Thoughts on the nature of hadrons

- Great to be here on the eve of a new era in hadron physics
- The light quark sector of QCD: a perfect problem
- Ordinary and extraordinary hadrons guided by large N_c
- Full-disclosure: not new, but perhaps not well-known

Thoughts on the nature of hadrons

- Great to be here on the eve of a new era in hadron physics
- The light quark sector of QCD: a perfect problem
- Ordinary and extraordinary hadrons guided by large N_c
- Full-disclosure: not new, but perhaps not well-known

RLJ hep-ph/0701038 AIP Conf. Proc. **964** (2007) 1-13.

And more recently:

- Weinberg, PRL **110**, 261601 (2013)
- Knecht & Peris, PRD **88** 036016 (2013)
- Cohen, Llanes-Estrada, Pelaez, & Ruiz de Elvira, PRD **90** 036003 (2014)

Light Quark QCD

$$\mathcal{L} = -\frac{1}{4}\mathrm{Tr}\, F^{\mu\nu}F_{\mu\nu} + \bar{q}\left(i\gamma_\mu D^\mu - m\right)q$$

- QCD with massless quarks: zero parameter, strongly coupled, non-Abelian gauge theory.
- Important flavor (esp. chiral) symmetries.
- All phenomena (hadrons, nuclei, etc.) are emergent.
- Prototype for a fundamental theory.
- Dynamics that confines quarks and builds hadrons is still obscure.
- Lattice QCD allows us to compute and perform "theoretical experiments" by deforming the theory.

The nature of hadronic resonances

- Ancient question: How should enhancements and resonances be described in hadronic scattering processes?

- How should the results of theory/model calculations with no open decay channels be compared with experiment?

The nature of hadronic resonances

- Ancient question: How should enhancements and resonances be described in hadronic scattering processes?

- How should the results of theory/model calculations with no open decay channels be compared with experiment?

  - Are "hadrons" necessarily associated with poles in the S-matrix?

  - Is there a useful "unitarization scheme" which begins with zero-width parameterization and then couples to open channels?

  - Are hadronic resonances generated by "forces" between the scattering hadrons?

  - Does one size fit all?

Summary – take aways...

- "Ordinary" hadrons are (Fano)-Feshbach resonances

  Bound states in confined channels that appear as resonances in the continuum of scattering channels.

  (Meson) widths vanish as $N_c \to \infty$

  A zero width approximation (eg, even as simple as a K-matrix parameterization) is a good starting point, at least conceptually

- <u>But these are not the only kind of hadrons</u>

"Extraordinary" hadrons --- Resemble the unitarized potential resonances of the (very) old bootstrap.

Generally disappear(!) as $N_c \to \infty$

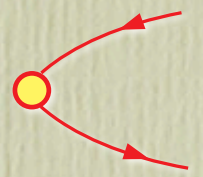
Zero-width unitarization scheme does not seem appropriate.

{$f_0(500)$, $K_0^*(800)$, $a_0(980)$, $f_0(980)$} and XYZ mesons are candidates.

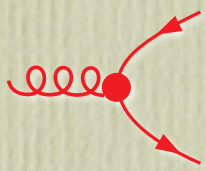
No fundamental distinction between "tetraquarks" and "meson-meson bound states".

Expectations at large N_c

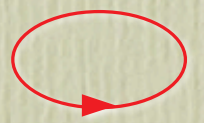
Rules



$$\frac{1}{\sqrt{N_c}}$$



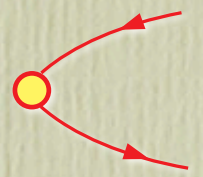
$$\frac{1}{\sqrt{N_c}}$$



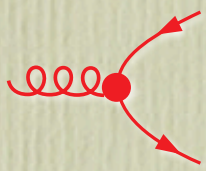
$$N_c$$

Expectations at large N_c

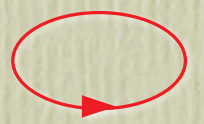
Rules



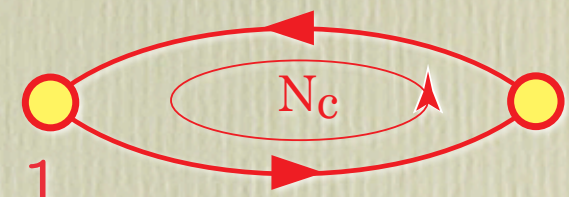
$$\frac{1}{\sqrt{N_c}}$$



$$\frac{1}{\sqrt{N_c}}$$



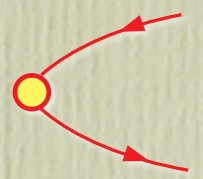
$$N_c$$



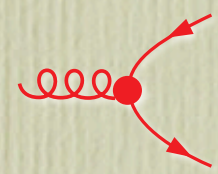
$$\frac{1}{\sqrt{N_c}} \qquad \frac{1}{\sqrt{N_c}}$$

