Exotic States

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Lecce

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Hidden charm and beauty hadrons reveal *tetraquarks* and *pentaquarks*

•Heavy quark pairs are difficult to be created or destroyed by QCD forces inside hadrons.

•Hadrons with a $c\bar{c}$ or $b\bar{b}$ pair ***and*** electrically charged ***must*** contain additional light quarks, ***realising the hypothesis advanced by Gell-Mann in the Sixties***

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

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. It is assuming that the lowest

•These are the exotic X, Y, Z mesons and the pentaquarks discovered over the last decade

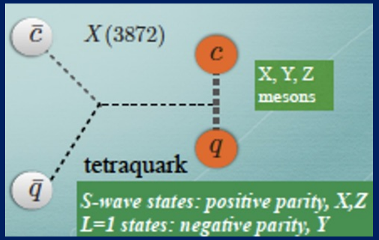
There are indeed new valence quark configurations !!

- Tetraquarks are more easy to find at the increase of the quark mass, just as pentaquarks

The presence of heavy quarks appears to increase the possibility of binding

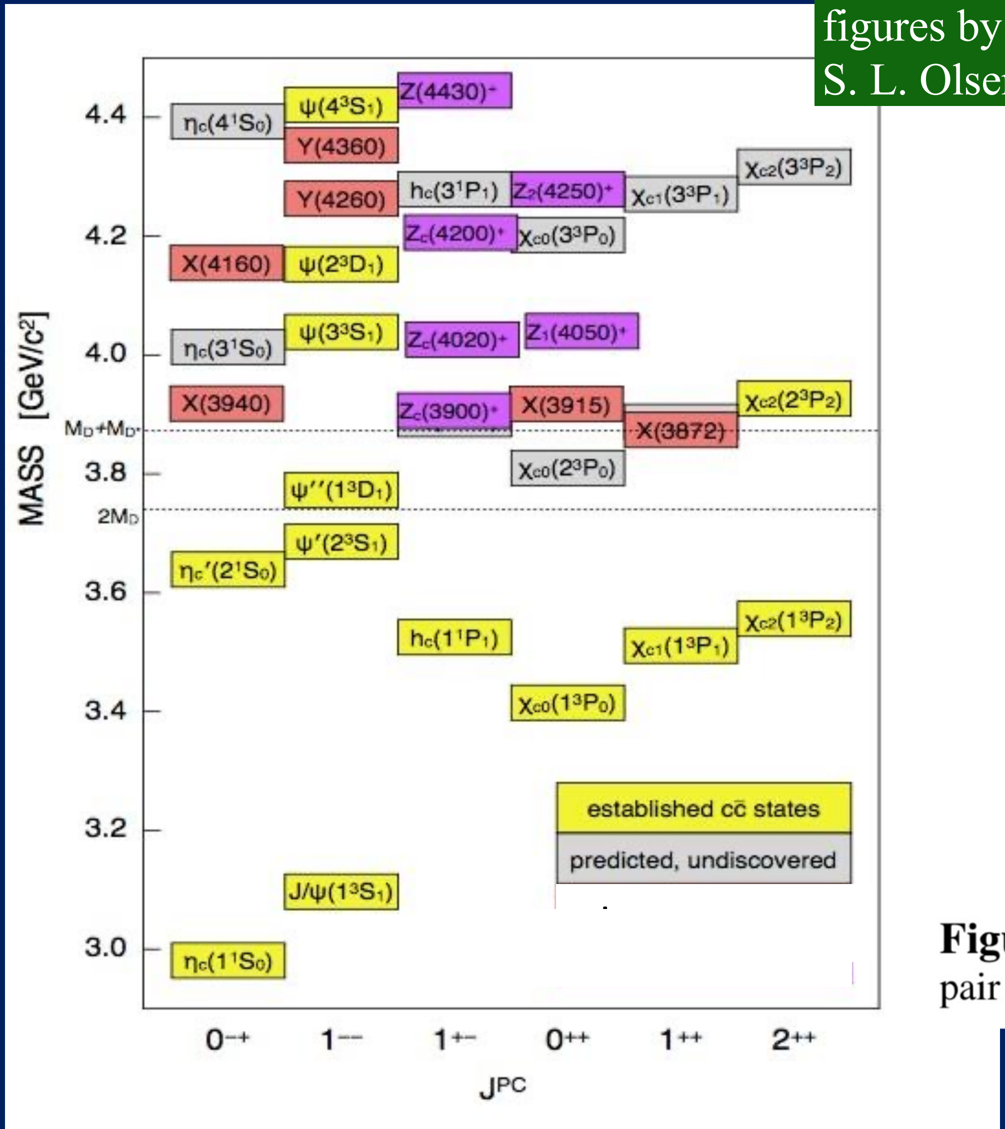
- Hidden heavy flavors have been the first, now we also have the LHCb open heavy flavor $X_0(2900)$ $J^P=0^+$ and $X_1(2900)$ $J^P=1^-$ in the D+ K- channel ($\bar{c}\bar{s}ud$ or D* K* molecule ?)
- First *unexpected charmonium* is the still controversial X(3872) (discovered by Belle 2003)
- Nearness to heavy pair threshold is to be expected, but the X(3872) is exceptionally close, we do not know yet if it is above or below the D0 D0* threshold, within some 80 keV.

Still controversial because very close to the threshold



Expected and Unexpected Charmonia

figures by:
S. L. Olsen, arXiv:1511.01589, arXiv:1812.10947,



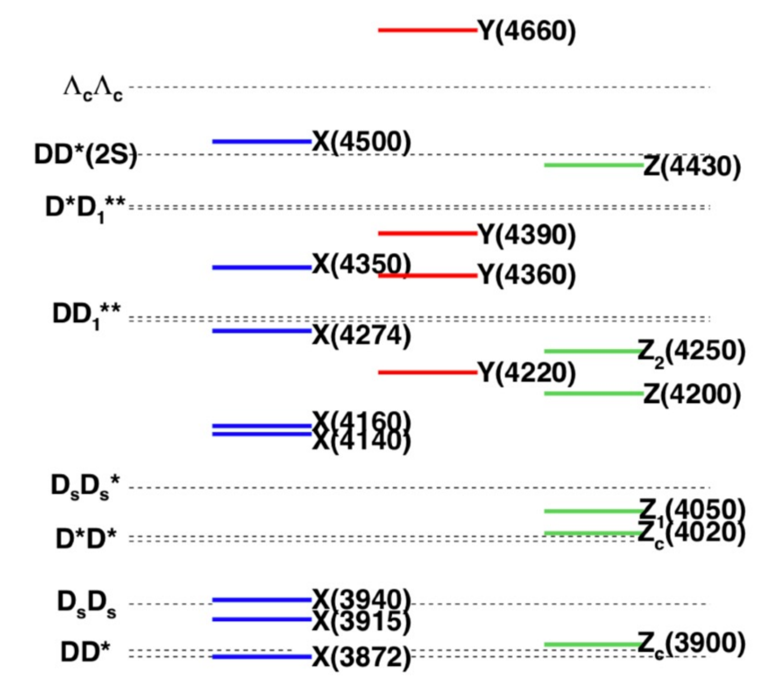
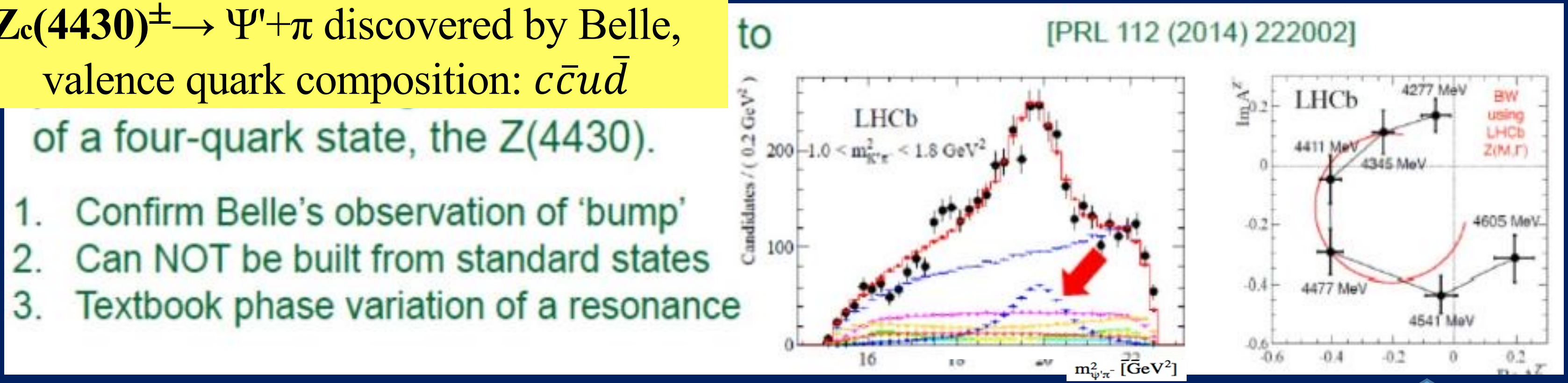


Figure 4. *XYZ* meson masses compared with charmed meson pair thresholds.

Explicit Tetraquarks:

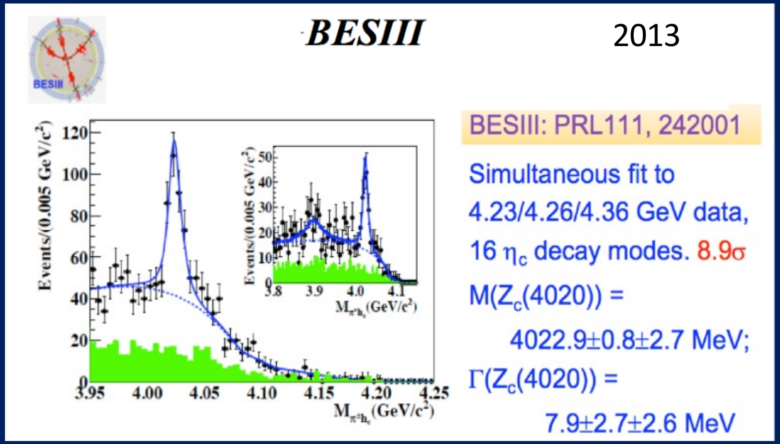
$Z_c(4430)^{\pm}$ 13.9 σ

$Z_c(4430)^{\pm}$ $\rightarrow \Psi' + \pi$ discovered by Belle,
valence quark composition: $c\bar{c}u\bar{d}$



"Observation of the resonant character of the $Z(4430)^{-}$ state".LHCb, *Physical Review Letters*. **112** (22): 222002(2014).

Argand diagram of Z(4430) is consistent with this structure being a resonance



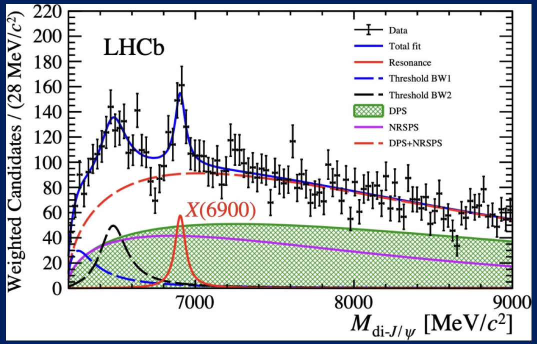
$Z_c(4020)^{\pm} \rightarrow h_c + \pi$

$Z_c(4020)^{\pm}$. 8.9σ

Recent reports of Exotic hadrons!

