Multiquark States

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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

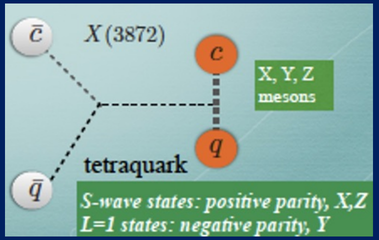
There are indeed new valence quark configurations !!

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

The presence of heavy quarks appears to increase the possibility of binding

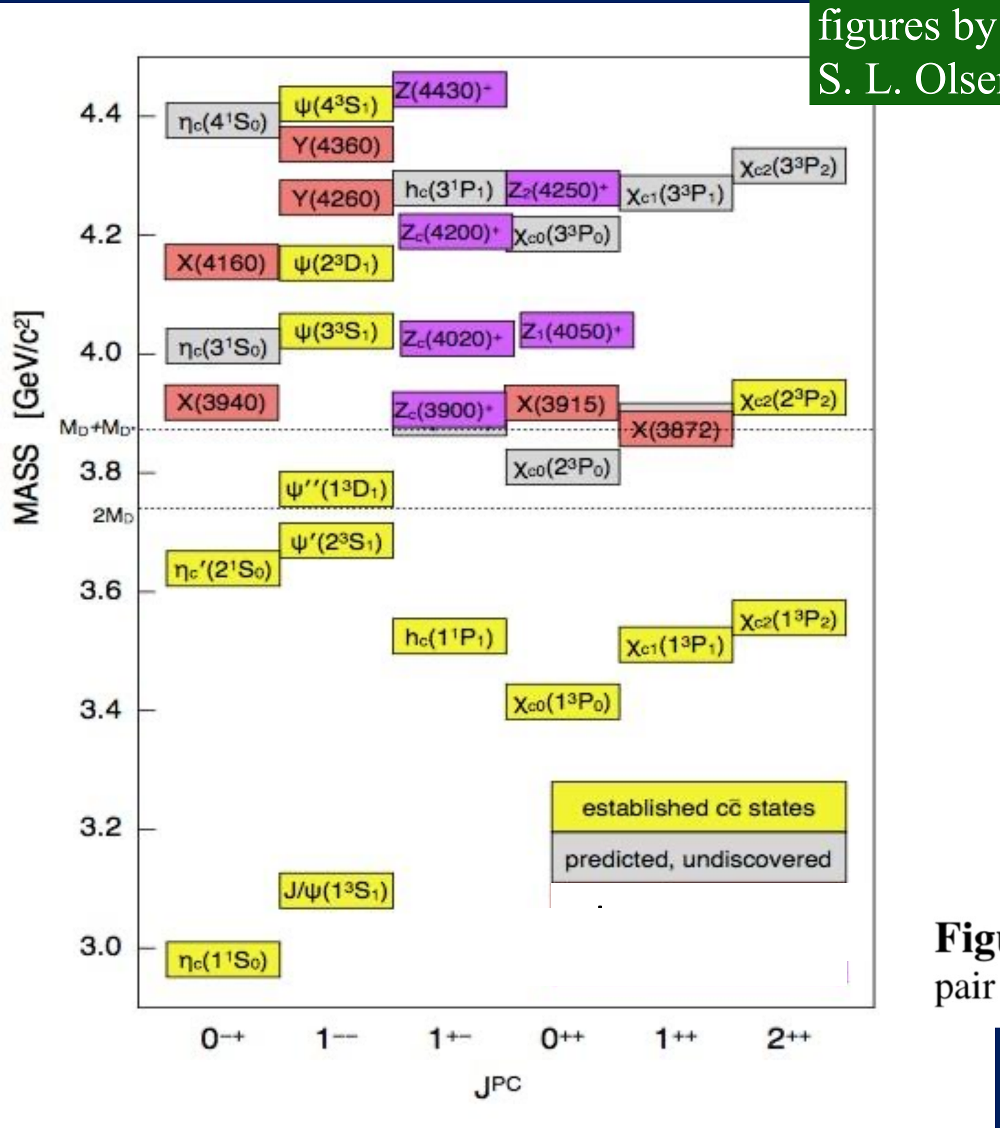
- Hidden heavy flavors have been the first, now we also have the LHCb open heavy flavor $X_0(2900)$ $J^P=0^+$ and $X_1(2900)$ $J^P=1^-$ in the D+ K- channel ($\bar{c}\bar{s}ud$ or D* K* molecule ?)
- First *unexpected charmonium* is the still controversial X(3872) (discovered by Belle 2003)

Still controversial because very close to the threshold



Expected and Unexpected Charmonia

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



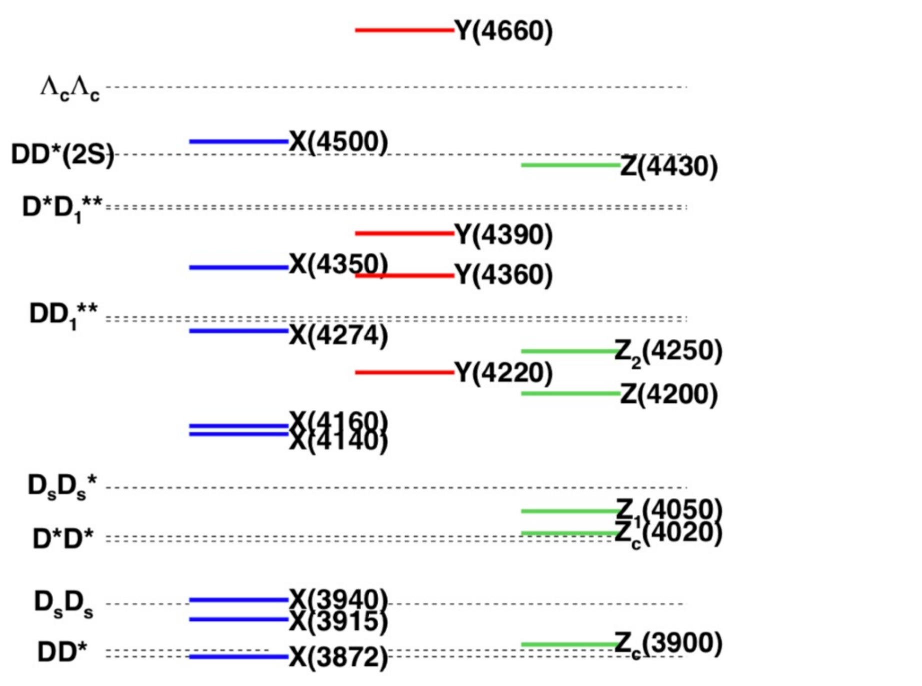
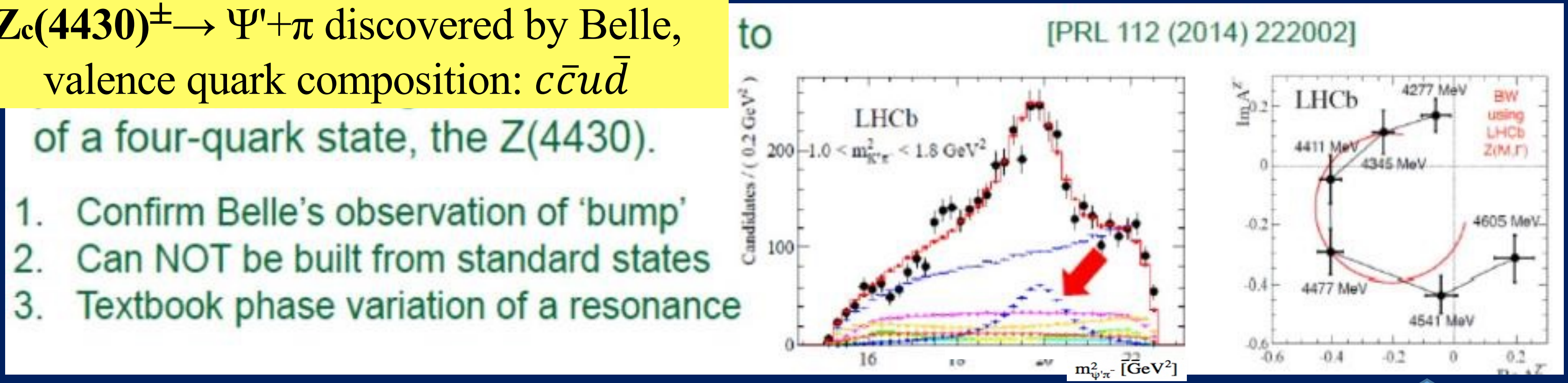


Figure 4. *XYZ* meson masses compared with charmed meson pair thresholds.

