EXOTIC SPECTROSCOPY: FROM PENTAQUARKS TO TETRAQUARKS

VI-th Collaboration Meeting of the MPD Experiment at the NICA Facility, 28-30 October 2020,VBLHEP,JINR,Dubna,Russia

30 October 2020

Elena Santopinto

INFN Genoa

Hadron spectroscopy: lab. for QCD@ work

Bulk of mass of hadrons

Confinement

X,Y, Z, etc. new hadron states

- Finally to claim new physics also in other sectors, a precise knowledge of non perturbative QCD observables is necessary if they are involved!

1. Hidden charm hadrons reveal *tetraquarks* and *pentaquarks*

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

•Hadrons with a c-cbar or b-barb 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

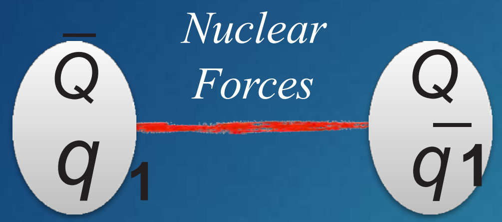
Baryons can now be constructed from quarks by using the combinations $(q\,q\,q)$, $(q\,q\,q\,q\,\bar{q})$, etc., while mesons are made out of $(q\,\bar{q})$, $(q\,q\,\bar{q}\,\bar{q})$, etc. It is assuming that the lowest

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

There are indeed new valence quark configurations !!

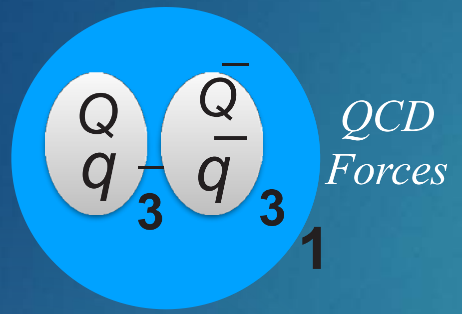
- First model of tetraquarks by R. Jaffe, as a model for the lightest scalar mesons
- Tetraquarks are more easy to find at the increase of the quark mass, just as pentaquarks
- Hidden heavy flavors have been the first, now we also have the LHCb open heavy flavor $X_0(2900)$ $J^P=0^+$ and $X_1(2900)$ $J^P=1^-$ in the $D^-\,K^+$ channel.
- First *unexpected charmonium* was the still controversial X(3872) (2003 Belle)
- 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.

No consensus, yet



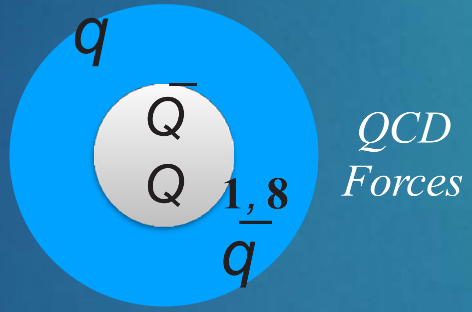
Hadron Molecule

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.



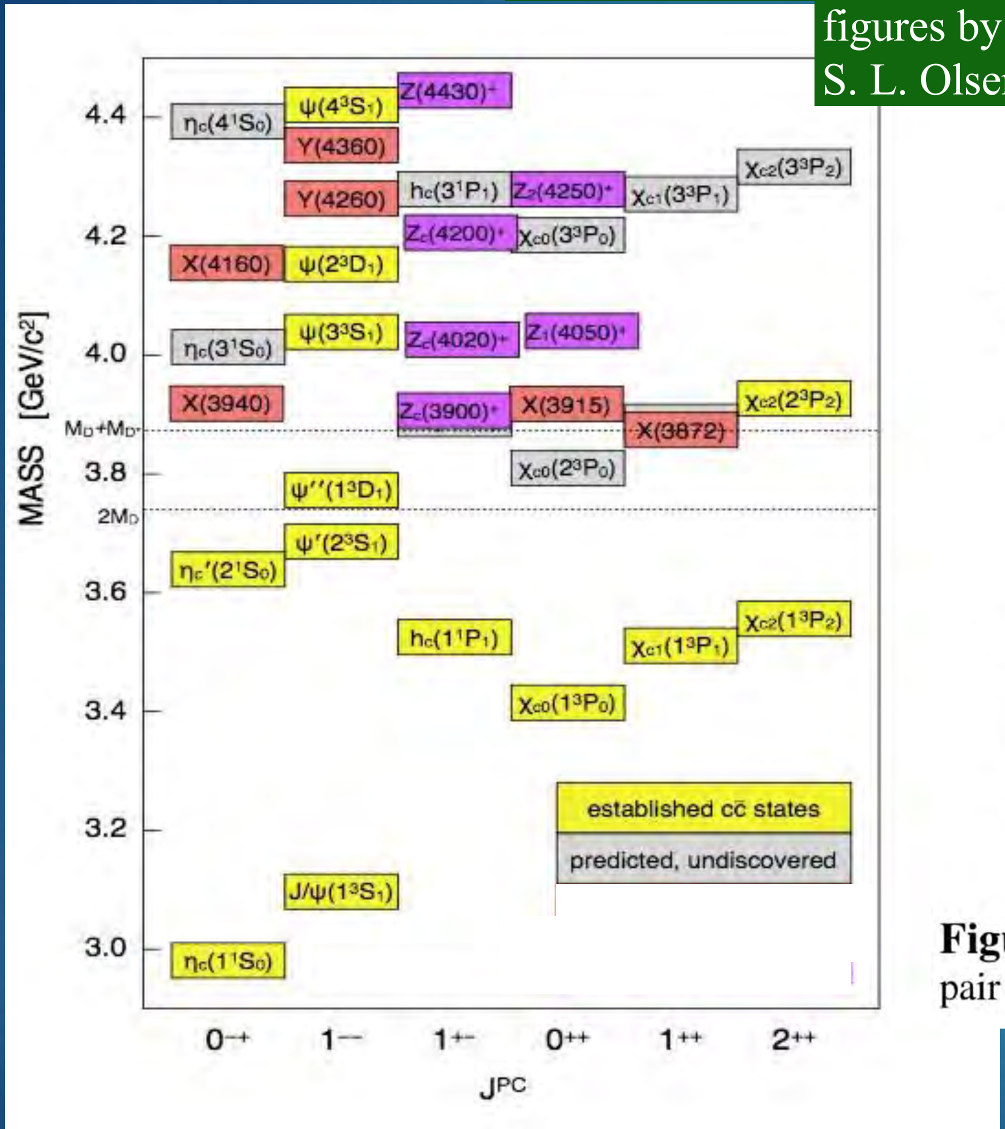
HadroCharmonium (1)
Quarkonium Adjoint Meson (8)

S. Dubynskiy, S. and M. B. Voloshin, Phys. Lett. **B 666**,(2008) 344.

E. Braaten, C. Langmack and D. H. Smith, Phys. Rev. **D 90** (2014) 01404

Expected and Unexpected Charmonia

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



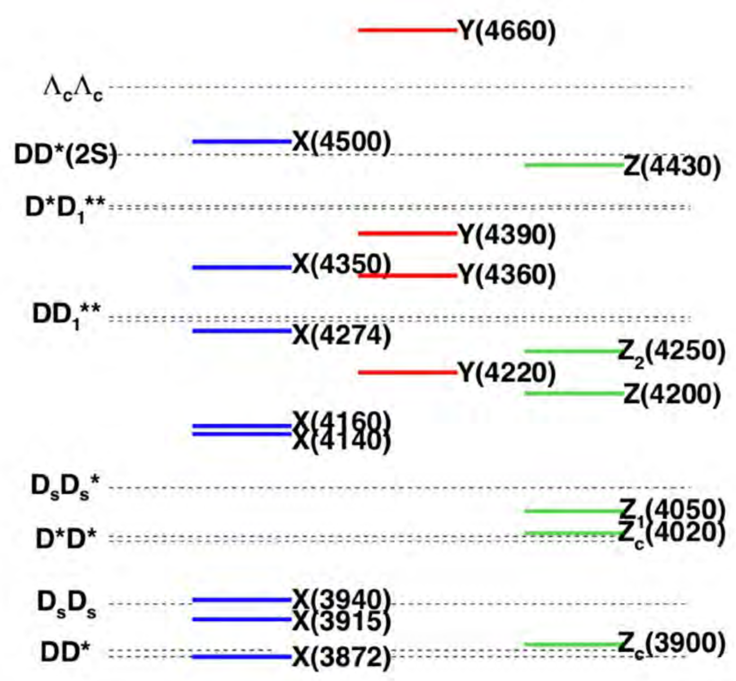
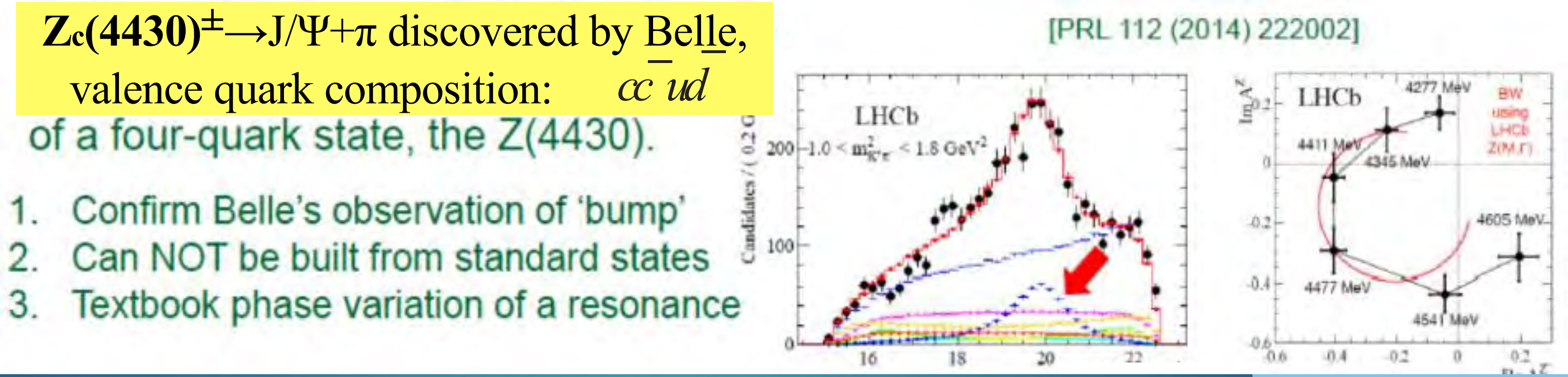


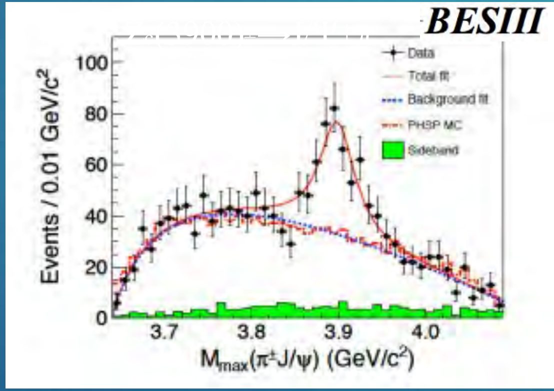
Figure 4. *XYZ* meson masses compared with charmed meson pair thresholds.

