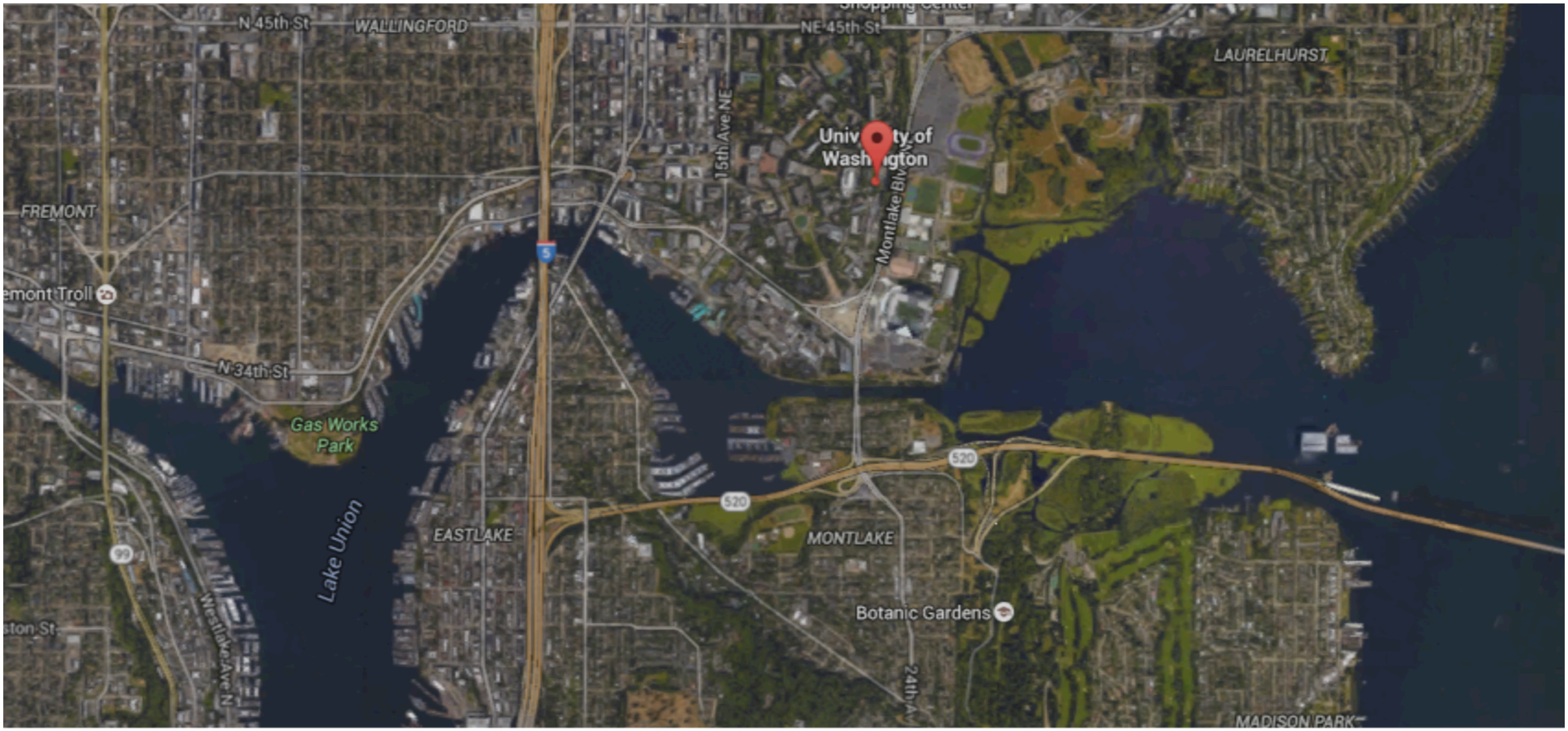
What Does Large Nc QCD Teach Us About Exotics?

TDC
R. F. Lebed

An Overview



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Botanic Gardens
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MADISON PARK

An overview

- Introduction
  - QCD vs the Quark Model
    - Exotics
  - Why Large Nc?
    - Glueballs, Hybrids
- The Conventional Wisdom
  - Tetraquarks can't exist at large Nc
- Weinberg's critique
  - "Proof" that narrow tetraquarks don't exist is flawed
- Overcoming Weinberg's critique
- QCD(AS) another variant of the the large Nc limit
  - Narrow tetraquarks must exist at large Nc in QCD(AS)
- Implications for the real world
- What about pentaquarks??

Introduction

- With the discovery of a multitude of X,Y, Z and now P_c states, it seems clear that at least some of these are exotic hadron resonances.
- All of these states contain heavy quarks.

This raises a key question: Are exotic hadrons a ubiquitous feature of hadron spectroscopy—with the exotics in light quarks systems simply being too wide or too hard to see for some other reason—or does their very existence depend on having heavy quarks?

This talk will focus on light quark systems to see whether we have good reason to believe that exotics should exist there. Large Nc arguments will be used (without spectacular success) to try to tease this out.

- History is full of Irony. The history of QCD is no exception: the naïve quark model was an essential ingredient in the development of QCD, but given the existence of QCD it very hard to understand why the quark model works at all for light quark systems.
- The phrase “Quark Model” is composed of two words—“quark” and “model”
  - Note that both of these are ambiguous

What does “quark” mean?

- It is a type of soft cheese product which exists (though hard to find) in the US but is really popular in German-speaking countries.

- It Is a nonsense word invented by James Joyce.

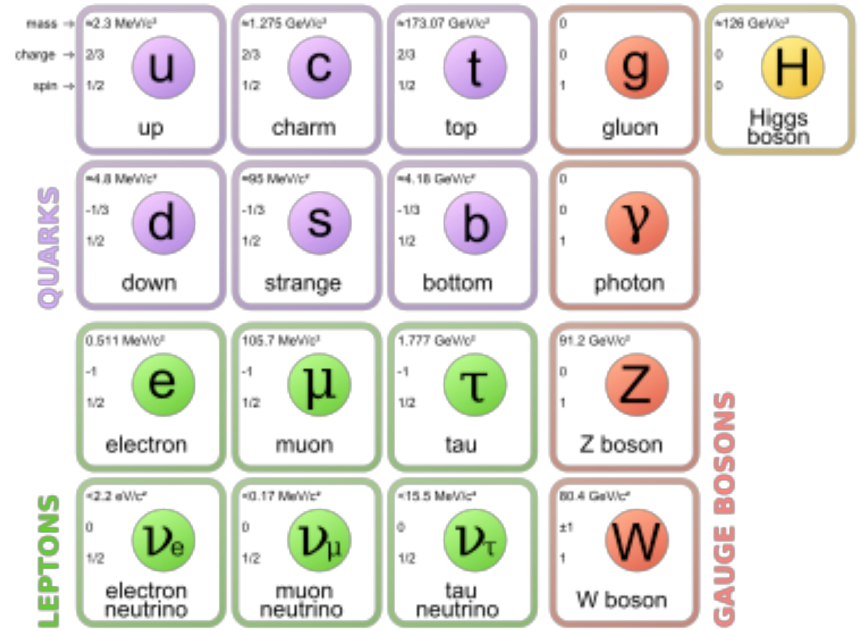
- It is an effective degree of freedom in the quark model.

- It is a fundamental degree of freedom in QCD.

All these meanings are fundamentally different*

***Except perhaps in the case of heavy quark systems where quark model “quarks” and QCD “quarks” can be pretty similar**

In what sense is the quark model a “model”?



- Note that from the modern perspective, the quark model is a “model” in the sense of a model ship rather than the standard model. It captures *some* aspects of the real thing but misses others.
- It is not a complete well-defined theory which at least in principle predict directly predict experimental observables like the standard model.
- It is definitely not beautiful like a supermodel.

  (At least in the light quark sector of the theory)

- However, the simple quark model still strongly influences the language that we use to describe hadrons and remains a basic way most hadronic physicists think about states.
- Exotic hadrons are ones which do not fit into the simplest quark model description (a meson is a quark-antiquark state and baryon three quarks) and are important in that they help clarify what QCD has and the quark model does not.
  - There are two types
    - Quantum number exotics. States which by their quantum numbers **cannot** be made in the simplest quark model. (eg. an isospin 2 meson)
    - Cryptoexotics. States which by their quantum numbers can be made in the simple quark model but which dynamically are dominated by components which are not of the quark model type.

- Why large Nc?
  - Many of the issues associated with the status of whether states are "really" quark model states contain intrinsic ambiguity. The hadronic states in nature are not typically bound states but resonances, while the simplest quark model describes bound states. Moreover, there can be mixing between different kinds of states (eg. a meson and a glueball).
  - In many cases these ambiguities vanish in the formal large Nc limit of QCD ('t Hooft 1973).

    For example

    - mesons become narrow at large Nc
    - Glueballs are unmixed with mesons in the usual large Nc limit.
  - The large Nc limit in many cases provides a good cartoon version of hadronic physics explaining many qualitative phenomena and occasionally giving a semi-quantitative tool to describe nature.

- Given the usefulness of the large Nc limit and 1/Nc expansion, one might hope that insights from large Nc might apply to the real world for exotics.
- What is the real world situation for light quark systems ?
  - The existence of glueballs remains controversial
  - There does seem to be evidence for least one hybrid state, the $\pi_1(1600)$
  - There is a long history of identifying various scalars as crypto-tetraquarks but it remains an open question. The key point is that "there are too many scalars".
  - The fo(980) is often thought to be a crypto-tetraquark with large amount of hidden strangeness. Evidence: despite having virtually no phase space the fo(980) decays into 2 kaons. How compelling is this?

- There is now strong evidence for exotics containing heavy quarks

  At least *some* of the reported XYZ states are tetraquarks.

  $P_c^+(4380)$ and $P_c^+(4450)$ are appears to be $c\bar{c}uud$

  – However the nature of these states could be deeply tied to heavy quark physics.

- Why is the case of heavy quarks so special from the large Nc perspective?

