Rutherford's Legacy in Particle Physics: Exploring the Proton

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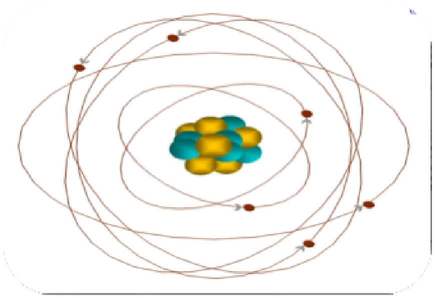
MIT

Rutherford's Legacy: Scattering Can Uncover Structure of Matter

Magnification
1

Bulk Matter

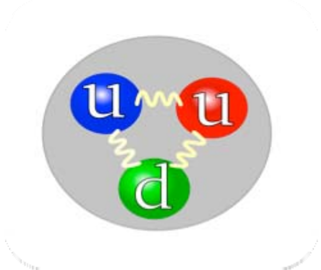


Magnification
100,000,000

Atom

Magnification
X 100,000

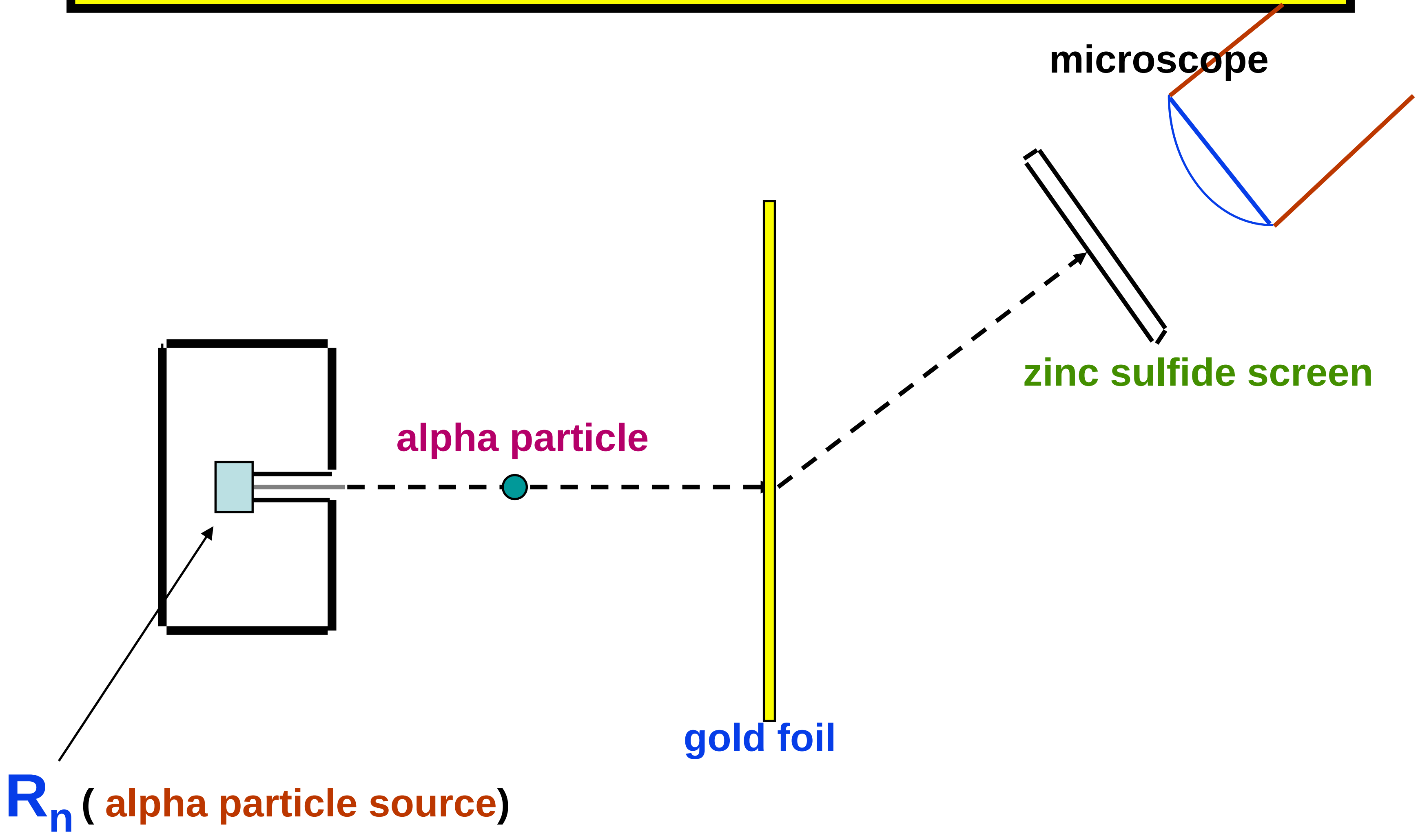
Nucleus



Magnification
X 10000

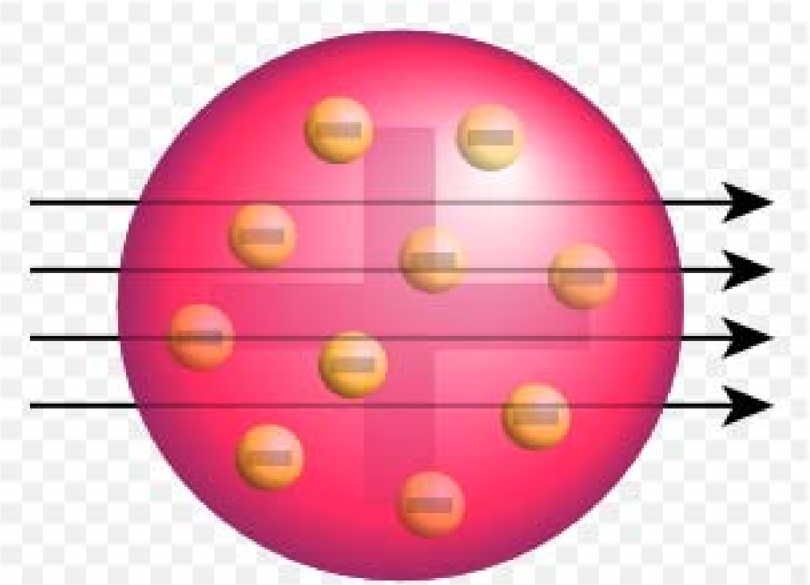
Quarks in Protons & Neutrons

Rutherford's Scattering Experiment - 1911



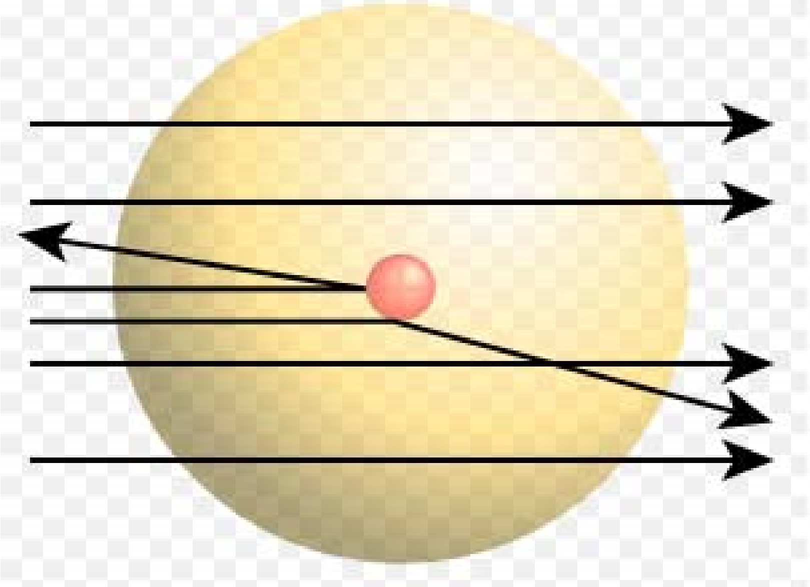
Rutherford in His Laboratory

Confirmed "solar system" model : ATOMIC NUCLEUS DISCOVERED



J.J. Thomson model

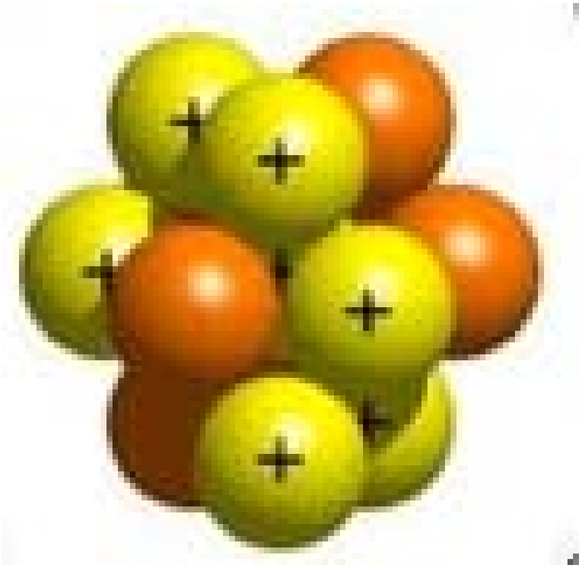
1904



Hantaro Nagaoka model

1904

Structure of Atomic Nucleus Uncovered



Proton Discovered in 1919
Neutron Discovered in 1932

