Exploring the Structure of the Proton

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MIT

SLAC Starts Operation in 1966

- CIT-MIT-SLAC Collaboration designed and constructed spectrometer complex to study structure of proton, utilizing ELASTIC SCATTERING

- Electron ideal probe:
  - Structure known: "point particle"
  - Interaction understood: QED

In 1950's, Hofstadter used Elastic e-p scattering to measure the proton's form factor & r.m.s. radius

What were the models of the proton at that time?

- Nuclear Democracy - Bootstrap Model
  - The S Matrix era - "Old Physics"
- Quark Model of Gell-Mann & Zweig
  - Quarks are the building blocks of the highly successful SU(3) classification scheme

“OLD PHYSICS”

NUCLEAR DEMOCRACY

BOOTSTRAP MODEL

Particles are composites of one another

$$p = \pi^{+} + n + \ldots..$$

$$n = \pi^{-} + p + \ldots...$$

Particles have diffuse substructures and no elementary building blocks

QUARK MODEL (1964)

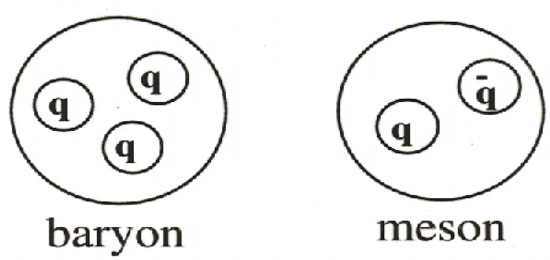
* 3 TYPES

  UP, DOWN, STRANGE

* SPIN 1/2

* FRACTIONAL CHARGES

up(+2/3), down(-1/3), strange(-1/3)



p = (u,u,d) n = (d,d,u)

Are Quarks Real?

MANY UNSUCCESSFUL SEARCHES

– **Accelerators, Cosmic rays, Terrestrial environment Sea water, Meteorites, Air, etc.**

FRACTIONAL CHARGES

– **Considered by many to be unreasonable**

<u>GENERAL POINT OF VIEW IN 1966</u>

Quarks most likely just mathematical representations

Useful but **NOT** ***real*** !

Particles have diffuse substructures and no elementary building blocks

Implausibility of Quark Model

" ...the idea that mesons and baryons are made primarily of quarks is hard to believe.."

M. Gell-Mann 1966

" Additional data are necessary and very welcome to destroy the picture of elementary constituents."

J. Bjorken 1967

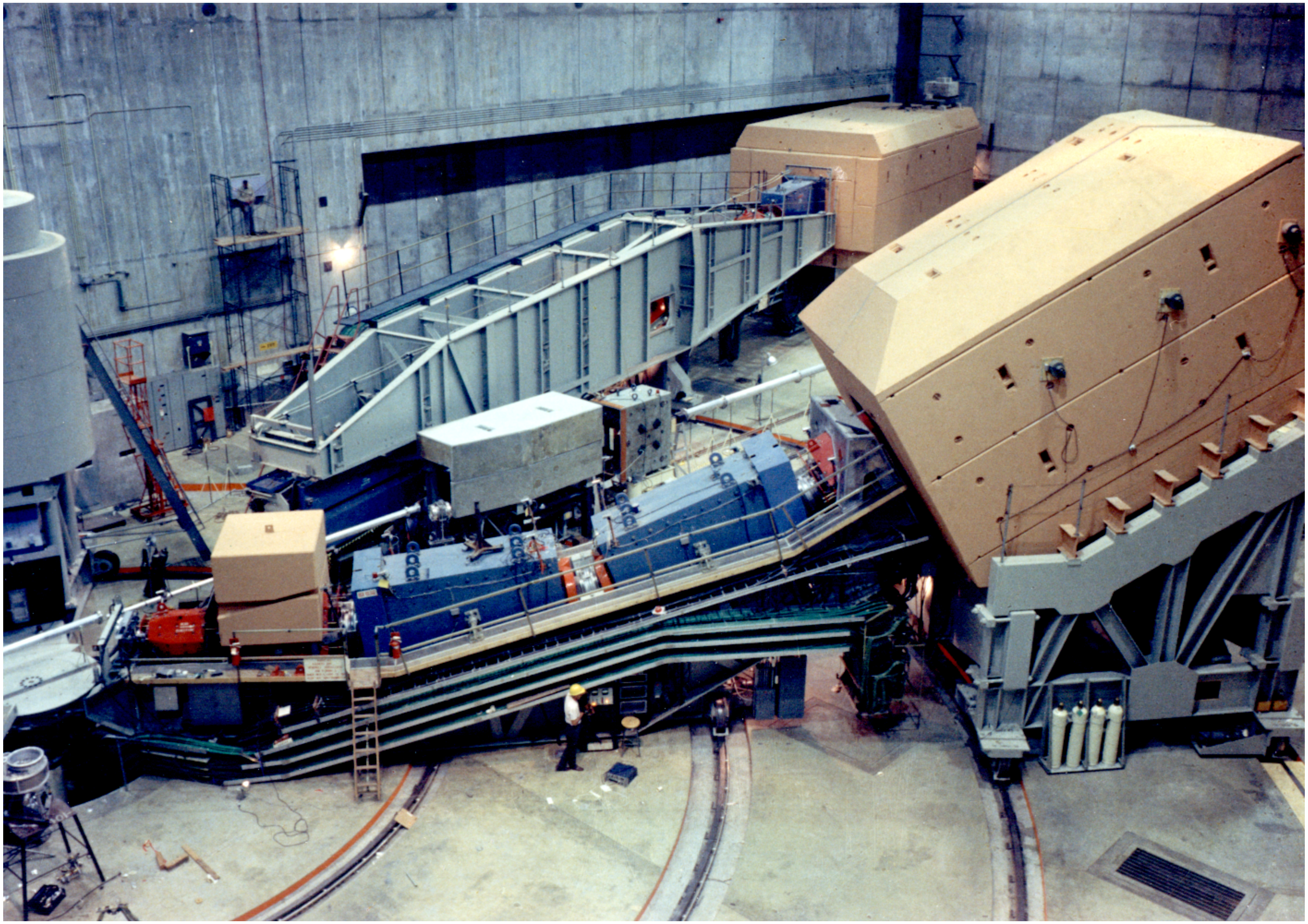
" I think Professor Bjorken and I constructed the sum rules in the hope of destroying the quark model."

K. Gottfried 1967

" Of course the whole quark idea is ill founded."

