The puzzling behavior of pentaquarks and tetraquarks

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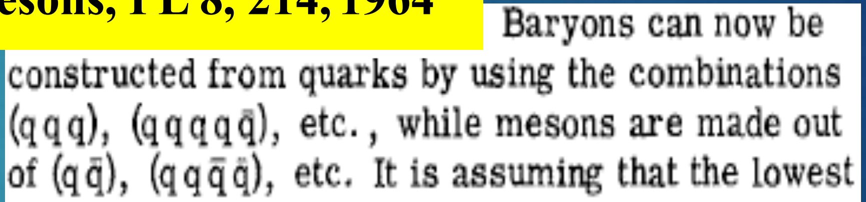
Colloquium

14 April, 2021

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

- Heavy quark pairs are difficult to be created or destroyed by QCD forces inside hadrons.
- Hadrons with a $c\bar{c}$ or $b\bar{b}$ pair ***and*** electrically charged ***must*** contain additional light quarks, ***realising the hypothesis advanced by Gell-Mann in the Sixties***

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

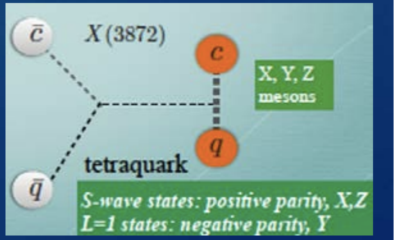


Baryons can now be constructed from quarks by using the combinations $(q\,q\,q)$, $(q\,q\,q\,q\,\bar{q})$, etc., while mesons are made out of $(q\,\bar{q})$, $(q\,q\,\bar{q}\,\bar{q})$, etc. It is assuming that the lowest

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

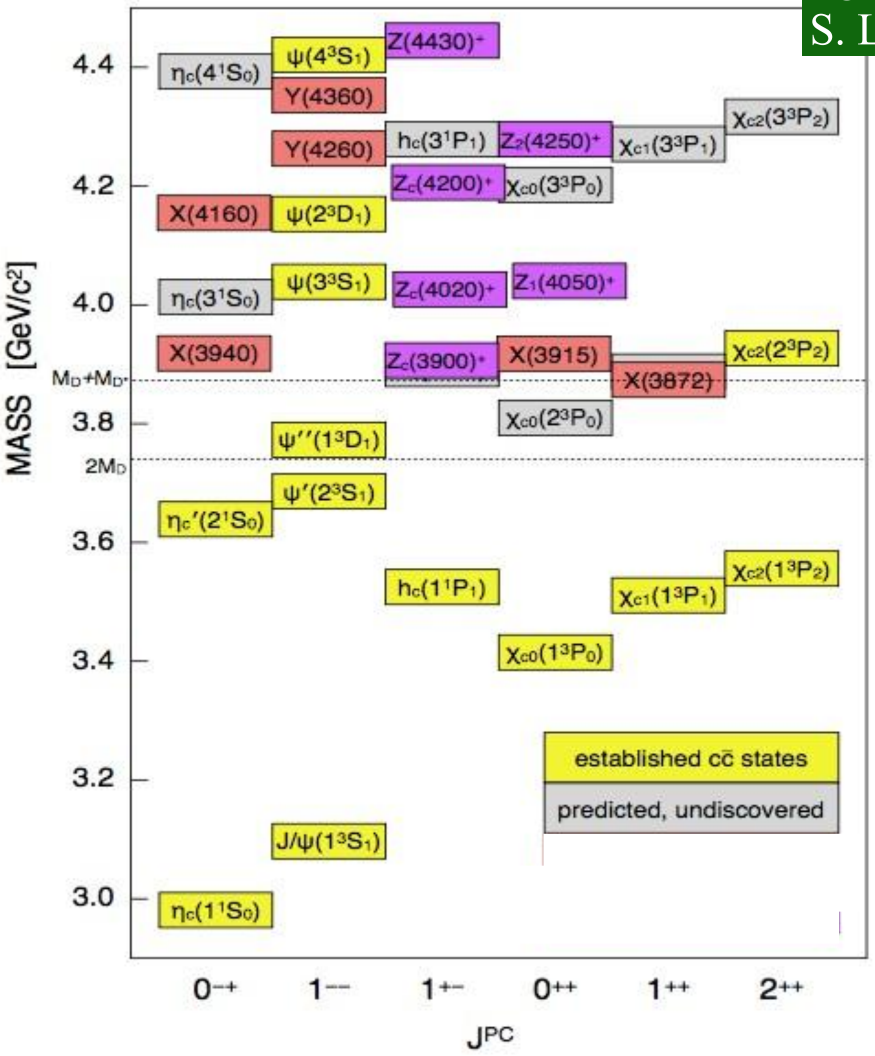
There are indeed new valence quark configurations !!

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



Expected and Unexpected Charmonia

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



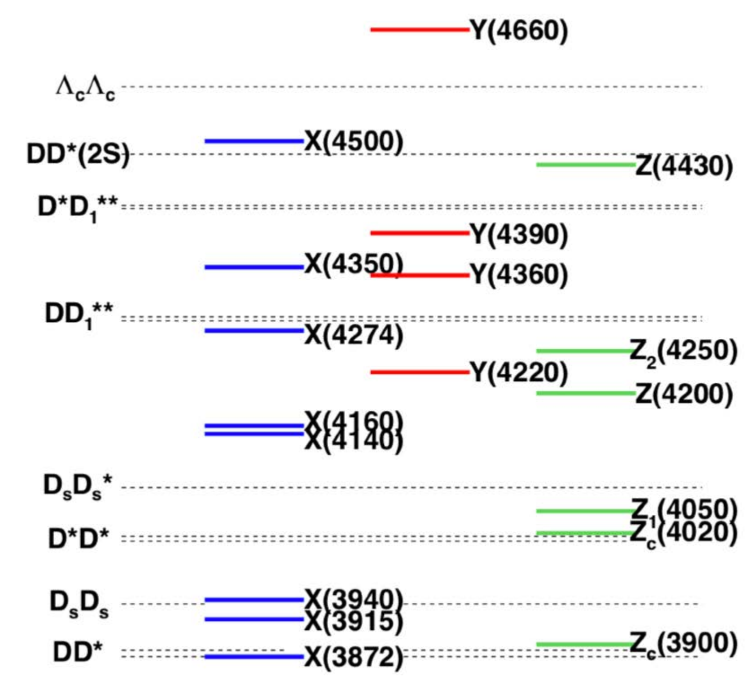
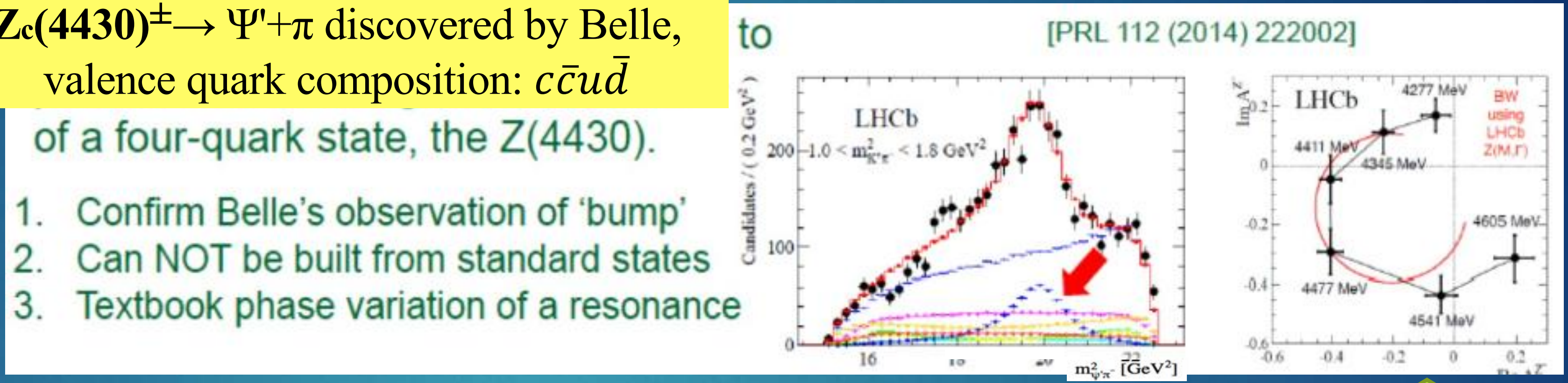


Figure 4. *XYZ* meson masses compared with charmed meson pair thresholds.

Explicit Tetraquarks:

$Z_c(4430)^{\pm}$ 13.9 σ

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



to

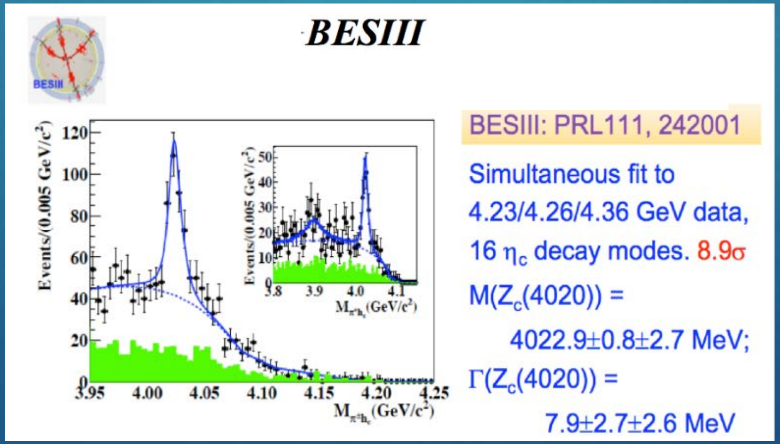
[PRL 112 (2014) 222002]

of a four-quark state, the Z(4430).

