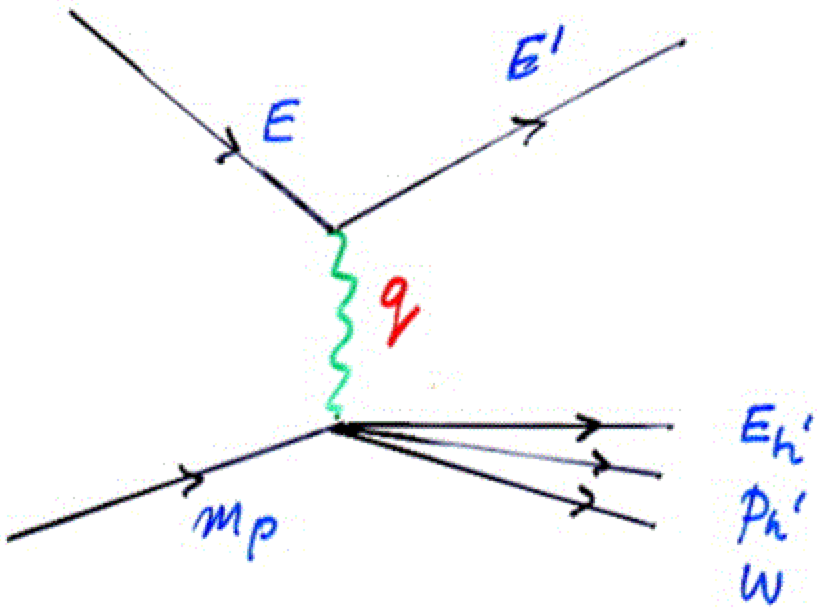
BACK TO INELASTIC SCATTERING!



PROTON HAS ENERGY TRANSFERED TO IT

q^2 HAS 2 COMPONENTS

ν ENERGY

$\bar{q}$ 3-MOMENTUM

$$q^2 = \nu^2 - |\bar{q}|^2$$ → VARY INDEPENDENTLY

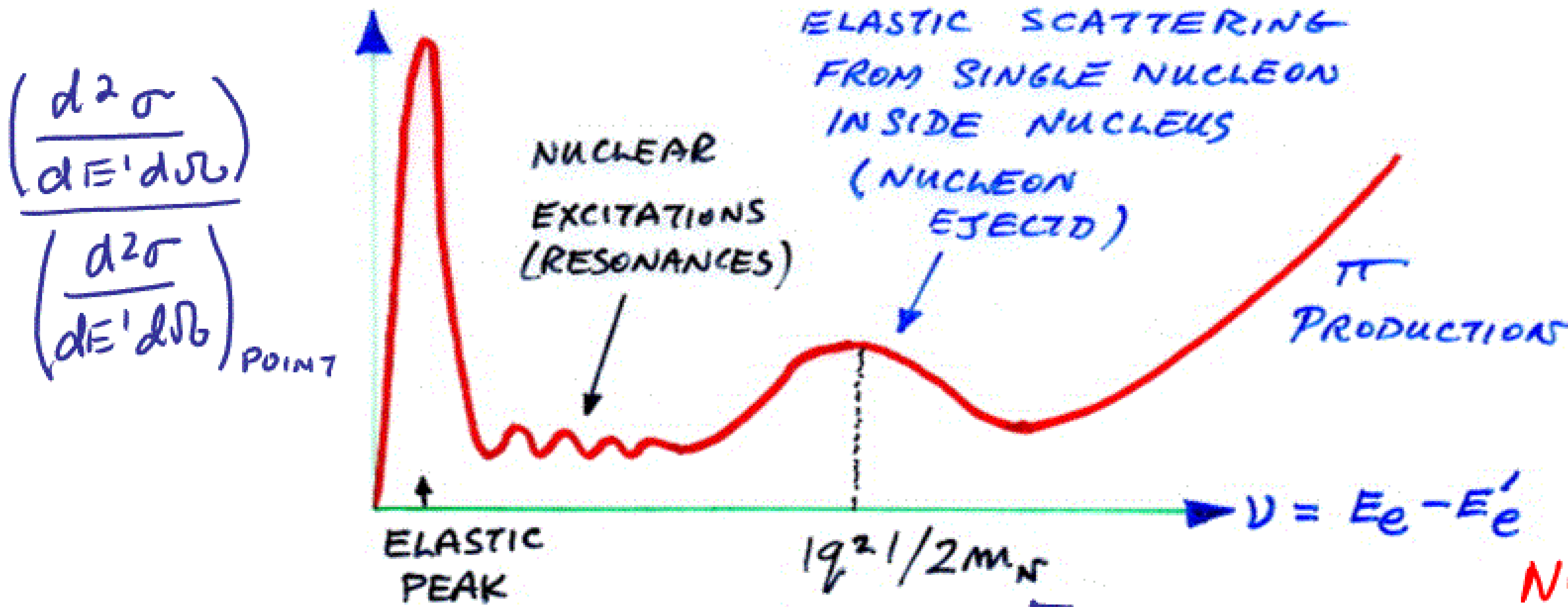
NOW HAVE 2 VARIABLES IN SCATTERING KINEMATICS

