Binding Mechanisms for exotic states

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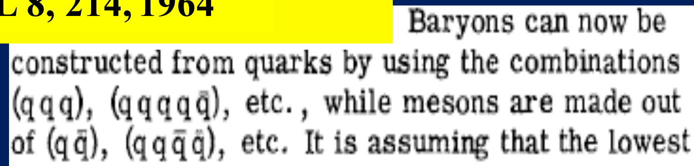
Hidden charm and beauty hadrons reveal *tetraquarks* and *pentaquarks*

•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

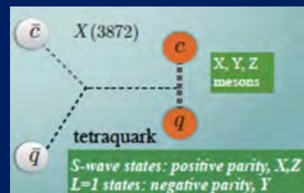
There are indeed new valence quark configurations !!

- 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

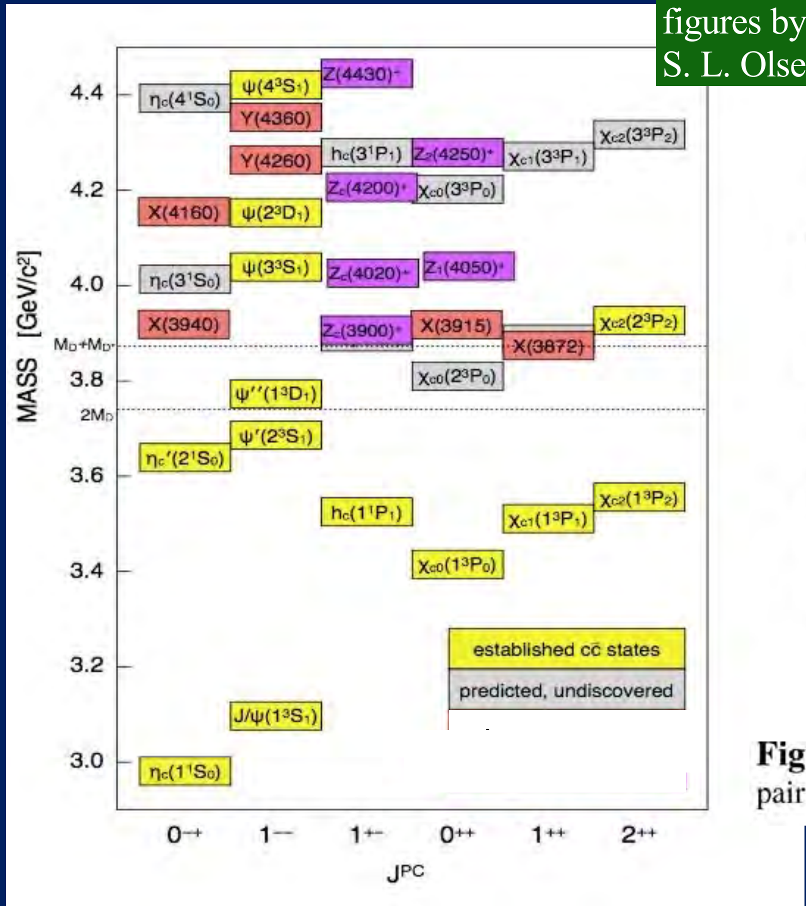
- Hidden heavy flavors have been the first, now we also have the LHCb open heavy flavor $X_0(2900)$ $J^P=0^+$ and $X_1(2900)$ $J^P=1^-$ in the D+ K- channel ($\bar{c}\bar{s}ud$ or D* K* molecule ?)
- First *unexpected charmonium* is the still controversial X(3872) (discovered by Belle 2003)

Still controversial because very close to the threshold



Expected and Unexpected Charmonia

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



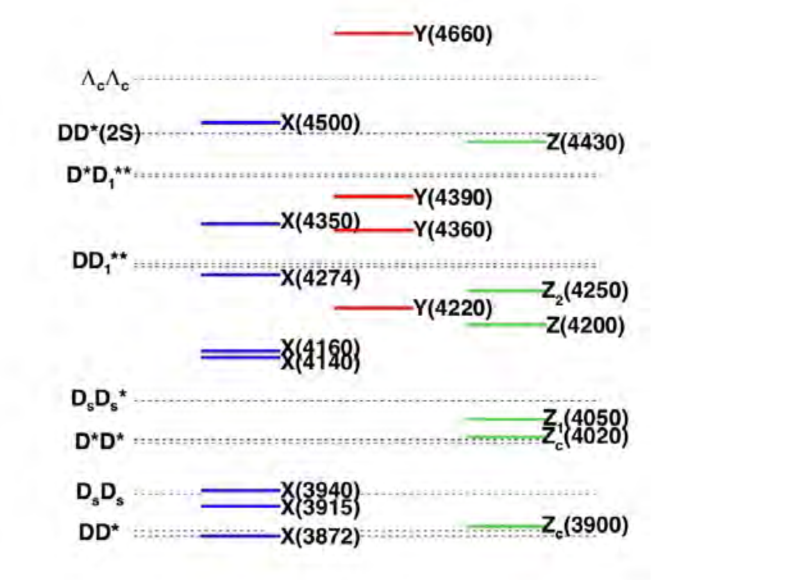
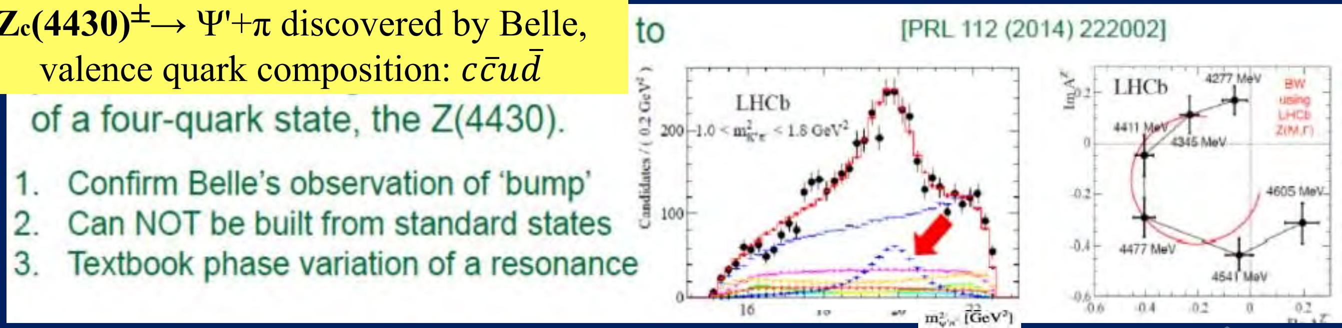


Figure 4. *XYZ* meson masses compared with charmed meson pair thresholds.

