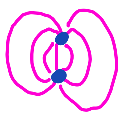
# The Confinement Mechanism

$g^2 \sim \frac{1}{\log r}$ ? ? ? ?

$10^{-14}$ cm $10^{-12}$ cm



$V \sim \frac{g^2}{r}$

$\frac{g^2}{4\pi} \sim 1$

Asymptotic freedom is not the confinement mechanism, but it is the reason that the mechanism, whatever it is, can coexist with free quark behavior at small distance.

The discovery of the mechanism played out over a period of about six years, between 1969 and 1975.

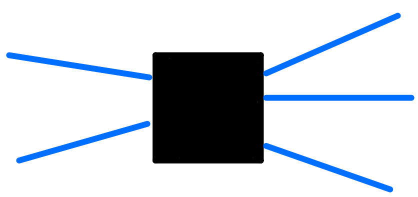
1965

Two schools of thought on hadrons

Berkeley Caltech

Berkeley: ~~QFT~~

A "black-box" — the S-matrix — that's all there is.



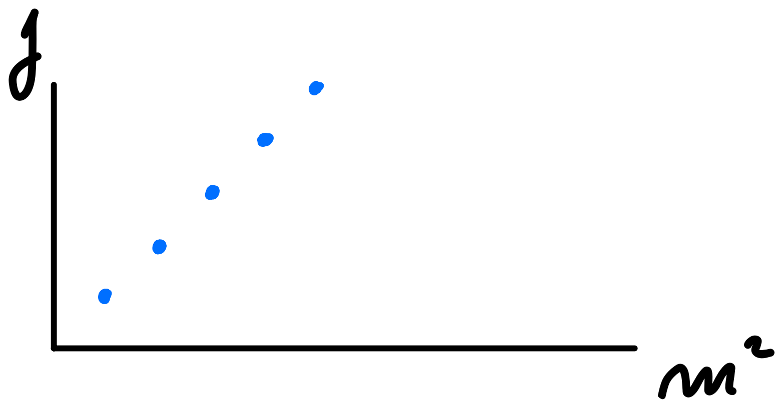
In principle no experiment can open the black box. Hadronic physics takes place on scales which are too small and too fast to resolve.

Unitarity, Lorentz invariance, analyticity,

"Bootstrap"

a mashup of ideas, some good, some not so good. One of the good ones:

Chew-Frautschi Regge trajectories 1961



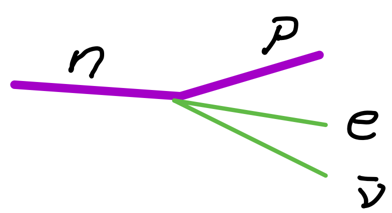

$$\boxed{m = \sqrt{J}\ ?}$$

Caltech:

The focus was on flavor symmetries

$SU(3)_L \times SU(3)_R$,

approximate conservation laws and the coupling of hadrons to photons and leptons.




The currents of the weak and electromagnetic interactions behaved as if hadrons were collections of free u, d, s quarks.

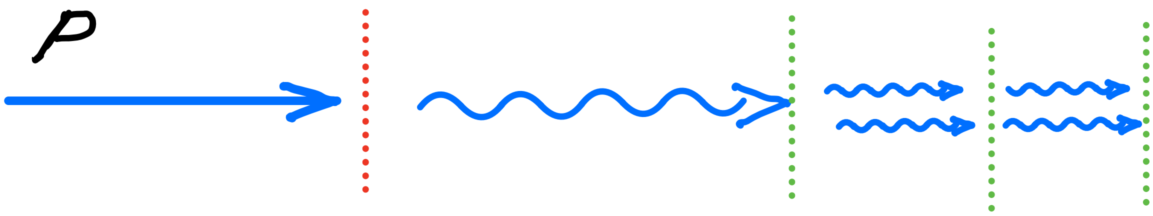
Gell-Mann: "Nature reads books on free field theory."

My own view: Open the black box

We can stretch things out, slow them down, in order to observe the internal motions.

The trick? The infinite momentum frame. weinberg 1966

Non-relativistic Galilean symmetry of QM of the IMF L.S. 1968




$$E = \sqrt{p^2 + m^2} \rightarrow p + \frac{m^2}{2p}$$

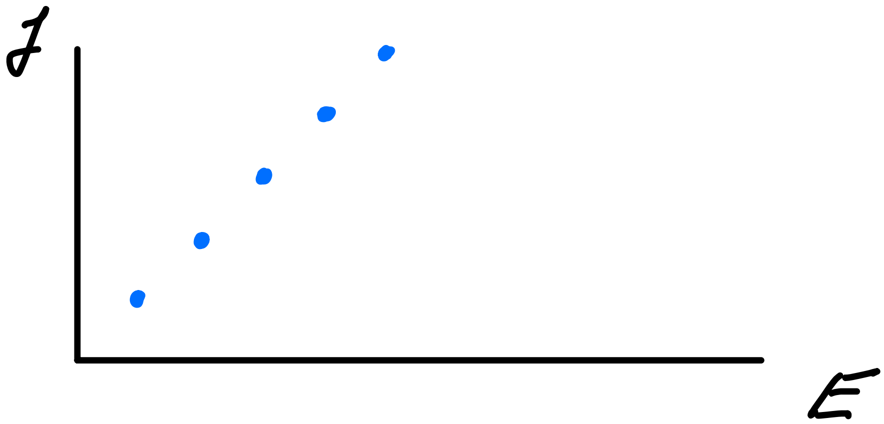
$$(E - p) = \frac{m^2}{2p}$$

$$H_{IMF} = p(E - p) = \frac{m^2}{2}$$

Energy in the IMF is

$$\boxed{E = \frac{m^2}{2}}$$

Chew-Frautschi, $m^2 \sim J$

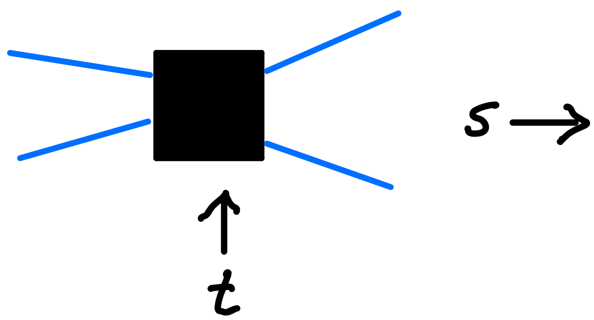



$E_{IMF} = J$ = integer spaced.

$\boxed{\text{Hadrons are Harmonic oscillators}}$

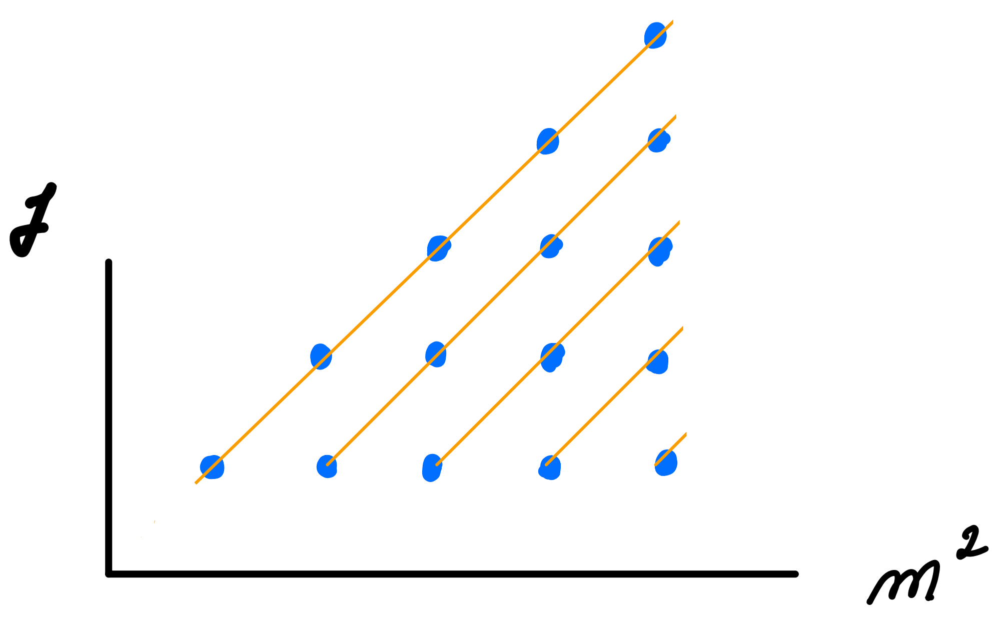
# Back to the S-matrix:

By 1968 Venezcano had constructed a solution to the bootstrap.