FORM FACTORS DEPEND ON ⟶ q^2, ν

$F(q^2) \longrightarrow W_1(q^2, \nu) \quad W_2(q^2, \nu)$ → STRUCTURE FUNCTIONS

ELASTIC   DEEP INELASTIC

REPRISE ON ELECTRON SCATTERING FROM NUCLEUS



QUASI-ELASTIC SCATTERING

- ENERGY TAKEN UP BY SINGLE NUCLEON

NUCLEUS

- FERMI MOTION OF NUCLEON IN NUCLEUS BROADENS QUASI ELASTIC PEAK

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

$$\nu = |q^2| / 2m_N$$

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

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

$$\underbrace{p_N^2}_{m_N^2} + q^2 + 2 p_N \cdot q = m_N^2$$

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

$$= 2 m_N \nu$$

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

DEEP INSIDE THE NUCLEON

STANFORD LINEAR ACCELERATOR

BASED ON MICROWAVE TECHNOLOGY USED BY HOFSTADTER

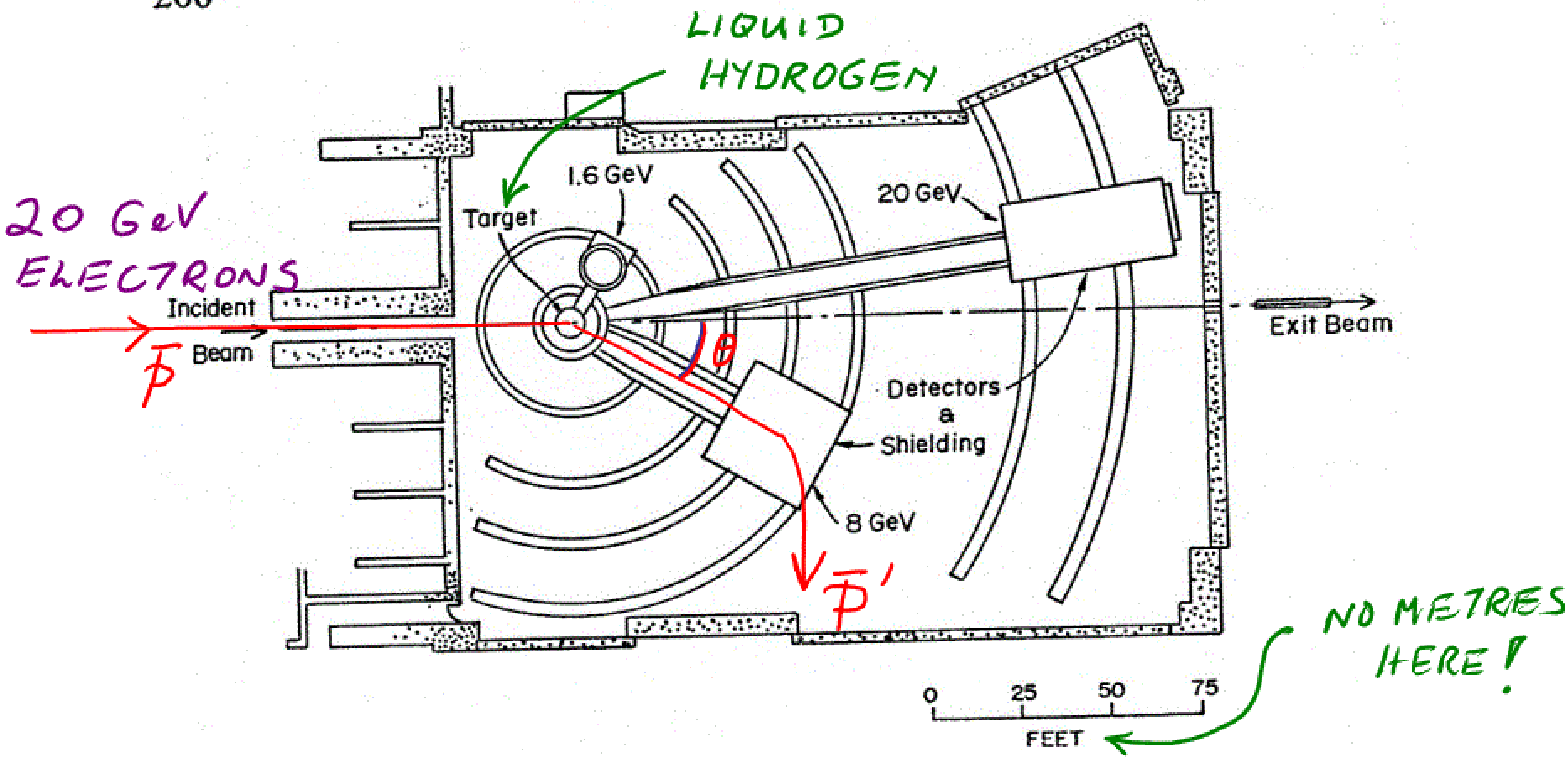
20 GeV/c ↳ 50 GeV/c

2 MILES LONG

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

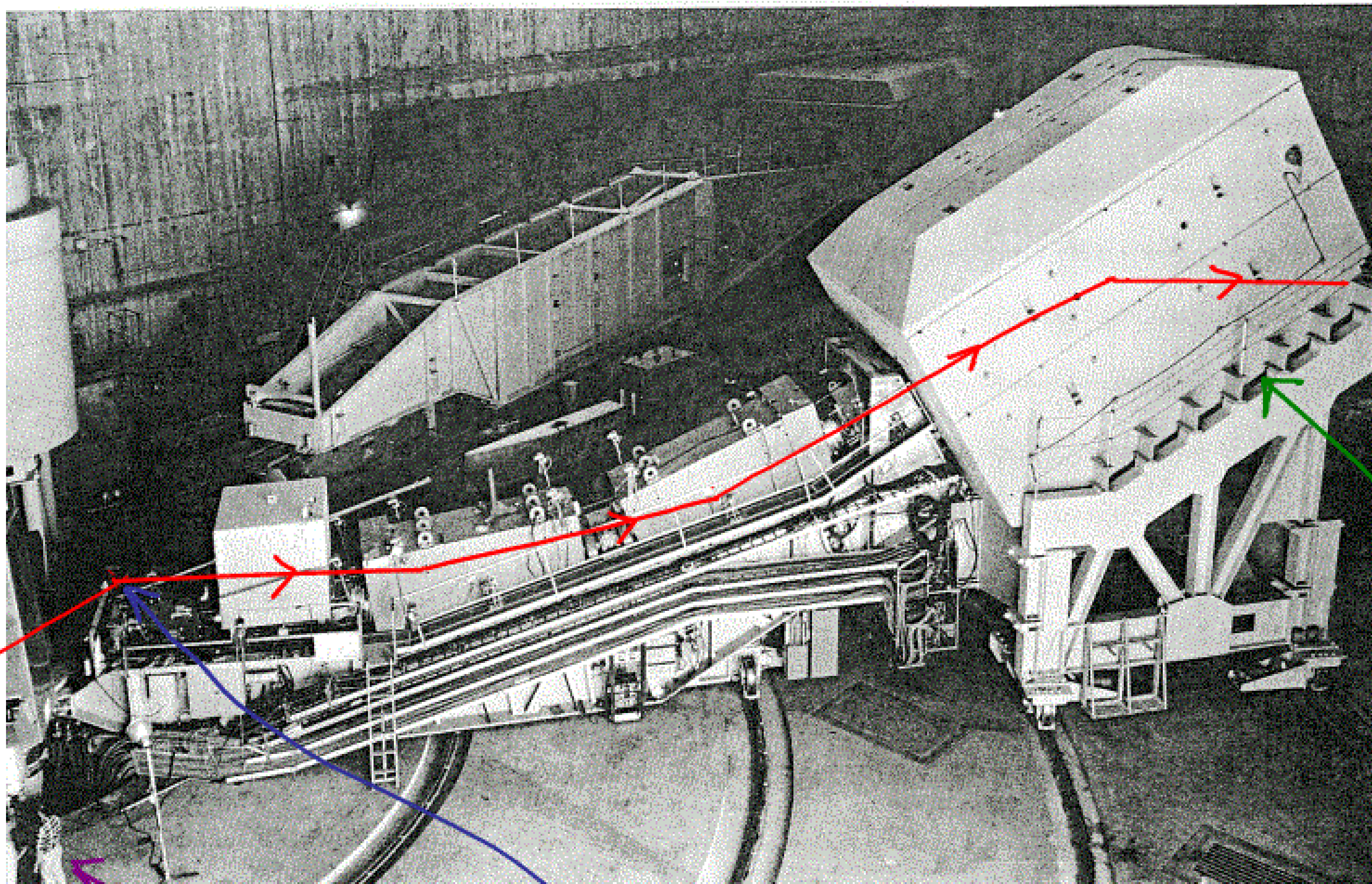
LHC $\$10^{10}$ IN 2005

SLAC SPECTROMETER



