Are Diquarks the Common Thread in Exotic Spectroscopy ?

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Exotic Hadron Spectroscopy 2017
University of Edinburgh-Higgs Centre, Dec. 11-13, 2017

1. Unanticipated charmonia..and more

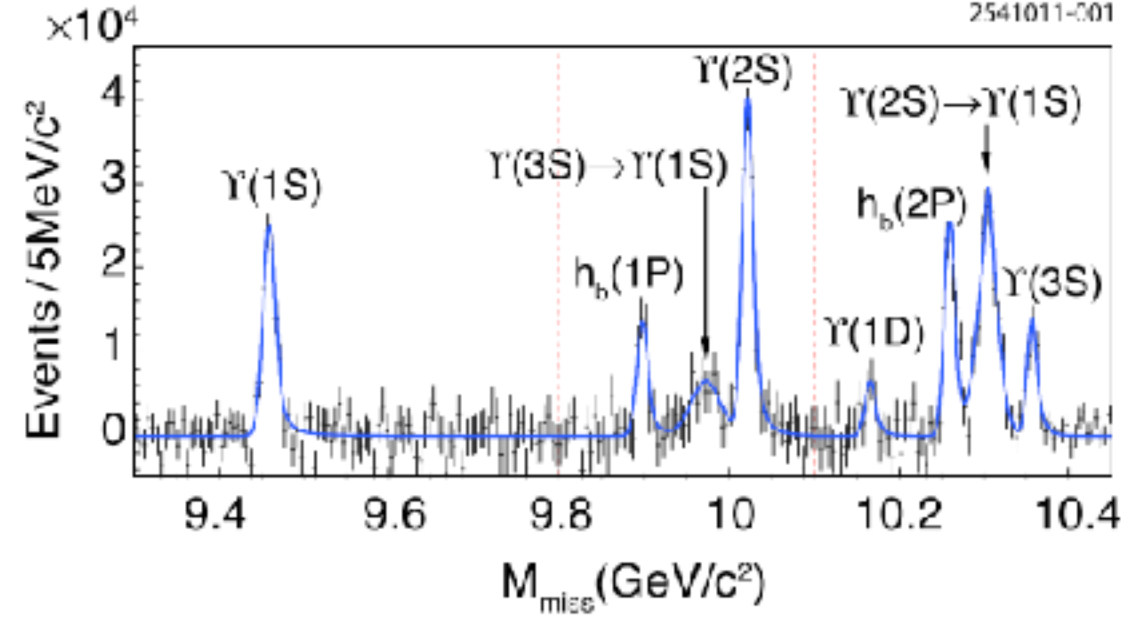


Figure 1: From Belle [31], the mass recoiling against $\pi^+\pi^-$ pairs, $M_{\rm miss}$, in e^+e^- collision

- 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

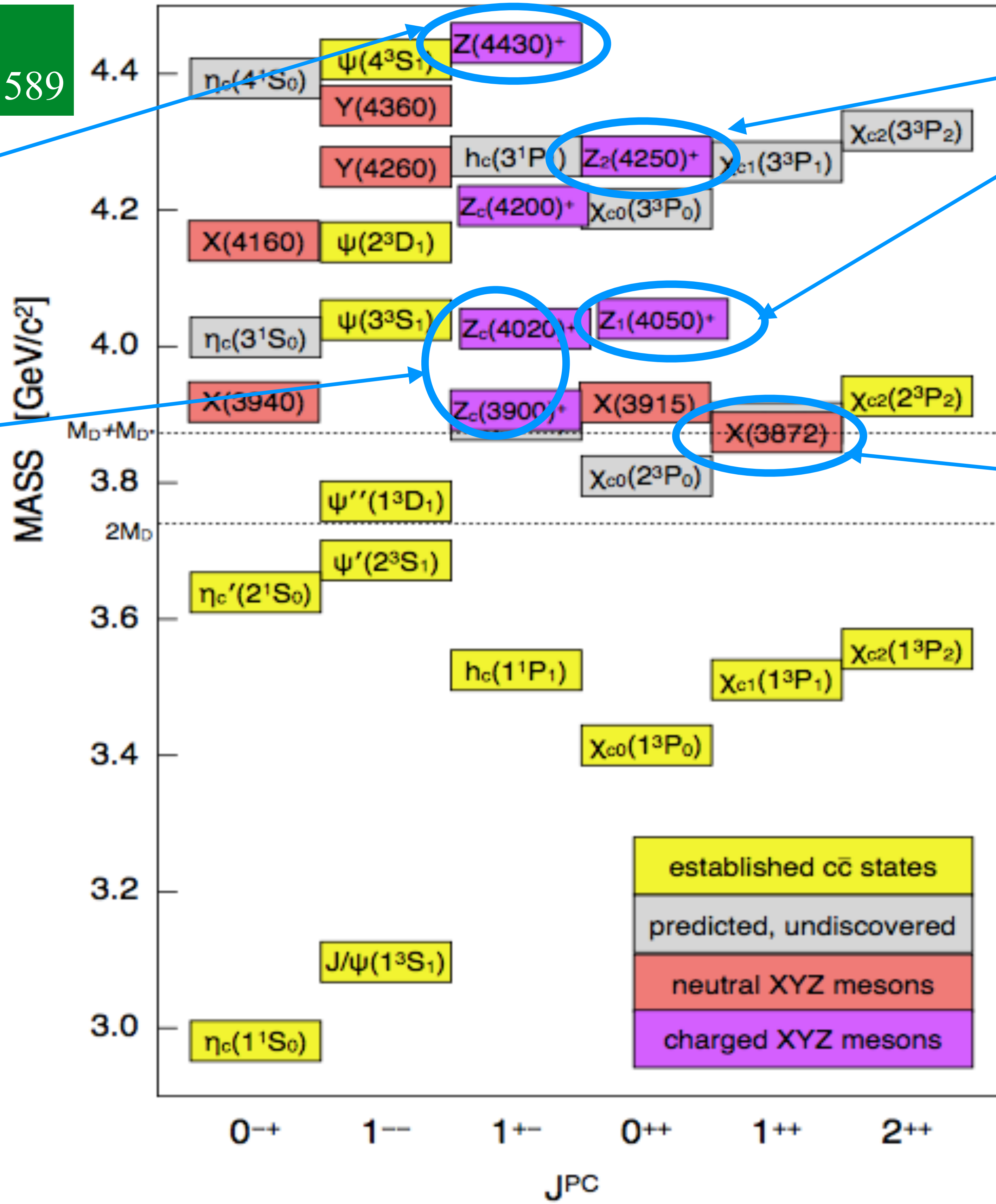
figure by:
S. L. Olsen, arXiv:1511.01589

2nd Unexpected
a radial excitation?

3rd case:
start a multiplet?

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

1st Unexpected



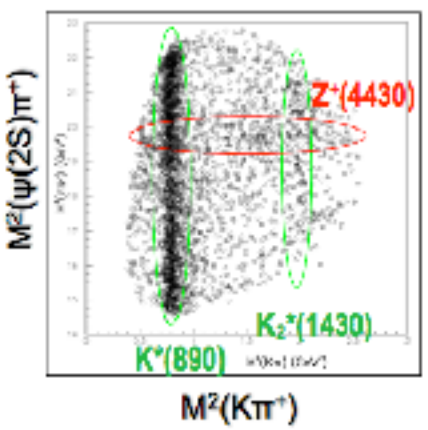
2. The new spectroscopy: $Z^{\pm}(4430)$

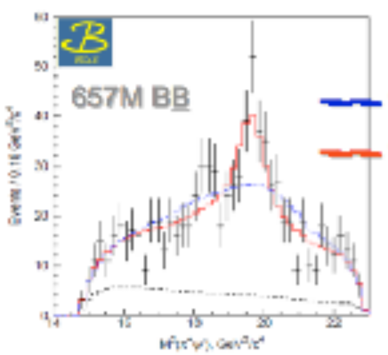
Belle observed $Z(4430)^{\pm} \to \psi(2S)\pi^{\pm}$

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





M²(ψ(2S)π⁺) after K* veto

Significance: 6.4σ

fit for model with K*'s only

fit for model with K*'s and Z

$$M = 4433\ ^{+15\ +19}_{-12\ -13}\ \mathrm{MeV}$$

$$\Gamma = 107\ ^{+86\ +74}_{-43\ -53}\ \mathrm{MeV}$$

PRD80, 031104 (2009)

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

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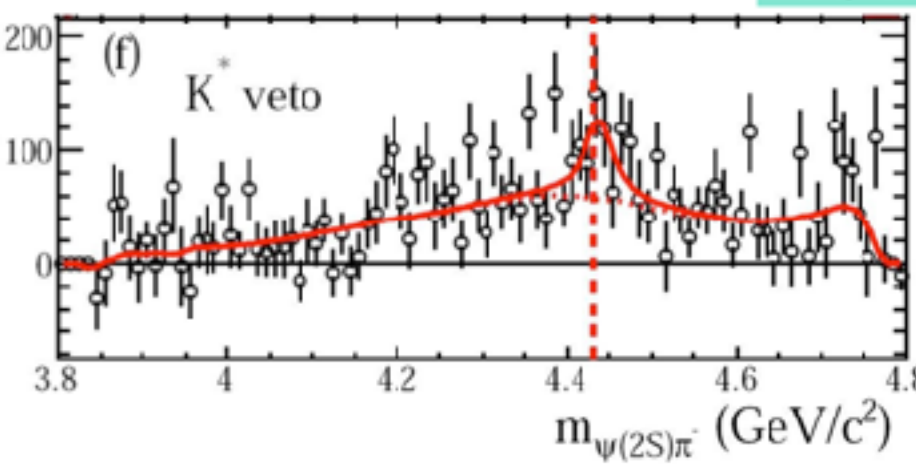
BaBar doesn't see a significant $Z(4430)^+$

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

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

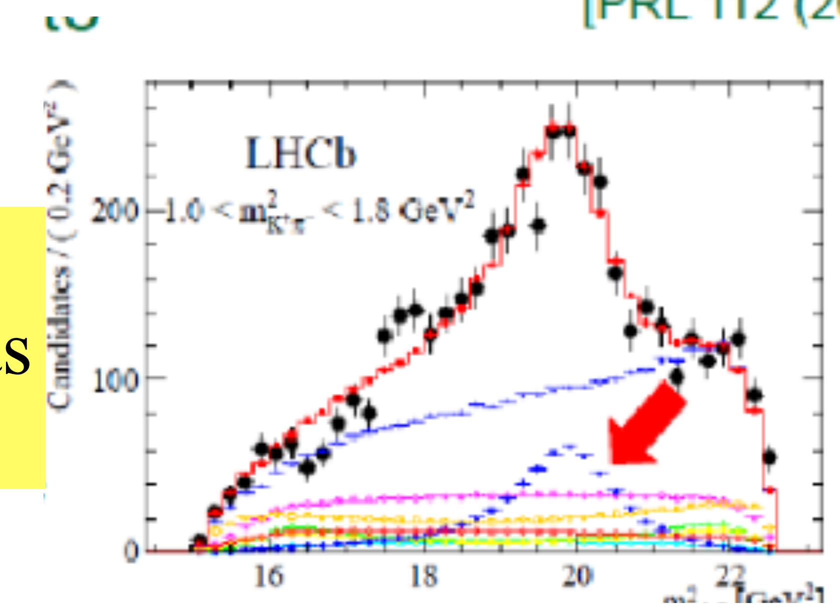
LHCB:

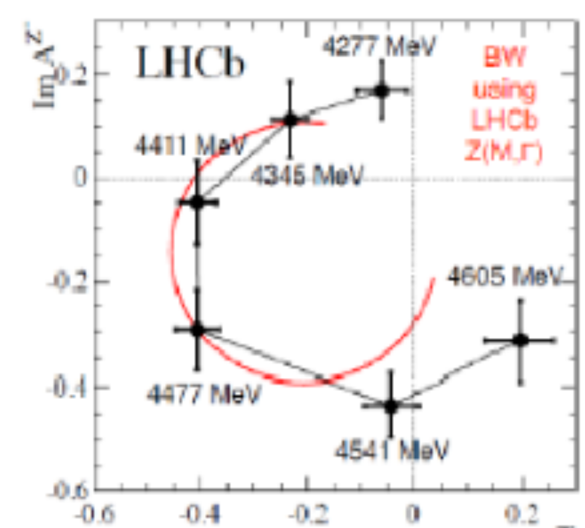
- confirms BELLE's observation of a bump

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

- Argand Plot shows 90^0 phase: Z is a genuine resonance

[PRL 112 (2014) 222002]



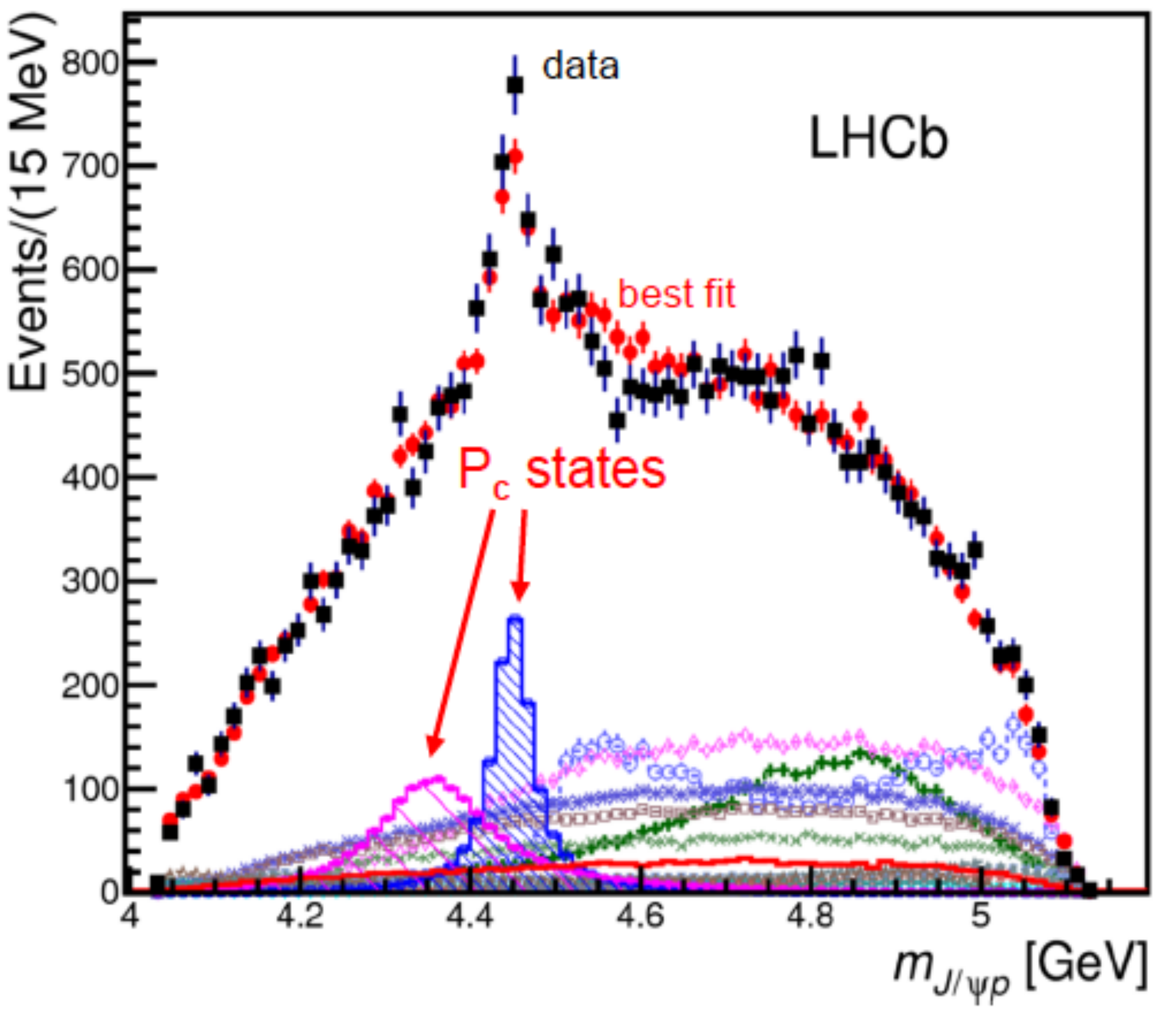


$J/\Psi p$ resonances consistent with pentaquark states

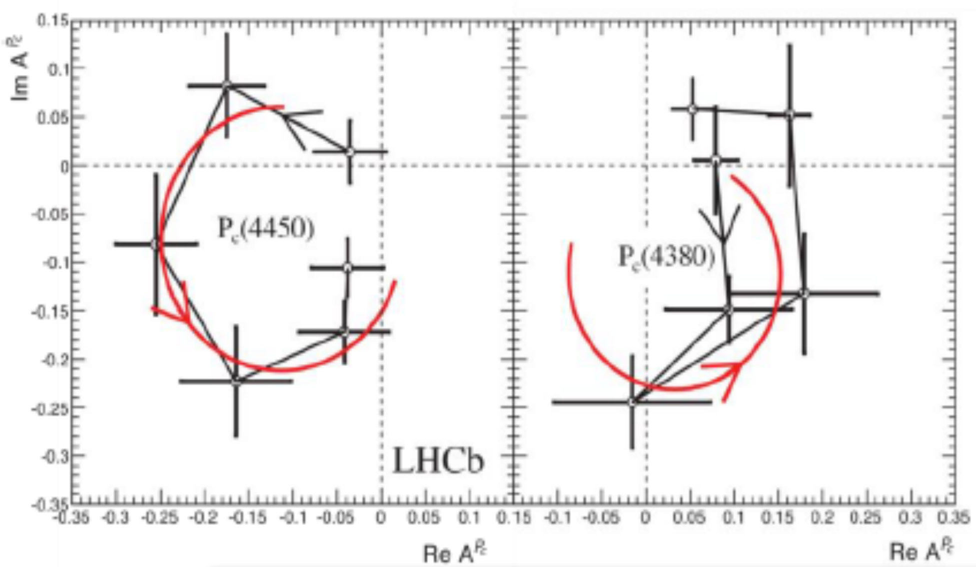
[PRL 115 (2015) 072001]

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.



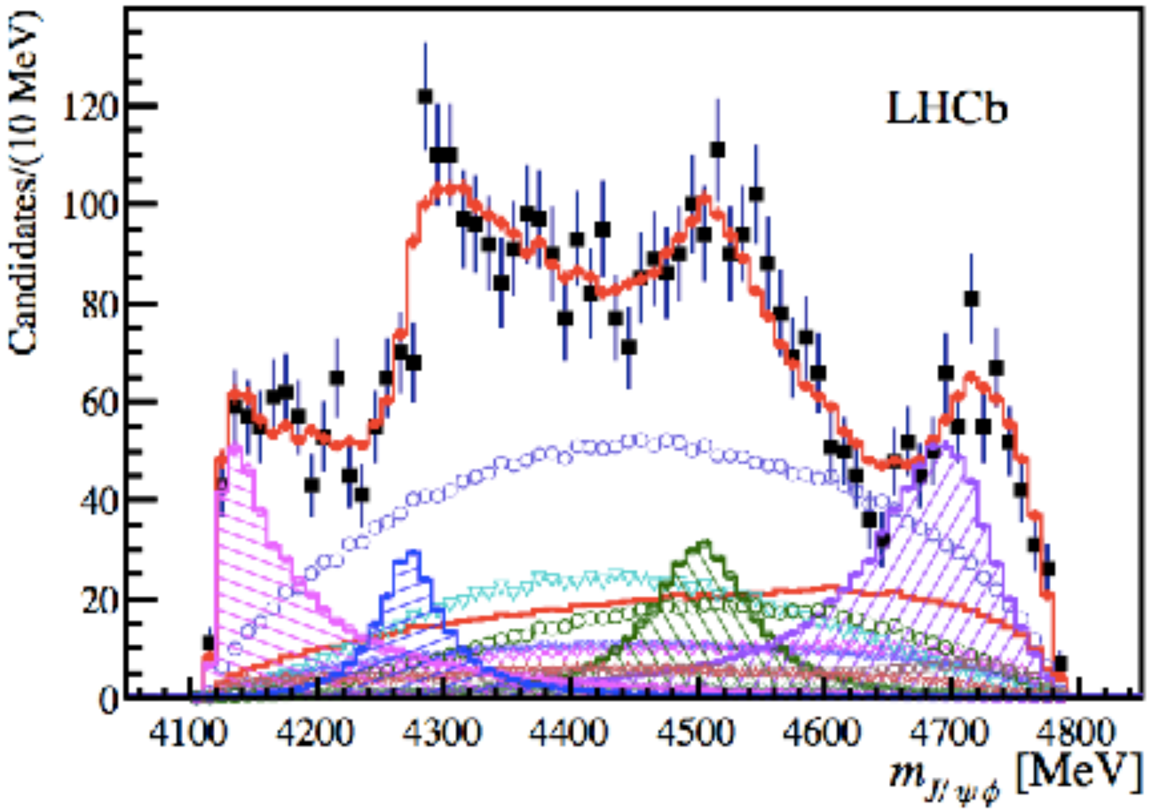
preferred fit
P(4380)=3/2$^-$, P(4450)=5/2$^+$

14/09/15

LHCb - SPC, September 2015

Old and new structures observed by LHCb

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



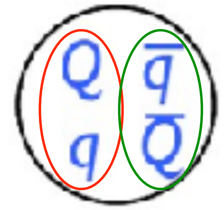
All $X(1^+)$				$16\pm3\,^{+6}_{-2}$
$X(4140)$	8.4σ	$4146.5\pm4.5\,^{+4.6}_{-2.8}$	$83\pm21\,^{+21}_{-14}$	$13.0\pm3.2\,^{+4.7}_{-2.0}$
ave.	Table 1	4147.1 ± 2.4	15.7 ± 6.3	
$X(4274)$	6.0σ	$4273.3\pm8.3\,^{+17.2}_{-3.6}$	$56\pm11\,^{+8}_{-11}$	$7.1\pm2.5\,^{+3.5}_{-2.4}$
CDF	[26]	$4274.4\,^{+8.4}_{-6.7}\pm1.9$	$32\,^{+22}_{-15}\pm8$	
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

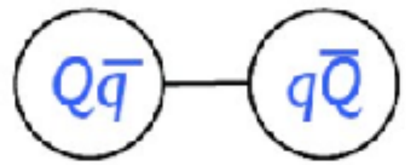
This Talk →

- compact tetraquark



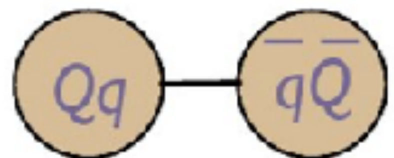
L. Maiani, A. Polosa, V. Riquer, F, Piccinini, Phys. Rev. D **89**, 114010 (2014) and reffs therein

- meson molecule



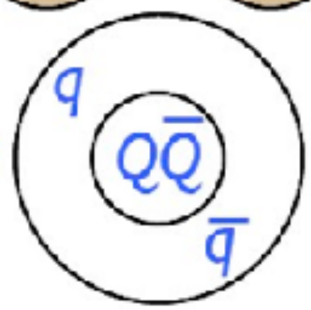
M.Cleven, F.K.Guo, C.Hanhart, Q.Wang and Q.Zhao, arXiv:1505.01771 and refs. therein

- diquark-onium



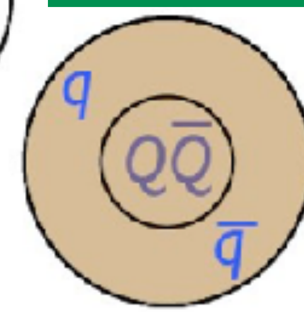
A. Ali, L. Maiani, A. D. Polosa and V. Riquer, Phys. Rev. D **91** (2015) 1, 017502 and refs. therein

- hadro-quarkonium



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

- quarkonium adjoint meson



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...

