# Bj at Stanford in the 60s

**Fred Gilman**

**November 9, 2024**

# Introduction

- Bj received his undergraduate degree in physics from MIT and then his PhD in 1959 from Stanford with Sid Drell as his advisor. Afterwards, he was a postdoctoral fellow in the Stanford physics department. During this time period, he was also able to be a visitor at CERN, the Institute for Advanced Study, and the Neils Bohr Institute in Copenhagen. He moved from the Stanford physics department to SLAC, once it was created, as a founding faculty member along with Pief Panofsky, Sid Drell, Dick Taylor, and Burt Richter

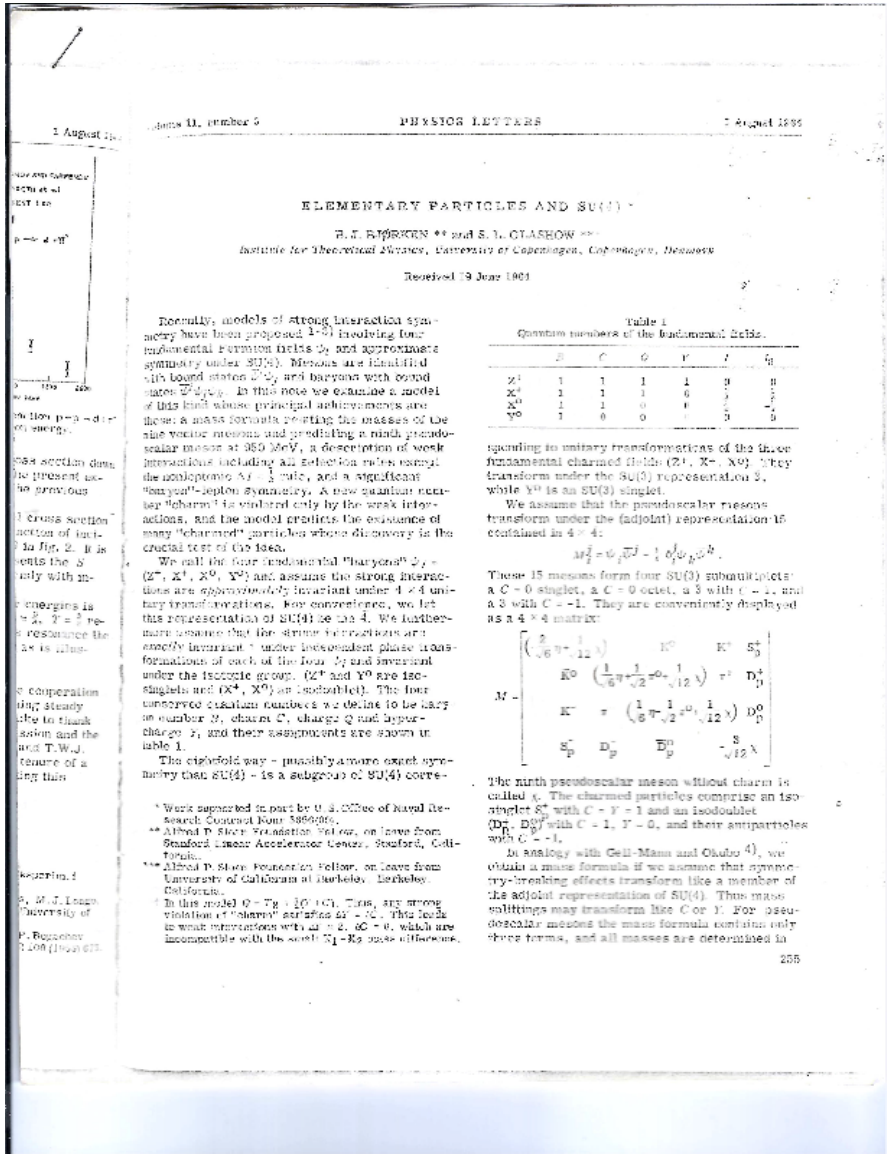
- He was the author of multiple groundbreaking papers in two areas in the 60s
  J. D. Bjorken and S. L. Glashow, "Elementary Particles and SU(4)"
  Phys. Lett. <u>11</u> 255-257 (1964) <u>proposing the charm quark</u>
  J. D. Bjorken, "Asymptotic Sum Rules at Infinite Momentum" (most cited paper)
  Phys. Rev. <u>179</u> 1547 (1969) <u>current algebra sum rules, scaling, quarks</u>

