Prelude to the QCD Revolution

Tumultuous times: 1962 - 1966/8 - 1972

Through the eyes of a student at Princeton and especially at SLAC 1968 – 1972

An old paradigm for the strong interactions was dying

And

A new paradigm was emerging

The transition was not ordinary "progress"
Instead – chaotic, somewhat incomprehensible at first, then rapid, compelling and complete

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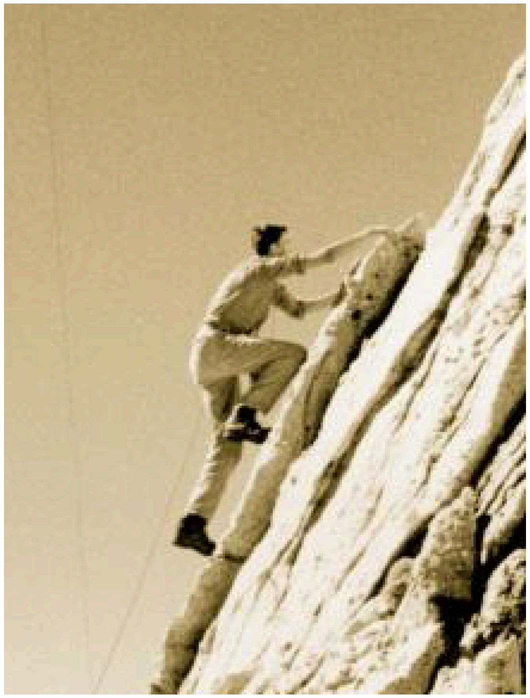
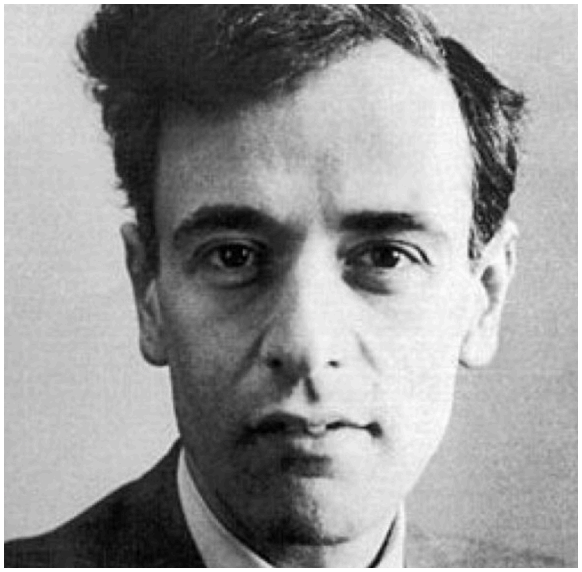
QCD was the creation of a whole generation of theorists and experimenters; though I shall focus on the critical role of Bj Bjorken



1950s saw the abandonment of QFT as a tool for strong interactions

Lev Landau (Pauli Memorial) 1961



"Almost 30 years ago [Rudolf] Peierls and myself noticed that in relativistic quantum theory no quantities concerning interacting particles can be measured, and the only observable quantities are the momenta and polarizations of freely moving particles. Therefore if we don't want to introduce unobservables, we may introduce in the theory as fundamental quantities only the scattering amplitudes.

"The [field] operators which contain unobservable information must disappear from the theory and, since a Hamiltonian can be built only from [field operators], we are driven to the conclusion that the Hamilton method for strong interactions is dead and must be buried…"

"The foundation of the new theory [of the strong interactions] must deal only with diagrams with 'free ends', ie. with scattering amplitudes and their analytic continuation. The physical basis of this technique [are] the unitarity conditions and the principle of locality of interaction which expresses itself in the analytic properties of the fundamental quantities of the theory, such as different kinds of dispersion relations."

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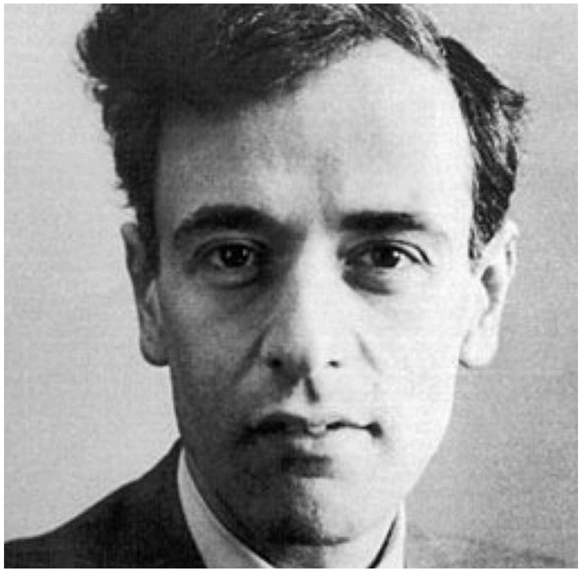

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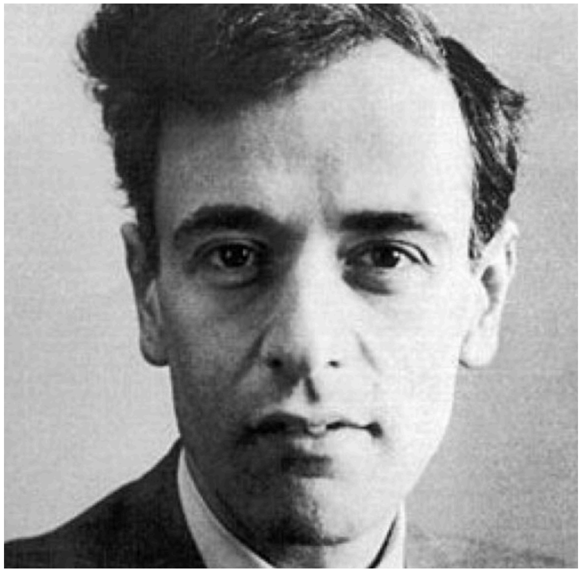

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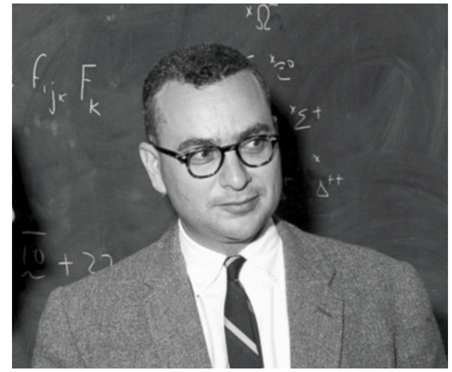
10 years later…



Murray Gell-Mann (Coral Gables 1971)

"…therefore, we should …conclude, so to speak, that Nature reads books on free field theory, as far as the Bjorken limit is concerned"

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I'll focus first on the events that led to Bjorken's remarkable 1966 paper and the confusion that characterized particle physics that year. I'll spend some time describing the internally contradictory models that were used at SLAC and elsewhere during my graduate students days, and how the tension between these contradictory concepts led to the emergence during 1968-72 of a new paradigm for the strong interactions based on permanently confined but weakly interacting quarks. Setting the stage for the discovery of asymptotic freedom the next year!