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

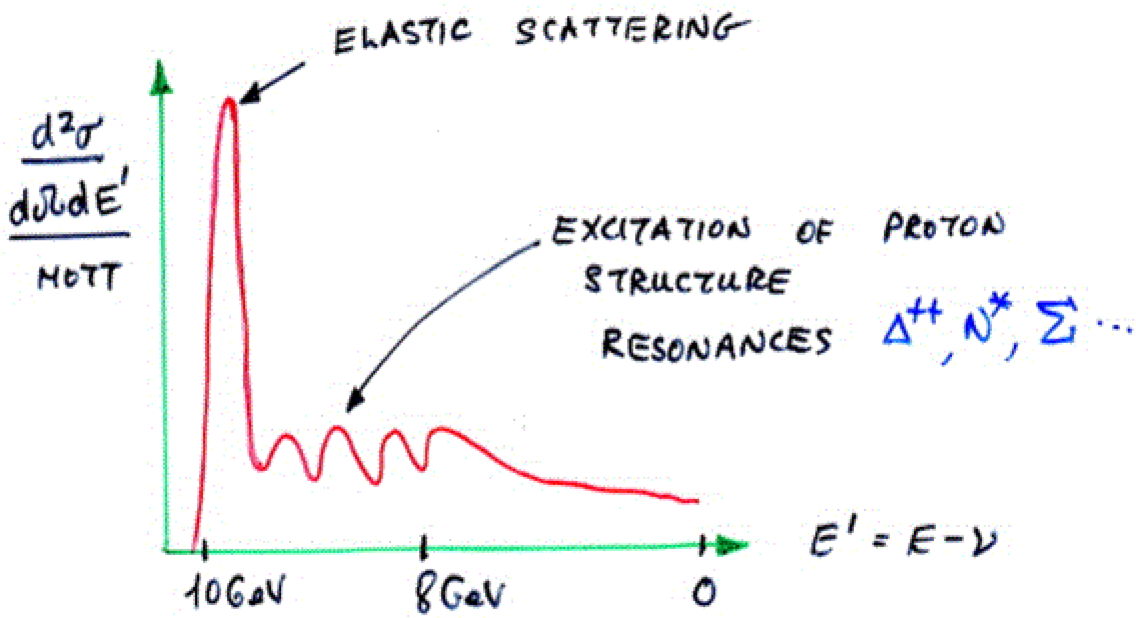
SLAC SPECTROMETER



INELASTIC SCATTERING RESULTS

ELASTIC SCATTERING FROM NUCLEI → NUCLEAR STRUCTURE

INELASTIC SCATTERING FROM PROTONS → PROTON STRUCTURE



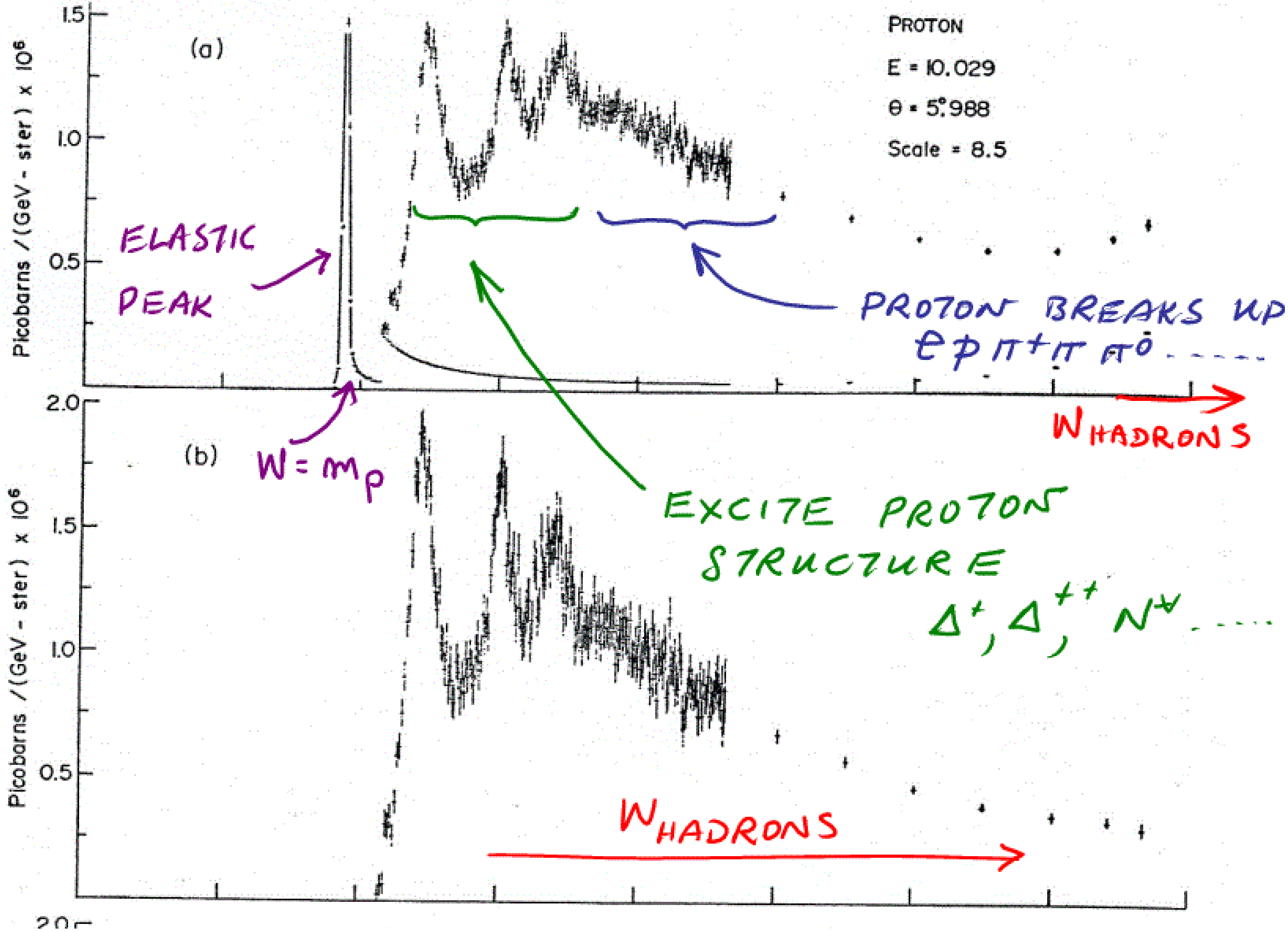
VERY SIMILAR TO SCATTERING FROM NUCLEI

EVIDENCE OF PROTON STRUCTURE

NO QUASI-ELASTIC PEAK. WHATEVER PROTON STRUCTURE IS → CANNOT BE KNOCKED OUT

CONFINED INSIDE PROTON

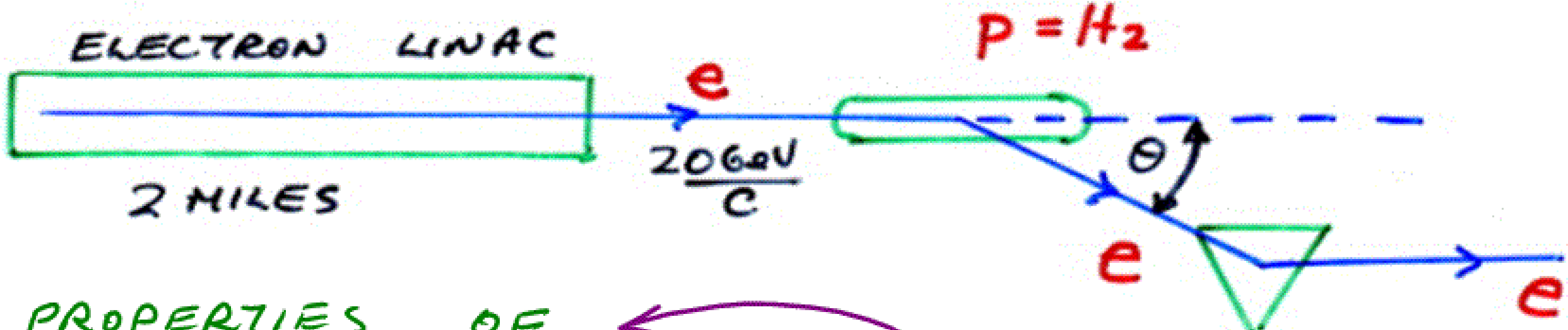
SLAC DATA $ep \to eX$



DEEP INELASTIC SCATTERING & DISCOVERY OF QUARKS

EXPRIMENT — R. E. TAYLOR — BORN MEDICINE
NOBEL PRIZE 1989 HAT-ALBERTA

THEORETICAL INTERPRETATIONS — RICHARD FEYNMAN
QUARK-PARTON MODEL



PROPERTIES OF RECOILING HADRONIC SYSTEM

ANALYZE MOMENTUM OF SCATTERED ELECTRON

$$\left.\begin{aligned} E_h &= \nu + m_p \\ \bar{p}_h &= \bar{p}_e - \bar{p}_e' \end{aligned}\right\}$$

$$W_h^2 = q^2 + m_p^2 + 2\nu m_p^2$$

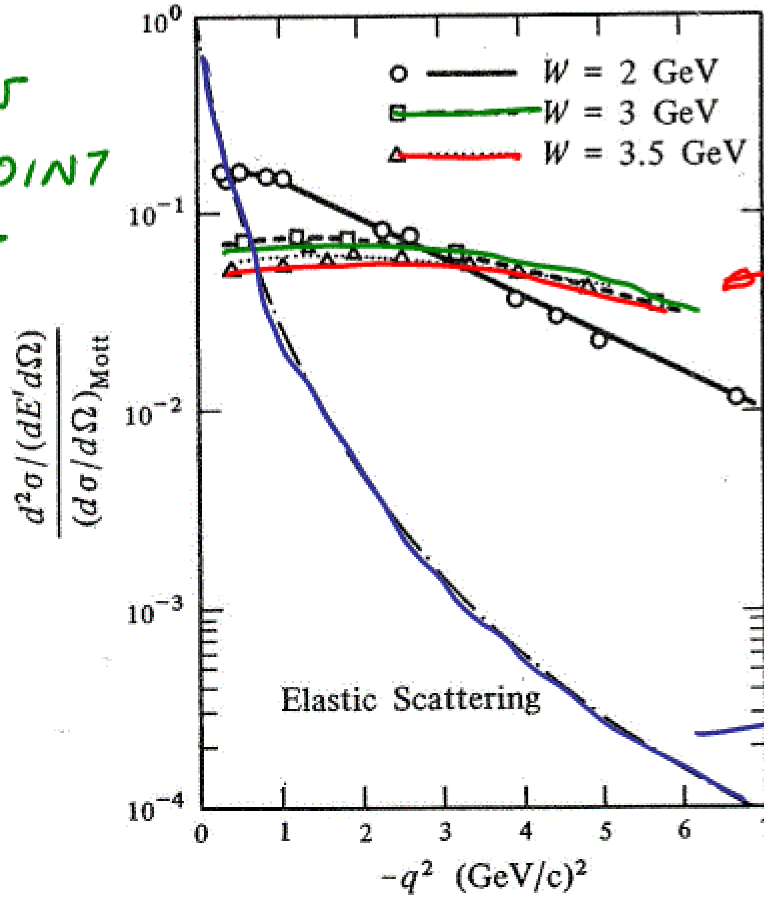