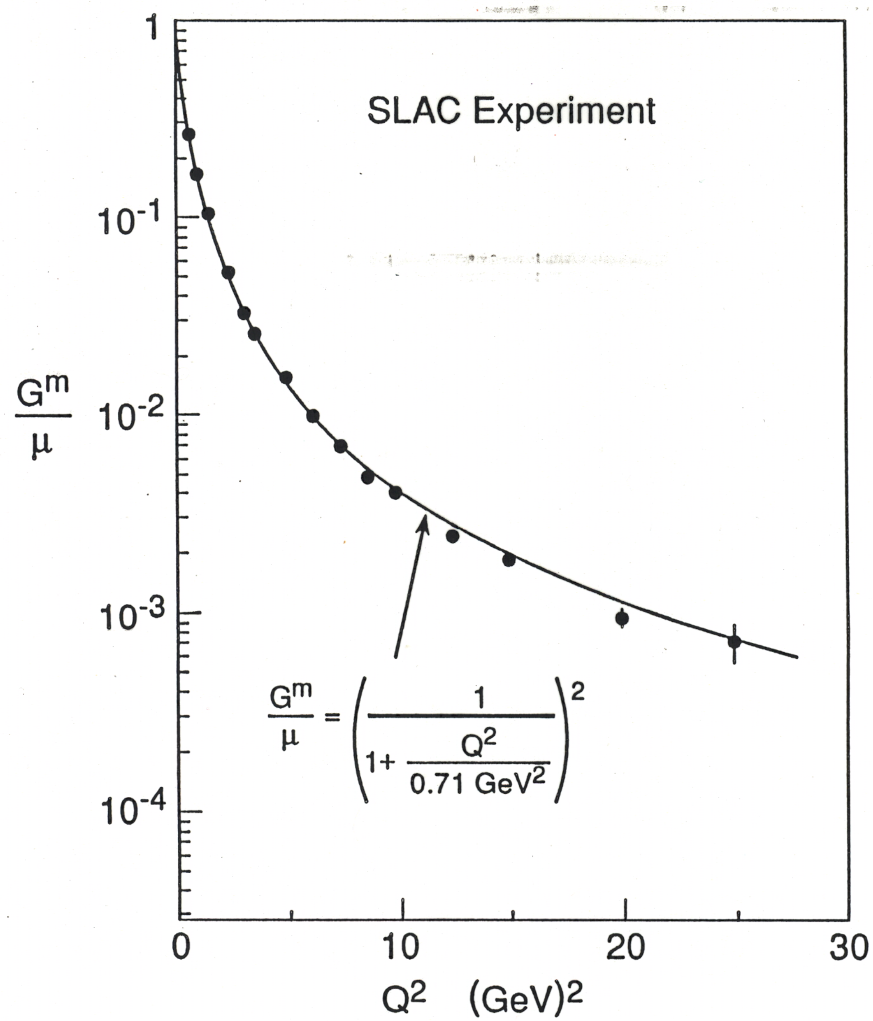
J.J. Kokkedee 1969

Stanford Linear Accelerator



SLAC Magnetic Spectrometers

Magnetic Form Factor of Proton



Extended earlier measurements at CEA & DESY

1967 MIT-SLAC begins Inelastic Program

$e + p \Rightarrow e + \text{Anything}$

Inelastic vs. Elastic Scattering

- **Elastic scattering provides information about the charge and magnetic moment distributions averaged over time**
- **Inelastic scattering can provide a "snapshot" of the structure**

$$\Delta t \approx h/\Delta E$$

ΔE is energy lost by electron.

$\Delta E = 2$ GeV $\quad \Delta t = 3\times10^{-25}$ sec

for $v \approx c$

motion during "snapshot" is

$\approx 10^{-14}$ cm.

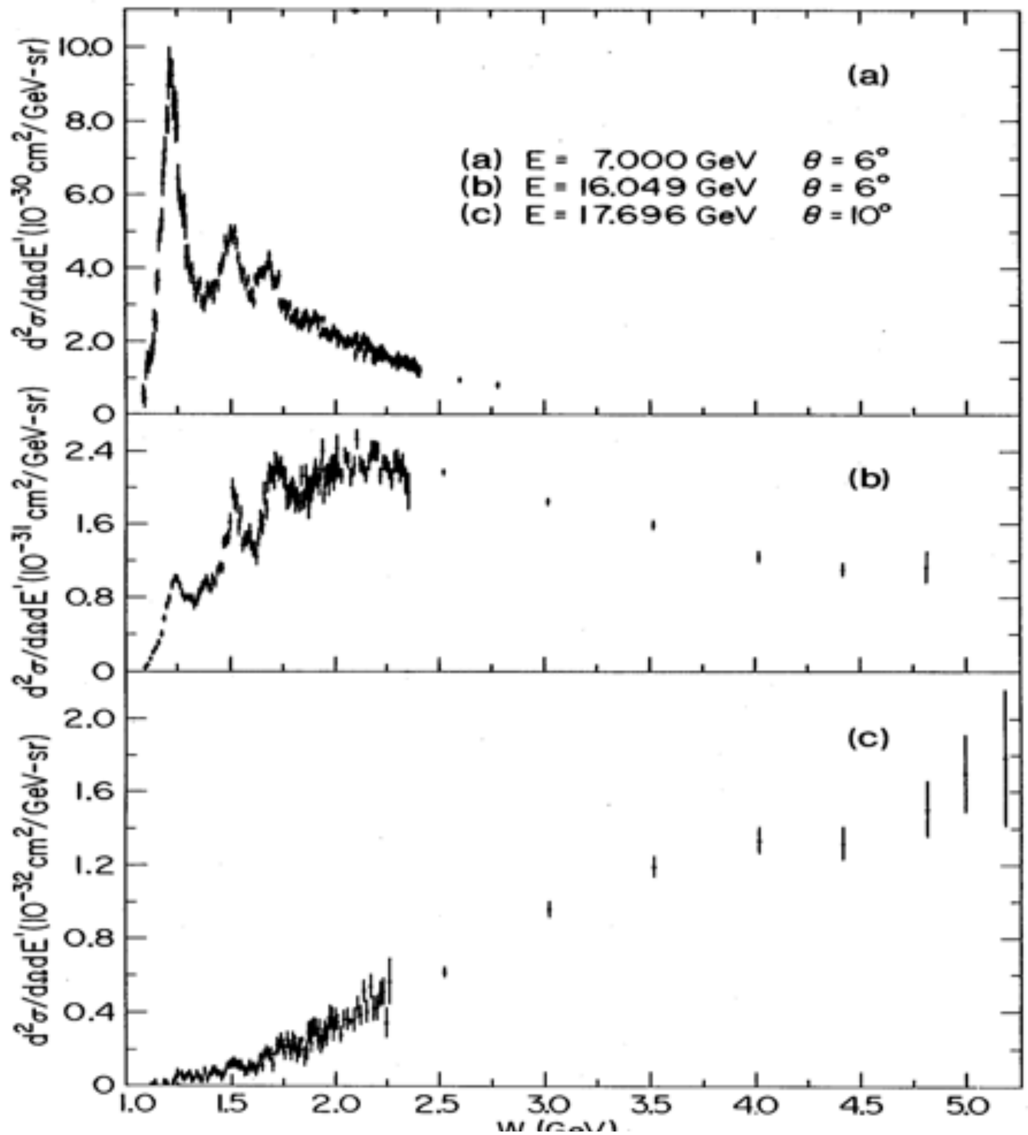
DEEP INELASTIC SCATTERING
REQUIRED FOR LARGE ΔE

MIT - SLAC Group

W.B. Atwood
E.D. Bloom
A. Bodek
M. Breidenbach
C. Buschhorn
R.L.A. Cottrell
D. Coward
H. DeStaebler
R. Ditzler
J. Drees
J. Elias
J.I. Friedman
G. Hartmann

