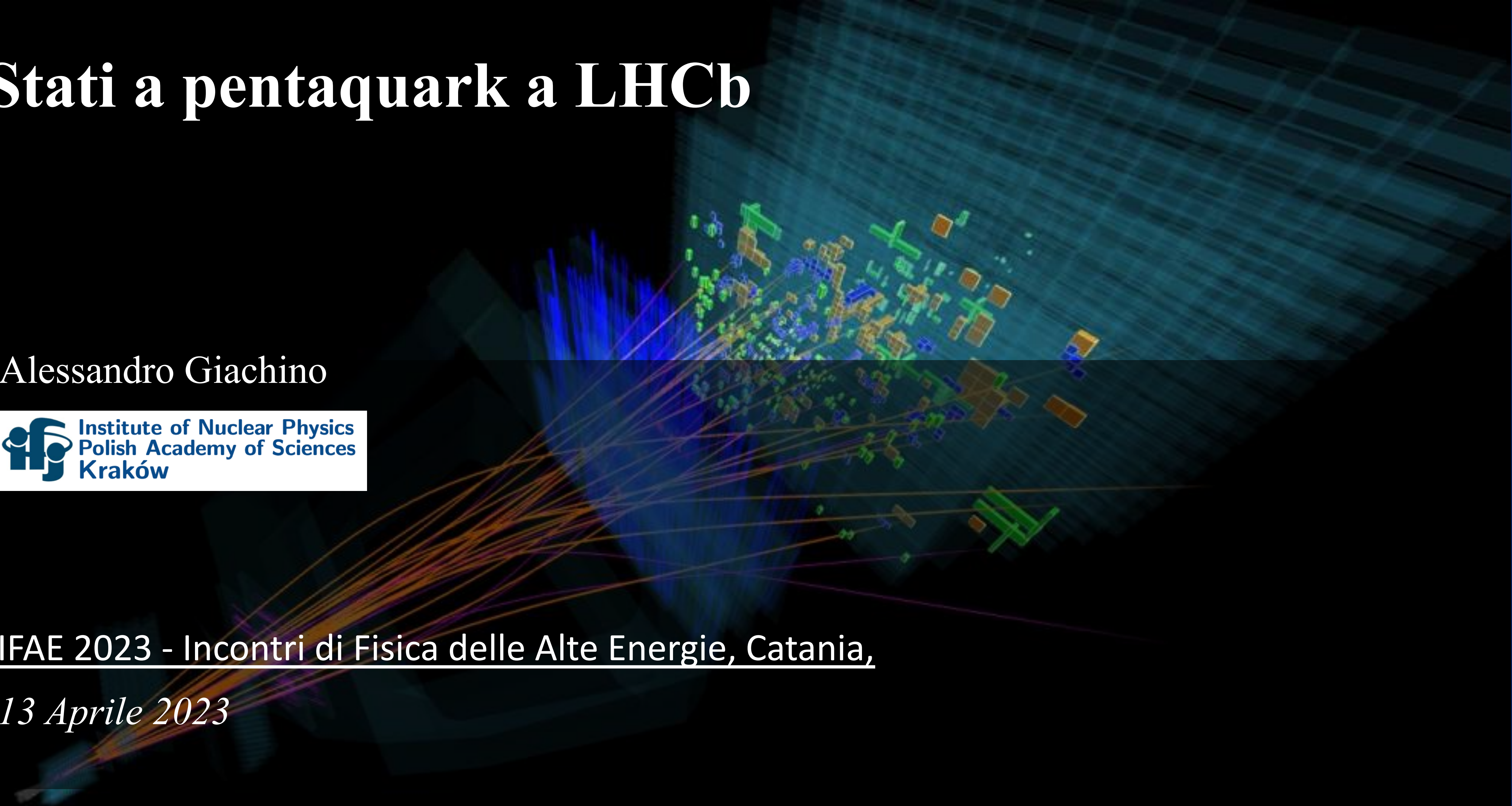

Stati a pentaquark a LHCb

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IFAE 2023 - Incontri di Fisica delle Alte Energie, Catania,

13 Aprile 2023

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Outline

PENTAQUARKS

Quick excursus on the experimental discoveries of the pentaquark states

Pentaquarks as compact $5q$ states [1]

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

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

The new strange pentaquark $P_{cs}(\mathbf{4338})$ as core+molecular components in a coupled channel approach **[5]** New

[1] E. Santopinto, A. G., Phys. Rev. D 96 (2017) 014014
[2]Y. Yamaguchi, E. Santopinto, Phys. Rev. D Phys.Rev. D 96 (2017) no.1, 014018
[3] Y. Yamaguchi, A. G., A. Hosaka, E. Santopinto, S. Tacheuchi, M. Takizawa, Phys .Rev. D96 (2017) no.11, 114031
[4] Y. Yamaguchi, H. Garcia-Tecocoatzi, A. G., A. Hosaka, E. Santopinto, S. Takeuchi and M. Takizawa Phys.Rev.D 101 (2020) 091502
[5] A. G., A. Hosaka, E. Santopinto , S. Tacheuchi, M. Takizawa, Y. Yamaguchi, Rich structure of the hidden-charm pentaquarks near threshold regions, e-Print: 2209.10413 (submitted on 21 September 2022)

