The puzzle of the Exotic Hadrons (XYZ)

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1. New States

Baryons can now be constructed from quarks by using the combinations (q q q), (q q q q q̄), etc., while mesons are made out of (q q̄), (q q q̄ q̄), etc. It is assuming that the lowest

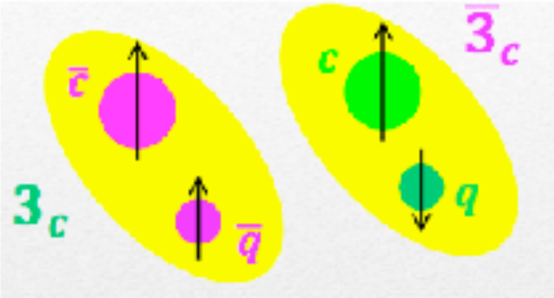
M. Gell-Mann, A Schematic Model of Baryons and Mesons, PL **8**, 214, 1964

- For long, we lived with the simplest paradigm:

$$\text{mesons} = q\bar{q}, \quad \text{baryons} = qqq$$

- Paradigm rested on the absence of I=2, ππ resonances and of S>0 baryons.
- The case had to be revisited, because the lowest lying, octet of scalar mesons- $f_0(980)$, $a_0(980)$, kappa(800) and sigma(600)- does not fit in the picture.
- The X(3872), narrow width, with decays into J/Psi+ 2π/3π, discovered by Belle in 2003, does not fit into the "charmonium" states,
- since then, Belle, BaBar, BES and LHcB have reported many other states that do not fit the charmonium picture, called X (1^{++}) and Y(1^{--}) states: molecules? hybrids? tetraquarks?
- In 2007, Belle observed a charged "charmonium", $Z^+(4430) \to \psi(2S) + \pi$, that could not be interpreted as molecule, but later Babar suggested it was simply a reflection of K* states
- LHCb has confirmed the $Z^+(4430)$ while other similar states, $Z^+(3900)$ and $Z^+(4020)$, have been discovered by BES III and confirmed by BELLE and by CLEOc.
- Pentaquark discovered (P-> Ψ p) by LHCb in 2015
- New structures in Ψ φ spectrum in 2016…. more to follow?

A new spectroscopy of mesons and baryons revealed



terminology of unanticipated charmonia

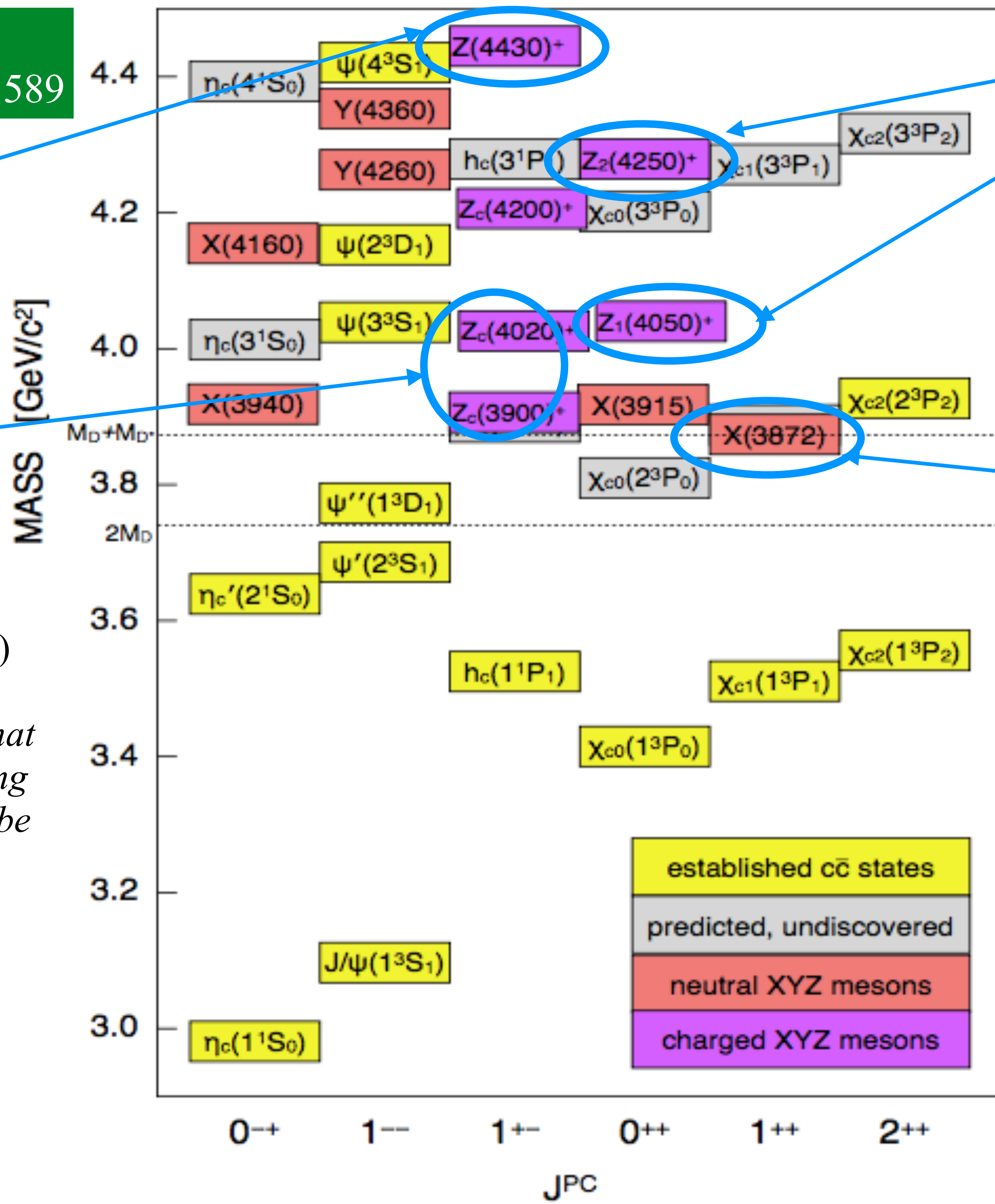
- X, e.g. X(3872): neutral, typically seen in J/Psi+pions, positive parity, $J^{PC}=0^{++}, 1^{++}, 2^{++}$
- Y, e.g. Y(4260): neutral, seen in e^+e^- annihilation with Initial State Radiation, therefore $J^{PC}=1^{--}$
- Z, eg. Z(4430): charged/neutral, typically positive parity, 4 valence quarks manifest, mostly seen to decay in $\Psi+\pi$ and some in $h_c(1P)+\pi$ (valence quarks: c c-bar u d-bar); Z_b observed (b b-bar u d-bar);
- open beauty Z(5568)->$B_s+\pi$ (b s-bar u d-bar) claimed by D0 but not confirmed by LHCb.

1. Expected and Unexpected Charmonia

figure by:
S. L. Olsen, arXiv:1511.01589

recent additions:
more than coincidence?
or
an almost filled multiplet?

2nd Unexpected
a radial excitation?



3rd case:
start a multiplet?

