Interpretation of Positive Parity, J/Ψ- φ Resonances at LHCb

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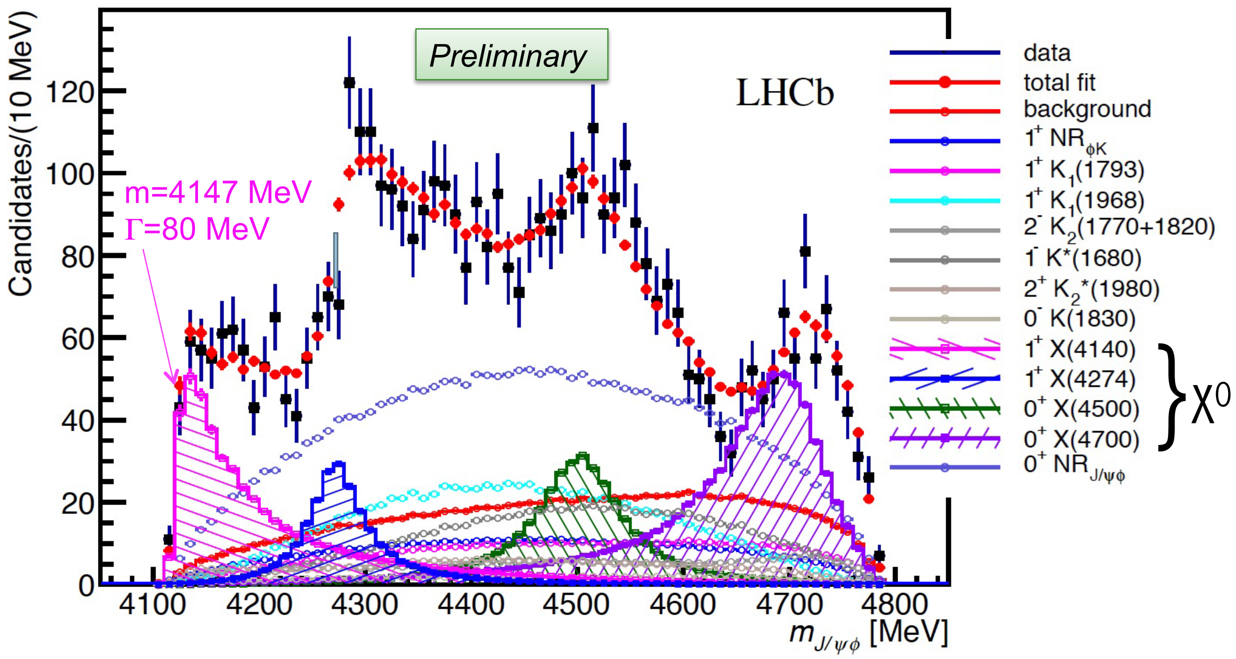
LHCb Workshop, CERN, Oct. 13, 2016

Jiao Tong University, Shanghai, Nov. 4, 2016

1. Old and new structures observed by LHCb arXiv:1606.07895

Results of fit: m(J/ψϕ)



- 4 visible structures fit with BW amplitudes

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Results of fit

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

Particle	J^P	Signif-icance	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			$46 \pm 11^{+11}_{-21}$

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

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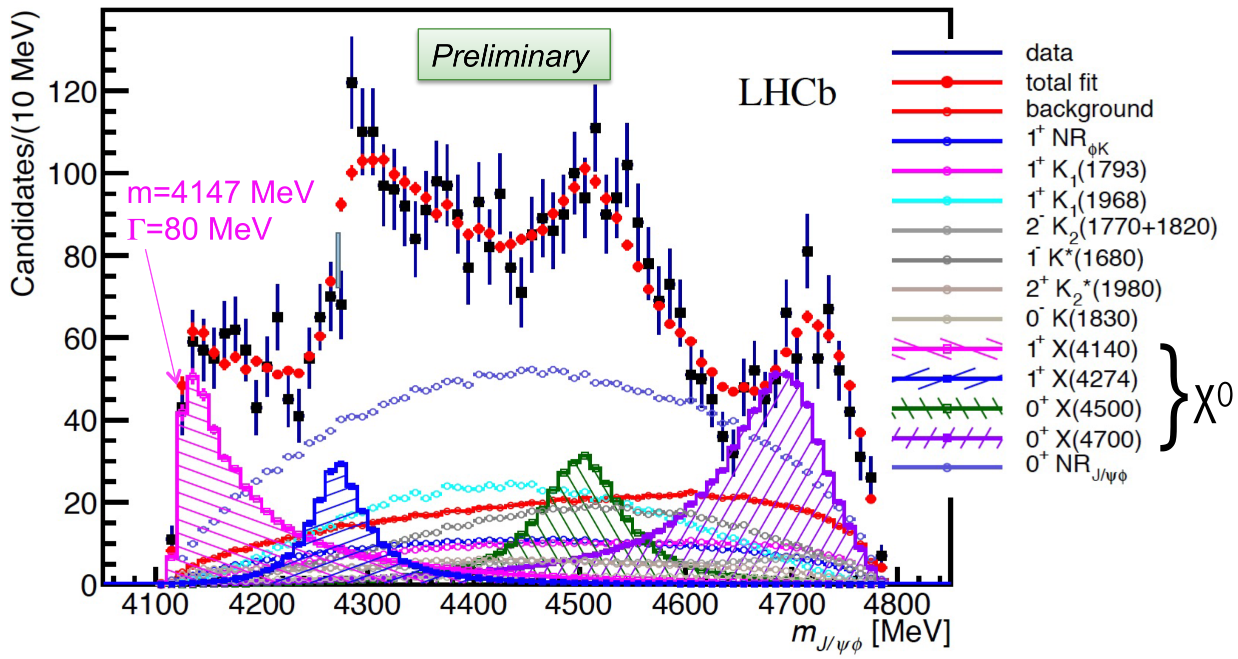

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We suggest to fit the structures in two tetraquark multiplets, S-wave ground state and the first radial excitation, with composition $[cs][\bar{c}\bar{s}]$**.** L. Maiani, A. Polosa, V. Riquer, PRD **94** (2016) 054026

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.

A surprise and a proposal.

2. Forces between colored objects (Han-Nambu)

- Interaction proportional to: $\frac{g^2}{q^2} \times 2\langle R|\mathbf{T}\cdot\mathbf{T}|R\rangle = \frac{g^2}{q^2}\left[C_2(R) - C_2(A) - C_2(B)\right]$
- quark-antiquark
  - singlet: attractive (-8/3)
  - octet: repulsive (+1/3)

- quark-quark
  - three bar: attractive (-4/3)
  - six: repulsive (+2/3)

$$C_2(R) = \mathbf{T}_R \cdot \mathbf{T}_R$$

R	$C_2(R)$
$\mathbf{1}$	0
$\mathbf{8}$	3
$\mathbf{3}, \bar{\mathbf{3}}$	4/3
$\mathbf{6}$	10/3

- quark-antiquark pairs bind in color singlet mesons;

- diquarks bind:

to another quark, to make a color singlet baryon

to an antidiquark, to make a color singlet tetraquark.