Explicit Tetraquarks:

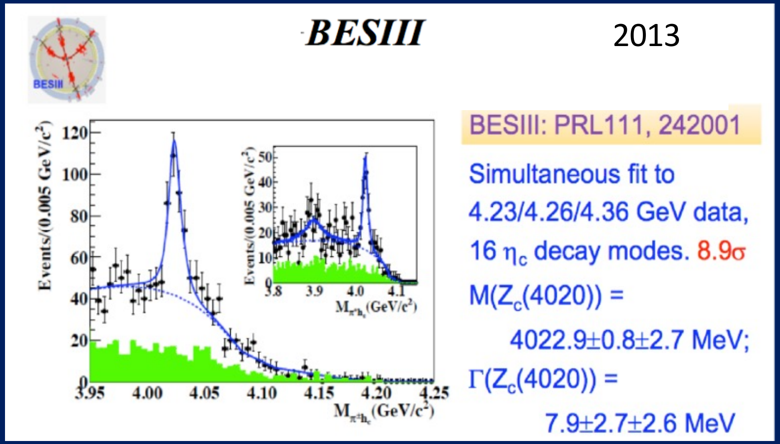
$Z_c(4430)^{\pm}$ 13.9 σ

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



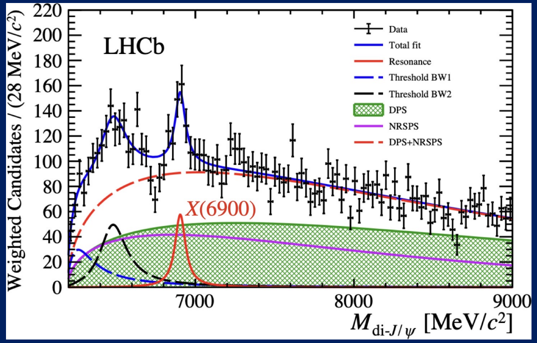
$Z_c(4020)^{\pm} \to h_c + \pi$

$Z_c(4020)^{\pm}$. 8.9σ

Recent reports of Exotic hadrons!

▷$X(6900)$ ($cc\bar{c}\bar{c}$)

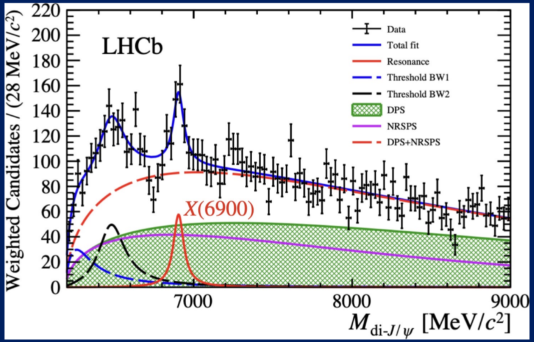
Science Bulletin 65 (2020) 1983



Recent reports of Exotic hadrons

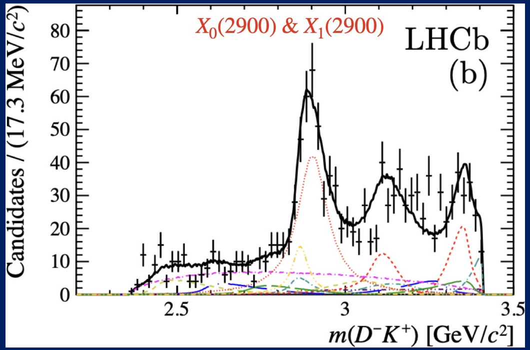
▷ $X(6900)$ $(cc\bar{c}\bar{c})$

Science Bulletin 65 (2020) 1983



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

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



3.9 standard deviation statistical significance

Amplitude analysis of $B^+ \to D^+ D^- K^+$

$X_{0,1}$ observed in $D^- K^+$ channel

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

ICHEP 2022, July 2022 , X(6600), X(6900) and X(7300)

CMS Collaboration, Jingqing Zhang et al., 2212.00504 [hep-ex], *PoS* ICHEP2022 775

of the three structures are 6.5σ, 9.4σ, and 4.1σ for $X(6600)$, $X(6900)$ and $X(7300)$, respectively. The measured masses and widths of three structures are summarized in Table 1.

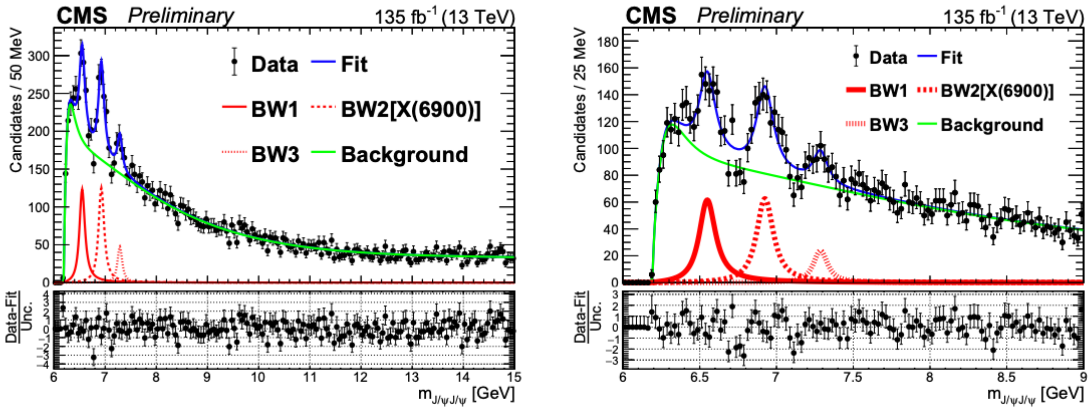


Figure 3: The CMS $J/\psi J/\psi$ mass spectrum with a fit consisting of three signal BW functions and a background model [12]. The left plot shows the fit over the full mass range, and on the right is the same fit expanded by only displaying masses below 9 GeV.

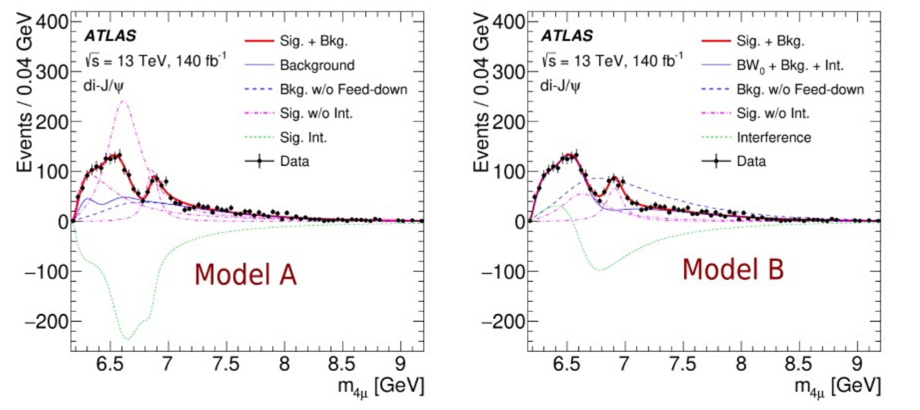
	BW1	BW2	BW3
m	$6552 \pm 10 \pm 12$	$6927 \pm 9 \pm 5$	$7287 \pm 19 \pm 5$
Γ	$124 \pm 29 \pm 34$	$122 \pm 22 \pm 19$	$95 \pm 46 \pm 20$
N	474 ± 113	492 ± 75	156 ± 56

6.5σ 9.4σ 4.1σ

Table 1: Summary of the fit results of the CMS $m(J/\psi J/\psi)$ distribution: the mass m and natural width Γ, in MeV, and the signal yields N are given for three signal structures [12]. The first uncertainties are statistical and the second systematic.

