Simons Center for Geometry and Physics

May 28-June 1, 2018

Exotic Hadrons and Flavor Physics

Multiquark States: the QCD String-Junction Picture

Gabriele Veneziano

based on

- G.C. Rossi and G. Veneziano, "A Possible Description of Baryon Dynamics in Dual and Gauge Theories," Nucl. Phys. B **123** (1977) 507.
- G.C. Rossi and G. Veneziano, "Electromagnetic Mixing of Narrow Baryonium States," Phys. Lett. **70B** (1977) 255.
- L. Montanet, G.C. Rossi and G. Veneziano, Phys. Rept. **63** (1980) 149.
- G.C. Rossi and G. Veneziano, "Isospin mixing of narrow pentaquark states," Phys. Lett. B **597** (2004) 338.
- G.C.Rossi and G. Veneziano, "The string-junction picture of multiquark states: an update," JHEP **1606** (2016) 041.

Disclaimers: 1) Only one approach to multiquark states covered; 2) Only some multiquark states covered; 3) Only qualitative.

Outline

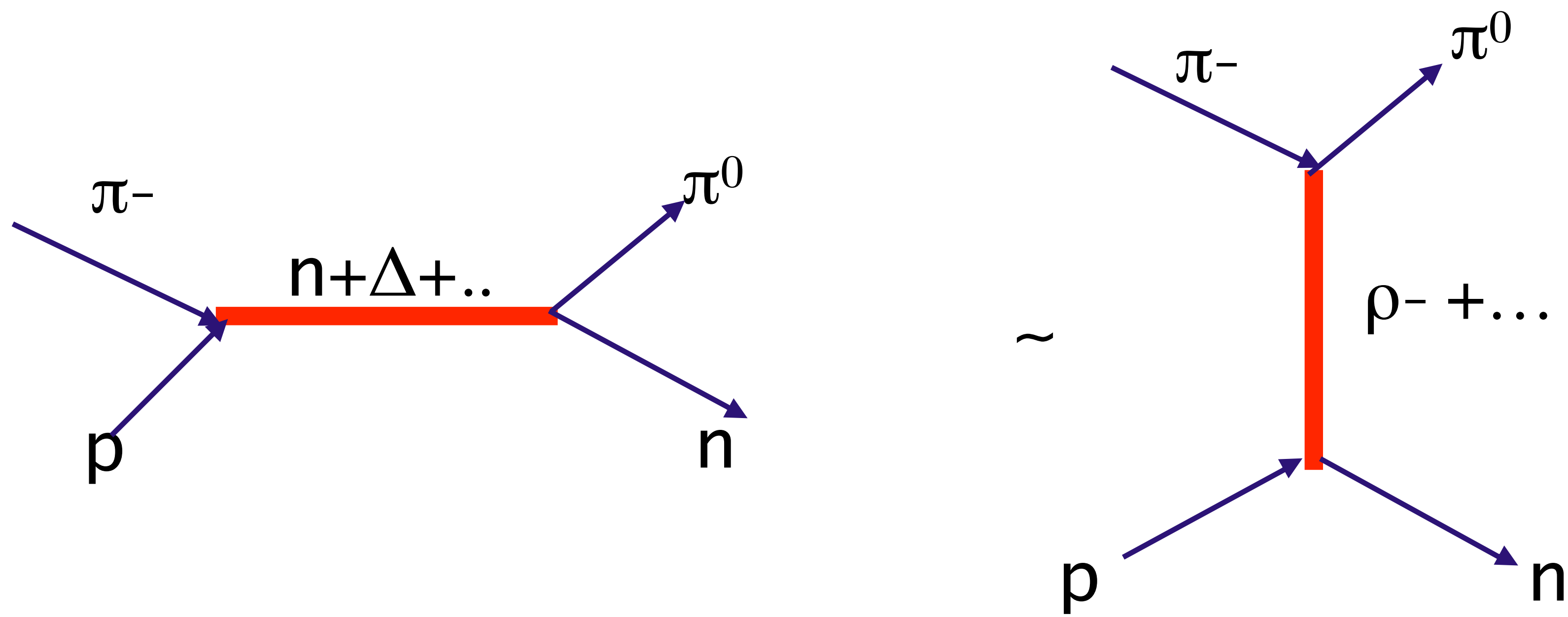
- Pre-QCD duality arguments
- Hadrons & gauge invariant QCD operators
- QCD @ large-N
  - mesons & glueballs: OZI rule
  - baryons a la Witten and a la GCR-GV
- LQCD @ strong coupling:
  - Mesons & glueballs: OZI
  - Baryons and multiquarks: JOZI
- OZI & JOZI selection rules
  - Phenomenological evidence
- Conclusions

Pre-QCD

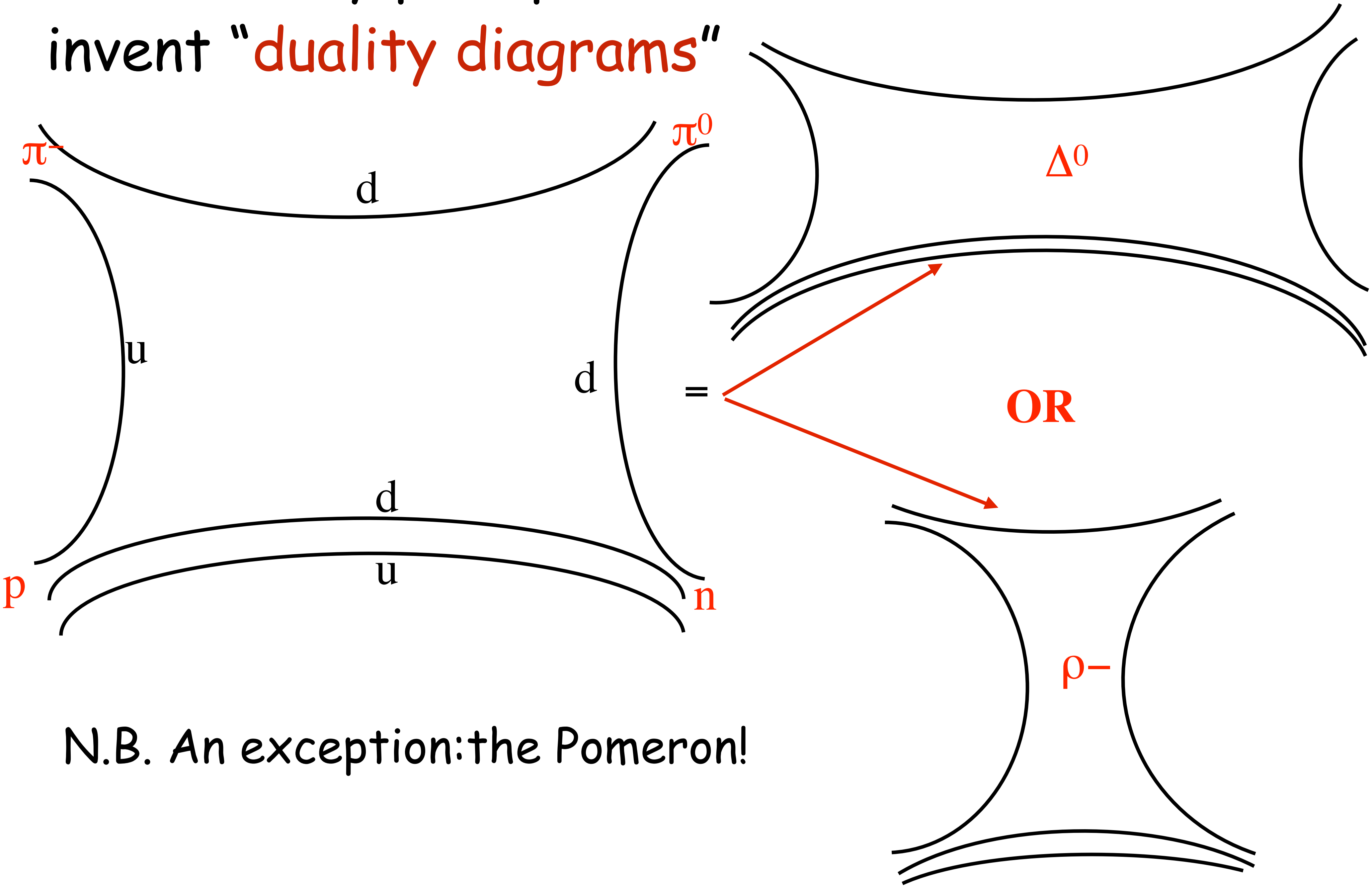
Dolen-Horn-Schmit duality (1967)

s-and t-channel descriptions of pion-nucleon charge exchange are, on average, equivalent, complementary,

DUAL

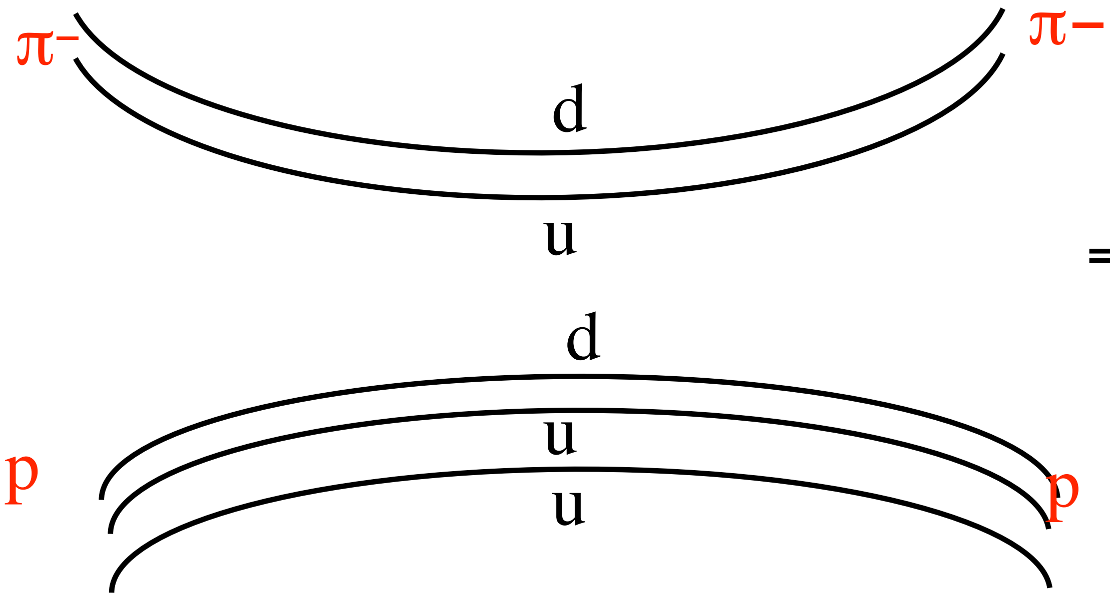


DHS duality prompted Harari and Rosner to invent "duality diagrams"



N.B. An exception: the Pomeron!

