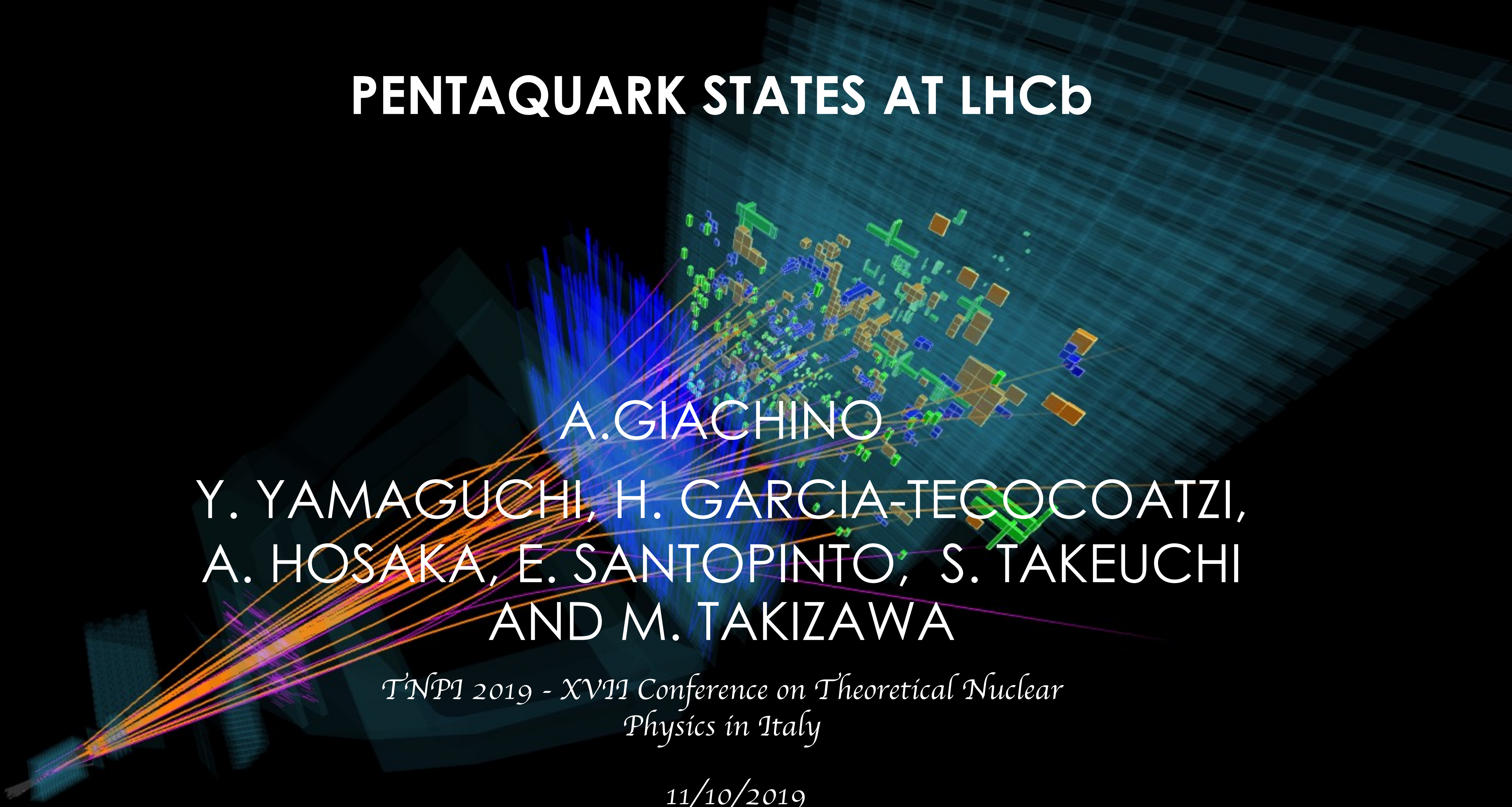

# PENTAQUARK STATES AT LHCb


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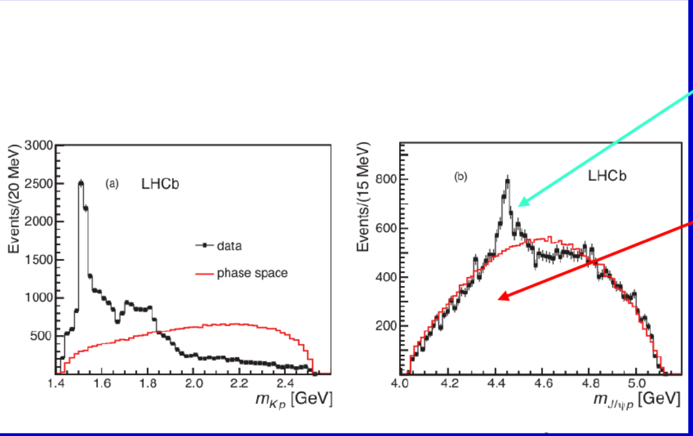
*11/10/2019*