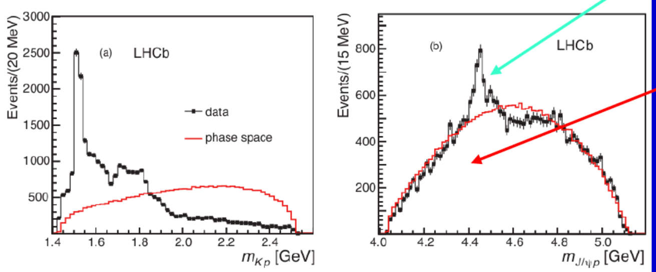
More new valence quark configurations

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

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

LHCb

Phys. Rev. Lett.115(2015) 072001



M _P_c^+(4450) = (4449.8 ± 8 ± 29)MeV

Γ = (39 ± 5 ± 19) MeV

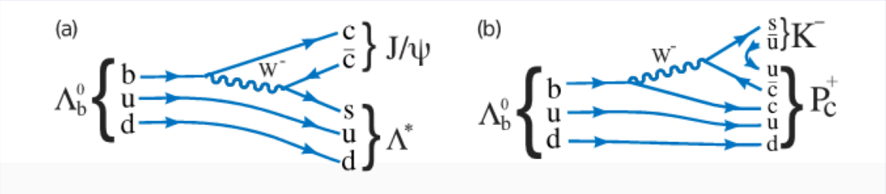
M_P_c^+(4380) = (4380 ± 1.7 ± 2.5)MeV

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

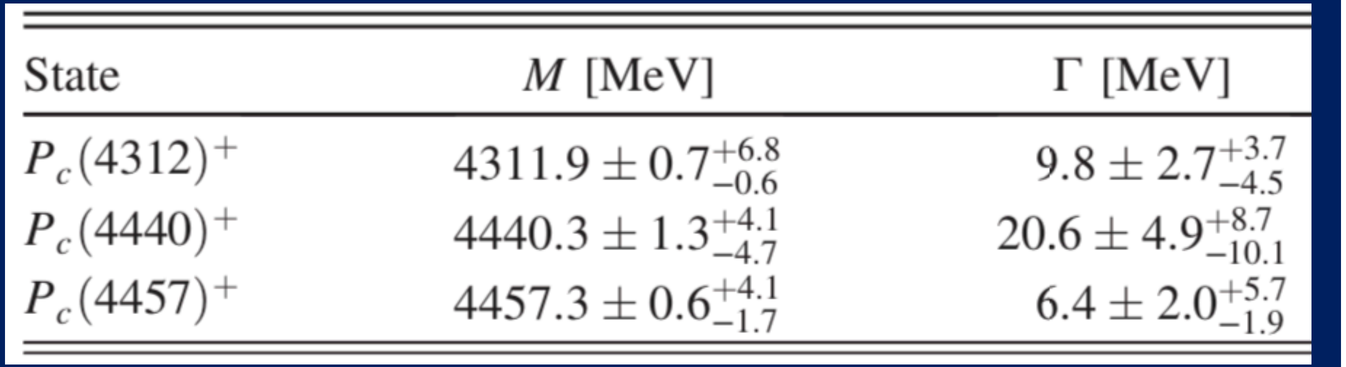
[2] R. Aaij *et al.* [LHCb Collaboration], Phys. Rev. Lett. **117** (2016) no.8, 082002

[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.

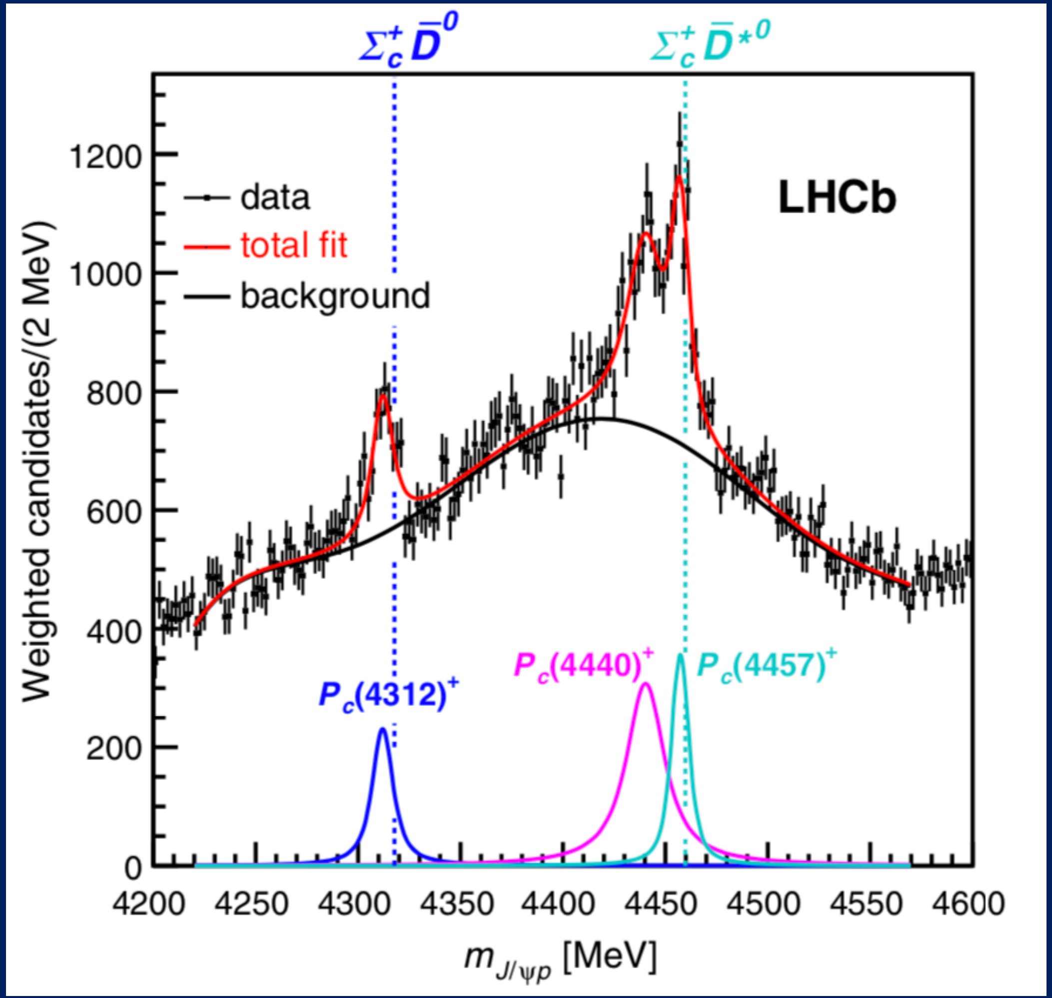
The masses and widths of the three narrow pentaquark states are as follows