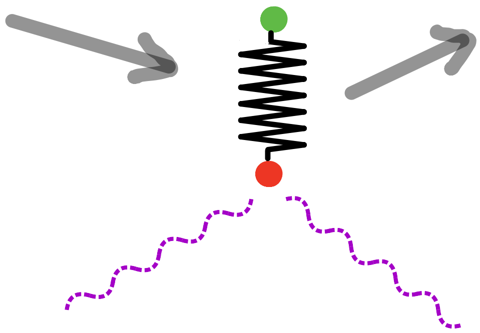

$$A(s,t) = g^2 \frac{\Gamma(-s)\,\Gamma(-t)}{\Gamma(-s-t)}$$

$$= g^2 \int x^{-s}(1-x)^{-t}\, dx$$




Exactly the spectrum of a 3-D harmonic oscillator!

1969 Nambu, L.S.



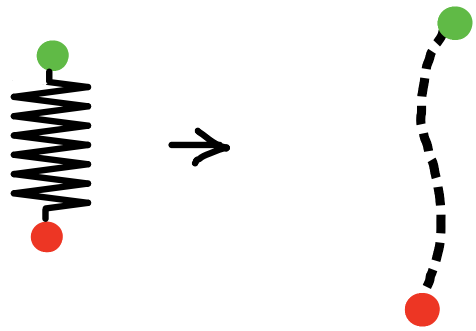
$$\int x^{-s}(e^{-x})^{-t}$$

Veneziano: $\int x^{-s}(1-x)^{-t}\,dx$

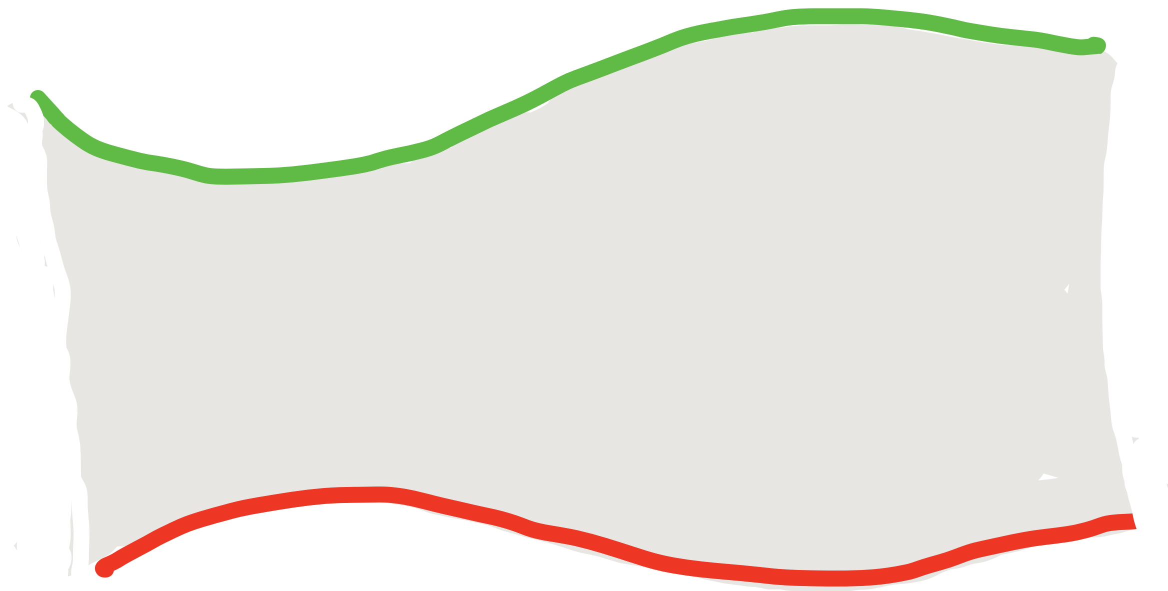
$$(1-x)^{-t} = e^{xt}\, e^{\frac{x^2}{2}t}\, e^{\frac{x^3}{3}t} \cdots$$

$\infty$ number of oscillators with frequencies

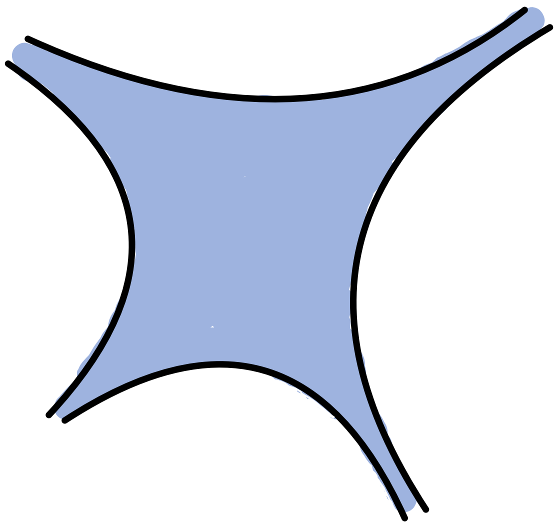
$\nu = 1, 2, 3, \dots$



$$\boxed{\text{spring theory} \rightarrow \text{string theory}}$$



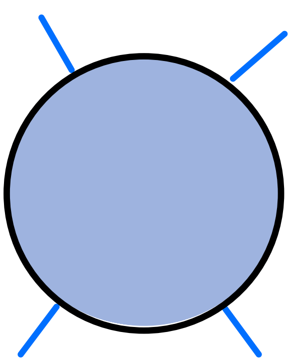
worldline $\rightarrow$ worldsheet



quarks running around the edges.

Chan, Patton
Harari
Rosner

Holger Bech Nielsen



Conducting disc model
string theory in momentum space

NSN

$$E_{IMF} = \frac{m^2}{2} = K + V$$

$$V \sim \frac{d^2}{2} \quad \text{(oscillator potential)}$$

Rest Frame

$V \sim d$

Energy $\sim$ separation

Nambu Goto, L.S., H. Noskowitz

E.P. Tryon 1972

"Confining Potential" $V \approx d$

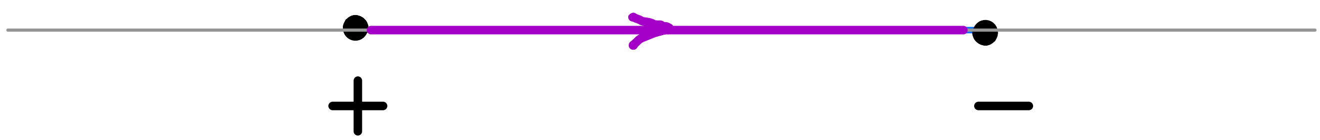
Is confinement possible in a genuine quantum field theory?

A. Casher, J. Kogut, L.S. 1972, 73

Possibly but only in a theory with vector forces – a gauge theory.

Massless (1+1) QED – the Schwinger model

charged fermions = quarks




potential energy = $g^2 d$

Electric flux lines are strings.

The Schwinger paper was difficult to understand, but the model was easy to solve.

Solution:

Massive Neutral bosons. No "quarks."

The bosons had properties very similar to hadrons (mesons).

Especially in massive case.

Kogut L.S 1974

Coleman, Jackiw, Susskind 1975

Axial current anomaly

$\eta \longrightarrow 3\pi$ puzzle  Kogut, L.S. (1974)

Existence of CP ($C$ in $D=2$) violating $\theta$ angle (Coleman Jackiw Susskind)

1974

't Hooft went further and solved the Large $N$ nonabelian Schwinger model (using infinite momentum techniques).