Are they Fundamental Particles ?

Prevailing model of the proton in the 1960's

NUCLEAR DEMOCRACY

BOOTSTRAP MODEL

Particles are composites of one another

$p = \pi n + \ldots\ldots$

$n = \pi p + \ldots\ldots$

Particles have diffuse substructures and no elementary building blocks

1964 **Gell-Mann & Zweig** proposed that protons and neutrons and other particles are composed of spin ½ constituents - QUARKS

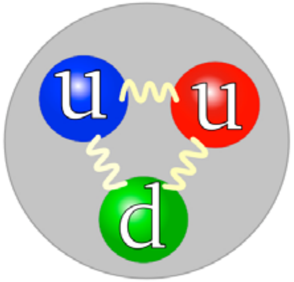
3 types

UP, DOWN, STRANGE

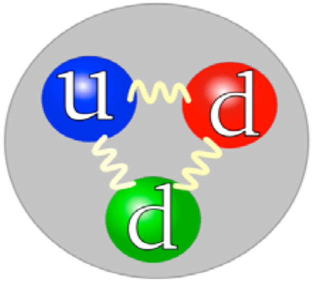
they have fractional charges

UP (+2/3)   DOWN (-1/3)   STRANGE (-1/3)

proton = (u, u, d)



neutron =(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

SLAC Starts Operation in 1966

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

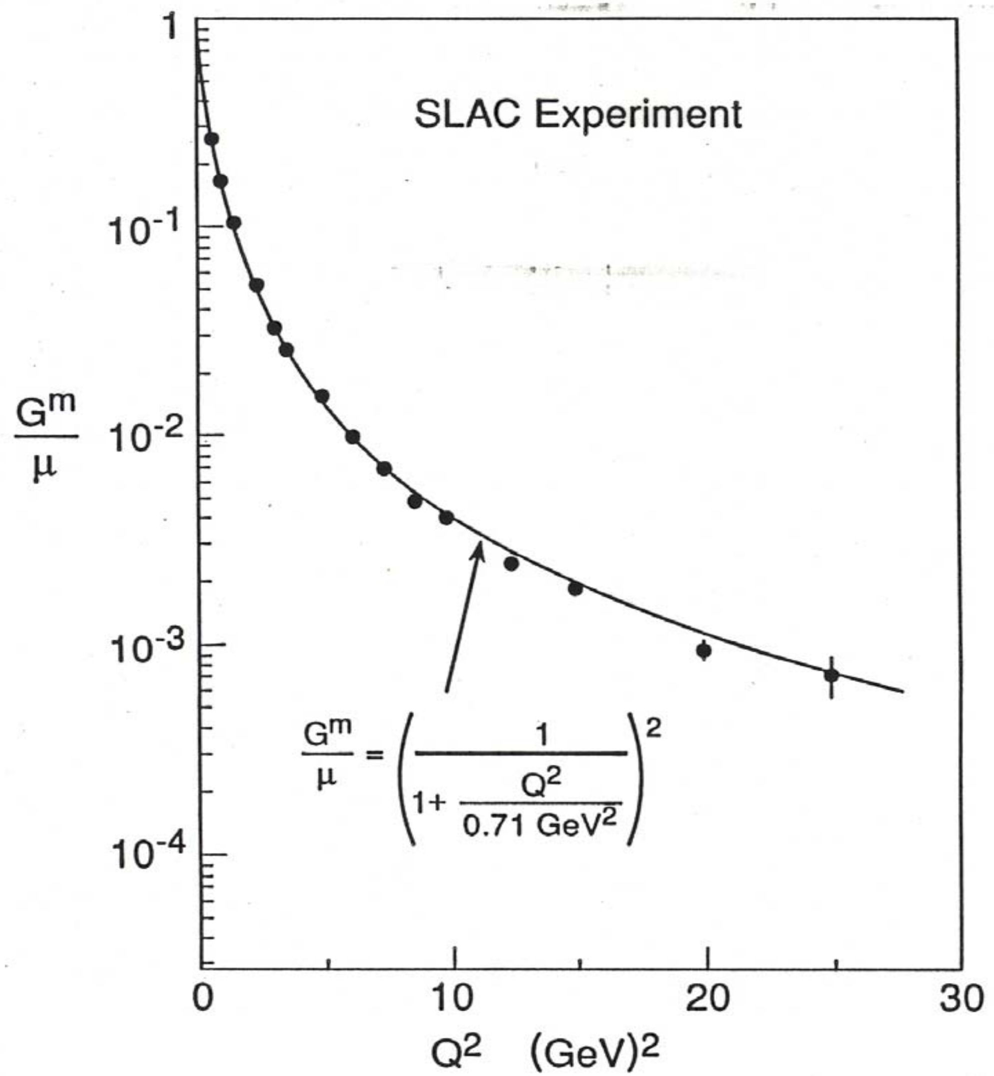
- Electron ideal probe:
  - Structure known: “point particle”
  - Interaction understood: QED