Explicit Tetraquarks:

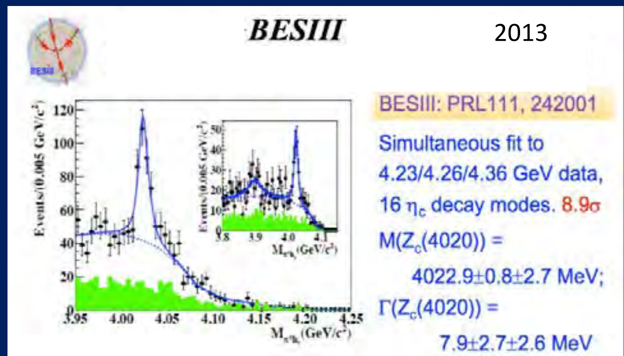
$Z_c(4430)^{\pm}$ 13.9 σ

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



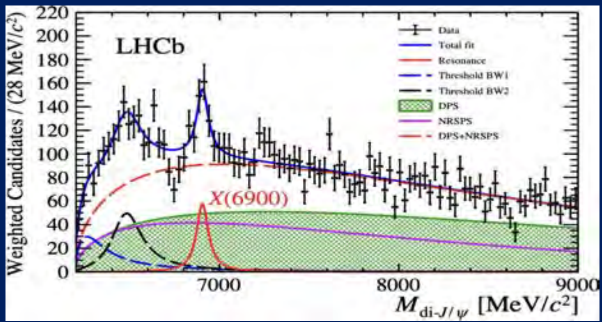
$Z_c(4020)^{\pm} \rightarrow h_c + \pi$

$Z_c(4020)^{\pm}$ 8.9σ

Recent reports of Exotic hadrons!

▷$X(6900)$ ($cc\bar{c}\bar{c}$)

LHCb, Science Bulletin 65 (2020) 1983



Confirmed by

G. Aad et al. (ATLAS), Phys. Rev. Lett. 131, 151902 (2023), 2304.08962.

Hayrapetyan et al. (CMS), Phys. Rev. Lett. **132**, 111901 (2024)

The LHCb collaboration also reported evidence of two additional structures in the same decay channel, peaking at approximately 6400 MeV and 7200 MeV

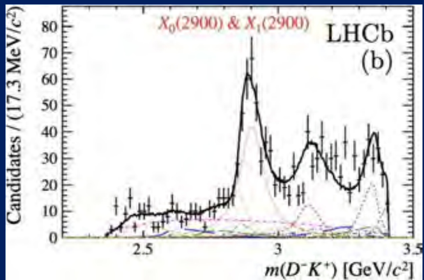
As well as confirming the X(6900), ATLAS reported a broad structure starting from the di-J/ψ threshold with a global statistical significance far exceeding 5 σ. ATLAS also explored the J/ψ ψ(2S) decay channel and reported an additional peak not seen in the di-J/ψ mode, with statistical significance larger than 3 σ.

Recently, CMS investigated the di-J/ψ mass spectrum and confirmed the previously discovered X(6900) state.
CMS also found two new states, X(6600) and X(7300) with 6.9 and 4.7 standard deviations.

Recent reports of Exotic hadrons

▷ $X_{0,1}$(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

$$X_0(2900): \ M = 2.866 \pm 0.007 \pm 0.002 \ \mathrm{GeV}/c^2, \quad \Gamma = 57 \pm 12 \pm 4 \ \mathrm{MeV},$$

$$X_1(2900): \ M = 2.904 \pm 0.005 \pm 0.001 \ \mathrm{GeV}/c^2, \quad \Gamma = 110 \pm 11 \pm 4 \ \mathrm{MeV},$$

Amplitude analysis of $B^+ \to D^{*\pm}D^{\mp}K^+$

LHCb, PRL133, 131902 (2024)

confirmed in a different production channel :

▷ ***$T^*_{\overline{cs}1}(2900)^0$***

LHCb, PRL133, 131902 (2024)

9 σ standard deviation

▷ ***$T^*_{\overline{cs}0}(2870)^0$***

0 LHCb, PRL133, 131902 (2024)

11 σ standard deviation

D^-K^+

$2887 \pm 8 \pm 6$
$92 \pm 16 \pm 16$

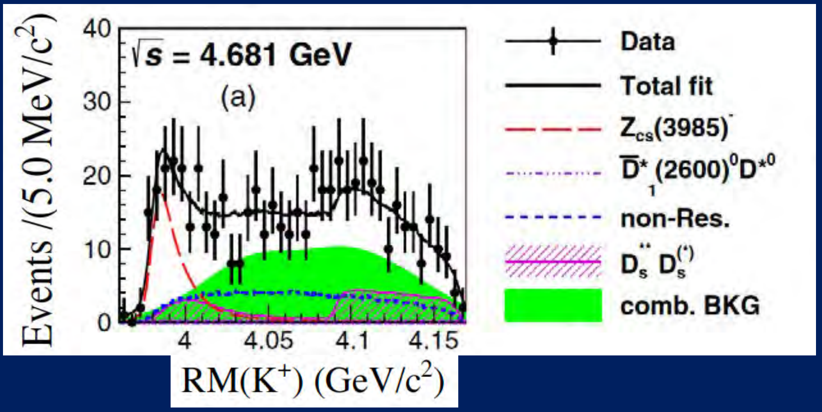
$2914 \pm 11 \pm 15$
$128 \pm 22 \pm 23$

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

Mass and width are respectively

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

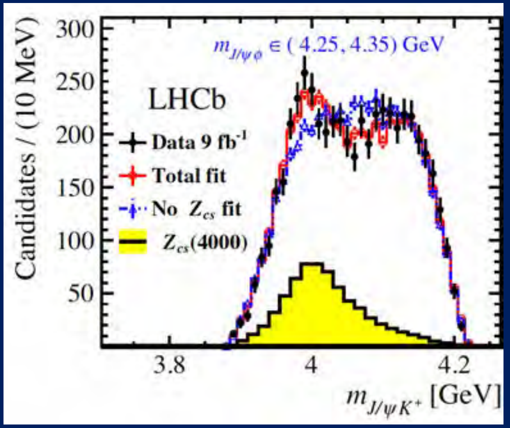
$$e^+e^- \to (Z_{cs}(3985)^-)K^+ \to (D_s^- D^{*0} + D_s^{-*} D^0)K^+$$



$\boldsymbol{Z_{cs}(4003)^+}$ ($c\bar{c}u\bar{s}$) (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

$$B^+ \to (Z^+_{cs}(4003))\phi \to (J/\Psi K^+)\,\phi$$



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).