# LHCb

Phys. Rev. Lett.115(2015) 072001

# Why pentaquark states?




M _$P_c^+$(4450) = (4449.8 ± 8 ± 29)MeV

Γ = (39 ± 5 ± 19) MeV

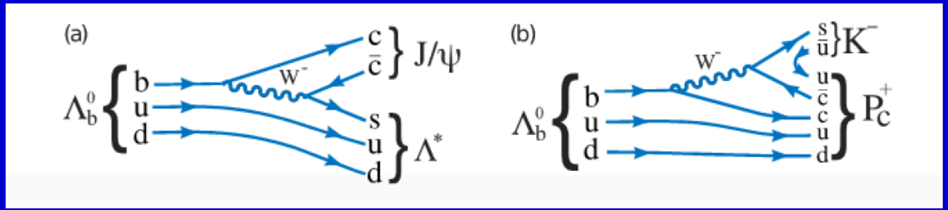
M_$P_c^+$(4380) = (4380 ± 1.7 ± 2.5)MeV

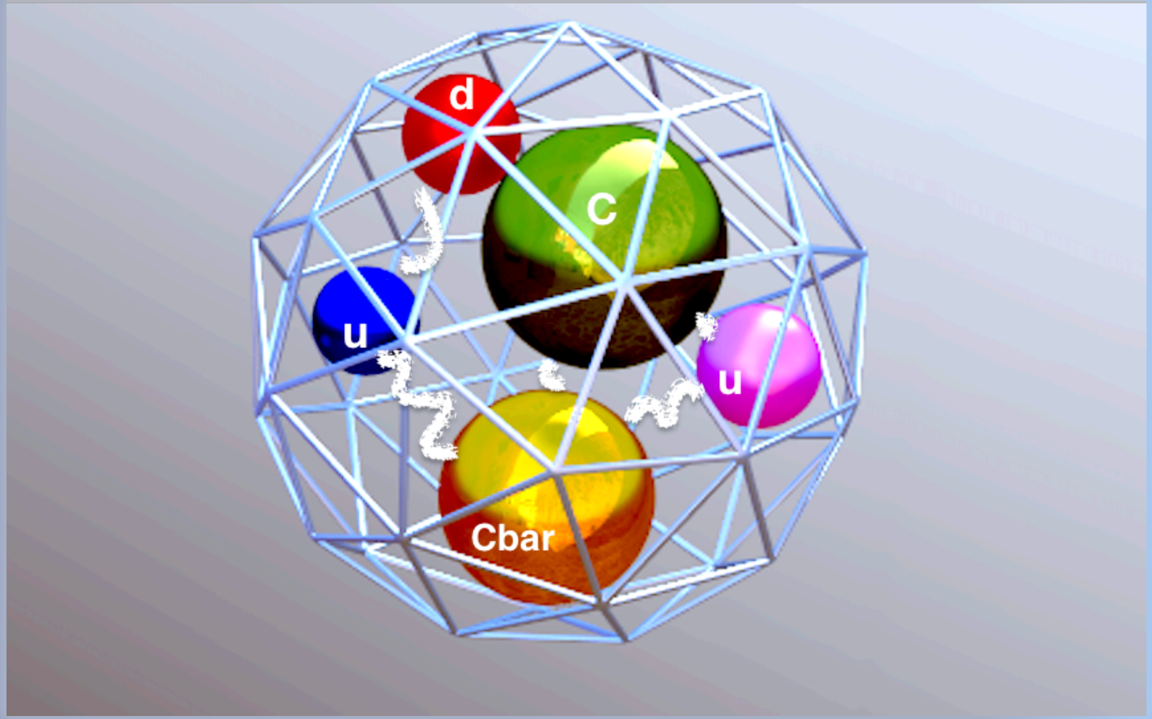
Γ =(205±18±86 )MeV

statistic significance greater then 9 sigma !

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

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




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

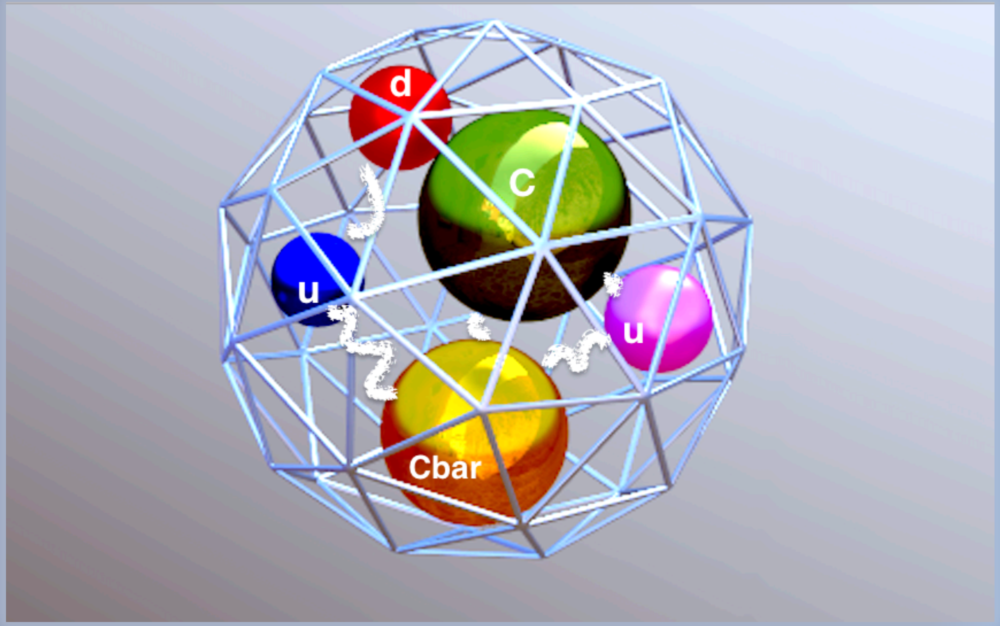
[2] R. Aaij *et al.* [LHCb Collaboration], Phys. Rev. Lett. **117** (2016) no.8, 082002