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).

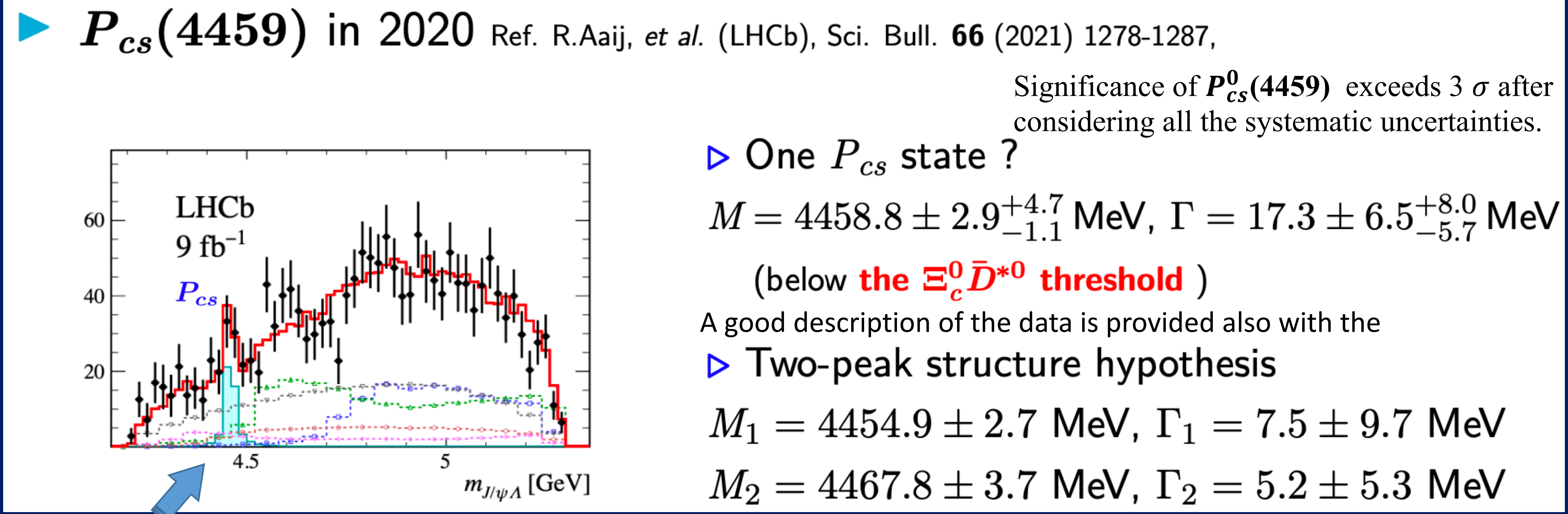
$\Lambda_b^0 \to J/\Psi pK^-$ channel ($P_c \to J/\Psi\, p$)



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 ($P_{cs} \to J/\Psi\ \Lambda$)



$P_{cs}(4459)$ in 2020 Ref. R.Aaij, *et al.* (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 ?