1. Confirm Belle's observation of 'bump'
2. Can NOT be built from standard states
3. Textbook phase variation of a resonance

"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



BESIII

BESIII: PRL111, 242001

Simultaneous fit to 4.23/4.26/4.36 GeV data, 16 η_c decay modes. 8.9σ

$M(Z_c(4020))$ = 4022.9±0.8±2.7 MeV;

$\Gamma(Z_c(4020))$ = 7.9±2.7±2.6 MeV

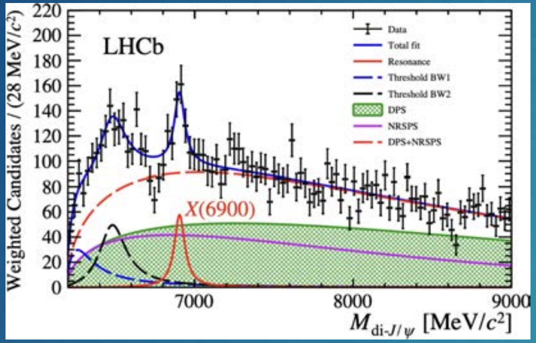
$Z_c(4020)^{\pm}$→h_c+π

$Z_c(4020)^{\pm}$. 8.9σ

Recent reports of Exotic hadrons!

▷ X(6900) $(cc\bar{c}\bar{c})$

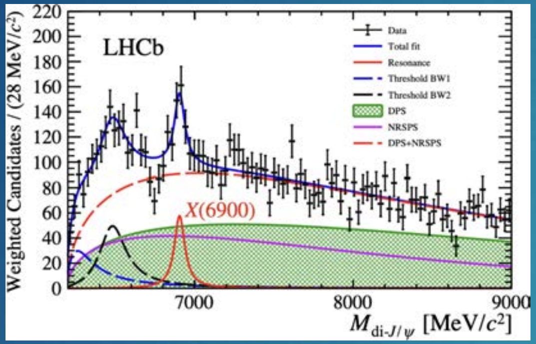
Science Bulletin 65 (2020) 1983



Recent reports of Exotic hadrons!

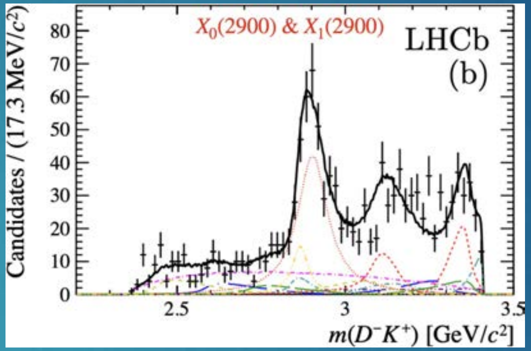
- ▷ X(6900) ($cc\bar{c}\bar{c}$)

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!

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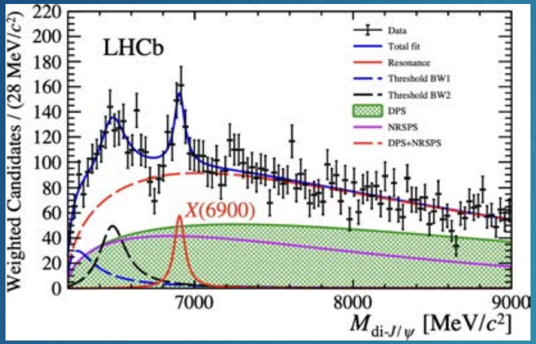
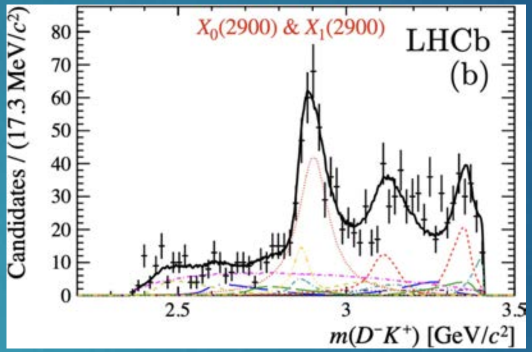
Science Bulletin 65 (2020) 1983



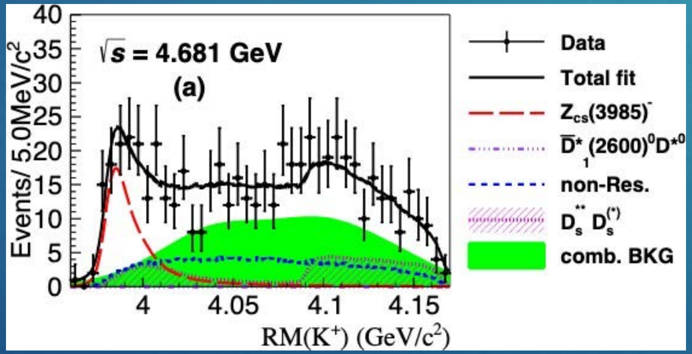
▷ $X_{0,1}(2900)$ $(\bar{c}\bar{s}ud)$

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



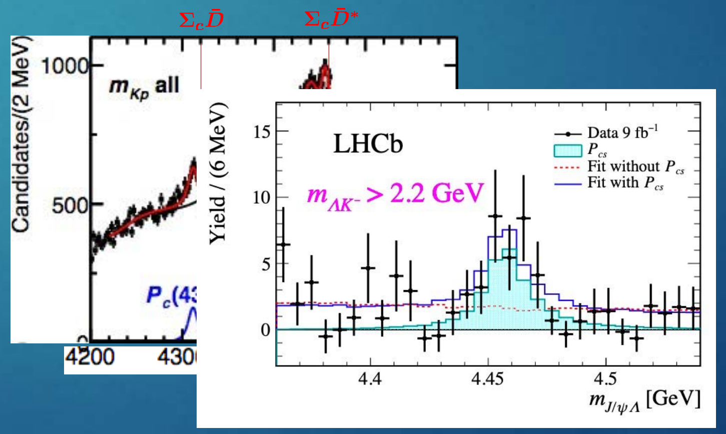
▷ Z_{cs} $(c\bar{c}s\bar{u})$

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



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

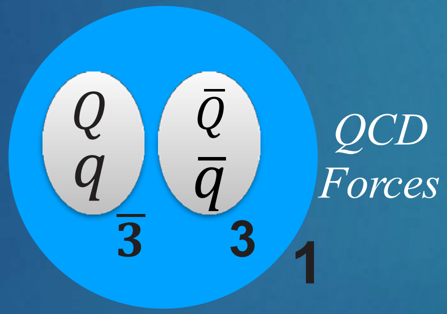
The mystery of conformation

- 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)



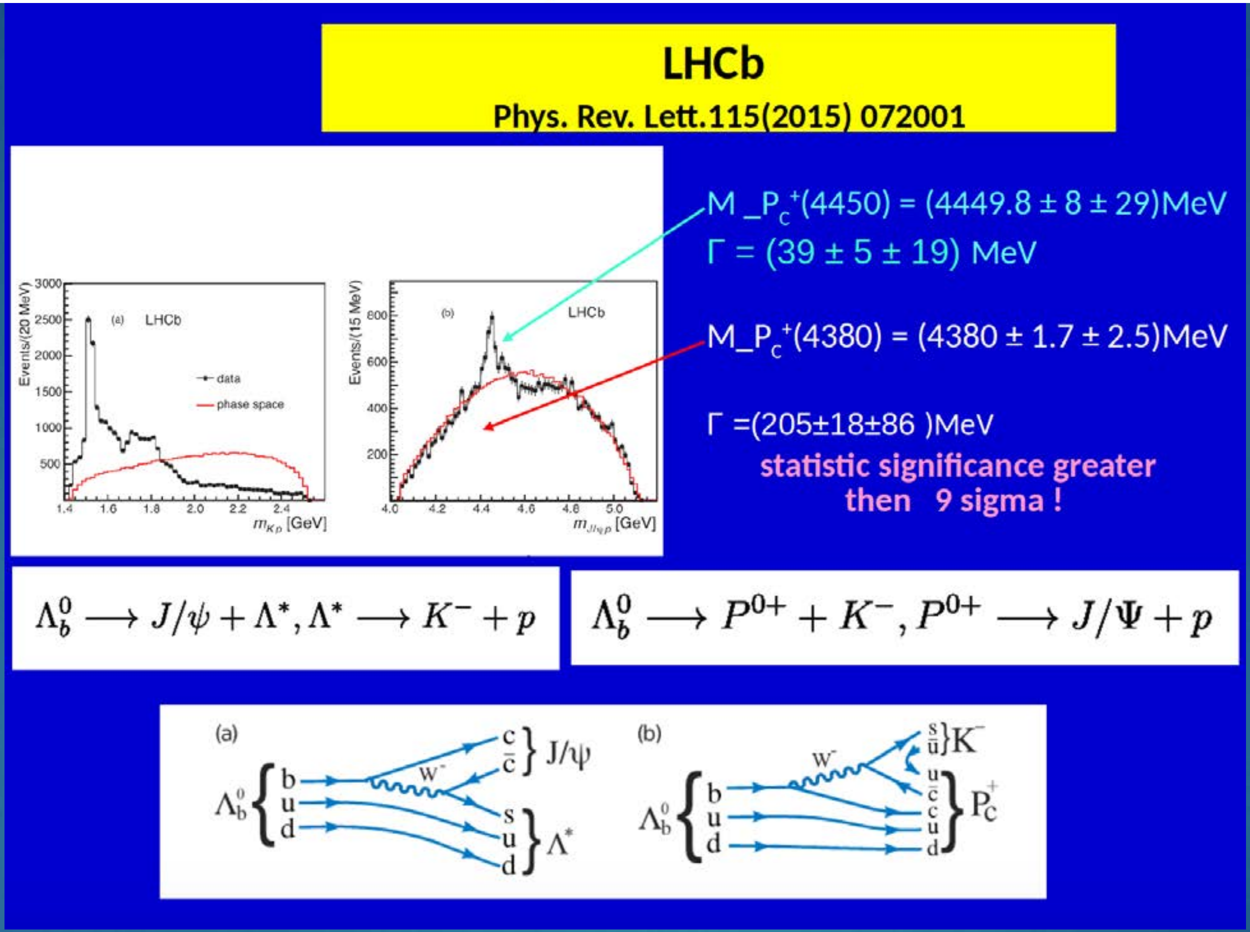
Compact Diquark-Antidiquark

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

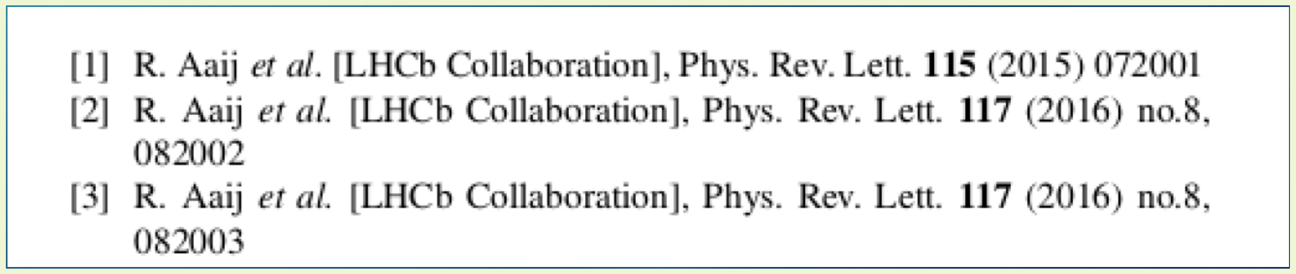
statistic significance greater then 9 sigma !

