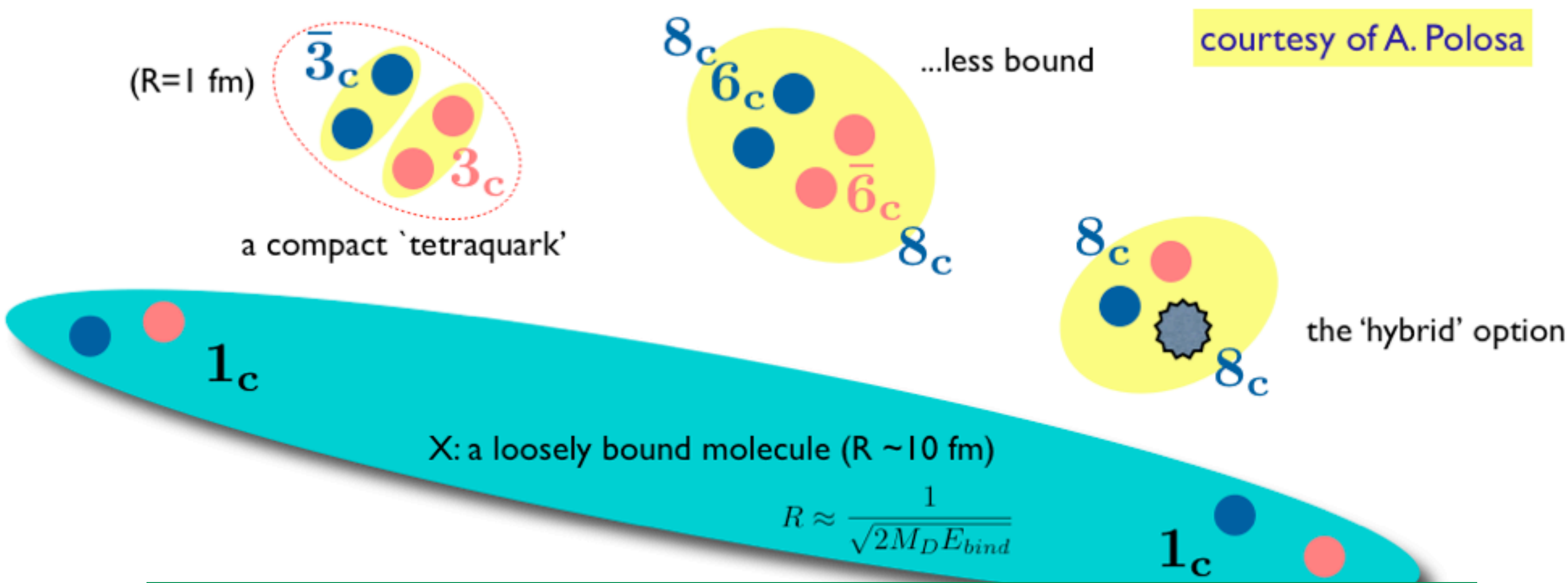
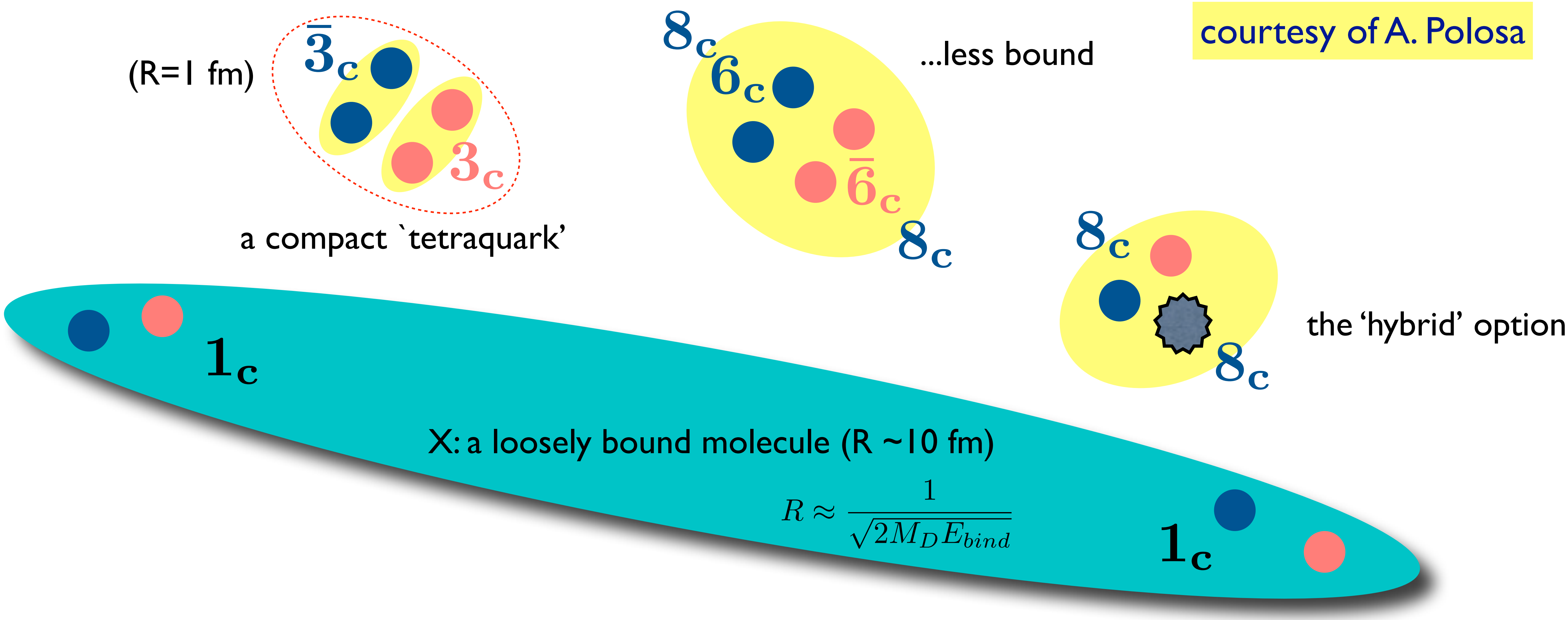