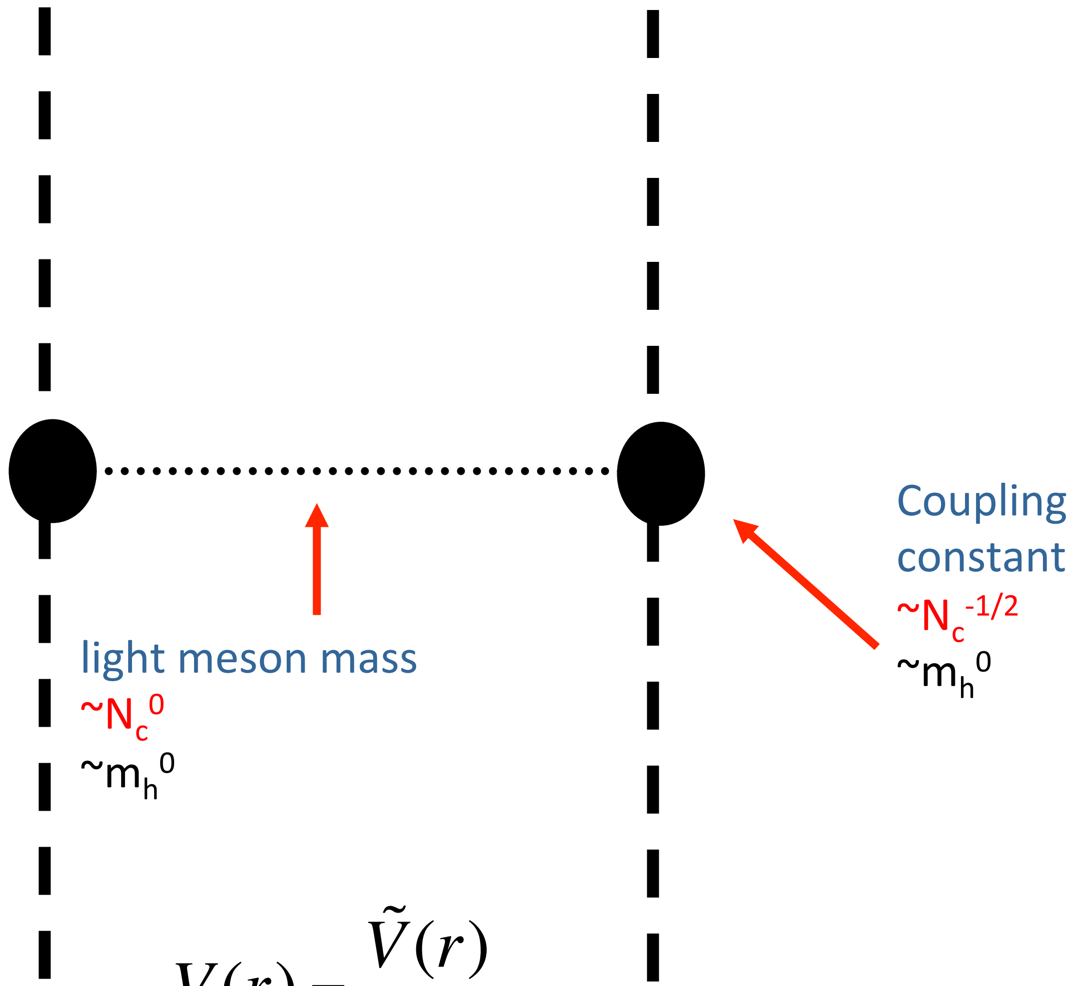
  Large Nc and heavy quark limits do not commute

  – Consider the interaction of two heavy-light mesons at long distance.
  – Assume the interaction is nonrelativistic
  – It can be described via a Schrödinger Eq.
  – The potential at long range is an effective local interaction due to meson exchange.
  – For now ignore the short-range part of the interaction which is not relevant to the big picture (if the long distance physics is attractive enough to cause them to bind, then the short distance effects will only change details of the binding)

Eg. potential between heavy mesons by the exchange of a light meson.

For large N_c and m_h, the range of potential is independent of N_c and m_h, while its strength scales as N_c^{-1}.

This behavior is true generally and not just for one-meson exchange.



$$V(r) = \frac{\tilde{V}(r)}{Nc}$$

with $\tilde{V}(r)$ independent of Nc

Consider form of Schrödinger eq.

$$\left(-\frac{\nabla^2}{M}+V(r)\right)\varphi = E\varphi$$

Reduced mass

E=k²/M

with $V(r)=\dfrac{\tilde{V}(r)}{Nc}$

and $M = m_h\left(1+\mathrm{O}(\Lambda_{QCD}/m_h)\right)$

$$\left(-\nabla^2+\frac{m_h V(r)}{N_c}\right)\varphi = k^2\varphi$$

$$\left(-\nabla^2 + \frac{m_h V(r)}{N_c}\right)\varphi = k^2 \varphi$$

Clearly the large *Nc* and large quark mass limits behave in opposite ways. At large quark mass the interaction becomes effectively strong, so it is easy to see why heavy mesons can bind into tetraquarks.

At large *Nc*, the interaction becomes weak and it is not clear why they should bind.

This raise the key question: Does large *Nc* QCD have tetraquarks with light quarks? (From a theory perspective consider massless quarks.)

The Conventional Wisdom for Tetraquarks At Large Nc

- Tetraquarks do not exist at large Nc. (Witten 1979; Coleman 1985)

Basic argument:

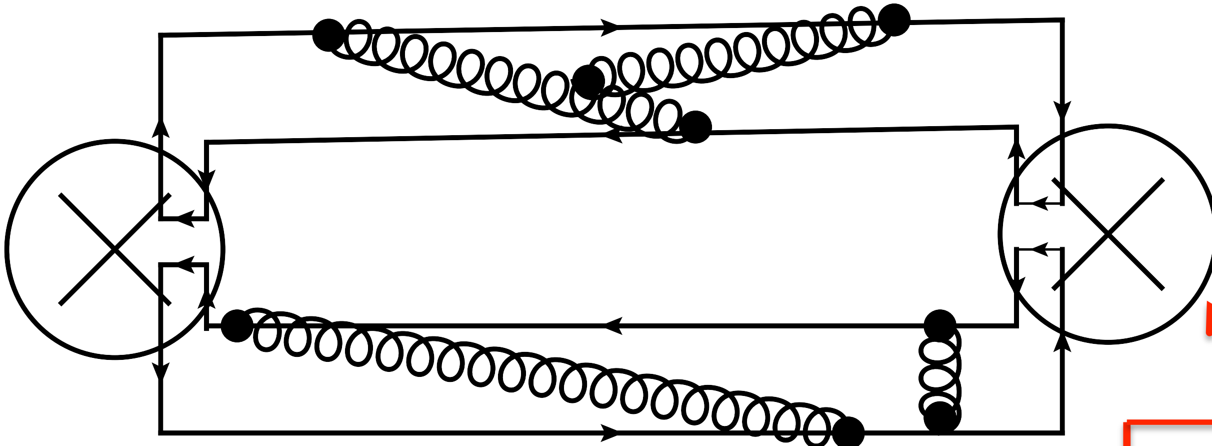
The standard method to study hadrons at large Nc is via a study of the correlation functions for sources with the appropriate quantum numbers. It is easy to show that with a minimal tetraquark source of two bilinears at the same point, the leading order diagram ($\mathcal{O}(N_c^2)$) is just a disconnected diagram which behaves like two non-interacticting meson. It does not act like a tetraquark.

A closely related statement is that $q\bar{q}q\bar{q}$ exotics are absent at $N = \infty$. One way to see this is that mesons at large N are non-interacting (the meson-meson interaction

is of order $1/N$) so that at large N two mesons would not be bound together into an exotic.

A related way to see that exotics are absent at $N = \infty$ is to try to write down an operator with the right quantum numbers to create an exotic. The only gauge-invariant $q\bar{q}q\bar{q}$ operators are products of two gauge-invariant $q\bar{q}$ operators. Thus, one could consider creating an exotic from the vacuum with an operator $K(x) = \bar{q}_i q^i \bar{q}_j q^j(x)$. But to leading order in $1/N$ one finds that $\langle K(x)K(y)\rangle$ factorizes as $\langle \bar{q}q(x)\bar{q}q(y)\rangle^2$ so that, instead of an exotic, we have two freely propagating mesons.

Disconnected graphs $\mathcal{O}(N_c^2)$



a typical diagram at quark/glue level: dominated by loops with planar gluons inside

Source

$$J = \bar{q}^a(x)q_a(x)\bar{q}^a(x)q_b(x)$$

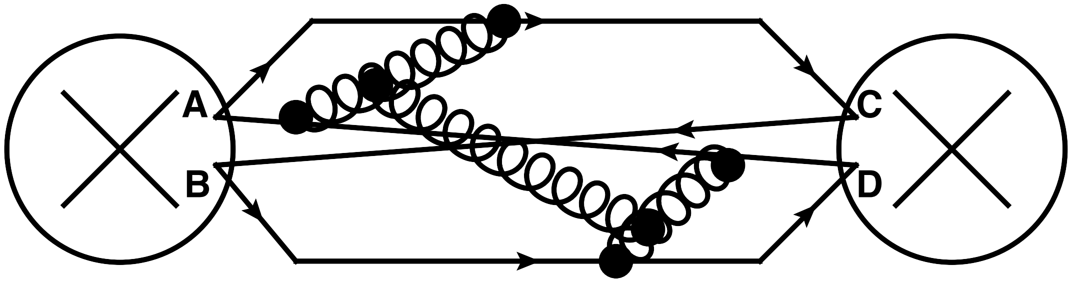
a,b are color indices

hadronic level two mesons

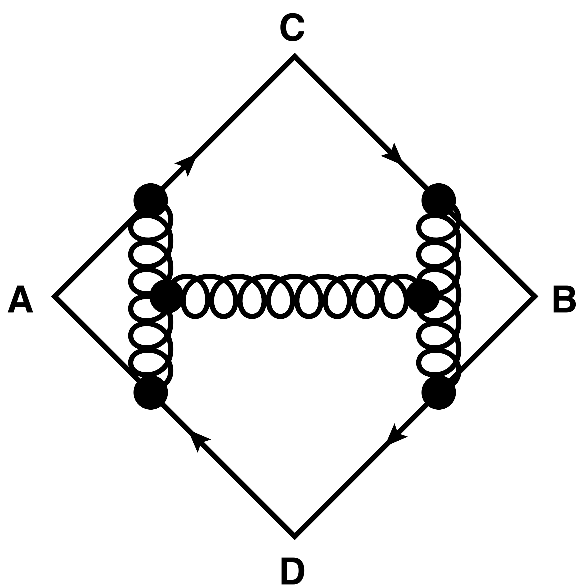
Weinberg's Critique

- Recently this has been called into question. Weinberg pointed out in 2013 that the standard argument is not valid.
- The argument is wrong for a very simple reason: the fact that leading order correlator implies that that the tetraquark operator "makes two meson and nothing else" is irrelevant. One needs to look at the leading diagrams in which the four quarks all interact—i.e. the leading connected diagram—to see states which look like to interacting mesons. *Whether or not these resonate into tetraquarks is separate question from whether the leading diagrams only make noninteracting mesons.*

Connected graphs $\mathcal{O}(N_c)$



A typical diagram at quark/glue level : dominated by a single loop with planar gluons inside. Written as a sensible looking space-time type diagram, it does not seem to be by a single loop with planar gluons inside.