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

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

P_c $(uud c\bar{c})$

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

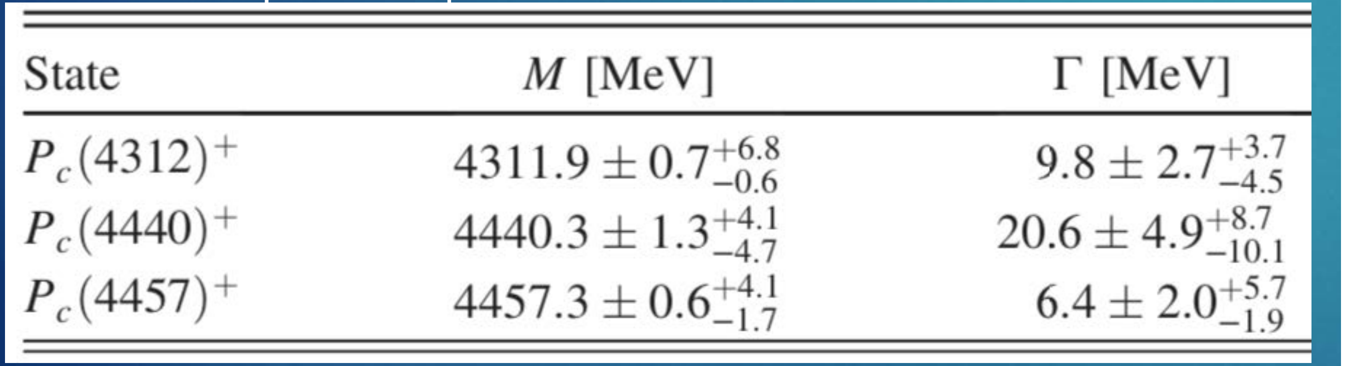
[2] R. Aaij *et al.* [LHCb Collaboration], Phys. Rev. Lett. **117** (2016) no.8, 082002

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

Why pentaquark states?

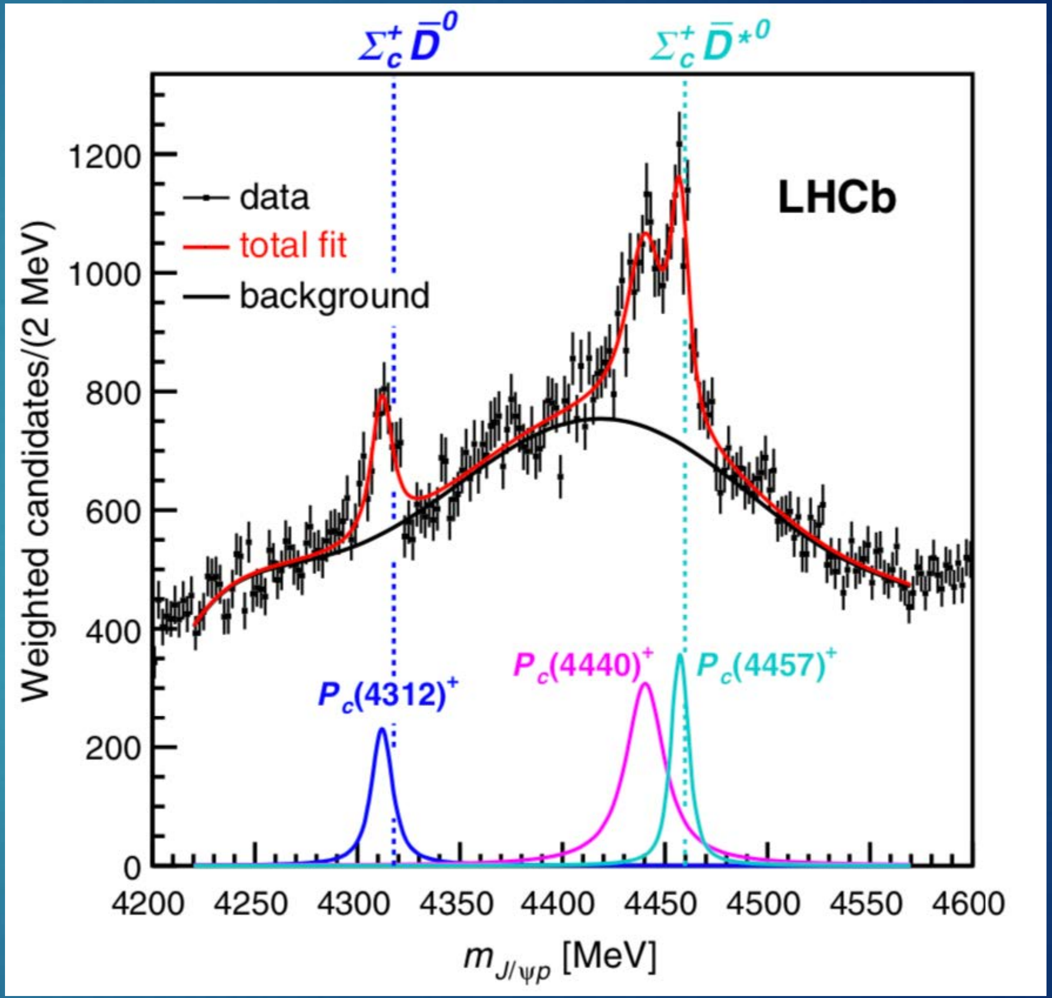
As well as revealing the new $P_c(4312)$ state, the LHCb 2019 analysis also uncovered a more complex structure of $P_c(4450)$, consisting of two narrow nearby separate peaks, $P_c(4440)$ and $P_c(4457)$ with the two-peak structure hypothesis having a statistical significance of 5.4 sigma with respect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

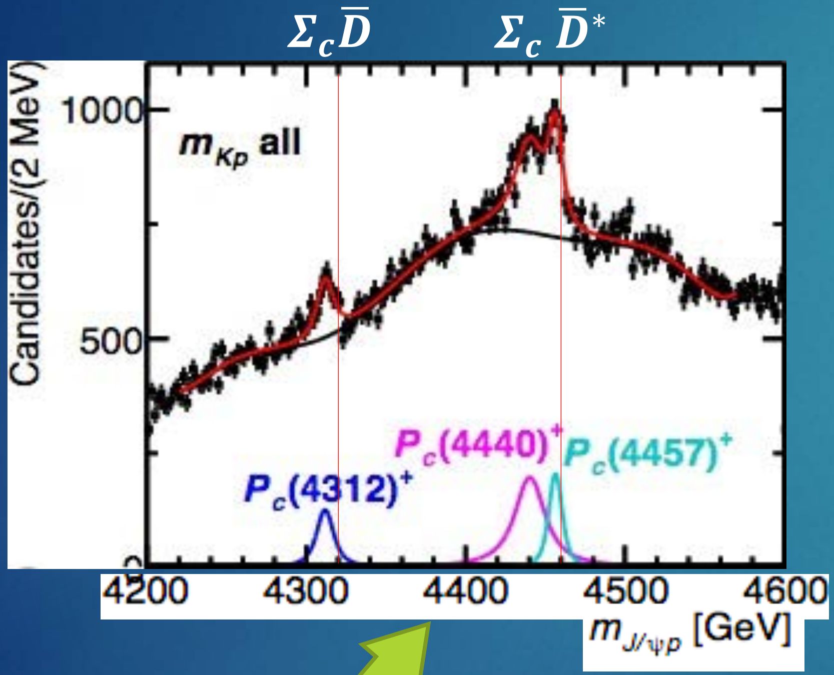


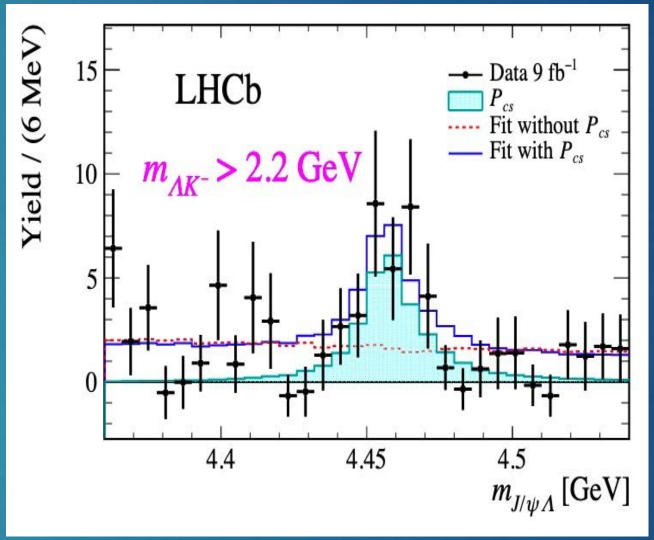
Number of events versus J/Psi p invariant mass [*]. The mass thresholds for the $\Sigma_c\, \overline{D}$ and $\Sigma_c\, \overline{D}^{\,*}$ final states are superimposed.

