Tetraquarks and Other Exotics

Bob Jaffe[**]

(Ancient) History and Context[*]

q.v. Jean-Marc Richard

[**]1977 − 2021 ⇒ 44 years
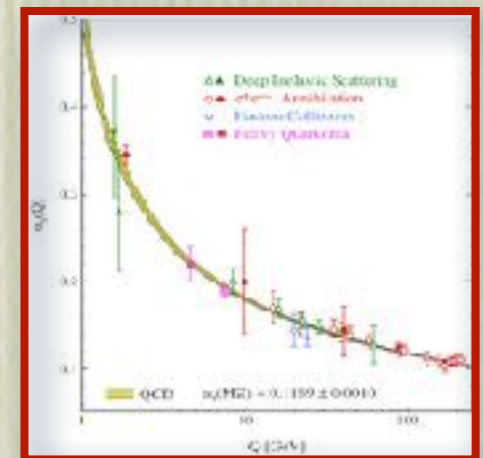
To the memory
of Gabriel Karl

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November 22, 2021

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Why QCD?

QCD – uniquely — complete, consistent, and correct

- 99.97% of the visible mass of the Universe

- Protons and neutrons: massive hadrons from (almost) massless quarks and gluons.

√ QCD at asymptotically short distances (collider physics)

√ QCD in the heavy quark sector

√ Numerical QCD on Euclidean lattices

X QCD in the light quark sector: no physical, heuristic, first principles predictive description of light-quark hadrons!

- No parameters! $\alpha_s = \alpha_s(Q^2)$

- Light hadrons form where QCD is strong.

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Why multiquark hadrons? (Again *q.v.* J.-M. Richard)

- **Are confining forces in QCD saturated at QQQ and $\bar{Q}Q$?**

  Is light-hadron QCD merely extended meson-nucleon chiral effective field theory or are multiquark hadrons required?

  Age old question: Why are there no exotics among the light hadrons?

- **Chromodynamic correlations**

  → Most attractive channel for QCD! $\Rightarrow$ Scalar, color singlet $Q\bar{Q}$

      Dynamical chiral symmetry breaking

  → Second most attractive channel? "Good" diquark correlation!

      $\Rightarrow$ absence of exotics among the light hadrons!

      $\Rightarrow$ possibly light tetraquark scalar mesons

      $\Rightarrow$ likely narrow/stable Tcc and Tbb states in the heavy quark sector

Outline

- Multiquark hadrons ⟺ exotics

- Earliest history

- False alarms

- Diquarks explain the absence of light exotics

- Diquarks predict light scalar mesons

- Tetraquarks or meson-molecules – a look at large N_c

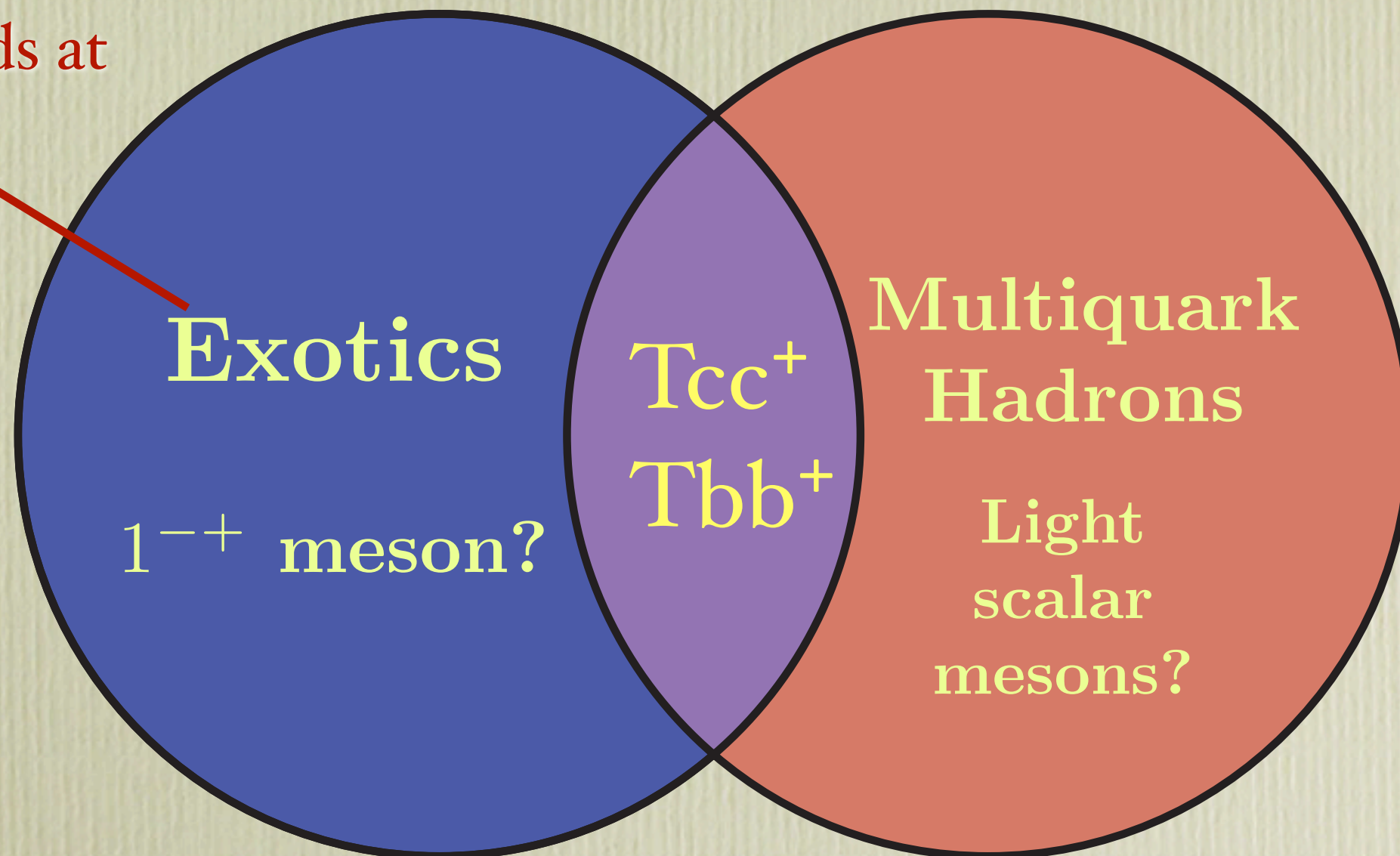- Light diquarks in the heavy quark sector

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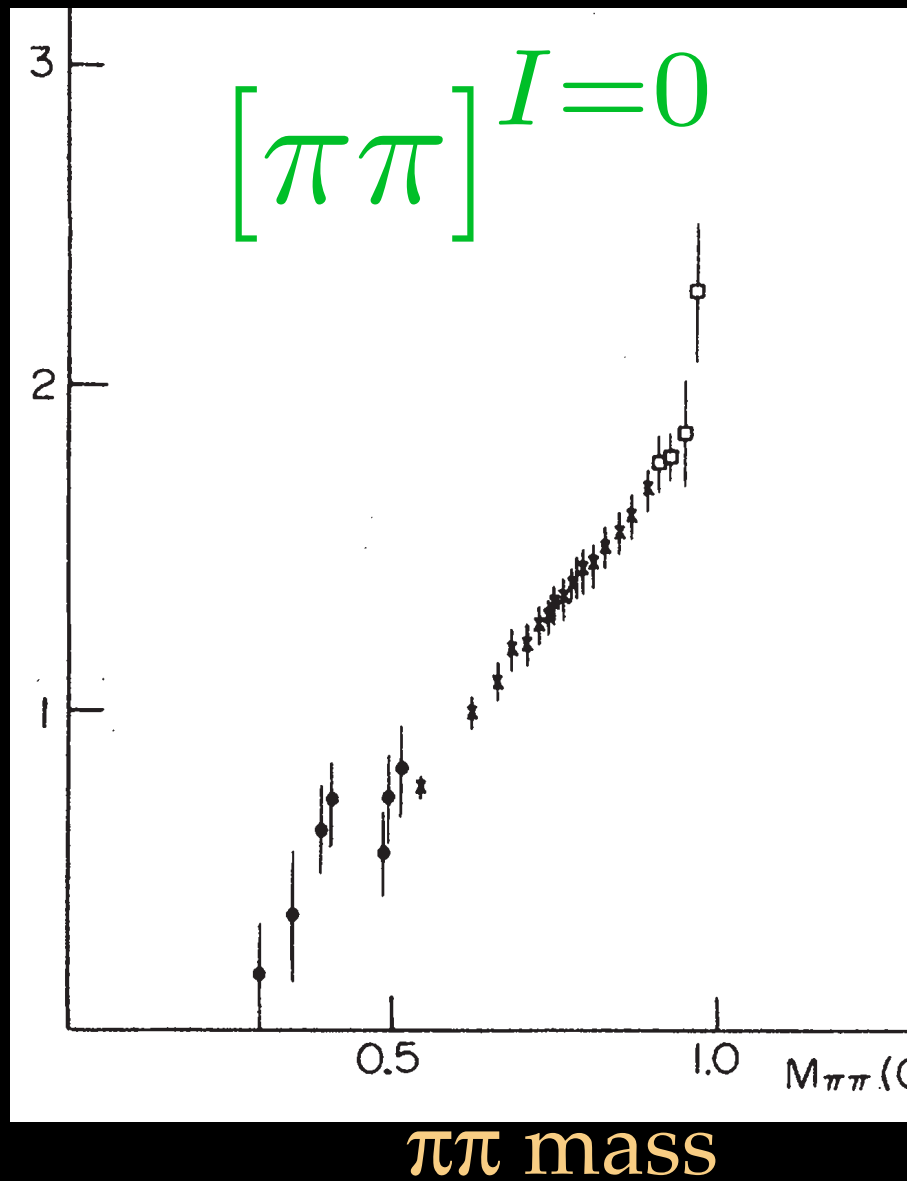Workshop: Double charm tetraquark and other exotics