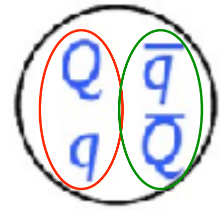
1st Unexpected

Maiani, Polosa, Riquer (2008)
a crucial consequence of a Z(4430) charged particle is that another charged state decaying into $\Psi(1S)\ \pi^{\pm}$ or $\eta_c\ \rho^{\pm}$ should be found around 3880 MeV
i.e. almost degenerate with X(3872)

Models for XYZ Mesons

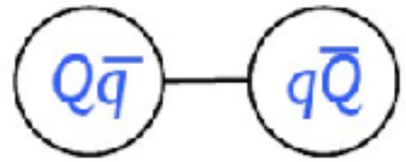
Quarkonium Tetraquarks

This Talk → • compact tetraquark



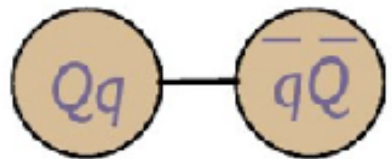
L. Maiani, A. Polosa, V. Riquer, F, Piccinini, Phys. Rev. D **89**, 114010 (2014) and reffs therein

Hanhart and Karliner' Talks → • meson molecule



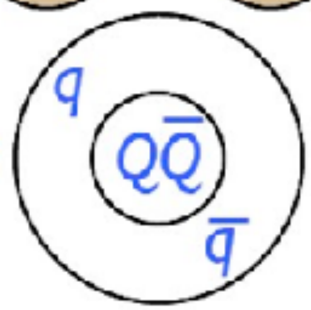
M.Cleven, F.K.Guo, C.Hanhart, Q.Wang and Q.Zhao, arXiv:1505.01771 and refs. therein

• diquark-onium



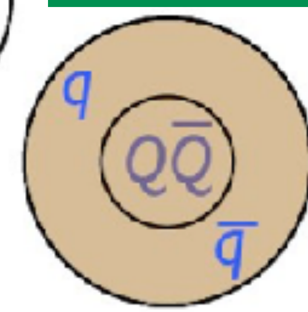
A. Ali, L. Maiani, A. D. Polosa and V. Riquer, Phys. Rev. D **91** (2015) 1, 017502 and refs. therein

• hadro-quarkonium



X.Li, M.B.Voloshin, Mod. Phys. Lett. **29**(2014) 12, 1450060 and refs. therein

• quarkonium adjoint meson



Few think that X, Y, Z are kinematic effects due to the opening of new channels: see E. S. Swanson, *Cusps and Exotic Charmonia*, arXiv:1504.07952 [hep-ph]
However, it takes a lot of unconventional dynamics to produce the X(3872) as a "cusp"
Also, the phase of Z(4430) goes at 90^0 at the peak, like a text-book Breit-Wigner resonance...

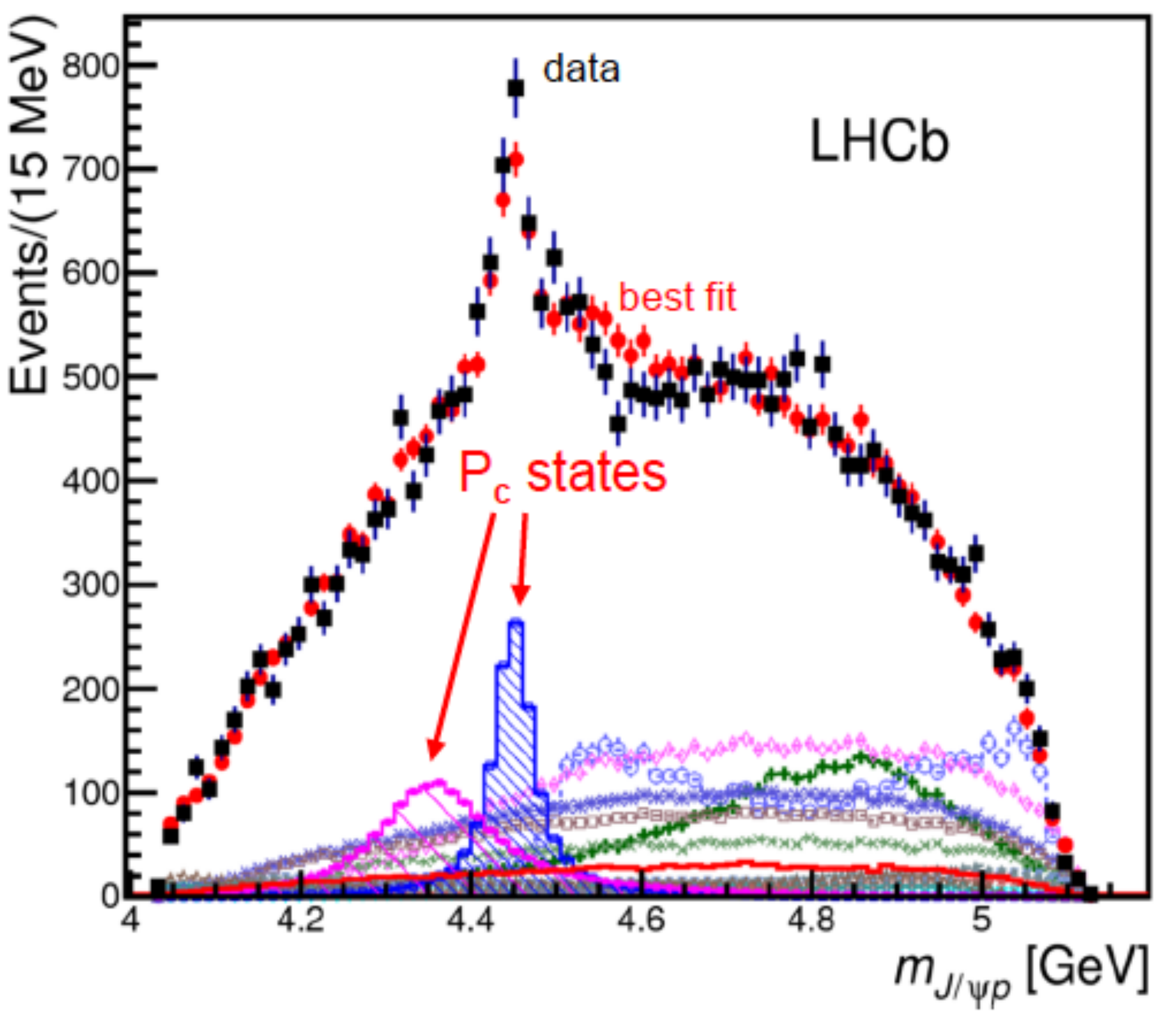
Sergio Bertolucci, Bologna 2015

$J/\Psi p$ resonances consistent with pentaquark states

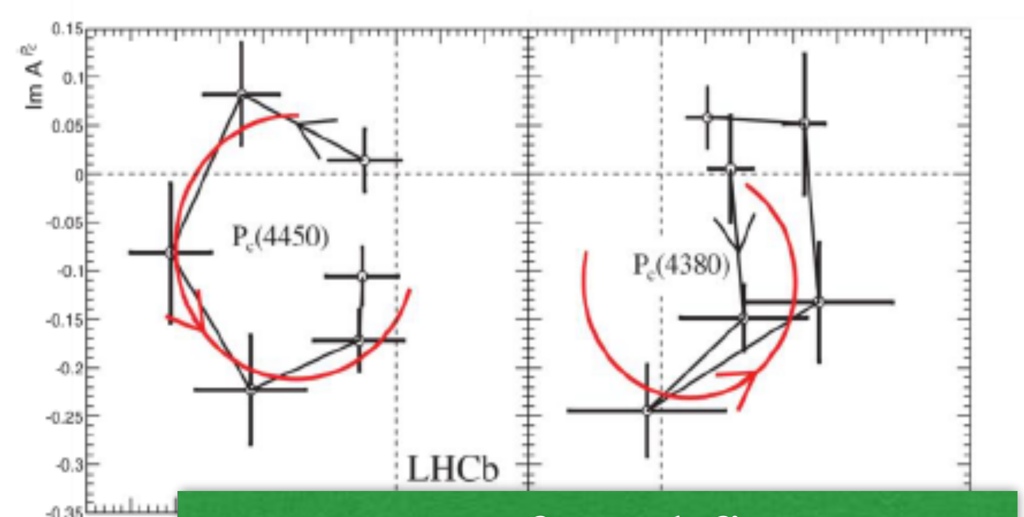
[PRL 115 (2015) 072001]

Need to add two states with content uudccbar.
Best fit has J=3/2 and 5/2 with opposite parities.