C.L. Jordan
H.W. Kendall
M. Mestayer
G. Miller
L.Mo
H. Piel
J.S. Poucher
M. Riordan
D. Sherden
M. Sogard
S. Stein
R.E. Taylor
R. Verdier

Increasing q^2

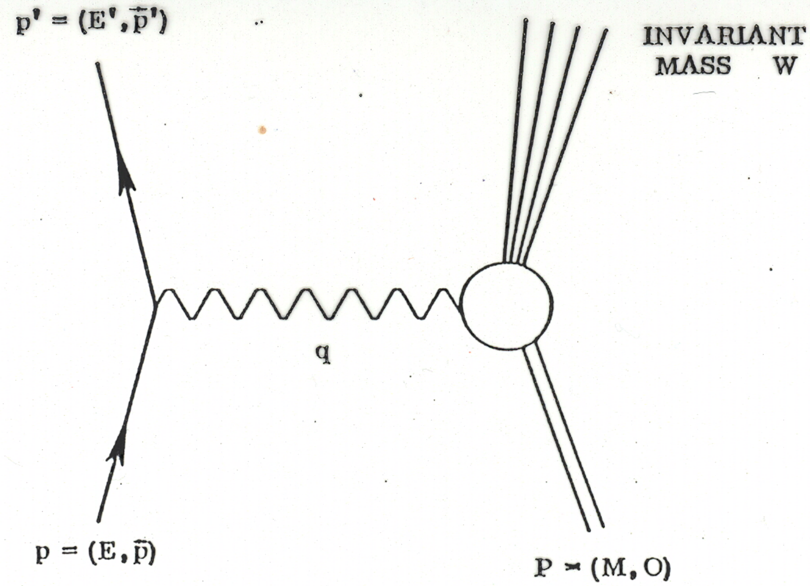


W (GeV)

Two Major Surprises

- **Bjorken Scaling** of Structure Functions

- **Weak q^2 dependence** of cross sections



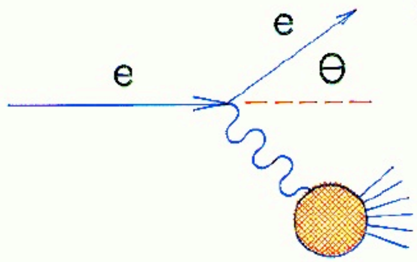
INVARIANTS

$$\nu = \frac{P.q}{M} = E - E'$$

$$q^2 = -(p - p')^2 = 4EE' \sin^2\frac{\theta}{2}$$

$$W^2 = 2M\nu + M^2 - q^2$$

Bjorken Scaling



$\nu = \Delta E$ for e

$q^2 = (\Delta p)^2 - (\Delta E)^2$

Scattering $\frac{d^2\sigma}{d\Omega\, dE} = \sigma_M \,(W_2 \;\; + 2W_1 \tan^2 \theta/2)$

Q.E.D. (understood) — Target (unknown)

Scaling — Bjorken (1967)