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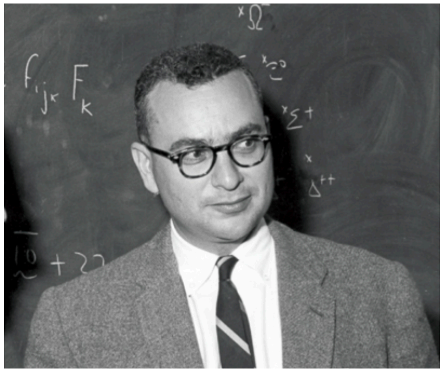

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Timeline and transition…

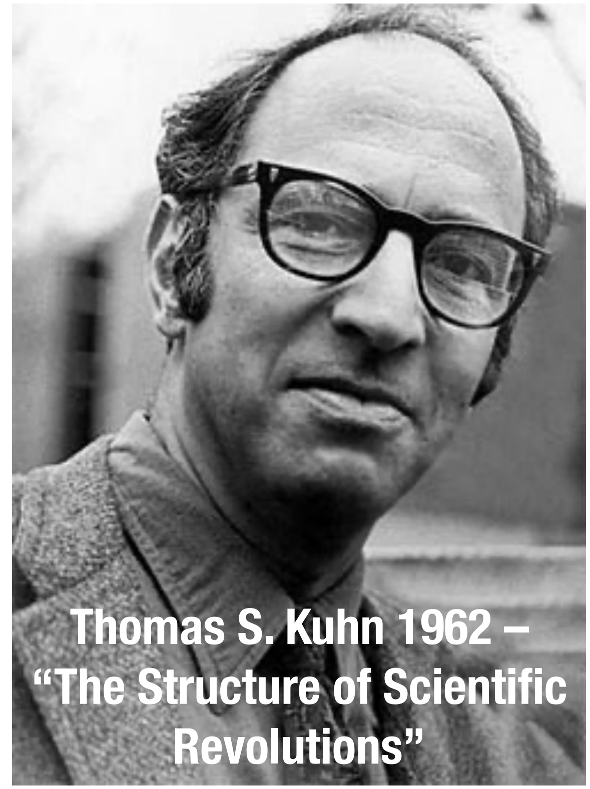
Analyticity Unitarity S-Matrix Theory Regge Theory	Era of confusion	Quarks Confinement QCD
1950s –1960	→	1972

- Field theory abandoned for strong interactions
- All hadrons equally "fundamental", strictly phenomenological
- No attempt at dynamics (no Hamiltonian)
- Long distances & low energies (and momentum transfer)

- Field theory resurrected!
- All hadrons emergent
- Lagrangian dynamics
- Short distances & high energies

Transitional era: an new paradigm emerges out from under and replaces an old one

During the interregnum, theorists were working with concepts that seemed manifestly inconsistent, but getting answers that describe experimental results correctly, whereas previously standard methods failed.



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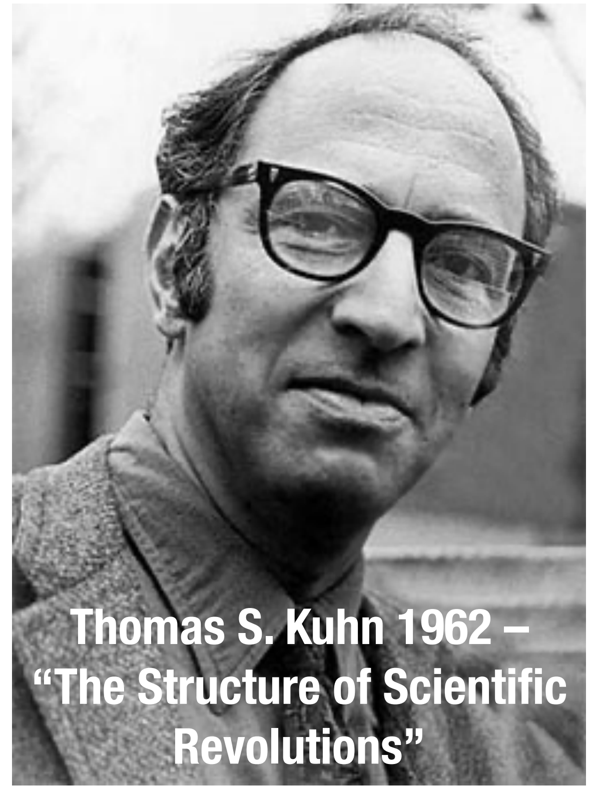
Thomas S. Kuhn 1962 –
“The Structure of Scientific Revolutions”

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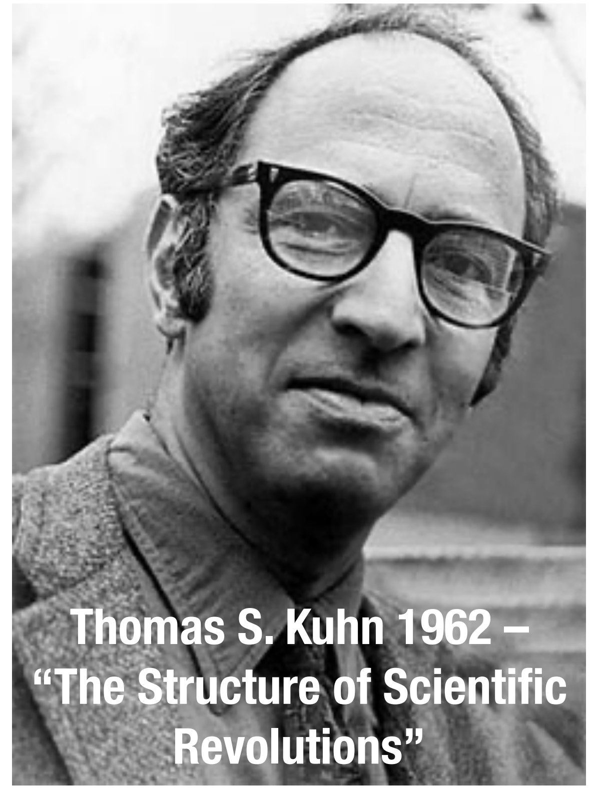

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"In the beginning"… Quarks

Gell-Mann, Zweig

1963-1964

Non-relativistic, "constituent" quark model

Current algebra

The constituent quark model –

R. H. Dalitz & students, G. Morpurgo, Struminsky et al, Lipkin, Meshkov …

Constituent, non-relativistic(?) quarks building hadrons…
Successful but <u>under-appreciated</u> (to say the least)


Dick Dalitz

* Why weren't they seen in the hadron spectrum?
* How could they be non-relativistic inside hadrons?
* Classification of states based on a symmetry – SU(6) x SO(3) (SU(6) = spin x $SU(3)_f$) which is inconsistent with relativity

Nevertheless, successful hadron spectroscopy:

Many ground state and orbitally excited meson and baryon resonances were predicted and identified by Dalitz and co-workers in the mid 1960s.


Giacomo Morpurgo

SU(6) x O(3) classification of hadrons in the NRQM:

A snapshot – first multiplets of excited mesons and baryons

Table 10-III. The (I, Y) substates of the four L = 1 nonets. Entries with a single underline represent resonances for which there is some evidence in the literature but which are not yet regarded as established states. Entries with a double underline are purely speculative, and their mass values have been estimated by use of the Schwinger relation with ϑ = 1, appropriate to an ideal nonet; m_1 denotes the unitary singlet mass, after the SU(3)-breaking effects are turned off.