Expectations at large N_c

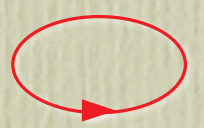
Rules



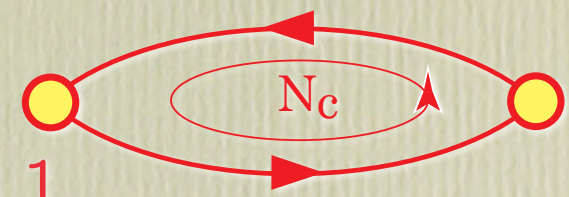
$$\frac{1}{\sqrt{N_c}}$$



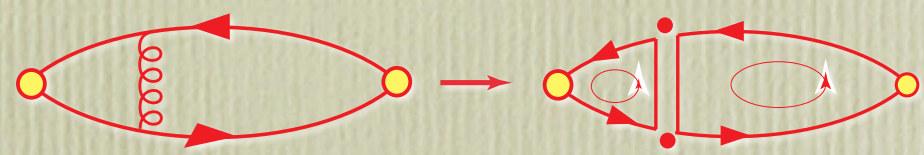
$$\frac{1}{\sqrt{N_c}}$$



$$N_c$$



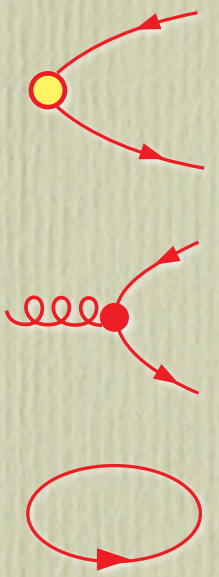
$$\frac{1}{\sqrt{N_c}} \qquad \frac{1}{\sqrt{N_c}}$$



$$\left[\frac{1}{\sqrt{N_c}}\right]^4 \longrightarrow 1$$

Expectations at large N_c

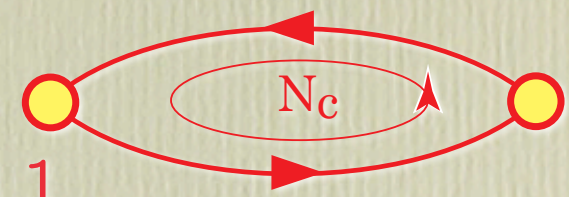
Rules



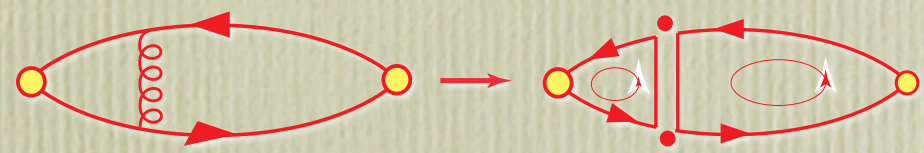
$$\frac{1}{\sqrt{N_c}}$$

$$\frac{1}{\sqrt{N_c}}$$

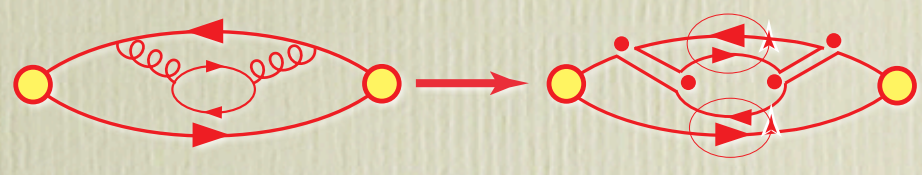
$$N_c$$



$$\frac{1}{\sqrt{N_c}} \qquad \frac{1}{\sqrt{N_c}}$$



$$\left[\frac{1}{\sqrt{N_c}}\right]^4 \to 1$$



$$\left[\frac{1}{\sqrt{N_c}}\right]^6 \to \frac{1}{N_c}$$

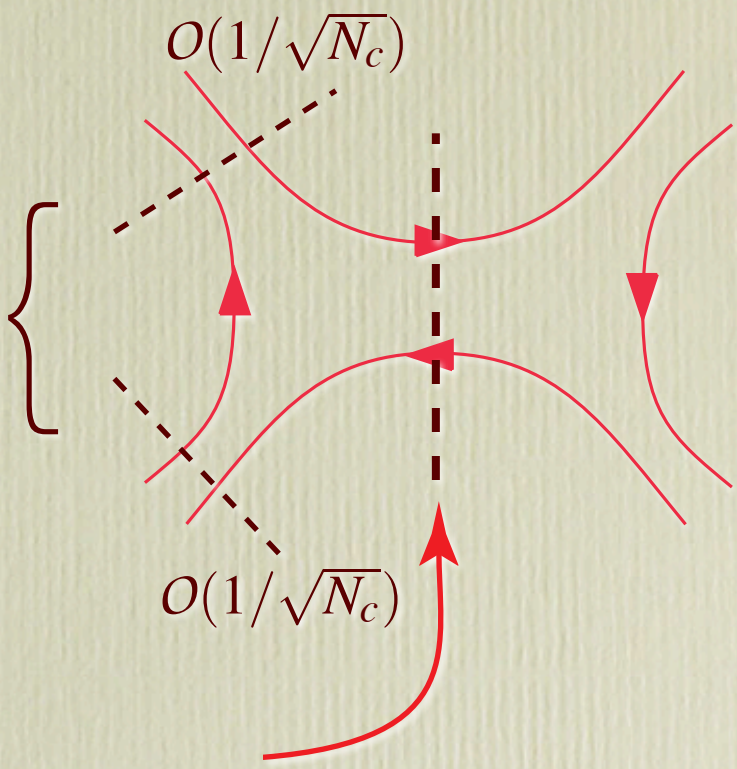
Ordinary Mesons

"Classic" example:

$$\pi\pi \longrightarrow \rho \longrightarrow \pi\pi$$

"In" and "out" states are ordinary hadrons, forming a continuum, and only couple to the "confined" channel by quark-antiquark annihilation, which is suppressed at large N_c