# Charm

- Bj was a visitor at the Neils Bohr Institute in 1964, as was Sheldon Glashow
- Earlier that year, the concept of quarks had been proposed by Murray Gell-Mann and (independently) by George Zweig: u, d, and s quarks composed all hadrons
- The u and d quarks formed an isospin doublet; while s was a singlet. Bjorken and Glashow proposed adding a fourth (charmed) quark, for “aesthetic” or “symmetry” reasons, as c and s formed a doublet like u and d. Many physicists rejected the concept of quarks altogether.
- Glashow, Iliopoulos, and Maiani (GIM mechanism) showed in 1970 that the charm quark is needed in an SU(2) x U(1) electroweak theory to suppress strangeness-changing processes in neutral K meson decays and mixing.

# “Elementary Particles and SU(4)”

B. J. Bjorken and S. L. Glashow



## ELEMENTARY PARTICLES AND SU(4) *

B. J. BJØRKEN ** and S. L. GLASHOW ***
*Institute for Theoretical Physics, University of Copenhagen, Copenhagen, Denmark*

Received 19 June 1964

Recently, models of strong interaction symmetry have been proposed [1-3] involving four fundamental Fermion fields $\psi_i$ and approximate symmetry under SU(4). Mesons are identified with bound states $\overline{\psi}\psi_i$ and baryons with bound states $\overline{\psi}\psi\psi\psi$. In this note we examine a model of this kind whose principal achievements are these: a mass formula relating the masses of the nine vector mesons and predicting a ninth pseudoscalar meson at 950 MeV, a description of weak interactions including all selection rules except the nonleptonic $\Delta I = \frac{1}{2}$ rule, and a significant "baryon"-lepton symmetry. A new quantum number "charm" is violated only by the weak interactions, and the model predicts the existence of many "charmed" particles whose discovery is the crucial test of the idea.

We call the four fundamental "baryons" $\psi_i$ = ($Z^+$, $X^+$, $X^0$, $Y^0$) and assume the strong interactions are *approximately* invariant under 4 × 4 unitary transformations. For convenience, we let this representation of SU(4) be the $\bar{4}$. We furthermore assume that the strong interactions are *exactly* invariant † under independent phase transformations of each of the four $\psi_i$ and invariant under the isotopic group. ($Z^+$ and $Y^0$ are isosinglets and ($X^+$, $X^0$) an isodoublet). The four conserved quantum numbers we define to be baryon number $B$, charm $C$, charge $Q$ and hypercharge $Y$, and their assignments are shown in table 1.

Table 1
Quantum numbers of the fundamental fields.

| | $B$ | $C$ | $Q$ | $Y$ | $I$ | $I_3$ |
|---|---|---|---|---|---|---|
| $Z^+$ | 1 | 1 | 1 | 1 | 0 | 0 |
| $X^+$ | 1 | 1 | 1 | 0 | $\frac{1}{2}$ | $\frac{1}{2}$ |
| $X^0$ | 1 | 1 | 0 | 0 | $\frac{1}{2}$ | $-\frac{1}{2}$ |
| $Y^0$ | 1 | 0 | 0 | 0 | 0 | 0 |

The eightfold way – possibly a more exact symmetry than SU(4) – is a subgroup of SU(4) corresponding to unitary transformations of the three fundamental charmed fields ($Z^+$, $X^+$, $X^0$). They transform under the SU(3) representation 3, while $Y^0$ is an SU(3) singlet.