INVARIANT MASS OF RECOILING HADRONIC SYSTEM

DISCOVERY OF PARTONS – SCALING

CROSS SECTION COMPARD TO POINT CROSS SECTIONS

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

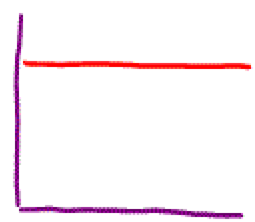
$\frac{d\sigma}{dq^2}$

q^2

FORM FACTOR

EXTENDED TARGET

INELASTIC



q^2

- NO FORM FACTOR
- POINT TARGET
- RUTHERFORD !

OBSERVED BEHAVIOR OF HIGHLY INELASTIC ELECTRON-PROTON SCATTERING

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DICK TAYLOR

(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-

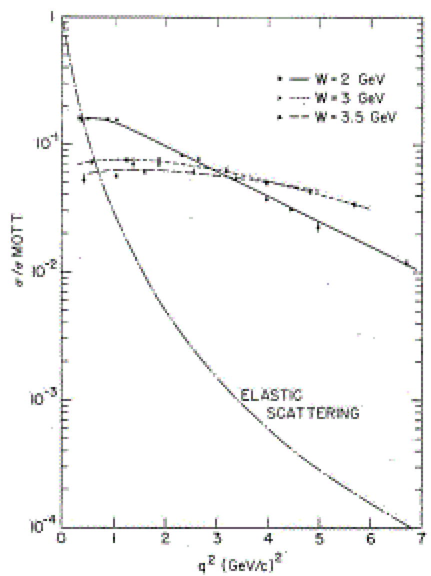


FIG. 1. $(d^2\sigma/d\Omega dE')/\sigma_{\rm Mott}$, in GeV^{-1}, vs q^2 for $W = 2$, 3, and 3.5 GeV. The lines drawn through the data are meant to guide the eye. Also shown is the cross section for elastic e-p scattering divided by $\sigma_{\rm Mott}$, $(d\sigma/d\Omega)/\sigma_{\rm Mott}$, calculated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

SEE LAST SLIDE

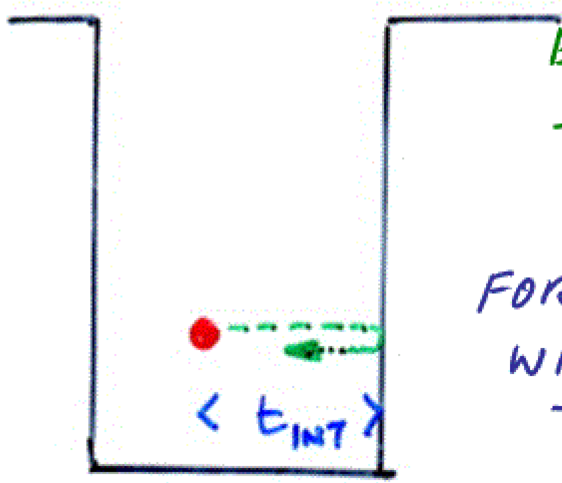
PARTON MODEL OF DEEP INELASTIC SCATTERING