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"Exotics" − Hadrons with quantum numbers not available to QQQ or $\overline{Q}Q$
"Multiquark hadrons" − Hadrons with "valence" quark content beyond QQQ or $\overline{Q}Q$

Eg. Hybrids at JLab

Exotics

1^{-+} meson?

Tcc$^+$
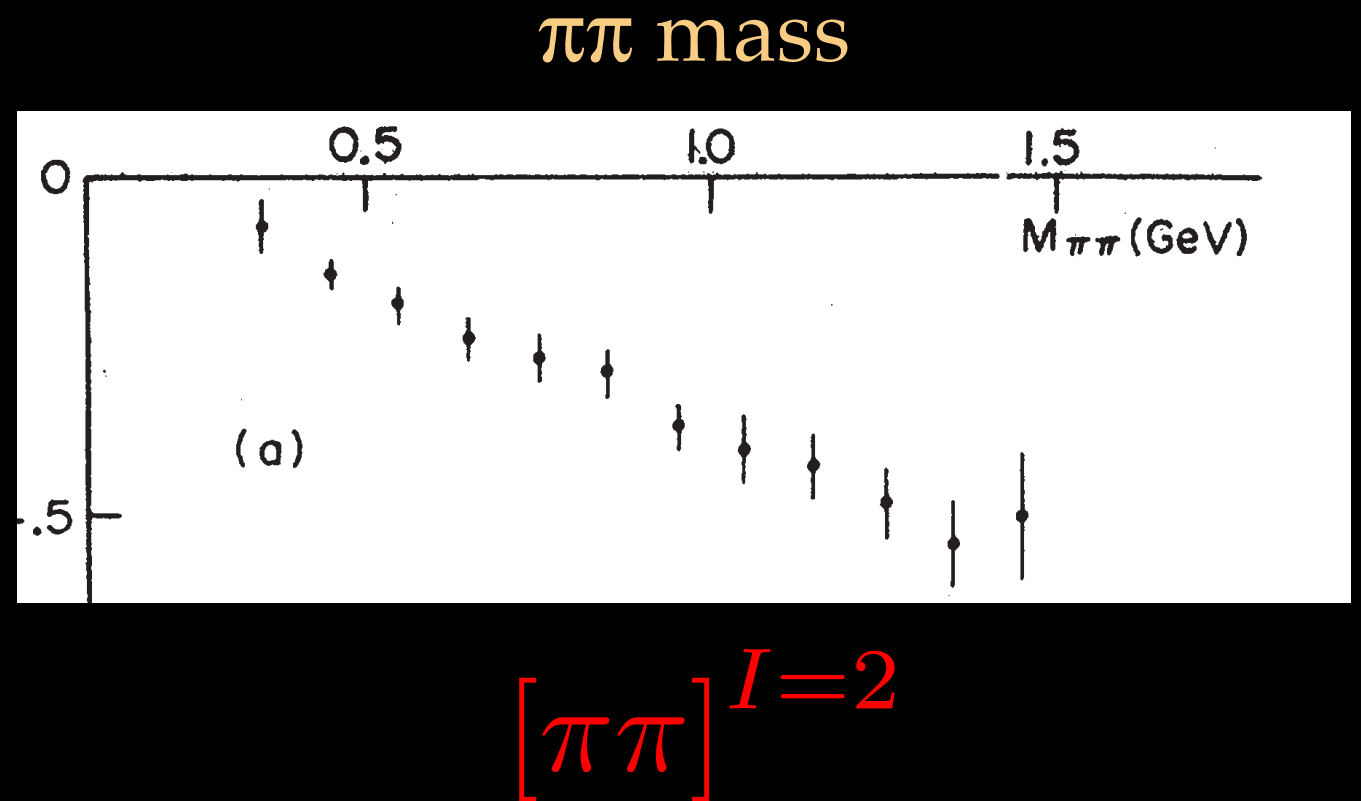**Tbb$^+$**

Multiquark Hadrons

Light scalar mesons?

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Prehistory: absence of exotics was noted long before quarks —

$[\pi\pi]^{I=0}$

I=0 phase shift

$\pi\pi$ mass

$\pi\pi$ mass

I=2 phase shift

$[\pi\pi]^{I=2}$

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1964: In the beginning there was Gell-Mann...

A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

If we assume that the strong interactions of baryons and mesons are correctly described in terms of the broken "eightfold way" [1-3], we are tempted to look for some fundamental explanation of the situation. A highly promised approach is the purely dynamical "boo trap" model for all the strongly interacting particles within which one may try to derive isotopic spin and strangeness conservation and broken eightfold symmetry from self-consistency alone [4]. Of course, with only strong interactions, the orientation of the asymmetry in the unitary space cannot be specified; one hopes that in some way the selection of specific components of the F-spin by electromagnetism and the weak interactions determines the choice of isotopic spin and hypercharge directions.

Even if we consider the scattering amplitudes of strongly interacting particles on the mass shell only and treat the matrix elements of the weak, electromagnetic, and gravitational interactions by means of dispersion theory, there are still meaningful and important questions regarding the algebraic properties of these interactions that have so far been dis-

ber $n_t - n_{\bar{t}}$ would be zero for all known baryons and mesons. The most interesting example of such a model is one in which the triplet has spin $\frac{1}{2}$ and $z = -1$, so that the four particles d^-, s^-, u^0 and b^0 exhibit a parallel with the leptons.

A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" [6] q and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations $(q\,q\,q)$, $(q\,q\,q\,q\,\bar{q})$, etc., while mesons are made out of $(q\,\bar{q})$, $(q\,q\,\bar{q}\,\bar{q})$, etc. It is assuming that the lowest baryon configuration $(q\,q\,q)$ gives just the representations **1**, **8**, and **10** that have been observed, while the lowest meson configuration $(q\,\bar{q})$ similarly gives just **1** and **8**.
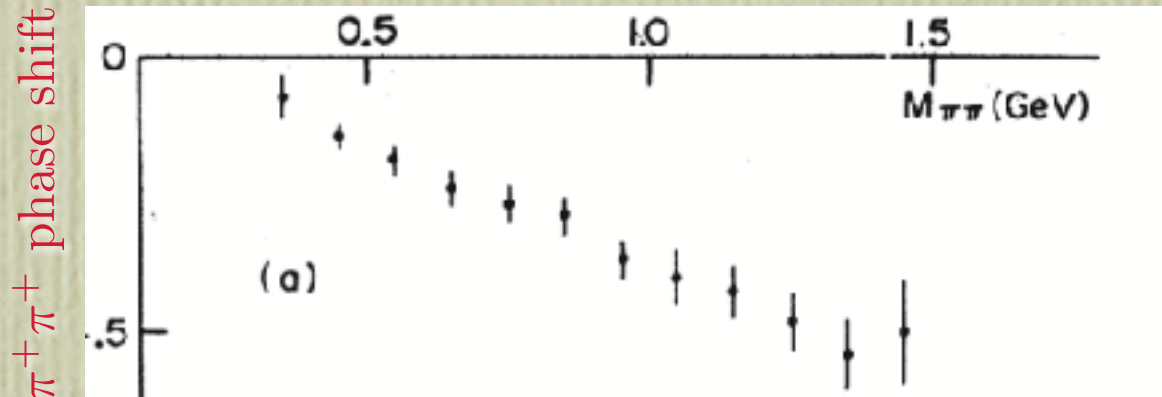
A formal mathematical model based on field theory can be built up for the quarks exactly as for p, n, Λ in the old Sakata model, for example [3]

Assumed absence of light exotic hadrons — origins?