A certified example of cusp: $K \to \pi^+\pi^0\pi^0$

Determination of the $a_0 - a_2$ pion scattering length from $K^+ \to \pi^+\pi^0\pi^0$ decay

Nicola Cabibbo [1, 2]
CERN, Physics Department
CH-1211 Geneva 23, Switzerland

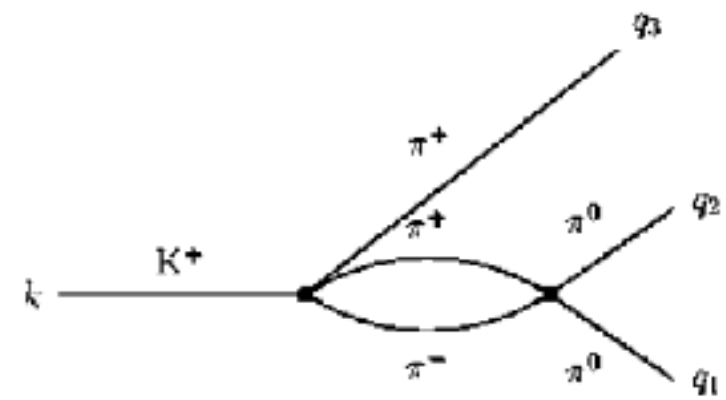
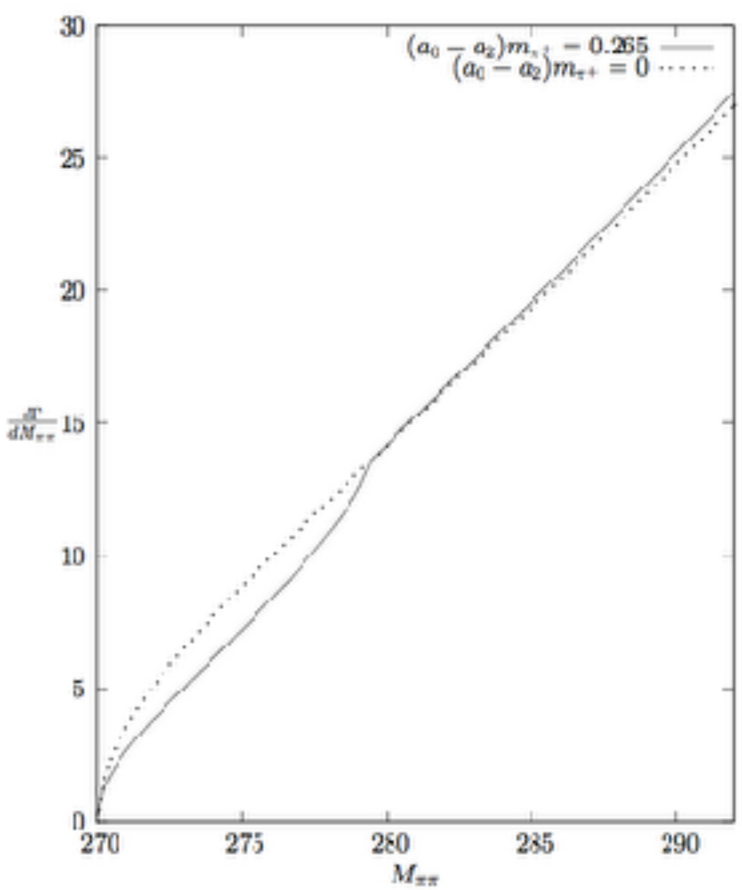


Figure 1: The $\pi\pi$ re-scattering diagram.



Theory

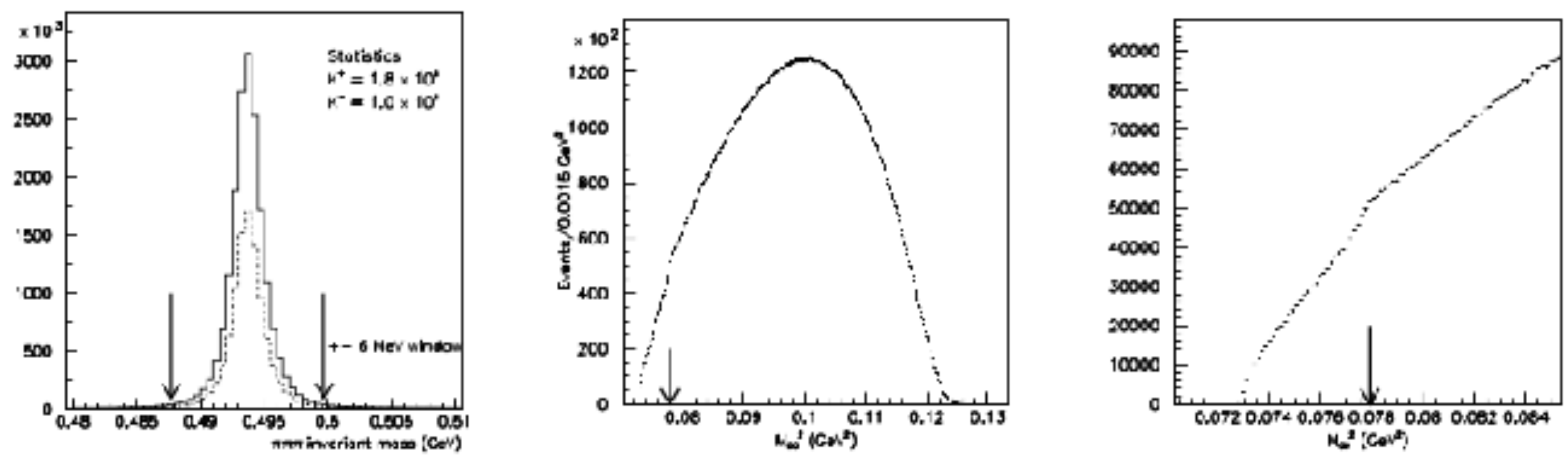


Figure 1: (Left) Invariant mass distribution of $\pi^\pm\pi^0\pi^0$ candidate events. (Middle) $\pi^0\pi^0$ invariant mass squared distribution. (Right) Zoom of the previous in the region around the value $M_{00} = 2m_+$ indicated by the arrow.

Data

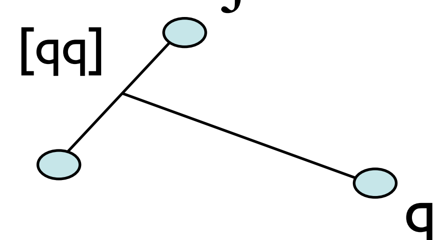
S. Giudici [NA48-CERN Collaboration], hep-ex/0505032

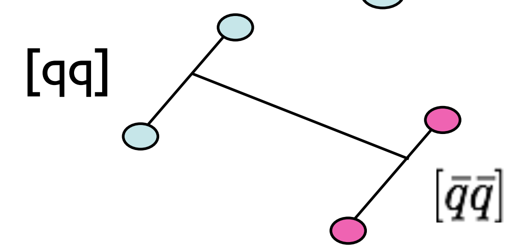
3. Diquarks

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





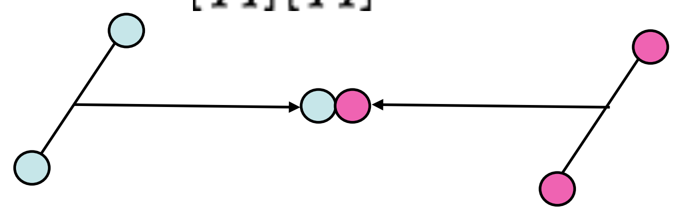
We expect many states: the string joining diquarks may have radial and orbital excitations

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

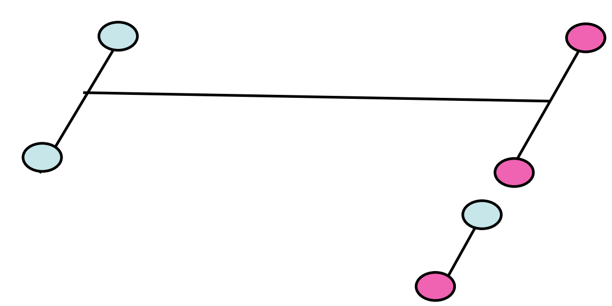
…We propose a simple criterion to decide whether a state is a genuine stringy exotic hadron - a tetraquark - or a “molecule”. If it is the former it should be on a (modified) Regge trajectory…..

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

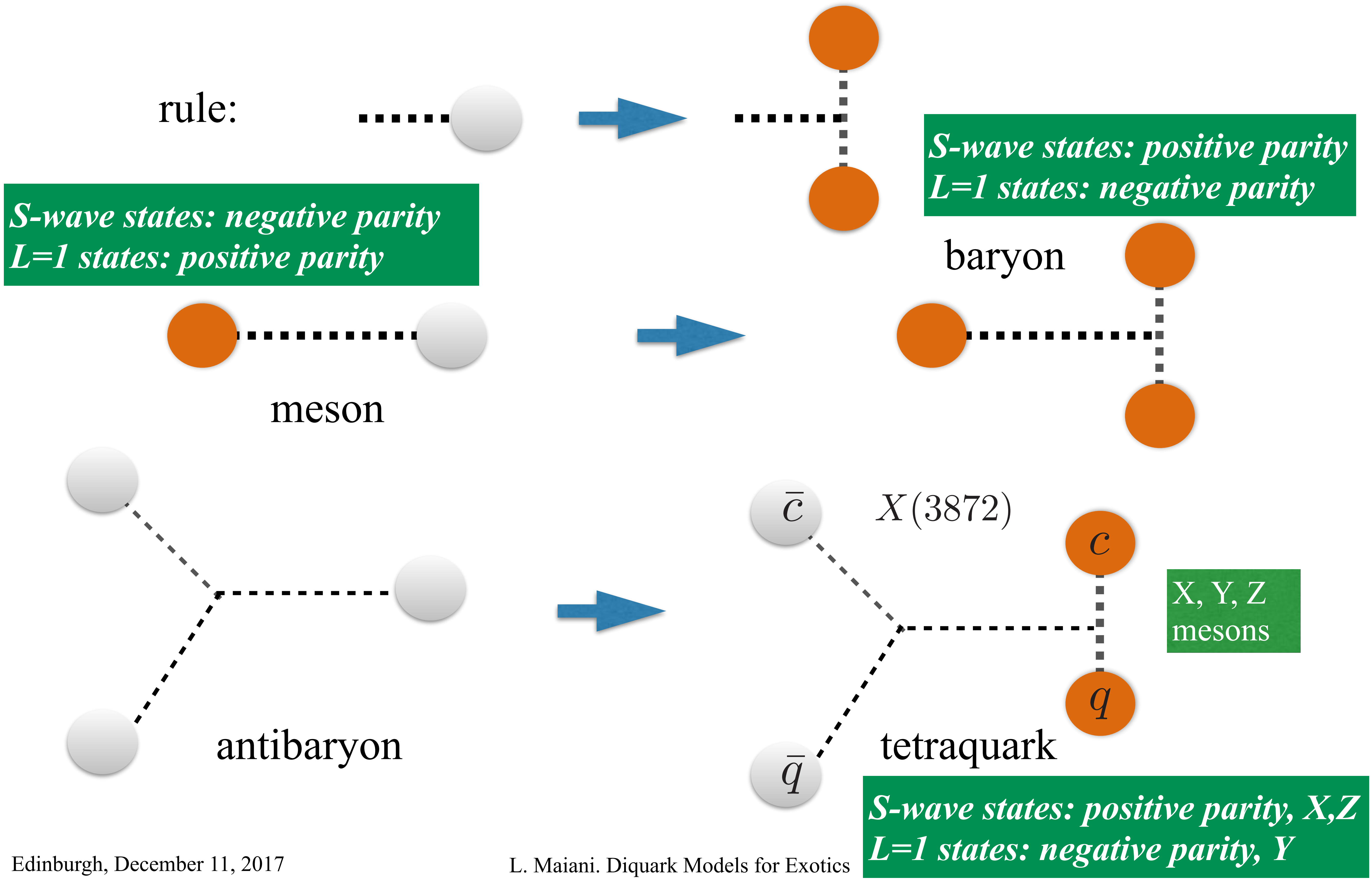
$$[qq][\bar{q}\bar{q}] \rightarrow B\bar{B}$$