ATLAS Confirmation of the X(6900) (>5 σ) Phys. Rev. Letters 131,151902, 2003)

Di-J/ψ channel

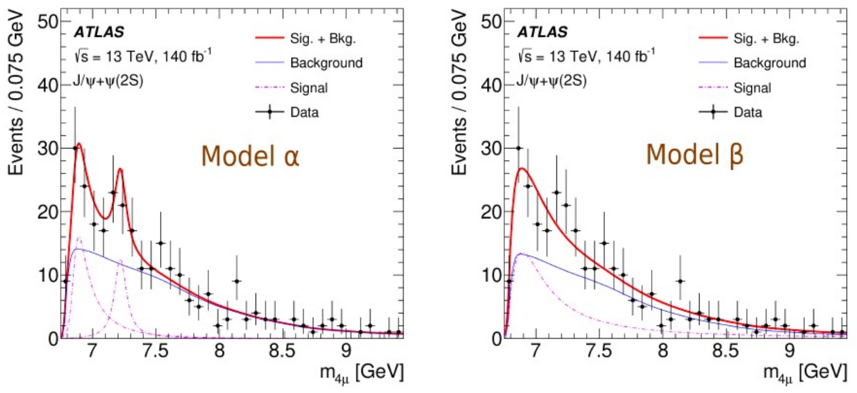


- Model A: 3 *interfering* BW resonances
- Model B: 1 BW interfering with SPS background, 1 BW standalone

di-J/ψ	model A	model B
m_0	$6.41 \pm 0.08^{+0.08}_{-0.03}$	$6.65 \pm 0.02^{+0.03}_{-0.02}$
Γ_0	$0.59 \pm 0.35^{+0.12}_{-0.20}$	$0.44 \pm 0.05^{+0.06}_{-0.05}$
m_1	$6.63 \pm 0.05^{+0.08}_{-0.01}$	—
Γ_1	$0.35 \pm 0.11^{+0.11}_{-0.04}$	
m_2	$6.86 \pm 0.03^{+0.01}_{-0.02}$	$6.91 \pm 0.01 \pm 0.01$
Γ_2	$0.11 \pm 0.05^{+0.02}_{-0.01}$	$0.15 \pm 0.03 \pm 0.01$
$\Delta s/s$	$\pm 5.1\%^{+8.1\%}_{-8.9\%}$	—

$J/\psi + \psi(2S)$ channel in ATLAS

(< 5 σ)



- Model α: same 3 resonances decaying to $J/\psi + \psi(2S)$ and a 4th standalone BW resonance – 4.7σ
  - parameters fixed from di-J/ψ fit
- Model β: a single BW resonance – 4.3σ
- 3σ significance of the 7.2 GeV resonance in model α

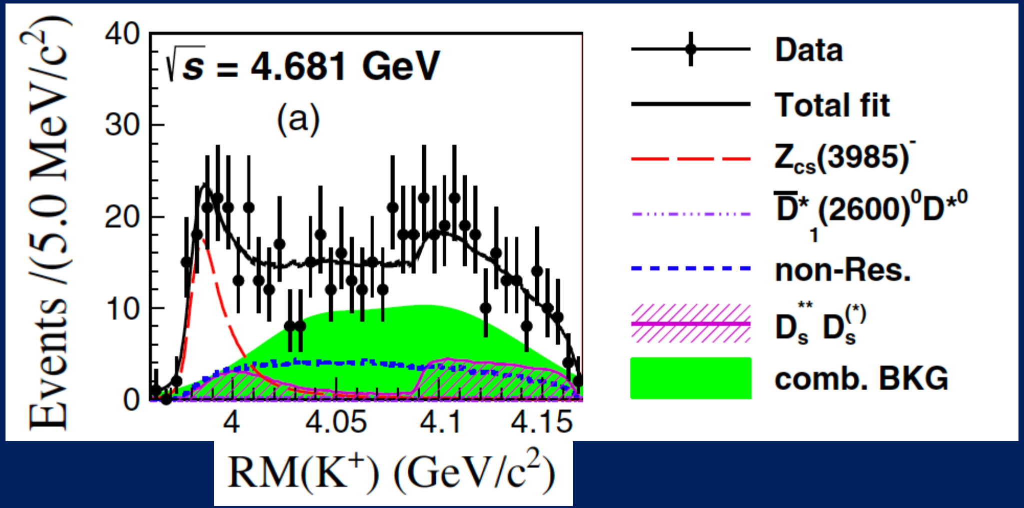
J/ψ+ψ(2S)	model α	model β
m_3 or m	$7.22 \pm 0.03^{+0.01}_{-0.03}$	$6.96 \pm 0.05 \pm 0.03$
Γ_3 or Γ	$0.09 \pm 0.06^{+0.06}_{-0.03}$	$0.51 \pm 0.17^{+0.11}_{-0.10}$
$\Delta s/s$	$\pm 21\% \pm 14\%$	$\pm 20\% \pm 12\%$

$Z_{cs}(3985)^-$ ($c\bar{c}s\bar{u}$) (BESIII, Phys. Rev. Lett. 126, 102001 (2021))   (5.3 statistical significance)

Mass and width are respectively

$(3982.5^{+1.8}_{-2.6} \pm 2.1)\ \mathrm{MeV}/c^2$ and $(12.8^{+5.3}_{-4.4} \pm 3.0)\ \mathrm{MeV}$

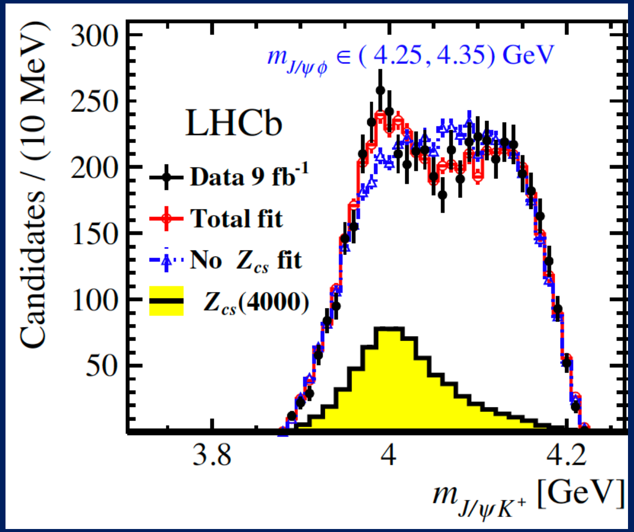
$$e^+e^- \rightarrow (Z_{cs}(3985)^-)K^+ \rightarrow (D_s^- D^{*0} + D_s^{-*} D^0)K^+$$



$Z_{cs}(4003)^+$ ($c\bar{c}u\bar{s}$) (LHCb, Phys. Rev. Lett. 127, 082001 (2021) (15 statistical significance)

$4003 \pm 6^{+4}_{-14}$ MeV, a width of $131 \pm 15 \pm 26$ MeV

$$B^+ \rightarrow (Z_{cs}^+(4003))\phi \rightarrow \ (J/\Psi K^+)\ \phi$$



Discovery of the doubly charmed T_{cc}^{+} in $D^0 D^0 \pi^+$ invariant mass distribution with a 22 standard deviations arXiv:2109.01038 (Nature Physics 2022) and arXiv:2109.01056 (Nature Physics Communication 2022).