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

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 $\Delta t = 3\text{x}10^{-25}$ sec

for $v \approx c$

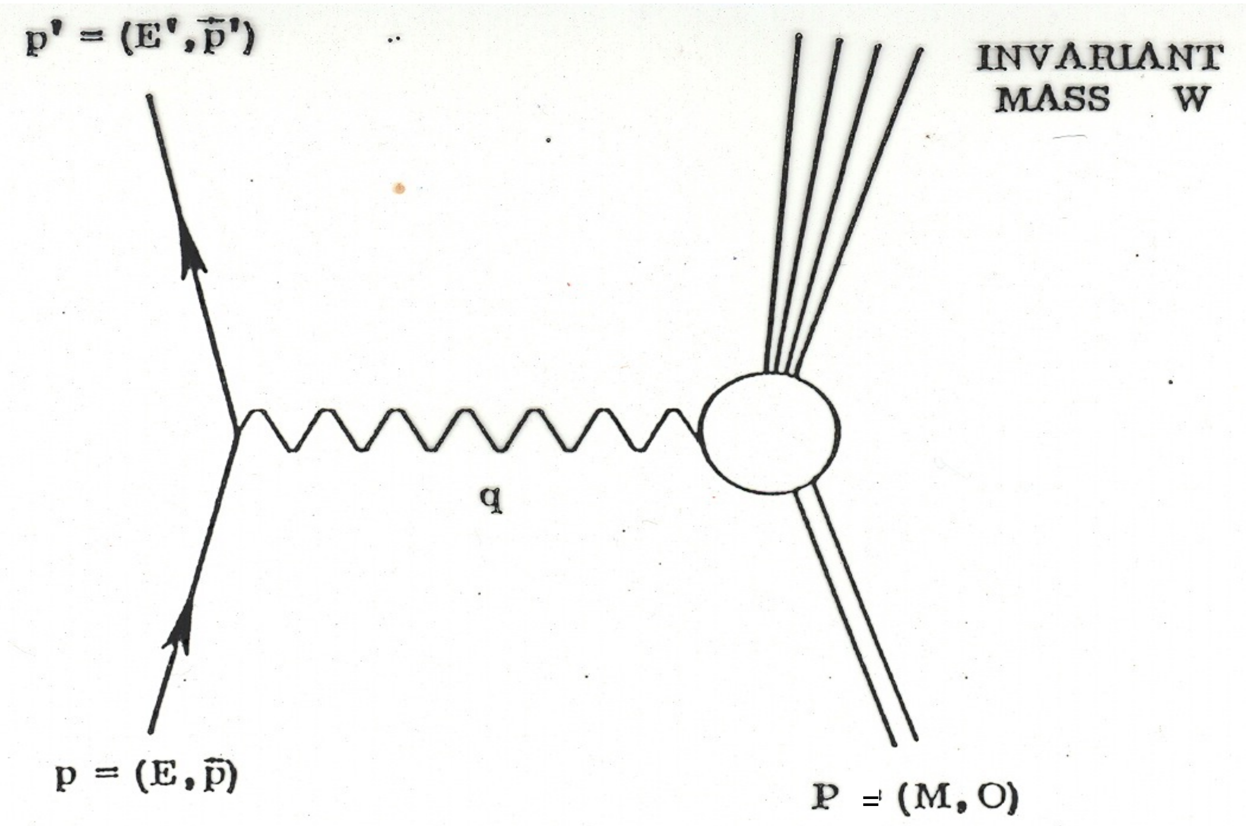
motion during "snapshot" is

$\approx 10^{-14}$ 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



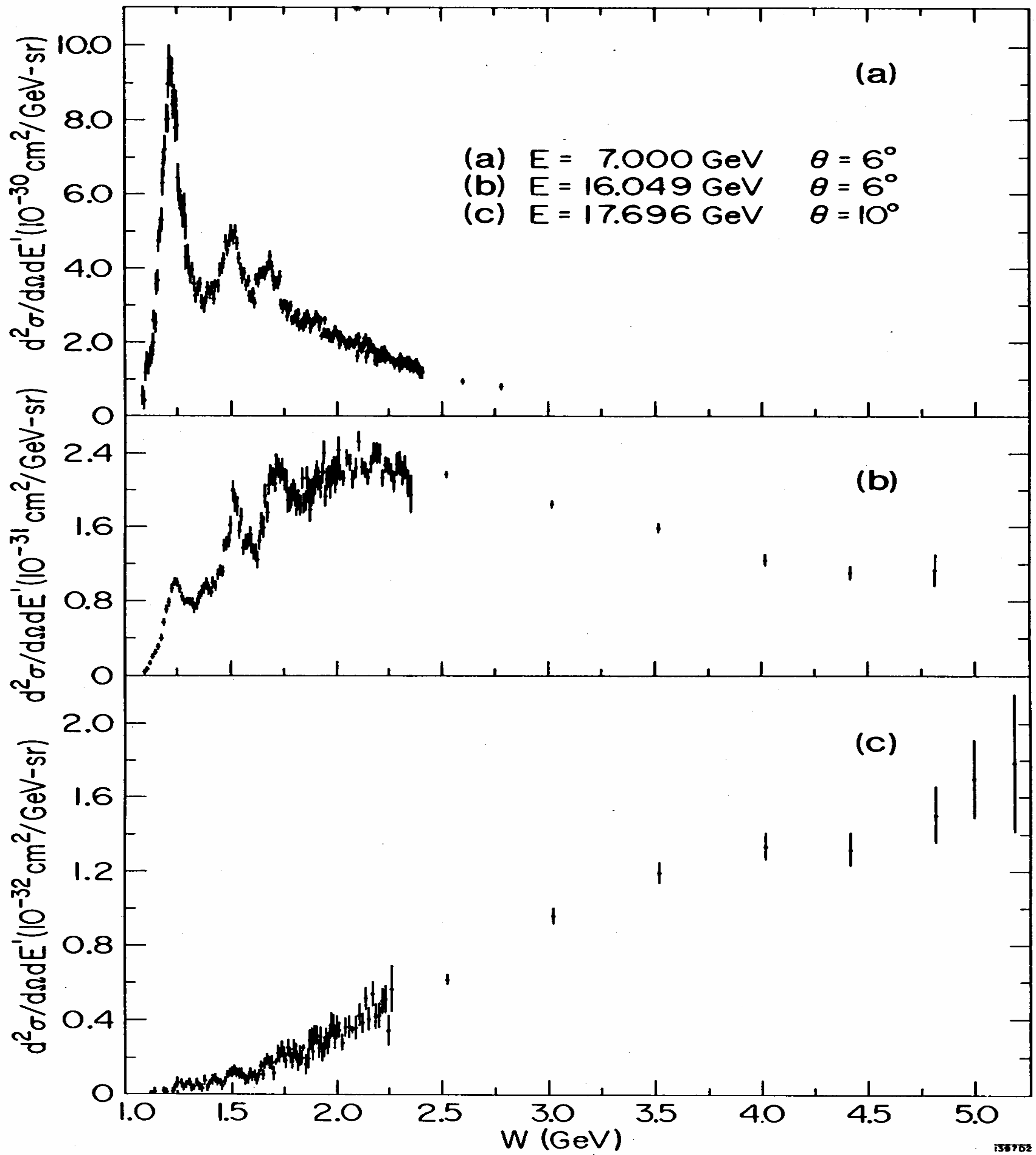
Invariants

$$\nu = P.q/M = E - E'$$

$$q^2 = -(p - p')^2 = 4EE' \sin^2(\theta/2)$$

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

Increasing q^2

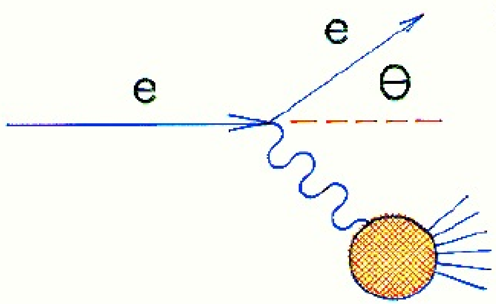


Two Major Surprises

- **Bjorken Scaling** of Structure Functions

- **Weak q^2 dependence** of Structure Functions

Bjorken Scaling



$\nu = \Delta E$ for e

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

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

Q.E.D. (understood) → σ_M

Target (unknown) → W_2, W_1

Scaling — Bjorken (1967)