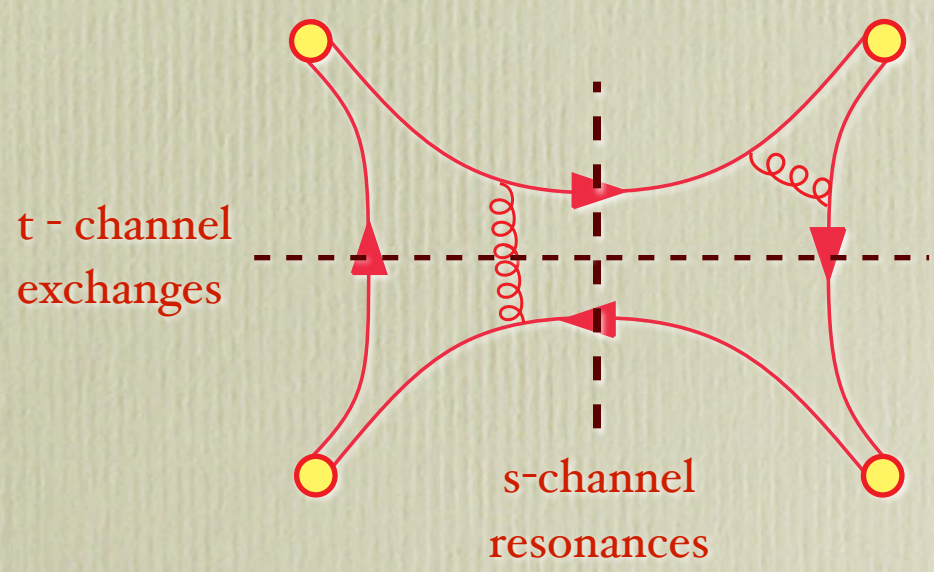
Resonance formation takes place by transition from <u>channel with continuum spectrum</u> (meson-meson, multiquark) to a channel with a discrete spectrum (confined channel) that has no asymptotic states



Confined channel, not in the Hilbert space of asymptotic states

Classic results:

- Meson widths vanish $\Gamma \sim \mathcal{O}(1/N_c)$ as $N_c \to \infty$
- Quark content becomes pure $Q\bar{Q}$
- Meson-meson scattering vanishes as $\mathcal{O}(1/N_c)$; ordinary mesons appear as narrow s-channel resonances dual to t-channel exchanges.