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

# Why pentaquark states?

Recently a new analysis has been reported [4] using nine times more data from the Large Hadron Collider than the 2015 analysis

When this combined dataset is fit with the same amplitude model used in Ref. [1], the $P_c(4380)$ and $P_c(4450)$ parameters are found to be consistent with the previous results.




[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

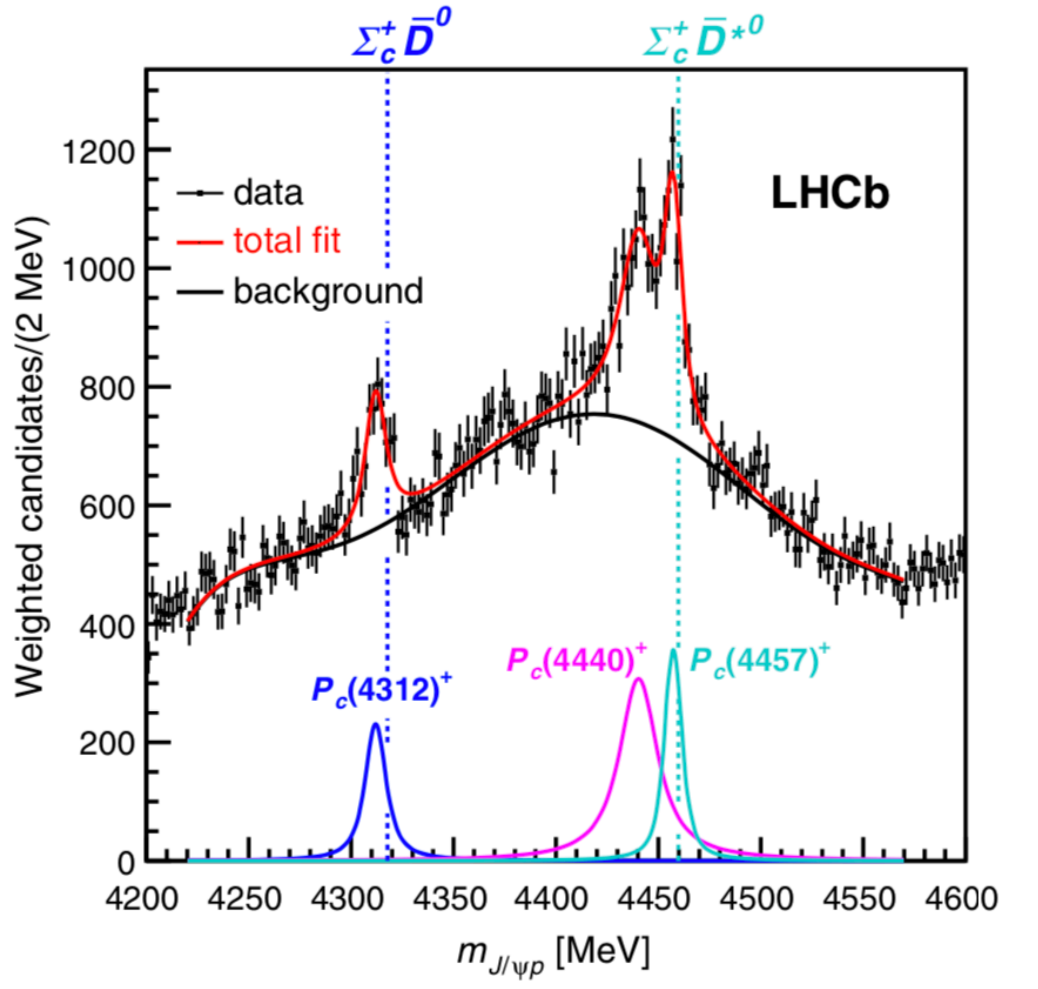
[4] R. Aaij et al. (LHCb), Phys. Rev. Lett. 122, 222001 (2019).

# Why pentaquark states?

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

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




Number of events versus J/Psi p invariant mass [4]. The mass thresholds for the $\Sigma_c\,\bar{D}$ and $\Sigma_c\,\bar{D}^*$ final states are superimposed.

