Tetraquarks and pentaquarks at LHCb

Quinto Incontro Nazionale di Fisica Nucleare INFN 2022

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Outline

PENTAQUARKS

Quick excursus on the experimental discoveries of the pentaquark states

Pentaquarks as compact *5q* states [1]

Pentaquarks as meson-baryon molecular states in a coupled channel approach [2]

Pentaquarks as core+molecular components in a coupled channel approach [3,4]

TETRAQUARKS

Fully heavy quark tetraquark decay widths in the diquark-antidiquark model [5,6] and the fully-charm tetraquark X(6900) discovered by LHCb (Science Bulletin, Volume 65, Issue 23, 1983 (2020))

[1] E. Santopinto, A. Giachino, Phys. Rev. D 96 (2017) 014014
[2]Y. Yamaguchi, E. Santopinto, Phys. Rev. D Phys.Rev. D 96 (2017) no.1, 014018
[3] Y. Yamaguchi, A. Giachino, A. Hosaka, E. S., S. Tacheuchi, M. Takizawa, Phys .Rev. D96 (2017) no.11, 114031
[4] Y. Yamaguchi, H. Garcia-Tecocoatzi, A. Giachino, A. Hosaka, E. Santopinto, S. Takeuchi and M. Takizawa Phys.Rev.D 101 (2020) 091502
[5] C.Becchi, A.Giachino, L.Maiani and E.Santopinto, Phys. Lett. B 806, 135495 (2020).
[6] C.Becchi, J. Ferretti, A. Giachino, L.Maiani and E.Santopinto, Phys.Lett. B 811 135952 (2020).

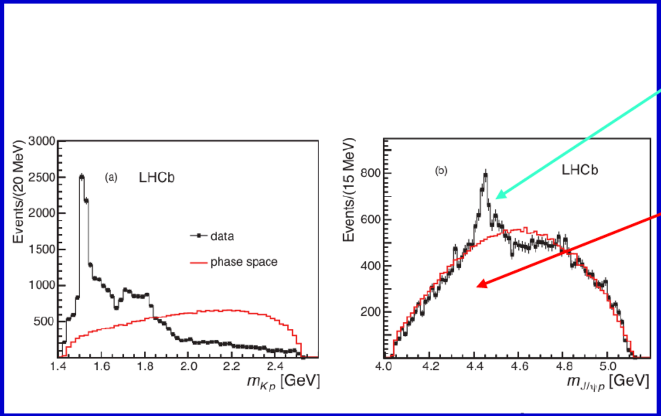
More new valence quark configurations

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

LHCb

Phys. Rev. Lett.115(2015) 072001

The **history** of **the pentaquark** discovery dates back to 2015



$M_P_c^+(4450) = (4449.8 \pm 8 \pm 29)$MeV

$\Gamma = (39 \pm 5 \pm 19)$ MeV

$M_P_c^+(4380) = (4380 \pm 1.7 \pm 2.5)$MeV

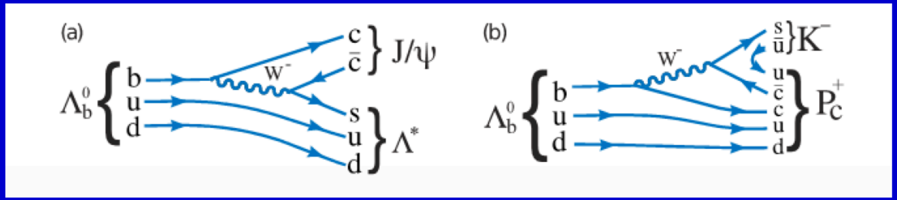
$\Gamma = (205 \pm 18 \pm 86)$MeV

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?

