Tetraquarks, pentaquarks ….
and all that

La Thuile, March 8, 2016

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Dedicated to Guido Altarelli,
a friend for the lifetime
we shared the privilege of seeing the
unfolding of the Standard Theory

***Abstract*.**

The discovery of two pentaquarks by LHCb and the $B_s\pi^+$ resonance by D0 have reinforced the case of "exotic' hadrons, which have diquarks and antidiquarks as basic units.

I review (i) the cases studied until know, the so called XYZ and pentaquark states, (ii) the theoretical basis for this concept and (iii) the implications for the existence of further states, in particular with baryon number equal to two (dibaryons).

1. New States

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.

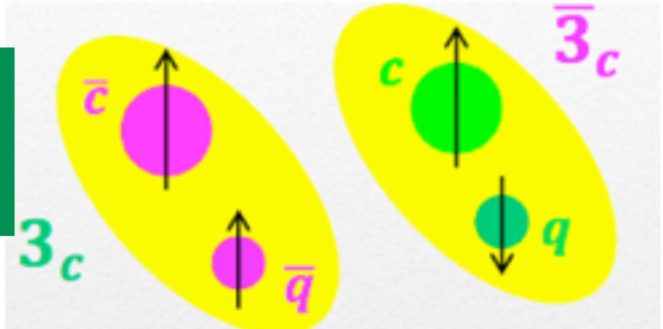
M. Gell-Mann, A Schematic Model of Baryons and Mesons, PL **8**, 214, 1964

- 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 established by BELLE and by BES III.
- Pentaquark discovered (P-> Ψ p) by LHCb in 2015
- Tetraquark reported days ago by D0, the Z(5568) -> B_s π, is charged, open charm, all different flavours

A new spectroscopy of mesons and baryons revealed



1. Conventional and less conventional Quarkonia

- The accuracy with which the spectra of Q Qbar states (Q=c, b) are predicted and measured makes it possible to discover new states "by difference"
- Terminology of Q-Qbar states in S and P wave:

$$\text{spin} = S,\ \text{orb. ang. mom.} = L,\ \text{tot. ang. mom.} = J:\ {}^{2S+1}L_J$$

$$\text{radial excitation} = n$$

$$\eta_c(1S) = {}^1S_0;\ J/\Psi(1S) = {}^3S_1$$

$$h_c(1P) = {}^1P_1,\ \chi_c(1P) = {}^3P_J$$

Particle Data Group:
S. Eidelman et al., DEVELOPMENTS IN HEAVY QUARKONIUM SPECTROSCOPY Updated March 2014;

Quarkonium Working Group:
N. Brambilla et al., arXiv:1404.3723v1 [hep-ph] 14 Apr 2014

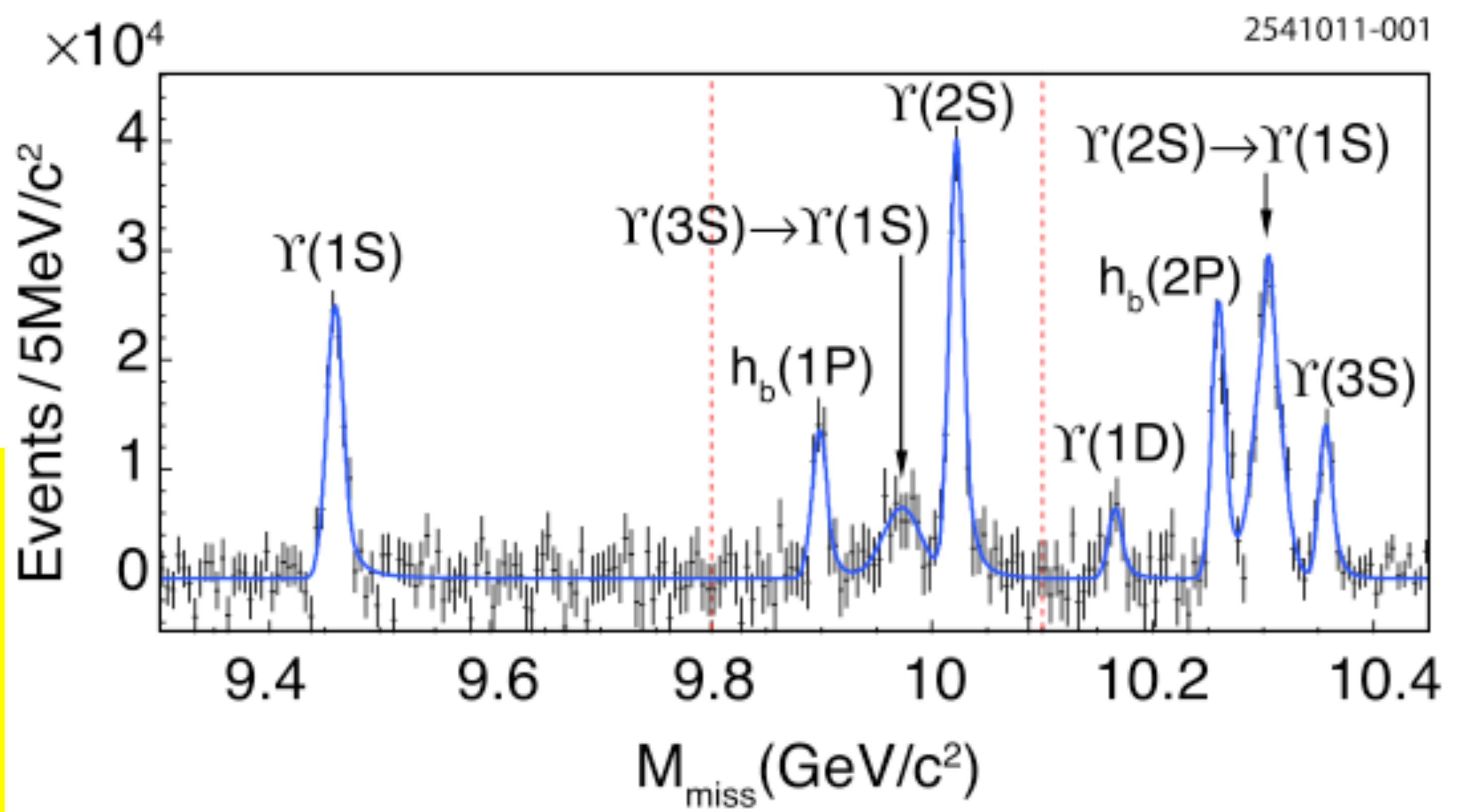


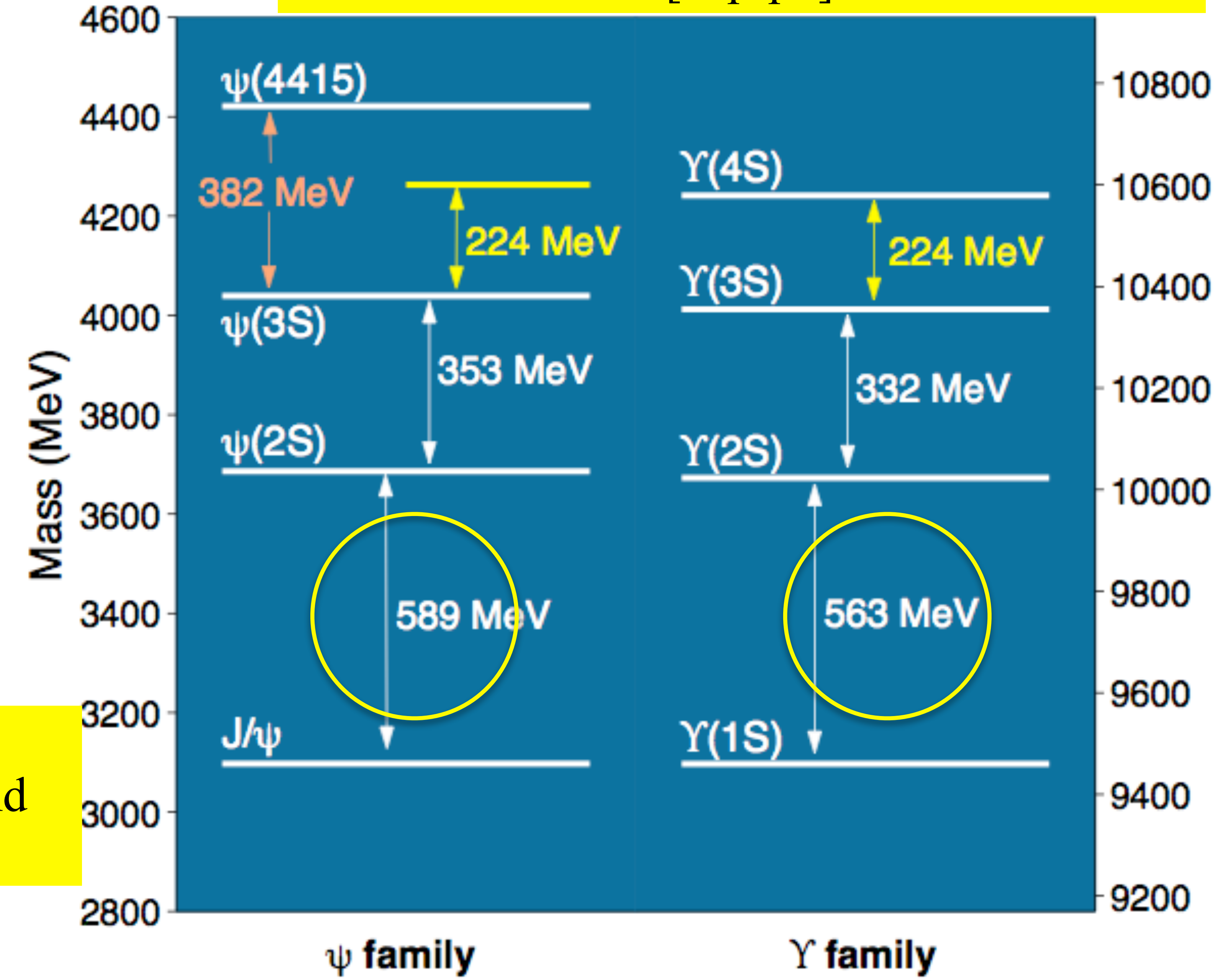
Figure 1: From Belle [31], the mass recoiling against $\pi^+\pi^-$ pairs, M_{miss}, in e^+e^- collision