JPC	Nonet states (I, Y)				m_1	Δ
	(1, 0)	(1/2, ±1)	(0, 0)	(0, 0)	(MeV)	$(MeV)^2$
2++	A2(1300)	K^*(1415)	f(1254)	f' (1514)	1238	3.1×10^5
1++	A1(1080)	K_c^*(1215)	D(1286)	D' (600-1000)?	?	3.1×10^5
0++	δ(962)	K^*(1080)	S(1330?)	S' (1060)	1200?	2.4×10^5
1+-	B(1200)	K^*(1313)	H(1006)	H' (1385?)	964?	2.8×10^5

Table 10-V. The baryonic resonance states with negative parity are tabulated. They are grouped in the SU(3) multiplets suggested by their spin determination or by their qualitative agreement with the mass systematics for baryonic multiplets, or according to our knowledge of their decay branching ratios. Ξ^*(1820) has been assigned to a decuplet on the basis of its $(\Sigma\bar{K})/(\Lambda\bar{K})$ ratio. The relationship of Y_0^*(2110) and $N_{1/2}^*$(2190) is quite uncertain at present; on the basis of mass systematics, it appears rather likely that Y_0^*(2110) will be found to be a unitary singlet state.

Spin-parity	Representation	Baryonic resonance states
$(1/2^-)$	{1}	Y_0^*(1405)
	{8}	$N_{1/2}^*$(1570), Y_0^*(1670), Y_1^*(1750),.
	{8}	$N_{1/2}^*$(1700),···
	{10}	$N_{3/2}^*$(1670),···
$(3/2^-)$	{1}	Y_0^*(1520)
	{8}	$N_{1/2}^*$(1518), Y_0^*(1700)?, Y_1^*(1660),.
	{10}	···, Ξ^*(1820)
$(5/2^-)$	{8}	$N_{1/2}^*$(1688), Y_1^*(1765), Y_0^*(1840)?,.
$(7/2^-)$	{8?}	$N_{1/2}^*$(2190), Y_0^*(2110),···

Current Algebra

1963/4 **Quarks (Gell-Mann, Zweig)**

1964 **Charge algebra and local charge density algebra**

$$[Q_\alpha, Q_\beta] = i f_{\alpha\beta\gamma} Q_\gamma$$
$$[Q^5_\alpha, Q^5_\beta] = i f_{\alpha\beta\gamma} Q_\gamma$$
$$[Q_\alpha, Q^5_\beta] = i f_{\alpha\beta\gamma} Q^5_\gamma$$

Postulated by Gell-Mann 1964

Algebra of charges of EM and weak (beta-decay) currents

$$[j^0_\alpha(x), j^0_\beta(y)]\Big|_{x^0=y^0} = i f_{\alpha\beta\gamma} \delta^3(\vec{x}-\vec{y}) j^0_\gamma(y), \text{etc.}$$

Algebra of charge densities

Short distance physics appears!

1965-66 **Adler/Weisberger Sum Rule & other successes of charge density algebra**

Fubini, Furlan, Adler, Weisberger, Dashen,…

1965 **Adler derives sum rule for total neutrino scattering cross section, which implicitly requires that inelastic neutrino scattering cross-sections are large at large momentum transfer. "Saturation" of Adler SR at large q^2 was prophetic, but was set aside…**

More later – a missed signal

> 1964 **Appearance of δ-function renewed interest in short distance behavior in QFT**

$$[a(\vec{x},t), b(\vec{y},t)] \propto \delta^3(\vec{x}-\vec{y})$$

Earlier activity on esp. on QED at short distances:
Renormalization group (Gell-Mann & Low, 1954) and high-energy limit of QED ~ QED at short distances, Landau pole in $\alpha(Q^2)$, contributed to abandonment of QFT in 1950s.

1965 What about local commutators of charge and current densities?

$$j^0(x) \text{ and } \vec{j}(y)$$

$$[j^0_\alpha(x), {j^k}_\beta(y)]\Big|_{x^0=y^0} = ?$$

$$[{j^k}_\alpha(x), {j^\ell}_\beta(y)]\Big|_{x^0=y^0} = ?$$

Many important applications and extensions of current algebra

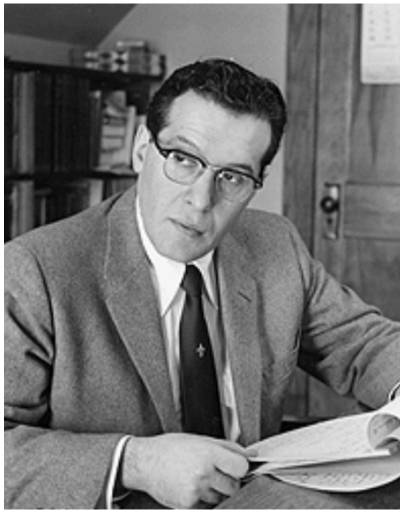
would be accessible if these relations could be understood

- **Integrals over inelastic electron and neutrino scattering !**

  Including polarization dependent phenomena

- **Total electron-positron annihilation cross section !**
- **Taming divergences in mass differences of hadrons**
- **Hadronic contributions to hyperfine splittings in hydrogen**

The problem of the Schwinger terms…



Julian Schwinger

1959-66 "Schwinger terms" spoiled the charge-density/current-density commutators…

1959 Julian Schwinger showed that a full current algebra (charge density and current density) was invalidated by the appearance of gradients of delta-functions – even in free field theory

$$[j^0_\alpha(x), j^k_\beta(y)]\big|_{x^0=y^0} = if_{\alpha\beta\gamma}\delta^3(\vec{x}-\vec{y})j^k_\gamma(y) + i\partial_{x^\ell}[\delta^3(\vec{x}-\vec{y})S^{k\ell}{}_{\alpha\beta}(y)]$$

likewise for current density commutators

Almost nothing was known about $S^{k\ell}$ in interacting QFTs…
c-number? operator?

1959-66 Schwinger's work was well known and inhibited extension of charge algebra to full algebra of currents

1961 Johnson “explains” origin of Schwinger terms

Ken Johnson showed that in general forward matrix elements of current correlation functions are not Lorentz covariant:

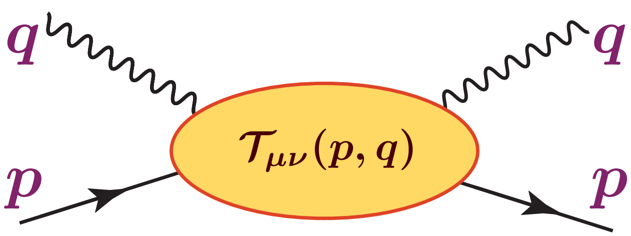
$$T_{\mu\nu}(p,q) = \int d^4x \; e^{iq\cdot x}\langle p|T(j_\mu(x)j_\nu(0))|p\rangle$$

is not in general a Lorentz tensor!

Ken Johnson

Schwinger terms are just what must be added to make physical amplitudes covariant

$$T^* = T + \text{Schwinger terms}$$



And Schwinger terms are local distributions at x = y
So, physical amplitude

$$\langle p|T^*(j_\mu(x)j_\nu(y))|p\rangle = \langle p|T(j_\mu(x)j_\nu(y))|p\rangle + \text{local distributions at } x=y$$

$$\mathcal{T}_{\mu\nu}(p,q) = \int d^4x \; e^{iq\cdot x}\langle p|T(j_\mu(x)j_\nu(0))|p\rangle + \text{polynomial in } q$$

1966 Bjorken-Johnson-Low (BJL) Limit

Bjorken and independently Johnson and F. Low: Schwinger terms could be isolated and discarded in forward matrix elements of current-current correlators in the short distance limit.