▷$X(6900)$ ($cc\bar{c}\bar{c}$)

Science Bulletin 65 (2020) 1983



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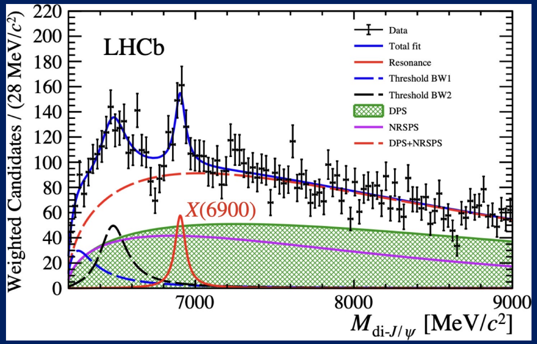
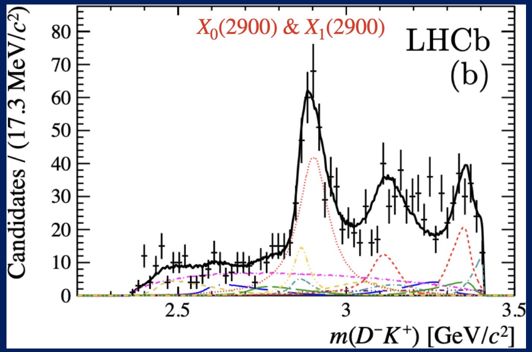
Science Bulletin 65 (2020) 1983



▷ $X_{0,1}(2900)$ $(\bar{c}\bar{s}ud)$

LHCb, PRL125, 242001 (2020), Phys. Rev. D 102, 112003 (2020)



3.9 standard deviation statistical significance

Amplitude analysis of $B^+ \to D^+ D^- K^+$

$X_{0,1}$ observed in $D^- K^+$ channel

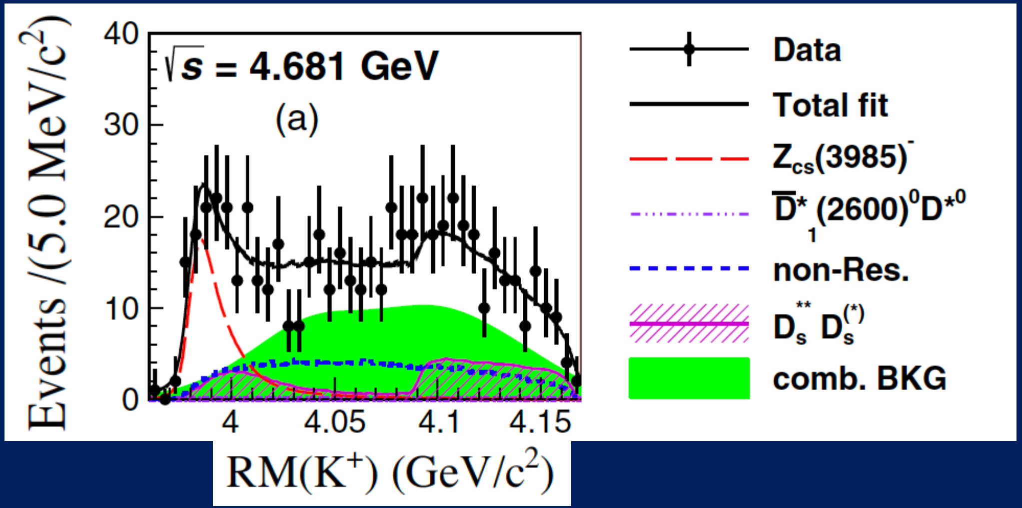
$$X_0(2900): \ M = 2.866 \pm 0.007 \pm 0.002 \ \mathrm{GeV}/c^2,$$
$$\Gamma = 57 \pm 12 \pm 4 \ \mathrm{MeV},$$
$$X_1(2900): \ M = 2.904 \pm 0.005 \pm 0.001 \ \mathrm{GeV}/c^2,$$
$$\Gamma = 110 \pm 11 \pm 4 \ \mathrm{MeV},$$

$Z_{cs}(3985)^-$ ($c\bar{c}s\bar{u}$) (BESIII, Phys. Rev. Lett. 126, 102001 (2021)) (5.3 statistical significance)

Mass and width are respectively

$(3982.5^{+1.8}_{-2.6} \pm 2.1)$ MeV$/c^2$ and $(12.8^{+5.3}_{-4.4} \pm 3.0)$ MeV

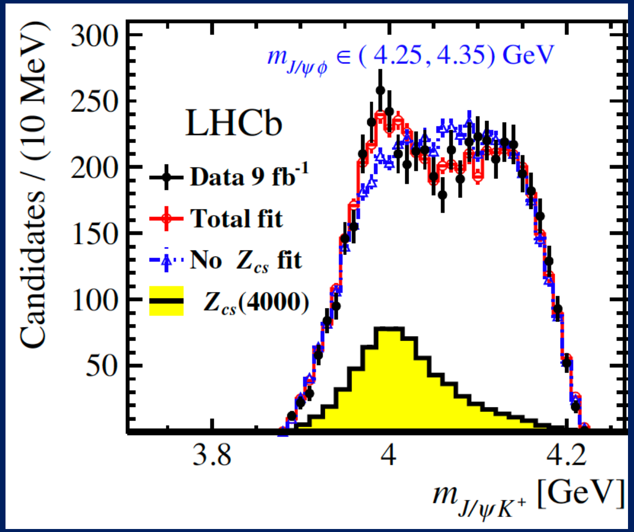
$$e^+e^- \to (Z_{cs}(3985)^-)K^+ \to (D_s^- D^{*0} + D_s^{-*} D^0)K^+$$



$Z_{cs}(4003)^+$ ($c\bar{c}u\bar{s}$) (LHCb, Phys. Rev. Lett. 127, 082001 (2021) (15 statistical significance)

$4003 \pm 6^{+4}_{-14}$ MeV, a width of $131 \pm 15 \pm 26$ MeV

$$B^+ \to (Z_{cs}^+(4003))\phi \to \ (J/\Psi K^+)\ \phi$$



Discovery of the doubly charmed T_{cc}^{+} in $D^0D^0\pi^+$ invariant mass distribution with a 22 standard deviations arXiv:2109.01038 (Nature Physics 2022) and arXiv:2109.01056 (Nature Physics Communication 2022).

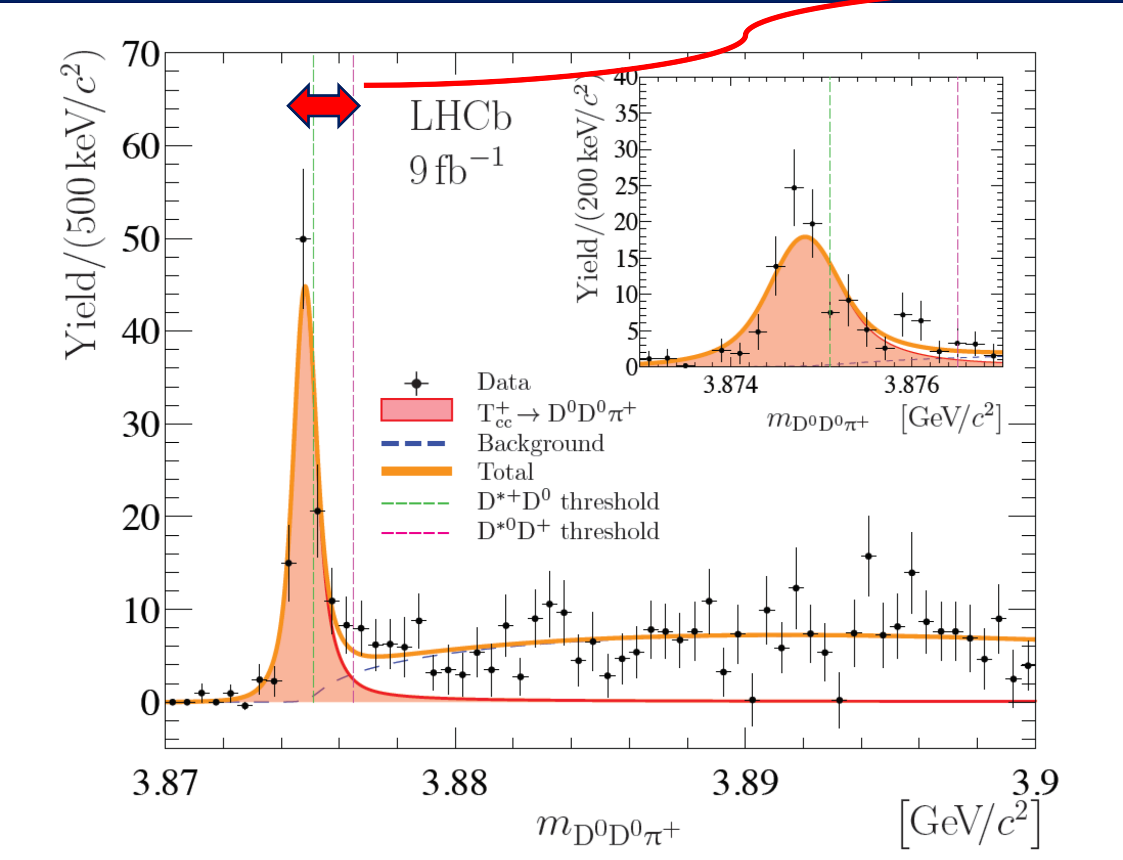
The minimal quark content for this newly observed state is $cc\bar{u}\bar{d}$

Mass and width

$$M \simeq 3875 \quad \text{MeV}$$
$$\Gamma \simeq 0.410 \quad \text{MeV}$$

'This is the narrowest exotic state observed to date'

'Moreover, a combination of the near-threshold mass, narrow decay width and its appearance in prompt hadroproduction show its genuine resonance nature. This is the first such exotic resonance ever observed.' (arXiv:2109.01038)



- Found to be below the $D^{*+}D^0$ threshold (with 4.3σ significance for "*below $D^{*+}D^0$*")

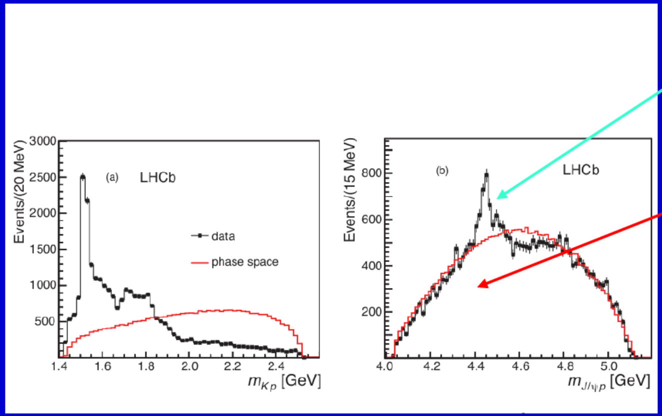
$D^{*+}D^0$ threshold is at 3875.1 MeV

More new valence quark configurations

$$\Lambda_b \to K^- + J/\psi + P$$

LHCb

Phys. Rev. Lett.115(2015) 072001



M $\_P_c^+(4450)$ = (4449.8 ± 8 ± 29)MeV

Γ = (39 ± 5 ± 19) MeV

M$_P_c^+(4380)$ = (4380 ± 1.7 ± 2.5)MeV

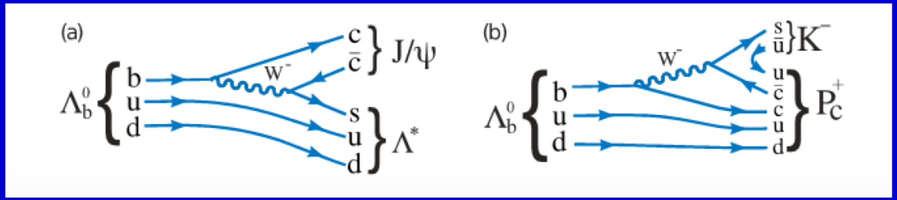
Γ =(205±18±86)MeV

statistic significance greater then 9 sigma !

