Multiquark states: from mesons and baryons to exotic tetraquarks and pentaquarks

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HADRONS 2021

13-17 September 2021

São José dos Campos, Brazil

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

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

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

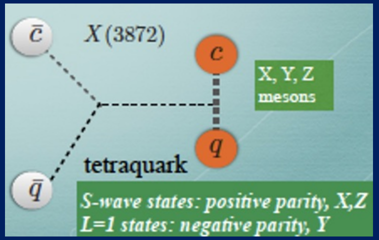
There are indeed new valence quark configurations !!

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

The precence oh heavy quarks appear to increase the possibility of bound

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

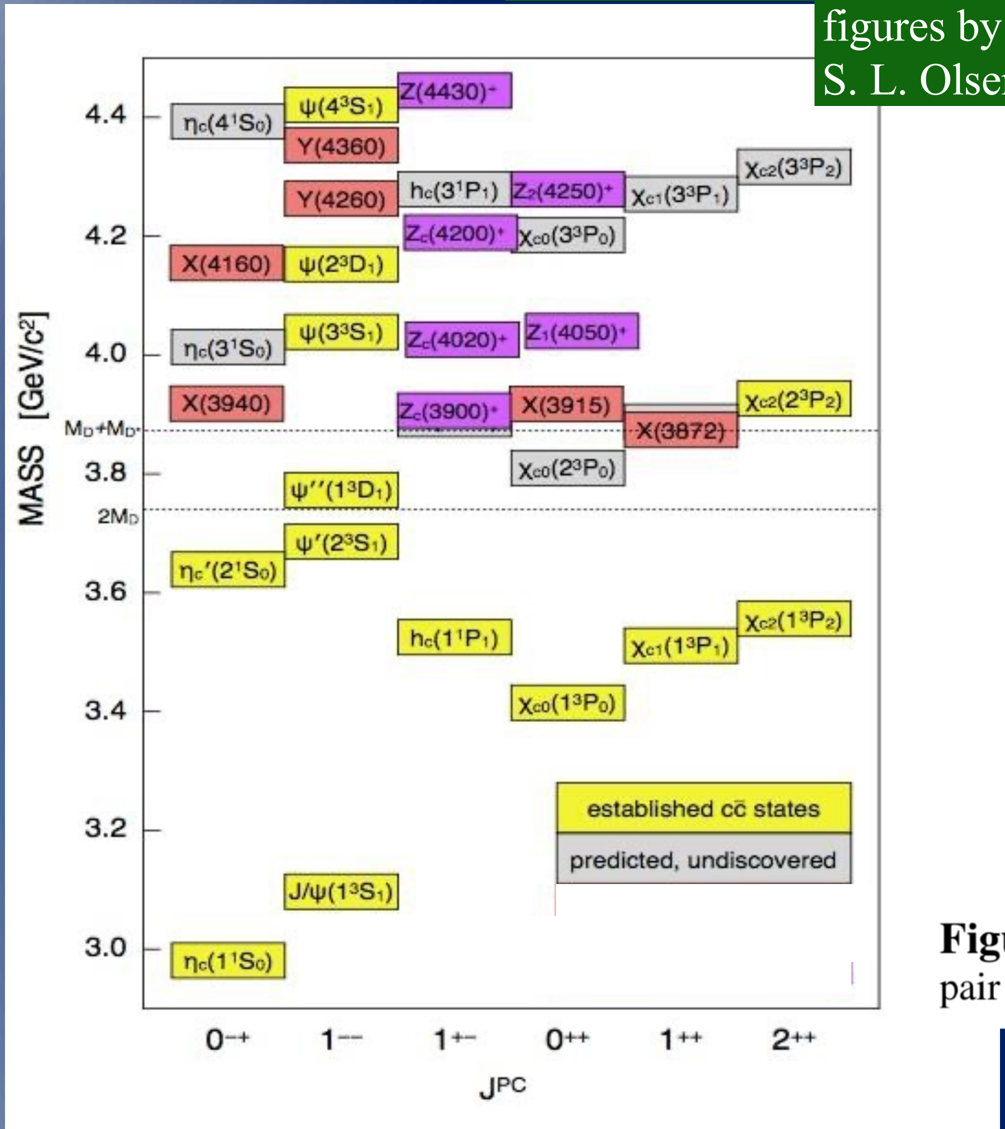
Still controversial because very close tp the threshold



Old but it give a good pictorical idea

Expected and Unexpected Charmonia

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



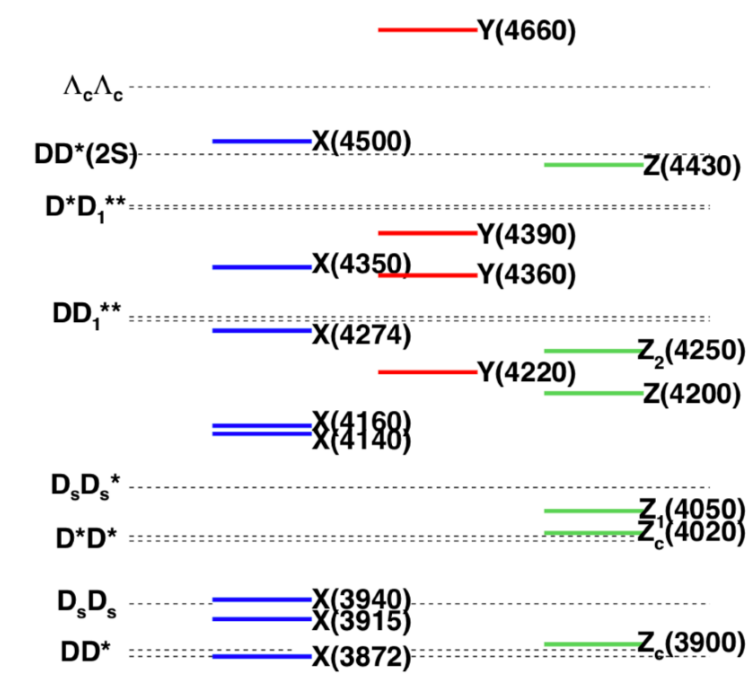
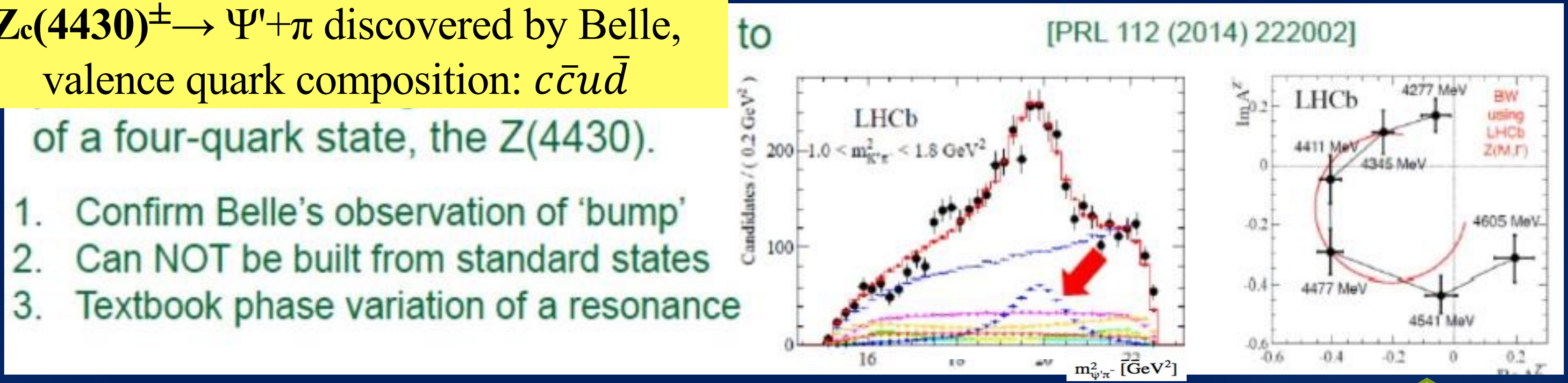


Figure 4. *XYZ* meson masses compared with charmed meson pair thresholds.