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More intense searches for exotics – 1960's — 1970's

$uud\bar{d}\bar{d}$

No $\pi^+\pi^+$ resonance

$\pi^+\pi^+$ phase shift

$uudd\bar{s}$

No pK^0/nK^+ resonance

$uud\bar{s}$

No π^+K^+ resonance

π^+K^+ phase shift

Argand amplitude
full circle $\rightarrow$ resonance

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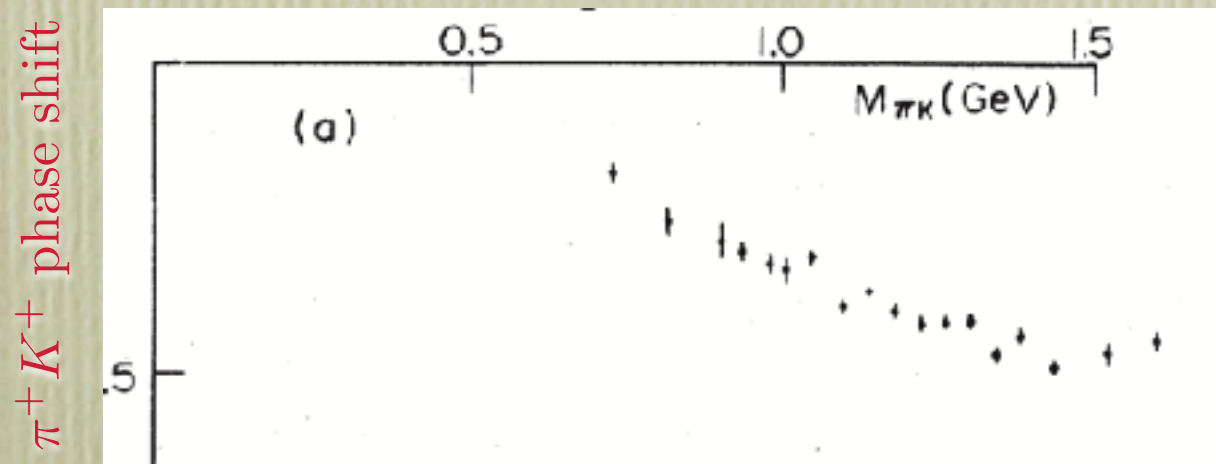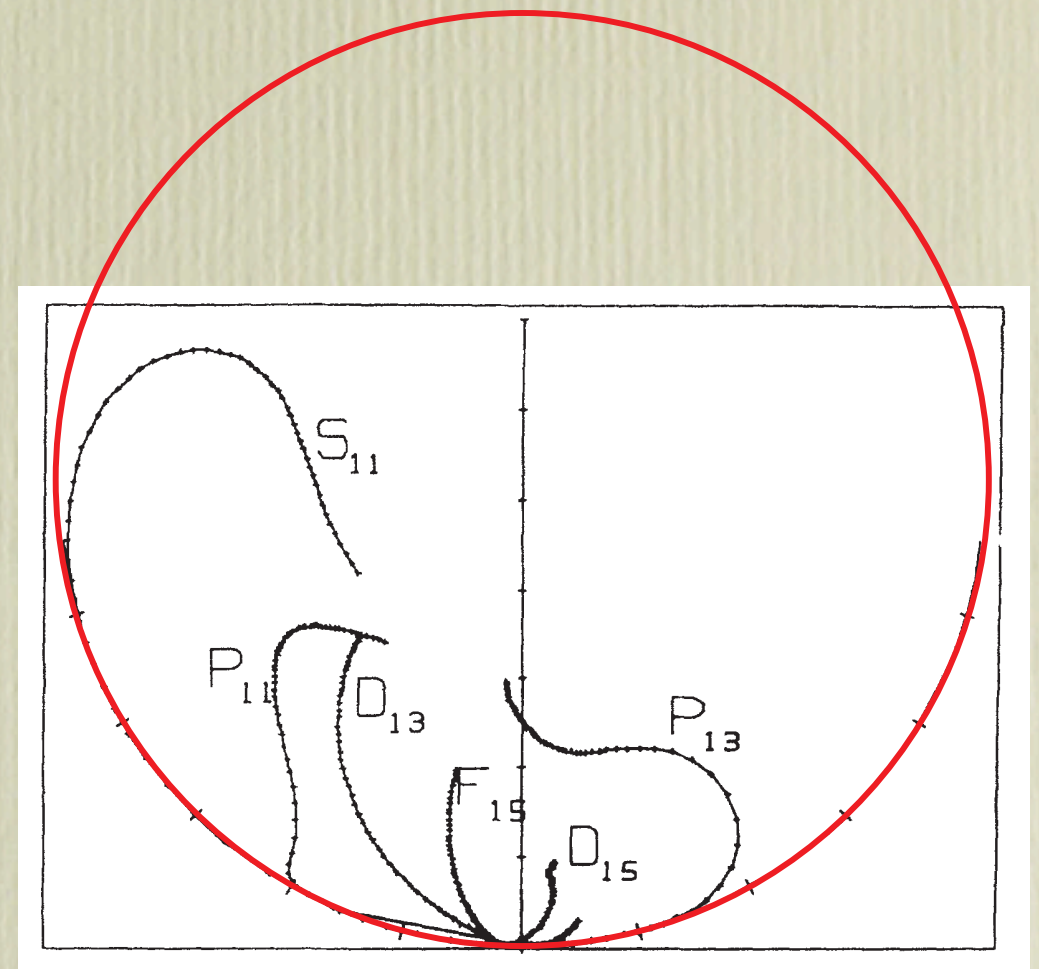
1968: Rosner & Harari   QCD + duality $\Rightarrow \bar{Q}\bar{Q}QQ$

GRAPHICAL FORM OF DUALITY*

Jonathan L. Rosner†
Physics Department, Tel-Aviv University, Ramat Aviv, Israel
(Received 3 February 1969)

We present a simple visual form of duality. It can be derived from SU(3) couplings for trajectories and the absence of resonances in most exotic channels, and has many physical implications.