P_c $(uudc\bar{c})$

$$\Lambda_b^0 \longrightarrow J/\psi + \Lambda^*, \Lambda^* \longrightarrow K^- + p$$

$$\Lambda_b^0 \longrightarrow P^{0+} + K^-, P^{0+} \longrightarrow J/\Psi + p$$



The LHCb observation [1] was further supported by another two articles by the same group [2,3]:

[1] R. Aaij *et al.* [LHCb Collaboration], Phys. Rev. Lett. **115** (2015) 072001

[2] R. Aaij *et al.* [LHCb Collaboration], Phys. Rev. Lett. **117** (2016) no.8, 082002

[3] R. Aaij *et al.* [LHCb Collaboration], Phys. Rev. Lett. **117** (2016) no.8, 082003

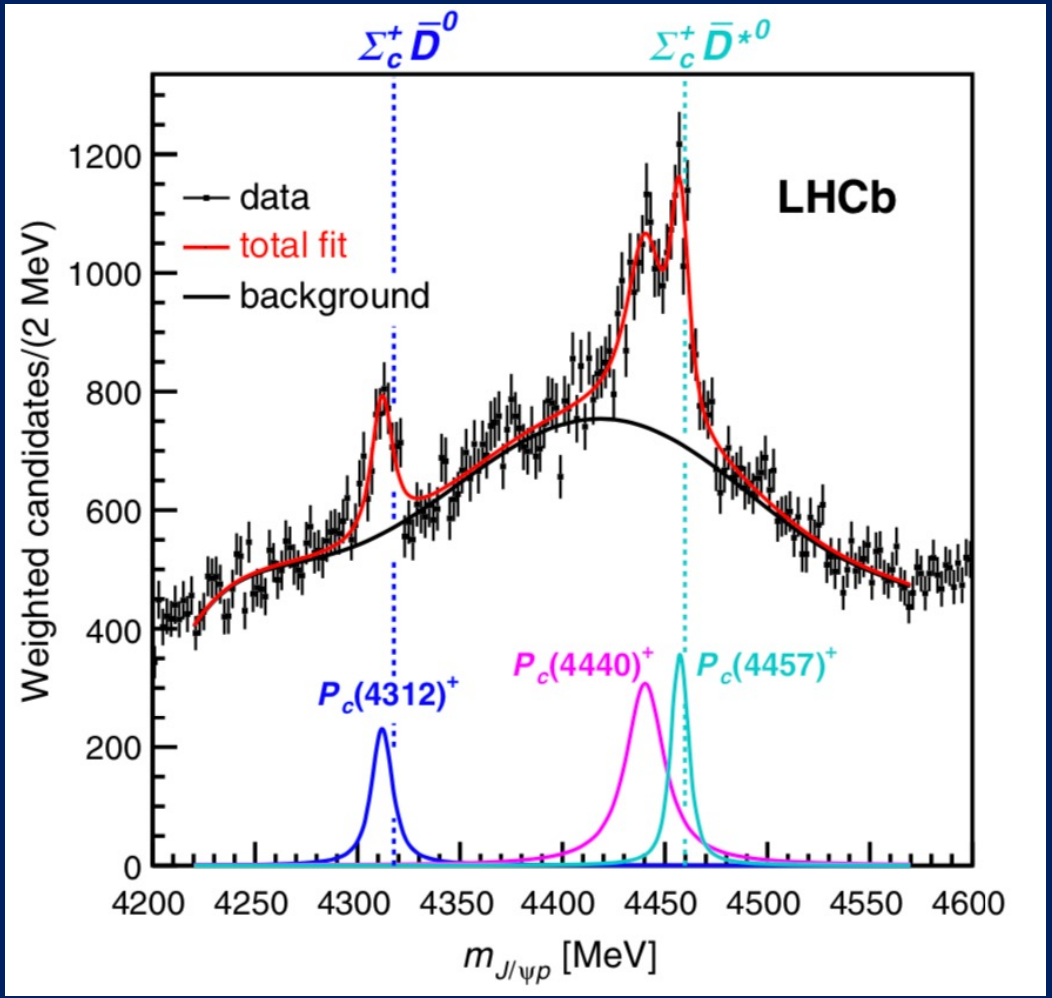
Why pentaquark states?

As well as revealing the new $P_c(4312)$ state with 7.3 sigma statistical significance, the LHCb 2019 analysis also uncovered a more complex structure of $P_c(4450)$, consisting of two narrow nearby separate peaks, $P_c(4440)$ and $P_c(4457)$ with the two-peak structure hypothesis having a statistical significance of 5.4 sigma with respect to the single-peak structure hypothesis.
The masses and widths of the three narrow pentaquark states are as follows

State	M [MeV]	Γ [MeV]
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+3.7}_{-4.5}$
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+8.7}_{-10.1}$
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+5.7}_{-1.9}$

[*] R. Aaij et al. (LHCb), Phys. Rev. Lett. 122, 222001 (2019).

$\Lambda_b^0 \to J/\Psi p K^-$ channel ($P_c \to J/\Psi\, p$)

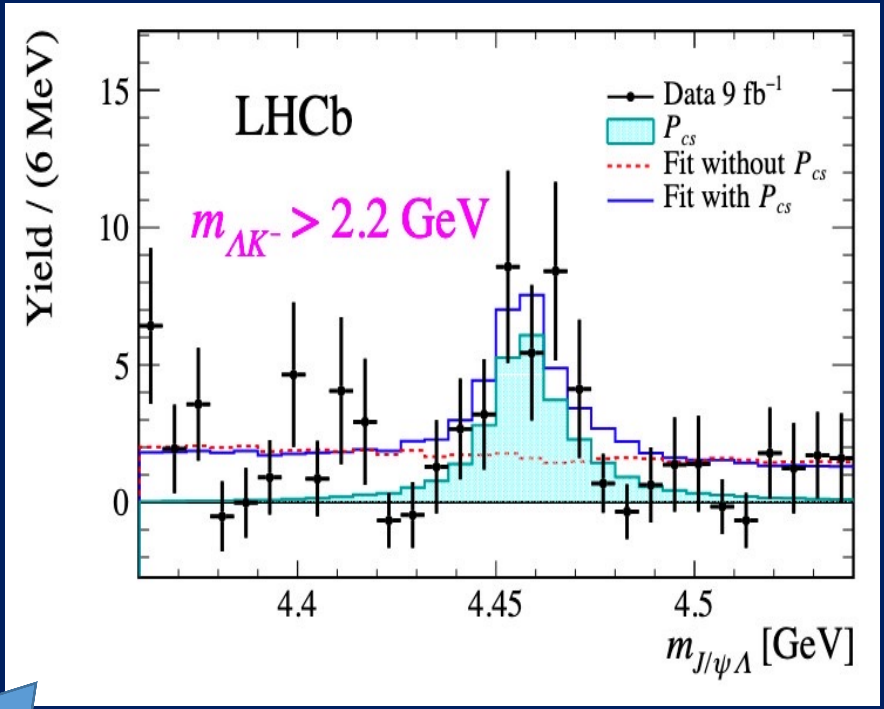


Number of events versus J/Psi p invariant mass [*]. The mass thresholds for the $\Sigma_c\, \bar{D}$ and $\Sigma_c\, \bar{D}^*$ final states are superimposed.

2021

P_{cs} ($\boldsymbol{udsc\bar{c}}$)

(2021) LHCb, *Sci.Bull.* 66 (2021) 1278-1287



$\Lambda_b^0 \to J/\Psi\Lambda K^-$ channel ($P_{cs} \to J/\Psi\ \Lambda$)

Significance of **P_{cs}^0(4459)** exceeds 3 σ after considering all the systematic uncertainties.

Mass of $P_{cs}(4459)^0$ 19 MeV below the $\Xi_c^0\bar{D}^{*0}$ threshold, similar to $P_c(4440)^+$ and $P_c(4457)^+$ pentaquark states.

August 2021

Evidence for a new structure in the $J/\psi p$ and $J/\psi\bar{p}$ systems in $B_s^0 \to J/\psi p\bar{p}$ decays

arXiv:2108.04720v1 [hep-ex] 10 Aug 2021

$$B_s^0 \to (P_c^+)\bar{p} \to (J/\Psi p)\bar{p}$$
$$\bar{B}_s^0 \to (P_c^-)p \to (J/\Psi\bar{p})\, p$$

$$M_{P_c} = 4337\ ^{+7}_{-4}\ ^{+2}_{-2}\ \text{MeV},$$
$$\Gamma_{P_c} = 29\ ^{+26}_{-12}\ ^{+14}_{-14}\ \text{MeV},$$

The $P_c(4437)$ statistical significance is in the range of 3.1 to 3.7 depending on the assigned J^P hypothesis:

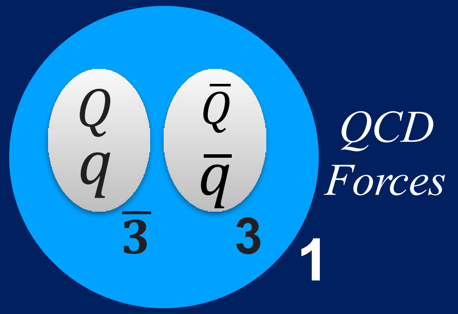
3.1 sigma for $J^P = \frac{1}{2}^+$

3.7 sigma for $J^P = \frac{3}{2}^+$

No consensus, yet

Hadronic Molecule

F-K. Guo, C. Hanhart, Christoph, U-G Meißner, Q. Wang, Q. Zhao, and B-S Zou, arXiv 1705.00141 (2017)



Compact Diquark-Antidiquark

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

Anwar,Ferretti nnd Santopinto, PRD98,0940015(2018)

For pentaquarks

Nuclear Forces

Hadronic Molecule?

$(\bar{D}\Sigma_c^*,\ \bar{D}^*\Sigma_c, \ldots)$

JaJun Wu,R. Molina, E. Oset,B. S.Zou,PRC84(2011)015202

QCD Forces

Compact pentaquark

$(5q)$

L. Maiani, D. Polosa and V. Riquer, Phys. Lett. Maiani, **B 749** (2015) 298.

E. Santopinto, A. Giachino, **Phys. Rev. D96** (2017) 014014

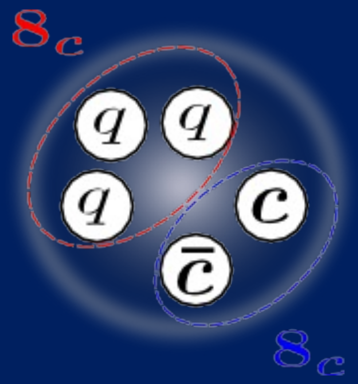
Nuclear Forces + *QCD Forces*

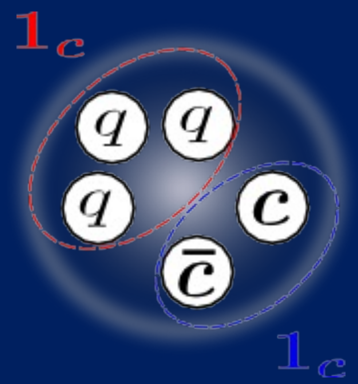
Baryon-meson molecule with 5-quark core

Y. Yamaguchi, A. Giachino, A. Hosaka, E. Santopinto, S. Takeuchi and M. Takizawa, Phys. Rev. D 96, no. 11, 114031 (2017).
Y. Yamaguchi, H. Garca-Tecocoatzi, A. Giachino, A. Hosaka, E. Santopinto, S. Takeuchi and M. Takizawa, Phys. Rev. D 101 (2020) no.9, 091502

Compact 5q state

- E. Santopinto, A. Giachino, **Phys. Rev. D96** (2017) 014014.
  P_c states by an algebraic model
- 5-quark configurations





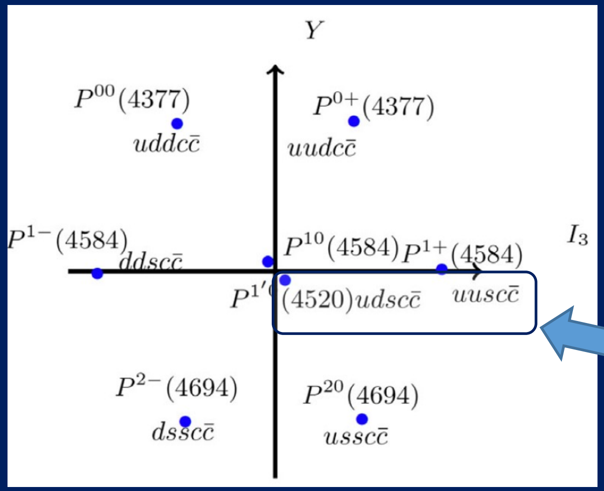
S_{q^3} = 1/2, 3/2, $S_{c\bar{c}}$ = 0, 1 S_{q^3} = 1/2, $S_{c\bar{c}}$ = 0, 1

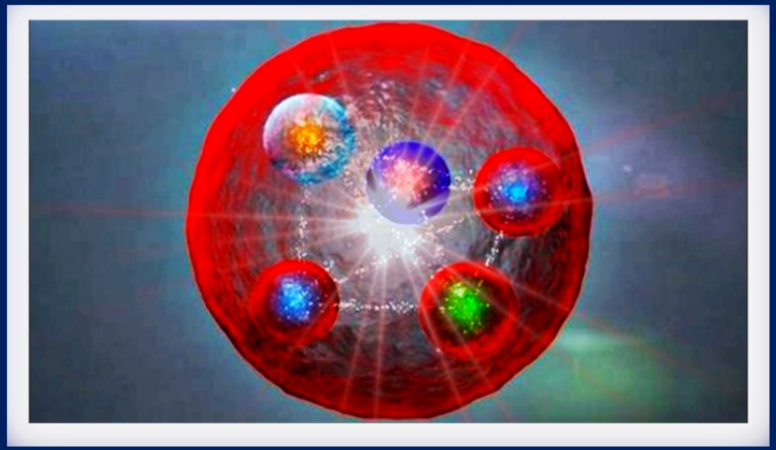
Using only simmetry considerations, and an equal spaced mass formula, we have predicted the strange pentaquark with I=0 Pcs(4457) for which LHCb reported evidence (LHCb, *Sci.Bull.* 66 (2021) 1278-1287) and suggested to look for it in the Λ J/Ψ channel (in fact cited by LHCb). According to our model also I=1 Pcs should exist (in the Σ J/Ψ channel) and I=1/2 Pcss (in Ξ J/Ψ channel)

Compact 5$\boldsymbol{q}$ state?