The Pomeron is dual to non-resonating multi-particle continuum (Harari-Freund)



= Pomeron exchange in t-channel

= 1 meson + 1 baryon in s-channel

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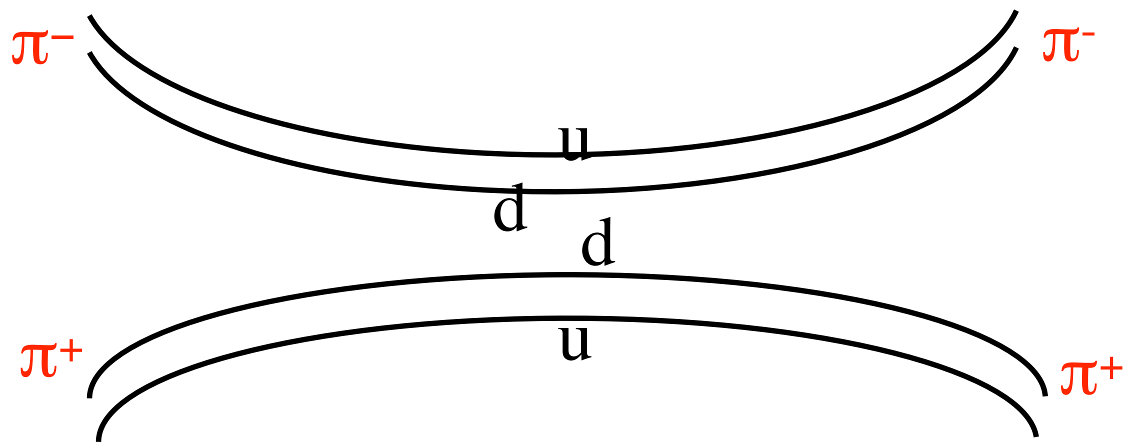
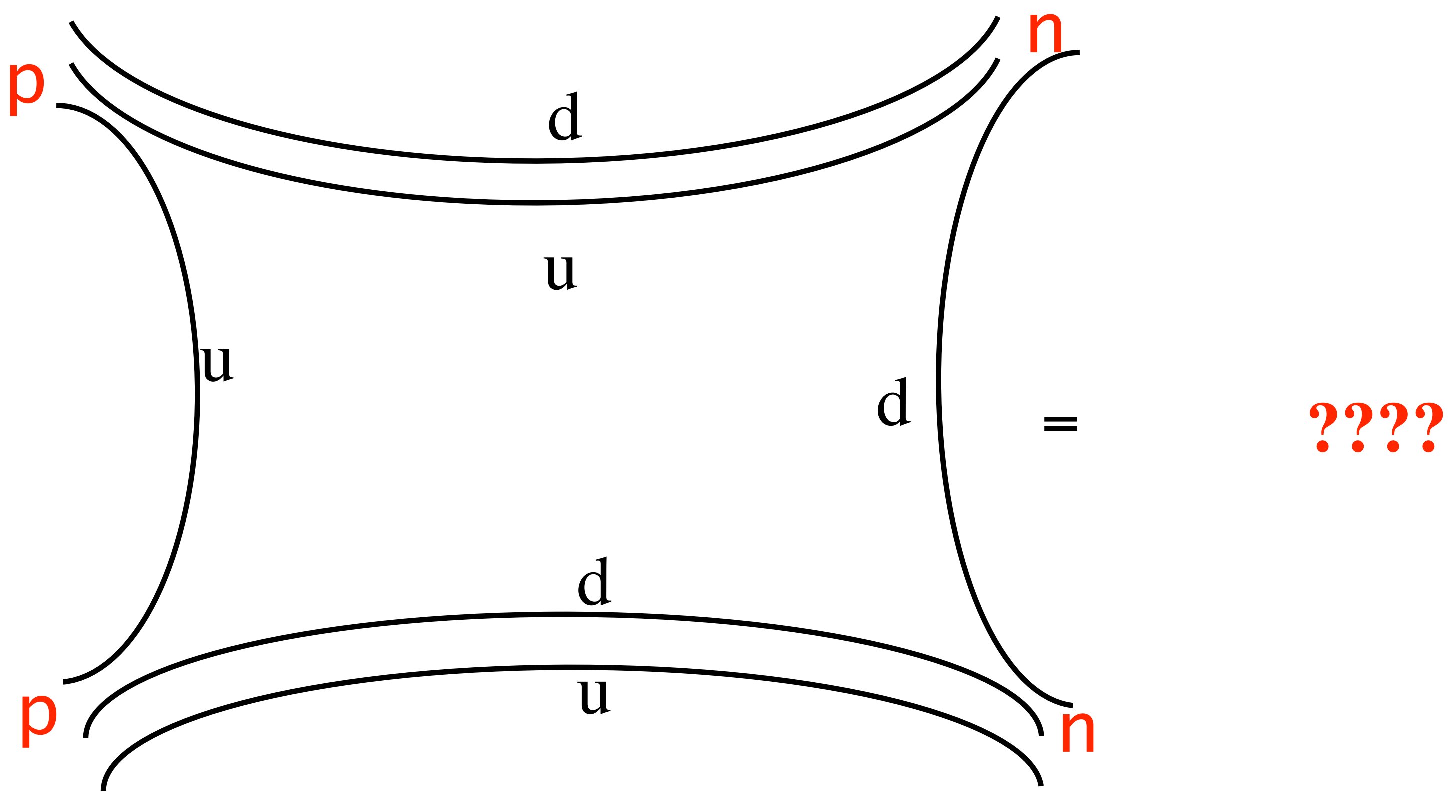


= Pomeron exchange in t-channel

= 2 mesons in s-channel

Rosner's diagram: what about proton antiproton?



Q: What is dual to qqbar mesons? Could it be the same 4-q intermediate state occurring in the $\pi\pi$ Pomeron diagram?
A: unlikely! => a new sector of 4q-states!

After QCD

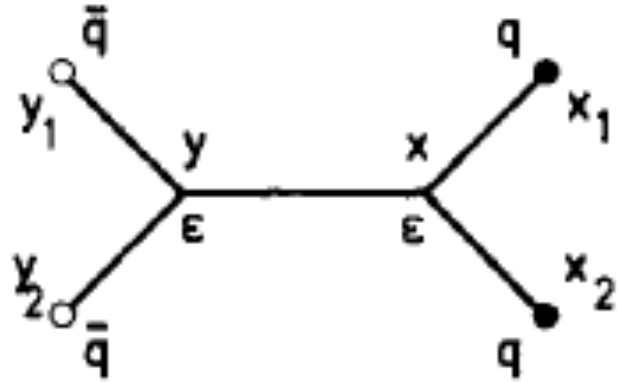
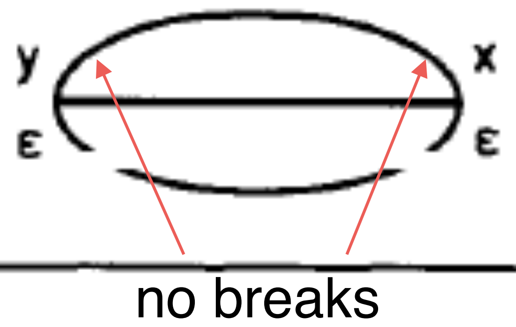
a) Hadrons and "irreducible" gauge-invariant operators