for $\nu \to \infty$ $\quad q^2 \to \infty$

with $\omega = \frac{2M\nu}{q^2}$ held fixed

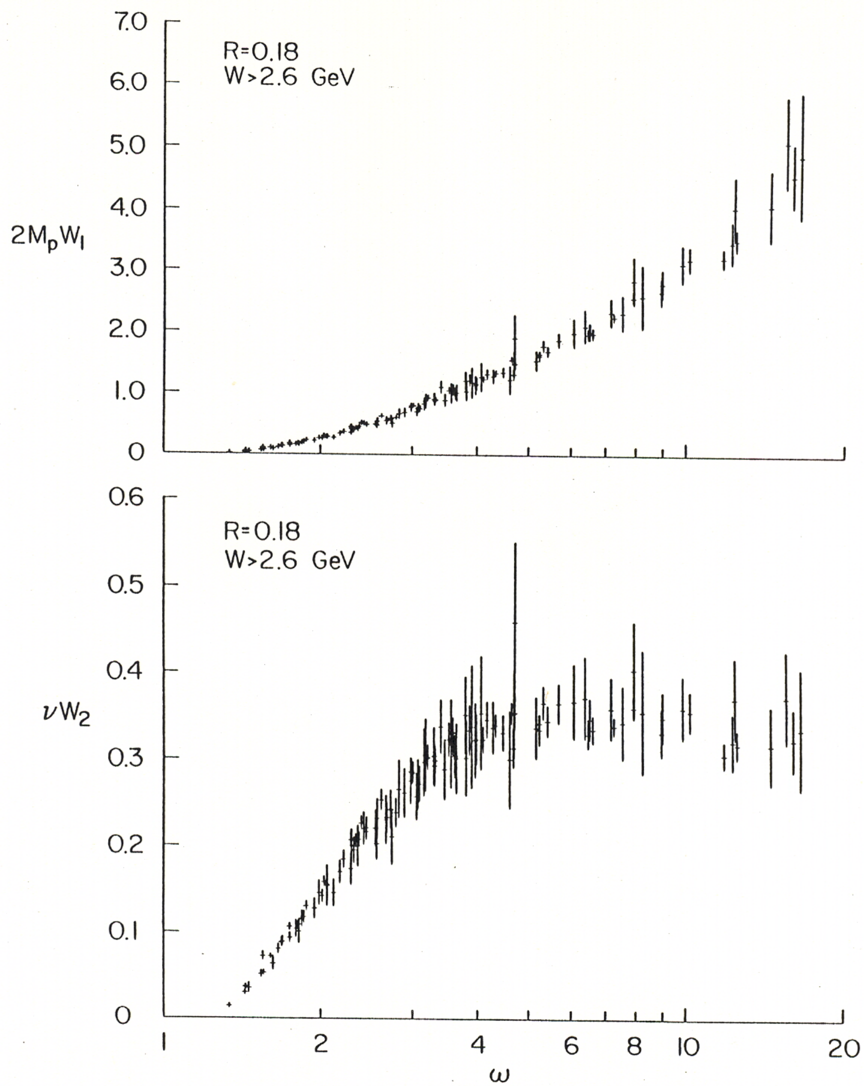
$$\nu W_2(\nu, q^2) \to F_2(\omega)$$

$$2MW_1(\nu, q^2) \to F_1(\omega)$$

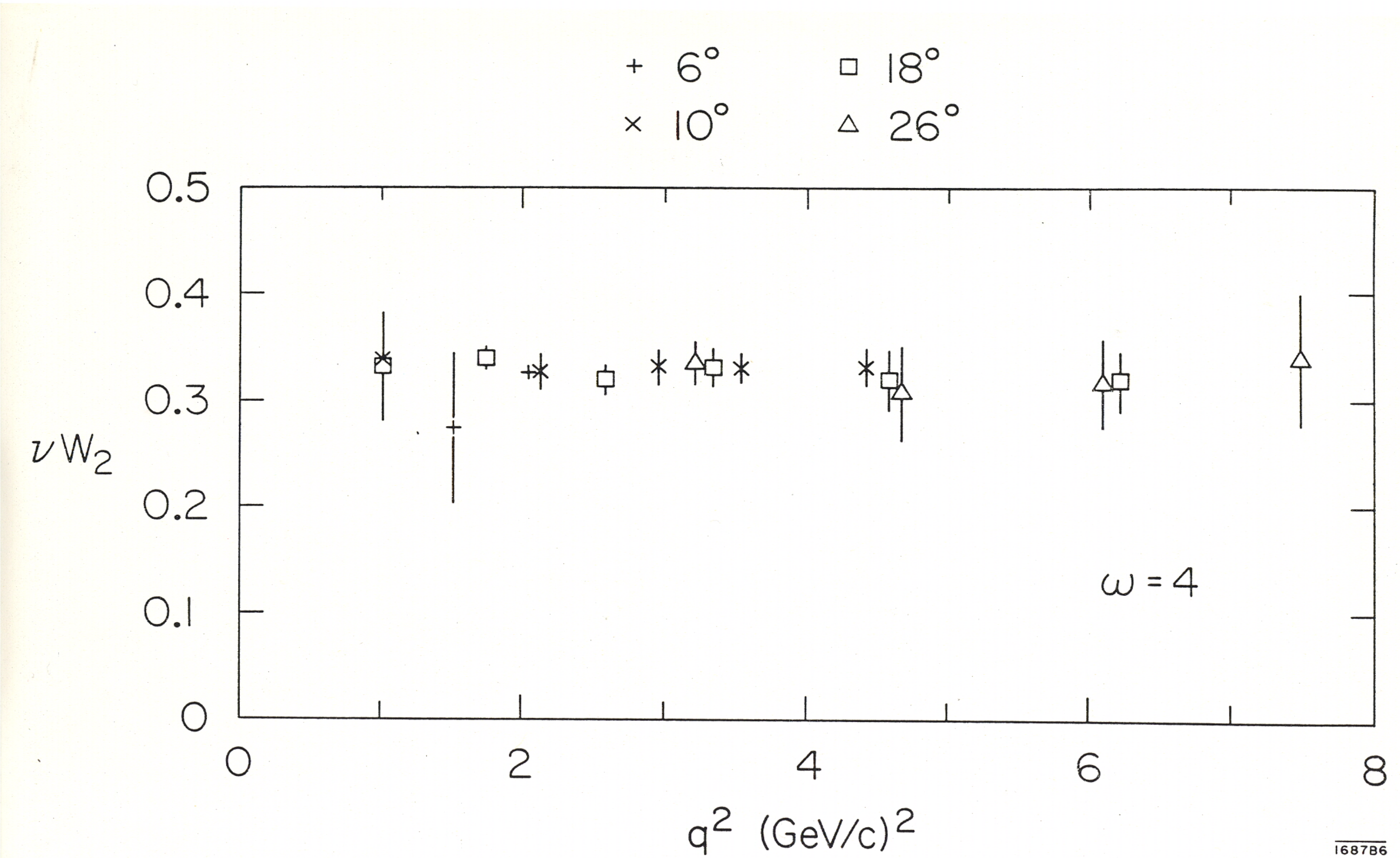
Experimental Test of Scaling

W > 2.6 GeV

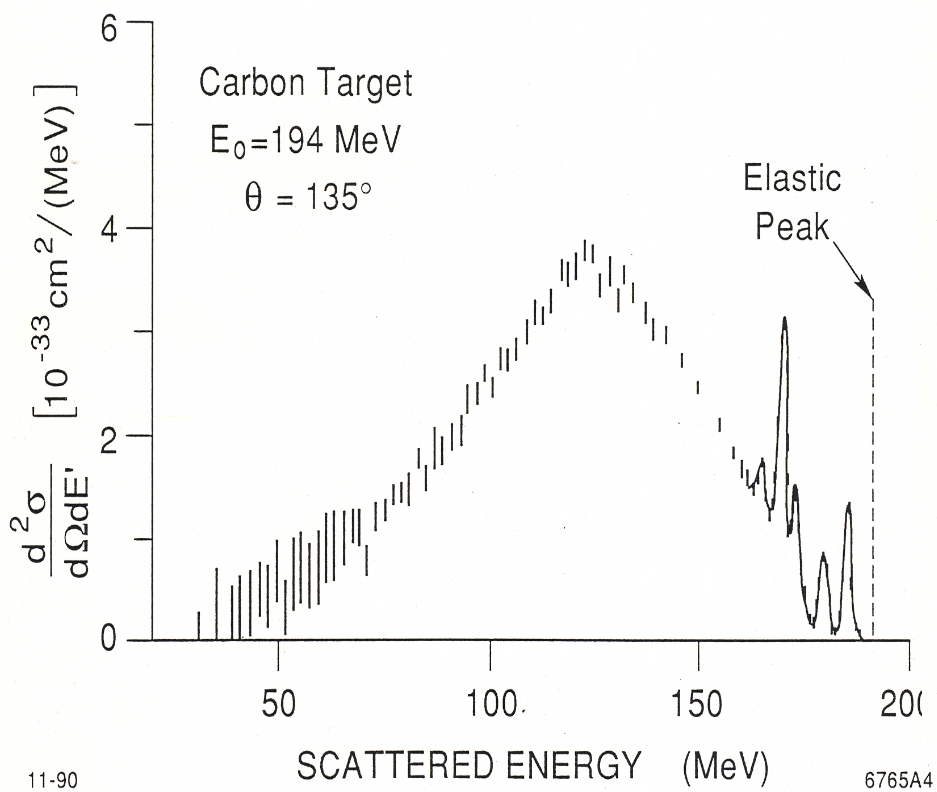
$2 < q^2 < 20\ (\mathrm{GeV})^2$

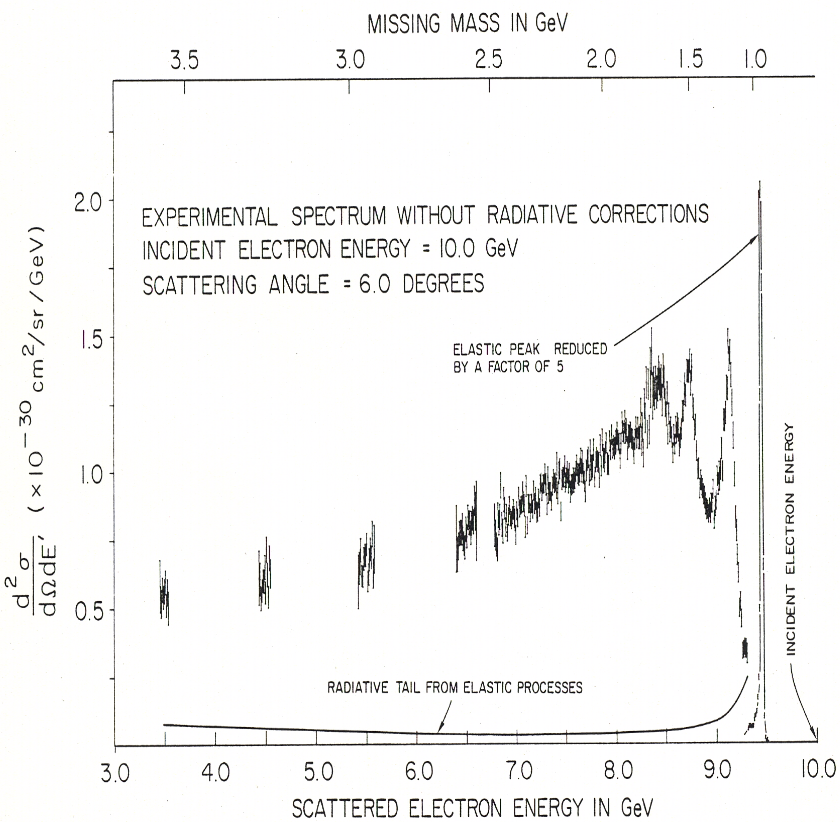


Test of Scaling 2

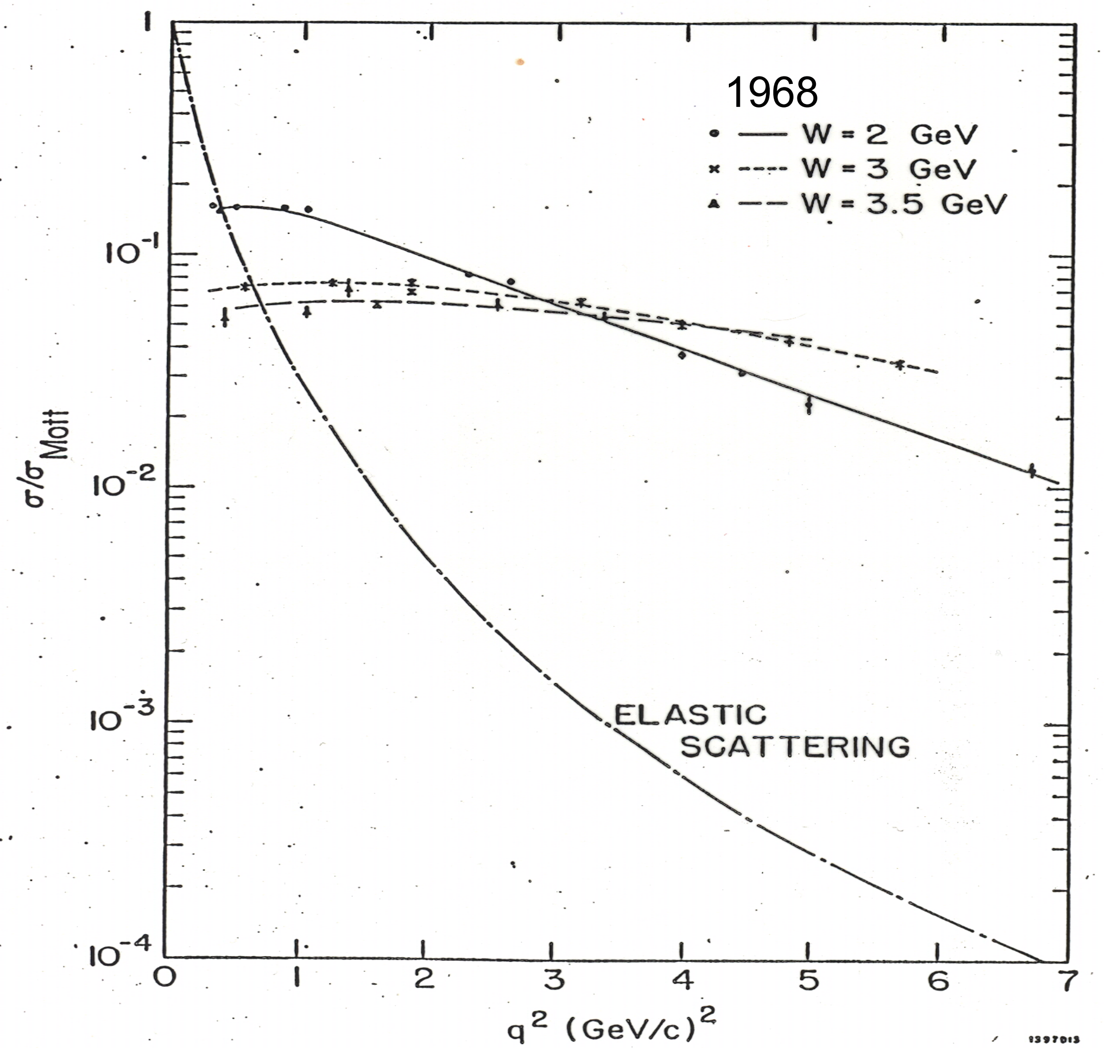


Comparison of e-Carbon & e-p Scattering





e-p Cross-sections divided by Mott Cross-section



MOMENTUM TRANSFER q