We have predicted the strange pentaquark with I=0, P_{cs}^0, for which LHCb reported evidence at M=4459 MeV and suggested to look for it in the Λ J/Ψ channel . According to our model also I=1 P_{cs} should exist (in the Σ J/Ψ channel) and I=1/2 P_{css} (in Ξ J/Ψ channel).

$$J^P = \frac{3}{2}^-$$



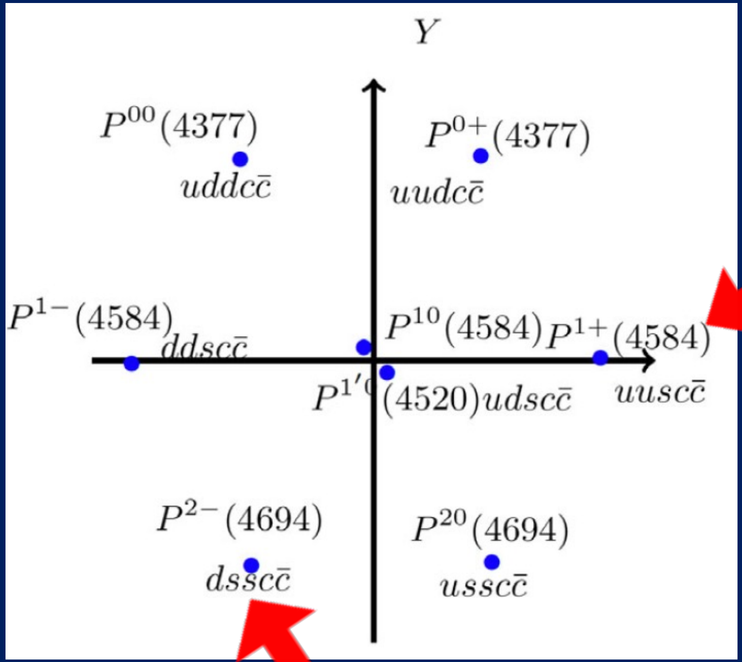


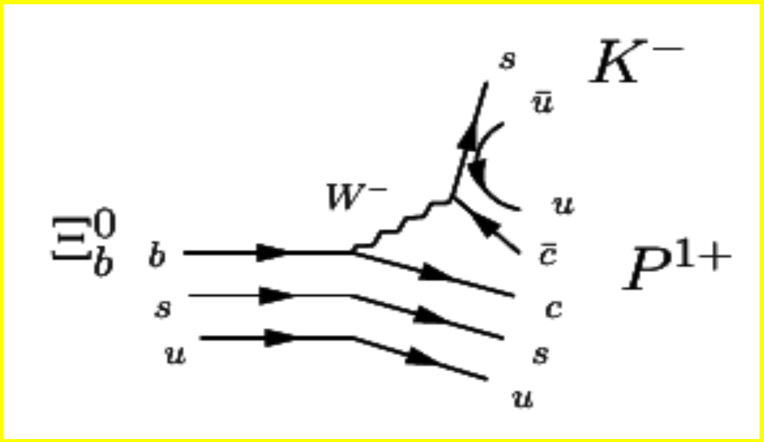
$P_{cs}^0(4459)$ The LHCb Coll. LHCb, *Sci.Bull.* 66 (2021) 1278-1287,
Evidence of a $J/\Psi\Lambda$ structure and observation of excited Ξ^- states in the $\Xi_b^- \to J/\Psi\Lambda K^-$ decay

from E. Santopinto and A. Giachino, **Phys. Rev. D96** (2017) 014014.

In which channels the other hidden charm pentaquarks which fill the SU(3) flavor octet can be observed?

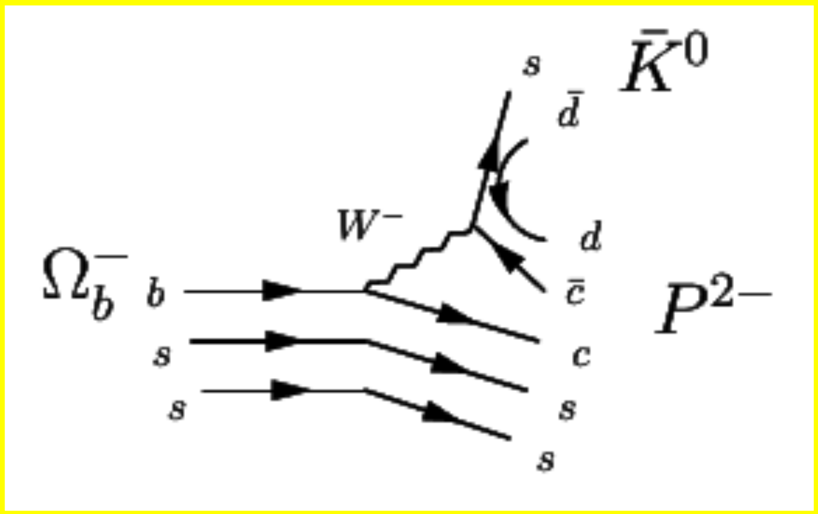
PHYSICAL REVIEW D **96**, 014014 (2017)
Compact pentaquark structures
Elena Santopinto and Alessandro Giachino





$$\Xi_b^0 \longrightarrow P^{1+} + K^-,\ P^{1+} \longrightarrow J/\Psi + \Sigma^+$$

$P^{1+}(4584)$ a $c\bar{c}uus$ state with isospin 1 so it can be observed in $J/\Psi\Sigma^+$ invariant mass spectrum; it is important to perform a an amplitude analysis of $\Xi_b^0 \to J/\Psi\Sigma^+K^-$ decays!



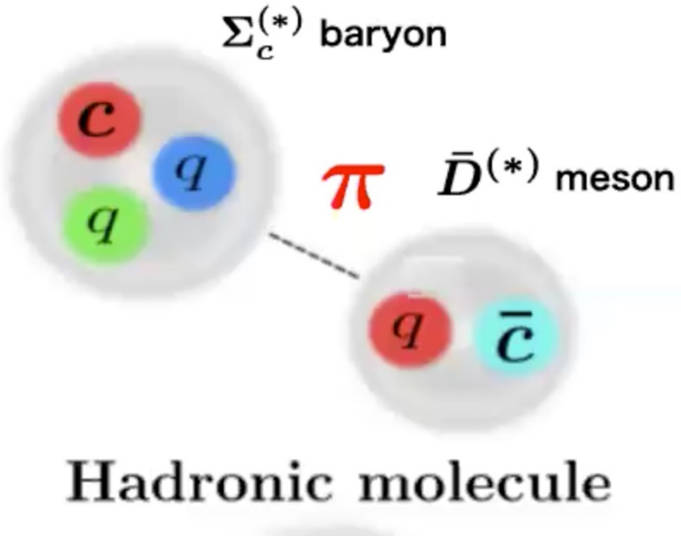
$$\Omega_b^- \to P^{2-} + \bar{K}^0, \qquad P^{2-} \to J/\Psi + \Xi^-.$$

$P^{2-}(4694)$ a $c\bar{c}uss$ state with isospin ½; this state can be observed in $J/\Psi\Xi^-$ invariant mass spectrum after performing an amplitude analysis of $\Omega_b^- \to J/\Psi\Xi^-\bar{K}^0$ decays!

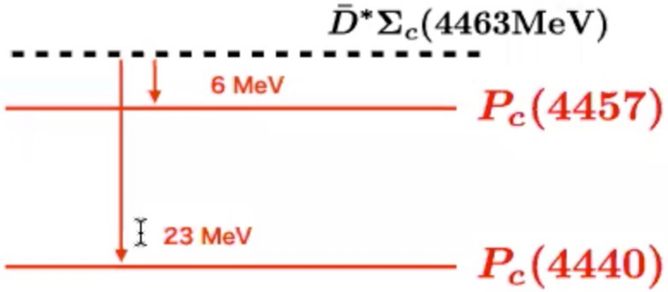
Hadronic molecules?

- ▶ Exotics as Hadronic molecule ⇒ Hadron (quasi) bound state

→ expected **near the thresholds**



$P_c = \bar{D}^{(*)}\Sigma_c^{(*)}$ molecules?



▷ Q. Interactions?: **Heavy hadron interactions** are not established yet…

⇒ Importance of π **exchange** is expected due to the heavy quark symmetry! S. Yasui and K. Sudoh, Phys. Rev. D **80** (2009), 034008

⇒ Hadronic molecular structure is favored?

Hidden-charm pentaquarks as a meson-baryon molecule with coupled channels for $\bar{D}^{(*)}\Lambda_c$ and $\bar{D}^{(*)}\Sigma_c$

Y. Yamaguchi, E. Santopinto, Phys. Rev. D Phys.Rev. D96 (2017) no.1, 014018

- Near the thresholds, resonances are expected to have an exotic structure, like the hadronic molecules.
- **The observed pentaquarks are found to be just below the $\bar{D}^*\Sigma_c$ ($P_c^+(4380)$) and the $\bar{D}^*\Sigma_c^*$ ($P_c^+(4450)$) thresholds. Moreover, the $\bar{D}^*\Lambda_c$ threshold is only 25 MeV below the $\bar{D}\Sigma_c$ threshold. For this reason, the $\bar{D}\Lambda_c$, $\bar{D}^*\Lambda_c$ channels are not irrelevant in the hidden-charm meson-baryon molecules.**

In Phys.Rev. D96 (2017) no.1, 014018 E. Santopinto e Y. Yamaguchi considered the coupled channel systems of $\bar{D}\Lambda_c$, $\bar{D}^*\Lambda_c$, $\bar{D}\Sigma_c$, $\bar{D}\Sigma_c^*$, $\bar{D}^*\Sigma_c$ and $\bar{D}^*\Sigma_c^*$ to predict the bound and the resonant states in the hidden-charm sector. The binding interaction between the meson and the baryon is given by the One Meson Exchange Potential (OMEP).

Upgrade of the model: Coupled channel between the meson-baryon states and the five quark states

- In the current problem of pentaquark P_c, there are two competing sets of channels: the meson-baryon (MB) channels and the five-quark channels.

CAN A COUPLE CHANNEL BETWEEN

THE MB CHANNELS AND THE CORE CONTRIBUTION

DESCRIBE IN A MORE REALISTIC WAY THE PENTAQUARK STATES ?

