Multiquarks Hadrons and QCD with Many Colours

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Bound states in strongly coupled systems
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Multiquarks Hadrons and QCD with Many Colours

SUMMARY

1. Are there Exotic Hadrons?
2. New Hadrons and Diquarks
3. Tetraquarks and new hadrons
4. X(3872) at Hadron Colliders
5. Tetraquarks in the Large $N_{colours}$ expansion
6. Conclusions

1. Unanticipated charmonia..and more

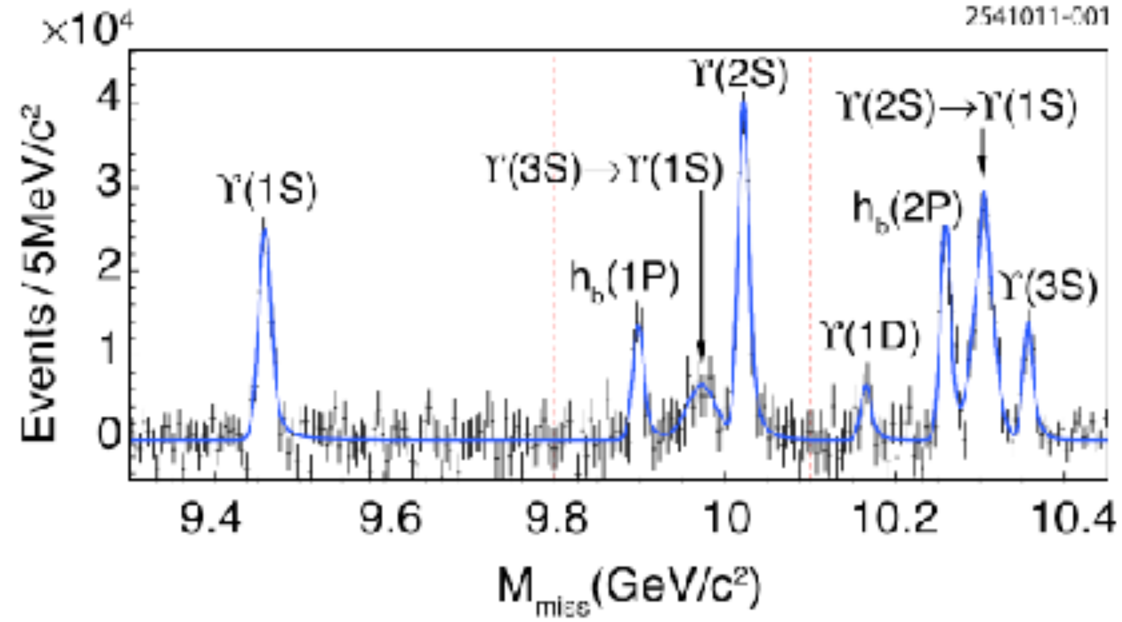
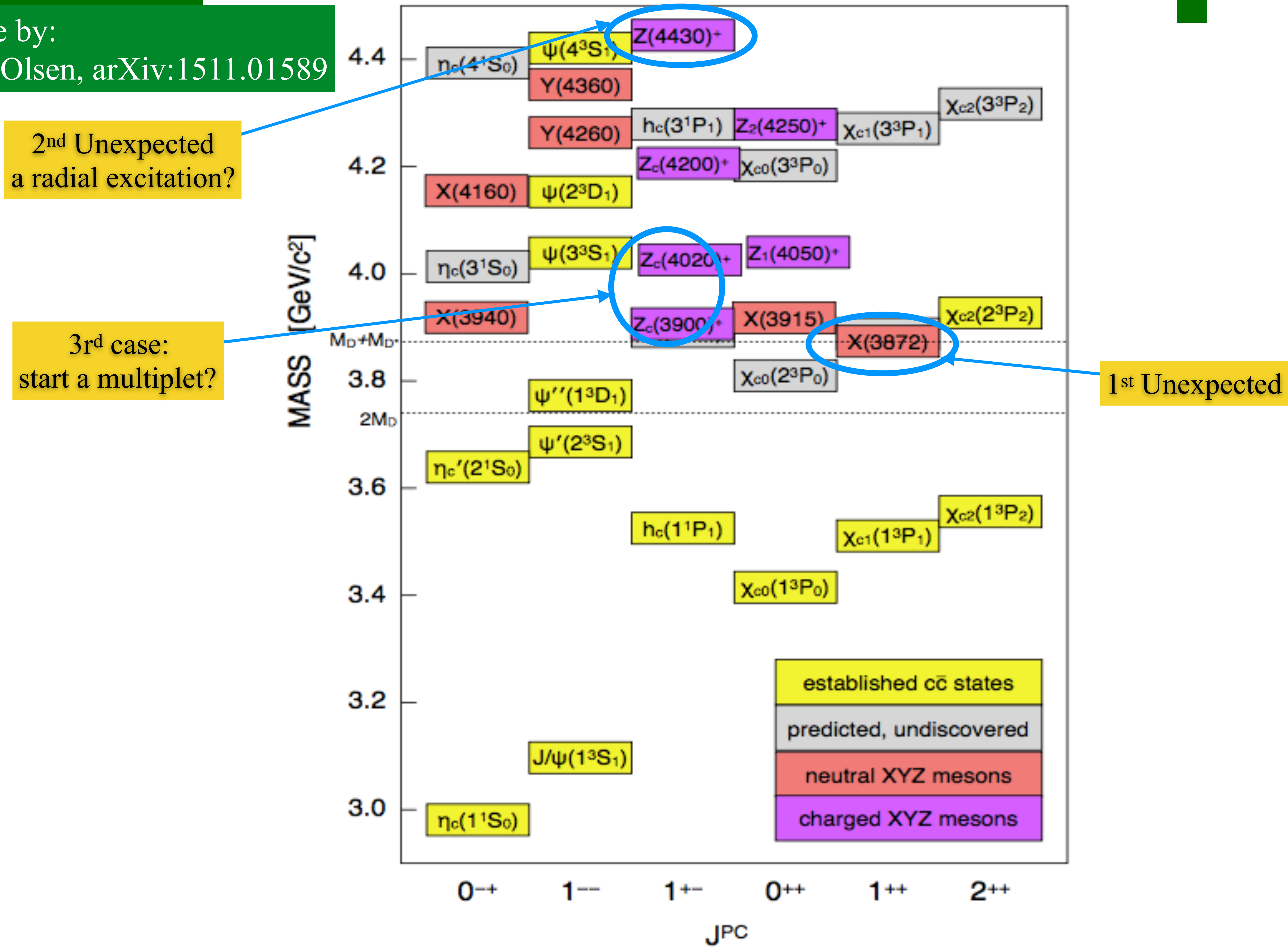


Figure 1: From Belle [31], the mass recoiling against $\pi^+\pi^-$ pairs, $M_{\rm miss}$, in e^+e^- collision

- Hidden charm/beauty resonances (peaks??) not fitting in the charmonium spectrum because of mass/decay properties or because charged
- 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 flavor states not yet seen or confirmed (Z(5568)->$B_s+\pi$ was claimed by D0, not confirmed by LHCb).

Expected and Unexpected Charmonia

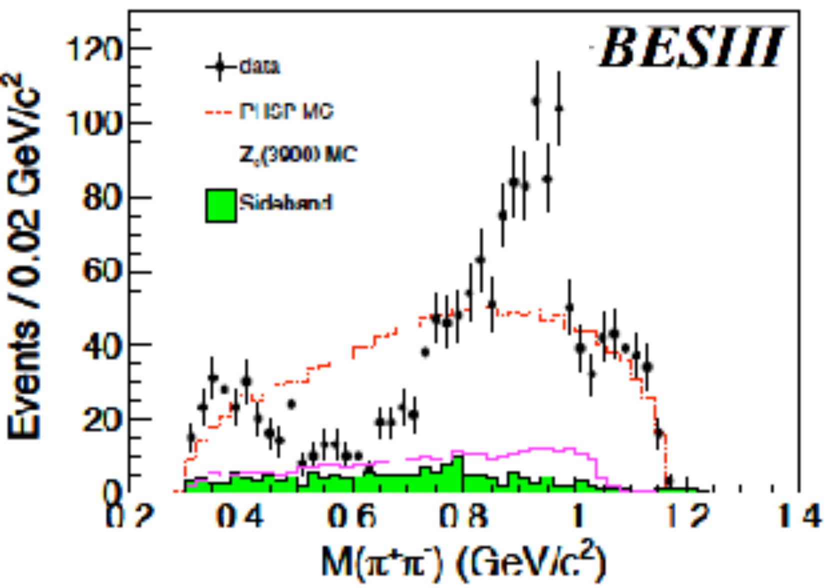
figure by:
S. L. Olsen, arXiv:1511.01589

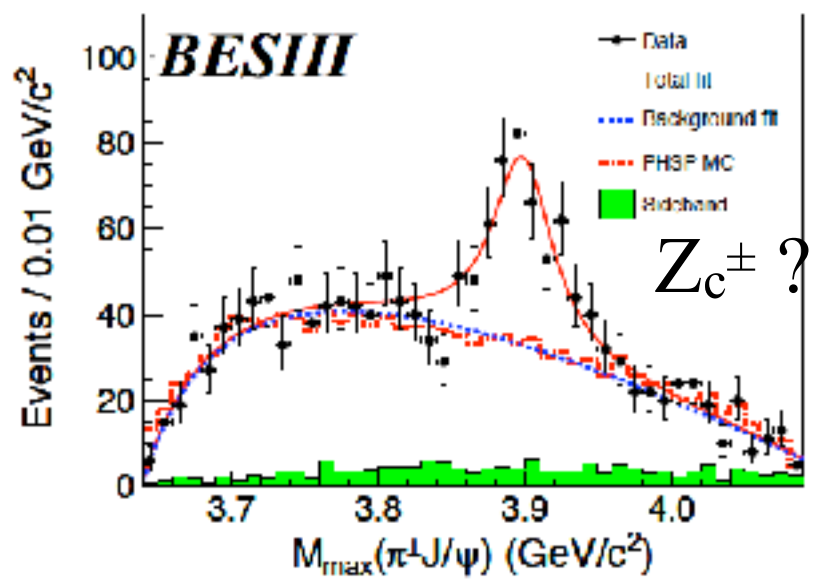


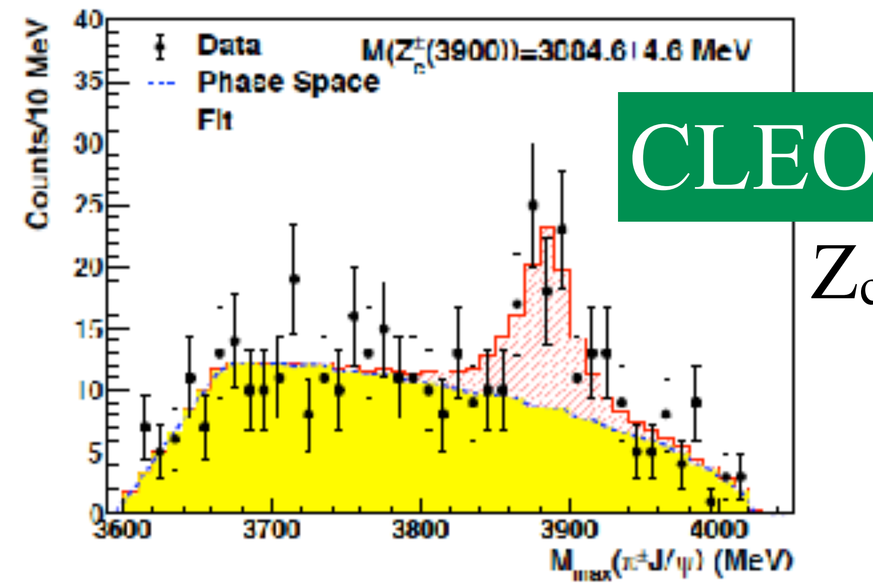
The unexpected $J^{PC}= 1^{--}$ resonance, Y(4260), and its unexpected $J^{PG}= 1^{++}$ descendants

Observed by BES III, BELLE and CLEO :

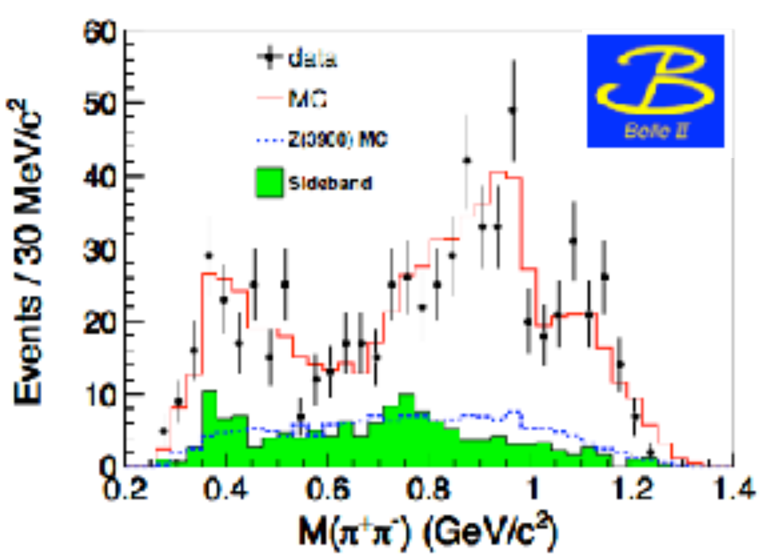
$$Y(4260) \to \begin{cases} f_0\ J/\Psi \to J/\Psi\ \pi^+\pi^- \\ Z_c\ \pi \to J/\Psi\ \pi^+\pi^- \quad \text{tetraquark de-excitation ?} \end{cases}$$