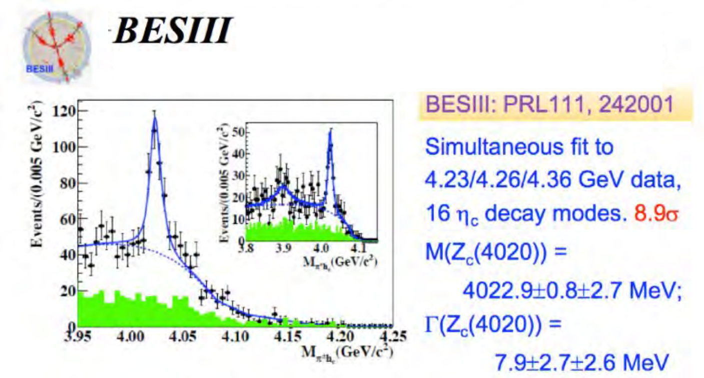
Explicit Tetraquarks

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



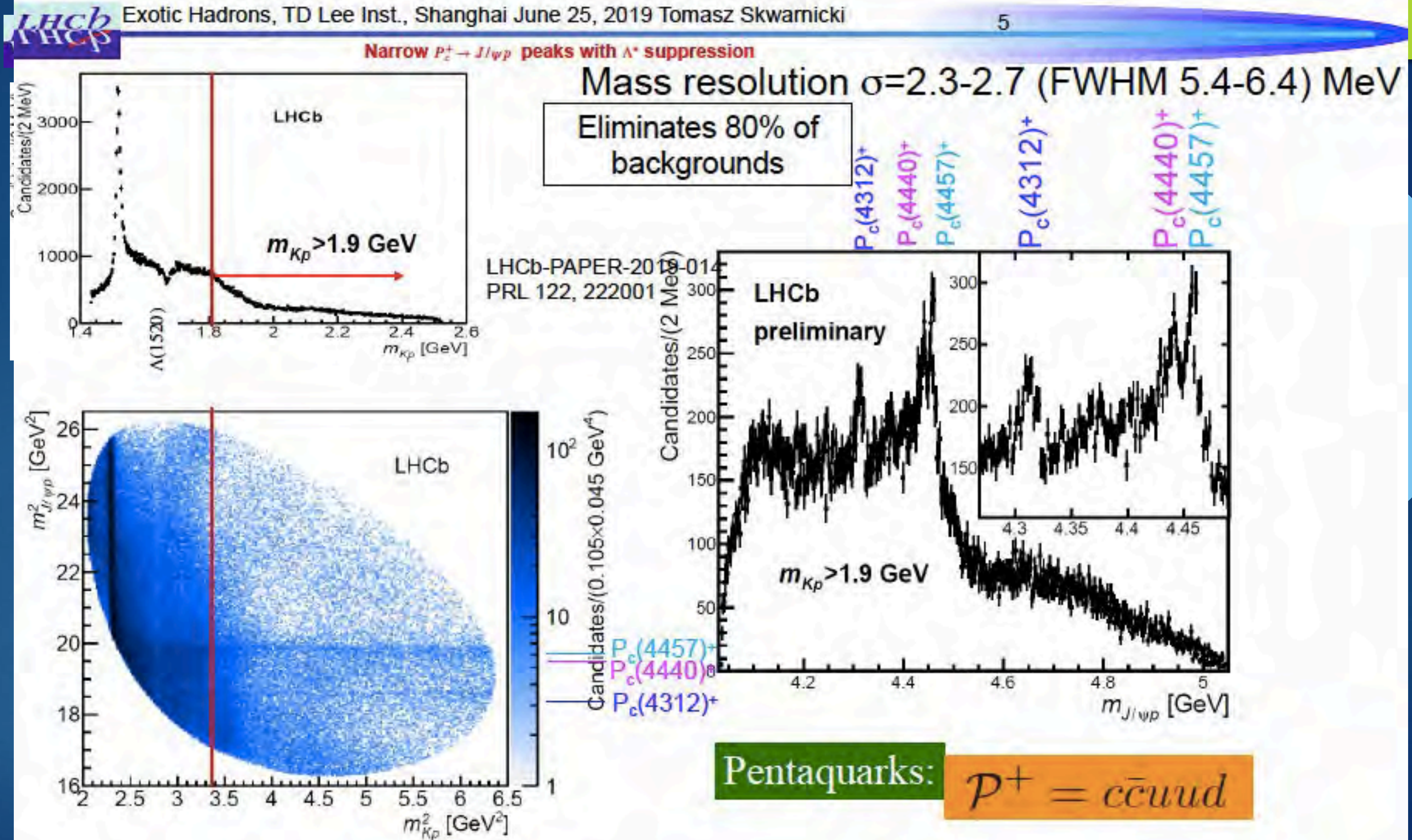
"Observation of the resonant character of the Z(4430)− state". *Physical Review Letters*. **112** (22): 222002.





More new valence quark configurations

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



Pentaquarks: $\mathcal{P}^+ = c\bar{c}uud$

Part 1: Pentaquark states

- The pentaquark as a compact five quark state [1]

The penataquark states as meson baryon molecuies [2]

- Hidden-charm and -bottom meson baryon molecules coupled with five-quark states [3], [4]
- Heavy quark spin symmetry with chiral tensor dynamics in lights of the recent LHCb Pentaquarks [5]

[1] E. Santopinto, A. Giachino, **Phys. Rev. D 96, 014014 (2017);**
[2] Y. Yamaguchi, E. Santopinto, **Phys. Rev. D Phys.Rev. D96 (2017) no.1, 014018**

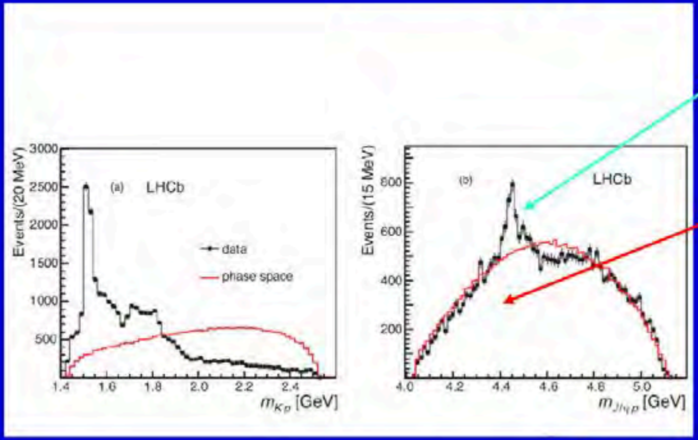
[3] Y. Yamaguchi, A. Giachino, A. Hosaka, E. Santopinto, S. Takeuchi, M. Takizawa, **Phys. Rev. D 96, 114031 (2017)**

[4] Y. Yamaguchi, H. Garcia-Tecocoatzi, A. Giachino, A. Hosaka, E. Santopinto, S. Takeuchi and M. Takizawa, **Few-Body Systems, DOI: 10.1007/978-3-030-32357-8_98 (2019)**

[5] Y. Yamaguchi, H. Garcia-Tecocoatzi, A. Giachino, A. Hosaka, E. Santopinto, S. Takeuchi and M. Takizawa arXiv:1907.04684**, accepted as Physical Review D Rapid Communication, April 2020**

Why pentaquark states?

LHCb
Phys. Rev. Lett.115(2015) 072001



M _P$_c^+$(4450) = (4449.8 ± 8 ± 29)MeV
Γ = (39 ± 5 ± 19) MeV

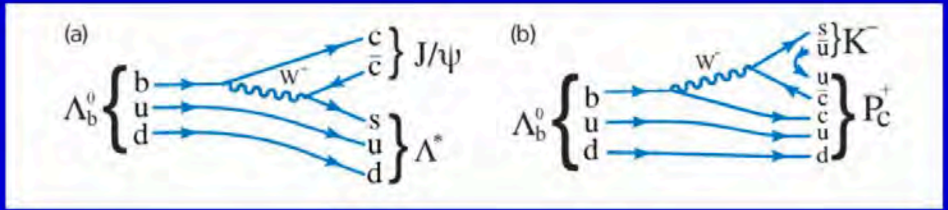
M_P$_c^+$(4380) = (4380 ± 1.7 ± 2.5)MeV

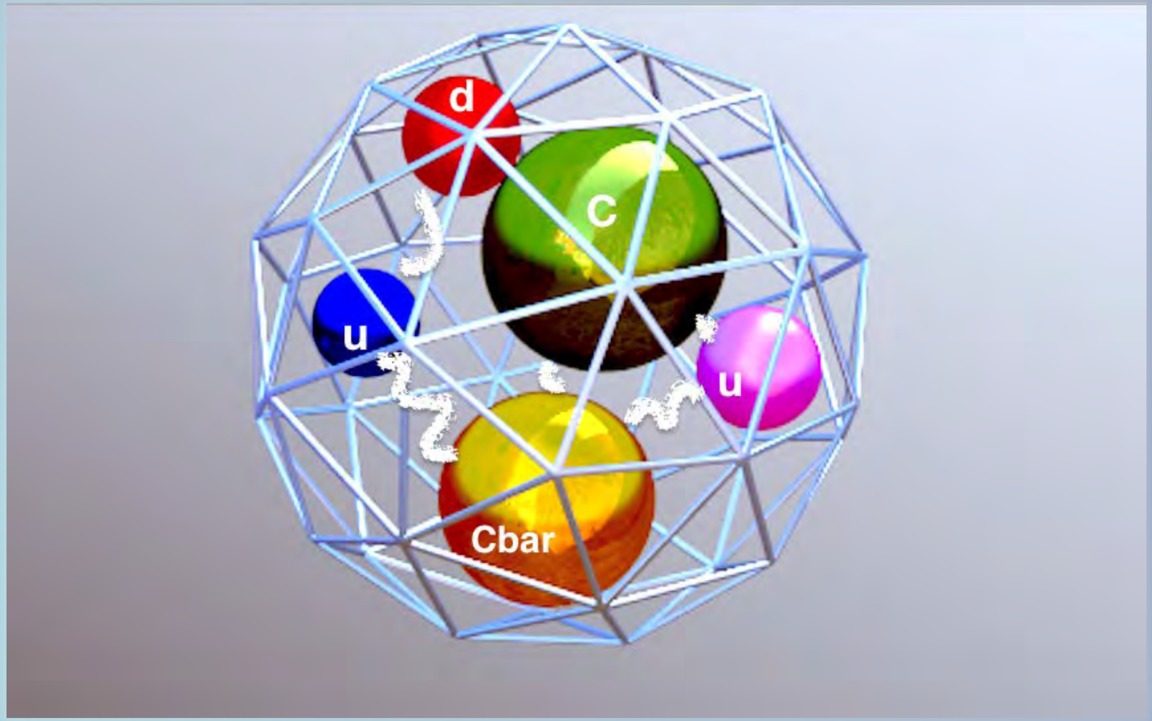
Γ =(205±18±86)MeV

statistic significance greater then 9 sigma !