Table IIa

Simplest mesons and baryons : colour structure and string picture

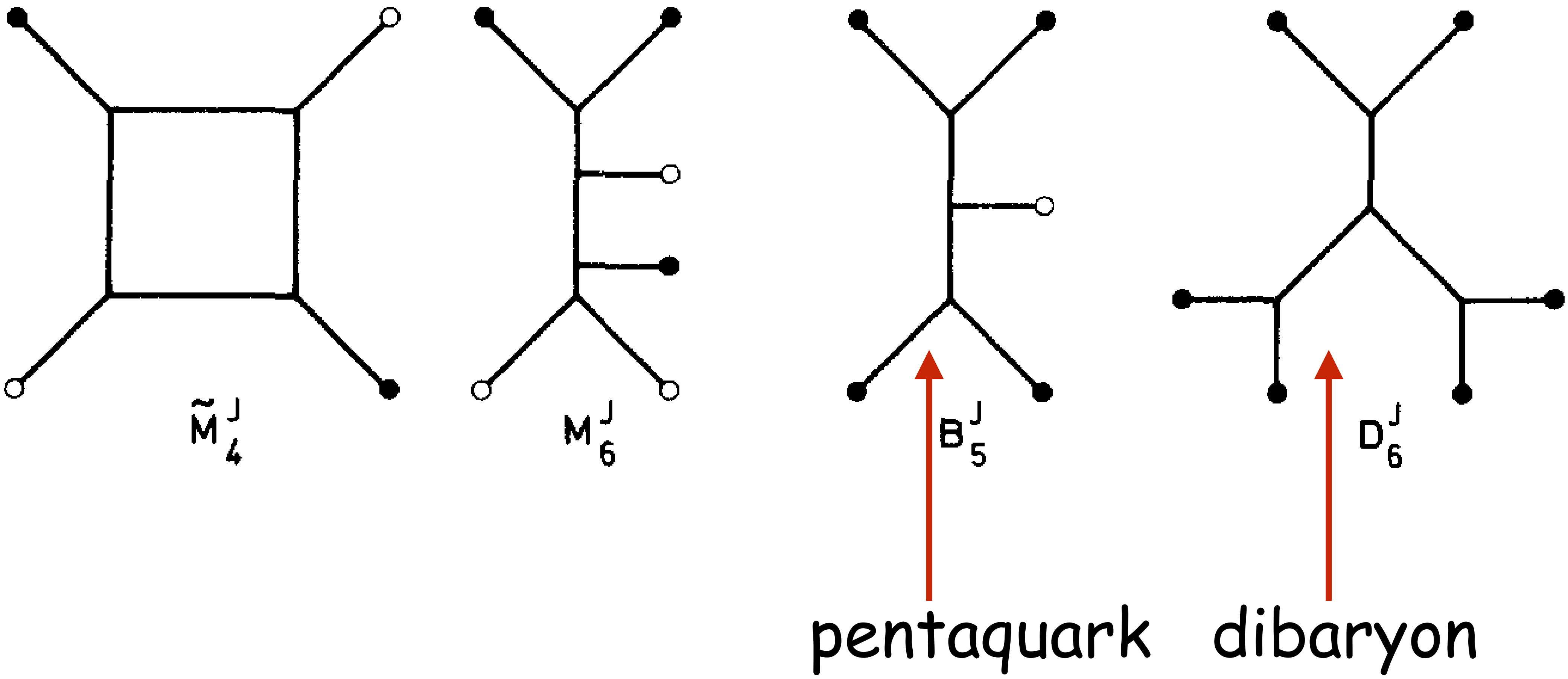
HADRON	GAUGE INVARIANT OPERATOR	STRING PICTURE
$M_2 = q\bar{q}$ meson	$\bar{q}^{j_2}(x_2)\left[P\exp\left(ig\int_{x_1}^{x_2} A_\mu\, dx^\mu\right)\right]^{j_1}_{j_2} q_{j_1}(x_1)$	
M_o = quarkless meson	$\mathrm{Tr}\left[P\exp\left(ig\oint A_\mu\, dx^\mu\right)\right]$	
$B_3 = qqq$ baryon	$\epsilon^{j_1 j_2 j_3}\left[P\exp\left(ig\int_{x_1}^{x} A_\mu\, dx^\mu\right) q(x_1)\right]_{j_1}$ $\left[P\exp\left(ig\int_{x_2}^{x} A_\mu\, dx^\mu\right) q(x_2)\right]_{j_2}\left[P\exp\left(ig\int_{x_3}^{x} A_\mu\, dx^\mu\right) q(x_3)\right]_{j_3}$	

onium families: colour structure and string picture. The symbol exp $\int_x^y$ is a shorthand for the path order exponential used in table 2a

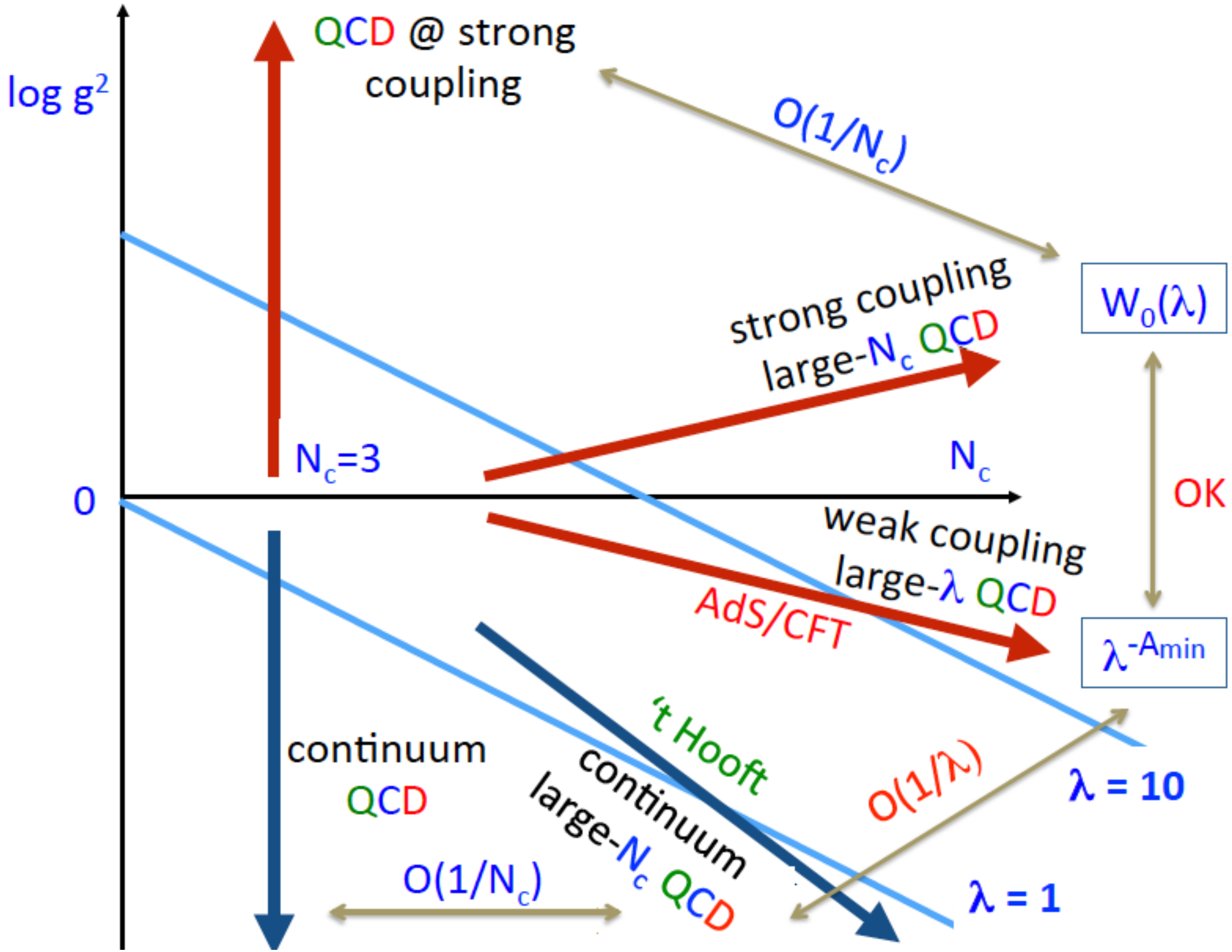
Gauge invariant operator	String picture
$\varepsilon_{j_1j_2j_3}\varepsilon^{k_1k_2k_3}\left[\bar{q}(y_1)\exp\int_y^{y_1}\right]^{j_1}\left[\bar{q}(y_2)\exp\int_y^{y_2}\right]^{j_2} \times\left[\exp\int_x^y\right]^{j_3}_{k_1}\left[\exp\int_{x_1}^x q(x_1)\right]_{k_2}\left[\exp\int_{x_2}^x q(x_2)\right]_{k_3}$	
$\varepsilon_{j_1j_2j_3}\varepsilon^{k_1k_2k_3}\left[\bar{q}(y_1)\exp\int_y^{y_1}\right]^{j_1} \times\left[\exp\int_x^y\right]^{j_2}_{k_1}\left[\exp\int_x^y\right]^{j_3}_{k_2}\left[\exp\int_{x_1}^x q(x_1)\right]_{k_3}$	
$\varepsilon_{j_1j_2j_3}\varepsilon^{k_1k_2k_3}\left[\exp\int_x^y\right]^{j_1}_{k_1}\left[\exp\int_x^y\right]^{j_2}_{k_2}\left[\exp\int_x^y\right]^{j_3}_{k_3}$	

Other multiquark states

(from G. C. Rossi & GV, Phys. Rep. 1982)