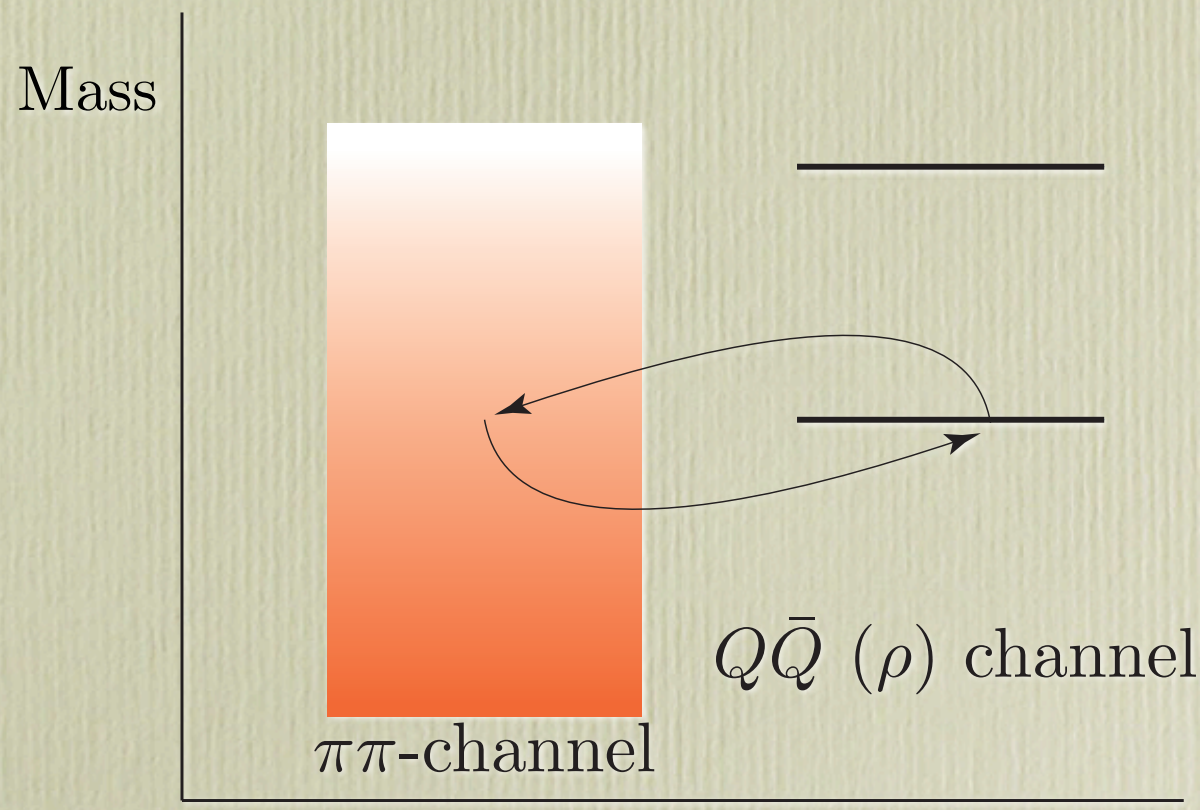


Ordinary hadrons as Feshbach resonances

U. Fano, Nuovo Cimento **12**, 154 (1935);
Phys. Rev. **124**, 1866 (1961).
H. Feshbach, Ann. Phys. (N.Y.) 5, 357 (1958).

Scattering particles couple to bound (confined) state in the continuum

$$\Psi = \begin{pmatrix} \psi_1 \\ \psi_2 \end{pmatrix} \begin{matrix} \longleftrightarrow \pi\pi \\ \longleftrightarrow \rho \end{matrix}$$



Non-relativistic example is easy to interpret

$$\Psi = \begin{pmatrix} \psi_1 \\ \psi_2 \end{pmatrix} \begin{matrix} \longleftrightarrow \pi\pi \\ \longleftrightarrow \rho \end{matrix}$$

$$\left.\begin{aligned} H_0\psi_1 \quad + \quad \frac{1}{\sqrt{N_c}} V\psi_2 &= E\psi_1 \\ H_0\psi_2 \quad + \quad \frac{1}{\sqrt{N_c}} V\psi_1 + \boxed{V_{\text{conf}}}\psi_2 &= E\psi_2 \end{aligned}\right\}$$

Exactly the structure that leads to Feshbach resonance, a bound state in the continuum, whose lifetime goes to infinity (width to zero) as

Only a discrete spectrum

$$\mathcal{H} = \begin{pmatrix} h_0 & V \\ V & h \end{pmatrix}$$

$$\mathcal{G}(E) = \frac{1}{E-h} \approx \frac{|\phi\rangle\langle\phi|}{E-E_0}$$

$$h|\phi\rangle = E_0|\phi\rangle$$

$$h_\ell|u_\ell\rangle + V\frac{|\phi\rangle\langle\phi|}{E-E_0}V|u_\ell\rangle = E|u_\ell\rangle$$

Confined channel "bound state" generates infinitely strong effective interaction in continuum

But ordinary $Q\overline{Q}$ meson resonances are not the only effect that remains at $\mathcal{O}(1/N_c)\ldots$

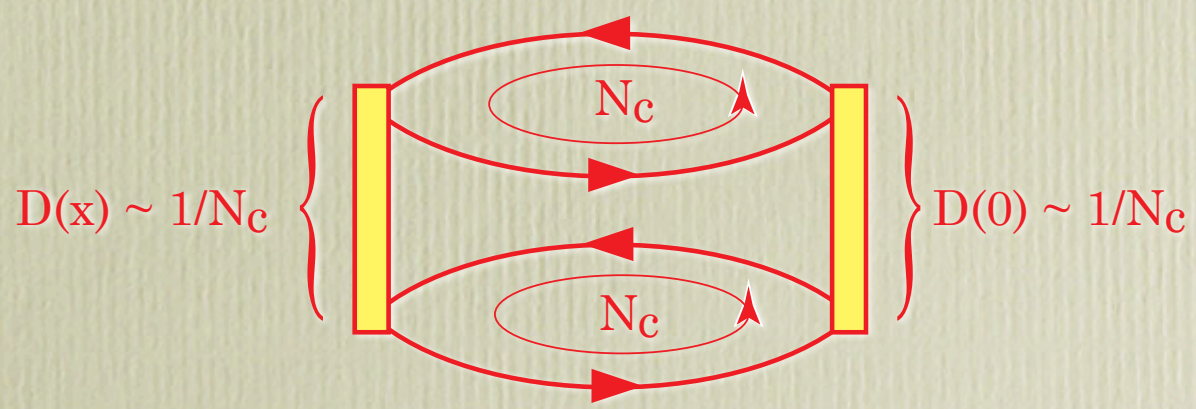
Extraordinary Mesons

Closer look at meson-meson scattering at large N_c.