Quarks confined

Color-neutral meson spectrum

$$V \approx g^2 d$$

Regge-like trajectories

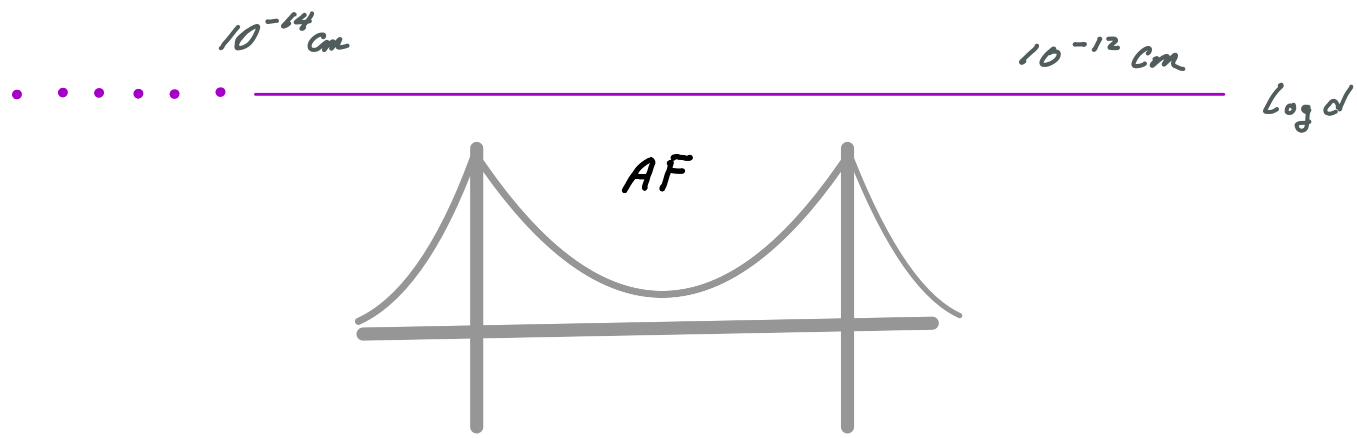
$$\boxed{\text{So, yes; a quantum field theory can confine.}}$$

But,

can a 4-D gft confine?

Earthquake July 1973

Asymptotic Freedom in QCD



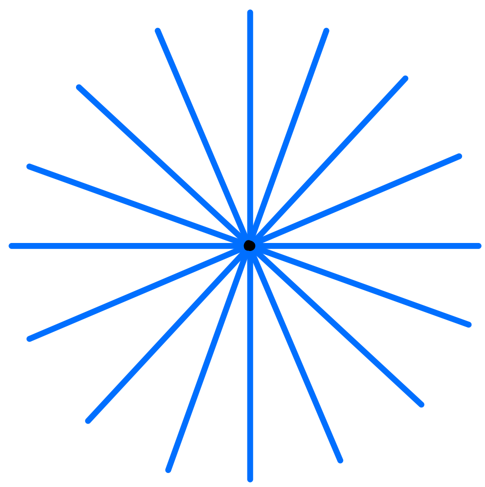
Two things were key to generalizing the (1+1) model:

1. Kinematical

The continuity of electric flux.

Flux lines can only end on charges

$\nabla \cdot E = \rho$



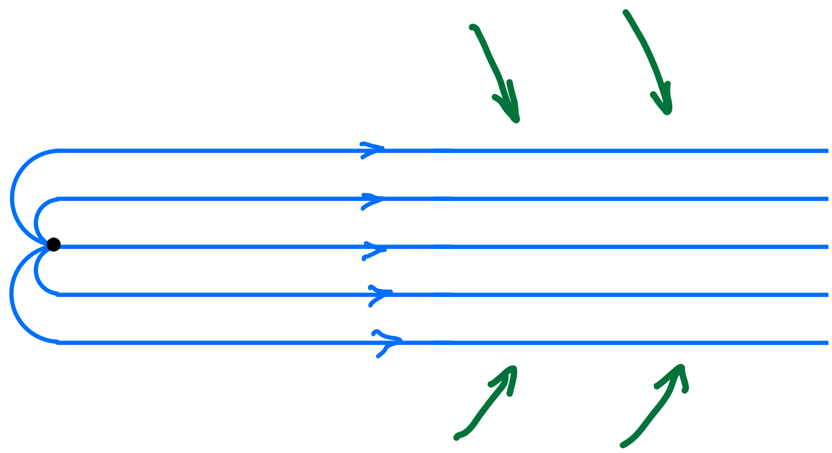
Dynamical

2. Nature abhors a chromoelectric field.

L.S., J.K. 1974

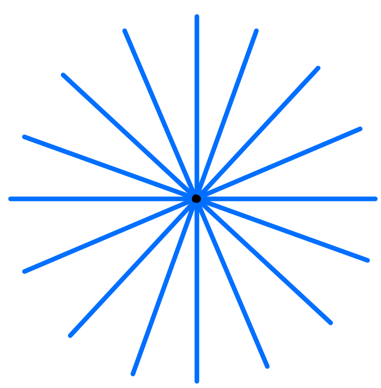
't Hooft

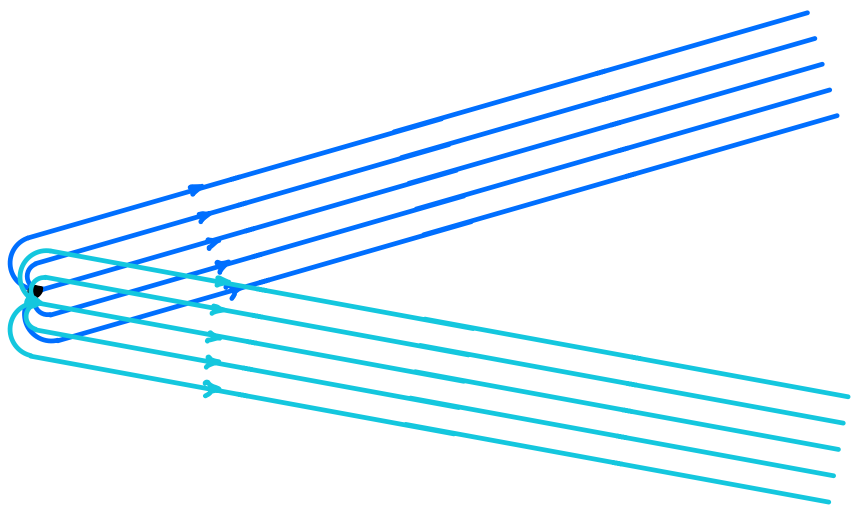
Nielsen, Olesen 1973



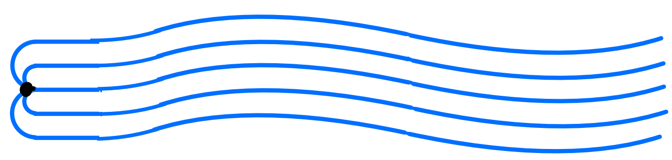
A new phenomenon

Among other things it entails a spontaneous symmetry breaking (of rotational invariance).