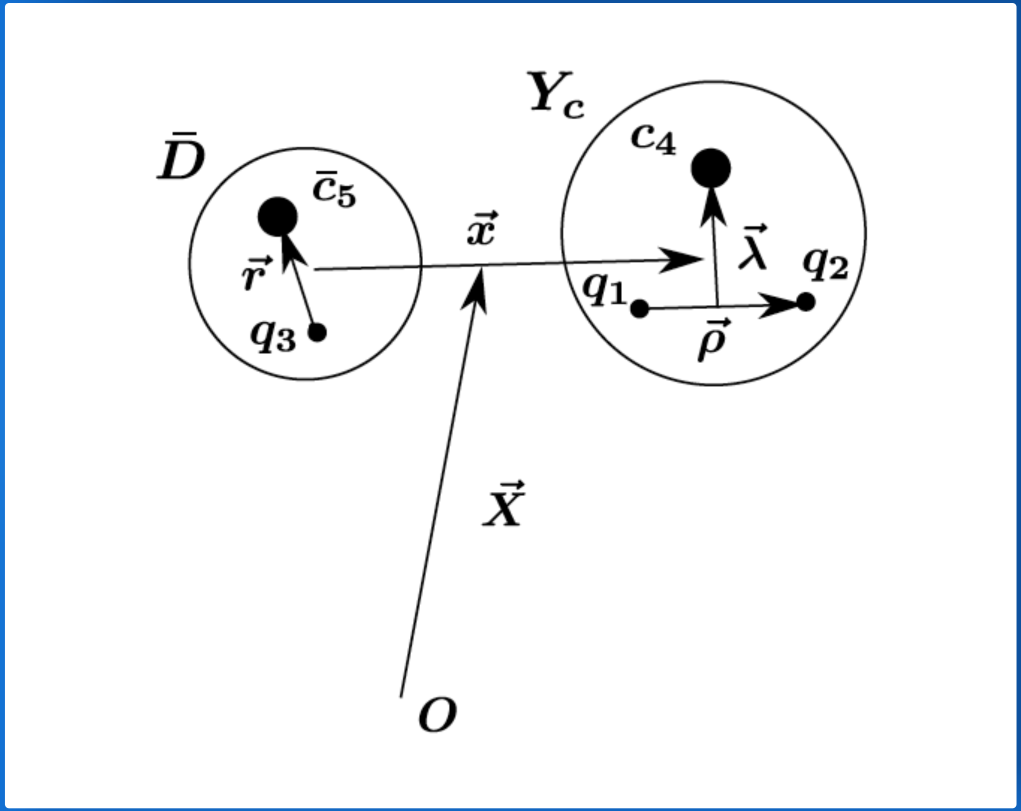
- In Ref. [1] we studied the hidden-charm pentaquarks by coupling the $\Lambda_c \bar{D}^{(*)}$ and $\Sigma_c^* \bar{D}^{(*)}$ meson-baryon channels to a $uudc\bar{c}$ compact core with a meson-baryon binding interaction satisfying the heavy quark and chiral symmetries.

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

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

# The Model in brief

The meson-baryon channels describe the dynamics at long distances, while the five-quark part describes the dynamics at short distances (of the order of 1 fm or less).




Free parameter $\frac{f}{f0}$

Kinetic energy and OPEP of the Meson-Baryon system

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

proportional to the spectroscopic factors $S_i^{\alpha}$:

$$V_{ij}^{5q} = -\frac{f}{f0}\sum_{\alpha} S_i^{\alpha} S_j^{\alpha}\, e^{-Ax^2}$$

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

# The Model in brief

We expressed the hidden-charm pentaquark masses and decay widths as functions of one free parameter $\frac{f}{f0}$, which is proportional to the coupling strength between the meson-baryon and 5-quark-core states

$$f_0 = C^{\pi}_{\Sigma_c \bar{D}^*}(r=0) \sim 6 \text{ MeV}$$ with $$C^{\pi}_{\bar{D}^*\Sigma_c}(r) \equiv -\frac{g g_1}{3 f_\pi^2} C(r)$$

Here, $f0$ is the strength of the one-pion exchange diagonal term for the $\Sigma_c \bar{D}^*$ meson-baryon channel

$$C(r) = \int \frac{d^3\vec{q}}{(2\pi)^3} \frac{m^2}{\vec{q}^{\,2} + m^2} e^{i\vec{q}\cdot\vec{r}} F(\Lambda, \vec{q})$$

$$V^{\pi}_{\bar{D}^*\Sigma_c - \bar{D}^*\Sigma_c}(r) = -\frac{g g_1}{3 f_\pi^2} \left[ \vec{S}\cdot\vec{\sigma}\, \boxed{C(r)} + S_{S\sigma}(\hat{r}) T(r) \right]$$

$$H\psi = E\psi,$$

$$\psi = (\psi^{MB}, \psi^{5q}),$$

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

coupled equation for the MB and 5q channels

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

**The BOUND AND RESONANT STATES are obtained by solving the coupled-channel Schrödinger equation with the One Pion Exchange and the five-quark potentials**

# The Model in brief

the key ingredients

**The OPEP is obtained by the effective Lagrangians for HEAVY MESONS (BARYONS) and the Nambu-Goldstone boson, satisfying the heavy quark and chiral symmetries**

**Philosophy of heavy quark spin-flavor symmetry**

Chiral perturbation theory for heavy hadrons is based on spontaneously broken $SU_L(3)\otimes SU_R(3)$ chiral symmetry for the light quarks, and spin-flavor symmetry for the heavy quarks.