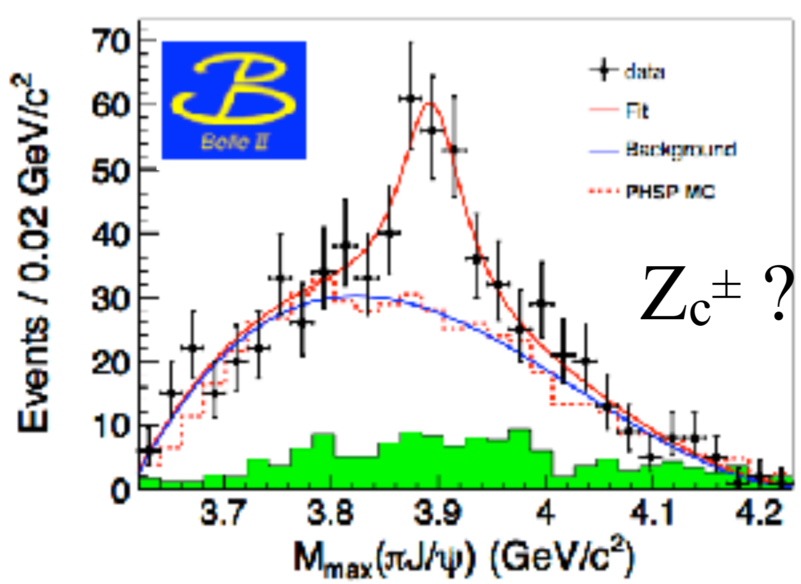


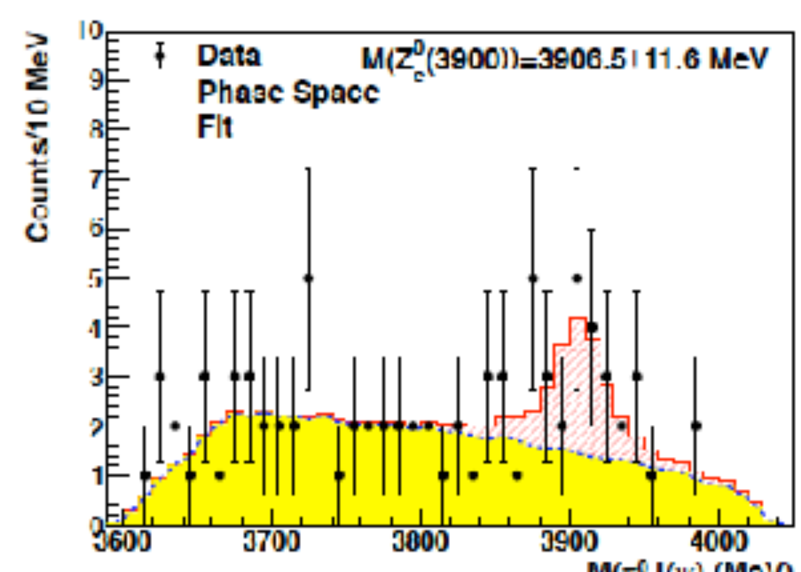




$Z_c^\pm$?







Z_c^0 ?

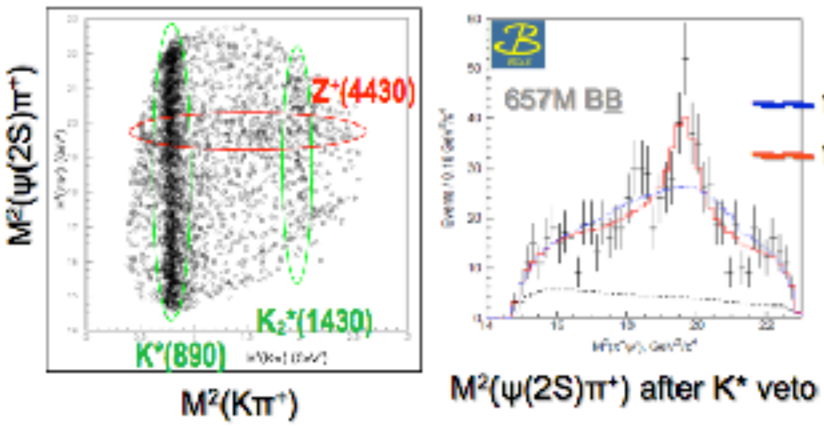
Z±(4430)

Belle observed $Z(4430)^\pm \to \psi(2S)\pi^\pm$

PRL100, 142001 (2008)

- Found in $\psi(2S)\pi^+$ from $B \to \psi(2S)\pi^+ K$. Z parameters from fit to $M(\psi(2S)\pi^+)$
- Confirmed through Dalitz-plot analysis of $B \to \psi(2S)\pi^+ K$
- $B \to \psi(2S)\pi^+ K$ amplitude: coherent sum of Breit-Wigner contributions
- Models: all known $K^* \to K\pi^+$ resonances only

  all known $K^* \to K\pi^+$ and $Z^+ \to \psi(2S)\pi^+$ ⇨ favored by data



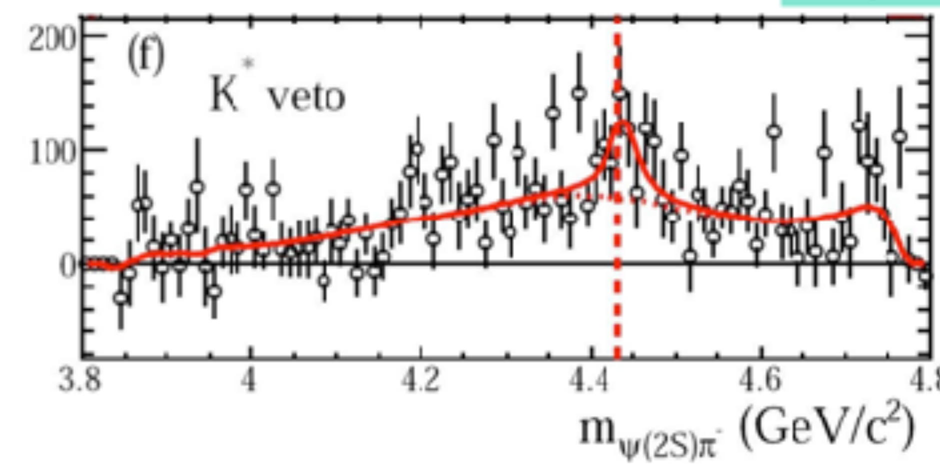
$$M = 4433\,^{+15\,+19}_{-12\,-13}\ \text{MeV}$$
$$\Gamma = 107\,^{+86\,+74}_{-43\,-53}\ \text{MeV}$$

PRD80, 031104 (2009)

- [cu][cd] tetraquark? neutral partner in $\psi'\pi^0$ expected
- $D^*\bar{D}_1(2420)$ molecule? should decay to $D^*\bar{D}^*\pi$ 42

BaBar doesn't see a significant $Z(4430)^+$

PRD79, 112001 (2009)



"For the fit … equivalent to the Belle analysis…we obtain mass & width values that are consistent with theirs,… but only ~1.9σ from zero; fixing mass and width increases this to only ~3.1σ."

$BF(B^0 \to Z^+K) \times BF(Z^+ \to \psi(2S)\pi^+) < 3.1 \times 10^{-5}$

Belle PRL: $(4.1 \pm 1.0 \pm 1.4) \times 10^{-5}$ 44

- Babar inserts in the fit all K* resonances is Belle effect due to K* reflections ???

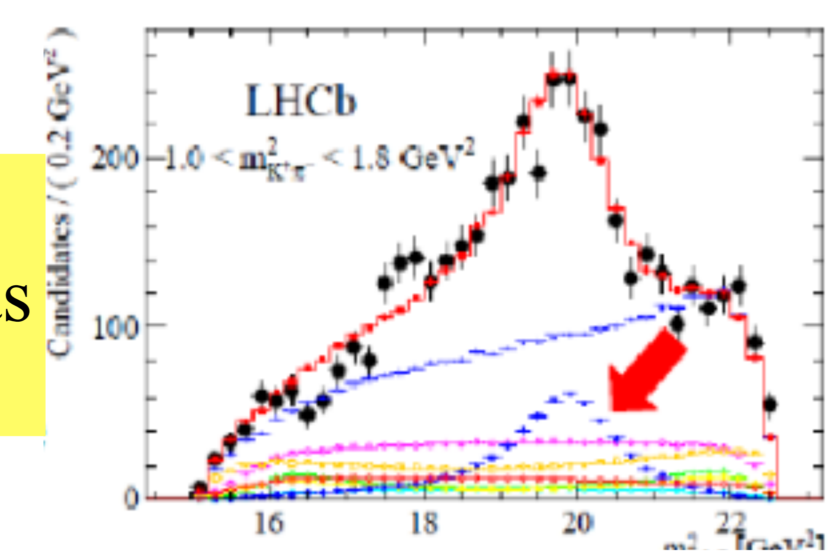
LHCB:

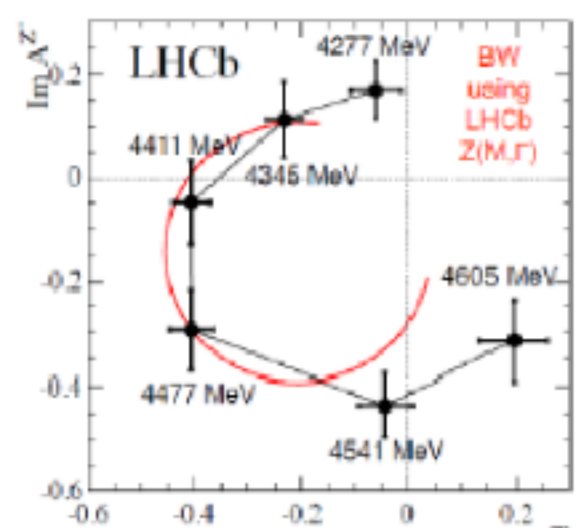
- confirms BELLE's observation of a bump

Can NOT be built from standard states: D^*D_1= in S-Wave may have J=1 but has negative parity

- Argand Plot shows 90⁰ phase: Z is a genuine resonance

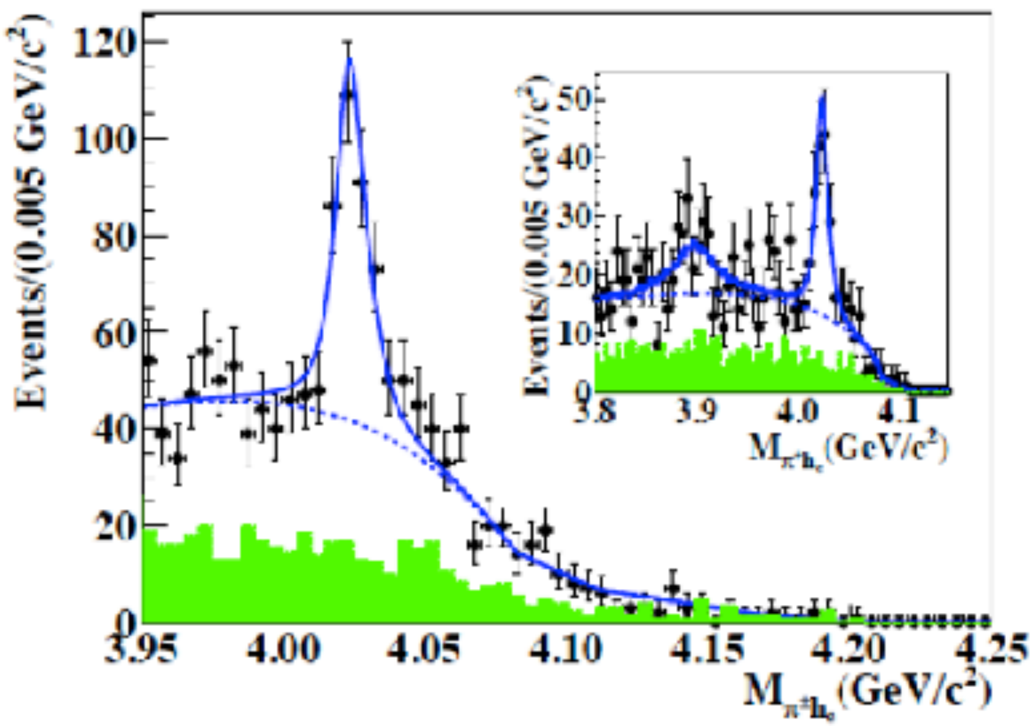
[PRL 112 (2014) 222002]





A second Z=Z(4020) in 2013

$e^+e^- \to \pi Z_c(4020) \to \pi^+\pi^- h_c(1P)$



BESIII: PRL111, 242001

Simultaneous fit to 4.23/4.26/4.36 GeV data, 16 η_c decay modes. 8.9σ

$M(Z_c(4020)) =$

$4022.9 \pm 0.8 \pm 2.7$ MeV;

$\Gamma(Z_c(4020)) =$

$7.9 \pm 2.7 \pm 2.6$ MeV

Close to $\bar{D}^*D^*$ threshold

$\sigma(e^+e^- \to \pi Z_c \to \pi^+\pi^- h_c)$:

$8.7 \pm 1.9 \pm 2.8 \pm 1.4$ pb @ 4.230 GeV

$7.4 \pm 1.7 \pm 2.1 \pm 1.2$ pb @ 4.260 GeV

$10.3 \pm 2.3 \pm 3.1 \pm 1.6$ pb @ 4.360 GeV

Significance: 8.9σ [$Z_c(4020)$]

No significant $Z_c(3900)$ (2.1σ)

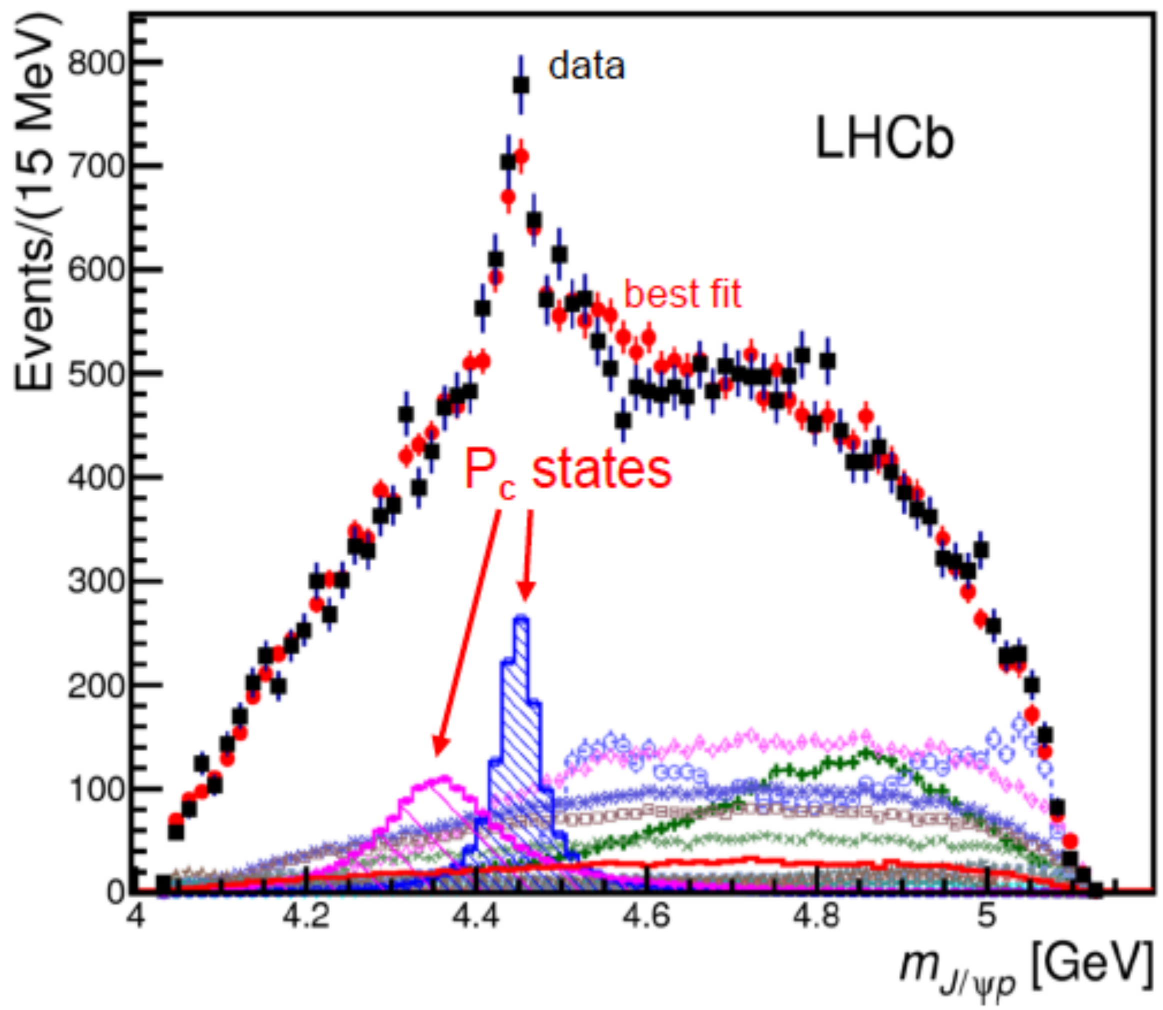
37

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

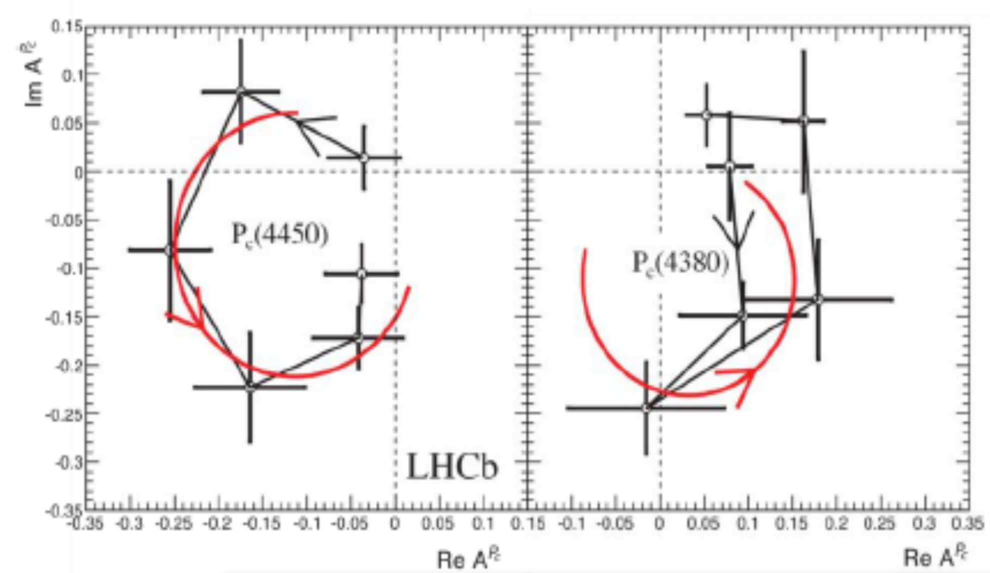
[PRL 115 (2015) 072001]

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

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



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

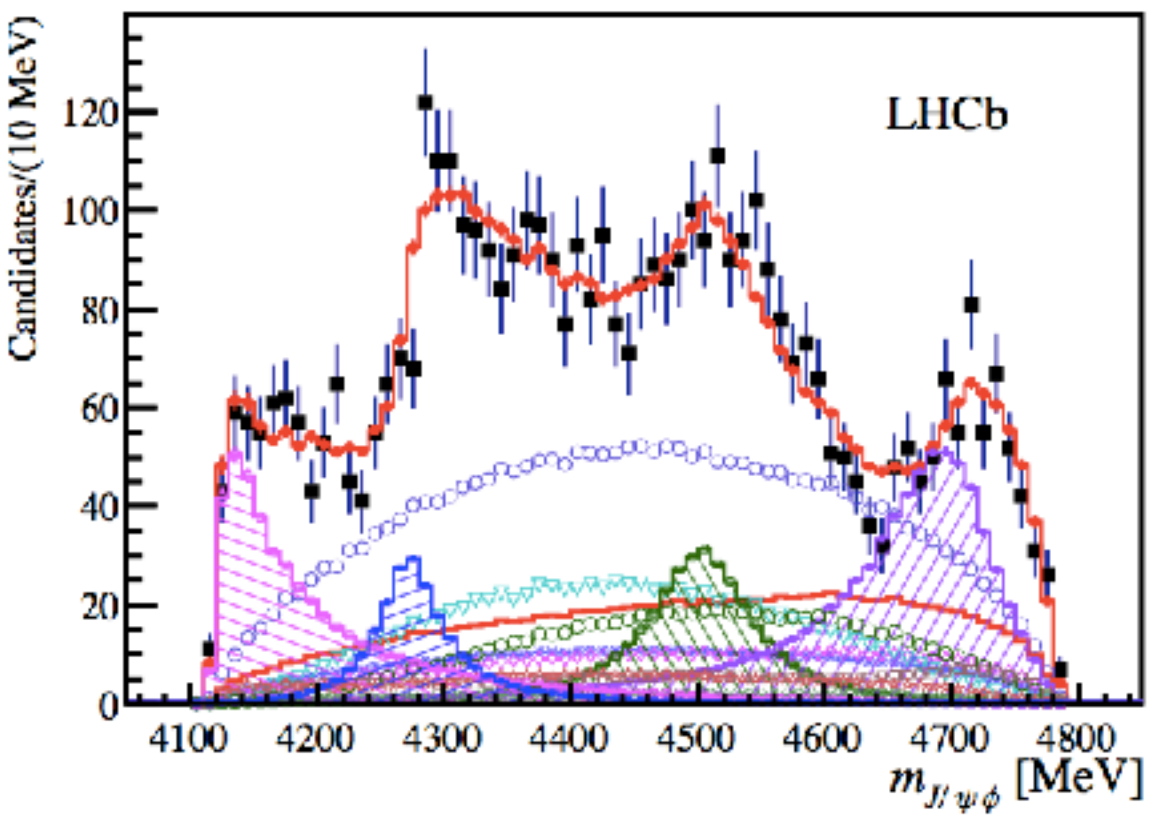


preferred fit
$P(4380)=3/2^-$, $P(4450)=5/2^+$

14/09/15 LHCb - SPC, September 2015

Old and new structures observed by LHCb in J/Ψ φ

R. Aaij et al. [LHCb Collaboration], Phys. Rev. Lett. 118 (2017) 022003

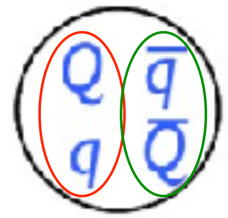


All $X(1^+)$				$16\pm3\ ^{+6}_{-2}$
$X(4140)$	8.4σ	$4146.5\pm4.5\ ^{+4.6}_{-2.8}$	$83\pm21\ ^{+21}_{-14}$	$13.0\pm3.2\ ^{+4.7}_{-2.0}$
ave.	Table 1	4147.1 ± 2.4	15.7 ± 6.3	
$X(4274)$	6.0σ	$4273.3\pm8.3\ ^{+17.2}_{-3.6}$	$56\pm11\ ^{+8}_{-11}$	$7.1\pm2.5\ ^{+3.5}_{-2.4}$
CDF	[26]	$4274.4\ ^{+8.4}_{-6.7}\pm1.9$	$32\ ^{+22}_{-15}\pm8$	
CMS	[23]	$4313.8\pm5.3\pm7.3$	$38\ ^{+30}_{-15}\pm16$	
All $X(0^+)$				$28\pm5\pm7$
$NR_{J/\psi\phi}$	6.4σ			$46\pm11\ ^{+11}_{-21}$
$X(4500)$	6.1σ	$4506\pm11\ ^{+12}_{-15}$	$92\pm21\ ^{+21}_{-20}$	$6.6\pm2.4\ ^{+3.5}_{-2.3}$
$X(4700)$	5.6σ	$4704\pm10\ ^{+14}_{-24}$	$120\pm31\ ^{+42}_{-33}$	$12\pm5\ ^{+9}_{-5}$

Models for XYZ Mesons

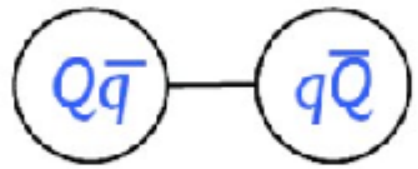
Quarkonium Tetraquarks

- compact tetraquark



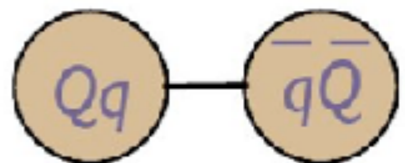
L. Maiani, A. Polosa, V. Riquer, F, Piccinini, Phys. Rev. D **89**, 114010 (2014) and reffs therein

- meson molecule



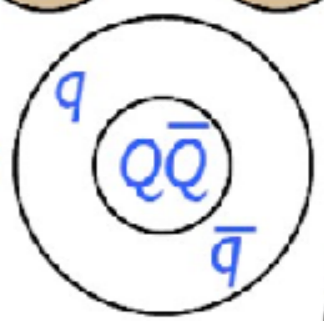
M.Cleven, F.K.Guo, C.Hanhart, Q.Wang and Q.Zhao, arXiv:1505.01771 and refs. therein

- diquark-onium



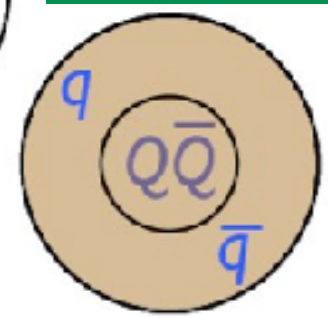
A. Ali, L. Maiani, A. D. Polosa and V. Riquer, Phys. Rev. D **91** (2015) 1, 017502 and refs. therein