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

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

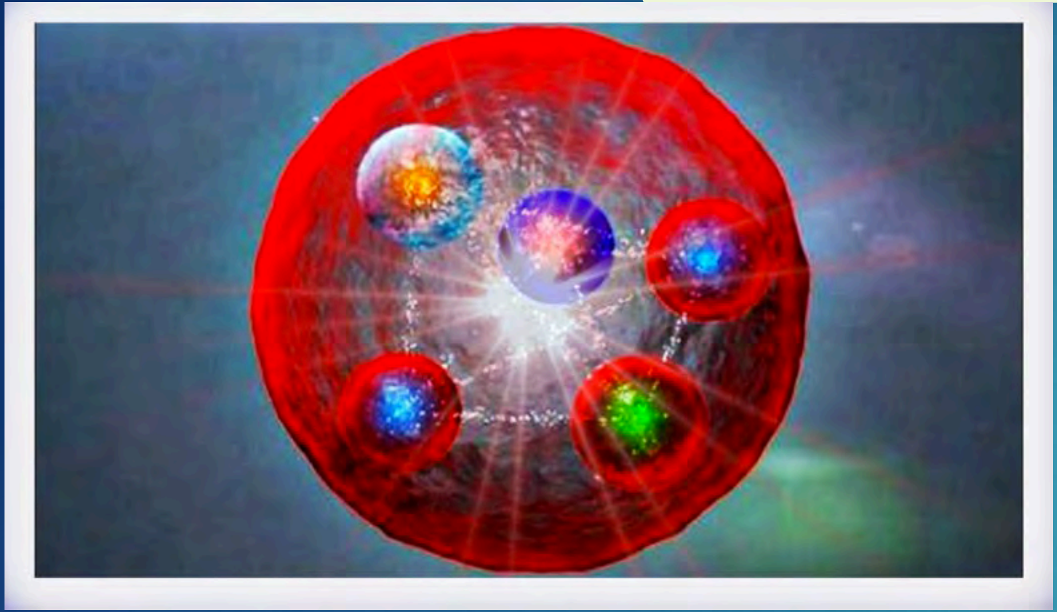




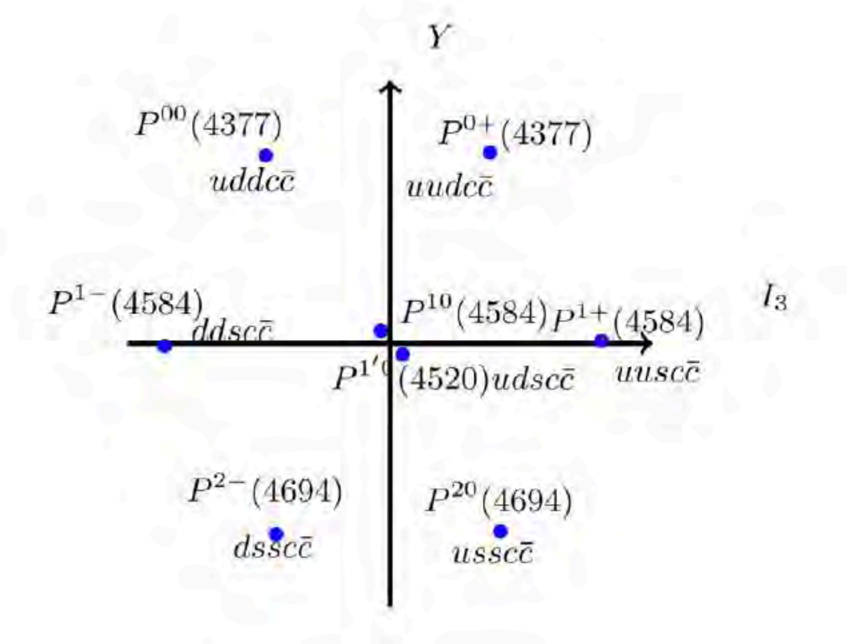
The LHCb observation [1] was further supported by another two articles by the same group [2,3]:

[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

The pentaquark as a compact five quark state [1]



- Using group theory techniques we found that the compact pentaquark states belong to to an SU(3) flavour octet.
- The masses of the octet pentaquark states were calculated by means of a Gürsey-Radicati mass formula extension.



- The partial decay widths were calculated by means of an effective Lagrangian:

$$\mathcal{L}^{3/2^\pm}_{PNJ/\psi} = i\bar{P}_\mu \left[\frac{g_1}{2M_N} \Gamma^\pm_\nu N \right] \psi^{\mu\nu} - i\bar{P}_\mu \left[\frac{ig_2}{(2M_N)^2} \Gamma^\pm \partial_\nu N + \frac{ig_3}{(2M_N)^2} \Gamma^\pm N \partial_\nu \right] \psi^{\mu\nu} + \text{H.c.}$$

where:

$$\Gamma^\pm_\nu = \begin{pmatrix} \gamma_\nu \gamma_5 \\ \gamma_\nu \end{pmatrix}, \Gamma^\pm = \begin{pmatrix} \gamma_5 \\ 1 \end{pmatrix}$$

Taking the $J^P = \frac{3}{2}^-$ case in the effective lagrangian, we obtained the following partial decay widths:

Initial state	Channel	Partial width [MeV]
$P^{1'0}$	$\Lambda J/\Psi$	7.94
P^{1-}, P^{10}, P^{1+}	$\Sigma J/\Psi$	7.21
P^{2-}, P^{20}	$\Xi J/\Psi$	6.35

[1] E. Santopinto, A. Giachino, **PHYSICAL REVIEW D 96, 014014 (2017);**

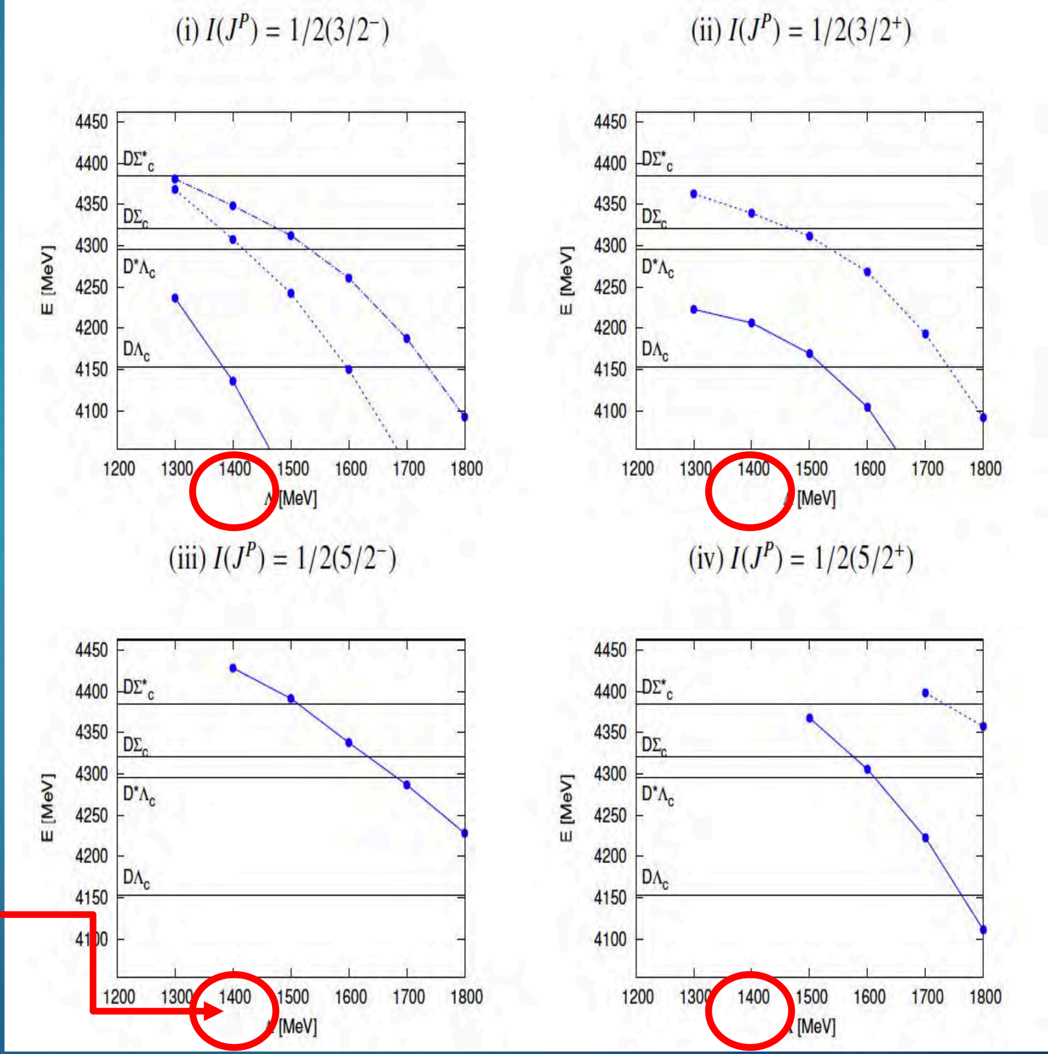
Hidden-charm pentaquarks as a meson-baryon molecule with coupled channels for $\bar{D}^{(*)}\Lambda_c$ and $\bar{D}^{(*)}\Sigma_c$