$P_c(4380)$:
$M = 4380 \pm 8 \pm 29$ MeV,
$\Gamma = 205 \pm 18 \pm 86$ MeV
$P_c(4450)$:
$M = 4449.8 \pm 1.7 \pm 2.5$ MeV
$\Gamma = 39 \pm 5 \pm 19$ MeV



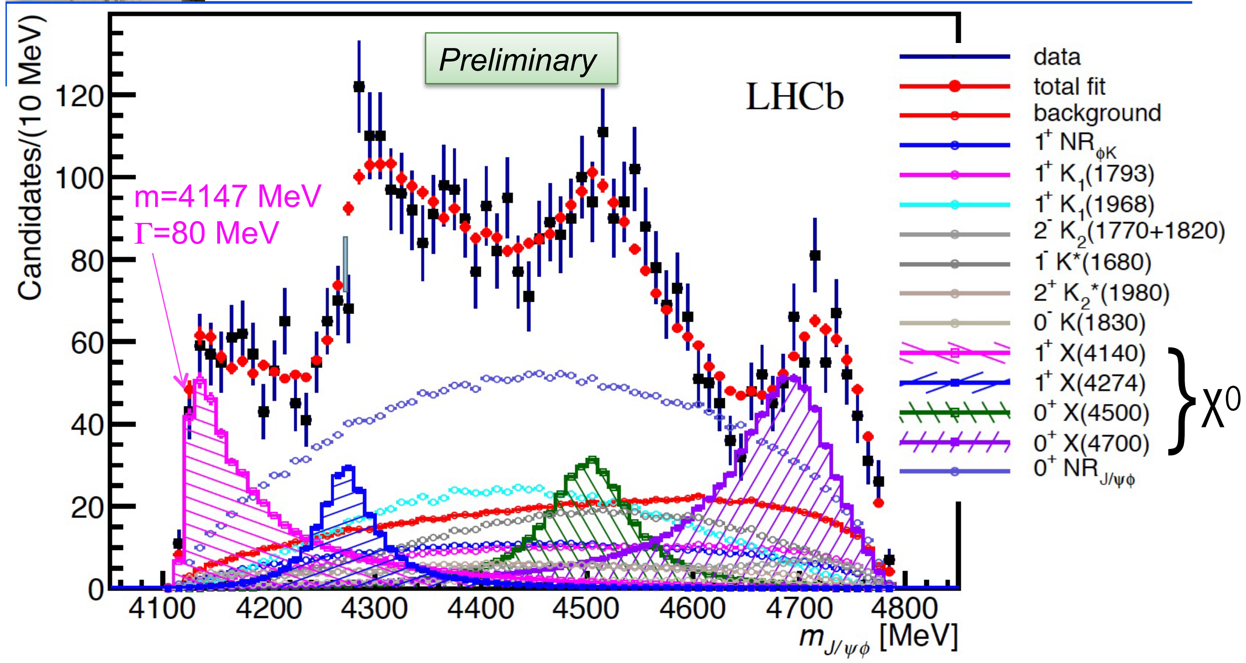
Clear resonant behaviour for narrow state,
Need more statistics to elucidate other state.



preferred fit
P(4380)=3/2⁻, P(4450)=5/2⁺

Old and new structures observed by LHCb
arXiv:1606.07895

Results of fit: m(J/ψφ)



- 4 visible structures fit with BW amplitudes

Results of fit

- J^P also measured all with >4σ significances

Particle	J^P	Significance	Mass (MeV)	Γ (MeV)	Fit Fraction (%)
X(4140)	1^+	8.4 σ	$4146.5 \pm 4.5^{+4.6}_{-2.8}$	$83 \pm 21^{+21}_{-14}$	$13.0 \pm 3.2^{+4.8}_{-2.0}$
X(4274)	1^+	6.0 σ	$4273.3 \pm 8.3^{+17.2}_{-3.6}$	$56 \pm 11^{+8}_{-11}$	$7.1 \pm 2.5^{+3.5}_{-2.4}$
X(4500)	0^+	6.1 σ	$4506 \pm 11^{+12}_{-15}$	$92 \pm 21^{+21}_{-20}$	$6.6 \pm 2.4^{+3.5}_{-2.3}$
X(4700)	0^+	5.6 σ	$4704 \pm 10^{+14}_{-24}$	$120 \pm 31^{+42}_{-33}$	$12 \pm 5^{+9}_{-5}$
NR	0^+	6.4 σ			$46 \pm 11^{+11}_{-21}$

- Four structures
- positive parity, J=0 and 1, positive charge conjugation
- X(4140) seen previously by CDF, D0, CMS and by BELLE

We suggest to fit the structures in two tetraquark multiplets, S-wave ground state and the first radial excitation, with composition $[cs][\bar{c}\bar{s}]$.

L. Maiani, A. Polosa, V. Riquer, PRD **94** (2016) 054026

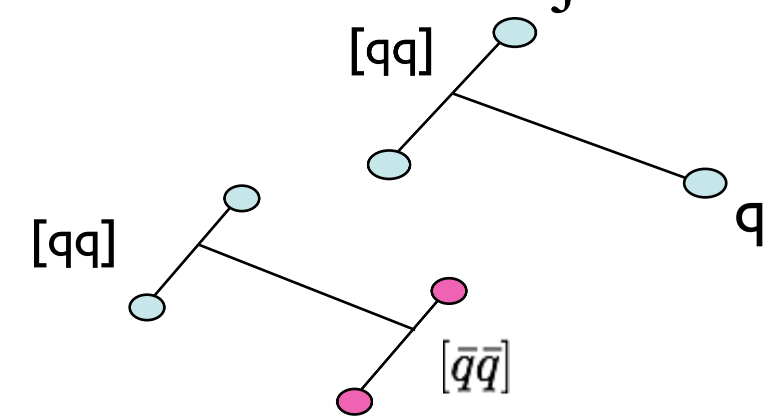
With the previously identified $[cq][\bar{c}\bar{q}]$ $(q = u,\ d)$ multiplet, the new resonances would make a step towards a ***full nonet*** of S-wave tetraquarks made by c c-bar with a pair of light (u, d, s) quarks.

2. Diquarks and molecules

- ***QCD forces and spin-spin are attractive in the completely antisymmetric diquark [qq']: the "good diquark" (Jaffe, 1977)***

$$\text{color} = \bar{3};\ \ SU(3)_{flavor} = \bar{3}; \text{spin} = 0$$

- result holds in QCD perturbative (one gluon exchange) and non perturbative (one instanton exchange)
- To form hadrons, good or bad diquarks need to combine with other colored objects:
- with q → baryon (e.g. Λ), Y-shape
- with $[\bar{q}\bar{q}]$ → scalar meson, H-shape (Rossi &Veneziano,)



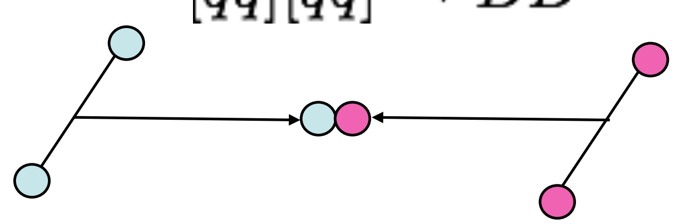
We expect many states: the string joining diquarks may have radial and orbital excitations

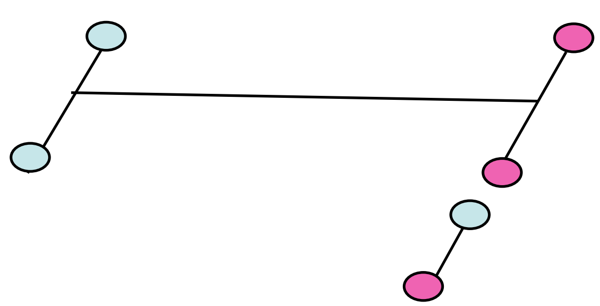
in different words:
J. Sonnenschein and D. Weissman, arXiv:1606.02732 [hep-ph].

