Multiquark States

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NSTAR2022

Santa Margerita Ligure

17-21 October 2022

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 q̄), etc., while mesons are made out of (q q̄), (q q q̄ q̄), etc. It is assuming that the lowest

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

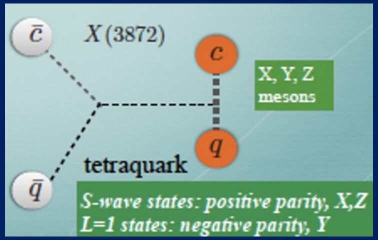
There are indeed new valence quark configurations !!

- 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

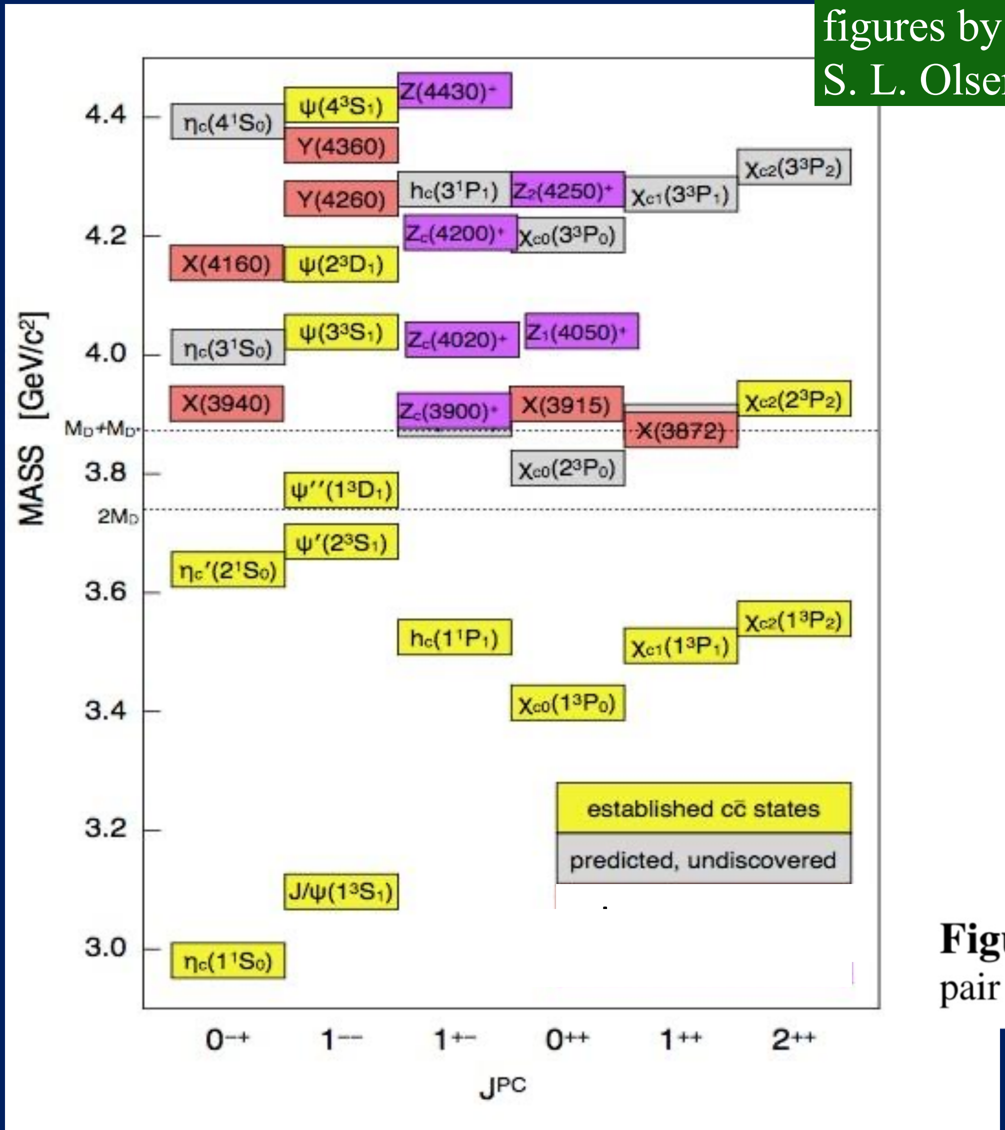
- Hidden heavy flavors have been the first, now we also have the LHCb open heavy flavor $X_0(2900)$ $J^P=0^+$ and $X_1(2900)$ $J^P=1^-$ in the D+ K- channel ($\bar{c}\bar{s}ud$ or D* K* molecule ?)
- First *unexpected charmonium* is the still controversial X(3872) (discovered by Belle 2003)

Still controversial because very close to the threshold



Expected and Unexpected Charmonia

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



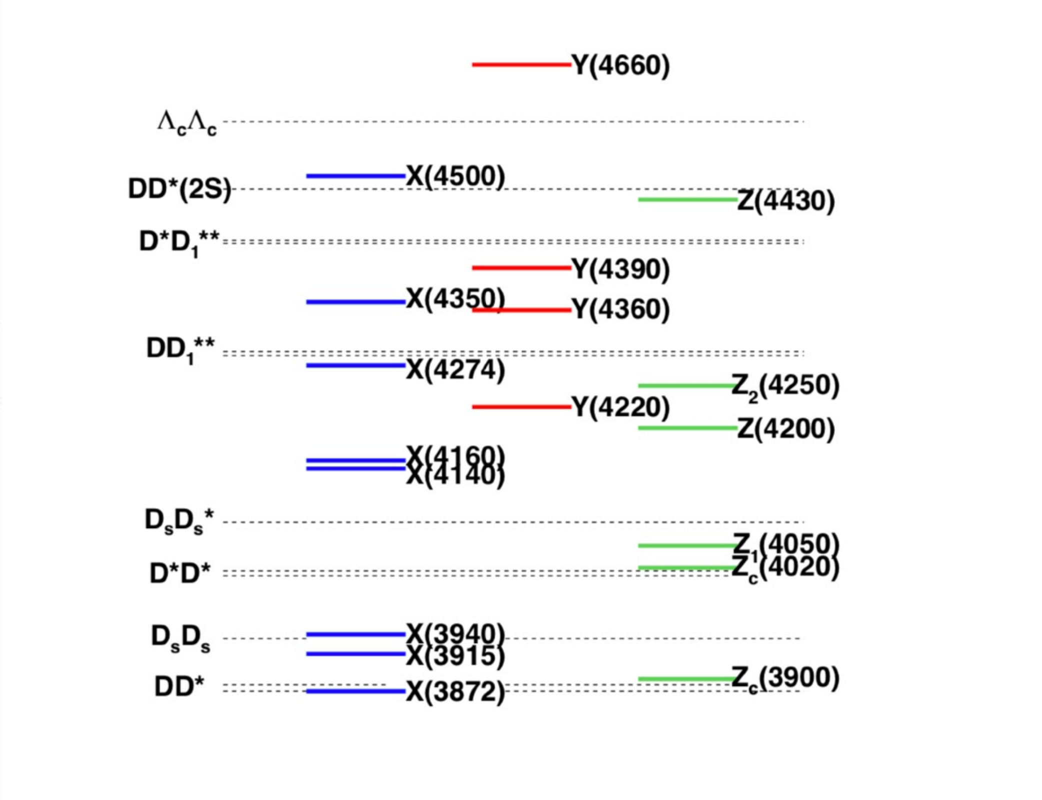
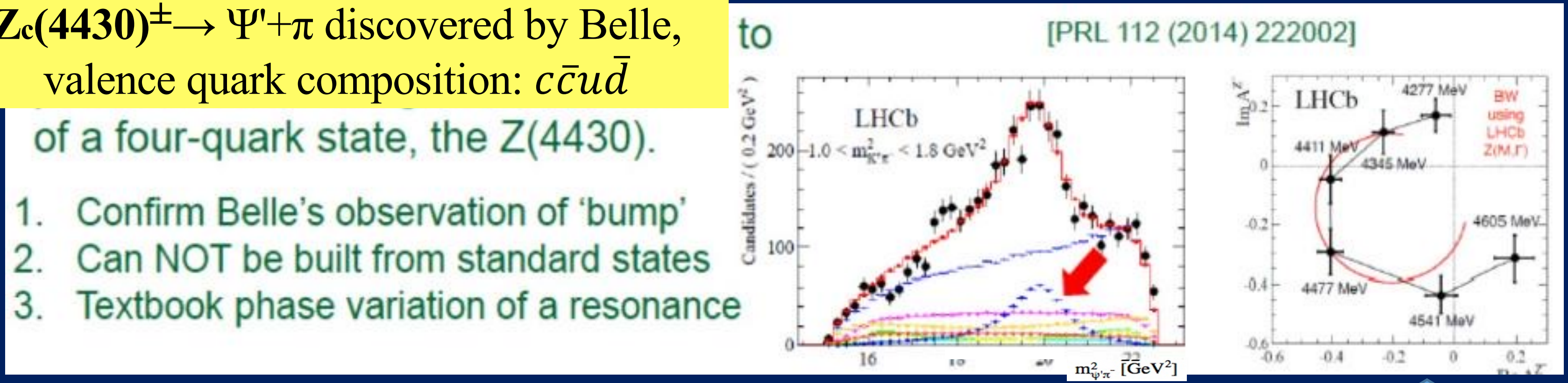


Figure 4. *XYZ* meson masses compared with charmed meson pair thresholds.

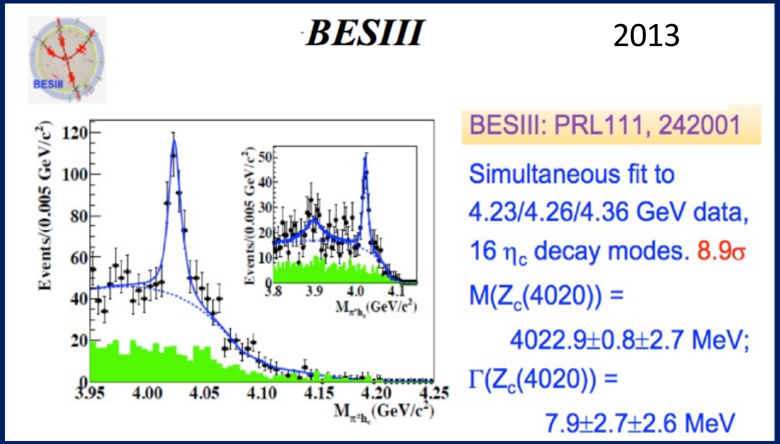
Explicit Tetraquarks:
$Z_c(4430)^{\pm}$ 13.9 σ

$Z_c(4430)^{\pm}$ $\rightarrow \Psi'+\pi$ 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



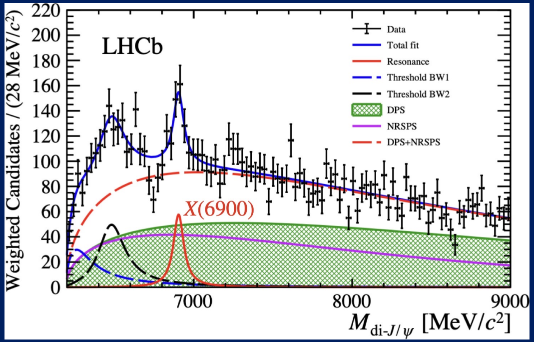
$Z_c(4020)^{\pm} \rightarrow h_c+\pi$

$Z_c(4020)^{\pm}$. 8.9σ

Recent reports of Exotic hadrons!