A very heavy quark bound inside a hadron moves more or less with the hadron's velocity v, and it is almost on shell.

$$P_H^\mu = M_Q v^\mu$$

$$P_Q^\mu = P_H^\mu + k^\mu = m_Q v^\mu + k^\mu,$$

$$[x, v] = \frac{[x, p]}{m_Q} - \frac{[x, k]}{m_Q} = \frac{i\hbar}{m_Q} - \frac{[x, k]}{m_Q} \to 0 \text{ if } m_Q \to \infty.$$

This means that the heavy quark cannot simultaneously have a well-defined position and momentum, but can have a well-defined position and velocity, which corresponds to the velocity of the hadron.

# The Model in brief

the key ingredients

Consider the heavy quark propagator in momentum space

$$S_F = \frac{1}{(2\pi)^4}\int d^4p e^{-ip_\mu x^\mu}\frac{\not p + m_Q}{p^2 - m_Q^2 + i\epsilon},$$

and substituting the parametrization of momentum of the heavy quark we obtain, for a residual momentum $k \ll m_Q$

$$i\frac{\not p + m_Q}{p^2 - m_Q^2 + i\epsilon} = i\frac{m_Q \not v + \not k + m_Q}{2m_Q vk + k^2 + i\epsilon} \simeq i\frac{m_Q \not v + m_Q}{2m_Q vk + i\epsilon} + i\frac{\not k}{2m_Q vk + i\epsilon}$$
$$\simeq i\frac{m_Q \not v + m_Q}{2m_Q vk + i\epsilon} = \frac{1+\not v}{2}\frac{i}{vk + i\epsilon} + \mathcal{O}\left(\frac{1}{m_Q}\right),$$

$$Q(x) = \frac{1+\not v}{2}Q(x) + \frac{1-\not v}{2}Q(x) = \hat{P}_+ Q(x) + \hat{P}_- Q(x) \equiv h_v(x) + H_v(x).$$

**$h_v(x)$ is the degree of freedom that remains dynamical in the low-energy theory, whereas $H_v(x)$ is integrated out and it will not appear in the EFT.**

# The Model in brief

**The effective Lagrangians for HEAVY MESONS and the Nambu-Goldstone boson, satisfying the heavy quark and chiral symmetries are [1,2,3,4,5,6]**

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

$$H_a = \frac{1+\not{v}}{2}\left[\bar{D}^*_{a\mu}\gamma^\mu - \bar{D}_a\gamma_5\right],$$

$$\bar{H}_a = \gamma_0 H_a^\dagger \gamma_0,$$


[1] A. V. Manohar and M. B. Wise, *Heavy Quark Physics*, Cambridge Monographs on Particle Physics, Nuclear Physics and Cosmology (Cambridge University Press, Cambridge, England, 2000), p. 191.

[2] M. B. Wise, Phys. Rev. D **45**, R2188 (1992).

[3] G. Burdman and J. F. Donoghue, Phys. Lett. B **280**, 287 (1992).

[4] T. M. Yan, H. Y. Cheng, C. Y. Cheung, G. L. Lin, Y. C. Lin, and H. L. Yu, Phys. Rev. D **46**, 1148 (1992); **55**, 5851(E) (1997).

[5] A. F. Falk and M. E. Luke, Phys. Lett. B **292**, 119 (1992) hep-ph/9206241.

[6] R. Casalbuoni, A. Deandrea, N. Di Bartolomeo, R. Gatto, F. Feruglio, and G. Nardulli, Phys. Rept. **281**, 145 (1997) hep-ph/9605342.

# The Model in brief

The effective Lagrangians for **HEAVY BARYONS** and the Nambu-Goldstone boson, satisfying the heavy quark and chiral symmetries are [7] [8]

$$\mathcal{L}_{\pi BB} = \frac{3}{2} g_1 (i v_\kappa) \varepsilon^{\mu\nu\lambda\kappa} \mathrm{tr}\left[\bar{S}_\mu A_\nu S_\lambda\right] + g_4 \mathrm{tr}\left[\bar{S}^\mu A_\mu B_{\bar{3}}\right] + \mathrm{H.c.}$$

$$S_\mu = \hat{\Sigma}^*_{c\mu} + \frac{\delta}{\sqrt{3}} (\gamma_\mu + v_\mu) \gamma_5 \hat{\Sigma}_c,$$

$$\bar{S}_\mu = \gamma_0 S^\dagger_\mu \gamma_0,$$

$$\hat{\Lambda}_c = \begin{pmatrix} 0 & \Lambda_c^+ \\ -\Lambda_c^+ & 0 \end{pmatrix}, \quad \hat{\Sigma}^{(*)}_{c(\mu)} = \begin{pmatrix} \Sigma^{(*)++}_{c(\mu)} & \frac{1}{\sqrt{2}}\Sigma^{(*)+}_{c(\mu)} \\ \frac{1}{\sqrt{2}}\Sigma^{(*)+}_{c(\mu)} & \Sigma^{(*)0}_{c(\mu)} \end{pmatrix}.$$


[7] T. M. Yan, H. Y. Cheng, C. Y. Cheung, G. L. Lin, Y. C. Lin, and H. L. Yu, Phys. Rev. D **46**, 1148 (1992); **55**, 5851(E) (1997).