Y. Yamaguchi, E. S., 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).

- In particular the bound and resonant states with $J^P = \frac{3}{2}^+, \frac{3}{2}^-, \frac{5}{2}^+$ and $\frac{5}{2}^-$ with isospin $I = \frac{1}{2}$ are studied by solving the coupled channel Schrödinger equations.
- Free parameter of the model: the cut-off parameter Λ ;
- Λ is fixed to reproduce the heaviest resonant



Coupled channel between the meson-baryon states

results

Λ [MeV]	1300	1400	1500	1600	1700	1800
$J^P = 3/2^-$	$4236.9 - i0.8$	4136.0	4006.3	3848.2	3660.0	3438.26
	$4381.3 - i11.4$	$4307.9 - i18.8$	$4242.6 - i1.4$	4150.1	4035.2	3897.3
	$4368.5 - i64.9$	$4348.7 - i21.1$	$4312.7 - i16.0$	$4261.0 - i7.0$	$4187.7 - i0.9$	4092.5
$J^P = 3/2^+$	$4223.0 - i97.9$	$4206.7 - i41.2$	$4169.3 - i5.3$	4104.2	3996.7	3855.8
	$4363.3 - i57.0$	$4339.7 - i26.8$	$4311.8 - i6.6$	$4268.5 - i1.3$	$4193.2 - i0.1$	4091.6
$J^P = 5/2^-$	—	$4428.6 - i89.1$	$4391.7 - i88.8$	$4338.2 - i56.2$	$4286.8 - i27.3$	$4228.3 - i7.4$
$J^P = 5/2^+$	—	—	$4368.0 - i9.2$	$4305.8 - i1.9$	$4222.7 - i1.4$	4111.1
	—	—	—	—	$4398.5 - i15.0$	$4357.8 - i8.2$

Good agreement for the mass and quantum numbers of the lightest pentaquark $P_c^+(4380)$

The masses and widths of the two observed pentaquark states; BE AWARE: the mass of the lightest one is a prediction, while the mass of the heaviest is fitted to fix the cut-off parameter Λ

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**

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

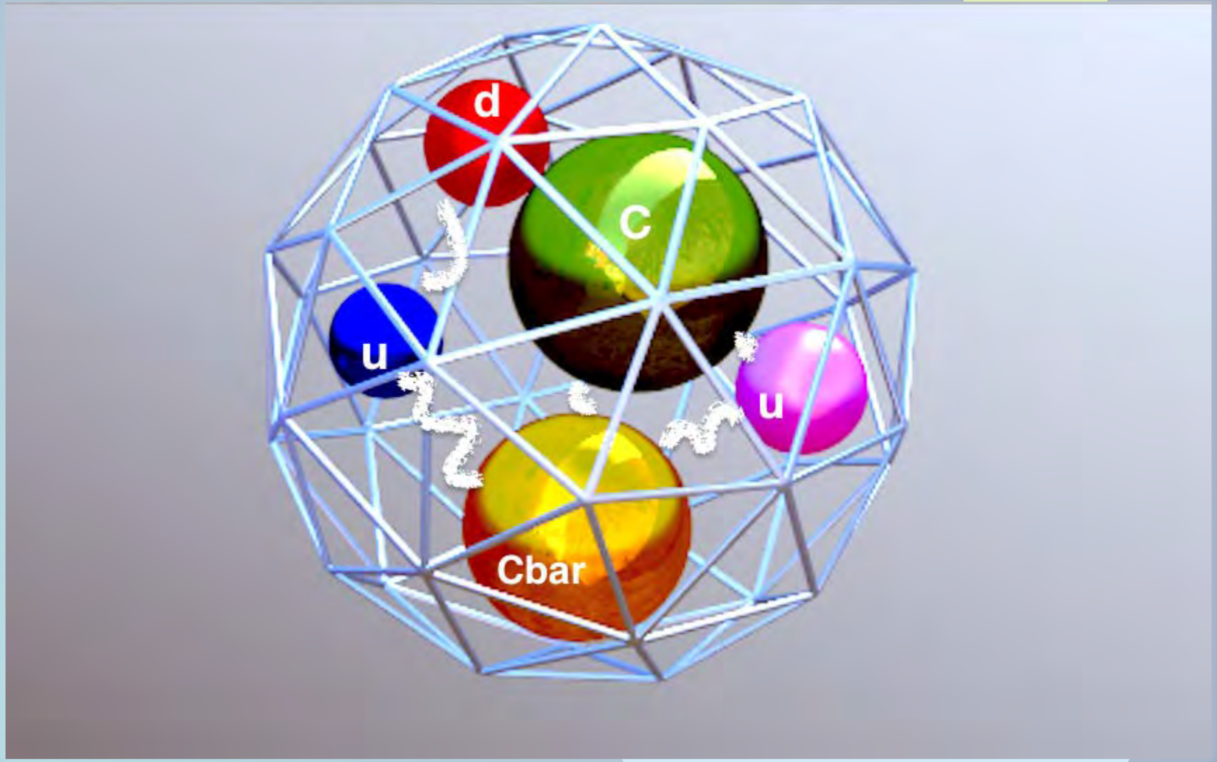
ADDITION OF THE CORE CONTRIBUTION

- 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

Recently a new analysis has been reported [4] using nine times more data from the Large Hadron Collider than the 2015 analysis

When this combined dataset is fit with the same amplitude model used in Ref. [1], the $P_c(4380)$ and $P_c(4450)$ parameters are found to be consistent with the previous results.



[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

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

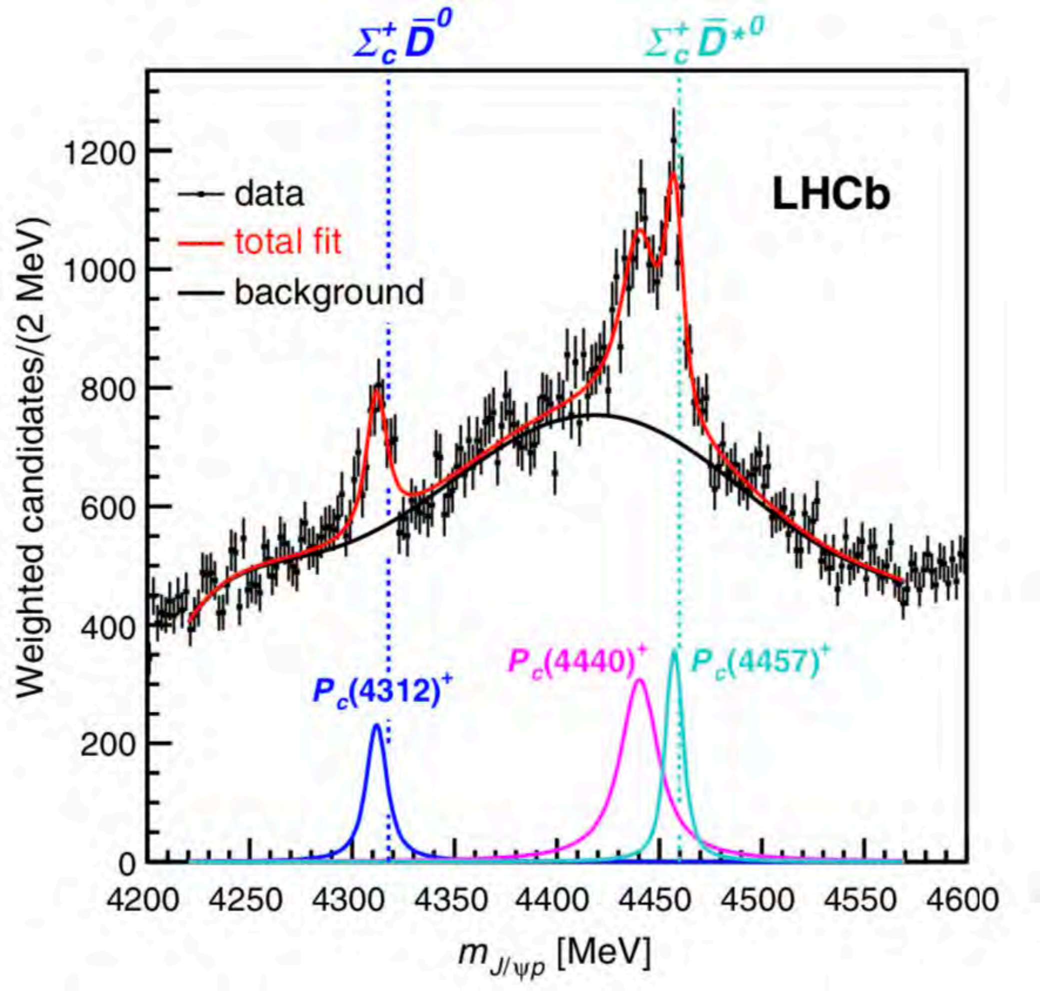
Why pentaquark states?

As well as revealing the new $P_c(4312)$ state, the 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]
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+3.7}_{-4.5}$
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+8.7}_{-10.1}$
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+5.7}_{-1.9}$

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



Number of events versus J/Psi p invariant mass [4]. The mass thresholds for the $\Sigma_c\,\bar{D}$ and $\Sigma_c\,\bar{D}^*$ final states are superimposed.

Hidden-charm and bottom meson-baryon molecules coupled with five-quark states [3], [4]

- In Refs. [3] , [4] 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.