Different QCD limits



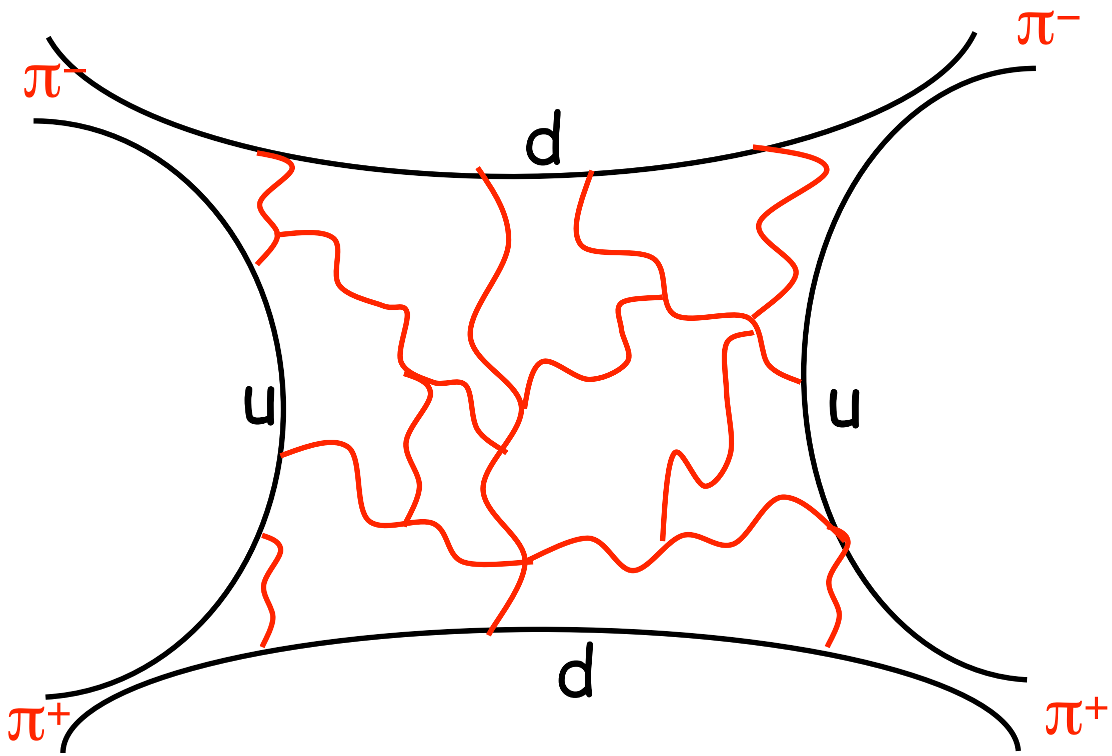
b) Large N considerations

Mesons & glueballs @ large N

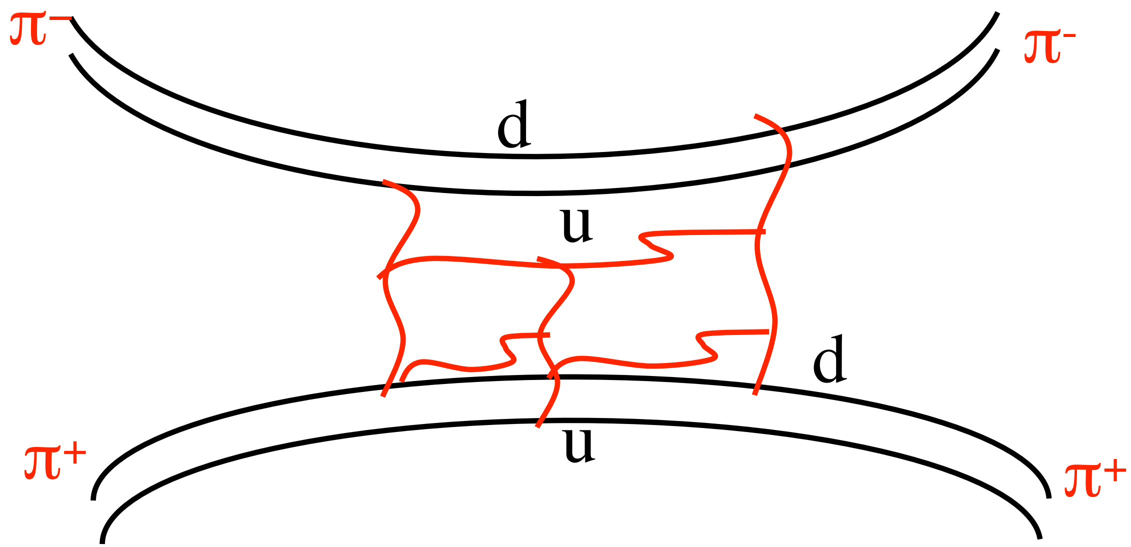
't Hooft 1974

(SU(N) QCD @ large N w/ N_f and $\lambda = g^2N$ fixed)

Duality diagrams correspond to the sum of planar diagrams bounded by quark propagators & filled with gluons.
Both quark loops and non-planar diagrams are excluded.
Hadrons do not decay (tree approximation of **a** string theory)



Similarly: Pomeron ~ glueballs



In 't Hooft's limit glueballs are also stable and do not mix w/ q-qbar states

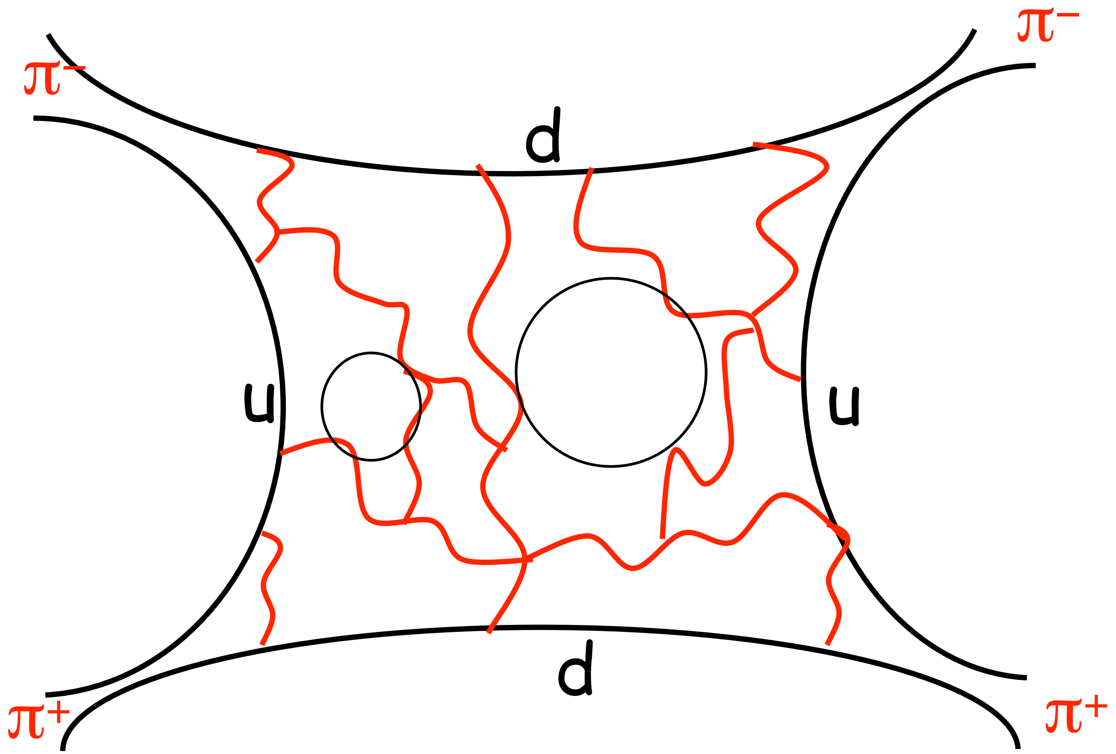
GV 1976

(SU(N)-QCD @ large N w/ N_f/N & $\lambda = g^2N$ fixed)

Planar diagrams w/ quark loops are included.

Hadrons get a finite width $O(N_f/N)$

Quarkonia decay via string breaking i.e. satisfy OZI (narrow!)



Glueballs and quarkonia mix at non-planar level

Baryons and baryonia @ large N

(E. Witten NPB, 1979)

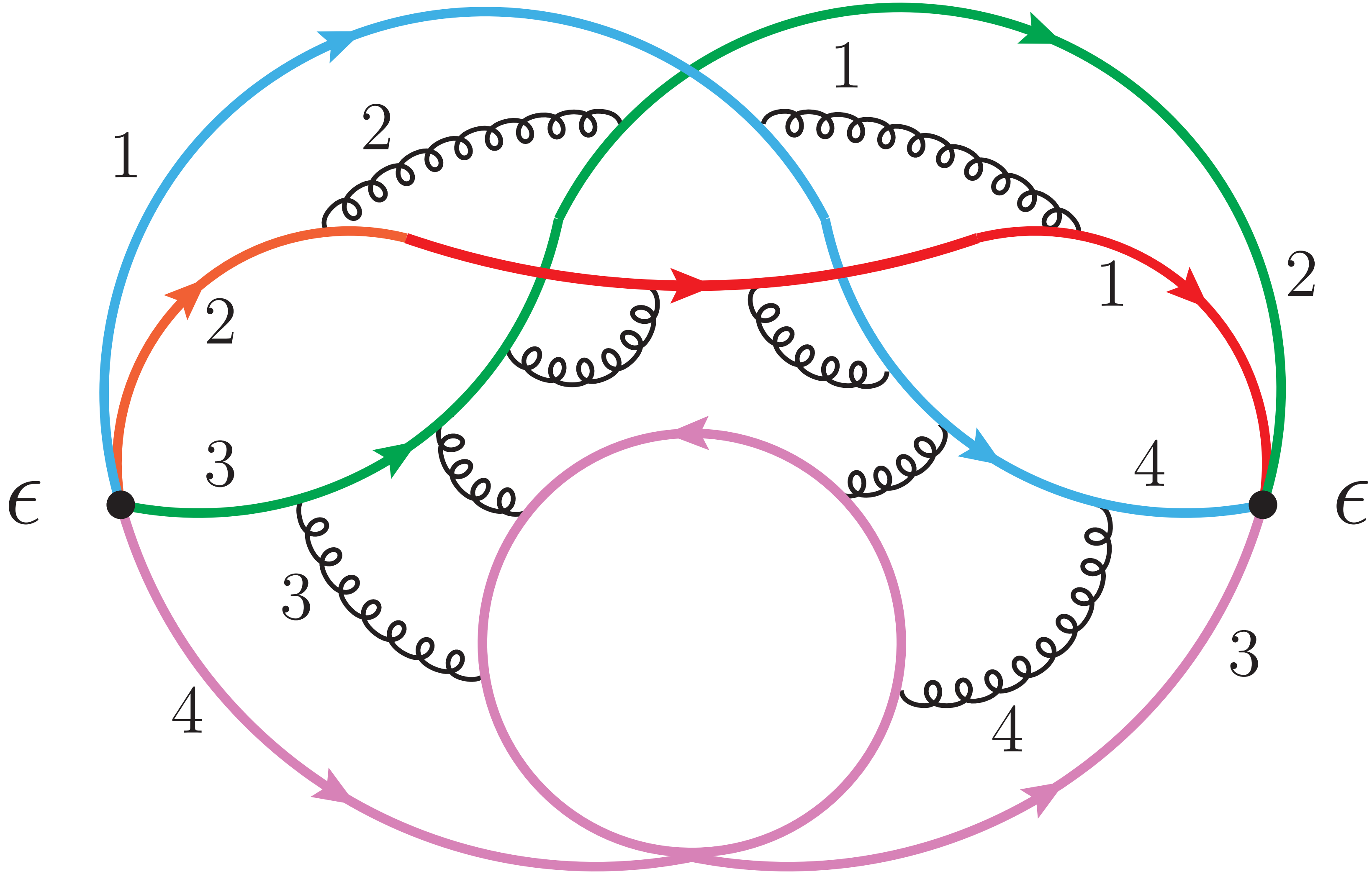
Baryons as solitons since

$M \sim N \sim g^{-2}$

N-body bound state problem

through n-body interactions ($n \leq N$)

Q: Can we define some analog of the large-N expansion for baryons?
A: Most likely yes through some new topological rules.
(G.C.Rossi & GV,1977 & 1603.05830)
It can be done for the n-body potential if $n \ll N$.