[8] Y. -R. Liu and M. Oka, Phys. Rev. D **85**, 014015 (2012) [arXiv:1103.4624 [hep-ph]].

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

**Based on the new LHCb results [4], in Ref. [5] we calculated the tensor contribution, fix this free parameter and we predict the three well-established pentaquark masses and widths consistently with the new data with the following quantum number assignments:**

$J^P(P_c(4312)) = \frac{1}{2}^-$, $J^P(P_c(4440)) = \frac{3}{2}^-$ **and** $J^P(P_c(4457)) = \frac{1}{2}^-$.

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

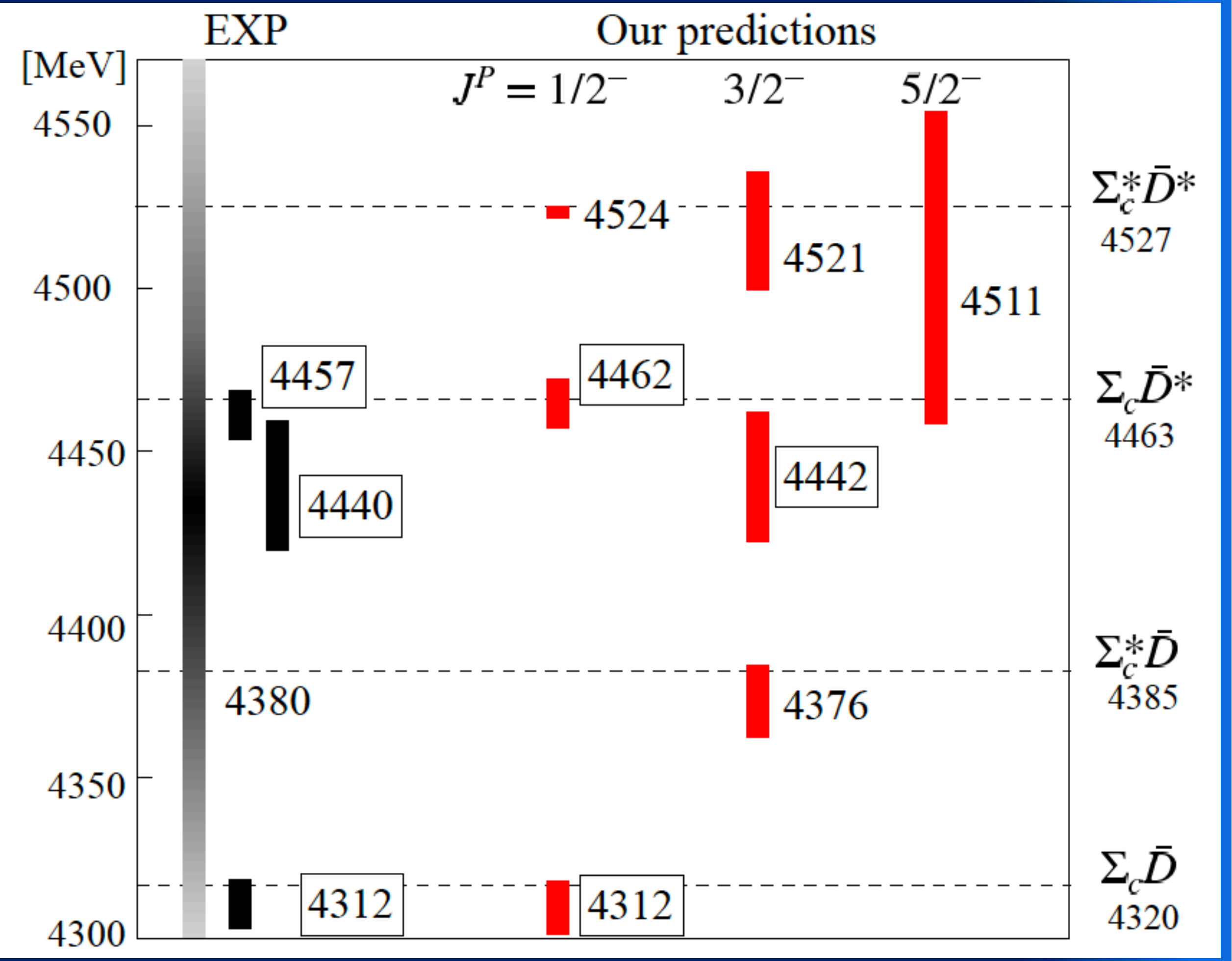

[4] R. Aaij et al. (LHCb), Phys. Rev. Lett. 122, 222001 (2019).

[5] Y. Yamaguchi, H. Garcia-Tecocoatzi, A. G., A. Hosaka, E. Santopinto, S. Takeuchi and M. Takizawa arXiv:1907.04684.