Radial excitations

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

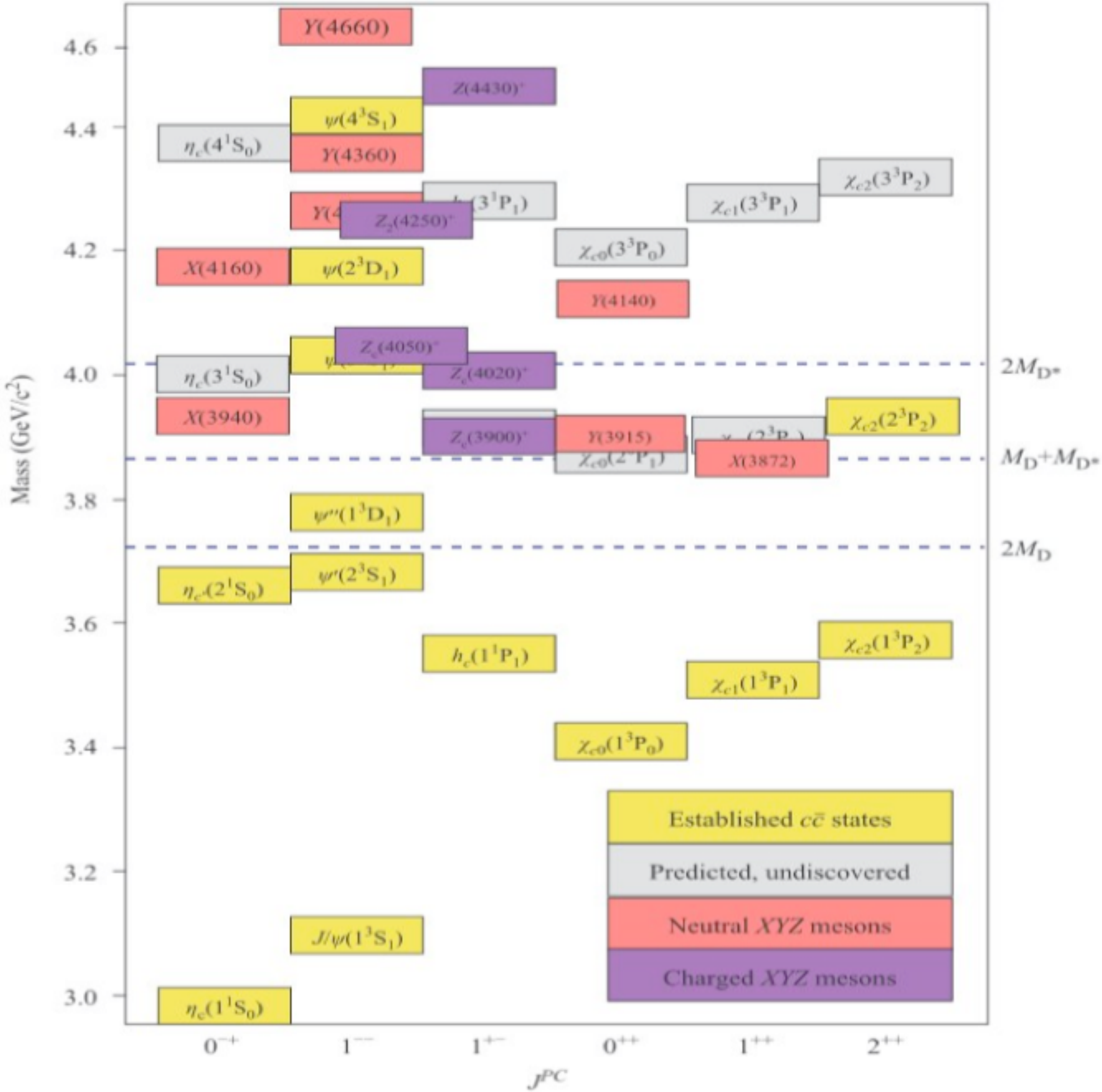
$$\chi_{bJ}(2P) - \chi_{bJ}(1P) \approx 360 \text{ MeV}$$
$$\chi_{cJ}(2P) - \chi_{cJ}(1P) \approx 437 \text{ MeV}$$

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



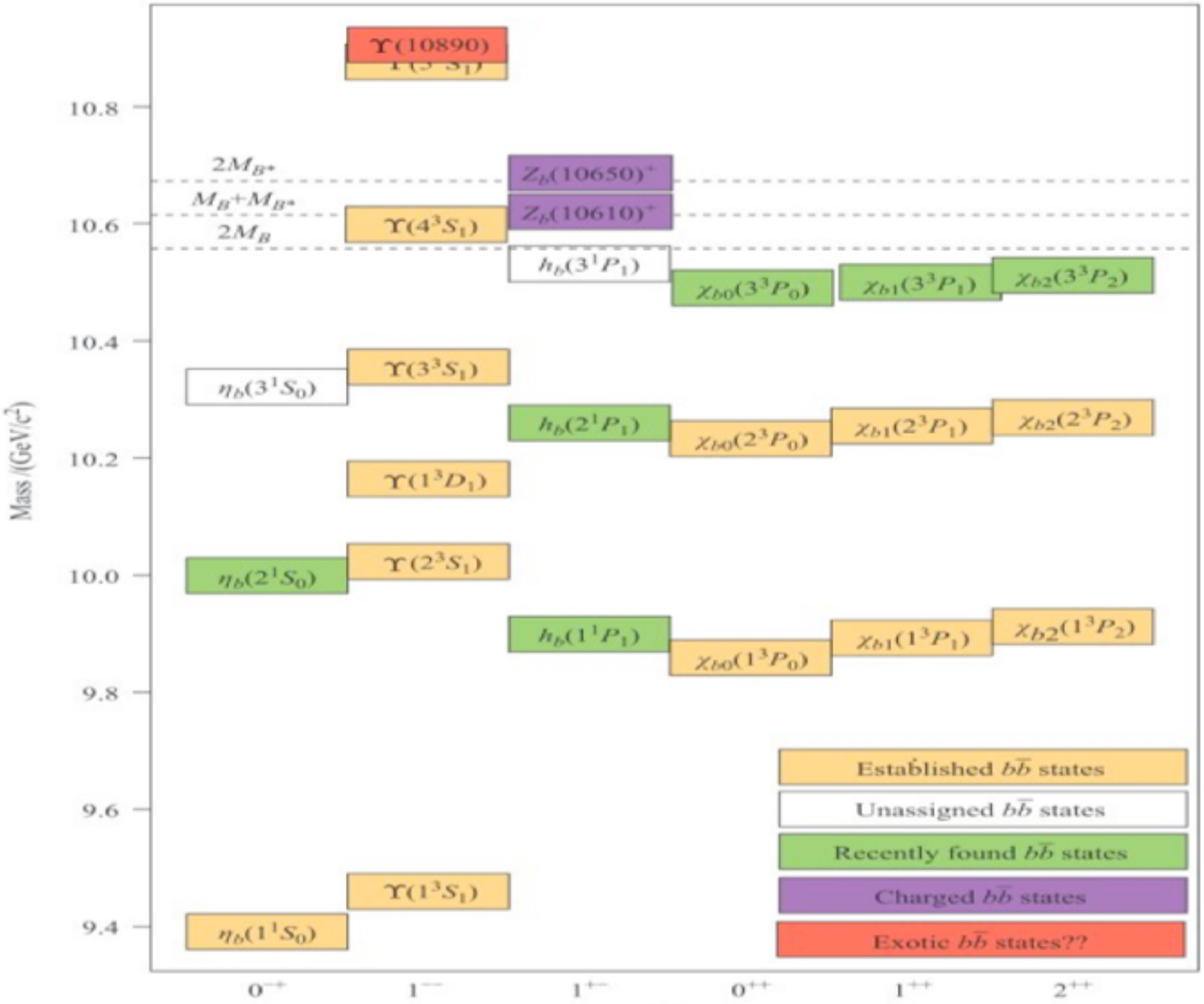
Is a diquark-antidiquark pair similar to a quark-antiquark pair? a very tightly bound diquark?

Charmonia and Charmonium-like Hadrons (Olsen, arxiv:1411.7738)



Exotic states in b-b bar

Bottomonia and Bottomonium-like Hadrons (Olsen, arxiv:1411.7738)



A. Ali, C. Hambrock, I. Ahmed and M. J. Aslam, Phys. Lett. B 684, 28 (2010);
A. Ali, C. Hambrock and M. J. Aslam, Phys. Rev. Lett. 104, 162001 (2010) [Erratum-ibid. 107, 049903 (2011)];
A. Ali, BELLE II ITIP, Krakow, 2015

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); now also open beauty Z(5568)->$B_s+\pi$ (b s-bar u d-bar).

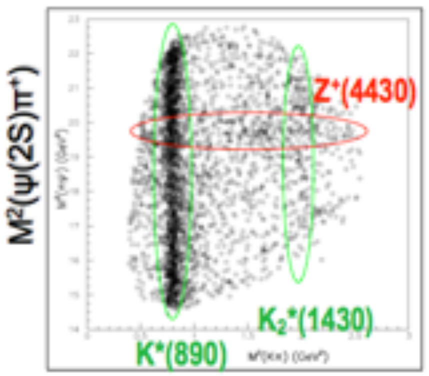
2. The new spectroscopy: $Z^{\pm}(4430)$ confirmed

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

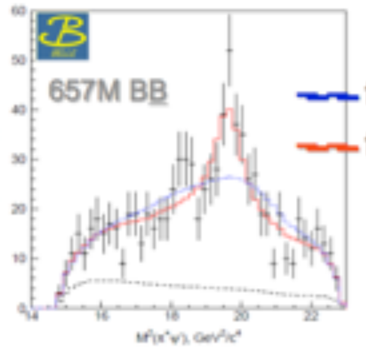
PRL100, 142001 (2008)

- 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



$M^2(K\pi^+)$



$M^2(\psi(2S)\pi^+)$ after K* veto

Significance: 6.4σ

fit for model with K*'s only

fit for model with K*'s and Z

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

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

PRD80, 031104 (2009)

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

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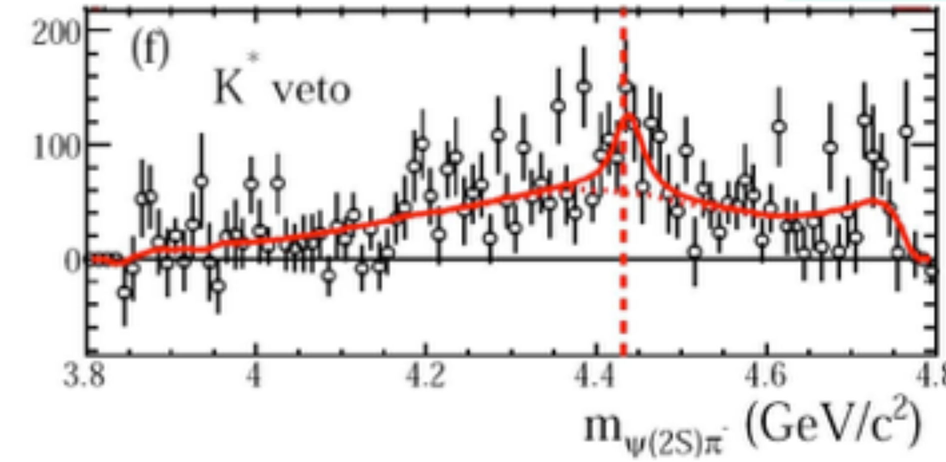
BaBar doesn't see a significant $Z(4430)^+$

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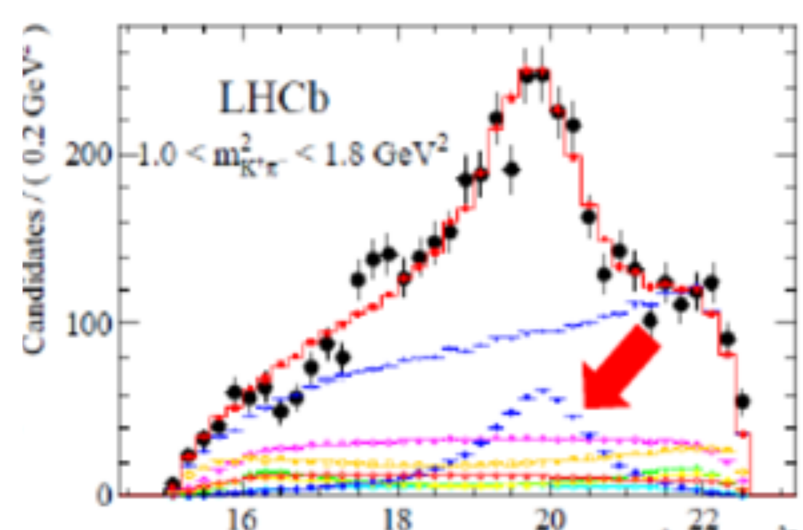
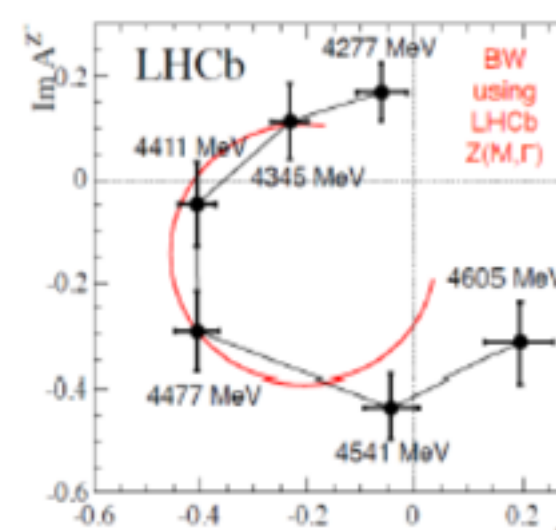
- Babar inserts in the fit all K* resonances
- is Belle effect due to K* reflections ???