…We propose a simple criterion to decide whether a state is a genuine stringy exotic hadron - a tetraquark - or a "molecule". If it is the former it should be on a (modified) Regge trajectory…..

Decays: the string topology is more related to Baryon-antiBaryon: B-antiB decay

$$[qq][\bar{q}\bar{q}] \to B\bar{B} \qquad [qq][\bar{q}\bar{q}] \to [qq][\bar{q}\bar{q}] + \text{meson}$$





Diquarks vs Molecules (cont'd)

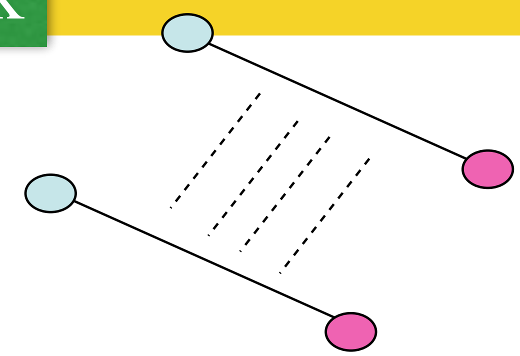
- The possibility of bound states of colourless hadrons raised by De Rujula, Georgi and Glashow;
- Has received a lot of attention for XYZ states:

A. De Rujula, H. Georgi and S. L. Glashow, Phys. Rev. Lett. 38 (1977) 317.

N. A. Tornqvist, Phys. Rev. Lett. **67**, 556 (1991); Z. Phys. C **61**, 525 (1994).
A. V. Manohar and M. B. Wise, Nucl. Phys. **B 399**, 17 (1993);
A. E. Bondar, A. Garmash, A. I. Milstein, R. Mizuk and M. B. Voloshin,
F. K. Guo, C. Hanhart and U. G. Meissner, Phys. Rev. Lett. **102**, 242004 (2009)
see also: M. Cleven, F. K. Guo, C. Hanhart, Q. Wang and Q. Zhao, Phys.\ Rev.\ D {\bf 92} (2015) no.1, 014005 and references therein.

see C. Hanhart's Talk

- Meson-meson molecules have a different string topology:
  - are they bound?
  - very few states: no orbital excitations or radial excitations expected



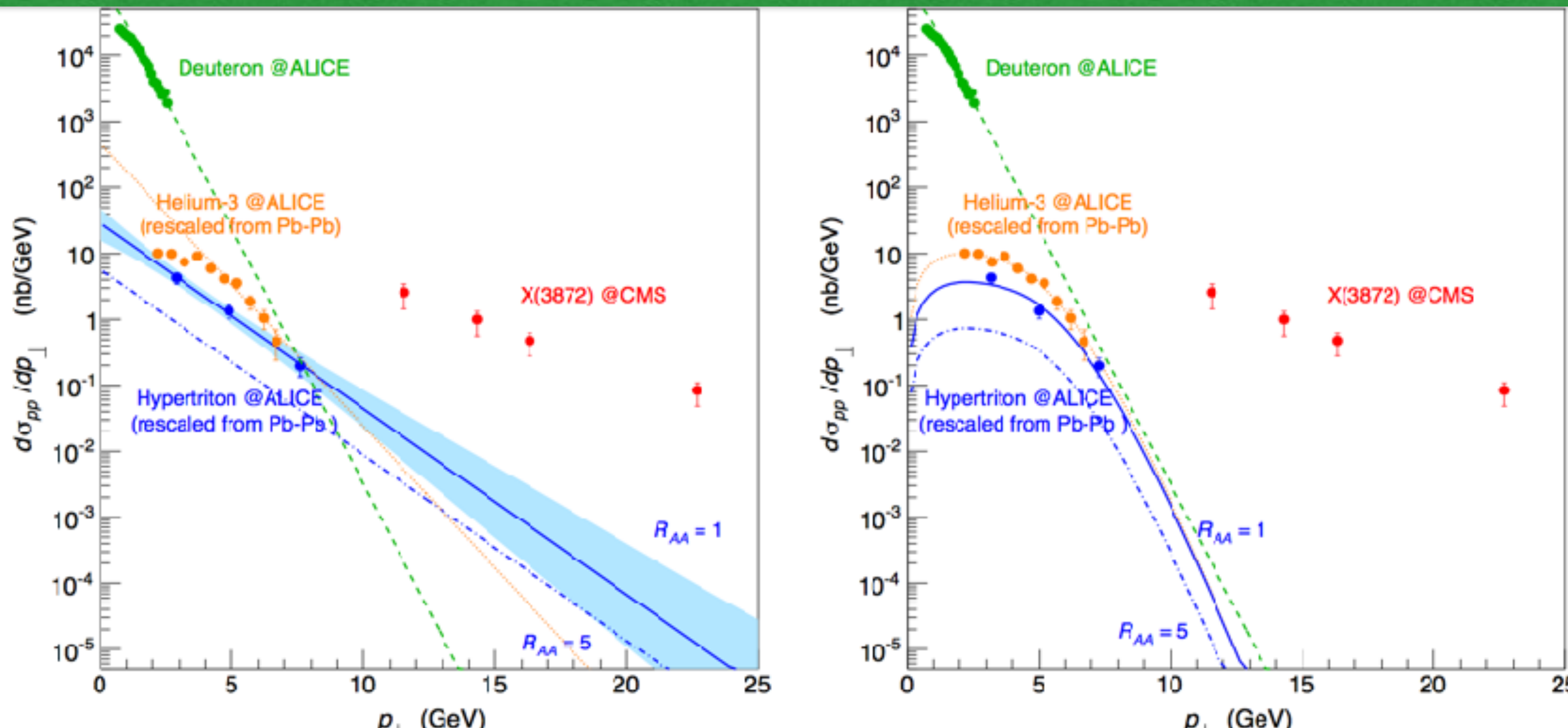
Nuclei obviously belong to the same class as hadron molecules, being 'made' by color singlet protons and neutrons

Alice has measured the production of light nuclei, deuteron, He^3 and hypertriton, H^3_Λ in relatively high p_T bins in Pb-Pb collisions, at s_{NN} = 2.76 TeV

The cross section of these processes can be used as reference for a discrimination between tetra quarks (hadrons made by coloured subconstituents) and molecules (hadrons made by color singlet constituents)

A. Esposito *et al.*, Phys. Rev. D **92** (2015) 3, 034028

Rescaling from Pb-Pb ALICE cross sections to p-p CMS cross section is done with: Glauber model (**left panel**) and blast-wave function (**right panel**}) (R_{AA} or R_{CP} =1)



Collective effects in Pb-Pb (e.g.quark-gluon plasma) **enhance nuclear cross sections** and therefore **reduce the cross section rescaled to p-p**.

- There is a vast difference in the probability of producing X(3872) and that of producing light nuclei, true "hadronic molecules", in high energy collisions
- high energy production of suspected exotic hadrons from quark-gluon plasma at Heavy Ion colliders can be a very effective tool to discriminate different models
- a long list of suspects: f_0(980), X(3872), $Z^\pm$(3900), $Z^\pm$(4020), $Z^\pm$(4430), X(4140)....

Deuteron vs X(3872) as molecular D*-D

- The inclusive production cross-sections of a D*D molecule or a deuteron depend on the relative momentum with which the pair D D* or NN has to be created, to produce the bound state.

C. Bignamini, B. Grinstein, F. Piccinini, A. D. Polosa and C. Sabelli, Phys. Rev. Lett. **103**, 162001 (2009)

- In the simplest treatment, this is given by the range of p supported by the wave function of the bound state, which can be estimated in various ways, in the one pion exchange approximation.