But topologically, in terms of color flow it is, and the Nc counting only depends on the topology of color flow.

- Whether tetraquarks do exist depends on the dynamics of these connected diagrams.
- Note that the logic by which tetraquarks must be absent since they do not appear in the $\mathcal{O}(N_c^2)$ leading order contribution to the correlator must be wrong
  - The same argument could be applied to a 4-quark source with the nonexotic quantum number of two-pions combined to a vector-isovector. The $\mathcal{O}(N_c^2)$ leading order contribution indeed just makes two non-interacting pions. However one cannot deduce from that a ρ meson does not exist. They do, and can be seen in the leading order connected contribitons $\mathcal{O}(N_c)$

- It is important to note, however, that Weinberg has **NOT** shown that tetraquarks do exist as narrow resonances at large Nc. Merely that the argument to disprove the existence of tetraquark is wrong.
- Indeed, it turns out that despite Weinberg's critique, Witten's original conclusion that tetraquarks do not exist as narrow states in large Nc QCD, can be shown to be correct—modulo—a small loophole (TDC and R.F. Lebed 2014) .

A sketch of the argument why there are no narrow tetraquarks at large Nc

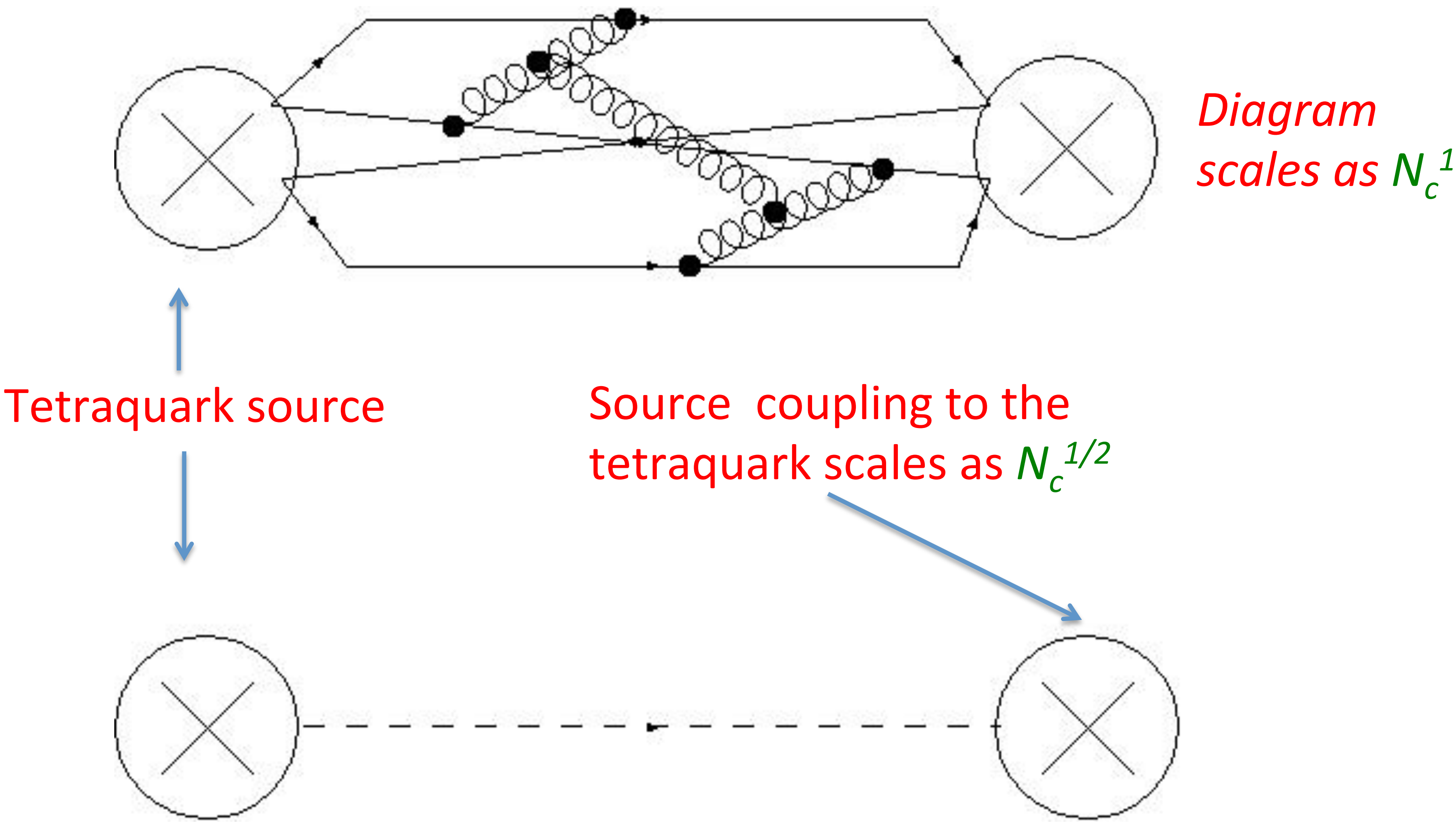
If quantum number exotic tetraquarks exist they will couple to ordinary meson with a coupling strength $\sim N_c^{-1/2}$.

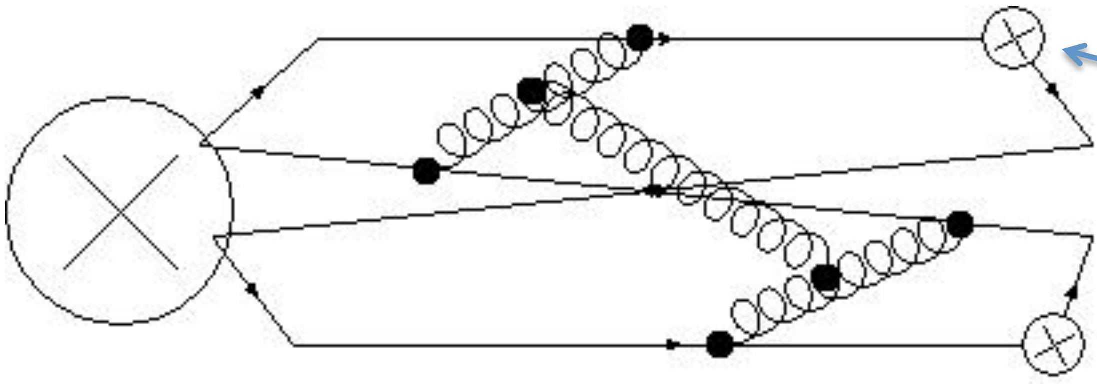
The logic is that like an ordinary meson source a putative tetraquark source only makes a physical state due to the one quark loop diagrams which are order $\sim N_c^{1}$.

This is the same counting as a meson source—the amplitude for making a physical tetraquark from the source will be $N_c^{1/2}$.

This implies that the tetraquark-meson-meson coupling will be $N_c^{-1/2}$.

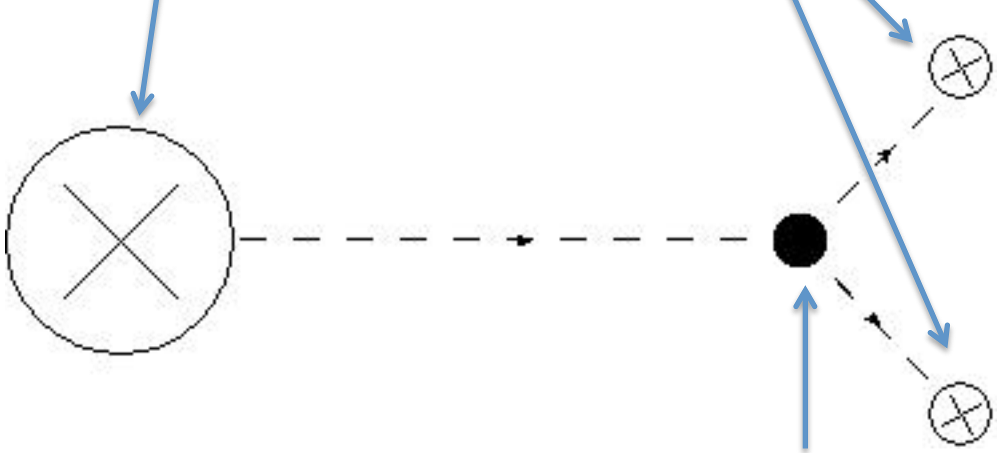
A typical connected color-flow planar diagram with tetraquark sources at the quark-gluon and hadronic levels





meson sources scales as $N_c^{1/2}$

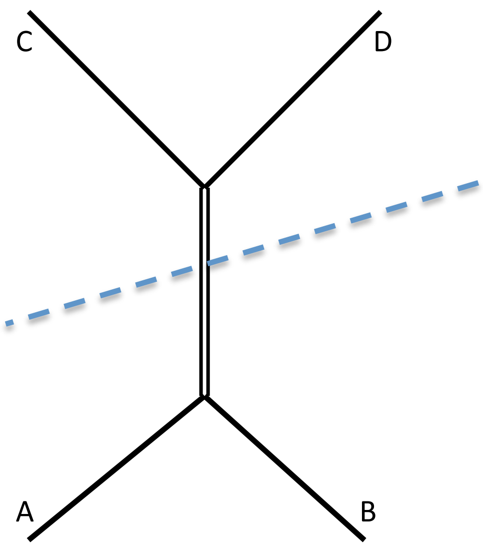
tetraquark sources scales as $N_c^{1/2}$
meson sources scales as $N_c^{1/2}$



Tetraquark-meson-meson vertex must scale as $N_c^{-1/2}$.
Overall diagram ~ N_c^{1} three souces~$N_c^{3/2}$ scaling of vertex needed to restore overall scaling.