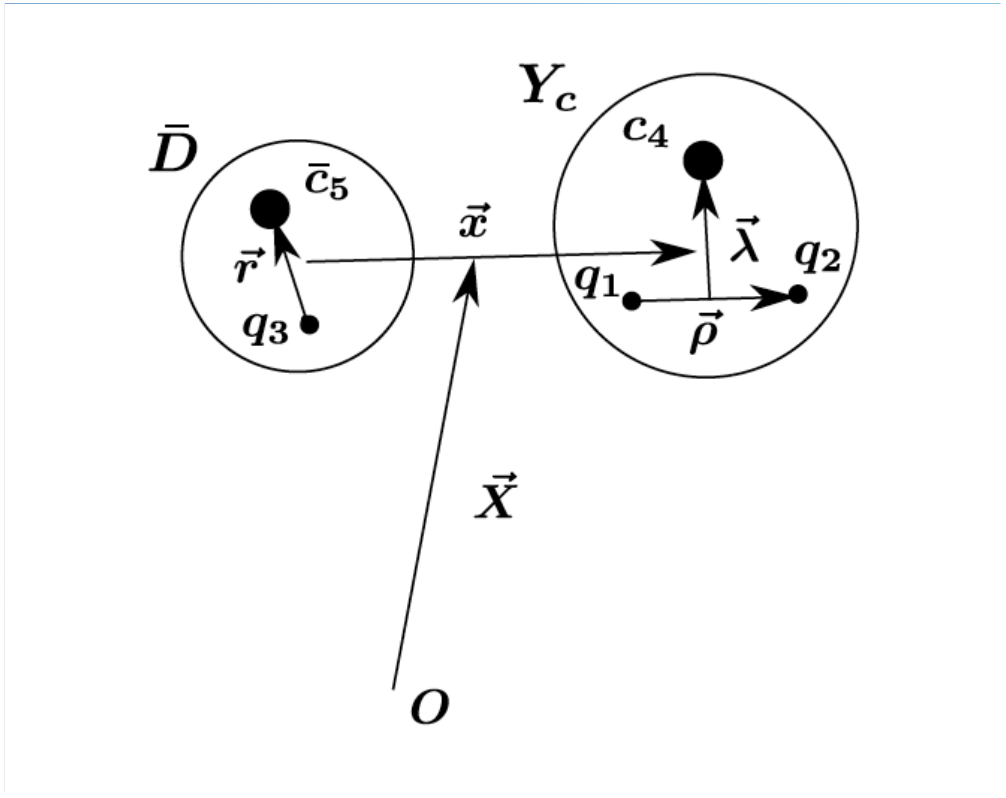
We predicted the three pentaquark states, $P_c(4312), P_c(4440)$ and $P_c(4457)$ two years before the experimental observation by LHCb

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

[4] Y. Yamaguchi, H. Garcia-Tecocoatzi, A. Giachino, A. Hosaka, E. Santopinto, S. Takeuchi and M. Takizawa, **Few-Body Systems, DOI: 10.1007/978-3-030-32357-8_98 (2019)**

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.

Heavy Quark Spin Symmetry with Chiral Tensor Dynamics in the Light of the Recent LHCb Pentaquarks [4]

Based on the new LHCb results [*], in Ref. [4] we calculated the tensor contribution, fix this free parameter and we predict the three well-established pentaquark masses and widths consistently with the new data with the following quantum number assignments:

$J^P(P_c(4312)) = \frac{1}{2}^-$, $J^P(P_c(4440)) = \frac{3}{2}^-$ **and** $J^P(P_c(4457)) = \frac{1}{2}^-$.

[*]

We find that the dominant components of these states are the nearby threshold channels:

$P_c(4312)$ is dominated by $\Sigma_c\,\bar{D}$

$P_c(4440)$ and $P_c(4457)$ are both dominated by $\Sigma_c\,\bar{D}^*$

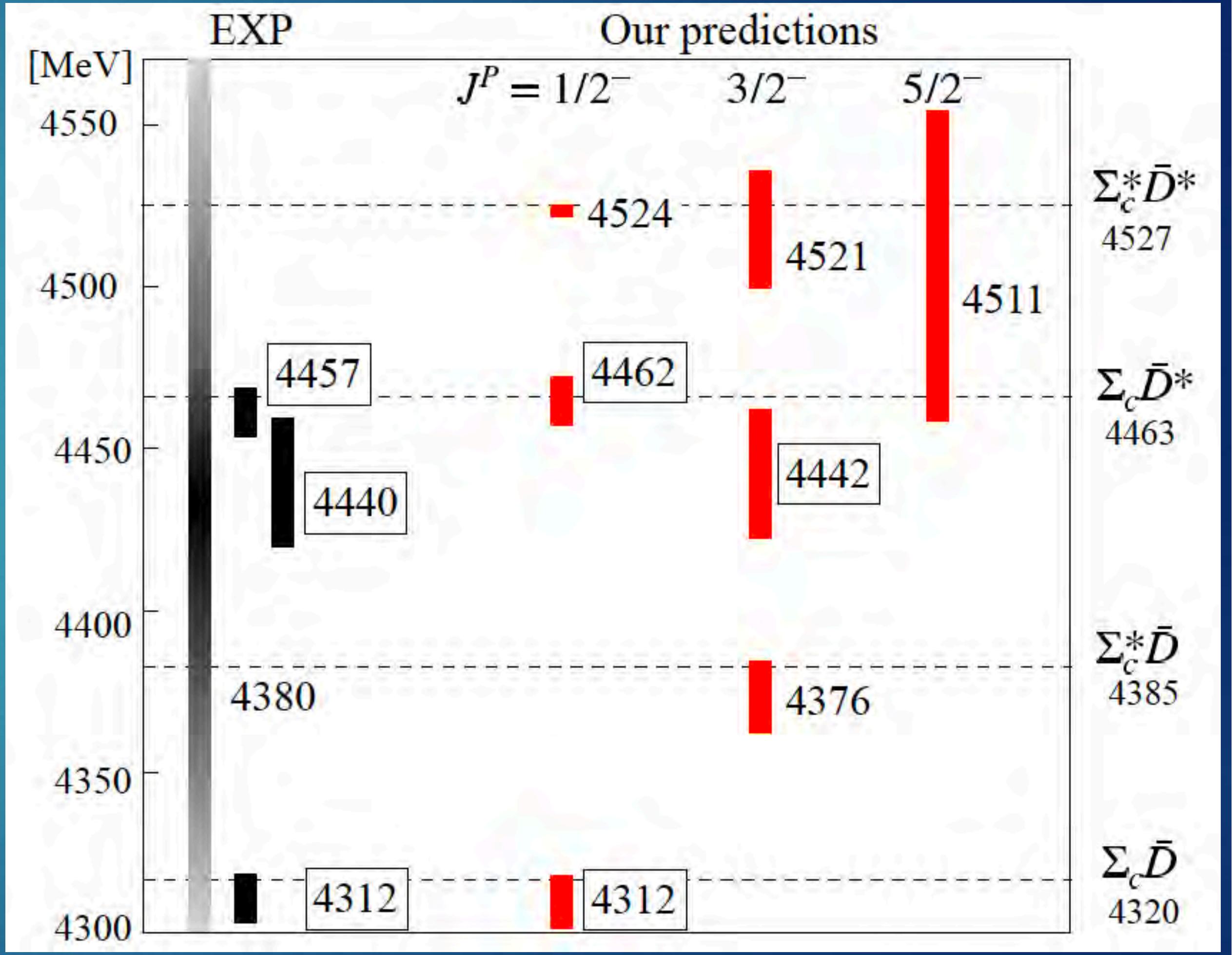
[*] R. Aaij et al. (LHCb), Phys. Rev. Lett. 122, 222001 (2019).

[4] Y. Yamaguchi, H. Garcia-Tecocoatzi, A. Giachino, A. Hosaka, E. Santopinto, S. Takeuchi and M. Takizawa arXiv:1907.04684, **accepted as Physical Review D Rapid Communication, April 2020**

results

State	Mass	Width	Our pred. (M,J^P,Γ)
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+3.7}_{-4.5}$	$(4312, \frac{1}{2}^-, 5)$
$P_c(4380)^+$	$4380 \pm 8 \pm 29$	$205 \pm 18 \pm 86$	$(4376, \frac{3}{2}^-, 8)$
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+8.7}_{-10.1}$	$(4442, \frac{3}{2}^-, 26)$
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+5.7}_{-1.9}$	$(4462, \frac{1}{2}^-, 6.6)$
			$(4524, \frac{1}{2}^-, 1.5)$
			$(4521\ \frac{3}{2}^-, 23)$
			$(4511\ \frac{5}{2}^-, 55)$

3 states still to be observed



agreement with the experimental masses and decay widths

Where does the $P_c(4440)$ and $P_c(4457)$ mass difference come from?

Since these two states are located near $\Sigma_c \bar{D}^*$ threshold and both states have the narrow widths, it is natural to consider them to form the spin doublet of 1/2 and 3/2 in S-wave. It is important to determine which of the above spin 1/2 and 3/2 states is more deeply bound.

There are two sources for the spin-dependent force in our model. One is the short range interaction by the coupling to the 5-quark-core states (the spectroscopic factor). The other is the long range interaction by the OPEP, especially the TENSOR TERM.

heavy quark and chiral symmetries

$$V_\pi^{ij}(r) = G_\pi^{ij}[\vec{\mathcal{O}}_1^i \cdot \vec{\mathcal{O}}_2^j C(r;m_\pi) + \boxed{S_{\mathcal{O}_1^i \mathcal{O}_2^j}(\hat{r}) T(r;m_\pi)]},$$

OPE Potential

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

Central part

Tensor operator:

$$S_{\mathcal{O}_1^i \mathcal{O}_2^j}(\hat{r}) = 3\vec{\mathcal{O}}_1^i \cdot \hat{r}\vec{\mathcal{O}}_2^j \cdot \hat{r} - \vec{\mathcal{O}}_1^i \cdot \vec{\mathcal{O}}_2^j$$

$$S_{\mathcal{O}}(\hat{r})T(r;m) = \int \frac{d^3\vec{q}}{(2\pi)^3} \frac{-\vec{q}^{\,2}}{\vec{q}^{\,2} + m^2} S_{\mathcal{O}}(\hat{q}) e^{i\vec{q}\cdot\vec{r}} \boxed{F(\Lambda, \vec{q})}$$

$$\boxed{F(\Lambda, m_\pi) = \frac{(\Lambda^2 - m_\pi^2)^2}{(\Lambda^2 + q^2)^2}}$$

Dipole form factor

Tensor part

To examine the effects of OPEP tensor interaction, we have investigated the energy of the resonant Pentaquark states of spin 1/2 and 3/2 around the $\Sigma_c \bar{D}^*$ threshold **without** the OPEP tensor term

In this case, the attractive force is not enough, and the resonant states turn into virtual states.