Coupled channel between the meson-baryon states and the five quark states

Hidden-charm and bottom meson-baryon molecules coupled with five-quark states,**Y. Yamaguchi, A. Giachino, A. Hosaka, E. S., S. Tacheuchi, M. Takizawa, Phys .Rev. D96 (2017) no.11, 114031**

- Thidden-charm pentaquarks as $\bar{D}\,\Lambda_c\,, \bar{D}^*\,\Lambda_c, \bar{D}\,\Sigma_c,$ $\bar{D}^*\,\Sigma_c,\ \bar{D}\Sigma_c^*,\ and\ \bar{D}^*\Sigma_c^*$, and molecules coupled to the five-quark states

ADDITION OF THE CORE CONTRIBUTION

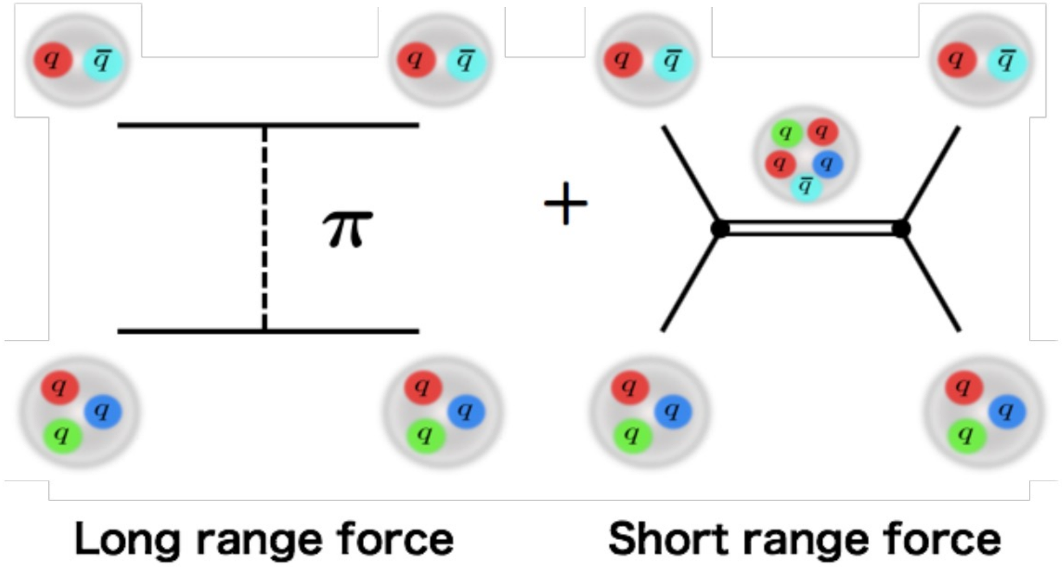
- For the first time some predictions for the hidden bottom pentaquarks as $\bar{D}\,\Lambda_c\,, \bar{D}^*\,\Lambda_c, \bar{D}\,\Sigma_c, \bar{D}^*\,\Sigma_c, \bar{D}\Sigma_c^*$ and $\bar{D}^*\Sigma_c^*$ molecules coupled to the five-quark states are provided.

- In particular, by solving the coupled channel Schrödinger equation, we study the the bound and resonant hidden-charm

Model setup in this study

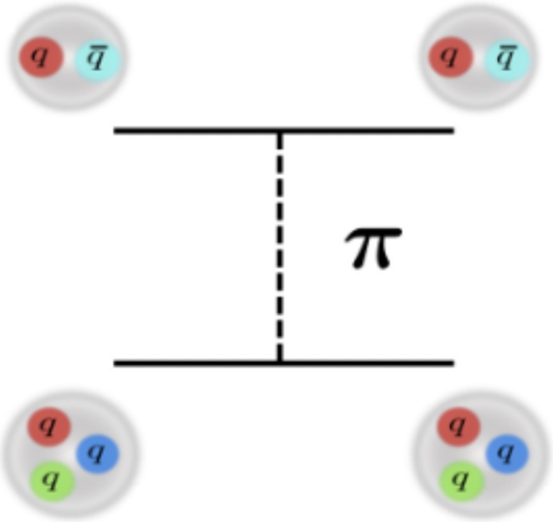
- **Hadronic molecule + Compact state $(5q)$**
  $\Rightarrow$ Meson-Baryon couples to $5q$ (Fashbach projection)

Meson-Baryon interactions



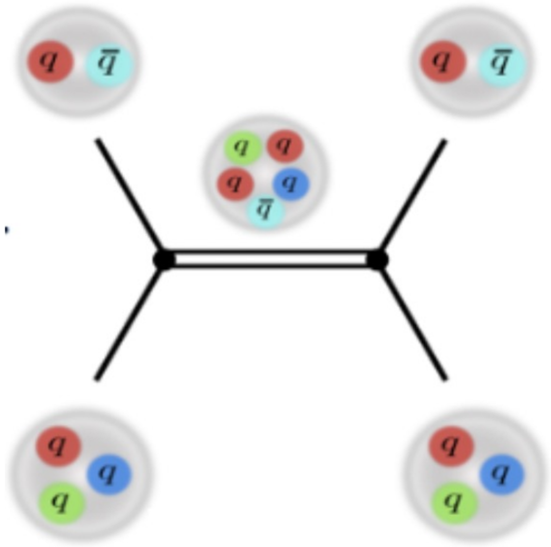
- ▷ **Long range** interaction: One pion exchange potential (OPEP)
- ▷ **Short range** interaction: $5q$ potential

1. Long range force: One pion exchange potential



Long range force

2. Short range force: 5-quark potential



Short range force

Hidden-charm and bottom meson-baryon molecules coupled with five-quark states [3]

- In Refs. [3] we studied the hidden-charm pentaquarks by coupling the $\Lambda_c \bar{D}^{(*)}$ and $\Sigma_c^* \bar{D}^{(*)}$ meson-baryon channels to a $uudc\bar{c}$ compact core with a meson-baryon binding interaction satisfying the heavy quark and chiral symmetries.

We predicted the three pentaquark states, $P_c(4312), P_c(4440)$ and $P_c(4457)$ two years before the experimental observation by LHCb.

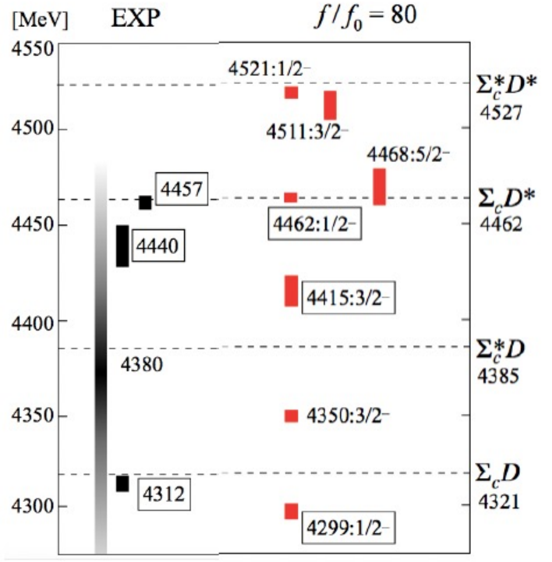
For this reason we wrote a Rapid Communication, Y. Yamaguchi, H. Garcia-Tecocoatzi, A. Giachino, A. Hosaka, E. Santopinto, S. Takeuchi and M. Takizawa Phys.Rev.D **101** (2020) 091502 (R)

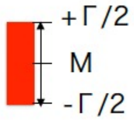
[3] Y. Yamaguchi, A. Giachino, A. Hosaka, E. Santopinto, S. Takeuchi, M. Takizawa, **Phys. Rev. D 96 114031 (2017)**

For New P_c states by LHCb in 2019

Y.Y., H.Garcia-Tecocoatzi, A.Giachino, A.Hosaka, E.Santopinto, S.Takeuchi, M.Takizawa, PRD **101** (2020) 091502(R)

$(f_0 = 6 \text{ MeV})$





Four-Heavy-Quark Tetraquarks

Observation claims of a 4muon peak in 2ϒ spectrum circulated in 2018-2019

- A Genova-Roma collaboration set up to compute lifetime & branching ratios for fully bottom 0^{++} tetraquark, also in view of the luminosity upgrade of LHCb;
- we also included the 2^{++} state (2^{++} has a production cross- section a factor 5 larger than 0^{++} and a larger 4μ Bf !)

C.Becchi, A.Giachino, L.Maiani and E.Santopinto, Phys. Lett. **B 806**, 135495 (2020).

- Very discouraging results were obtained for the 4 muon channel of 4b tetraquarks: σ~0.1fb or less, made the positive claims rather unlikely.

- In March 2020, we realised that fully charmed tetraquarks would be more favorable.
- Our paper on fully charmed tetraquarks appeared on ArXiv on June 25.

C.Becchi, J. Ferretti, A. Giachino, L.Maiani and E.Santopinto, arXiv:2006.14388, Phys.Lett. **B 811** (2020) 135952

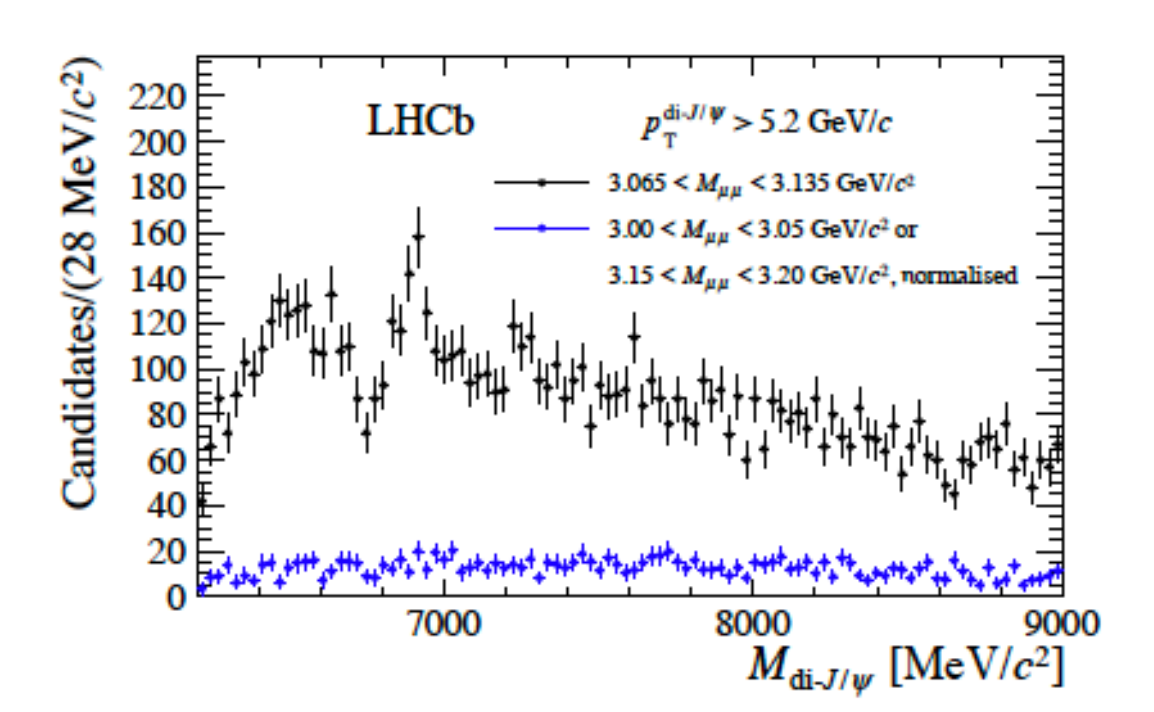
Tetraquark picture of 2 J/Ψ resonances

Describing the X(6900) structure with a Breit Wigner lineshape, its mass and natural width are determined to be (arXiv:2006.16957, 30 Jun 2020, now Science Bulletin, Volume 65, Issue 23, 1983 (2020)):

$$m[X(6900)] = 6905 \pm 11 \pm 7\,\mathrm{MeV}/c^2$$

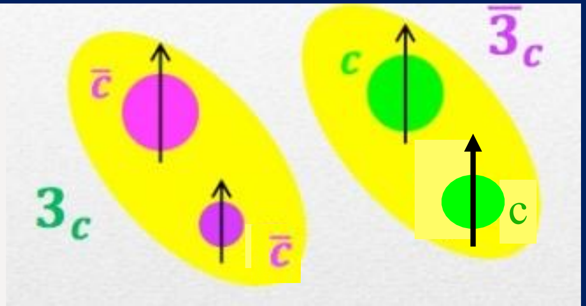
$$\Gamma[X(6900)] = 80 \pm 19 \pm 33\,\mathrm{MeV},$$

The statistical significance of X(6900) is greater than 5.1 σ



Tetraquark constituent picture of 2 J/Ψ resonances

$$[cc]_{(S=1)}[\bar{c}\bar{c}]_{(S=1)}$$

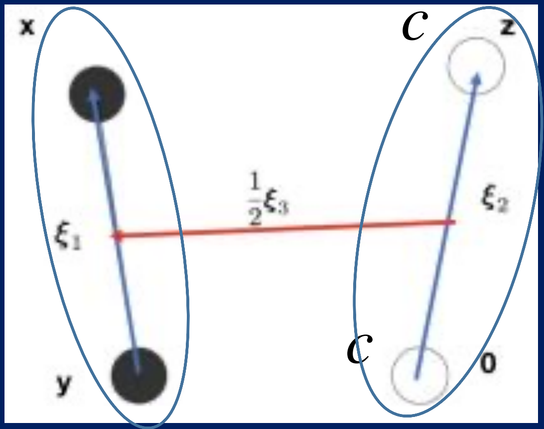


- [cc] in color $\bar{\mathbf{3}}$
- total spin of each diquark, S=1 (color antisymmetry and Fermi statistics)
- S-wave: positive parity

S-wave, fully charm tetraquarks

- C=+1 states: $J^{PC} = 0^{++}, 2^{++}$, decay in 2 J/Ψ, S-wave
- C=-1 states: $J^{PC} = 1^{+-}$, no decay in 2 J/Ψ, S-wave
- masses computed as diquark antidiquark system by Bedolla, Ferretti, Roberts,Santopinto, arXiv:1911.00960, Eur.Phys.J.**C80(**2020)1004
  - QCD inspired potential (**Coulomb+linear potential**), h.o. variational method, the diquarks are treated as frozen .
  - Authors include computation of the energy levels of radial and orbital excitations.