A sketch of the argument why there are no narrow quantum number exotic tetraquarks at Large Nc

If quantum number exotic tetraquarks exist they will couple to ordinary meson with a coupling strength ~$N_c^{-1/2}$. Thus it **must** appear in the s-channel of scattering for incident mesons at that order (which is leading order).



This is based on standard Mandelstam type dispersion analysis. The scattering amplitude can depend on two of the Mandelstam variables (say t, and s). At fixed t, the dispersion relation is

$$T(s,t) = \text{pole terms} + \frac{1}{\pi^2} \int_{\text{threshold}}^{\infty} ds' \, \frac{\rho(s',t)}{s - s' + i\varepsilon}$$

A tetraquark if it exists must appear as a sharp structure in ρ with a width ~$1/N_c$; it will become a δ function at large N_c.

- To proceed use standard assumptions
  - Scaling with N_c of physical observables will match the N_c scaling of the leading order family of diagrams.
  - A cut in the diagram corresponds to intermediate particles going on-shell
- Focus on the the scattering amplitude and in particular the spectral function
  - A key point is that the LSZ reduction relates the scattering amplitude to the **amputated** 4-point function—not the 4-pt function itself.
  - That is it multiplies by inverse propagators to eliminate singularities associated with the incident and final particles

$$T = Z_A^{-1/2} Z_B^{-1/2} Z_C^{-1/2} Z_D^{-1/2} (q_A^2 - m_A^2)(q_B^2 - m_B^2)(q_C^2 - m_C^2)(q_D^2 - m_D^2)\Pi_4^{ABCD}\left(q_A, q_B, q_C, q_D\right)$$

4 point function in momentum space for currents A, B,,C, D

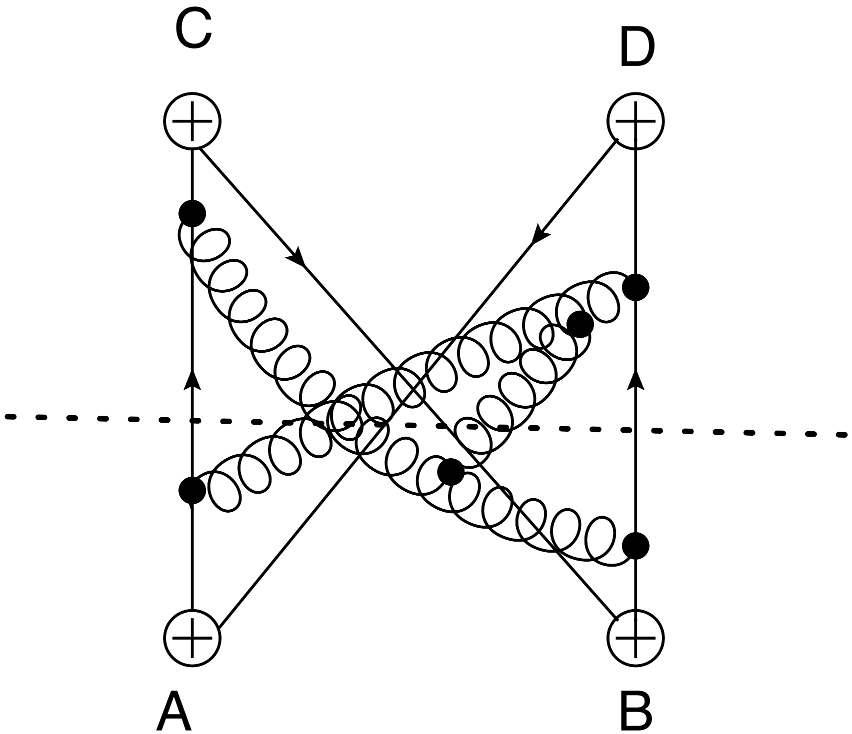
$$Z_A = \left|(q_A^2 - m_A^2)\Pi_2^{AA}\left(q_A\right)\right|$$

There is a topological argument that amputated 4-point functions at leading order in Nc for **every diagram** in an exotic channel only has singularities in the s-channel associated with the asymptotic mesons (either initial or final) in the sense that the cut has two color singlets carry the initial or final four momenta of each.

Thus there are no singularities associated with intermediate object.

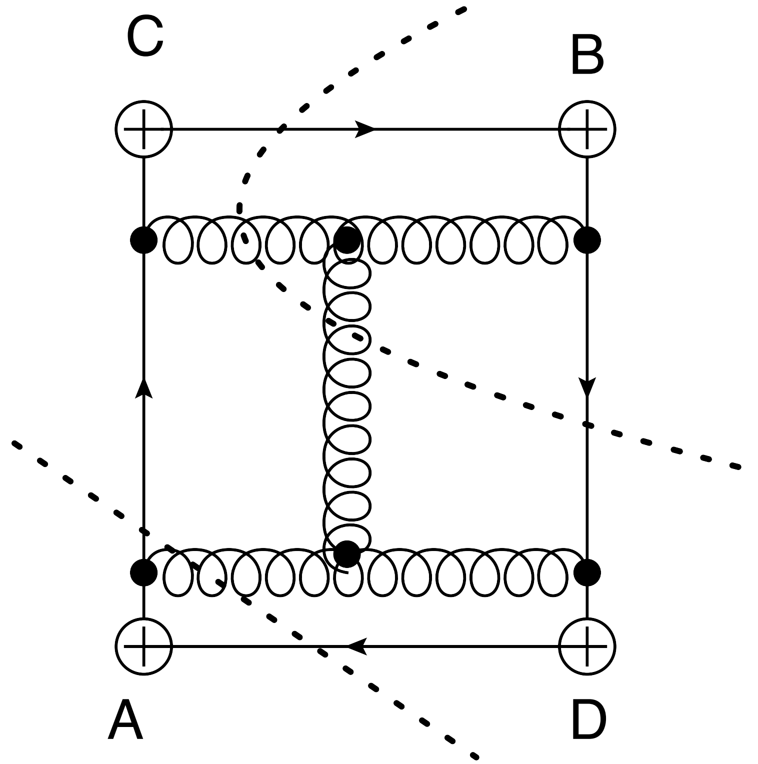
Key point is to distinguish between a space-time description of the process A+B➔C+D from the topology of the color flow

A typical contribution to the full 4-pt function



Space-time diagram

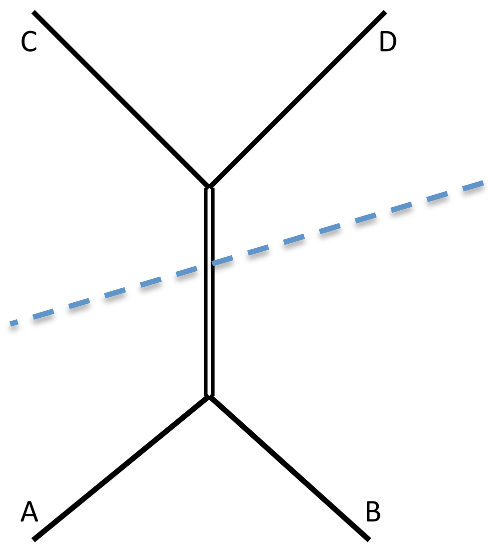
This behavior is generic and occurs in all diagrams associated with exotic channels



Topologically equivalent planar graph. Note that the cut has broken into two parts and each part carries the 4-momenta inserted at A or B

- Note that the nature of the cut when drawn as a space-time diagram is such that you might think it is associated with a tetraquark.
- However from the diagram drawn in planar form, it is clear that one is merely cutting corners. These carry exactly the momentum brought in at A & B and thus correspond to on-shell incident or mesons.
  - Hence when going to the scattering amplitude from the 4-point function (i.e. amputating the external legs) the contribution from cuts of the diagram will vanish.
- Simple to show by looking at **all** topologically distinct classes of order Nc diagram that this is generic and exotic channels do not have tetraquark cuts in the s-channel.

Recall that, if exotic tetraquarks exist they will couple to ordinary meson with a coupling strength ~$N_c^{-1/2}$. Thus it **must** appear at leading order as a singularity in the s-channel of scattering for incident mesons at leading order in the scattering amplitude.



Since no amputated diagrams have s-channel cuts at leading order we conclude that quantum number exotic tetraquarks do not appear at large Nc.

An analogous argument shows that for non exotic channels there are s-channel cuts but they are pure q-qbar and not tetraquarklike

- Thus, at large Nc, there are no tetraquarks in either exotic or nonexotic channels.
  - This depends on standard assumptions used in large Nc analysis. In particular, it depends on perturbative graphs capturing the correct leading Nc counting.
  - There is a loophole; if tetraquarks were to exist for some unknown reason and couple to mesons more weakly than $N_c^{-1/2}$ there is no inconsistency. But there is no reason to expect that this scenario occurs; it seems very unlikely.
    - It would mean that if tetraquarks exist it is only due to subleading connected graphs.