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

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

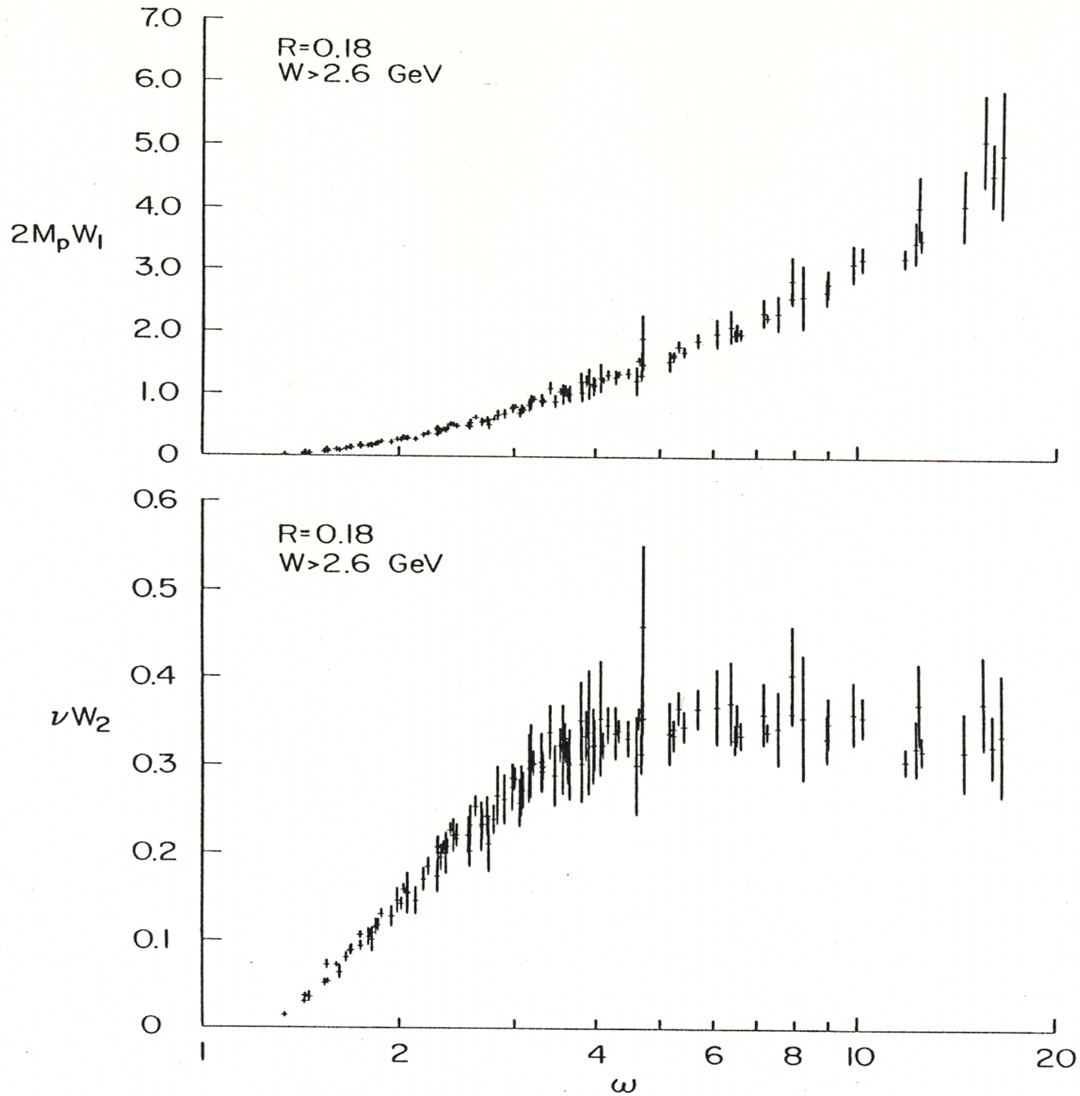
$$\nu W_2(\nu, q^2) \to F_2(\omega)$$

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

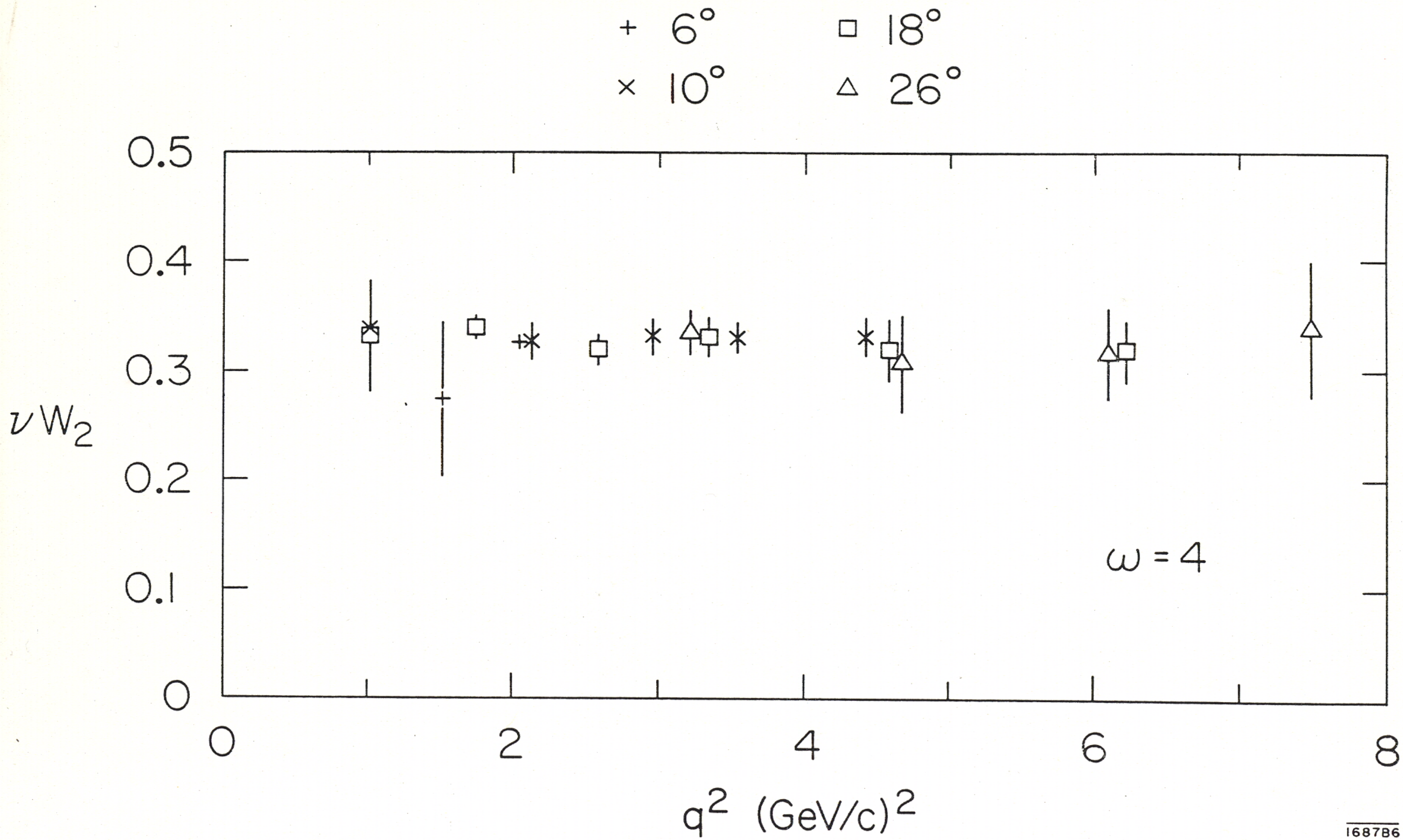
Experimental Test of Scaling

W > 2.6 GeV