$$[qq][\bar{q}\bar{q}] \rightarrow [qq][\bar{q}\bar{q}] + \text{meson}$$

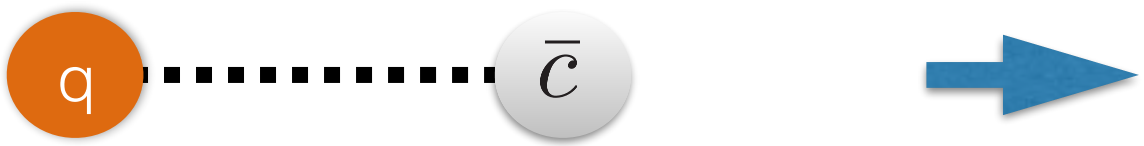


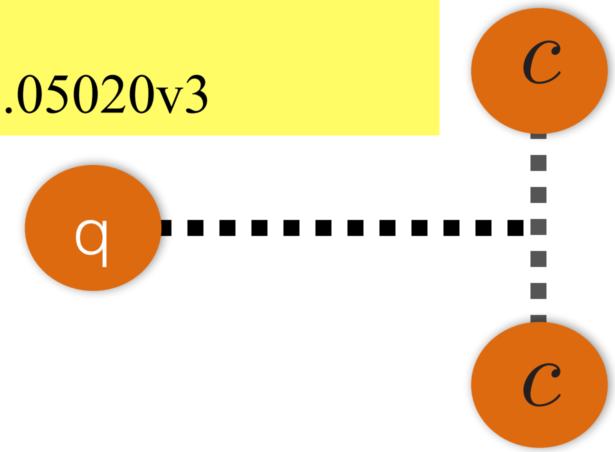
Replacing: antiquark → diquark makes new objects



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

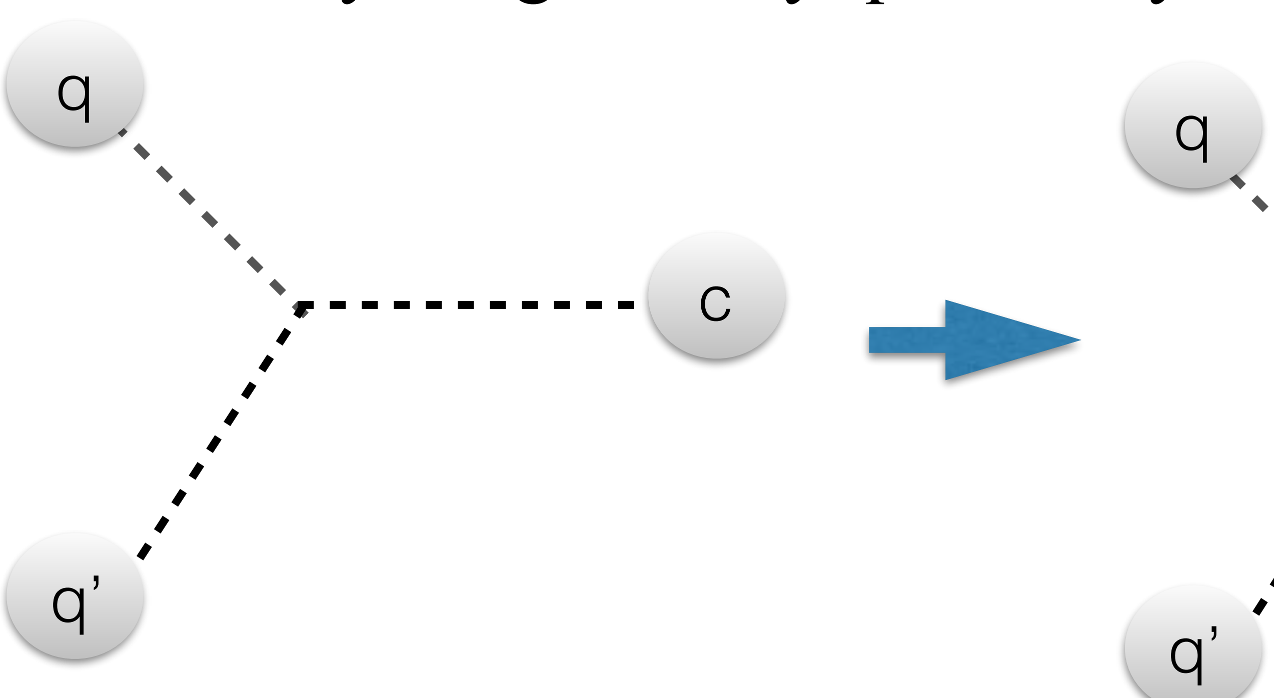


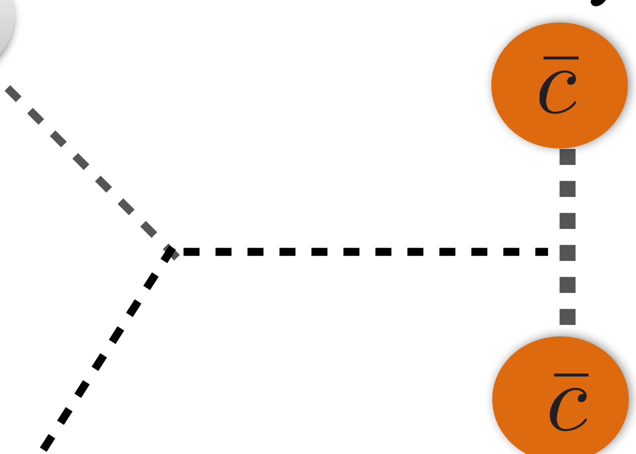


- Doubly heavy baryons are related to single quark heavy mesons
- QCD forces are mainly spin independent, so there is an approximate symmetry relating masses of DH baryons to SH mesons: e.g. $M(\Xi^*_{cc}) - M(\Xi_{cc}) = \frac{3}{4}[M(D^*) - M(D)]$

similarly: single heavy quark baryons….

…. are related to doubly heavy tetraquark



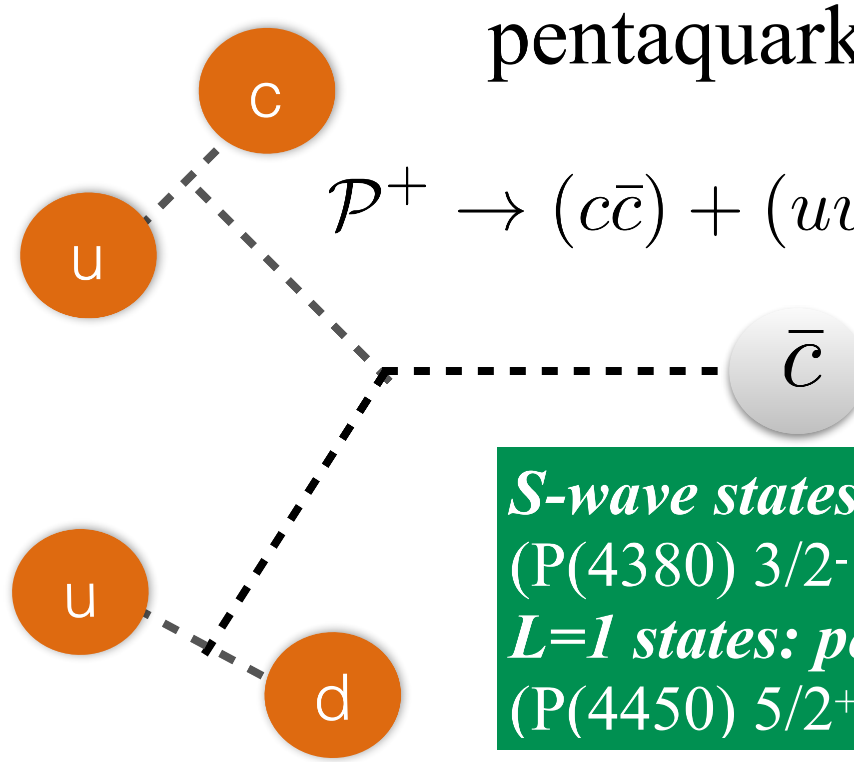


Esposito, M. Papinutto, A. Pilloni, A. D. Polosa, and N. Tantalo, Phys. Rev. D88, 054029 (2013)
M. Karliner and J. L. Rosner, arXiv:1707.07666 [hep-ph].
E. J. Eichten and C. Quigg, arXiv:1707.09575 [hep-ph].

- More about and further references in M. Karliner talk.