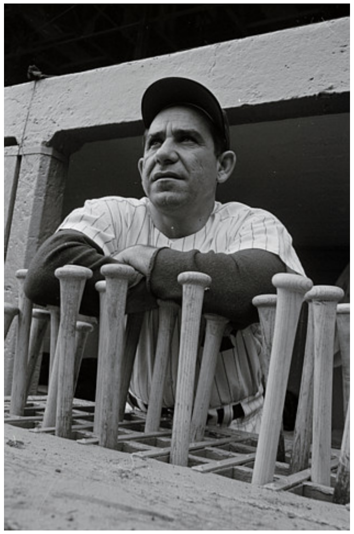
- Since large Nc QCD has no narrow tetraquarks (if we dismiss an implausible loophole) it helps supports the notion that tetraquarks can only arise in QCD when heavy quarks play a role.
- However, things turn out to be not so clear…
- There is another variant of large Nc QCD where narrow tetraquarks DO exist

QCD (AS)

- **The large Nc limit of QCD is not unique**
  - **For gluons there is a unique prescription SU(3)➔SU(Nc)**
  - **However for quarks, we can choose different representations of the gauge group**
  - **Asymptotic freedom restricts the possibilities to the fundamental (F), adjoint (Adj), two index symmtetric (S), two index anti-symmtetric (AS).**
    - **Adj transforms like gluons (traceless fundamental color-anticolor); dimension Nc^2-1; 8 for Nc=3 (unlike our world).**
    - **S transforms like two colors (eg fundamental quarks) with indices symmetrized; dimension ½Nc(Nc+1); 6 for Nc=3 (unlike our world).**
    - **AS transforms like two colors (eg fundamental quarks) with indices antisymmetrized; dimension ½Nc(Nc-1); 3 for Nc=3 (just like our world).**

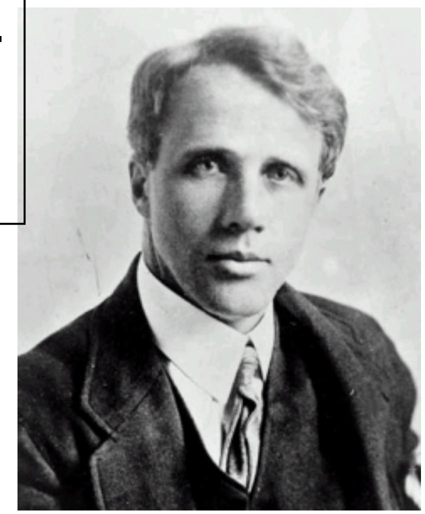
- Note that Nc=3 quarks in the AS representation are indistinguishable from the (anti-)fundamental. (In essence antisymmetric r b is the same as $\bar{g}$.)
- However quarks in the AS and F extrapolate to large Nc in **different ways.**
  - The large Nc limits are physically different
  - The 1/Nc expansions are different.
  - A priori it is not obvious which expansion is better
  - It may well depend on the observable in question
- The idea of using QCD (AS) at large Nc is old
  - It was mentioned in passing in `t Hooft's original paper
  - Corrigan &Ramond (1979)
  - Idea was rediscovered and revived in early 2000's by Armoni, Shifman and Veneziano who discovered a remarkable equivalence that emerges at large Nc.

Two Roads to Large Nc QCD



Quarks in Fundamental

Quarks in 2-index anti-symmetric



"When you come to a fork in the road, take it."

--The late, great Yogi Berra, American baseball player, coach and part-time philosopher

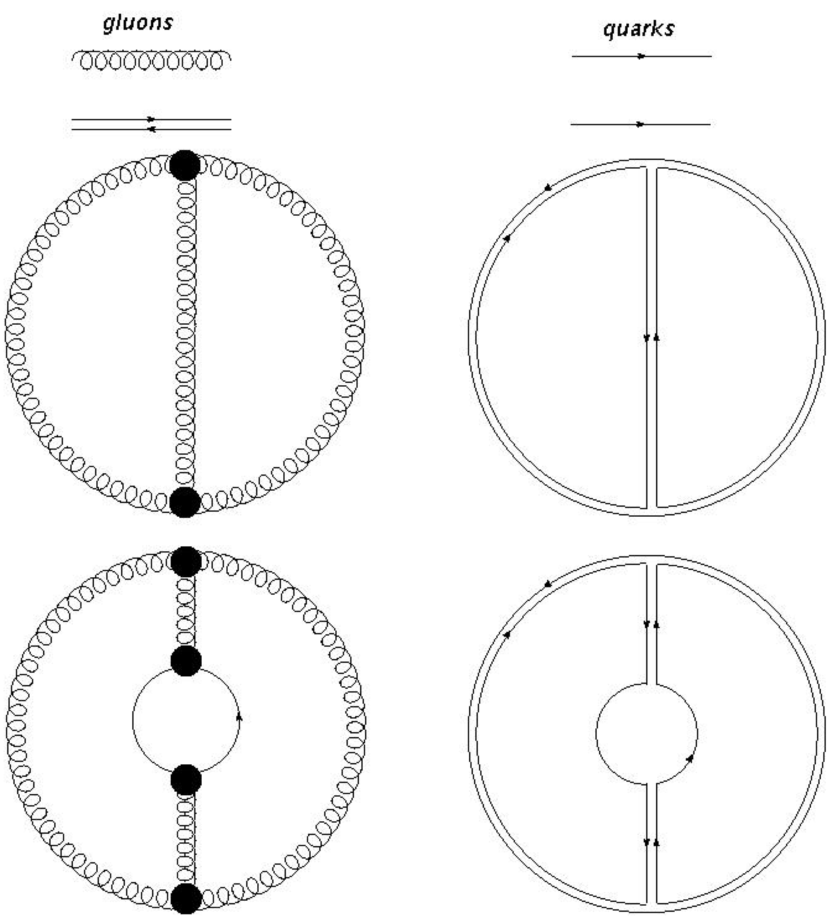
"Two roads diverged in a wood, and I—
I took the one less traveled by And that has made all the difference."

--Robert Frost, American poet

Large Nc QCD

Principal difference between QCD(AS) and QCD(F) at large Nc is in the role of quarks loops

Easy to see this using `t Hooft color flow diagrams



$$\left.\begin{matrix} g^2 \sim 1/N_c \\ 3 \text{ color loops } N_c^3 \end{matrix}\right\} N_c^2$$

$$\left.\begin{matrix} g^4 \sim 1/N_c^2 \\ 3 \text{ color loops } N_c^3 \end{matrix}\right\} N_c$$

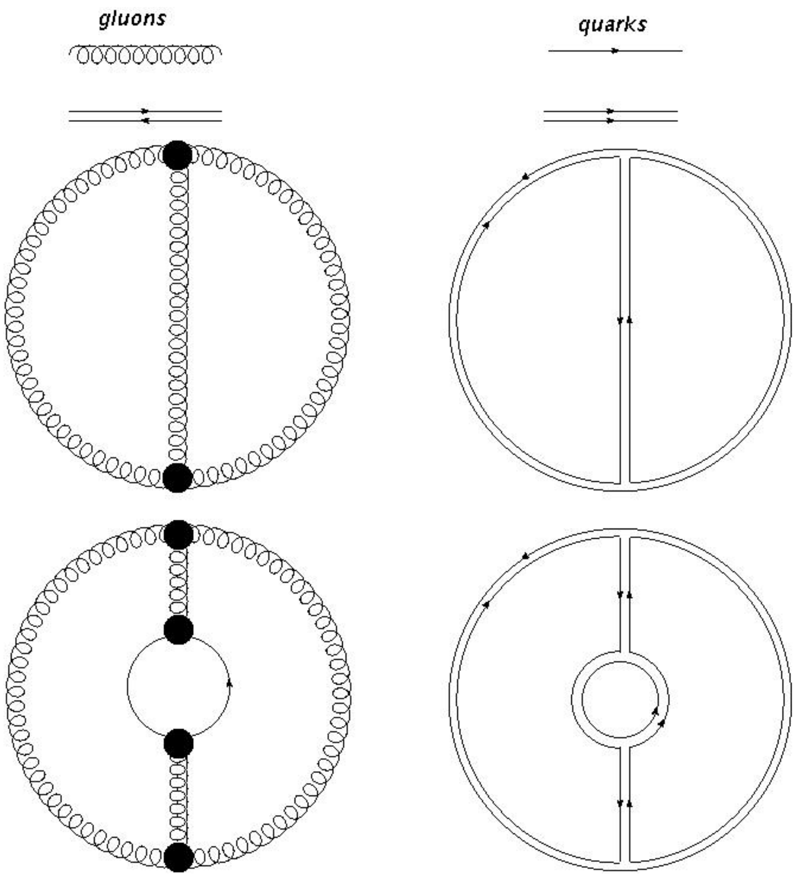
Recall the ‘t Hooft large Nc limit keeps $g^2 N_c$ fixed
So $g^2 \sim 1/N_c$

QCD(F)

Insertion of a planar quark loops yields a 1/Nc suppression.

Leading order graphs are made of planar gluons

QCD(AS)



$$\left.\begin{matrix} g^2 \sim 1/N_c \\ \text{3 color loops } N_c^3 \end{matrix}\right\} N_c^2$$

Insertion of a planar quark loops does not lead to a 1/Nc suppression.

$$\left.\begin{matrix} g^4 \sim 1/N_c^2 \\ \text{4 color loops } N_c^4 \end{matrix}\right\} N_c^2$$

Leading order graphs are made of planar gluons and quarks

Principal phenomenological difference between the two is the inclusion of quark loop effects at leading order in QCD(AS). Whether this is a bug or a feature depends upon the observable. In baryon spectrscopy based on emergent symmetry, both QCD(AS) and QCD(F) appear to have predictive power (Cherman, Cohen & Lebed 2009, 2012).

- QCD(AS) naturally includes quark loops. Thus one might expect that in cryptoexotic channels tetraquarks will mix with ordinary mesons at leading order.
  - This can be shown to be correct.

- More interestingly, in quantum number exotic channels, QCD(AS) **MUST** have narrow tetraquarks at large Nc (i.e. narrow states which have at least 2 quarks and 2 antiquaks)Cohen&Lebed 2014.