$Q^2\bar{Q}^2$ "dual to"
ordinary meson exchange

Meson Exchange

Meson Resonance

Baryon Resonance

Exotic Resonance

VOLUME 21, NUMBER 13   PHYSICAL REVIEW LETTERS   23 SEPTEMBER 1968

POSSIBILITY OF BARYON-ANTIBARYON ENHANCEMENTS WITH UNUSUAL QUANTUM NUMBERS

Jonathan L. Rosner
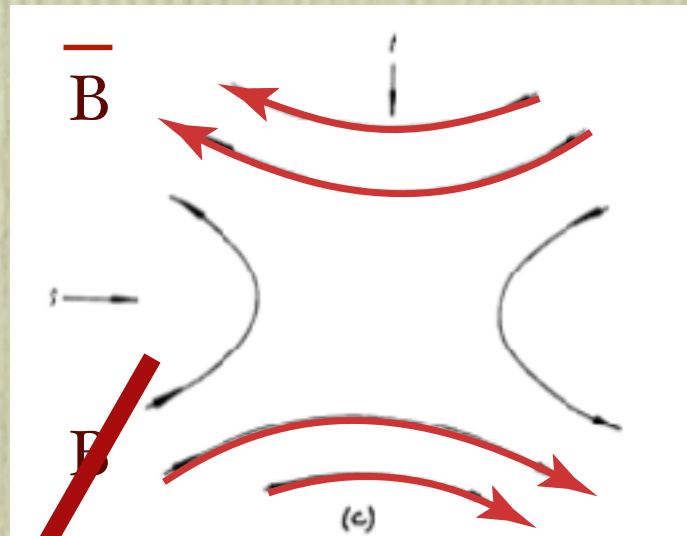Physics Department, Tel-Aviv University, Tel-Aviv, Israel
(Received 15 August 1968)
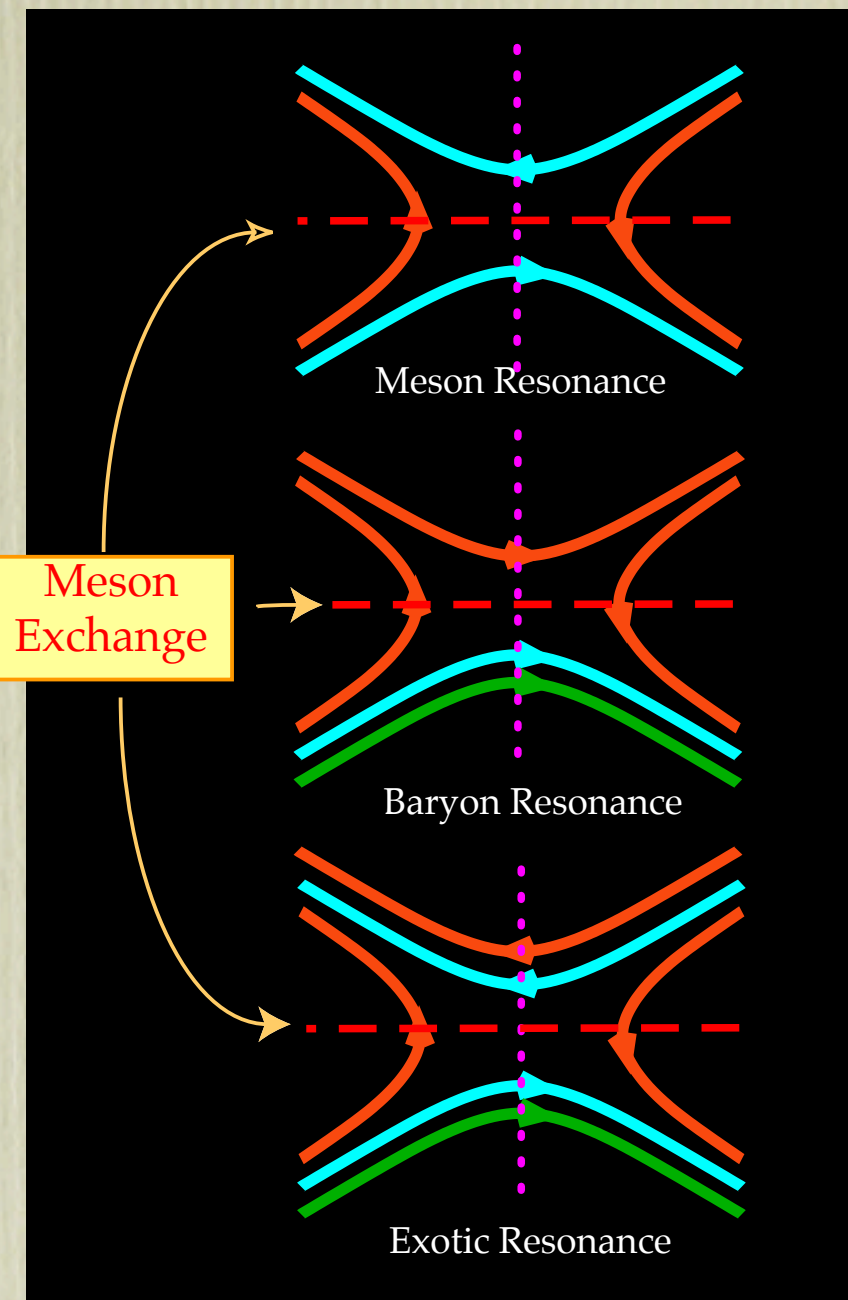
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Multiquark/exotic states in baryon-antibaryon annihilation ?? — circa 1974–1980

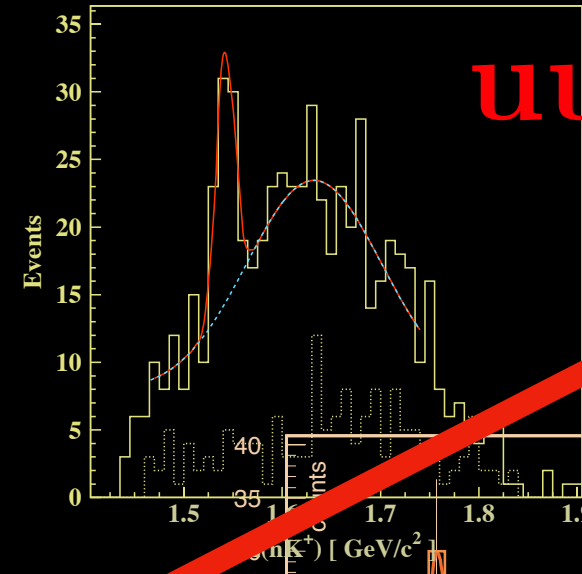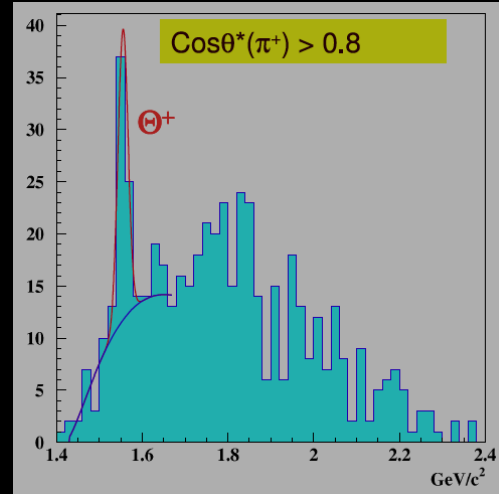$\overline{B}$

$Q^2\bar{Q}^2$ "dual to" ordinary meson exchange

S(1936), T(2200), U(2400), M(2020), ...

Example: gamma spectrum observed in proton-antiproton annihilation at rest

They all failed to be confirmed in subsequent experiments
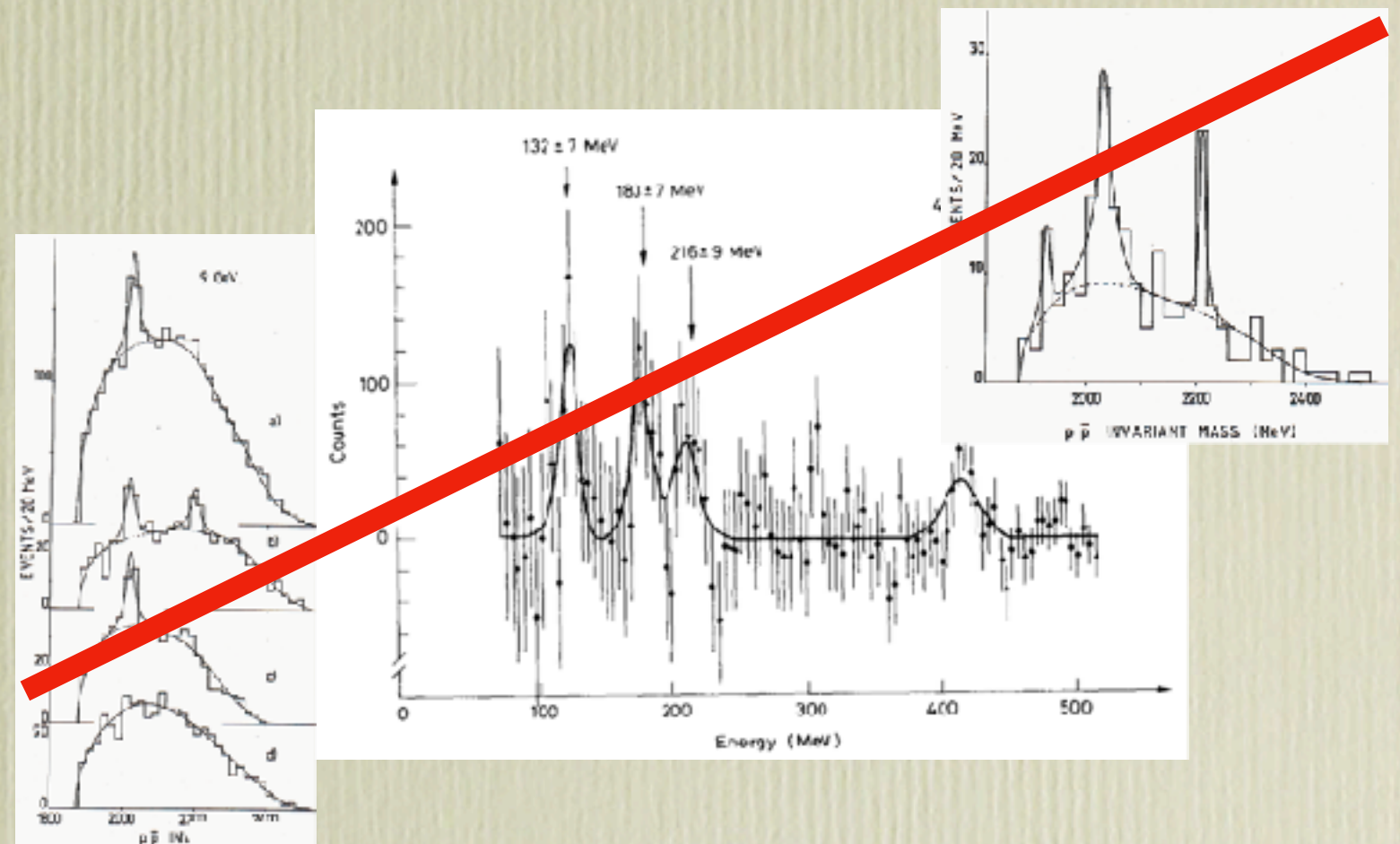
Probably broad states lost in the multi-meson continuum?