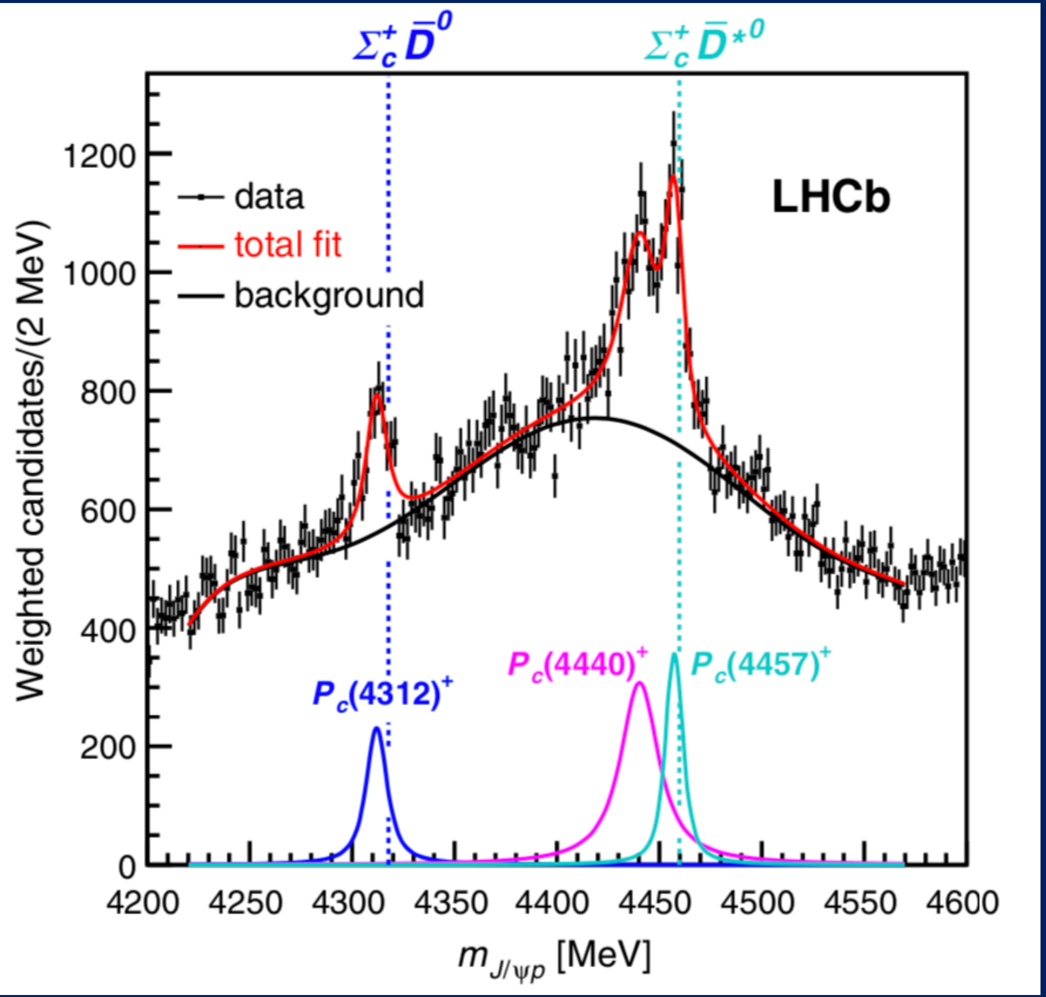
As well as revealing the new $P_c(4312)$ state with 7.3 sigma statistical significance, the LHCb 2019 analysis also uncovered a more complex structure of $P_c(4450)$, consisting of two narrow nearby separate peaks, $P_c(4440)$ and $P_c(4457)$ with the two-peak structure hypothesis having a statistical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



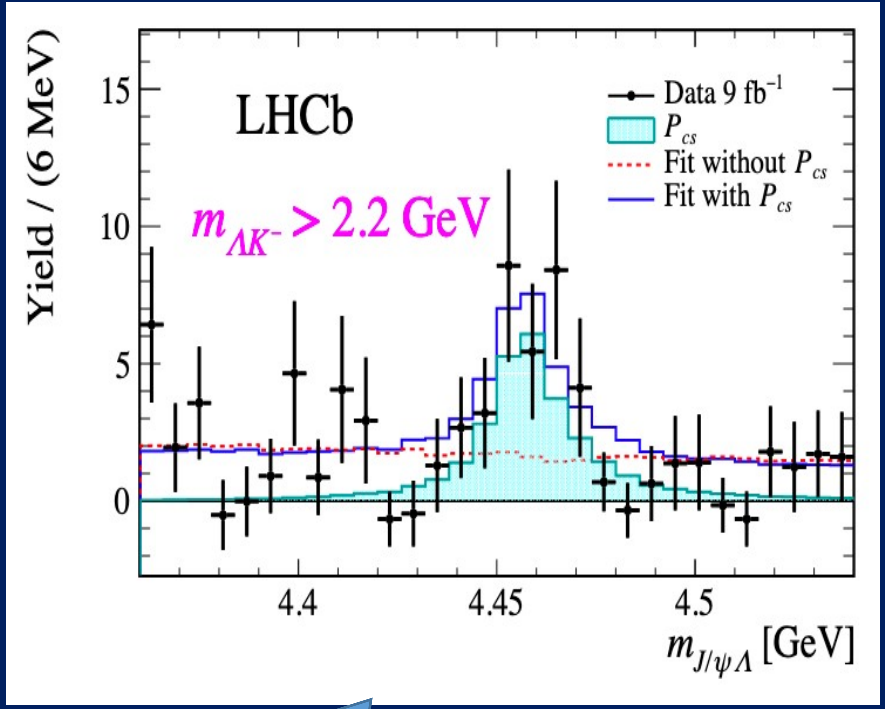
Number of events versus J/Psi p invariant mass [*]. The mass thresholds for the $\Sigma_c\,\bar{D}$ and $\Sigma_c\,\bar{D}^*$ final states are superimposed.