The tensor term is necessary to form resonant states

QUANTITATIVELY

We found that the tensor interaction gives about 4 MeV attraction for the $J^P = \frac{1}{2}^-$ and 15 MeV for the $J^P = \frac{3}{2}^-$ state

That is, more attraction is found in the $J^P = \frac{3}{2}^-$ state than in the $J^P = \frac{1}{2}^-$ state

The tensor interaction provides attraction through channel couplings such as S-D and D-D.

$\Sigma_c \bar{D}^*$ with $J^P = \frac{1}{2}^-$ consists of ^{2}S, ^{4}D

$\Sigma_c \bar{D}^*$ with $J^P = \frac{3}{2}^-$ consists of ^{4}S, ^{2}D and ^{4}D

Notation $^{2S+1}$L e.g. ^{2}S means Σ_c and $\bar{D}^*$ in S wave so that J=S=1/2

For the $\frac{3}{2}^-$ state there are three combinations of such channel couplings, while for $\frac{1}{2}^-$ state there is only one.

More channels available imply more attraction

Since the obtained mass difference between $\boldsymbol{P_c(4440)}$ **and** $\boldsymbol{P_c(4457)}$ is 20 MeV the remaining 9 MeV is considered to come from the the short range interaction in our model.

We find that the tensor interaction by the one-pion exchange potential provides a major contribution to the mass difference between Pc (4440) and Pc (4457)

It is interesting and should be emphasized that the present set of heavy baryon states is the first example where the role of the tensor force can be compared in two partner states.

For nucleon systems only spin 1 state (deuteron) is available without partners!

Four-Heavy-Quark Tetraquarks

- Proposed as early as 1975

Z.Maki, Ki. Ohnishi, T. Teshima, I. Umemura, *Progr. Theor.Physs.* 54, 823 (1975); Kuang-Ta Chao, *Zei.für Phys. C* **7**, 317 (1981)
L. Heller and J. A. Tjon, *On Bound States of Heavy $Q^2\bar{Q}^2$ Systems*, Phys. Rev. **D 32**, 755 (1985);
A. V. Berezhnoy, A. V. Luchinsky and A. A. Novoselov, *Tetraquarks Composed of 4 Heavy Quarks*, Phys. Rev. **D 86**, 034004 (2012).

- Widely considered after the observation of doubly heavy baryons together with doubly heavyTs

W.Chen, H.X.Chen, X.Liu, T.G.Steele and S.L.Zhu, Phys. Lett. **B 773**, 247 (2017); Y.Bai, S.Lu and J.Osborne, arXiv:1612.00012 [hep-ph]; Z.G.Wang, Eur. Phys. J. **C 77**, 432 (2017); M.Karliner, S.Nussinov and J.L.Rosner, Phys. Rev. **D 95**, 034011 (2017); J.M.Richard, A.Valcarce and J.Vijande, Phys. Rev. **D 95**, 054019 (2017); J.Wu, Y.R.Liu, K.Chen, X.Liu and S.L.Zhu, Phys. Rev. **D 97**, 094015 (2018); M.N.Anwar, J.Ferretti, F.K.Guo, E.Santopinto and B.S.Zou, Eur. Phys. J. **C 78**, 647 (2018); A.Esposito and A.D.Polosa, Eur. Phys. J. **C 78** , 782 (2018); M.A.Bedolla, J.Ferretti, C.D.Roberts and E.Santopinto, arXiv:1911.00960 [hep-ph].

- observation claims of a 4muon peak in 2Y 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 update of LHCb;
- we have 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 are obtained for the 4 muon channel of 4b tetraquarks: xsection*Bf~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.

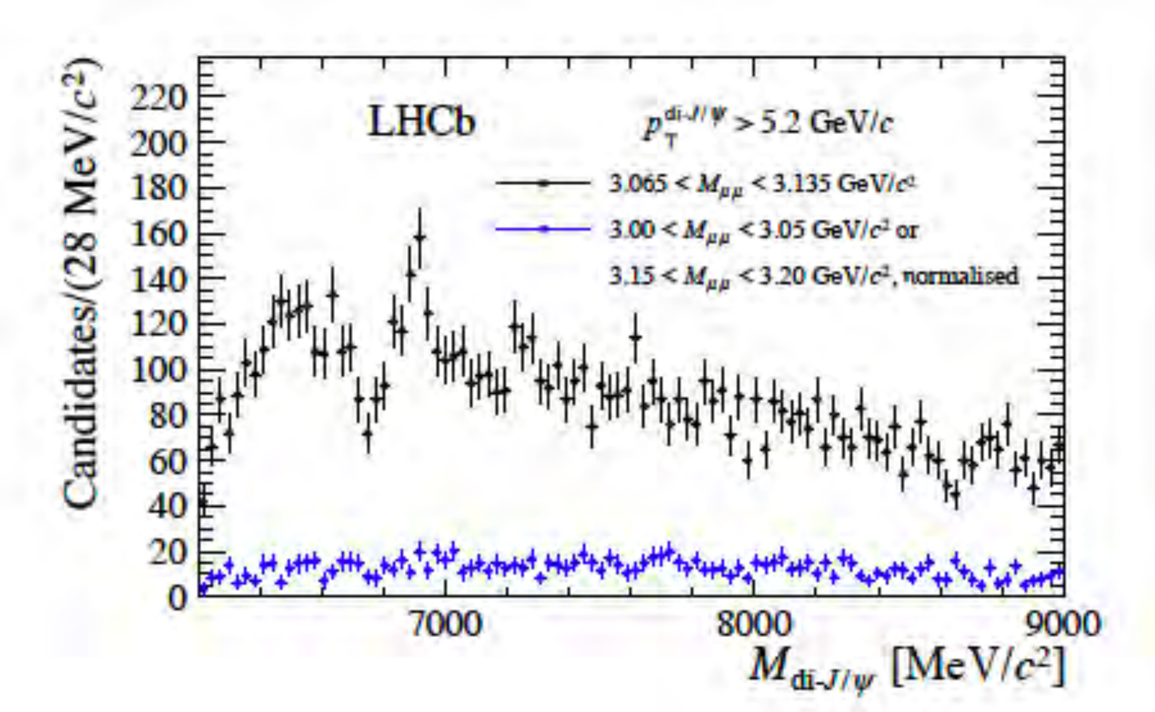
C.Becchi, J. Ferretti, A.Giachino, L.Maiani and E.Santopinto, arXiv:2006.14388 [hep-ph].

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):

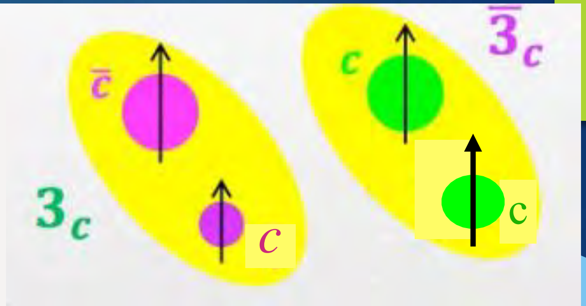
$$m[X(6900)] = 6905 \pm 11 \pm 7\,\mathrm{MeV}/c^2$$

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



Tetraquark constituent picture of 2 J/Ψ

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

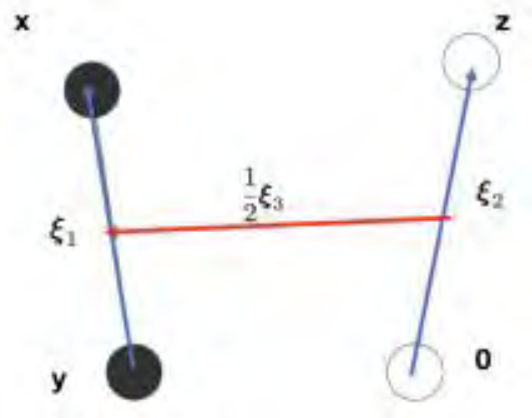


- [cc] in color $\bar{3}$
- total spin of each diquark, S=1 (color antisymmetry and Fermi statistics)
- S-wave: positive parity

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 by M.A.Bedolla, J.Ferretti, C.D.Roberts and E.Santopinto, arXiv:1911.00960 [hep-ph], EPJC2020
  - 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**

See L. Maiani, hep-ph/2008.01637 to appear in Science Bulletin

arXiv:1911.00960 [hep-ph] Bedolla, Ferretti, Roberts, Santopinto, EPJC2020

Decays and branching fractions

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

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

- Four possible annihilations:
  - $\boxed{1}$ 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);
  - $\boxed{2}$ 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):
  - $\Gamma = |\Psi_T(0)|^2 \cdot |\mathbf{v}| \cdot \sigma(c\bar{c} \to f)$

- Branching fractions are independent from $|\Psi_T(0)|^2$
- Total rates: see later.

Branching Ratio Results

$[cc\bar{c}\bar{c}]$	$\eta_c +$ any	$D_q\bar{D}_q$ $(m_q < m_c)$	$D_q^*\bar{D}_q^*$	$J/\Psi +$ any	$J/\Psi + \mu^+\mu^-$	4μ
$J^{PC} = 0^{++}$	0.77	0.019	0.057	$7.5 \cdot 10^{-4}$	$4.5 \cdot 10^{-5}$	$2.7 \cdot 10^{-6}$
$J^{PC} = 2^{++}$	0	0	0.333	$4.4 \cdot 10^{-3}$	$2.6 \cdot 10^{-4}$	$1.6 \cdot 10^{-5}$

TABLE I: Branching fractions of fully-charmed tetraquarks, assuming S-wave decay.

$[bb\bar{b}\bar{b}]$
4μ
$7.2 \cdot 10^{-7}$
$20 \cdot 10^{-7}$

- Branching ratios in 4 muons are more favorable in 4 c than in 4 b tetraquarks
- Among 4 c, the ratio is more favorable for the 2^{++} (a factor 6)
- In addition 2^{++} is produced in pp collision with a statistical factor 2J+1=5

$$B_{4\mu}(2^{++}) : B_{4\mu}(0^{++}) \sim 6 : 1; \; \sigma(2^{++}) : \sigma(0^{++}) = 5 : 1$$

A visibility ratio 30:1 !!