We assume that the pseudoscalar mesons transform under the (adjoint) representation 15 contained in 4 × 4:

$$M_i^j = \psi_i\overline{\psi}^j - \frac{1}{4}\,\delta_i^j\,\psi_k\overline{\psi}^k\,.$$

These 15 mesons form four SU(3) submultiplets: a $C = 0$ singlet, a $C = 0$ octet, a 3 with $C = 1$, and a 3 with $C = -1$. They are conveniently displayed as a 4 × 4 matrix:

$$M = \begin{bmatrix} \left(\frac{2}{\sqrt{6}}\eta+\frac{1}{\sqrt{12}}\chi\right) & K^0 & K^+ & S_p^+ \\ \bar{K}^0 & \left(\frac{1}{\sqrt{6}}\eta+\frac{1}{\sqrt{2}}\pi^0+\frac{1}{\sqrt{12}}\chi\right) & \pi^+ & D_p^+ \\ K^- & \pi^- & \left(\frac{1}{\sqrt{6}}\eta-\frac{1}{\sqrt{2}}\pi^0+\frac{1}{\sqrt{12}}\chi\right) & D_p^0 \\ S_p^- & D_p^- & \overline{D}_p^0 & -\frac{3}{\sqrt{12}}\chi \end{bmatrix}$$

The ninth pseudoscalar meson without charm is called $\chi$. The charmed particles comprise an isosinglet $S_p^+$ with $C = Y = 1$ and an isodoublet ($D_p^+$, $D_p^0$) with $C = 1$, $Y = 0$, and their antiparticles with $C = -1$.

In analogy with Gell-Mann and Okubo [4], we obtain a mass formula if we assume that symmetry-breaking effects transform like a member of the adjoint representation of SU(4). Thus mass splittings may transform like $C$ or $Y$. For pseudoscalar mesons the mass formula contains only three terms, and all masses are determined in

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* Work supported in part by U.S. Office of Naval Research Contract Nonr 3656(08).

** Alfred P. Sloan Foundation Fellow, on leave from Stanford Linear Accelerator Center, Stanford, California.

*** Alfred P. Sloan Foundation Fellow, on leave from University of California at Berkeley, Berkeley, California.

† In this model $Q = I_3 + \frac{1}{2}(Y + C)$. Thus, any strong violation of "charm" satisfies $\Delta Y = \Delta C$. This leads to weak interactions with $\Delta Y = 2$, $\Delta C = 0$, which are incompatible with the small $K_1 - K_2$ mass difference.

# Charm is Found

- The November Revolution showed the existence of charm-anticharm states.

  1976 brought mesons containing a charm quark and u, d, or s antiquarks, as well as baryons containing a charm quark.

- For the Topical Conference at the end of the 1976 SLAC Summer Institute, I asked Shelly Glashow to come and give a talk. The Bjorkens, Glashows, and Gilmans drove together to San Francisco for a terrific celebratory dinner, followed by coffee at Caffe Trieste in San Francisco.

# Current Algebra
# The Essence of Quarks Distilled to a Lie Algebra

- Quarks initially *seemed* to have two fatal problems: 1. No “free” quarks and 2. Statistics – the ground states for baryons were symmetric.
- It was Gell-Mann’s genius to focus on the weak and electromagnetic interactions, which were formulated in terms of currents, and require that they behave as if composed of quark fields.

  i.e., the vector and axial-vector electromagnetic and weak currents have commutation relations as if composed of u, d, and s quarks at every point of space and time.
- The commutator of two of these currents gives another of the currents.