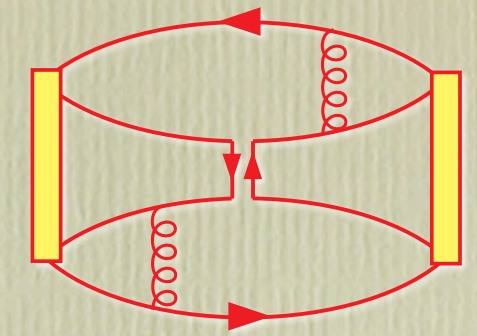
Generic normalized two meson source

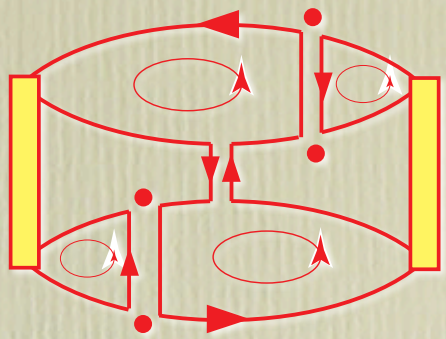
$$D(x) \equiv \frac{1}{N_c}\bar{q}\bar{q}qq(x)$$

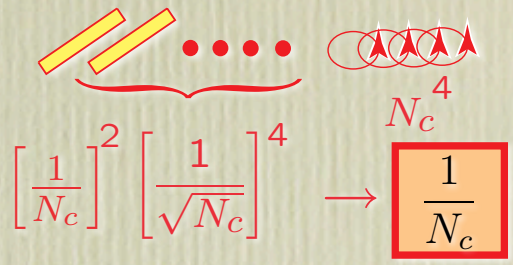
$$\langle 0|D(x)D(0)|0\rangle \sim 1 \quad \text{as } N_c \to \infty$$



All meson-meson interactions are $\mathcal{O}(1/N_c)$. t-channel exchange of narrow ordinary mesons build up narrow s-channel ordinary-meson resonances.

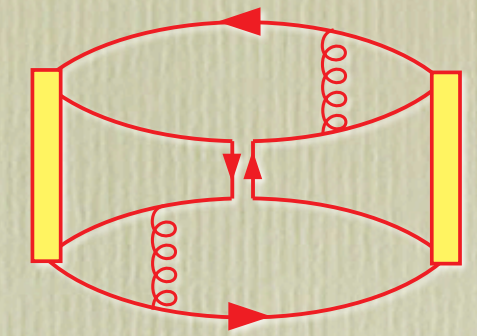


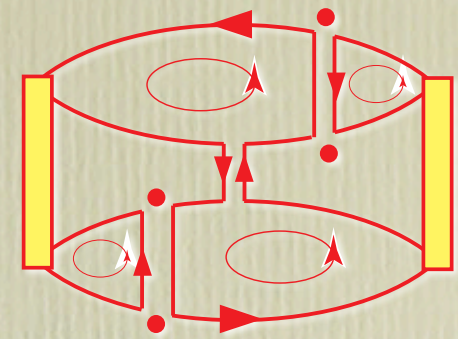


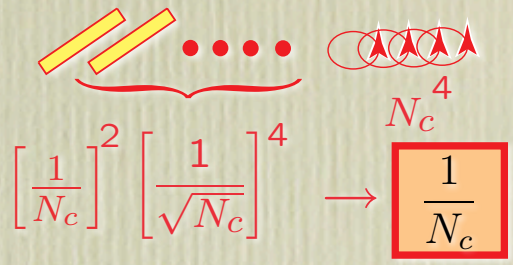


Additionally – quark exchange diagrams are also $\mathcal{O}(1/N_c)$ but do not couple to ordinary (narrow) meson resonances. Off the narrow ordinary-meson resonances, quark exchange is the dominant meson-meson interaction as $N_c \to \infty$

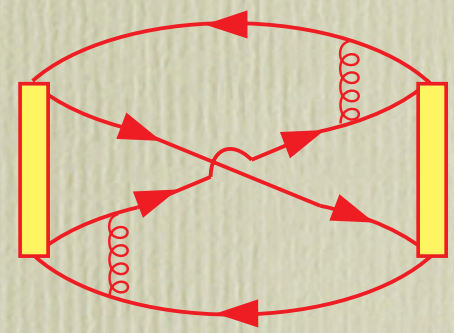
All meson-meson interactions are $\mathcal{O}(1/N_c)$. t-channel exchange of narrow ordinary mesons build up narrow s-channel ordinary-meson resonances.