▷ $X(6900)$ ($\boldsymbol{cc\overline{cc}}$)

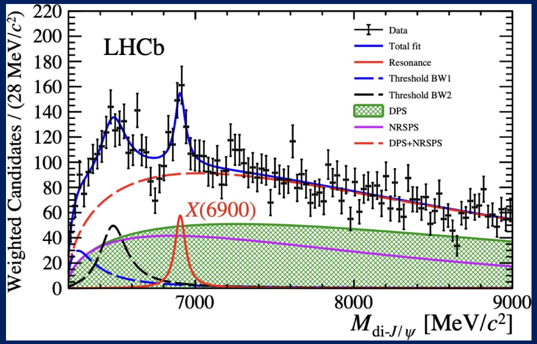
Science Bulletin 65 (2020) 1983



Recent reports of Exotic hadrons!

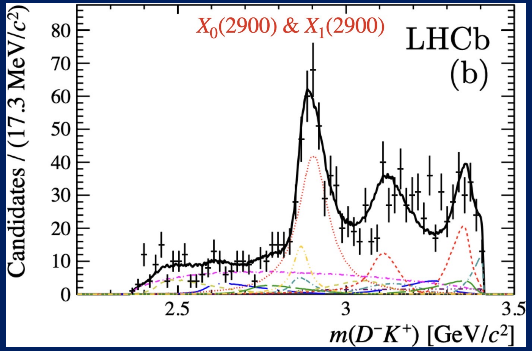
▷ $X(6900)$ $(cc\bar{c}\bar{c})$

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

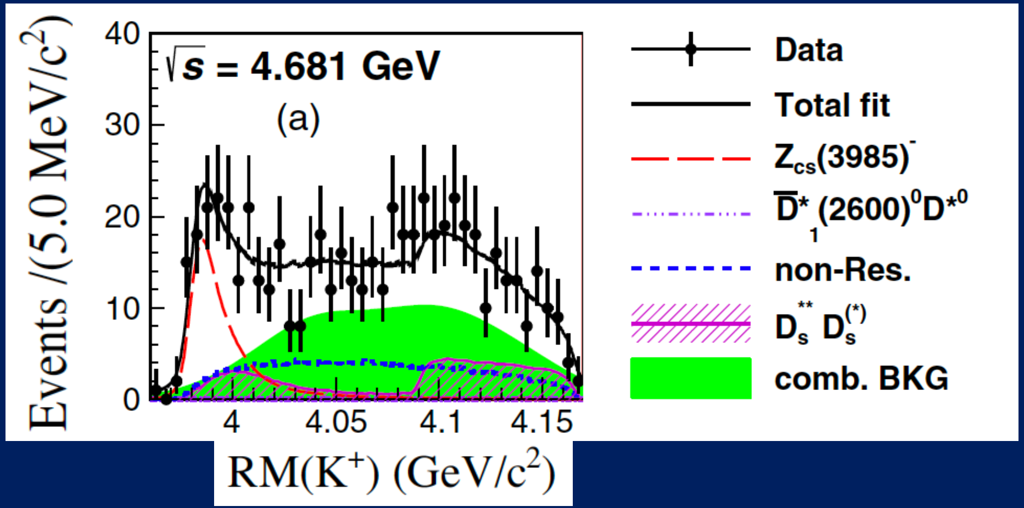
$$X_0(2900):\ M = 2.866 \pm 0.007 \pm 0.002\ \mathrm{GeV}/c^2,$$
$$\Gamma = 57 \pm 12 \pm 4\ \mathrm{MeV},$$
$$X_1(2900):\ M = 2.904 \pm 0.005 \pm 0.001\ \mathrm{GeV}/c^2,$$
$$\Gamma = 110 \pm 11 \pm 4\ \mathrm{MeV},$$

$\boldsymbol{Z_{cs}(3985)^-}$ ($c\bar{c}s\bar{u}$) (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

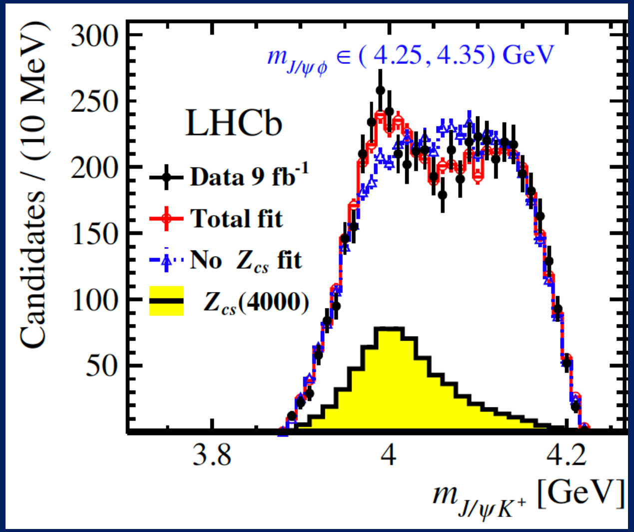
$$e^+e^- \to (Z_{cs}(3985)^-)K^+ \to (D_s^- D^{*0} + D_s^{-*} D^0)K^+$$



$\boldsymbol{Z_{cs}(4003)^+}$ ($c\bar{c}u\bar{s}$) (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).

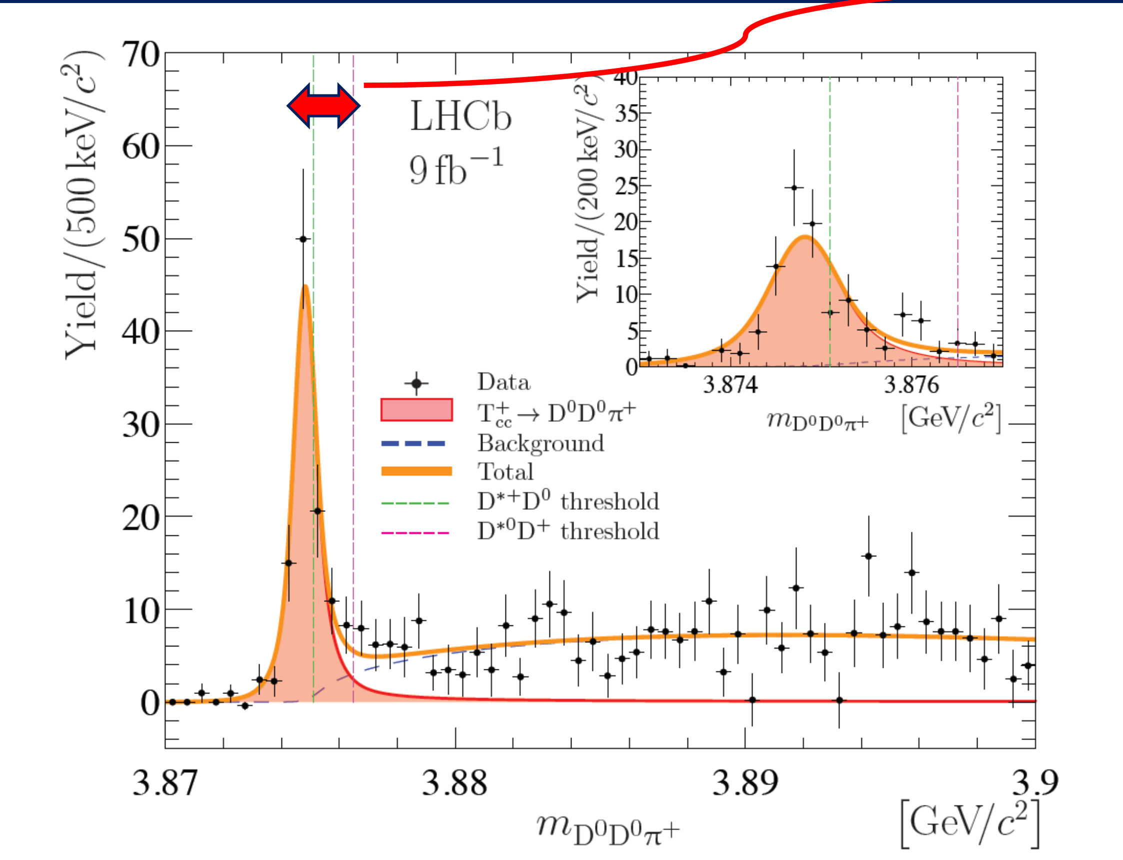
The minimal quark content for this newly observed state is $cc\bar{u}\bar{d}$

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* $D^{*+}D^0$”)

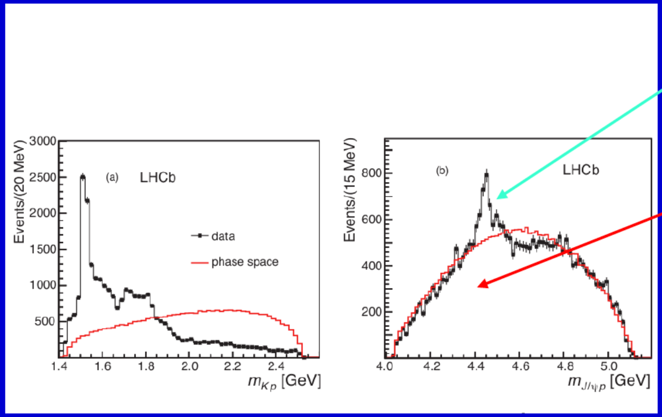
$D^{*+}D^0$ threshold is at 3875.1 MeV

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

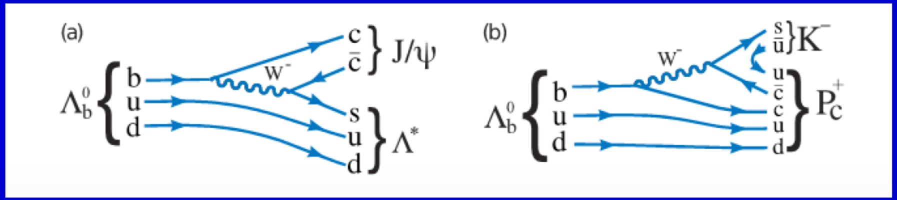
Γ =(205±18±86)MeV

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?

