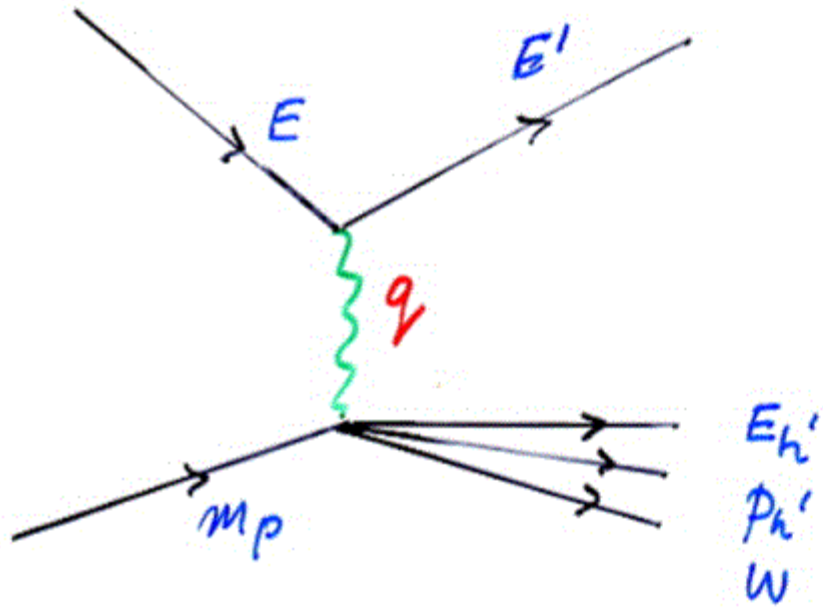


BACK TO INELASTIC SCATTERING!



PROTON HAS ENERGY TRANSFERRED TO IT

q^2 HAS 2 COMPONENTS

ν ENERGY

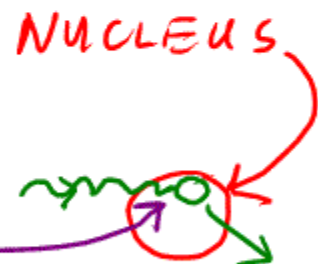
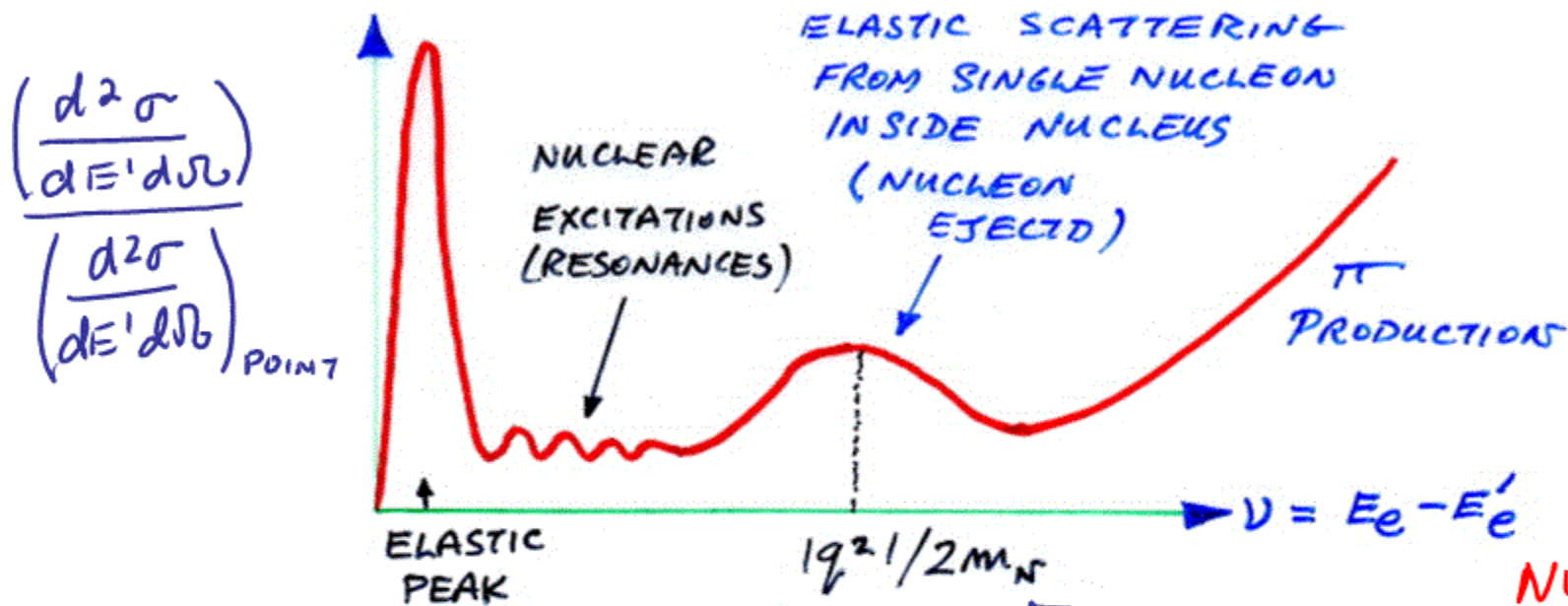
\vec{q} 3-MOMENTUM

$$q^2 = \nu^2 - |\vec{q}|^2 \rightarrow \text{VARY INDEPENDENTLY}$$

NOW HAVE 2 VARIABLES IN SCATTERING KINEMATICS
FORM FACTORS DEPEND ON \vec{q}^2, ν

$F(q^2)$ \rightarrow $W_1(q^2, \nu)$ $W_2(q^2, \nu)$ \rightarrow STRUCTURE FUNCTIONS
ELASTIC DEEP INELASTIC

REPRISE ON ELECTRON SCATTERING FROM NUCLEUS



QUASI-ELASTIC SCATTERING

- ENERGY TAKEN UP BY SINGLE NUCLEON
- FERMI MOTION OF NUCLEON IN NUCLEUS BROADENS QUASI ELASTIC PEAK

$$R \cdot p_{FERMI} \sim \hbar \rightarrow p_F \sim p_{NUCLEON} \sim \frac{\hbar}{R} \sim 100 \text{ MeV}/c$$