XYZ states and a New Paradigm for Spin Interactions in Tetraquarks

L. Maiani, Roma Sapienza and IFT, Madrid

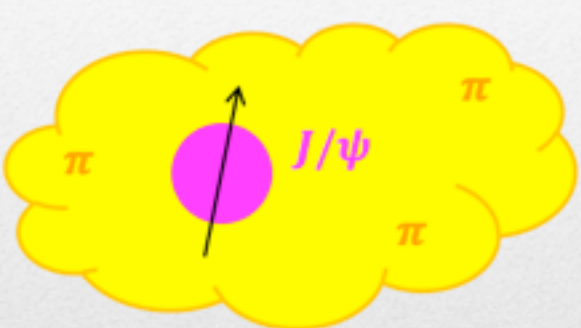
Tetra b quarks: Ali, Hambrock, Wang,Phys. Rev. D 85 (2012) 054011.

X Y Z as compact tetraquarks ?



Hadro-charmonium

Voloshin arXiv:1304.0380



A $c\bar{c}$ state surrounded by light matter

Decay into $\eta_c\,\rho$ forbidden by HQSS

quark (heavy or light)

antiquark

gluon

Z(4430) as a radially excited tetraquark

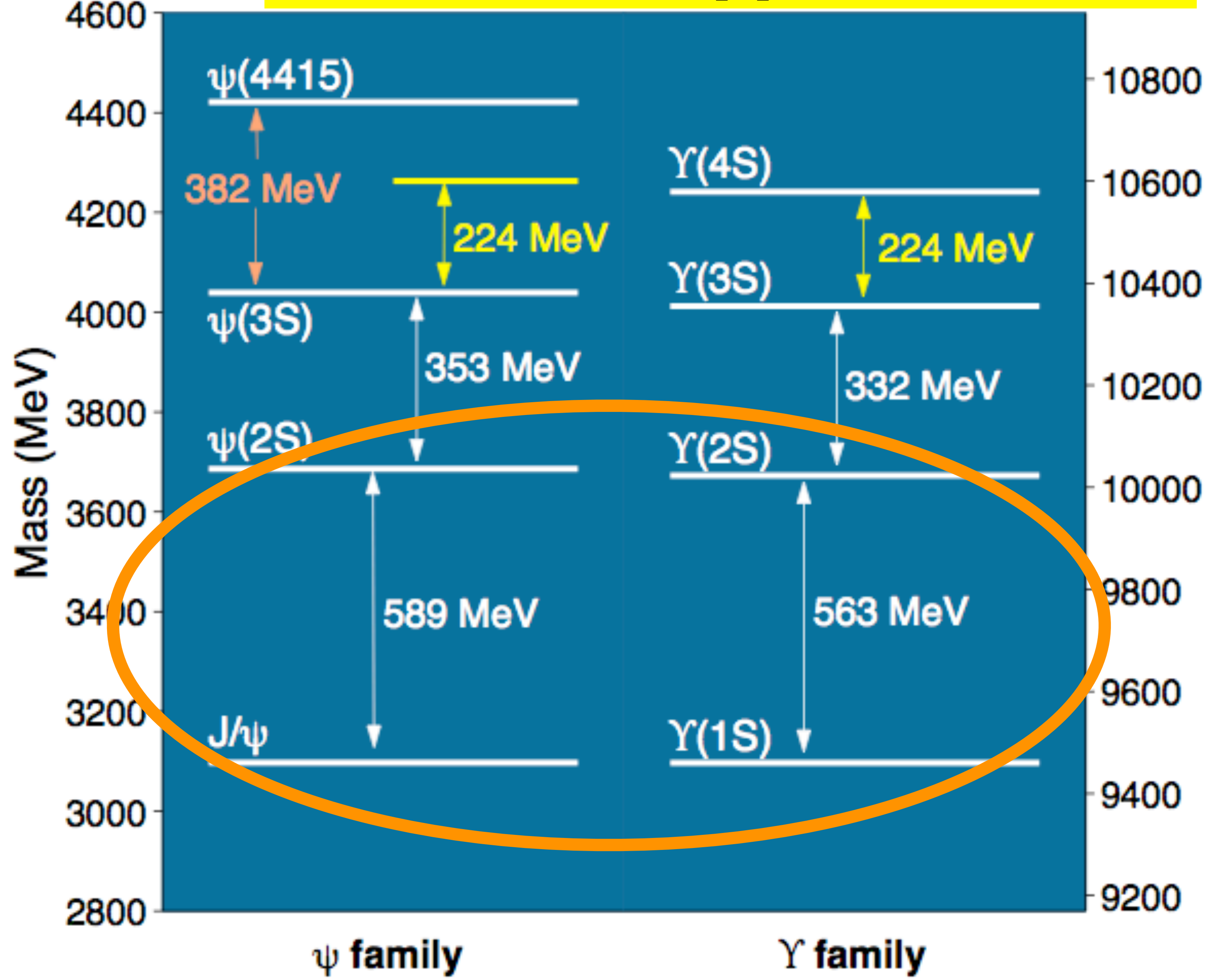
- in 2007 we classified the Z(4430) as a tetraquark, the radial excitation of the S-wave companion of X(3872)
- this was because of its decay into $\psi(2S)+\pi$ and to its mass ~550 MeV larger than the X
- We noted: *A crucial consequence of a Z(4430) charged particle is that a charged state decaying into* $\psi(1S)+\pi^{\pm}$ *or* $\eta_c+\rho^{\pm}$ *should be found around 3880 MeV* (i.e. almost degenerate with X(3872))
- The $Z_c(3900)$ has now been seen by BES III and Belle with the anticipated decay:
  - $Z^+ (3900) \to \psi(1S)+\pi^+$
- a neutral partner is suggested by CLEO,
- The further observation of Z(4020) by the BES III Collaboration reinforces the tetraquark picture, which looks more attractive and constrained as compared to some years ago
- The Z(4430) decay into $\psi(2S)$ as indication of a radially excited tetraquark is confirmed by S. Brodski *et al*. (arXiv:1406.7281 [hep-ph])