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

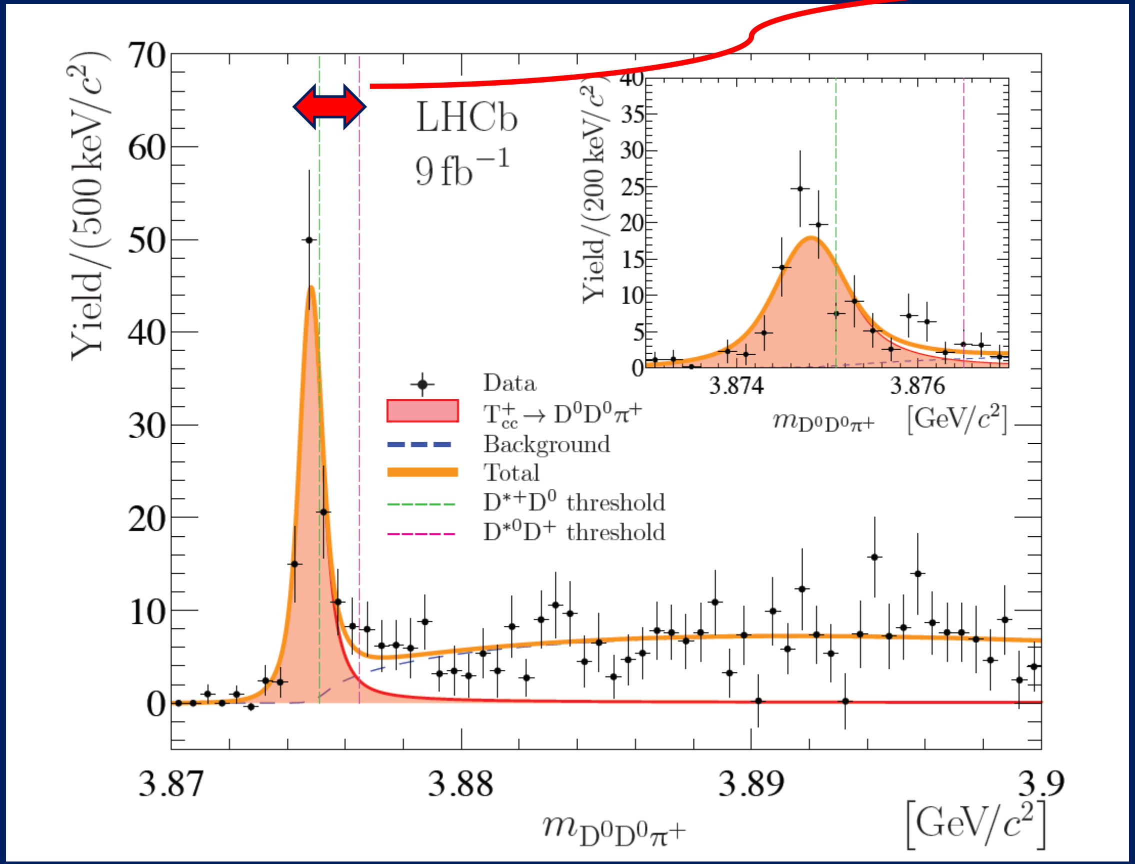
Mass and width

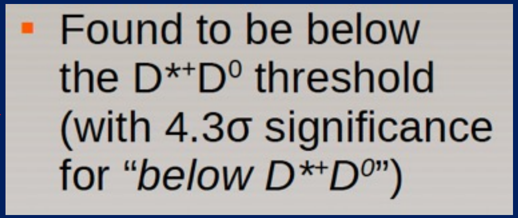
$M \simeq 3875$ MeV

$\Gamma \simeq 0.410$ 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.' *Nature Physics* **volume 18**, pages 751–754 (arXiv:2109.01038)





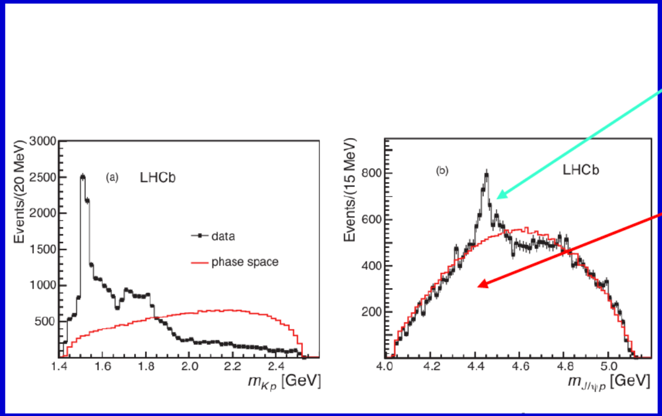
$D^{*+}D^0$ threshold is at 3875.1 MeV

More new valence quark configurations

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

LHCb

Phys. Rev. Lett.115(2015) 072001



M _P_c^+(4450) = (4449.8 ± 8 ± 29)MeV

Γ = (39 ± 5 ± 19) MeV

M_P_c^+(4380) = (4380 ± 1.7 ± 2.5)MeV

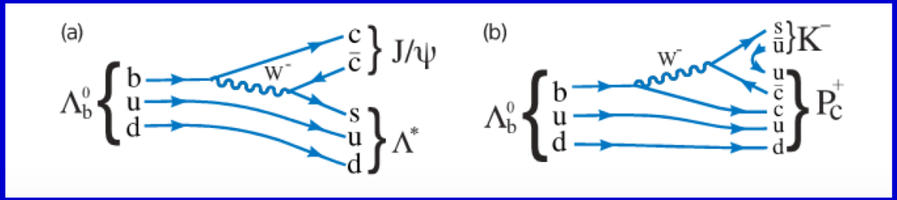
Γ =(205±18±86)MeV

statistic significance greater then 9 sigma !

P_c **(uudcc̄)**

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

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



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?

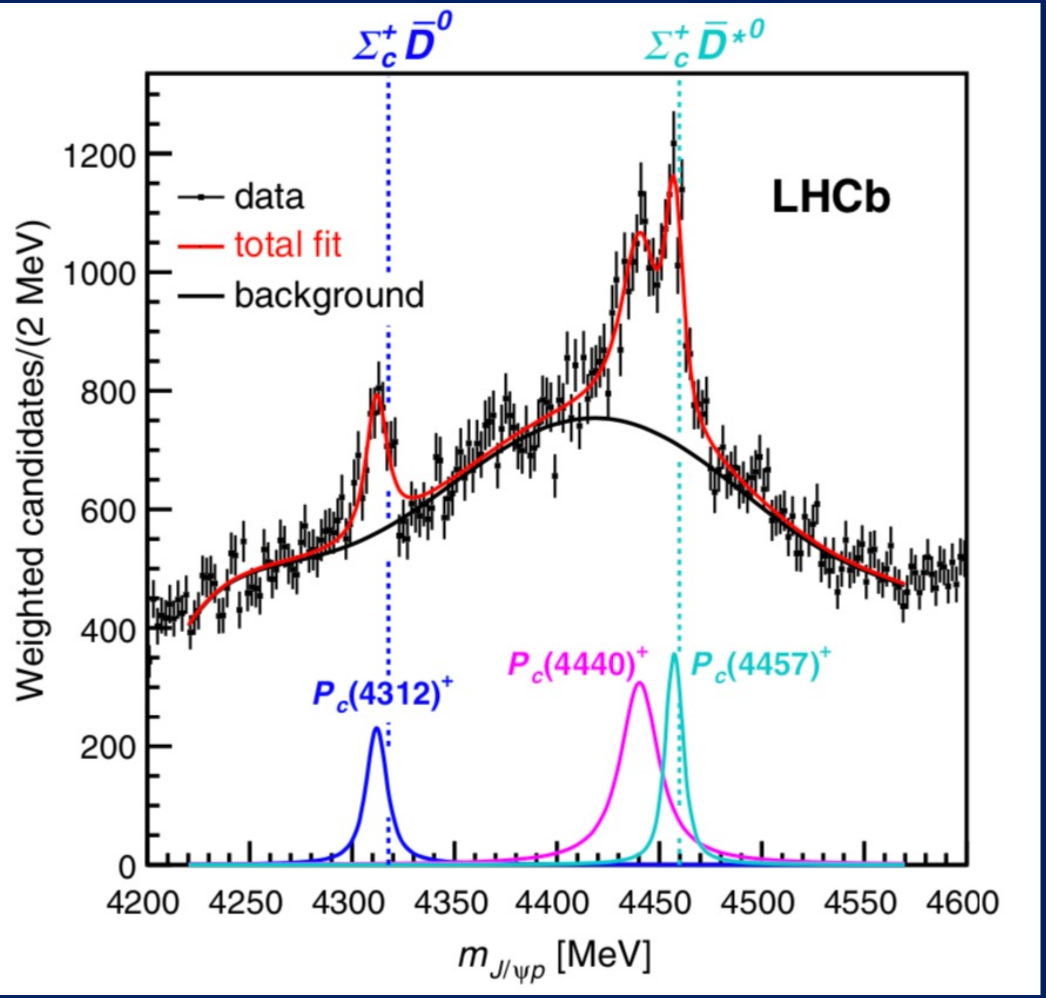
As well as revealing the new $P_c(4312)$ state with 7.3 sigma statistical significance, the LHCb 2019 analysis also uncovered a more complex structure of $P_c(4450)$, consisting of two narrow nearby separate peaks, $P_c(4440)$ and $P_c(4457)$ with the two-peak structure hypothesis having a statistical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