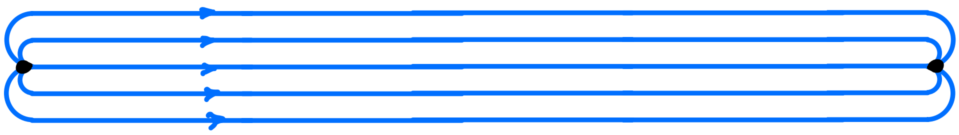


And Goldstone bosons

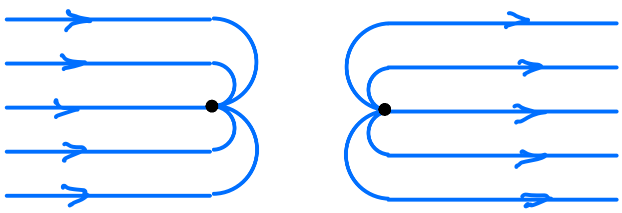


string modes

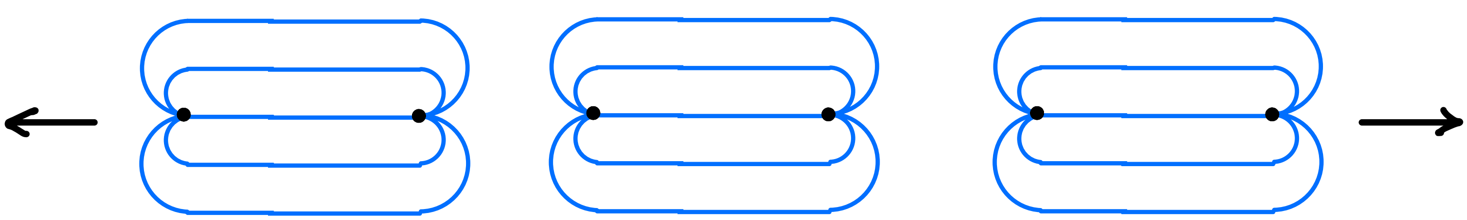
# Confinement



$$V \sim d$$

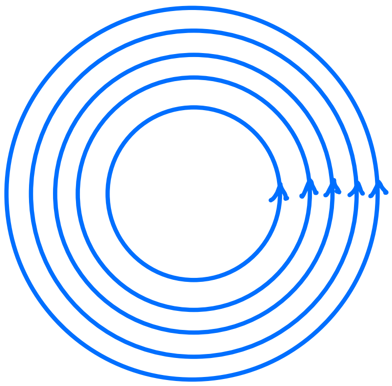


strings break
but no free
quarks



meson jets

Glue balls (closed strings)



Can a field theory really behave this way?

A relativistic Model

L.S., J.K. March 1974

't Hooft July 1974

# Polarizable vacuum

$$\mathcal{L} = \epsilon \int F_{\mu\nu}^2 \, d^4x$$
$$+ \mathcal{L}(\epsilon)$$

$\epsilon(x)$ = local permittivity

Sign of $(\epsilon - 1)$ related to $\beta$-function.

Abelian Gauge theory, $\beta > 0$

$\epsilon$ is greater than 1. Debye Screening

Asymptotically free theories

$\epsilon < 1$.

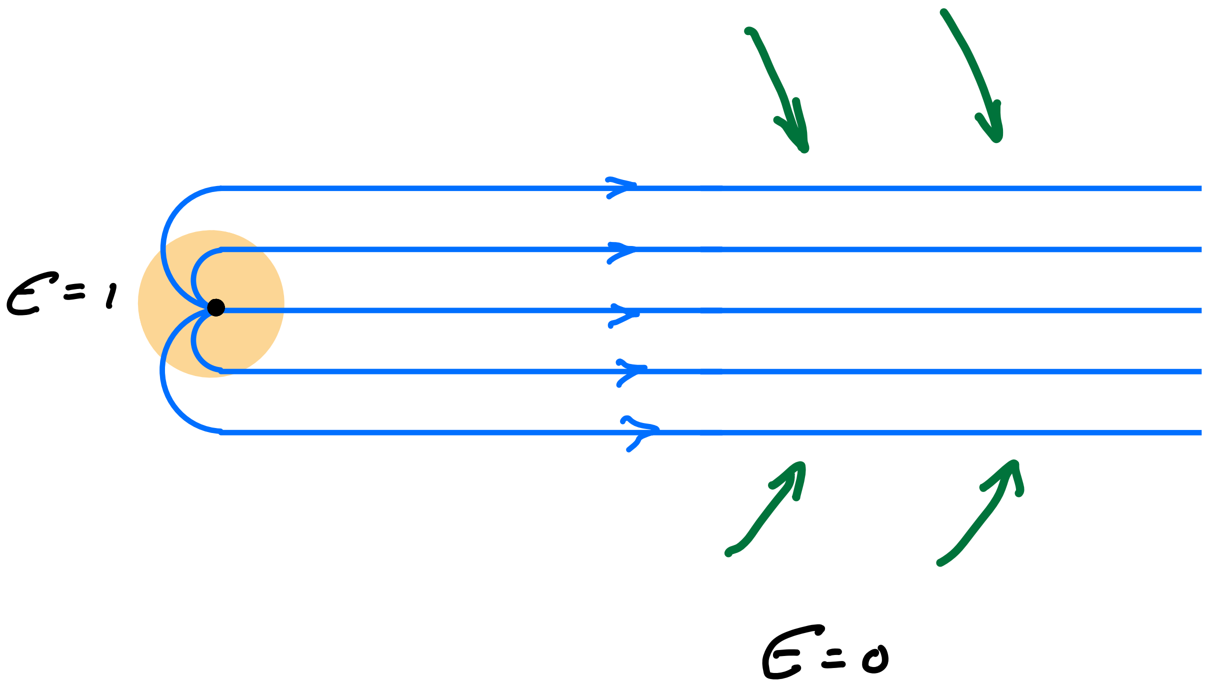
antiscreening

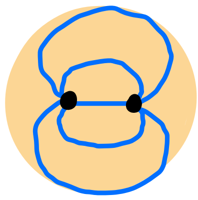
Assume $\mathcal{L}(\epsilon)$ favors

$\epsilon = 0.$

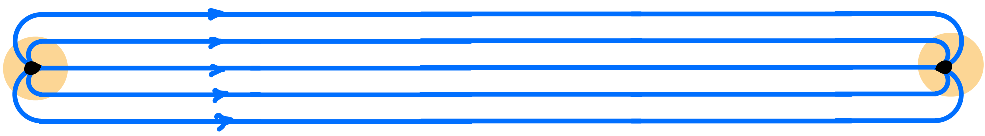
L.S., J.K. Feb 74

't Hooft July 74





$$V = \frac{g^2}{r}$$

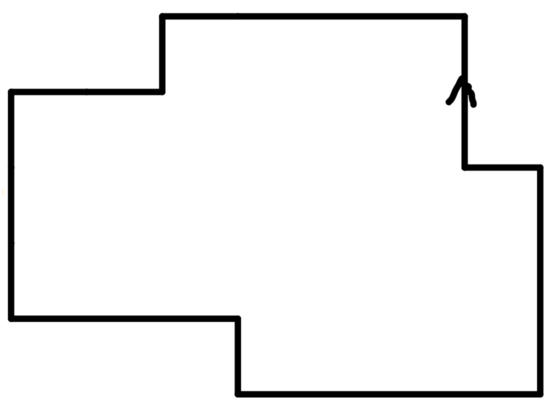


$$V \sim r$$

Feb 1974 Another quake

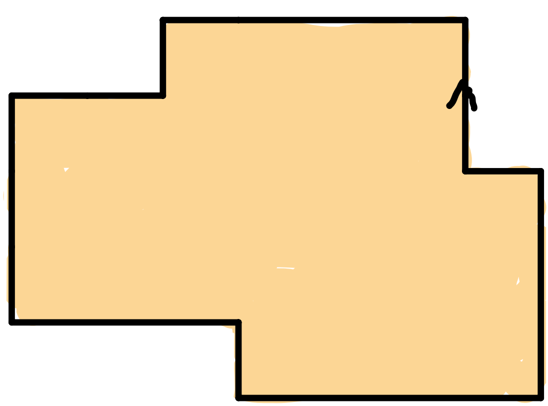
Wilson (Building on Wegner 1971) creates

