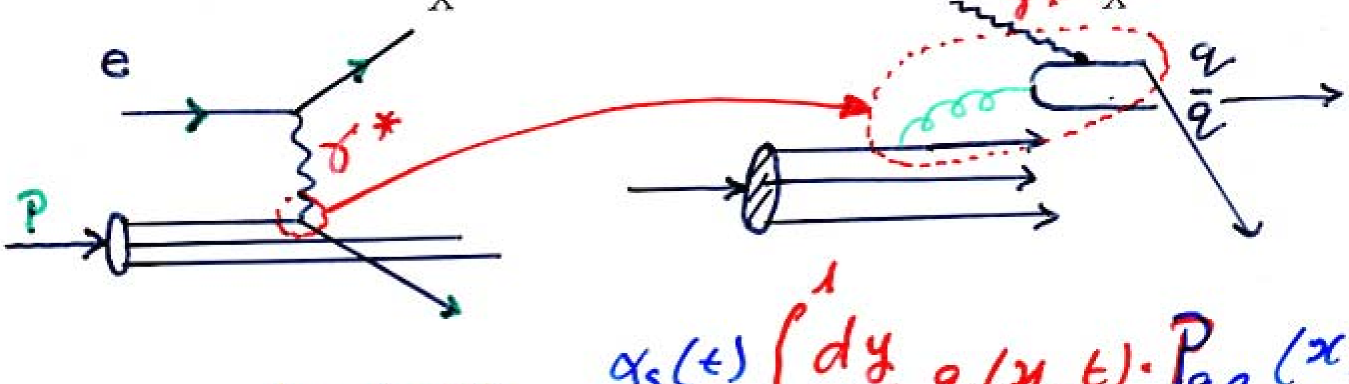


Figure 8.12 (b) Momentum distributions of quarks (Q) and antiquarks ($\bar{Q}$) in the nucleon, at a value of q^2 of order 10 GeV^2, obtained from results on neutrino and antineutrino scattering in experiments at CERN and Fermilab. The neutrino and antineutrino differential cross-sections measure the structure functions F_2 and F_3 in Eq. (8.17), and the difference and sum of these, through Eq. (8.23), give the quark and antiquark populations weighted by the momentum fraction x. The antiquarks ($\bar{Q}$) are concentrated at small x, the region of the so-called quark-antiquark "sea." The "valence" quarks of the static quark model ($Q - \bar{Q}$) are concentrated toward $x = 0.2$.



QCD Evolution of Structure Function



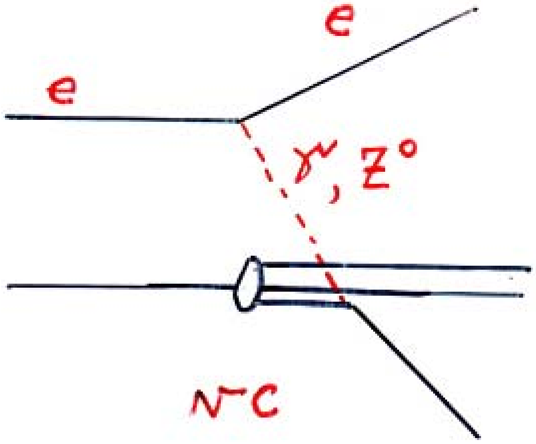


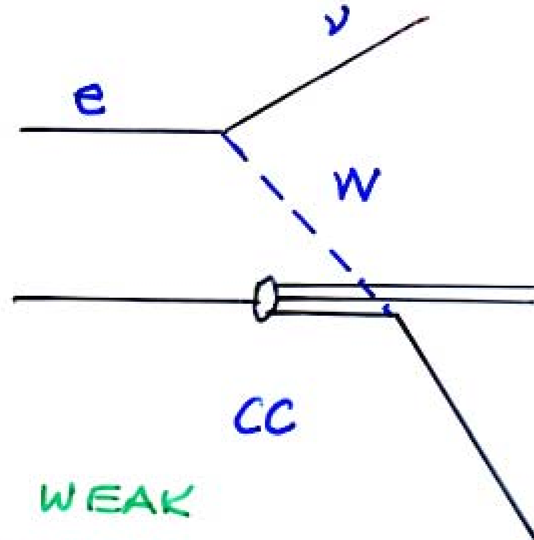
$$\frac{dq(x,t)}{dt} = \frac{\alpha_s(t)}{2\pi}\int_x^1 \frac{dy}{y}\, q(y,t)\cdot P_{qq}(x/y)$$

$\ln\left(\frac{Q^2}{Q_0^2}\right) \leftrightarrow \ln Q^2$

EVOLUTION

SPLITTING FUNCTION





- EM ≈ WEAK
- W PROPAGATOR