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

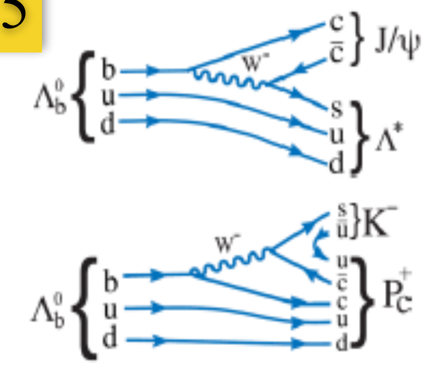
[PRL 112 (2014) 222002]





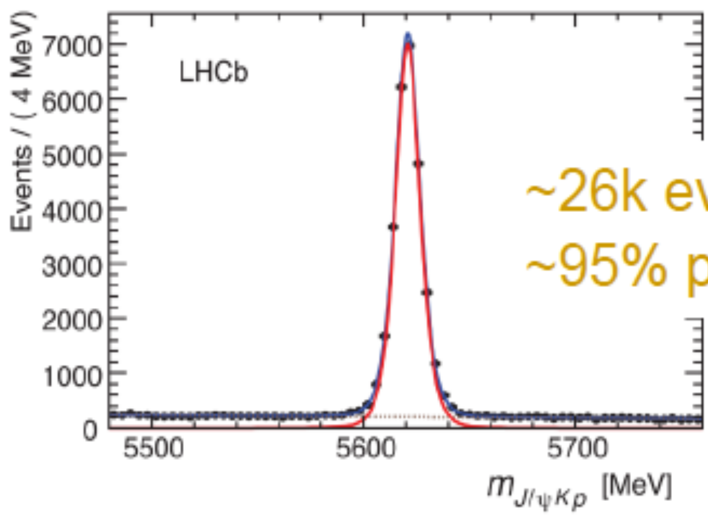
Sergio Bertolucci, Bologna 2015

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



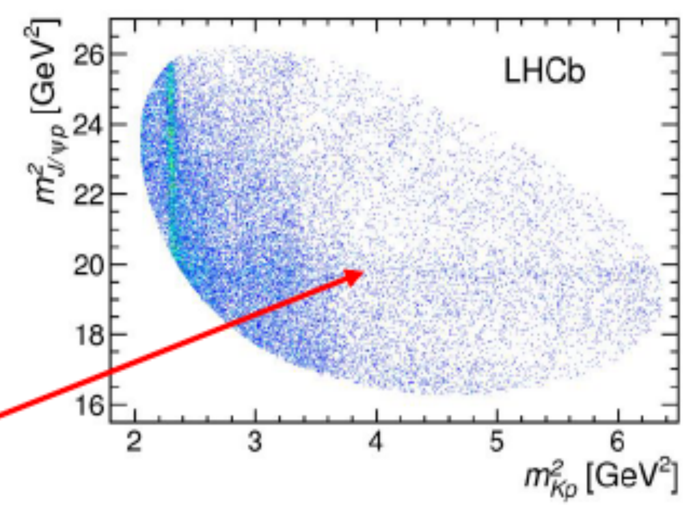
[PRL 115 (2015) 072001]

Large & pure sample of $\Lambda_b \to J/\Psi p K$ decays



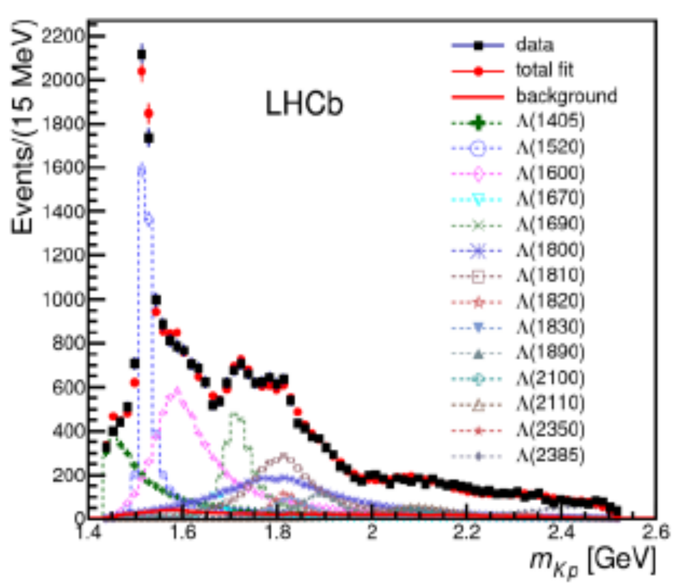
~26k events
~95% purity

Distinctive structure in $J/\Psi p$ spectrum

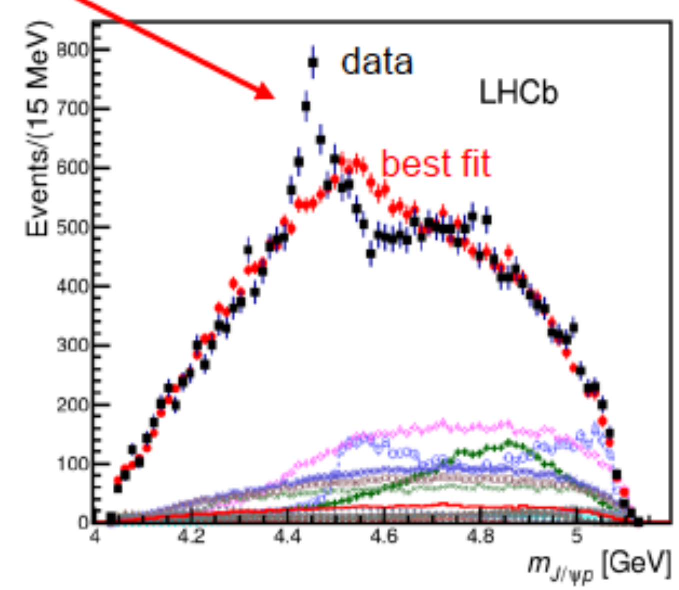


?

Amplitude model of conventional states can reproduce Kp spectrum well enough…



…but cannot describe the J/Ψ projection at all.



14/09/15

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LHCb - SPC, September 2015

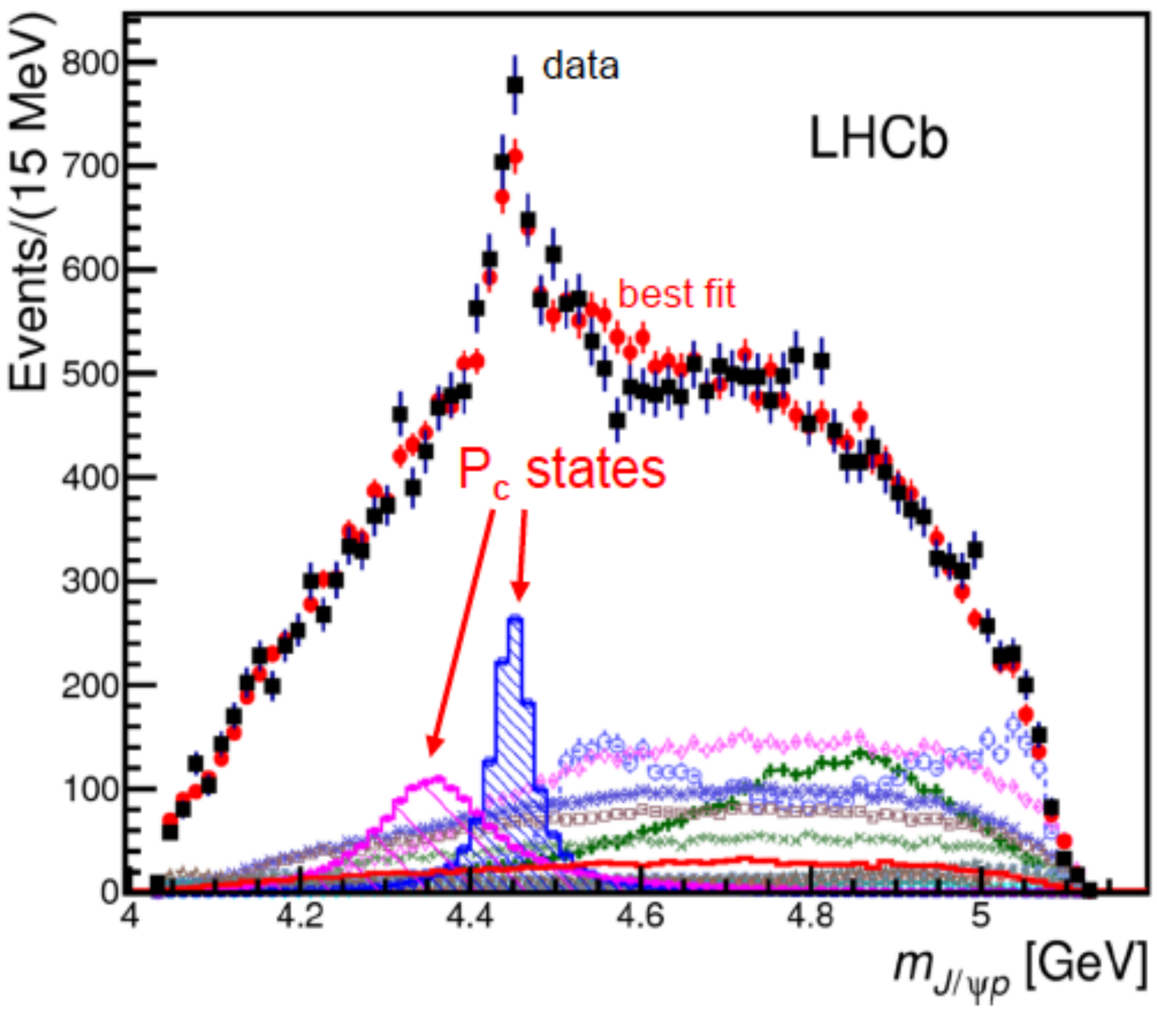
Sergio Bertolucci, Bologna 2015

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

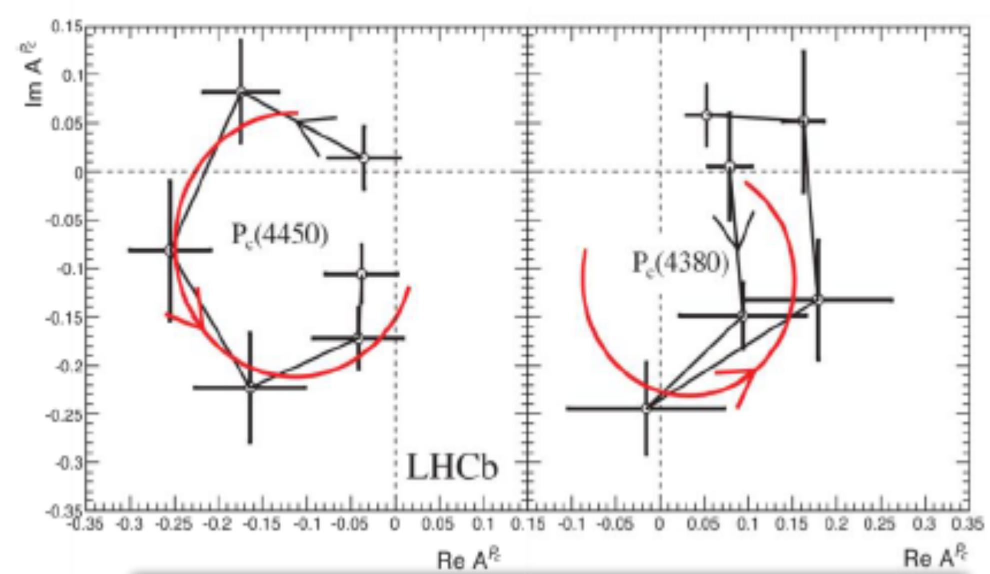
[PRL 115 (2015) 072001]

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.