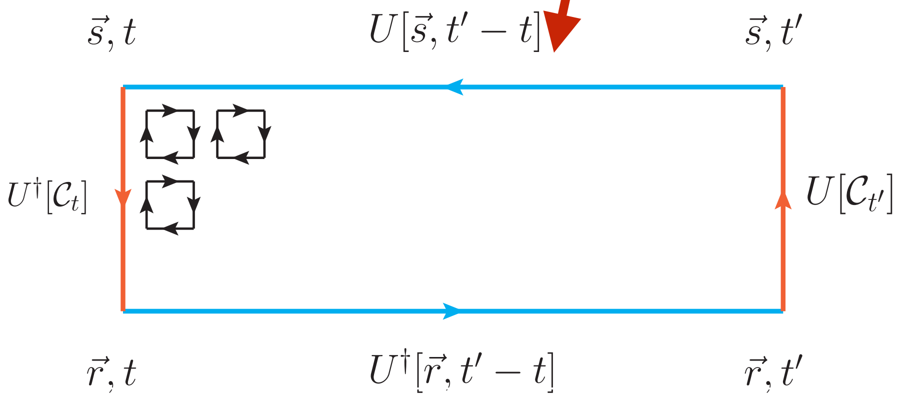


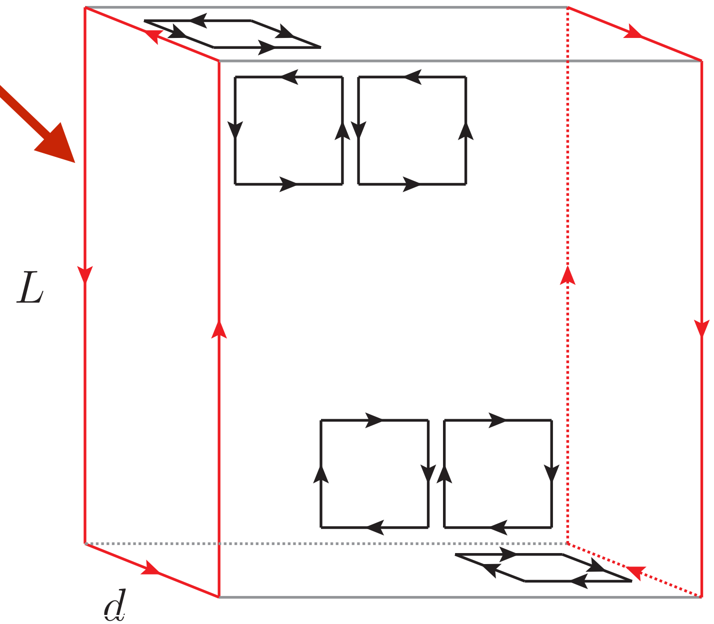
Leading (clown) diagrams for n=4 potential @ large N (colors => flavor)

c) LQCD @ strong ('t Hooft)-coupling

Mesons & glueballs

Meson/glueball propagators and corresponding Wilson loops show confining potential





with a string tension:

$$\kappa = \frac{1}{a^2} \log g^2 N$$

twice as large for closed

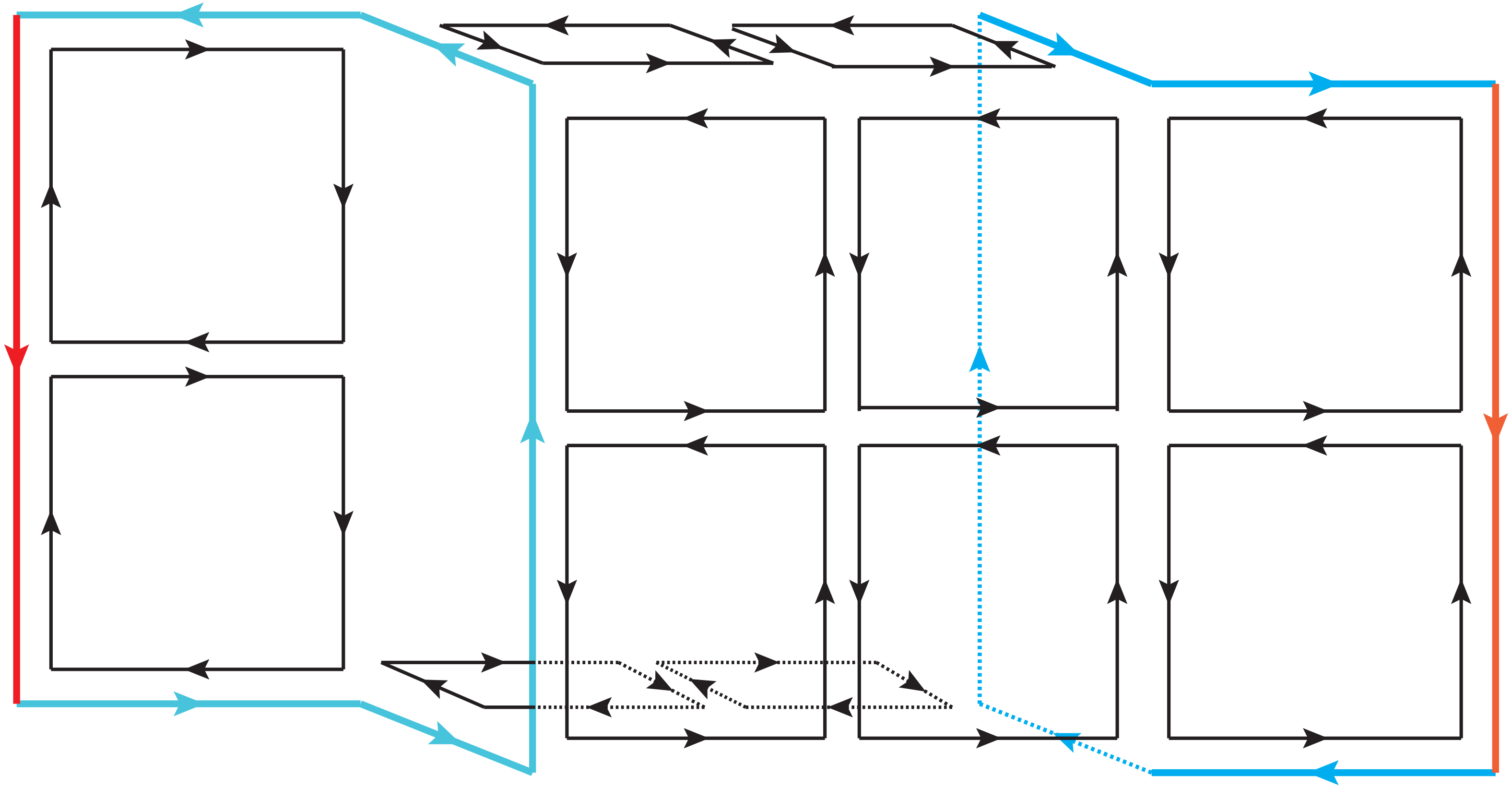
$$\kappa = \frac{1}{a^2} \log g^2 N$$

Note that the tension depends on the combination $\lambda = g^2N$, the 't Hooft coupling.

Indeed, one can argue (O' Brien-Zuber '85) that the strong-coupling expansion, at least for the meson sector, is actually a large-λ expansion*).

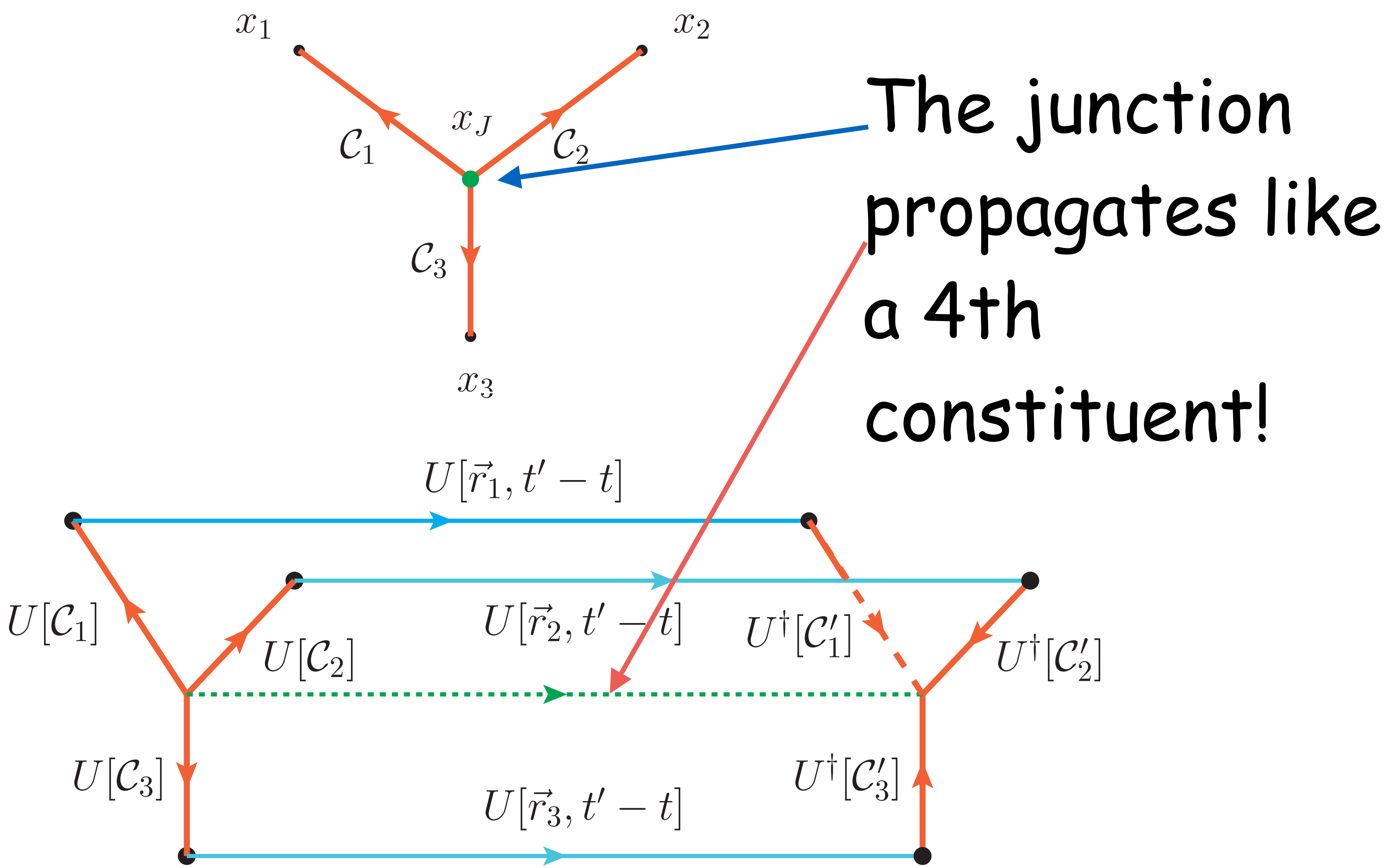
*) Also much used (SUGRA-limit) in the AdS/CFT correspondence (Maldacena).