Jacobi coordinates in the tetraquark



2 J/Ψ mass spectrum

	$cc\bar{c}\bar{c}$	
J^{PC}	$N[(S_D, S_{\bar{D}})S, L]J$	E^{th} [MeV]
0^{++}	1[(1, 1)0, 0]0	5883
0^{++}	2[(1, 1)0, 0]0	6573
0^{++}	1[(1, 1)2, 2]0	6835
0^{++}	3[(1, 1)0, 0]0	6948
0^{++}	2[(1, 1)2, 2]0	7133
0^{++}	3[(1, 1)2, 2]0	7387
1^{+-}	1[(1, 1)1, 0]1	6120
1^{+-}	2[(1, 1)1, 0]1	6669
1^{+-}	1[(1, 1)1, 2]1	6829
1^{+-}	3[(1, 1)1, 0]1	7016
1^{+-}	2[(1, 1)1, 2]1	7128
1^{+-}	3[(1, 1)1, 2]1	7382
1^{--}	1[(1, 1)0, 1]1	6580
1^{--}	1[(1, 1)2, 1]1	6584
1^{--}	2[(1, 1)0, 1]1	6940
1^{--}	2[(1, 1)2, 1]1	6943
1^{--}	3[(1, 1)0, 1]1	7226
1^{--}	3[(1, 1)2, 1]1	7229
0^{-+}	1[(1, 1)1, 1]0	6596
0^{-+}	2[(1, 1)1, 1]0	6953
0^{-+}	3[(1, 1)1, 1]0	7236
1^{++}	1[(1, 1)2, 2]1	6832
1^{++}	2[(1, 1)2, 2]1	7130
1^{++}	3[(1, 1)2, 2]1	7384
2^{++}	1[(1, 1)2, 0]2	6246
2^{++}	1[(1, 1)2, 2]2	6827
2^{++}	1[(1, 1)0, 2]2	6827
2^{++}	2[(1, 1)2, 0]2	6739
2^{++}	3[(1, 1)2, 0]2	7071
2^{++}	2[(1, 1)2, 2]2	7125
2^{++}	2[(1, 1)0, 2]2	7126
2^{++}	3[(1, 1)2, 2]2	7380
2^{++}	3[(1, 1)0, 2]2	7380

6537 — 0^{++} S-wave

7227 — 1st Radial excitation

The prediction includes an *a priori* unknown additive constant (to fix the zero of the energy for confined states) which is to be determined from one mass of the spectrum.

In the paper the constant was taken (provisionally) from calculations of meson masses

- The upshot: you give the mass of 2^{++} (say: 6900 MeV) and Bedolla *et al.* predict the mass differences

7481 — 1^{++} D-wave

6900 (input) — 2^{++} S-wave

arXiv:1911.00960, Bedolla, Ferretti, Roberts, Santopinto, Eur.Phys.J. **C80** (2020) 1004

Decays and branching fractions

- Decays take place via $c\bar{c}$ annihilation. The starting point is to bring the $c\bar{c}$ pairs together

$$\mathcal{T}(J=0^{++}) = \left|(cc)^1_{\bar{3}}(\bar{c}\bar{c})^1_3\right\rangle^0_1 = -\frac{1}{2}\left(\overset{1}{\sqrt{\frac{1}{3}}\left|(c\bar{c})^1_1(c\bar{c})^1_1\right\rangle^0_1} - \overset{2}{\sqrt{\frac{2}{3}}\left|(c\bar{c})^1_8(c\bar{c})^1_8\right\rangle^0_1}\right) + \frac{\sqrt{3}}{2}\left(\overset{1}{\sqrt{\frac{1}{3}}\left|(c\bar{c})^0_1(c\bar{c})^0_1\right\rangle^0_1} - \overset{2}{\sqrt{\frac{2}{3}}\left|(c\bar{c})^0_8(c\bar{c})^0_8\right\rangle^0_1}\right)$$

- Four possible annihilations:
  - 1 a color singlet pair of spin 1 (0) annihilates into a J/Ψ (η_c), the other pair rearranges into the available states (near threshold: J/Ψ or η_c again);
  - 2 a color octet, spin 1 pair annihilates into a pair of light quark flavours, q=u,d,s and the latter recombine with the spectator pair to produce a pair of lower-lying, open-charm mesons. A similar process from color octet spin 0 pair is higher order in α_s and neglected.

- Rates are computed with the formula (well known in atomic physics):

$$\Gamma = |\Psi_{\mathcal{T}}(0)|^2 \cdot |\mathbf{v}| \cdot \sigma(c\bar{c} \to f)$$

- Branching fractions are independent from $|\Psi_{\mathcal{T}}(0)|^2$
- Total rates: see later.

C.Becchi, J. Ferretti, A.Giachino, L.Maiani and E.Santopinto, arXiv:2006.14388, Phys.Lett. **B 811** (2020) 135952

2J/Ψ and 4μ cross sections

- We give the upper bound: $\sigma_{theo.}(\mathcal{T} \to 4\mu) \leq \sigma(pp \to 2\ J/\Psi)[B(J/\Psi \to 2\ \mu)]^2$
- With: $\sigma(pp \to 2\ J/\Psi) \simeq 15.2$ nb (LHCb @ 13 TeV, Aaij : 2016bqq)

The limiting cross sections (in fb) are shown in the table

$[cc][\bar{c}\bar{c}]$	Decay channel	BF in $\mathcal{T}$ decay	Cross section upper limit (fb)
$J=0^{++}$	$\mathcal{T} \to D^{(*)+}D^{(*)-} \to e+\mu+\ldots$	$2.3\ 10^{-3}$	$3.6\cdot 10^4$ (36 pb)
	$\mathcal{T} \to D^{(*)0}\bar{D}^{(*)0} \to e+\mu+\ldots$	$0.36\ 10^{-3}$	$0.55\cdot 10^4$ (6 pb)
	$\mathcal{T} \to 4\mu$	$2.6\ 10^{-6}$	39
$J=2^{++}$	$\mathcal{T} \to D^{*+}\bar{D}^{*-} \to e+\mu+\ldots$	$7.0\ 10^{-3}$	$53\cdot 10^4$ (532 pb)
	$\mathcal{T} \to D^{*0}\bar{D}^{*0} \to e+\mu+\ldots$	$1.1\ 10^{-3}$	$8.3\cdot 10^4$ (83 pb)
	$\mathcal{T} \to 4\mu$	$1.0\ 10^{-5}$	780

780:39=20 !!

$B_{4\mu}(2^{++}) : B_{4\mu}(0^{++}) \sim$ 4:1; $\sigma(2^{++}) : \sigma(0^{++}) = 5 : 1$

A visibility ratio 20:1 !!

- Branching ratios in 4 muons are more favorable in 4 c than in 4 b tetraquarks
- Among 4 c, the Branching Ratio is more favorable for the 2^{++} (a factor 4)
- In addition 2^{++} is produced in pp collision with a statistical factor 2J+1=5

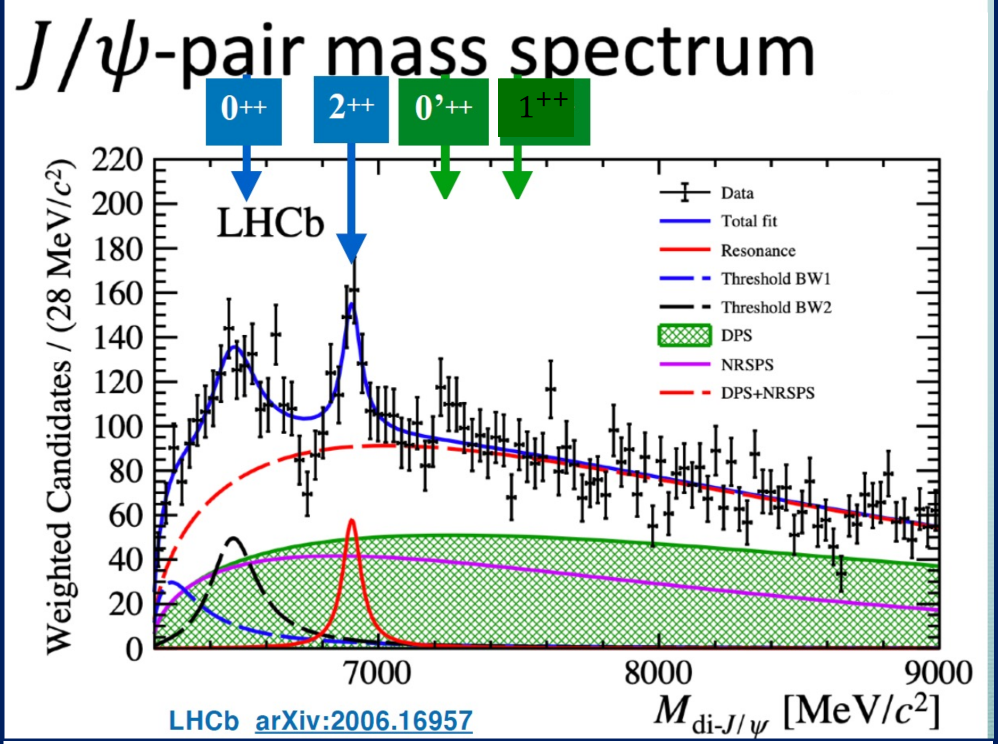
C.Becchi, J. Ferretti, A.Giachino, L.Maiani and E.Santopinto, arXiv:2006.14388, Phys.Lett. **B 811** (2020) 135952

Total widths and mass spectrum

- Total widths are proportional to the ratio: $\xi = |\Psi_T(0)|^2 / |\Psi_{J/\Psi}(0)|^2$
- we determine ξ from models

$$\xi = 4.6 \pm 1.4$$

$$\Gamma(0^{++}) \cong \Gamma(2^{++}) = (97 \pm 30)\ \text{MeV}$$

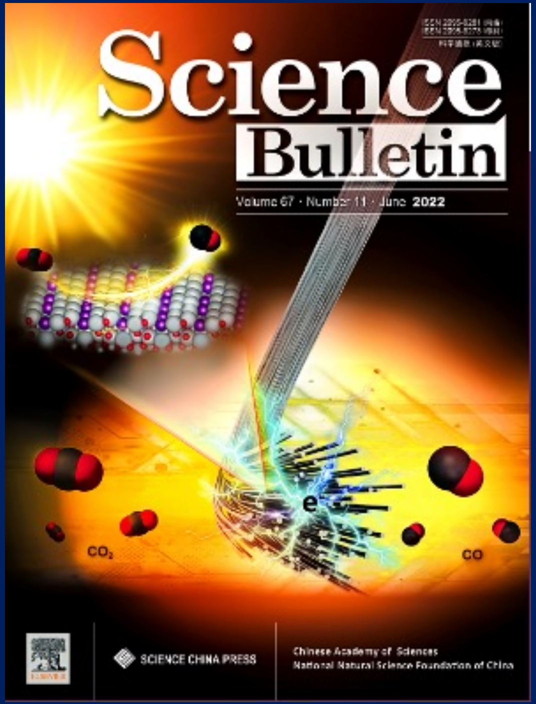


Science Bulletin, Volume 65, Issue 23, 1983 (2020)

C.Becchi, J. Ferretti, A.Giachino, L.Maiani and E.Santopinto, arXiv:2006.14388, Phys.Lett. **B 811** (2020) 135952

Predictions of exotic strange hidden charm tetraquark and pentaquarks,

published on Science Bulletin 2022 (Impact Factor 11,78) :



The new Pcs.4459.; Zcs.3985.; Zcs.4000. and Zcs.4220. and the possible emergence of flavor pentaquark octets and tetraquark nonets