Explicit Tetraquarks:

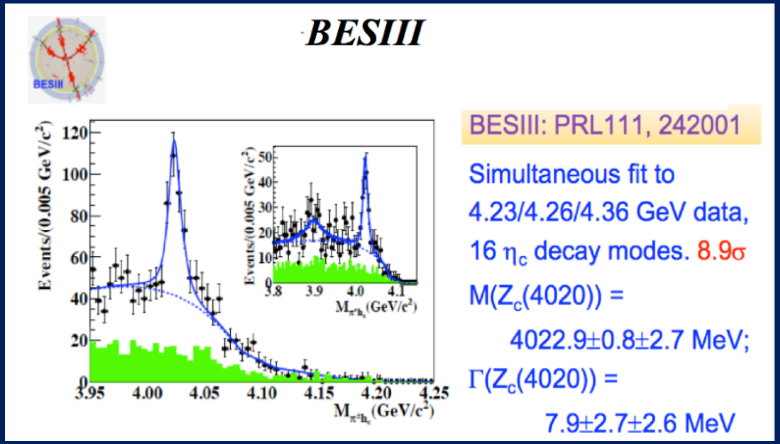
$Z_c(4430)^{\pm}$ 13.9 σ

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



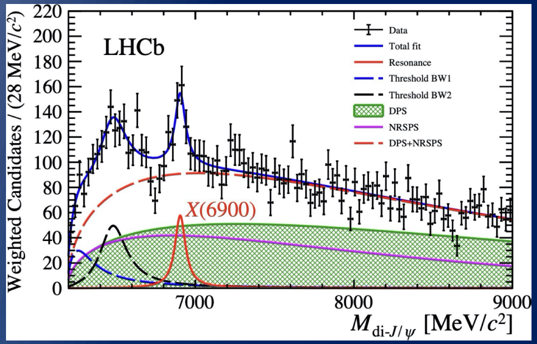
$Z_c(4020)^{\pm} \rightarrow h_c + \pi$

$Z_c(4020)^{\pm}$. 8.9σ

Recent reports of Exotic hadrons!

▷ $X(6900)$ $(\boldsymbol{cc\bar{c}\bar{c}})$

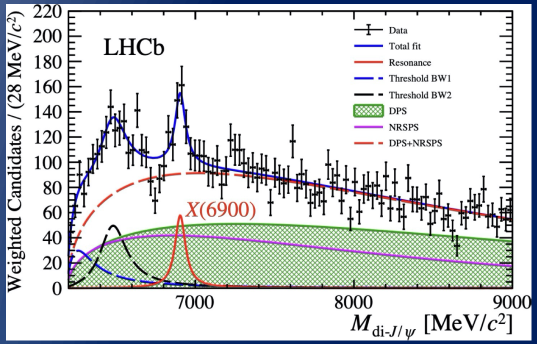
Science Bulletin 65 (2020) 1983



Recent reports of Exotic hadrons!

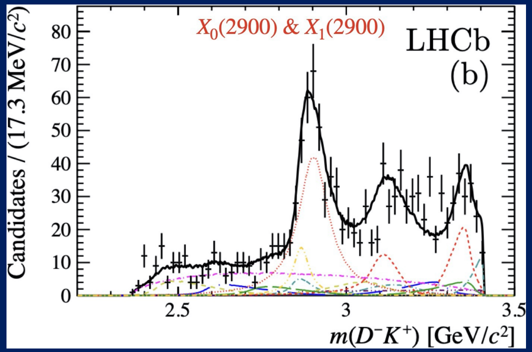
▷ $X(6900)$ **($cc\bar{c}\bar{c}$)**

Science Bulletin 65 (2020) 1983



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

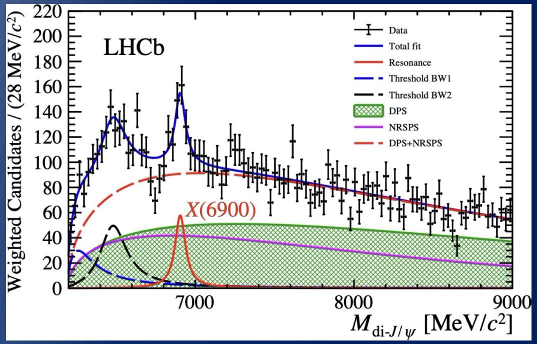
LHCb, PRL125, 242001 (2020), Phys. Rev. D 102, 112003 (2020)



Recent reports of Exotic hadrons!

▷ $X(6900)$ $(cc\bar{c}\bar{c})$

Science Bulletin 65 (2020) 1983



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

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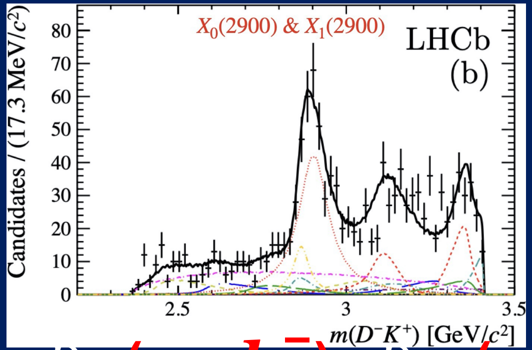
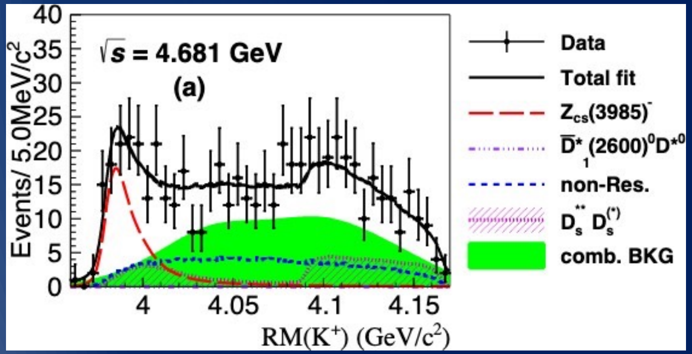


▷ Z_{cs} $(c\bar{c}s\bar{u})$

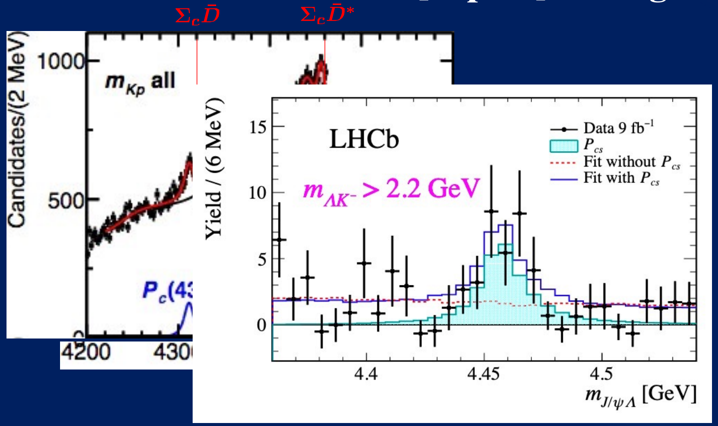
BESIII Phys. Rev. Lett. 126, 102001 (2021)]



▷ P_c $(uudc\bar{c})$, P_{cs} $(udsc\bar{c})$

LHCb PRL**115**(2015)072001, PRL**122**(2019)222001，2012.10380

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



► Many exotics have been reported by Experiments (Belle, BESIII, LHCb, ...)