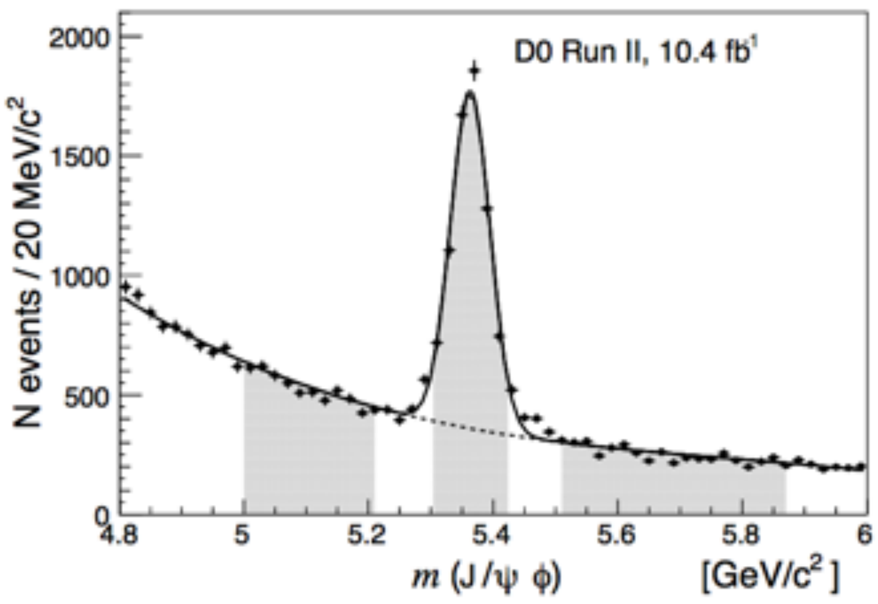


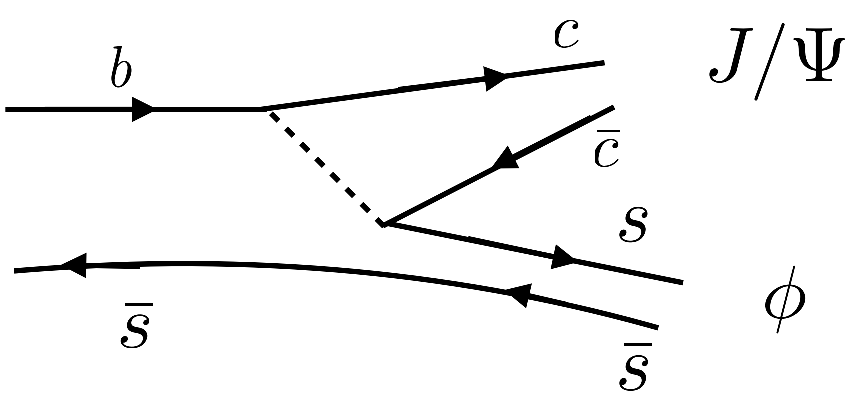
preferred fit
P(4380)=3/2⁻, P(4450)=5/2 ⁺

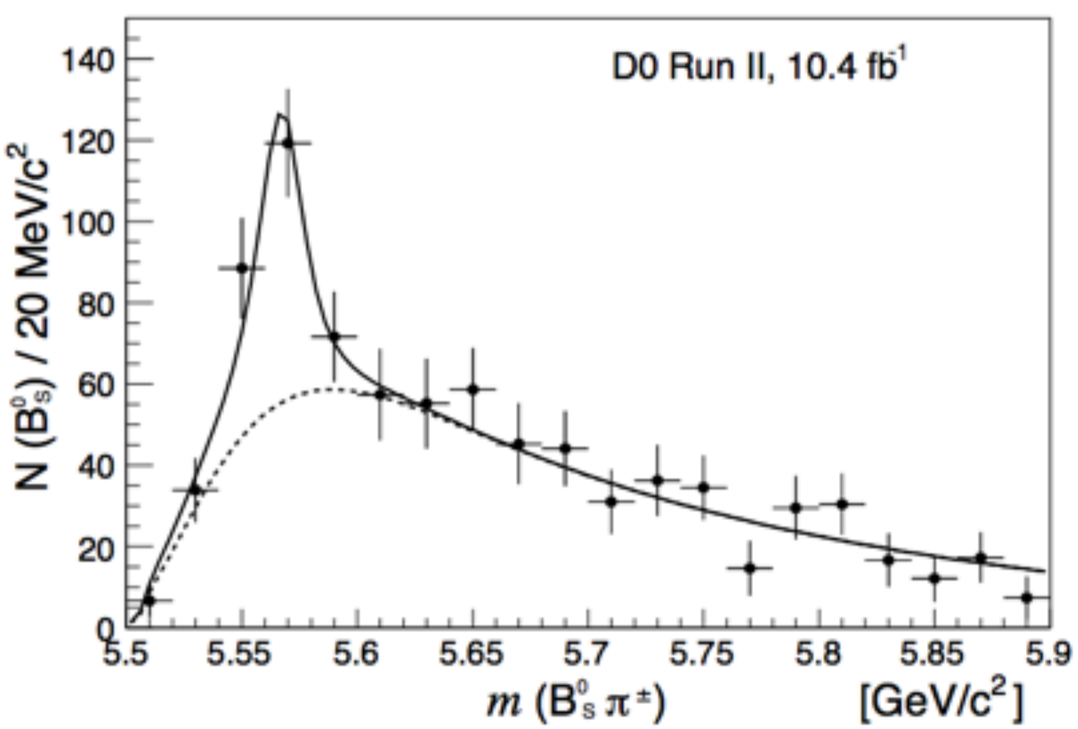
14/09/15 LHCb - SPC, September 2015

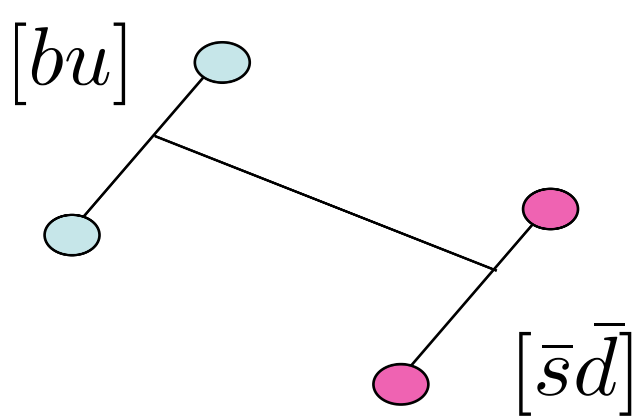
D0 result (2016)

V. M.Abazov *et al*. [D0 Collaboration], *Observation of a new B_s^0 π± state*
Submitted to: Phys.Rev.Lett., [arXiv:1602.07588 [hep-ex]]





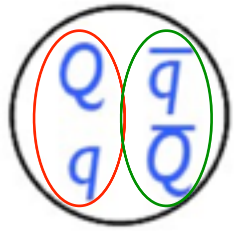




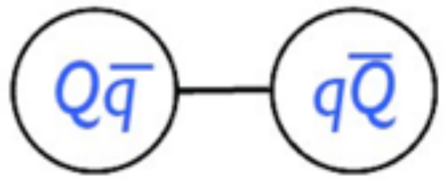
Models for *XYZ* Mesons

Quarkonium Tetraquarks

- compact tetraquark

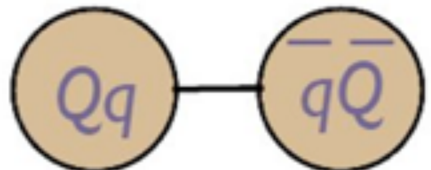


- meson molecule



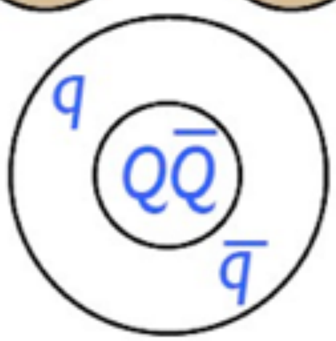
M.Cleven, F.K.Guo, C.Hanhart, Q.Wang and Q.Zhao, arXiv:1505.01771 and refs. therein

- diquark-onium



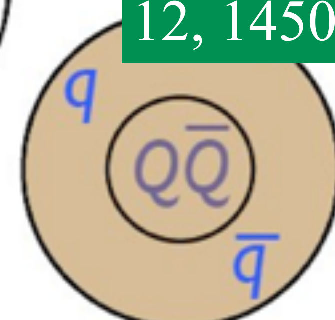
A. Ali, L. Maiani, A. D. Polosa and V. Riquer, Phys. Rev. D **91** (2015) 1, 017502 and refs. therein