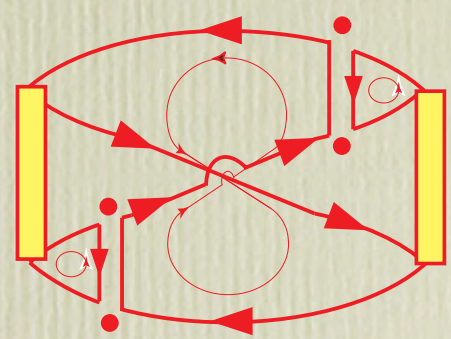


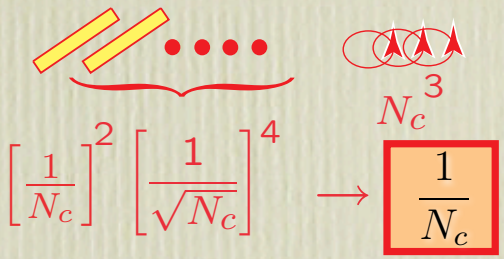




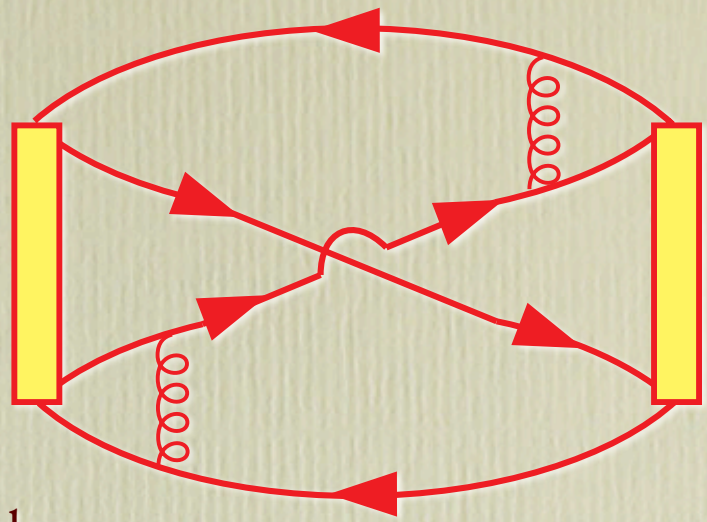
Additionally – quark exchange diagrams are also $\mathcal{O}(1/N_c)$ but do not couple to ordinary (narrow) meson resonances. Off the narrow ordinary-meson resonances, quark exchange is the dominant meson-meson interaction as $N_c \to \infty$







Quark exchange is the dominant force between mesons off resonance at large N_c



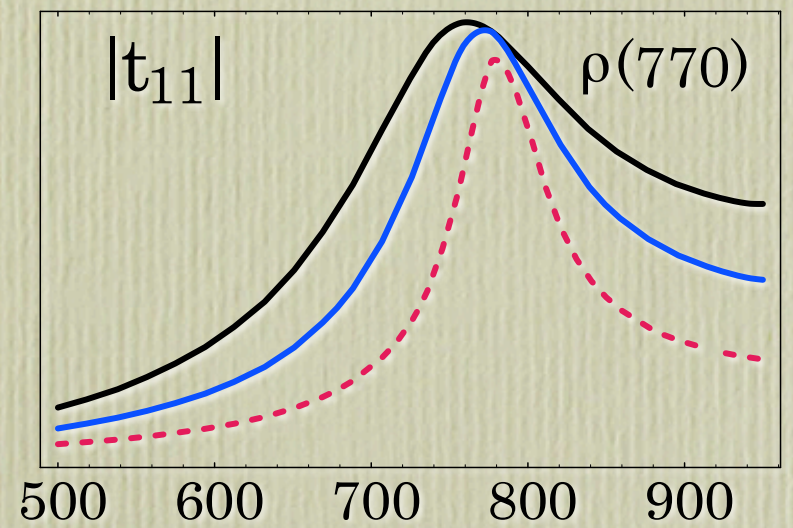
Implications

- In any fixed basis, eg. $M_{12}M_{34}$ quark exchange mixes color octet components into the wavefunction, so the force is fundamentally chromodynamic.
- The range of the force is determined by the distance at which hadrons 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.
- Extraordinary hadrons --- if they exist at all --- disappear as $N_c \to \infty$; they merely subside into the hadron-hadron continuum.

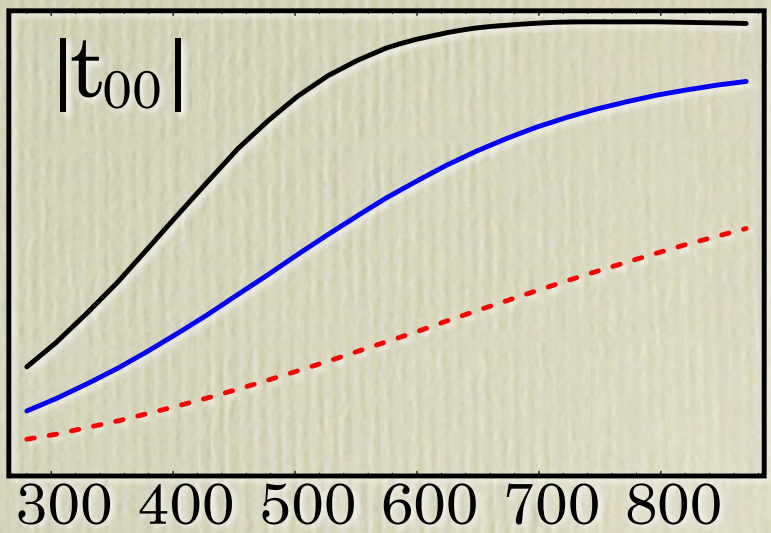
- No one knows how to calculate scattering amplitudes in QCD, so how can these ideas be tested?

- Meson-meson scattering can be studied as a function of N_c using unitized chiral dynamics†

J. Pelaez & collaborators



$N_c = 3$
$N_c = 5$
$N_c = 10$



N_c dependence of ϱ consistent with "ordinary meson"

N_c dependence of $f_0(500)$ is not consistent with "ordinary meson"

†I understand that there is model dependence here!