$$v = |q^2| / 2m_N$$

- NUCLEON INSIDE NUCLEUS ABSORBS 4-MOMENTUM q^2 FROM VIRTUAL γ
- INITIAL 4-MOMENTUM OF NUCLEON P_N

$$(P_N + q)^2 = m_N^2$$

$$m_N^2 \rightarrow P_N^2 + q^2 + 2P_N \cdot q = m_N^2$$

$$|q^2| = 2P_N \cdot q = 2(m_N, 0)(v, \vec{q})$$

$$= 2m_N v$$

$$v = \frac{|q^2|}{2m_N}$$

DEEP INSIDE THE NUCLEON



BASED ON
MICROWAVE
TECHNOLOGY
USED BY
HOFSTADTER

20 GeV/c
↳ 50 GeV/c

2 MILES
LONG

$\$114 \times 10^6$
IN 1965

LHC $\$10^{10}$
IN 2005

STANFORD LINEAR ACCELERATOR

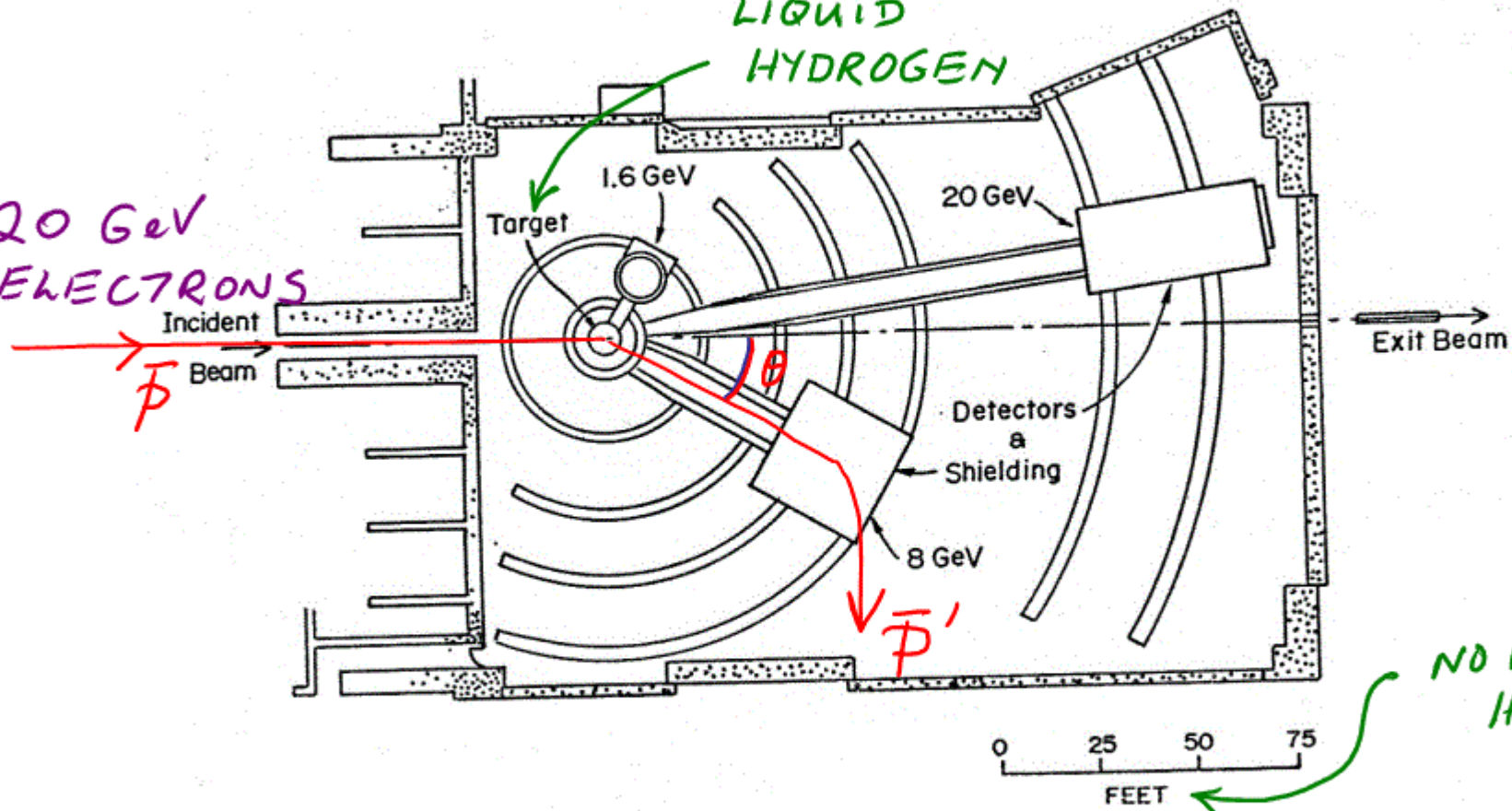
SLAC SPECTROMETER

206

FRIEDMAN & KENDALL

LIQUID
HYDROGEN

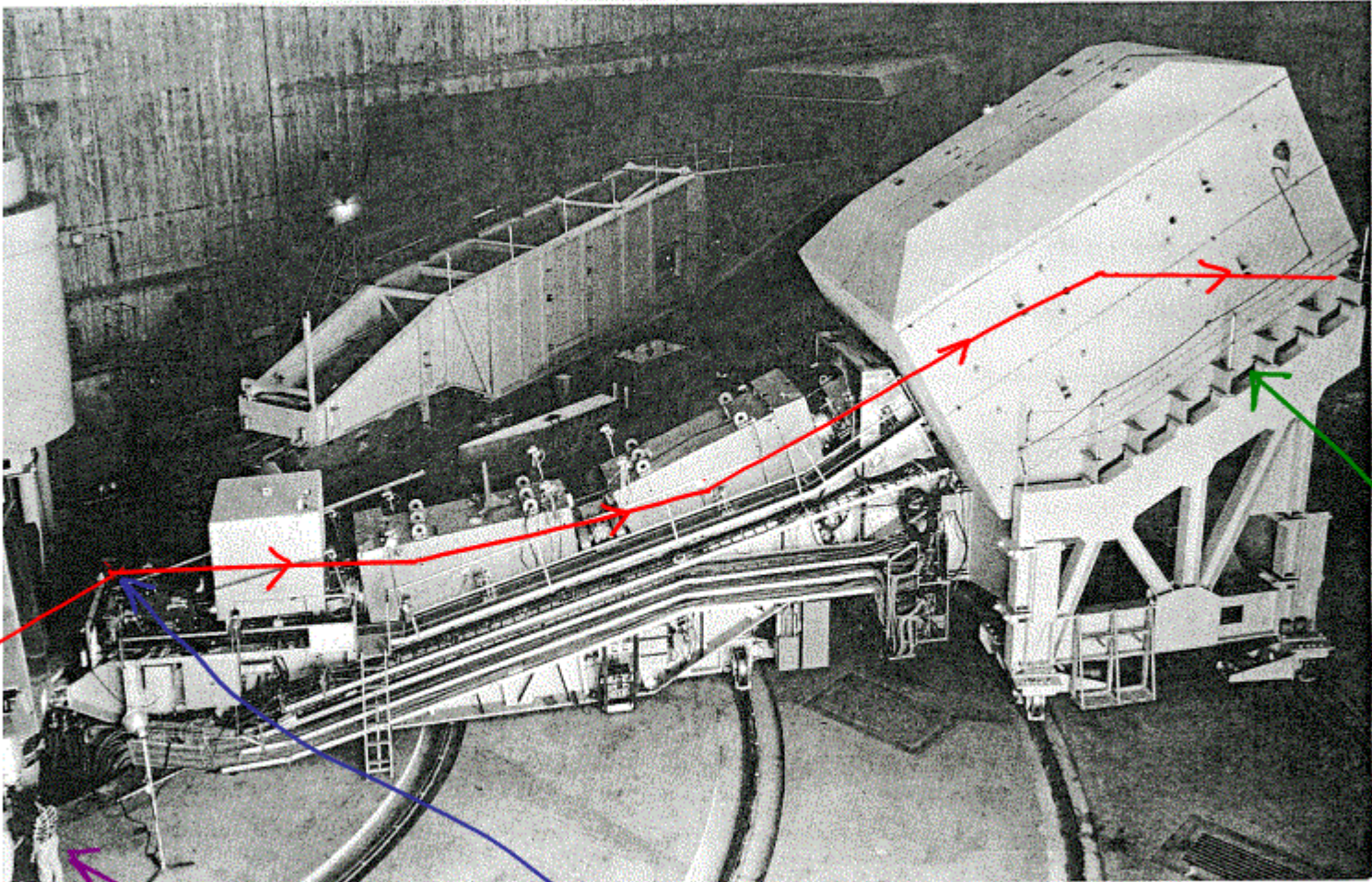
20 GeV
ELECTRONS



NO METRES
HERE!