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





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

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

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.

For pentaquarks

Nuclear Forces

Hadronic Molecule?

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

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

QCD Forces

Compact pentaquark

$(5\,q)$

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*

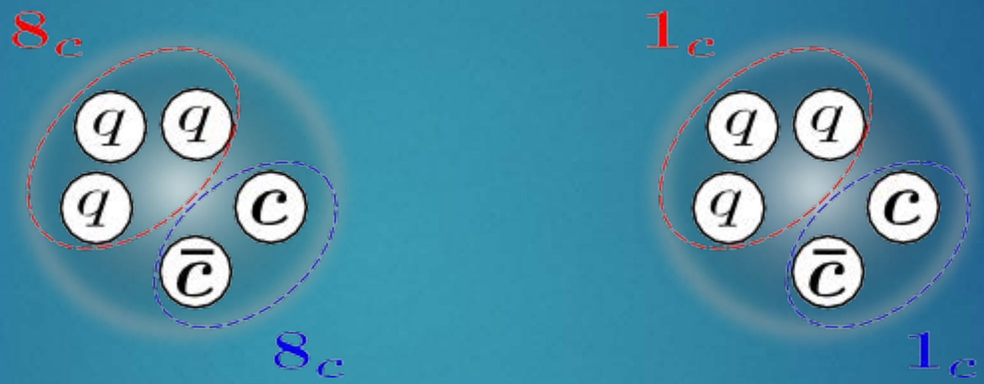
Baryon-meson molecule with 5-quark core

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.
  P_c states by an algebraic model
- 5-quark configurations



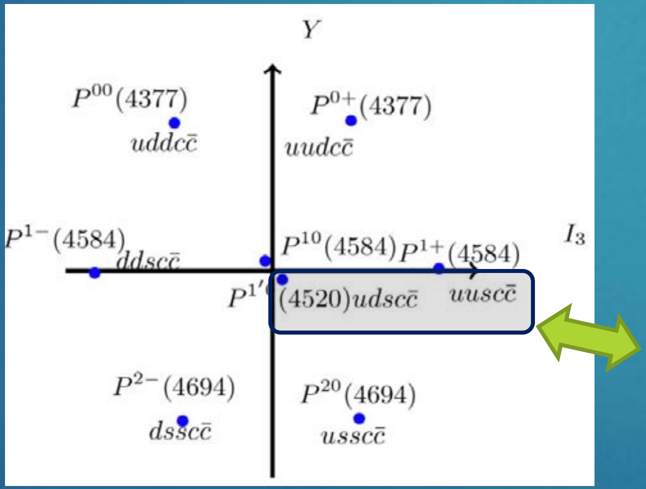
S_{q^3} = 1/2, 3/2, $S_{c\bar{c}}$ = 0, 1 S_{q^3} = 1/2, $S_{c\bar{c}}$ = 0, 1

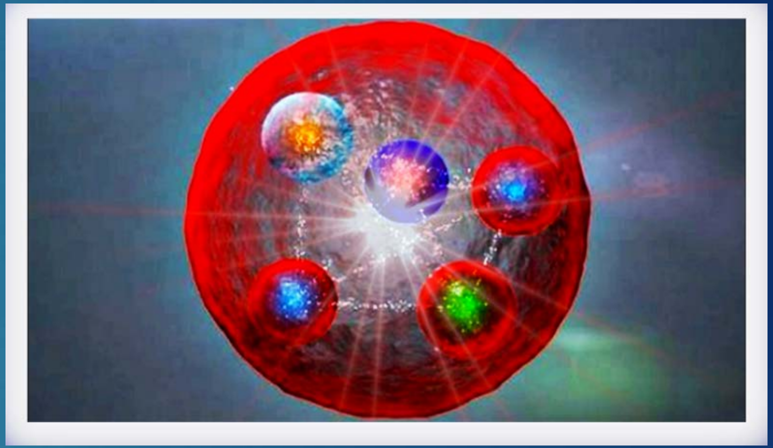
Using only simmetry considerations, we have predicted the strange pentaquark with I=0 Pcs(4457) for which LHCb reported evidence (R. Aaij et al. [LHCb], arXiv:2103.01803) and suggested to look for it in the Λ J/Ψ channel (in fact cited by LHCb). According to our model also I=1 Pcs should exist (in the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

Compact 5q 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).

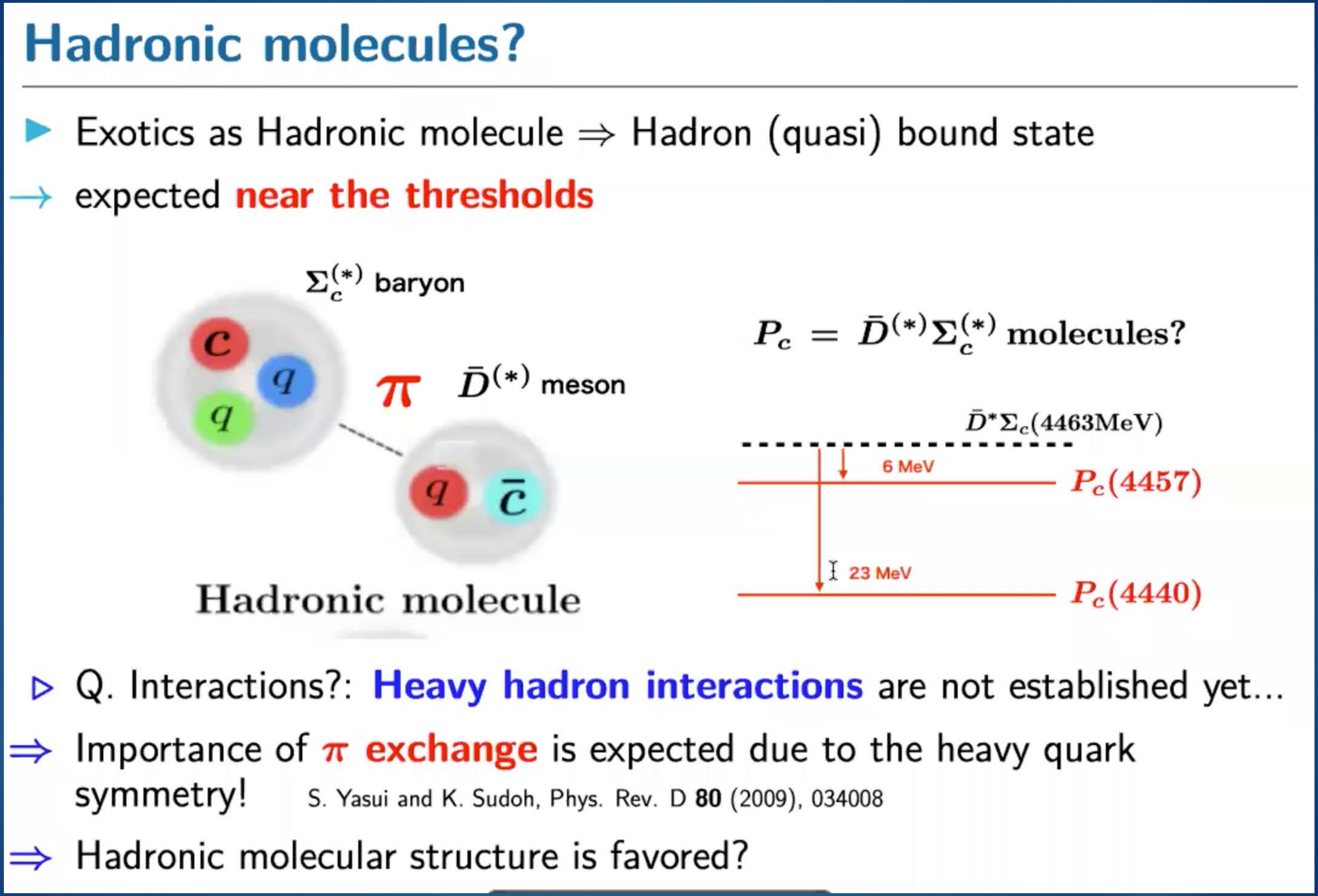
$$J^P = \frac{3}{2}^-$$





$P_{cs}^{0}(4459)$ 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?