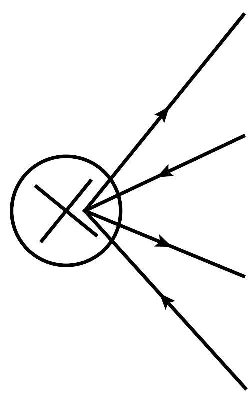
Key ingredient: there are single color trace tetraquark sources in QCD(AS). That is the source cannot be broken up into two separate color singlets (except for N_c^{-2} contbitutions). This cannot be done in QCD(F)

$$J(x) = \sum_{\substack{A,B \\ a,b,c,d}} C_{AB} \, \overline{q}^{ab}(x)\Gamma_A q_{bc}(x)\overline{q}^{cd}(x)\Gamma_B q_{da}(x)$$

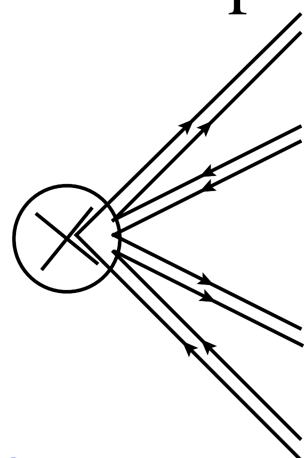
Γ_A, Γ_B are matrices in Dirac-flavor space.

a,b,c,d are fundamental color indices

choice of C_{AB} fixes quantum #s; for simplicty chose an exotic

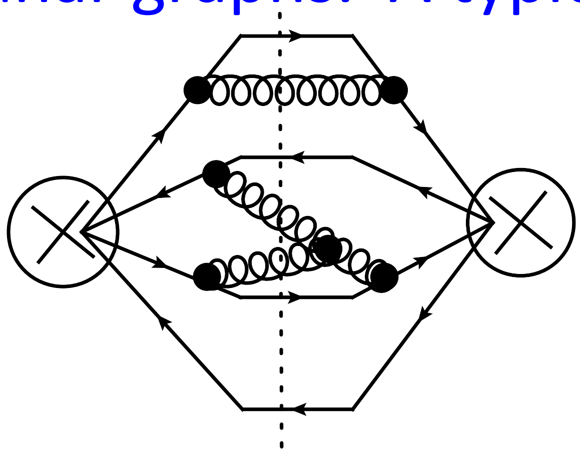


Source as a Feynman diagram

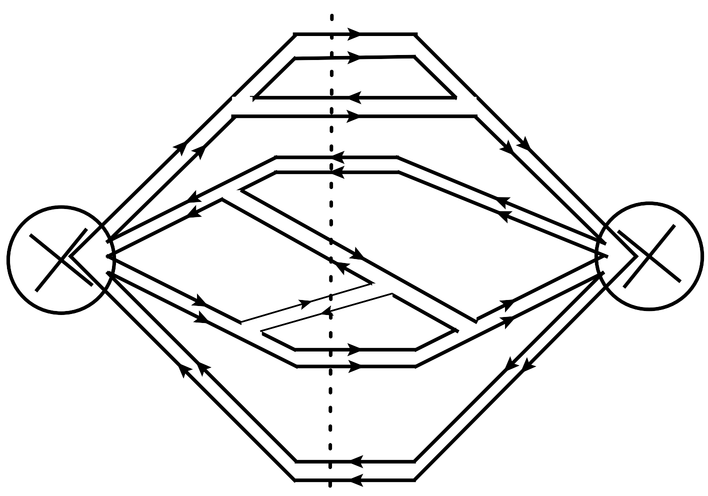


Source as a color-flow diagram

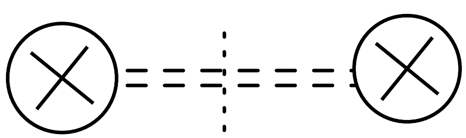
Look at the JJ correlation function. It is dominated by planar graphs. A typical diagram scales as N_c^4



Feynman diagram

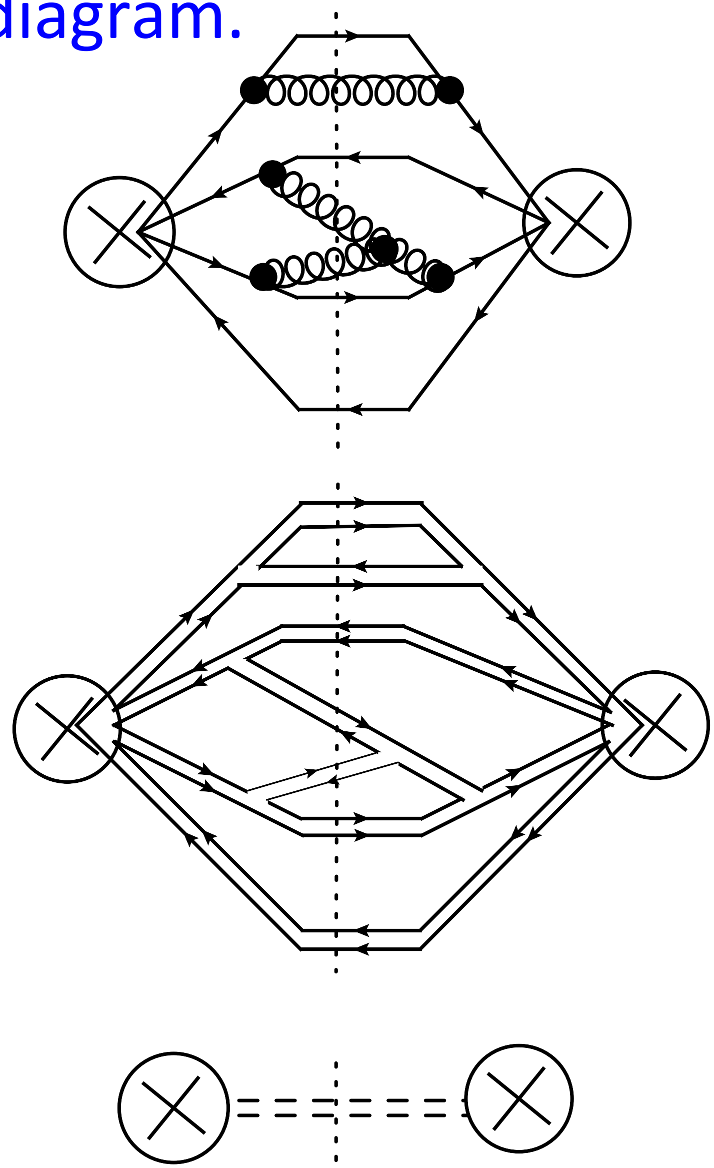


Color-flow diagram; 7 color loops $\sim N_c^7$; 6 factors of g $\sim N_c^{-3}$; overall scaling $\sim N_c^4$



Hadronic level diagram: propagation of a single tetraquark

The reason this corresponds to a single tetraquark hadron can be understood in terms of a cut of the diagram.



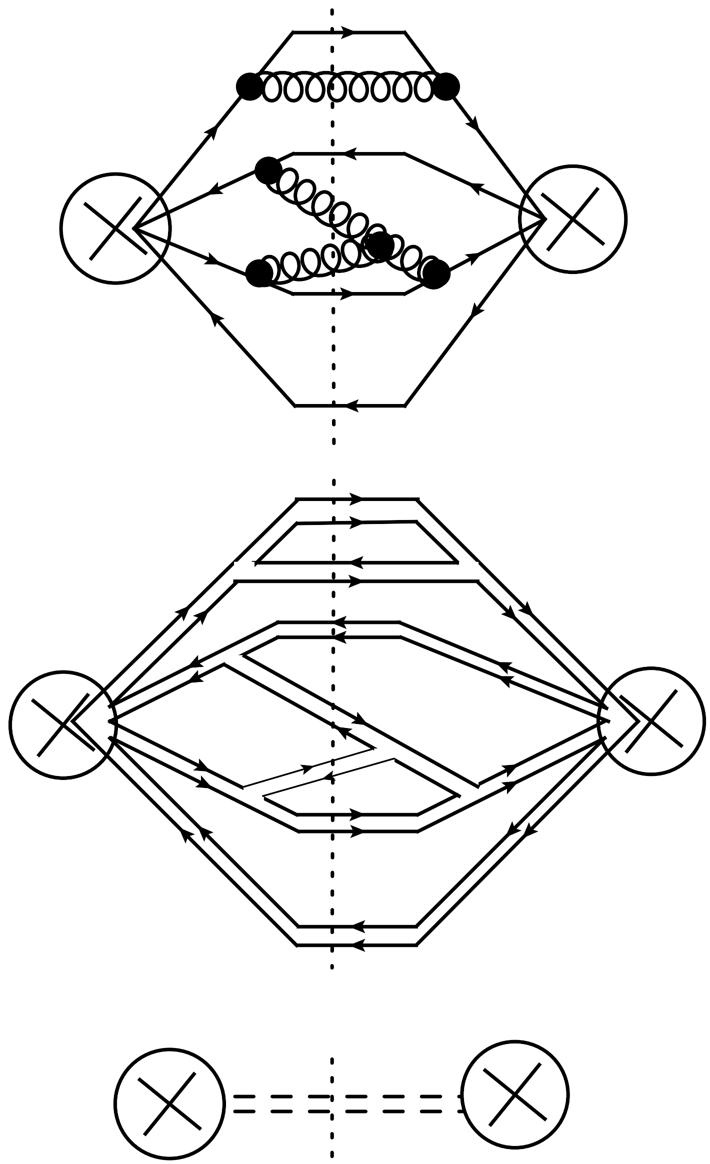
Short dashed line indicates a cut which reveals the intermediate state structure of the diagram.

The cut shown here corresponds to a state of the form

$$\bar{q}^{ab} q_{bc} A^{c}_{d} A^{d}_{e} \bar{q}^{ef} A^{g}_{f} q_{ga}$$

This is a single color-trace object. It can not be divided into two separate color singlets (except by a $1/N_c^2$ contribution)

This is generic: all cuts yield single-color trace objects



If one includes confinement, this implies that the state must be a single hadron at leading order. It cannot break up into two color singlet hadrons since all intermediate states consist of a single indivisible color singlet.

It must be narrow as components with more than one hadron are suppressed in the 1/Nc expansion.

- This can be seen to be true self-consistently
  - One can use standard kind of large Nc analysis for correlators with appropriate changes to account for QCD(AS) to deduce that a generic multi-hadron vertex scales as $N_c^{\,2-n}$ where n is the number of hadrons (mesons, glueballs, hybrids, tetraquarks…). This is true whether or not one has exotic channels. The only constraint is that quantum numbers do not exclude the vertex.
  - Thus, tetraquark width $\sim N_c^{-2}$

as advertised, the tetraquark is narrow

- This can be generalized.
  - The same kind of analysis will yield narrow hexaquarks, octaquarks etc.
  - Again, for all types of hadrons an n point hadronic vertex will (if allowed by quantum numbers) scale as N_c^{2-n}.