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

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

A good description of the data is provided also with the

▷ Two-peak structure hypothesis

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

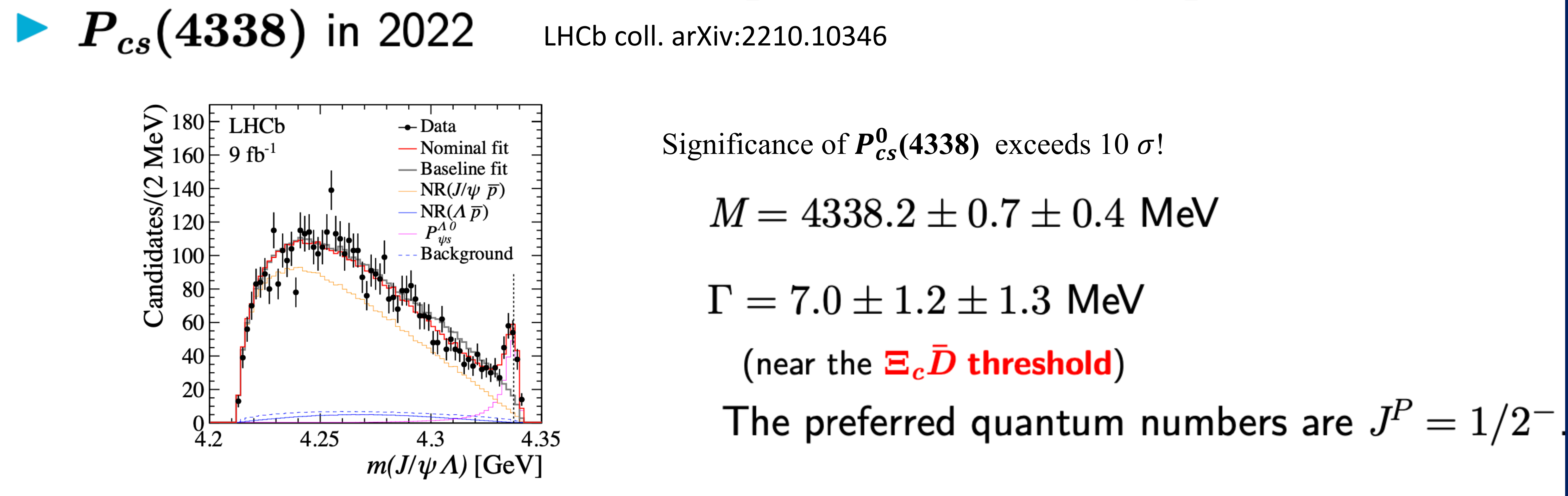
$$M_2 = 4467.8 \pm 3.7\ \text{MeV},\ \Gamma_2 = 5.2 \pm 5.3\ \text{MeV}$$

The mass of P_{cs}(4459) is about 19 MeV below the $\Xi^0_c\ \bar{D}^{*0}$ threshold.

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

2022 New

$B^- \to J/\Psi \Lambda \bar{p}$ 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!

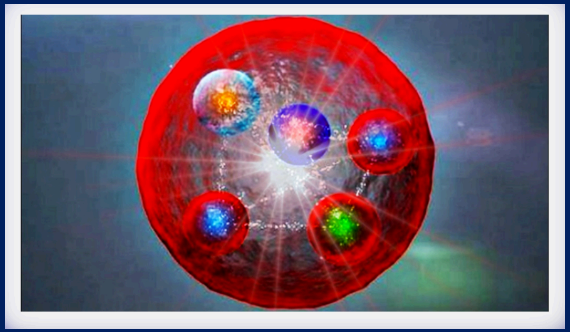
$$M = 4338.2 \pm 0.7 \pm 0.4\ \text{MeV}$$

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

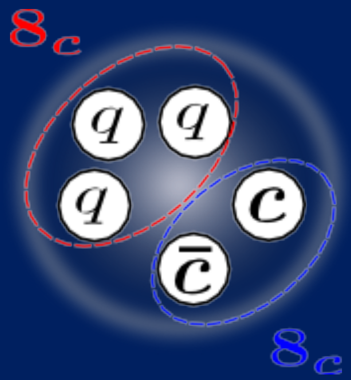
(near the $\Xi_c\bar{D}$ **threshold**)

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

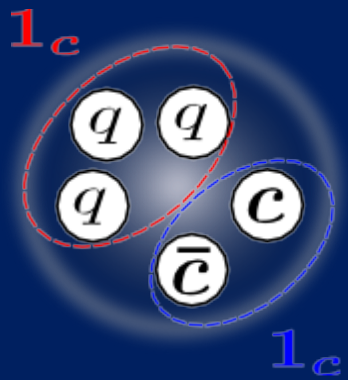
Pentaquark as compact $5q$ states



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



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



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

Using only simmetry considerations, and an equal spaced mass formula, we have **predicted Pcs(4459) 3 years in advance and suggested to look for it in the Λ J/Ψ channel.** According to our model also I=1 Pcs should exist (in the Σ J/Ψ channel) and I=1/2 Pcss (in Ξ J/Ψ channel)

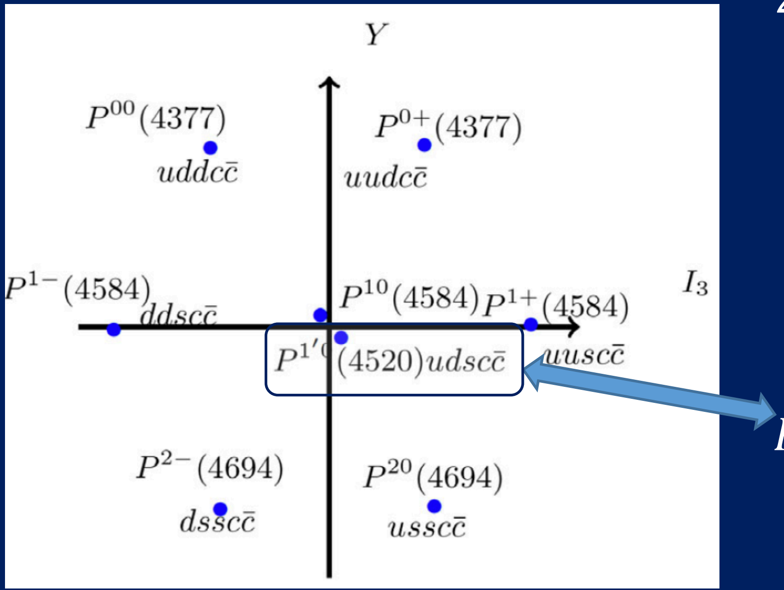
The discovery paper by LHCb cited our paper

Cited also by PDG2021 and PDG2022 !