Observation of the doubly charmed T_{cc}^{+} in $D^0D^0\pi^+$ invariant mass distribution with a 22 standard deviations arXiv:2109.01038, arXiv:2109.01056 (2 September 2021)

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

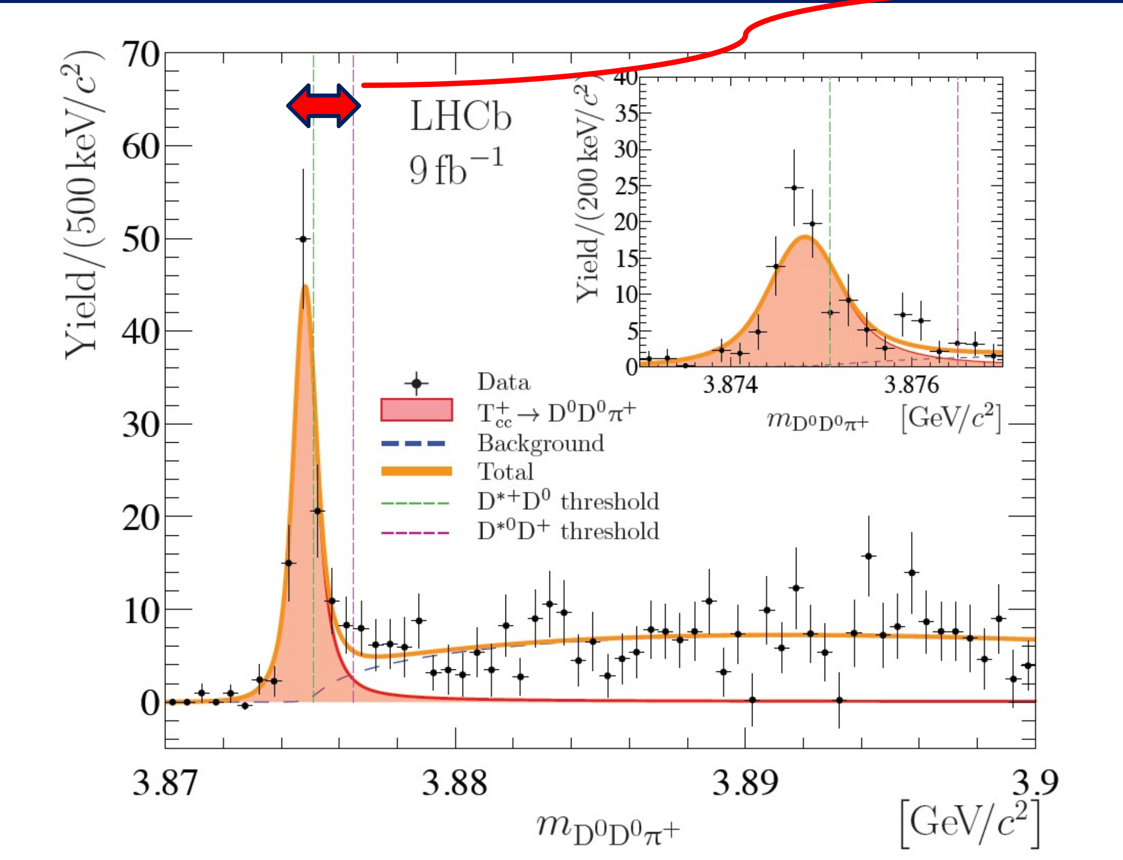
Mass and width

$M \simeq 3875$ MeV

$\Gamma \simeq 0.410$ 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

Summary of Results

- A narrow peak in $D^0D^0\pi^+$ below D^0D^{*+} threshold is observed with S>20σ
- Naive BW parameters:

$$\delta m_{\mathrm{BW}} = -273 \pm 61 \pm 5\,{}^{+11}_{-14}\,\mathrm{keV}/c^2\,,$$
$$\Gamma_{\mathrm{BW}} = 410 \pm 165 \pm 43\,{}^{+18}_{-38}\,\mathrm{keV}\,,$$

$$\begin{aligned}\boldsymbol{M} &= M_{D^{*+}D^0} - \delta m_{BW} \\ &= (3875.1 - 0.273 \pm 0.061 \pm 0.005^{+0.011}_{-0.014})\mathrm{MeV} \\ &= \left(\mathbf{3874.83 \pm 0.061 \pm 0.005^{+0.011}_{-0.014}}\right)\mathbf{MeV}\end{aligned}$$

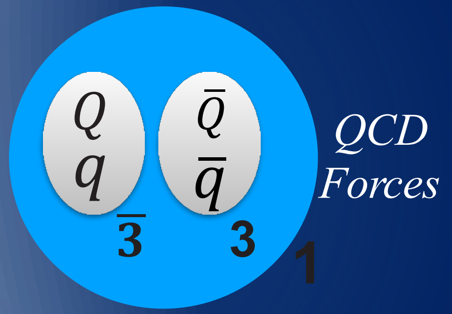
The mystery of conformation

- Currently one of the unresolved questions about tetraquarks concerns the arrangement of their structure. We know that they are made up of 4 quarks but we do not know how tight the bond of these components is. According to some physicists, the tetraquark can be thought of as a compact object, like the proton or the neutron. Another hypothesis represents them as molecular states, such as structure composed of 2 meson substructures. In a similar way for pentaquarks we can think of them as compact 5 quarks or as baryon –meson molecular states.

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.

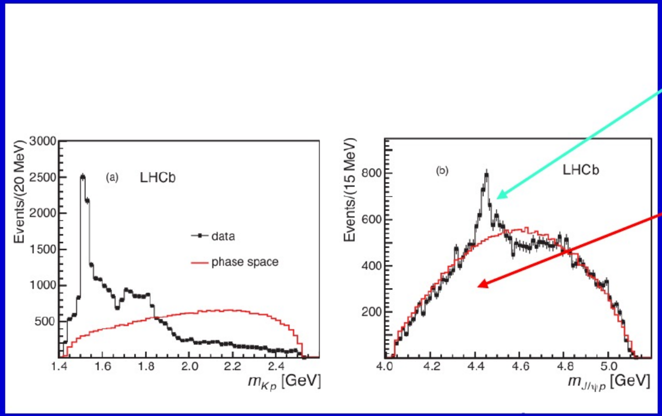
M. Anwar, J. Ferretti, E. Santopinto, Phys. Rev. **D 98** (2018) 094015

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

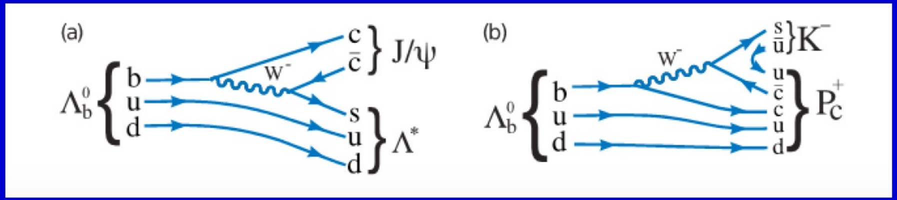
Γ =(205±18±86)MeV

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]:

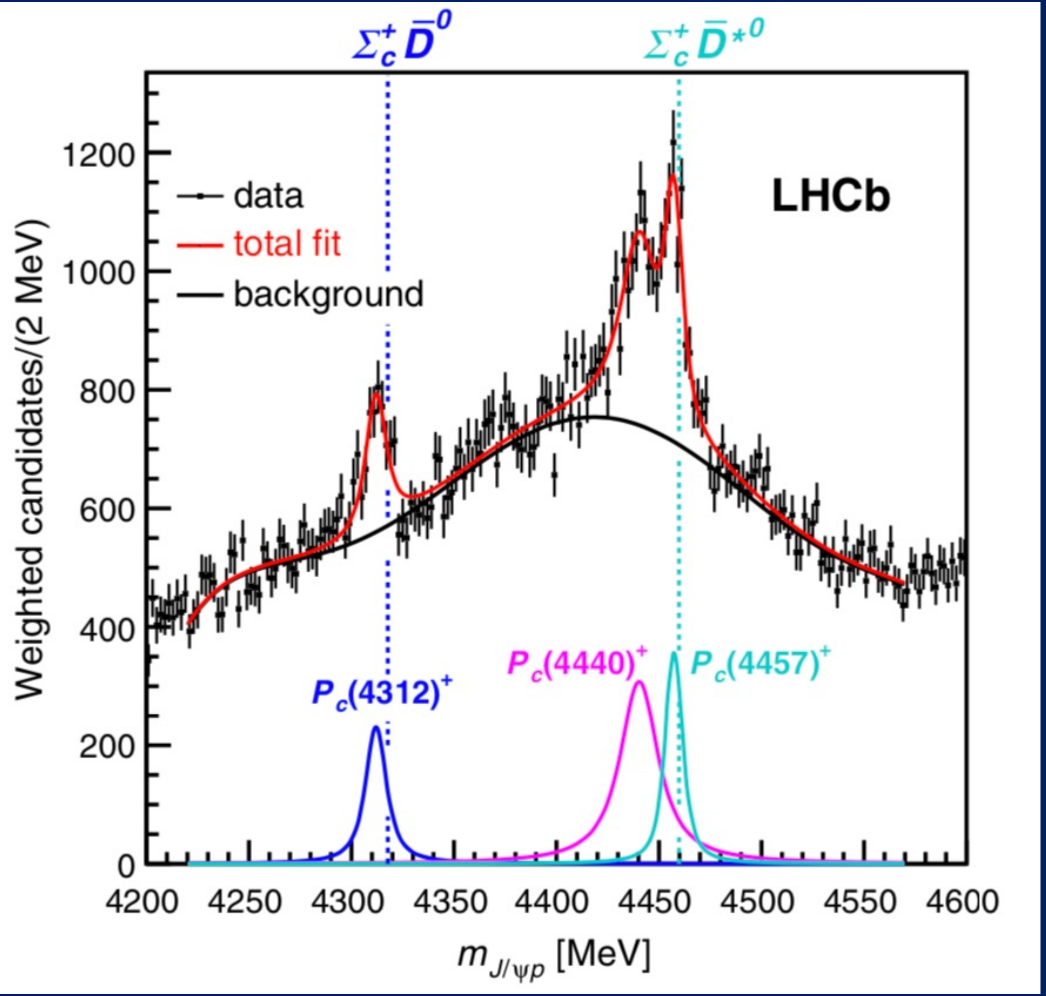
[1] R. Aaij *et al.* [LHCb Collaboration], Phys. Rev. Lett. **115** (2015) 072001
[2] R. Aaij *et al.* [LHCb Collaboration], Phys. Rev. Lett. **117** (2016) no.8, 082002
[3] R. Aaij *et al.* [LHCb Collaboration], Phys. Rev. Lett. **117** (2016) no.8, 082003