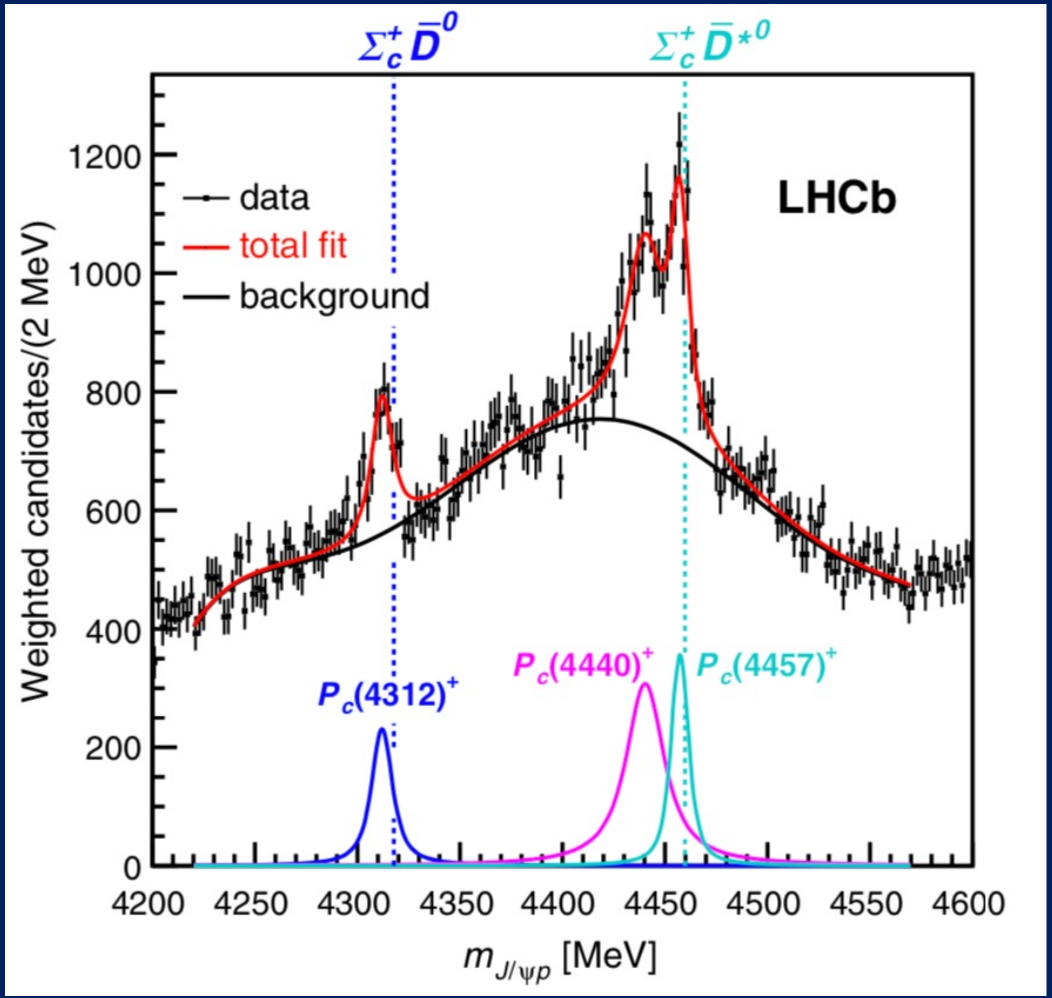
As well as revealing the new $P_c(4312)$ state with 7.3 sigma statistical significance, the LHCb 2019 analysis also uncovered a more complex structure of $P_c(4450)$, consisting of two narrow nearby separate peaks, $P_c(4440)$ and $P_c(4457)$ with the two-peak structure hypothesis having a statistical 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 ($P_c \to J/\Psi\, p$)

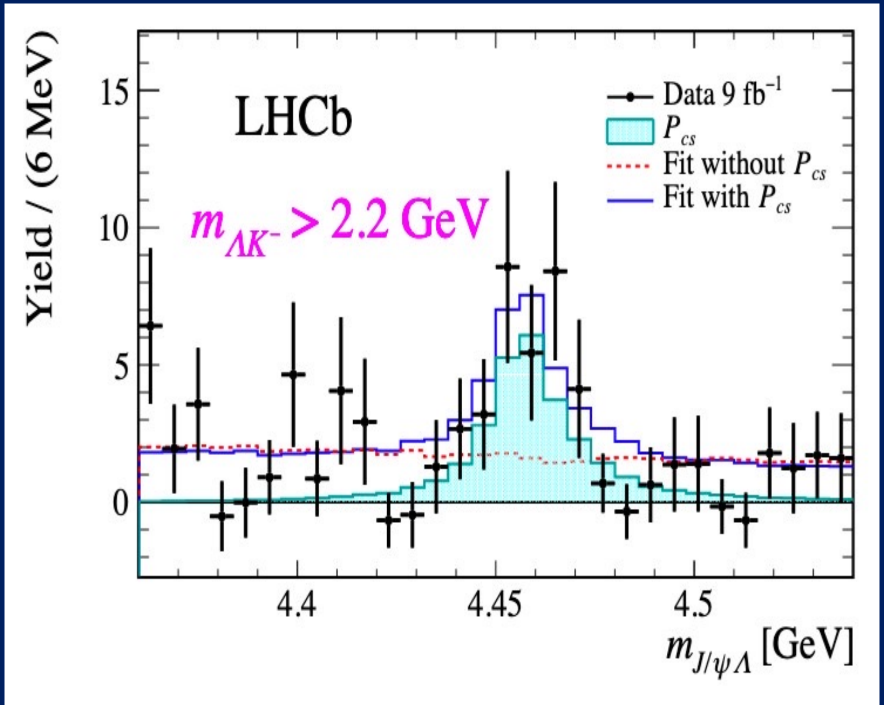


Number of events versus J/Psi p invariant mass [*]. The mass thresholds for the $\Sigma_c\, \bar{D}$ and $\Sigma_c\, \bar{D}^*$ final states are superimposed.

2021

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

(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.

- ▷ One P_{cs} state ?

$M = 4458.8 \pm 2.9^{+4.7}_{-1.1}$ MeV, $\Gamma = 17.3 \pm 6.5^{+8.0}_{-5.7}$ MeV

(below **the $\Xi_c^0 \bar{D}^{*0}$ threshold**)

- ▷ Two-peak structure hypothesis

$M_1 = 4454.9 \pm 2.7$ MeV, $\Gamma_1 = 7.5 \pm 9.7$ MeV

$M_2 = 4467.8 \pm 3.7$ MeV, $\Gamma_2 = 5.2 \pm 5.3$ MeV

Mass of $P_{cs}(4459)^0$ 19 MeV below the $\Xi_c^0\overline{D}^{*0}$ 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

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

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

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 $\boldsymbol{J^P = \frac{1}{2}^+}$

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

New

Very recently the LHCb Collaboration announced the observation of a new strange pentaquark

$\boldsymbol{P_{cs}(4338)}$ [*]

significance > 10 σ

$$M_{P_{cs}} = 4338.2 \pm 0.7 \pm 0.4\,\mathrm{MeV}$$

$$\Gamma_{P_{cs}} = 7.0 \pm 1.2 \pm 1.3\,\mathrm{MeV}$$

⇒ Spin-parity:
J = ½ determined
P = -1 favored, ½$^+$ rejected @90% CL

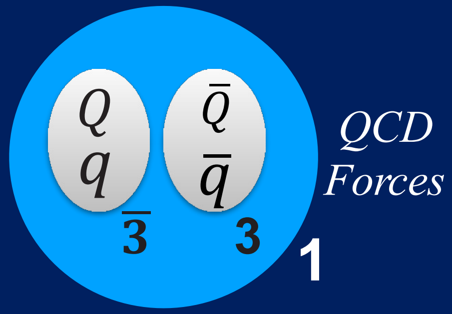
This new state has been observed in the $B^- \to J/\Psi\Lambda\bar{p}$ decay process as a resonance in $J/\Psi\Lambda$ invariant mass (minimal quark content $c\bar{c}$uds) with a statistical significance > **10 standard deviations** [*]

* E. Spadaro Norella and C. Chen (LHCb), Particle Zoo 2.0: New Tetra- and Pentaquarks at LHCb, CERN Seminar, **5th July (2022).**

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

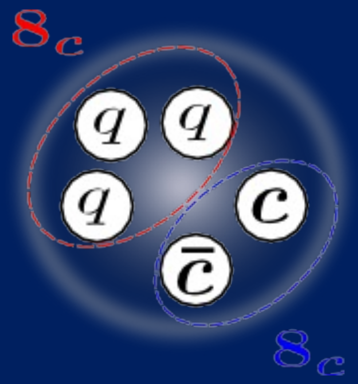
L. Maiani, F. Piccinini, A. D. Polosa and V. Riquer, Phys. Rev. **D 89** (2014) 114010.

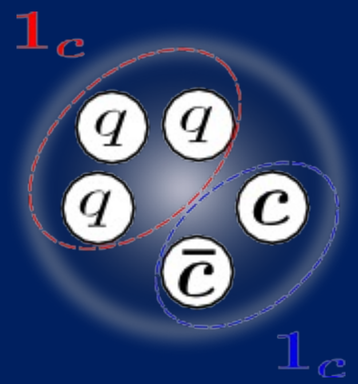
For pentaquarks

Nuclear Forces	Hadronic Molecule? $(\bar{D}\Sigma_c^*,\ \bar{D}^*\Sigma_c,...)$	JaJun Wu,R. Molina, E. Oset,B. S.Zou,PRC84(2011)015202
QCD Forces	Compact pentaquark $(5\,q)$	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, ePrint: 1604.03769.
  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

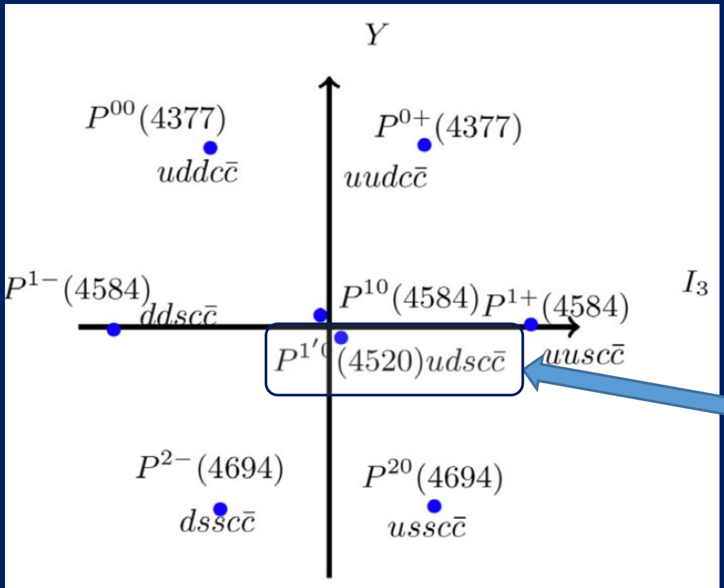
Using only simmetry considerations, and an equal spaced mass formula, we have predicted the strange pentaquark with I=0 Pcs(4457) for which LHCb reported evidence (LHCb, *Sci.Bull.* 66 (2021) 1278-1287) and suggested to look for it in the Λ J/Ψ channel (in fact cited by LHCb). According to our model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

A compact model has been proposed also in S. Takeuchi, M.Takizawa, Phys.Lett.B 764 (2017) 254-259, e-Print: 1608.05475

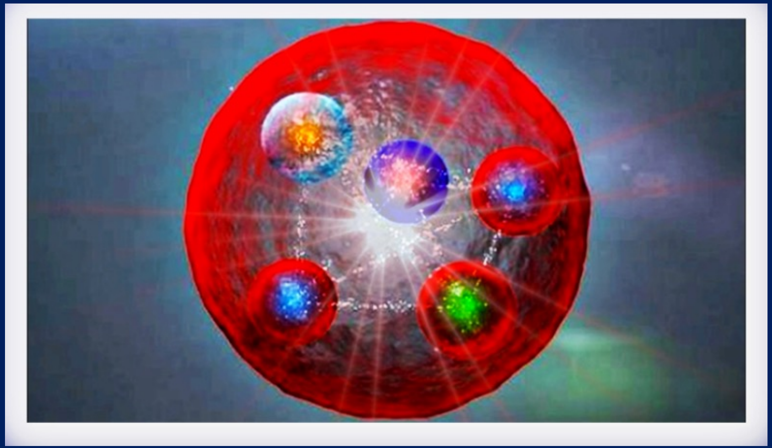
Pentaquark as compact $5q$ states

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.