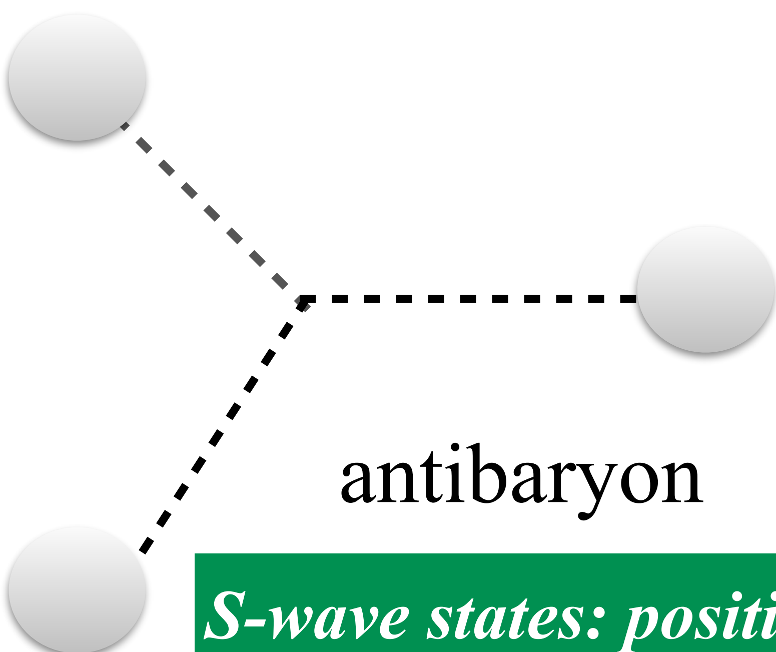
L. Maiani, A. D. Polosa and V. Riquer, PLB **749** (2015) 289

pentaquark



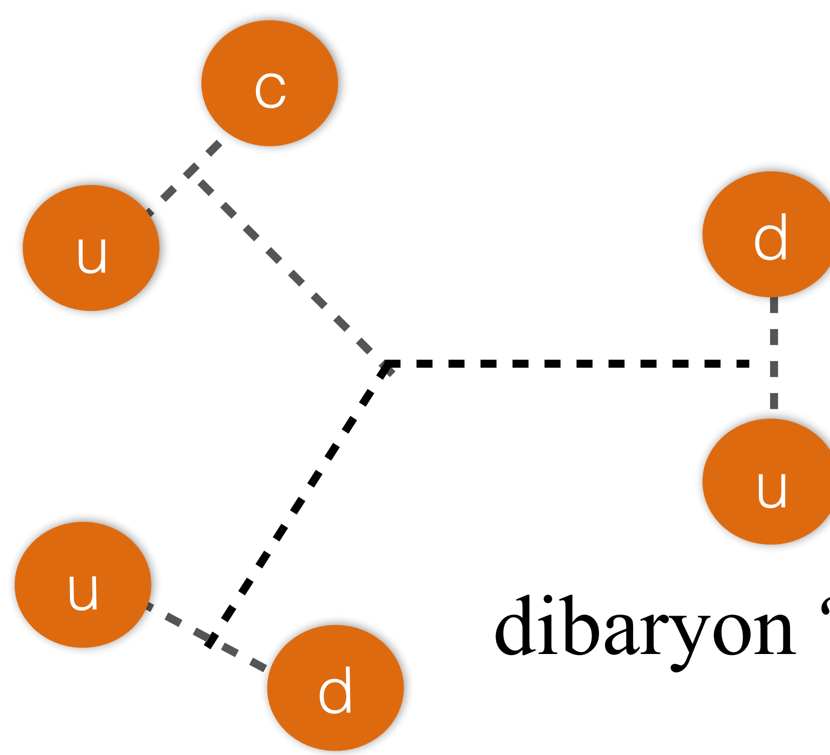
$$\mathcal{P}^{+} \to (c\bar{c}) + (uud) = J/\Psi + p$$

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

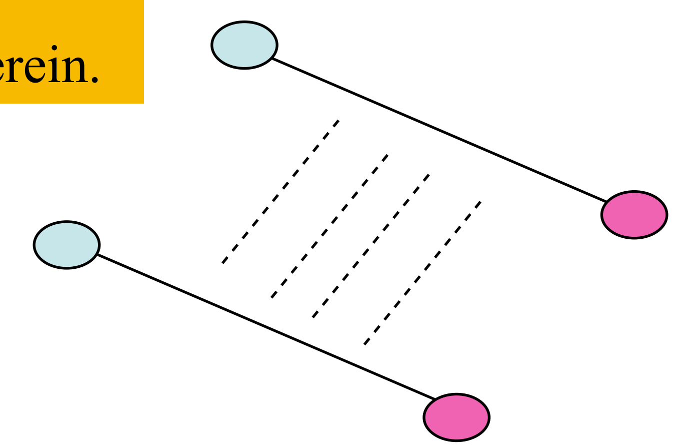
4. Diquarks vs molecules

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

A. De Rujula, H. Georgi and S. L. Glashow, PRL 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, PR **D84** (2011) 054010;
F. K. Guo, C. Hanhart and U. G. Meissner, PRL **102**, 242004 (2009)
see also:
M. Cleven, F. K. Guo, C. Hanhart, Q. Wang and Q. Zhao, PR **D92** (2015) and references therein.

- Meson-meson molecules have a different string topology:
  - are they bound?
  - one pion exchange: attractive in I=0, what about Z^+ states
  - very few states: no orbital excitations or radial excitations expected



- Nuclei belong to the class of 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)

X(3872) production @ LHC

4   4 Measurement of the cross section ratio

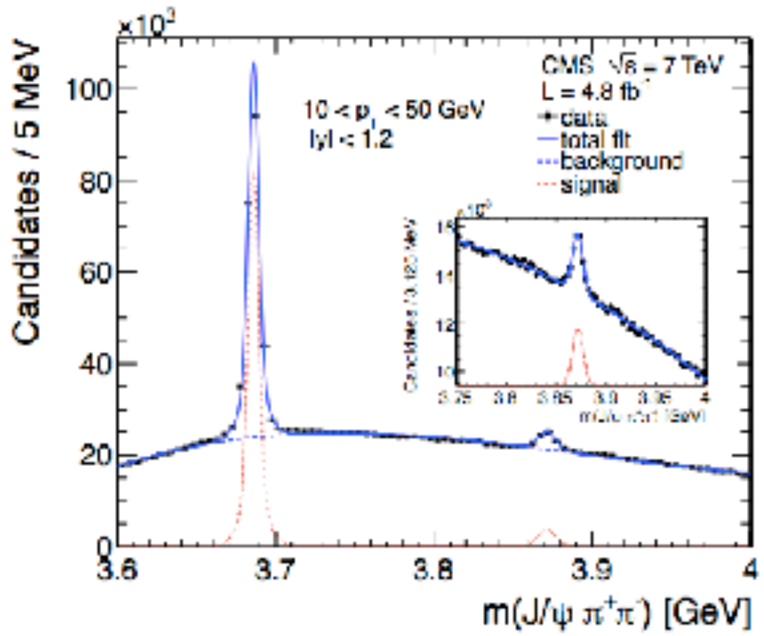
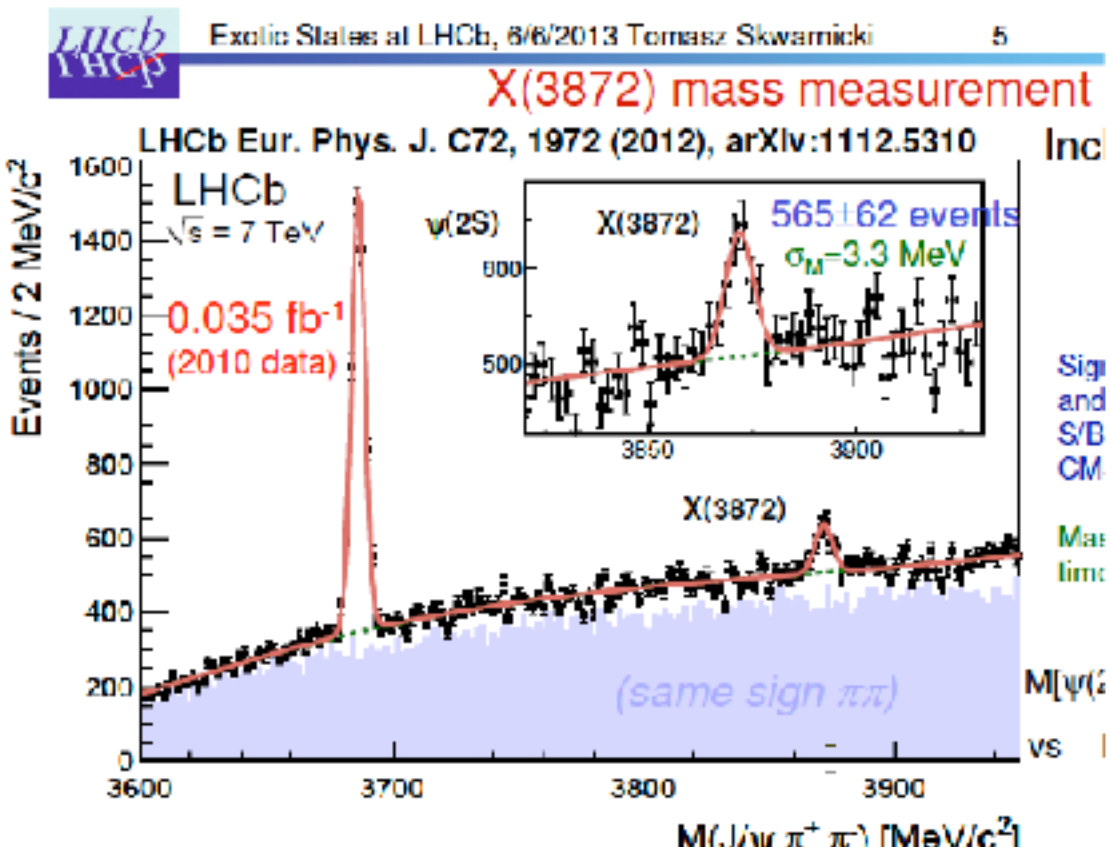
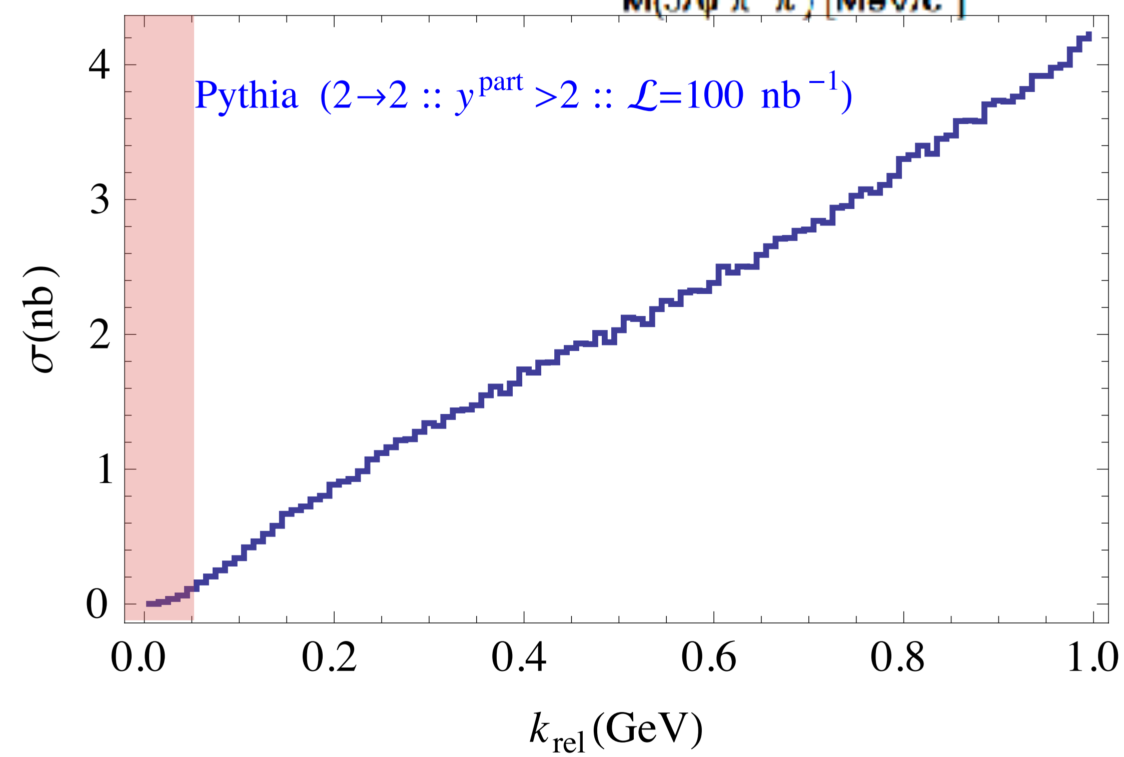


Figure 1: The $J/\psi\pi^+\pi^-$ invariant-mass spectrum for $10 < p_T < 50$ GeV and $|y| < 1.2$. The lines represent the signal-plus-background fits (solid), the background-only (dashed), and the signal-only (dotted) components. The inset shows an enlargement of the X(3872) mass region.