Constituent quark model

Old days: Sakharov&Zeldovich

In QCD: De Rujula, Georgi and Glashow, PRL 38 (1977) 317

Revisited & applied to tetraquarks: L.M., A. Polosa, V. Riquer, F, Piccinini, PRD 71 (2005) 014028

- color string forces produce an overall spin-independent potential that confines quarks inside a definite volume (bag), with some wave functions $\psi(x_1,x_2,x_3)$
- residual quark-quark or quark-antiquark interactions are color-magnetic, spin-spin, forces of the form

$$H_{ij} = \frac{g^2}{m_1 m_2}(T_1 \cdot T_2)\ \mathbf{s}_i \cdot \mathbf{s}_j\ \delta^{(3)}(x_1 - x_2)$$

- T are the color charges, g the color coupling, the form is derived from the non relativistic limit of QCD
- if i,j are in a color representation R , the formula simplifies to (CF is a color factor similar to the one introduced for color interactions)

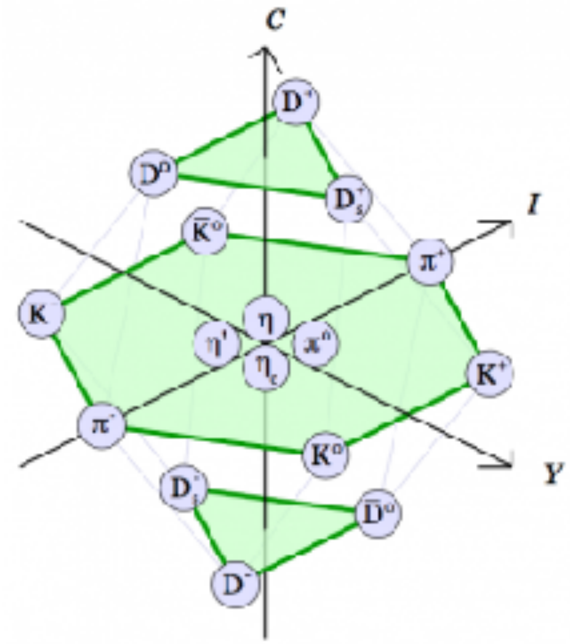
$$\mathbf{H}_{ij} = 2\kappa_{ij}\ \mathbf{s}_i \cdot \mathbf{s}_j$$

$$\kappa_{ij} = \mathrm{CF(R)} \times \frac{g^2}{m_1 m_2}\ |\psi(0)|^2$$

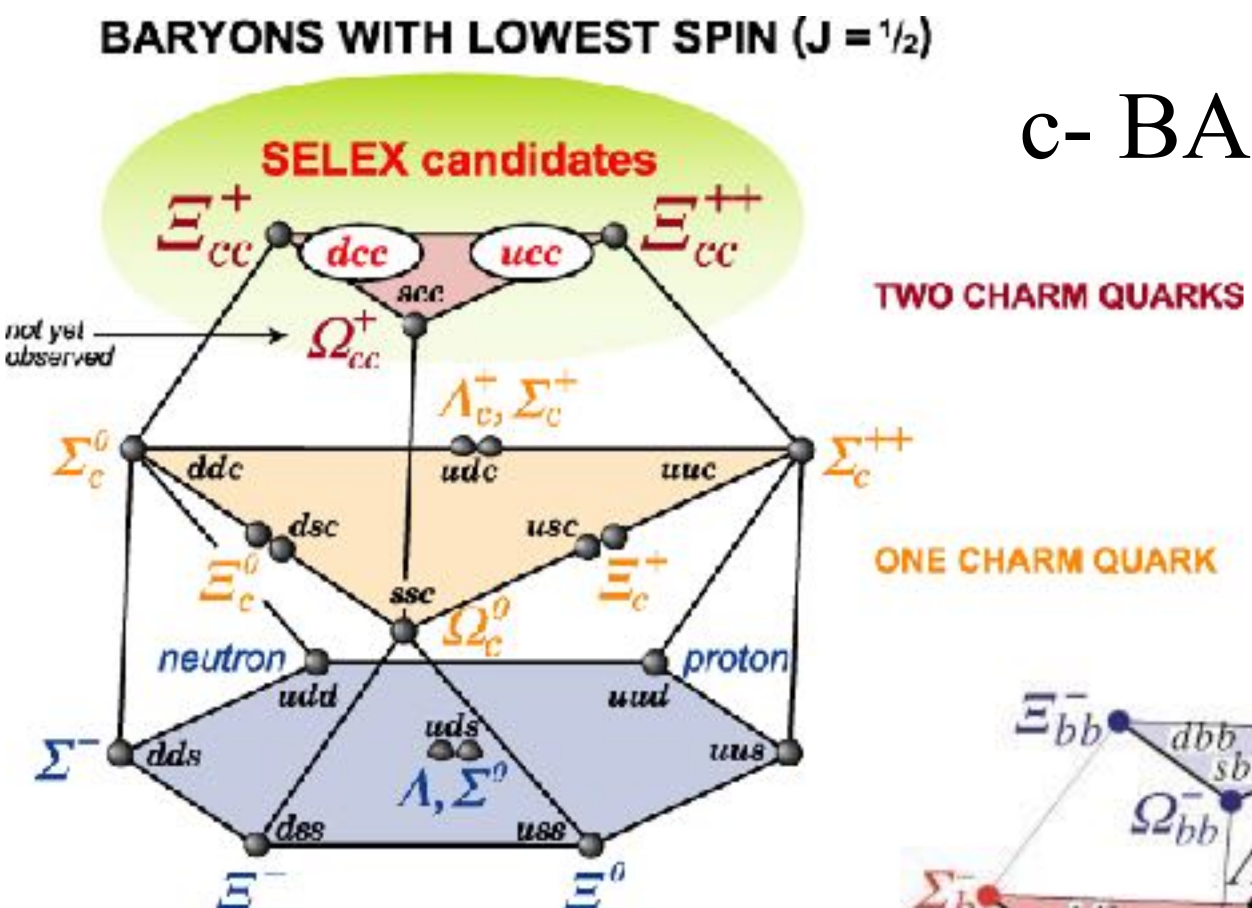
$$H = \sum_i m_i + \sum_{i<j} 2\kappa_{ij}\, \mathbf{s}_j \cdot \mathbf{s}_j \qquad \kappa_{ij} = \mathrm{CF(R)} \times \frac{g^2}{m_1 m_2}\, |\psi(0)|^2$$

- the Hamiltonian can be developed to first order in the small mass differences, like m_s-$m_{u,d}$,
- there is also a first order contribution from the spin-spin interaction, which is very crucial for baryons
- one usually assumes that the wave function overlap is the same in all mesons and all baryons, but this is dubious in the case of hadrons with a very heavy quark, c or b.
- Works well for mesons and baryons (too well?)
- Few parameters: m_u, m_d, m_s, m_c, m_s, κ_{ij}
- same values of masses, within ±30 MeV, reproduce masses of different hadrons
- κ_{ij} scale approx. like $1/m_i m_j$ and not far from scaling with color factors