BLJ-Limit:

$$\lim_{BJL} \equiv \lim_{\substack{q^0 \to i\infty \\ p \text{ fixed}}} \Rightarrow \lim \left\{q^2 \to -\infty, p \cdot q \to i\infty, p \cdot q/q^2 \to 0\right\}$$

Schwinger terms

$$\lim_{BJL} \mathcal{T}_{\mu\nu} = \lim_{BJL} \int d^4x\, e^{iq\cdot x} \langle A|T(j_\mu(x) j_\nu(0))|B\rangle + \text{ polynomial in } q^0$$

$$= \sum_{n=1}^{\infty} \left(\frac{1}{q^0}\right)^n \times \langle A|\text{ETCs of currents \& } \underline{\text{their time derivatives}}|B\rangle +$$

$$+ \text{ polynomial in } q^0$$

Hamiltonian?

Schwinger terms are real, and do not appear in dispersion relations, which relate integrals over physical observables to equal time commutators (ETCs)

SUM RULES!

1966 Bjorken-Johnson-Low (BJL) Limit

- BJL program: relate energy-integrals (moments) of physical observables to local matrix elements of currents with their time derivatives: Sum Rules
- What Hamiltonian to choose to evaluate time derivatives?

Johnson & Low (realists!):

BJL limit does not exist in renormalized perturbation theory: commutators are logarithmically divergent because interactions (Hamiltonian) even in simple QFTs modify short distance behavior of operator products (commutators)

Thus: Interactions modify short distance behavior: Presages anomalous dimensions and RG evolution

Bjorken (the optimist!):

Assumed operator commutators on RHS of sum rules exist and are finite as in free field theory, though matrix elements in hadronic states are unknown.

Became known as "formal" or "canonical" quantum field theory

Immediate application to deep inelastic phenomena!

Applications of the Chiral $U(6) \otimes U(6)$ Algebra of Current Densities*

J. D. Bjorken
Stanford Linear Accelerator Center, Stanford University, Stanford, California
(Received 14 March 1966)

Consequences of the local commutation relations of vector and axial currents proposed by Gell-Mann are explored: (1) A recipe for detecting and isolating Schwinger terms in the commutators, proportional to derivatives of the δ function, is discussed. (2) Under assumptions of smooth asymptotic behavior of form factors for forward scattering of the isovector current from a proton, we show that the $U(3)\otimes U(3)$ algebra for the time components of the currents implies the $U(6)\otimes U(6)$ algebra for space components, at least for spin-averaged diagonal single-particle states. (3) The derivation of the Adler-Weisberger formula for G_A/G_V is sharpened by giving arguments that, at fixed energy, the forward π-p Green's function satisfies an unsubtracted dispersion relation in the pion mass. (4) A lower bound for inelastic electron-nucleon scattering at high momentum transfer is derived on the basis of $U(6)\otimes U(6)$.

nonvanishing, and is computed. (8) A speculative argument is presented that the rate $e^+ + e^- \to$ hadrons is comparable to the rate $e^+ + e^- \to \mu^+ + \mu^-$ in the limit of large energies.

Thus,

$$\int_0^\infty \frac{d\nu'}{\nu'} \frac{d}{dq^2 d\nu'} \times [\sigma_p{}^{\uparrow\uparrow} - \sigma_p{}^{\downarrow\uparrow} - \sigma_n{}^{\uparrow\uparrow} + \sigma_n{}^{\downarrow\uparrow}] \to \frac{-8\pi\alpha^2}{3q^4 E}\left(\frac{G_A}{G_V}\right). \quad (6.18)$$

Something may be salvaged from this worthless equation by constructing an inequality[18]:

$$\lim_{q^2\to-\infty} \lim_{E\to\infty} q^4 E \int_0^\infty \frac{d\nu}{\nu'}\left[\frac{d\sigma_p}{dq^2 d\nu'} + \frac{d\sigma_n}{dq^2 d\nu'}\right] > \frac{8\pi\alpha^2}{3}\left|\frac{G_A}{G_V}\right|. \quad (6.19)$$

From Bjorken's 1966 paper on U(6) x U(6) algebra of currents

- Integrals over inelastic electron and neutrino scattering !

  Are bounded from below by free field theory (scaling) results

  Including polarization dependent phenomena

  Obey (the first) DIS sum rule in terms of hadron axial charges

- Total electron-positron hadronic annihilation cross section !

  Scales proportional to $e^+ e^- \to \mu^+\mu^-$ cross section

- Taming divergences in EM mass differences of hadrons

  Divergences are absorbed into quark mass renormalization

- Hadronic contributions to hyperfine splittings in hydrogen

  Can be computed in terms of DIS data

Adler's neutrino sum rule: a missed opportunity

In 1965 Steve Adler derived a sum rule for (what is now known as the neutrino (and antineutrino) structure function $F_2^{\nu,\overline{\nu}}(x,Q^2)$ which in modern notation reads

$$\int_0^1 \frac{dx}{x}(F_2^{\overline{\nu}}(x,Q^2) - F_2^{\nu}(x,Q^2)) = 2$$

Adler's derivation relies only on the charge-density algebra and therefore has no problem with Schwinger terms,

And

The sum rule is valid for all Q^2. How can sum rule be satisfied at large Q^2?

Complex coordination of infinite tower of rapidly falling resonances? Or Bjorken scaling? The problem was not examined until Bjorken raised the question with Adler at the Varenna summer school in 1967. Adler (and Treiman) put the question of "saturation" aside; Bj continued to think about it.

Evidence for DIS scaling in 1965.*

*See T. Y. Cao, "From Current Algebra to Quantum Chromodynamics" (Cambridge, 2010)

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Some quotes from the ICHEP Conference Berkeley 1966

- "We consider three hypothetical and probably fictitious quarks…"

  "Now what is going on? What are these quarks? … It is hard to see how deeply bound states of such heavy real quarks could look like qq, say, rather than a terrible mixture of $q\bar{q}$, $q\bar{q}q\bar{q}$, and so on. …the idea that mesons and baryons are made primarily of quarks is difficult to believe, since we know that, in the sense of dispersion theory, they are mostly, if not entirely, made up out of one another. The probability that a meson consists of a real quark pair rather than two mesons or a baryon and antibaryon must be quite small. Thus it seems that whether or not real quarks exist, the q and $\bar{q}$ we have been talking about are mathematical entities."

  Murray Gell-Mann, Introductory Talk

- "This provides us with an unfamiliar situation, but one which has much qualitative correspondence with the experimental data… The [hadrons] should be regarded as rather analogous to molecules whose constituent atoms are quarks. Such a … model appears especially unfamiliar in terms of the conventional ideas of field theory today … if it works well, then it will be the task of field theory to show how such a model can arise from … some field theory."

  Q (Maglić): "Does this model rely on the existence of physical quarks?"
  A (Dalitz): "… if there do not exist real particles, this model has no interest"

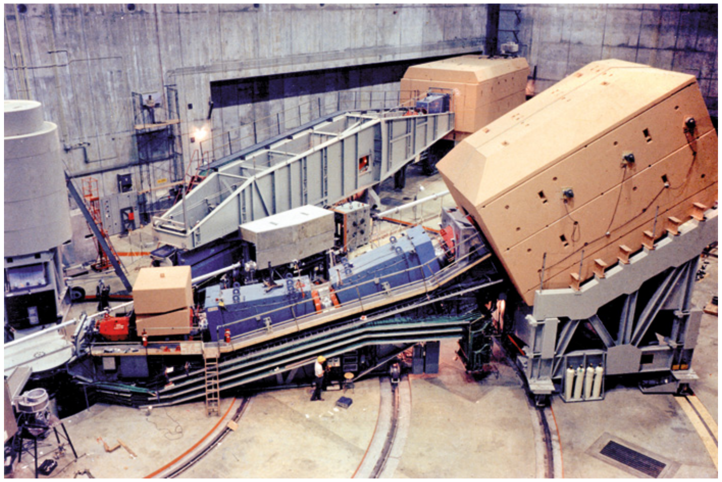
  Richard Dalitz, Symmetries and the Strong Interactions

- "… what would I like to see measured? … I'd very much like to see inelastic electron or muon cross sections measured…Also there are some sum rules, asymptotic statements derived by Bjorken and others, as to how these inelastic cross sections behave in energy, … which can be checked experimentally."