FORM FACTOR $G(q^2) = \int \rho(r) e^{iq \cdot r} d^3r$

point distribution function $\rho(r) = \delta(r)$

$$G(q^2) = 1$$

" POINT-LIKE" ⇒ WEAK q^2 DISTRIBUTION

Results suggested "point-like" Constituents

Non–Constituent Models proposed to explain Scaling

"OLD PHYSICS"

Vector Dominance

Resonance Models { Veneziano; N's and Δ's }

Regge Poles

Diffraction Models

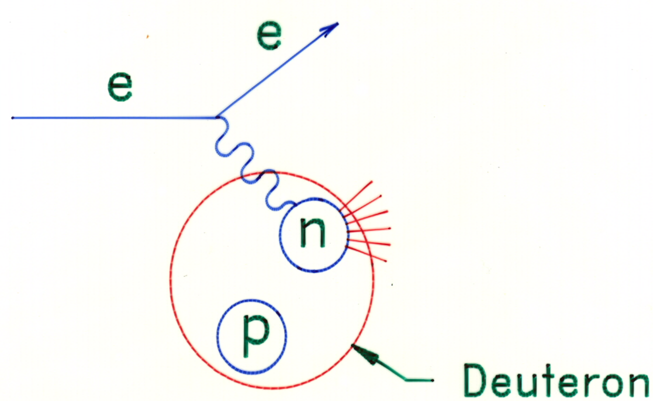
LATER DATA SETS (After 1970)

$$e + p \rightarrow e + \text{Anything}$$

$$e + d \rightarrow e + \text{Anything}$$

* More statistics – greater range of angles
* Extracted Neutron cross–section and Structure Functions