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

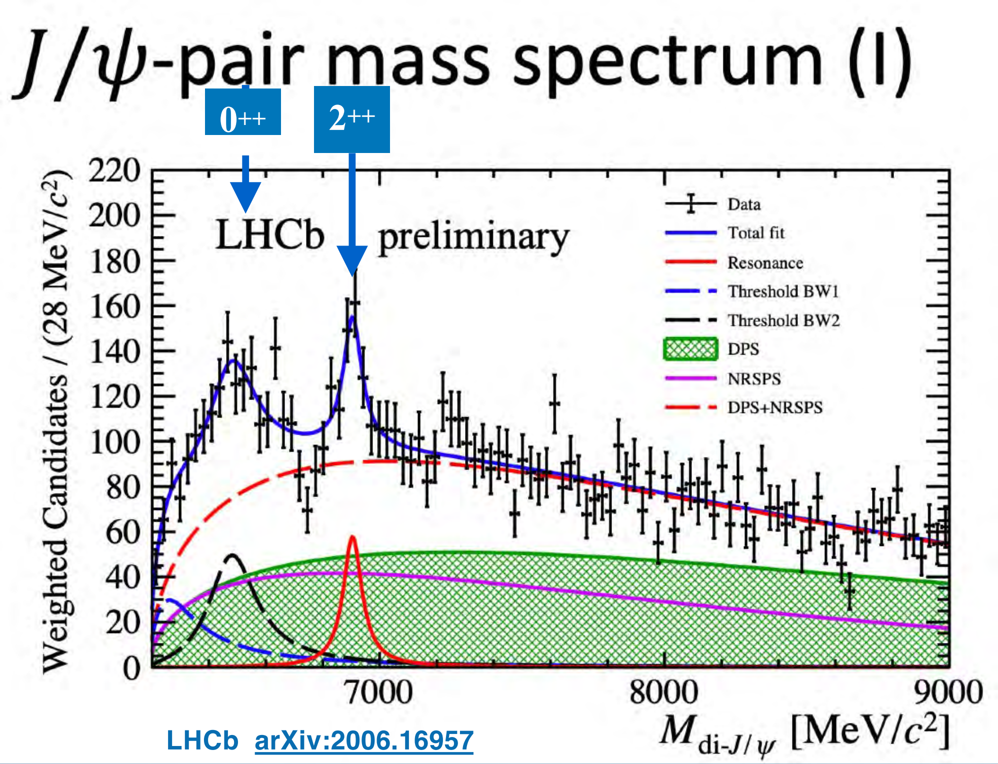
$[cc][\bar{c}\bar{c}]$	Decay Channel	BF in $\mathcal{T}$ decay	Cross section upper limit (fb)
$J = 0^{++}$	$\mathcal{T} \to D^{(*)+}D^{(*)-} \to e + \mu + \ldots$	$4.3\ 10^{-3}$	$6.5 \cdot 10^4$(65 pb)
	$\mathcal{T} \to D^{(*)0}\bar{D}^{(*)0} \to e + \mu + \ldots$	$0.67\ 10^{-3}$	$1.0 \cdot 10^4$(10 pb)
	$\mathcal{T} \to 4\mu$	$2.7\ 10^{-6}$	40
$J = 2^{++}$	$\mathcal{T} \to D^{*+}\bar{D}^{*-} \to e + \mu + \ldots$	$6.3\ 10^{-3}$	$9.6 \cdot 10^4$(96 pb)
	$\mathcal{T} \to D^{*0}\bar{D}^{*0} \to e + \mu + \ldots$	$0.98\ 10^{-3}$	$1.5 \cdot 10^4$(15 pb)
	$\mathcal{T} \to 4\mu$	$1.6\ 10^{-5}$	238

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, using the spread of values as an error and find

$$\xi = 4.6 \pm 1.4$$

$$\Gamma(0^{++}) = 97 \pm 30 \text{ MeV}; \Gamma(2^{++}) = 64 \pm 20 \text{ MeV}$$



Fully-c states. Results from few other studies

J^{PC}	RDM Herein	QCD sum rules Chen *et al.*	Diquark model Karliner and Rosner	Quark model G.-J. Wang *et al.*	Quark model Liu *et al.*	Quark model Yang. *et al.*	Quark model Liu *et al.*	QCD sum rules Z.-G. Wang
0^{++}	6.537	6.44 ± 0.15	6.192	$6.371^{\dagger}$	$6.487^{\dagger}$	6.423	$6.455^{\dagger}$	5.99 ± 0.08
2^{++}	6.900	6.51 ± 0.15	6.429	6.432	6.524	7.026	6.524	6.09 ± 0.08
$0'^{++}$	7.227	6.46 ± 0.16	6.871	$6.483^{\dagger}$	$6.518^{\dagger}$	6.650	$6.550^{\dagger}$	6.48 ± 0.08
1^{++}	7.481 (D-wave)	–	–	–	–	–	–	–

- Relativized Diquark Model results (RDM) from M. A. Bedolla, arXiv:1911.00960, EPJC 2020.
- Diquark model from M. Karliner and J. L. Rosner, arXiv:2009.04429.
- QCD sum rules results from: W. Chen *et al*., Phys. Lett. B **773**, 247 (2017); Z. G. Wang, arXiv:2009.05371.
- The results denoted as "Quark model" come from 4-body calculations of the tetraquark spectrum in a potential model. See: G. J. Wang, *et al*., Phys. Rev. D **100**, 096013 (2019); M.-S. Liu *et al*., Phys. Rev. D **100**, 016006 (2019); G. Yang et al., arXiv:2009.00238; M. S. Liu, *et al*., arXiv:2006.11952.
- The entries highlighted by † are the results of mixing 3 anti-3 and 6 anti-6 color combinations with different weights.

Conclusions: Spin and Parity necessary to distinguish different models

Other tetraquark predictions can be found in:

Spectroscopy of the hidden-charm $[qc][\bar{q}\bar{c}]$ and $[sc][\bar{s}\bar{c}]$ tetraquarks in the relativized diquark model

Muhammad Naeem Anwar (Beijing, Inst. Theor. Phys. and Beijing, GUCAS and IAS, Julich and JCHP, Julich), Jacopo Ferretti (Beijing, Inst. Theor. Phys. and Yale U.), Elena Santopinto (INFN, Genoa) (May 16, 2018)

Published in: *Phys.Rev.D* 98 (2018) 9, 094015 • e-Print: 1805.06276 [hep-ph]

Hidden-charm and bottom tetra- and pentaquarks with strangeness in the hadro-quarkonium and compact tetraquark models

J. Ferretti (Yale U. and Jyvaskyla U.), E. Santopinto (INFN, Genoa) (Jan 4, 2020)

Published in: *JHEP* 04 (2020) 119 • e-Print: 2001.01067 [hep-ph]

Other open problems in charmonia spectroscopy and/or in open charm mesons can be found in :

#41 Quark structure of the $X(3872)$ and $\chi_b(3P)$ resonances

J. Ferretti (INFN, Genoa and Mexico U.), G. Galatà (INFN, Genoa and Mexico U.), E. Santopinto (INFN, Genoa) (Jan 17, 2014)

Published in: *Phys.Rev.D* 90 (2014) 5, 054010 • e-Print: 1401.4431 [nucl-th]

#44 Interpretation of the X(3872) as a charmonium state plus an extra component due to the coupling to the meson-meson continuum

J. Ferretti (INFN, Genoa and Mexico U.), G. Galatà (INFN, Genoa and Mexico U.), E. Santopinto (INFN, Genoa) (Feb 27, 2013)

Published in: *Phys.Rev.C* 88 (2013) 1, 015207 • e-Print: 1302.6857 [hep-ph]

Open-flavor strong decays of open-charm and open-bottom mesons in the $^3P_0$ model

J. Ferretti (Mexico U., ICN and INFN, Rome and Rome U.), E. Santopinto (INFN, Genoa) (Jun 14, 2015)

Published in: *Phys.Rev.D* 97 (2018) 11, 114020 • e-Print: 1506.04415 [hep-ph]

Spectroscopy of the hidden-charm $[qc][\bar{q}\bar{c}]$ and $[sc][\bar{s}\bar{c}]$ tetraquarks in the relativized diquark model

Muhammad Naeem Anwar (Beijing, Inst. Theor. Phys. and Beijing, GUCAS and IAS, Julich and JCHP, Julich), Jacopo Ferretti (Beijing, Inst. Theor. Phys. and Yale U.), Elena Santopinto (INFN, Genoa) (May 16, 2018)

Published in: *Phys.Rev.D* 98 (2018) 9, 094015 • e-Print: 1805.06276 [hep-ph]

PHYS. REV. D **98,** 094015 (2018)

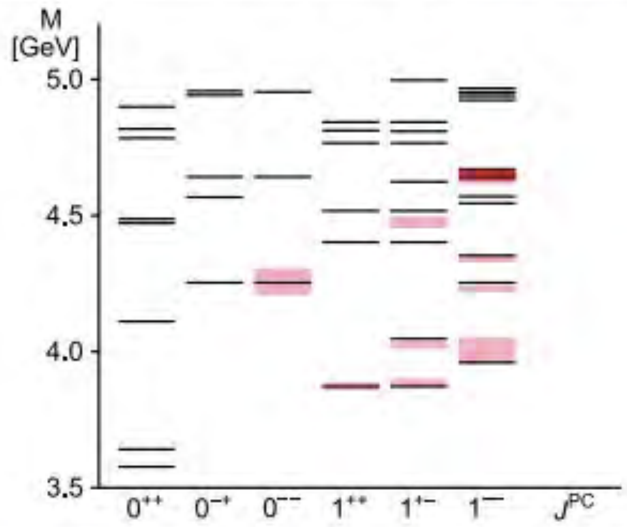


FIG. 1. The $qc\bar{q}\bar{c}$ tetraquark spectrum (lines), obtained by solving the eigenvalue problem of Eq. (5), is compared to the existing experimental data for *XYZ* exotics (boxes). For the numerical values, see Tables II and III.

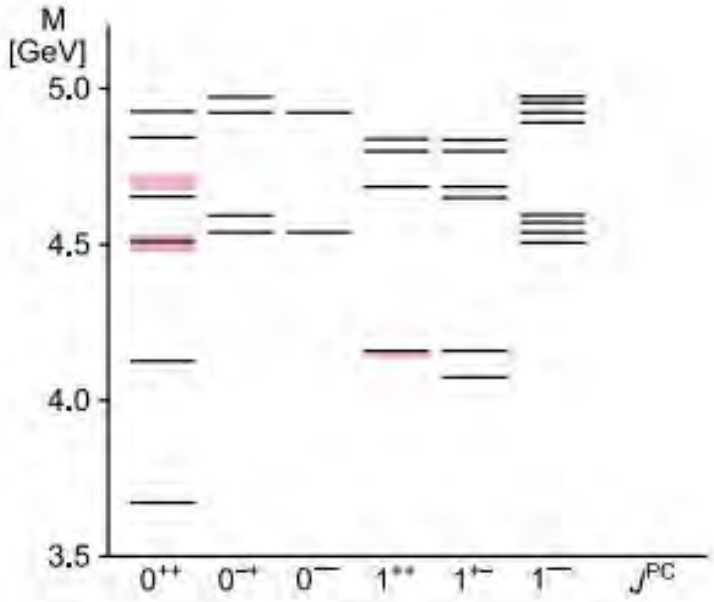


FIG. 2. As Fig. 1, but for $s\bar{s}c\bar{c}$ tetraquark states.