  Sidney Drell, closing comment in Electromagnetic Interactions

1967-1968 A resonance between theory and experiment

- 1967 Bjorken muses — How could structure functions be large at large q^2?
  How could Adler neutrino sum rule be saturated at large q^2?
  Unpublished, incomplete paper ⇒ scaling in ν/q^2



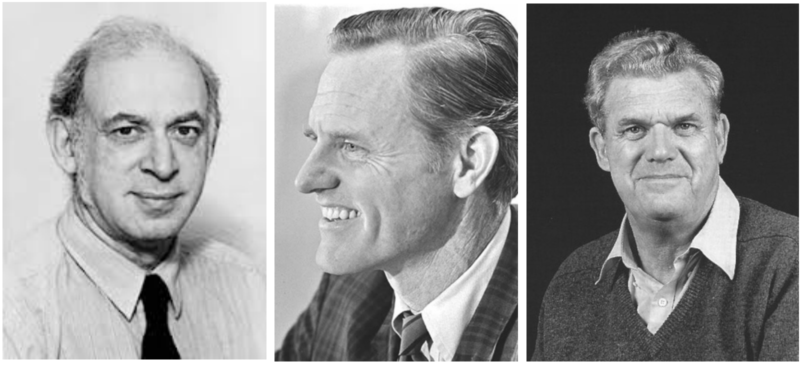
SLAC End Station A

- 1967 SLAC inelastic electron scattering experiments begin – originally focused on resonance production, but (not motivated by theorists) observe large cross section for inelastic scattering

- Early 1968 Bjorken discusses scaling with Friedman, Kendall, Taylor and collaborators

- Summer 1968 ICHEP: SLAC/MIT group presents inelastic data without showing scaling…

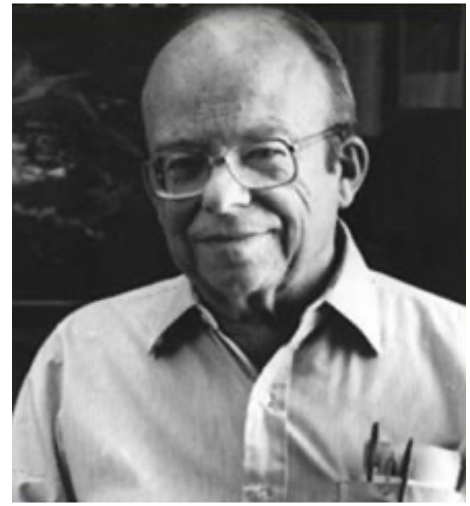
- But Panofsky in summary talk…



Jerry Friedman, Henry Kendall, Richard Taylor

1967-1968 Deep inelastic scattering

- **But Panofsky in summary talk…**



The qualitatively striking fact is that these cross sections for inelastic electron and muon scattering leading to the continuum are very large and decrease much more slowly with momentum transfer than the elastic scattering cross sections

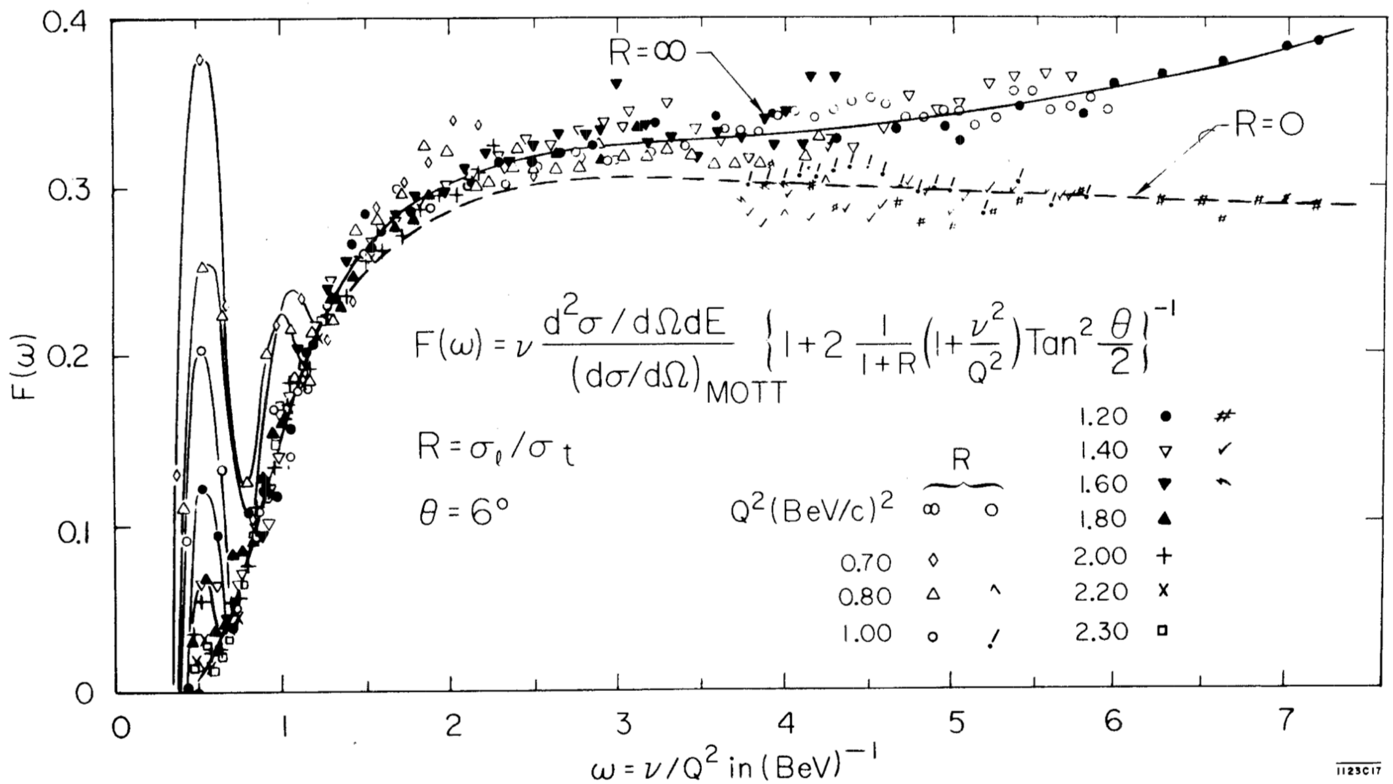
At least qualtitatively, using the variable ν/q^2 leads to a fairly universal representation of the "deep" inelastic continuum covered so far.