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The Θ^+ baryon in K^+n scattering, *etc.* 2003-2005
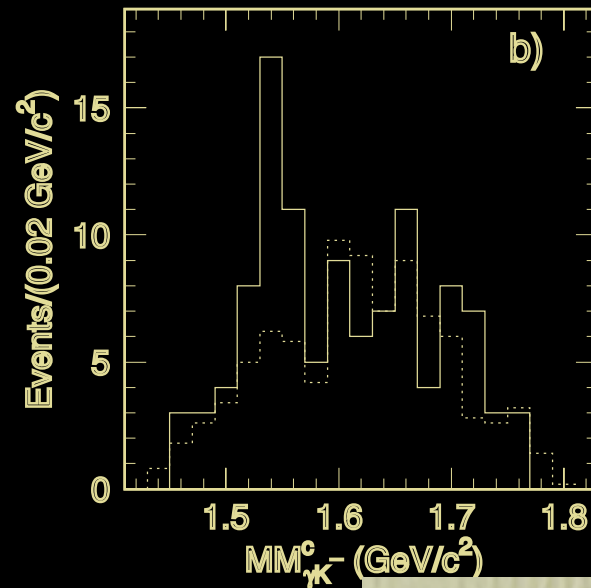
uudd$\bar{s}$?

Failed to be confirmed by later, high statistics experiments (!)
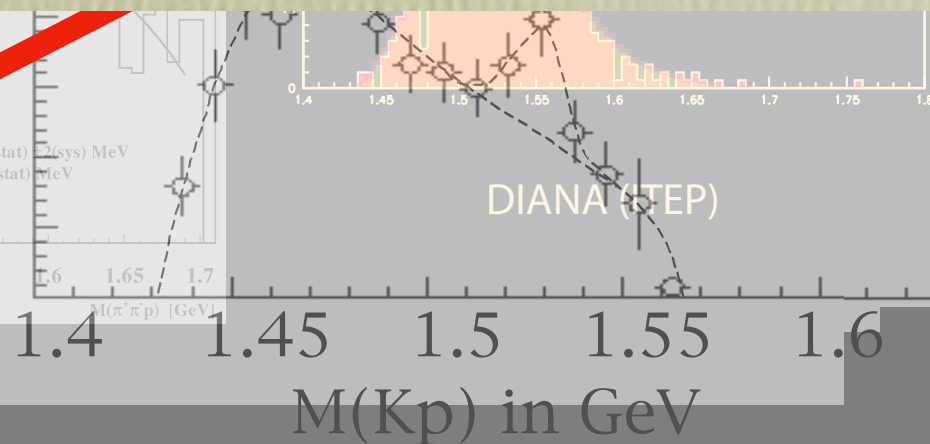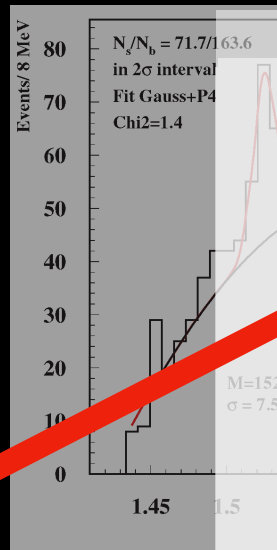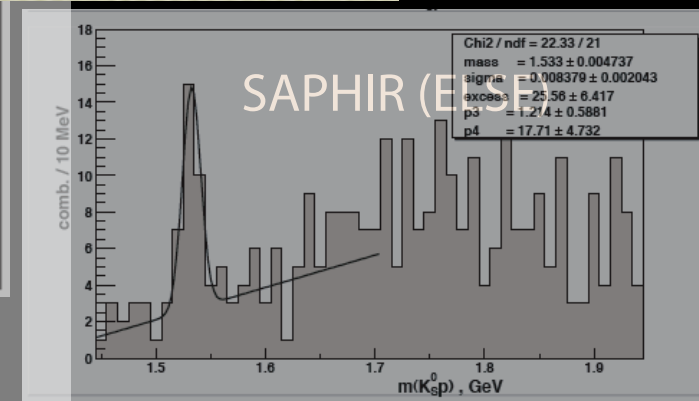
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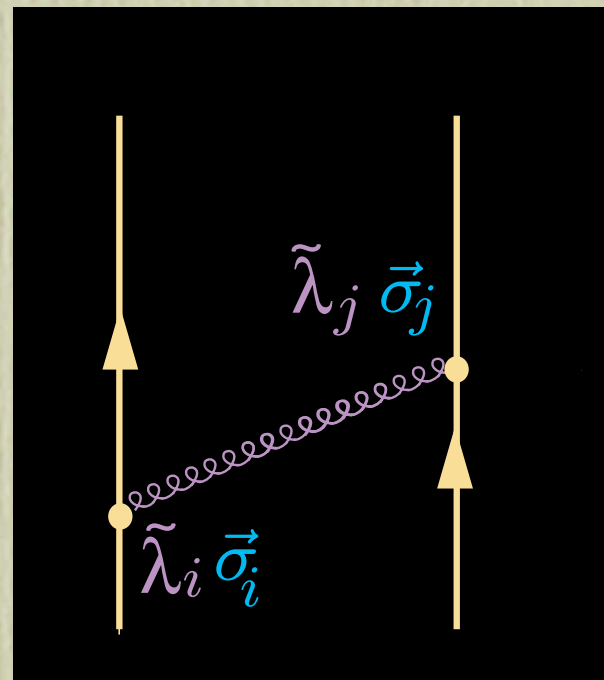Workshop: Double charm tetraquark and other exotics

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Meanwhile — (1977 - today)
Diquarks: strong correlations in QCD

Chiral symmetry breaking

$$Q\overline{Q}\,^{1_f}\,1_c\,0_s$$

$$QQ\,^{\overline{3}_f}\,\overline{3}_c\,0_s$$

"Good diquark correlation"

$[\overline{su}]$ $[\overline{ds}]$ $[\overline{ud}]$

$[ud]$ $[ds]$ $[su]$
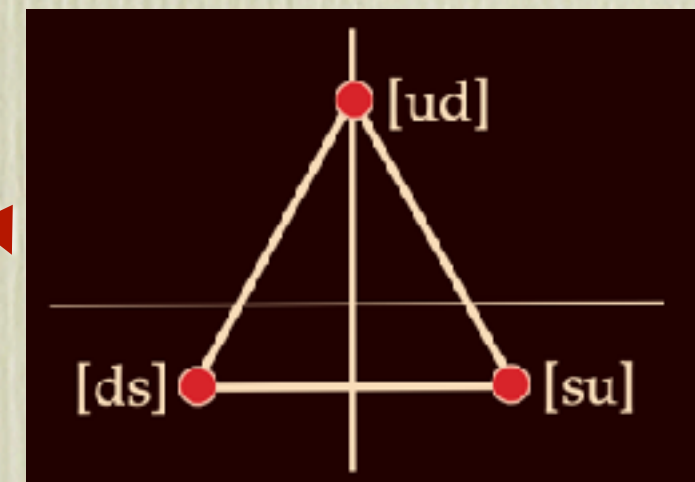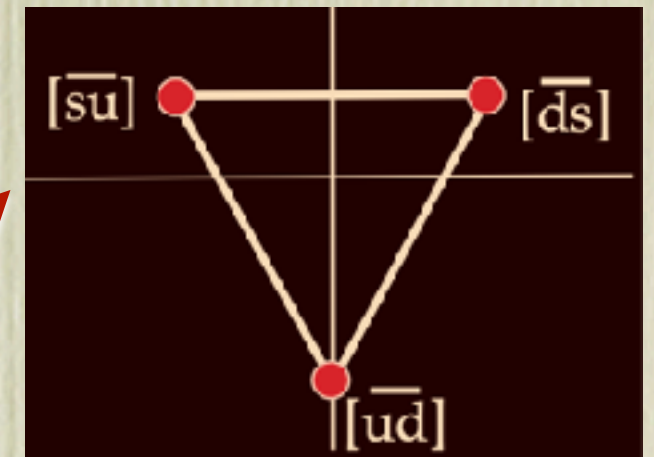
"Good" diquark dominance
 $\Rightarrow$ no light-quark exotic mesons
 $\Rightarrow$ "crypto-exotic" tetraquarks?