  => an algebra of currents = a current algebra . SU(3) x SU(3)

# Current Algebra
# The Adler Weissberger Sum Rule

Let $Q^i$ and $Q_A{}^j$ be the vector and axial-vector charges; A schematic recipe:

* Take the expectation value of $[Q_A{}^+, Q_A{}^-] = 2\,Q^3$ between proton states,

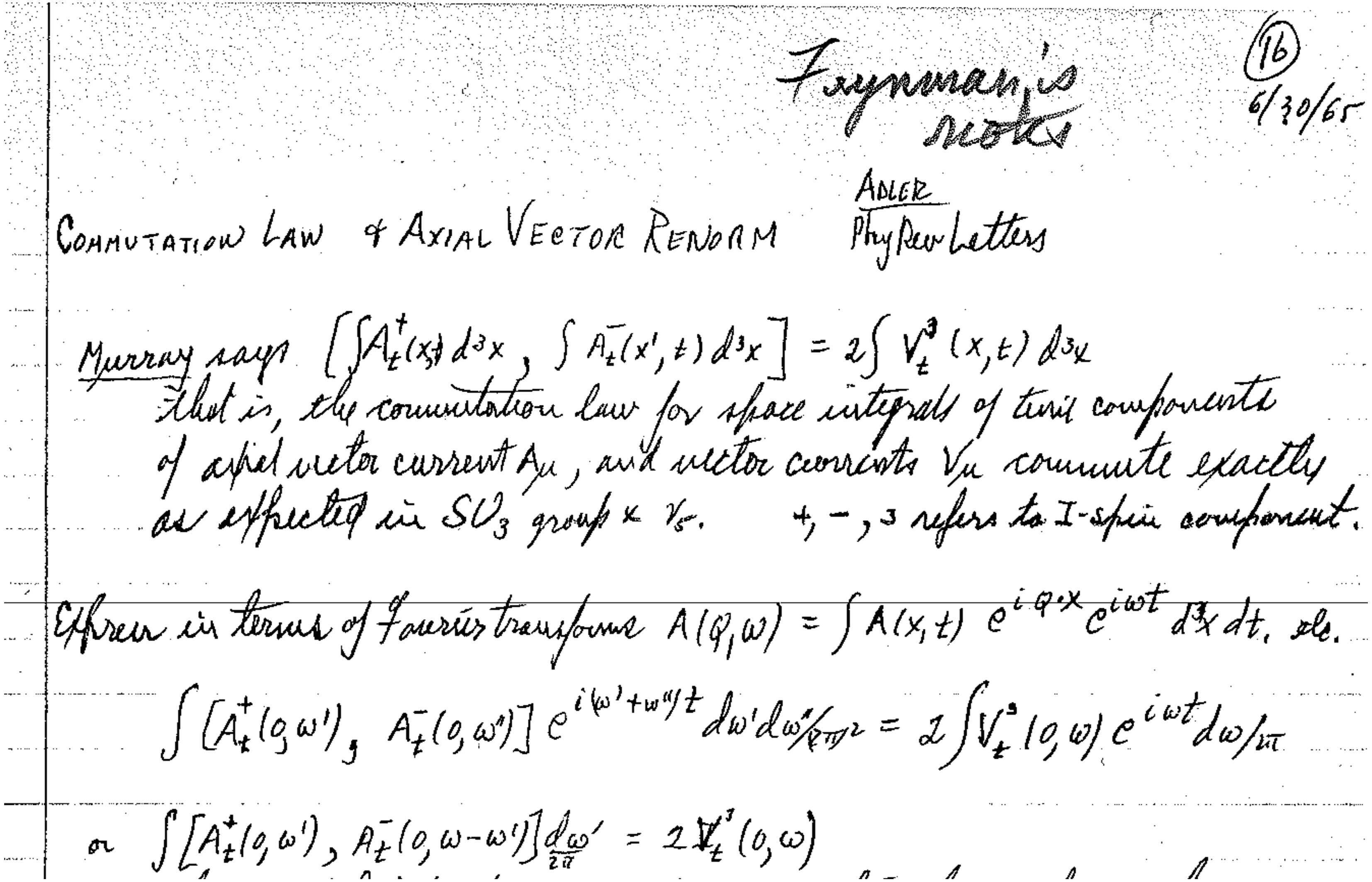
* Insert a complete sum of intermediate states