Therefore theoretical speculations are focused on the possibility that these data might give evidence on the behaviour of point-like, charged structures within the nucleon

- **Autumn 1968 –1969: Scaling from sum rules (Bjorken) and partons (Feynman)**

1967-1968 Deep inelastic scattering

- **But Panofsky in summary talk…**



- **Autumn 1968 –1969: Scaling from sum rules (Bjorken) and partons (Feynman)**

Responses to scaling – threads in 1968-70

- **BJL limit plus infinite momentum limit (of Fubini & Furlan) "predict" scaling**
  Cornwall & Norton, Callan & Gross, Bjorken …
- **Formulation of field theory at infinite momentum and quantization on the null-plane** Weinberg, Bardakci & Halpern, Susskind, Kogut & Soper, Cornwall & Jackiw…
- **Quark light-cone algebra in free field theory & formally in "gluon models"**
  Frishman, Brandt & Preparata, Fritzsch & Gell-Mann, Gross & Treiman, Llewellyn Smith, …
- **Operator product expansion at short distances**
  Wilson…
- **Broken scale invariance, Q^2 evolution and the renormalization group**
  Callan, Symanzik, Wilson, Christ, Hasslacher, & Mueller
- **Parton model for DIS – free field theory at short distances in momentum space**
  Feynman, Bjorken & Paschos, Drell, Levi & Yan, Llewellyn Smith…
- **Parton model – liberated from OPE! – Drell-Yan processes, fragmentation functions** Drell & Yan, Brodsky, Gunion, RLJ…

Outline

- Overview: 1962/1972
- Origins of Bjorken's 1966 paper – a turning point in the history of the strong interactions
- Snapshot of 1966: confusion, contradiction. 1968: Then DIS data from SLAC
- **1968 – 1972: The canonical "quark-gluon" model (as seen at SLAC) and the paradox of confinement**
- Afterward: strings to bags – an extended model and heuristic picture of hadrons

SLAC Theory Group & Emerging QCD in 1968-1972
Some of the dramatis personae*

- Faculty: Bj Bjorken, Sid Drell
- Research Staff: Stan Brodsky, Fred Gilman (Geoff West)
- Sabbatical and Long-term Visitors: Ken Johnson, Ken Wilson, Haim Harari, T. D. Lee

- Postdocs/fellows /visitors: Tom Appelquist, David Broadhurst, Frank Close, John Ellis, Yitzhak Frishman, Jack Gunion, Don Levy, Chris Llewellyn Smith, Manny Paschos, Tung-Mow Yan
- Graduate Students: Mike Creutz, Joe Kiskis, John Kogut, Inga Karliner, Joel Primack, Dave Soper, RLJ

* Apologies to some forgotten and many working on electroweak interaction theory, PCAC, spectroscopy, S-matrix theory.

The "canonical", quark-gluon model

Theorists were enthusiastically using ideas from canonical quantum field theory. They knew their results failed order-by-order perturbation theory, but they used them anyway and got the right answers.

Ingredients

- Quantum theory of quarks
- Free field theory at short distances
- Vector gluons for chiral symmetry
- Color for statistics and (by 1969) for factor of 3 in π^0 decay

Canonical = BJL results

- Callan-Gross Relation
- Momentum Sum Rule
- Gross Llewellyn Smith Sum Rule
- Bjorken Spin Sum Rule
- 18/5 Relation

Llewellyn Smith 1971:

It can be shown formally that in many renormalizable interacting field theories the most singular part of the LCC is the same as in free field theory[4] (apart from a gauge factor $\exp(ig\int_0^y \phi_\mu(z)dz^\mu)$ if there is a vector interaction).

Formally has come to be an euphemism meaning "by methods which ignore the subtleties of field theory and are known to fail in perturbation theory".

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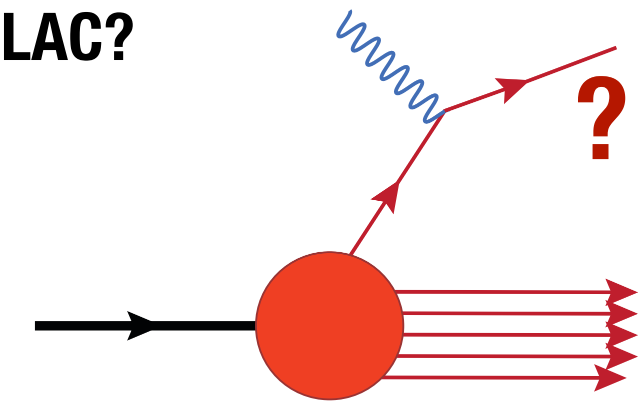
1970-1972 “Quark confinement” – began to be discussed in HEP community and certainly at SLAC

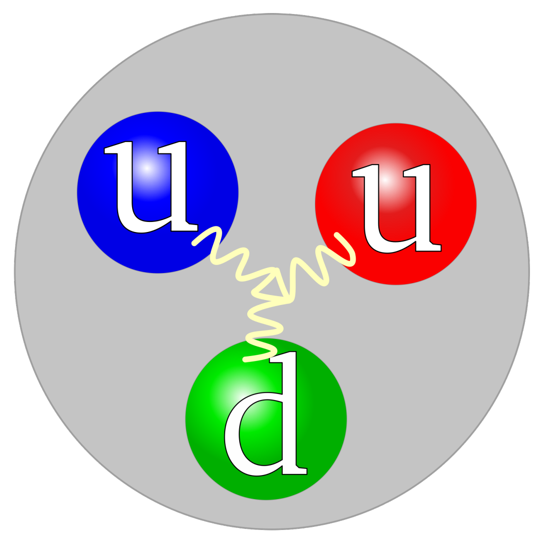
If partons are quarks with free-field light-cone behavior, confinement — very strong forces — is problematic…

- Why are quarks not seen in the final state at SLAC?
- How can quarks be bound into hadrons?



Ken Johnson: Can hadrons be made of (weakly coupled) constituent quarks permanently confined to the interior of hadrons?

April 1972: K. Johnson ‘Can quarks be kept inside’ Confinement doesn’t violate any sacred principles of QFT.



By 1972: a consensus — QCD — had emerged…

- Color –> Triality = color singlet selection rule — Gell-Mann (Nambu 1966)
- Colored vector gluons — Fritzsch, Gell-Mann, Leutwyler (Yang & Mills 1953)
- Yang-Mills theories are unitary & renormalizable — ’t Hooft, Veltmann
- Unbroken $SU(3)_c$ Yang-Mills field theory describes hadrons

Finally 1973 – Asymptotic freedom explains approximate free-field behavior near the light cone

Gross & Wilczek, Politzer

But important questions remained…

- Why is scaling “precocious” in q^2? $q^2 > 0.5$ GeV^2, no sign of “higher twist”
- Quarks in hadrons at zeroth order: “free but confined”?
- What is the physical mechanism of confinement and chiral symmetry violation?
- Construct a heuristic description of confined quarks in QCD?

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Meanwhile analytic S-matrix theory advanced in late 1960s

Analytic S-matrix + duality ⇒ Veneziano model ⇒ strings

- Finite Energy Sum Rules — Dolan, Horn, Schmid; Logunov, Soloviev, Tavkhelidze; Igi, Matsuda
- Duality — Freund, Harari, Rosner,…
- Dual Resonance Model — Veneziano
- Veneziano Model = Massless, relativistic string — Nambu, Goto, Goldstone, Goddard, Rebbi, Thorn
- Could a string model serve as a phenomenological model of quarks confined to hadrons? Geometrical degrees of freedom?