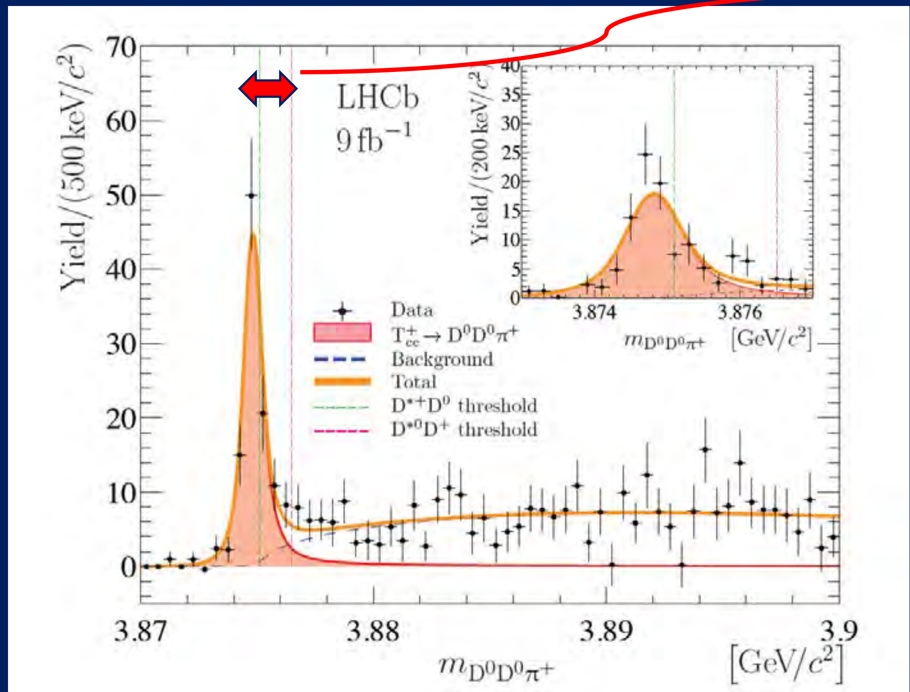
The minimal quark content for this newly observed state is $cc\bar{u}\bar{d}$

Mass and width

$$M \simeq 3875 \quad \text{MeV}$$
$$\Gamma \simeq 0.410 \ \ \text{MeV}$$

'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)



- Found to be below the $D^{*+}D^0$ threshold (with 4.3σ significance for "*below* $D^{*+}D^0$")

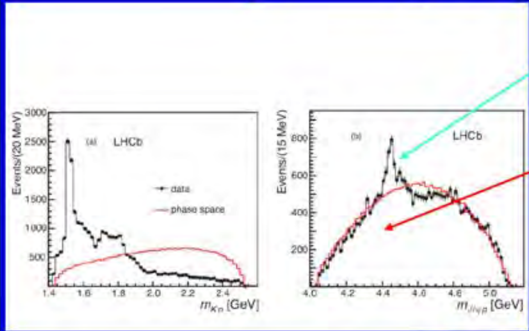
$D^{*+}D^0$ threshold is at 3875.1 MeV

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

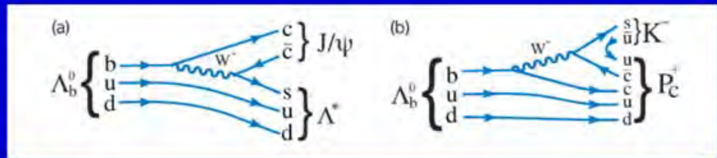
M_P$_c^+$(4380) = (4380 ± 1.7 ± 2.5)MeV

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 ($uudc\bar{c}$)

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?

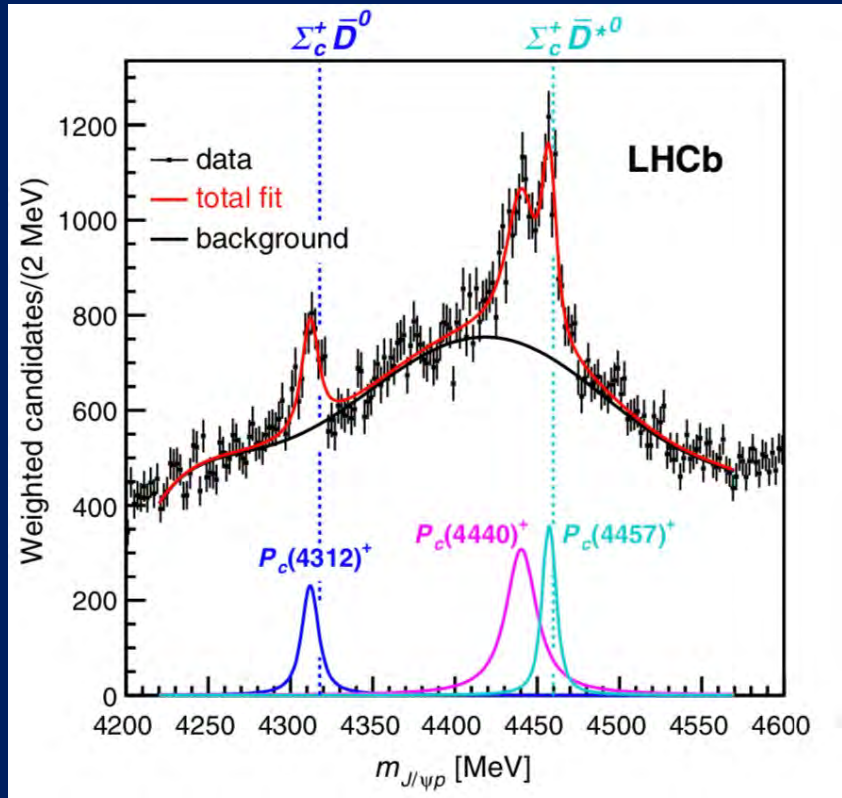
As well as revealing the new $P_c(4312)$ state with 7.3 sigma statistical significance, the LHCb 2019 analysis also uncovered a more complex structure of $P_c(4450)$, consisting of two narrow nearby separate peaks, $P_c(4440)$ and $P_c(4457)$ with the two-peak structure hypothesis having a statistical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



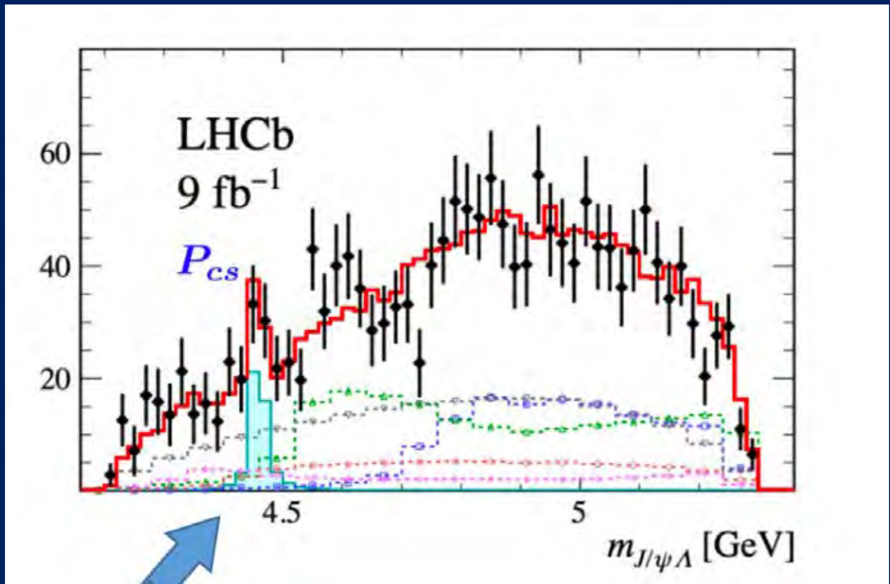
Number of events versus J/Psi p invariant mass [*]. The mass thresholds for the $\Sigma_c\ \bar{D}$ and $\Sigma_c\ \bar{D}^*$ final states are superimposed.