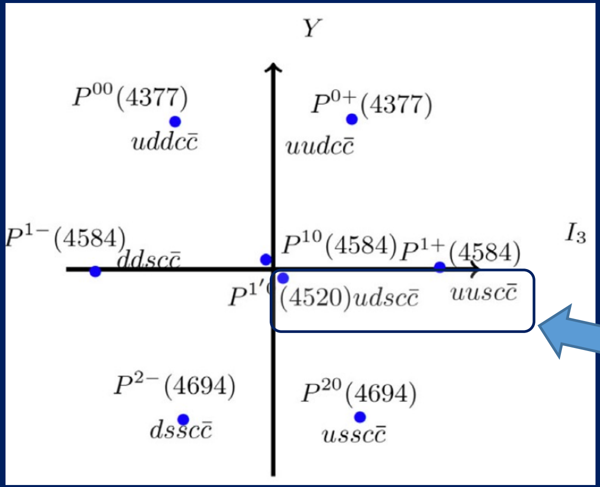
This state was also predicted in 2010 within coupled-channel unitary approach with the local hidden gauge formalism by [*]

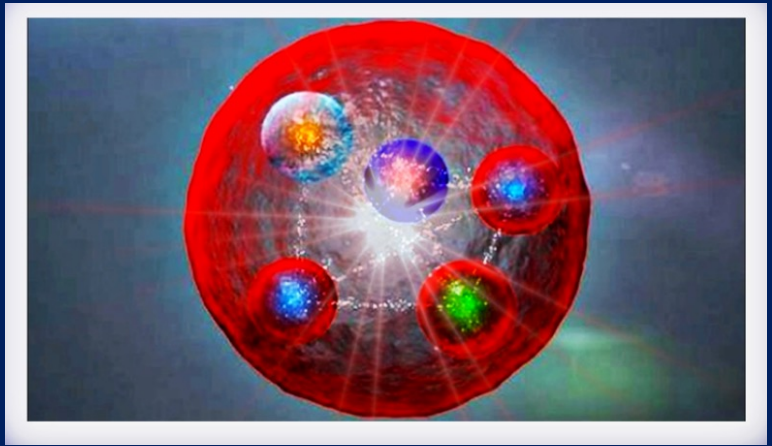
[*] Wu J-J, Molina R, Oset E, et al. Prediction of narrow N^* and Λ^* resonances with hidden charm above 4 GeV. Phys Rev Lett 2010;105:232001.

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

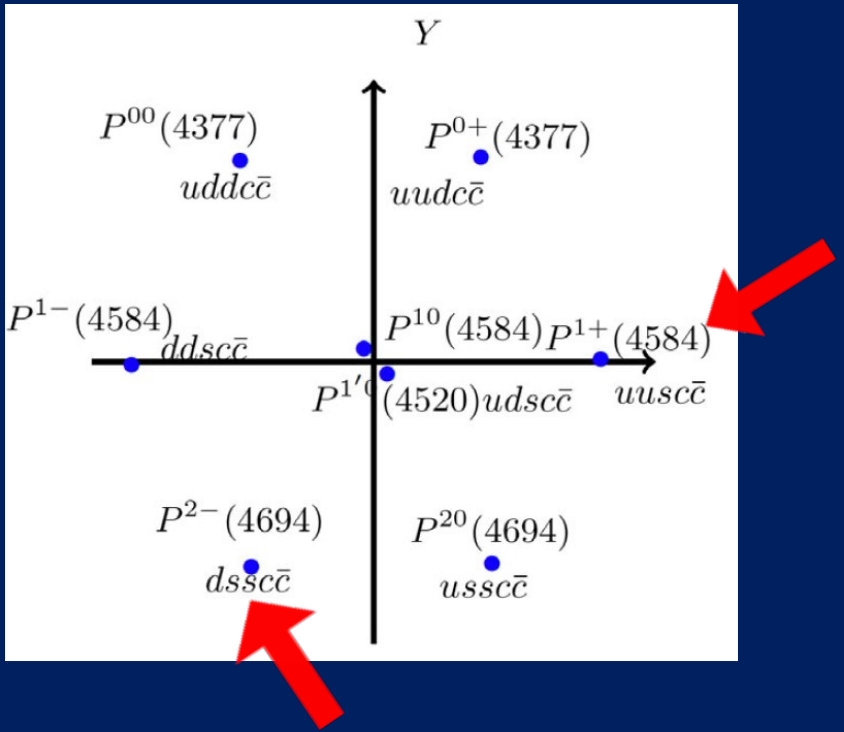
from E. Santopinto and A. Giachino, **Phys. Rev. D96** (2017) 014014.

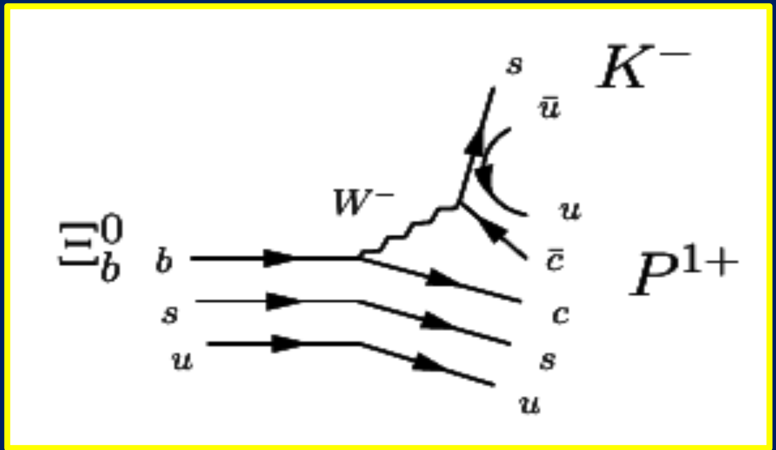
In which channels the other hidden charm pentaquarks which fill the SU(3) flavor octet can be observed?

PHYSICAL REVIEW D 96, 014014 (2017)

Compact pentaquark structures

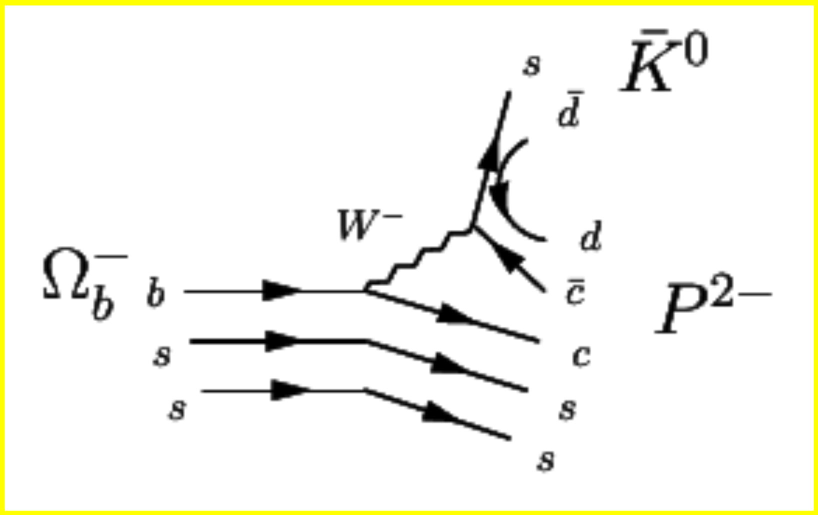
Elena Santopinto and Alessandro Giachino





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

$P^{1+}(4584)$ a $c\bar{c}uus$ state with isospin 1 so it can be observed in $J/\Psi\Sigma^+$ invariant mass spectrum in the $\Xi_b^0 \rightarrow J/\Psi\Sigma^+K^-$ decays!



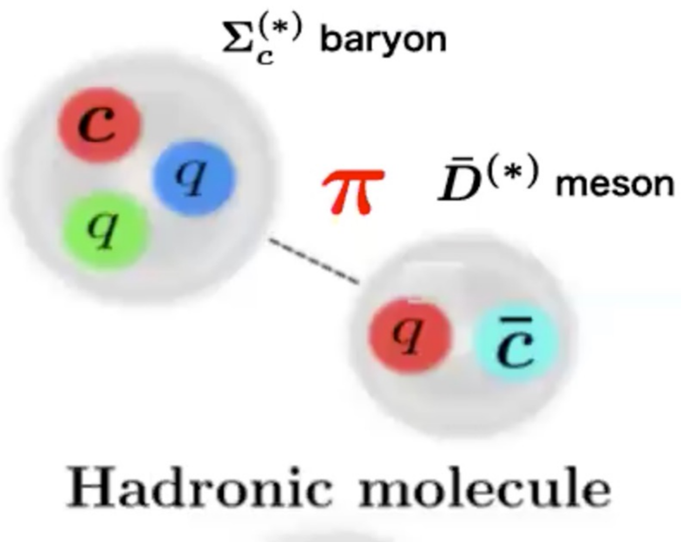
$$\Omega_b^- \rightarrow P^{2-} + \bar{K}^0, \qquad P^{2-} \rightarrow J/\Psi + \Xi^-.$$

$P^{2-}(4694)$ 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 $\Omega_b^- \rightarrow J/\Psi\Xi^-\bar{K}^0$ decays!

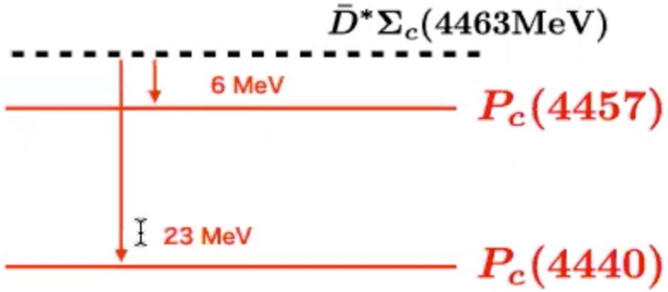
Hadronic molecules?