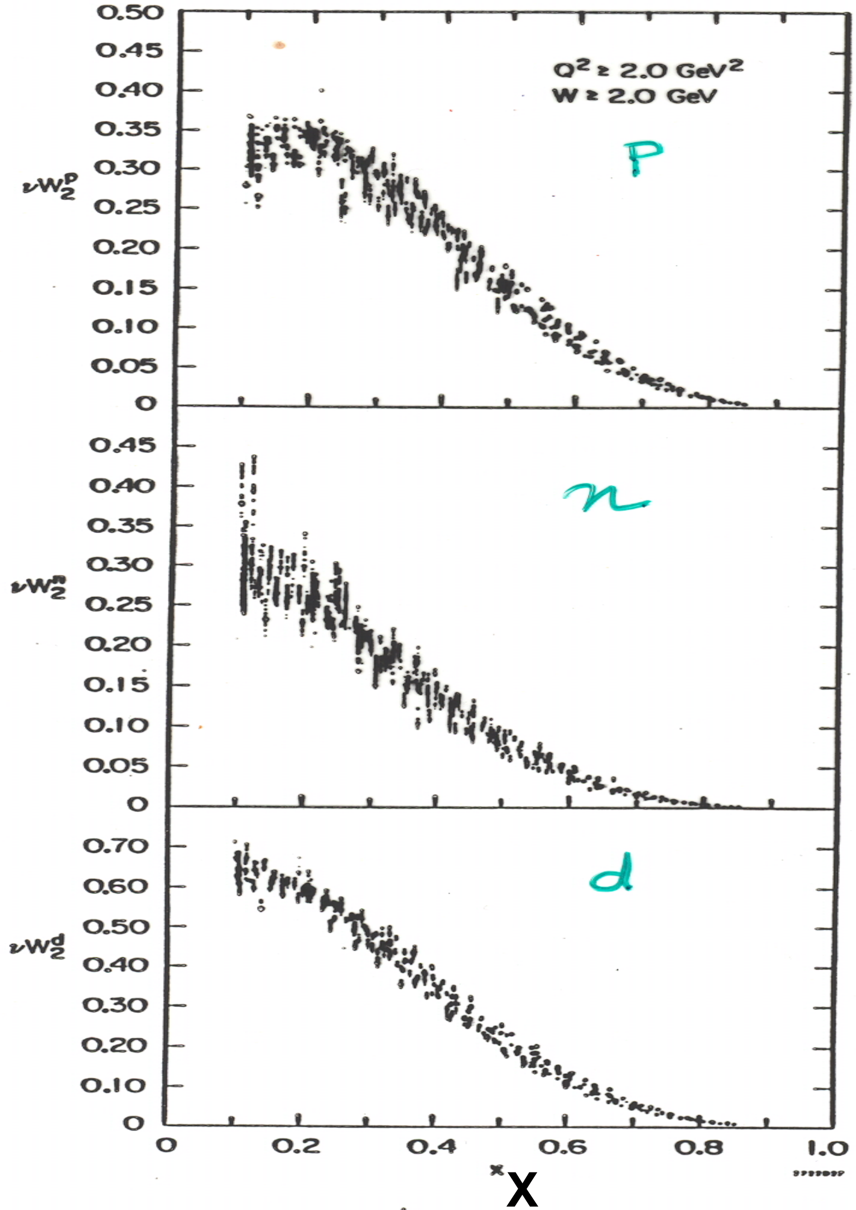
Impulse Approximation used to obtain Neutron results



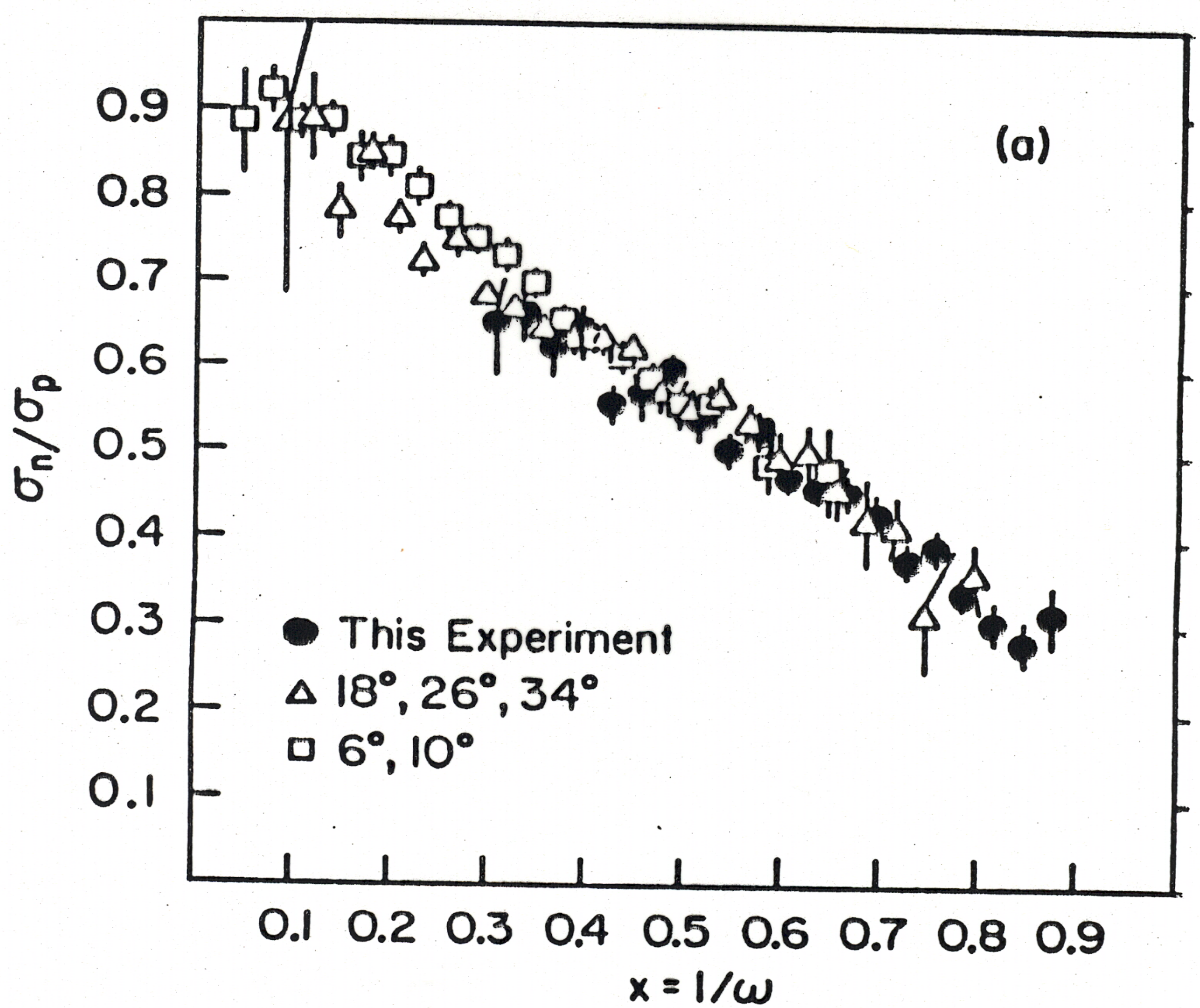
$$\sigma_n = \sigma_d - \sigma_p$$

Applied "Smearing" Corrections to eliminate Fermi Motion

Scaling Observed in Deuteron and Neutron Scattering



n / p Scattering



COMPARISON OF σ_n/σ_p *WITH MODELS*

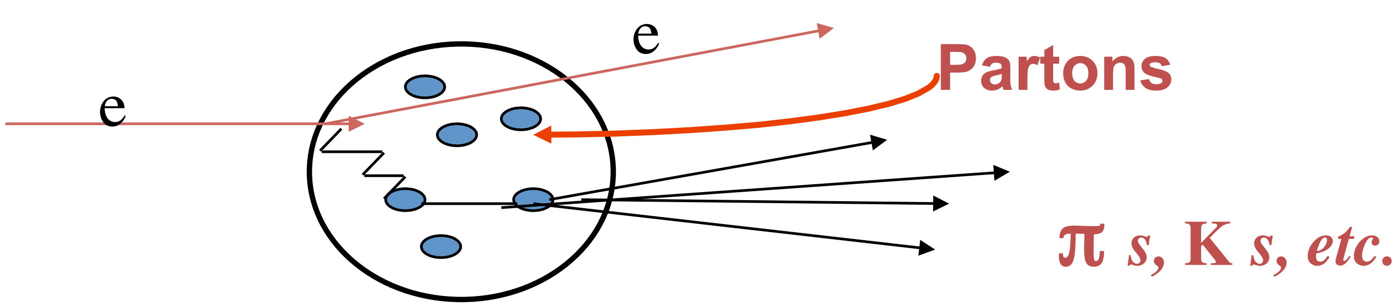
Model	σ_n/σ_p at $x \approx 0.85$
Diffraction	1
Resonance	~ 0.7
Regge	~ 0.6
Duality	0.47
Parton (Bare Nucleon + Pions)	0.10
Quark	≥ 0.25
Experiment	$0.30 \pm .03$

- **Many attempts were made to use "Old Physics" models to explain results without success.**
- But **<u>Quark model</u>** was not regarded as valid by most physicists.