- hadro-quarkonium



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

- quarkonium adjoint meson



- kinematic effects due to the opening of new channels

E. S. Swanson, Int. J. Mod. Phys. **E 25** (2016) 1642010

2. New Hadrons and Diquarks

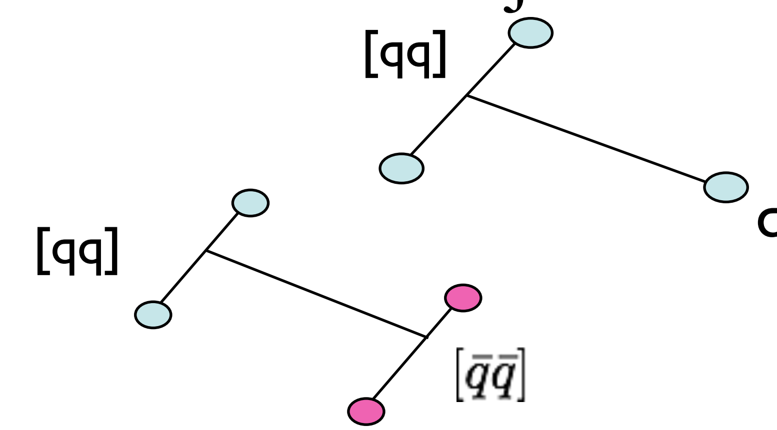
- ***QCD forces and spin-spin are attractive in the completely antisymmetric diquark [qq']: the "good diquark" (Jaffe, 1977)***

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

- result holds in QCD perturbative (one gluon exchange) and non perturbative (one instanton exchange), see e.g. T. Schafer and E. V. Shuryak, Rev. Mod. Phys. 70 (1998) 323

- To form hadrons, good or bad diquarks need to combine with other colored objects:

- with q $\to$ baryon (e.g. Λ), Y-shape
- with $[\bar{q}\bar{q}] \to$ scalar meson, H-shape (Rossi &Veneziano,)



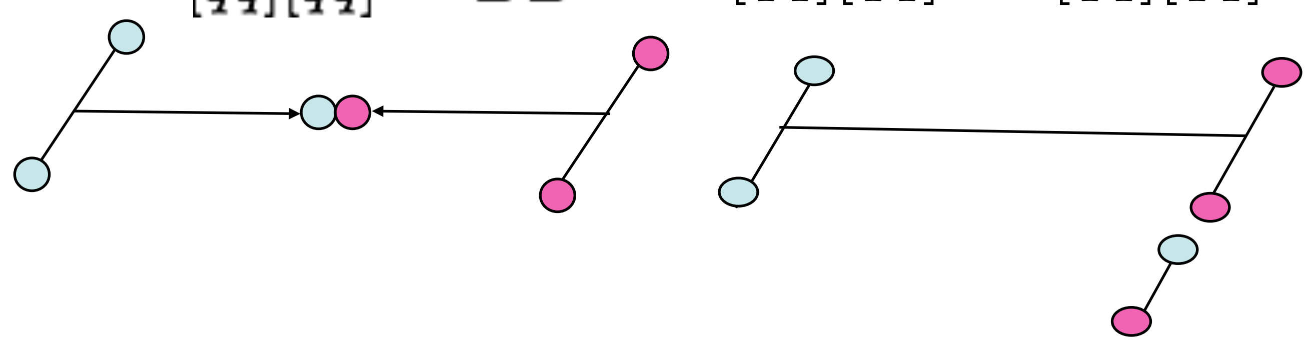
We expect many states: the string joining diquarks may have radial and orbital excitations

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

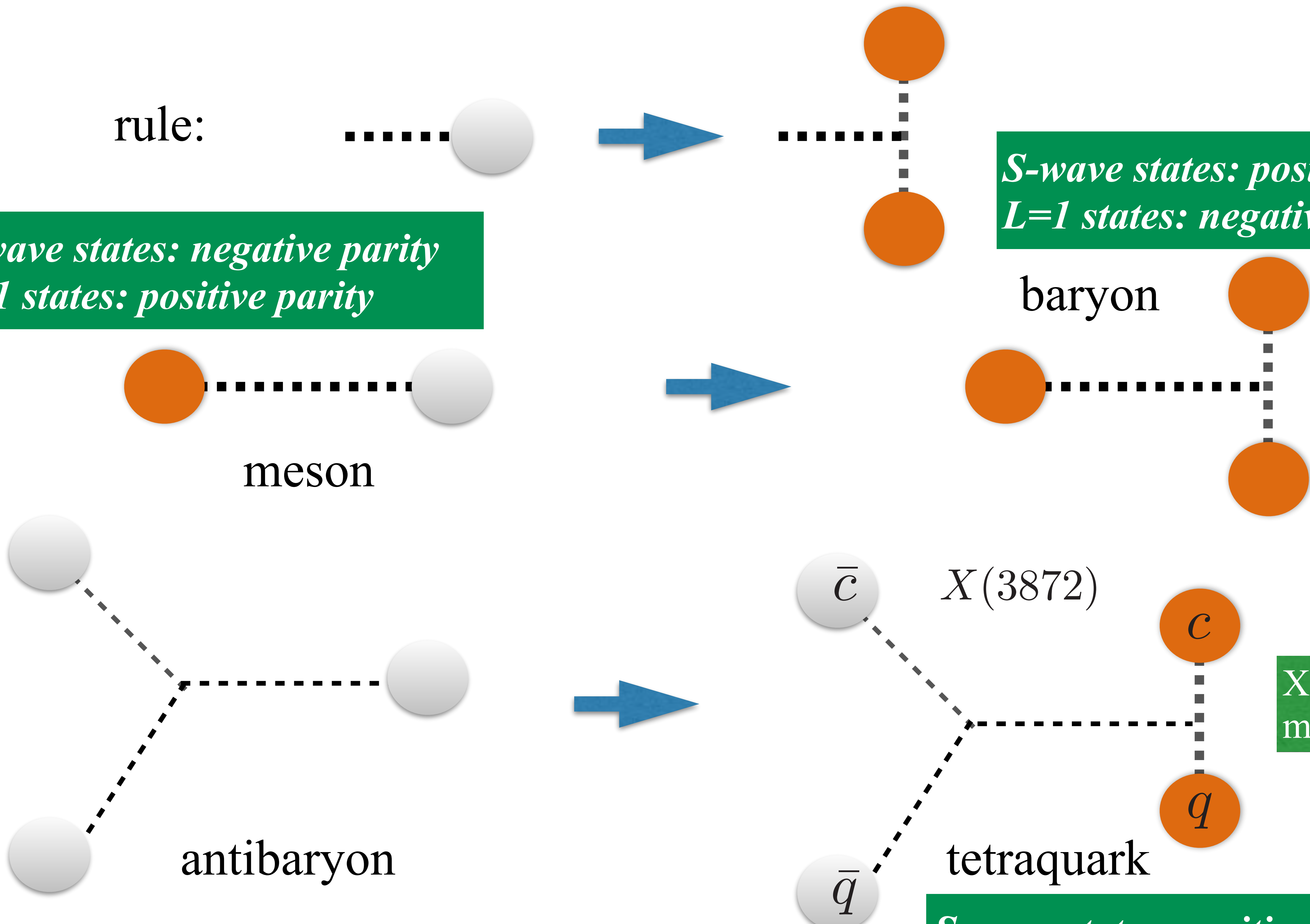
…We propose a simple criterion to decide whether a state is a genuine stringy exotic hadron - a tetraquark - or a "molecule". If it is the former it should be on a (modified) Regge trajectory…..

Decays: the string topology is related to B-antiB decay or tetraquark de-excitation

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



Replacing: antiquark → diquark makes new objects



S-wave states: positive parity
L=1 states: negative parity

S-wave states: negative parity
L=1 states: positive parity

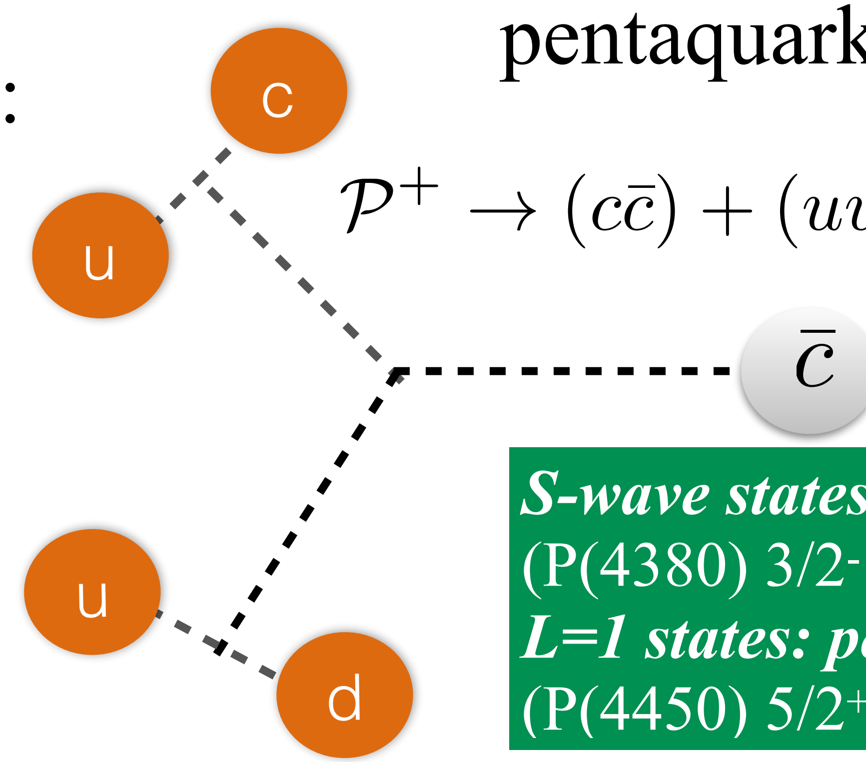
S-wave states: positive parity, X,Z
L=1 states: negative parity, Y

L. Maiani, A. D. Polosa and V. Riquer, PLB **749** (2015) 289

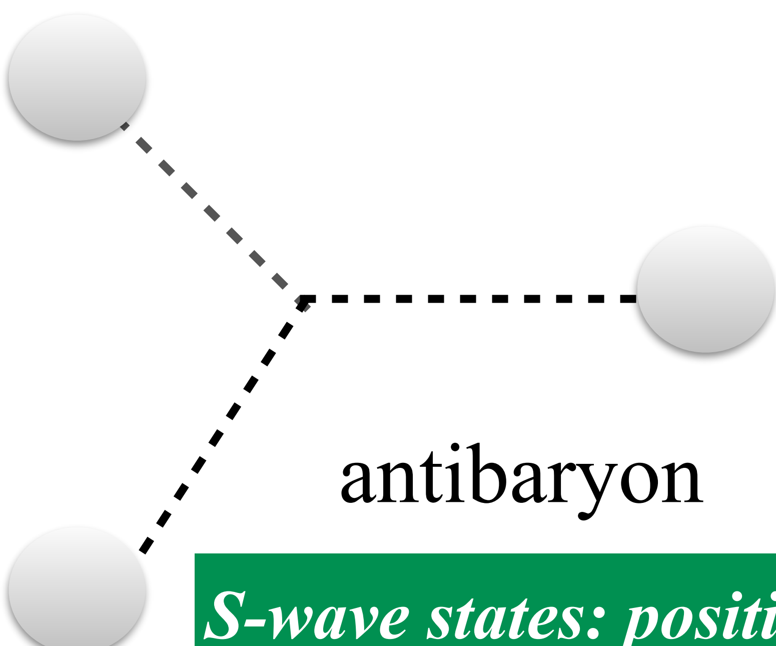
in baryon:

pentaquark

$$\mathcal{P}^+ \to (c\bar{c}) + (uud) = J/\Psi + p$$

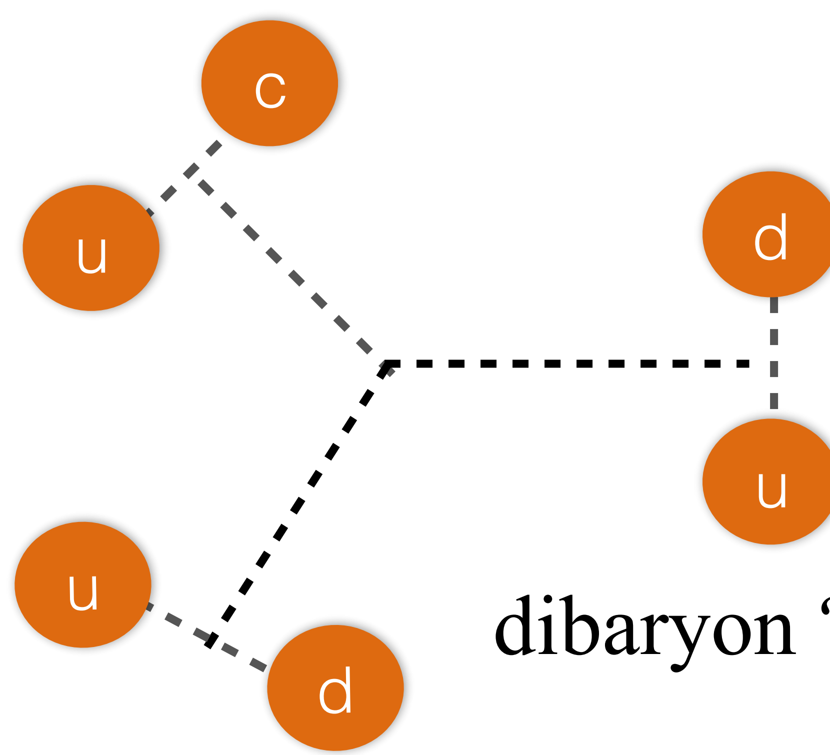


S-wave states: negative parity
(P(4380) $3/2^-$?)
L=1 states: positive parity
(P(4450) $5/2^+$?)



antibaryon

S-wave states: positive parity
L=1 states: negative parity

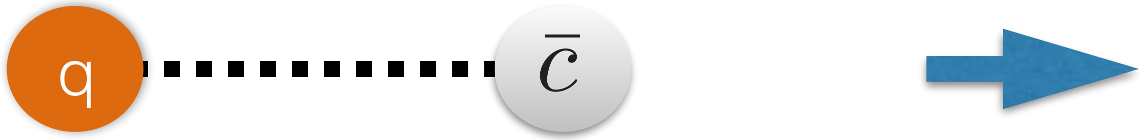


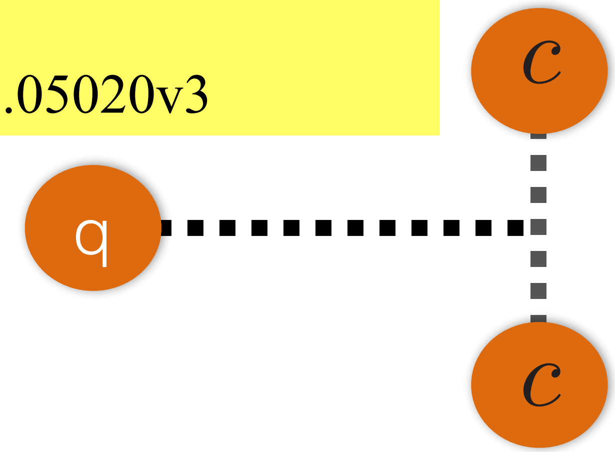
dibaryon ???