- 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 $\bar{D}^{(*)}\Sigma_c^{(*)}$

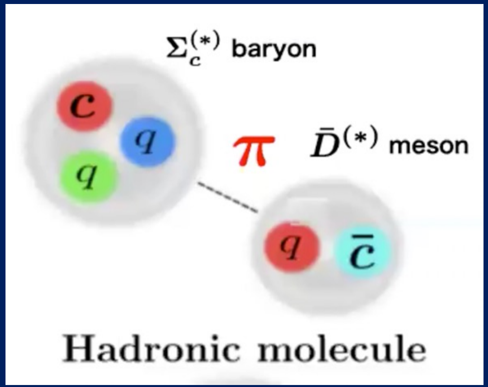
Y. Yamaguchi, E. Santopinto, Phys. Rev. D Phys.Rev. D96 (2017) no.1, 014018

This description is motivated by the fact that the observed pentaquarks are found to be just below the $\Sigma_c\bar{D}$ theshold$\left(P_c(4312)\right)$, $\Sigma_c^*\,\bar{D}$ $\left(P_c(4380)\right)$ and $\Sigma_c\bar{D}^*$ $(P_c(4440)$ and $P_c(4457))$

Near the threshold, resonances are expected to have an exotic structure, like the hadronic 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).



Similar but not equal to the work by Oset [*].

[*] Wu J-J, Molina R, Oset E, et al. Prediction of narrow N^* and Λ^* resonances with hidden charm above 4 GeV. Phys Rev Lett 2010;105:232001.

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. G., 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 charm pentaquarks as $\bar{D}\,\Lambda_c$,$\bar{D}^*\,\Lambda_c$,$\bar{D}\,\Sigma_c$,$\bar{D}^*\,\Sigma_c$,$\bar{D}\Sigma_c^*$ and $\bar{D}^*\Sigma_c^*$ 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)

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

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.

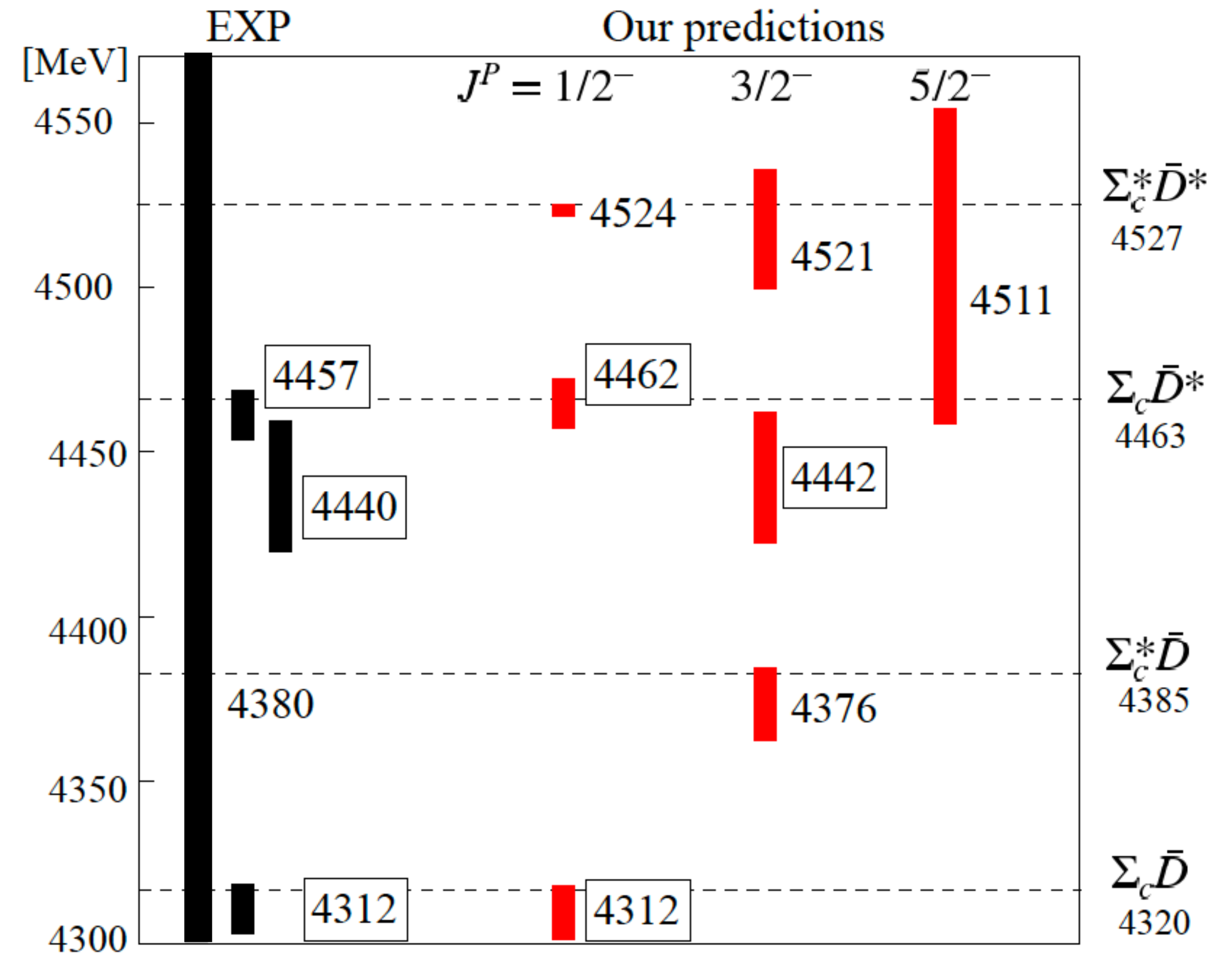
We predicted the three pentaquark states, $P_c(4312), P_c(4440)$ and $P_c(4457)$ two years before the experimental observation by LHCb.

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

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

results

Y. Yamaguchi, H. Garcia-Tecocoatzi, A. G., A. Hosaka, E. Santopinto, S. Takeuchi and M. Takizawa Phys.Rev.D **101** (2020) 091502 (R)



The predicted pentaquark masses and widths are consistent with the experimental data with the following quantum number assignments:

$$J^P(P_c(4312)) = \frac{1}{2}^-,$$

$$J^P(P_c(4440)) = \frac{3}{2}^-$$

and

$$J^P(P_c(4457)) = \frac{1}{2}^-$$

New

Very recently the LHCb Collaboration announced the observation of a new strange pentaquark $P_{cs}(4338)$ [*]

significance > 10 σ

$$M_{P_{cs}} = 4338.2 \pm 0.7 \pm 0.4\,\mathrm{MeV}$$

$$\Gamma_{P_{cs}} = 7.0 \pm 1.2 \pm 1.3\,\mathrm{MeV}$$

⇒ Spin-parity:
J = ½ determined
P = -1 favored, $½^+$ rejected @90% CL

This new state has been observed in the $B^- \to J/\Psi\Lambda\bar{p}$ decay process as a resonance in $J/\Psi\Lambda$ invariant mass (minimal quark content $c\bar{c}uds$) with a statistical significance > **10 standard deviations** [*]

* E. Spadaro Norella and C. Chen (LHCb), Particle Zoo 2.0: New Tetra- and Pentaquarks at LHCb, CERN Seminar, **5th July (2022).**

e-Print: 2209.10413 [hep-ph]

[Submitted on 21 Sep 2022]

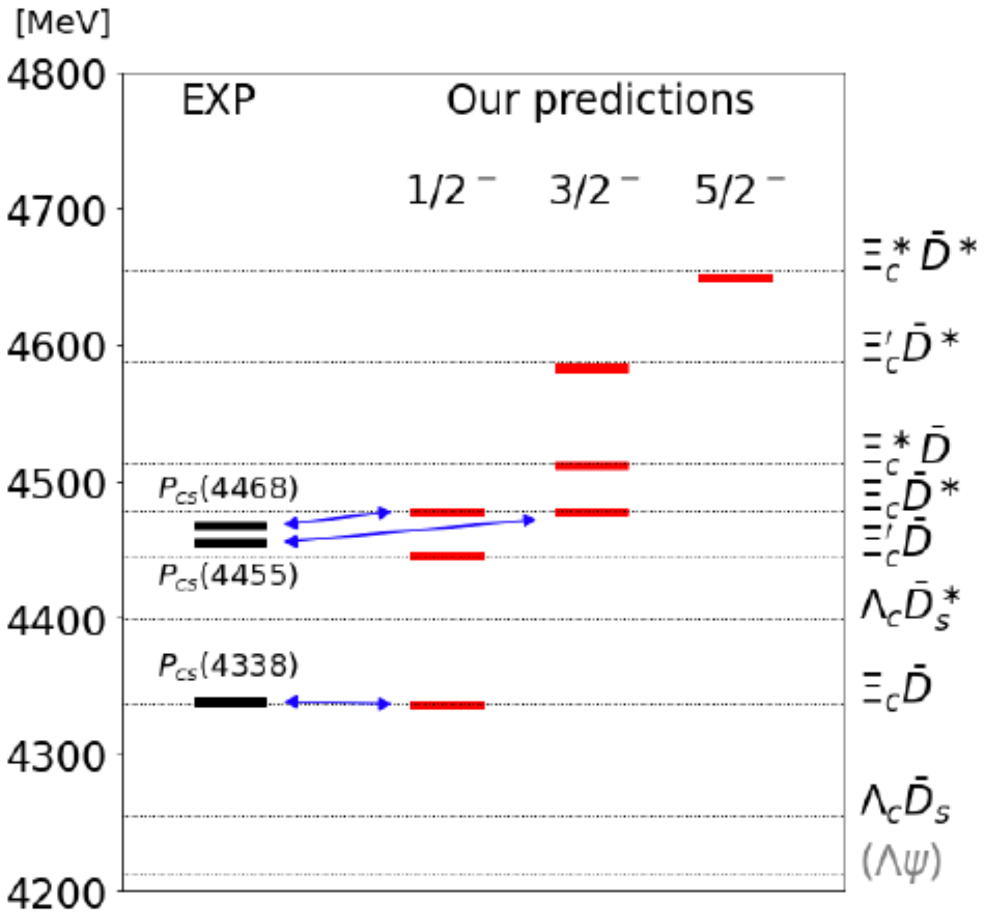
Rich structure of the hidden-charm pentaquarks near threshold regions

Alessandro Giachino, Atsushi Hosaka, Elena Santopinto, Sachiko Takeuchi, Makoto Takizawa, Yasuhiro Yamaguchi

The recent abundant observations of pentaquarks and tetraquarks by high-energy accelerator facilities indicate the realization of the conjecture by Gell-Mann and Zweig, and by De Rujula, Georgi and Glashow [1–3]. We construct a coupled-channel model for the hidden-charm pentaquarks with strangeness whose quark content is $uds c\bar{c}$, P_{cs}, described as $\Lambda_c \bar{D}_s^{(*)}, \Xi_c^{(\prime *)} \bar{D}^{(*)}$ molecules coupled to the five-quark states. These molecules are formed by the suitable cooperation of heavy quark and chiral symmetries. We reproduce the experimental mass and quantum numbers J^P of $P_{cs}(4338)$ for which LHCb has just announced the discovery. We make other predictions for new P_{cs} states as molecular states near threshold regions that can be studied by LHCb.