Miscellaneous Thoughts on the Description of Extraordinary Hadrons

I. The low energy meson-meson s-wave is very special

0^{++} quantum numbers

$$\bar{q}q \ \underline{p\text{-wave}} \ (s\text{-wave has } \textit{negative} \text{ parity})$$

$$\pi\pi \text{ or } \bar{q}\bar{q}qq \ \underline{s\text{-wave}}$$

Diquark correlations can be important in the $\bar{q}\bar{q}qq$ s-wave

$$f_0(600) \ \kappa(800) \ f_0(980) \ a_0(980)$$

Contrast the 1^{--} channel:

$$\bar{q}q \ s\text{-wave}$$

$$\pi\pi \text{ or } \bar{q}\bar{q}qq \ p\text{-wave}$$

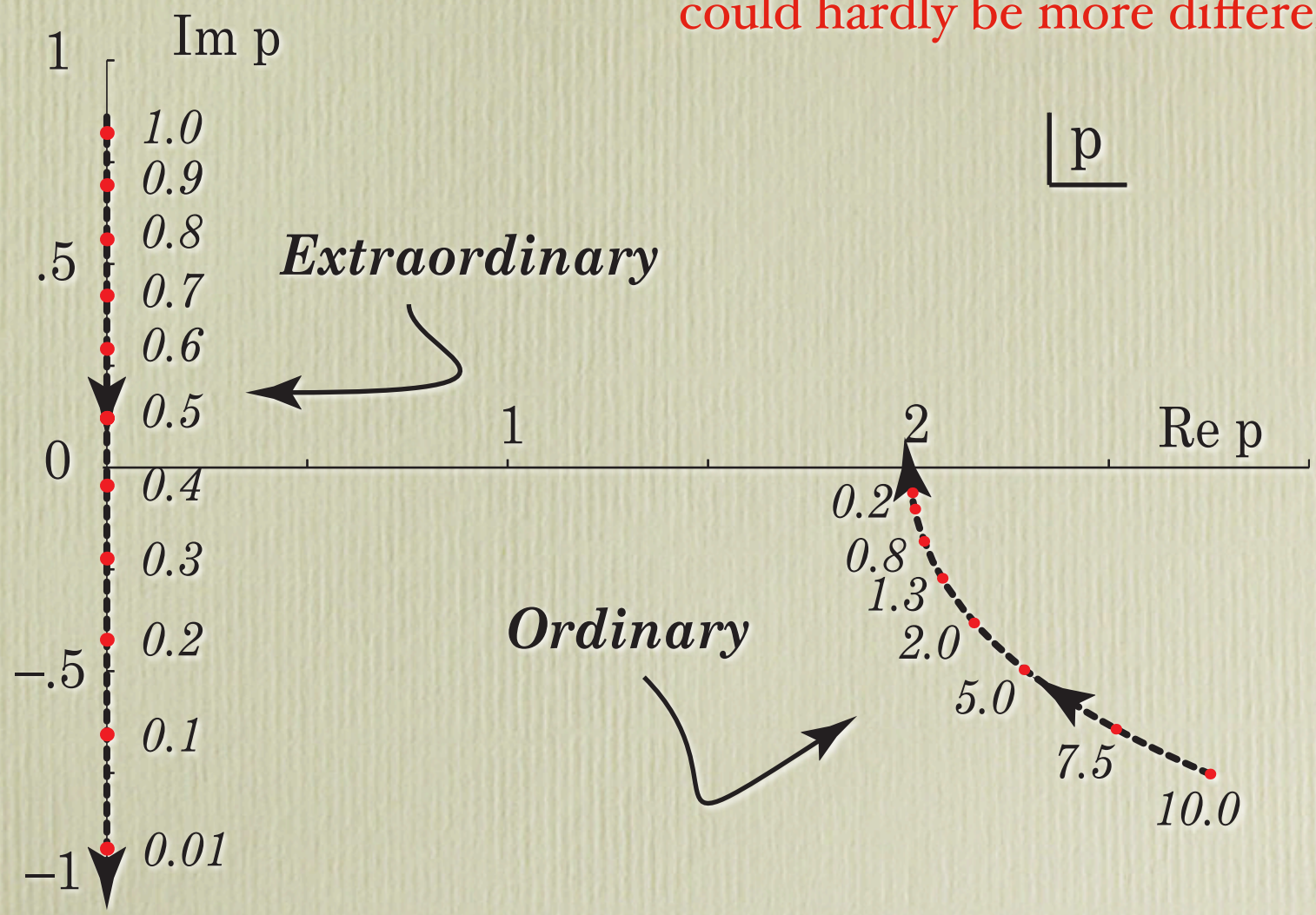
Generically the meson-meson, meson-baryon, and baryon-baryon **s-wave** is where unusual enhancements are expected and often seen

Jonathan L. Rosner *Effects of S-wave thresholds*
Phys.Rev.D74:076006, 2006 hep-ph/0608102