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"Good" diquark correlation explains absence of exotics

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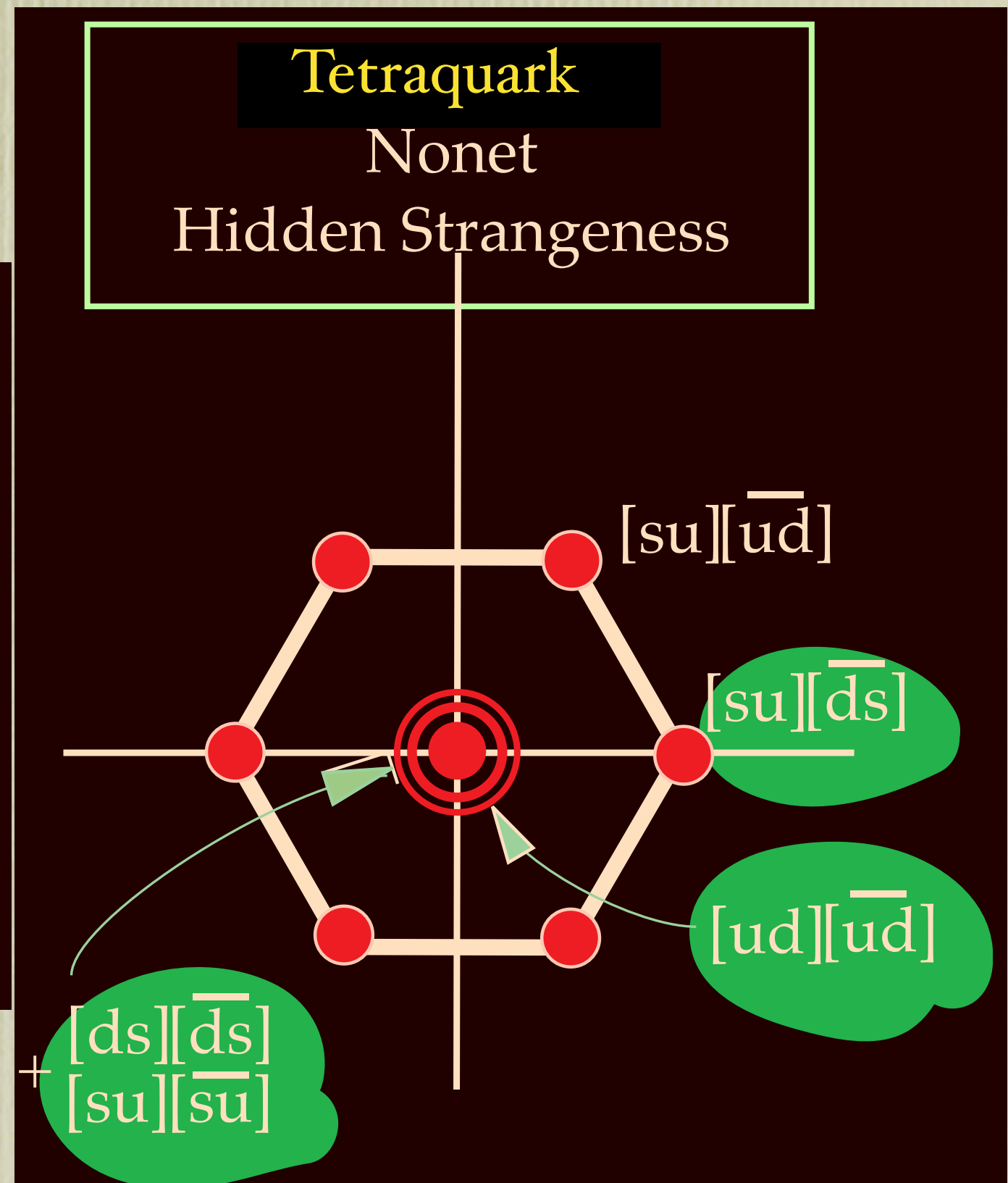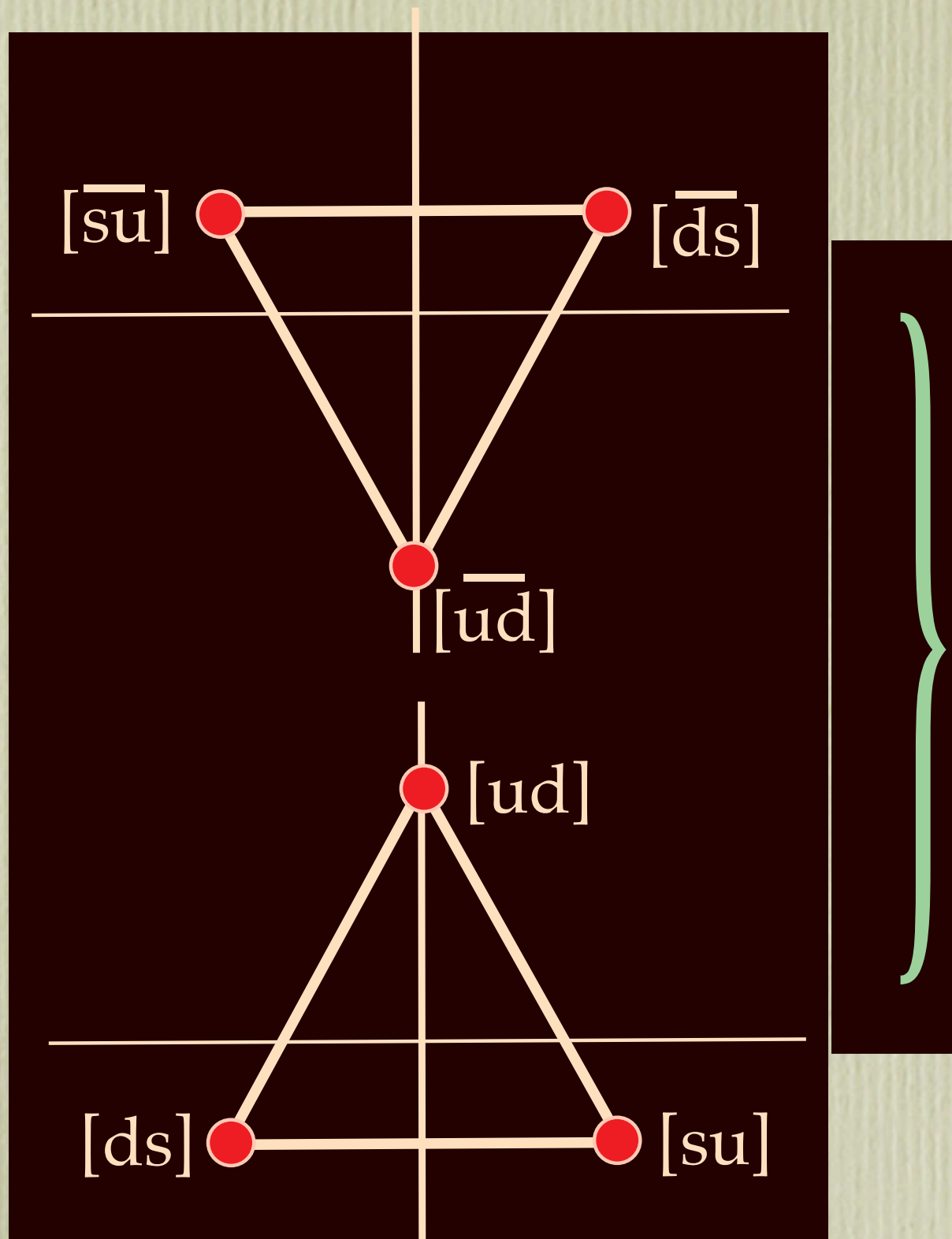
Tetraquark Scalar Nonet (RLJ 1977)
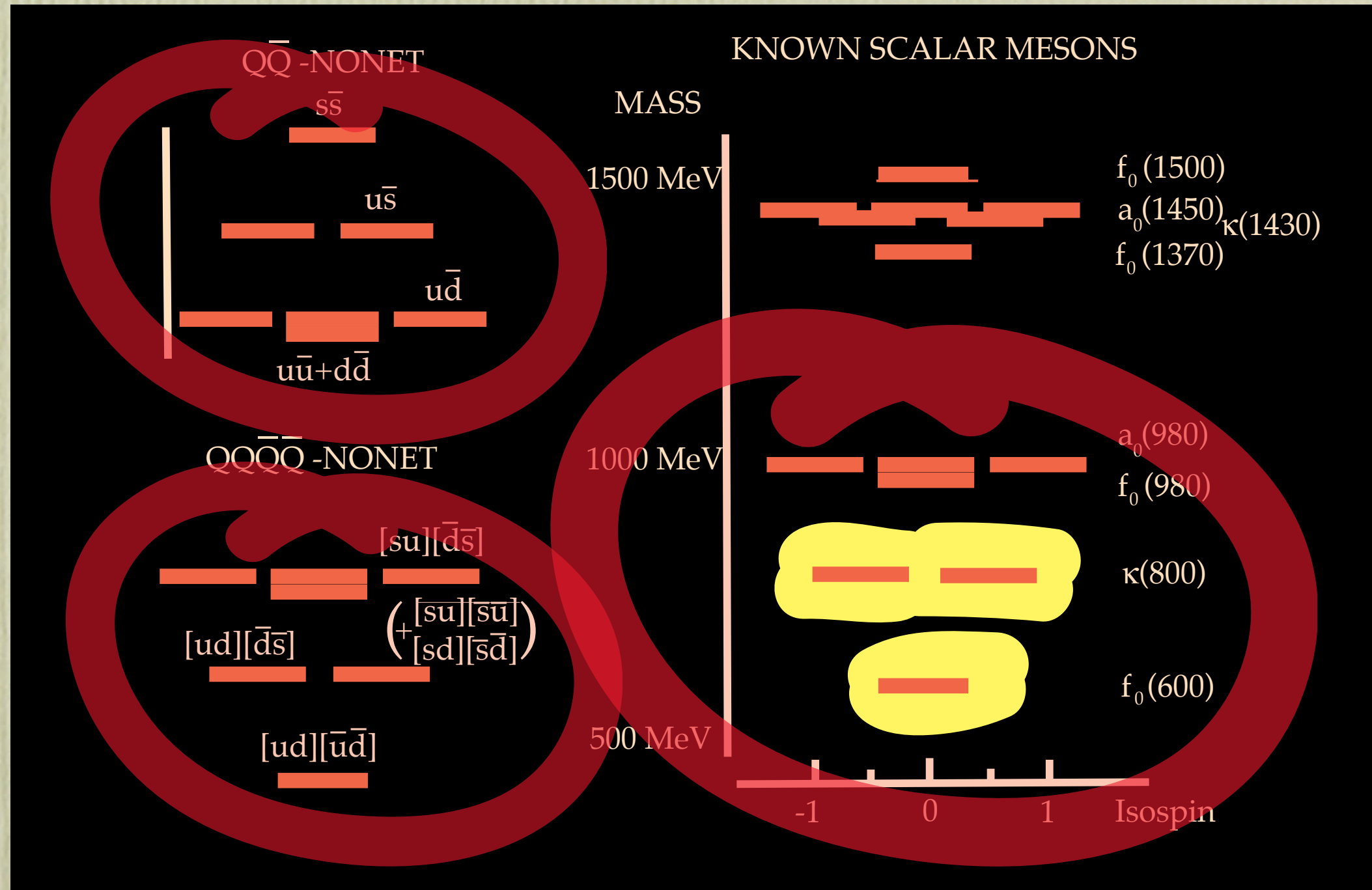
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The Scalar Nonet:

Same spectral regularities stimulated Nathan Isgur and his students to examine a possible meson-meson molecule origin for light scalar nonet. Based on Isgur – Karl quark model

Fundamental multiquark ⇔ molecule ambiguity that has plagued exotic/multiquark spectroscopy ever since

$$[Q^2] - [\bar{Q}^2] \quad \text{or} \quad [Q\bar{Q}] - [Q\bar{Q}]$$

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$[Q^2] - [\bar{Q}^2]$ or $[Q\bar{Q}] - [Q\bar{Q}]$?

- Lots of evidence of diquark correlations elsewhere in hadron spectrum and interactions

  RLJ: https://arxiv.org/abs/hep-ph/0409065

- Hadronic molecule and multiquark ambiguities:
  − Any bound state, no matter what the nature of the effects that bind it, becomes molecular as the binding energy goes to zero (at threshold)

  RLJ: Nucl. Phys. **A 804** (2008) 25-47

- Power counting in the Large N_c limit suggests that meson-meson molecules may in fact be bound by chromodynamic (eg. diquark) interactions:
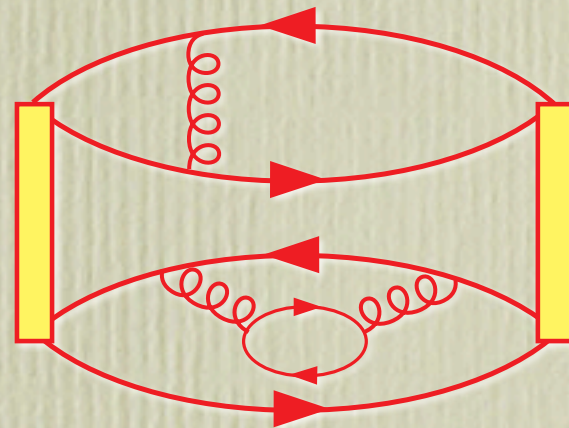
  RLJ: Nucl. Phys. **A 804** (2008) 25-47

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The $Q^2\bar{Q}^2$ system at large N_c

QCD interactions within a meson survive at large N_c

$$\mathcal{O}(1) \text{ as } N_c \to \infty$$

$$\frac{1}{N_c}^2 \left[\frac{1}{\sqrt{N_c}}\right]^4 \xrightarrow{N_c^4} \boxed{1}$$
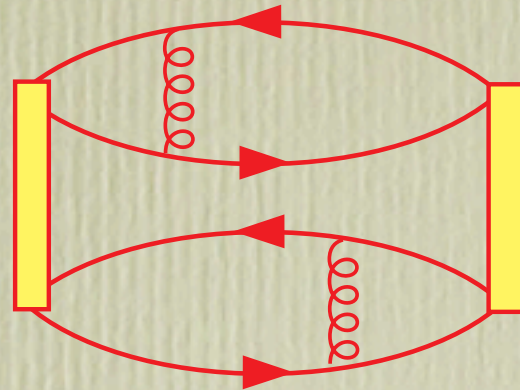
Each meson becomes a pure quark-antiquark state since quark loops are suppressed as $N_c \to \infty$

$$\mathcal{O}(1/N_c) \text{ as } N_c \to \infty$$

$$\left[\frac{1}{N_c}\right]^2 \left[\frac{1}{\sqrt{N_c}}\right]^6 \xrightarrow{N_c^4} \boxed{\frac{1}{N_c}}$$