2020

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

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

Significance of $\boldsymbol{P^0_{cs}}$**(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 $\Sigma^+_c\ \bar{D}^{*0}$ 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 $J^P = \frac{1}{2}^+$

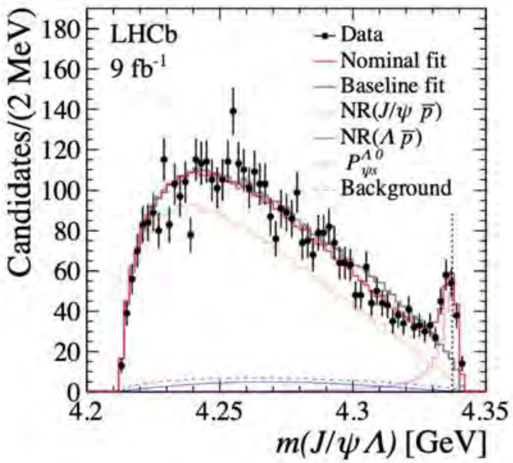
3.7 sigma for $J^P = \frac{3}{2}^+$

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!

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

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

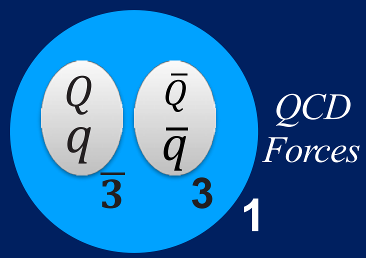
(near the $\Xi_c \bar{D}$ **threshold**)

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

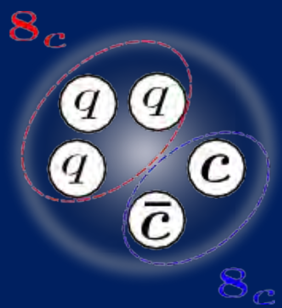
Nuclear Forces — Hadronic Molecule? $(\bar{D}\Sigma_c^*,\ \bar{D}^*\Sigma_c,\ldots)$ — JaJun Wu,R. Molina, E. Oset,B. S.Zou,PRC84(2011)015202

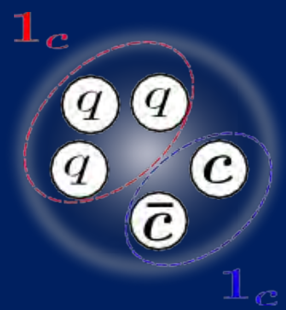
QCD Forces — Compact pentaquark $(5q)$ — E. Santopinto, A. Giachino, **Phys. Rev. D96** (2017) 014014

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



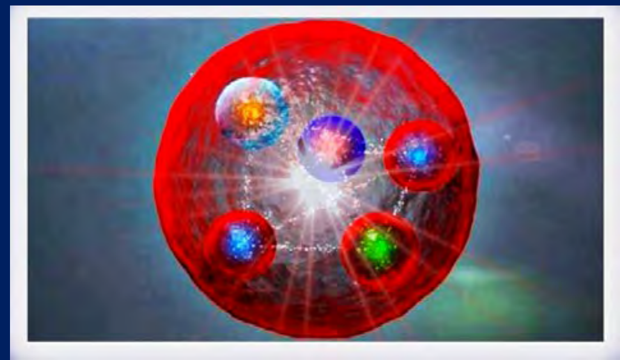


S_{q^3} = 1/2, 3/2, $S_{c\bar{c}}$ = 0, 1 S_{q^3} = 1/2, $S_{c\bar{c}}$ = 0, 1

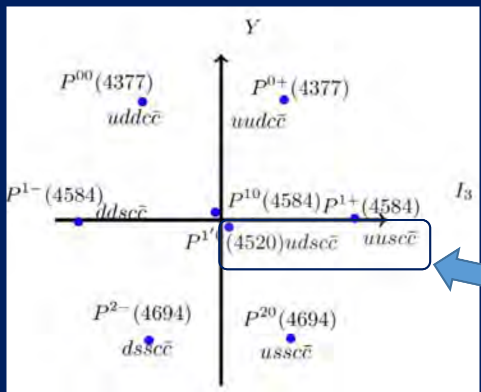
Using only simmetry considerations, and an equal spaced mass formula, we have predicted the strange pentaquark with I=0 Pcs(4457) for which LHCb reported evidence (LHCb, *Sci.Bull.* 66 (2021) 1278-1287) and suggested to look for it in the Λ J/Ψ channel (in fact cited by LHCb). According to our model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

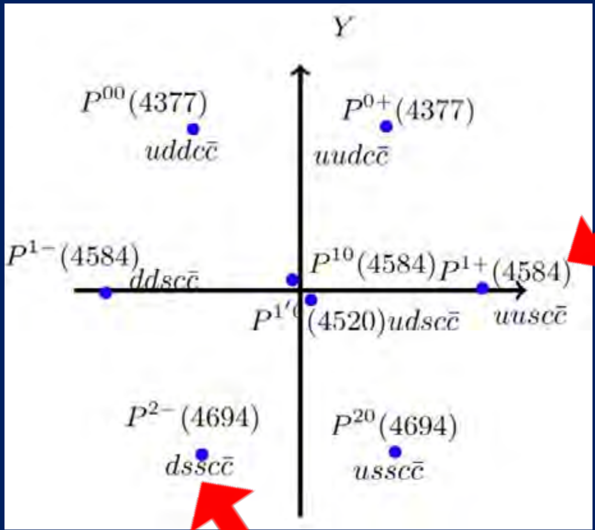
from E. Santopinto and A. Giachino, **Phys. Rev. D96** (2017) 014014

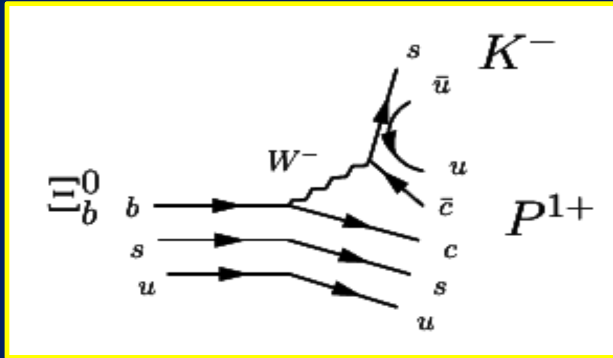
In which channels the other hidden charm pentaquarks which fill the SU(3) flavor octet can be observed?