MEASURE SCATTERING ANGLE θ
AND FINAL STATE MOMENTUM \vec{p}'
OF SCATTERED ELECTRONS

SLAC SPECTROMETER



20 GeV
ELECTRONS

PHYSICIST

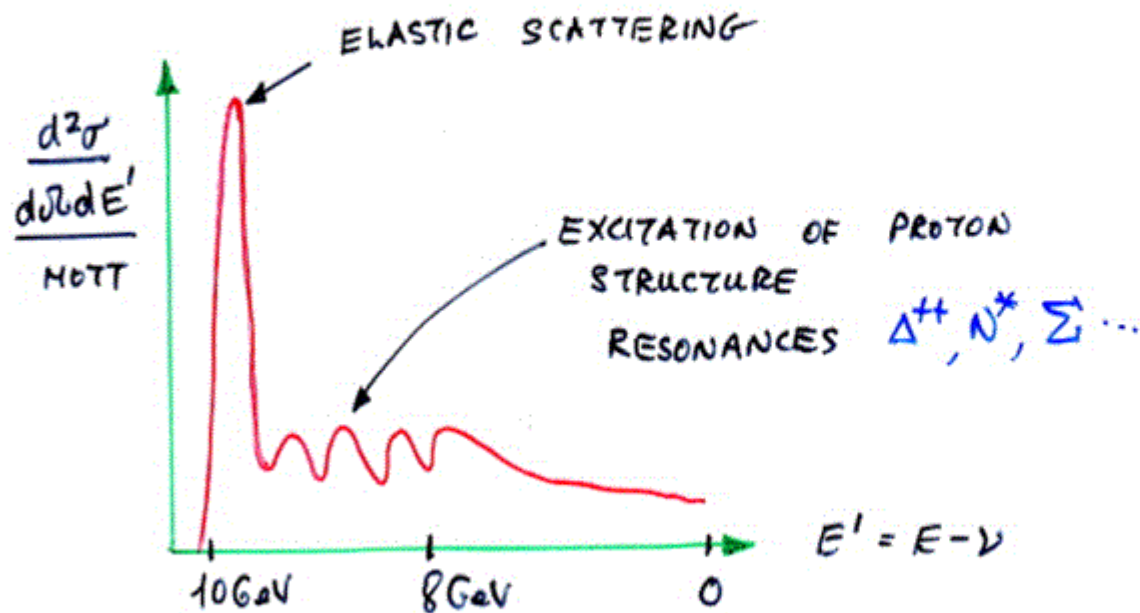
TARGET

SPECTROMETER
MAGNET

INELASTIC SCATTERING RESULTS

ELASTIC SCATTERING FROM NUCLEI \rightarrow NUCLEAR STRUCTURE

INELASTIC SCATTERING FROM PROTONS \rightarrow PROTON STRUCTURE



VERY SIMILAR TO SCATTERING FROM NUCLEI
EVIDENCE OF PROTON STRUCTURE

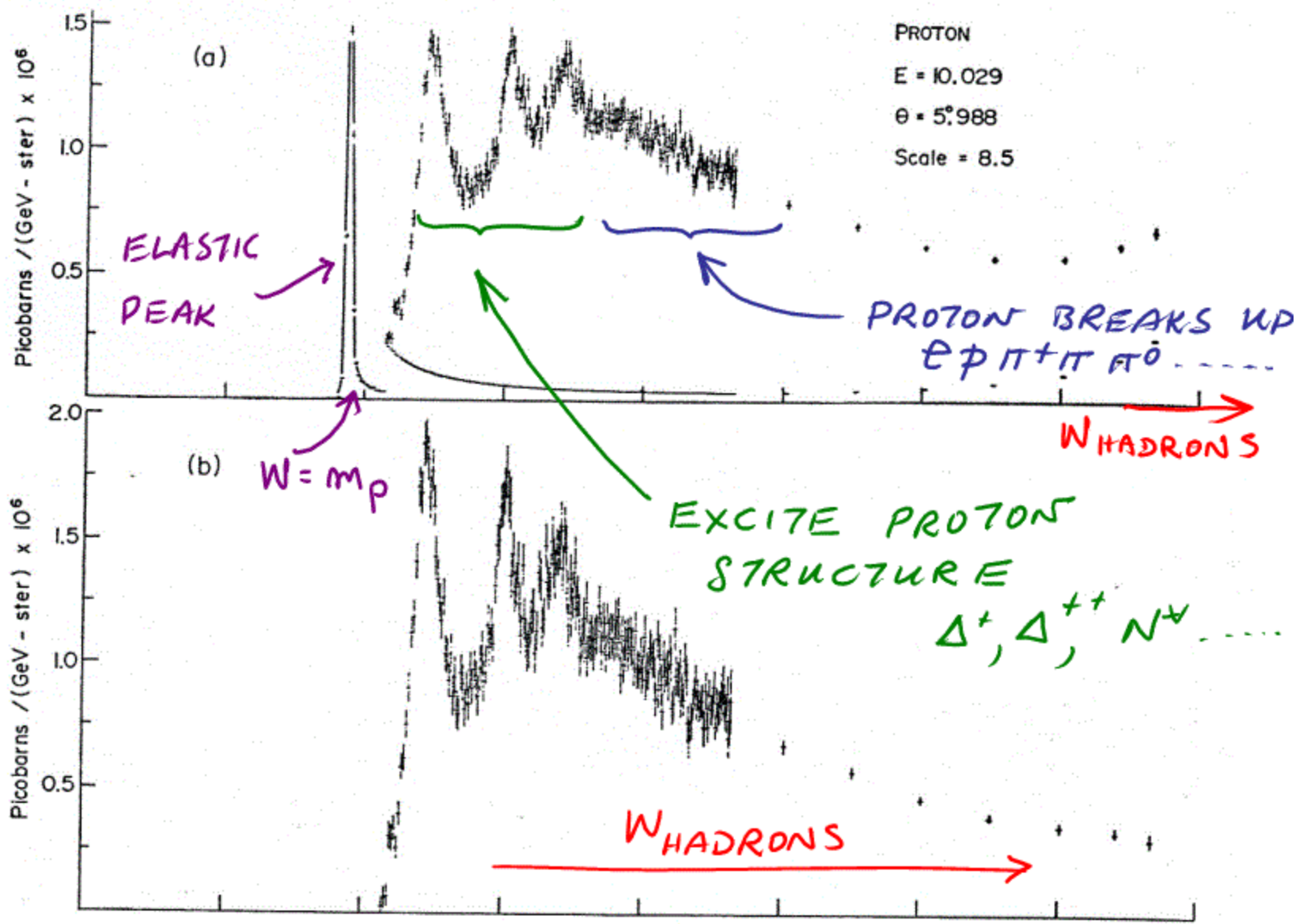
NO QUASI-ELASTIC PEAK. WHATEVER PROTON STRUCTURE IS \rightarrow CANNOT BE KNOCKED OUT
CONFINED INSIDE PROTON