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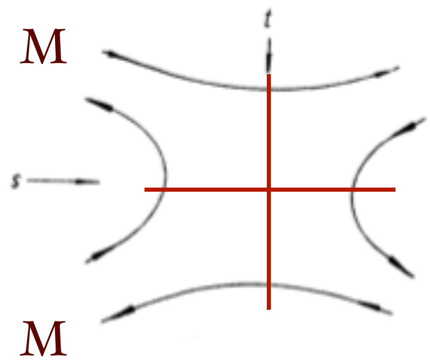

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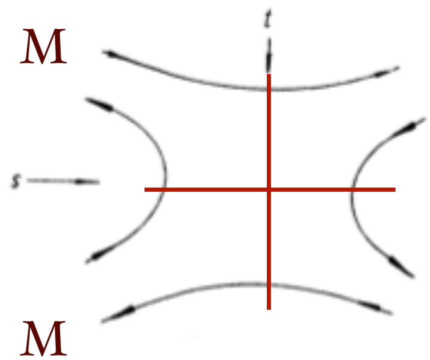


Freund, Harari, Rosner,…

- Dual Resonance Model

Veneziano

$$A = \frac{\beta(t)}{\sin \pi\alpha(t)}\left[-\frac{\sin \pi\big(\alpha(s)+\alpha(t)\big)}{\sin \pi\alpha(s)}\frac{\Gamma\big(\alpha(s)+\alpha(t)-1\big)}{\Gamma\big(\alpha(s)\big)}+\frac{\Gamma\big(1-\alpha(u)\big)}{\Gamma\big(2-\alpha(u)-\alpha(t)\big)}\right]$$

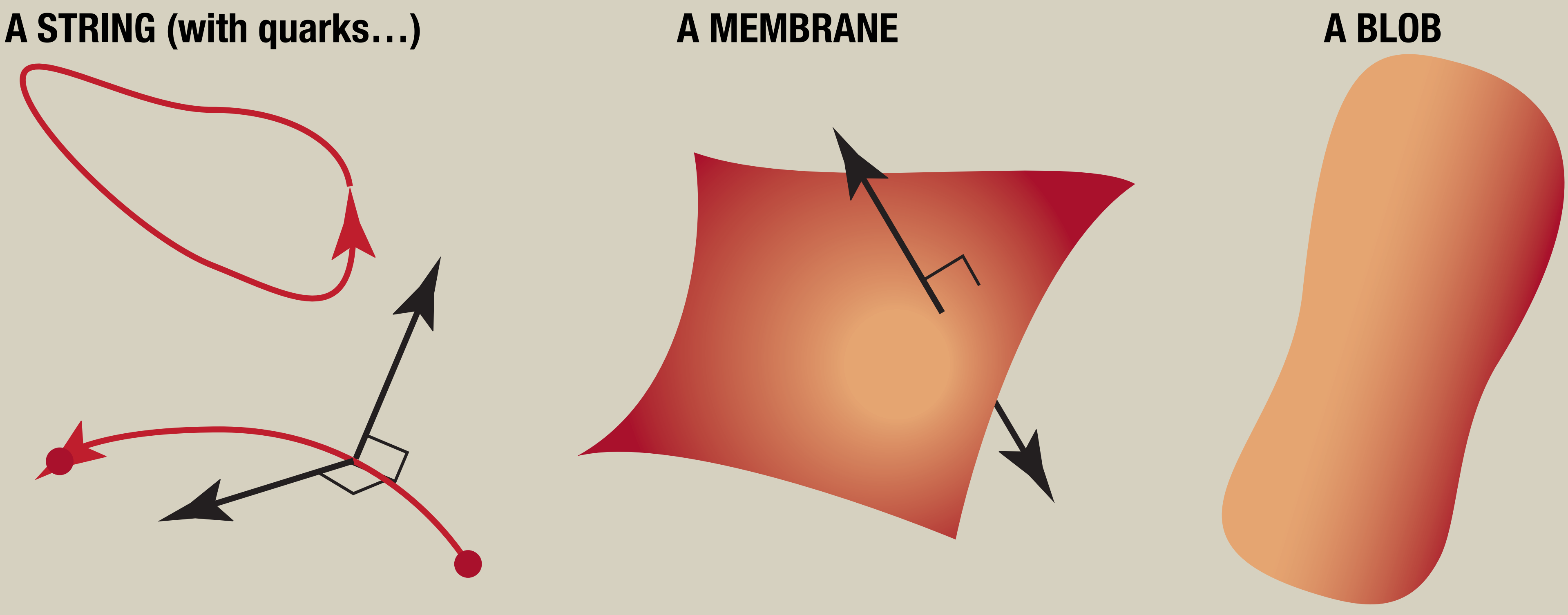
- Veneziano Model = Massless, relativistic string

Nambu, Goto, Goldstone, Goddard, Rebbi, Thorn

- Could a string model serve as a <u>phenomenological</u> model of quarks confined to hadrons? Geometrical degrees of freedom?

1973 — A string, a membrane, blob ⇒ a bag

Confinement — Hadrons are extended domains in which quarks interact weakly but cannot "get out". Geometric models? Strings? Unwanted geometric excitations not seen in observed spectra.



TWO (TRANSVERSE) GEOMETRIC DEGREES OF FREEDOM

ONE (TRANSVERSE) GEOMETRIC DEGREES OF FREEDOM

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A STRING (with quarks…)

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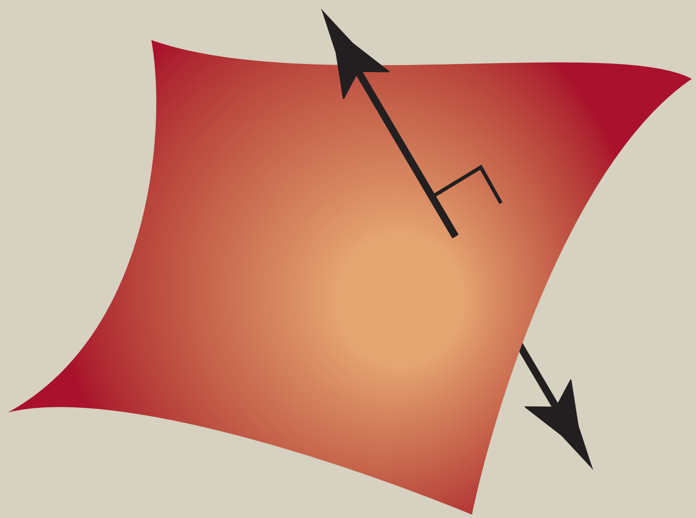
A MEMBRANE