- hadro-quarkonium



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

- quarkonium adjoint meson



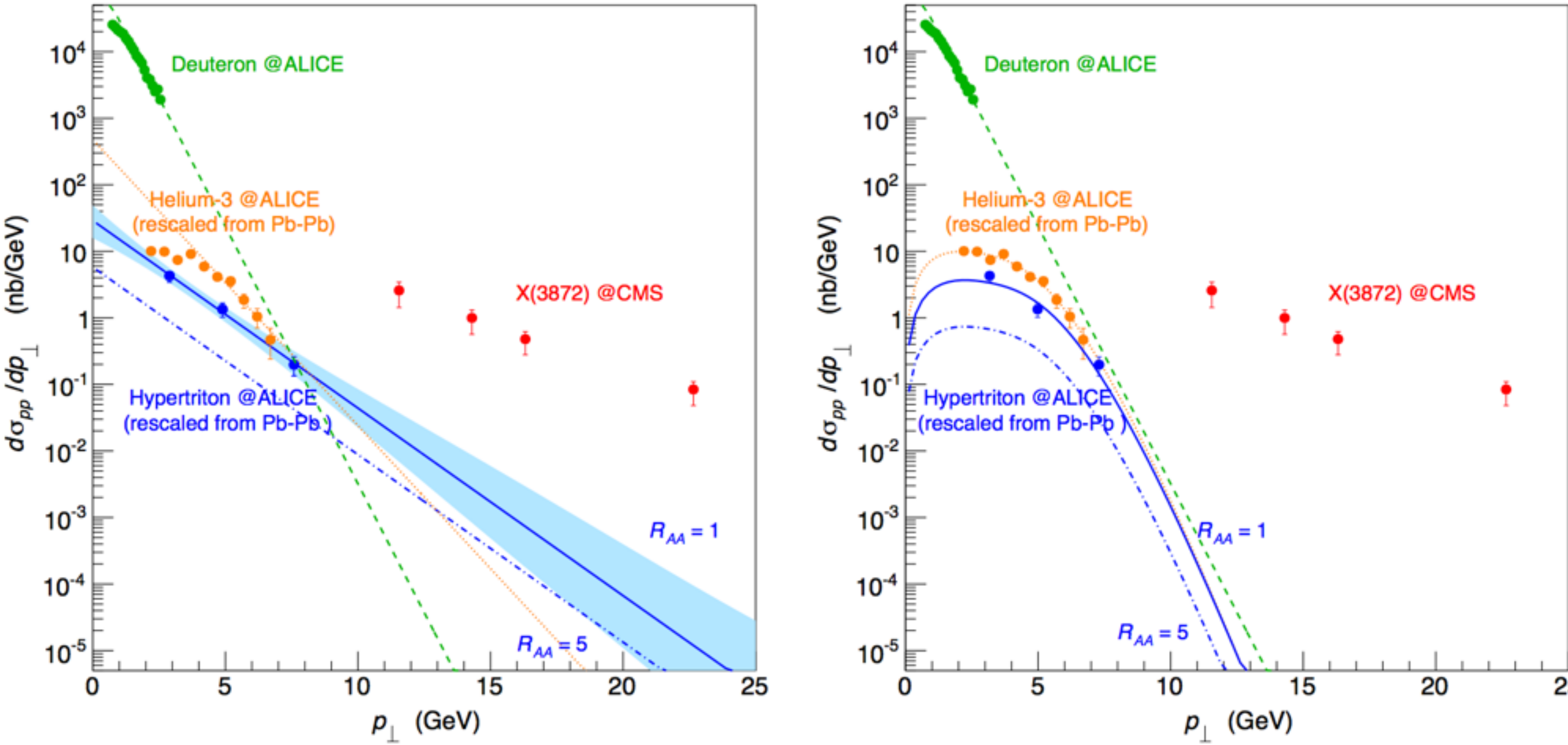
Few think X, Y, Z are only kinematic effects due to the opening of new channels: see E. S. Swanson, *Cusps and Exotic Charmonia*, arXiv:1504.07952 [hep-ph]
However, it takes a lot of unconventional dynamics to produce the X(3872) as a "cusp"
Also, the phase of Z(4430) seems to go at 90^0 at the peak,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

3. Light nuclei (antinuclei) as 'reference candle'

- genuine multi quark hadron states (hadrons that can be described as made by colored subconstituents) or only hadron molecules (hadrons that can be described as made by cold singlets constituents) ?
- Nuclei obviously belong to the second class, being 'made' by color singlet protons and neutrons
- but what about X, Y or Z states?
- 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 the above cases.

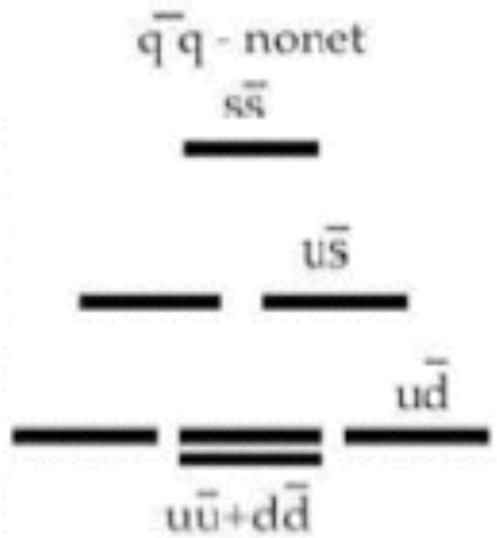
A. Esposito, A. Guerrieri, L. Maiani, F. Piccinini, A. Pilloni, A.Polosa and V. Riquer, Phys. Rev. D **92** (2015) 3, 034028

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)

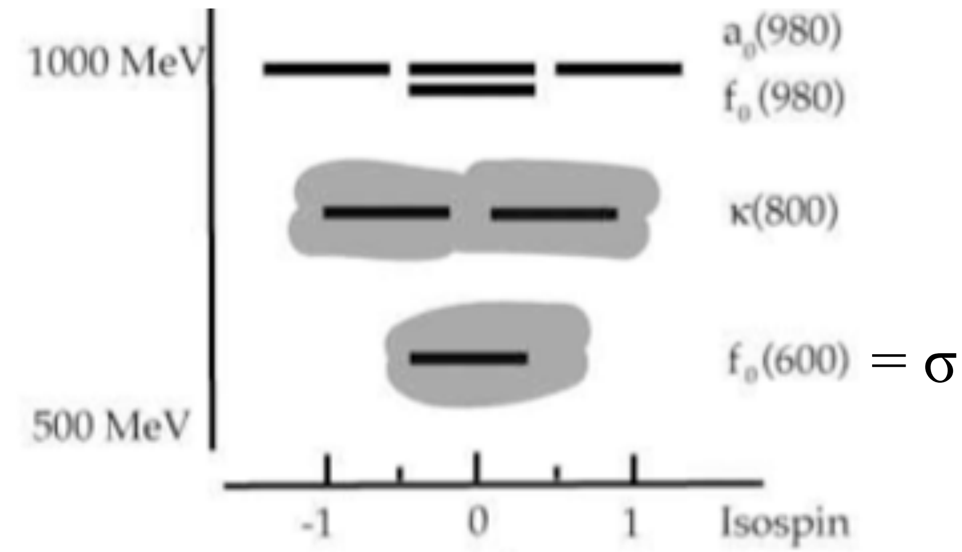


Collective effects in Pb-Pb (e.g.quark-gluon plasma) **enhance nuclear cross sections** and therefore **reduce the cross section rescaled to p-p**.

4. Diquarks and the octet of light scalar mesons

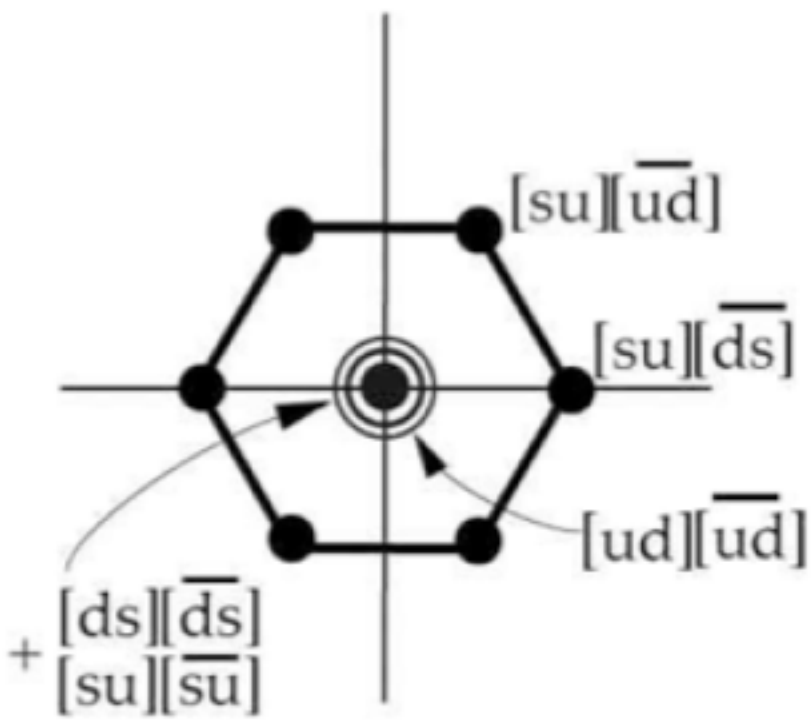


???????

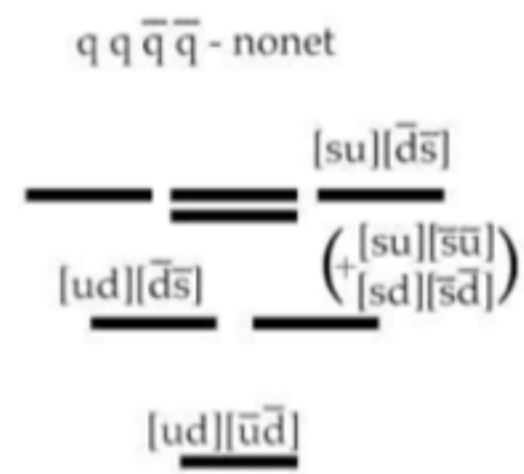


(c)

Antisymmetric tetraquarks work better



(a)



(b)

Diquarks vs molecules

QCD forces are attractive (1 gluon exchange and/or instantons) for diquark [qq']: color = 3bar, SU(3) flavour = 3bar, spin=0, spin-spin force also attractive: *good diquark* (Jaffe, 1977)

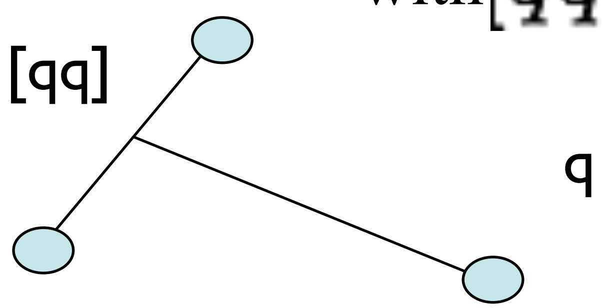
-makes a simple unit to form color singlets (Jaffe & Wilcezck, 2003)

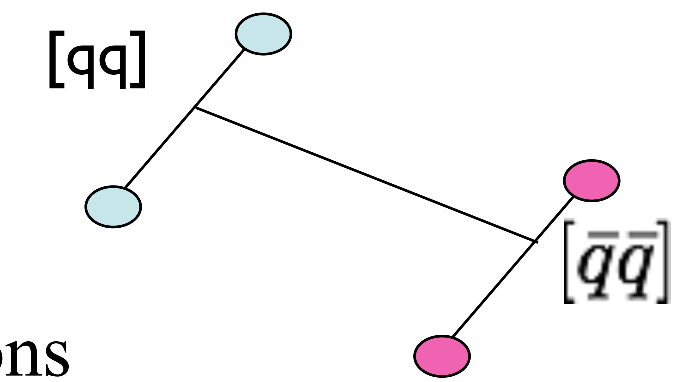
- [cq] may make a stable configuration even for spin 1, *bad diquark,* since spin-spin interactions, repulsive in spin 1, decrease with mass)

Diquark needs 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, 1980)



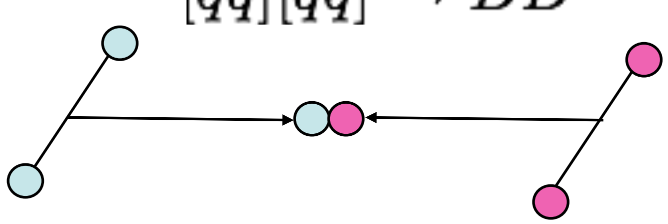


Many states: tetraquarks may have radial and orbital excitations

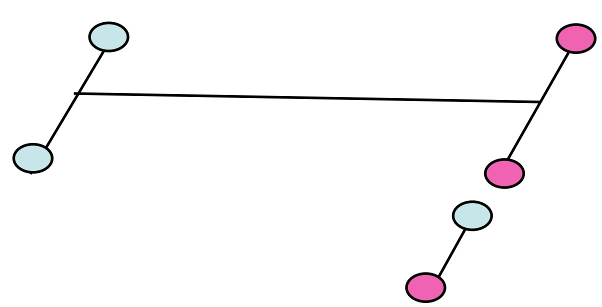
string topology is more related to Baryon-antiBaryon:

if you break the string,

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



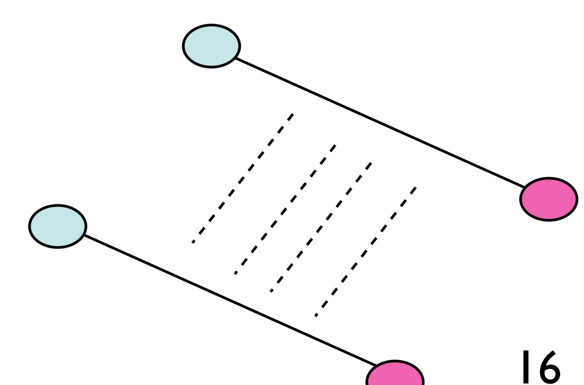
$[qq][\bar{q}\bar{q}] \to [qq][\bar{q}\bar{q}] + \text{meson}$