Substitution with diquark (antidiquark) reproduces qualitatively ***all we have seen in Exotic Hadrons until now****…* and more

A new sensation: doubly heavy baryons

M. Savage, M. B. Wise, PLB **248**,1990;
N. Brambilla, A. Vairo and T. Rosch, PRD **72,** 2005; T. Mehen, arXiv:1708.05020v3

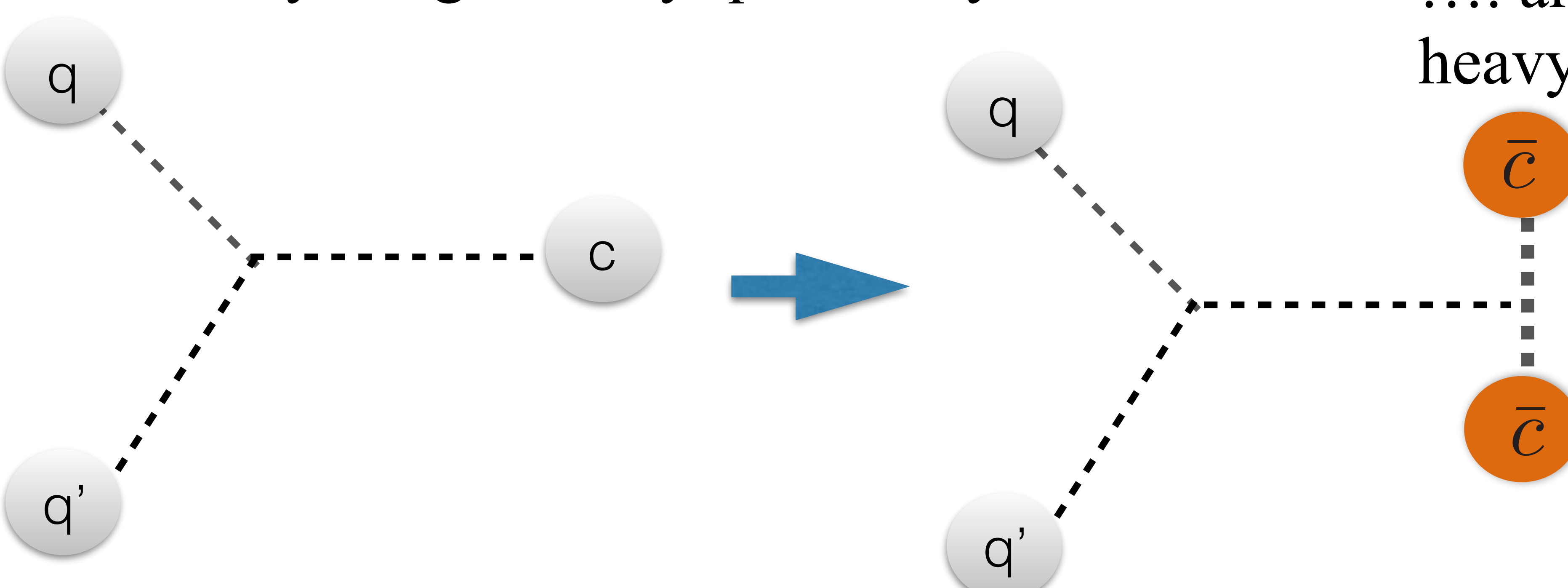




- Doubly heavy baryons are related to single quark heavy mesons
- QCD forces are mainly spin independent, so there is an approximate symmetry relating masses of DH baryons to SH mesons: e.g. $M(\Xi^*_{cc}) - M(\Xi_{cc}) = \frac{3}{4}[M(D^*) - M(D)]$

similarly: single heavy quark baryons….

…. are related to doubly heavy tetraquark



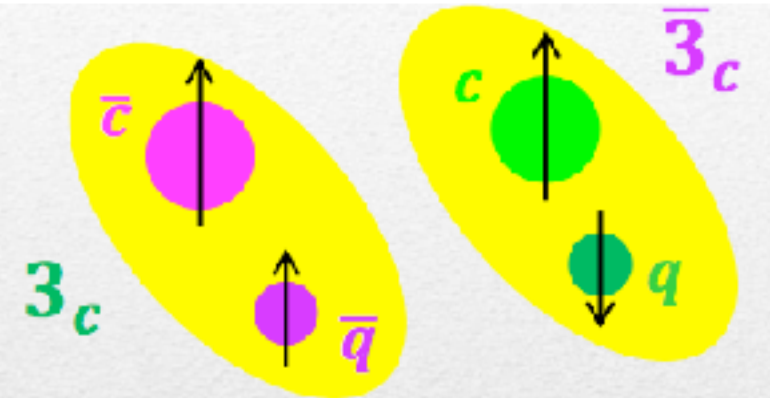
Esposito, M. Papinutto, A. Pilloni, A. D. Polosa, and N. Tantalo, Phys. Rev. D88, 054029 (2013)
M. Karliner and J. L. Rosner, arXiv:1707.07666 [hep-ph].
E. J. Eichten and C. Quigg, arXiv:1707.09575 [hep-ph].

Double Beauty tetraquarks may be stable for the strong interactions !!!!

3. Tetraquark constituent picture of unexpected quarkonia

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

$$[cq]_{S=0,1}[\bar{c}\bar{q}']_{S=0,1}, \;\; L=0$$



- 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: $|s,\bar{s}\rangle_J$

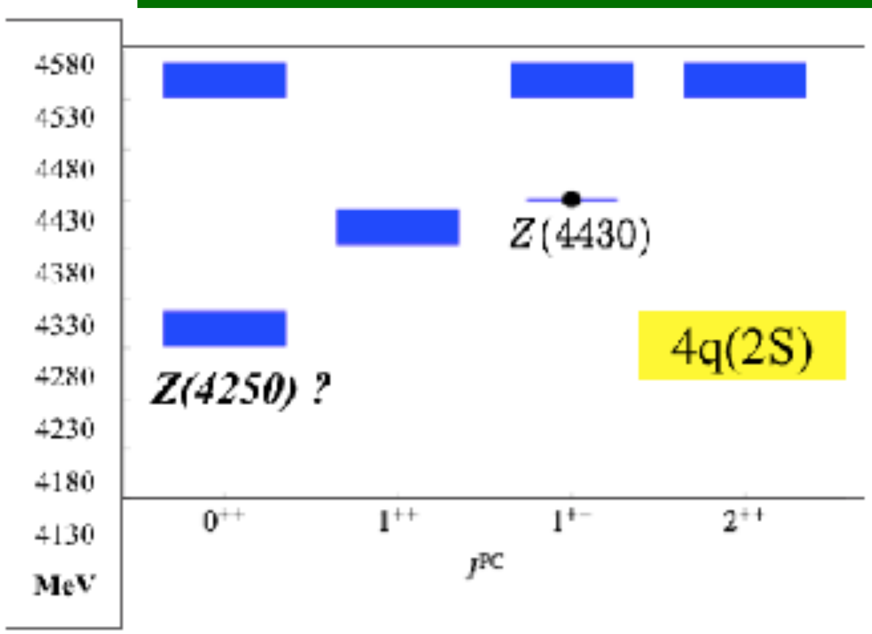
$$J^P=0^+ \quad C=+ \quad X_0=|0,0\rangle_0,\;\; X_0'=|1,1\rangle_0$$

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

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

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

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



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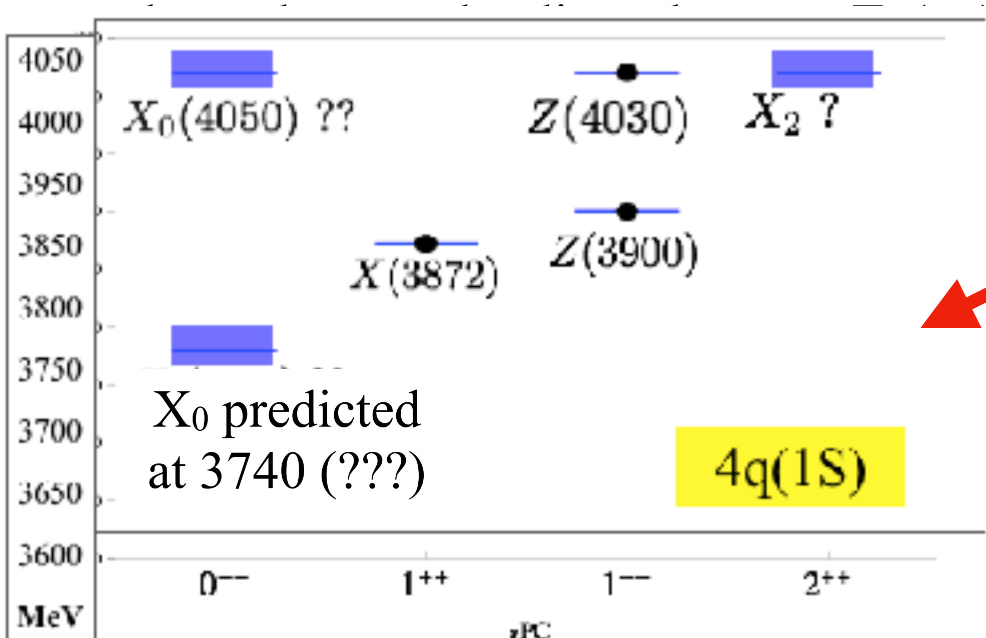
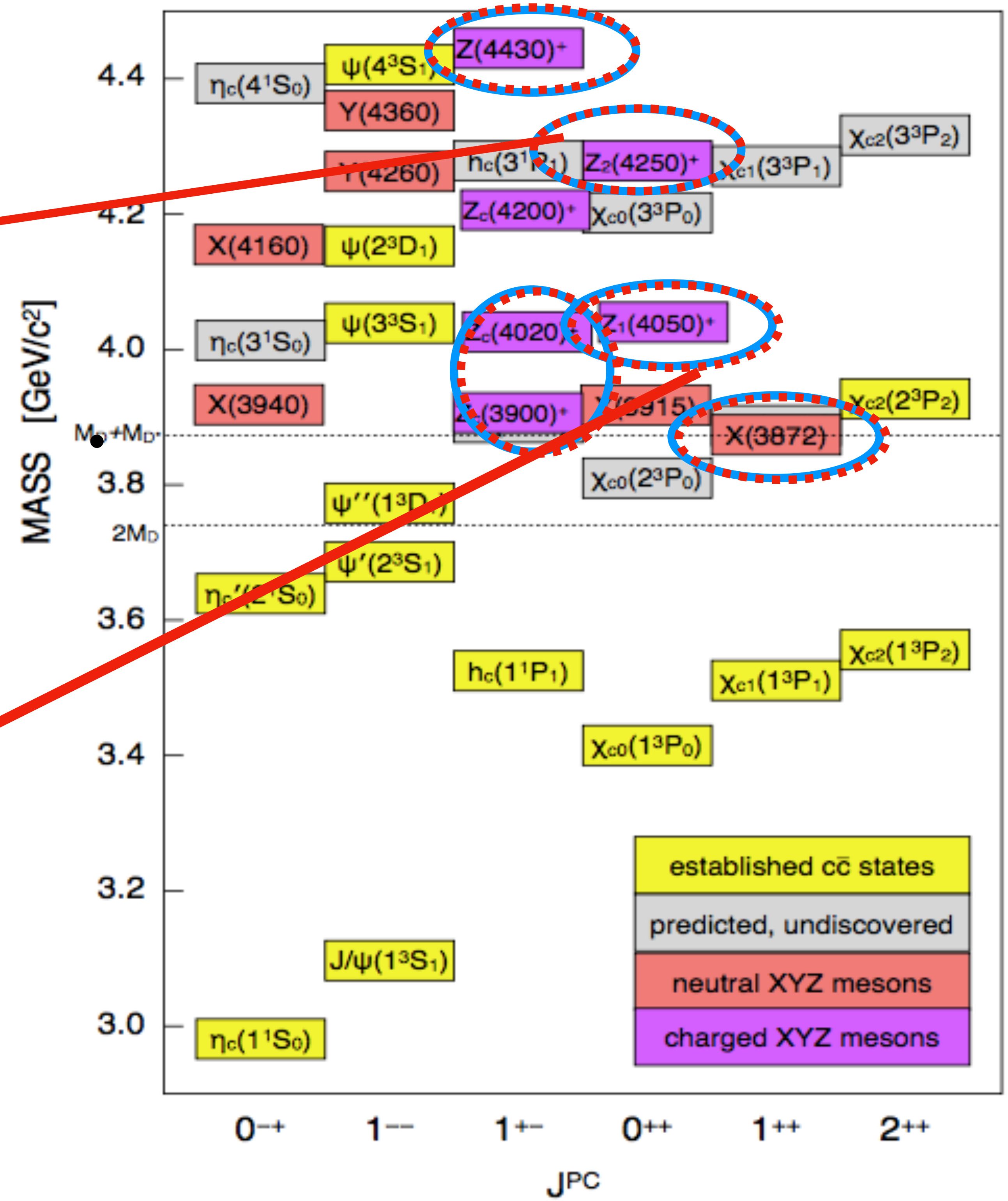
$$\Delta E_r(cq) = 530 \text{ MeV}$$