# results

| State | Mass | Width | Our pred. $(M, J^P, \Gamma)$ |
|---|---|---|---|
| $P_c(4312)^+$ | $4311.9 \pm 0.7^{+6.8}_{-0.6}$ | $9.8 \pm 2.7^{+3.7}_{-4.5}$ | $(4312, \frac{1}{2}^-, 5)$ |
| $P_c(4380)^+$ | $4380 \pm 8 \pm 29$ | $205 \pm 18 \pm 86$ | $(4376, \frac{3}{2}^-, 8)$ |
| $P_c(4440)^+$ | $4440.3 \pm 1.3^{+4.1}_{-4.7}$ | $20.6 \pm 4.9^{+8.7}_{-10.1}$ | $(4442, \frac{3}{2}^-, 26)$ |
| $P_c(4457)^+$ | $4457.3 \pm 0.6^{+4.1}_{-1.7}$ | $6.4 \pm 2.0^{+5.7}_{-1.9}$ | $(4462, \frac{1}{2}^-, 6.6)$ |
| | | | $(4524, \frac{1}{2}^-, 1.5)$ |
| | | | $(4521\ \frac{3}{2}^-, 23)$ |
| | | | $(4511\ \frac{5}{2}^-, 55)$ |

**3 states still to be observed**




**agreement with the experimental masses and decay widths**


[5] Y. Yamaguchi, H. Garcia-Tecocoatzi, A. G., A. Hosaka, E. Santopinto, S. Takeuchi and M. Takizawa arXiv:1907.04684.

## Where does the $P_c(4440)$ and $P_c(4457)$ mass difference come from?

Since these two states are located near $\Sigma_c \bar{D}^*$ threshold and both states have the narrow widths, it is natural to consider them to form the spin doublet of 1/2 and 3/2 in S-wave. It is important to determine which of the above spin 1=2 and 3=2 states is more deeply bound.

There are two sources for the spin-dependent force in our model. One is the short range interaction by the coupling to the 5-quark-core states (the spectroscopic factor). The other is the long range interaction by the OPEP, especially the TENSOR TERM.

heavy quark and chiral symmetries

$$V_\pi^{ij}(r) = G_\pi^{ij}[\vec{\mathcal{O}}_1^i \cdot \vec{\mathcal{O}}_2^j C(r;m_\pi) + \boxed{S_{\mathcal{O}_1^i \mathcal{O}_2^j}(\hat{r}) T(r;m_\pi)}],$$

OPE Potential

$$C(r;m) = \int \frac{d^3\vec{q}}{(2\pi)^3} \frac{m^2}{\vec{q}^{\,2}+m^2} e^{i\vec{q}\cdot\vec{r}} \boxed{F(\Lambda,\vec{q})}$$

Central part

Tensor operator:

$$S_{\mathcal{O}_1^i \mathcal{O}_2^j}(\hat{r}) = 3\vec{\mathcal{O}}_1^i \cdot \hat{r}\vec{\mathcal{O}}_2^j \cdot \hat{r} - \vec{\mathcal{O}}_1^i \cdot \vec{\mathcal{O}}_2^j$$

$$F(\Lambda, m_\pi) = \frac{(\Lambda^2 - m_\pi^2)^2}{(\Lambda^2 + q^2)^2}$$

$$S_{\mathcal{O}}(\hat{r}) T(r;m) = \int \frac{d^3\vec{q}}{(2\pi)^3} \frac{-\vec{q}^{\,2}}{\vec{q}^{\,2}+m^2} S_{\mathcal{O}}(\hat{q}) e^{i\vec{q}\cdot\vec{r}} \boxed{F(\Lambda,\vec{q})}$$

Dipole form factor

Tensor part

To examine the effects of OPEP tensor interaction, we have investigated the energy of the resonant Pentaquark states of spin 1/2 and 3/2 around the $\Sigma_c \bar{D}^*$ threshold **without** the OPEP tensor term

In this case, the attractive force is not enough, and the resonant states turn into virtual states.

**The tensor term is necessary to form resonant states**

## QUANTITATIVELY

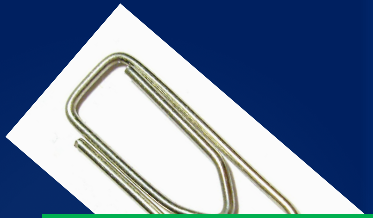
We found that the tensor interaction gives about 4 MeV attraction for the $J^P = \frac{1}{2}^-$ and 15 MeV for the $J^P = \frac{3}{2}^-$ state

That is, more attraction is found in the $J^P = \frac{3}{2}^-$ state than in the $J^P = \frac{1}{2}^-$ state


The tensor interaction provides attraction through channel couplings such as S-D and D-D.