SLAC DATA $e p \rightarrow e X$

210

FRIEDMAN & KENDALL

PROTON
E = 10.029
 $\theta = 5.988$
Scale = 8.5

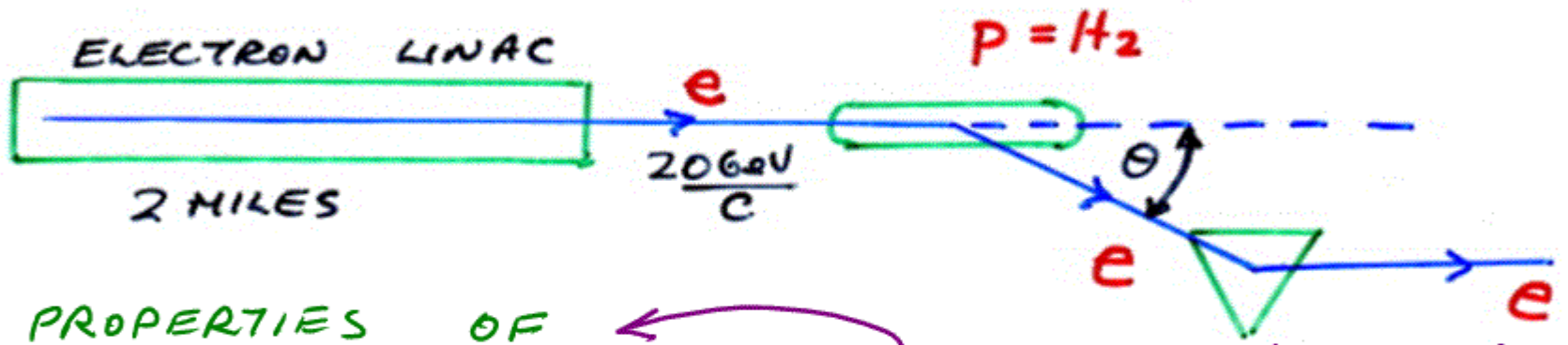


20

DEEP INELASTIC SCATTERING & DISCOVERY OF QUARKS

EXPERIMENT — R. E. TAYLOR — BORN MEDICINE
 NOBEL PRIZE 1989 HAZ-ALBERTA

THEORETICAL INTERPRETATION — RICHARD FEYNMAN'S
 QUARK-PARTON MODEL



PROPERTIES OF RECOILING HADRONIC SYSTEM

ANALYZE MOMENTUM OF SCATTERED ELECTRON

$$\left. \begin{aligned} E_h &= V + m_p \\ \vec{P}_h &= \vec{P}_e - \vec{P}_e' \end{aligned} \right\}$$

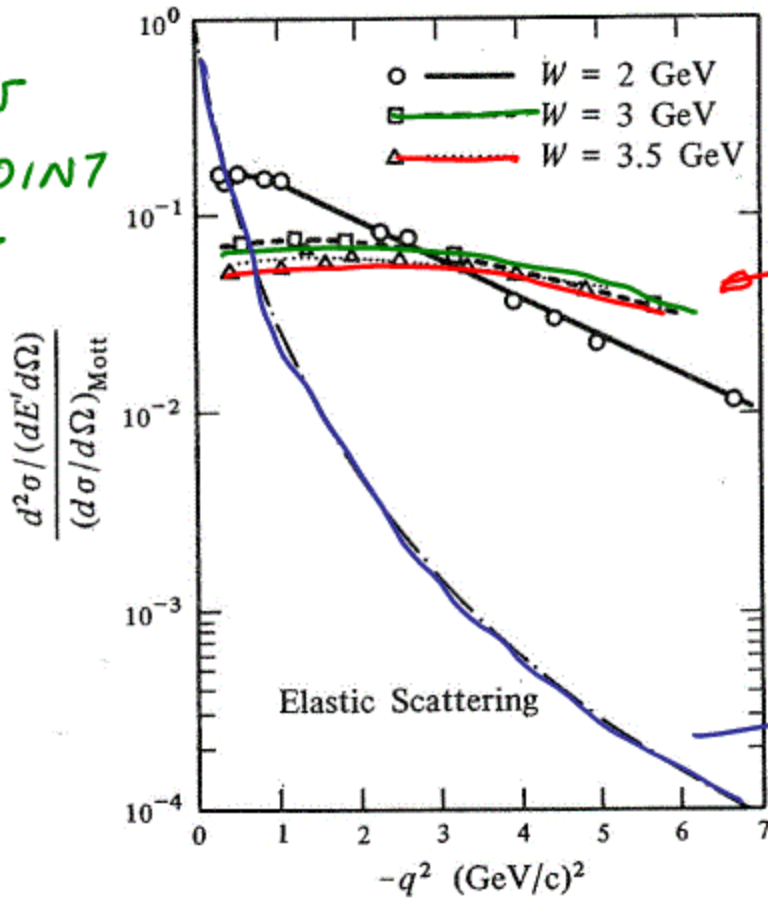
$$W_h^2 = q^2 + m_p^2 + 2V m_p^2$$

INVARIANT MASS OF RECOILING HADRONIC SYSTEM

DISCOVERY OF PARTONS - SCALING

CROSS SECTION COMPARED TO POINT CROSS SECTION

RUN @ FIXED W^2
MEASURE $\frac{d\sigma}{dq^2}$

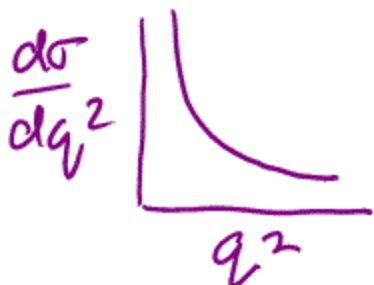


MASS OF RECOILING HADRONIC SYSTEM

INDEPENDENT OF q^2
NO FORM FACTOR
POINT TARGET

$W = m_p$
FORM FACTOR

ELASTIC



FORM FACTOR
EXTENDED TARGET

INELASTIC



• NO FORM FACTOR
• POINT TARGET
• RUTHERFORD!

OBSERVED BEHAVIOR OF HIGHLY INELASTIC ELECTRON-PROTON SCATTERING

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Department of Physics and Laboratory for Nuclear Science,*
Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

and

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Stanford Linear Accelerator Center,† Stanford, California 94305

(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, $(d^2\sigma/d\Omega dE')/(d\sigma/d\Omega)_{\text{Mott}}$, 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

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

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 $\theta = 10^\circ$, is included. The q^2 dependence of the deep continuum is also consider-

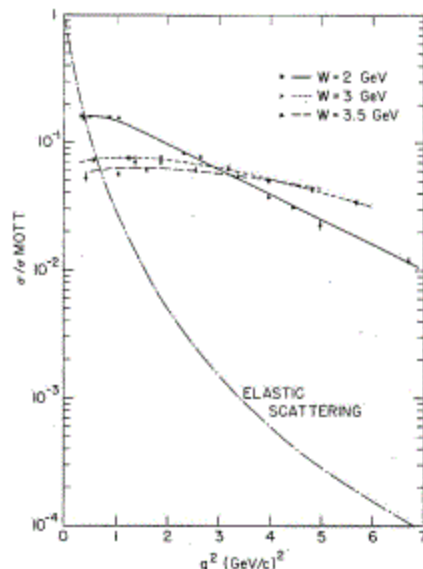


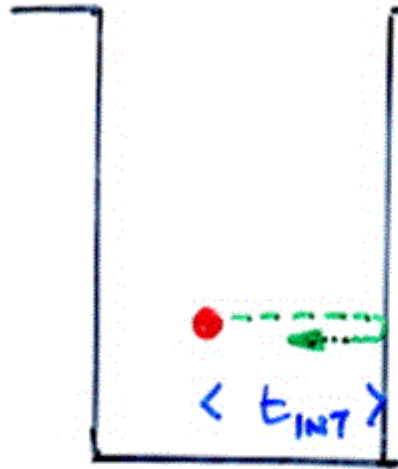
FIG. 1. $(d^2\sigma/d\Omega dE')/\sigma_{\text{Mott}}$, in GeV^{-1} , vs q^2 for $W = 2, 3, \text{ and } 3.5$ GeV. The lines drawn through the data are meant to guide the eye. Also shown is the cross section for elastic e - p scattering divided by σ_{Mott} , $(d\sigma/d\Omega)/\sigma_{\text{Mott}}$, calculated for $\theta = 10^\circ$, 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.