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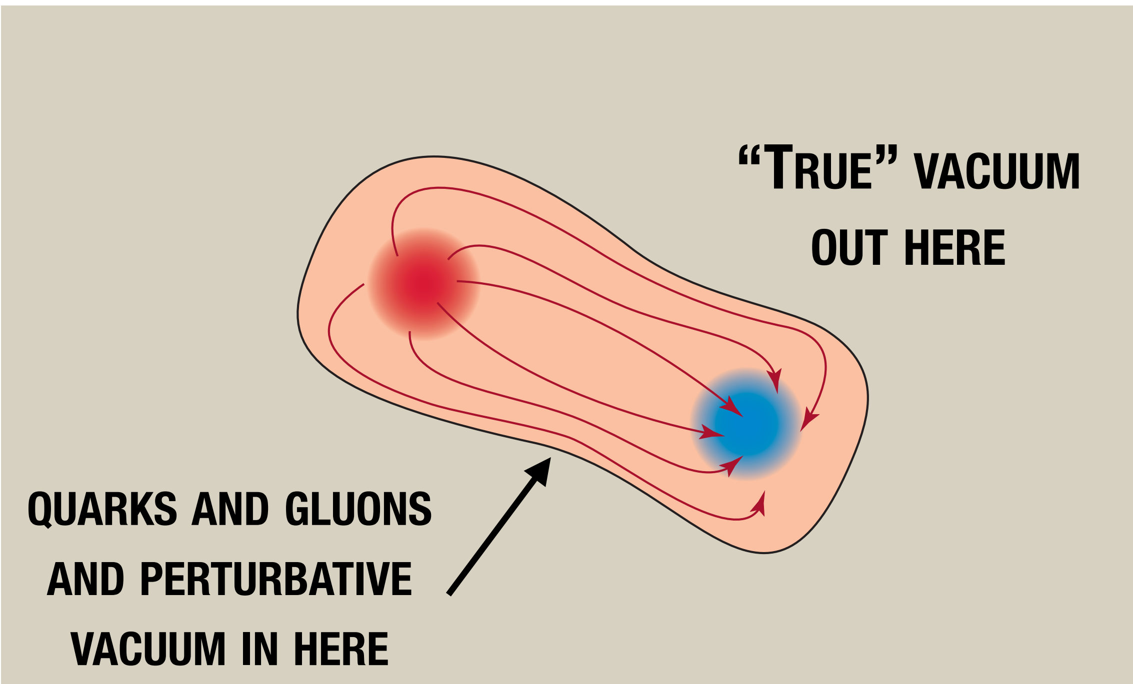
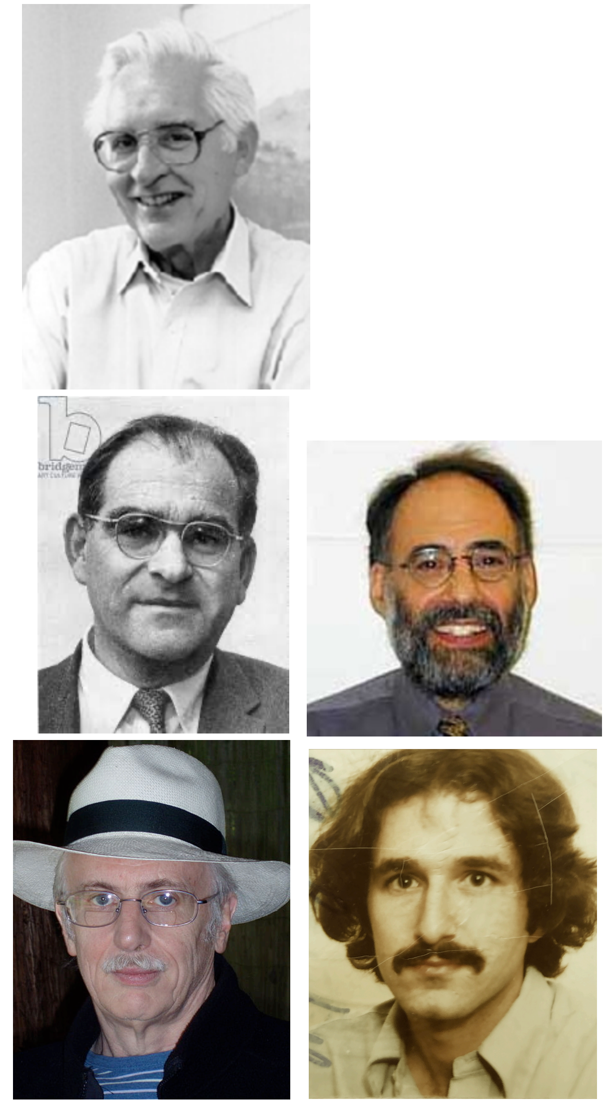
1973 An MIT (QCD) Bag

- An extended object – A blob (3-dimensional generalization of a string)
- Relativistically covariant
- With <u>no geometrical degrees of freedom</u>
- Over which QCD fields (quark, gluon) are defined

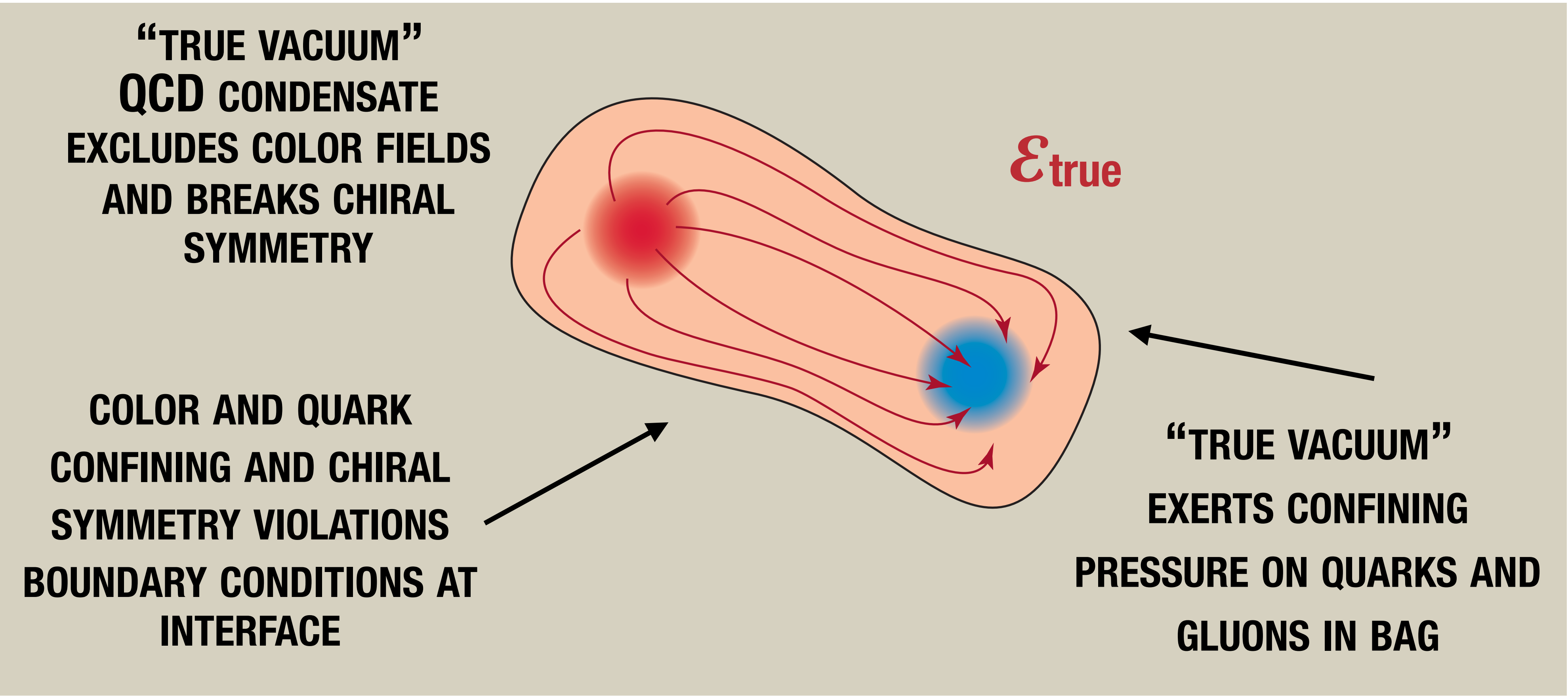




CHODOS, JOHNSON, THORN, WEISSKOPF, RLJ

A (QCD) Bag

- Dual (E <-> B) color Meißner effect: true vacuum of QCD excludes color electric fields
- Energy difference $\mathcal{E}_{pert} - \mathcal{E}_{true} \equiv B \sim 150\ \mathrm{MeV/fm}^3$ (confining "Bag" pressure)
- ≈ Nearly massless, relativistic asymptotically free, but permanently confined quarks and gluons with a single scale ~ 150 MeV



THANK YOU!