2021

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

(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

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

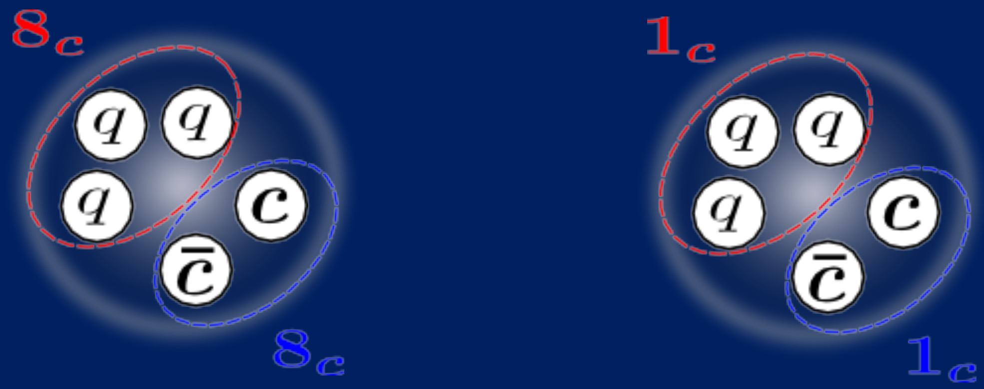
The $P_c(4437)$ statistical significance is in the range of 3.1 to 3.7 depending on the assigned J^P hypothesis:

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

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

Pentaquark as compact $5q$ states

- 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 Pcs(4459) 3 years in advance and suggested to look for it in the Λ J/Ψ channel.** 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)

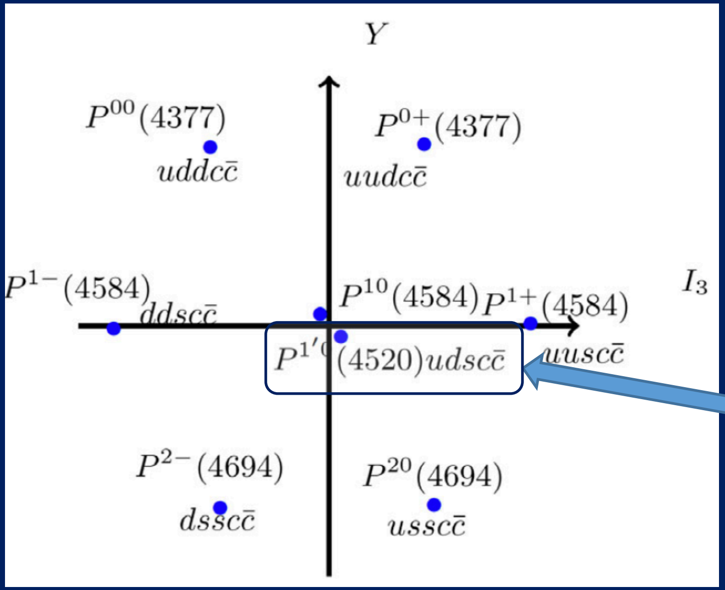
The discovery paper by LHCb cited our paper

Cited also by PDG2021 (update)!