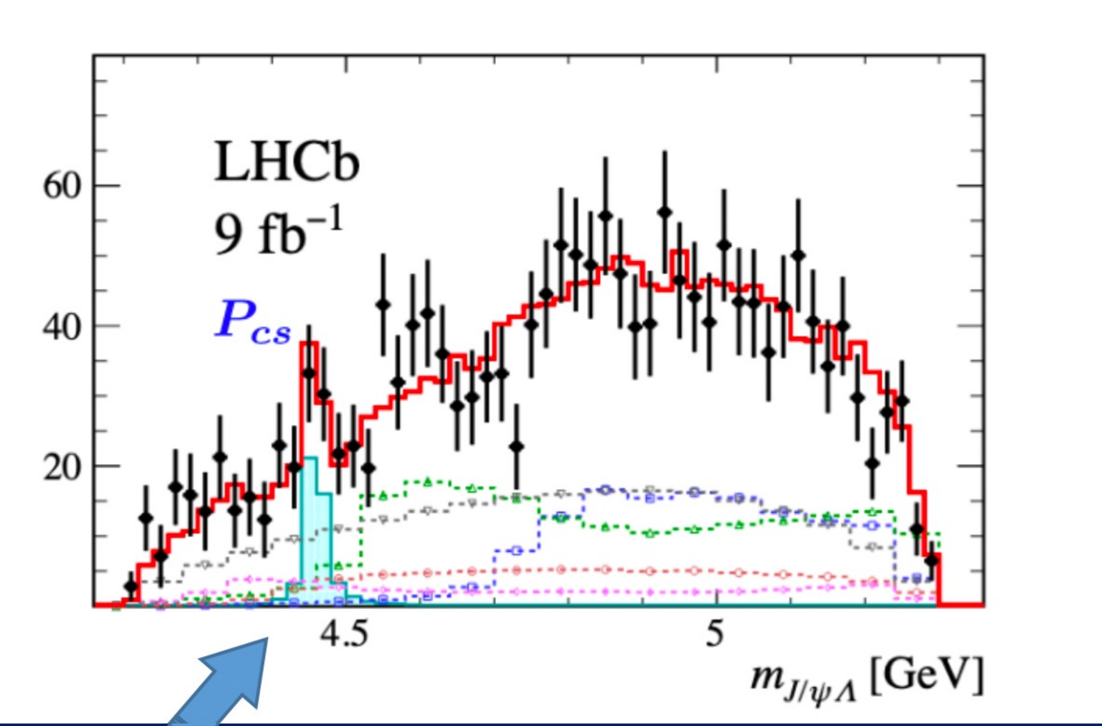
Number of events versus J/Psi p invariant mass [*]. The mass thresholds for the $\Sigma_c\, \bar{D}$ and $\Sigma_c\, \bar{D}^*$ final states are superimposed.

2020

$\Lambda_b^0 \to J/\Psi \Lambda K^-$ **channel** ($P_{cs} \to J/\Psi\ \Lambda$)

P_{cs} $(uds c\bar{c})(4459)$ LHCb, *Sci.Bull.* 66 (2021) 1278-1287

Significance of $\boldsymbol{P_{cs}^0}$**(4459)** exceeds 3 σ after considering all the systematic uncertainties.



▷ One P_{cs} state ?

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

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

A good description of the data is provided also with the

▷ Two-peak structure hypothesis

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

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

The mass of ***Pcs***(4459) is about 19 MeV below the $\Xi_c^0\ \bar{D}^{*0}$ threshold

This is similar to the two ***Pc***(4440) and ***Pc***(4457) which are just below the Σ^+_c. $\bar{D}^{*0}$ threshold

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,
Phys. Rev. Lett. 128,062001 (2022)

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

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

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

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

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

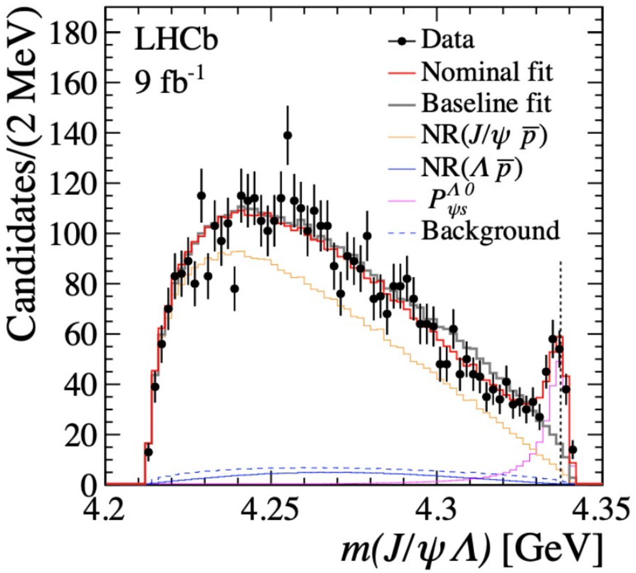
Pcs(4338) October 2022.

- the Pcs(4338) was announced by LHCb at around M = 4338 MeV in the

$$B^- \to J/\Psi\Lambda\bar{p} \text{ channel } (P_{cs} \to J/\Psi\ \Lambda)$$

▶ $P_{cs}(4338)$ in 2022

LHCb coll. arXiv:2210.10346



Significance of $P^0_{cs}(4338)$ exceeds 10 σ!

$$M = 4338.2 \pm 0.7 \pm 0.4 \text{ MeV}$$

$$\Gamma = 7.0 \pm 1.2 \pm 1.3 \text{ MeV}$$

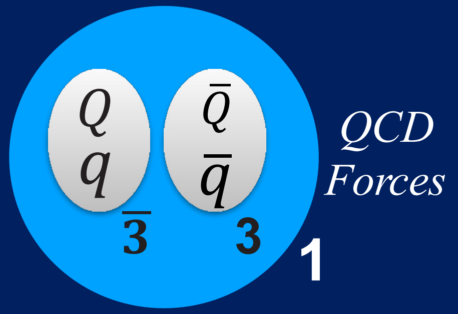
(near the **$\Xi_c\bar{D}$ threshold**)

The preferred quantum numbers are $J^P = 1/2^-$

No consensus, yet

Hadronic Molecule

F-K. Guo, C. Hanhart, Christoph, U-G Meißner, Q. Wang, Q. Zhao, and B-S Zou, arXiv 1705.00141 (2017)



Compact Diquark-Antidiquark

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

For pentaquarks

Nuclear Forces

Hadronic Molecule?