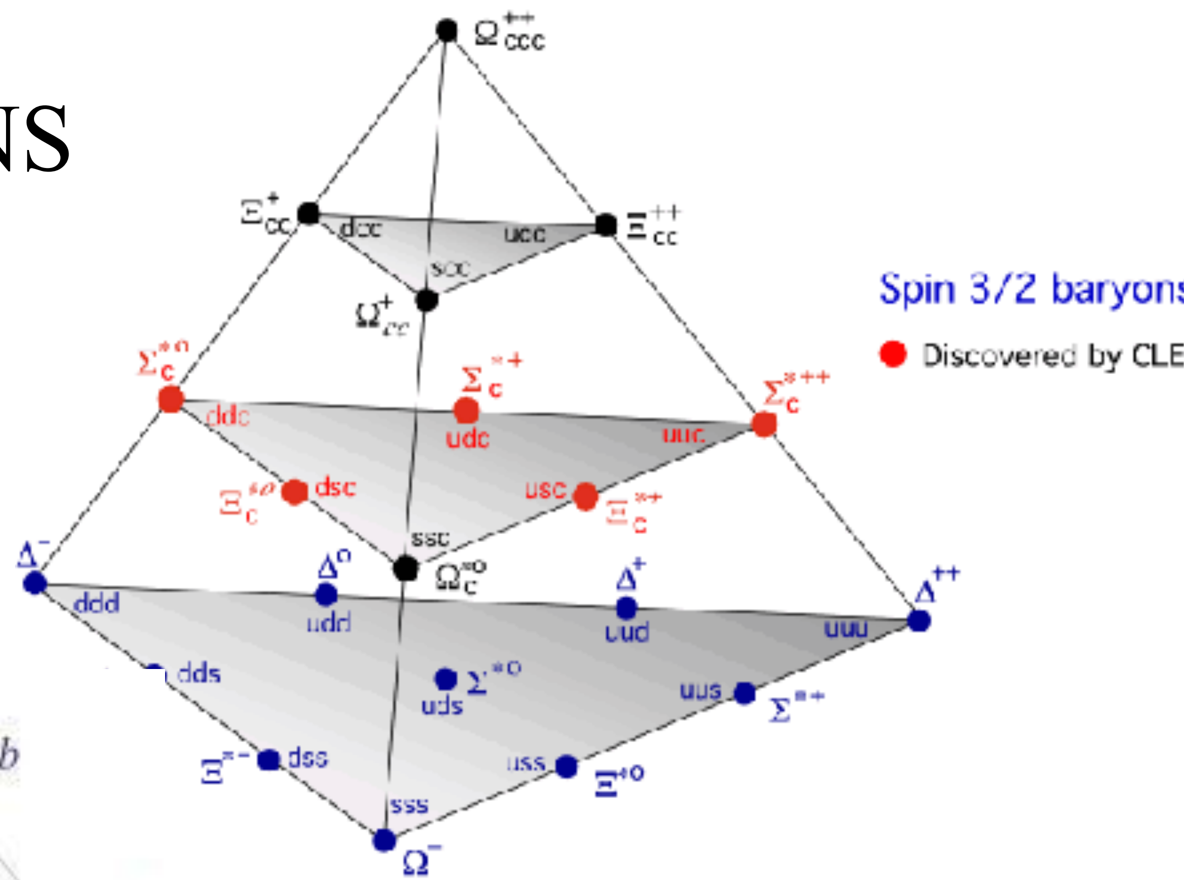
MESONS

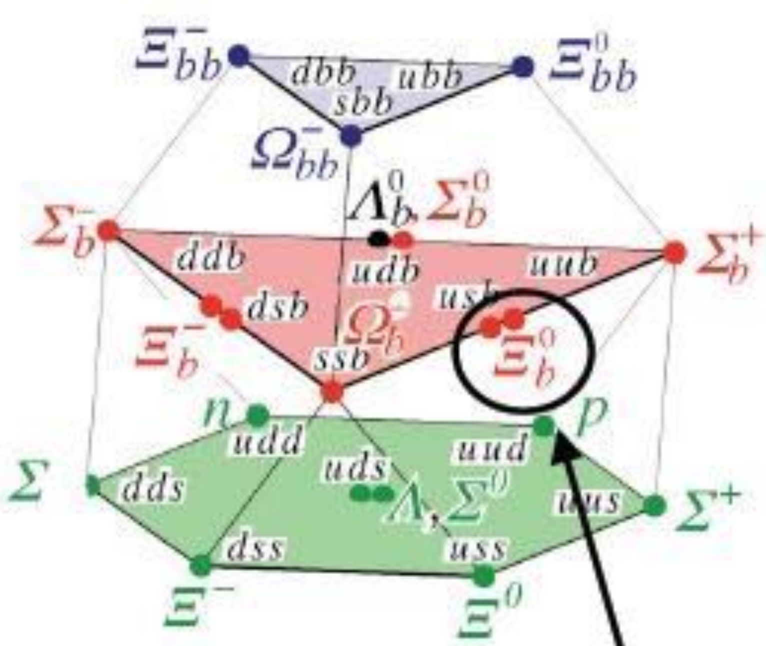


+ similar multiplet of vector mesons



c- BARYONS





b- BARYONS

Data from PdG live

MESONS	q	s	c	b
mass(MeV)	308	484	1664	5005

BARYONS	q	s	c	b
mass(MeV)	362	540	1710	5044

MESONS	$q\bar{q}$	$q\bar{s}$	$s\bar{s}$	$c\bar{q}$	$c\bar{s}$	$b\bar{q}$	$b\bar{s}$
$(\kappa_{ij})_1$(MeV)	318	200	103	69	72	23	24
$(\kappa_{ij})_1\ m_i m_j/\Lambda^3_{QCD}$	1.9	1.9	1.5	2.3	3.7	0.7	1.2

BARYONS	qq	qs	ss	cq	cs	bq	bs
$(\kappa_{ij})_{\bar{3}}$ (MeV)	98	59	23	15	50	2.5	38
$(\kappa_{ij})_{\bar{3}}\ m_i m_j/\Lambda^3_{QCD}$	0.82	0.74	0.43	0.57	2.7	0.29	6.6

$-$	$\frac{(q\bar{q})_1}{(qq)_{\bar{3}}}$	$\frac{(q\bar{s})_1}{(qs)_{\bar{3}}}$	$\frac{(s\bar{s})_1}{(ss)_{\bar{3}}}$	$\frac{(c\bar{q})_1}{(cq)_{\bar{3}}}$	$\frac{(c\bar{s})_1}{(cs)_{\bar{3}}}$	$\frac{(b\bar{q})_1}{(bq)_{\bar{3}}}$	$\frac{(b\bar{s})_1}{(bs)_{\bar{3}}}$
$\frac{\kappa_{MES}}{\kappa_{BAR}}$	3.2	3.4	4.5	4.7	1.6	9.2	0.6

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$(\kappa_{q\bar{q}})_1 >> (\kappa_{cq})_{\bar{3}}$

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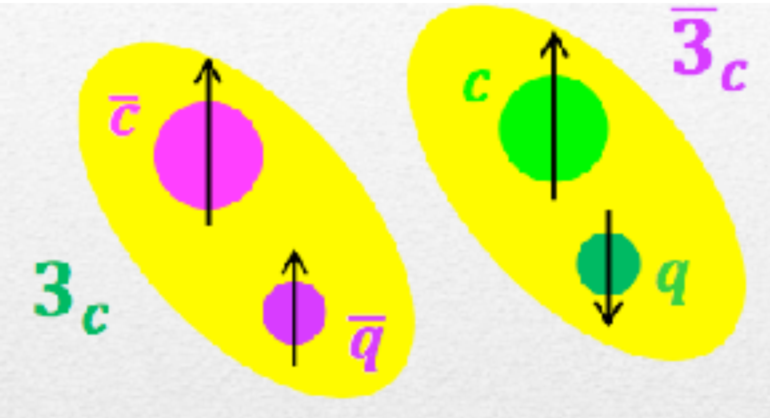
3.Tetraquark constituent picture of unexpected quarkonia

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

- I=1, 0
- S-wave: positive parity
- total spin of each diquark, S=1, 0 $[cq]_{S=0,1}[\bar{c}\bar{q}']_{\bar{S}=0,1}$
- neutral states may be mixtures of isotriplet and isosinglet
- mass splitting described by



$$\mathbf{H} = 2m_{(diquark)} + \sum_{i<j} 2\kappa_{ij}(\mathbf{s}_i \cdot \mathbf{s}_j)$$