?

- **Theoretical contribution that helped resolve puzzle:**
  - **R. Feynman -- Parton Model**

Parton Model (*Feynman 1968*)



1) Electrons scatter from bound constituents (partons)

2) Partons recoil and interact internally, producing known particles, π' s, K' s, etc.

3) If partons are point-like, F_2 and F_1 scale in
$X = q^2 / 2M\nu = 1/\omega$

4) Scaling variable x is fractional momentum of struck Parton

5) $F_2(x)$ is related to momentum distribution of Partons in proton

If Partons are Quarks

1) They must be spin 1/2 particles

2) They must have fractional charges consistent with the quark model

SEPARATION OF W_1 AND W_2

Requires Measurements of cross sections at constant W and q^2 (vary E, E', θ)

$$R = \frac{W_2}{W_1}\left(1 + \frac{\nu^2}{q^2}\right) - 1 \qquad R = \sigma_L / \sigma_T$$

PARTON MODEL :

Callan -Gross

Spin $\frac{1}{2}$ $\quad R \rightarrow 0 \quad$ as $\quad \nu \rightarrow \infty$

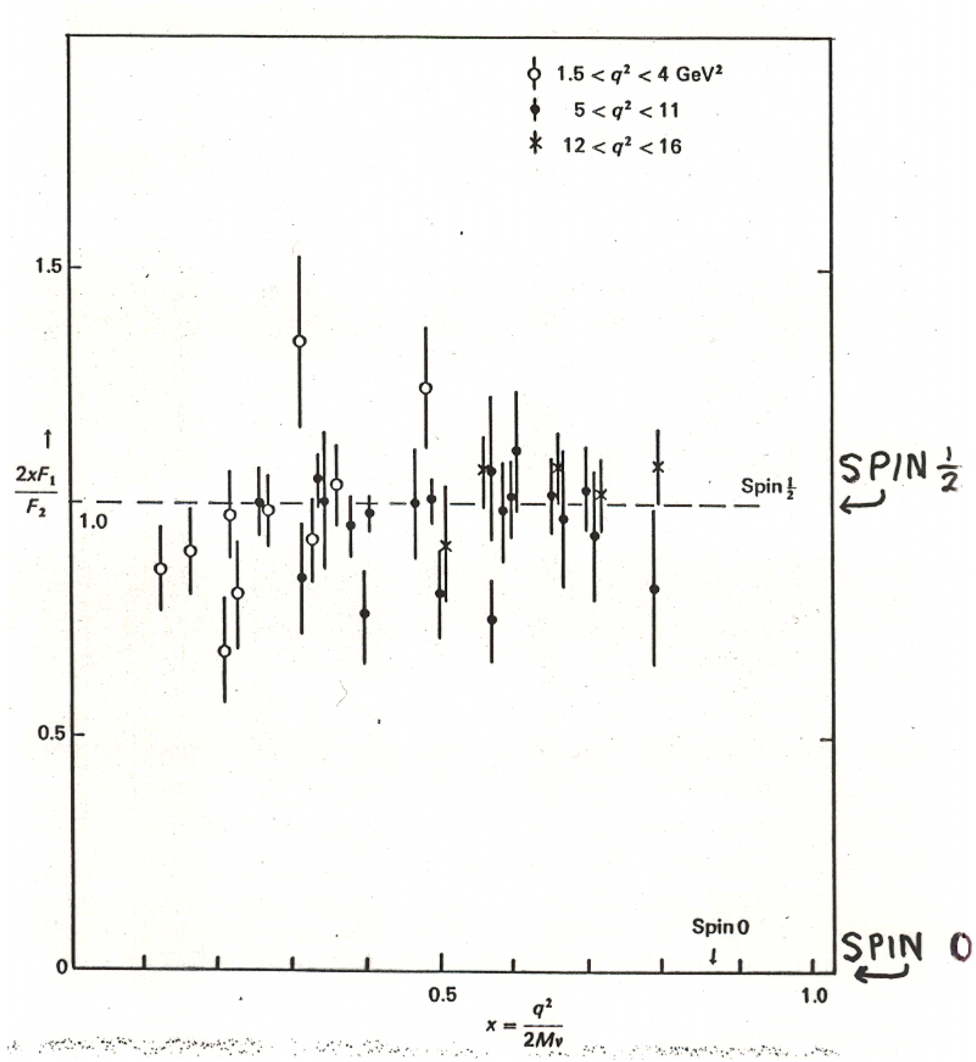
$$F_2 = 2xF_1$$

Comparisons of forward and backward scattering answered the question:

What is the the spin of the partons?

Spin 1/2

Spin 0



$F_2(x)$ Sum Rule Provided Information about Parton Charges

$$\int_1^{\infty} \frac{\nu W_2}{\omega^2}\, d\omega = \int_0^1 F_2(x)dx = \left\langle Q^2 \right\rangle_{AVG} * \begin{pmatrix}\text{Fraction of}\\ \text{Nucleon's}\\ \text{Momentum}\\ \text{carried by}\\ \text{Partons}\end{pmatrix}$$

If Partons are Quarks

$$\frac{1}{2}\int \frac{[\nu W_2^P + \nu W_2^n]d\omega}{\omega^2} = \frac{1}{2}\int \left[F_2^p(x) + F_2^n(x)\right]dx$$

$$= \left[\frac{Q_u^2 + Q_d^2}{2}\right] * \begin{pmatrix}\text{Fraction of}\\ \text{Nucleon's}\\ \text{Momentum}\\ \text{carried by}\\ \text{Quarks}\end{pmatrix}$$

$$= \underbrace{\left[\frac{5}{18}\right]}_{0.28} * \left\{ \; ? \; \right\}$$

Experiment $\Rightarrow$ $0.14 \pm .006$

CONCLUSION: CONSISTENT WITH QUARK MODEL IF

- **QUARKS CARRY 1/2 MOMENTUM**
- **GLUONS CARRY OTHER HALF**

Do Partons have Fractional Charges (+2/3, -1/3)?