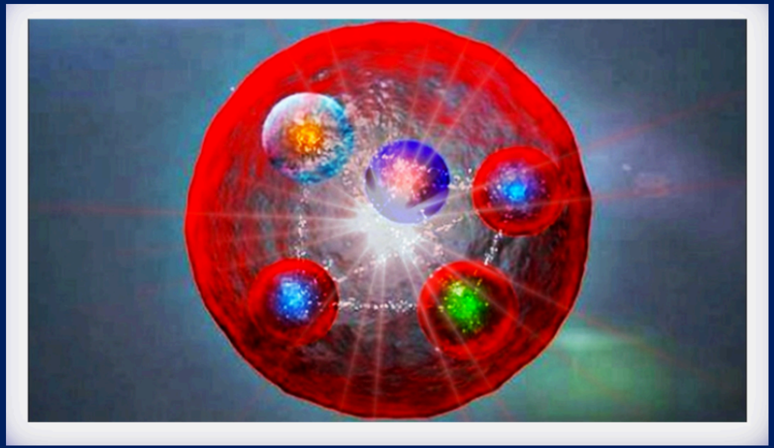
Pentaquark as compact $5q$ states

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 $\Xi_b^- \rightarrow J/\Psi\Lambda K^-$ decay

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

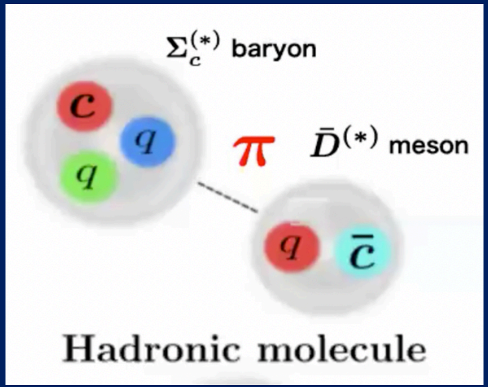
Hidden-charm pentaquarks as a meson-baryon molecule with coupled channels for $\bar{D}^{(*)}\Lambda_c$ and $\bar{D}^{(*)}\Sigma_c^{(*)}$

Y. Yamaguchi, E. Santopinto, Phys. Rev. D 96 (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).**



This was the first calculation in which a full coupled channel has been performed

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

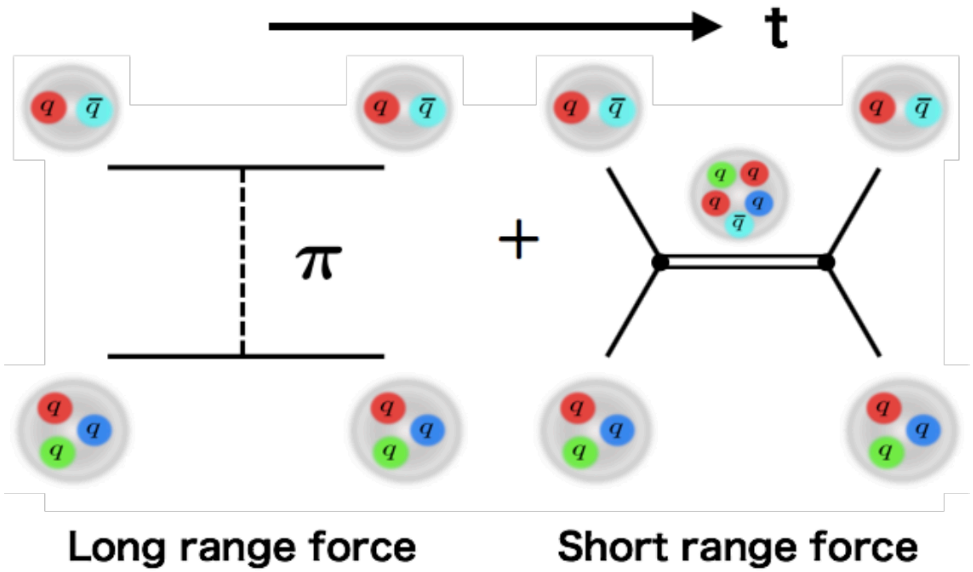
- For the first time some predictions for the hidden charm pentaquarks as $\bar{D}\,\Lambda_c$, $\bar{D}^*\,\Lambda_c$, $\bar{D}\,\Sigma_c$, $\bar{D}^*\,\Sigma_c$, $\bar{D}\Sigma_c^*$ and $\bar{D}^*\Sigma_c^*$ molecules coupled to the five-quark states are provided.

- 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)

Meson-Baryon interactions



- **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.