3. Radial excitations

- Spacing of radial excitations are the same in S-wave Charmonia and Bottomonia;
- gap between 1P-2P states is smaller :

$$\chi_{bJ}(2P) - \chi_{bJ}(1P) \approx 360 \text{ MeV}$$
$$\chi_{cJ}(2P) - \chi_{cJ}(1P) \approx 437 \text{ MeV}$$

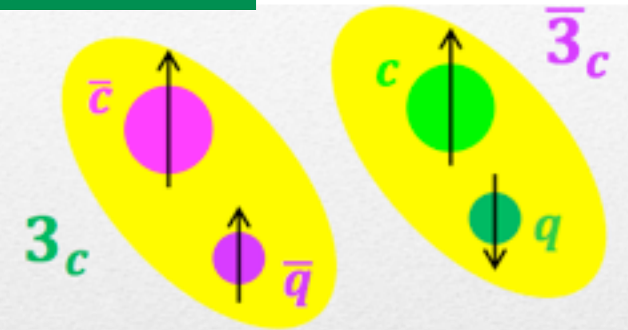
L.-P. He, D.-Y. Chen, X. Liu and T. Matsuki arXiv:1405.3831 [hep-ph].



4. A Tetraquark picture of unexpected quarkonia

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

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



- q, q'=u,d so that I=1, 0
- positive parity: S-wave
- total spin of each diquark, S=1,0
- neutral states may be mixtures of iso triplet and singlet
- mass splitting due to spin-spin interactions (like e.g. in the non-relativistic costituent quark model)

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

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

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

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

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

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

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

X(3872)=X_1
Z(3900), Z(4020)=lin. combs. of Z&Z' that diagonalize H
X(3940)=X_2 ??

Mass spectrum: the new paradigm

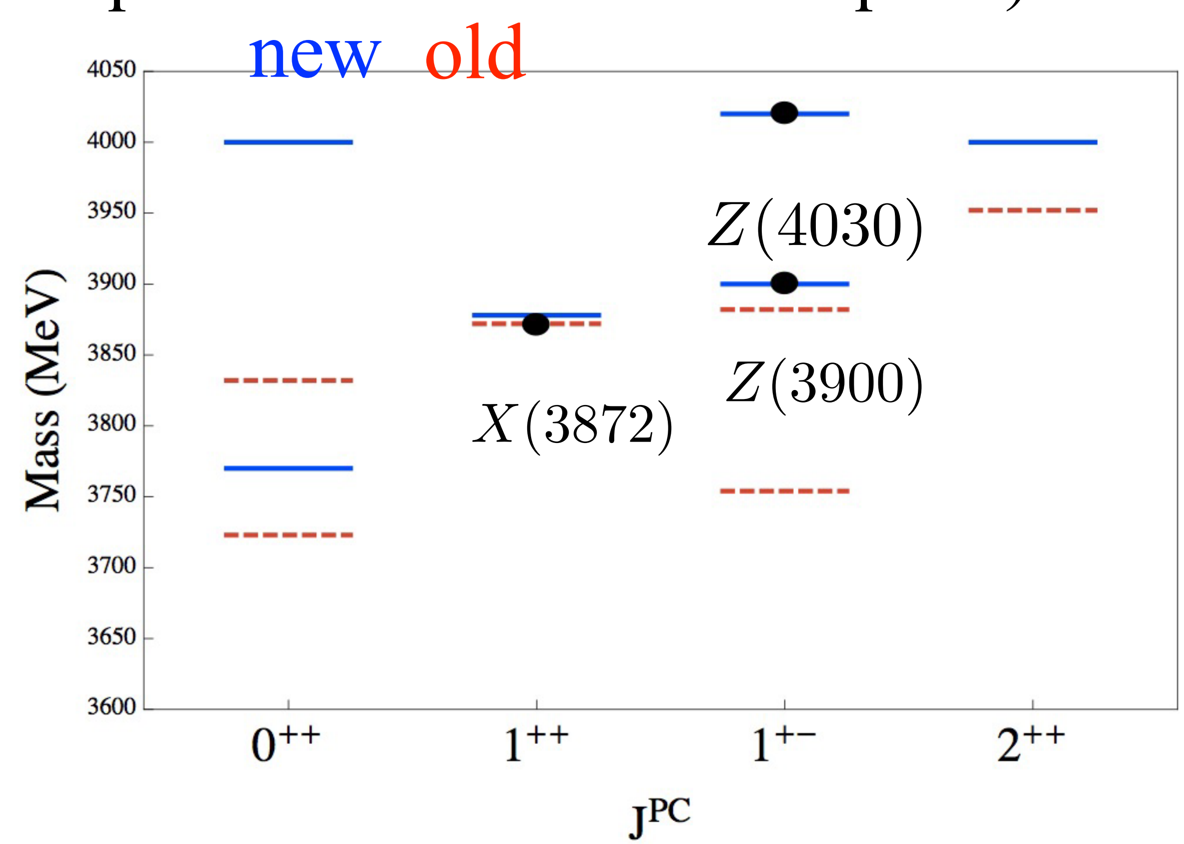
A. Polosa, V. Riquer, F, Piccinini, PRD **89**, 114010 (2014)

- A tentative mass spectrum for the S-wave tetraquarks was derived in the 2005 paper, based on an extrapolation of the spin-spin interactions in conventional S-wave mesons and baryons.