* Express the result as the one nucleon contribution plus an integral

$g_A{}^2$ + a weighted integral over a difference of cross sections = 1

- Discovered in 1965 by Steve Adler (Harvard) and Bill Weissberger (SLAC)
  (Sidney Coleman and FJG made them aware of each other’s work.)
  Bj is the first person thanked in Bill Weissberger’s paper.
- Using PCAC and known cross sections, the A -W sum rule “worked.”
- Bj derived several other important sum rules in the mid-60s

# Another Derivation after A+W: Feynman’s Notebook 1965
# “Murray says” Use of Infinite Momentum (Copy to FJG in 1966)



Feynman's notes

(16)

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ADLER
Phy Rev Letters

COMMUTATION LAW & AXIAL VECTOR RENORM

Murray says $\left[\int A_t^+(x,t)\,d^3x\,,\ \int A_t^-(x',t)\,d^3x\right] = 2\int V_t^3(x,t)\,d^3x$

That is, the commutation law for space integrals of time components of axial vector current $A_\mu$, and vector currents $V_\mu$ commute exactly as expected in $SU_3$ group × $\gamma_5$. +, −, 3 refers to I-spin component.

Express in terms of Fourier transforms $A(Q,\omega) = \int A(x,t)\, e^{iq\cdot x} e^{i\omega t}\, d^3x\, dt$, etc.

$$\int [A_t^+(0,\omega'),\ A_t^-(0,\omega'')]\, e^{i(\omega'+\omega'')t}\, d\omega' d\omega''/(2\pi)^2 = 2\int V_t^3(0,\omega)\, e^{i\omega t}\, d\omega/2\pi$$

or $\displaystyle\int [A_t^+(0,\omega'),\ A_t^-(0,\omega-\omega')]\frac{d\omega'}{2\pi} = 2V_t^3(0,\omega)$

# Current Algebra
# Deep Inelastic Scattering of Electrons and Neutrinos

- The algebra of current densities leads to sum rules for deep inelastic scattering of electrons or neutrinos of the form

$$\int_0^\infty W_2\,(p\cdot q\,,\,q^2\,)\,d\nu = 1$$

where p is the four-momentum of the initial nucleon, q is the four-momentum transferred to the proton, and $\nu = p\cdot q\,/M$ is the energy transferred to the nucleon when initially at rest. The structure function $W_2$ is a Lorentz scalar.

- There are an infinity of sum rules, one for each value of $q^2$. We have effectively converted the commutation relations at every point in real space-time to an infinity of sum rules in momentum-energy space.

# Opening Session of the 1966 ICHEP at UC Berkeley

From R to L, Row 1:  Gell-Mann, Goldberger, …,
Row 2:   Bjorken, Beg, Ne'eman, Glashow, Sommerfield

# III International Symposium on Electron Photon Interactions at High Energy @ SLAC September 1967

- Bj gave a prophetic plenary talk:

  "Theoretical Ideas on Inelastic Electron and Muon Scattering," starting with "It is an indication of the state of the subject that I am going to talk about that only one paper was contributed to this conference on the theory of inelastic electron scattering. It cannot be stressed too much how ignorant we are of what goes on in this area. Furthermore, I think that it is a region which is unique in particle physics in that we may be able to learn in other ways."

- In the talk, Bj argued for point-like constituents of the nucleon being seen in the forthcoming deep inelastic electron scattering experiments to be done at SLAC in End Station A.

# III International Symposium on Electron Photon Interactions at High Energy @ SLAC (continued)

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I had just arrived at SLAC as a postdoc and was able to attend the Symposium. (I had met Bj when I gave a seminar at SLAC early in 1966.)