$\boxed{\text{Euclidian Lattice gauge theory}}$



$Amp = e^{-I}$

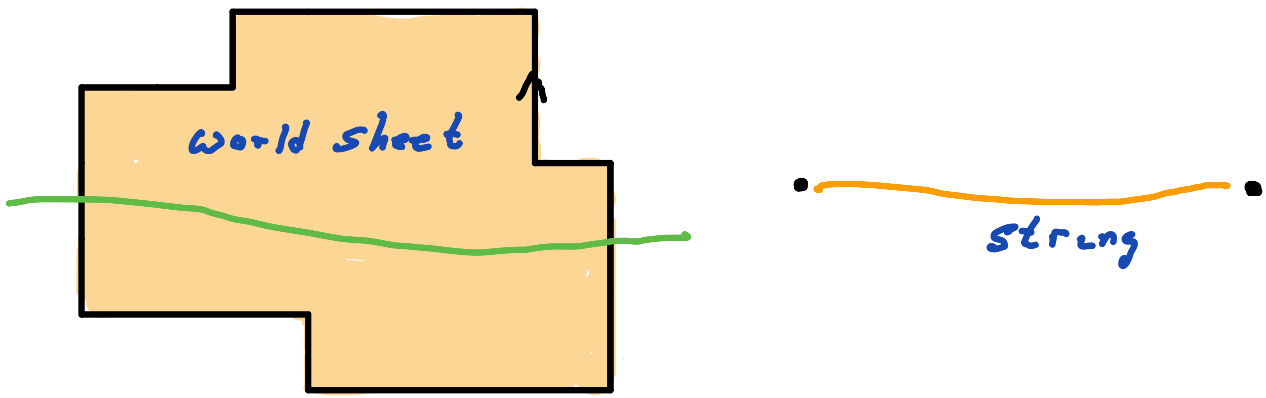
$I = \text{perimeter}$



$I = \text{Area}$

much harder to separate quarks

# Relation to string theory

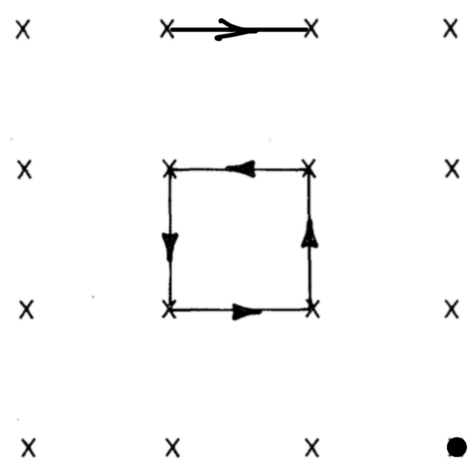



Can L.G.T. be used for real time processes? Not in it's Euclidean formulation.

What was needed was a real-time Hamiltonian form.

Hamiltonian lattice gauge theory

(Kogut Susskind 1974)



Electric links

Magnetic plaquettes

Quarks sites

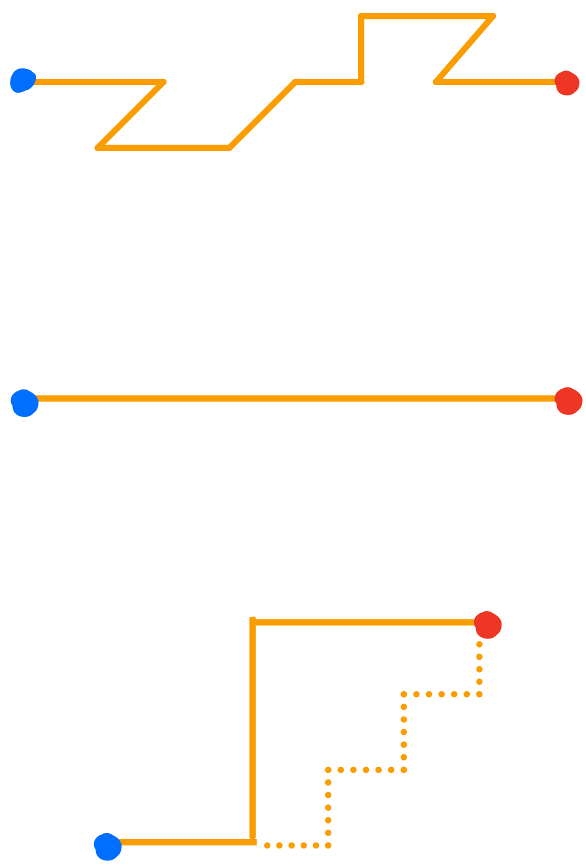
$$\frac{g^2}{2a}\sum_{r,n} Q_+{}^2(r,n) + \frac{4}{ag^2}\sum \mathrm{tr}U_{1/2}(r,n)\,U_{1/2}(r+n,m)\,U_{1/2}(r+n+m,\,-n)\,U_{1/2}(r+m,\,-m)$$

$$+a^{-1}\sum \psi^\dagger(\cdot\cdot)\,\frac{\vec{\sigma}\circ\vec{n}}{i}\,U(r,n)\,\psi(r+n) + m_0\sum(-1)^r\,\psi^\dagger(r)\,\psi(r)\,.$$

In strongly coupled limit chromoelectric <u>flux</u> <u>is</u> <u>quantized</u>.

$$\vec{E}|0\rangle = 0 \qquad \text{(vacuum)}$$

"Nature abhors an electric field"



$V \sim g^2 d$

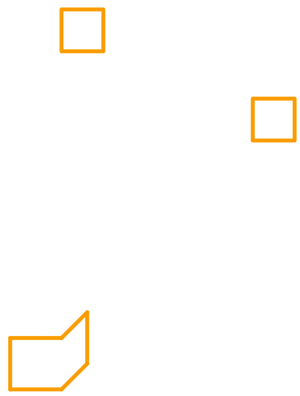
A lattice gauge theory can be used for real-time processes! Decays, scattering, Meson jet production? $e^+e^- \longrightarrow$ Hadrons.

$$H_E = \frac{g^2}{2a} \sum_{r,n} Q_+{}^2(r,n)$$

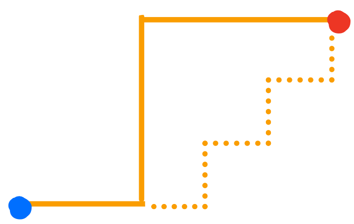
$$H_q = +a^{-1} \sum \psi^\dagger(\cdots) \frac{\vec{\sigma} \circ \vec{n}}{i} U(r,n)\,\psi(r+n)$$

$$H_M = \frac{4}{ag^2} \sum \mathrm{tr} U_{1/2}(r,n)\, U_{1/2}(r+n,m)\, U_{1/2}(r+n+m,\,-n)\, U_{1/2}(r+m,\,-m)$$

Perturbation in $1/g^2$ creates Electric field fluctuations.



Removes degeneracies



Especially interesting:

It allows <u>systematic</u> <u>computations</u>

of masses, moments, $g_A/g_V$, $f_\pi$, ............

perturbation theory in $1/g^2 = x$

Pade approximants. to continue to

$x = \infty$.

Glueballs Kogut, Sinclair, L.S. 1976

(closed strings)



Nuclear Physics B114 (1976) 199–236


# A QUANTITATIVE APPROACH TO LOW-ENERGY QUANTUM CHROMODYNAMICS

John KOGUT *
*Laboratory of Nuclear Studies, Cornell University, Ithaca, New York 14853*

D.K. SINCLAIR **
*Department of Theoretical Physics, University of Oxford, Oxford OX1 3PQ, England*

Leonard SUSSKIND ***
*Belfer Graduate School of Science, Yeshiva University, New York, N.Y. 10033*
*Department of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel*

Received 21 June 1976

A general method for solving the low-energy spectrum of an infrared unstable field theory is presented. The method involves a strong coupling expansion of the lattice approximation to the theory. Ultimately the results must be continued to zero-coupling constant in accord with the asymptotic freedom of such theories. The method is applied to the pure gauge field (glueball) part of quantum chromodynamics. The spectrum of lowest-lying states consists of a scalar and tensor which are almost degenerate and an axial vector with mass ~1.6 times the scalar mass.

The same procedure applied to the Abelian gauge theory yields unstable results which may indicate the presence of a phase transition.