DICK TAYLOR

SEE LAST SLIDE

PARTON MODEL OF DEEP INELASTIC SCATTERING

- DATA \rightarrow SCATTERING FROM FREE POINT CHARGES
- HADRONS \rightarrow QUARKS NOT FREE \rightarrow TIGHTLY BOUND



EXAMINE QUARKS DURING
SHORT SPACE-TIME
INTERVAL - MOTION FROZEN

FOR TIME $\ll t_{INT}$ QUARK
WILL APPEAR FREE EVEN
THO' TIGHTLY BOUND

\rightarrow IMPULSE APPROXIMATION

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

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

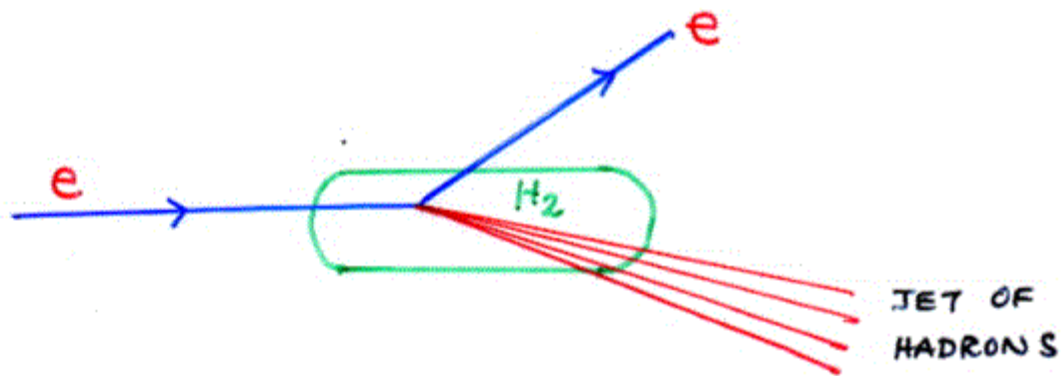
TO INVESTIGATE A SMALL SPACE-TIME
INTERVAL (E, \vec{p}) BOTH LARGE

SHORT "4-WAVELENGTH"

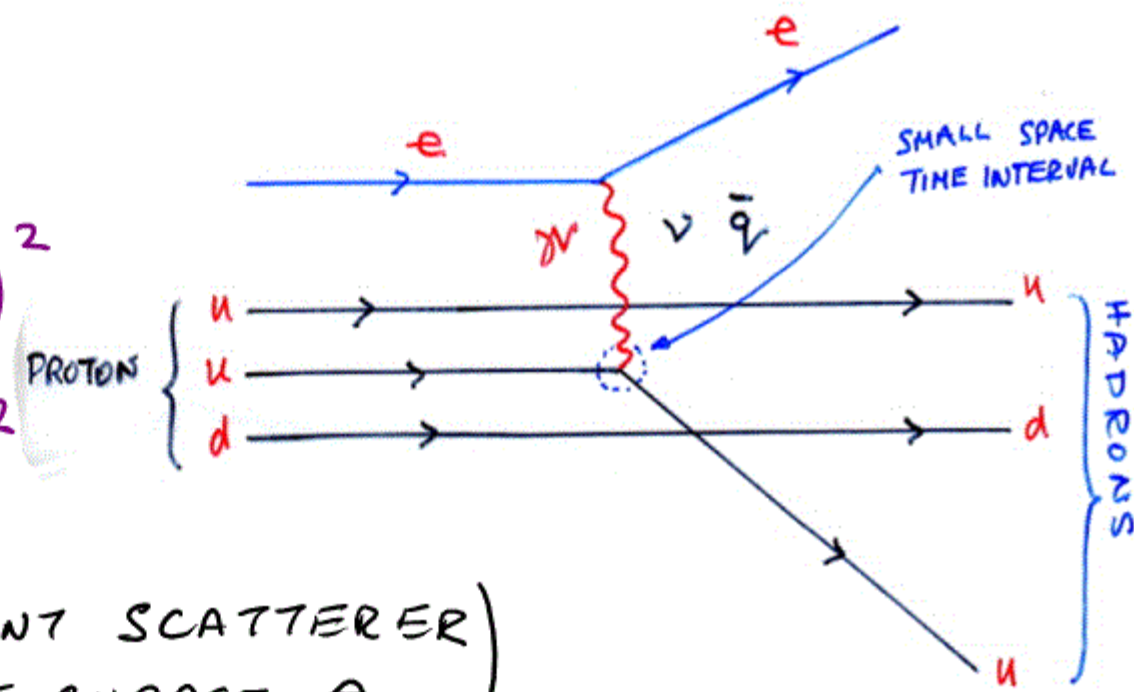
SMALL SPACE-TIME INTERVAL

PHYSICAL INTERPRETATION

EXPERIMENT:



FEYMAN DIAGRAM:



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

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

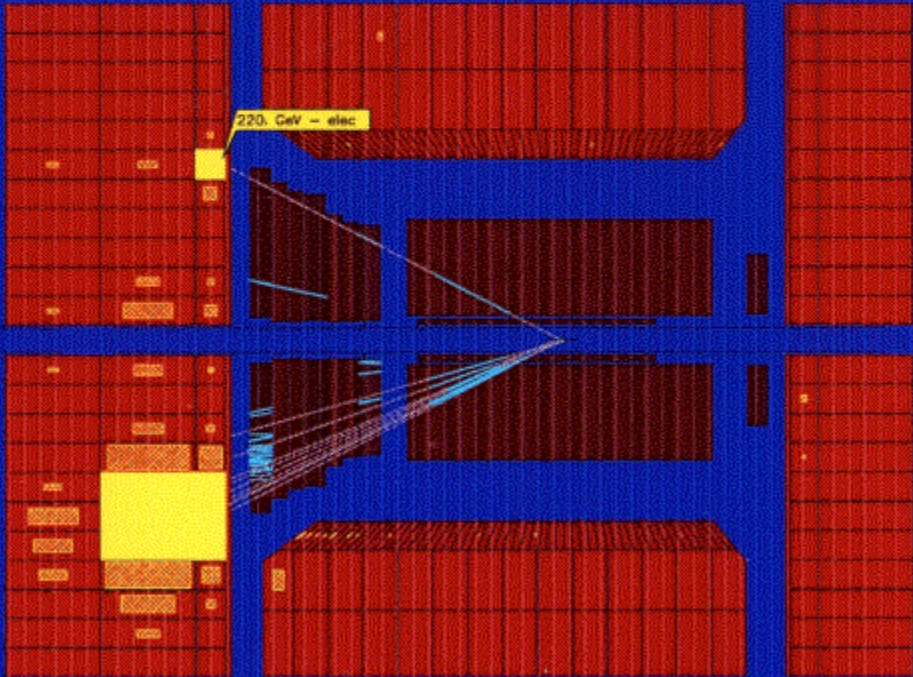
u
 u
 d

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

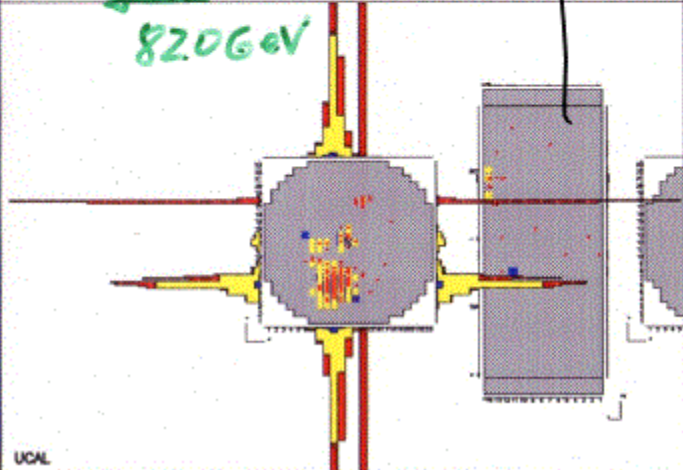
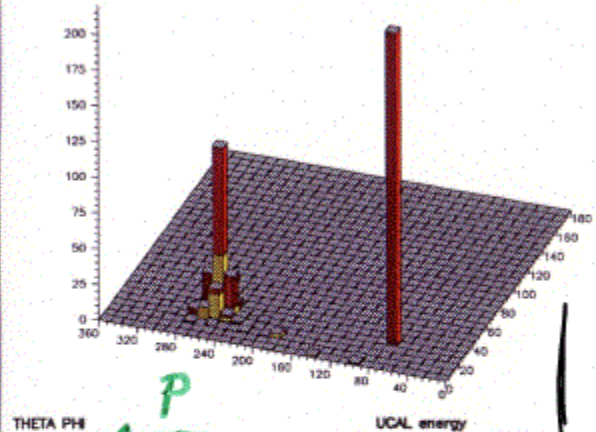
ELECTRON - PROTON SCATTERING @ HERA

ZEUS Zeus Run 13796 Event 11907
 E= 400.3 Eb= 217.3 pt= 8.2 pz= 437.2 E-pz= 85.1 Ef= 467.0 Eb= 2.8 Er= 0.4
 Tf= -0.2 Tr= 99.0 Lw= 0.3 Lp= 1.3 FNC= 0 BCN= 85 FLJ= 10822F20 0000000
 e- x=4899 y=539 QZ=22660 DA x=5434 BZ=24855 JB y=503 pH [0.180] 3-Nov-1995 00h34m46s File: /events/same/leg/ermit2

e^-
 →
 30 GeV



ZB



UCAL

RATIOS OF CROSS SECTIONS

IN $\sigma_{DIS} \sim \frac{1}{3} e^2$ KINEMATIC FACTORS
DEPENDING ON EXPERIMENT
— DROPS OUT IN RATIOS

NEUTRONS d du

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

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

DEUTERIUM \rightarrow SAME # PROTONS + NEUTRONS
 \rightarrow SAME u & d QUARKS (ISOSCALAR TARGET)

$$\sigma_d = e^2 \left\{ \frac{1}{6} \left[3 \cdot \left(\frac{1}{2}\right)^2 + 3 \left(\frac{2}{3}\right)^2 \right] \right\} \sim \frac{e^2}{2} \cdot \frac{5}{9}$$

$$\frac{\text{LIQUID DEUTERIUM}}{\text{LIQUID HYDROGEN}} = \frac{\sigma_d}{\sigma_p} = \frac{e^2}{2} \cdot \frac{5}{9} \cdot \frac{3}{e^2} = \frac{5}{6} \quad \checkmark$$

DEEP INELASTIC SCATTERING & SCALING

PROTON 4-MOMENTUM P

EACH PARTON HAS 4-MOMENTUM xP

PARTON ABSORBS q FROM VIRTUAL γ

$$(xP + q)^2 \sim m_{\text{PARTON}}^2 \sim 0 \quad \text{— THEY BEHAVE LIKE THIS}$$

$$x^2 p^2 + q^2 + 2x P \cdot q = 0$$

$$\rightarrow x^2 p^2 = x^2 M_{\text{PROTON}}^2 \ll q^2 \Rightarrow q^2 + 2x P \cdot q = 0$$

$$x = \frac{-q^2}{2P \cdot q} \quad \checkmark \quad 2(M_P, 0)(\gamma q^2) = 2M_P \gamma$$