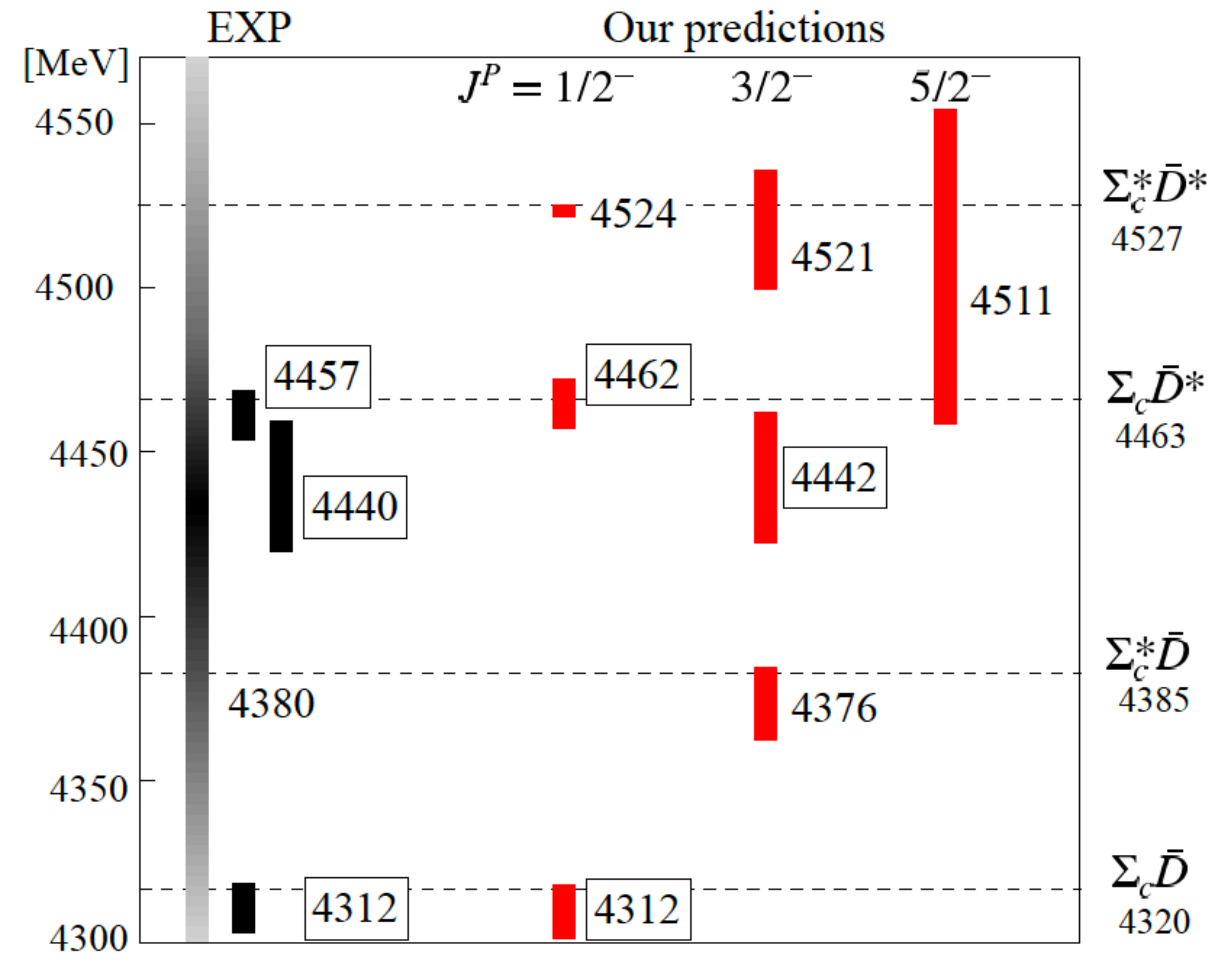
We predicted the three pentaquark states, $P_c(4312), P_c(4440)$ and $P_c(4457)$ two years before the experimental observation by LHCb.

For this reason we wrote a Rapid Communication, Y. Yamaguchi, H. Garcia-Tecocoatzi, A. 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)**

results

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



Cited by PDG2020! Together with Y. Yamaguchi, A. Giachino, A. Hosaka, E. Santopinto, S. Takeuchi, M. Takizawa, PRD **96** (2017) 114031.