J. Ferretti, E. Santopinto (July 2022)
Science Bulletin 67 (2022) 1209–1212
doi.org/10.1016/j.scib.2022.04.010

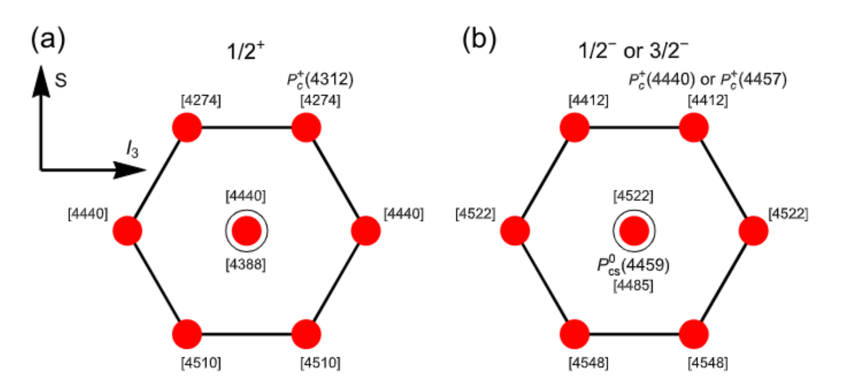
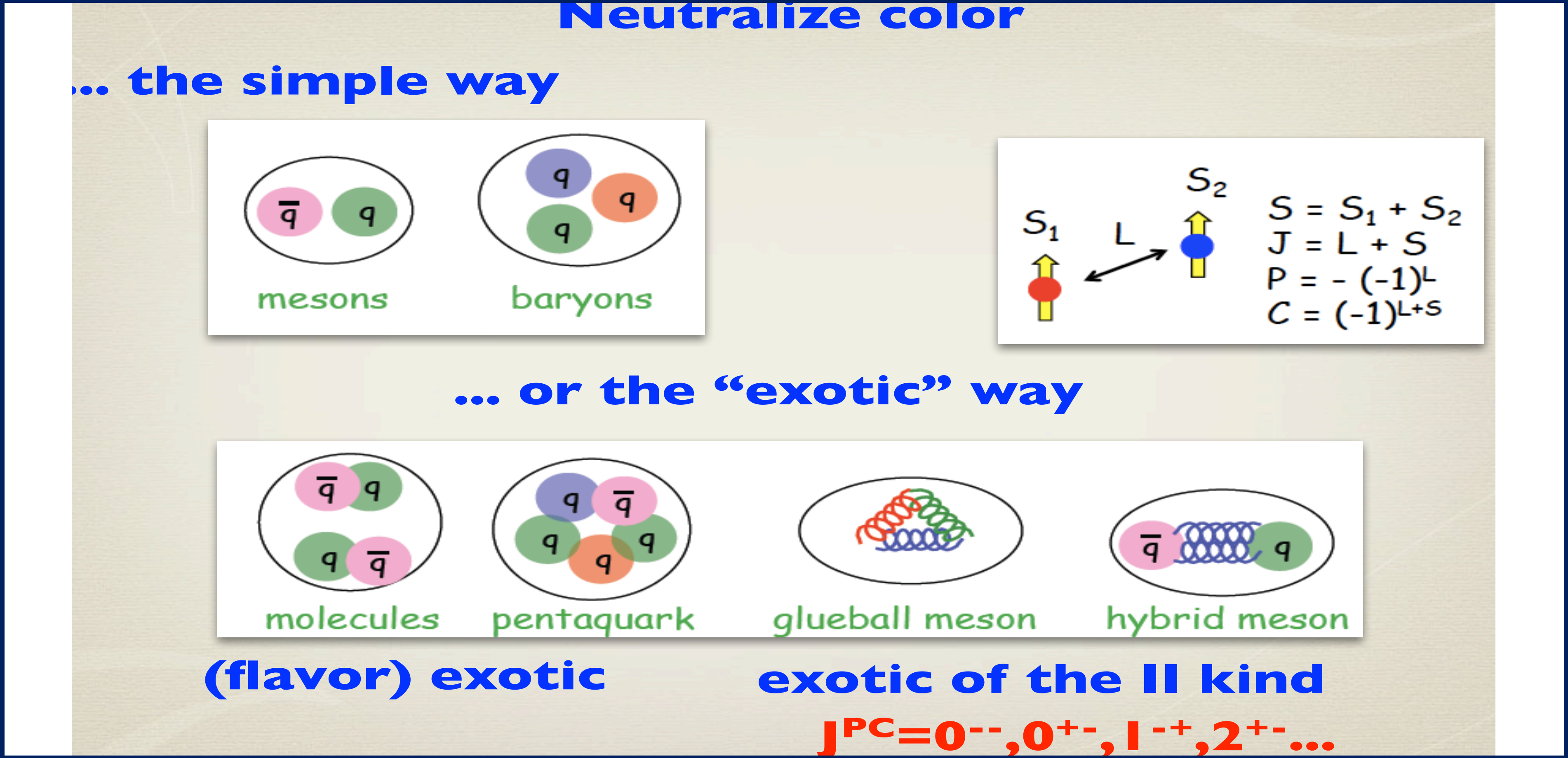


Fig. 2. (Color online) $J^P = \frac{1}{2}^+$ pentaquark octet, made up of the bound states of octet baryons plus the $\chi_{c0}(1P)$ (a), and $J^P = \frac{1}{2}^-$ or $J^P = \frac{3}{2}^-$ pentaquark octet, made up of the bound states of octet baryons plus the $\psi(2S)$ (b). The predicted hadro-charmonium masses are reported inside square brackets, the experimental ones are inside round brackets. See the Supplementary materials for more details.

Thanks for your attention!

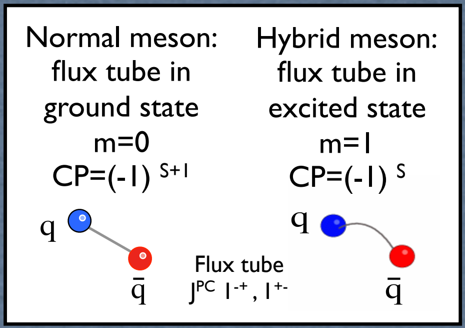
The gluons and the meson spectrum



Gluonic excitation models

Flux tube model

- Gluonic field confined in a tube between q and anti-q
- Linear Regge trajectories
- Hybrid mesons as transverse oscillation of the tube
- Flux-tube breaking give rise to meson decay



Lightest multiplet
$(0,1,2)^{-+},(0,1,2)^{+-}, 1^{--}, 1^{++}$

Bag model

- Quarks confined inside a cavity
- Full relativistic
- Gluonic excitation: gluonic field modes by boundary conditions

Lightest multiplet
$(0,1,2)^{-+},1^{--}$

CQM + constituent gluon

- qq + massive transverse quasi-gluon ($J_g^{P_gC_g}$)
- Gluon adds in relative S-wave to a qq pair is S-wave or P-wave

qq in S-wave + $J_g^{P_gC_g}=1^{--}$ in S-wave

Lightest multiplet
$(0,1,2)^{++},1^{+-}$

qq in P-wave + $J_g^{P_gC_g}=1^{--}$ in S-wave

Lightest multiplet
$0^{--},(1^{--})^3,(2^{--})^2,3^{--},0^{-+},0^{-+},1^{-+}, 2^{-+}$

or in Cb gauge QCD :
P.Guo,A.Szczepaniak,Galatà, Vasallo, E.S. ,PRD78,056003(2008)

- Repulsive 3-body force selects $J_g^{P_gC_g}=1^{+-}$ in relative P-wave added to a qq pair is S-wave or P-wave

qq in S-wave + $J_g^{P_gC_g}=1^{+-}$ in P-wave

Lightest multiplet
$(0,1,2)^{-+},1^{--}$

qq in P-wave + $J_g^{P_gC_g}=1^{+-}$ in P-wave

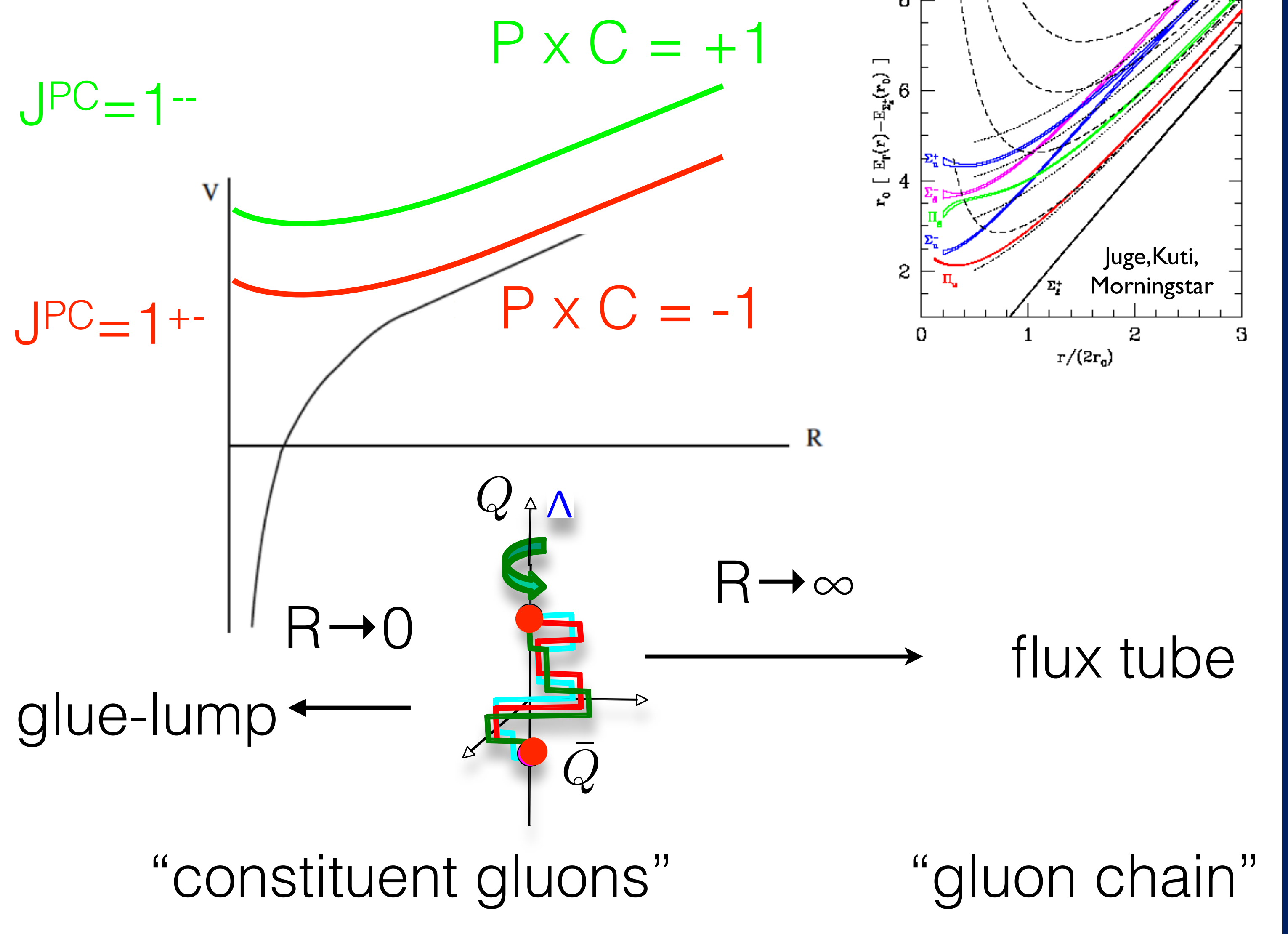
Lightest multiplet
$0^{+-},(1^{+-})^3,(2^{+-})^2,3^{+-}, (0,1,2)^{++}$

Starting from the study of the glue-lamp (lamp of gluons or “ constituent gluon”) as obtained from QCD in physical gauge

Gluelamp in Cb gauge QCD:
P.Guo,A.Szczepaniak,G.Galatà,A. Vassallo, E.S.,PRD78,056003(2008)

it is easy to study the ccbar –gluon system, i.e. the hybrids (next two slides)

Flux tube and strings



Gluelamp
Guo,Szczpaniak,Vassallo,E.S.,PRD2008

Greensite e Thorn’s chain model
Ostrander,Szczpaniak,Vassallo,E.S,PRD2014

Charmonia (qq bar) & hybrids (qqg)