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

in the $|S, \bar{S}\rangle_J$ basis we have the following states

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

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

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

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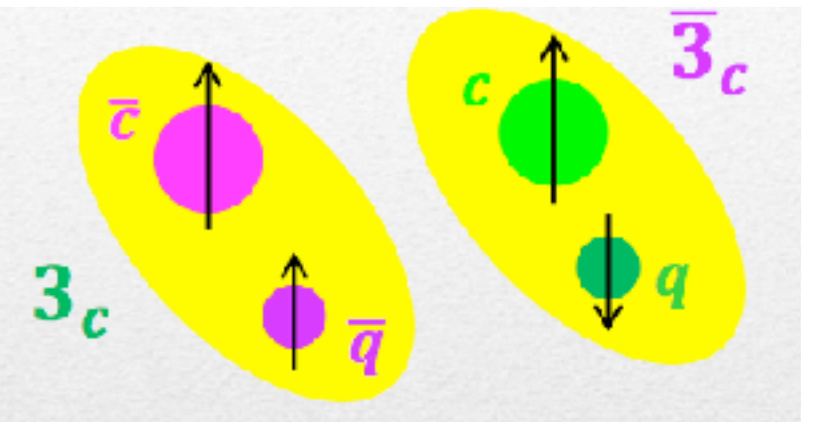

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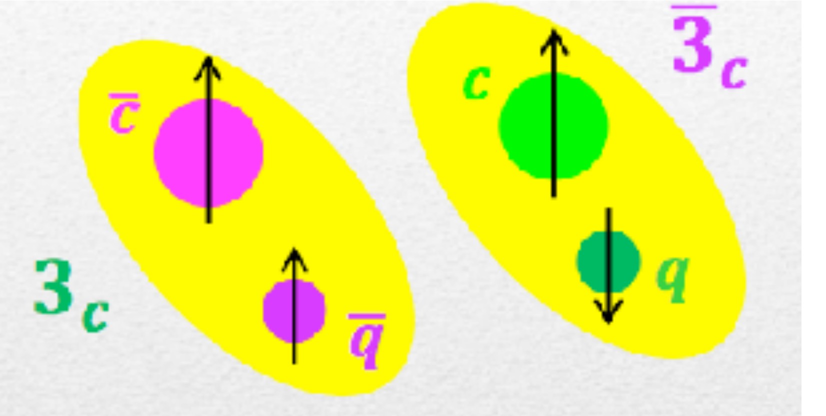

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X(3872)=X_1
Z(3900), Z(4020)=lin. combs. of Z&Z' that diagonalize H
X(3940)=X_2 ??

Can we extrapolate spin-spin couplings from mesons and baryons?

Phenomenology confirms

- q-qbar interaction in tetra quarks is not directly deducible from the meson spectrum, since the q-qbar pair in tetra is in a superposition of color octet and singlet.
- using one-gluon dominance, we estimate $\kappa_{q\bar{q},\ tetra} = \frac{1}{4}(\kappa_{q\bar{q}})_1$
- if we take $(\kappa_{q\bar{q}})_1$ from mesons, we obtain a value of $\kappa_{q\bar{q},\ tetra} >> (\kappa_{cq})_{\bar{3}}$ from baryons and this leads to the wrong ordering of the Z(3900) and Z(4030) with respect to X(3872):

$$X(3872):\ \mathcal{C} = +,\ S_{c\bar{c}} = S_{q\bar{q}} = 1$$

$$Z:\ \mathcal{C} = -,\ S_{c\bar{c}} = 1,\ S_{q\bar{q}} = 0,\ or\ S_{c\bar{c}} = 0,\ S_{q\bar{q}} = 1$$

- $Z(S_{q\ qbar}=1) = Z_{deg}$ is ~ degenerate with X: Z_{deg}=Z(3900)
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- A simple explanation of the dominance of inter-diquark interaction could be that diquarks and antidiquarks are at such relative distance in the hadron, as to suppress the overlap probability, unlike what happens, e.g., in the usual baryons

Parameters

- The spectrum of 1S ground states is 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 common quantity, the radial excitation energy, ΔE_r expected to be mildly dependent on the diquark mass: $E_r(cq) \sim \sim E_r(cs)$

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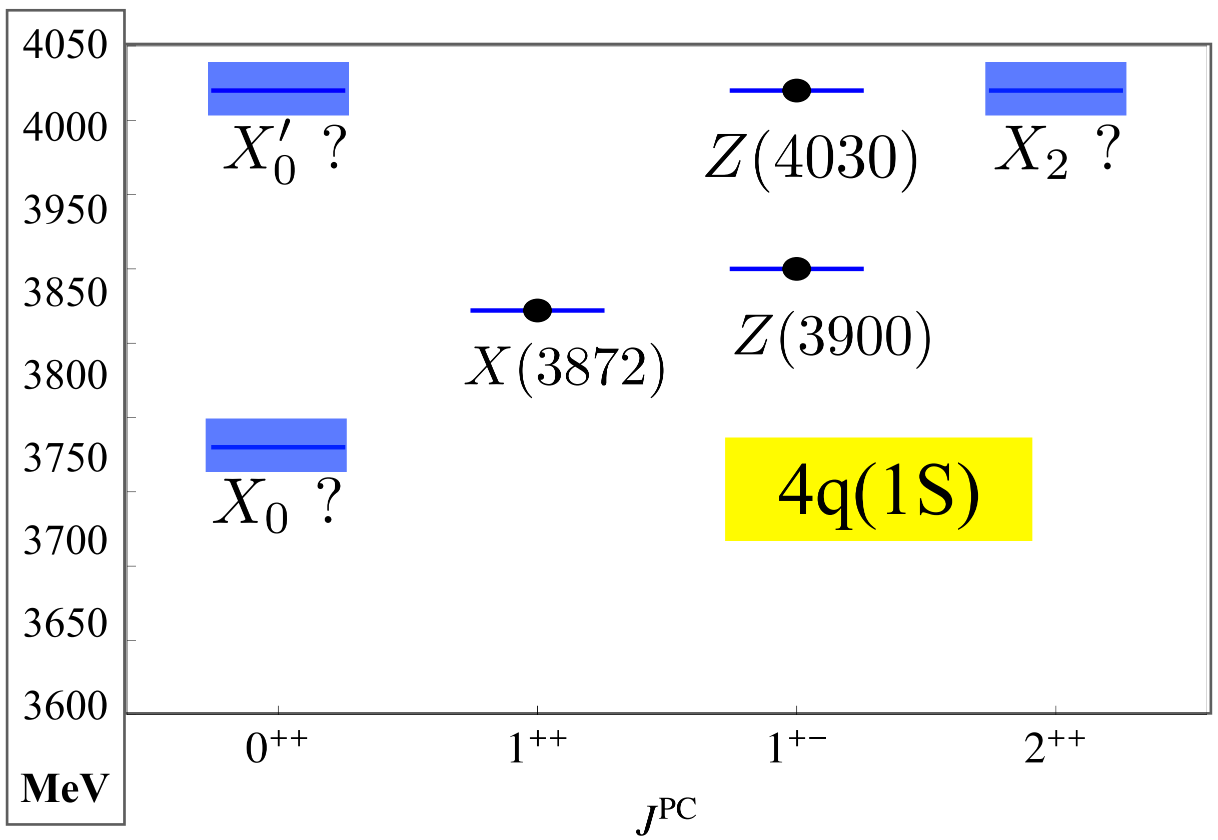