Bj and Joan were married at the end of the Symposium, While they were away on their honeymoon, I was enlisted by a secretary to make a transcription of his talk from the tape recording to help him in writing up his talk.

# Scaling in Deep Inelastic Electron-Proton Scattering

- The inelastic scattering data in the spring of 1968 showed large cross sections, much bigger than predicted they fell off with increasing $q^2$ like the form factors for the proton and neutron. Instead, they were roughly of order that might be expected if the current algebra sum rules to be correct. The SLAC – MIT Collaboration was cautious, checking radiative corrections, and comparing data at different scattering angles.

- Bj asked for the data be plotted in terms of the variable $\nu / q^2$ to see if that single variable describes $\nu W_2 (\nu, q^2)$ as $\nu$ and $q^2 \rightarrow \infty$ , i.e., if <u>scaling</u> holds in that limit.

# Why $\nu / q^2$ ? What's Scaling?

- The Lorentz-invariant structure functions $W_1$ and $W_2$ depend on the Lorentz invariant variables $p \cdot q = M\nu$ and $q^2$ (M = mass of target nucleon)

$\nu W_2 (\nu, q^2) = (p \cdot q / M) \; W_2 (p \cdot q / M, q^2)$ is dimensionless

If the scattering occurs off point-like objects as $\nu$ and $q^2 \rightarrow \infty$,
(i.e., no other quantity with dimensions enters the calculation )

=> $\nu W_2 (\nu, q^2)$ cannot be a function of $\nu$ and $q^2$ independently,
but only a function of the ratio $p \cdot q / q^2 = M \nu / q^2$ corresponds to scaling

Define the variable $\omega = 2 \, p \cdot q / q^2 = 2M\nu / q^2$ to give the scaling variable a name

# Scaling and Sum Rules

What happens to the sum rule when scaling holds as $\nu$ and $q^2 \to \infty$ ?

$$\int_0^\infty W_2\,(p\cdot q\,,\,q^2)\,d\nu = 1 \quad \text{for any given } q^2$$

$$= \quad \int_0^\infty \nu W_2\,(p\cdot q\,,\,q^2)\ \ (d\nu\,/\,\nu) \ \ = 1$$

$$= \quad \int_0^\infty \nu W_2\,(2p\cdot q\,/q^2)\ \ (d\nu\,/\nu) \ \ = 1$$

$$\to \quad \int_0^\infty \nu W_2\,(\omega\,)\ \ (d\omega\,/\omega) \ \ = 1 \quad \text{as } \nu \text{ and } q^2 \to \infty \ ,$$

All the sum rules become the same in the scaling limit, $\nu$ and $q^2 \to \infty$ ,

# XIV International Conference on HEP September 1968

- Pief Panofsky was the rapporteur at Vienna for inelastic electron and muon scattering. SLAC data on photoproduction and electroproduction were just beginning to join those from other labs. There was lots of pressure to show early, exciting results.

- The electroproduction data were presented in the parallel session by Jerry Friedman and showed the first evidence of scaling.

- In Pief’s plenary talk, a few slides near the (rushed) end were devoted to deep inelastic scattering, only one slide at the end was fully focused on scaling.