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

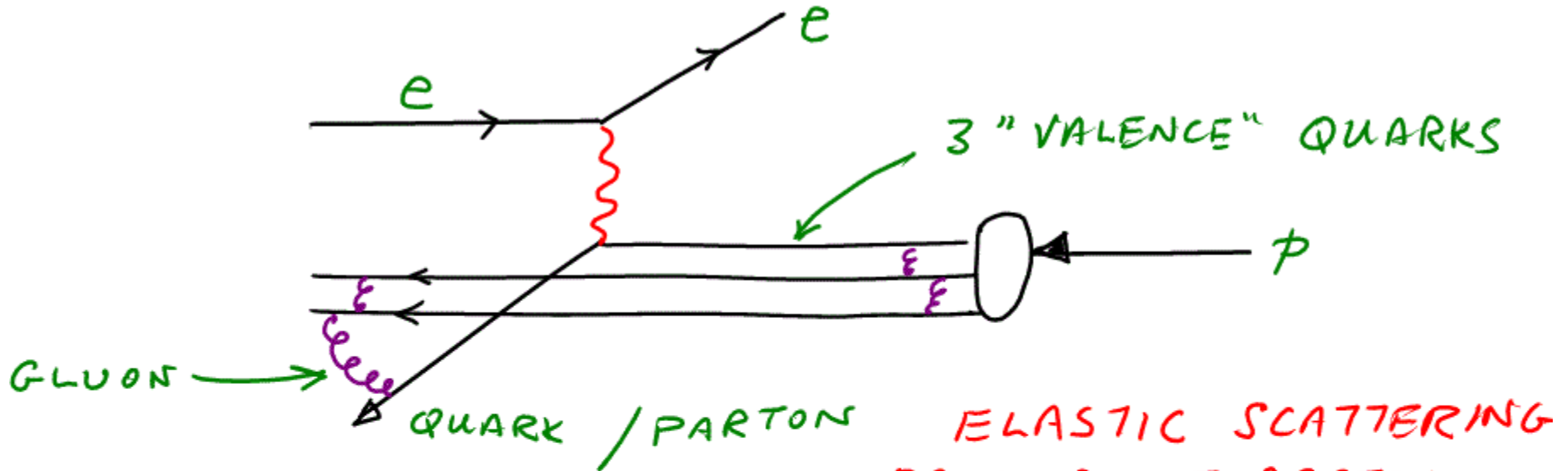
SCALING

→ DIMENSION LESS
ONLY ONE SCATTERING VARIABLE

→ ELASTIC POINT SCATTERING

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

VISUALIZATION OF SCALING



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

$$xP = (xE, x\vec{p})$$

$$x = q/P \quad (0 < x < 1)$$

QUARK/PARTON
MOMENTUM DISTRIBUTION
INSIDE PROTON

$$W_1(q^2, \nu)$$

$$W_2(q^2, \nu)$$



$$F_1(x)$$

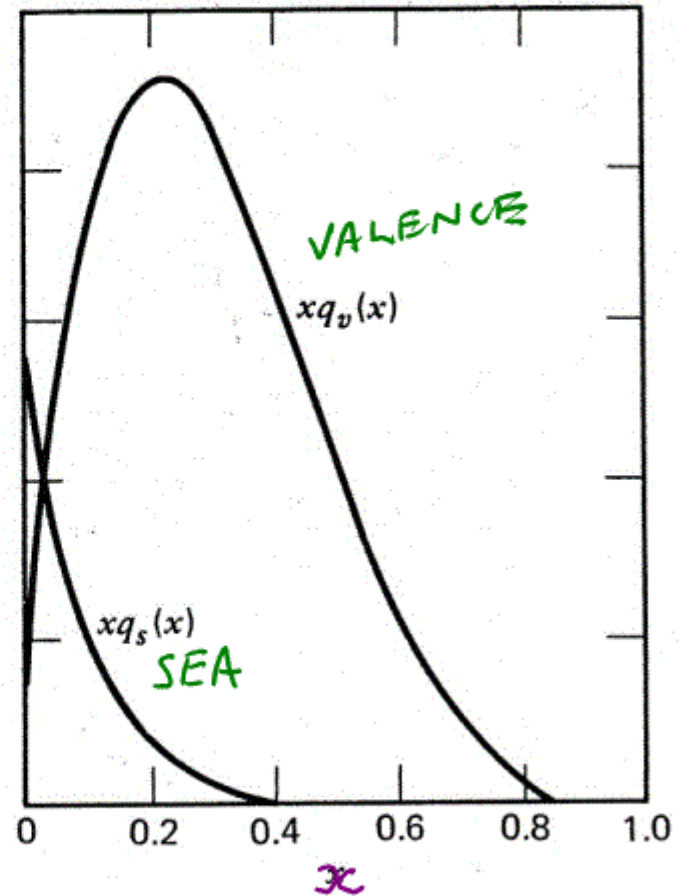
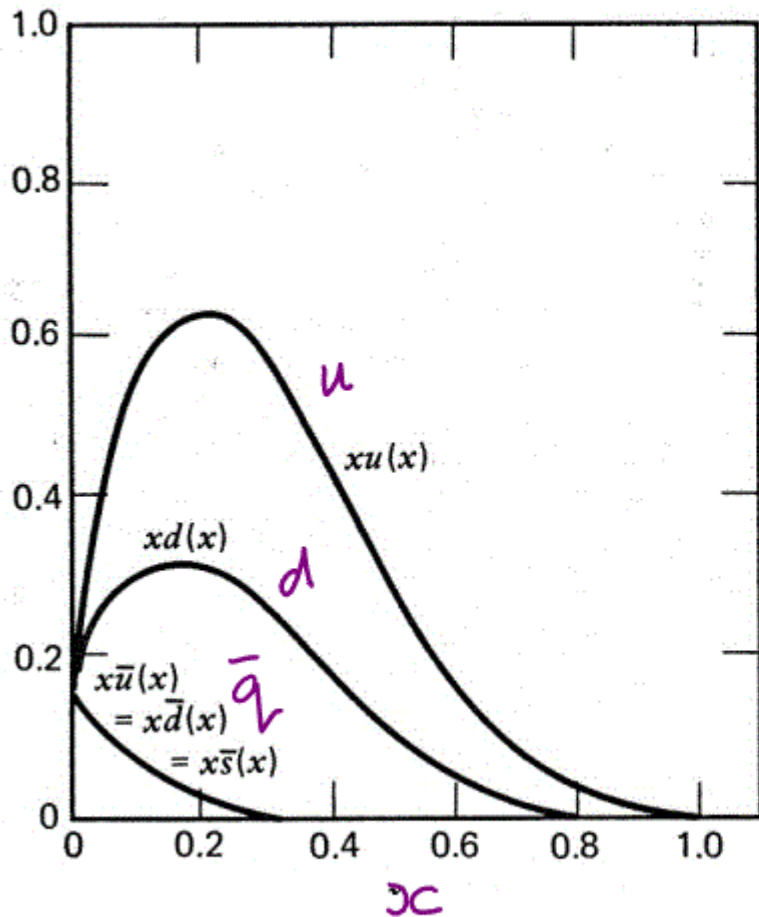
$$F_2(x)$$

SCALE

INVARIANCE

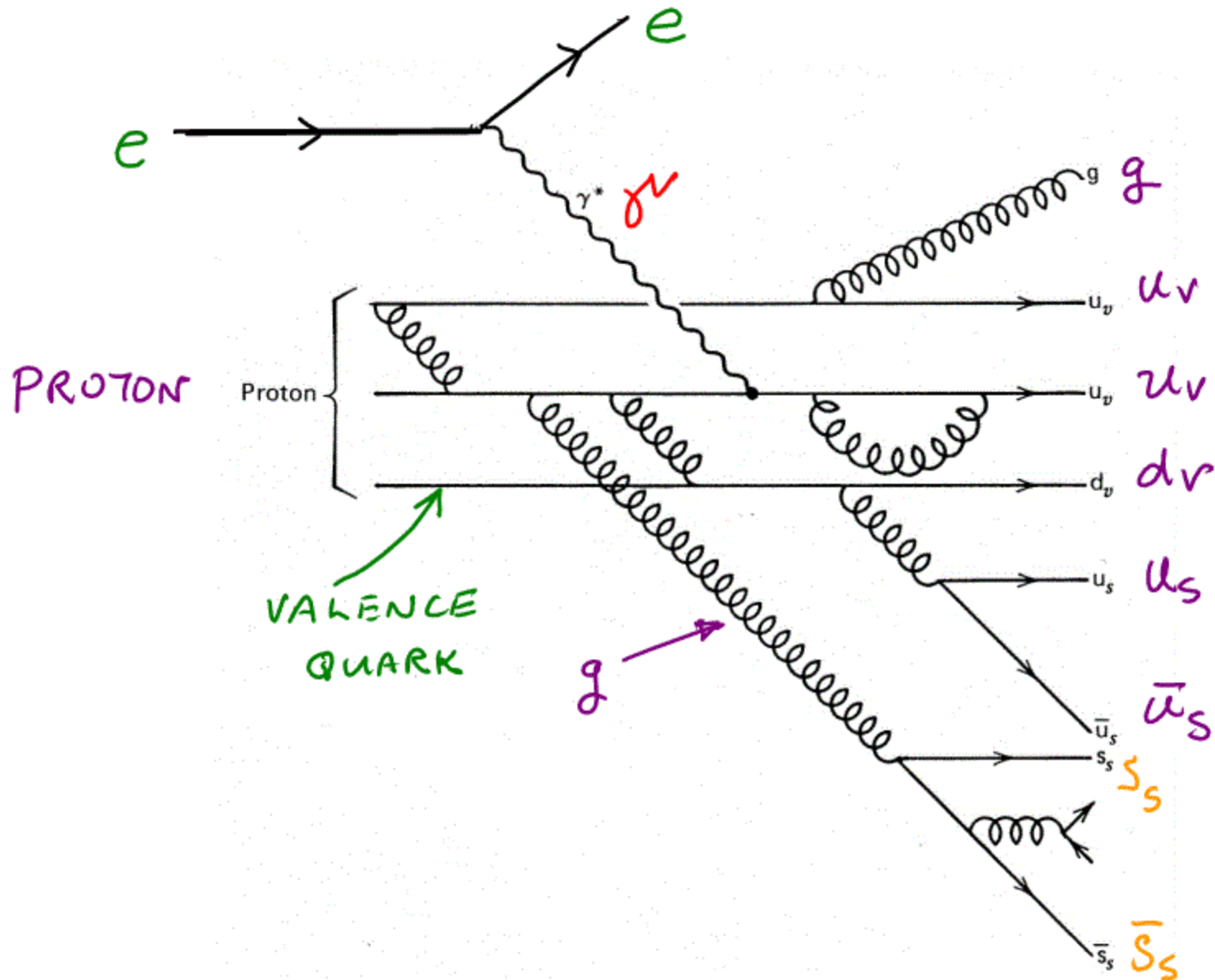
ONE VARIABLE

STRUCTURE FUNCTIONS



THESE ARE THE MOMENTUM DISTRIBUTIONS OF VARIOUS QUARK SPECIES INSIDE PROTON

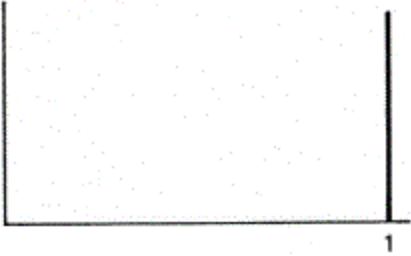
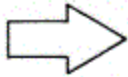
WHERE DO THE ANTIQUARKS COME FROM?