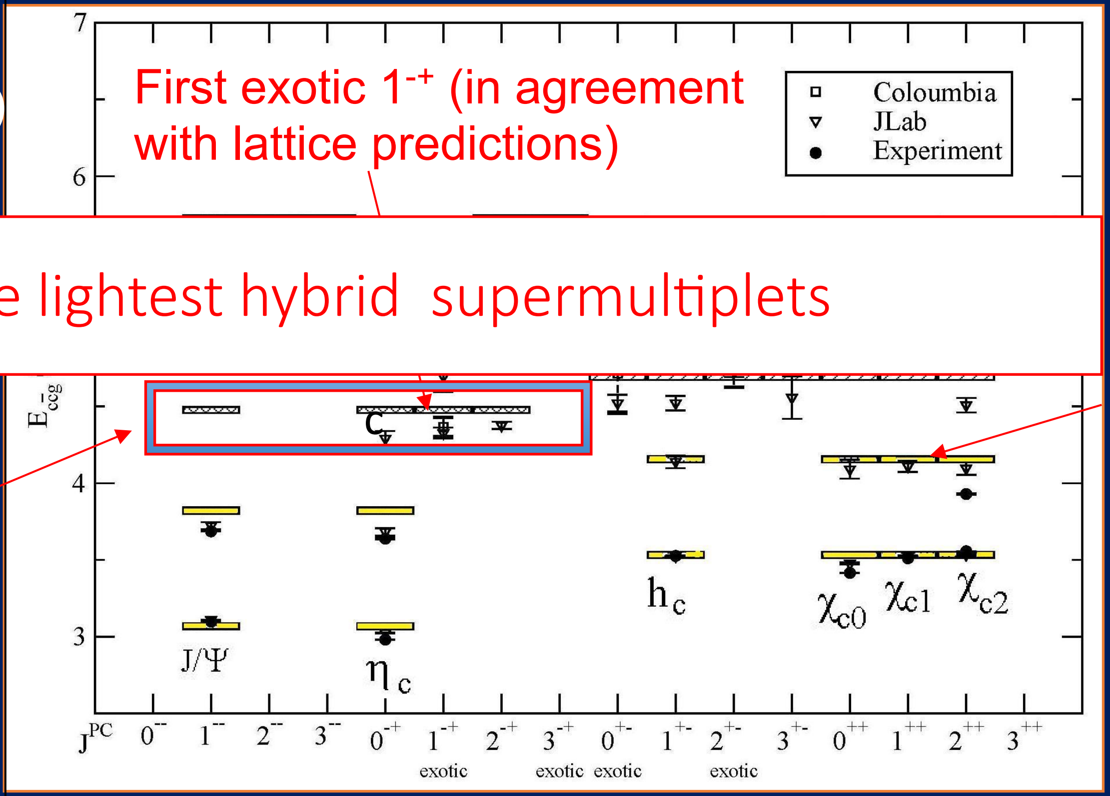
$J_g^{PC} = 1^{+-}, 1^{--}$

$J_g^{P_g}$	This work [GeV]	J^{PC}	Lattice [14] [GeV]
1^+	4.476	$0^{-+}, 1^{-+}, 2^{-+}, [1^{--}]$	4.291(48),4.327(36),4.376(24), [?]
1^-	4.762	$1^{+-}, 2^{++}, [0^{++}, 1^{++}]$	4.521(48),4.508(48), [?,?]
2^+	5.144	$1^{-+}, [2^{--}, 2^{-+}, 3^{-+}]$	4.696(103), [?,?,?]
2^-	5.065	$2^{+-}, [1^{++}, 2^{++}, 3^{++}]$	4.733(42), [?,?,?]

[14]:J. J. Dudek, R. G. Edwards, N. Mathur, and D. G.Richards, Phys. Rev. D 77, 034501 (2008).

c-cbar states (yellow)

hybrids (gray-dashed)



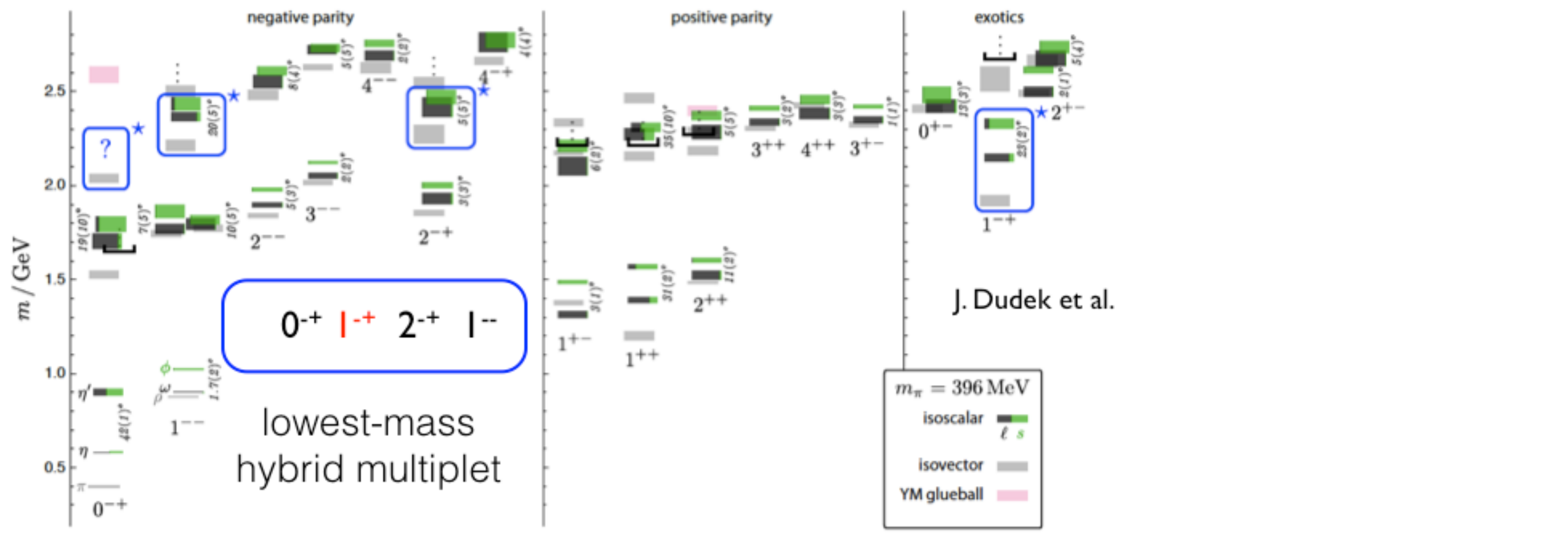
The lightest hybrid supermultiplets

Y(4260)

X(3872)

Guo,Szczepaniak, Galatà,Vassallo, E.S. , **Phys.Rev.D78:056003,2008**.

The ligthest hybrid supermultiplet predicted (and explained)for charmonia by QCD in physical gauge , $1^{--}(0,1,2)^{-+}$, it is predicted also for light quarks by LQCD

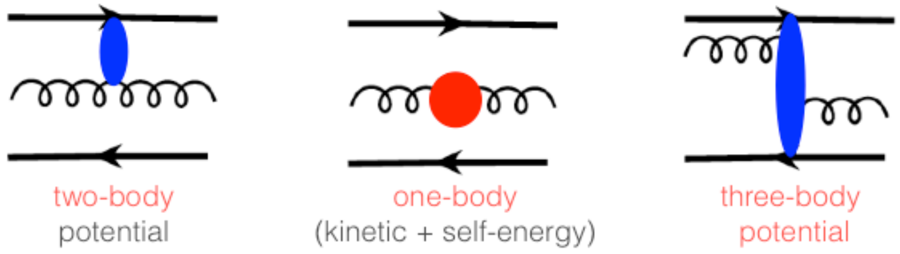


Physical gauge QCD (Hamiltonian)

J^{PC} glue → J^{PC} $Q\bar{Q}$

$$1^{+-} \times 0^{-+}_{S_{Q\bar{Q}}} = \boxed{1^{--}}$$

$$1^{+-} \times 1^{--}_{S_{Q\bar{Q}}=1} = \boxed{0^{-+}, 1^{-+}, 2^{-+}}$$

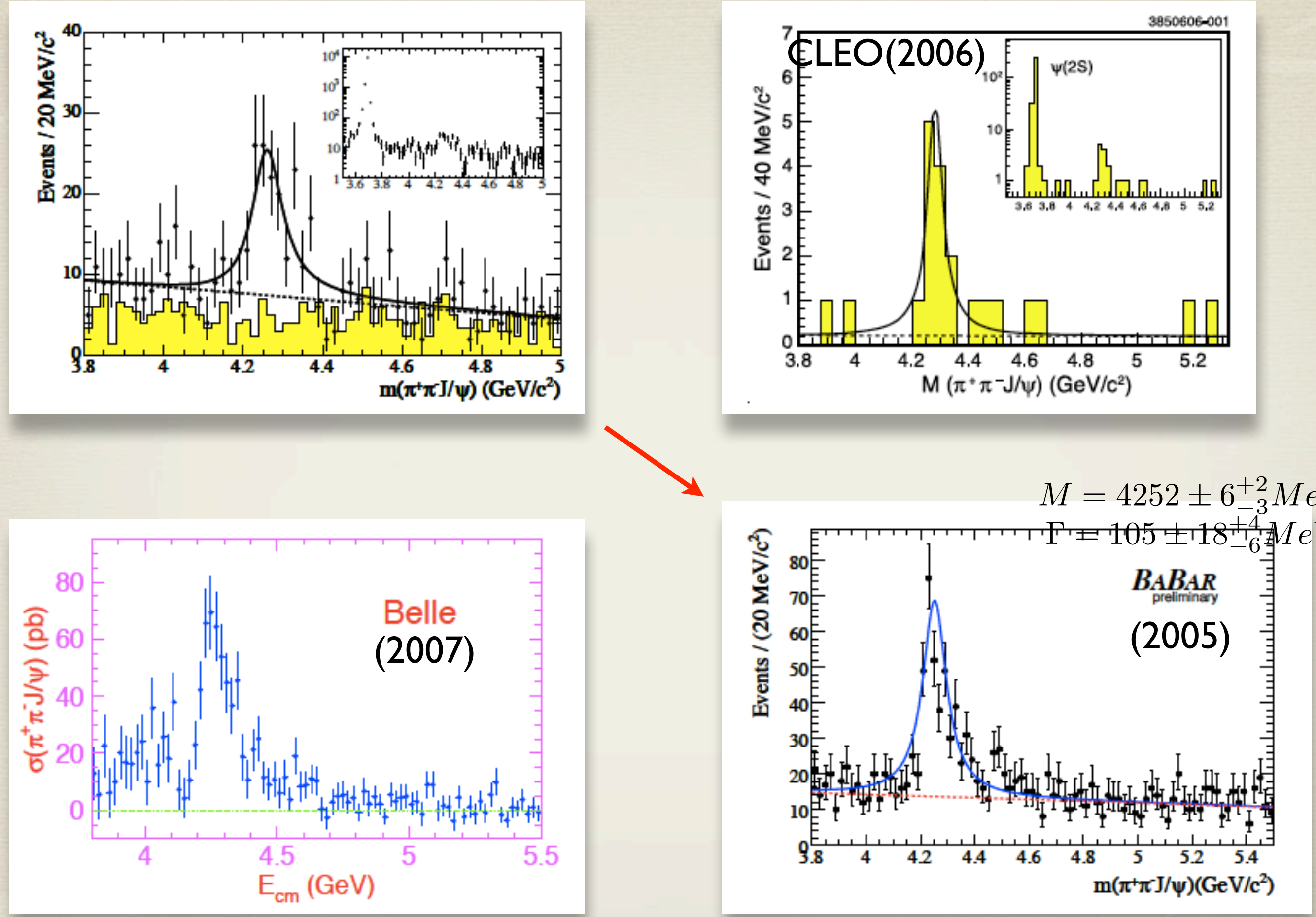


Guo,Szczpaniak,Galatà,Vassallo, E.S.,PRD2008

20XX experimental confirmation - discovery ?

• **Y(4260)** **discovered by BaBar in J/ψ $\pi^+\pi^-$ (2005) confirmed by CLEO,Belle other modes from BaBar**

$J^{PC}=1^{--}$ (from e^+e^-) width O(100MeV)



$M = 4252 \pm 6^{+2}_{-3} MeV$

$\Gamma = 105 \pm 18^{+4}_{-6} MeV$

✱ **Theory: Hybrid candidate**

•

No

- If, one the other hand, we place a constituent gluon as a Pwave gluonic field excitation, so that Jg = 1+−, we appear to be able to successfully describe both the lightest hybrid supermultiplet of (0, 1, 2)−+, 1−− (by having qq̄ in an S-wave) and the heavier exotic states, 0+−, (2+−)2 (with qq̄ in a P -wave).