  Not many in the audience that day understood the significance

# XIV International Conference on HEP @ Vienna
# Panofsky's Plenary Talk

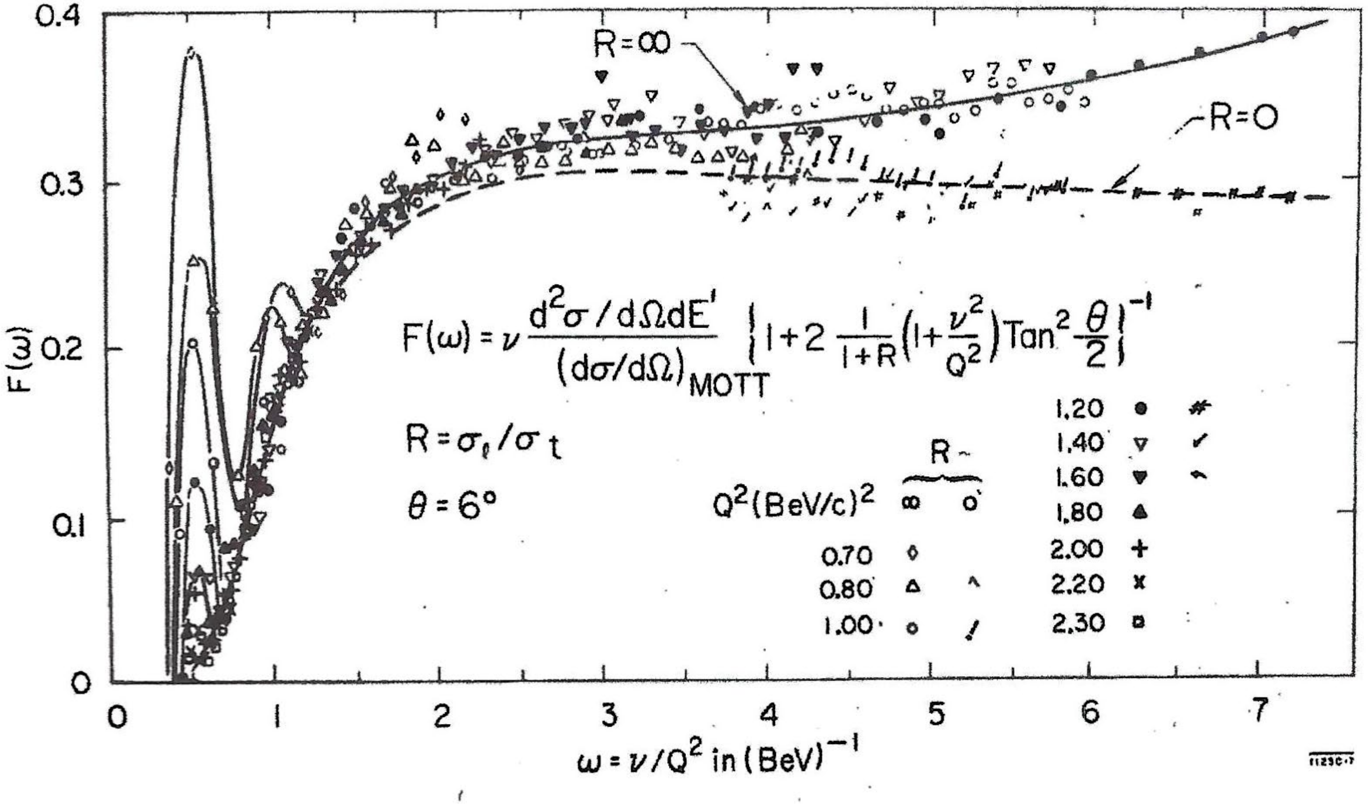

Fig. 22

# Scaling a la Feynman

- During the Vienna Conference, Feynman came from Caltech to visit his sister, who lived not far from Stanford. He spent a day at SLAC and talked with both theorists and experimentalists, including getting briefed on the deep inelastic scattering data.
- The SLAC data could be analyzed in the approach to understanding hadronic collisions at very high energies which he had been developing using "partons" Treating collisions in the infinite momentum frame, a given parton had a fraction x of the four-momentum p of its parent (a nucleon in this case). When struck by a virtual photon with four-momentum q, and neglecting masses,

$$2\,x\,q\cdot p + q^2 = 0 \quad \Rightarrow \quad x = -\,q^2/(2\,q\cdot p) = 1/\omega$$

- The parton description was soon adopted by the community. $x$, $f(x)$
- Within one year, scaling and the existence of point-like quarks was established.

# Bj at Stanford in the 60s

We were privileged to share these amazing times

with Bj
one of the amazing people.