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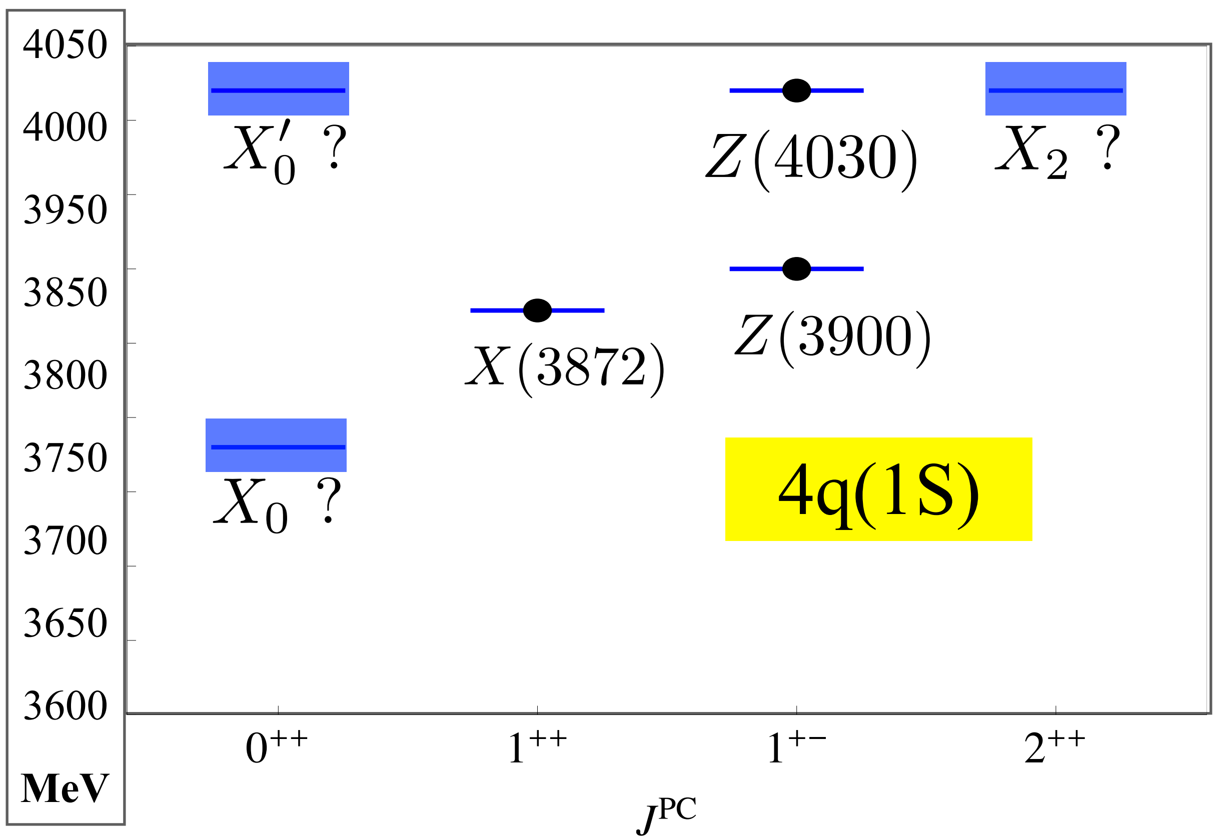