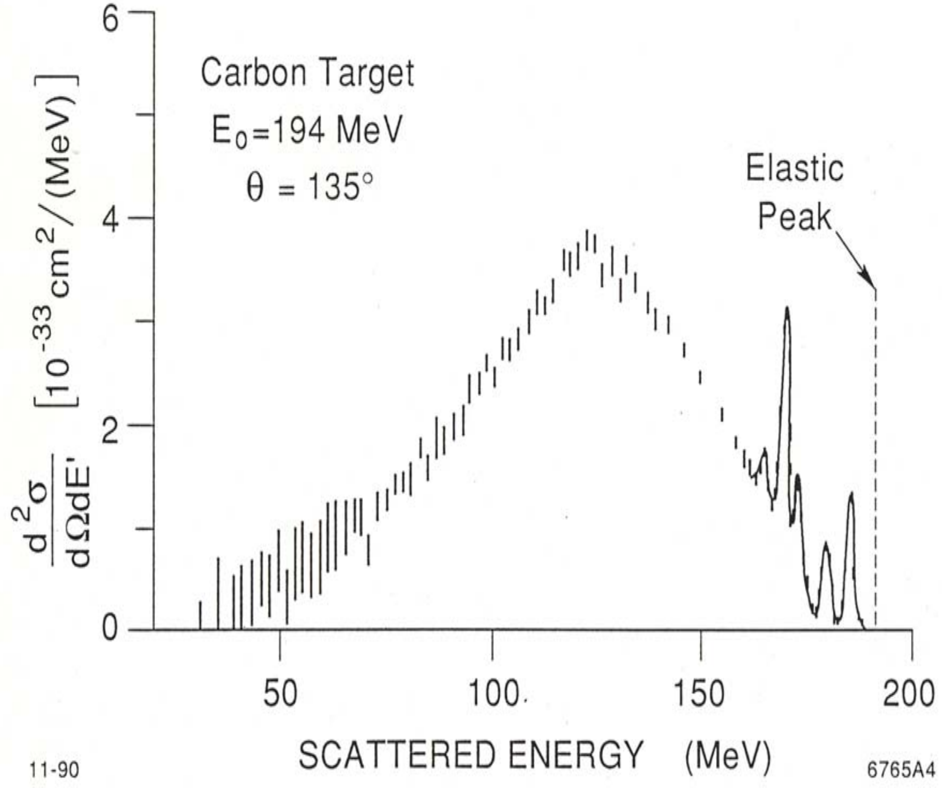
$2 < q^2 < 20\ (\text{GeV})^2$

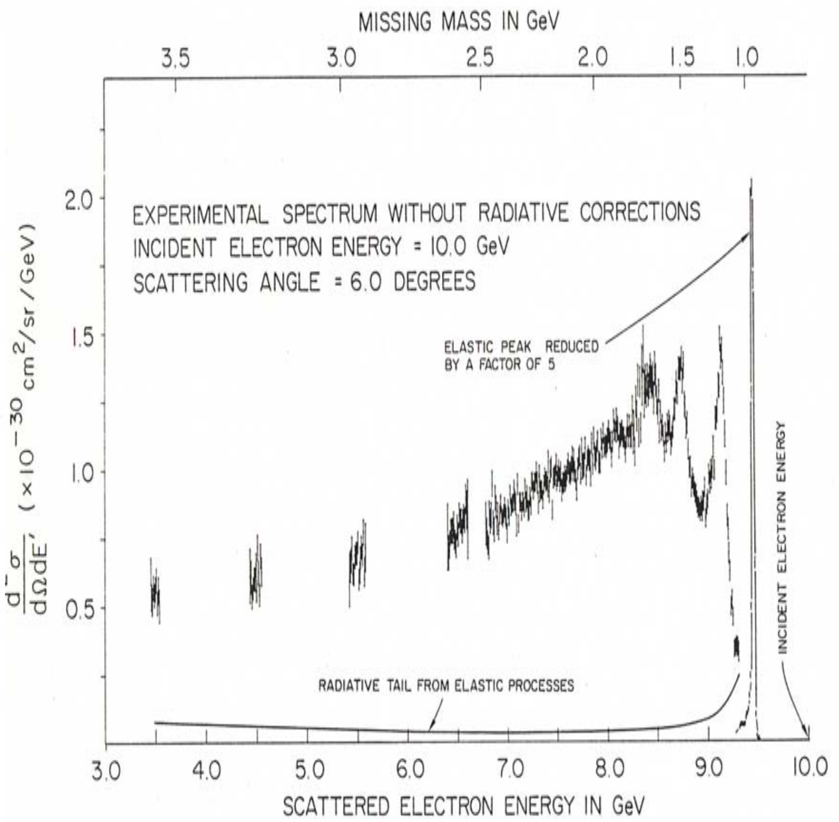


Test of Scaling 2

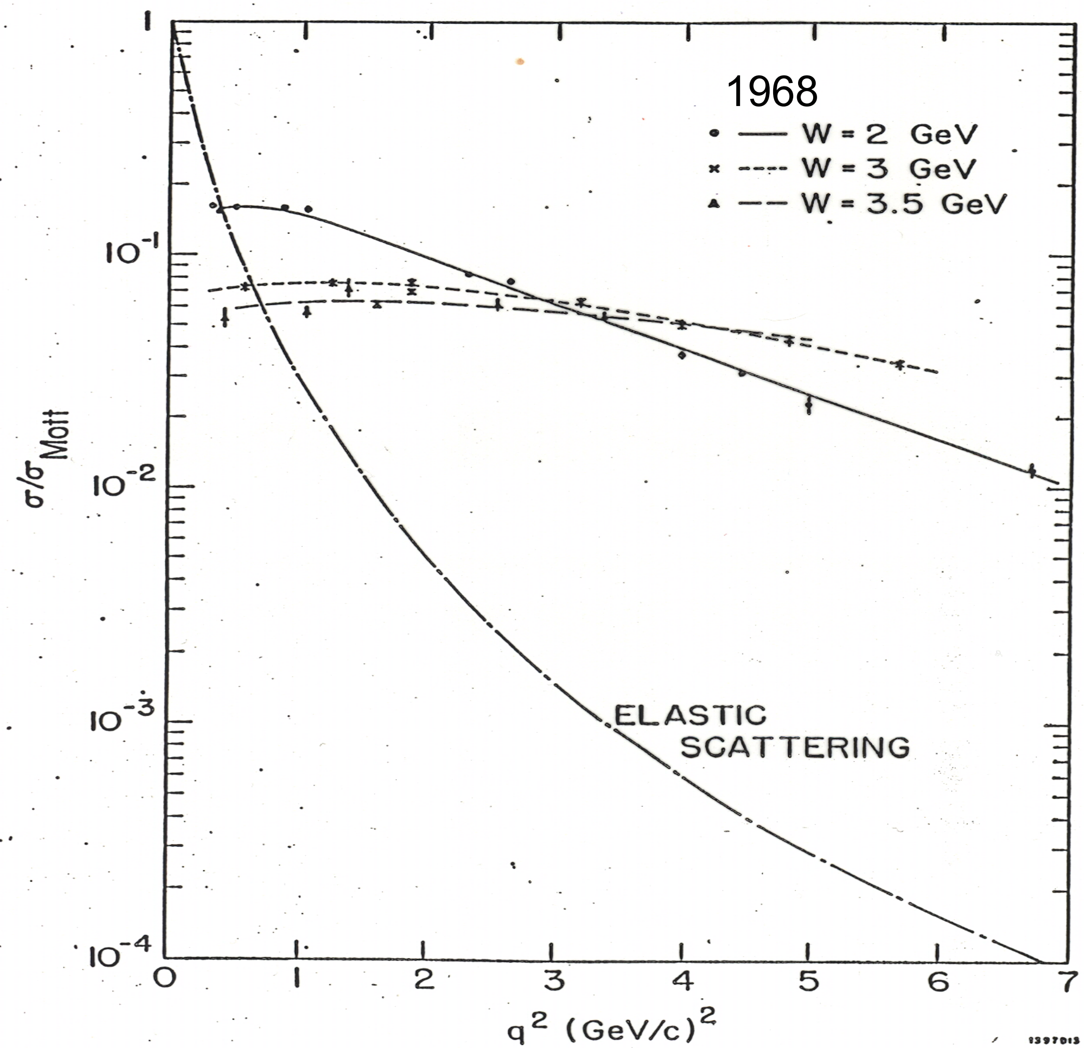


Comparison of e-Carbon & e-p Scattering





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

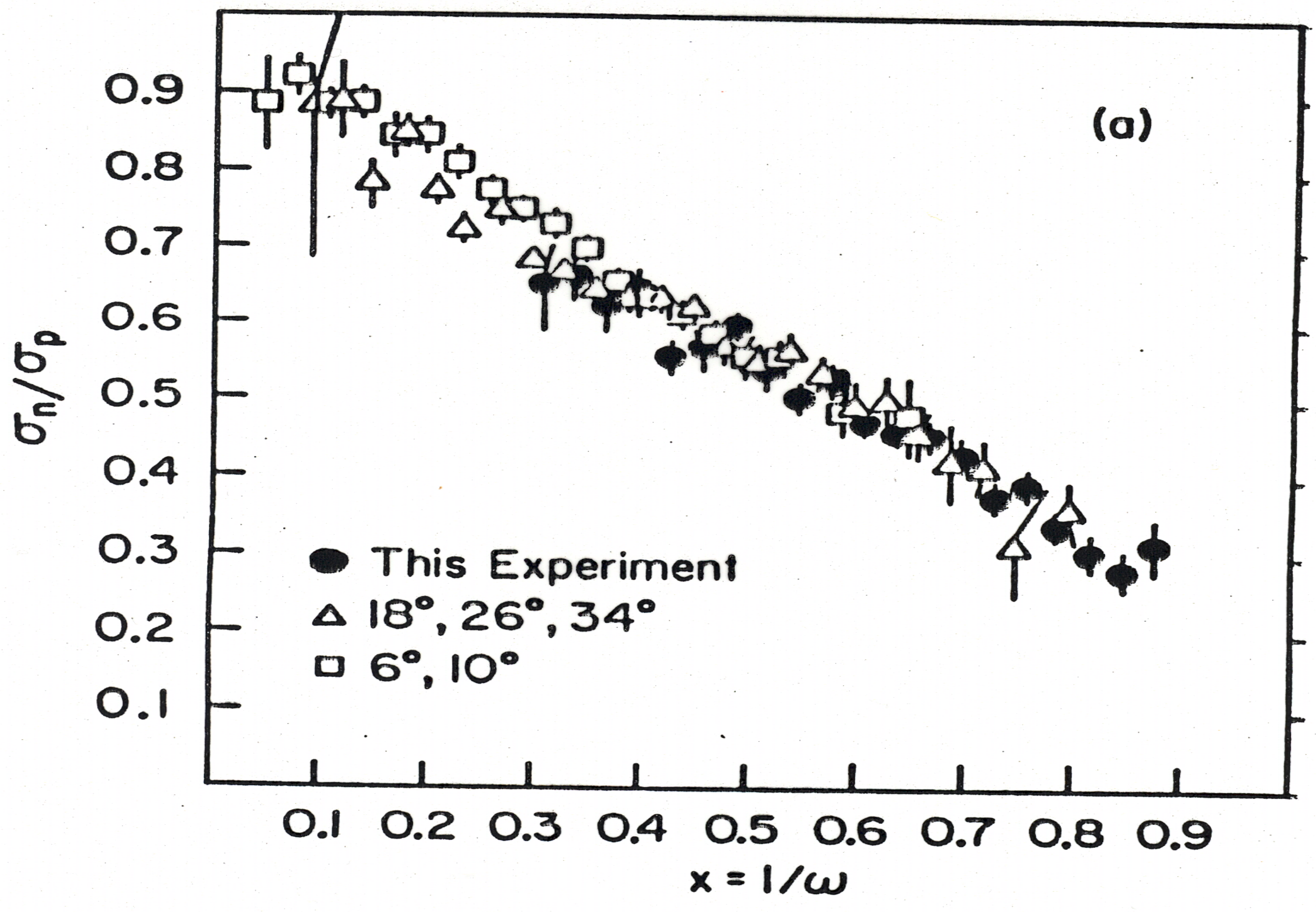