Non – Relativistic limit

$$\mathcal{L}_{\pi NN} = \frac{g_{\pi N}}{f_\pi}\, \chi_N^\dagger \sigma_i \chi_N \, (\partial^i \pi)$$

$$\mathcal{L}_{\pi D^* D} = \frac{g_{\pi D}}{f_\pi} \bar{D}_i^* D (\partial^i \pi)$$

	g	B.E. (MeV)	R (fm)	$\bar{p}$ (MeV)
deuteron	1.4	-2.2	2.1	105
$X = D^* - D$ (1a)	0.37 (2)	-0.2	10	18
$X = D^* - D$ (1b)	2	-0.1	14	14
$X = D^* - D$ (3)	–	0.30 ± 0.40	$5.8^{+\infty}_{-2}$	49

(1a) L. Maiani, A. Polosa, approximate evaluation; (1b) same authors, numerical solution of the Schroedinger equation; (2) R. Casalbuoni, F. Feruglio (1996); (3) P. Artoisenet, E. Braaten (2009).

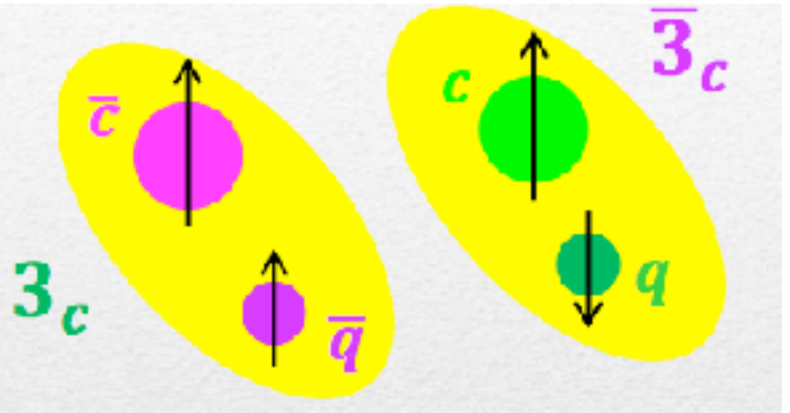
- Bignamini et al. estimate that p∼300 MeV is required for the CMS cross section of X(3872), which is quite larger than what supported by the low binding energy of D*D, which is smaller that the p range in the deuteron.
- Artoisenet and Braaten (2009) argue that final state interactions of D* D may allow for a much larger range of p and make D*D molecule consistent with CMS cross section.
- However, low energy interactions of D*D an NN are very similar, so the argument would increase all cross sections: the mistery would be then why the (extrapolated) deuteron cross section is so much smaller.
- will deuteron flatten at larger p_T ?

For compact tetraquarks, the comparison would be with the ψ’ cross section, which is indeed very similar to X

3. Tetraquark constituent picture of unexpected quarkonia

L.Maiani, F.Piccinini, A.D.Polosa and V.Riquer, Phys. Rev. D 71 (2005) 014028

$$[\mathrm{cq}]_{s=0,1}[\bar{c}\bar{q}']_{\bar{s}=0,1}$$



- I=1, 0
- S-wave: positive parity
- total spin of each diquark, S=1, 0
- neutral states may be mixtures of isotriplet and isosinglet
- mass splitting due to spin-spin interactions (e.g. the non-relativistic costituent quark mode

$$H = 2M_{diquark} - 2\sum_{i<j}\kappa_{ij}(\vec{s}_i\cdot\vec{s}_j)\,\frac{\lambda_i^A}{2}\frac{\lambda_j^A}{2}$$

The S-wave, $J^P=1^+$ charmonium tetraquarks

- use the basis: $|s,\bar{s}\rangle_J$

$$\mathrm{J^P} = 0^+ \quad C=+ \quad X_0 = |0,0\rangle_0,\ X_0' = |1,1\rangle_0$$

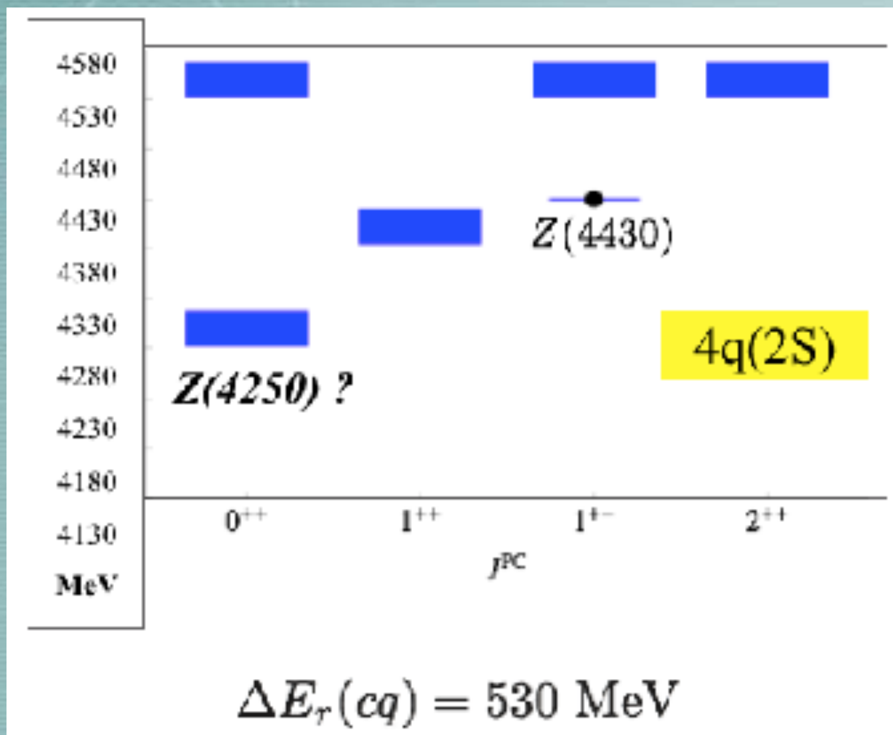
$$\mathrm{J^P} = 1^+ \quad C=+ \quad X_1 = \frac{1}{\sqrt{2}}\left(|1,0\rangle_1 + |0,1\rangle_1\right)$$

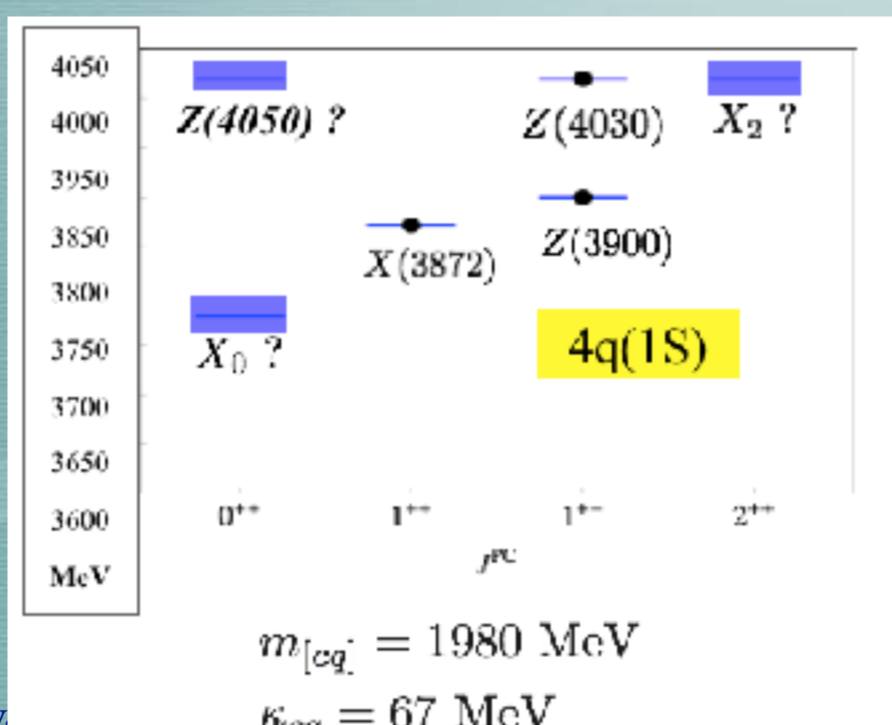
$$\mathrm{J^P} = 1^+ \quad G=+ \quad Z = \frac{1}{\sqrt{2}}\left(|1,0\rangle_1 - |0,1\rangle_1\right),\ Z' = |1,1\rangle_1$$