- Comparisons of Electron Scattering and Neutrino Scattering provided the answer.
- First results came from Large Heavy Liquid Bubble Chamber "Gargamelle" (1971-1974)

EARLY NEUTRINO AND ANTI - NEUTRINO RESULTS

CERN -- **Large Heavy - Liquid Bubble Chamber -**

" Gargamelle " (1971 - 74)

1) Observed neutrino and anti-neutrino scattering probability increased linearly with energy

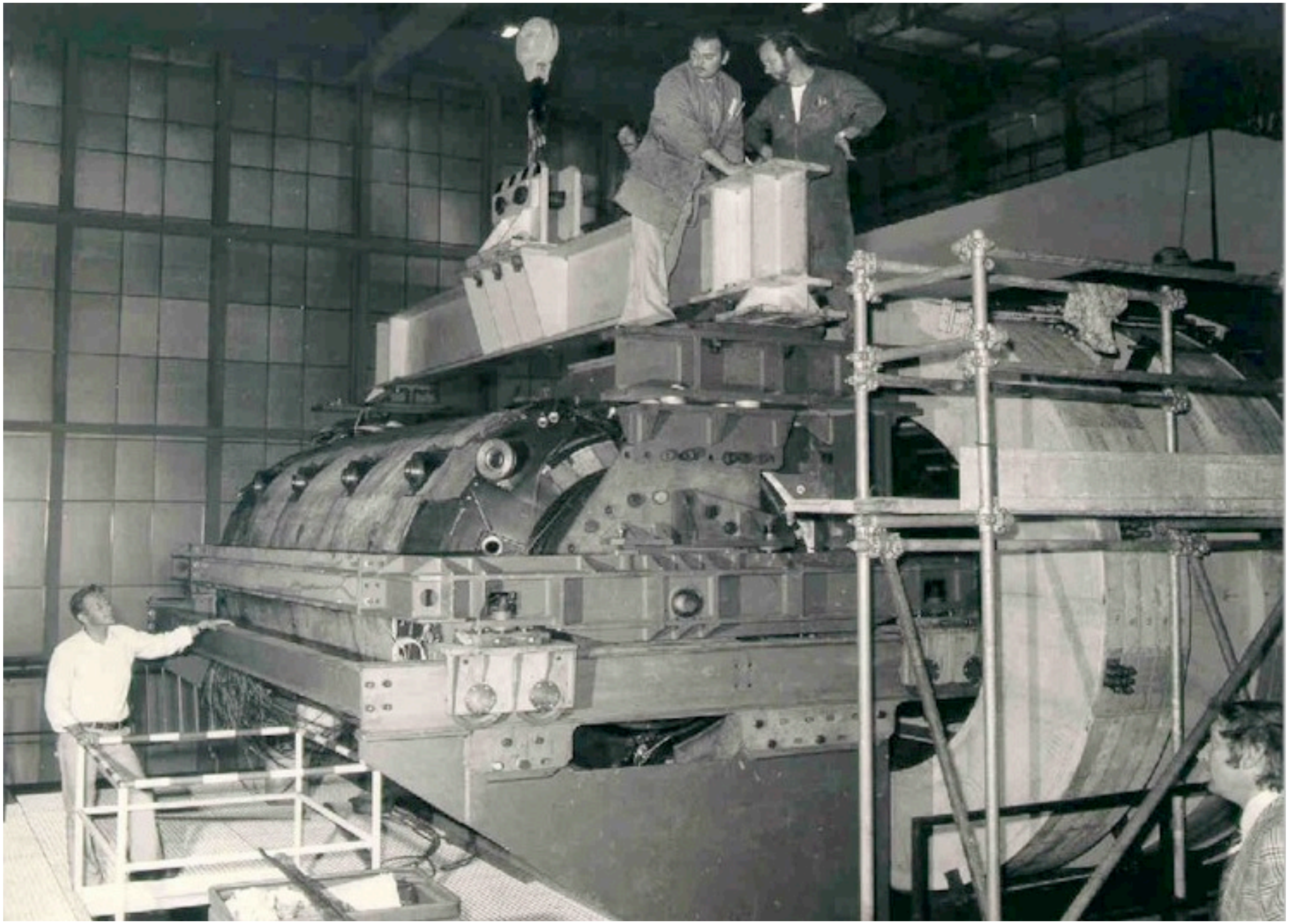
   ** confirmed existence of "point-like" constituents

2) Comparisons of electron and neutrino scattering

   ** confirmed fractional charges of constituents

STRONG VALIDATION OF QUARK MODEL

GARGAMELLE

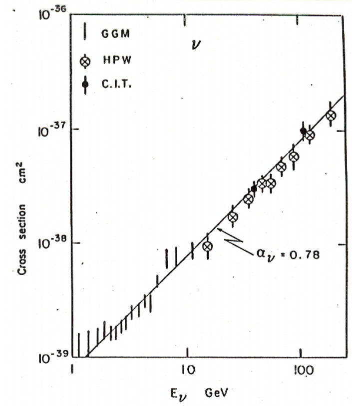


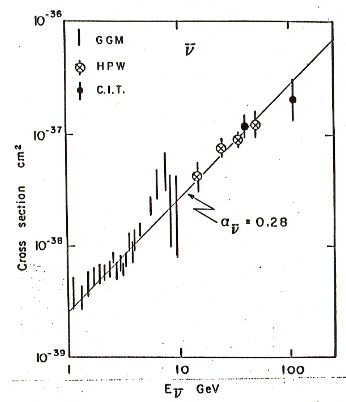
5 meters **12000 liters of Freon**

Neutrino and Anti-neutrino Scattering

Linear rise of scattering cross sections confirmed

point-like constituents in proton and neutron





Comparison of electron & neutrino scattering in the quark model (1972-1974)

$$\frac{\int [F_2^{\nu n}(x) + F_2^{\nu p}(x)]dx}{\int [F_2^{en}(x) + F_2^{ep}(x)]dx} =$$

$$= \frac{2}{(Q_u^2 + Q_d^2)}$$

$$= \frac{2}{(2/3)^2 + (1/3)^2}$$

$$= 3.6$$

Experimental Value (MIT-SLAC, CERN) = 3.4 ± 0.7

VALIDATION OF QUARK MODEL

OTHER NEUTRINO RESULTS

* $\frac{1}{2}\int\left[F_2^{\nu p}(x)+F_2^{\nu n}(x)\right]dx = \left(\begin{array}{c}\text{Total Fraction of}\\ \text{Nucleon's Momentum}\\ \text{carried by Quarks}\end{array}\right)$

Experimental Value (Gargamelle)

$= 0.49 \pm .07$

Half of Momentum carried by
Quarks as suggested by
Electron Scattering results

* $\frac{1}{2}\int\left[F_3^{\nu p}(x)+F_3^{\nu n}(x)\right]dx =$ Number of Valence Quarks

$= 3$

Experimental Value (Gargamelle)

$= 3.2 \pm 0.6$

Consistent with Quark Model

Partons are Quarks

- Constituents have spin 1/2
- Constituents have fractional charges consistent with quark model --- *from electron and neutrino sum rules*

Model of Nucleon

(1) 3 valence quarks ------ p(uud), n(ddu)

(2) quark-antiquark sea ---- vacuum polarization

(3) Gluons ----- neutral particles responsible for binding quarks that carry 1/2 of nucleon's momentum