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

EXAMINE QUARKS DURING SHORT SPACE - TIME INTERVAL – MOTION FROZEN

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

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



FOR TIME << t_{INT} QUARK WILL APPEAR FREE EVEN THO' TIGHTLY BOUND

→ IMPULSE APPROXIMATION

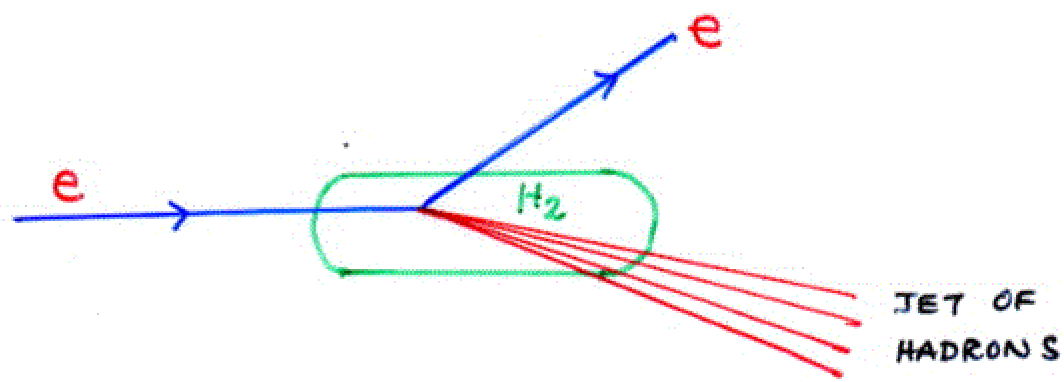
TO INVESTIGATE A SMALL SPACE-TIME INTERVAL $(E, \vec{p})$ BOTH LARGE

SHORT "4-WAVELENGTH"

SMALL SPAC-TIME INTERVAL

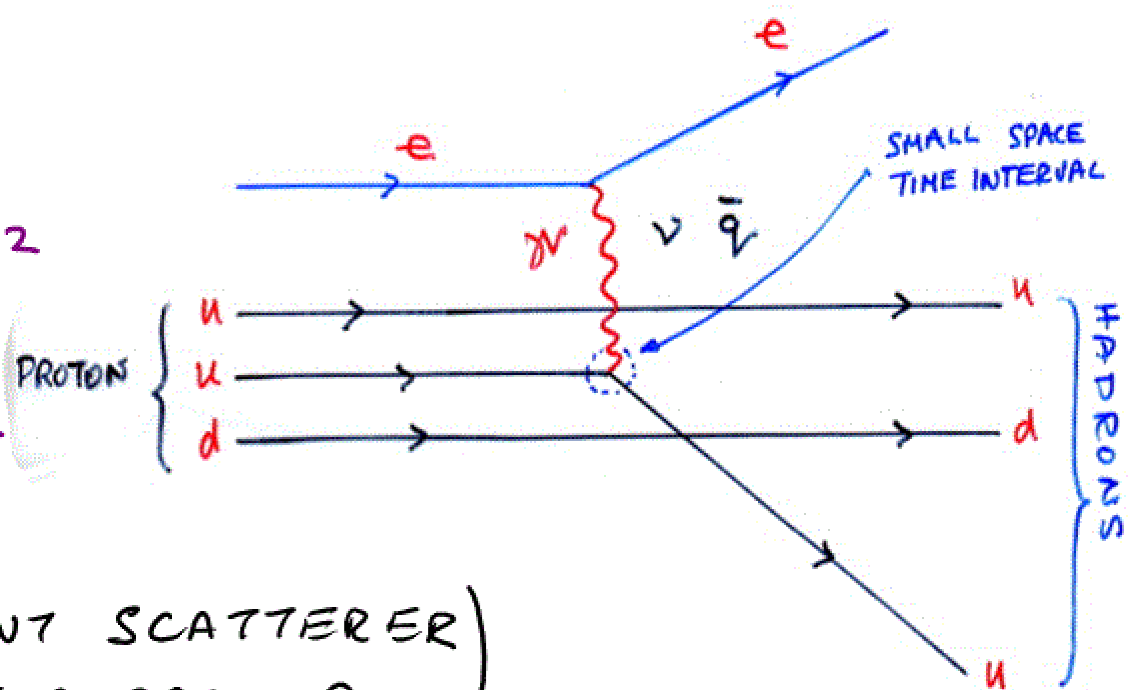
PHYSICAL INTERPRETATION

EXPERIMENT:



MEAN $(\text{CHARGE})^2$

FEYMAN DIAGRAM:



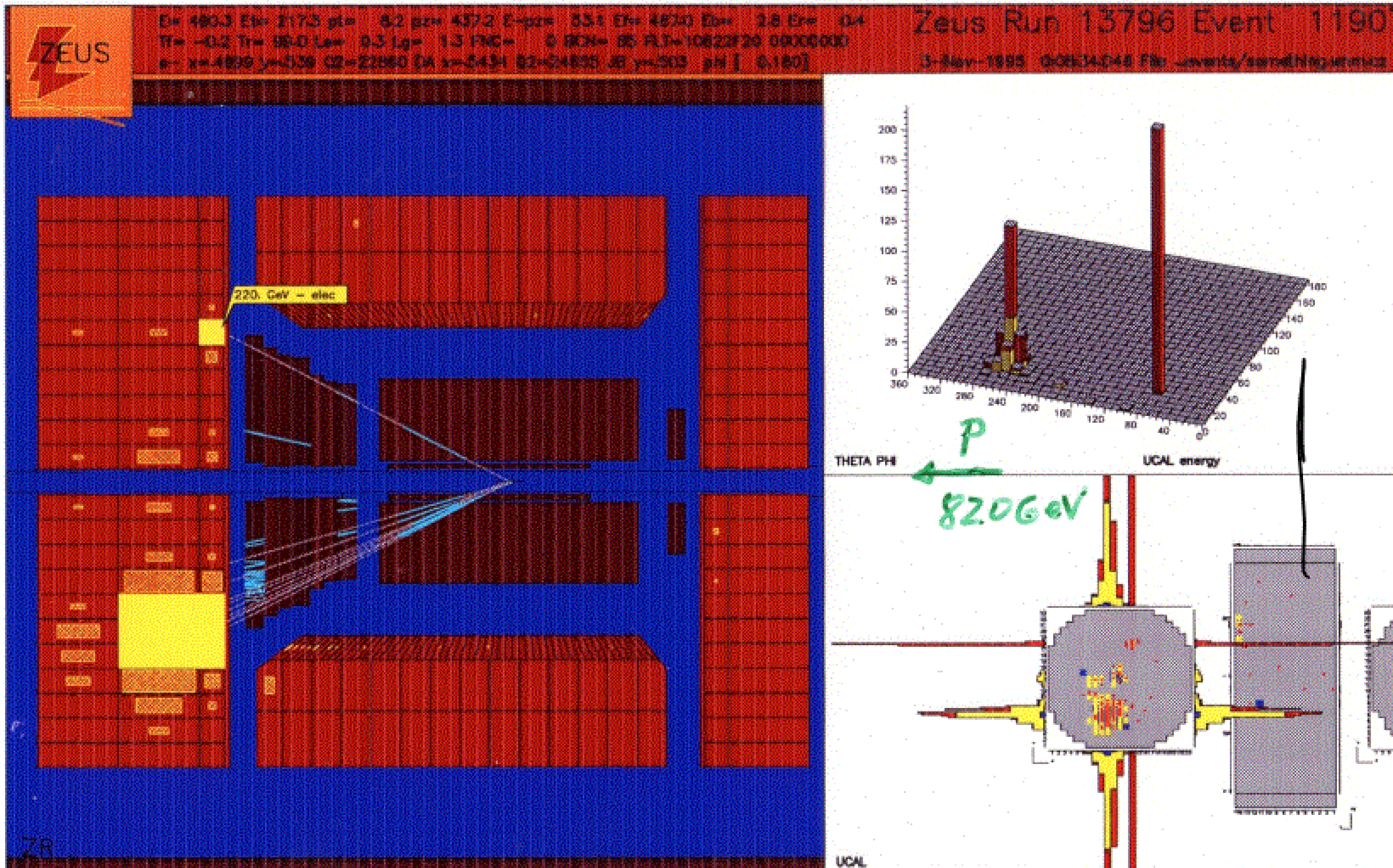
$$\sigma = |A|^2 \sim \left(e \cdot \langle \text{QUARK CHARGE} \rangle\right)^2$$