Pentaquark as compact $5q$ states

We have predicted the strange pentaquark with I=0, P_{cs}^{0}, for which LHCb reported evidence at M=4459 MeV and suggested to look for it in the Λ J/Ψ channel . According to our model also I=1 P_{cs} should exist (in the Σ J/Ψ channel) and I=1/2 P_{css} (in Ξ J/Ψ channel).

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



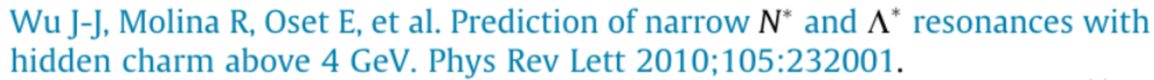
$P_{cs}^{0}(4459)$

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

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

This state was also predicted in 2010 within coupled-channel unitary approach with the local hidden gauge formalism by [*]

[*]



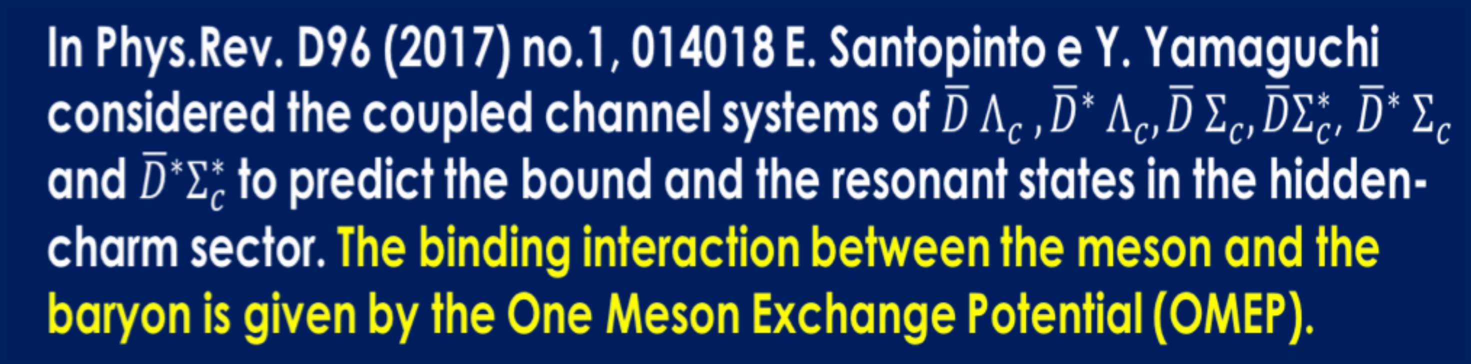
Wu J-J, Molina R, Oset E, et al. Prediction of narrow N^* and Λ^* resonances with hidden charm above 4 GeV. Phys Rev Lett 2010;105:232001.

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

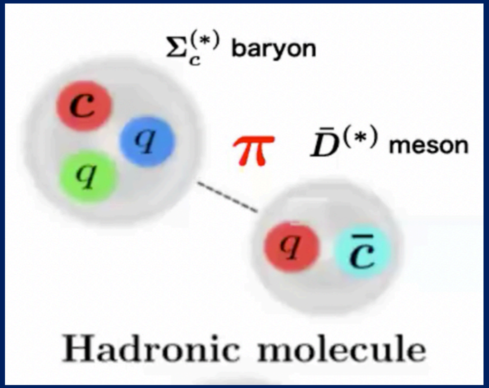
Y. Yamaguchi, E. Santopinto, Phys. Rev. D Phys.Rev. D96 (2017) no.1, 014018

This description is motivated by the fact that the observed pentaquarks are found to be just below the $\Sigma_c\bar{D}$ theshold$\left(P_c(4312)\right)$, $\Sigma_c^*\,\bar{D}$ $\left(P_c(4380)\right)$ and $\Sigma_c\bar{D}^*$ $(P_c(4440)$ and $P_c(4457))$

Near the threshold, resonances are expected to have an exotic structure, like the hadronic molecules



In Phys.Rev. D96 (2017) no.1, 014018 E. Santopinto e Y. Yamaguchi considered the coupled channel systems of $\bar{D}\,\Lambda_c$, $\bar{D}^*\,\Lambda_c$, $\bar{D}\,\Sigma_c$, $\bar{D}\Sigma_c^*$, $\bar{D}^*\,\Sigma_c$ and $\bar{D}^*\Sigma_c^*$ to predict the bound and the resonant states in the hidden-charm sector. The binding interaction between the meson and the baryon is given by the One Meson Exchange Potential (OMEP).



This 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

- In the current problem of pentaquark P_c, there are two competing sets of channels: the meson-baryon (MB) channels and the five-quark channels.