The results and the tecnical details were presented yesterday by Yasuhiro Yamaguchi during his talk:

Hidden-charm pentaquarks as a hadronic molecule coupled to compact multiquarks


[MeV]
4800
4700
4600
4500
4400
4300
4200
EXP
Our predictions
1/2 ⁻
3/2 ⁻
5/2 ⁻
$P_{cs}(4468)$
$P_{cs}(4455)$
$P_{cs}(4338)$
$\Xi_c^* \bar{D}^*$
$\Xi'_c \bar{D}^*$
$\Xi_c^* \bar{D}$
$\Xi_c \bar{D}^*$
$\Xi'_c \bar{D}$
$\Lambda_c \bar{D}_s^*$
$\Xi_c \bar{D}$
$\Lambda_c \bar{D}_s$
$(\Lambda\psi)$

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

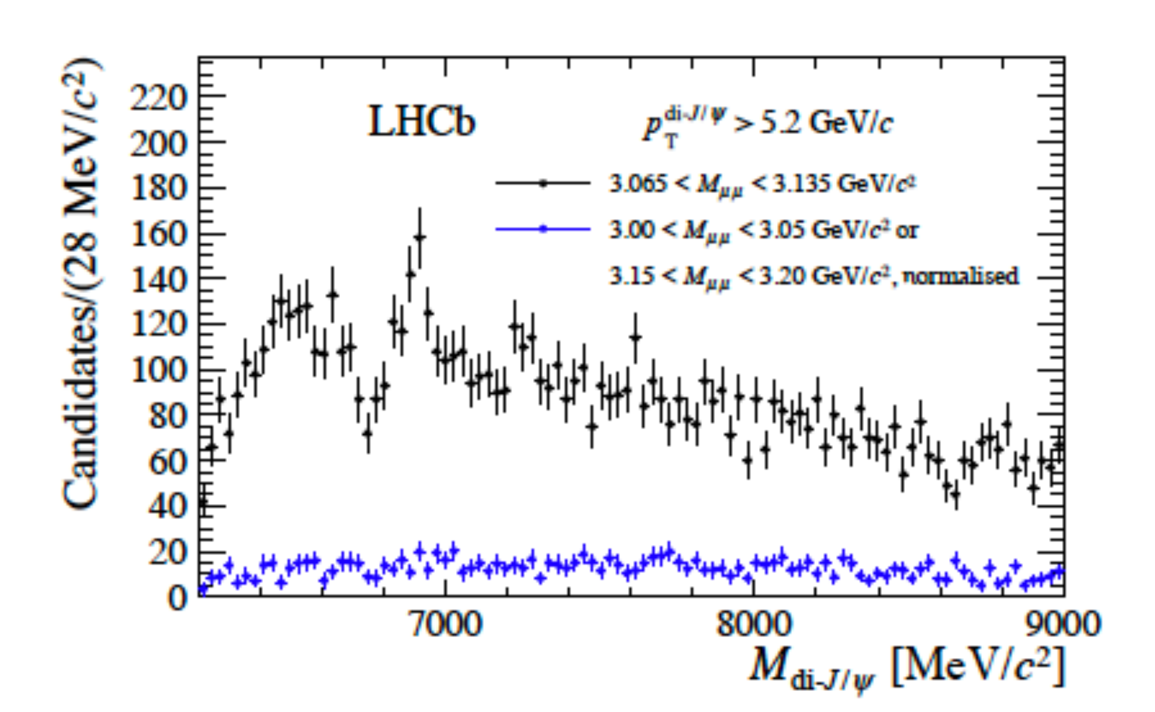
Tetraquark picture of 2 J/Ψ resonances

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)):

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

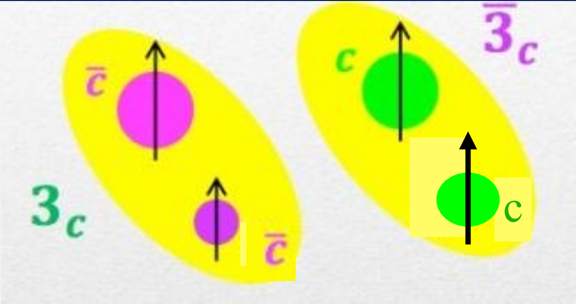
$$\Gamma[X(6900)] = 80 \pm 19 \pm 33\,\mathrm{MeV},$$

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



Tetraquark constituent picture of 2 J/Ψ resonances

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

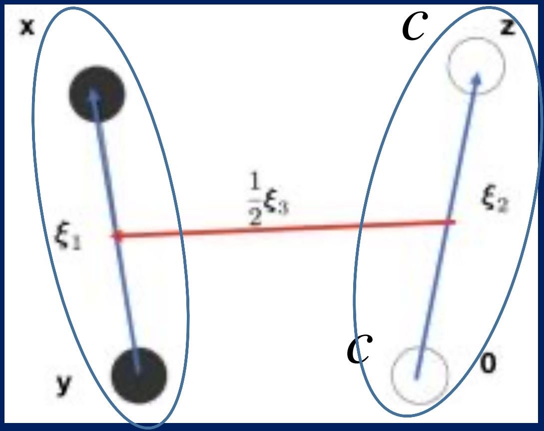


- [cc] in color $\bar{\mathbf{3}}$
- total spin of each diquark, S=1 (color antisymmetry and Fermi statistics)
- S-wave: positive parity

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

	$c c \bar{c} \bar{c}$	
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

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

- 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: $\sigma_{theo.}(\mathcal{T} \to 4\mu) \le \sigma(pp \to 2\ J/\Psi)[B(J/\Psi \to 2\ \mu)]^2$
- 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

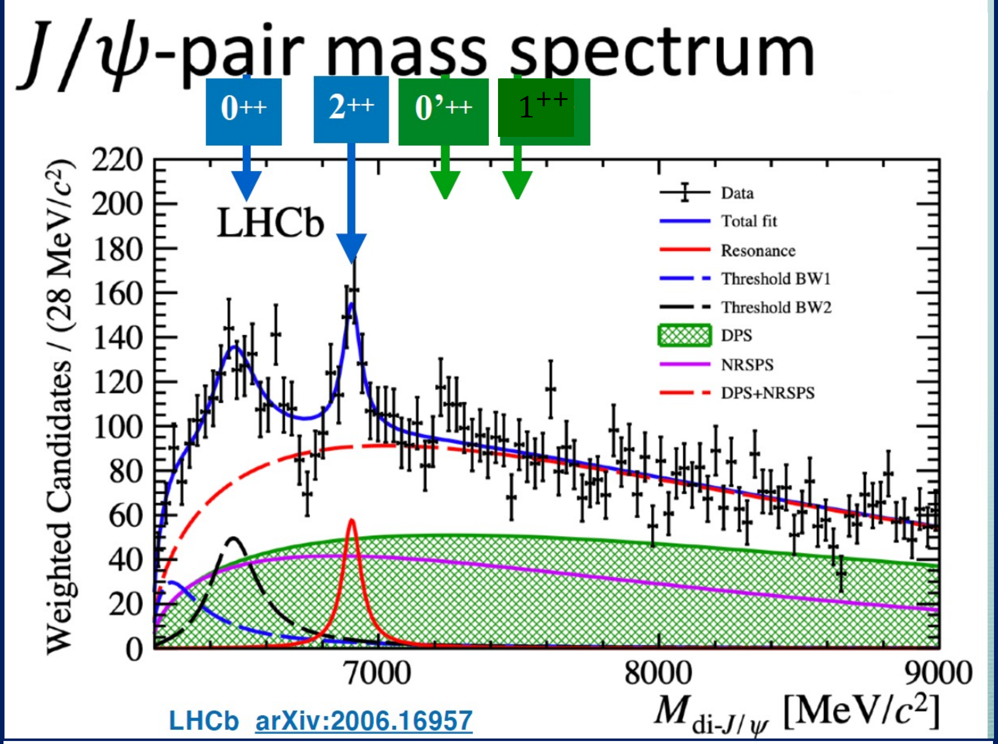
C.Becchi, J. Ferretti, A.Giachino, L.Maiani and E.Santopinto, arXiv:2006.14388, Phys.Lett. **B 811** (2020) 135952

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

$$\xi = 4.6 \pm 1.4$$

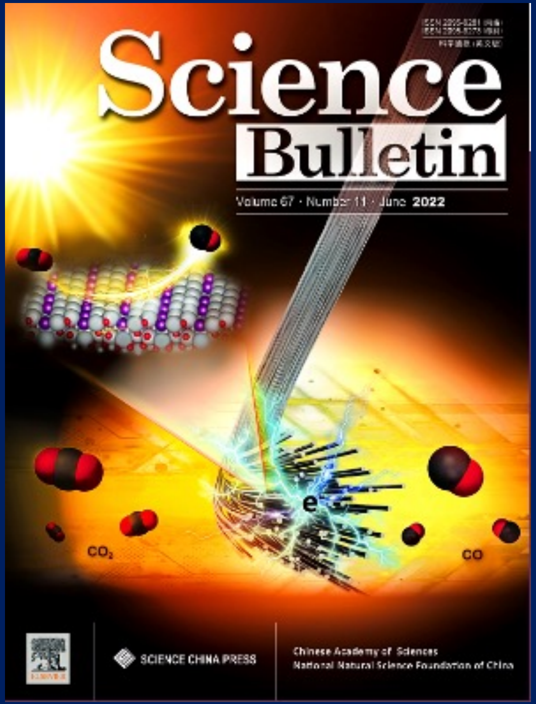
$$\Gamma(0^{++}) \cong \Gamma(2^{++}) = (97 \pm 30)\ \mathrm{MeV}$$