Meson-glueball mixing (and OZI-violation) suppression at large N and/or at large λ

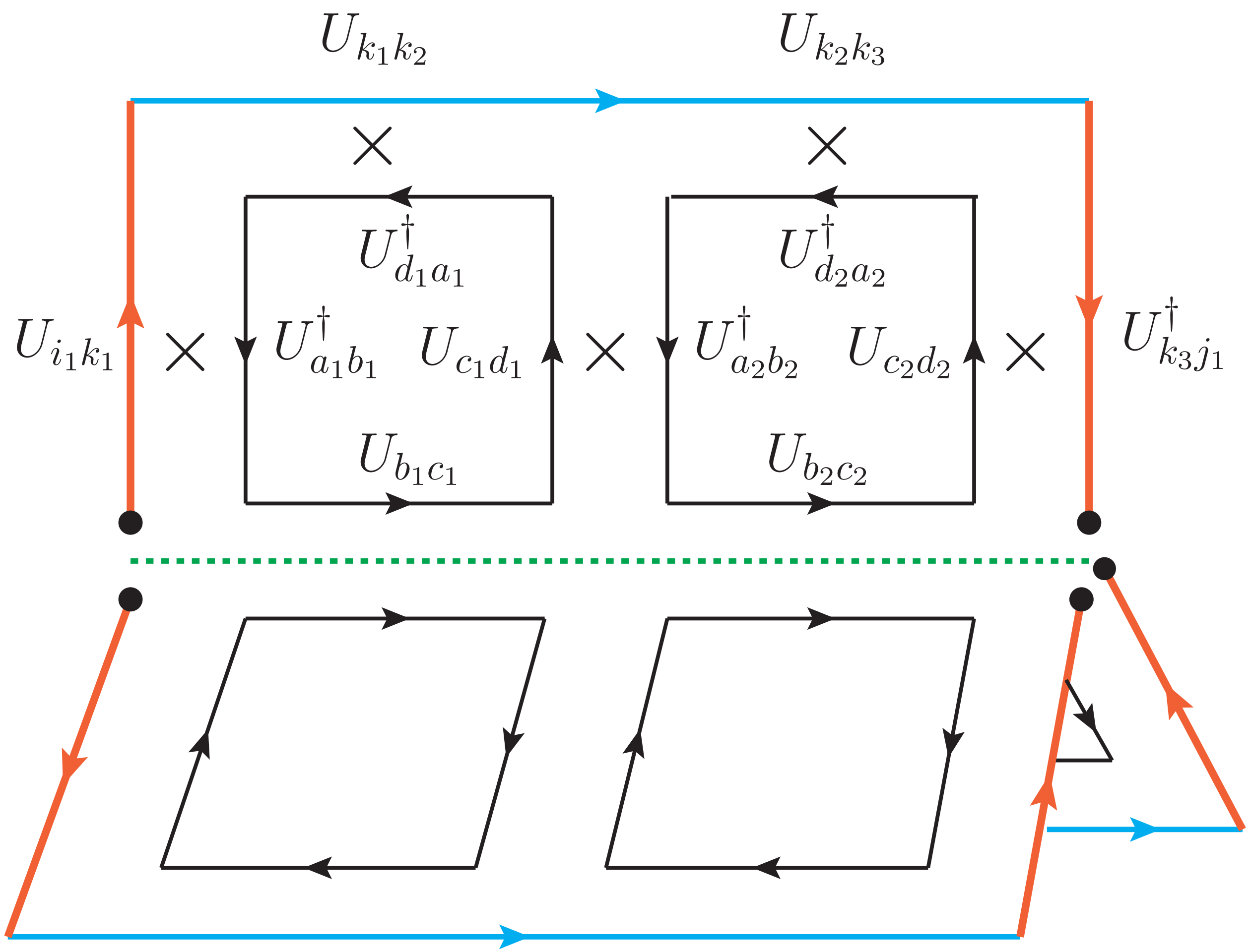


Baryons and baryonia @ strong-coupling in LQCD

Baryons and their propagator



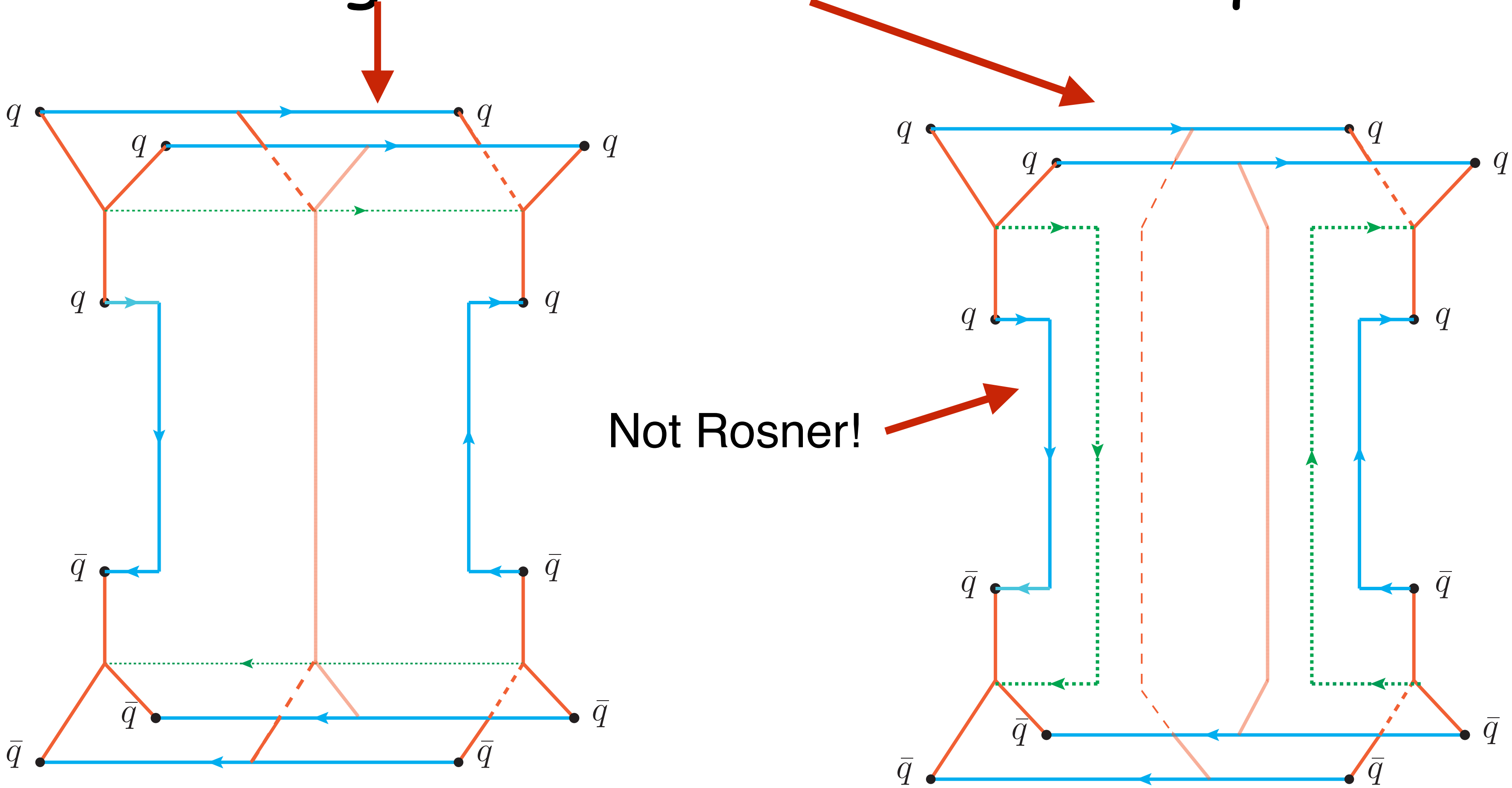
Baryonic Wilson loop in strong coupling LQCD



Tiling w/ the minimum number of tiles....