PHYSICAL REVIEW D 96, 014014 (2017)

Compact pentaquark structures

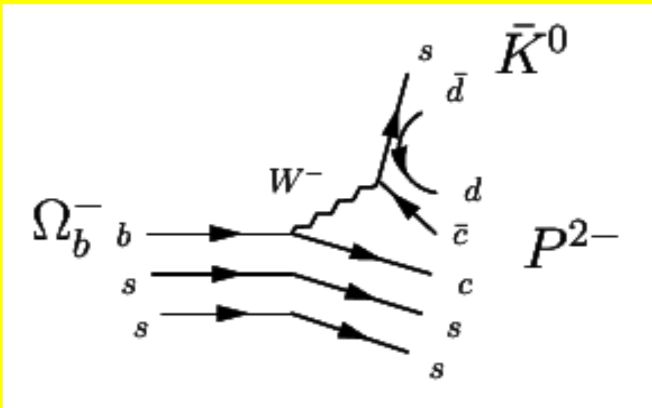
Elena Santopinto and Alessandro Giachino





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

$P^{1+}(4584)$ 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 $\Xi_b^0 \to J/\Psi\Sigma^+K^-$ decays!



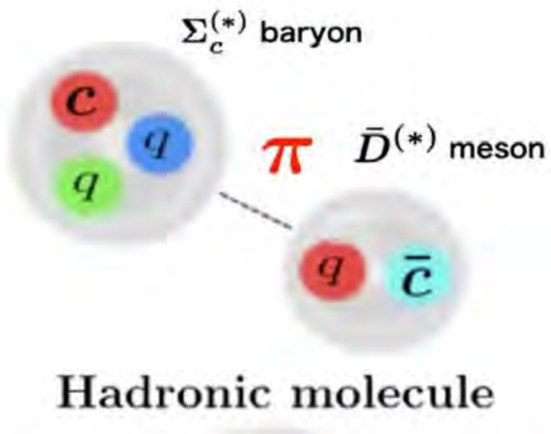
$$\Omega_b^- \to P^{2-} + \bar{K}^0, \qquad P^{2-} \to J/\Psi + \Xi^-.$$

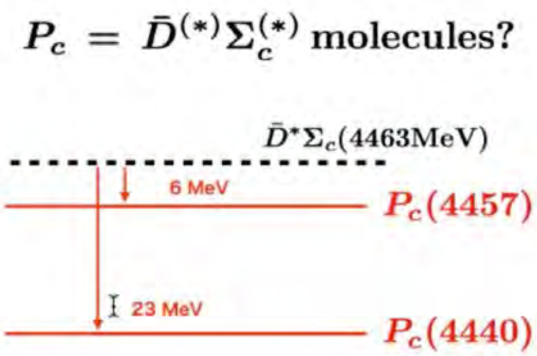
$P^{2-}(4694)$ a $c\bar{c}uss$ state with isospin ½; this state can be observed in $J/\Psi\Xi^-$ invariant mass spectrum after performing an amplitude analysis of $\Omega_b^- \to J/\Psi\Xi^-\bar{K}^0$ decays!

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?

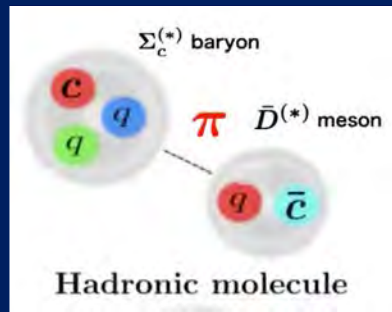
Hidden-charm pentaquarks as a meson-baryon molecule with coupled channels for $\bar{D}^{(*)}\Lambda_c$ and $\bar{D}^{(*)}\Sigma_c^{(*)}$

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)

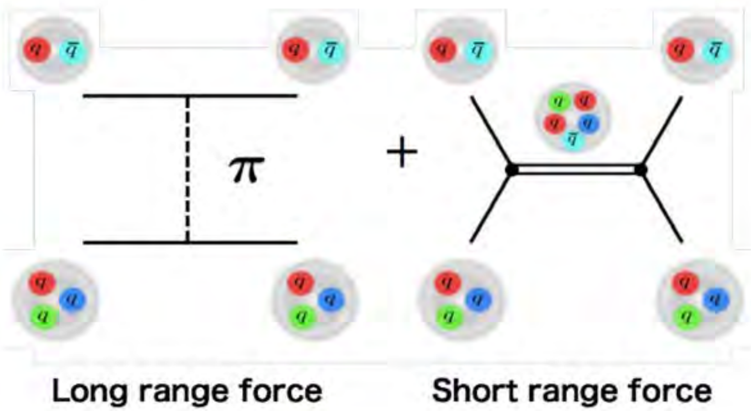
- **Long range** interaction: One pion exchange potential (OPEP)
- **Short range** interaction: $5q$ potential

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

Model setup in this study

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

Meson-Baryon interactions

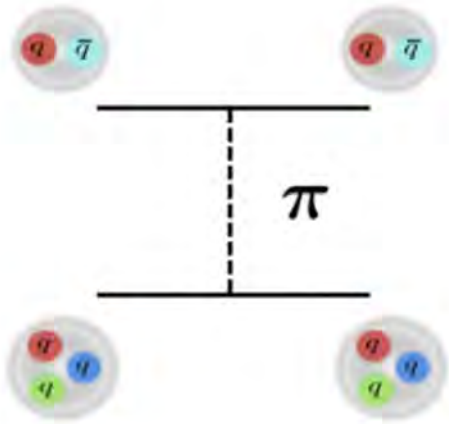


- **Long range** interaction: One pion exchange potential (OPEP)
- **Short range** interaction: $5q$ potential

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

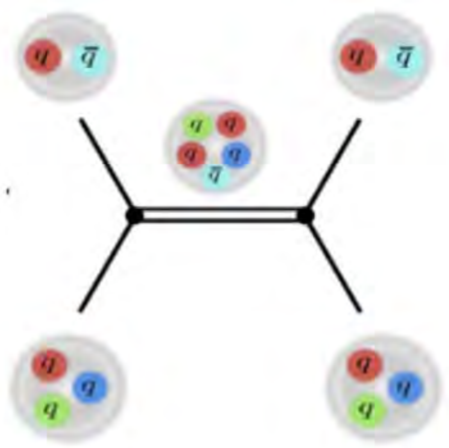
(see next slides)

1. **Long range force: One pion exchange potential**



Long range force

2. Short range force: 5-quark potential



Short range force

EFFECTIVE LAGRANGIANS

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

In Dirac space

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

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

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

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

Definition of the axial current

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

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].