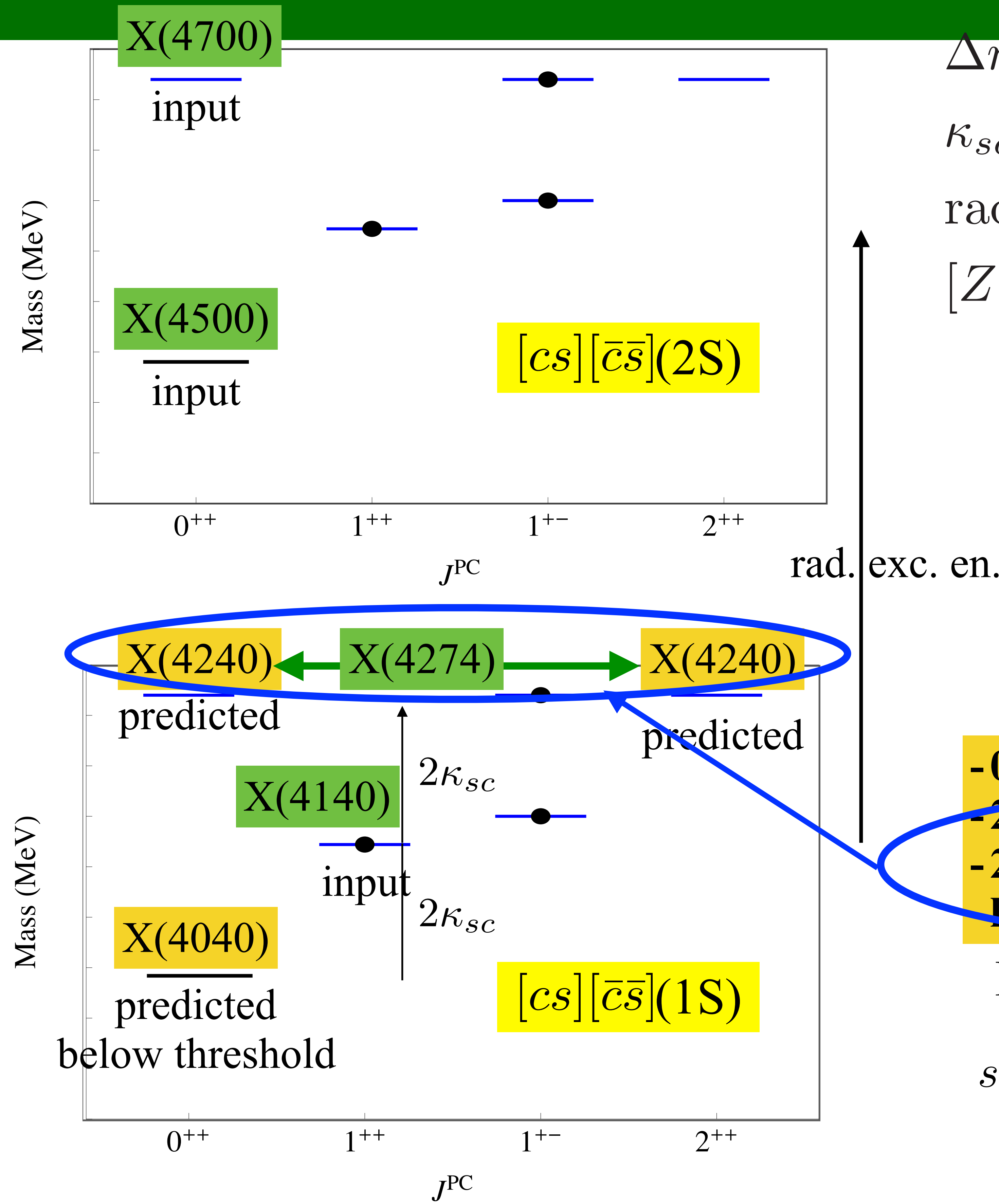


$$m_{[cq]} = 1980 \text{ MeV}$$

$$\kappa_{cq} = 67 \text{ MeV}$$



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:

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

$$s_{c\bar{c}} = 0 : \eta_c + \phi, h_c + \phi \ (P - wave)$$

4. X(3872) production @ LHC

4 Measurement of the cross section ratio

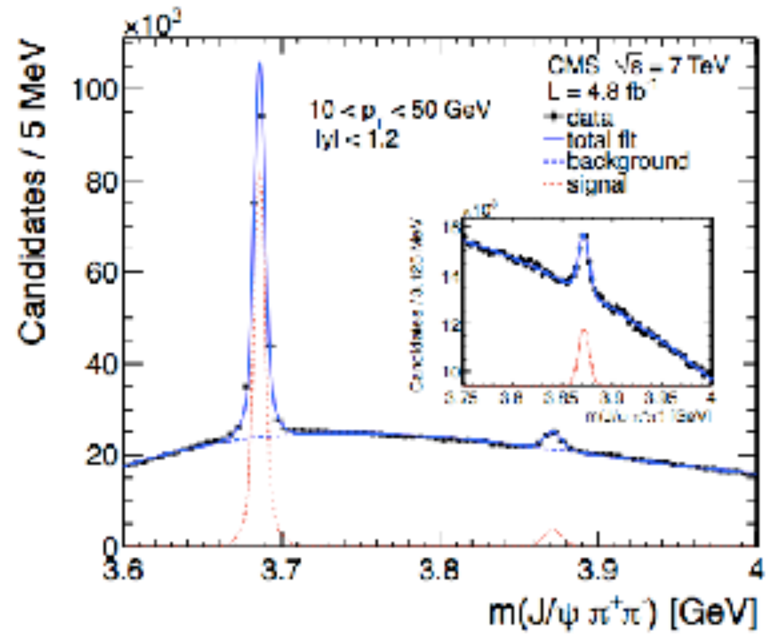
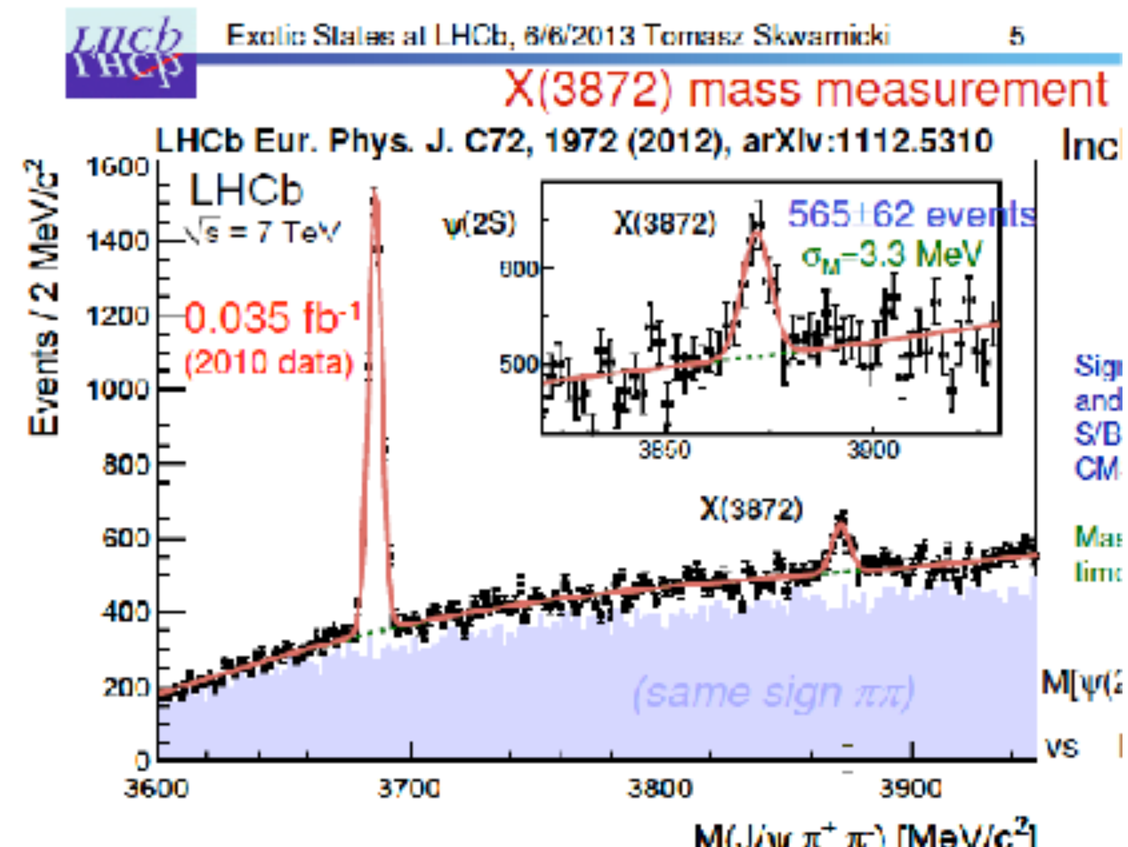
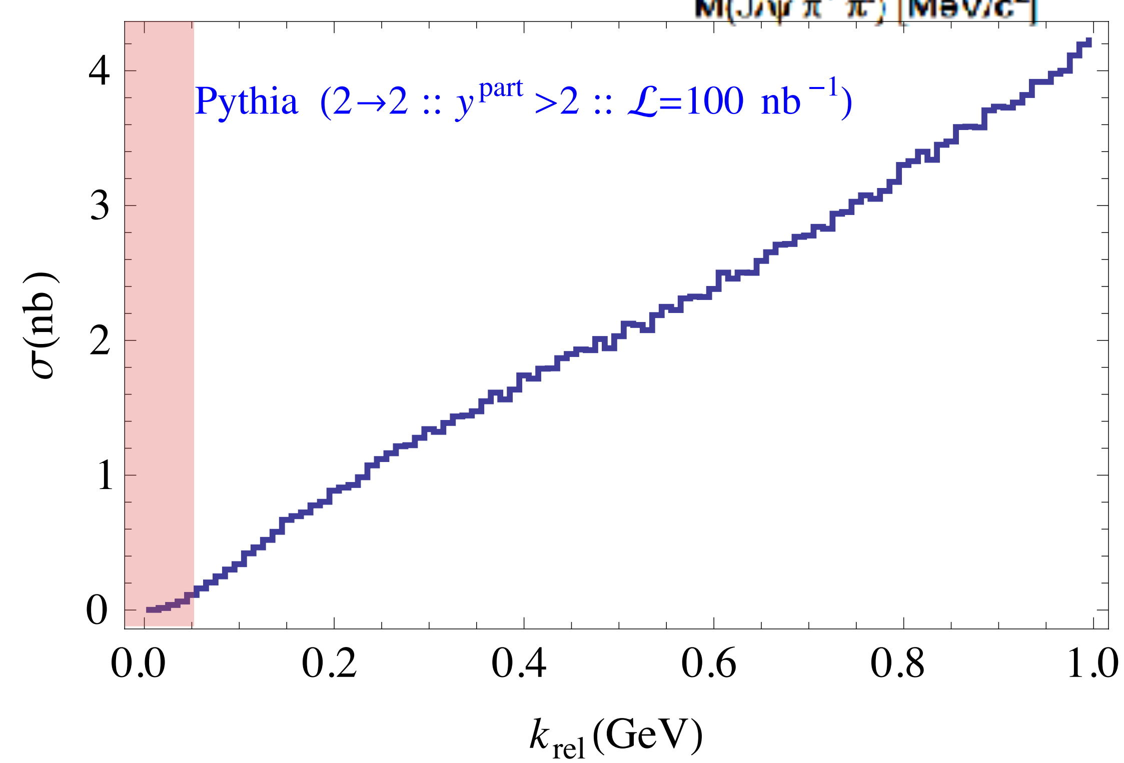


Figure 1: The $J/\psi\pi^+\pi^-$ invariant-mass spectrum for $10 < p_T < 50$ GeV and $|y| < 1.2$. The lines represent the signal-plus-background fits (solid), the background-only (dashed), and the signal-only (dotted) components. The inset shows an enlargement of the X(3872) mass region.