Summary for QCD(AS)

- Tetraquarks (as well as higher multi-quark hadrons) exist as narrow resonances in the large Nc limit of QCD(AS).
- Non-exotic tetraquarks exist and mix with ordinary mesons.
- The generic n-hadronic vertex will (if allowed by quantum numbers) scale as N_c^{2-n}.
- The width of all hadrons with phase space to decay will scale as N_c^{-2}.

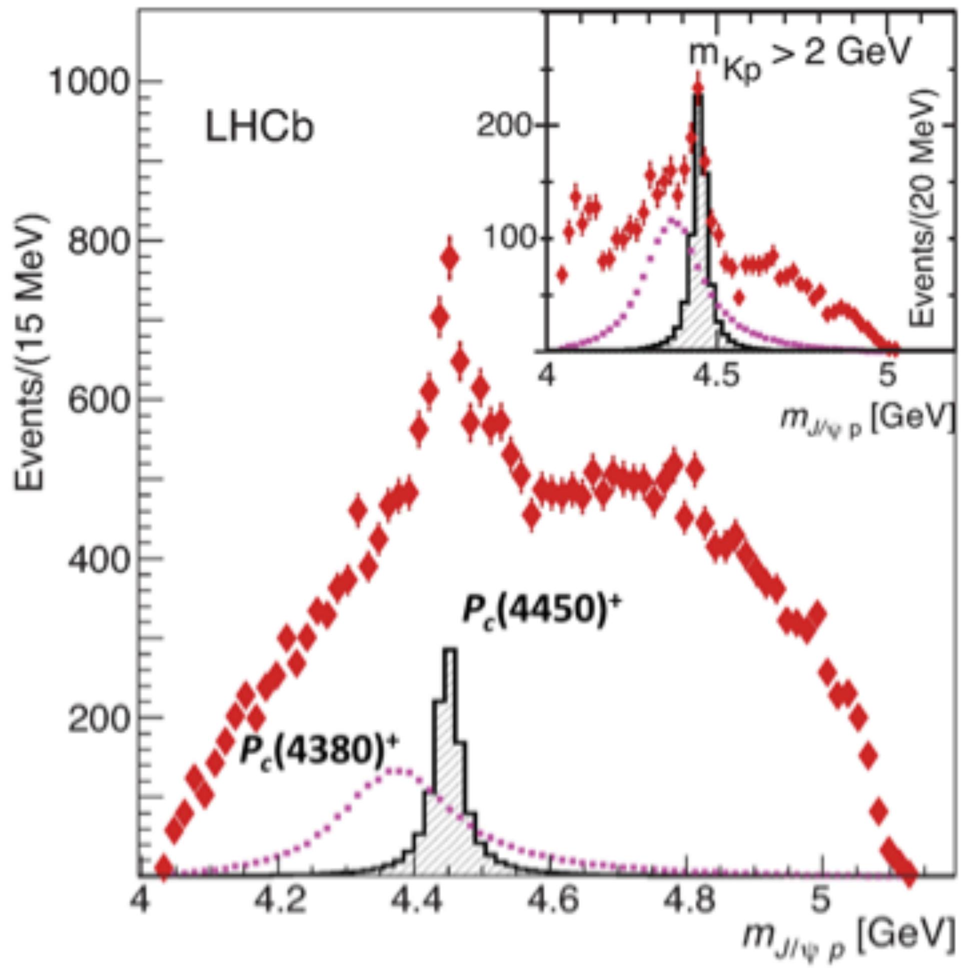
- If it is a close cousin and the real world resembles QCD(AS) at large Nc then one expects narrow exotic tetraquarks to exist.
- This does not mean that one can necessarily find cryptoexotic tetraquarks; parametrically, tetraquarks and ordinary mesons will mix at leading order. However, nothing in principle prevents such a state from being *dynamically* dominated by tetraquark components numerically. It is just not *parametically* isolated at large Nc

- Generic large Nc arguments neither support nor disfavor the existence of tetraquarks composed of light quarks in the real world. Is the real world is closer (in this aspect) to QCD(F) at large Nc or to QCD(AS) at large Nc? This is a dynamical question.

The bottom line for tetraquarks

Whether narrow tetraquarks made of light quarks exist in the real world is a dynamical issue which generic large Nc arguments do not help answer. However, large Nc arguments based on QCD(AS) show they cannot be excluded as incompatible with QCDlike theories

What about Pentaquarks?



Ancient History

- The Θ^+ pentaquark was predicted by Diakonov, Petrov and Polyakov(DPP) in 1997 on the basis of large Nc considerations
  - It was done in the context of a chiral soliton model , but the predicition only depended on the collective quantization which *appeared* to depend only on the large Nc structure and not on any details of the model and hence might be believed to be a model-indpendent prediction of large Nc.
  - Numerous experiments in the early part of this century designed "discovered" or "confirmed" the Θ^+ at masses near that predicted by DPP when looking over data taken for other purposes.

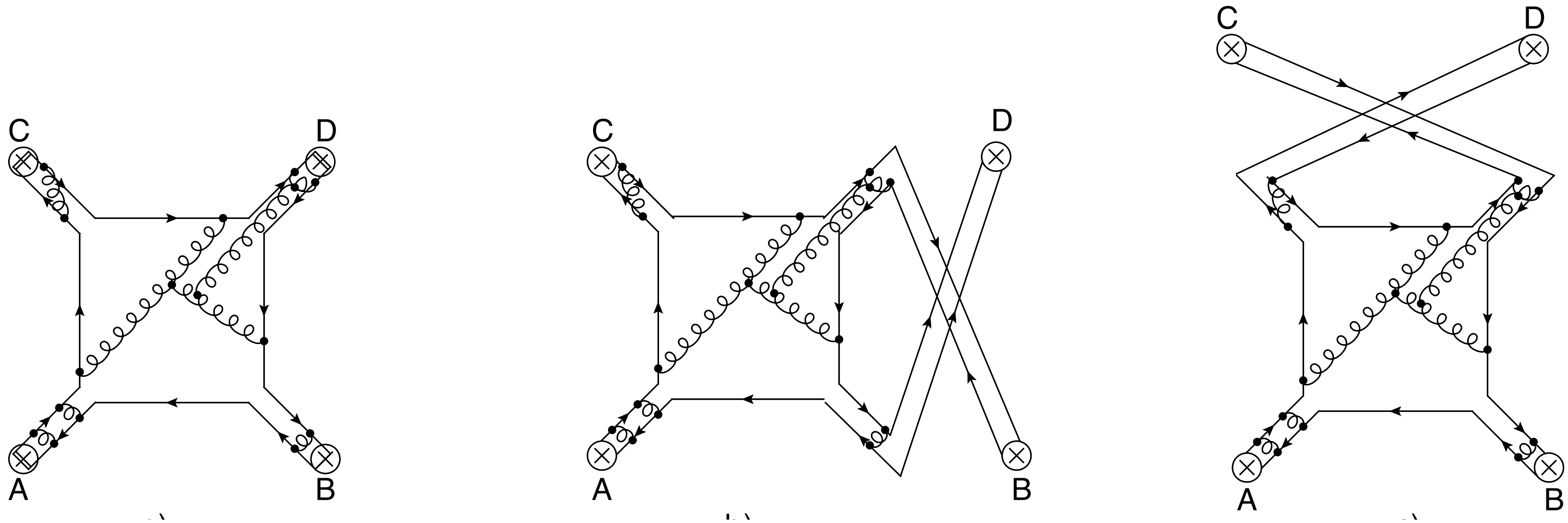
- However
  - On the theory side it was shown (TDC (2003); Klebanov and Oyang 2004)) that the collective quantization procedure used by DPP was inconsistent with large Nc counting rules.
    - Thus the detailed prediction of where a pentaquark should be at large Nc was wrong.
    - It was also shown that large Nc considerations alone neither require nor exclude pentaquark resonances. However, if they exist, Pentaquark widths are of order Nc^0.
  - The experimental discovery of the Θ^+ was largely discredited when a high statistics dedicated experiments at Jefferson lab failed to see it, even though they had similar conditions and much better statistics to claimed discoveries.

– It was also shown theoretically that heavy pentaquarks (i.e. containing one heavy antiquark **must** exist in the combined large Nc and heavy quark limits (TDC , P. Hohler and R.F. Lebed (2005)) such states are stable in this limit and have a vibrational spectrum). However the case of two heavy quarks was not considered.
  - The reason these bind is essentially the one given earlier in the talk; heavy particles see more effective attraction.
  - It was argued, however, that real world parameters were far enough from the combined limit that group structure is unlikely to be seen and it is an open question as to whether they would bind.
  - It is not surprising that the first clear evidence for pentaquarks involves heavy flavor.

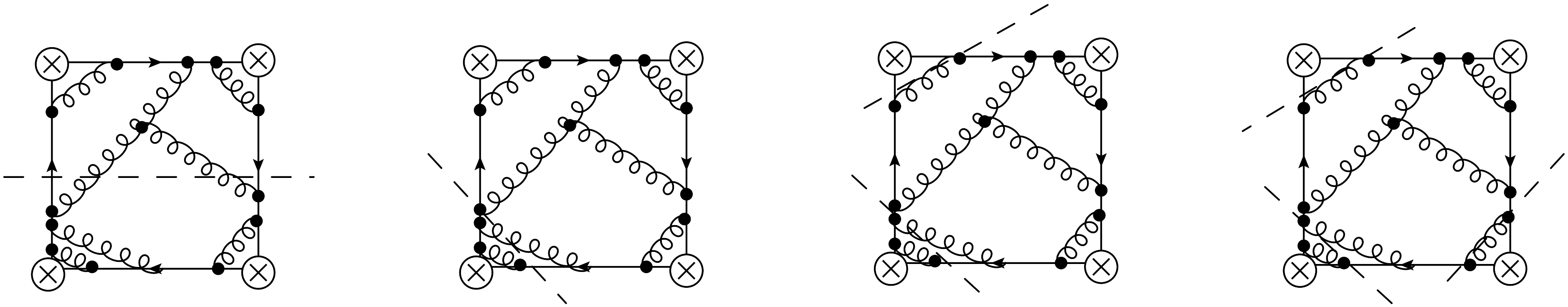
What about Pentaquarks in QCD(AS)?