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

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

ELECTRON - PROTON SCATTERING @ HERA

e
30 GeV



RATIOS OF CROSS SECTIONS

IN $\sigma_{DIS} \sim \frac{1}{3} e^2$

KINEMATIC FACTORS DEPENDING ON EXPERIMENT
— DROPS OUT IN RATIOS

NEUTRONS ddu

MEAN $(\text{CHARGE})^2$

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

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

DEUTERIUM → SAME # PROTONS + NEUTRONS
→ SAME # u + d QUARKS (ISOSCALAR TARGET)

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

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

DEEP INELASTIC SCATTERING & SCALING

PROTON 4-MOMENTUM P

EACH PARTON HAS 4-MOMENTUM xP

PARTON ABSORBS q FROM VIRTUAL γ

$$(xP+q)^2 \sim m^2_{PARTON} \sim 0$$ — THEY BEHAVE LIKE THIS

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

$$x^2P^2 = x^2 M^2_{PROTON} \ll q^2 \Rightarrow q^2 + 2xP\cdot q = 0$$

$$x = \frac{-q^2}{2P\cdot q}$$

$$2(M_p, 0)(\nu\ q^2) = 2M_p\nu$$

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

→ DIMENSIONLESS

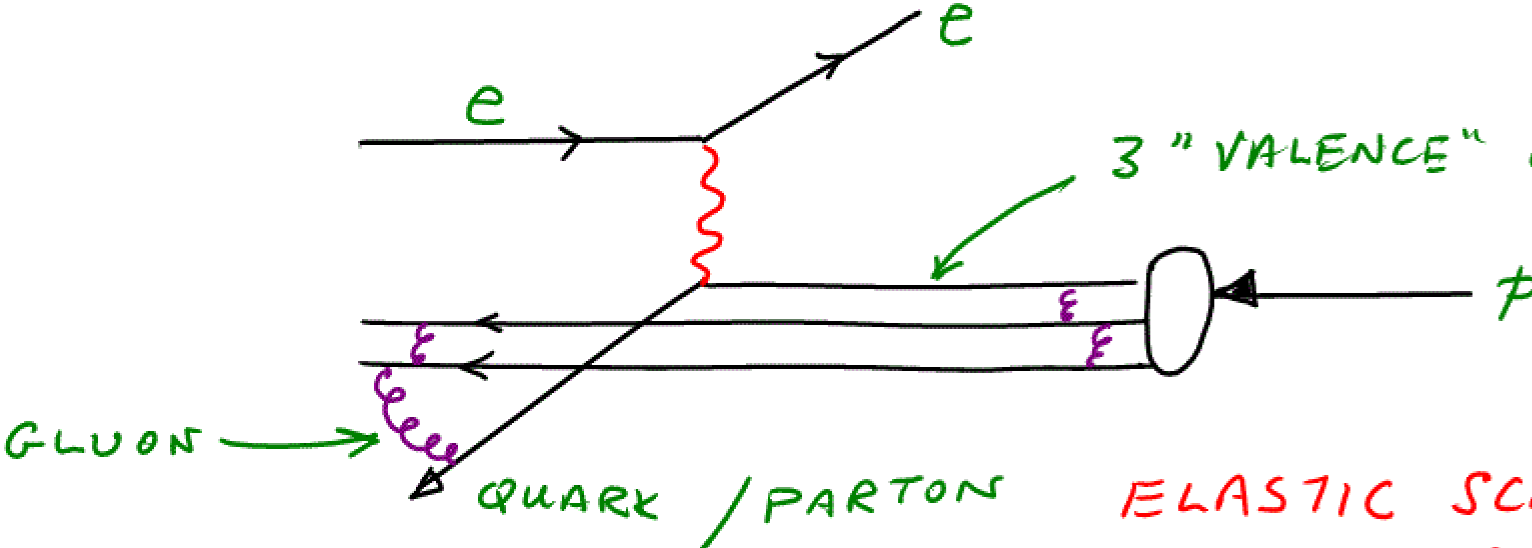
ONLY ONE SCATTERING VARIABLE

→ ELASTIC POINT SCATTERING

SCALING

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

VISUALIZATION OF SCALING



ELASTIC SCATTERING FROM POINT PARTON

$$x = \frac{\text{QUARK MOMENTUM}}{\text{PROTON MOMENTUM}} \longrightarrow xP = (xE, x\vec{p})$$