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

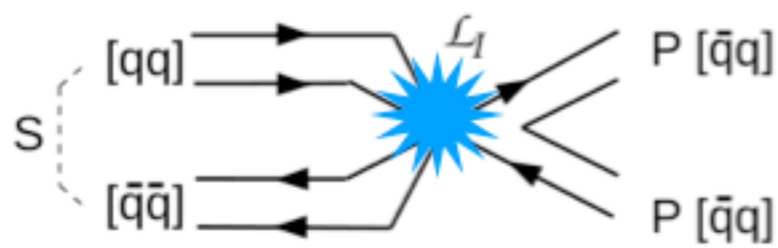
Meson-meson molecules have a different string topology:

- are they bound?
- very few states

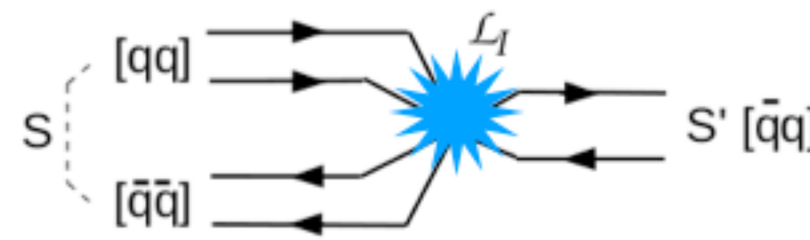


Non-perturbative instantons: may explain two or three further puzzles

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)

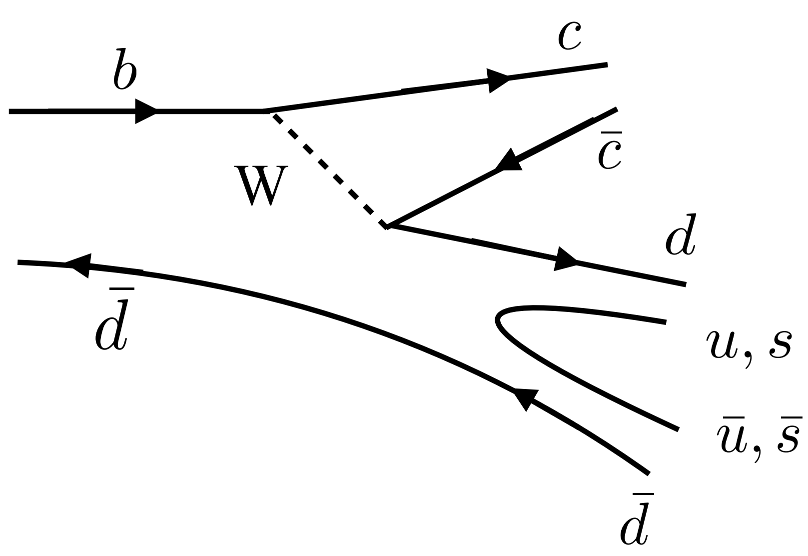


(b)

- (a) the decay $f_0(980) \to 2\pi$ ($f_0 = \dfrac{([su][\bar{s}\bar{u}] + u \to d)}{\sqrt{2}}$)
- (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: $Y(4260) = \dfrac{([cu][\bar{c}\bar{u}] + u \to d)}{\sqrt{2}}$, the u-ubar or d-dbar pair in Y may give rise to the observed decay:

$$Y(4260) \to J/\Psi + f_0(q\bar{q})_{off-shell} \to J/\Psi + f_0([qq][\bar{q}\bar{q}])$$

The decay $B^0 \to \Psi f_0$ v.s. $B^0 \to \Psi \sigma$

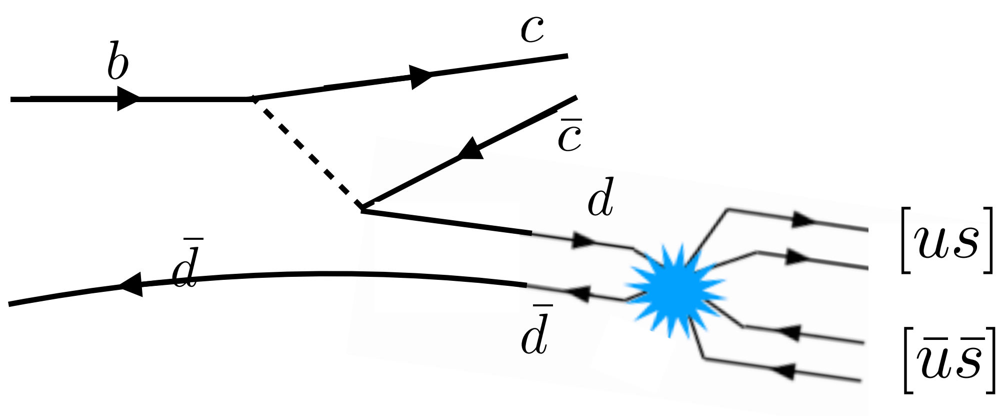


S. Stone and L. Zhang, Phys. Rev. Lett. **111** (2013) 6, 062001

$$M_{vac}(B^0 \to \Psi f_0) = -M_{vac}(B^0 \to \Psi a_0) = \mathcal{A}$$
$$= \frac{1}{\sqrt{2}} M_{vac}(B^0 \to \Psi\sigma)$$

ratio $(\Psi f_0) : (\Psi\sigma)$ (phase space corrected) < 0.2

However, instantons provide another amplitude (A. Polosa, L.M. unpublished):



$$M_{Inst}(B^0 \to \Psi f_0) = -M_{Inst}(B^0 \to \Psi a_0) = \mathcal{B}$$

In total: $$\Gamma(\Psi f_0) + \Gamma(\Psi a_0) \geq \Gamma(\Psi\sigma) \times \frac{phs(\Psi f_0)}{phs(\Psi\sigma)}$$

Suppression of Ψ f_0 mode must be compensated by the Ψ a_0 mode

Can $B^0 \to \Psi\, \eta\pi^0$ or $B^- \to \Psi\, \eta\pi^-$ be seen ?

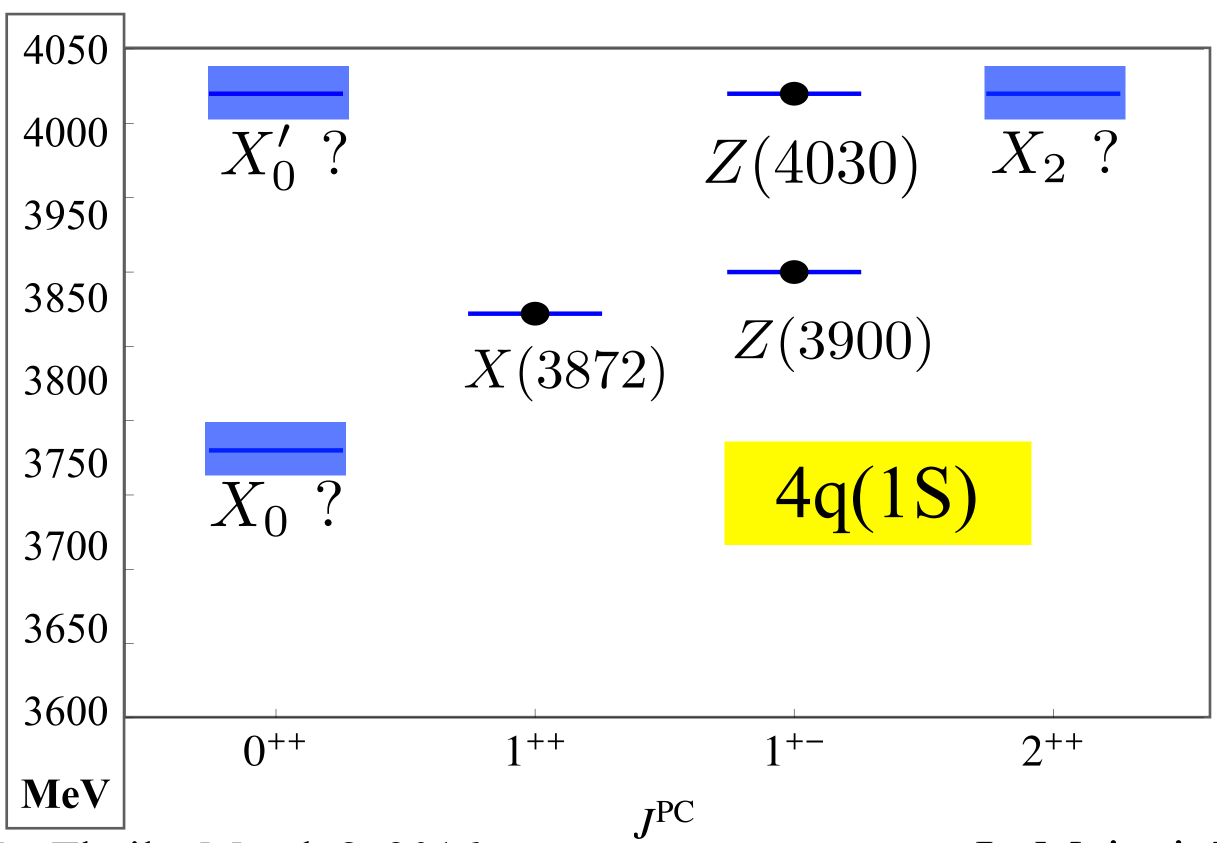
5. Mass spectrum: the new paradigm

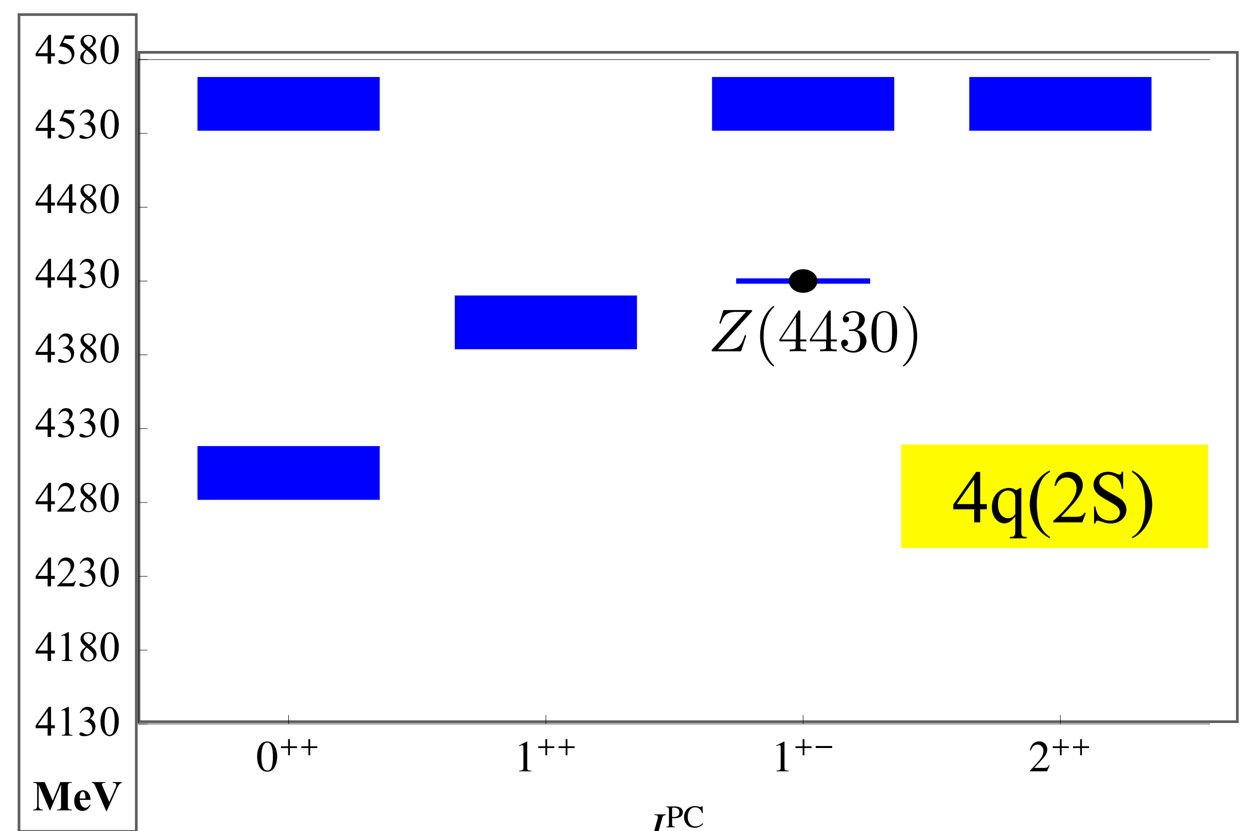
A. Polosa, V. Riquer, F, Piccinini, PRD **89**, 114010 (2014)