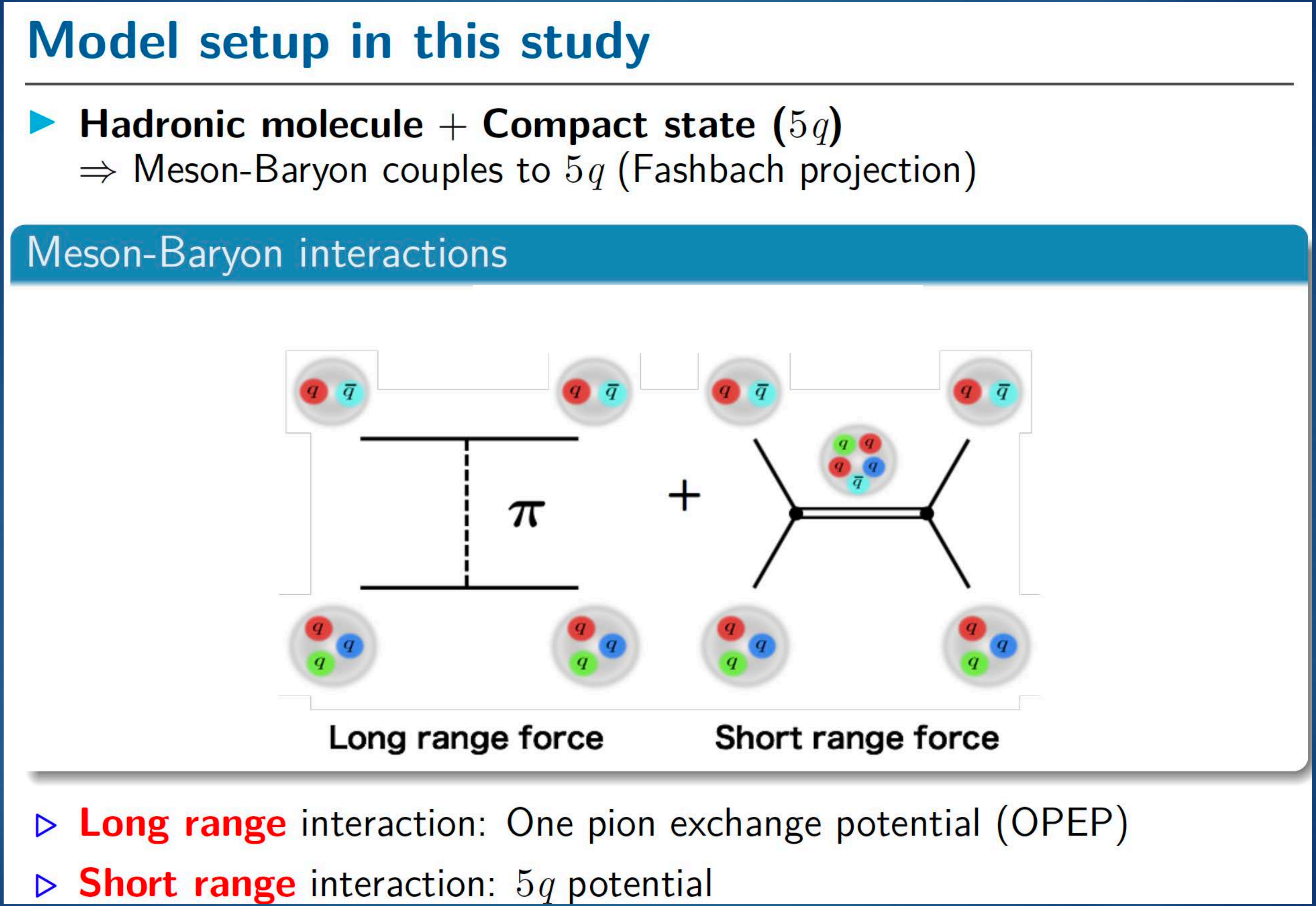
- Exotics as Hadronic molecule ⇒ Hadron (quasi) bound state

→ expected **near the thresholds**

- 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 force

Short range force

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

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

Based on the 2019 LHCb results [*], in Ref. [1] by fixing the free parameter proportional to the coupling strength between the meson-baryon and 5-quark-core states we could reproduce in detail the experimental masses and widths already calculated in [2] . The predicted pentaquark masses and widths are consistent with the new data with the following quantum number assignments: $J^P\left(P_c(4312)\right) = \frac{1}{2}^-$, $J^P\left(P_c(4440)\right) = \frac{3}{2}^-$ and $J^P\left(P_c(4457)\right) = \frac{1}{2}^-$.

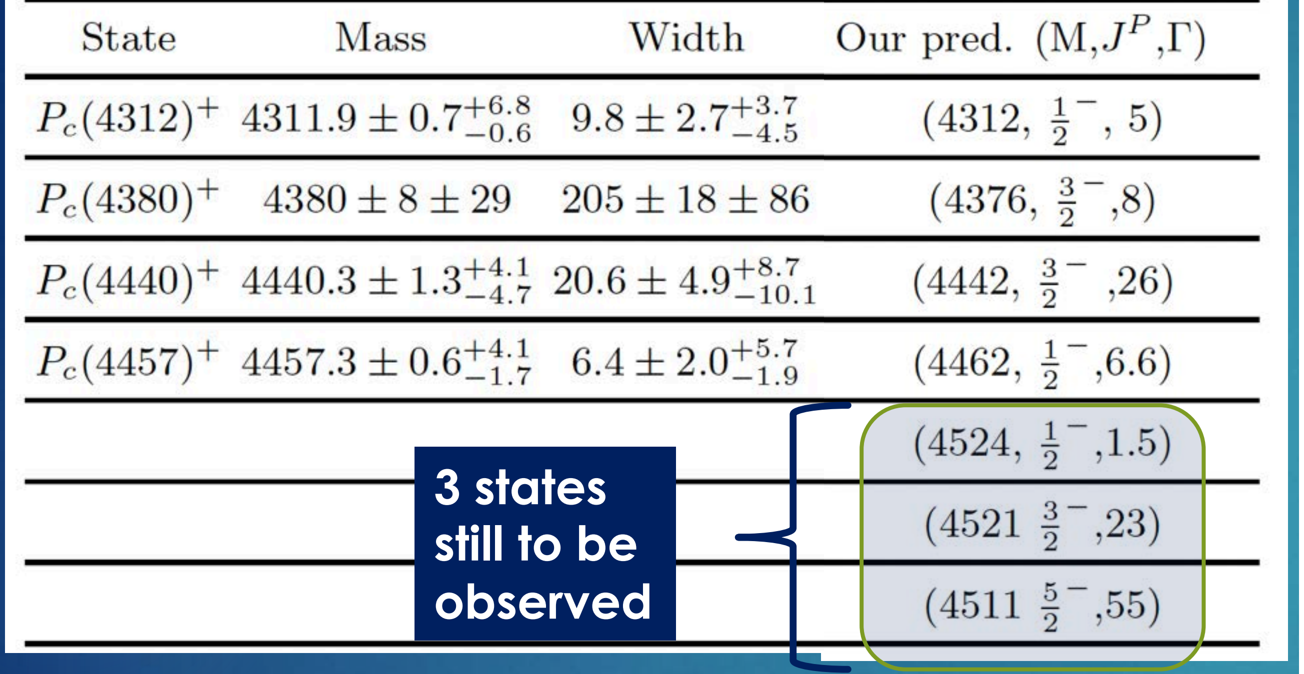
We find that the dominant components of these states are the nearby threshold channels: $P_c(4312)$ is dominated by $\Sigma_c\,\bar{D}$, $P_c(4440)$ and $P_c(4457)$ are both dominated by $\Sigma_c\,\bar{D}^*$

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

[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

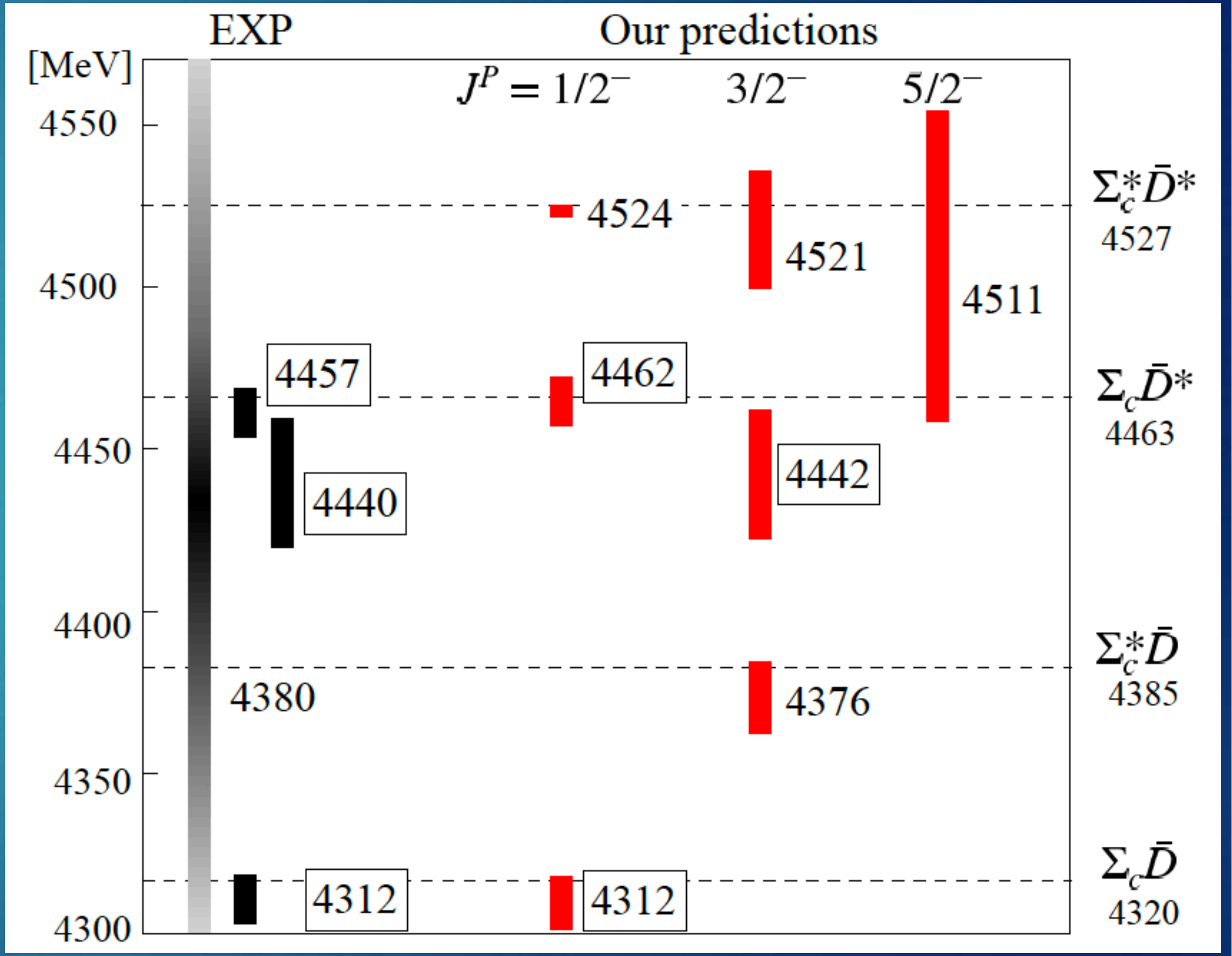
results

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



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

Cited by PDG2020! Togheter 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).