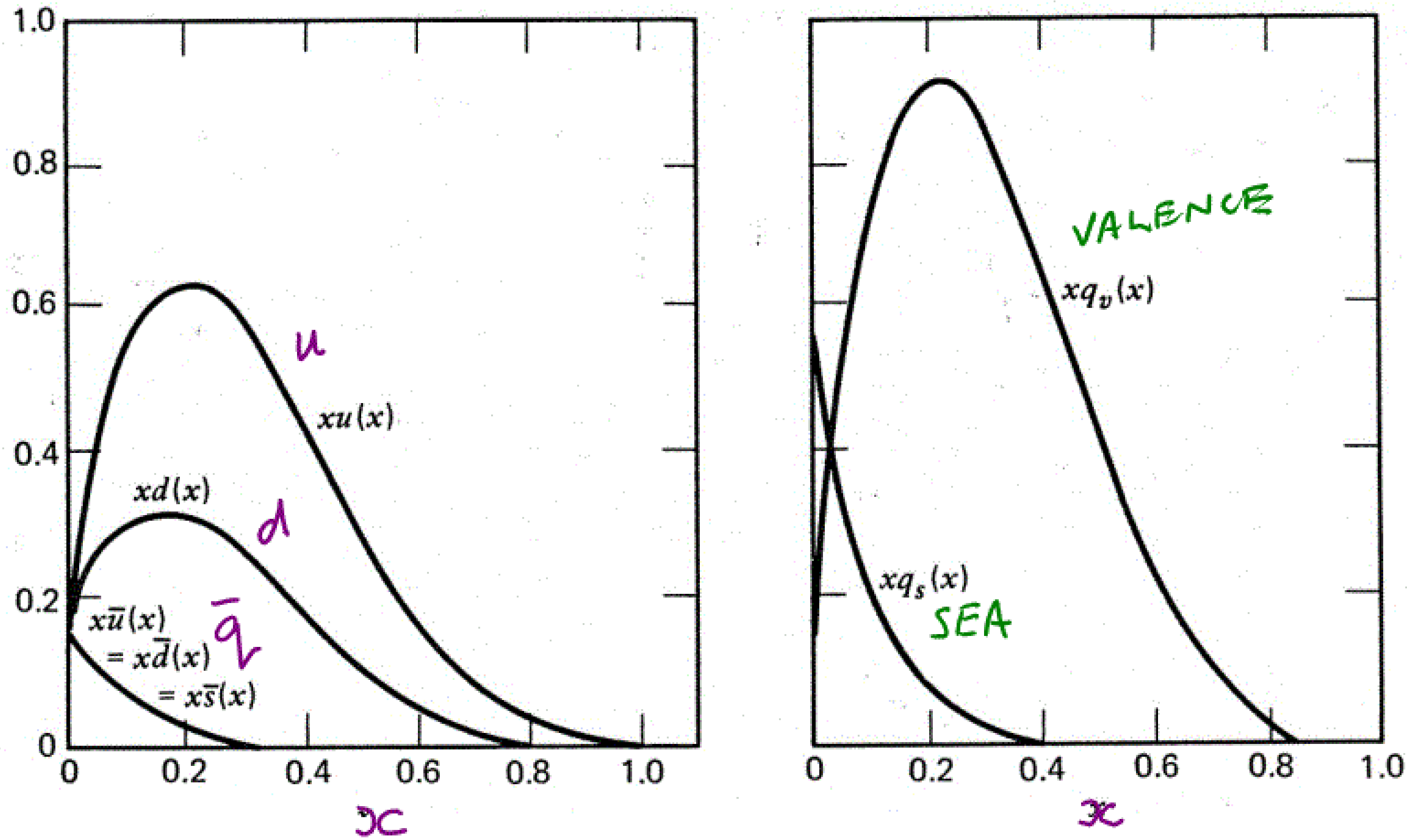
$$x = q/P \quad (0 < x < 1)$$

QUARK/PARTON MOMENTUM DISTRIBUTION INSIDE PROTON

$$\left.\begin{matrix} W_1(q^2, \nu) \\ W_2(q^2, \nu) \end{matrix}\right. \longrightarrow \left.\begin{matrix} F_1(x) \\ F_2(x) \end{matrix}\right\} \text{ SCALE INVARIANCE}$$