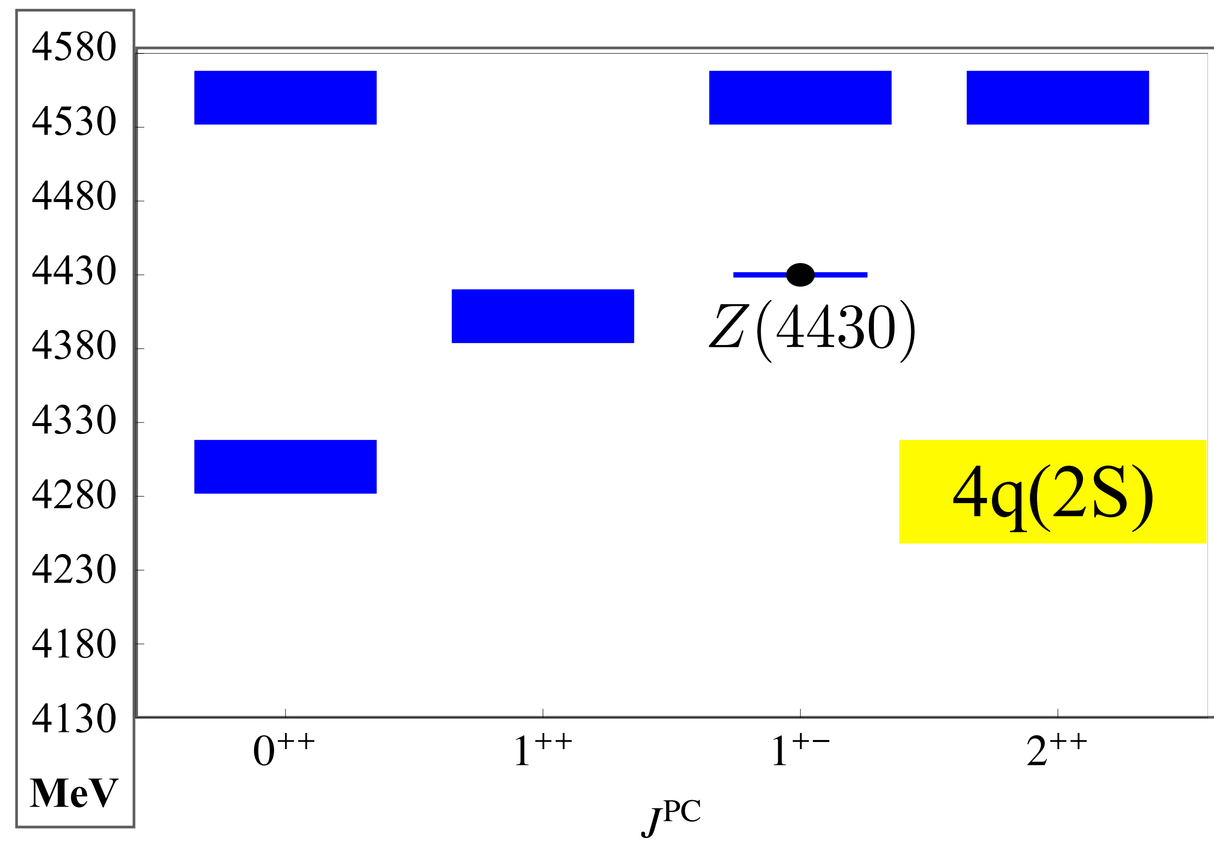

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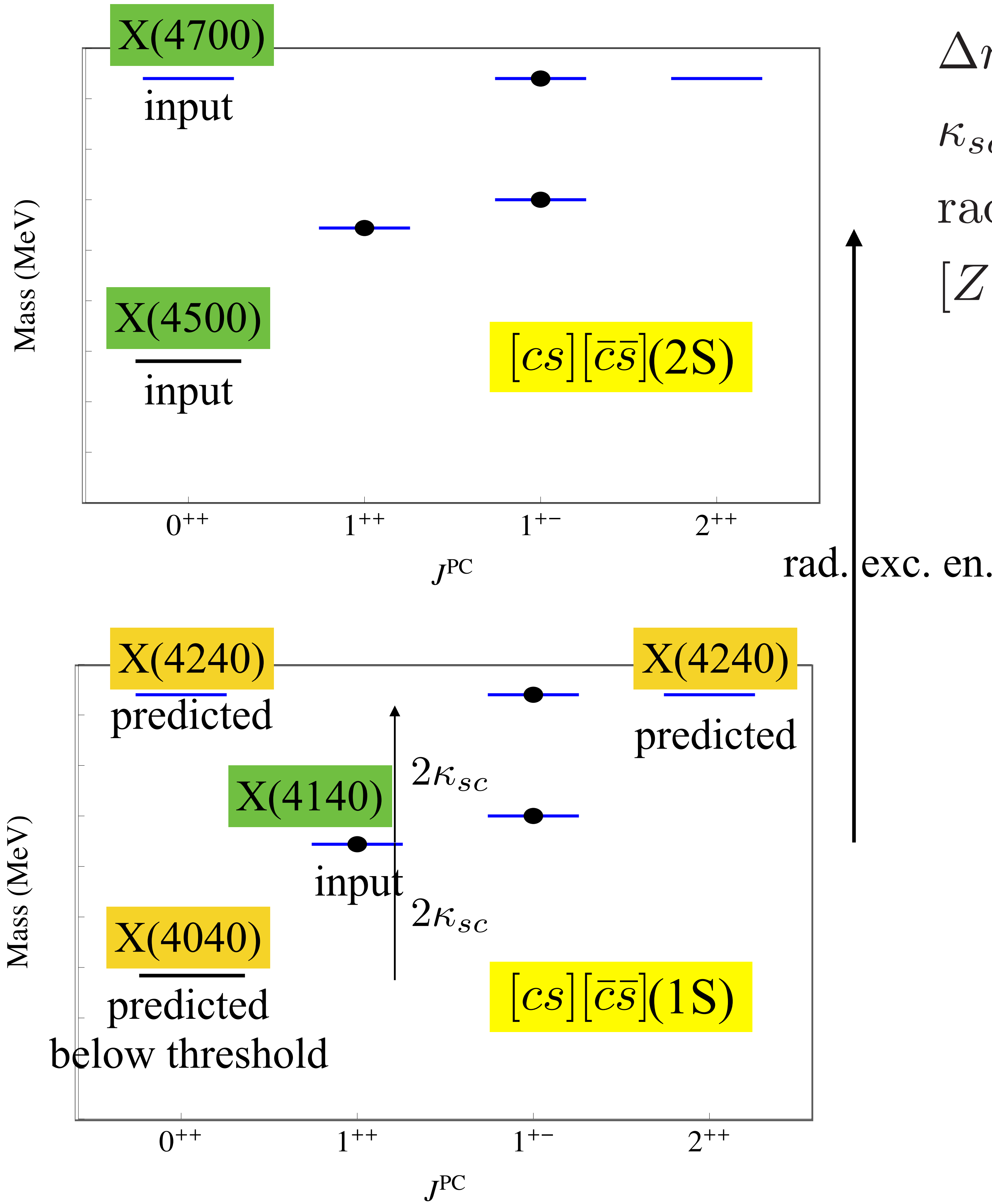
$$\Delta E_r(cq) = 530 \text{ MeV}$$

4. 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$]$

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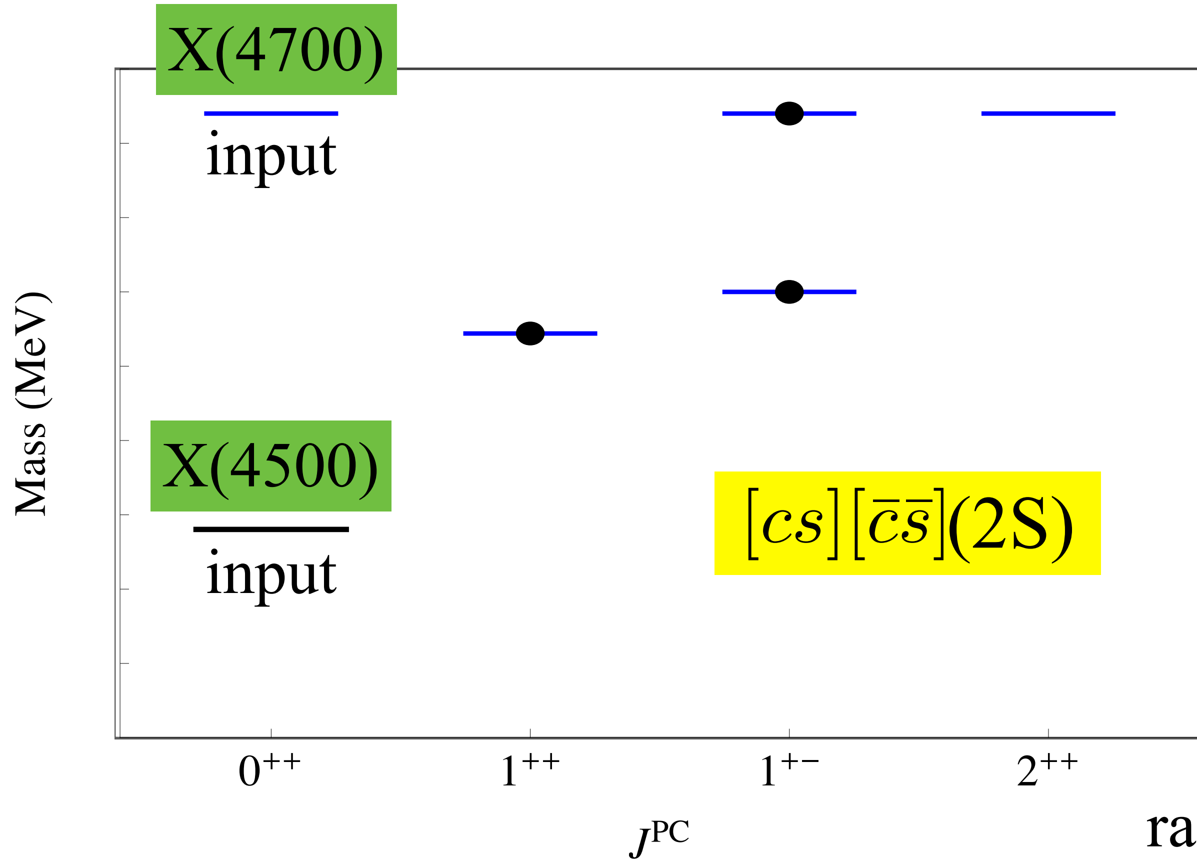