Why pentaquark states?

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



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.

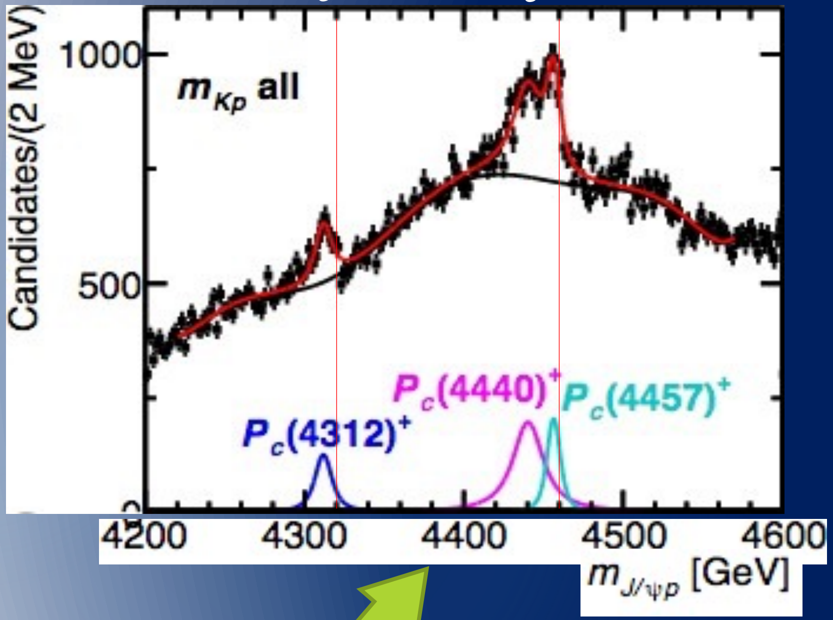
[*] R. Aaij et al. (LHCb), Phys. Rev. Lett. 122, 222001 (2019).

2021

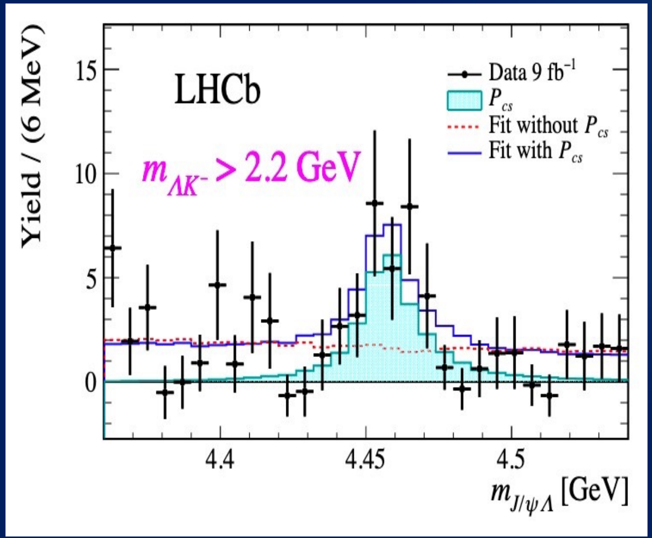
▷ P_c ($uudc\bar{c}$), P_{cs} ($udsc\bar{c}$)

LHCb PRL**115**(2015)072001, PRL**122**(2019)222001, (2021) LHCb, arXiv: 2012.10380

$\Sigma_c\bar{D}$ $\Sigma_c\bar{D}^*$



New narrow $P_c(4312)^+$ observed in 2019 at LHCb, $P_c(4450)^+$ is resolved to two states. (with 10 times statistics)



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

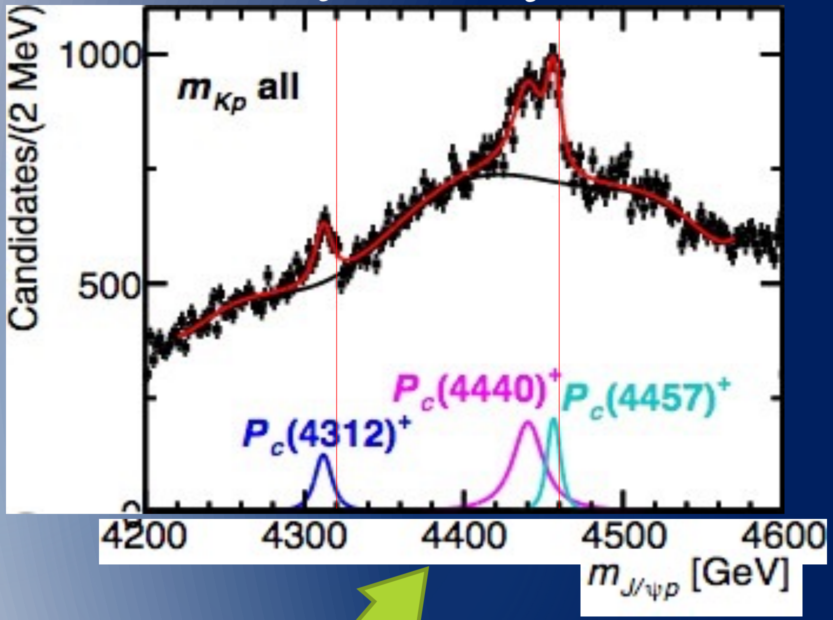
Mass of $P_{cs}(4459)^0$ 19 MeV below the $\Xi^0_c\bar{D}^{*0}$ threshold, similar to $P_c(4440)^+$ and $P_c(4457)^+$ pentaquark states.

2021

▷ P_c $(uudc\bar{c})$, P_{cs} $(udsc\bar{c})$

LHCb PRL**115**(2015)072001, PRL**122**(2019)222001, (2021) LHCb, arXiv: 2012.10380

$\Sigma_c \bar{D}$ $\Sigma_c \bar{D}^*$



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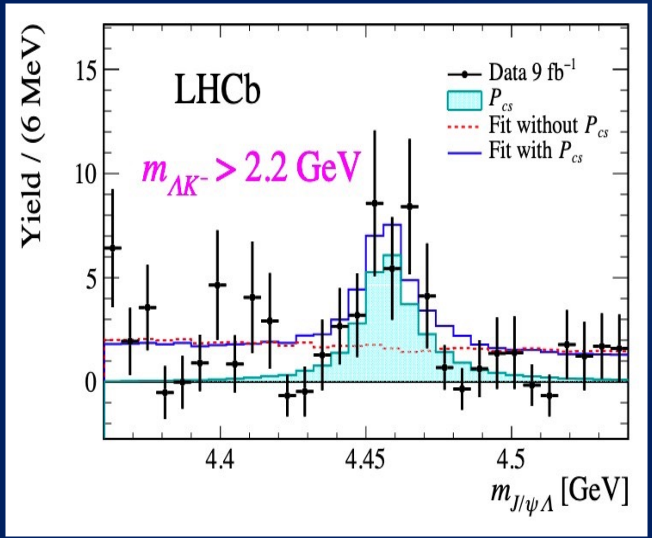

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Mass of $P_{cs}(4459)^0$ 19 MeV below the $\Xi^0_c \bar{D}^{*0}$ threshold, similar to $P_c(4440)^+$ and $P_c(4457)^+$ pentaquark states.