Resonance Models { Veneziano; N's and Δ's }

Regge Poles

Diffraction Models

n / p Scattering

From Comparison of e + d & e + p Inelastic 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” to explain results without success

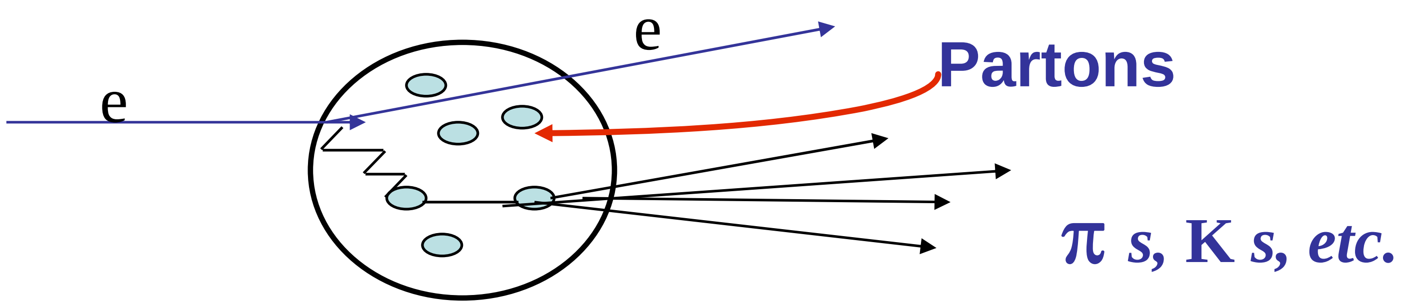
But Quark Model was not regarded as valid by most physicists

?