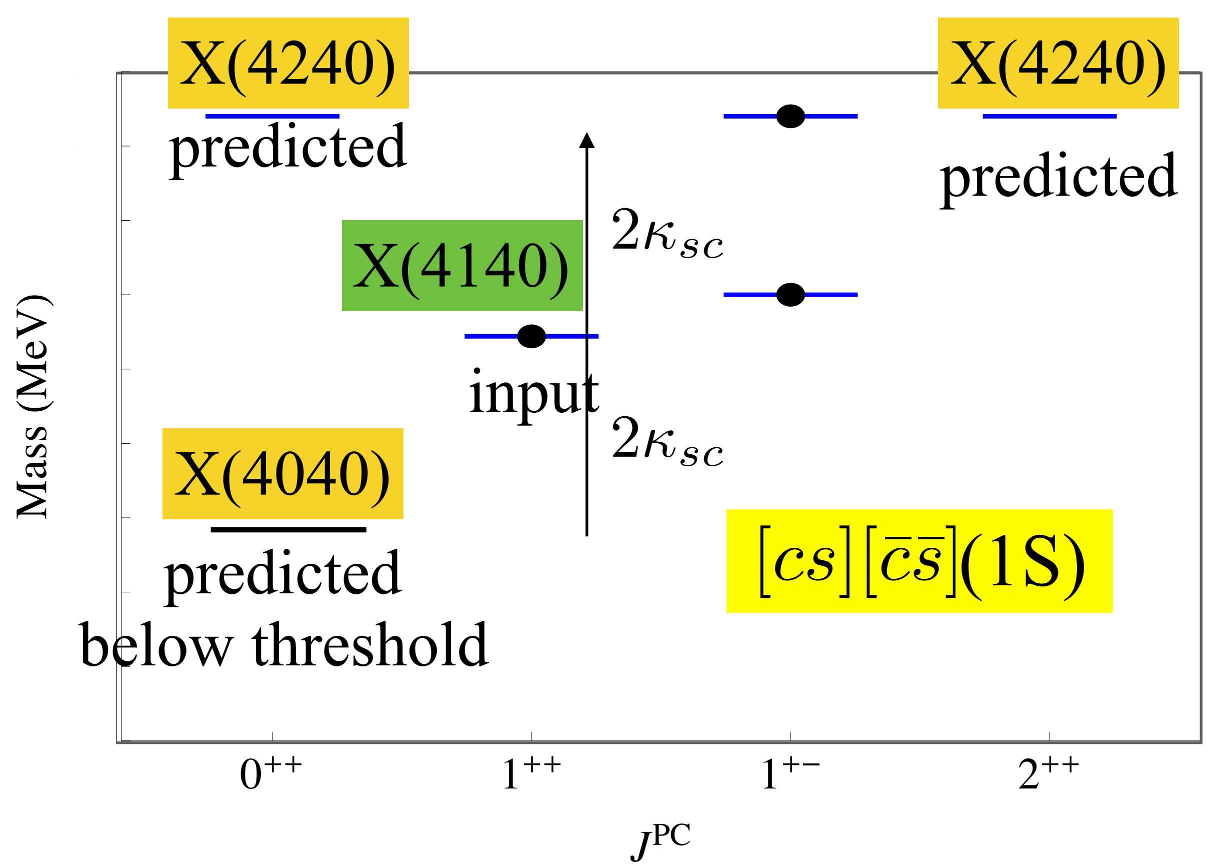

rad. exc. en.

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$X(4140) - X(3872) \sim 270$ MeV;

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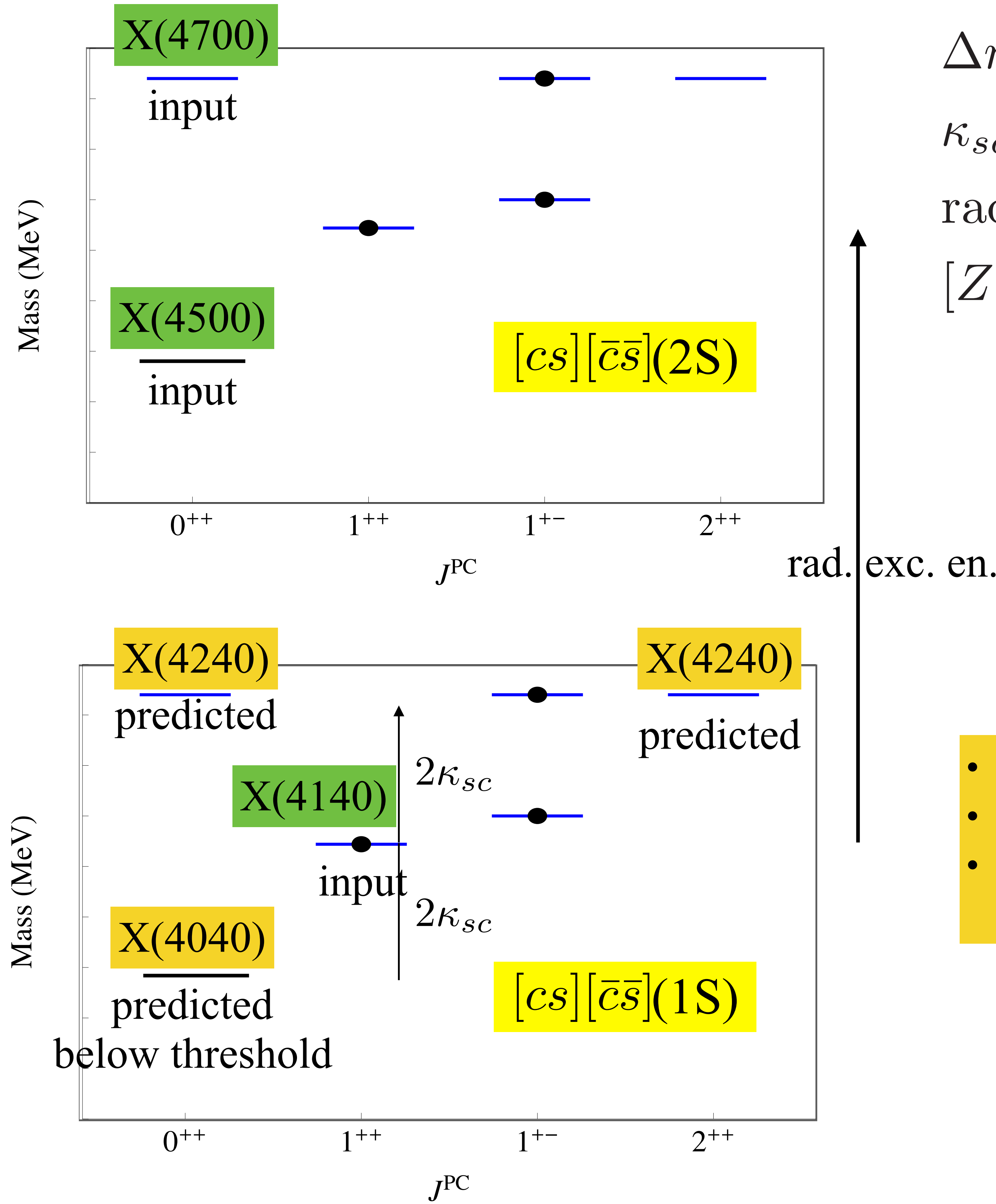

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- **0^{++} ?**
- **2^{++} ?**
- **2 unresolved, almost degenerate lines with $0^{++} + 2^{++}$??**

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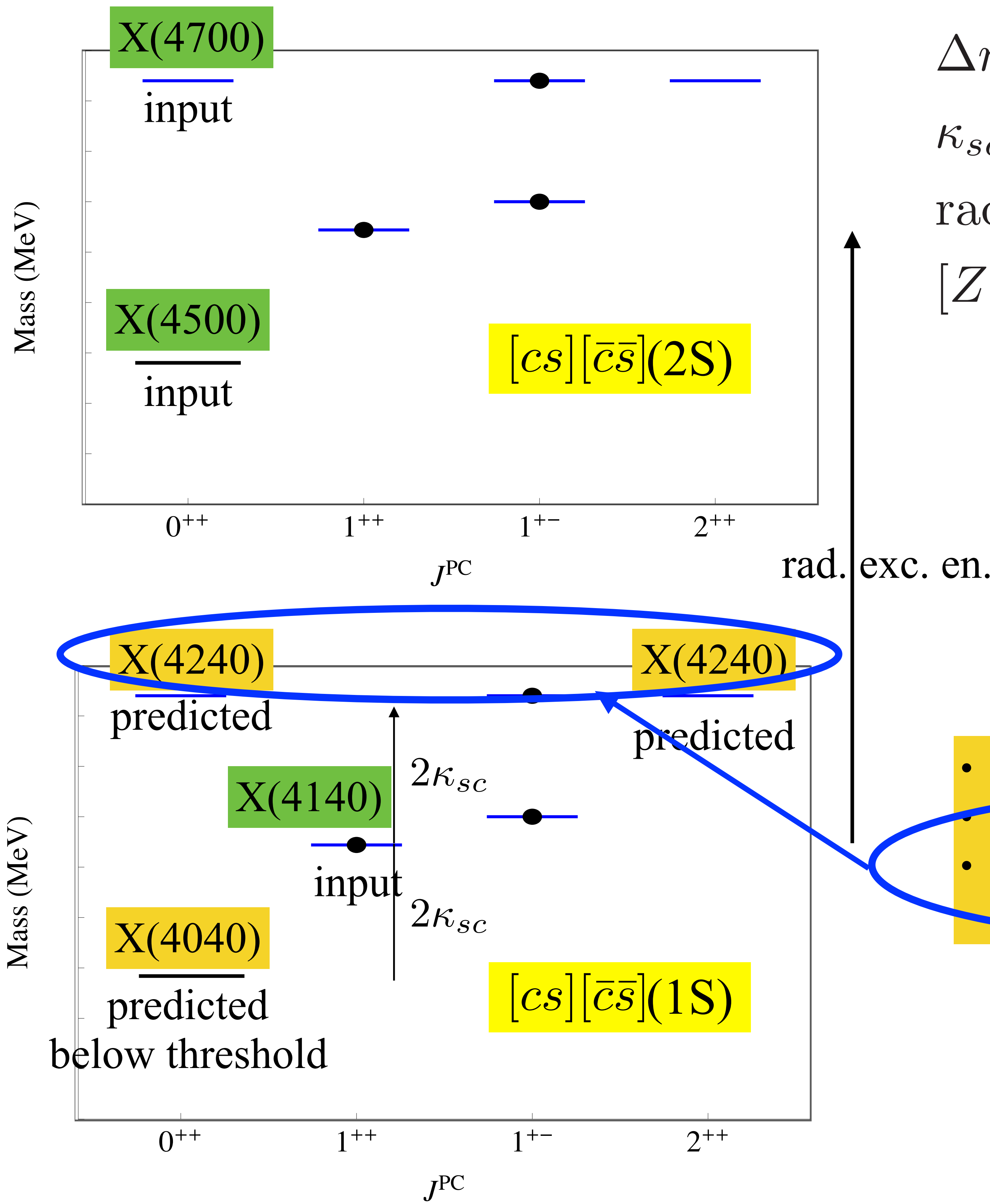