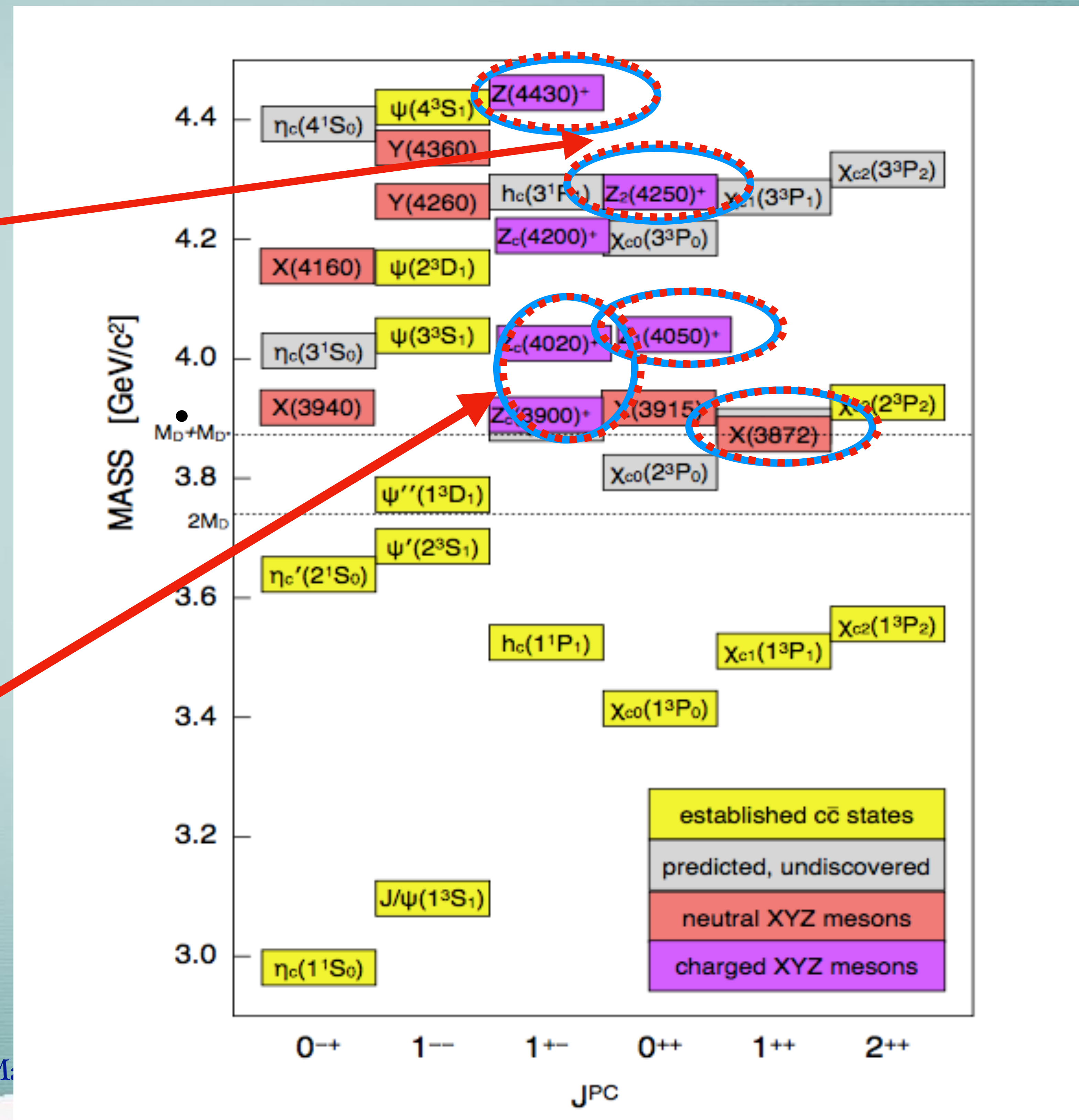
$$\mathrm{J^P} = 2^+ \quad C=+ \quad X_2 = |1,1\rangle_2$$

X(3872)=X_1
Z(3900), Z(4020)=lin. combs. of Z&Z' that diagonalize H

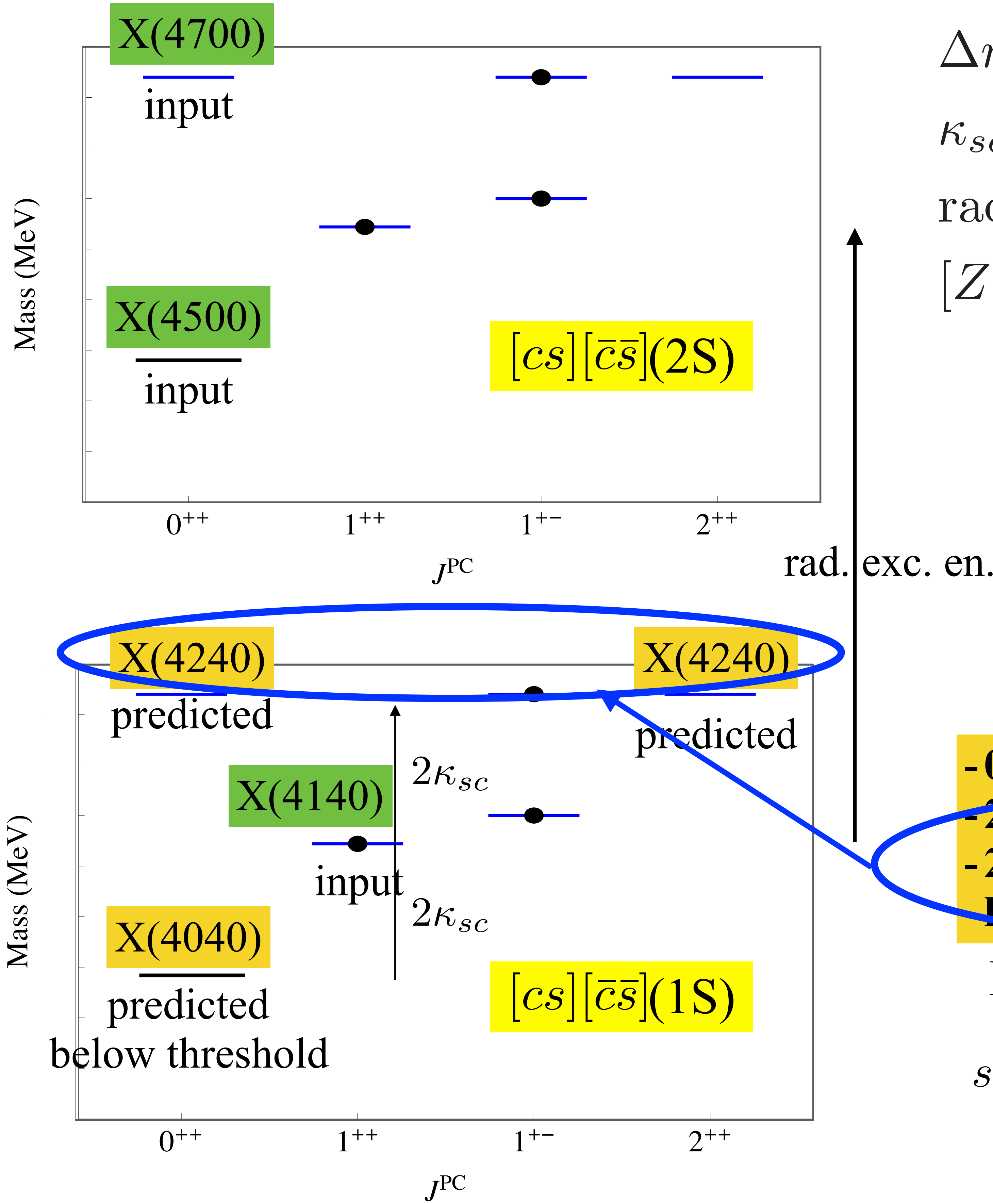
- A simple ansatz: spin-spin interaction dominated by inter-diquark interaction
- The spectrum of 1S ground states characterised by two quantities:
  - the diquark mass, $m_{[cq]}$
  - the spin-spin interaction inside the diquark or the antidiquark, κ_{cq}.
- The first radially excited, 2S, states are shifted up by a radial excitation energy, ΔE_r mildly dependent on the diquark mass: $E_r(cq) \sim \sim E_r(cs)$