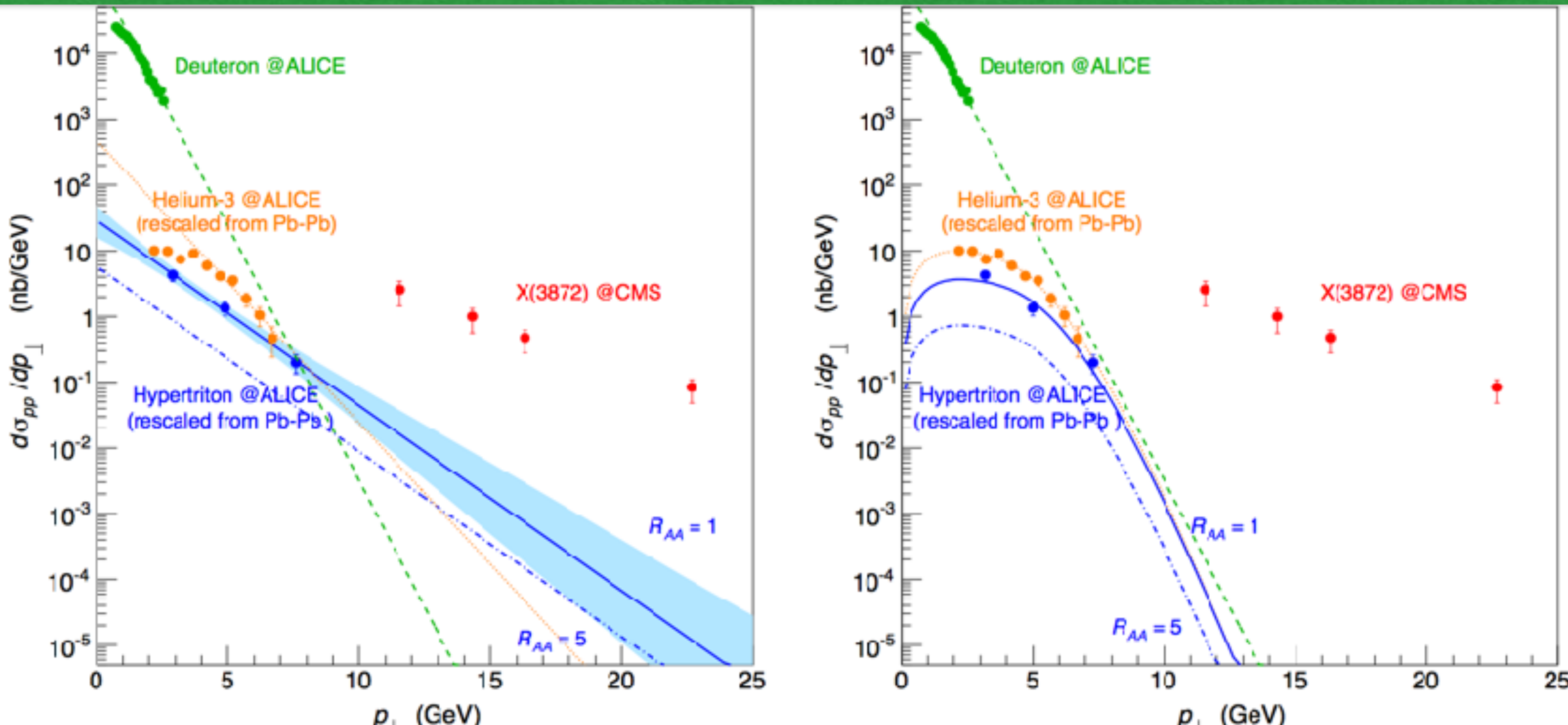
- Production at Colliders speaks against extended objects;
- using Pythia to estimate the probability to find a D-Dbar pair in the relevant phase space, factors of 10^{-2} with respect to the X(3872) cross section measured by CDF (~ 30 nb) are found.



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**.

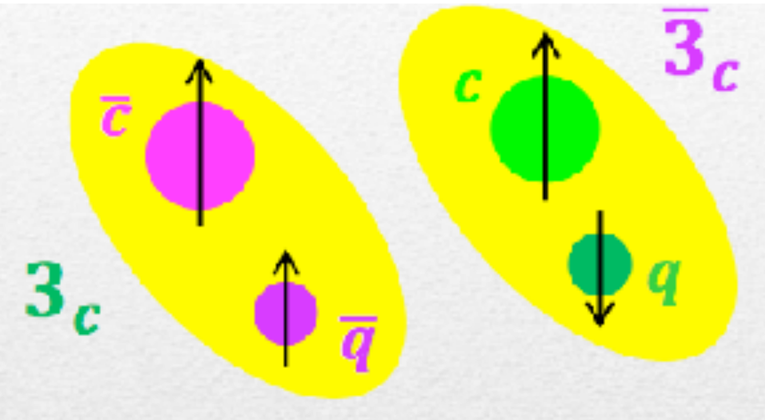
- There is a vast difference in the probability of producing X(3872) and that of producing light nuclei, true “hadronic molecules”, in high energy collisions
- high energy production of suspected exotic hadrons from quark-gluon plasma at Heavy Ion colliders can be a very effective tool to discriminate 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. 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: $|s,\bar{s}\rangle_J$

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

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

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

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

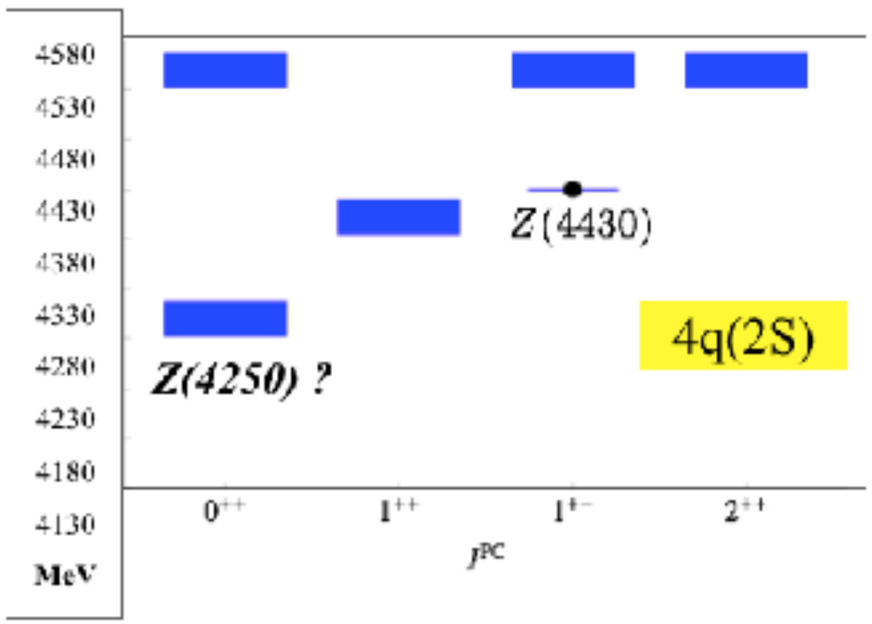
X(3872)=X_1
Z(3900), Z(4020)=lin. combs. of Z&Z' that diagonalize H

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

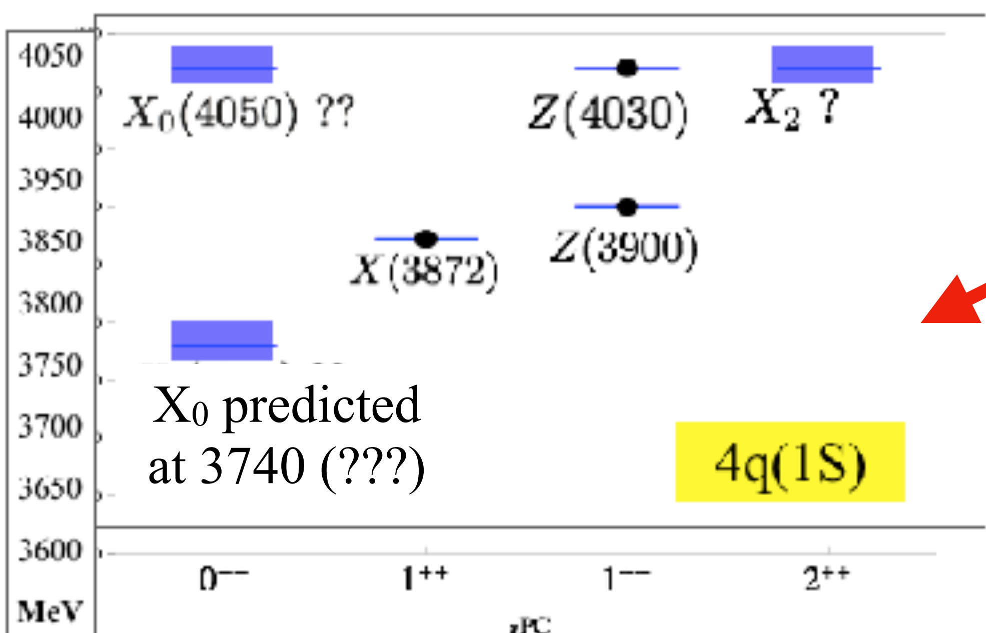
- Spin-spin interactions are expected to be proportional to the overlap probability $|\psi(0)|^2$ of the two quarks/antiquarks involved.
- No symmetry principle says that overlap functions in tetraquarks have to be the same as in baryons or mesons
- spin-spin couplings in tetra quarks should be considered as free parameters to be determined from the mass spectrum

Phenomenology

- A simple ansatz reproduces Z states ordering: spin-spin interaction is dominated by interactions of constituents inside the same diquark or antidiquark
- constituents are ***not*** uniformely mixed in the bag, rather clump into two separate entities: diquarkonium (see later).
- 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 radial excitation energy, ΔE_r, mildly dependent on the diquark mass: $E_r\,(cq) \sim\, \sim E_r\,(cs)$