$\Sigma_c \bar{D}^*$ with $J^P = \frac{1}{2}^-$ consists of $^2$S, $^4$D

$\Sigma_c \bar{D}^*$ with $J^P = \frac{3}{2}^-$ consists of $^4$S, $^2$D and $^4$D



Notation $^{2S+1}$L e.g. $^2$S means $\Sigma_c$ and $\bar{D}^*$ in S wave so that J=S=1/2

**For the $\frac{3}{2}^-$ state there are three combinations of such channel couplings, while for $\frac{1}{2}^-$ state there is only one.**

**More channels available imply more attraction**

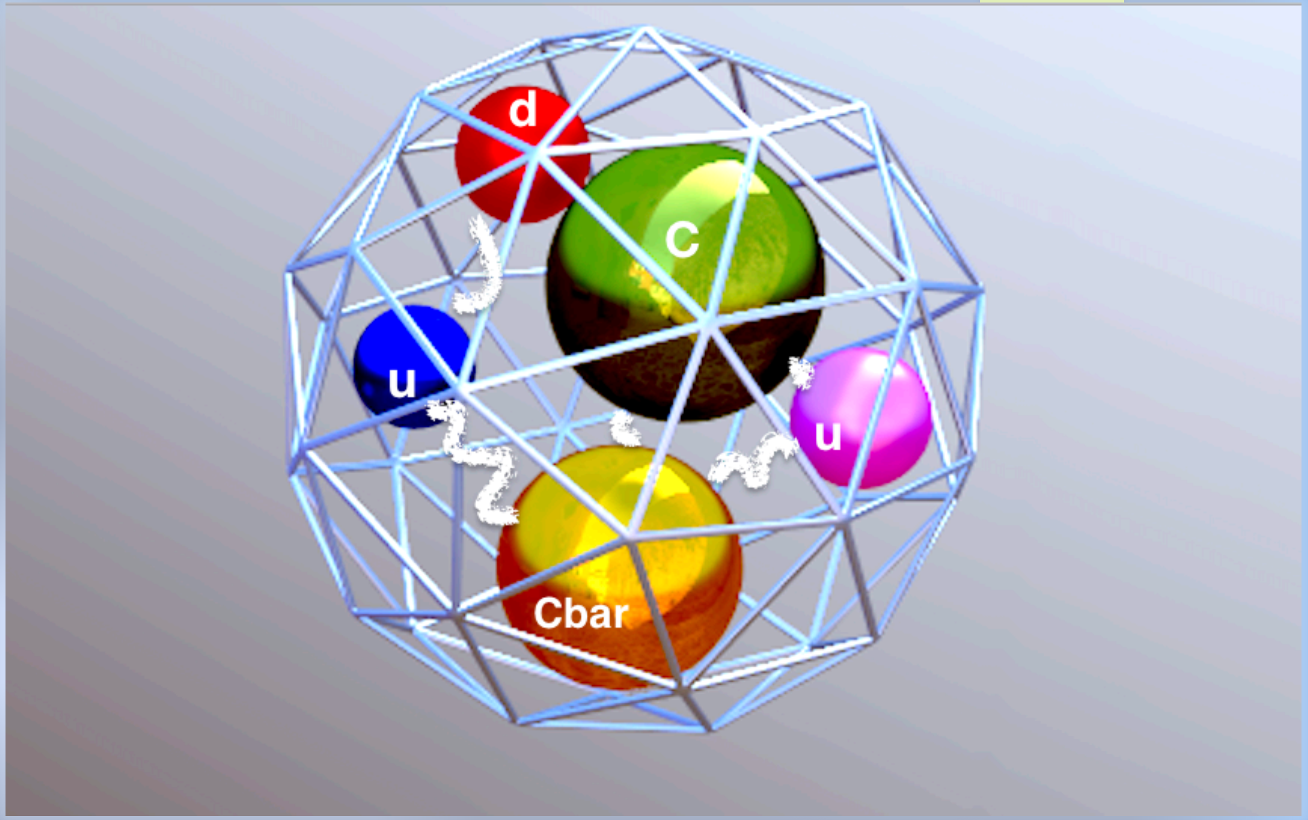
Since the obtained mass difference between $\boldsymbol{P_c(4440)}$ **and** $\boldsymbol{P_c(4457)}$ is 20 MeV the remaining 9 MeV is considered to come from the the short range interaction in our model.

We find that the tensor interaction by the one-pion exchange potential provides a major contribution to the mass difference between Pc (4440) and Pc (4457)

It is interesting and should be emphasized that the present set of heavy baryon states is the first example where the role of the tensor force can be compared in two partner states.

For nucleon systems only spin 1 state (deuteron) is available without partners!

# CONCLUSION




By coupling the open charm meson-baryon channels to a compact $uud c\bar{c}$ core with an interaction satisfying the heavy quark and chiral symmetries, we predict the masses and decay widths of the three new pentaquark states reported by LHCb in agreement with the experimental results.

We point out that the three pentaquark states have quantum numbers:

$$J^P\left(P_c(4312)\right) = \frac{1}{2}^- ,$$
$$J^P\left(P_c(4440)\right) = \frac{3}{2}^-$$
$$J^P\left(P_c(4457)\right) = \frac{1}{2}^-$$

We found that both the short range interaction provided by the coupling to the 5-quark-core states and the long range interaction provided by the one-pion exchange potential make contributions to the attraction between $\Sigma_c$ and $\bar{D}^*$.

The importance of what we referred to as the chiral tensor dynamics is a universal feature for the heavy hadrons with light quarks.

# Thanks for your attention