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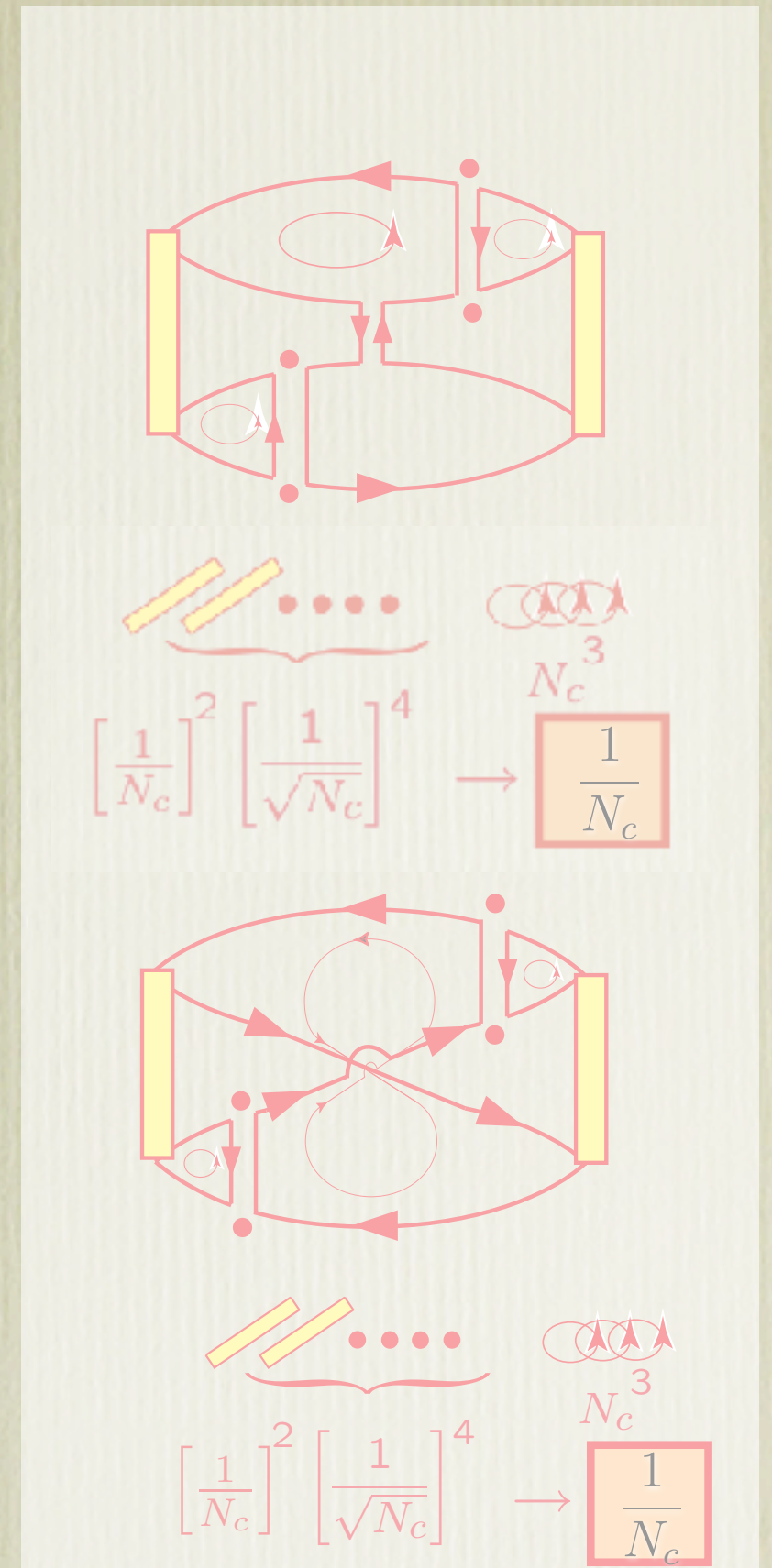
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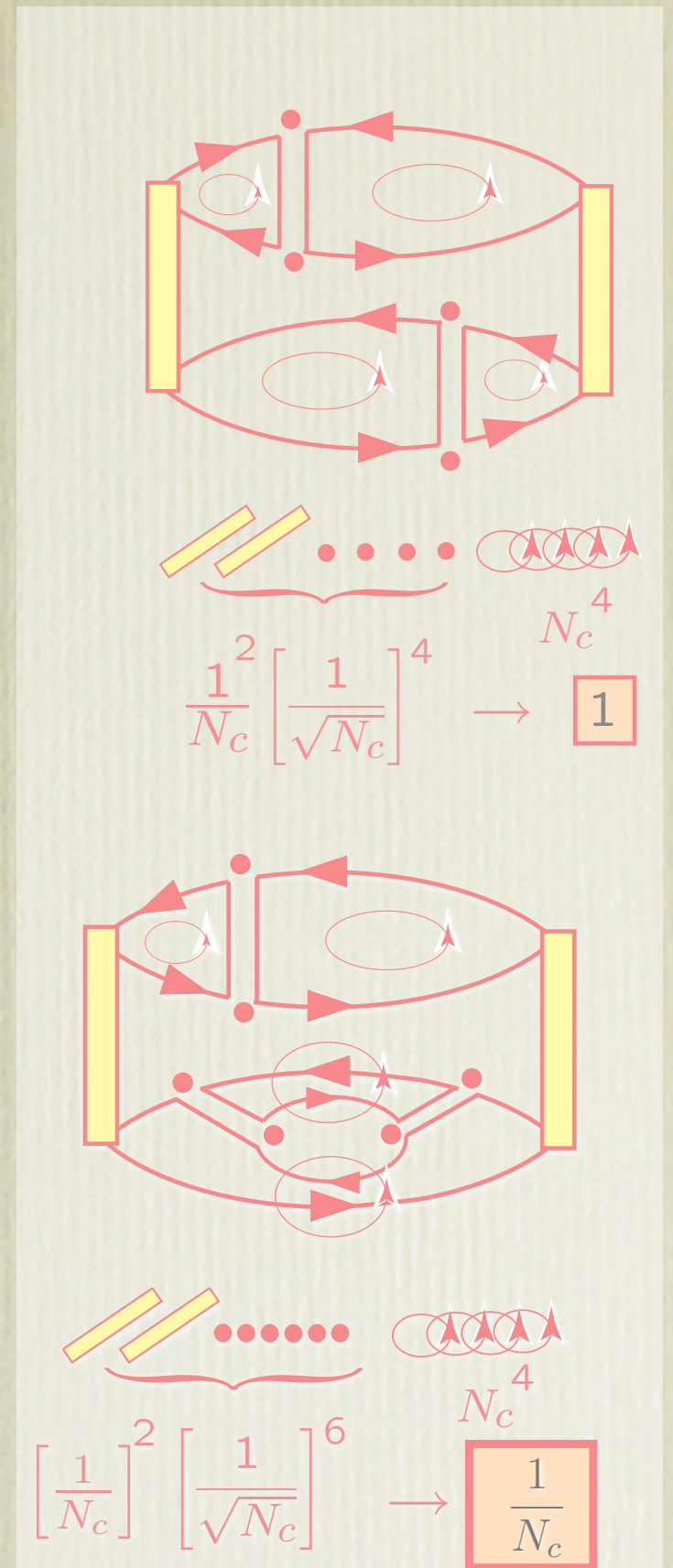
Residual MM-interaction at large N_c?

1. Quark − antiquark (meson) exchange, dual to s-channel meson resonances

$$\mathcal{O}(1/N_c) \text{ as } N_c \to \infty$$
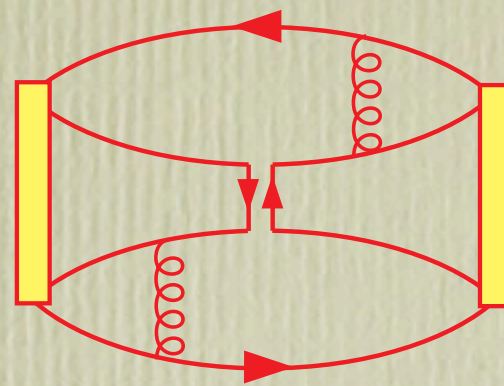
$1/N_c$

Same, dominant order in N_c
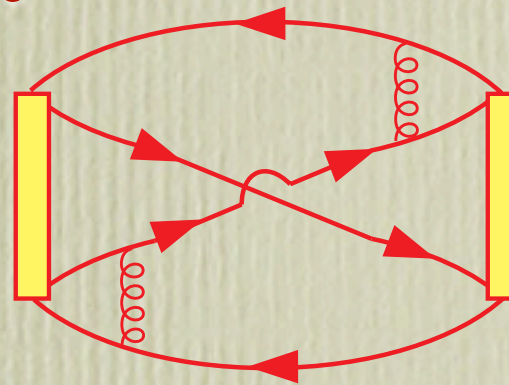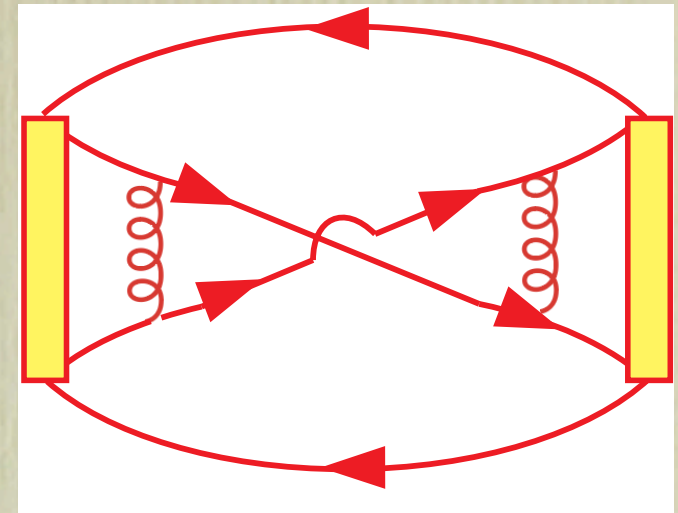
2. But also (non-planar) quark exchange off resonance Distinct from t-channel meson exchange

$$\mathcal{O}(1/N_c) \text{ as } N_c \to \infty$$

$1/N_c$

$$\left[\frac{1}{N_c}\right]^2 \left[\frac{1}{\sqrt{N_c}}\right]^4 \rightarrow \boxed{\frac{1}{N_c}}$$

N_c^3

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Quark exchange is the dominant force
between mesons away from s-channel
meson resonances at large N_c

Implications

- Quark exchange mixes color octet components into the $Q\bar{Q}$ wave functions, so the force is fundamentally chromodynamic, and dominated (at lowest order) by diquark correlations

- Range of the force ⇔ hadron overlap, of order 1 fermi.

- Attractive, repulsive, capable of generating bound/virtual states .

- No coupling to confined channels, so the interactions are "potential-like". Non-relativistic analog would be simply the Schrödinger equation with an open channel potential.

- In short: Qualitatively, may generate meson-meson enhancements/molecules bound by diquark correlations at large N_c

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Present day: Enter heavy quark exotics

- **Heavy diquark – light anti-diquark states:**

$$[\mathbf{HH}]^{\bar{\mathbf{3}}_c}[\bar{\mathbf{u}}\bar{\mathbf{d}}]^{\mathbf{3}_c\,\mathbf{3}_f\,\mathbf{0}_s}$$

- **Today T_{cc}^+ Tetraquark or molecular DD^* bound state?**

$$[\mathbf{cc}]^{\bar{\mathbf{3}}_c}[\bar{\mathbf{u}}\bar{\mathbf{d}}]^{\mathbf{3}_c\,\mathbf{3}_f\,\mathbf{0}_s} \quad \text{or} \quad D^0 D^{*+} \ \text{molecule}$$

- **Tomorrow! T_{bb}^+ Tetraquark predicted well below BB^* theshold?**

$$[\mathbf{bb}]^{\bar{\mathbf{3}}_c}[\bar{\mathbf{u}}\bar{\mathbf{d}}]^{\mathbf{3}_c\,\mathbf{3}_f\,\mathbf{0}_s} \text{stable hadron!?}$$

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THANK YOU

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