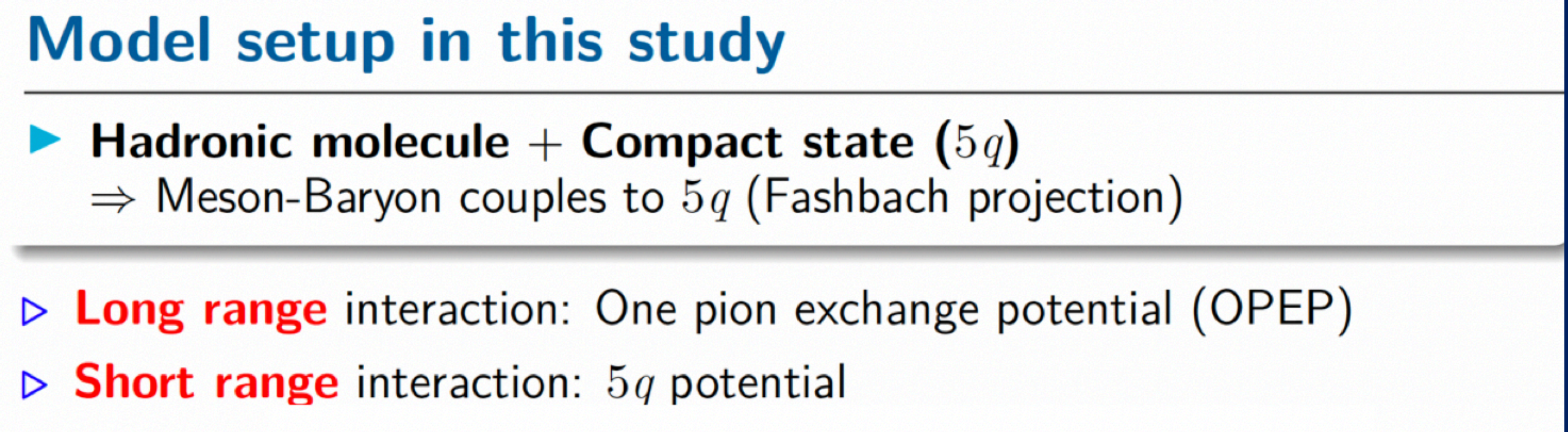
CAN A COUPLE CHANNEL BETWEEN

THE MB CHANNELS AND THE CORE CONTRIBUTION

DESCRIBE IN A MORE REALISTIC WAY THE PENTAQUARK STATES ?

Coupled channel between the meson-baryon states and the five quark states

Hidden-charm and bottom meson-baryon molecules coupled with five-quark states, **Y. Yamaguchi, A. 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 $(5q)$**
  ⇒ 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

(see next slides)

EFFECTIVE LAGRANGIANS

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

In Dirac space

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

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

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

⟺ Definition of the axial current

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

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)
$v_\mu \to (1,0,0,0)$

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

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

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

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

The phase factor $\delta = -1$

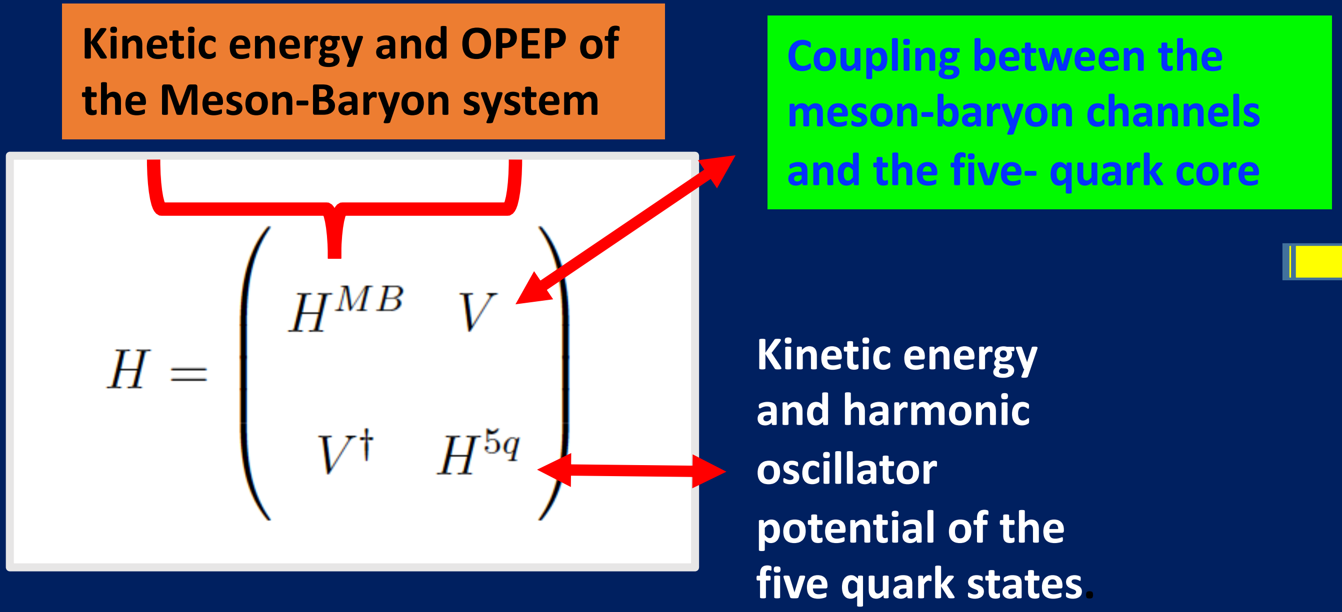
$$B_{\bar{3}} = \begin{pmatrix} 0 & \Lambda_c^+ & \Xi_c^+ \\ -\Lambda_c^+ & 0 & \Xi_c^0 \\ -\Xi_c^+ & -\Xi_c^0 & 0 \end{pmatrix}, \quad B_6 = \begin{pmatrix} \Sigma_c^{++} & \frac{1}{\sqrt{2}}\Sigma_c^+ & \frac{1}{\sqrt{2}}\Xi_c^{\prime +} \\ \frac{1}{\sqrt{2}}\Sigma_c^+ & \Sigma_c^0 & \frac{1}{\sqrt{2}}\Xi_c^{\prime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

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

$g_1 = (\sqrt{8}/3) g_4 = 1$ 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