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

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

The final signicance including systematic uncertainties is equal to 3.1 standard deviations

In this new analysis no evidence for the Pc(4312) is found

For pentaquarks

Nuclear Forces

Hadronic Molecule?

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

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

Predetti intorno ai 4 GeV mbut at leadt they had the idea

QCD Forces

Compact pentaquark

$(5q)$

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

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

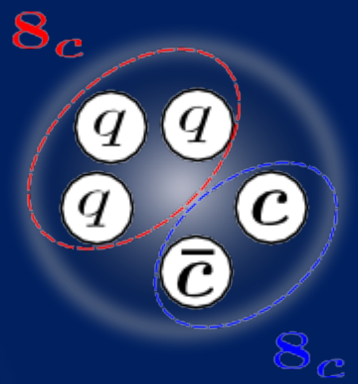
Nuclear Forces + *QCD Forces*

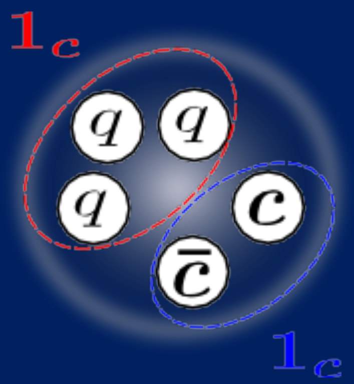
Baryon-meson molecule with 5-quark core

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

Compact 5*q* state?

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





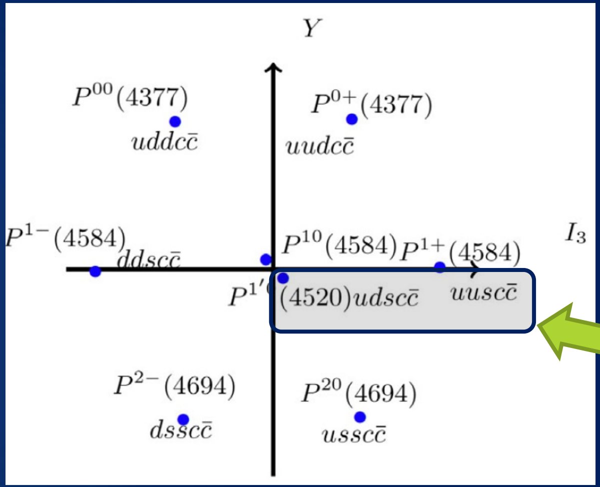
S_{q^3} = 1/2, 3/2, $S_{c\bar{c}}$ = 0, 1 S_{q^3} = 1/2, $S_{c\bar{c}}$ = 0, 1

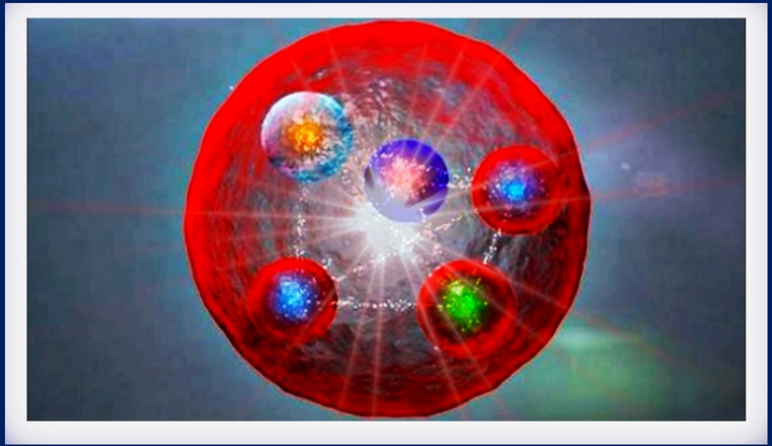
Using only simmetry considerations, we have predicted the strange pentaquark with I=0 Pcs(4457) for which LHCb reported evidence (R. Aaij et al. [LHCb], arXiv:2103.01803) and suggested to look for it in the Λ J/Ψ channel (in fact cited by LHCb). According to our model also I=1 Pcs should exist (in the Σ J/Ψ channel) and I=1/2 Pcss (in Ξ J/Ψ channel)

Compact 5*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 (we have been cited by LHCb in arXiv:2012.10380). 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).

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





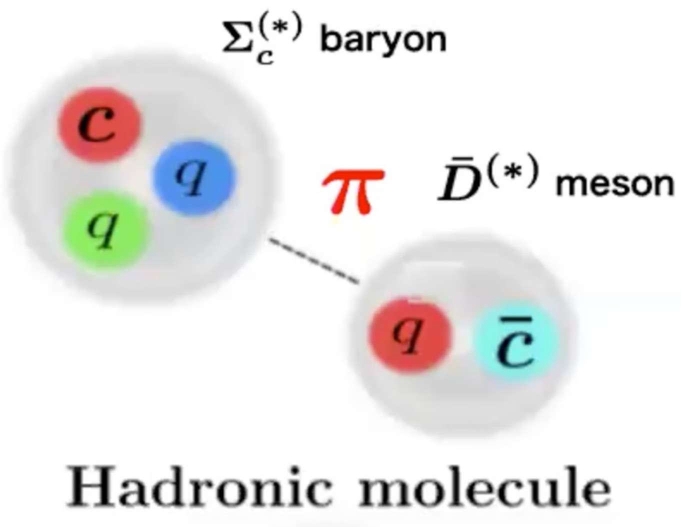
$P_{cs}^0(4459)$ The LHCb Coll. arXiv:2012.10380, Evidence of a $J/\Psi\Lambda$ structure and observation of excited Ξ^- states in the $\Xi_b^- \to J/\Psi\Lambda K^-$ decay

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

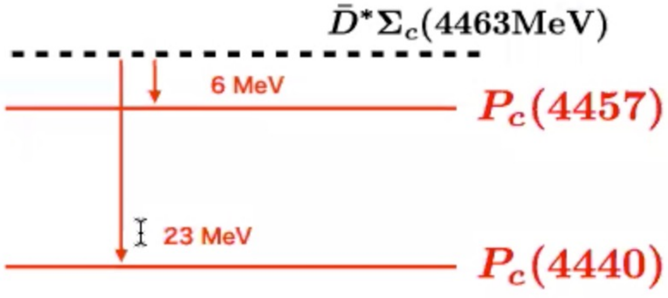
Hadronic molecules?

- 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...

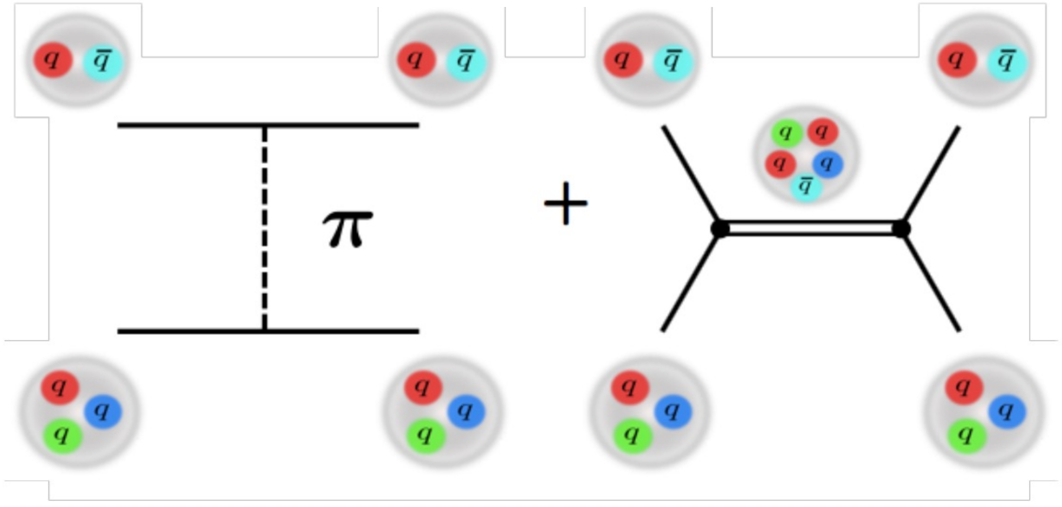
⇒ Importance of **π exchange** is expected due to the heavy quark symmetry! S. Yasui and K. Sudoh, Phys. Rev. D **80** (2009), 034008

⇒ Hadronic molecular structure is favored?