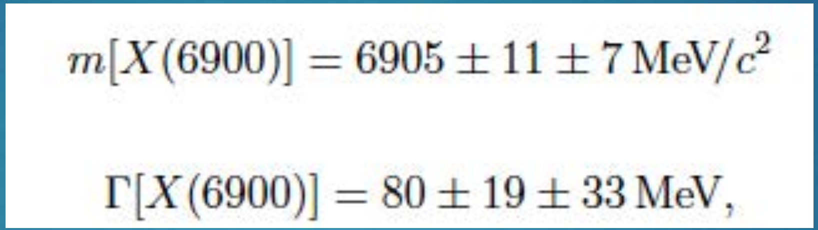
- Very discouraging results were obtained for the 4 muon channel of 4b tetraquarks: $\sigma \sim 0.1$fb or less, made the positive claims rather unlikely.

- 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

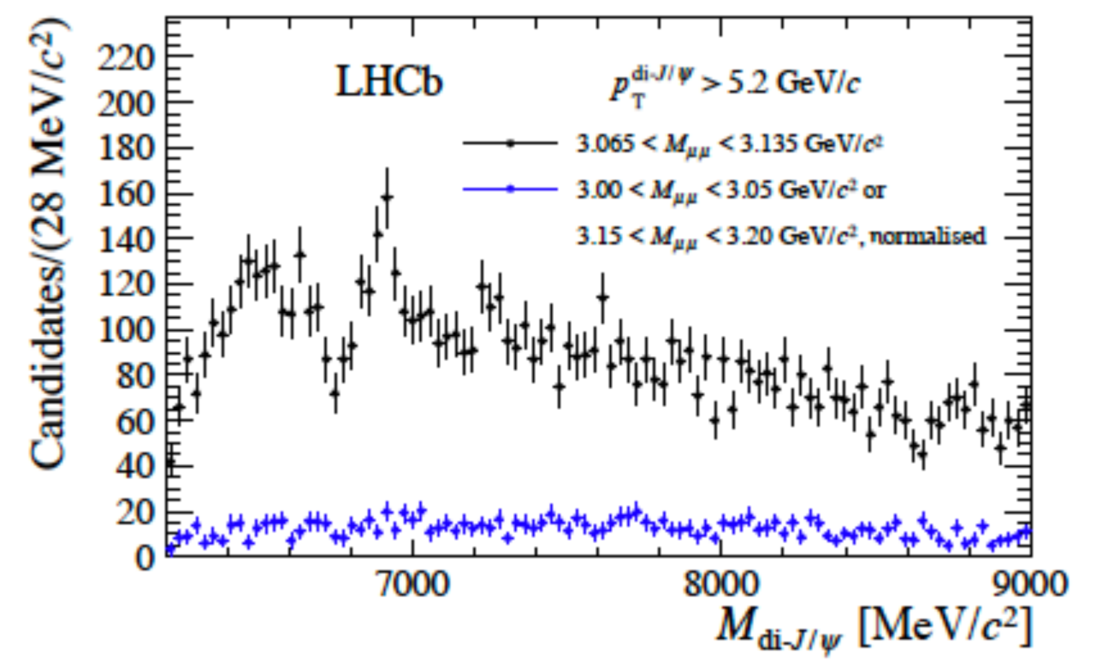
Describing the X(6900) structure with a Breit Wigner lineshape, its mass and natural width are determined to be (arXiv:2006.16957, 30 Jun 2020, now Science Bulletin, Volume 65, Issue 23, 1983 (2020)):



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

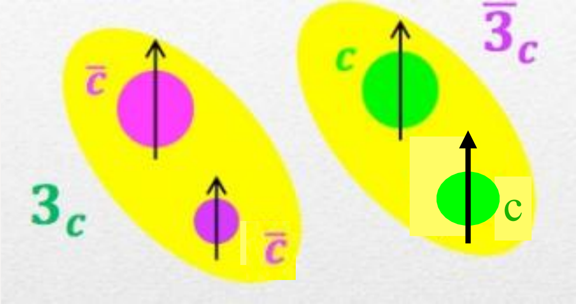
$$\Gamma[X(6900)] = 80 \pm 19 \pm 33\,\mathrm{MeV},$$

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



Tetraquark constituent picture of 2 J/Ψ

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

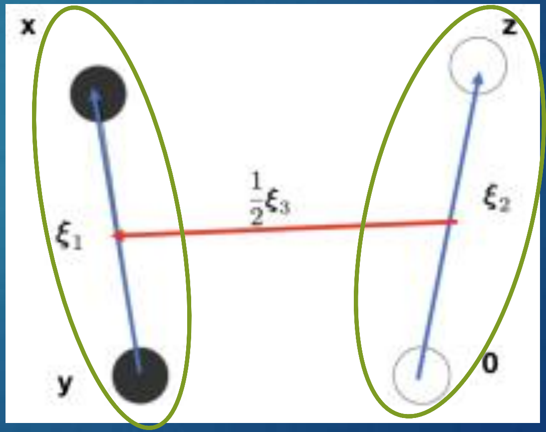


- [cc] in color $\bar{\mathbf{3}}$
- total spin of each diquark, S=1 (color antisymmetry and Fermi statistics)
- S-wave: positive parity

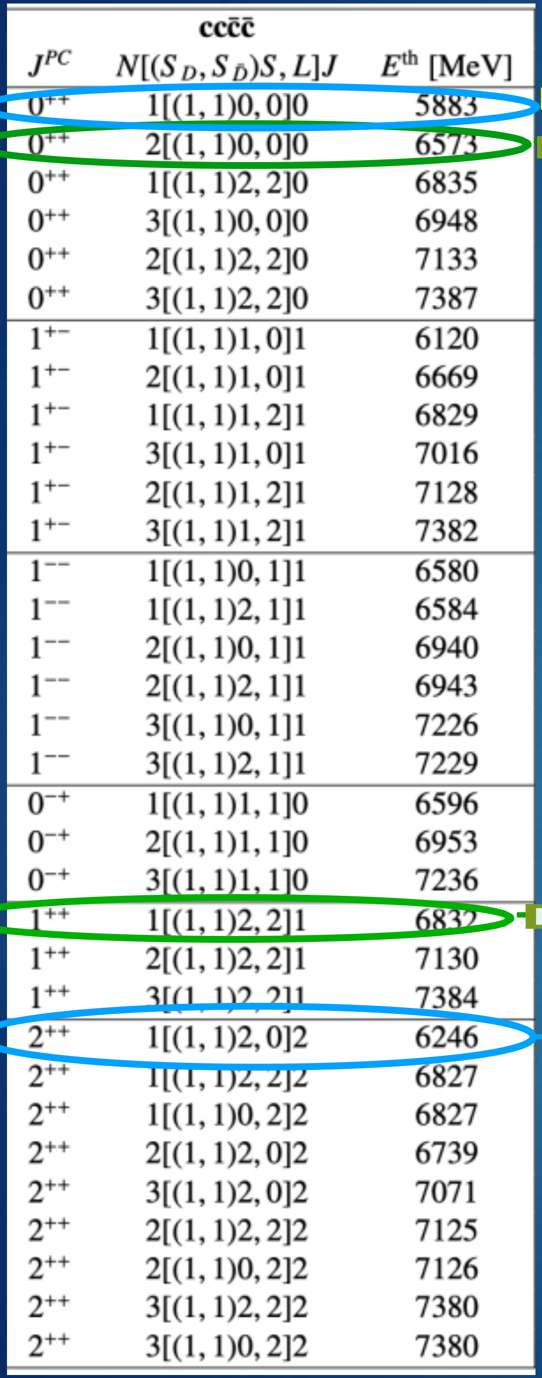
S-wave, fully charm tetraquarks

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

Jacobi coordinates in the tetraquark



2 J/Ψ mass spectrum



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

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

6537 **0^{++} S-wave**
7227 **1st Radial excitation**

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

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

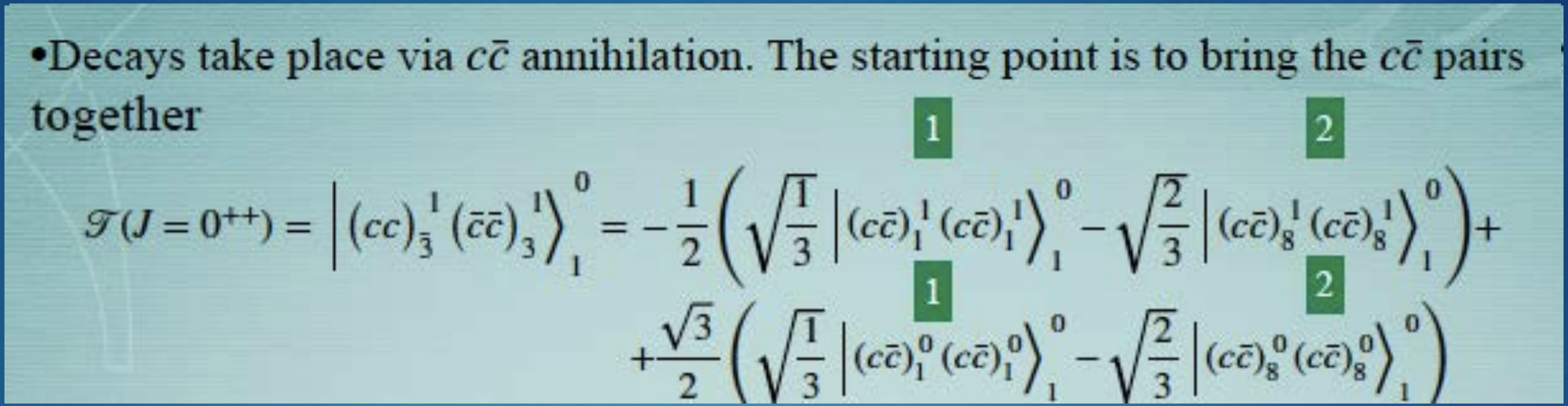
- The upshot: you give the mass of 2^{++} (say: 6900 MeV) and Bedolla *et al.* predict the mass differences

7481 **1^{++} D-wave**

6900 (input) **2^{++} S-wave**

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

Decays and branching fractions



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

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

•Four possible annihilations:

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):