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

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

QCD Forces

Compact pentaquark

$(5\,q)$

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

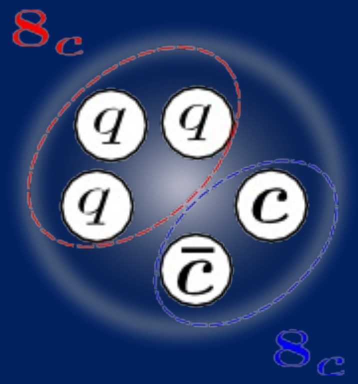
Nuclear Forces + *QCD Forces*

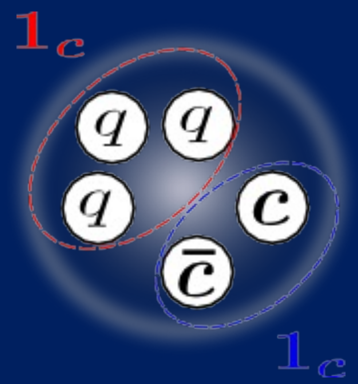
Baryon-meson molecule with 5-quark core

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





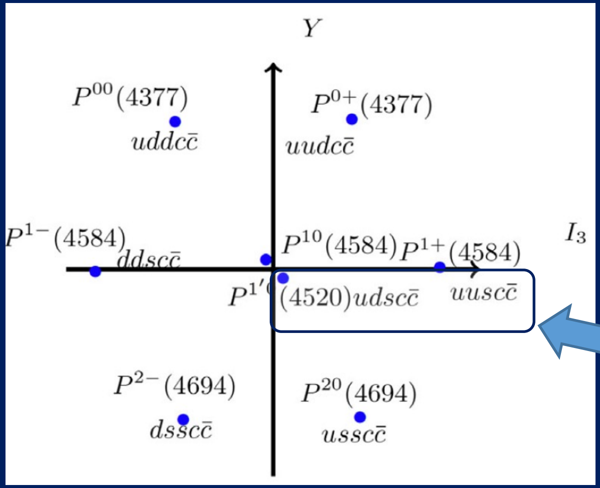
S_{q^3} = 1/2, 3/2, $S_{c\bar{c}}$ = 0, 1 S_{q^3} = 1/2, $S_{c\bar{c}}$ = 0, 1

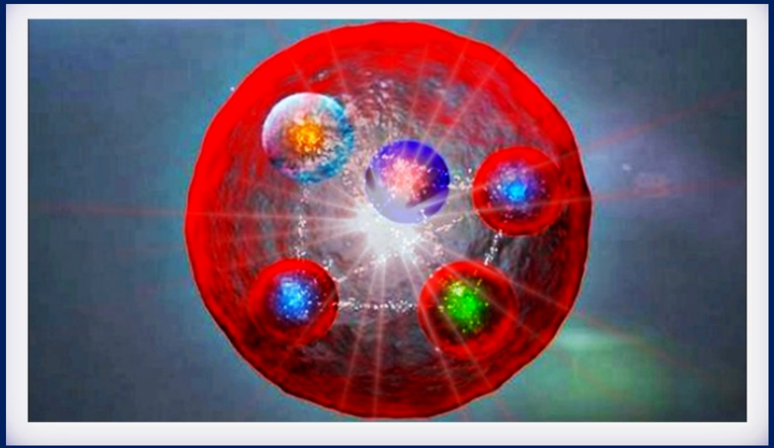
Using only simmetry considerations, and an equal spaced mass formula, we have predicted the strange pentaquark with I=0 Pcs(4457) for which LHCb reported evidence (LHCb, *Sci.Bull.* 66 (2021) 1278-1287) and suggested to look for it in the Λ J/Ψ channel (in fact cited by LHCb). According to our model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

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 . According to our model also I=1 P_{cs} should exist (in the Σ J/Ψ channel) and I=1/2 P_{css} (in Ξ J/Ψ channel).

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





$P_{cs}^{0}(4459)$ The LHCb Coll. LHCb, *Sci.Bull.* 66 (2021) 1278-1287,

Evidence of a $J/\Psi\Lambda$ structure and observation of excited Ξ^- states in the $\Xi_b^- \to J/\Psi\Lambda K^-$ decay

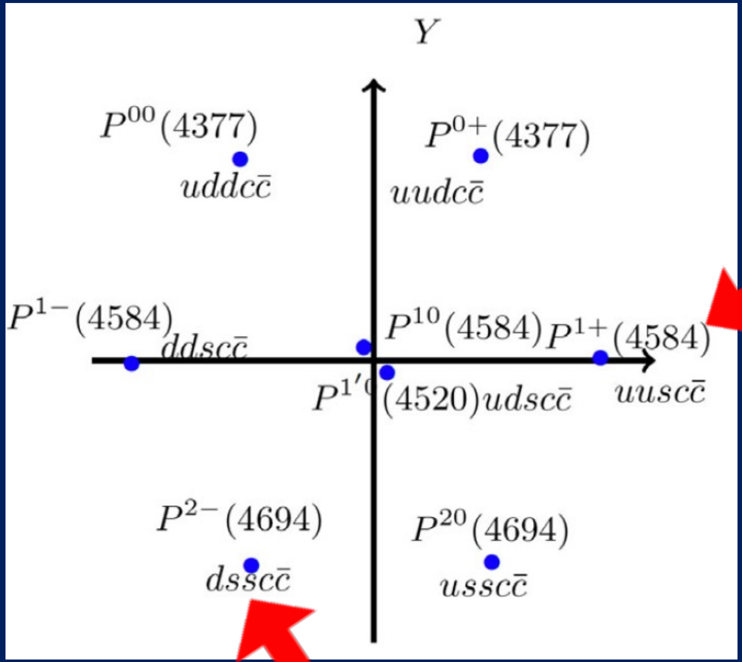
from E. Santopinto and A. Giachino, **Phys. Rev. D96** (2017) 014014

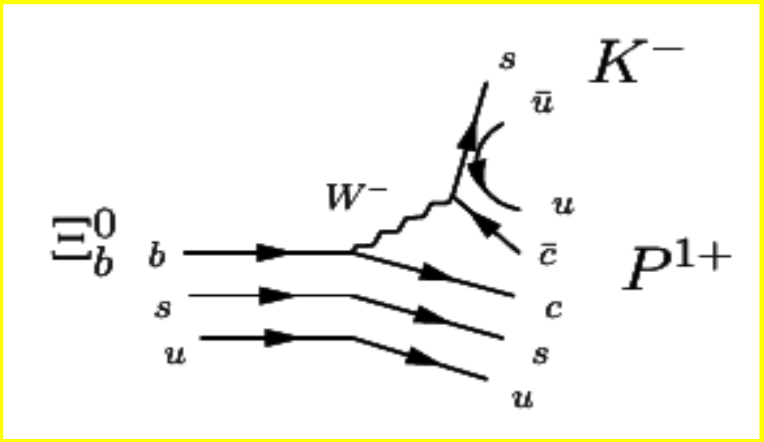
In which channels the other hidden charm pentaquarks which fill the SU(3) flavor octet can be observed?

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

Compact pentaquark structures

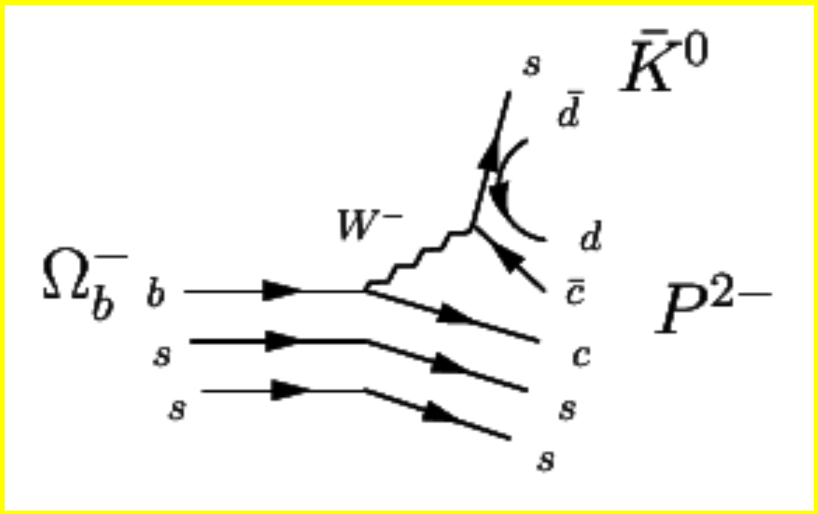
Elena Santopinto and Alessandro Giachino





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

$P^{1+}(4584)$ a $c\bar{c}uus$ state with isospin 1 so it can be observed in $J/\Psi\Sigma^+$ invariant mass spectrum; it is important to perform a an amplitude analysis of $\Xi_b^0 \rightarrow J/\Psi\Sigma^+K^-$ decays!