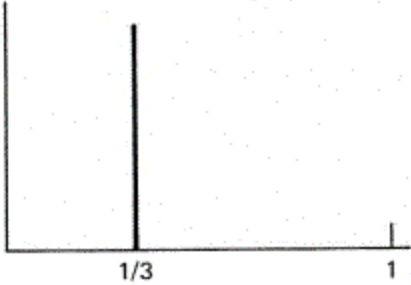
If the Proton is

then $F_2^{ep}(x)$ is

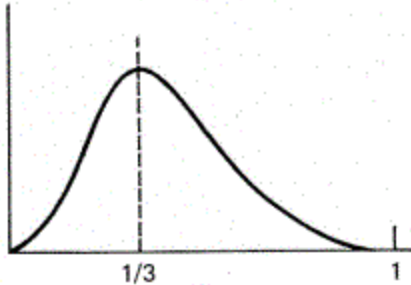
A quark



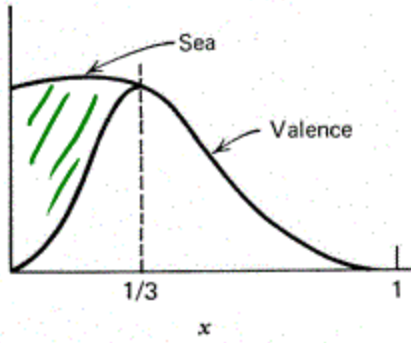
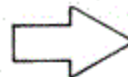
Three valence quarks



Three bound valence quarks

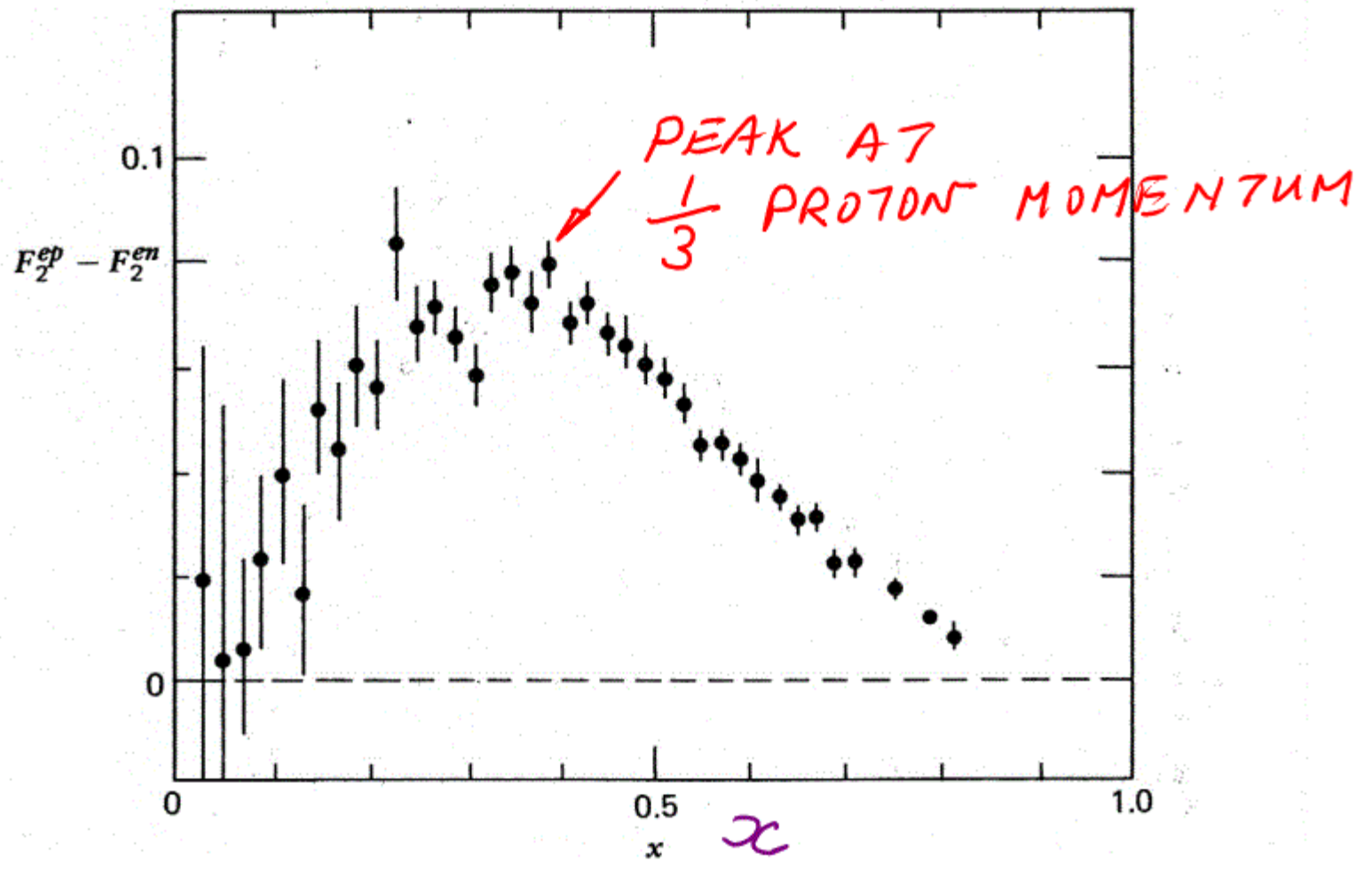


Three bound valence quarks + some slow debris, e.g., $g \rightarrow q\bar{q}$



Small x

MOMENTUM DISTRIBUTION OF VALENCE QUARKS.



NEUTRON & PROTON HAVE SAME SEA DISTRIBUTION \rightarrow DIFFERENCE \rightarrow VALENCE

SUMMARY

• FOR DEEP INELASTIC SCATTERING IN GENERAL

- TWO KINEMATIC VARIABLES $q \equiv q(\nu, \vec{p})$
- TWO STRUCTURE FUNCTIONS

$$W_1(\nu, q^2)$$

$$W_2(\nu, q^2)$$

2 VARIABLES

- FOR LARGE q^2 OR W_H STRUCTURE FUNCTIONS DEPEND ON ONE VARIABLE $x = q^2/2M_p\nu$

STRUCTURE FUNCTIONS $\rightarrow F_1(x) F_2(x)$

- ARISES FROM ELASTIC SCATTERING FROM

POINT PARTONS
(QUARKS)

NO LENGTH SCALE
SCALE INVARIANCE