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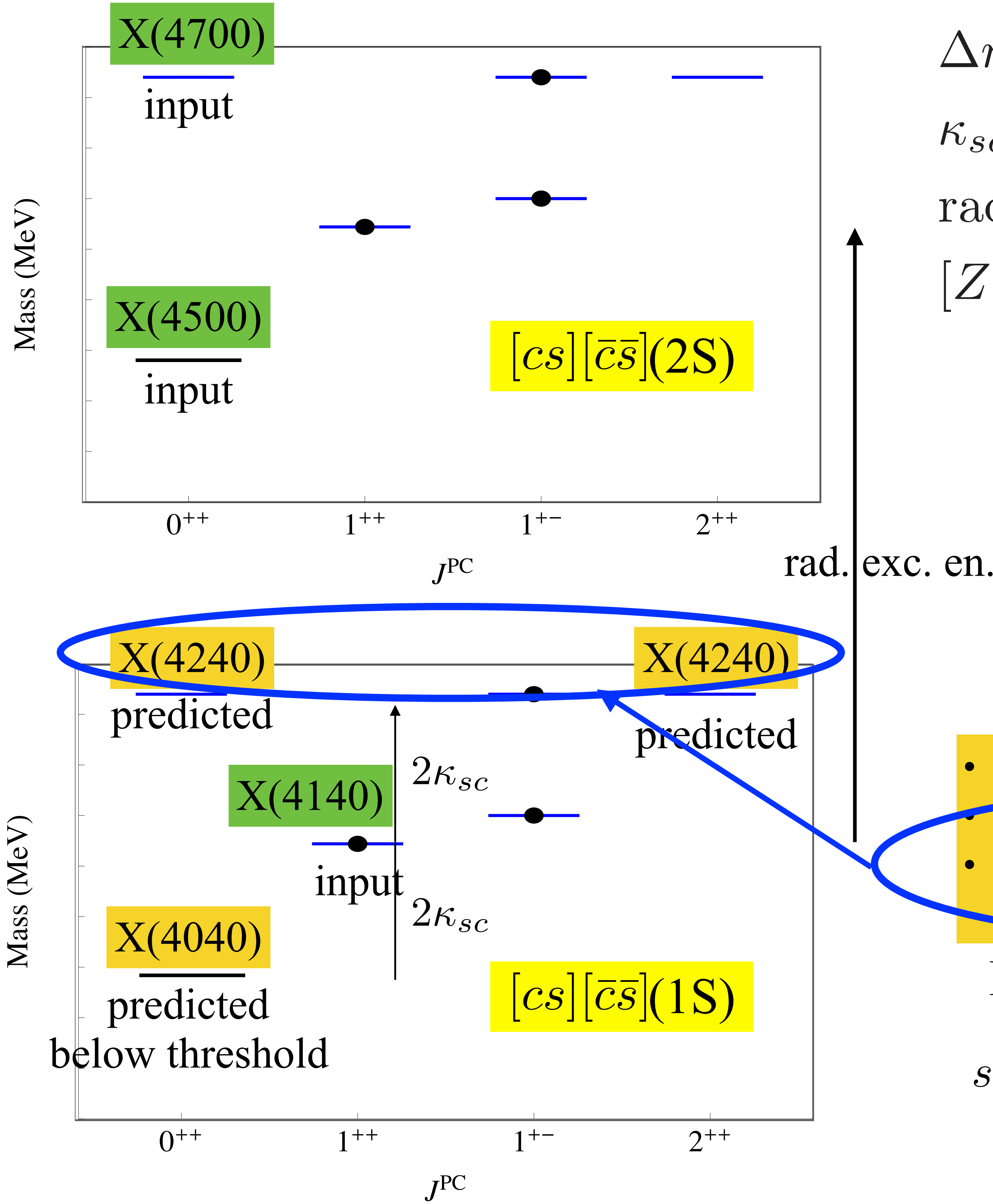

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Decay modes of $J^P=1^+$, C=-1:

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

Summary Table

radial	particle	J^{PC}	input	predicted	notes
$1S$	X_0	0^{++}		4040	**below the $J/\Psi\ \phi$ threshold**
$1S$	X	1^{++}	4140		$--$
$1S$	$X^{(1)}$	1^{+-}		4140	decays in $\chi_c\phi$? ($M \geq 4435$)
$1S$	$X^{(2)}$	1^{+-}		4240	decays in $\eta_c\phi$?
$1S$	X'_0	0^{++}		4240	part of 4274 structure?
$1S$	X'_2	2^{++}		4240	part of 4274 structure?
$2S$	X_0	0^{++}	4500		$--$
$2S$	X	1^{++}		4600	$--$
$2S$	$X^{(1)}$	1^{+-}		4600	$S_{c\bar{c}} = 1$ decays in $\chi_c\phi$?
$2S$	$X^{(2)}$	1^{+-}		4700	$S_{c\bar{c}} = 0$ decays in $\eta_c(2S)\phi$?
$2S$	X'_0	0^{++}	4700		$--$
$2S$	X'_2	2^{++}		4700	decays in $J/\Psi\phi$, $\psi'\phi$?

Table 1: Input and predicted masses for $1S$ and $2S$ cs tetraquarks.

5. 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.

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: $M(X_s) \sim \dfrac{4140 + 3872}{2} \sim 4006$

$$[M(J/\Psi) + M(K^*) \sim 4000]$$

- are they visible at LHCb/BELLE/BES III?

6.Conclusions

- J/Ψ-φ resonances go well with simple, S-wave, tetraquarks…
- ….except for the puzzling 1^{++} duplication of X(4140) and X(4270)
- model predicts two almost degenerate states around 4240: could X(4270) be a complex of two unresolved lines with $J^{PC} = 0^{++}, 2^{++}$??????????????????????
- if duplication of 1^{++} is confirmed, diquarks with color 6 could be an option, but….are there other similar duplications?
- could the X(3940) be 1^{++} as well ??
- Experimental clarification is essential for progress