- Preceding discussion about pentaquarks was in the context of QCD(F). Does anything significant change for QCD(AS)?
  - Given the radical differences between QCD(AS) and QCD(F) for tetraquarks one might imagine a similar thing here.
  - However as far as I can see that this not the case here: appart from a change in scaling rules ($1/N_c \rightarrow 1/N_c^2$) the qualitative results are the same as in QCD(F)
    - Collective quantization a la DPP is not valid; no Θ^+ predicted
    - Whether pentaquarks exist is a matter of dynamical detail; if the do they have widths of order unity.
    - In extreme heavy quark and large Nc limit, pentaquarks, exist and have a vibrational spectra.

Back ups

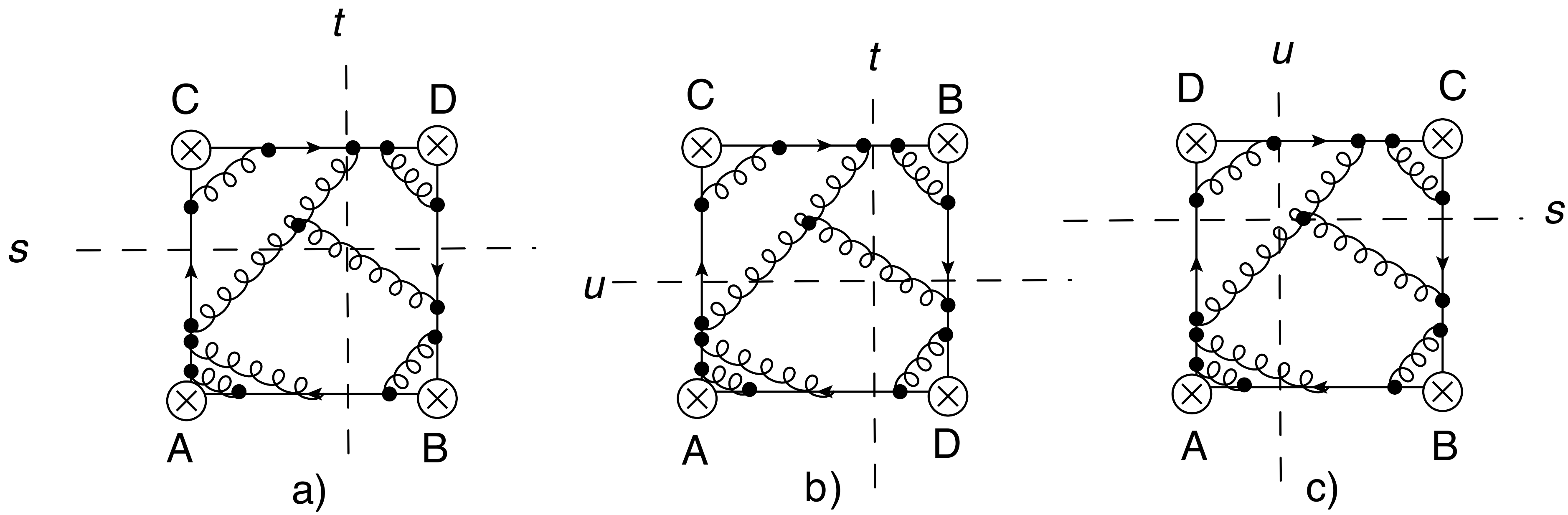


Relating leading space-time diagrams to topological ones. Topologically all that matters is order of the four corners. Moreover, time-reversal invariance means ABCD is identical to ADCB. Thus, there are only three classes of diagrams ABCD, ADBC and ABDC.



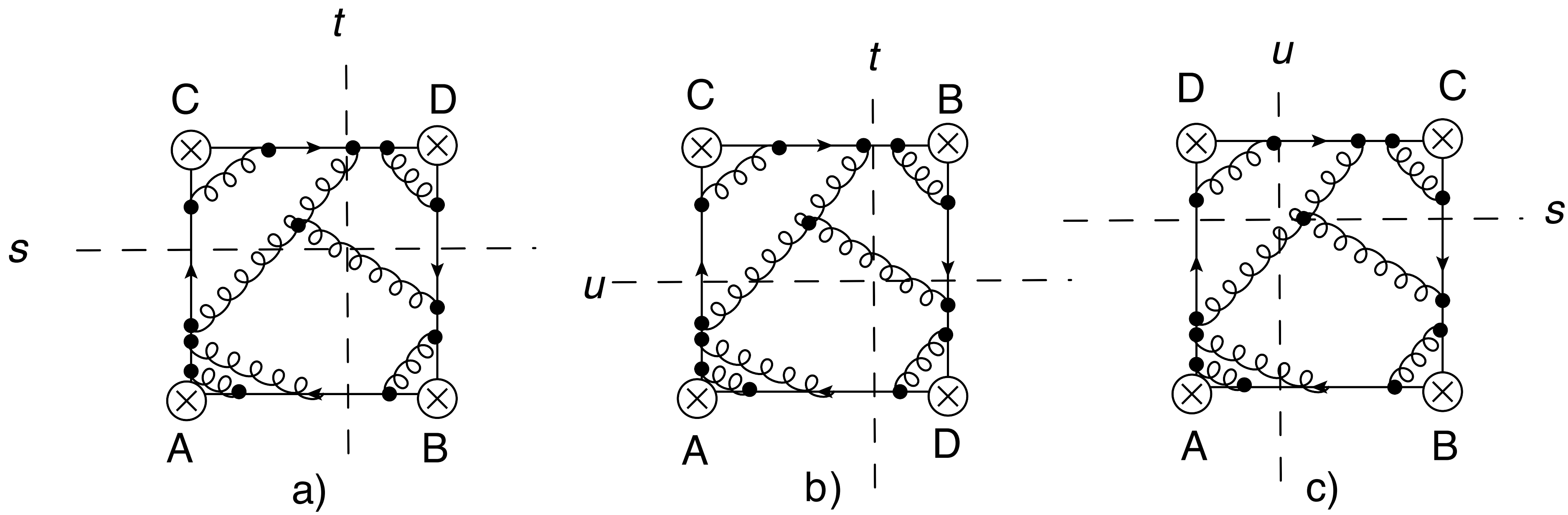
I) II) III) IV)

Broad categories of cuts. Note that except for category I) these all cut through a corner. These corner cuts all are associated with the momentum carried in at the corner and are eliminated when looking at the amputated diagram, AKA the scattering amplitude. Thus the only singularities in category I that could be associated with scattering going through a tetraquark. We will show below that this is not possible for exotic channels by looking at theses in detail



Type I cuts. The three topological classes in terms of ordering are given here. Note that for each there are cuts in only two of the tree Mandelstam variables.

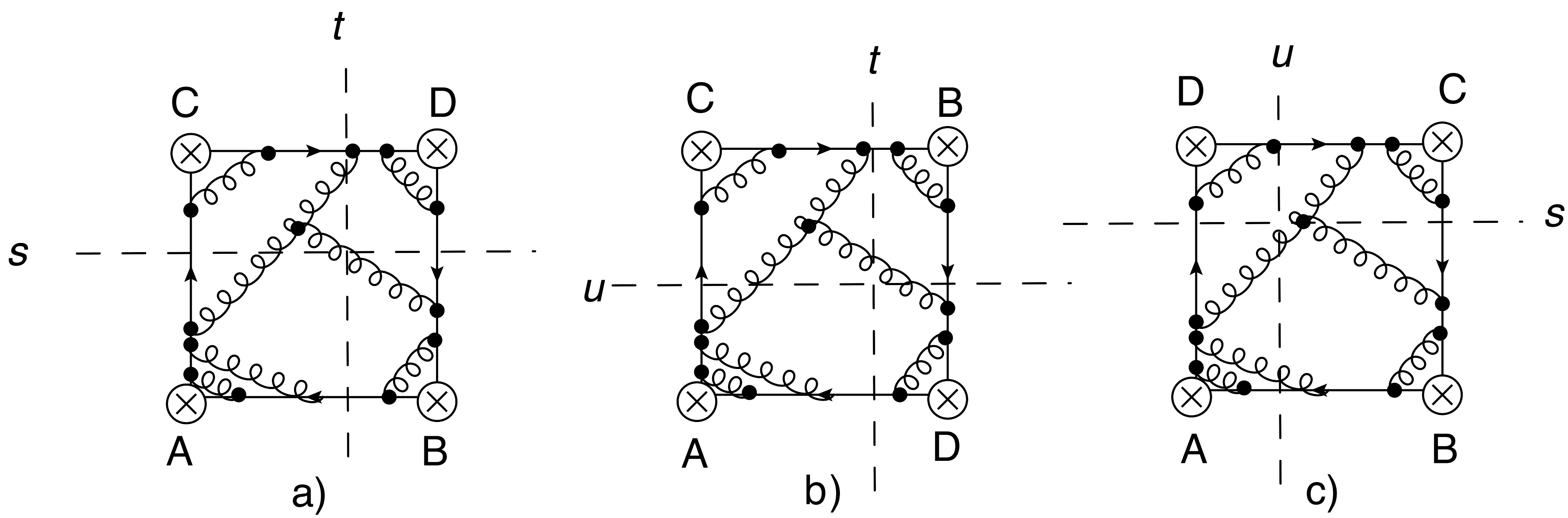
S-channel cuts exist in type a) and c) but not b). If we can show that in exotic channels only have topology b) then there is no s-channel cut at leading order in 1/Nc expansion and hence no tetra quark



Note that in a) and c) type diagrams A & B are adjacent to each other. If the channel is a flavor exotic (say isospin 2), then a quark line (isospin ½) cannot run past an adjacent A&B since doing so must change its isospin to 3/2 or 5/2 but cannot keep it as ½.

Thus, as advertised only b is possible and it has no s-channel cut.

What about non-exotic channels in QCD(F ?)



The non-exotic channels **do** have s-channel singularities a) and c) are not forbidden by quantum numbers. But note they cut exactly one quark-antiquark pair. Thus they are associated with ordinary mesons. They are NOT tetraquarks.