## 1. Introduction

Quantum chromodynamics † (QCD) is a precise formulation of the quark model. In principle QCD should allow computation of the hadron spectrum with accuracy limited only by our imprecise knowledge of new degrees of freedom and interactions at very small distances. At present only the short distance properties of QCD are tractable [2]. A new unconventional method must be devised to solve the low-energy behavior of QCD. In this paper we describe a systematic sequence of approxima-

Mesons and baryons 1977





PHYSICAL REVIEW D VOLUME 15, NUMBER 4 15 FEBRUARY 1977

# Strong-coupling calculations of the hadron spectrum of quantum chromodynamics

T. Banks,* S. Raby,* and L. Susskind*†
*Tel Aviv University, Ramat Aviv, Israel*

J. Kogut*‡
*Laboratory of Nuclear Studies, Cornell University, Ithaca, New York 14853*

D. R. T. Jones,§ P. N. Scharbach,§ and D. K. Sinclair‖
*Department of Theoretical Physics, University of Oxford, Oxford 0X1-3PQ, England*

(Received 13 August 1976)

We present calculations of the low-energy mass spectrum and matrix elements of quantum chromodynamics. We employ an isospin doublet of massless quarks and analyze the theory from the strong-coupling limit using a particularly simple lattice Hamiltonian. In the strong-coupling limit the vacuum state has exact local color symmetry, but spontaneously breaks those elements of chiral symmetry which are present in the lattice Hamiltonian. Expansions for masses ($\pi$, $\rho$, $\omega$, $\sigma$, $A_1$, $B$, $f$, and nucleon) and matrix elements ($g_A$) in the reciprocal coupling constant are analytically continued to the continuum limit using Padé approximants. The results are in surprisingly good agreement with experiment except for the pion mass. This single failure is traced to the lack of full chiral symmetry in the theory for large lattice spacing and the lack of significant spin-spin forces in low orders of strong-coupling perturbation theory. Higher-order calculations should resolve this problem, but a more realistic Hamiltonian suggested by renormalization-group analyses also looks promising.

## I. INTRODUCTION

Quantum chromodynamics[1] is a promising candidate for the theory of strong interactions. The theory consists of several flavors of colored quarks which interact with flavor-neutral colored Yang-Mills gluons in a locally color-gauge-invariant fashion. The short-distance properties of the theory are computable since the theory's invariant charge vanishes at short distances.[2] In addition, there are reasons to believe that the theory is strongly coupled at large distances in such a way that its low-energy spectrum consists of only color-singlet hadrons.[3] The hope is that the spectrum of these field-theoretic bound states

In this paper we couple an isodoublet of massless colored quarks to the Yang-Mills fields and calculate various meson and baryon masses and matrix elements. We choose to restrict ourselves to the SU(2) flavor group for several reasons. First, we are interested in the lowest-lying part of the hadron spectrum. Heavy quarks are not expected to be important here. In addition, the success of current-algebra sum rules and partial conservation of axial-vector current (PCAC) strongly suggest that chiral symmetry is spontaneously broken and the pion appears as a Goldstone boson of strong interactions. It remains an important challenge to theorists to see if this physical picture can be obtained explicitly from a

Zeroth order meson-nucleon mass ratios are all equal and have value

$$\frac{m^0_{meson}}{m^0_{nucleon}} = 1.25$$

The axial coupling is

$$g^0_A = 3.$$

Fourth order + pade gives

$$\frac{m_\rho}{m_N} = 0.822 \qquad (0.820)$$

$$\frac{m_\omega}{m_N} = 0.824 \qquad (0.834)$$

$$\frac{m_\sigma}{m_N} = .972 \qquad (0.8 - 1.1 \text{ broad})$$

$$\frac{m_B}{m_N} = 1.05 \qquad (1.32)$$

$$\frac{m_f}{m_N} = 1.17 \qquad (1.35)$$

$$\frac{m_{A_1}}{m_N} = 1.12 \qquad (1.17)$$

$$g_A = 1.81 \qquad (1.24)$$

$$\frac{m_\pi}{m_N} \approx .8 \qquad (\ 0\ )$$

?

Modern high precision Monte Carlo confirms the results and can accurately calculate the string tension.

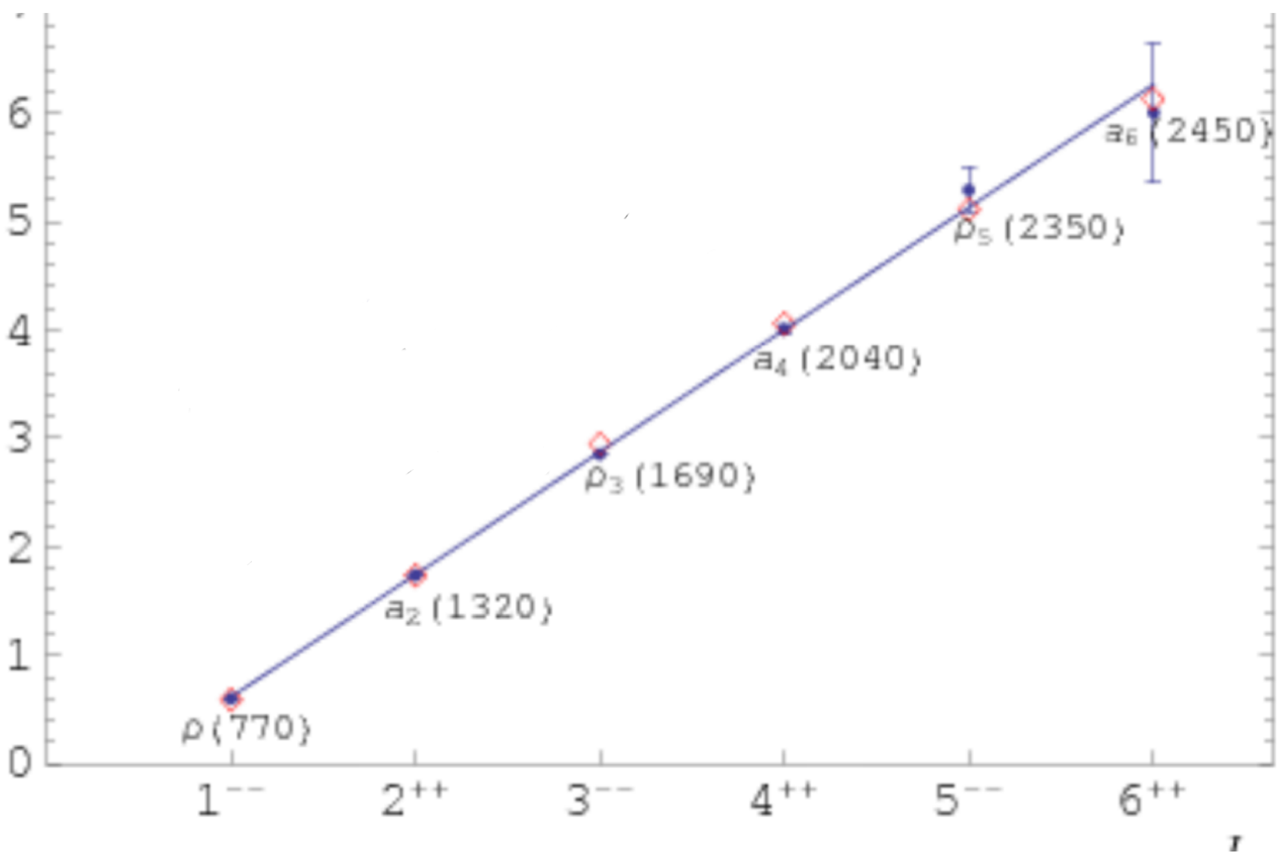
$$\boxed{\text{QCD really is Stringy.}}$$

But are hadrons stringy?