EFFECTIVE LAGRANGIANS

Coupling between the heavy baryons and the light pseudoscalar mesons [2]:

In Flavour space

$$\mathcal{L}_{psBB} = \frac{3}{2} g_1 i v_\kappa \epsilon^{\mu\nu\lambda\kappa} \mathrm{tr}[\bar{S}_\mu A_\nu S_\lambda] + g_4 \mathrm{tr}[\bar{S}^\mu A_\mu B_{\bar{3}}] + \mathrm{H.c.}, \quad (10)$$

$$S_\mu = B^*_{6\mu} + \frac{\delta}{\sqrt{3}}(\gamma_\mu + v_\mu)\gamma_5 B_6, \qquad \bar{S}_\mu = \gamma_0 S^\dagger_\mu \gamma_0.$$

The phase factor $\delta = -1$

$$B_{\bar{3}} = \begin{pmatrix} 0 & \Lambda_c^+ & \Xi_c^+ \\ -\Lambda_c^+ & 0 & \Xi_c^0 \\ -\Xi_c^+ & -\Xi_c^0 & 0 \end{pmatrix}, \quad B_6 = \begin{pmatrix} \Sigma_c^{++} & \frac{1}{\sqrt{2}}\Sigma_c^+ & \frac{1}{\sqrt{2}}\Xi_c'^+ \\ \frac{1}{\sqrt{2}}\Sigma_c^+ & \Sigma_c^0 & \frac{1}{\sqrt{2}}\Xi_c'^0 \\ \frac{1}{\sqrt{2}}\Xi_c'^+ & \frac{1}{\sqrt{2}}\Xi_c'^0 & \Omega_c^0 \end{pmatrix}$$

$$B_6^* = \begin{pmatrix} \Sigma_c^{*++} & \frac{1}{\sqrt{2}}\Sigma_c^{*+} & \frac{1}{\sqrt{2}}\Xi_c^{*+} \\ \frac{1}{\sqrt{2}}\Sigma_c^{*+} & \Sigma_c^{*0} & \frac{1}{\sqrt{2}}\Xi_c^{*0} \\ \frac{1}{\sqrt{2}}\Xi_c^{*+} & \frac{1}{\sqrt{2}}\Xi_c^{*0} & \Omega_c^{*0} \end{pmatrix},$$

$g_1 = (\sqrt{8}/3) g_4 = 1$ is obtained from Quark Model

[2] Y. R. Liu and M. Oka, Phys. Rev. D **85**, 014015 (2012) doi:10.1103/PhysRevD.85.014015 [arXiv:1103.4624 [hep-ph]].

- From the effective Lagrangians introduced above, we obtain the pseudoscalar meson exchange potentials
- The coupled channel Hamiltonian is obtained by coupling the meson-baryon channels to the compact five-quark states

Kinetic energy and OPEP of the Meson-Baryon system

$$H = \begin{pmatrix} H^{MB} & V \\ V^{\dagger} & H^{5q} \end{pmatrix}$$

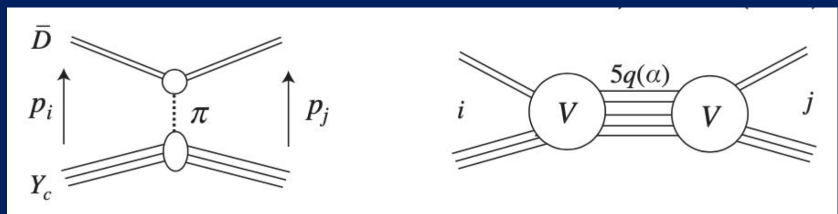
Coupling between the meson-baryon channels and the five- quark core

Kinetic energy and harmonic oscillator potential of the five quark states.

$$H^{MB}\psi^{MB} + V\psi^{5q} = E\psi^{MB}\,,$$
$$V^{\dagger}\psi^{MB} + H^{5q}\psi^{5q} = E\psi^{5q}\,.$$

$$\left(K^{MB} + V^{\pi} + V\frac{1}{E - H^{5q}}V^{\dagger}\right)\psi^{MB} = E\psi^{MB}.$$

coupled channel Schrödinger equation



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.

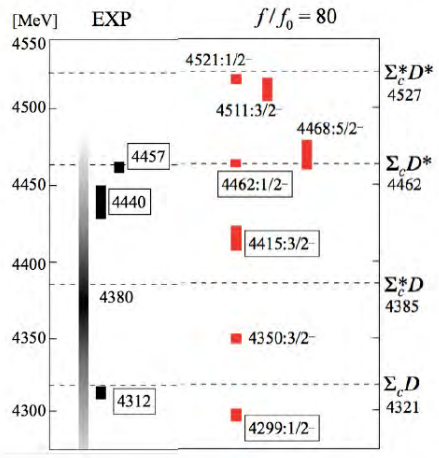
We predicted the three pentaquark states, $P_c(4312), P_c(4440)$ and $P_c(4457)$ two years before the experimental observation by LHCb.

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)

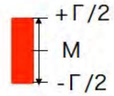
[3] Y. Yamaguchi, A. Giachino, A. Hosaka, E. Santopinto, S. Takeuchi, M. Takizawa, **Phys. Rev. D 96 114031 (2017)**

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)



($f_0 = 6$ MeV)



New

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

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

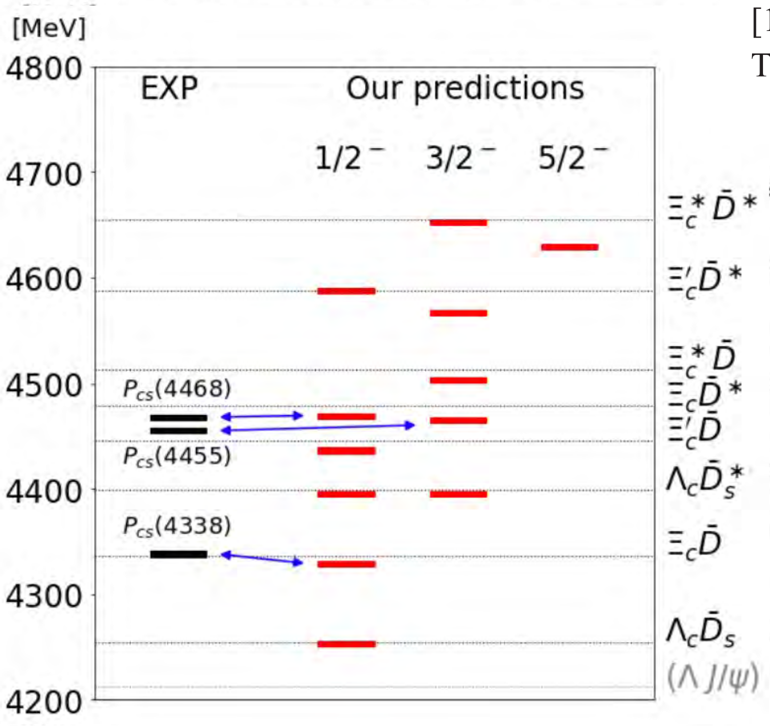
This new state has been observed in the $B^- \to J/\Psi\Lambda\bar{p}$ decay process as a resonance in $J/\Psi\Lambda$ invariant mass (minimal quark content $c\bar{c}$uds) with a statistical significance > **10 standard deviations** [*]