Trajectories of poles in the complex k-plane as a function of coupling

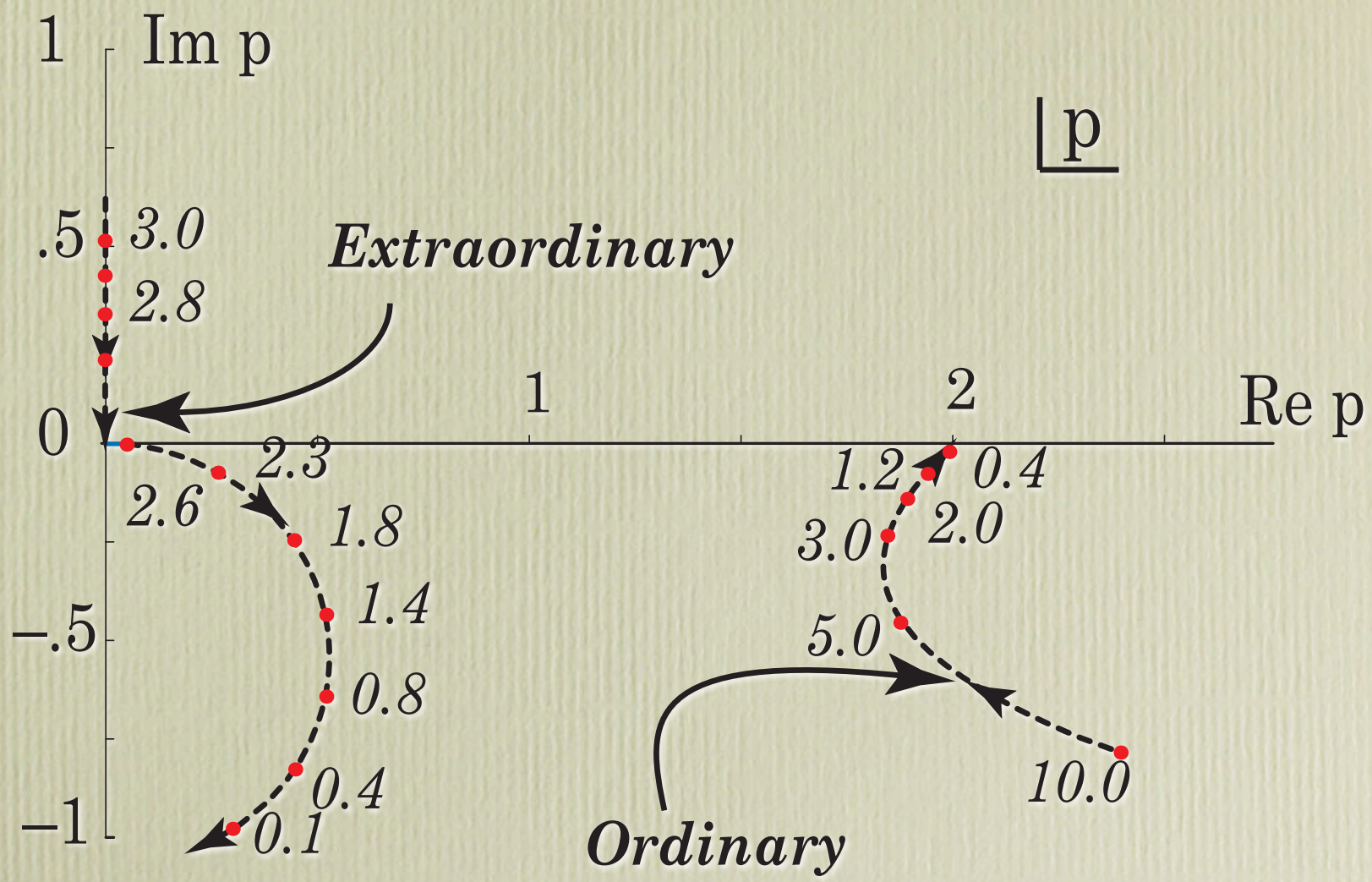
S-wave

Ordinary and extraordinary resonances could hardly be more different!



P-wave

Ordinary and extraordinary resonances could hardly be more different!



II. There is no clear distinction between a meson-meson molecule and a $\bar{q}\bar{q}qq$ state

$f_0(980)$ or $X(2873)$ a meson-meson molecule or $\bar{q}\bar{q}qq$ state?

could (will) be debated forever, but the distinction is not meaningful when a state is near or above its prominent decay threshold.

Consider a (non-relativistic) system with binding energy B

$$B \to 0 \quad \text{kinematics requires} \quad \sqrt{\langle r^2 \rangle} \to \sqrt{\frac{2MB}{\hbar^2}}$$

Even if all the (attractive) interaction comes from a chromodynamic force that has no simple parameterization in terms of meson exchange potentials --- nevertheless the system has nearly unit probability to be found as separate mesons.

Simple and elegant model, where hadrons interact <u>only by quark exchange</u> forces, but meson molecules meson molecules $\Leftrightarrow$ $\bar{q}\bar{q}qq$ states

F. Lenz, J.T. Londergan, E.J. Moniz, R. Rosenfelder, M. Stingl, K. Yazaki
Quark Confinement And Hadronic Interactions, Annals Phys.170:65,1986

Summary – take aways…

- "Ordinary" hadrons are (Fano)-Feshbach resonances
- But these are not the only kind of hadrons

"Extraordinary" hadrons --- Resemble the unitarized potential resonances of the (very) old bootstrap.

Disappear(!) as $N_c \to \infty$

Zero-width unitarization scheme does not seem appropriate.

{$f_0(500)$, $K_0^*(800)$, $a_0(980)$, $f_0(980)$} and XYZ mesons are candidates.

No fundamental distinction between "tetraquarks" and "meson-meson bound states".