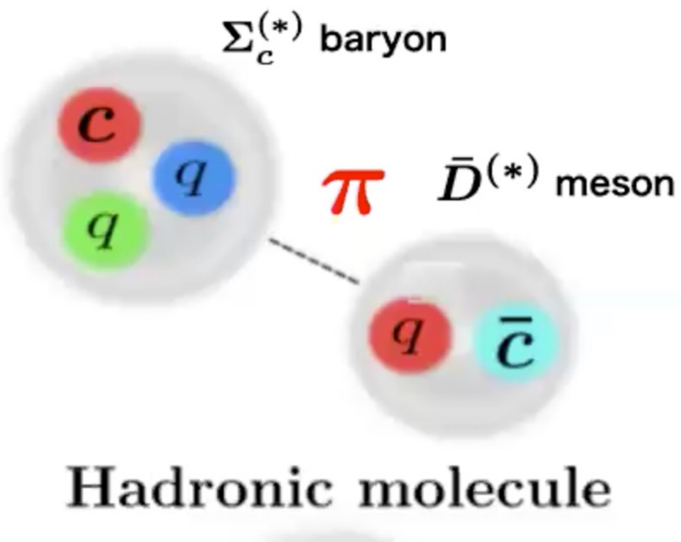
$$\Omega_b^- \rightarrow P^{2-} + \bar{K}^0, \qquad P^{2-} \rightarrow J/\Psi + \Xi^-.$$

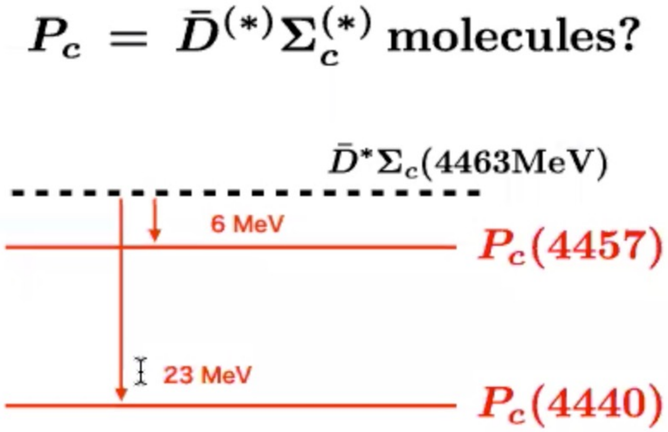
$P^{2-}(4694)$ a $c\bar{c}uss$ state with isospin ½; this state can be observed in $J/\Psi\Xi^-$ invariant mass spectrum after performing an amplitude analysis of $\Omega_b^- \rightarrow J/\Psi\Xi^-\bar{K}^0$ decays!

Hadronic molecules?

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

→ expected **near the thresholds**





▷ Q. Interactions?: **Heavy hadron interactions** are not established yet...

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

⇒ Hadronic molecular structure is favored?

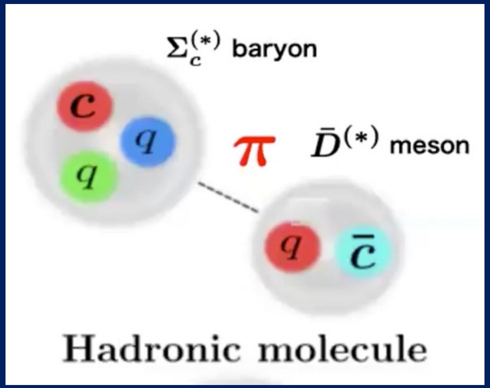
Hidden-charm pentaquarks as a meson-baryon molecule with coupled channels for $\bar{D}^{(*)}\Lambda_c$ and $\bar{D}^{(*)}\Sigma_c^{(*)}$

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

This description is motivated by the fact that the observed pentaquarks are found to be just below the $\Sigma_c\bar{D}$ theshold$\big(P_c(4312)\big)$, $\Sigma_c^*\,\bar{D}$ $\big(P_c(4380)\big)$ 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 the similar to the work by Wu et al. [*] but it is based on SU(3) flavor symmetry

Upgrade of the model: Coupled channel between the meson-baryon states and the five quark states

Hidden-charm and bottom meson-baryon molecules coupled with five-quark states, **Y. Yamaguchi, A. G., A. Hosaka, E. Santopinto, S. Tacheuchi, M. Takizawa, Phys .Rev. D96 (2017) no.11, 114031**

Model setup in this study

- **Hadronic molecule + Compact state ($5q$)**
  $\Rightarrow$ Meson-Baryon couples to $5q$ (Fashbach projection)

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

Meson-baryon interactions are obtained from the EFFECTIVE LAGRANGIANS satisfying the heavy quark and chiral symmetries

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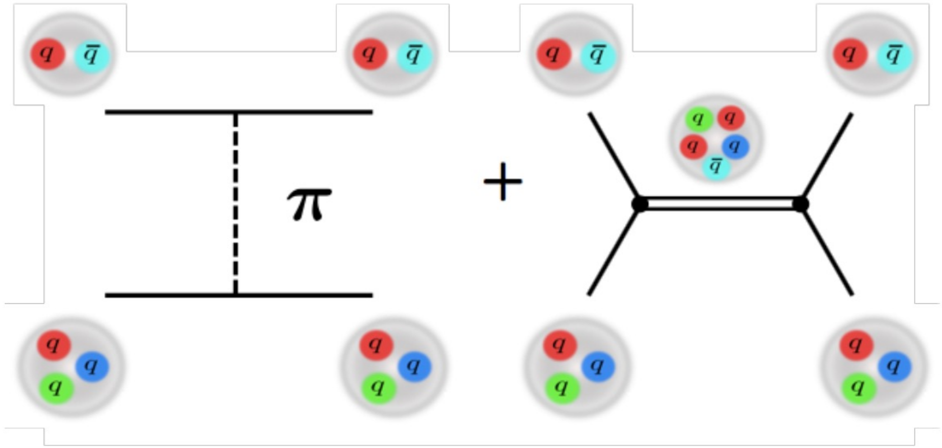
Meson-Baryon interactions

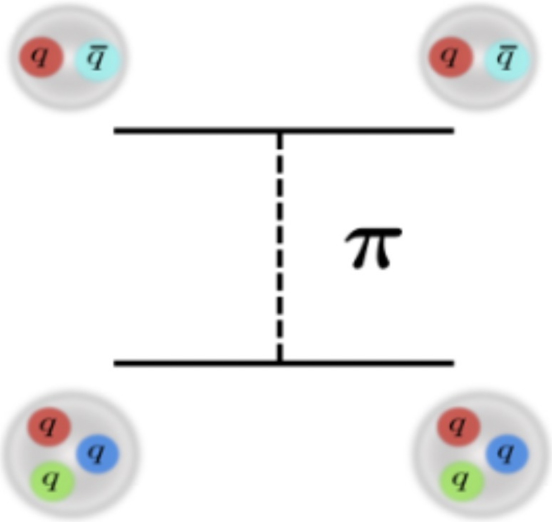


- **Long range** interaction: One pion exchange potential (OPEP)
- **Short range** interaction: $5q$ potential

Meson-baryon interactions are obtained from the EFFECTIVE LAGRANGIANS satisfying the heavy quark and chiral symmetries

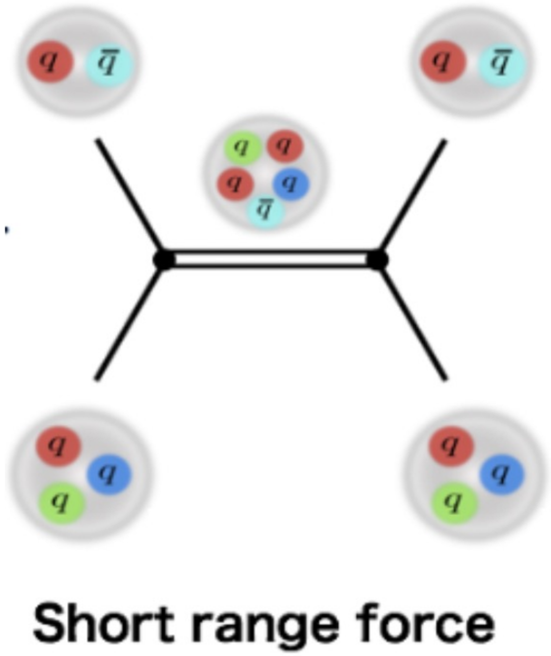
(see next slides)