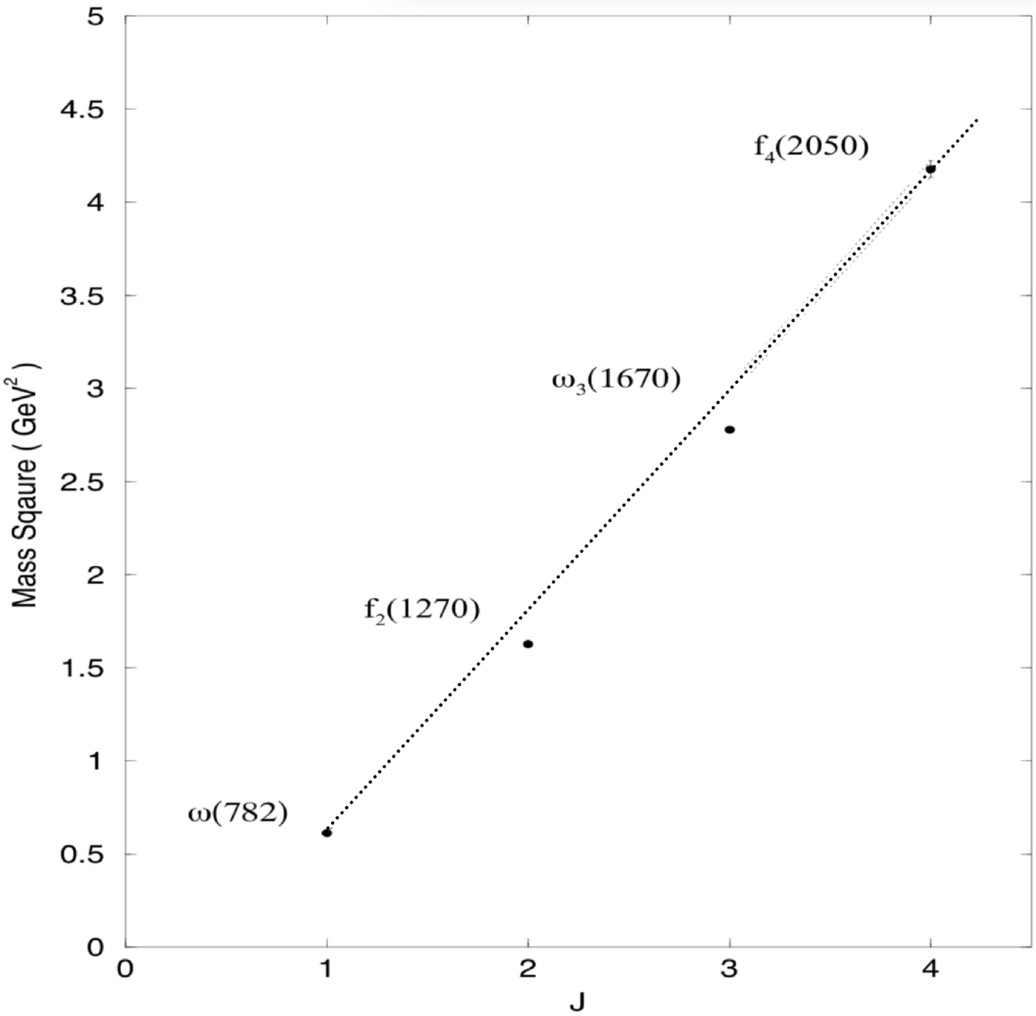
Experimental Confirmation – Hadrons are strings?

Linear Regge trajectories

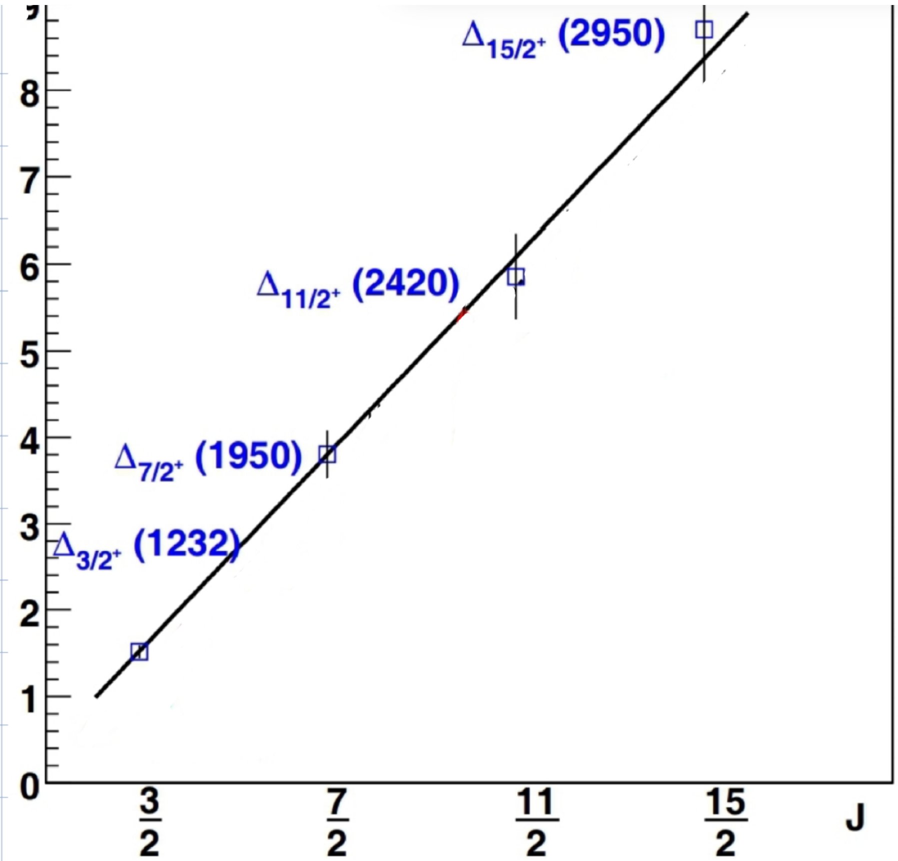
$\rho$ - trajectory



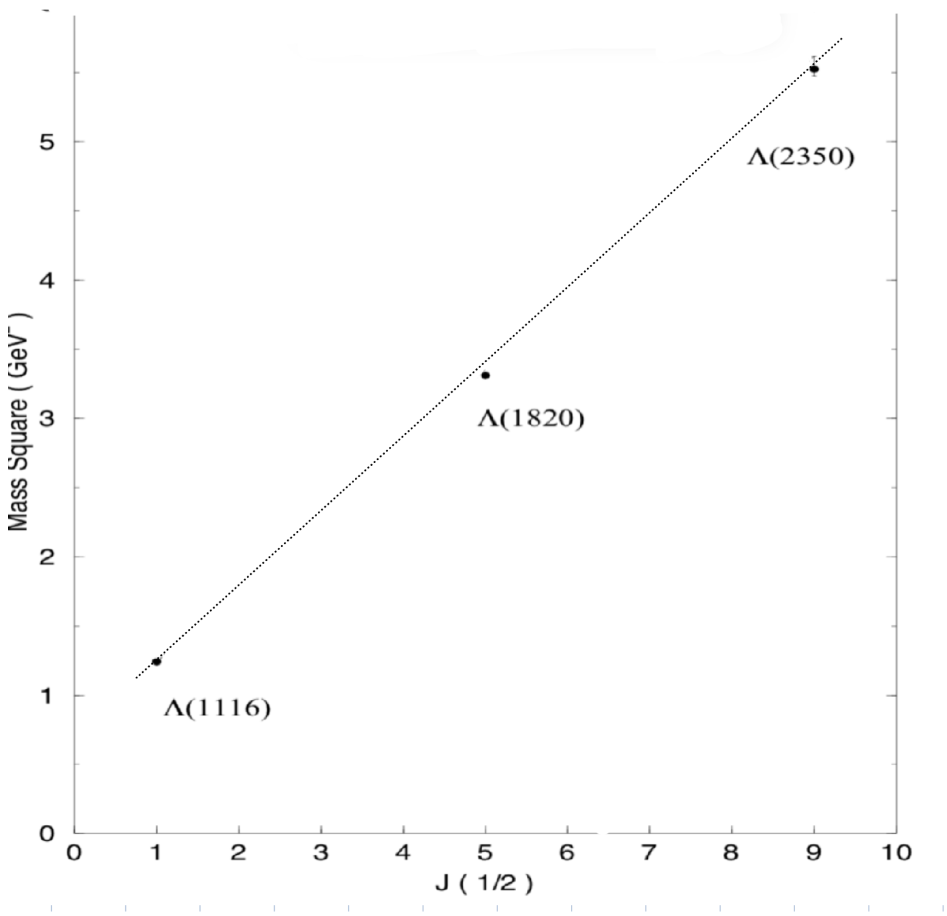
ω - trajectory



$\Delta\ ^3/_2$ (Bayon # = 1)



Strangeness 1 baryon (uds)




Daughter Trajectories ?