- Does NOT agree with the observed level ordering of X(3872), Z(3900) and Z(4020)

- A new, simple paradigm accounts for the observed: the dominant interactions are those ***between quarks in the same diquark*** (antiquarks in the same antidiquark):

$$H \approx 2\kappa_{qc} \, (s_q \cdot s_c + s_{\bar{q}} \cdot s_{\bar{c}}) =$$
$$= \kappa_{qc} \left[s(s+1) + \bar{s}(\bar{s}+1) - 3 \right]$$



- H is diagonal in the basis of diquark spin and counts the number of spin=1 diquarks
- one Z is degenerate with X(3872), the other is heavier;
- κ~67 MeV from fit (larger than in baryons).

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 was somehow tarnished by a theorem of S. Coleman: *tetraquarks correlators for N→∞ reduce to disconnected meson-meson propagators*

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 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*;

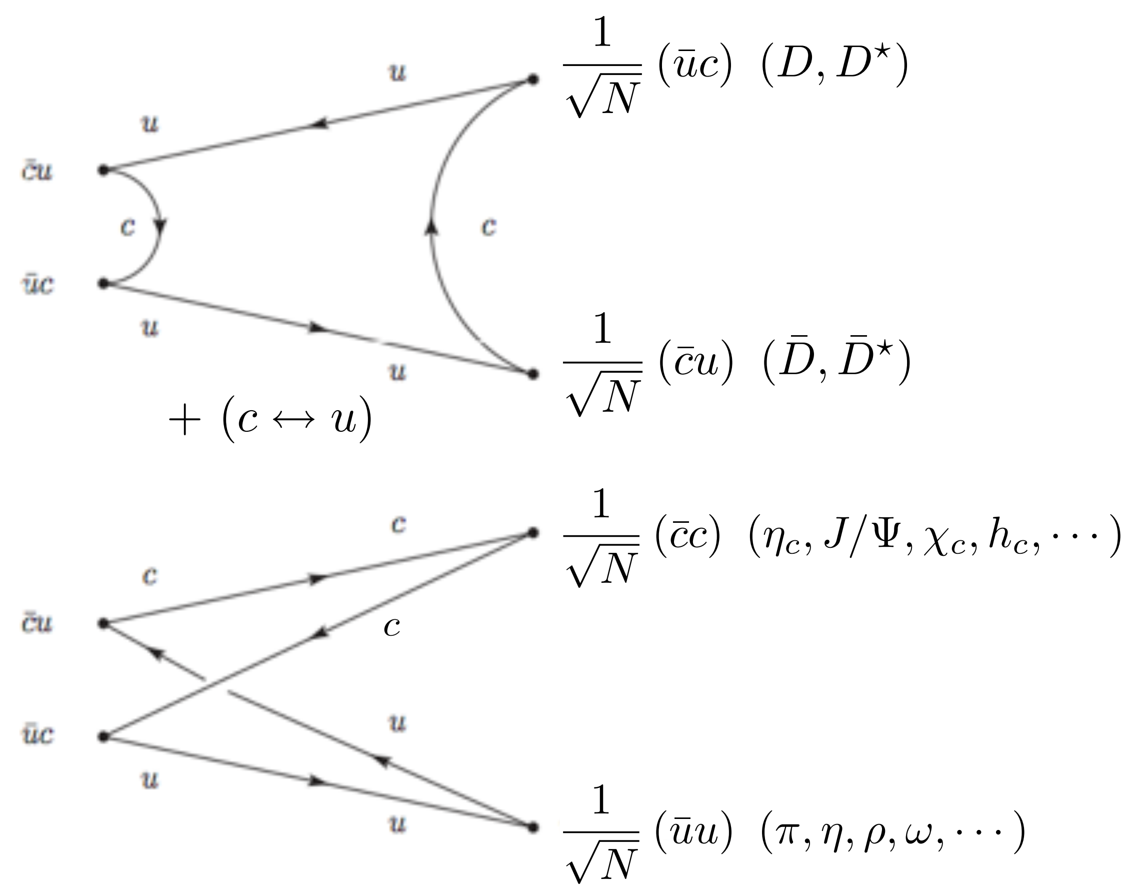
S. Weinberg, PRL 110, 261601 (2013),

- rather, the real issue is the width of the tetraquark state: it may increases for large N, to the point of making the state undetectable;
- Weinberg's conclusions is the 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).