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 July 2022



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

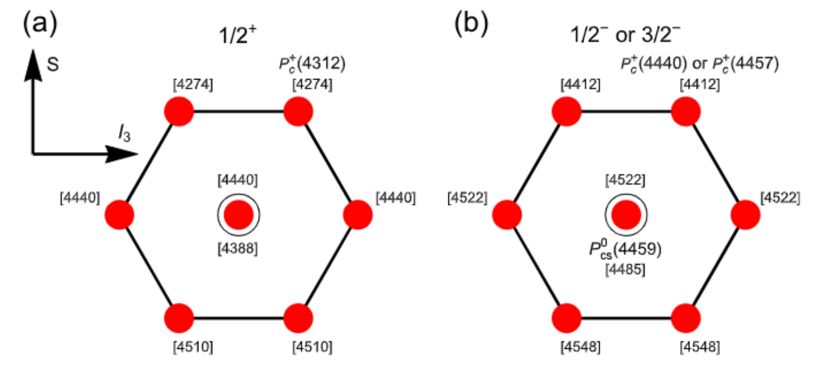
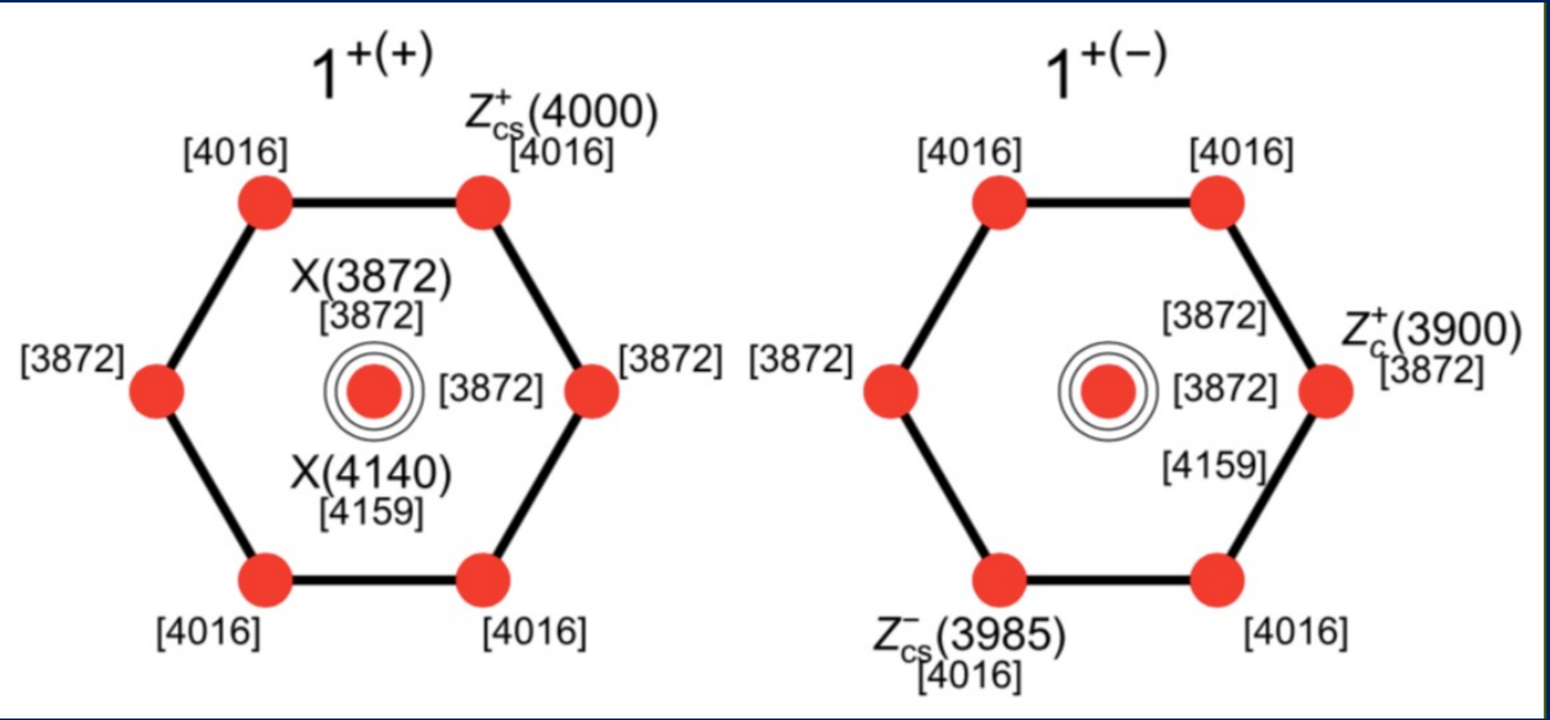


Fig. 2. (Color online) $J^P = \frac{1}{2}^+$ pentaquark octet, made up of the bound states of octet baryons plus the $\chi_{c0}(1P)$ (a), and $J^P = \frac{1}{2}^-$ or $J^P = \frac{3}{2}^-$ pentaquark octet, made up of the bound states of octet baryons plus the $\psi(2S)$ (b). The predicted hadro-charmonium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

Hidden-charm tetraquarks in the diquark-antidiquark model

M. Naeem Anwar, J. Ferretti and E. Santopinto, PRD **98**, 094015 (2018) [only tetraquarks with null strangeness]
J. Ferretti and E. Santopinto, JHEP **04**, 119 (2020) [tetraquarks with a strangeness content]
J. Ferretti and E. Santopinto, arXiv:2111.08650, accepted on Sci. Bull. [SU(3) flavor tetraquark multiplets]

If the light (*q* anti-*q*, with *q* = *u*, *d* or *s*) and heavy (*c* anti-*c*) degrees of freedom are somehow decoupled because of their large mass difference, then the tetraquark multiplet structure is provided by the light component (*c* anti-*c* being in flavor singlet) → emergence of $SU(3)_f$ multiplets in the hidden-charm sector.

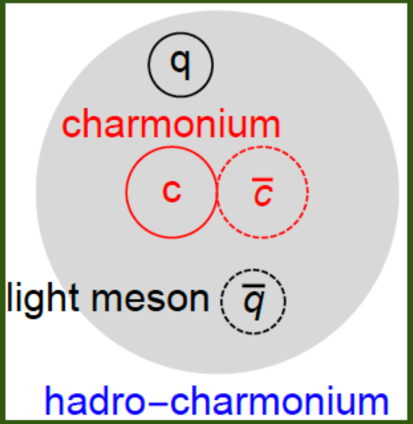


Compact tetraquark multiplets. Theoretical predictions (in square brackets) for the masses are compared to the experimental data (when available). **By C = ±1 nonets we refer to the sign of charge conjugation of the neutral-non-strange members.**

Hadro-charmonium (hadro-quarkonium) model

The idea of the hadro-charmonium model was introduced by Dubynskiy and Voloshin in Phys. Lett. B **666**, 344 (2008).

In the hadro-charmonium picture a colorless heavy quarkonium "kernel", *Q* anti-*Q*, interacts with a larger light quark "shell", *q* anti-*q* or *qqq*, through Multiple gluon-exchange forces (the QCD analogue of van der Waals forces between molecules)



Tetraquarks and pentaquarks in the hadro-charmonium model

J. Ferretti, Phys. Lett. B 782, 702 (2018)

J. Ferretti, E. Santopinto, M. Naeem Anwar and M.A. Bedolla, Phys. Lett. B **789**, 562 (2019)

J. Ferretti and E. Santopinto, JHEP **04**, 119 (2020)

$$H_{\rm hc} = M_\psi + M_\chi + V_{\rm hc}(r) + T_{\rm hc}$$

M_ψ = charmonium mass
M_χ = light baryon/meson mass
$T_{\rm hc}$ = kinetic energy
$V_{\rm hc}$ = hadro-charmonium potential

Tetraquark Z_{cs} states in the hadro-charmonium model

J. Ferretti and E. Santopinto, JHEP **04**, 119 (2020); arXiv:2111.08650, accepted on Sci. Bull.

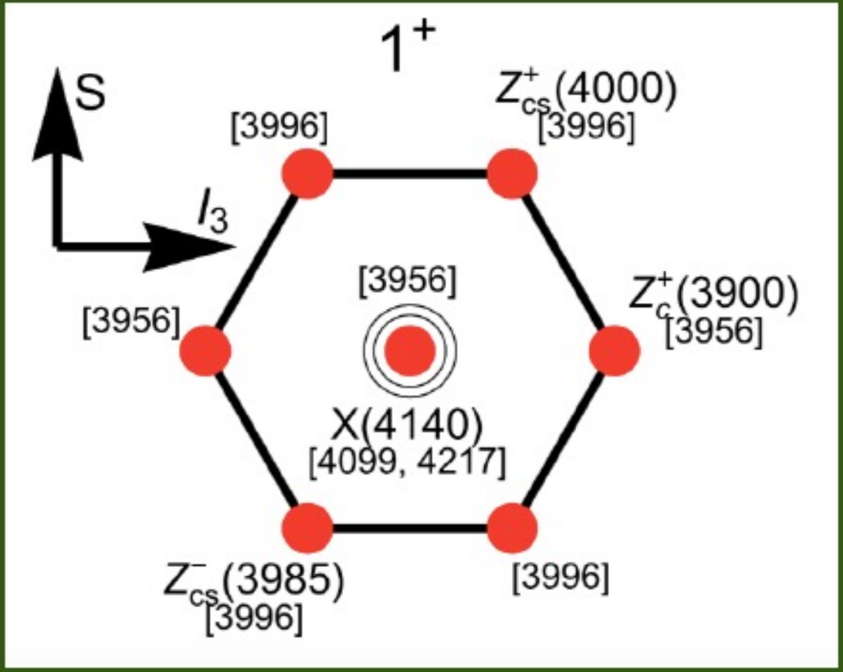
Composition	Quark content	$\alpha_{\psi\psi}(n\ell)$ [GeV^{-3}]	$J^P_{\rm tot}$	Mass (Binding) [MeV]
$\chi_{c0}(1P)\otimes K$	$n\bar{s}c\bar{c}$ ($s\bar{n}c\bar{c}$)	11	0^-	3886 (−22)
$\eta_c(2S)\otimes K$	$n\bar{s}c\bar{c}$ ($s\bar{n}c\bar{c}$)	18	0^+	3948 (−183)
$\chi_{c1}(1P)\otimes K$	$n\bar{s}c\bar{c}$ ($s\bar{n}c\bar{c}$)	11	1^-	3981 (−23)
$\psi(2S)\otimes K$	$n\bar{s}c\bar{c}$ ($s\bar{n}c\bar{c}$)	18	1^+	3996 (−184)
$h_c(1P)\otimes K$	$n\bar{s}c\bar{c}$ ($s\bar{n}c\bar{c}$)	11	1^-	3996 (−23)
$\chi_{c2}(1P)\otimes K$	$n\bar{s}c\bar{c}$ ($s\bar{n}c\bar{c}$)	11	2^-	4027 (−23)

Z_{cs}(3985) & Z_{cs}(4003)

J Ferretti, E. Santopinto (July 2022),Science Bulletin 67 (2022) 1209–1212

.

In the hadro-charmonium model there is only one multiplet with $J^P = 1^+$ → either the two Z_{cs} states belong to the same multiplet (unlikely) OR the two Z_{cs} states have a different nature (e.g. one is hadro-charmonium and the other is a molecular state)



Possibility to use the tetraquark multiplet structure (in combination with predictions for the decay widths, production cross-sections …) to discriminate among the different interpretations

How to validate or not these models in future analysis

1) The study of J^P quantum numbers (the quantum numbers are often still to be measured)

2) As written is

PHYSICAL REVIEW D **96**, 014014 (2017)

Compact pentaquark structures

Elena Santopinto and Alessandro Giachino

We observe that, if the compact pentaquark description is correct, the other octet states will also be observed by the LHC_b Collaboration. By contrast, if the pentaquark is mainly a molecular state, it is not necessary that all the states of that multiplet should exist.

by the emergence or not of complete SU(3) flavor multiplets

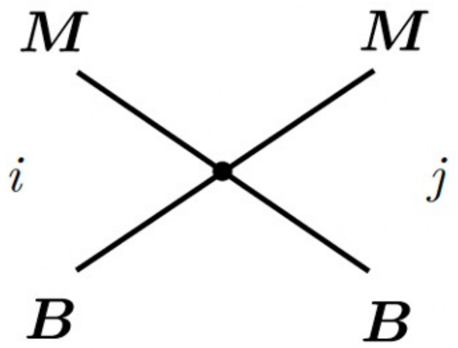
3)By studying their decays

4)By studying different production mechanisms

Thanks for your attention!