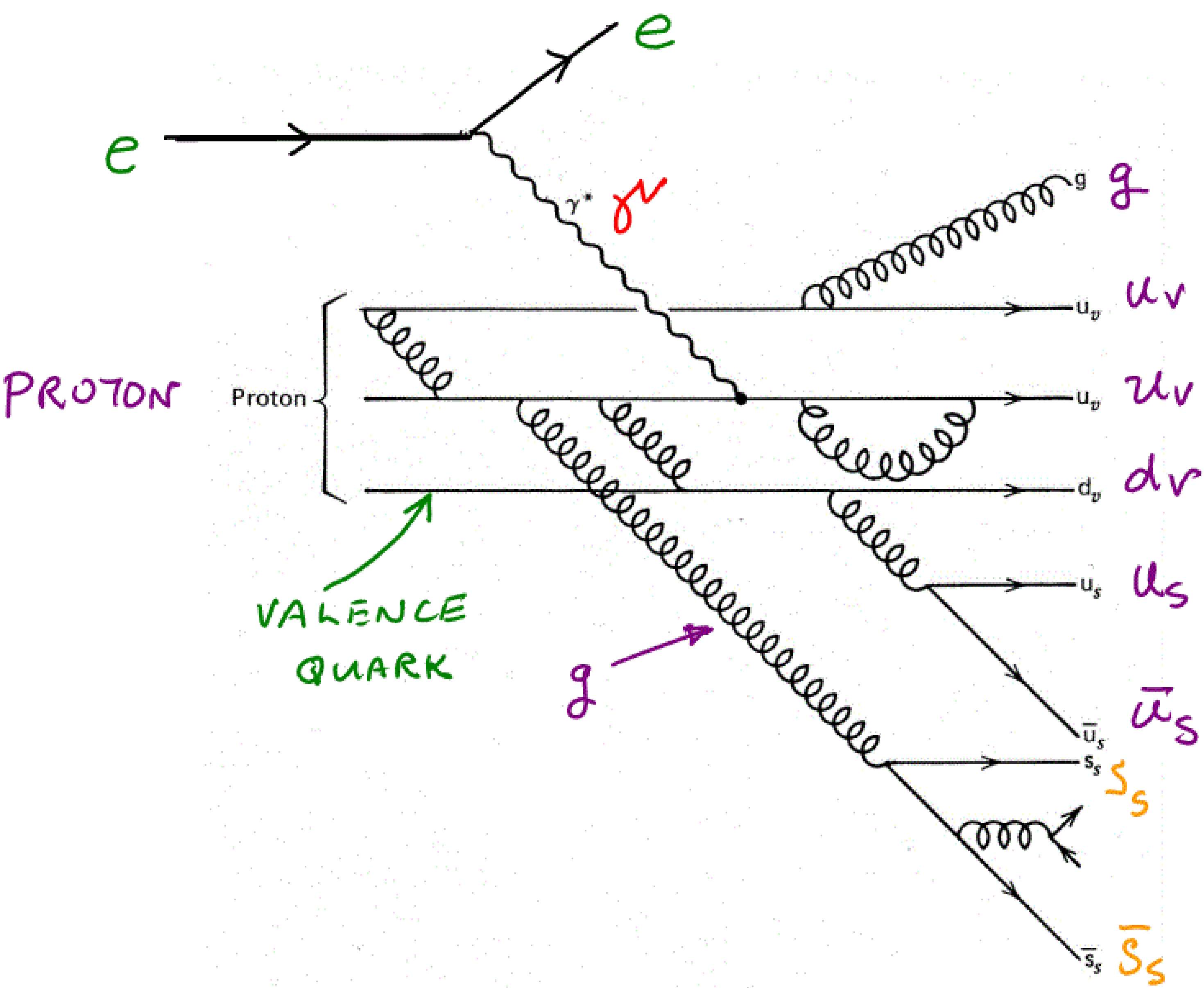
ONE VARIABLE

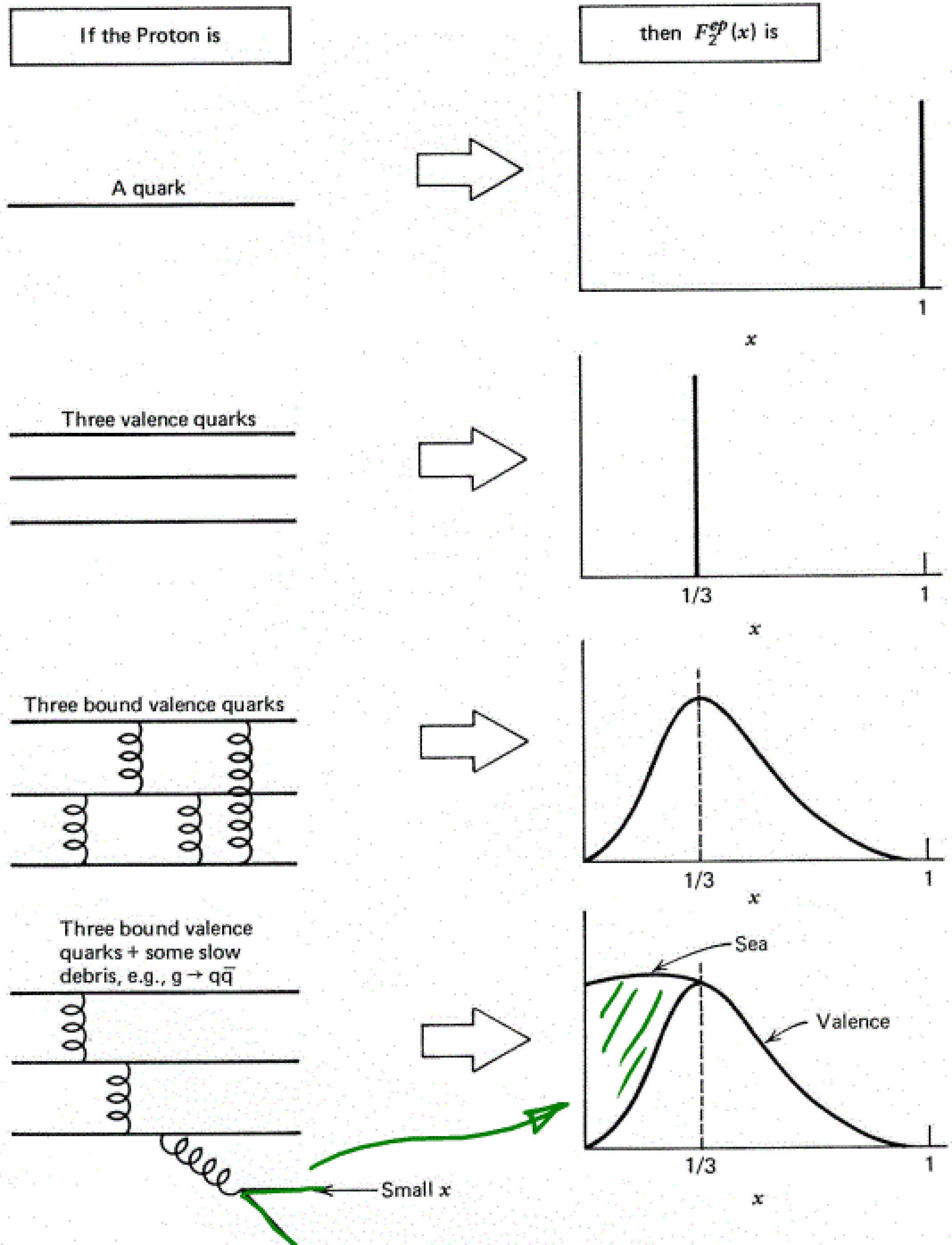
STRUCTURE FUNCTIONS



THESE ARE THE MOMENTUM DISTRIBUTIONS OF VARIOUS QUARK SPECIES INSIDE PROTON

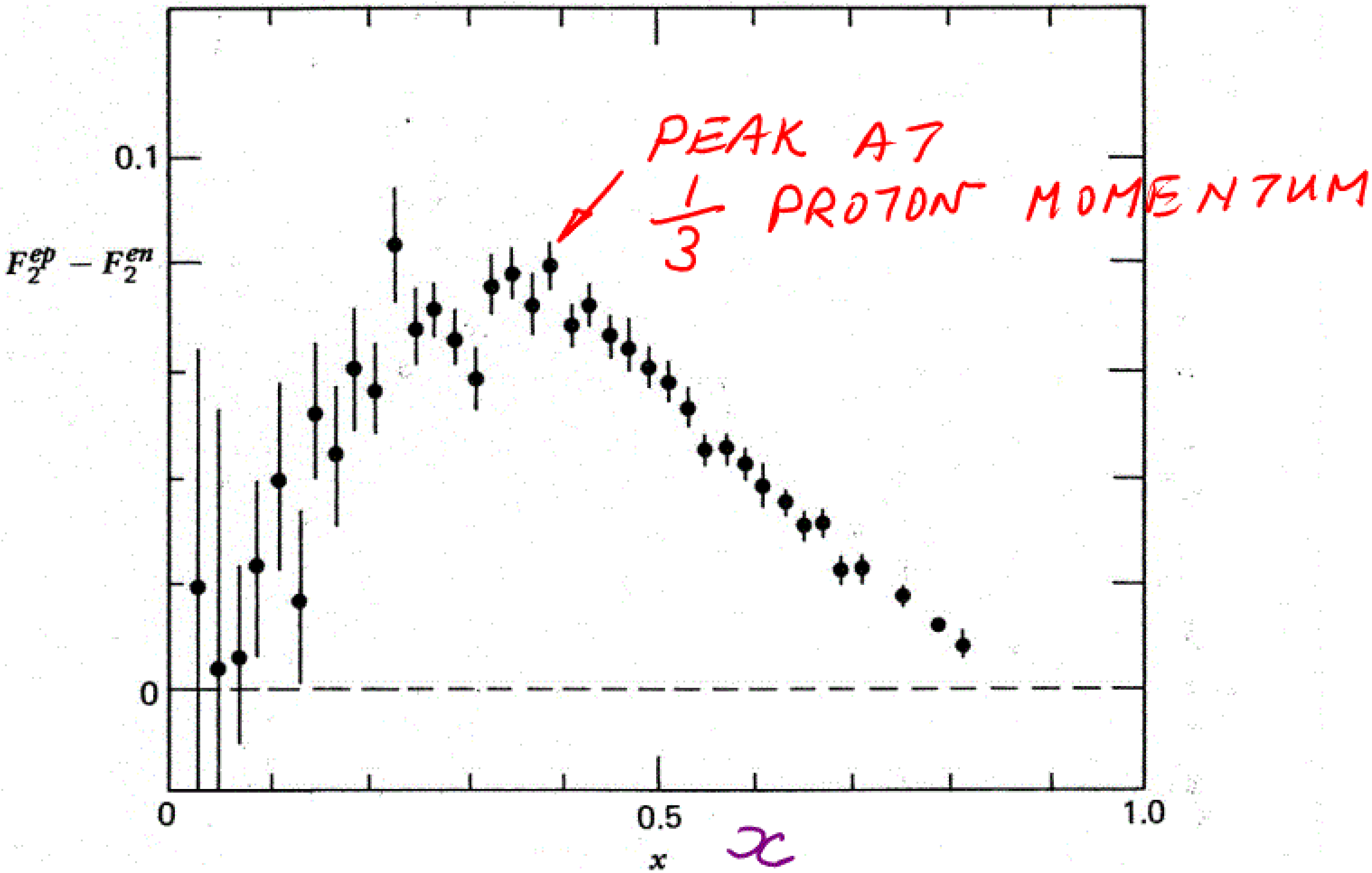
WHERE DO THE ANTIQUARKS COME FROM?





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

MOMENTUM DISTRIBUTION OF VALENCE QUARKS



NEUTRON + PROTON HAVE SAME SEA DISTBIBUTION → DIFFERENCE → VALENCE

SUMMARY

- FOR DEEP INELASTIC SCATTERING IN GENERAL
  - TWO KINEMATIC VARIABLES $q \equiv q(\nu, \vec{p})$
  - TWO STRUCTURE FUNCTIONS

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

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

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

- ARISES FROM ELASTIC SCATTERING FROM

  POINT PARTONS (QUARKS) $\rightarrow$ NO LENGTH SCALE

  SCALE INVARIANCE