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: $\sigma\sim 0.1$fb 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

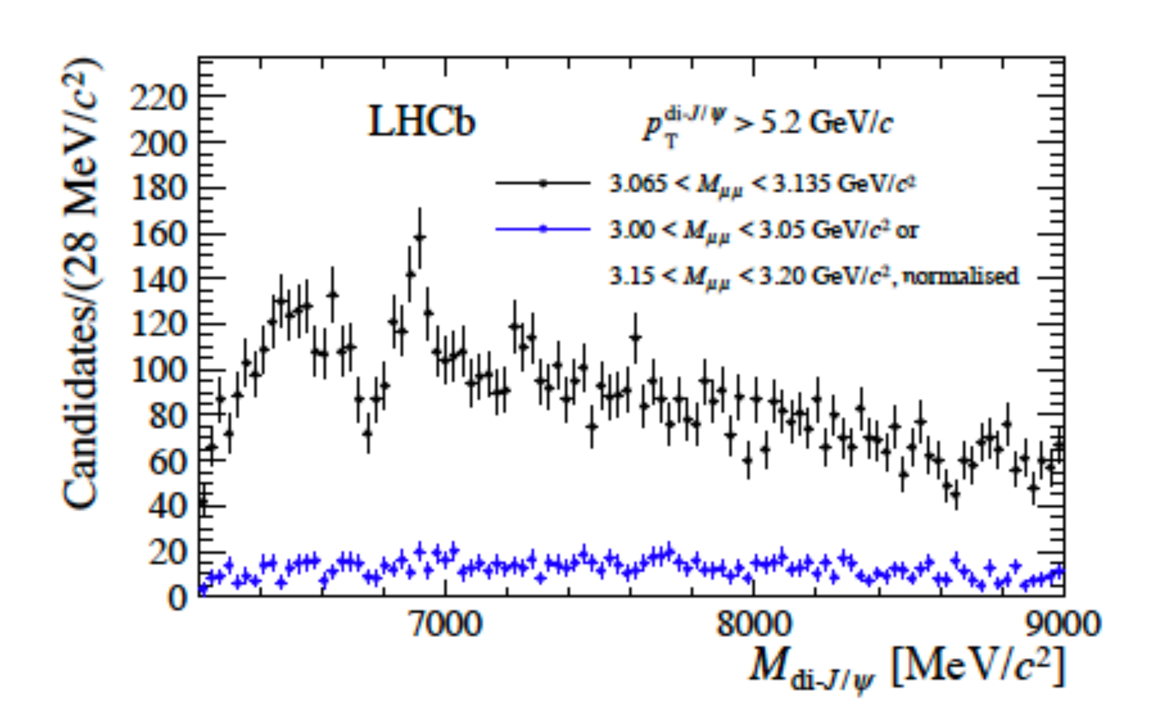
Tetraquark picture of 2 J/Ψ resonances

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)):

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

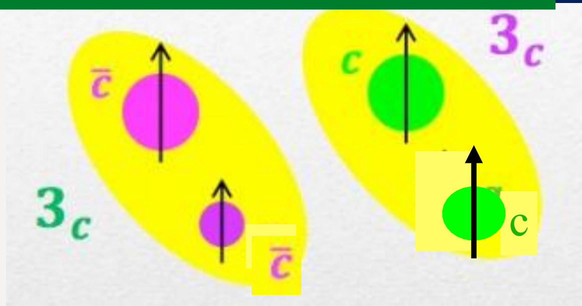
$$\Gamma[X(6900)] = 80 \pm 19 \pm 33\,\mathrm{MeV},$$

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

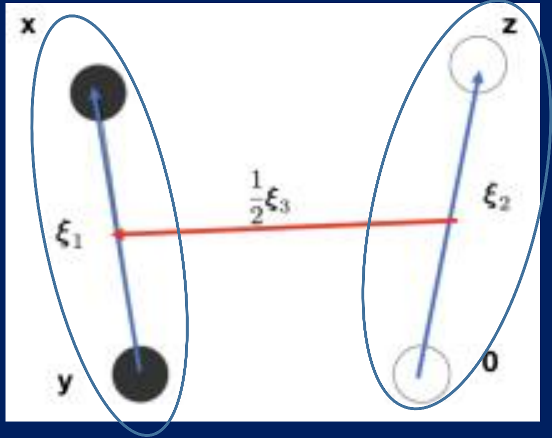
S-wave, fully charm tetraquarks

- 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 with an an Hamiltonian introduced in Anwar, Ferretti and Santopinto, PRD **98**, 094015 (2018

$$H = E_0 + \sqrt{q^2 + m_D^2} + \sqrt{q^2 + m_{\bar{D}}^2} + V_{conf} + V_{OGE}$$