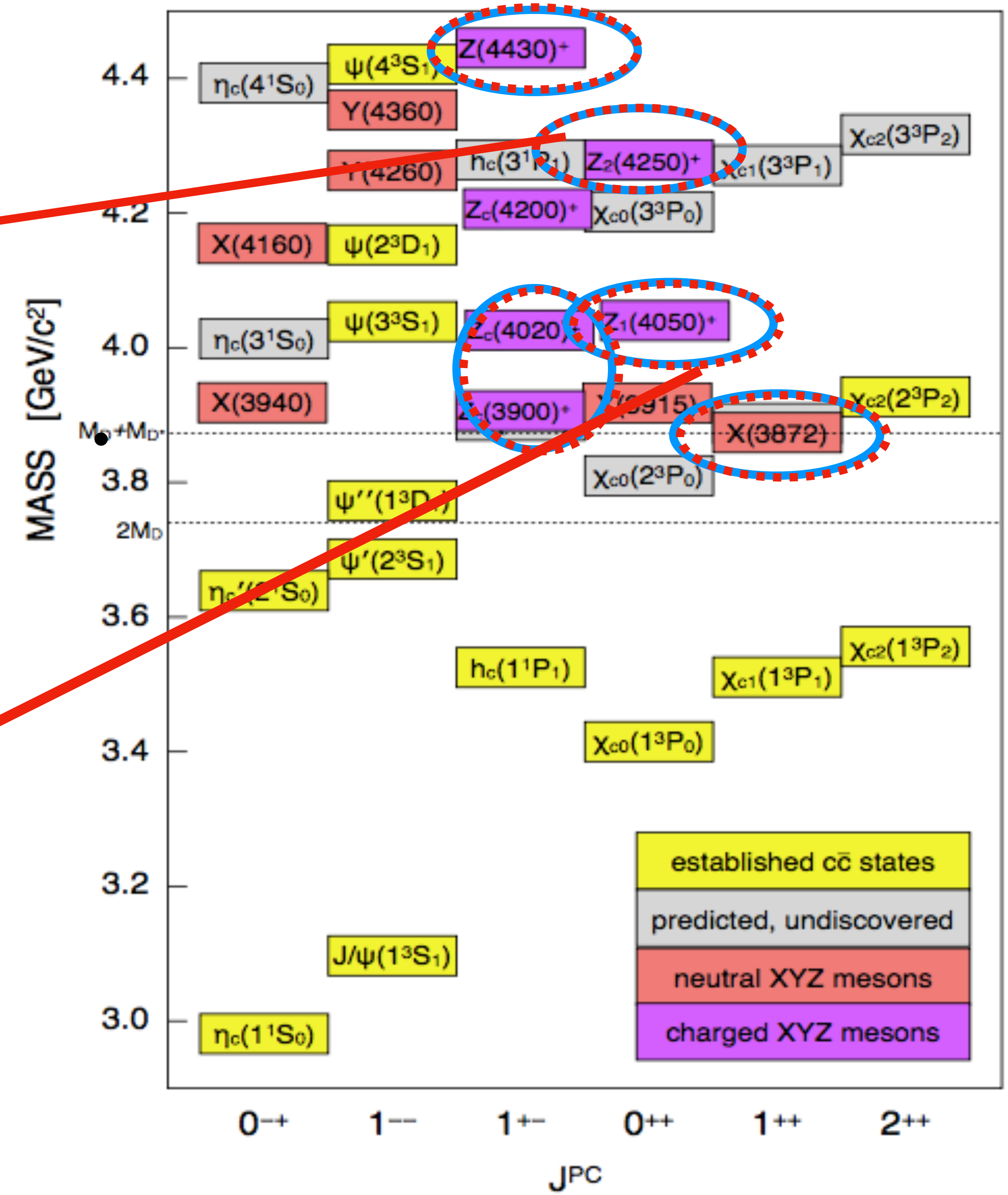


$\Delta E_r(cq) = 530$ MeV

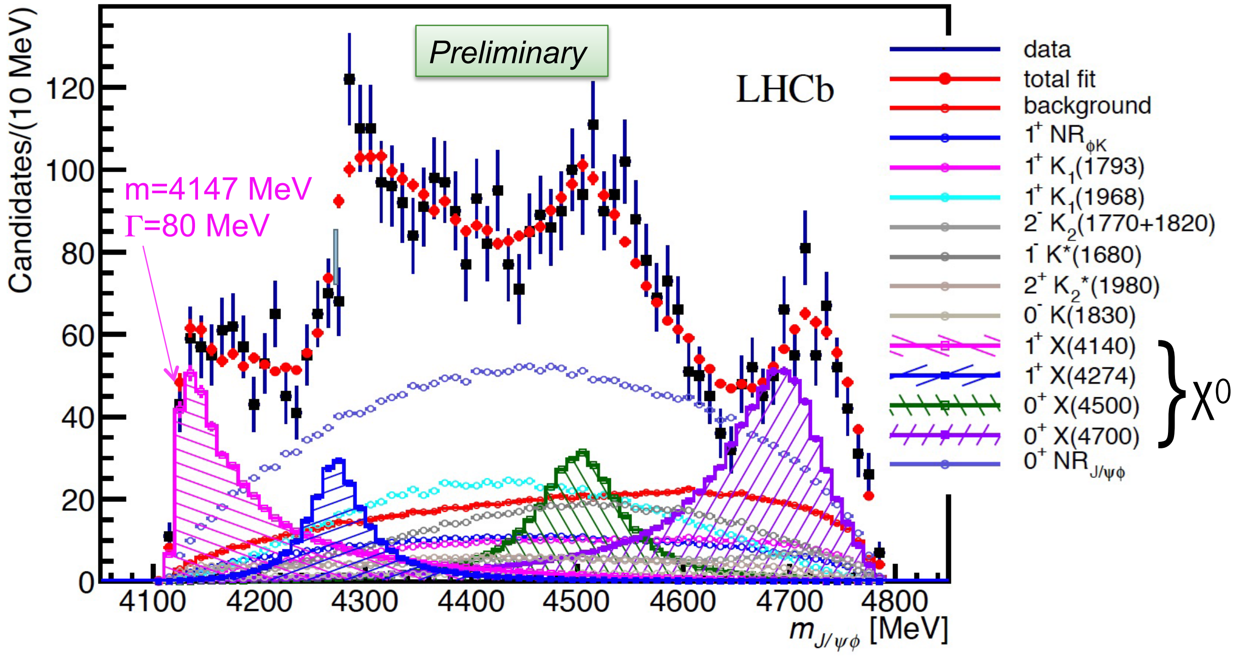


$m_{[cq]} = 1980$ MeV

$\kappa_{cq} = 67$ MeV



Old and new structures observed by LHCb
arXiv:1606.07895



- 4 visible structures fit with BW amplitudes

28 Recontres de Blois, June 2, 2016

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Results of fit

- J^P also measured all with $>4\sigma$ 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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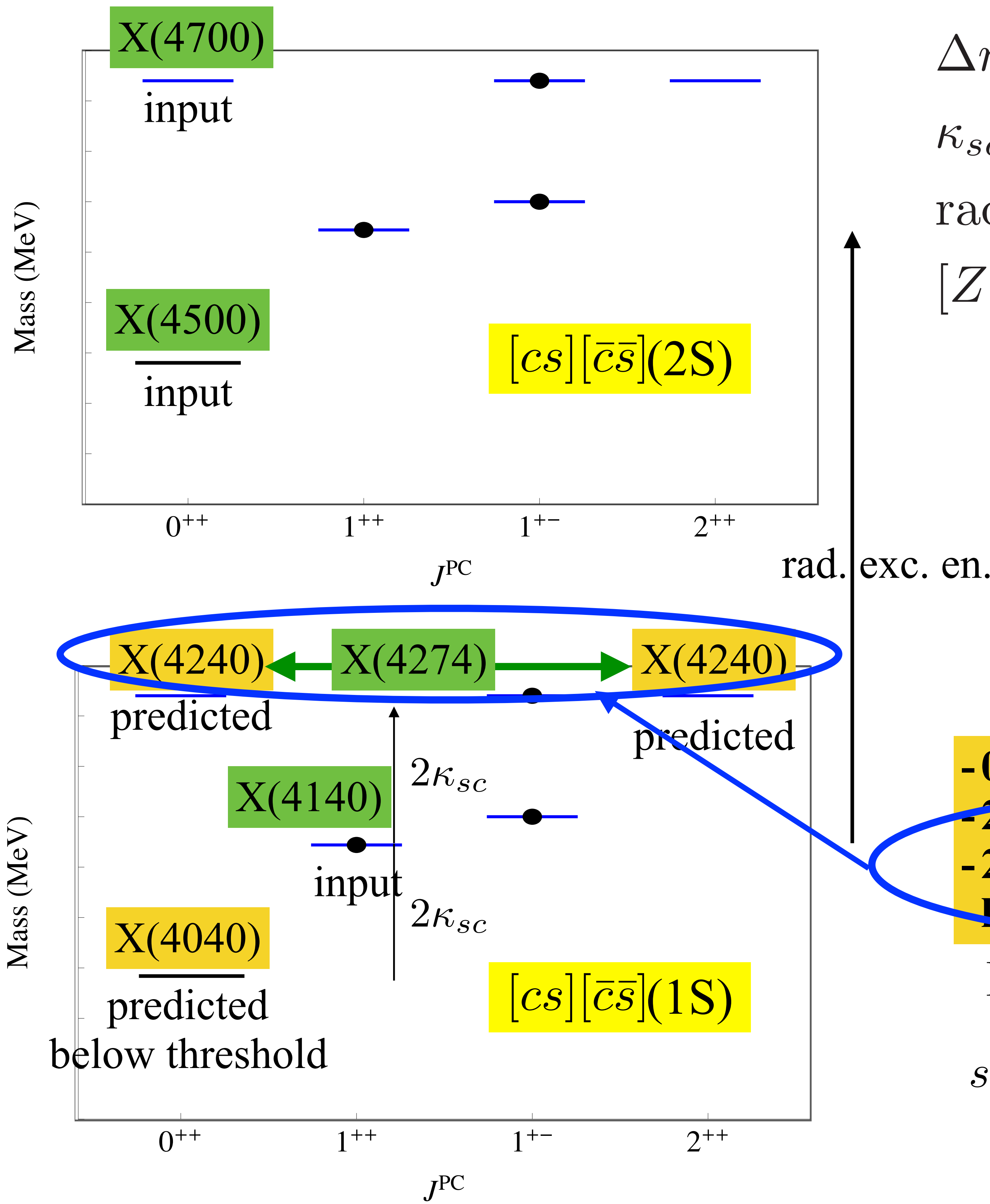
- Four structures
- positive parity, J=0 and 1, positive charge conjugation
- X(4140) seen previously by CDF, D0, CMS and by BELLE

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.

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:

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

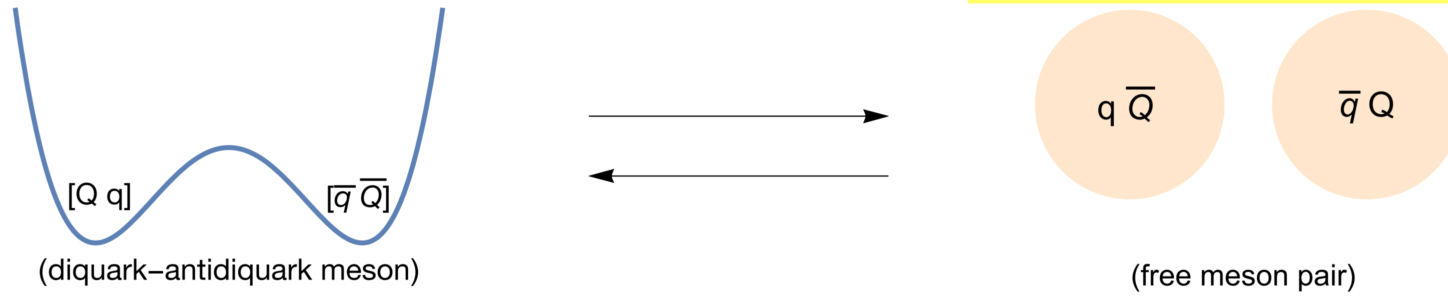
$$s_{c\bar{c}} = 0 : \eta_c + \phi, h_c + \phi \ (P - wave)$$

what about the strange members of the nonet?

- We expect strangeness= ±1 tetraquarks: $X_{\bar{s}} = [cq][\bar{c}\bar{s}]; \;\; X_s = [cs][\bar{c}\bar{q}]$
- partners of X(4140) should decay in: $J/\Psi + K^*/\bar{K}^* \to \mu^+\mu^- + \pi + K_S$
- or: $J/\Psi + K/\bar{K} \to \mu^+\mu^- + K_S$
- 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?