B-Bbar scattering in strong coupling LQCD:

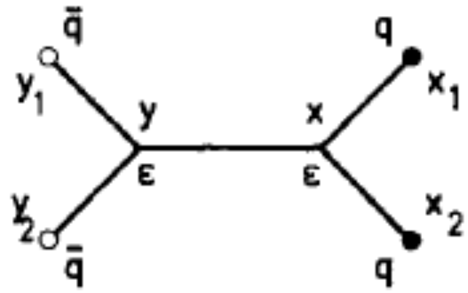
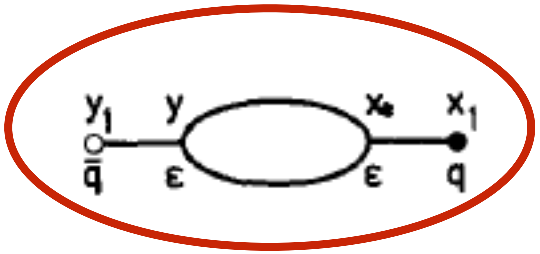
Rosner's diagram & and one w/ same quark-flow



s-channel scattering w/ tetraquark states dual to qqbar mesons

s-channel annihilation w/ 2-meson states dual to 2-q states with junctions

The three ($N_c = 3$) baryonium families: colour structure and string picture. The symbol $\exp\int_x^y$ is a shorthand for the path ordered exponential used in table 2a

Hadron	Gauge invariant operator	String picture
M_4^J = baryonium with $qq\bar q\bar q$ quantum numbers	$\varepsilon_{j_1j_2j_3}\varepsilon^{k_1k_2k_3}\left[\bar q(y_1)\exp\int_y^{y_1}\right]^{j_1}\left[\bar q(y_2)\exp\int_y^{y_2}\right]^{j_2} \times\left[\exp\int_x^y\right]^{j_3}_{k_1}\left[\exp\int_{x_1}^x q(x_1)\right]_{k_2}\left[\exp\int_{x_2}^x q(x_2)\right]_{k_3}$	
M_2^J = baryonium with $q\bar q$ quantum numbers	$\varepsilon_{j_1j_2j_3}\varepsilon^{k_1k_2k_3}\left[\bar q(y_1)\exp\int_y^{y_1}\right]^{j_1} \times\left[\exp\int_x^y\right]^{j_2}_{k_1}\left[\exp\int_x^y\right]^{j_3}_{k_2}\left[\exp\int_{x_1}^x q(x_1)\right]_{k_3}$	
M_0^J = quarkless baryonium	$\varepsilon_{j_1j_2j_3}\varepsilon^{k_1k_2k_3}\left[\exp\int_x^y\right]^{j_1}_{k_1}\left[\exp\int_x^y\right]^{j_2}_{k_2}\left[\exp\int_x^y\right]^{j_3}_{k_3}$	

OZI rule

Large-N expansions and strong coupling expansions support the usual OZI rule suppressing decays that proceed via q-qbar annihilation wrt decays by string breaking (& creation of a q-qbar pair).

Well obeyed (also wrt mixing) in vector mesons; badly broken in light pseudoscalar sector.
Reasons (Cf. WV solution of U(1) problem):

Light masses of quasi NG bosons

Large anomaly contribution in that channel (also responsible for "spin crisis"?)

JOZI rule (G.C. Rossi and GV, 1977)

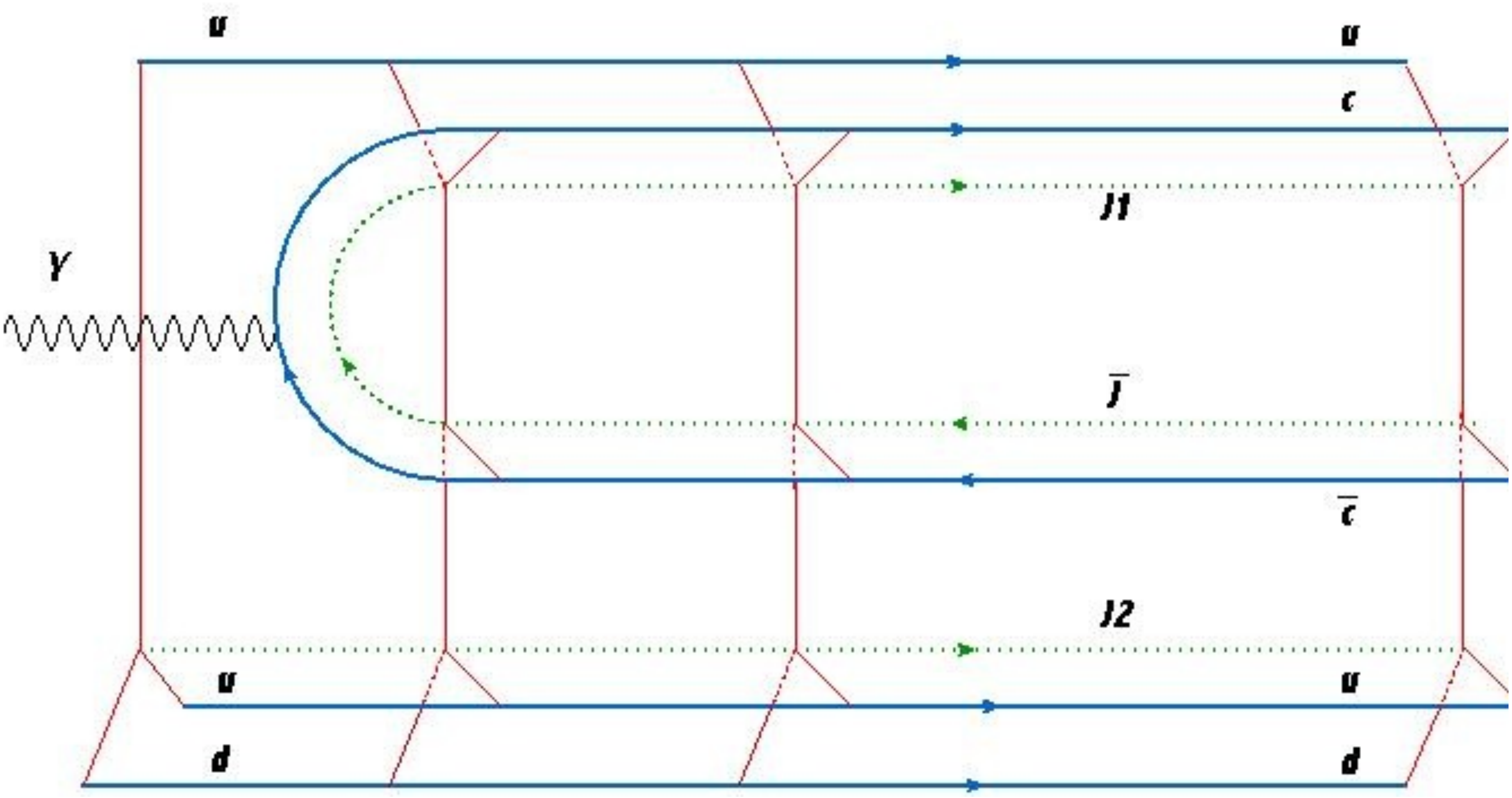
Large-N expansions (Witten 1979, G.C.R. & GV 2016) and strong coupling expansions (G.C.R. & GV 2016) also support a junction OZI (JOZI) rule suppressing decays that proceed via junction-antijunction annihilation (leading to mesonic decays) wrt decays by string breaking (leading to baryonic decays)

Mesophobic tetraquarks (unlike molecular tetraquarks that should love mesons... clear distinction?)

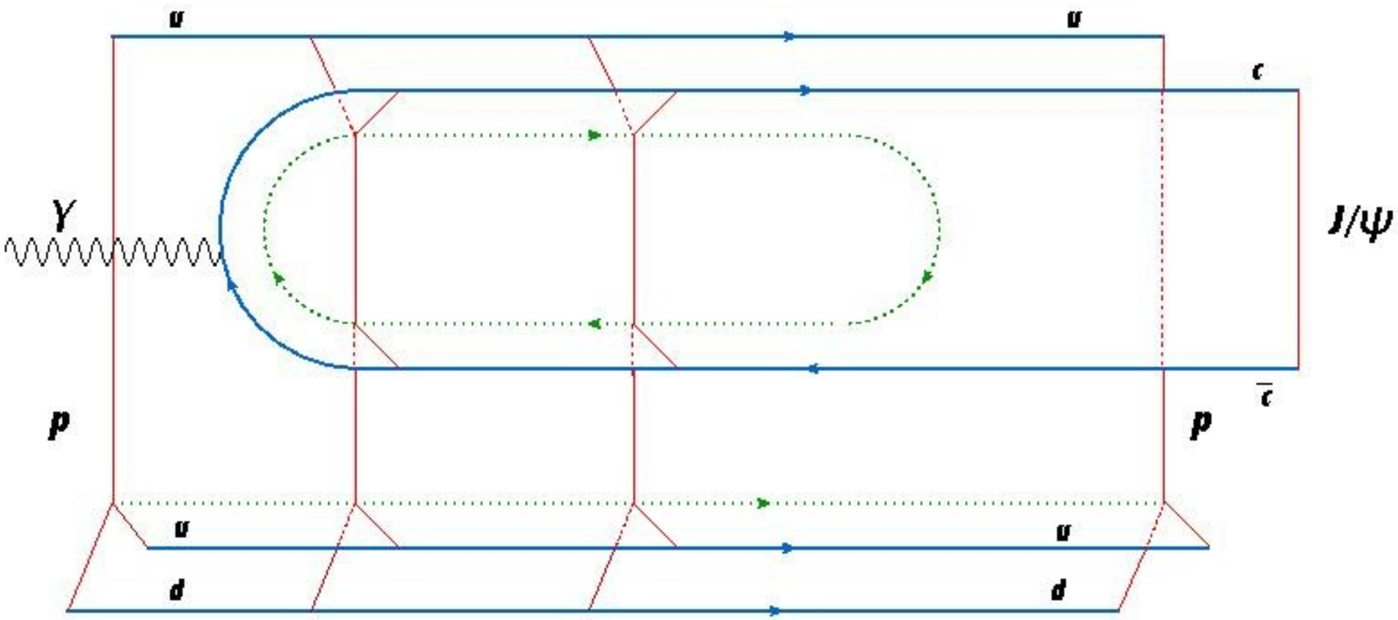
We thus expect (some) tetraquark states lying below threshold for baryonic decays to be unusually narrow.

A systematic analysis still to be done.