- 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 pattern: dominant interactions are those ***between quarks in the same (tightly bound?) diquark*** (or 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 total spin and counts the number of spin=1 diquarks
- one Z is degenerate with X(3872), the other is heavier;
- κ_{qc}~60 MeV from fit (larger than κ_{qc} in baryons).





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 with L=1:

	spin composition:$\|s,\bar{s},S,L>_J$	$P(s_{c\bar{c}}=1)$	$P(s_{c\bar{c}}=0)$	assign.
Y_1	$\|0,0;0,1\rangle_1$	0.75	0.25	$Y(4008)$
Y_2	$\frac{1}{\sqrt{2}}(\|1,0;1,1\rangle_1+\|0,1;1,1\rangle_1)$	1	0	$Y(4260)$
Y_3	$\|1,1;0,1\rangle_1$	0.25	0.75	$Y(4230)$
Y_4	$\|1,1;2,1\rangle_1$	1	0	$Y(4630)$

- The 4 states $Y_{(1\text{-}4)}$ are identified with Y(4008), Y(4260), Y(4220)
- The identical spin structure implied in the model for Y(4260) and X(3872) suggests the decay

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

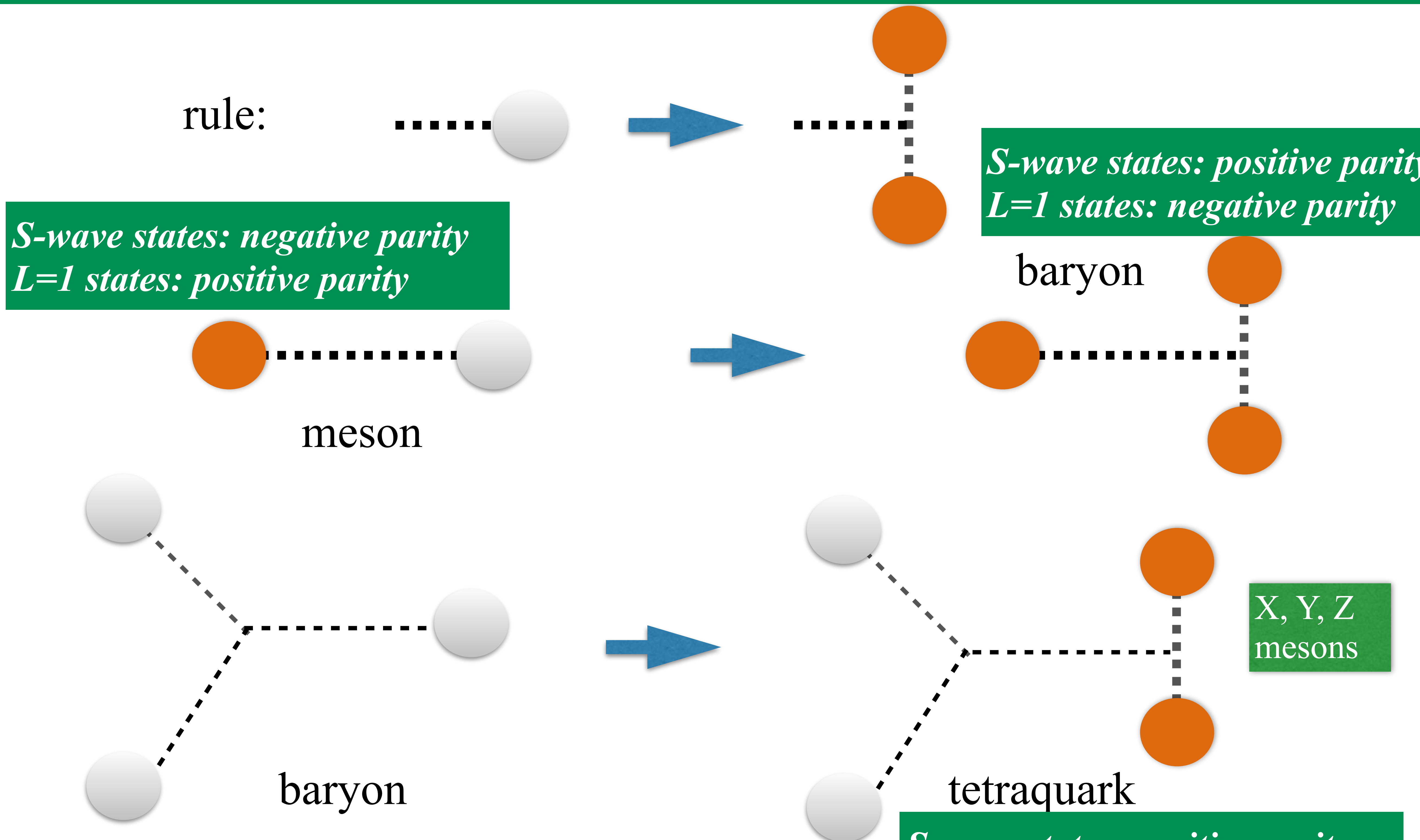
$$Y(4260) \rightarrow X(3872) + \gamma$$

to be an ***unsuppressed E$_1$ transition***, with ΔL=1 and ΔSpin =0, similar to the observed transitions of charmonium χ states.

The D0 tetraquark: what can we say? yet (discussion ongoing between Roma-DESY)

- The decay $Z(5568) \to B_s^0\, \pi^\pm$, if S-wave, implies $J^P=0+$, i.e. a state with $S_{bu}=S_{s\,bar\,d\,bar}=0$
- it could also be $Z(5568+50) \to B_s^{0*}\, \pi \to B_s^0\, \pi\, \gamma$(50 MeV, not seen), i.e. $J^P=1+$
- assume $J^P=0+$; mass can be parametrised in terms of:
  - bu diquark mass and κ_{bu} (b-u spin-spin interaction) both taken from Zb, Zb' masses)
  - $m(a_0)/2$ and the ***unknown*** $\Delta\kappa_{sd}$ (the difference of spin-spin coupling in the sd diquark in the Z(5568) and the same coupling inside the a_0)
  - to reproduce 5568 we need $\Delta\kappa_{sd} \sim 135$ MeV
  - with this, we can predict the mass of the analogous state [cu][s bar d bar] ~ 2160-2170 MeV decaying into $D_s\, \pi^\pm$; it is well below the two states D_s(2317), 0^+, and D_s(2460), 1^+
- It would be interesting to see if there are other states in the decay channel $B_s^{0*}\, \pi$, $J^P=1+$ with $S_{s\,bar\,d\,bar}=1$ ("bad" diquark), some 400 MeV higher ("bad" diquarks exist in baryons)

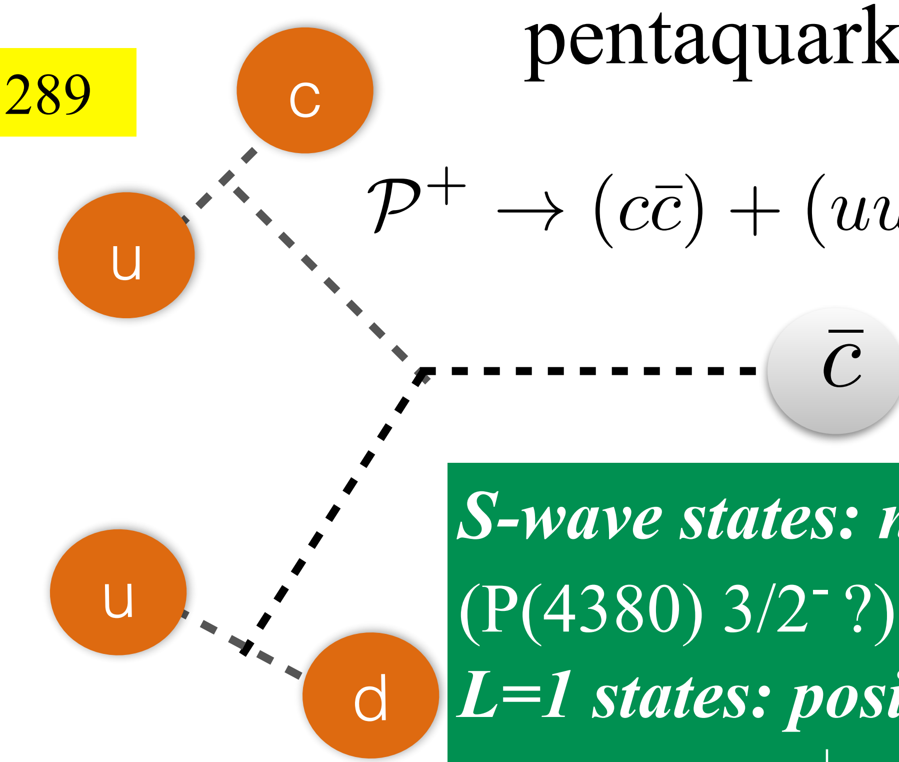
6. Replacing antiquark → diquark makes new objects



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

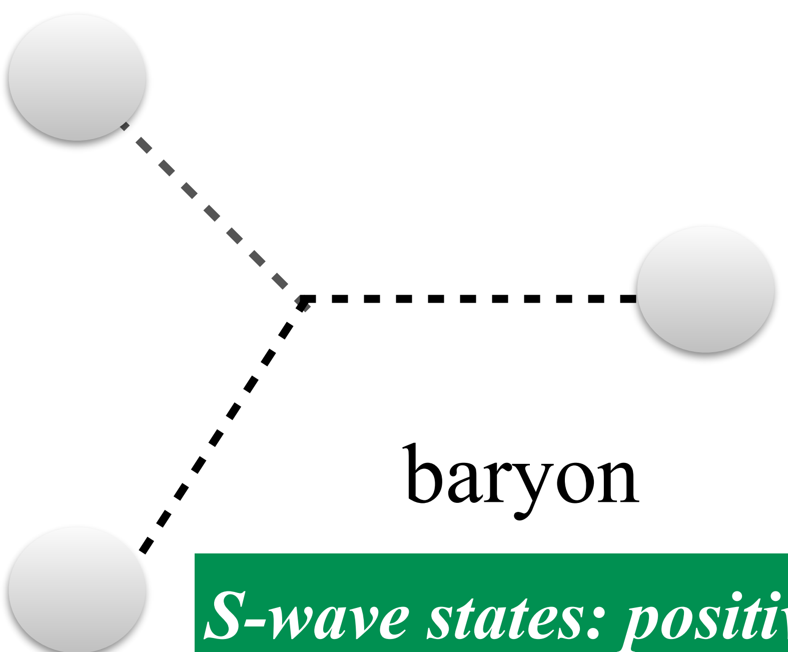
more spectacular results for 2 and 3 substitutions in baryons