6. Going inside the tetraquark: the X_u, X_d and $X^{\pm}$ puzzles

LM, A. Polosa and V. Riquer, in preparation



- The attraction that generates the diquark implies that diquarks, or antidiquarks, are segregated in two different potential wells, separated in space.
- QCD confining forces prevail at large distances, where the diquarks see each other as QCD point charges.
- At shorter distances the internal structure is felt and the competing interactions that tend to dissociate the diquark, e.g, attraction between quarks and antiquarks, produce repulsive forces between diquark and antidiquark and a rise in the potential.

A. Selem and F. Wilczek, Hadron systematics and emergent diquarks, hep-ph/0602128.

- A phenomenological basis is provided by the mass ordering in Z(3900) vs Z(4020):
  - spin-spin interactions between light quark and antiquark located in different diquarks are definitely smaller than one would guess from the same interactions within mesons;
  - spin-spin interaction inside the diquark is about four times larger that the same interaction in the diquarks inside charmed baryon states.

1. The decay puzzle

- Tunneling of light quarks rearranges the diquark-antidiquark state (left panel) into two open-charm color singlets: X(3872) → D^0 $Dbar^{*0}$.
- A common mechanism (tunneling of light quarks) describes well the data for open-charm decay widths of X and Z (left: width of X(4140) from CMS, right from LHCb)

$$\delta = Q_{value};\ p_{decay} = A\sqrt{\delta}, \text{from the fit}: A = 10.3 \pm 1.3\ \text{MeV}^{1/2}$$

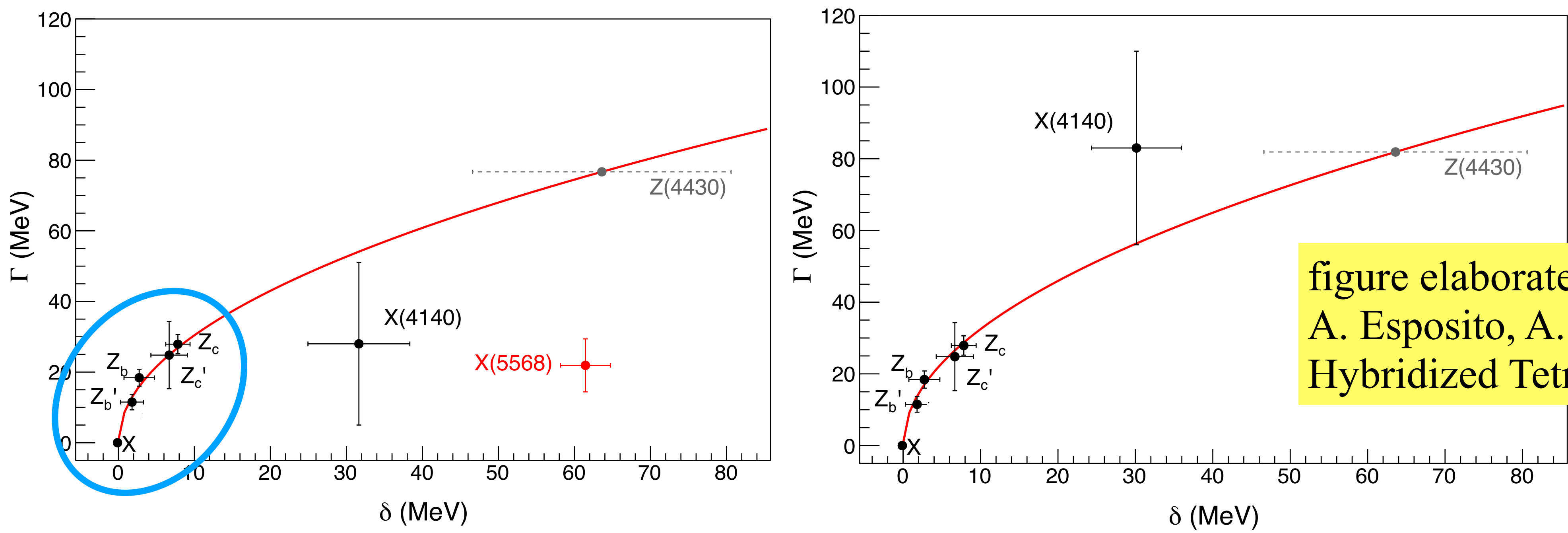


figure elaborated from:
A. Esposito, A. Pilloni and A. D. Polosa,
Hybridized Tetraquarks, PL **B**758 (2016) 292

- Decay into hidden-charm channels, X(3872) →J/Ψ+ρ^0, requires tunneling of a c-qbar pair, with exponentially suppressed amplitude:

$$\frac{\mathcal{A}(\text{hidden charm})}{\mathcal{A}(\text{open charm})} \sim \frac{\exp(-\sqrt{2m_c E L})}{\exp(-\sqrt{2m_q E L})}$$

E, L= height and length of the barrier

the exponential suppression of the amplitude for charmonium decays may overcome the unfavourable ratio of phase space for open charm channels

2. Isospin breaking in tetraquarks

- why don't we see two distinct X_u and X_d around 3872 MeV?
- quark mass difference only: $\Delta(M_{Xu}-M_{Xd}) \simeq m_u - m_d \simeq 6$ MeV
- however, one must account (mainly) for electrostatic interactions inside diquarks and between diquark and antidiquark
- Karliner & Rosner: from isospin differences in baryons determine the relevant parameters, that scale with the diquark radius and the baryon radius.

M. Karliner and J. L. Rosner, PR **D96**, 033004 (2017)

- For baryons: $R_{2q} \sim R_B$
- For tetraquarks there are two radii, $R_{cq},\ R_{tetra}\ :\ \lambda = R_{tetra}/R_{cq}$
- λ = free parameter, $(R_B/R_{cq})^3 \sim (\kappa_{cq})_{tetra}/(\kappa_{cq})_B \sim 4$

−	$\lambda = 1$	$\lambda = 3$
$M(X_u) - M(X_d)$	-6.1 ± 0.1	-1.2 ± 0.3
$M(X_u) - M(X^+)$	-5.31 ± 0.05	-1.34 ± 0.12

Table 1: Numerics of X_u-X_d mass differences (MeV) vs λ.

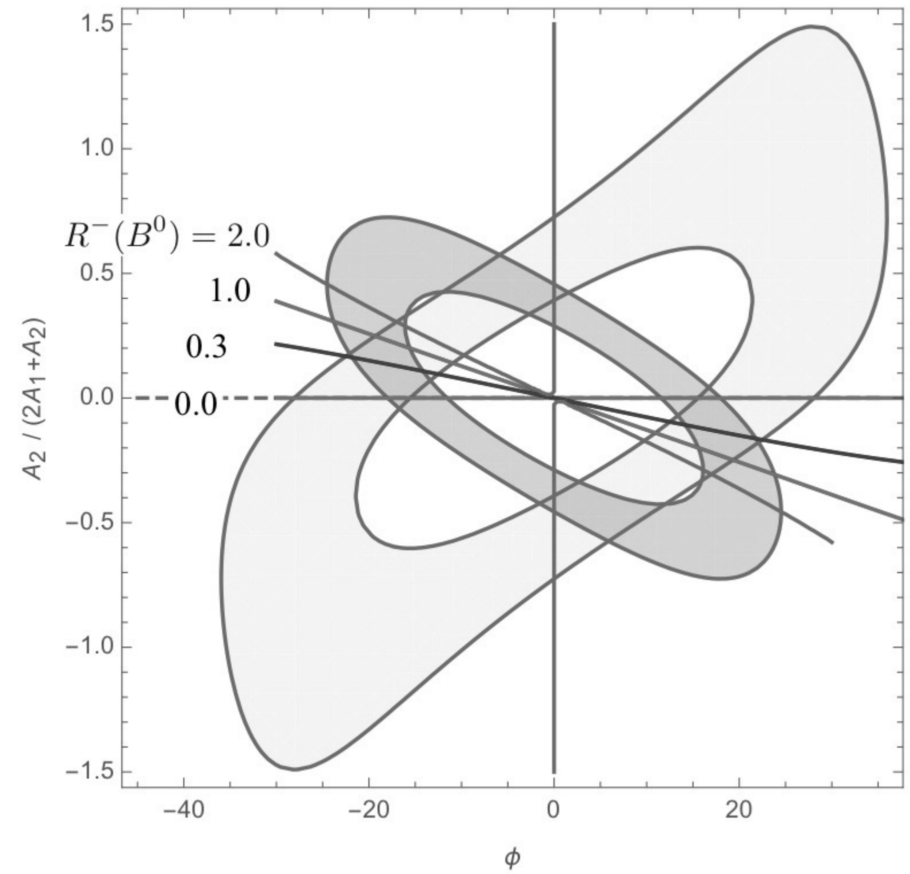
- a surprising result: X_u and X_d may be degenerate within the present experimental resolution of ∼1 MeV
- reasonable values for radii. In fermi: R_B= 1, R_{cq}= 0.6, R_{tetra}= 2
- Experimental resolution is the key to the puzzle ?

3. Where is it the $X^\pm$? $[cu][\bar{c}\bar{d}]$

- The charged X has been searched in B^0 and B^+ decays: $B \to K X^+$ with the experimental upper limits:

$$R^-(B^0) = \frac{\Gamma(B^0 \to K^+X^-,\ X^- \to J/\Psi + \rho^-)}{\Gamma(B^0 \to K^0X(3872),\ X(3872) \to J/\Psi + \rho^0)} < 1$$

$$R^+(B^+) = \frac{\Gamma(B^+ \to K^0X^+,\ X^+ \to J/\Psi + \rho^+)}{\Gamma(B^0 \to K^0X(3872),\ X(3872) \to J/\Psi + \rho^0)} < 1$$



- Ratios are equal to 2 for X(3872) with Isospin=1, which however is a very restrictive hypothesis
- we have reanalysed B decays using the experimental ratios of $\Gamma(X \to J/\Psi\ 3\pi)/\Gamma(X \to J/\Psi\ 2pi)$, with X(3872) produced in B^0 and B^+ decays, under the hypothesis that X is made of two unresolved lines, X_u and X_d, see figure
- The preferred region corresponds mostly to $R^-(B^0)<1$, with 0.3 in the central region

SUMMARY. Under the two wells hypothesis, the key to the problems are: resolution (to see the two lines under X(3872)) and statistics (to go to branching fractions <1 to see the $X^\pm$). Will time tell ??

7. Conclusions

- There are “structures” beyond (q q-bar) or (qqq) states, but we do not know yet if this is a reflection of known particles in a new context (hadron molecules? threshold effects?) or the indication of a new class of quark bound states;
- Constituent Quark Model: q-q forces are attractive in color 3-bar
- Diquarks ***may be*** a useful organising principle, to classify the structure of exotic mesons and pentaquarks, indeed the only one to give a unified explanation of all the exotics seen thus far
- ***However it is not without problems***…
- The scheme predicts many more states than seen…
- ***is resolution the answer*** ???
- …future experiments at colliders are expected to provide further clarification

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)
- ***Open heavy flavour exotics*** are an important target: we would like to to see the nonets
- ***Y states***: new data, picture still confused…Many states missing, notably X^+, Y^+,…
- ***Pentaquarks***: two states is important! can we find more?
- ***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: all quarks of the Gell-Mann-Zweig construction are replaced by diquarks, thus completing the saturation possibilities of one and three QCD strings.
- ***Doubly heavy tetraquarks*** are crucial (TeraZ colliders ?) and may provide a definitive proof of existence of tetraquarks = diquarks-antidiquarks
- 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 at LHC and e^+e^- colliders.

Hadron Spectroscopy to teach us something fundamental about the, mostly unknown, non-perturbative QCD