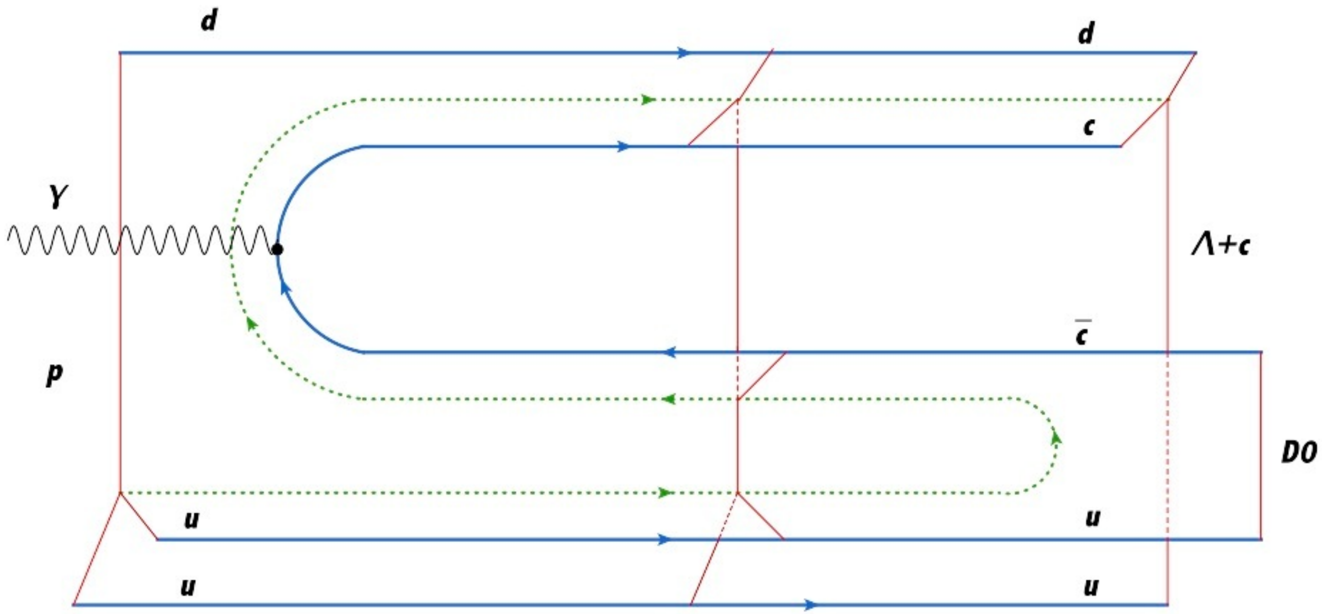
Photoproduction of $P_c^+(4450)$ in junction picture



and possible final states via



junction
loop



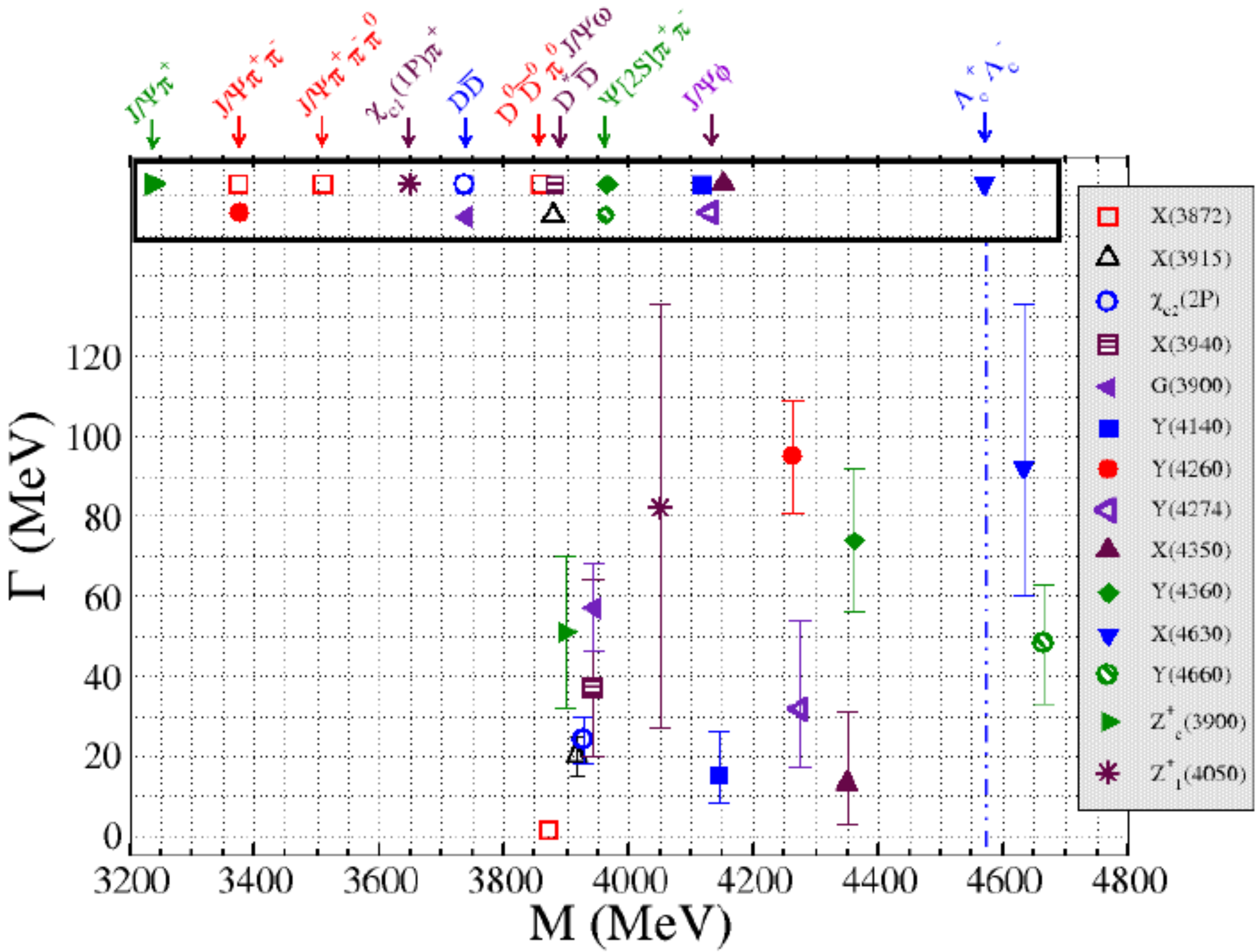
junction
snake

Conclusions

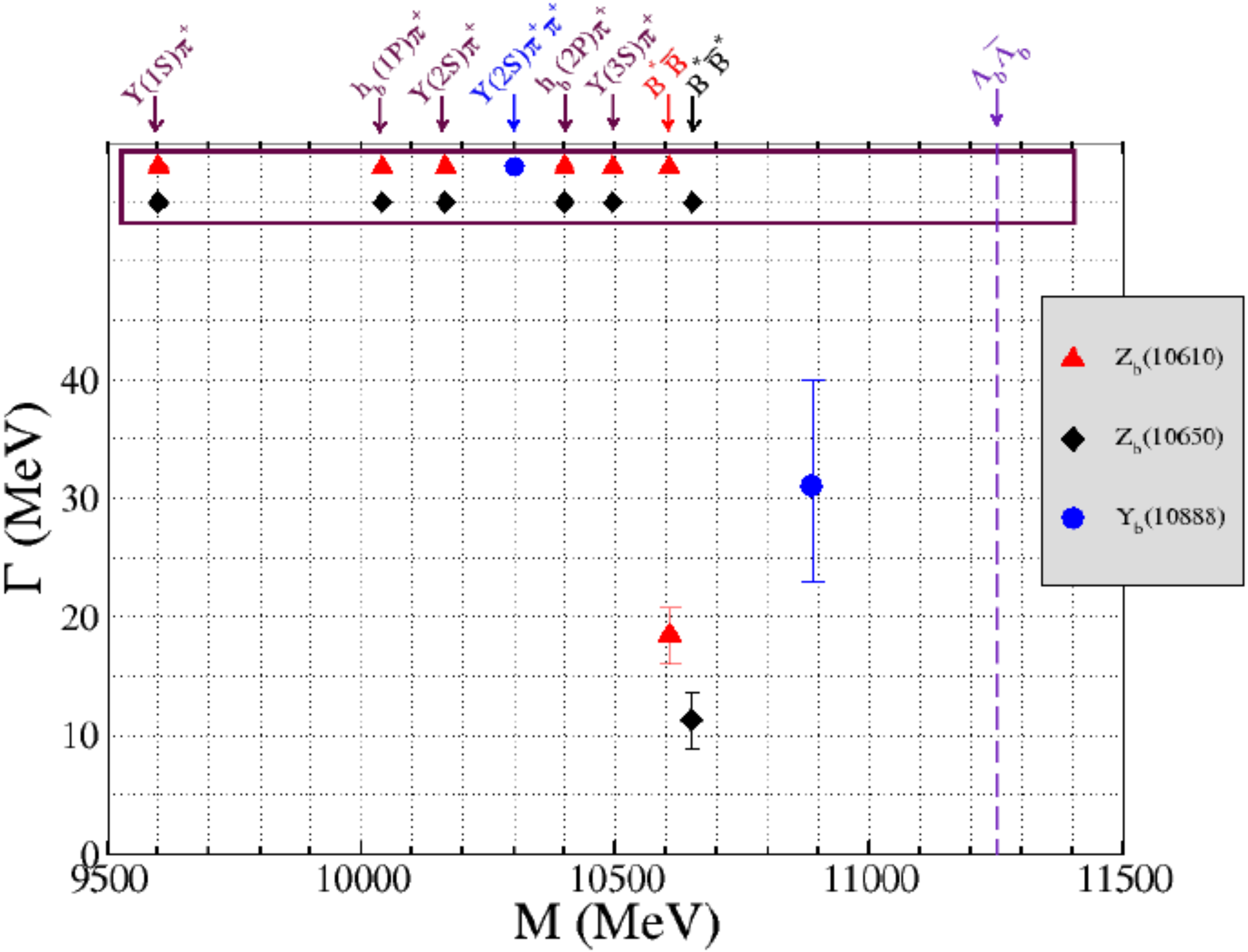
- The prediction of (baryonium) tetraquark states is ~50 years old and predates QCD
- Within QCD several non-perturbative expansions confirm that prediction neatly distinguishing channels w/ and w/out hidden baryon number (junctions)
- They also support both the old OZI rule and its JOZI generalization, implying that **some** tetraquarks should be mesophobic
- There is some phenomenological support for the baryonium nature of **some** tetraquark states
- More work is needed to separate them from other exotic multiquark states (e.g. molecules) with very different properties.

Thank You!

c-tetraquarks



b-tetraquarks



pentaquarks