Decay amplitudes in 1/N expansion

- By Fierz rearrangements, tetraquark operators can be reduced to products of color singlet bilinears;
- interpolating field operators have to be multiplied by powers of N, such as to make the connected two-point correlators to be normalized to unity;
- one loop amplitude with insertions of quark color singlet operators gives a factor N.

$$\mathcal{Q} = \frac{1}{\sqrt{N}}[cu][\bar{c}\bar{u}]$$



- two independent amplitudes

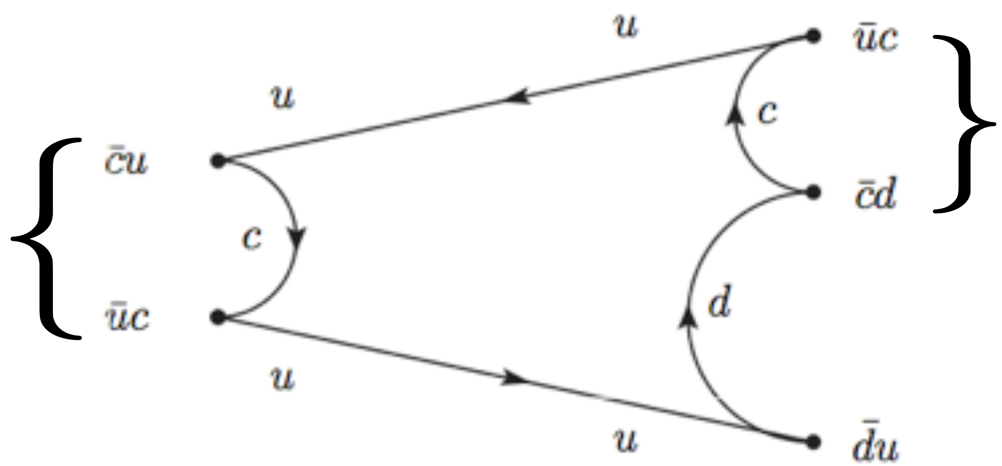
- The result is that *decay amplitudes into two mesons are of order*: $\frac{1}{N^{3/2}}N = \frac{1}{\sqrt{N}}$
- These two amplitudes were introduced long ago for tetraquark light scalar decay: reassuringly, they turn out both to be leading in 1/N.

L. Maiani, F.Piccinini, A. D. Polosa, V. Riquer, PRL **B93**, 212002 (2004)

further decay amplitudes

- tetraquark de-excitation amplitudes by meson emission, e.g. $Y(4260) \to Z_c(3900) + \pi$, are also of order $1/\sqrt{N}$

$$Y(4260) = \frac{1}{\sqrt{N}}[cu][\bar{c}\bar{u}]$$

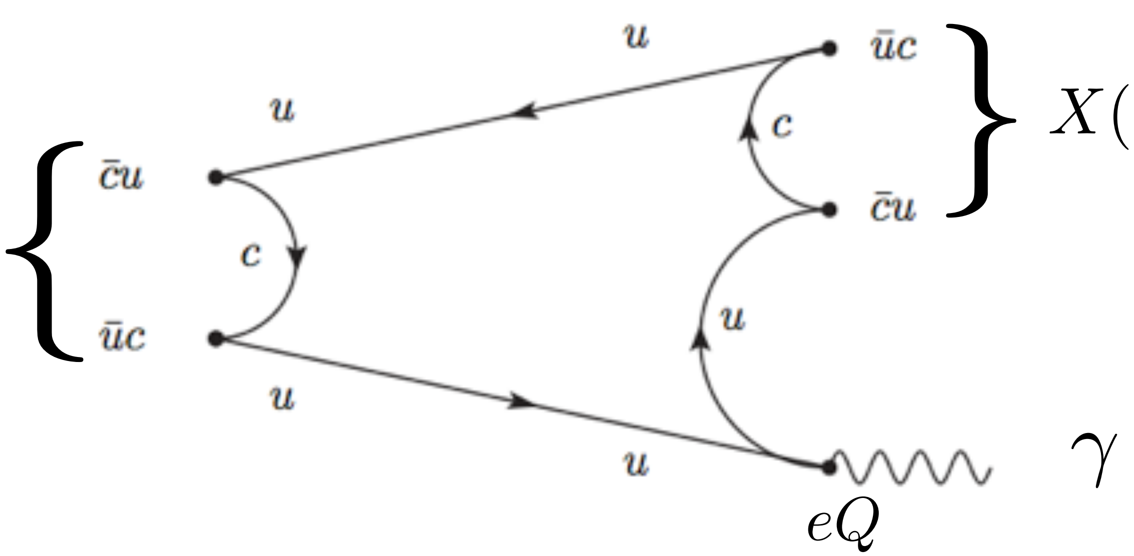


$$Z_c^-(3900) = \frac{1}{\sqrt{N}}[cd][\bar{c}\bar{u}]$$

$$\pi^+ = \frac{1}{\sqrt{N}}(u\bar{d})$$

- however, e.m. currents need no normalization factor, so that the deexcitation amplitudes via photon emission are of order eQ ×1.

$$Y(4260) = \frac{1}{\sqrt{N}}[cu][\bar{c}\bar{u}]$$



$$X(3872) = \frac{1}{\sqrt{N}}[cu][\bar{c}\bar{u}]$$

Non-perturbative instantons: may explain two or three further puzzles

G. 't Hooft, G. Isidori, L. Maiani, A. D. Polosa and V. Riquer, PL **B662** (2008) 424.
A. H. Fariborz, R. Jora and J. Schechter, PR **D77** (2008) 094004.

(a) (b)

- (a) the decay $f_0(980) \rightarrow 2\pi$ ($f_0 = \frac{([su][\bar{s}\bar{u}] + u \rightarrow d)}{\sqrt{2}}$)
- (b) the mixing of light (tetraquark) scalar mesons with q-qbar mesons, the latter being made by $a_0(1474)$ (I=1), $K_0(1412)$, (I=1/2), and three isosinglets: $f_0(1370)$, $f_0(1507)$ and $f_0(1714)$ (one could be a glueball);
- (c)= (b) in the reverse:
  - with: $Y(4260) = \frac{([cu][\bar{c}\bar{u}] + u \rightarrow d)}{\sqrt{2}}$, the u-ubar or d-dbar pair in Y may give rise to the observed decay:

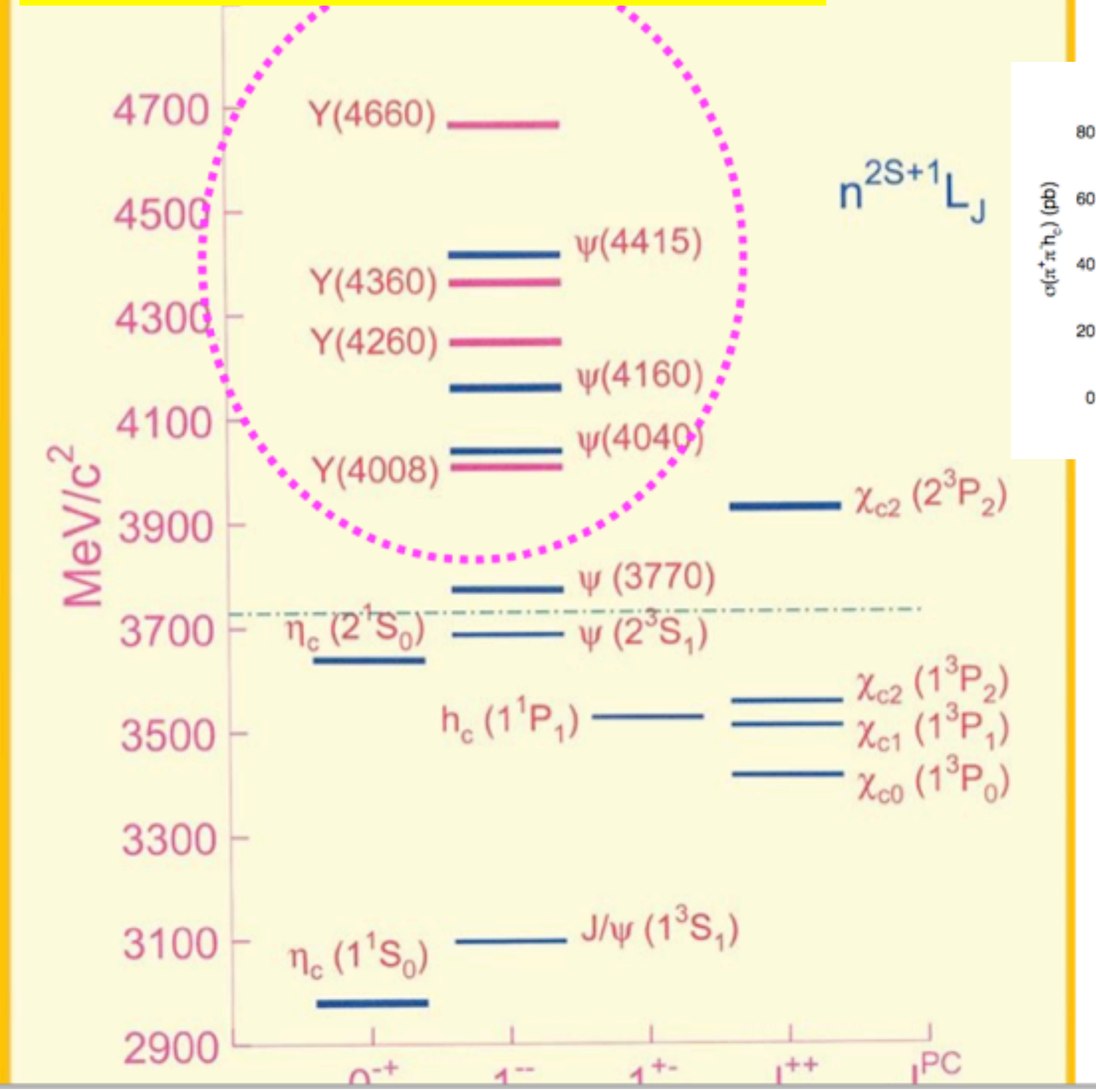
$$Y(4260) \rightarrow J/\Psi + f_0 = J/\Psi + \pi^+ + \pi^-$$

6. Selection rules

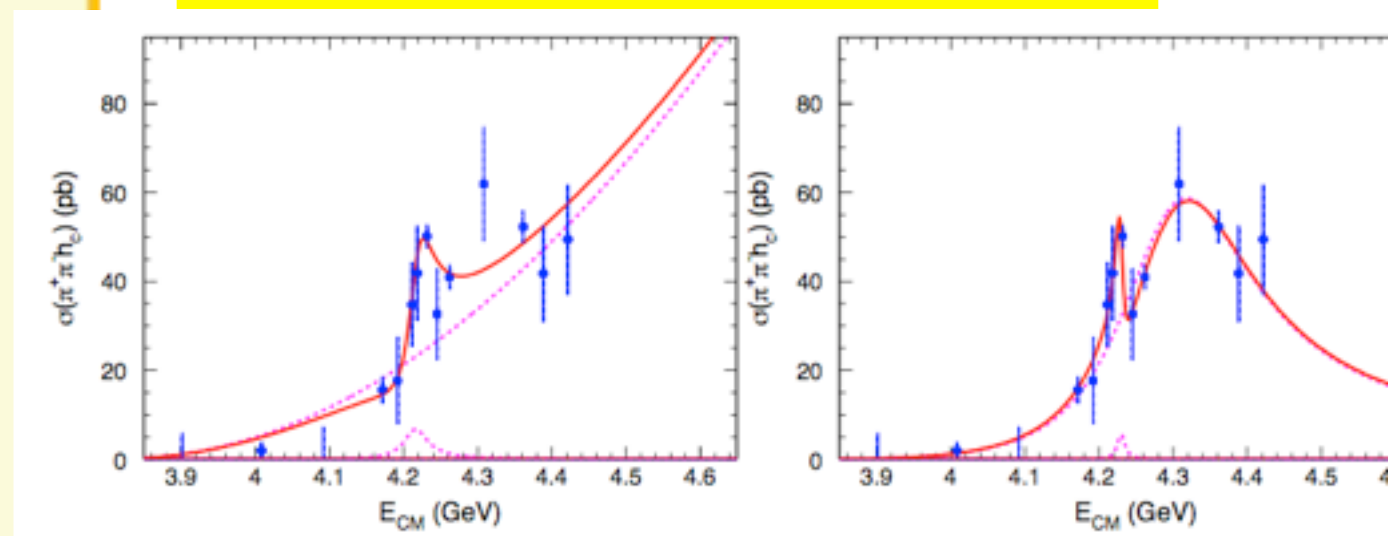
- Conservation of the heavy quark spin is well established in QCD: decays indicate the value of c-cbar spin in the initial wave function:
  - X(3872): S(c-cbar)=1$\rightarrow$ J/Ψ yes, but no η_c
  - Y(4230): both χ_c (S (c-cbar) =1) and h_c (S (c-cbar) =0)
- conservation of light quark spin is not reliable:
  - initial spin composition not necessarily reflected in K K* vs K*K* decay modes
- observed X, Y, Z in the new paradigm of spin-spin coupling respect these rules, as far as we can see !
- more precise measurements of different decay channel will be of the outmost importance.