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

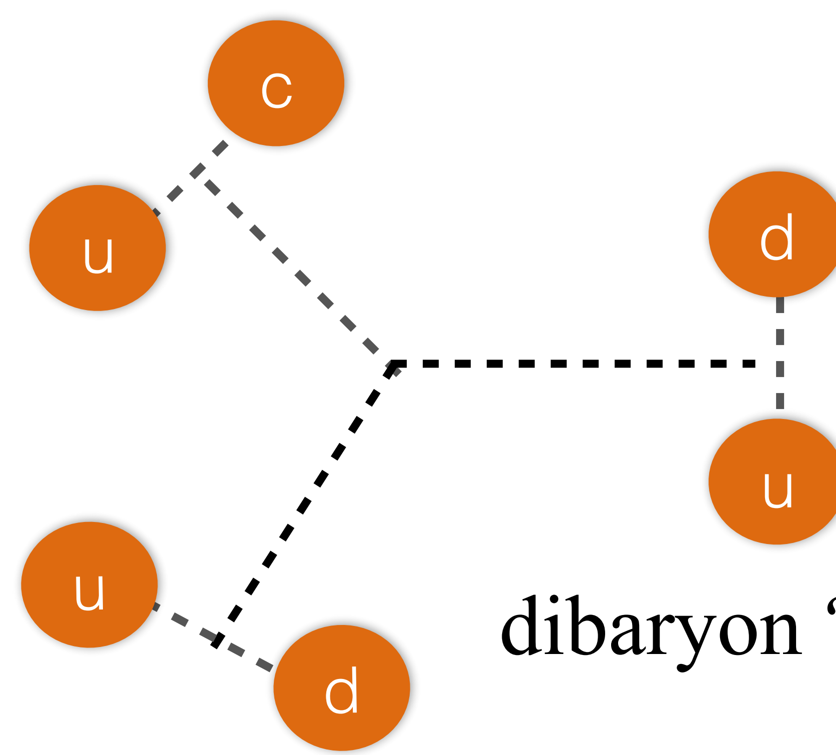


$$\mathcal{P}^+ \to (c\bar{c}) + (uud) = J/\Psi + p$$

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



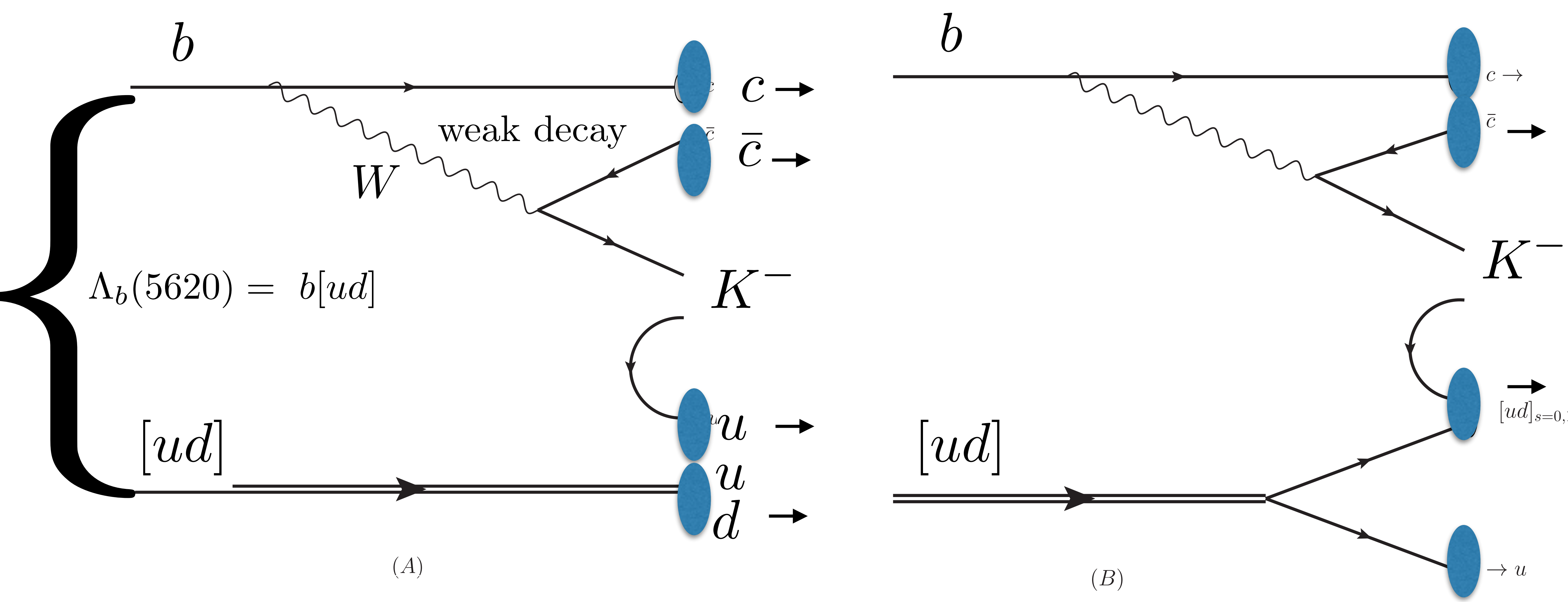
S-wave states: positive parity
L=1 states: negative parity



Two amplitudes for Pentaquark production in the decay of $\Lambda_b(5620)$

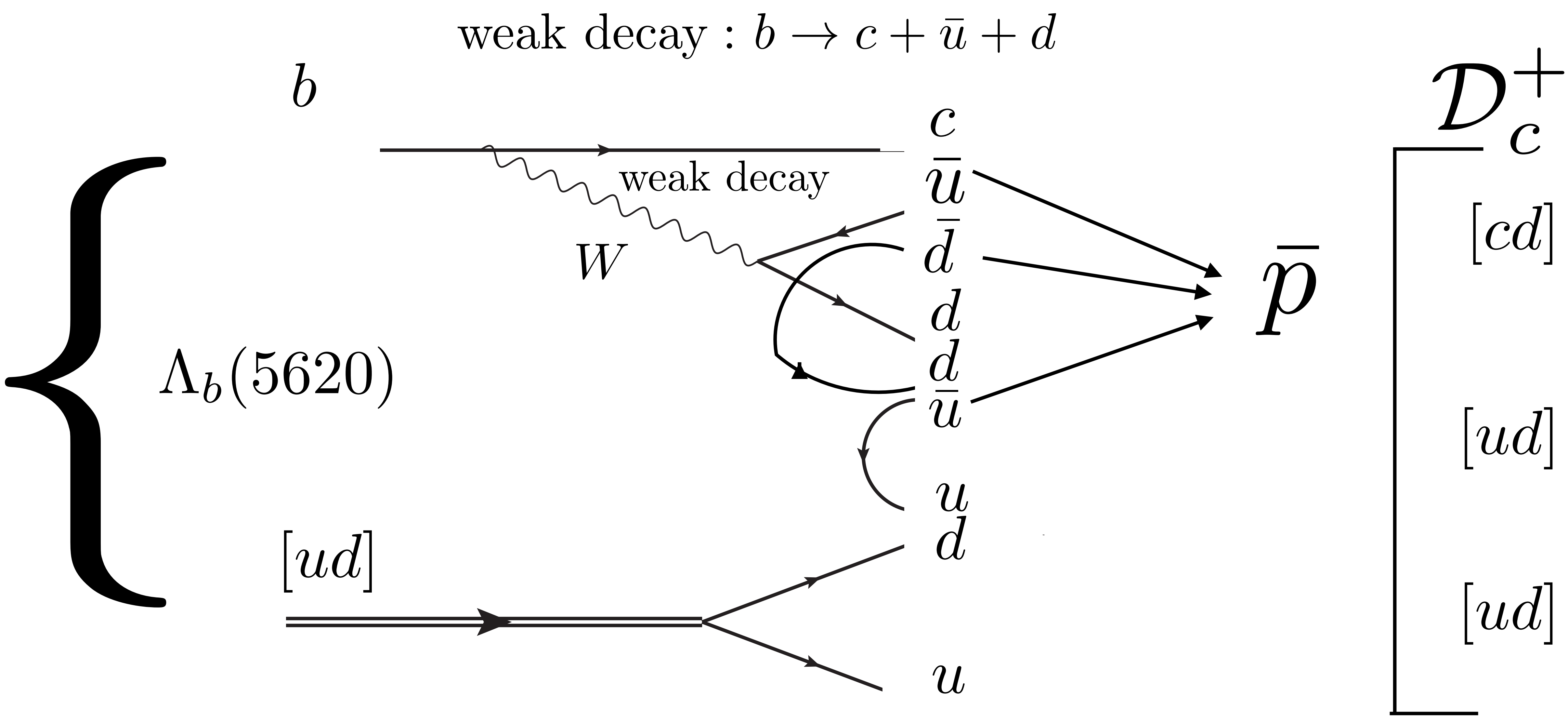
L. Maiani, A. D. Polosa and V. Riquer, *The New Pentaquarks in the Diquark Model,* Phys. Lett. **B 750**, 37 (2015)

$$\text{weak decay}: b \to c + \bar{c} + s$$



$$\longrightarrow \quad \mathcal{P}^+ \text{ constituents} = \bar{c}[cu][ud]$$

Production of hypothetical charmed Dibaryonium in $\Lambda_b(5620)$ decay



$$\Lambda_b(5620) \to \bar{p} + \mathcal{D}_c^+ \qquad M(\mathcal{D}_c^+) < 4682 \text{ MeV}$$

Dibaryon decays

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

- A dibaryon could decay in several different ways
- By string breaking, into baryon+pentaquark, e.g.:

$$\mathcal{D}_c^+ = [cd][ud][ud] \to p + \mathcal{P}_c^0 = p + \bar{u}[cd][ud] \to p + (D^0 + n, \text{ or } \pi^- + \Lambda_c);$$

$$M(\mathcal{D}_c^+) > 3740 \text{ MeV}$$

- By quark rearrangement, into two baryons, e.g.:

$$\mathcal{D}_c^+ \to p + \Sigma_c^0 \to p + \Lambda_c^+ + \pi^-$$

$$M(\mathcal{D}_c^+) > 3390 \text{ MeV}$$

- By beta decay of the c quark ($c \to s(d) + e^+ + \nu_e$), lifetime $\approx 10^{-12}$ s:

$$\mathcal{D}_c^+ \to e^+\nu_e + \Sigma^- + p, \; M(\mathcal{D}_c^+) > 2135$$

$$\mathcal{D}_c^+ \to e^+\nu_e + \Delta^- + p, \; M(\mathcal{D}_c^+) > 2170$$

8. Conclusions

- Coincidence of exotic hadrons with thresholds: less and less evident;
- Diquarks seem to be a useful organising principle, to classify the structure of exotic mesons, pentaquark and yet to be discovered 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 we could complete a second layer of hadron spectroscopy, following the Gell-Mann Zweig layer and completing the saturation possibilities of one and three QCD strings;
- until now, exotics seen 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,
- we look forward to exciting times for hadron spectroscopy: maybe we can understand QCD better.