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

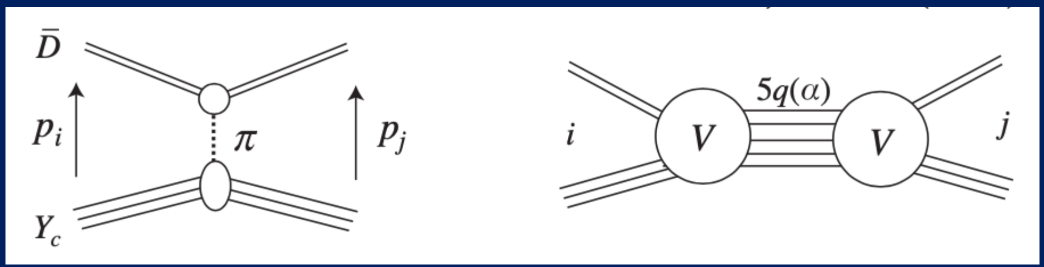
Coupling between the meson-baryon channels and the five- quark core

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

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

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

coupled channel Schrödinger equation



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**

By diagonalizing the coupled channel Hamiltonian we studied the the bound and resonant hidden-charm and hidden-bottom pentaquark states for

$$J^P = \frac{1}{2}^-, \frac{3}{2}^-, \frac{5}{2}^- \text{ and isospin } I = \frac{1}{2}.$$

Both masses and decay widths have been calculated
by using the Complex Scaling Method (CSM)

Coupled channel between the meson-baryon states and the five quark states

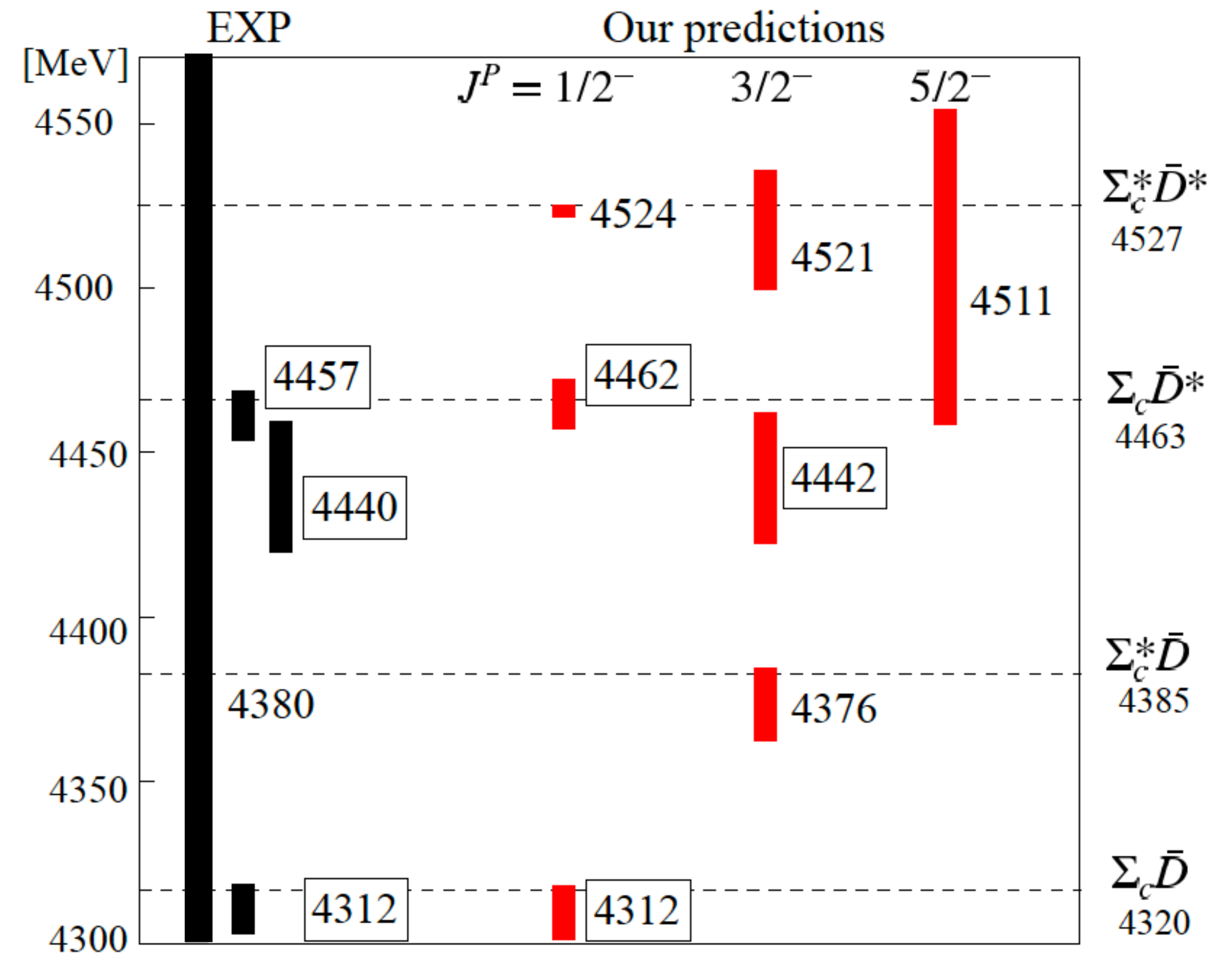
Hidden-charm and bottom meson-baryon molecules coupled with five-quark states,**Y. Yamaguchi, A. G., A. Hosaka, E. Santopinto, S. Tacheuchi, M. Takizawa, Phys .Rev. D96 (2017) no.11, 114031**