7. What are the Y states?

Changzheng YUAN, IHEP Beijing, 2014



later BES III has observed another one: Y(4230) which decays in $h_c\,\pi\,\pi$



or maybe two? (narrow and wide)

Our survey:

- $Y(4660)$ and $Y(4360)$, decaying into $\psi(2S)\pi$
- $Y(4630)$ decaying into $\Lambda_c\bar{\Lambda}_c$
- $Y(4220)$, narrow (and $Y(4290)$, wide ???) in $h_c(1P)+\pi$, BES III
- $Y(4260)$ and $Y(4008)$ decaying into $J/\psi+\pi$,

Y- tetraquarks

- Tetraquark states with $J^{PC}=1^{--}$ can be obtained with odd values of the orbital angular momentum L=1, 3 and diquark and antidiquark spins s, s bar=0,1.

- use the notation: |s,s bar; S,L>$_{J=1}$, and charge conjugation invariance we get four states

	spin composition
Y_1	$\|0,0;0,1\rangle_1$
Y_2	$\frac{1}{\sqrt{2}}(\|1,0;1,1\rangle_1 + \|0,1;1,1\ \rangle_1)$
Y_3	$\|1,1;0,1\rangle_1$
Y_4	$\|1,1;2,1\rangle_1$

Interpretation of Y states:

- leave aside the $L=3$ state (too heavy);

- $Y(4360)$ and $Y(4660)$ = radial excitations of $Y(4008)$ and $Y(4260)$ (decay into $\psi(2S)$, $\Delta M \sim 350, 400$ MeV in the range of ΔM of $L=1$ charmonia and bottomonia);

- the 4 states Y_{1-4} identified with $Y(4008)$, $Y(4260)$, $Y(4230)$ (the narrow structure in the h_c channel) and $Y(4630)$.

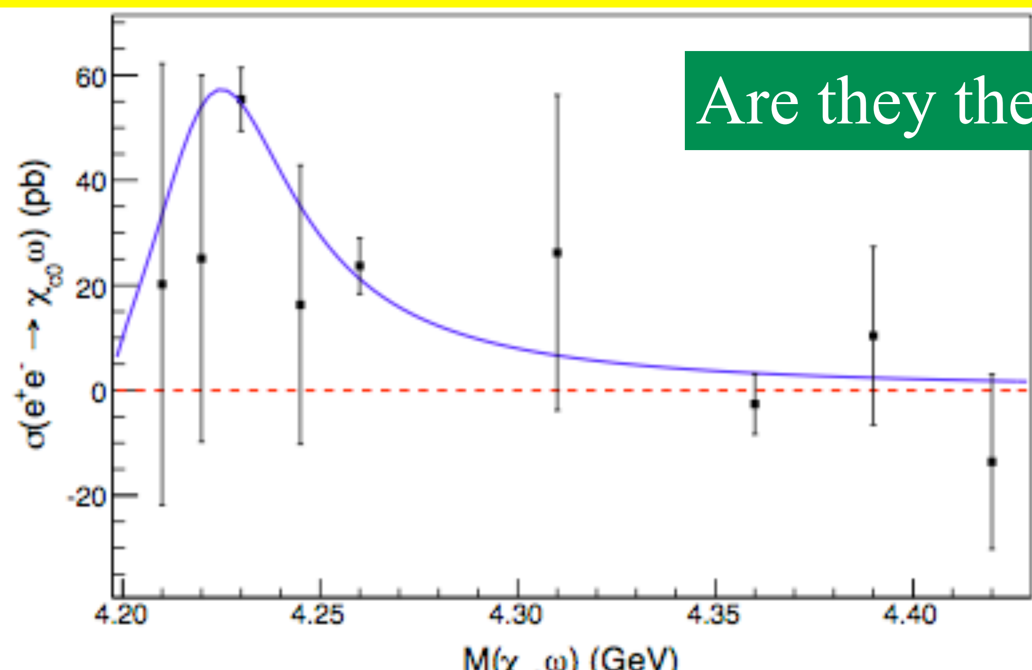
Y states, decay patterns and very tentative assignements