1. Long range force: One pion exchange potential



Long range force

2. Short range force: 5-quark potential



EFFECTIVE LAGRANGIANS

Coupling between the heavy mesons and the light pseudoscalar mesons [1]:

In Dirac space

$$\mathcal{L}_{psHH} = g_\pi \mathrm{Tr}[H_b \gamma_\mu \gamma_5 A^\mu_{ba} \bar{H}_a],$$

$$H_a = \frac{1+\not{v}}{2}[P^*_{a\mu}\gamma^\mu - P_a\gamma_5], \qquad \bar{H}_a = \gamma_0 H_a^\dagger \gamma_0,$$

$$\langle 0|P|Q\bar{q}(0^-)\rangle = \sqrt{M_H}$$
$$\langle 0|P^{*\mu}|Q\bar{q}(1^-)\rangle = \epsilon^\mu \sqrt{M_H}$$

$$A_\mu = \frac{i}{2}(\xi^\dagger \partial_\mu \xi - \xi \partial_\mu \xi^\dagger),$$

Definition of the axial current

$$\xi = e^{\frac{i M}{2 f \pi}}, \; f_\pi = 92.3 \text{ MeV}$$

M is the traceless 3 × 3 Hermitian matrix of the pseudoscalar mesons

$$\mathcal{M} = \sqrt{2}\begin{pmatrix} \frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & \pi^+ & K^+ \\ \pi^- & -\frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & K^0 \\ K^- & \bar{K}^0 & -\frac{2}{\sqrt{6}}\eta \end{pmatrix}$$

Static limit approximation (= non relativistic limit)
$v_\mu \to (1,0,0,0)$

The coupling constant g_π is determined by the strong decay of $D^* \to D\pi$

[1] R. Casalbuoni, A. Deandrea, N. Di Bartolomeo, R. Gatto, F. Feruglio and G. Nardulli, Phys. Rept. **281**, 145 (1997) doi:10.1016/S0370-1573(96)00027-0 [hep-ph/9605342].

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.

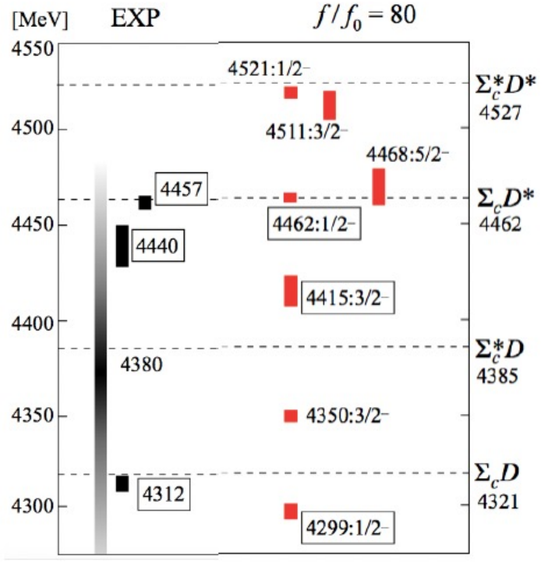
We predicted the three pentaquark states, $P_c(4312), P_c(4440)$ and $P_c(4457)$ two years before the experimental observation by LHCb.

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)

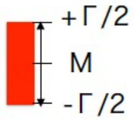
[3] Y. Yamaguchi, A. Giachino, A. Hosaka, E. Santopinto, S. Takeuchi, M. Takizawa, **Phys. Rev. D 96 114031 (2017)**

For New P_c states by LHCb in 2019

Y.Y., H.Garcia-Tecocoatzi, A.Giachino, A.Hosaka, E.Santopinto, S.Takeuchi, M.Takizawa, PRD **101** (2020) 091502(R)



$(f_0 = 6\ \mathrm{MeV})$



New

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

significance > 10 σ

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

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

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

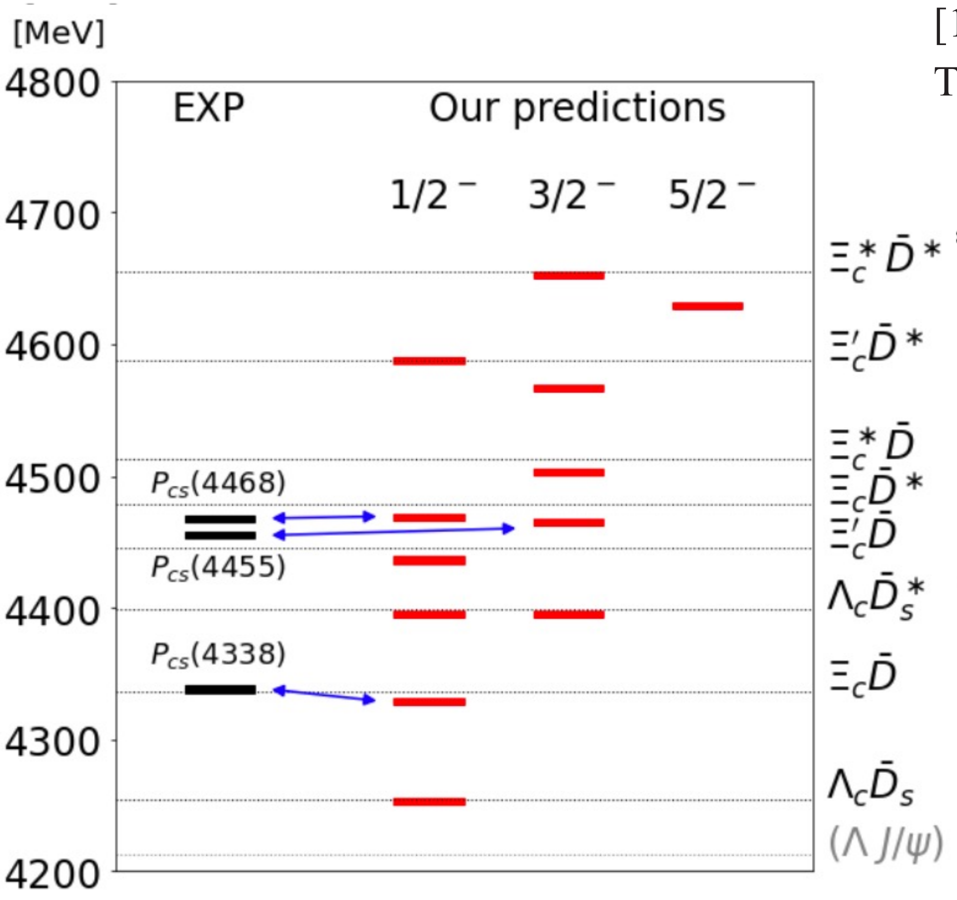
This new state has been observed in the $B^- \to J/\Psi\Lambda\bar{p}$ decay process as a resonance in $J/\Psi\Lambda$ invariant mass (minimal quark content $c\bar{c}$uds) with a statistical significance > **10 standard deviations** [*]

[*] Aaij et al. (LHCb collaboration), arXiv:2210.10346, Phys. Rev. Lett. **131**, 031901 – Published 17 July 2023

In [1] we constructed a coupled-channel model for the hidden-charm pentaquarks with strangeness whose quark content is $uds c\bar{c}$, P_{cs}, described as $\Lambda_c \bar{D}_s^{(*)}$, $\Xi_c^{(\prime,*)} \bar{D}^{(*)}$ molecules coupled to the five-quark states. The meson baryon interactions satisfy heavy quark and chiral symmetries.

We reproduce the experimental mass and quantum numbers J^P of Pcs(4338) for which LHCb has just announced the discovery. We make other predictions for new Pcs states as molecular states near threshold regions that can be studied by LHCb.

Comparing EXP with the predicted masses



[1] A.Giachino , A. Hosaka ,E. Santopinto, S. Takeuchi, M. Takizawa , Y. Yamaguchi, Phys. Rev. D 108, 074012 (2023)

Consistence with the two-peak structure hypothesis by LHCb, $P_{cs}(4468)$ and $P_{cs}(4455)$

Thanks for your attention!