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

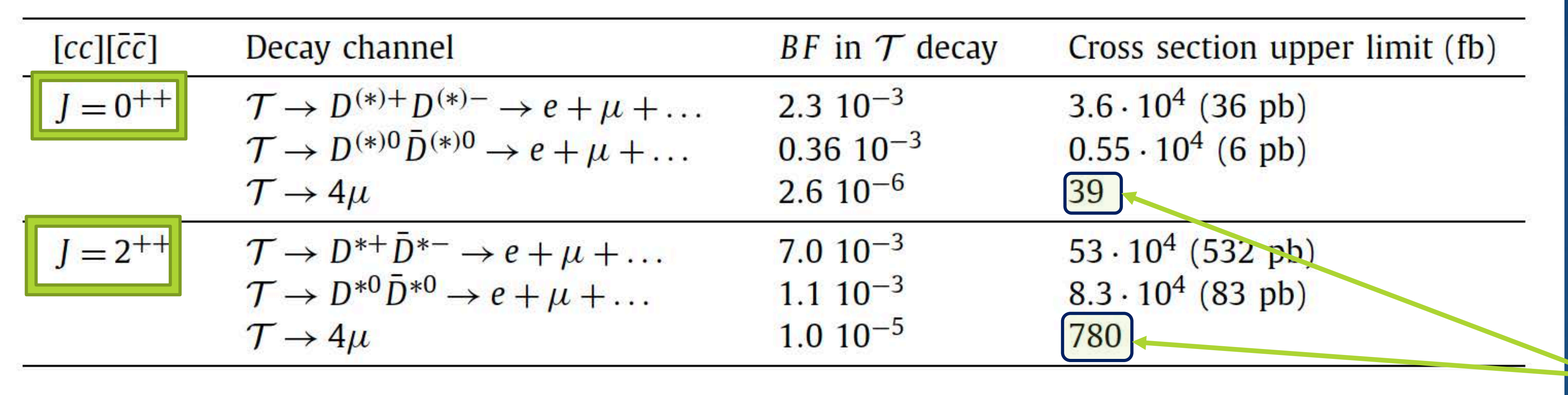
- Branching fractions are independent from $|\Psi_{\mathcal{T}}(0)|^2$
- Total rates: see later.

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)
$J=0^{++}$	$\mathcal{T} \to D^{(*)+}D^{(*)-} \to e+\mu+\dots$	$2.3\ 10^{-3}$	$3.6\cdot10^4$ (36 pb)
	$\mathcal{T} \to D^{(*)0}\bar{D}^{(*)0} \to e+\mu+\dots$	$0.36\ 10^{-3}$	$0.55\cdot10^4$ (6 pb)
	$\mathcal{T} \to 4\mu$	$2.6\ 10^{-6}$	39
$J=2^{++}$	$\mathcal{T} \to D^{*+}\bar{D}^{*-} \to e+\mu+\dots$	$7.0\ 10^{-3}$	$53\cdot10^4$ (532 pb)
	$\mathcal{T} \to D^{*0}\bar{D}^{*0} \to e+\mu+\dots$	$1.1\ 10^{-3}$	$8.3\cdot10^4$ (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

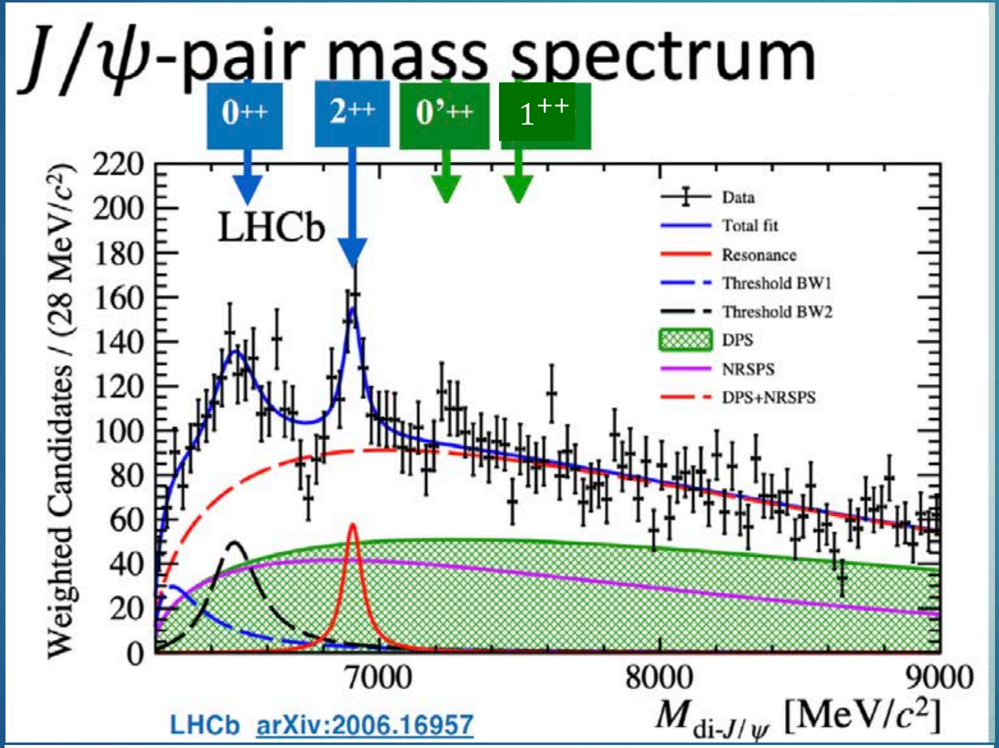
C.Becchi, J. Ferretti, A.Giachino, L.Maiani and E.Santopinto, arXiv:2006.14388, Phys.Lett. **B 811** (2020) 135952