[*] 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 $udsc\bar{c}$, 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 $P_{cs}(4455)$

Fully charmed tetraquark production at the LHC experiments

I. Belov, A. Giachino, E. Santopinto, 2409.12070 [hep-ph]

$$\sigma_{pp} = \iint dx_1 dx_2\, G(x_1,\mu)\, G(x_2,\mu) \int dt\, \frac{d\widehat{\sigma}(s,t,\mu)}{dt}$$

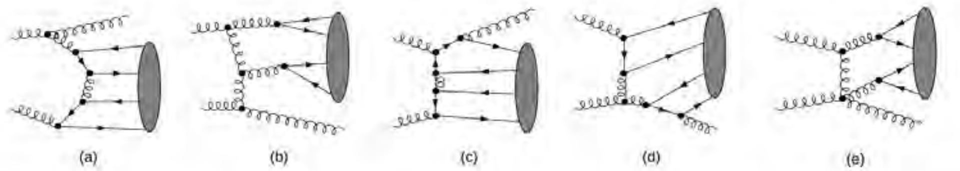


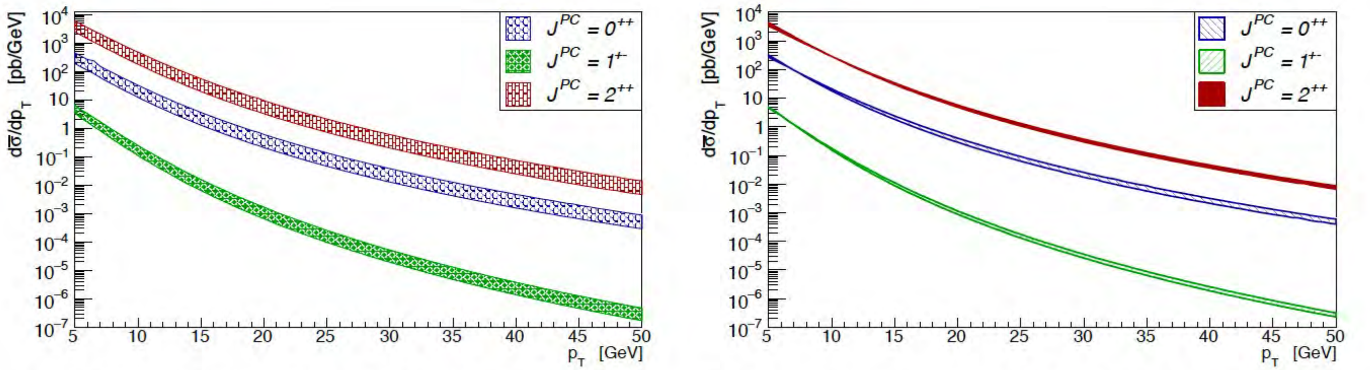
FIG. 1: Some of the Feynman diagrams for the $gg \to T_{4c} + g$ process: ISR (a-b), FSR (c-d), and Rest (e). The gray blob represents the tetraquark in the final state.

Inputs

- pQCD. CTEQ18 NLO
- Wave functions by G. J. Wang, L. Meng, M. Oka, S.L. Zhu , PRD 104, 036016 (2021)

Reduced cross sections for LHCb

I. Belov, A. Giachino, E. Santopinto, 2409.12070 [hep-ph]



(a) The band corresponds to the $E_T/2 \leq \mu \leq 2E_T$ scale variation, while M and α^2 are fixed to their average values.

(b) The band corresponds to the variation of the spectroscopy parameters M and α^2, while the scale is fixed to E_T.

FIG. 2: $d\overline{\sigma}/dp_T$ as a function of p_T for the $pp \to T_{4c}(J^{PC}) + X$ process within the forward acceptance $2 < y < 5$ and p_T-window $5 < p_T(\mathrm{GeV}) < 50$.

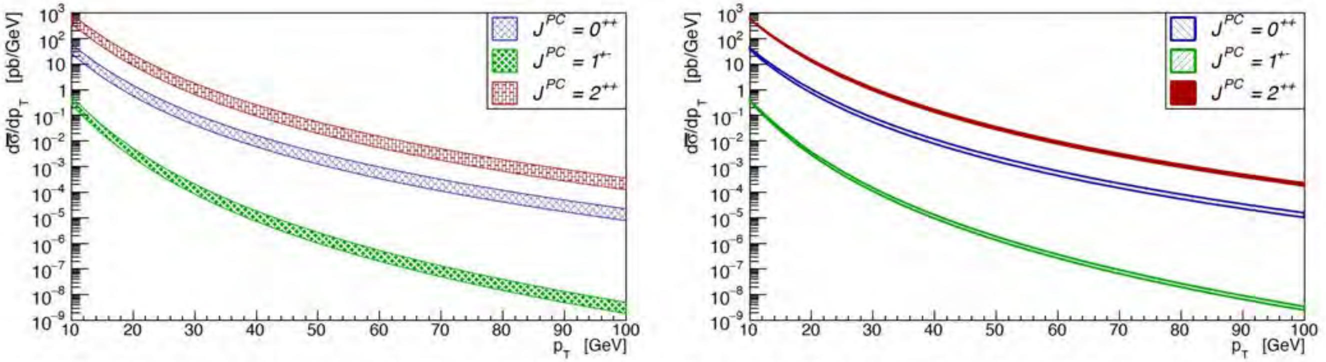
$$\sigma = \Phi(nS)\, \overline{\sigma}(\mu, \langle M \rangle, \langle \alpha^2 \rangle)$$

$$\Phi(nS) = 10^{10} \phi(nS)$$

$$\phi = |\Psi(0,0,0)|^2/M^9,$$

Reduced cross sections for CMS and ATLAS

I. Belov, A. Giachino, E. Santopinto, 2409.12070 [hep-ph]



(a) The band corresponds to the $E_T/2 \leq \mu \leq 2E_T$ scale variation, while M and α^2 are fixed to their average values.

(b) The band corresponds to the variation of the spectroscopy parameters M and α^2, while the scale is fixed to E_T.