Theoretical contribution that helped resolve puzzle

Feynman’s 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

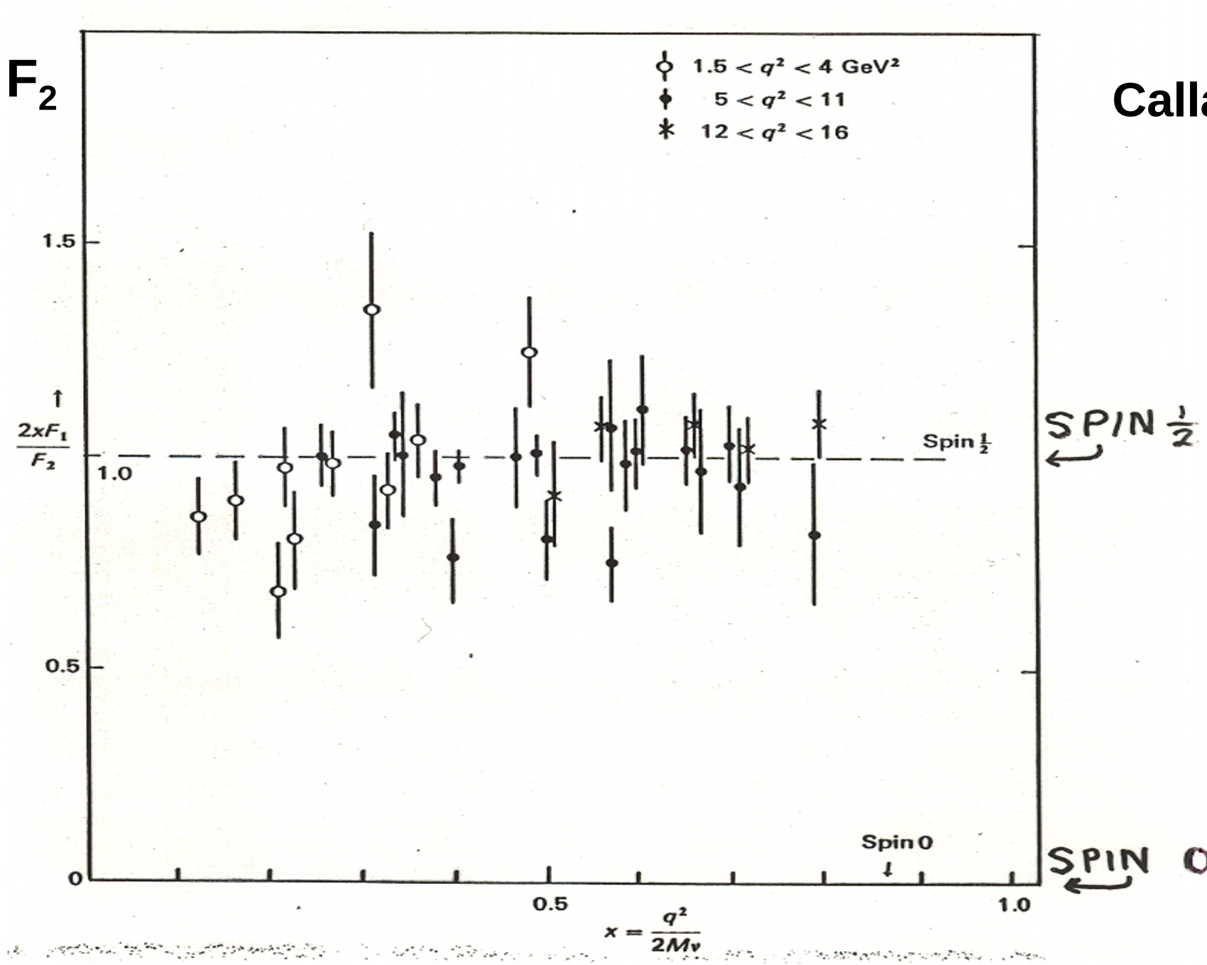
Comparisons of forward and backward scattering answered the question:
What is the the spin of the partons?