Model: 5-quark potential

- 5-quark potential $\Rightarrow$ **Local Gaussian potential** is employed.
  Massive M_{5q} (few hundred MeV above $\bar{D}^{*}\Sigma_{\rm c}^{*}$) $\rightarrow$ **Attractive**

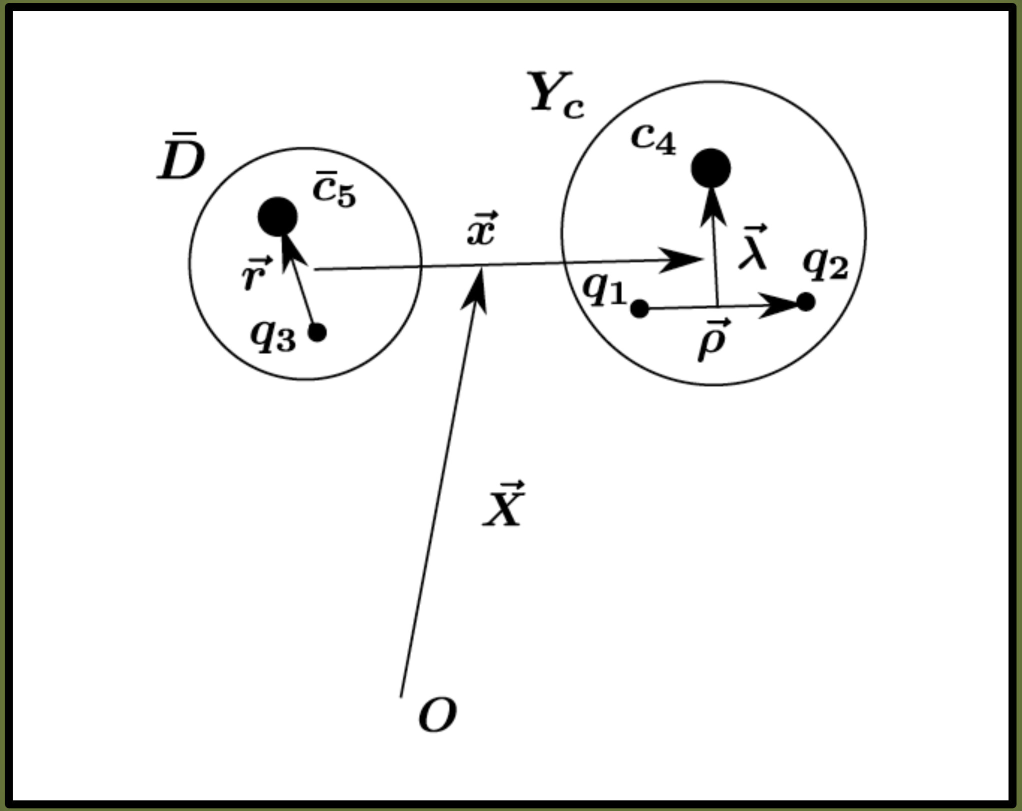


$$\Rightarrow -f S_i S_j e^{-\alpha r^2}$$

Channel $i, j = \bar{D}^{(*)}\Lambda_{\rm c},\ \bar{D}^{(*)}\Sigma_{\rm c}^{(*)}$ with $S-$wave

The Model in brief

The meson-baryon channels describe the dynamics at long distances, while the five-quark part describes the dynamics at short distances (of the order of 1 fm or less).



Free parameter $\frac{f}{f0}$

Kinetic energy and OPEP of the Meson-Baryon system

$$H = \begin{pmatrix} H^{MB} & V \\ V^{\dagger} & H^{5q} \end{pmatrix}$$

proportional to the spectroscopic factors S_i^{α}:

$$V_{ij}^{5q} = -\frac{f}{f0} \sum_{\alpha} S_i^{\alpha} S_j^{\alpha} \, e^{-Ax^2}$$

Kinetic energy and harmonic oscillator potential of the five quark states.

The Model in brief

We expressed the hidden-charm pentaquark masses and decay widths as functions of one free parameter $\frac{f}{f0}$, which is proportional to the coupling strength between the meson-baryon and 5-quark-core states

$$f_0 = C^{\pi}_{\Sigma_c \bar{D}^*}(r=0) \sim 6\ \mathrm{MeV}$$

with

$$C^{\pi}_{\bar{D}^*\Sigma_c}(r) \equiv -\frac{gg_1}{3f_\pi^2} C(r)$$

Here, $f0$ is the strength of the one-pion exchange diagonal term for the $\Sigma_c\ \bar{D}^*$ meson-

$$C(r) = \int \frac{d^3\vec{q}}{(2\pi)^3} \frac{m^2}{\vec{q}^{\,2} + m^2} e^{i\vec{q}\cdot\vec{r}} F(\Lambda, \vec{q})$$

$$V^{\pi}_{\bar{D}^*\Sigma_c - \bar{D}^*\Sigma_c}(r) = -\frac{gg_1}{3f_\pi^2}\left[\vec{S}\cdot\vec{\sigma}C(r) + S_{S\sigma}(\hat{r})T(r)\right]$$

$$H\psi = E\psi,$$

$$\psi = (\psi^{MB}, \psi^{5q}),$$

$$H = \begin{pmatrix} H^{MB} & V \\ V^{\dagger} & H^{5q} \end{pmatrix}$$

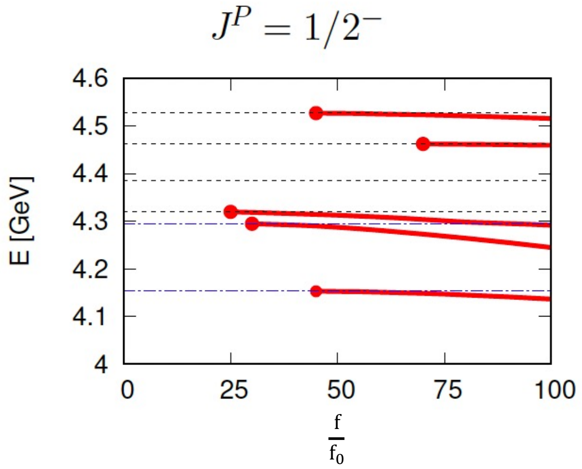
coupled equation for the MB and 5q channels

$$H^{MB}\psi^{MB} + V\psi^{5q} = E\psi^{MB},$$
$$V^{\dagger}\psi^{MB} + H^{5q}\psi^{5q} = E\psi^{5q}.$$

The BOUND AND RESONANT STATES are obtained by solving the coupled-channel Schrödinger equation with the One Pion Exchange and the five-quark potentials

Results ($\frac{f}{f_0}$ vs E) of charm $\bar{D}Y_c$ for $J^P = 1/2^-$

- Energy with $V_\pi + V^{5q}$. (Y.Y. *et al*, PRD**96** (2017), 114031)

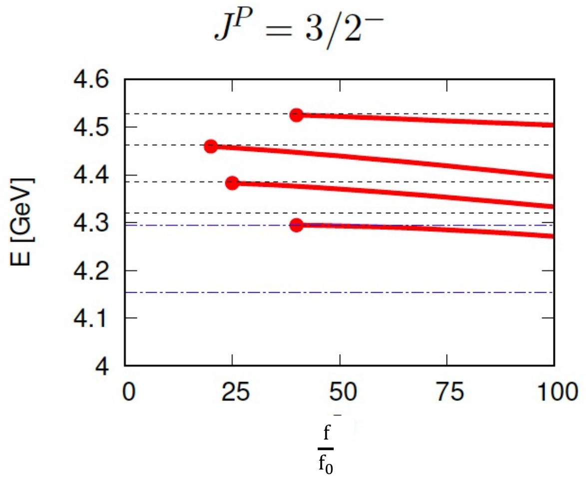


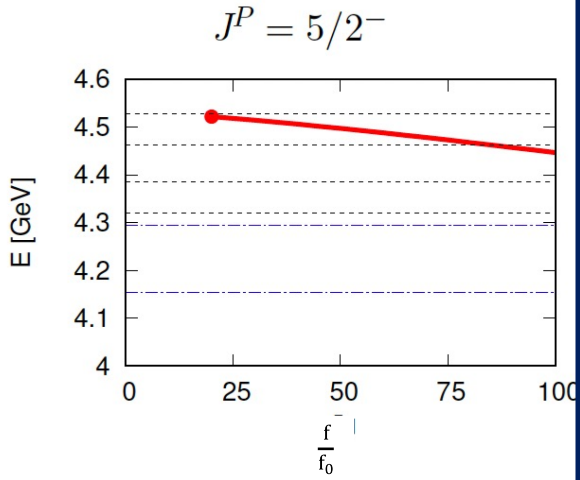
Dashed line: Thresholds, **Red line: Energy obtained**

- For small $\frac{f}{f_0}$, no resonances
  $\Rightarrow$ The OPEP attraction is not enough to generate a state
- 5q potential is necessary to generate resonances near the thresholds

Results ($\frac{f}{f_0}$ vs E) for $J^P = 3/2^-, 5/2^-$

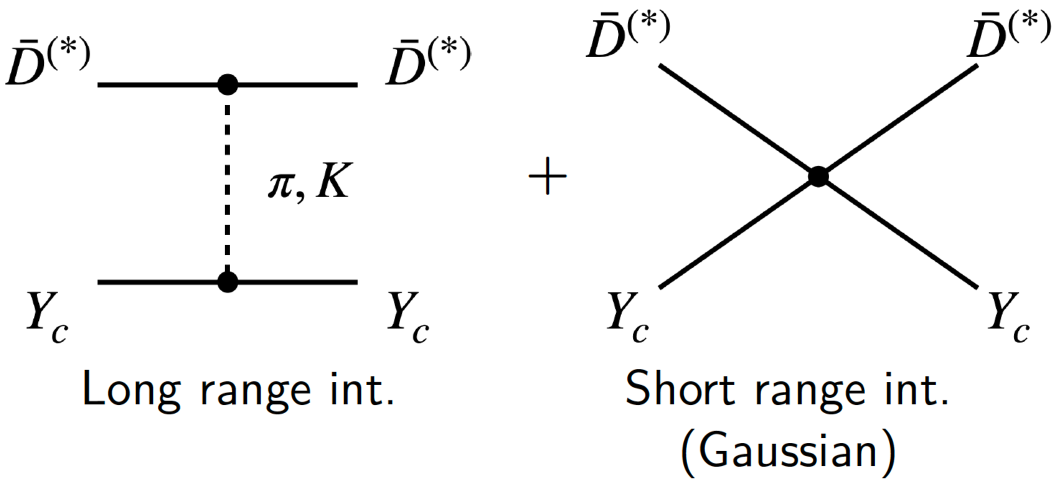
- Energy with $V_\pi + V^{5q}$ (Y.Y. *et al*, PRD**96** (2017), 114031)





- For small $\frac{f}{f_0}$ no resonances
  $\Rightarrow$ The OPEP attraction is not enough to generate a state
- 5q potential is necessary to generate resonances near the thresholds

Numerical Results for Strange Hidden Charm



Bound state and Resonance

- Coupled-channel Schrödinger equation for $\bar{D}_s\Lambda_c$, $\bar{D}_s^*\Lambda_c$, $\bar{D}\Xi_c$, $\bar{D}^*\Xi_c$, $\bar{D}\Xi_c'$, $\bar{D}\Xi_c^*$, $\bar{D}^*\Xi_c'$, $\bar{D}^*\Xi_c^*$ (8 MB components).
- Method: Gaussian expansion method + Complex scaling method
- For $J^P = 1/2^-, 3/2^-, 5/2^-$ (Negative parity)

The gluons and the meson spectrum