Ask me later

Pion jets

Ask me later

Hadrons are Strings.

# Magnetic properties of confining vacuum

Monopole condensation transition?

✓ Abelian L.G.T.

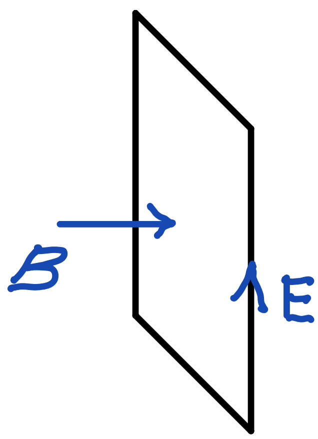
✓ supersymmetric versions of QCD

✗ $Z_2$ L.GT

✗ QCD

} magnetic Spaghetti

(Nielsen, Olesen 1979)




$$\Delta E \; \Delta B \geq \frac{\hbar}{2}$$

Nature Abhors a chromoelectric field $\quad E|0\rangle = 0$

A confining vacuum has wildly fluctuating Magnetic field. subject only to flux continuity

"Magnetic Spaghetti"

't Hooft large N and planar diagrams

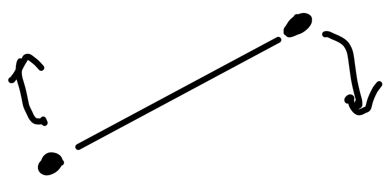
(1973)

fishnet
Nielsen Olesen

Large $N_c$
't Hooft

Where are the daughters?

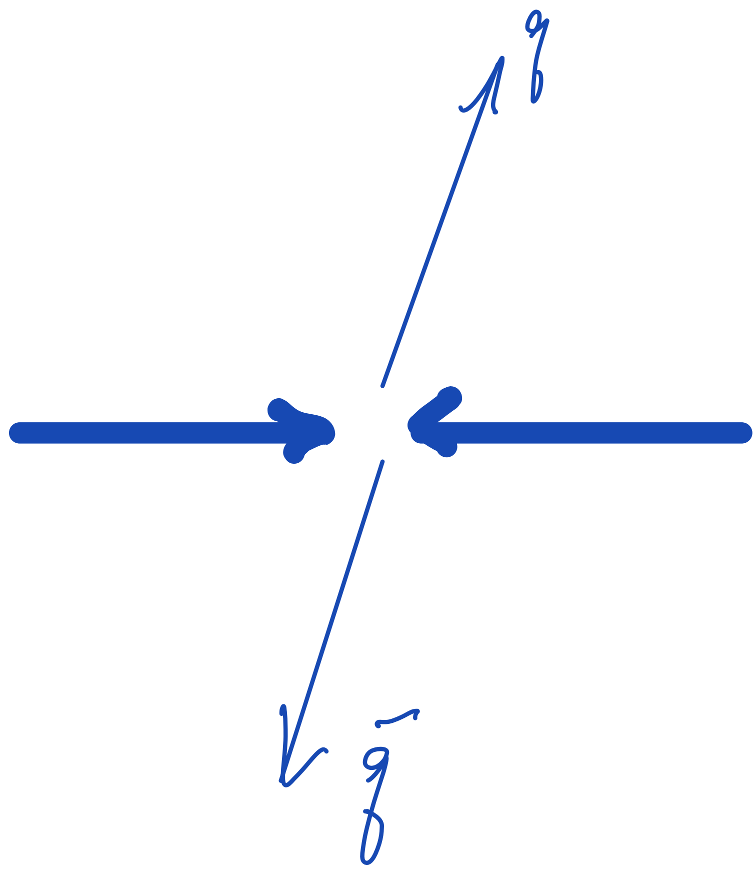
Leading trajectory

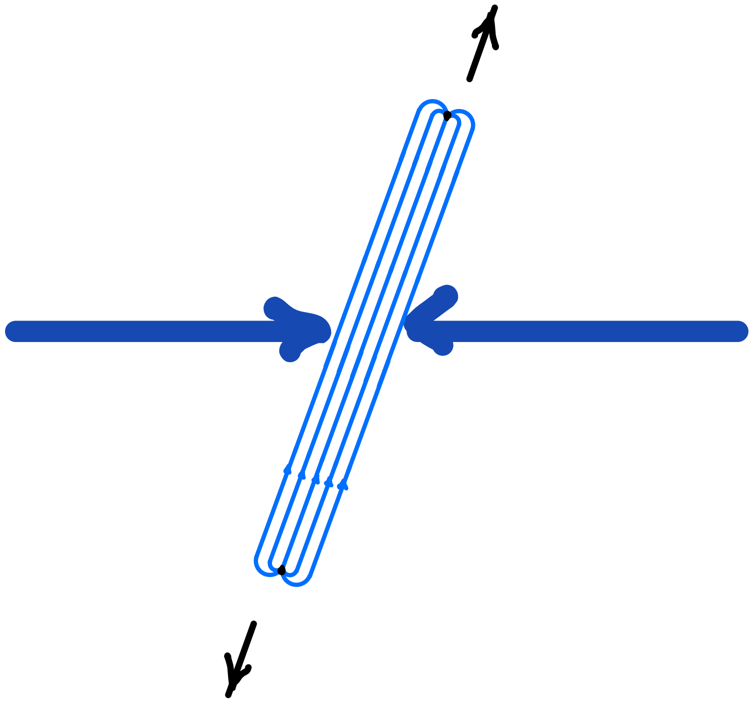


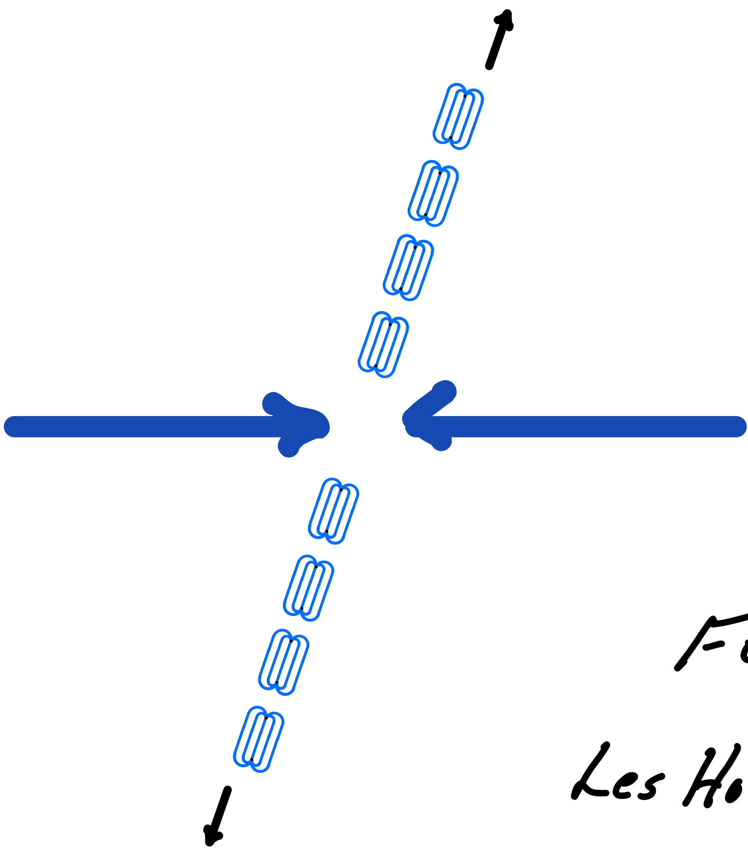
Sub leading

More crowded. Messy. Lot's of opportunity for "splitting."

# Jets







Feynman

Les Houches 1976

The confinement mechanism seems obvious seem simple and obvious today. It was neither. It's discovery played out over a period of about six years between 1969 and 1975. It did not discover itself. The principle players were (alphabetically)

Y. Nambu
H.B. Nielsen
L.S.
G. 't Hooft
K. G. Wilson