	$J/\Psi+\pi\pi$	$\psi(2S)+\pi\pi$	$h_c+\pi\pi$	$\chi_{c0}+\omega$	$\Lambda_c+\bar{\Lambda}_c$		$P(S_{c\bar{c}}=1)$	$P(S_{c\bar{c}}=0)$
$S_{c\bar{c}}$	1	1	0	1	1			
Y(4008)	seen	-	-	-	-	Y_1	0.75	0.25
Y(4220)	-	-	seen	seen	-	Y_3	0.25	0.75
Y (4260)	seen	-	-	-	-	Y_2	1	0
$Y(4360)$	-	seen	-	-	-	Y_1'	1	0
Y(4630)	-	-	-	-	seen	Y_4	1	0
Y(4660)	-.	seen	-	-	-	Y_2'	1	0

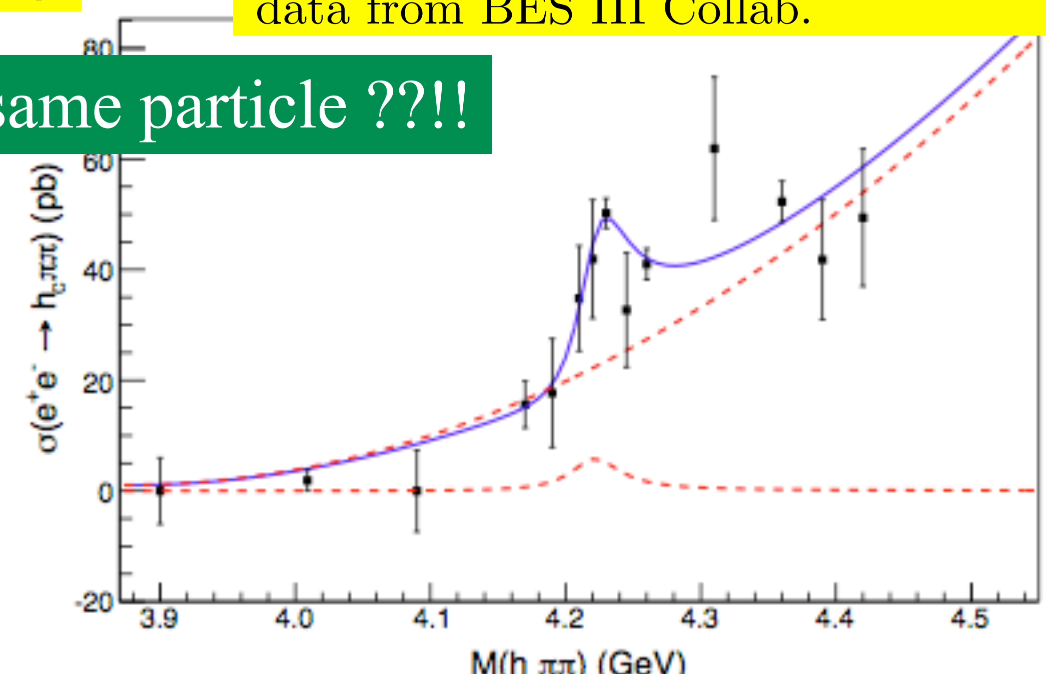
M. Ablikim *et al.* [BESIII Collaboration], arXiv:1410.6538 [hep-ex].

C. Z. Yuan, Chin. Phys. C **38** (2014) 043001
data from BES III Collab.

Are they the same particle ??!!



$$Y(4230) \to \chi_c + \omega$$



$$Y(4230) \to h_c + \pi^+ + \pi^-$$

Y(4230) has $S_{c\,cbar}$ =1 and $S_{c\,cbar}$ = 0 decays, as required by Y_3

Radiative decays

- The identical spin structure implied in the model for Y(4260) and X(3872) suggests the decay

$$Y(4260) \rightarrow X(3872) + \gamma$$

M.Ablikim et al. [BESIII Collaboration], arXiv:1310.4101 [hep-ex]

to be an unsuppressed E_1 transition, with $\Delta L=1$ and $\Delta Spin=0$, similar to the observed transitions of the charmonium χ states.

- The decay rate could provide a first estimate of the radius of the tetraquark.
- A comparison of the spin structures in Y and X states provides selection rules for E_1 transitions that should provide a better identification of the levels.
- The assignments made produce the table:

$$Y_4 = Y(4630) \rightarrow \gamma + X_2 \quad (J^{PC} = 2^{++}) = \gamma + X(3940), \;\; ??$$
$$Y_3 = Y(4220) \rightarrow \gamma + X_0' \quad (J^{PC} = 0^{++}) = \gamma + X(3916), \;\; ??$$
$$Y_2 = Y(4260) \rightarrow \gamma + X_1 \quad (J^{PC} = 1^{++}) = \gamma + X(3872), \;\; \text{seen}$$
$$Y_1 = Y(4008) \rightarrow \gamma + X_0 \quad (J^{PC} = 0^{++}) = \gamma + X(3770\;??), \;\; ??$$

8. Conclusions

- The confirmation of the Z(4430) reinforces the evidence for hidden-charm tetraquarks.
- We made a new assumption on spin-spin couplings: diquark building blocks are more compact than what was thought before and spin-spin forces outside diquarks are suppressed. The new Ansatz allows for a good description of the 1^+ sector, Z(3900), Z(4020) and X(3872).
- A consistent description of the Y particles is obtained, in qualitative agreement with heavy quark spin conservation. One state decaying in h_c is required and seen, but not two!
- The same spin structure is associated with Y(4260) and X(3872): the radiative transition observed by BES III could be a dominant E_1 transition, like in charmonia. Selection rules are given.
- NOT ALL PINK AND ROSY, several unanswered questions:
  - Why charged partners of the X and Y states have not been observed, unlike Z?
  - Are there the two neutral, almost degenerate, X particles around 3872 MeV, as required by the presence of u and d quarks?
  - Will better resolution experiments resolve the puzzle?
  - Is there something missing in the theory so that missing states should be missing?

Further investigations are needed, JOIN IN !!!