J/Ψ-φ structures and S-wave tetraquarks



$\Delta m = m_{cs} - m_{cq} = 129$ MeV;
$\kappa_{sc} = 50$ MeV ($\kappa_{qc} = 67$ MeV)
radial excit. $= 460$ MeV
$[Z(4430) - Z(3900) = 530$ MeV$]$

NOTE :
$X(4140) - X(3872) \sim 270$ MeV;
$\phi(1020) - \rho(770) \sim 244$ MeV

X(4274) cannot be 1^{++}

- **0^{++} ?**
- **2^{++} ?**
- **2 unresolved, almost degenerate lines with $0^{++} + 2^{++}$??**

Decay modes of $J^P=1^+$, C=-1:

$$s_{c\bar{c}} = 1 : J/\Psi + \eta, \chi_c + \eta \ (P - wave)$$
$$s_{c\bar{c}} = 0 : \eta_c + \phi, h_c + \phi \ (P - wave)$$

what about the strange members of the nonet?

- We expect strangeness= ±1 tetra quarks: $X_{\bar{s}} = [cq][\bar{c}\bar{s}];\ X_s = [cs][\bar{c}\bar{q}]$
- partners of X(4140) should decay in: $J/\Psi + K^*/\bar{K}^* \to \mu^+\mu^- + \pi + K_S$
- while partners of C=-1 states decay in: $J/\Psi + K/\bar{K} \to \mu^+\mu^- + K_S$
- Mass can be estimated at: $$M(X_s) \sim \frac{4140 + 3872}{2} \sim 4006$$ $$[M(J/\Psi) + M(K^*) \sim 4000]$$
- are they visible at LHCb/BELLE/BES III?

Variations on the theme

- J/Ψ-φ spectrum obtained with meson&baryon spin-spin parameters does not fit with experiment

N.V. Drenska, R. Faccini and A. D. Polosa, Phys. Rev. **D** 79 (2009) 077502

- QCD sum rules with tetra quark currents tried with some success and support X(4500) and X(4700) to be higher excitations, radial or D-wave

Z. G. Wang, arXiv:1607.00701 [hep-ph];

- flavour SU(3) nonet including J/Ψ-φ has been considered in:

R. Zhu, Phys Rev. **D** 94 (2016) 054009

- diquarks in color 6 have been considered by several authors

J. Wu *et al.*, arXiv:1608.07900 [hep-ph]

- if at all bound, tetraquarks made by color 6 diquarks would double the spectrum

- an option if X(4270) turns out to be a pure 1^{++} resonance?

- basic masses of diquark in color 3 and 6 must be different: X(4270)-X(4140) is not due only to spin-spin interactions and will be essentially incalculable.

4. Molecules and tetraquarks: a second look

- Can we describe exotic hadrons in terms of conventional forces between "canonical hadrons" (q-qbar, qqq) ?
- Answer cannot be but: YES !
  - we do not claim that exotic hadrons correspond to new degrees of freedom beyond standard QCD (e.g. new constituents)
  - Exotic hadrons are poles in the canonical hadron S-matrix

The Old Bootstrap idea:

- forces generate S-Matrix poles
- the poles thus generated must coincide with the particles that generate the forces

Old Bootstrap was applied to π-π scattering:

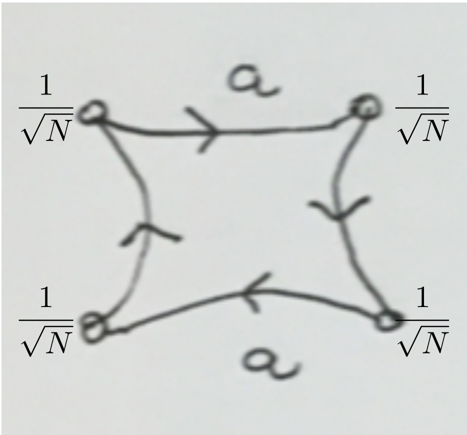
- force generate by ρ exchange
- bound state thus generated must coincide ρ
- i.e. ρ is a ππ molecule !!!????!!!!

It did not work !

Duality (Dolen, Horn, Schmid, 1968)

- we learn very early that particles may be exchanged in the s and in the t channels
- in field theory (finite number of fields) we have to add the amplitudes corresponding to the s and t channel Feynman diagrams (e.g. photon exchange)
- it is the Feynman's sum over independent histories
- the reason is that the amplitude (a) has a pole in the s-channel and it cannot produce a pole in the t-channel, as in (c), and viceversa
- With infinitely many poles, the situation is different.
- Dolen, Horn, Schmid made the proposition that in π-N scattering, the sum over s-channel resonances has to reproduce a Regge behaviour, that is to reproduce the poles in the t-channel (duality of s and t channels)
- should we put separately the s-channel poles (resonances) and the t-channel poles (forces) we would make a ***double counting***

DHS duality holds in QCD, in leading $1/N_{color}$ meson-meson scattering amplitude



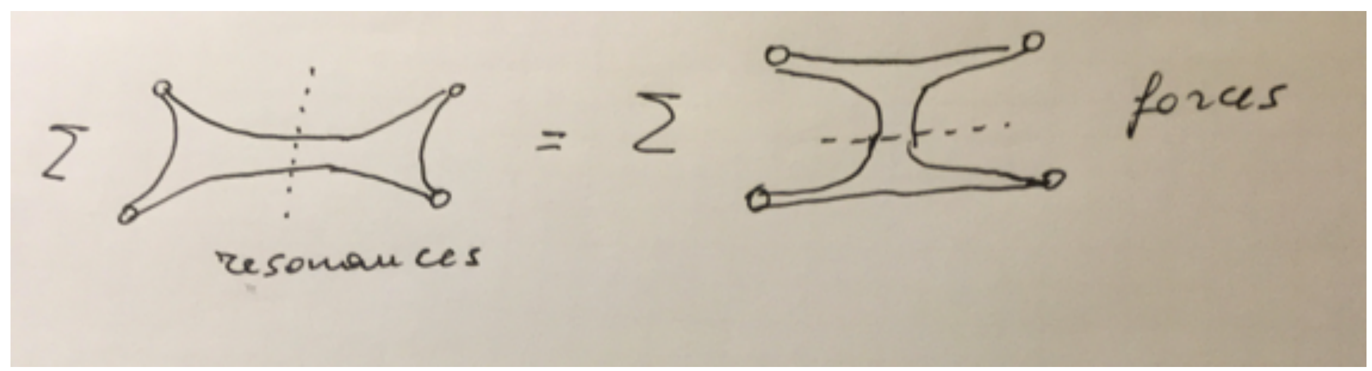
$\sim \frac{1}{N}$

Meson-meson scattering

in large N_c limit

G. 't~Hooft,~Nucl.~Phys. **B72** (1974) 461;
Comm. Math. Phys. **88** (1983) 1.

- there is ***only one quark amplitude***, (the sum of al planar diagrams with quark on the edge) of order 1/N for normalised field insertions
- cutting along the s channels, one finds an infinite series of poles (the q-qbar mesons we found in the propagator), but this sum has to reproduce as well the poles in the t-channel!
- graphically