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

In Refs. [1] , [2] we studied the hidden-charm pentaquarks by coupling the $\Lambda_c\bar{D}^{(*)}$ and Σ_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. This studies followed two previous investigations of the pentaquark states thought as purely $uudc\bar{c}$ five quark states [3] and as meson-baryon molecules in a coupled channel approach [4].

The predicted pentaquark masses and widths are consistent with the new data by LHCb [*][**] with the following quantum number assignments:

$J^P\left(P_c(4337)\right) = \frac{1}{2}^-$, $J^P\left(P_c(4440)\right) = \frac{3}{2}^-$ and $J^P\left(P_c(4457)\right) = \frac{1}{2}^-$.

[*] R. Aaij *et al*. (LHCb Collaboration) Phys. Rev. Lett. **122**, 22200

[**] R. Aaij *et al*. (LHCb Collaboration) arXiv:2108.04720v1

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

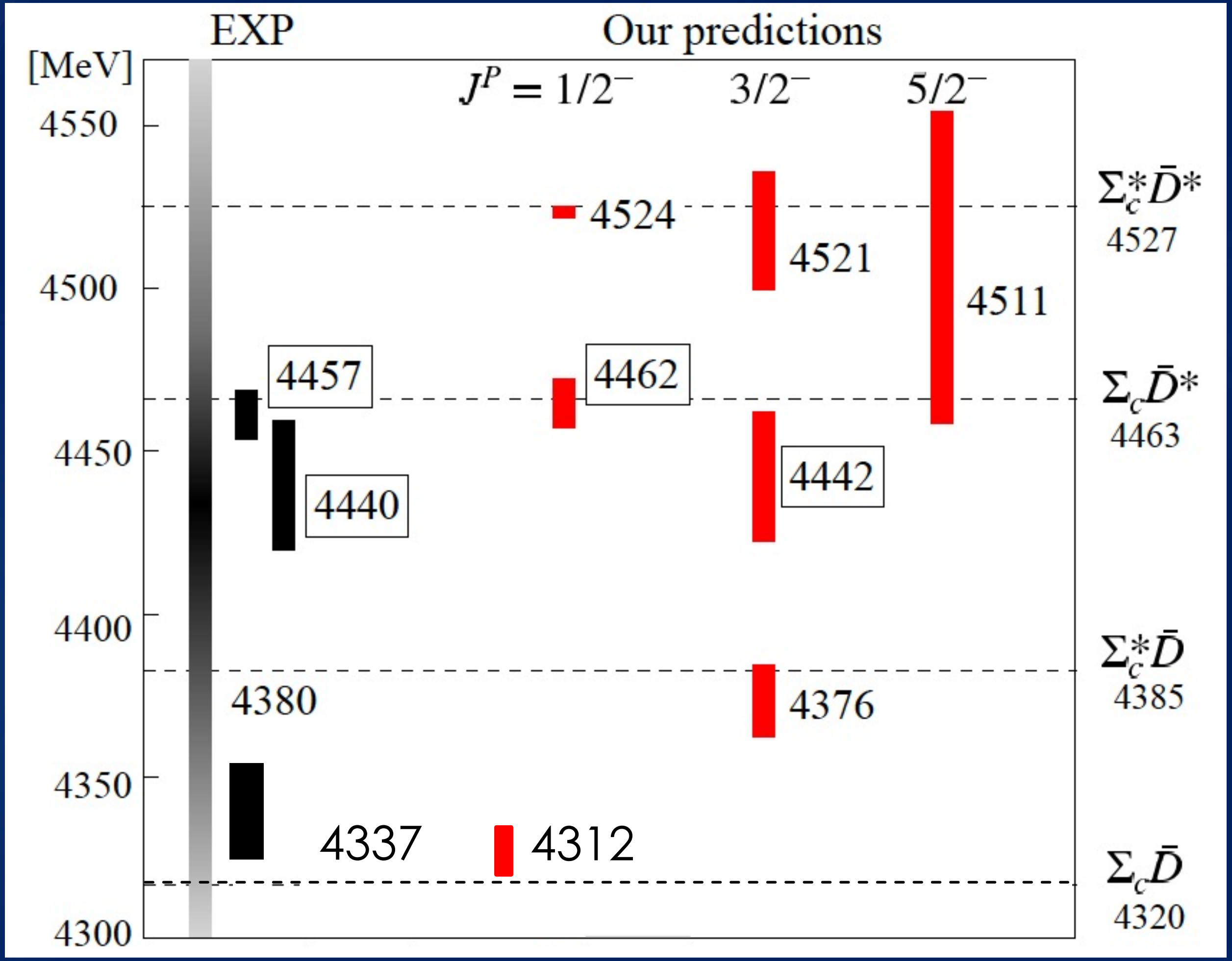
[2] Y.Yamaguchi, A.Giachino, A.Hosaka, E.Santopinto, S.Takeuchi, M.Takizawa, PRD **96** (2017) 114031(R) Phys.Rev. **D96** (2017) 114031

[3] E. Santopinto and A. Giachino in Phys. Rev. D 96 , 014014 (2017)

[4] Y. Yamaguchi and E. Santopinto Phys.Rev.D 96 (2017) 1, 014018

results

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



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

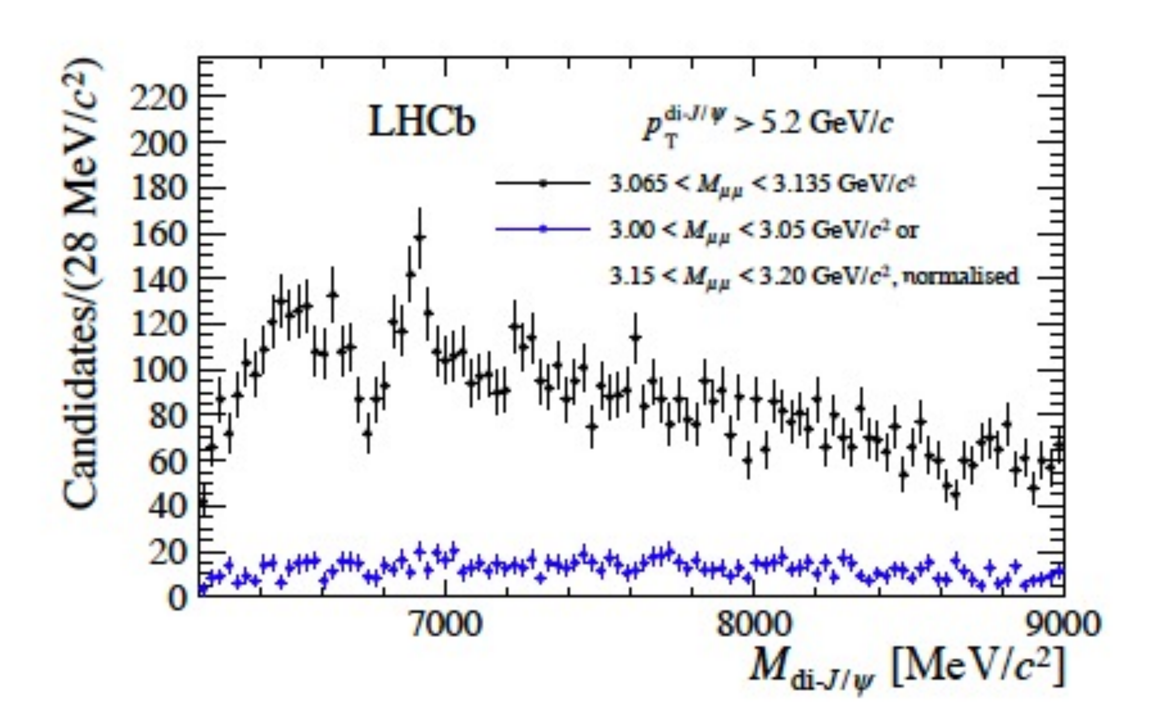
Tetraquark picture of 2 J/Ψ resonances

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)):