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. G., A. Hosaka, E. Santopinto, S. Takeuchi and M. Takizawa Phys.Rev.D **101** (2020) 091502 (R)

results

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



The predicted pentaquark masses and widths are consistent with the experimental data with the following quantum number assignments:

$$J^P(P_c(4312)) = \frac{1}{2}^-,$$

$$J^P(P_c(4440)) = \frac{3}{2}^-$$

and

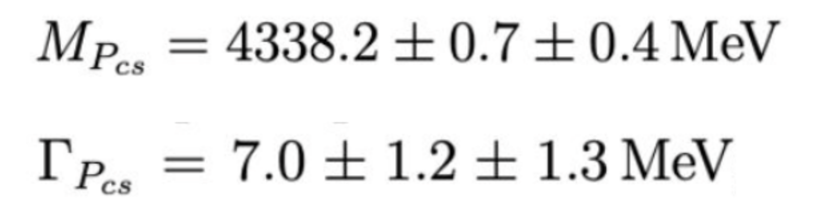
$$J^P(P_c(4457)) = \frac{1}{2}^-$$

Cited by PDG2021 and PDG2022! Together with Y. Yamaguchi, A. G., A. Hosaka, E. Santopinto, S. Takeuchi, M. Takizawa, PRD **96** (2017) 114031.

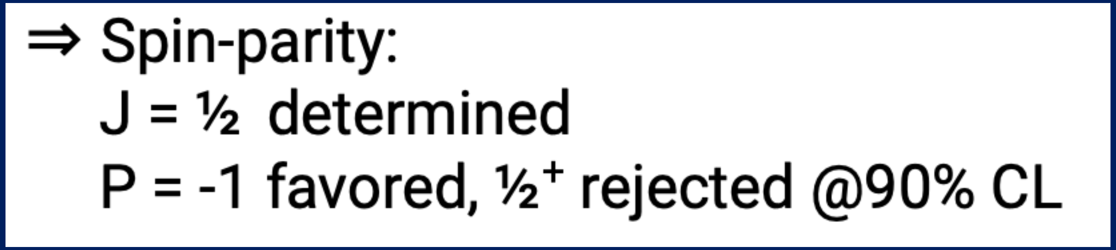
New

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** [*]

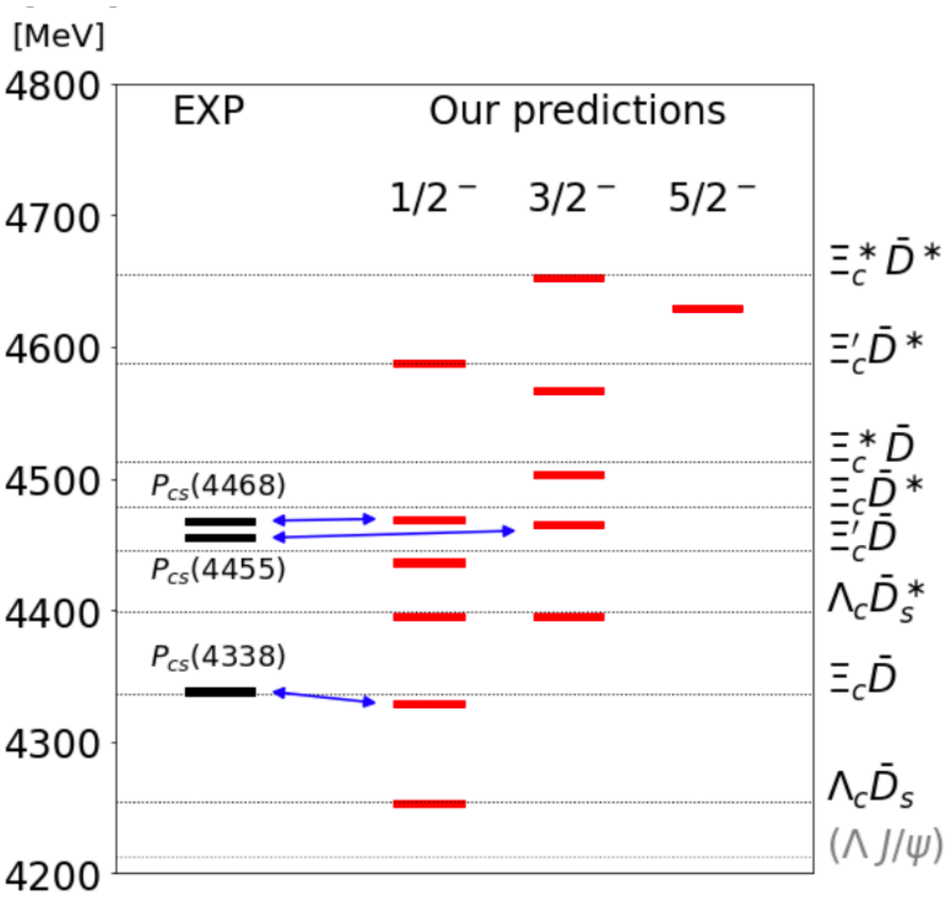
[*] Aaij et al. (LHCb collaboration), arXiv:2210.10346

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.Y, arXiv:2209.10413 [hep-ph]



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

Conclusions:

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

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

Three of my articles have been cited by the Particle Data Group

Many thanks for your attention!