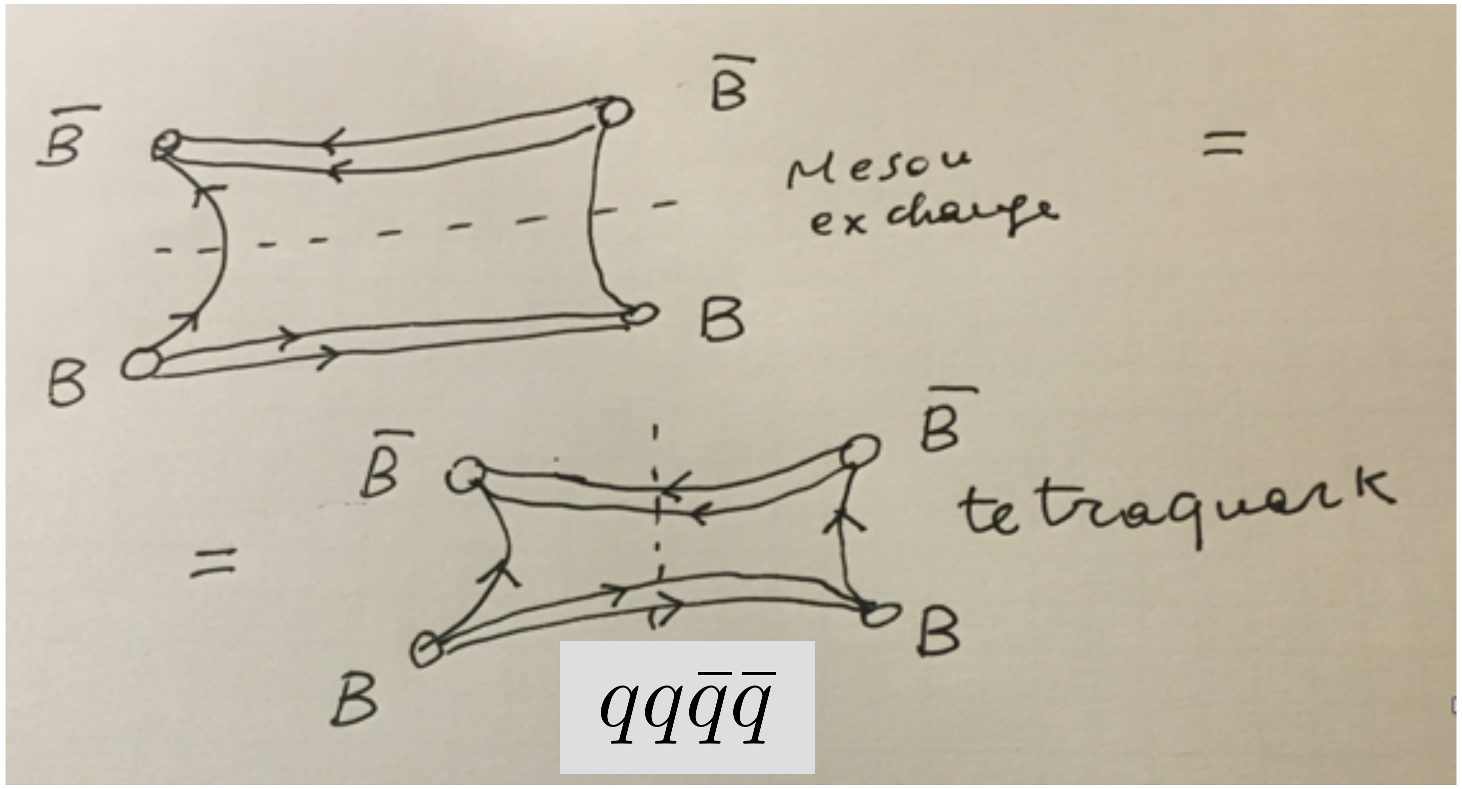


- once again: if we add meson-meson forces due to the exchange of all mesons, we produce a given meson-meson resonance, which however has quantum number and properties dictated by the quark-antiquark bound state
- this solves the existential problem: is the ρ a resonance due to π-π forces or is a q-qbar state? same for the Δ: a P- π resonance or a three quark state?
- the two pictures coincide

… when we describe forces with infinitely many exchanges, as required by QCD !

Duality and tetraquarks (Rossi and Veneziano, 1977)

- Applying the DHS duality to Baryon-Antibaryon scattering, one concludes that the B-Bbar forces give rise to ***tetraquarks*** in the s-channel



Is a B-Bbar resonance a molecule or a tetraquark?

Tetraquarks in 1/N expansion
S. Coleman, *Aspects of Symmetry*, Cambridge University Press, Cambridge, England, (1985).
S. Weinberg, Phys. Rev. Lett. **110**, 261601 (2013).
M. Knecht and S. Peris, Phys. Rev. **D 88**} (2013) 036016
L. Maiani, A. D. Polosa and V. Riquer, JHEP 1606 (2016) 160
G. Rossi and G. Veneziano, arXiv:1603.05830 [hep-th]

…exemplified in our context…

- rather dubious:
  - X(3872), Z(3900),…=D D* with 1 π exchange ???
  - X(4140),… = D_s D_s* with 1 η exchange ????
- $SU(3)_{flavor}$ effects would be much more dramatic than simply m_s-m_q first order effects (as required by QCD).
- For canonical hadrons, Constituent Quark Model gives a reasonably good approximation to spectroscopy, with guiding symmetry: $SU(6)_{flavor} \otimes O(3)_{orbital}$, for light flavors;
- we may use a similar guide for exotic hadrons, which come in different parities
  - X, Z: parity +, S-wave tetraquarks (even q-qbar pairs, L=0)
  - Y: parity -, P-wave, L=1, tetraquark
  - $P(3/2^{-})$, S-wave pentaquark $\left([ud]_{s_{qq}=1}[uc]\ \bar{c},\ L=0\right)$
  - $P(5/2^{+})$, P-wave, L=1 $\left([ud]_{s_{qq}=0}[uc]\ \bar{c},\ L=1\right)$

5. Conclusions

- Data have conclusively shown that there are "structures" beyond (q q-bar) or (qqq) states, but we do not know yet if this is a reflection of known dynamics in a new context (molecules? threshold effects?) or the indication of a new class of quark bound states;
- Constituent Quark Model predicts that q-q forces are attractive in color 3-bar and this is the basis to think that diquarks are a useful unit to build up more complex hadrons
- Diquarks seem to be a useful organising principle, to classify the structure of exotic mesons and pentaquarks, even if not without problems...
- experiments at colliders may provide further discrimination

Conclusions (cont'd)

- S-wave multiplets are slowly filling up;
- J/Ψ-φ resonances go well with simple, S-wave, tetraquarks....except for the puzzling 1^{++} duplication of X(4140) and X(4270)
- Y states: new data, picture still confused…Many states still missing !
- An important prediction: dibaryons.
- Dibaryons can be searched for in Λ_b decays for a wide range of masses (from 4680 down to 2135 MeV);
- if found, dibaryons would complete a second layer of hadron spectroscopy, following the Gell-Mann Zweig layer and completing the saturation possibilities of one and three QCD strings.
- Open heavy flavour exotics is the new frontier
- exotics seen until now contain heavy quark flavours: an experimental reexamination of the lack of existence of light exotic mesons ("bad" diquarks) and positive strangeness baryons is in order.
- Much remains to be done, in theory and experiments, LHCb and electro-positron colliders to play a crucial role.

Hadron Spectroscopy is not simple "botanics". It may teach us something fundamental about the, essentially unknown, non-perturbative QCD