$2xF_1 / F_2$

Callan-Gross

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

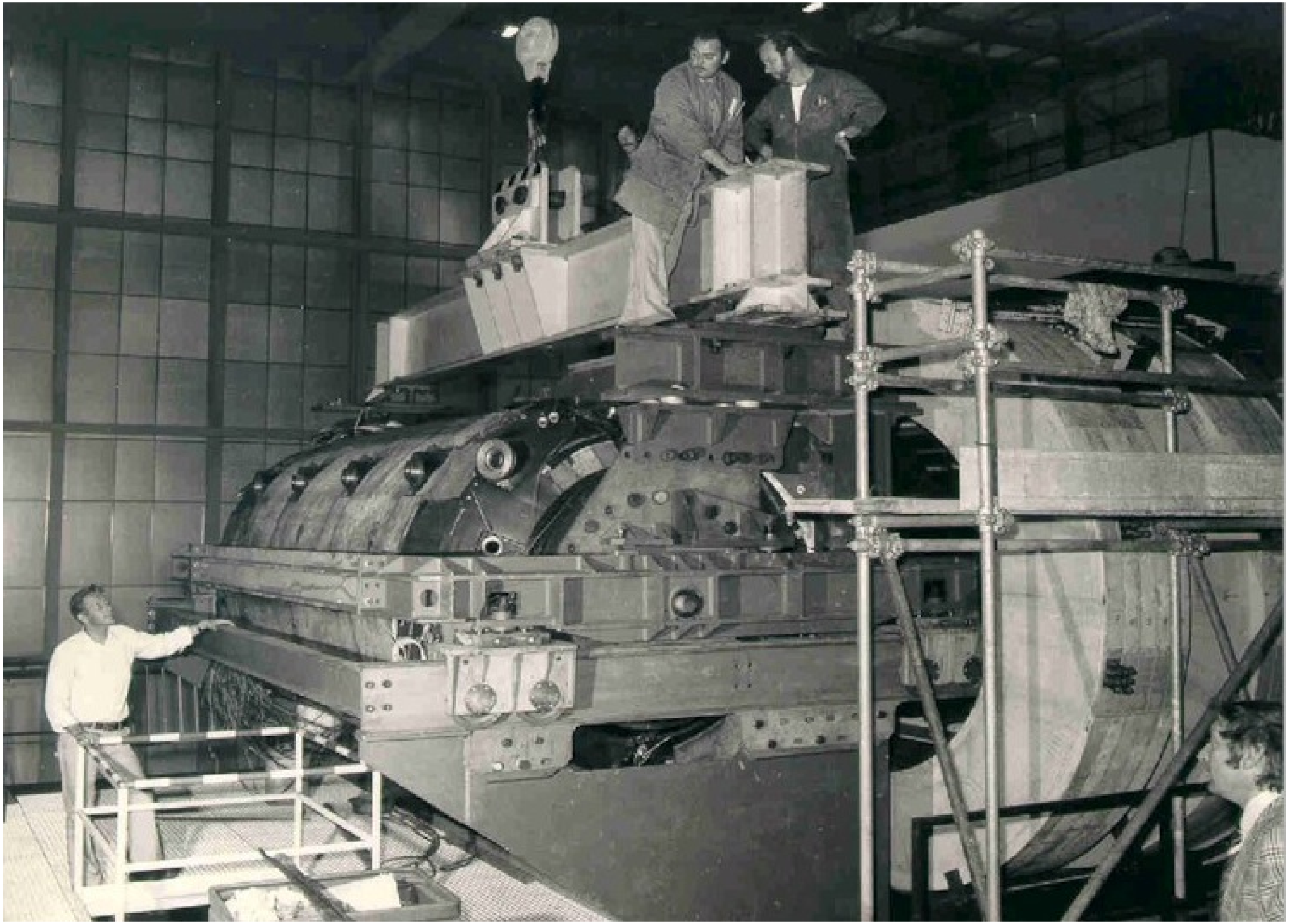
*** QUARKS CARRY 1/2 MOMENTUM**

*** GLUONS CARRY OTHER HALF**

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

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

GARGAMELLE

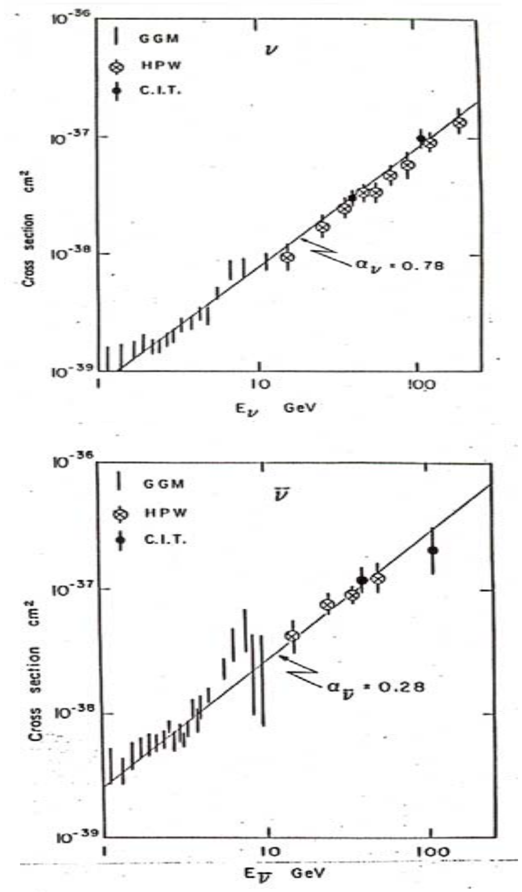


5 meters **12000 liters of Freon**

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)

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

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

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

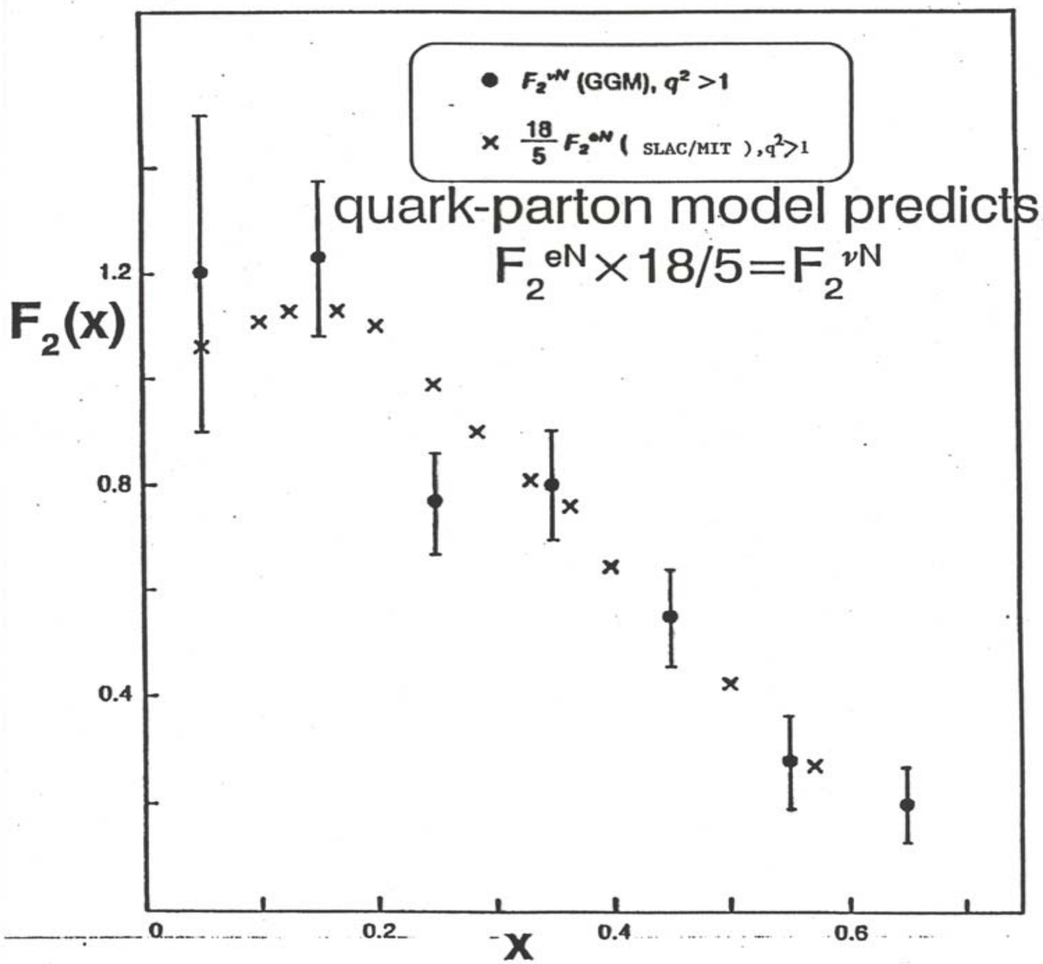
$$= 3.6$$

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

VALIDATION OF QUARK MODEL

First comparison of $F_2^{\nu N}$ measured in ν-nucleon scattering in the Gargamelle heavy-liquid Bubble chamber at CERN.

1974



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 ± .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 ± 0.6

Consistent with Quark Model

There have been a number of important experiments that provided further verification of the quark model and discovered new quarks.

Properties of Quarks

Flavor	u	d	s	c	b	t
Mass	~ 2 MeV	~ 5 MeV	~100 MeV	~ 1.3 GeV	~ 4 GeV	173 GeV
Charge	2/3	-1/3	-1/3	2/3	-1/3	2/3
Spin	1/2	1/2	1/2	1/2	1/2	1/2

SIZE OF QUARKS < 10^{-17} cm.

Scattering Results Point to a New Type of Force

Development of Quark Model and QCD

1973 **Quantum Chromodynamics**

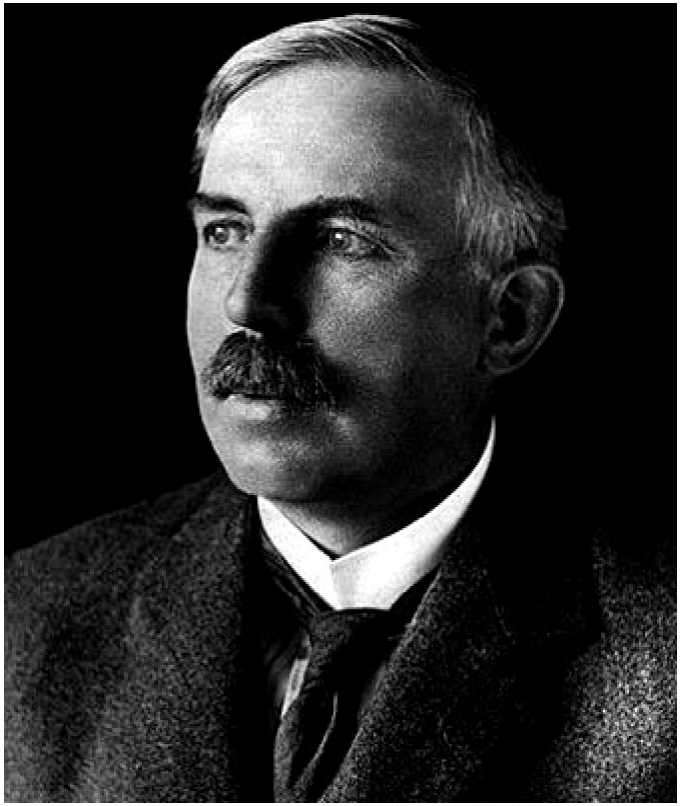
coupling constant α_s

Force increases with distance

$$\alpha_s \sim \frac{1}{\ln\left(\frac{q^2}{\Lambda^2}\right)}$$

- Asymptotic Freedom
- Infra-red slavery - suggests confinement

Confinement explains why free quarks not seen in nature



In addition to his seminal discoveries, Rutherford has provided a legacy that has advanced nuclear and particle physics and continues to uncover the structure of matter