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

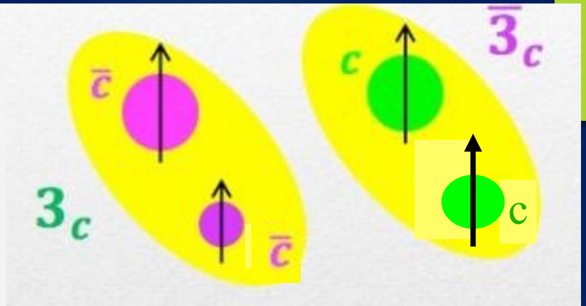
$$\Gamma[X(6900)] = 80 \pm 19 \pm 33\,\mathrm{MeV},$$

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



Tetraquark constituent picture of 2 J/Ψ

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

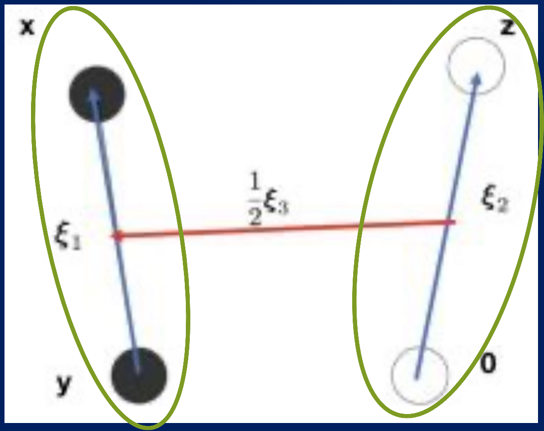


- [cc] in color $\bar{3}$
- total spin of each diquark, S=1 (color antisymmetry and Fermi statistics)
- S-wave: positive parity

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
  - QCD inspired potential (Coulomb+linear potential), h.o. variational method, the diquarks are treated as frozen .
  - Authors include computation of the energy levels of radial and orbital excitations.

Jacobi coordinates in the tetraquark



2 J/Ψ mass spectrum

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

6537 — **0^{++} S-wave**

7227 — **1st Radial excitation**

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

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

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

7481 — **1^{++} D-wave**

6900 (input) — **2^{++} S-wave**

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

Decays and branching fractions

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

1 2

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

1 2

$$+\frac{\sqrt{3}}{2}\left(\sqrt{\frac{1}{3}}\left|(c\bar{c})^0_1(c\bar{c})^0_1\right\rangle^0_1 - \sqrt{\frac{2}{3}}\left|(c\bar{c})^0_8(c\bar{c})^0_8\right\rangle^0_1\right)$$

• 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):
  - $\Gamma = |\Psi_T(0)|^2 \cdot |\mathbf{v}| \cdot \sigma(c\bar{c} \to f)$

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

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 !!

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

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

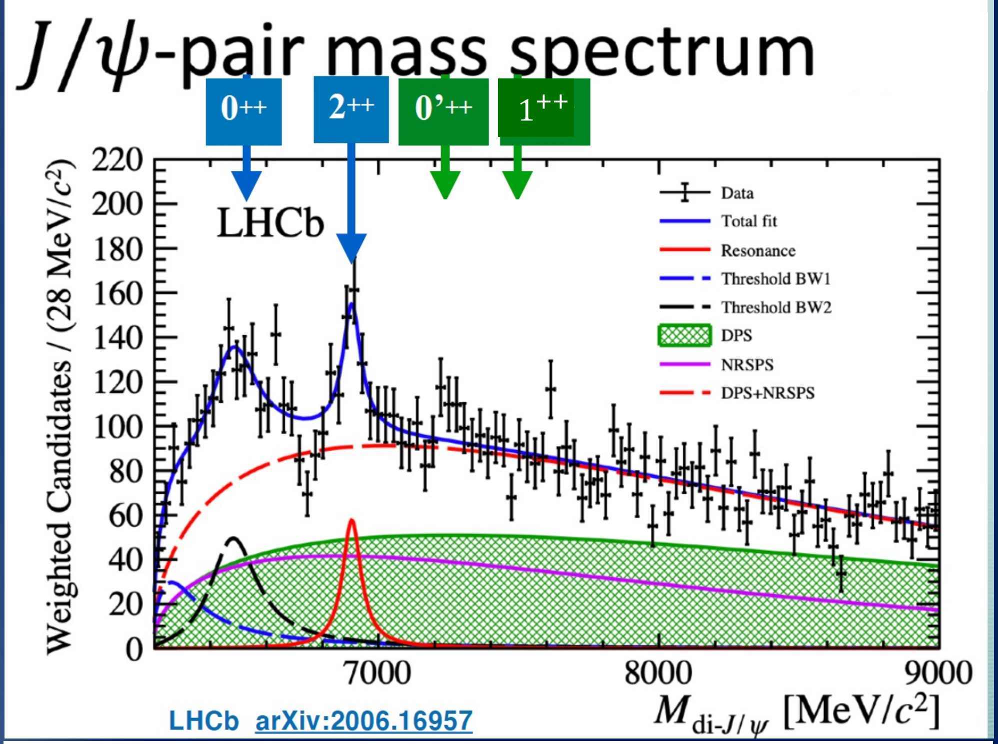
C.Becchi, J. Ferretti, A.Giachino, L.Maiani and E.Santopinto, arXiv:2006.14388, Phys.Lett. **B 811** (2020) 135952