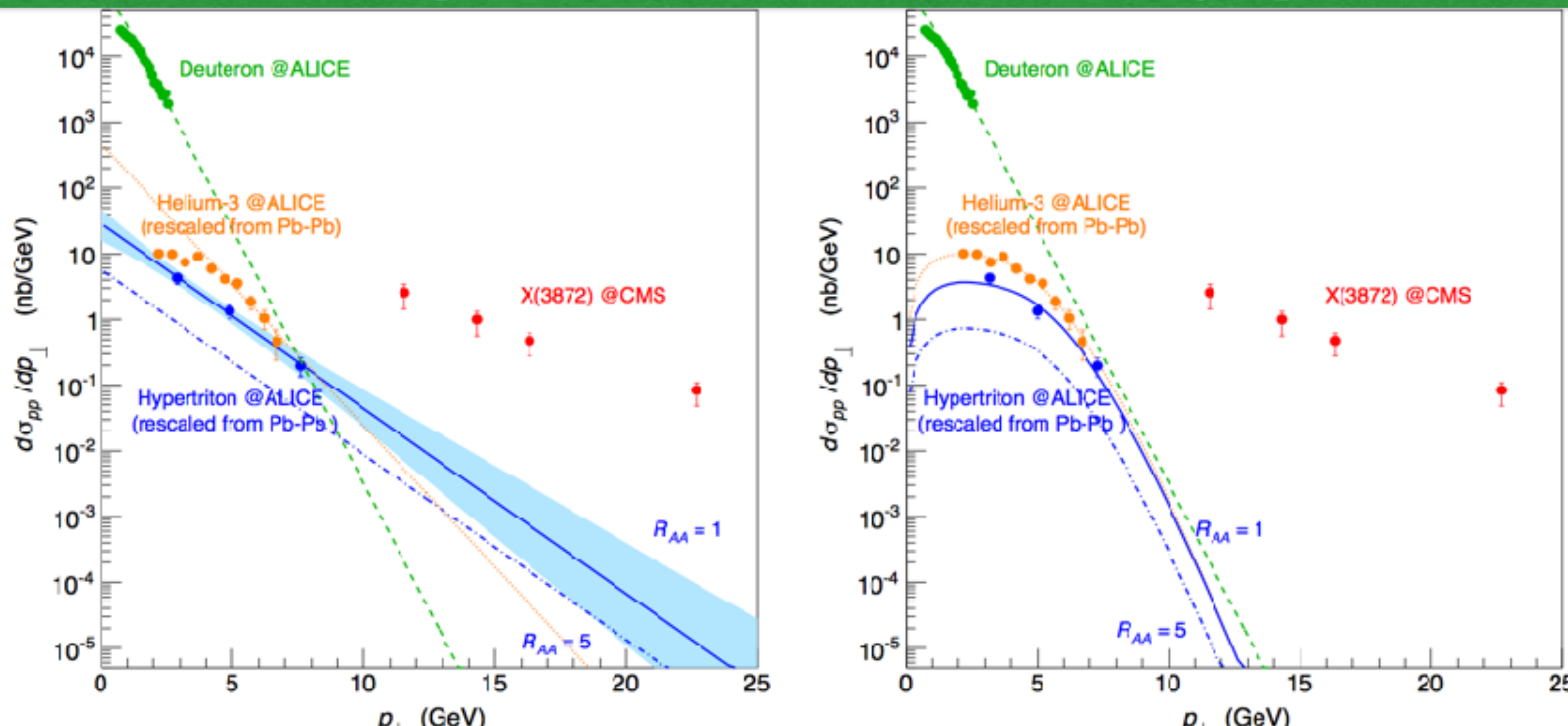
- Production at Colliders speaks against extended objects;
- using Pythia to estimate the probability to find a D-Dbar pair in the relevant phase space, factors of 10^{-2} with respect to the X(3872) cross section measured by CDF (~ 30 nb) are found.



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

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)….

Can mixing with charmonium save the molecule?

5. Tetraquarks in the large N expansion

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

- Respectability of tetraquarks wasgreatly damaged by a theorem of S. Coleman: *tetraquarks correlators for N→∞ reduce to disconnected meson-meson propagators* (of order N^2) S. Coleman, Aspects of Symmetry (Cambridge University Press, Cambridge, England, 1985), pp. 377–378.
- The argument was reexamined by S. Weinberg who argued that if the connected tetraquark correlator (of order N) develops a pole, it will be irrelevant that it is of order 1/N with respect to the disconnected part: *at the pole the connected part will dominate anyhow*; S. Weinberg, PRL 110, 261601 (2013),
- the real issue is the width of the tetraquark state: it could increase for large N, to the point of making the state undetectable;
- Weinberg's conclusions is that the decay rate goes like 1/N, making tetraquarks a respectable possibility.
- Weinberg's discussion has been enlarged by M. Knecht and S. Peris (arXiv: 1307.1273) and further considered by T. Cohen and R. Lebed et al. (arXiv: 1401.1815, arXiv:1403.8090).

QCD at large N in a nutshell

Quark-guon coupling

$$\mathcal{L}_{QCD} = g_{\rm QCD}\ \bar{q}\frac{\lambda^A}{2} g^A_\mu \gamma^\mu q$$

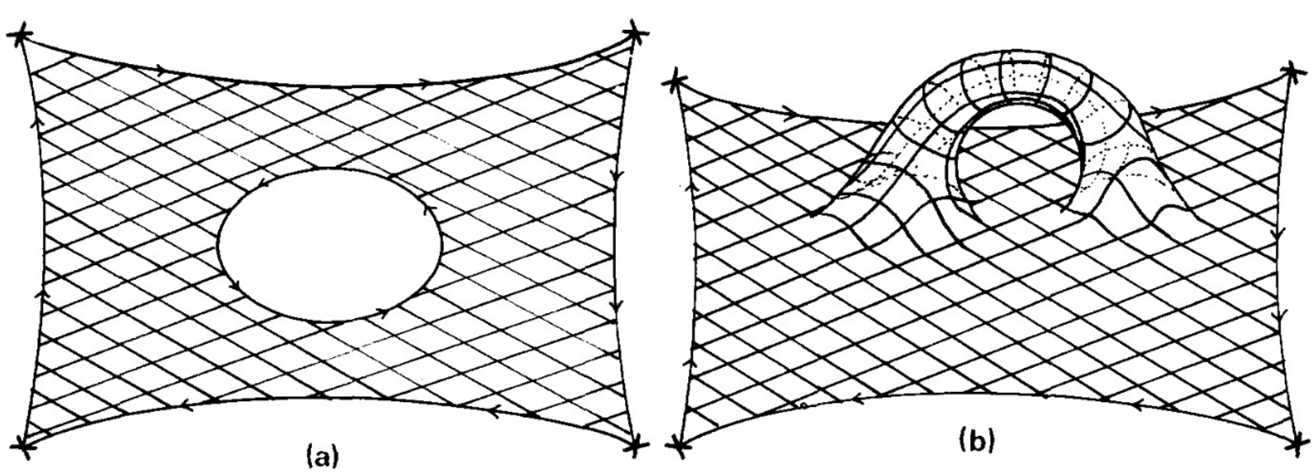
’t-Hooft shows that in the limit $N \to \infty$ with

$$g_{\rm QCD} \to 0, g_{\rm QCD} \cdot \sqrt{N} = \text{fixed}$$

only planar diagrams with quarks at the edge survive.

Diagrams with k quark loops are of order N^k, with a coefficient which is a non trivial, non perturbative function of the reduced coupling, sometime referred to as the ’t-Hooft coupling

$$\lambda = g^2_{\rm QCD} \cdot N$$



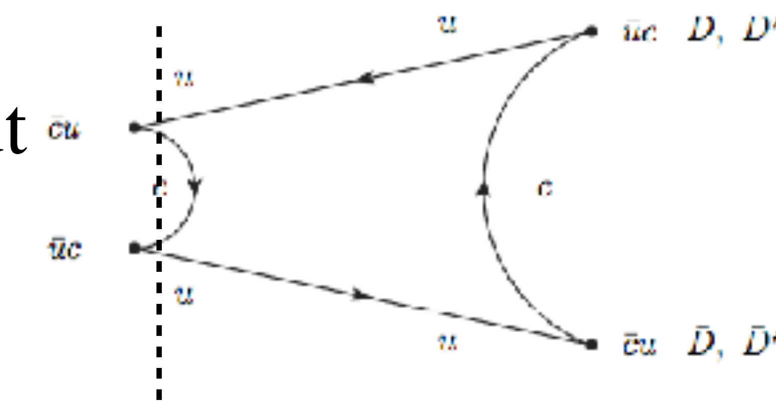
Order of diagram: $N^k,\ k = 2 - L - 2H$

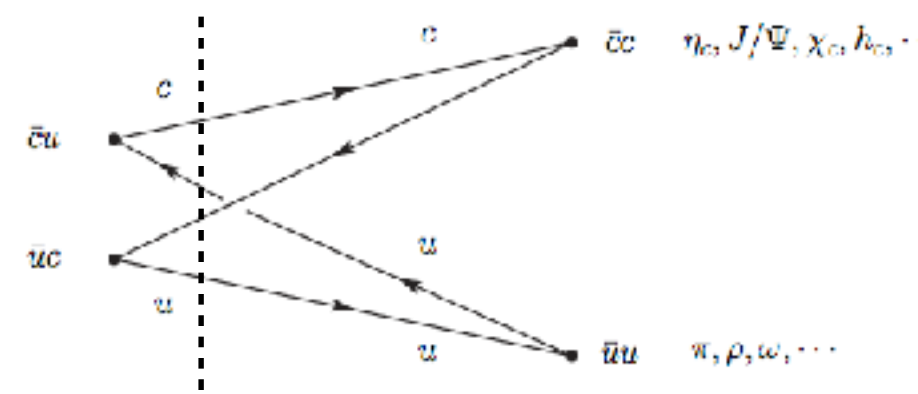
L = n. of fermion loops
H = n. of handles

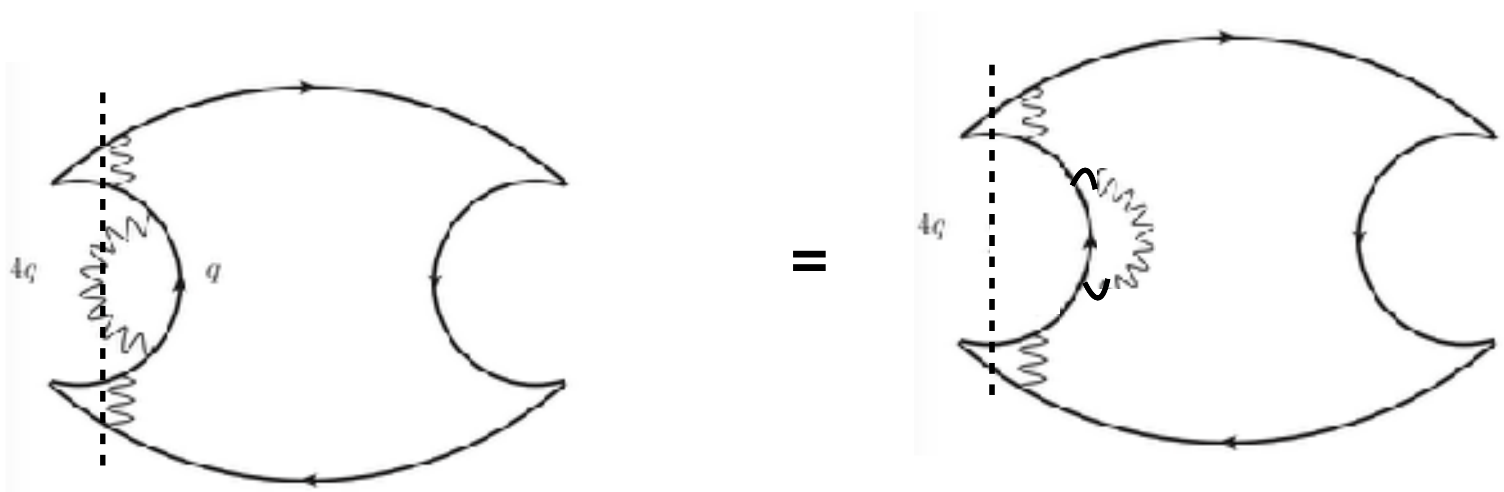
Need to go beyond planar diagrams

L. Maiani, A. D. Polosa and V. Riquer, JHEP 1606 (2016) 160

- The typical diagrams of order N show a 4 quarks cut
- but: are these ***free quarks***?
- No: The same order applies if we fill the quark loop by a multigluon, ***planar*** diagram('t-Hooft)
- It would seem that the planar interactions may resolve the problem

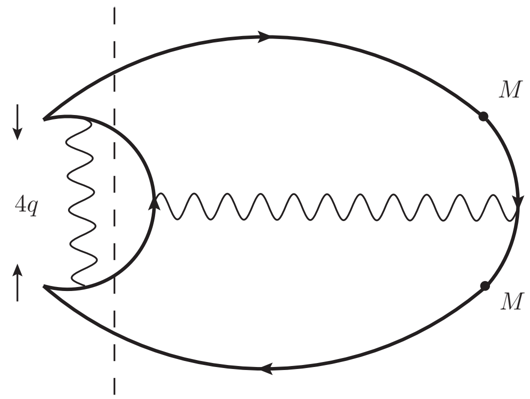






- however, for planar gluons the cut corresponds to a pair of ***free mesons***!