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

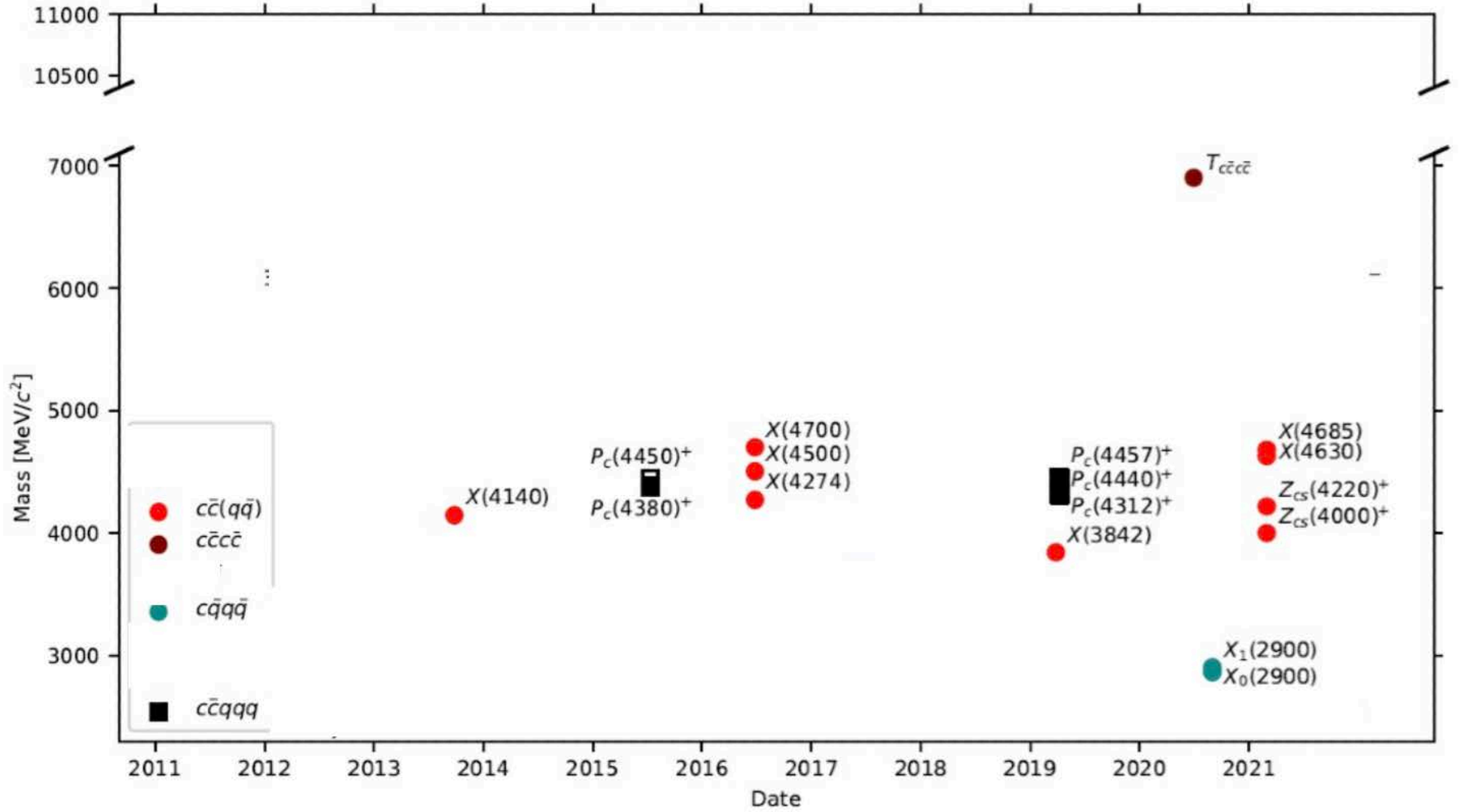
$$\xi = 4.6 \pm 1.4$$

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

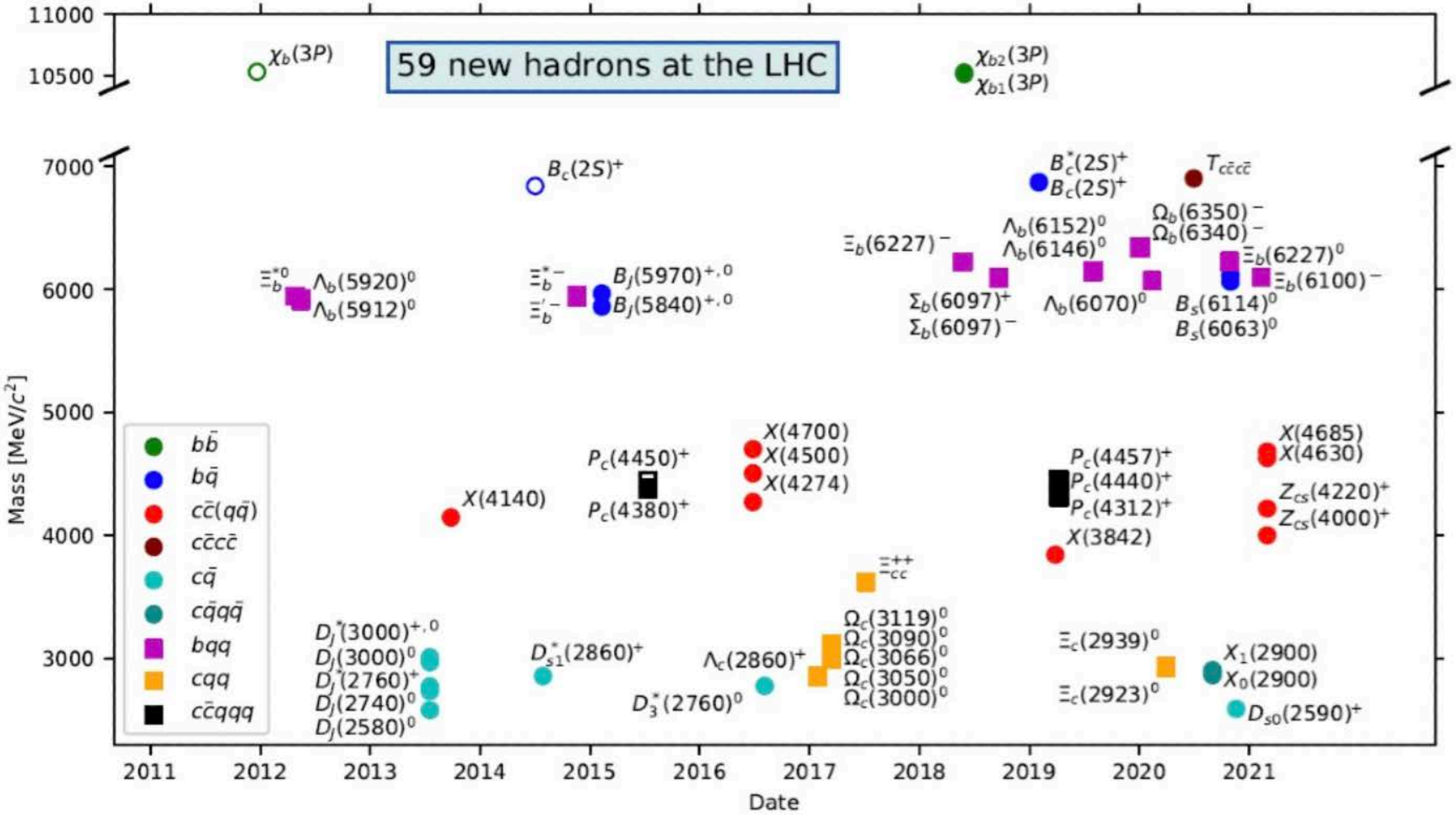


Science Bulletin, Volume 65, Issue 23, 1983 (2020)

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/c^2]
Date
11000
10500
7000
6000
5000
4000
3000
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
$b\bar{b}$
$b\bar{q}$
$c\bar{c}(q\bar{q})$
$c\bar{c}c\bar{c}$
$c\bar{q}$
$c\bar{q}q\bar{q}$
bqq
cqq
$c\bar{c}qqq$
$\chi_b(3P)$
$\chi_{b2}(3P)$
$\chi_{b1}(3P)$
$B_c(2S)^+$
$B_c^*(2S)^+$
$B_c(2S)^+$
$T_{c\bar{c}c\bar{c}}$
$\Omega_b(6350)^-$
$\Omega_b(6340)^-$
$\Lambda_b(6152)^0$
$\Lambda_b(6146)^0$
$\Xi_b(6227)^-$
$\Xi_b(6227)^0$
$\Xi_b(6100)^-$
$\Sigma_b(6097)^+$
$\Sigma_b(6097)^-$
$\Lambda_b(6070)^0$
$B_s(6114)^0$
$B_s(6063)^0$
Ξ_b^{*0}
$\Lambda_b(5920)^0$
$\Lambda_b(5912)^0$
Ξ_b^{*-}
$\Xi_b^{'-}$
$B_J(5970)^{+,0}$
$B_J(5840)^{+,0}$
$X(4700)$
$X(4500)$
$X(4274)$
$P_c(4450)^+$
$P_c(4380)^+$
$X(4140)$
$P_c(4457)^+$
$P_c(4440)^+$
$P_c(4312)^+$
$X(3842)$
$X(4685)$
$X(4630)$
$Z_{cs}(4220)^+$
$Z_{cs}(4000)^+$
Ξ_{cc}^{++}
$D_J^*(3000)^{+,0}$
$D_J(3000)^0$
$D_J^*(2760)^+$
$D_J(2740)^0$
$D_J(2580)^0$
$D_{s1}^*(2860)^+$
$\Lambda_c(2860)^+$
$D_3^*(2760)^0$
$\Omega_c(3119)^0$
$\Omega_c(3090)^0$
$\Omega_c(3066)^0$
$\Omega_c(3050)^0$
$\Omega_c(3000)^0$
$\Xi_c(2939)^0$
$\Xi_c(2923)^0$
$X_1(2900)$
$X_0(2900)$
$D_{s0}(2590)^+$

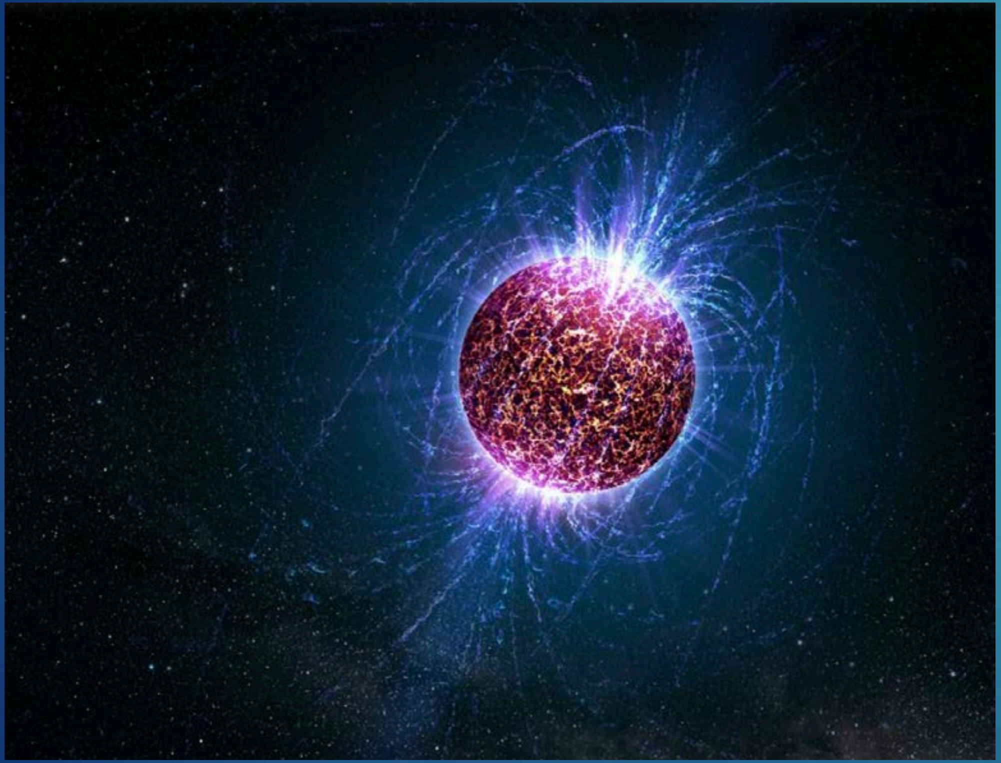
Summing up

- So far many exotics have been observed and many other are still to be discovered, but for some of the already discovered exotics, we have still to understand their structure.

- The study of tetraquark states with different production mechanisms can be strategic:
- 1) New discovery !
- 2) make clear the structure of the existing states
- 3) about charmonia states still many open questions to understand.

Interdisciplinary Connections

The impact of the research field regarding exotic states on other branches of research is of various kinds. Some hints: ex. in neutron stars.



There are multiple ideas about what might occur in neutron stars. It has been hypothesised that the centre of a neutron star is a Bose–Einstein condensate, a state of matter in which all subatomic particles act as a single quantum-mechanical entity. A neutron star with a Bose–Einstein condensate centre, for instance, is likely to have a smaller radius than one made from ordinary material such as neutrons.

Adam Mann, Nature 2020

Where the sum of neutron and proton chemical potentials is equal to that of the $d^*(2380)$ it becomes energetically favourable for the system to store baryons in the form of $d*(2380)$, making the $d^*(2380)$population stable
This can have important consequences such as the possible formation of a Bose-Einstein condensate of $d^*(2380)$ in the interior of neutron stars.
From I. Vidaña et. al, Phys. Lett. B**781**, 112 (2018)

Interdisciplinary Connections

Light hexaquarks (uuddss) have been recenlty proposed as quasi-stable candidate of dark matter (G.R. Farrar, G. Zaharijas, Phys. Rev. D70 (2004) 014008), even though the required mass turned out to be excluded by the stability of Oxygen as from the upper limit put by Super-Kamiokande as shown by Gross, Polosa, Strumia, Urbano and Xue in Phys. Rev. D 98, 063005 (2018).

Measurements that have attracted a strong interest in the electroweak and BSM communities, as B to rho pi for the CKM measurement and B^0 to K^{*0} mu^+ mu for the search for new physics, are known to be susceptible to the presence of 4-quark states, light in the former case and with hidden charm in the latter. In fact, Patrick Koppenburg, former LHCb physics coordinator, has written “I hope that the study of exotics bring us to a better modeling of the strong interaction, which is very much needed to understand, for instance, the anomalies we see in B-meson decays.”

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!