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

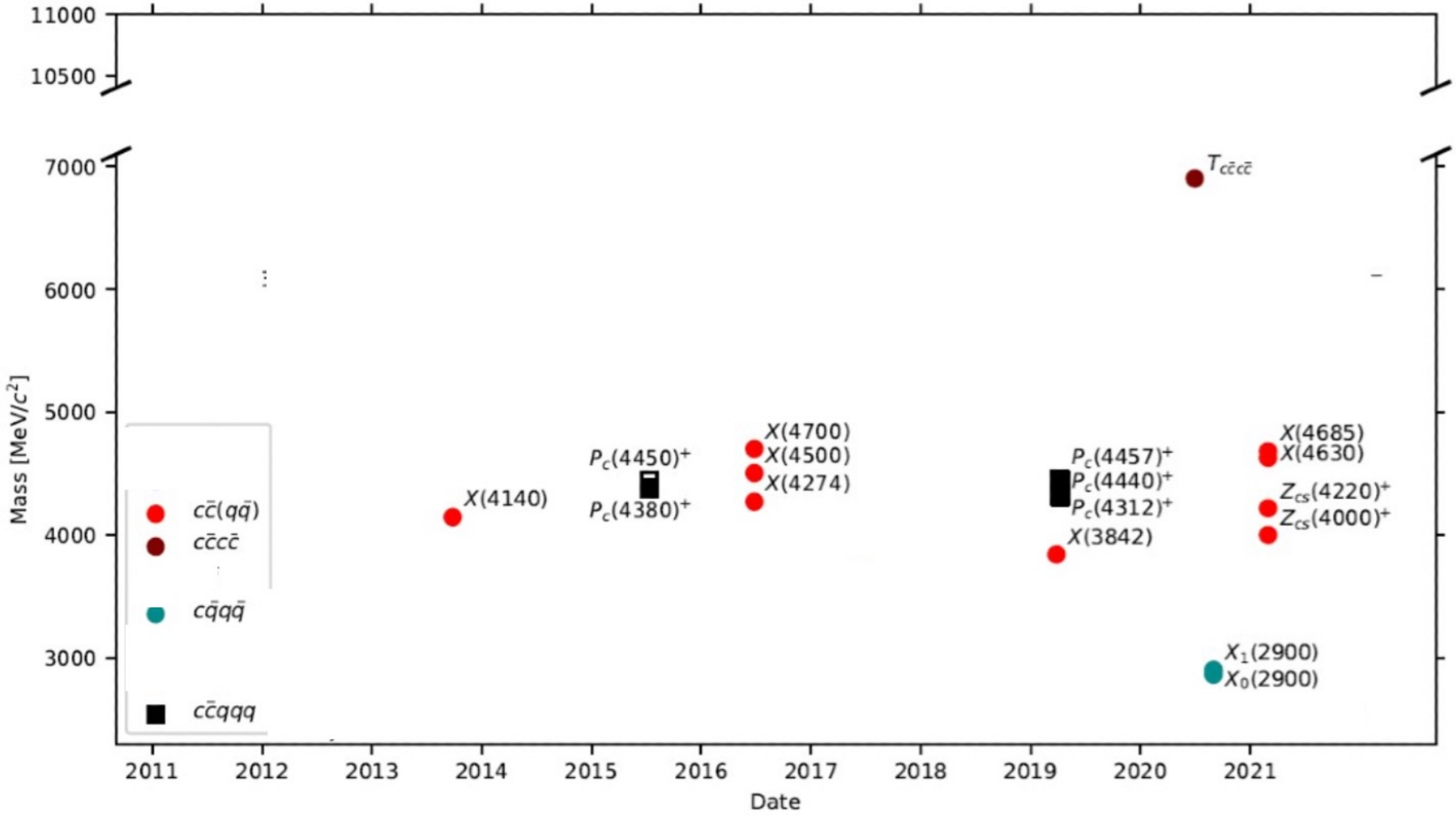
$$\xi = 4.6 \pm 1.4$$

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

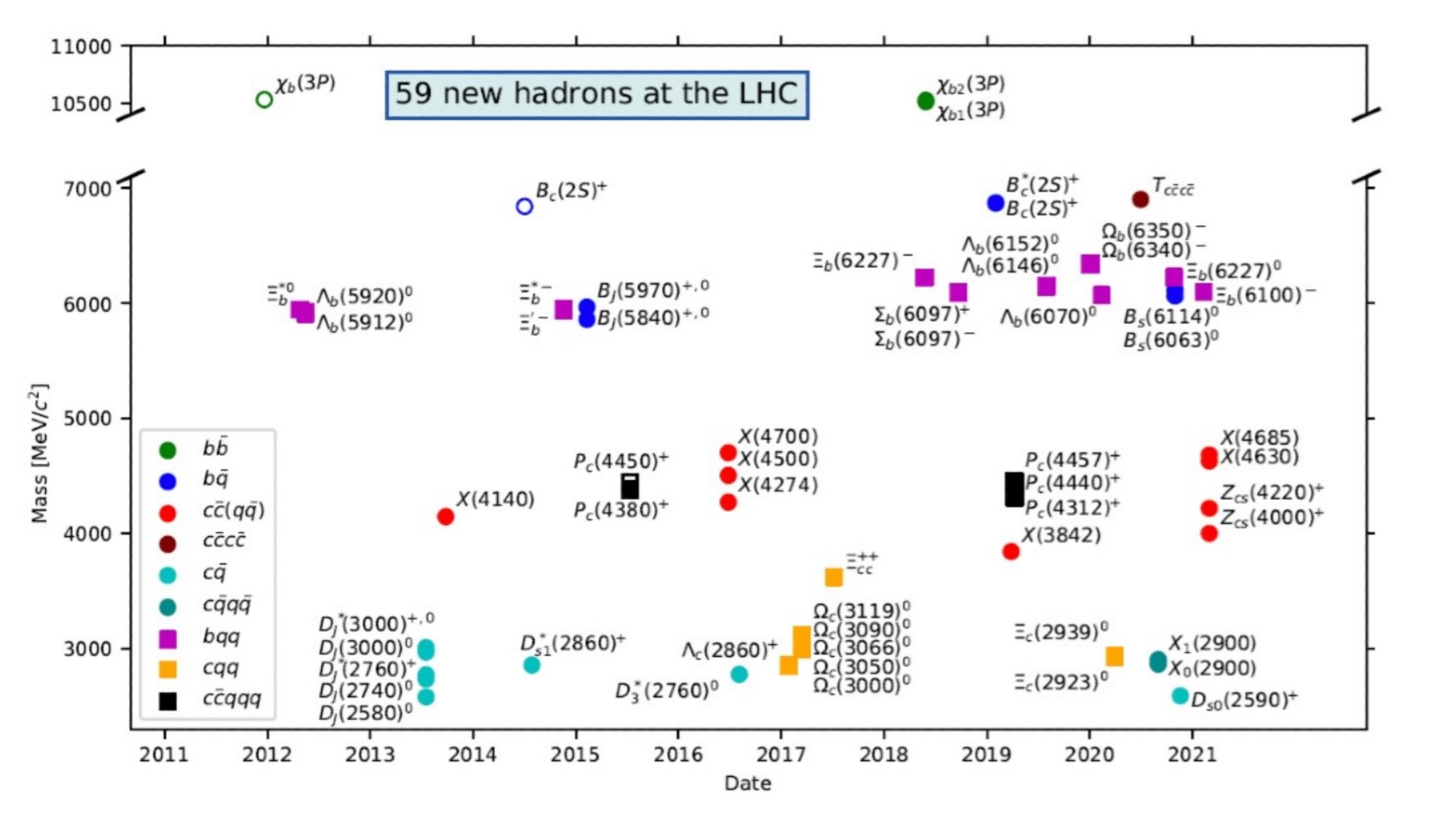


Science Bulletin, Volume 65, Issue 23, 1983 (2020)

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



16 (Traquarks and pentaquarks) discovered by LHC from 2011 up to now!


59 new hadrons at the LHC
Mass [MeV/c²]
Date
$b\bar{b}$
$b\bar{q}$
$c\bar{c}(q\bar{q})$
$c\bar{c}c\bar{c}$
$c\bar{q}$
$c\bar{q}q\bar{q}$
bqq
cqq
$c\bar{c}qqq$
$\chi_b(3P)$
$\chi_{b2}(3P)$
$\chi_{b1}(3P)$
$B_c(2S)^+$
$B_c^*(2S)^+$
$B_c(2S)^+$
$T_{cc\bar{c}\bar{c}}$
Ξ_b^{*0}
$\Lambda_b(5920)^0$
$\Lambda_b(5912)^0$
Ξ_b^{*-}
$\Xi_b^{\prime -}$
$B_J(5970)^{+,0}$
$B_J(5840)^{+,0}$
$\Xi_b(6227)^-$
$\Sigma_b(6097)^+$
$\Sigma_b(6097)^-$
$\Lambda_b(6152)^0$
$\Lambda_b(6146)^0$
$\Lambda_b(6070)^0$
$\Omega_b(6350)^-$
$\Omega_b(6340)^-$
$\Xi_b(6227)^0$
$\Xi_b(6100)^-$
$B_s(6114)^0$
$B_s(6063)^0$
$X(4140)$
$P_c(4450)^+$
$P_c(4380)^+$
$X(4700)$
$X(4500)$
$X(4274)$
$P_c(4457)^+$
$P_c(4440)^+$
$P_c(4312)^+$
$X(3842)$
$X(4685)$
$X(4630)$
$Z_{cs}(4220)^+$
$Z_{cs}(4000)^+$
Ξ_{cc}^{++}
$D_J^*(3000)^{+,0}$
$D_J(3000)^0$
$D_J^*(2760)^+$
$D_J(2740)^0$
$D_J(2580)^0$
$D_{s1}^*(2860)^+$
$\Lambda_c(2860)^+$
$D_3^*(2760)^0$
$\Omega_c(3119)^0$
$\Omega_c(3090)^0$
$\Omega_c(3066)^0$
$\Omega_c(3050)^0$
$\Omega_c(3000)^0$
$\Xi_c(2939)^0$
$\Xi_c(2923)^0$
$X_1(2900)$
$X_0(2900)$
$D_{s0}(2590)^+$

Summary

- The field of exotics has been established both experimentally and theoretically as a hot topic

- Recognition that some really fundamental questions on how hadronic structures are created are still unanswered. Ongoing and near-future experiments are likely to provide enough information to answer them.

Thanks for your attention!