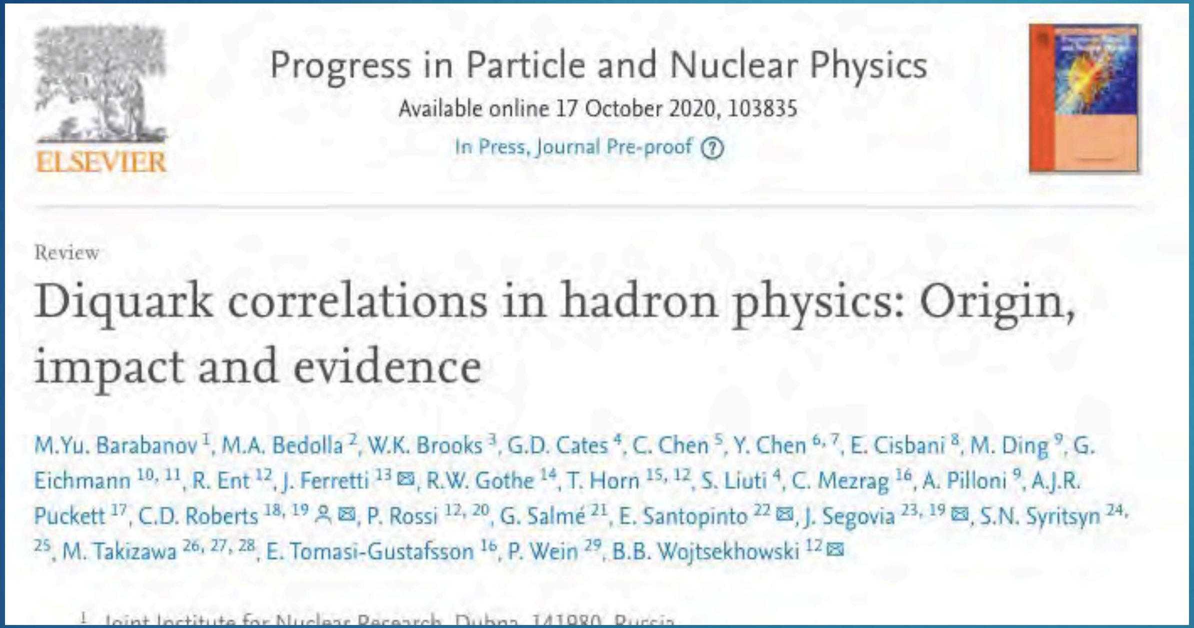
Hidden-charm and bottom tetra- and pentaquarks with strangeness in the hadro-quarkonium and compact tetraquark models

J. Ferretti (Yale U. and Jyvaskyla U.), E. Santopinto (INFN, Genoa) (Jan 4, 2020)

Published in: *JHEP* 04 (2020) 119 • e-Print: 2001.01067 [hep-ph]

$cs\bar{c}\bar{n}$								
J^{PC}	$N[(S_D,S_{\bar{D}})S,L]J$	E^{th} [MeV]	J^{PC}	$N[(S_D,S_{\bar{D}})S,L]J$	E^{th} [MeV]	J^{PC}	$N[(S_D,S_{\bar{D}})S,L]J$	E^{th} [MeV]
0^{++}	1[(1,1)0,0]0	3657	1^{++}	1[(1,0)1,0]1	4016	0^{-+}	1[(1,0)1,1]0	4396
0^{++}	1[(0,0)0,0]0	3852	1^{++}	2[(1,0)1,0]1	4544	0^{-+}	1[(1,1)1,1]0	4580
0^{++}	2[(0,0)0,0]0	4383	1^{++}	1[(1,0)1,2]1	4658	0^{-+}	2[(1,0)1,1]0	4783
0^{++}	2[(1,1)0,0]0	4496	1^{++}	1[(1,1)2,2]1	4825	0^{-+}	2[(1,1)1,1]0	4960
0^{++}	3[(0,0)0,0]0	4747	1^{++}	3[(1,0)1,0]1	4906	0^{-+}	3[(1,0)1,1]0	5093
0^{++}	1[(1,1)2,2]0	4830	1^{++}	2[(1,0)1,2]1	4982	0^{-+}	3[(1,1)1,1]0	5265
0^{++}	3[(1,1)0,0]0	4913	1^{++}	2[(1,1)2,2]1	5147			
0^{++}	2[(1,1)2,2]0	5151	1^{++}	3[(1,0)1,2]1	5261			
0^{++}	3[(1,1)2,2]0	5427	1^{++}	3[(1,1)2,2]1	5423			
1^{--}	1[(0,0)0,1]1	4234	2^{++}	1[(1,1)2,0]2	4232	1^{+-}	1[(1,0)1,0]1	4016
1^{--}	1[(1,0)1,1]1	4396	2^{++}	1[(0,0)0,2]2	4497	1^{+-}	1[(1,1)1,0]1	4061
1^{--}	1[(1,1)0,1]1	4558	2^{++}	2[(1,1)2,0]2	4739	1^{+-}	2[(1,0)1,0]1	4544
1^{--}	1[(1,1)2,1]1	4583	2^{++}	1[(1,1)2,2]2	4818	1^{+-}	2[(1,1)1,0]1	4637
1^{--}	2[(0,0)0,1]1	4622	2^{++}	1[(1,1)0,2]2	4819	1^{+-}	1[(1,0)1,2]1	4658
1^{--}	2[(1,0)1,1]1	4783	2^{++}	2[(0,0)0,2]2	4824	1^{+-}	1[(1,1)1,2]1	4822
1^{--}	2[(1,1)0,1]1	4942	2^{++}	3[(1,1)2,0]2	5092	1^{+-}	3[(1,0)1,0]1	4906
1^{--}	2[(1,1)2,1]1	4962	2^{++}	3[(0,0)0,2]2	5105	1^{+-}	2[(1,0)1,2]1	4982
1^{--}	3[(0,0)0,1]1	4935	2^{++}	2[(1,1)0,2]2	5140	1^{+-}	3[(1,1)1,0]1	5010
1^{--}	3[(1,0)1,1]1	5093	2^{++}	2[(1,1)2,2]2	5140	1^{+-}	2[(1,1)1,2]1	5144
1^{--}	3[(1,1)0,1]1	5250	2^{++}	3[(1,1)0,2]2	5416	1^{+-}	3[(1,0)1,2]1	5261
1^{--}	3[(1,1)2,1]1	5268	2^{++}	3[(1,1)2,2]2	5416	1^{+-}	3[(1,1)1,2]1	5420
0^{--}	1[(1,0)1,1]0	4396						
0^{--}	2[(1,0)1,1]0	4783						
0^{--}	3[(1,0)1,1]0	5093						

Advertinsing a new review article on Diquarks correlations!



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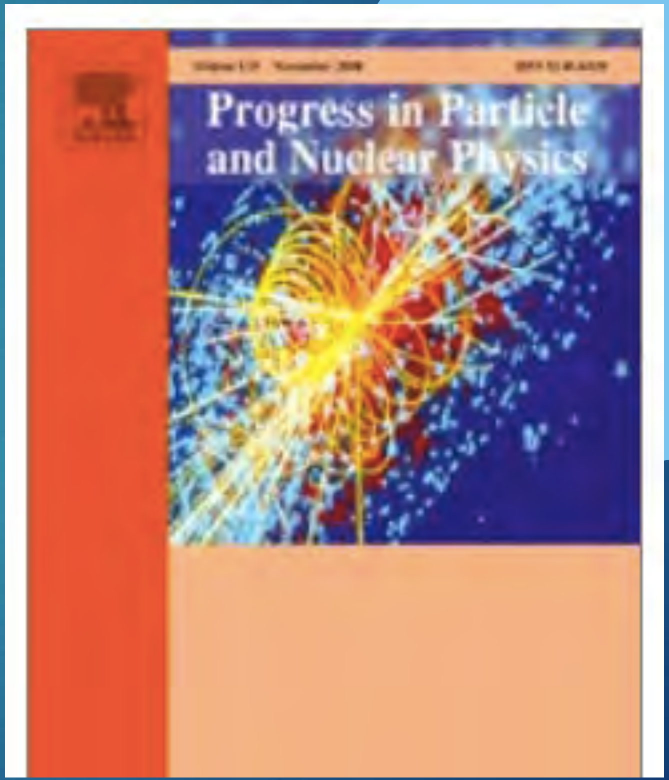
Review

Diquark correlations in hadron physics: Origin, impact and evidence

M.Yu. Barabanov [1], M.A. Bedolla [2], W.K. Brooks [3], G.D. Cates [4], C. Chen [5], Y. Chen [6, 7], E. Cisbani [8], M. Ding [9], G. Eichmann [10, 11], R. Ent [12], J. Ferretti [13], R.W. Gothe [14], T. Horn [15, 12], S. Liuti [4], C. Mezrag [16], A. Pilloni [9], A.J.R. Puckett [17], C.D. Roberts [18, 19], P. Rossi [12, 20], G. Salmé [21], E. Santopinto [22], J. Segovia [23, 19], S.N. Syritsyn [24, 25], M. Takizawa [26, 27, 28], E. Tomasi-Gustafsson [16], P. Wein [29], B.B. Wojtsekhowski [12]

[1] Joint Institute for Nuclear Research, Dubna, 141980, Russia



Summing up

- Up to now, we have many tetraquarks states, other are still to be discovered, and moreover for some of the already discovered tetraquarks, we have still to understand their structure.

- The study of tetraquark states with pp or heavy ions can be strategic:
- 1) New discovery !
- 2) make clear the structure of the existing states(heavy ion study can help to discriminate between molecular nature or diquark structure)
- 3) about charmonia states still many open questions to understand.

Thanks for your attention**!**