FIG. 3: $d\overline{\sigma}/dp_T$ as a function of p_T for the $pp \to T_{4c}(J^{PC}) + X$ process within the central acceptance $|y| < 2$ and p_T-window $10 < p_T(\text{GeV}) < 100$.

$$\sigma = \Phi(nS)\, \overline{\sigma}(\mu, \langle M \rangle, \langle \alpha^2 \rangle)$$

$$\Phi(nS) = 10^{10} \phi(nS)$$

$$\phi = |\Psi(0,0,0)|^2/M^9,$$

I. Belov, A. Giachino, E. Santopinto, 2409.12070 [hep-ph]

TABLE IV: From left to right: percentage of color configurations, mass in GeV, modulus squared of the four-body wave function at the origin in GeV^9, reduced wave function $\phi = |\Psi(0,0,0)|^2/M^9$, and root mean squared radii in fm.

		$\vert\bar{3}\otimes 3\rangle$	$\vert 6\otimes\bar{6}\rangle$	Mass	$10^3\vert\Psi(0,0,0)\vert^2$	$10^{10}\phi$	$\sqrt{\langle r^2_{12(34)}\rangle}$	$\sqrt{\langle r^2\rangle}$
Ref. [26]	$0^{++}(1S)$	31.9%	68.1%	6.405	1.20	0.661	0.52	0.31
	$0'^{++}(1S)$	67.7%	32.3%	6.498	0.88	0.426	0.51	0.36
	$0^{++}(2S)$	10.6%	89.4%	6.867	0.22	0.065	0.65	0.35
	$0'^{++}(2S)$	89.7%	10.3%	7.007	0.50	0.124	0.49	0.47
	$1^{+-}(1S)$	100%	0%	6.481	1.17	0.580	0.48	0.37
	$1^{+-}(2S)$	100%	0%	6.954	0.17	0.045	0.61	0.44
	$1^{+-}(3S)$	100%	0%	7.024	0.12	0.029	0.66	0.42
	$2^{++}(1S)$	100%	0%	6.502	0.88	0.243	0.49	0.39
	$2^{++}(2S)$	100%	0%	6.917	0.12	0.033	0.55	0.60
	$2^{++}(3S)$	100%	0%	7.030	0.11	0.026	0.64	0.46

[26] G. J. Wang, L. Meng, M. Oka, S.L. Zhu , PRD 104, 036016 (2021)

For the future, it can be usefull to have:

- Efficiencies from ATLAS and CMS
- The absolute value of the cross section from LHCb, CMS, ATLAS

Theoretical predictions for the Numbers of events

$N_{\rm sig}(0^{++}) \sim 100 \div 1000\,,$	$N_{\rm sig}(2^{++}) \sim 1000 \div 10000\,,$	for $1S$,
$N_{\rm sig}(0^{++}) \sim 10\,,$	$N_{\rm sig}(2^{++}) \sim 100\,,$	for $2S$,
$N_{\rm sig}(0^{++}) \sim 10,$	$N_{\rm sig}(2^{++}) \sim 100\,,$	for $3S$,

$$N_{\rm sig} \approx \varepsilon \mathcal{L}\, \Phi\, \overline{\sigma}(pp \to\ T_{4c} + X) \cdot {\rm Br}(T_{4c} \to J/\psi\, J/\psi)$$

$\mathcal{L}$ denotes the integral luminosity

$$N_{\rm LHCb}(6905) = 252 \pm 63$$

in qualitative agreement with LHCb!

Thanks for your attention!

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.

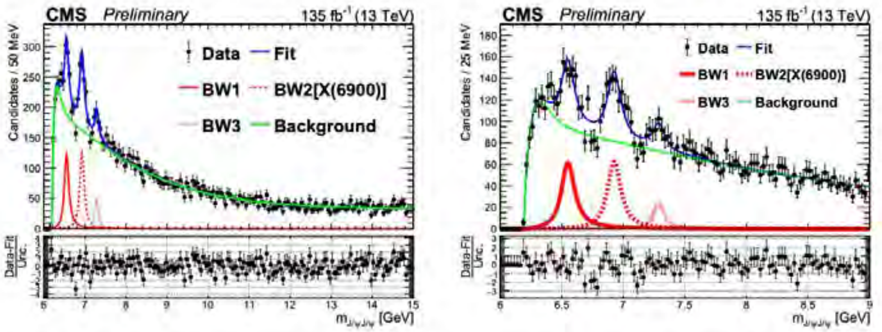


Figure 3: The CMS $J/\psi J/\psi$ mass spectrum with a fit consisting of three signal BW functions and a background model [12]. The left plot shows the fit over the full mass range, and on the right is the same fit expanded by only displaying masses below 9 GeV.

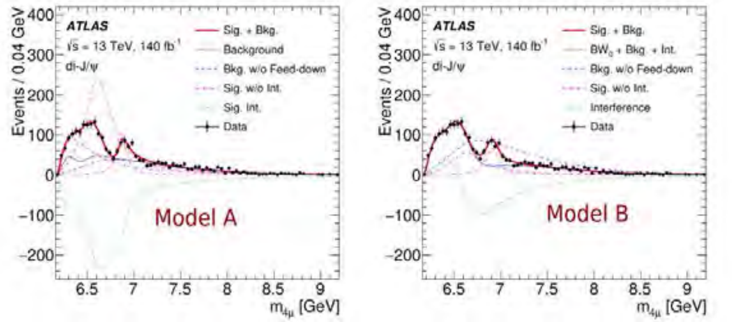
	BW1	BW2	BW3
m	$6552 \pm 10 \pm 12$	$6927 \pm 9 \pm 5$	$7287 \pm 19 \pm 5$
Γ	$124 \pm 29 \pm 34$	$122 \pm 22 \pm 19$	$95 \pm 46 \pm 20$
N	474 ± 113	492 ± 75	156 ± 56

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, 2023)

Di-J/ψ channel

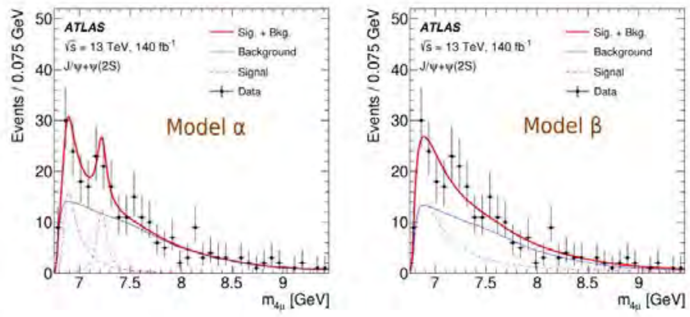


- Model A: 3 *interfering* BW resonances
- Model B: 1 BW interfering with SPS background, 1 BW standalone

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

$J/\psi+\psi(2S)$	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	$0.09 \pm 0.06^{+0.06}_{-0.03}$	$0.51 \pm 0.17^{+0.11}_{-0.10}$
$\Delta s/s$	$\pm 21\% \pm 14\%$	$\pm 20\% \pm 12\%$