- We need to introduce (at least) one ***non planar*** interaction between the free mesons:



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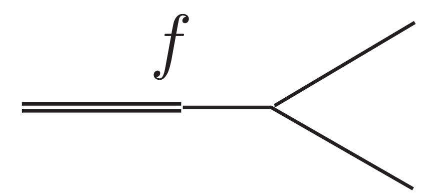
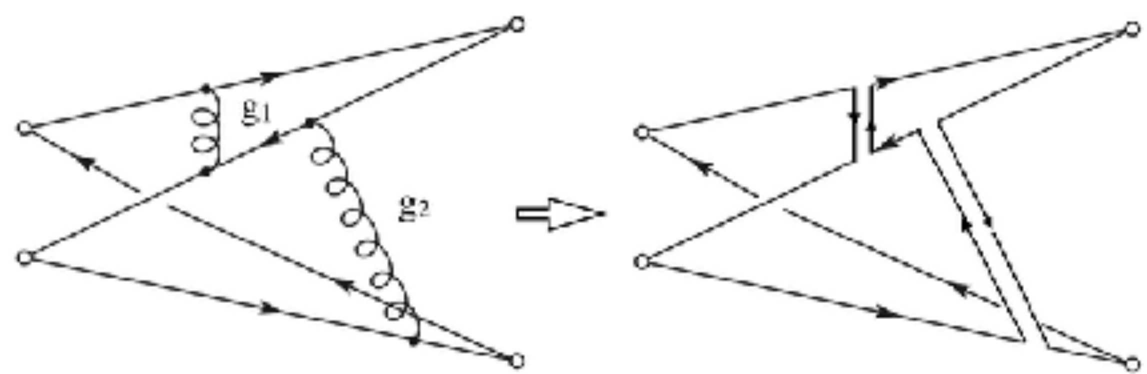


$$\propto \frac{1}{N} \to f \propto \frac{1}{N\sqrt{N}}$$

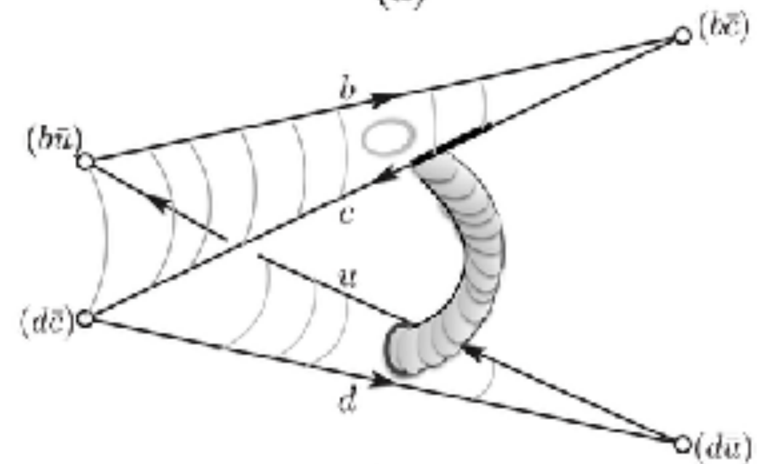
- Similarly:



(a)

$$\propto \frac{1}{N}$$

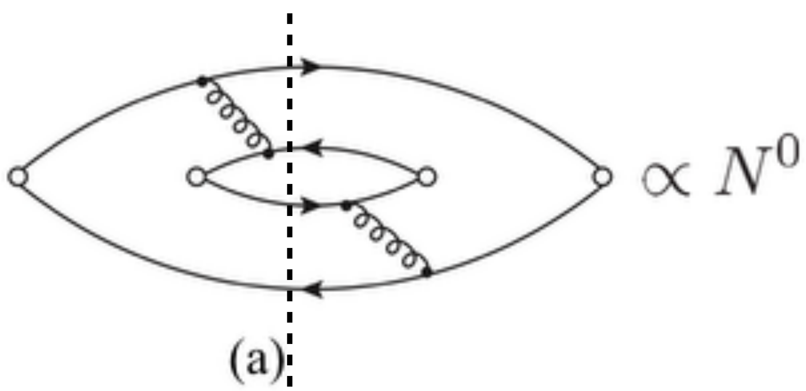
- i.e. one topological handle

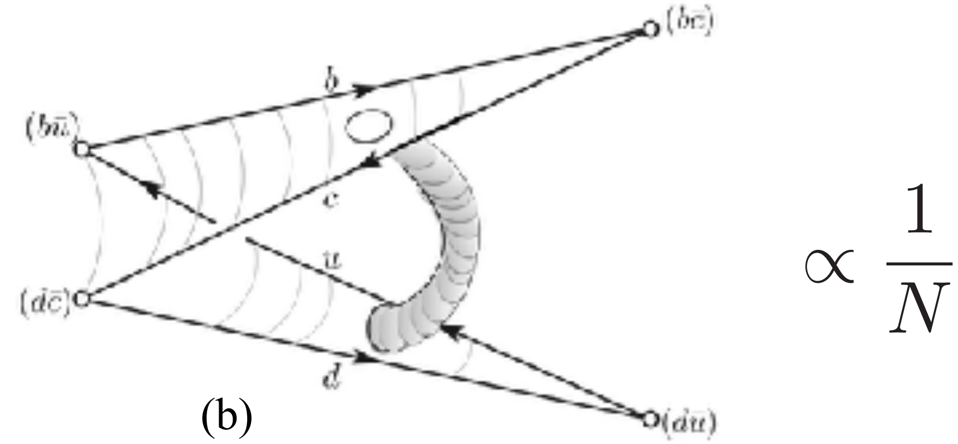


(b)

W. Lucha, D. Melikhov and H. Sazdjian, Phys. Rev. D 96 (2017) no.1, 014022

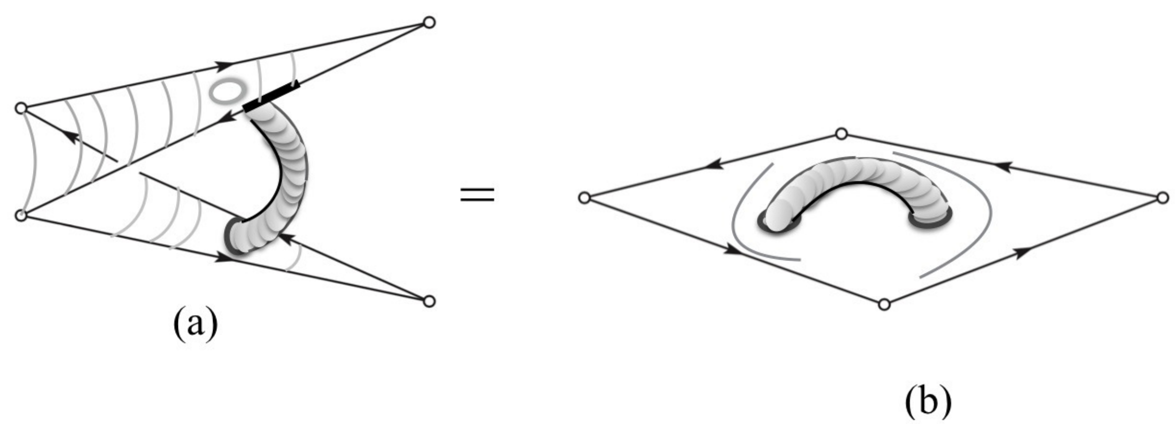
- meson meson scattering described by diagram (a)
- assume tetraquark s-channel poles in (a) and (b) → consistency of the two diagrams requires ***two tetraquarks*** with same flavours !!

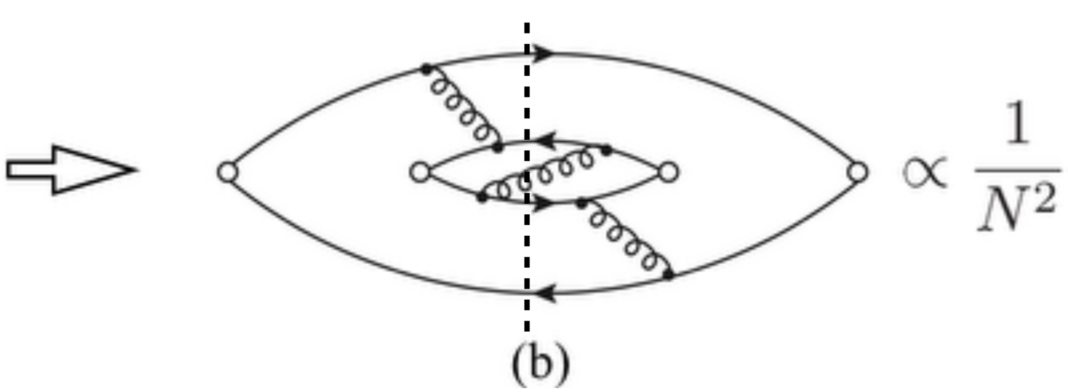


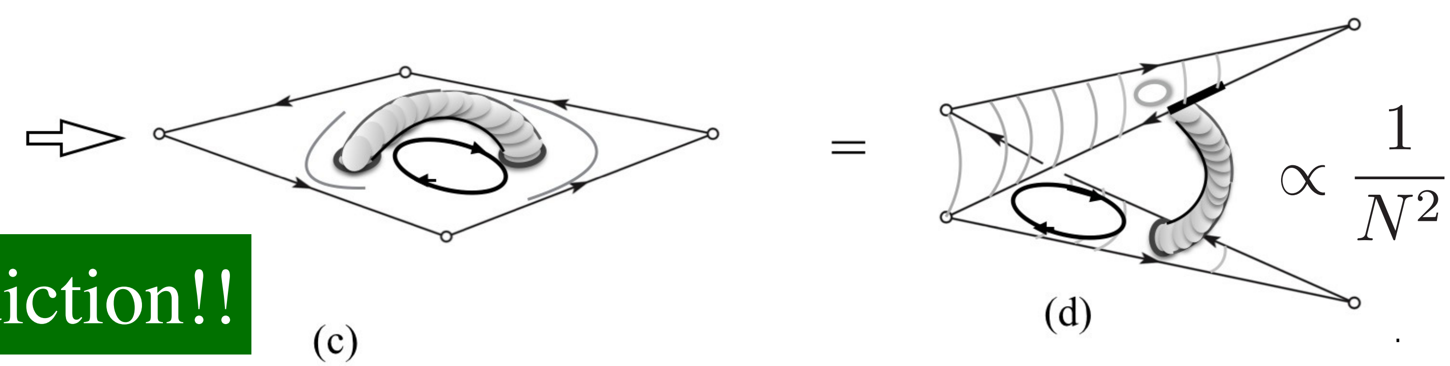


L. Maiani, A.D. Polosa, V. Riquer, in preparation

- However, the cut in (a) corresponds to two non interacting mesons: needs non planar interaction (b), non perturbatively: one topological handle
- and for consistency, one more fermion loop in the zig-zag diagram:





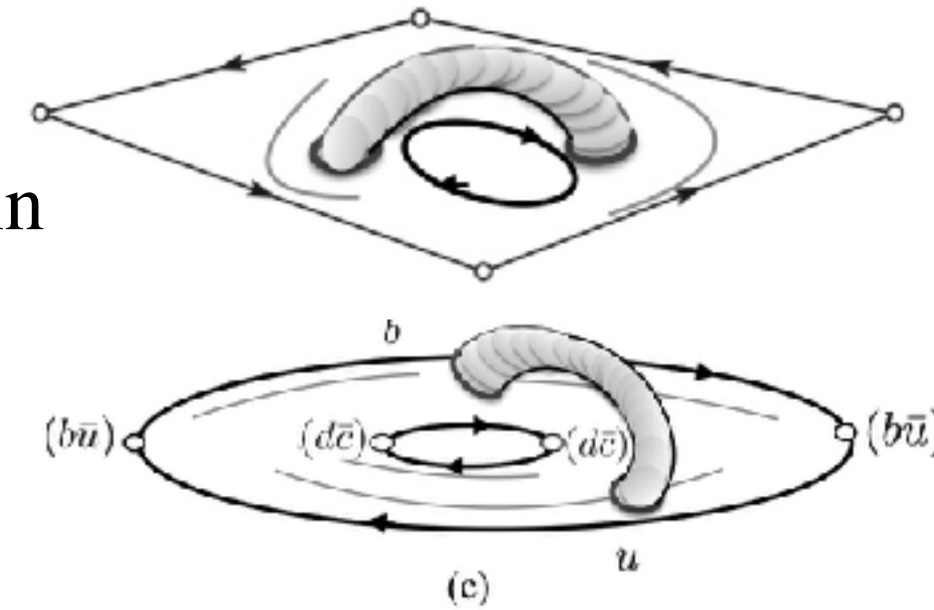


- The same order resolves the contradiction!!

our results: meson-meson scattering

L. Maiani, A.D. Polosa, V. Riquer, in preparation

Only one diagram is relevant, with meson insertions distributed on the two fermion loops



1. for given flavours, ***one tetraquark suffices*** to obtain a consistent solution (qq are attractive in color 3-bar and repulsive in 6, one tetraquark only)
2. decay amplitudes:

$$A(T \to M_1 + M_2) \propto \frac{1}{N^2}$$ (Tetraquarks are observable)

$$A(T \to T' + M) \propto \frac{1}{\sqrt{N}}$$

$$A(T \to T' + \gamma) \propto eN^0$$

3. The decays: Y→Z+π and Y→X+γ are ***allowed transitions***

4. ***neutral hidden-charm tetraquarks mix with charmonia*** to order: $\frac{1}{N\sqrt{N}}$
   they may have ***charmonia-like decays***
   Y states ***may annihilate into e⁺ e⁻*** via mixing.

6. Conclusions

- Exotic Hadrons are there
- More data are needed to sort out the right theory
- High Energy Colliders to play an oversll imprtant role
- Diquarks explanation has startling consequences
  - abundant production at Colliders
  - many states
  - stable double heavy tetraquarks
  - pentaquarks lead to dibaryons