- 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



Hamiltonian contains OGE + confining potential. Parameters fitted to XYZ tetra-quark candidate

Decays and branching fractions

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

$$\mathcal{T}(J=0^{++}) = \left|(cc)^{1}_{\bar{3}}\,(\bar{c}\bar{c})^{1}_{3}\right\rangle^{0}_{1} = -\frac{1}{2}\left(\sqrt{\frac{1}{3}}\left|(c\bar{c})^{1}_{1}(c\bar{c})^{1}_{1}\right\rangle^{0}_{1} - \sqrt{\frac{2}{3}}\left|(c\bar{c})^{1}_{8}(c\bar{c})^{1}_{8}\right\rangle^{0}_{1}\right) + \frac{\sqrt{3}}{2}\left(\sqrt{\frac{1}{3}}\left|(c\bar{c})^{0}_{1}(c\bar{c})^{0}_{1}\right\rangle^{0}_{1} - \sqrt{\frac{2}{3}}\left|(c\bar{c})^{0}_{8}(c\bar{c})^{0}_{8}\right\rangle^{0}_{1}\right)$$

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

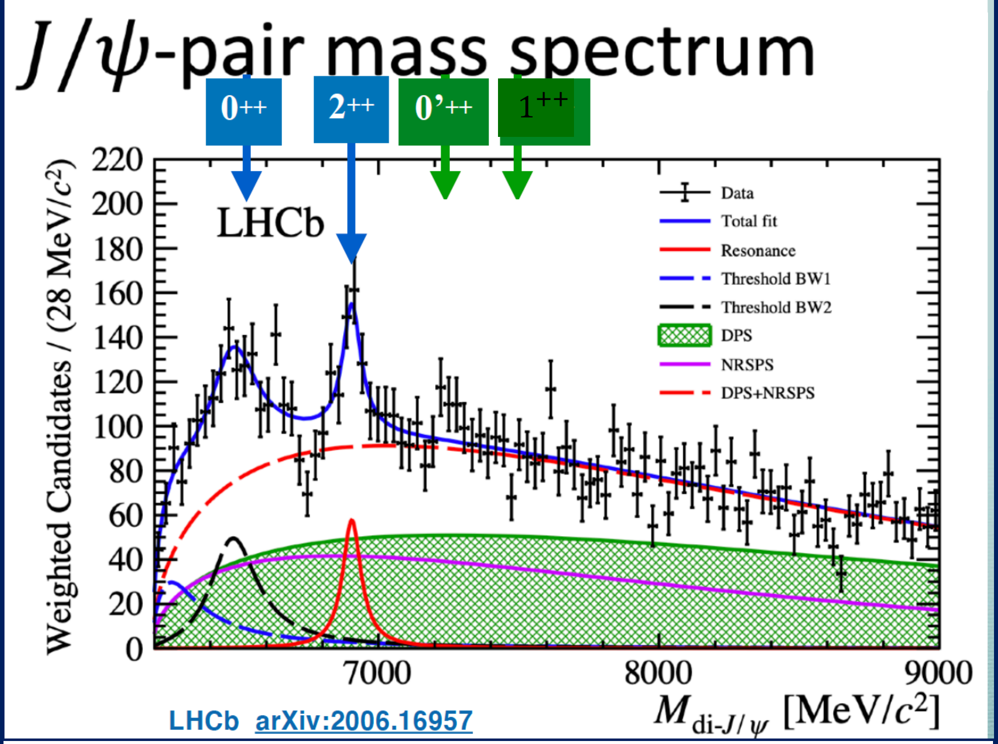
- Branching ratios in 4 muons are more favorable in 4 c than in 4 b tetraquarks
- Among 4 c, the Branching Ratio is more favorable for the 2^{++} (a factor 4)
- In addition 2^{++} is produced in pp collision with a statistical factor 2J+1=5

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

$$\xi = 4.6 \pm 1.4$$
$$\Gamma(2^{++}) = (97 \pm 30)\ \text{MeV}$$



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

Conclusions:

The field of exotic is a hot topic - new discoveries each two-three months

One of my article has predicted the Pcs pentaquark before the LHCb observation and in fact it has been cited by LHCb

The same for the fully charm tetraquark: we predicted the fully-charm tetraquark before its experimental discovery

Three of my articles have been cited by the Particle Data Group (PDG2021 update)

Thanks for your attention!