# HIDDEN-CHARM AND BOTTOM PENTAQUARK STATES

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INFN GENOVA

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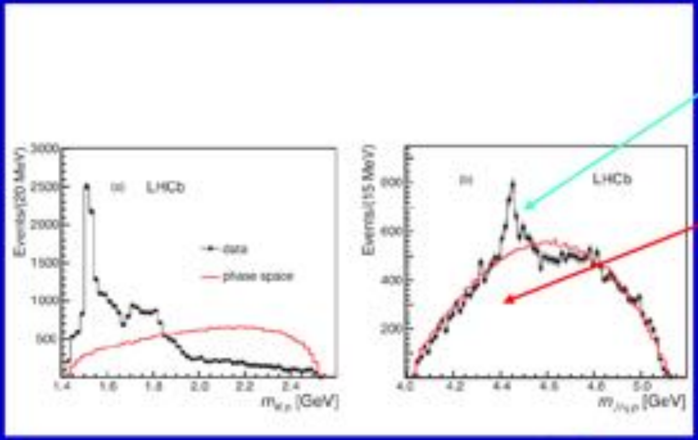
**Based on**
**E. S., A. Giachino, Phys.Rev. D 96 (2017) no.1, 014014**
**Y. Yamaguchi, E. Santopinto,Phys. Rev. D Phys.Rev. D96 (2017) no.1, 014018**
**Y. Yamaguchi, A. Giachino, A. Hosaka, E. Santopinto, S. Tacheuchi, M. Takizawa,**
**arXiv:1709.00819**

# Why pentaquark states?

**LHCb**

Phys. Rev. Lett.115(2015) 072001




$M_P_c^+(4450) = (4449.8 \pm 8 \pm 29)$MeV

$\Gamma = (39 \pm 5 \pm 19)$ MeV

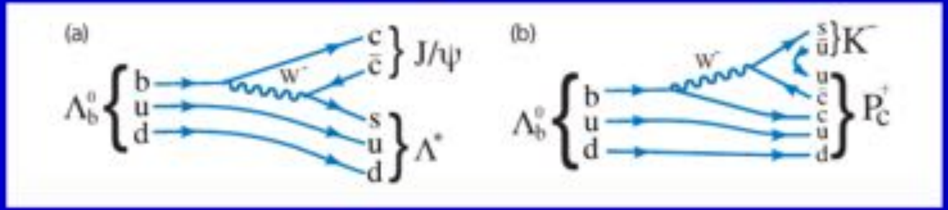
$M_P_c^+(4380) = (4380 \pm 1.7 \pm 2.5)$MeV

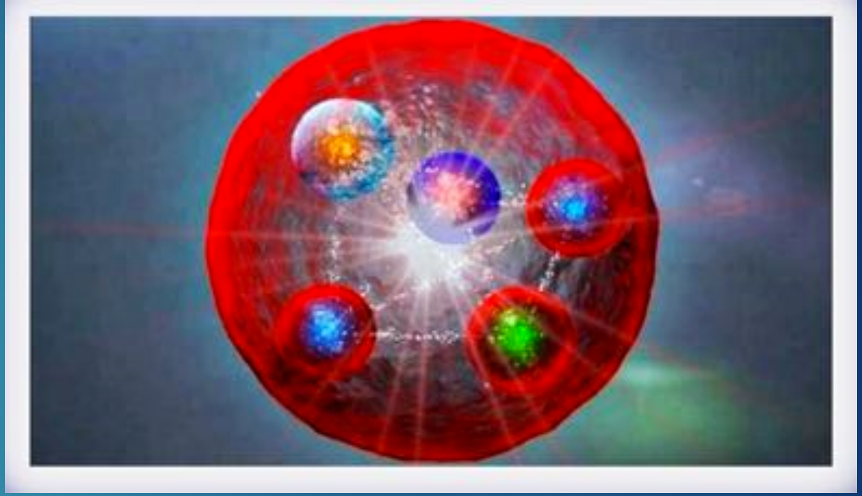
$\Gamma = (205 \pm 18 \pm 86)$MeV

statistic significance greater then 9 sigma !

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

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



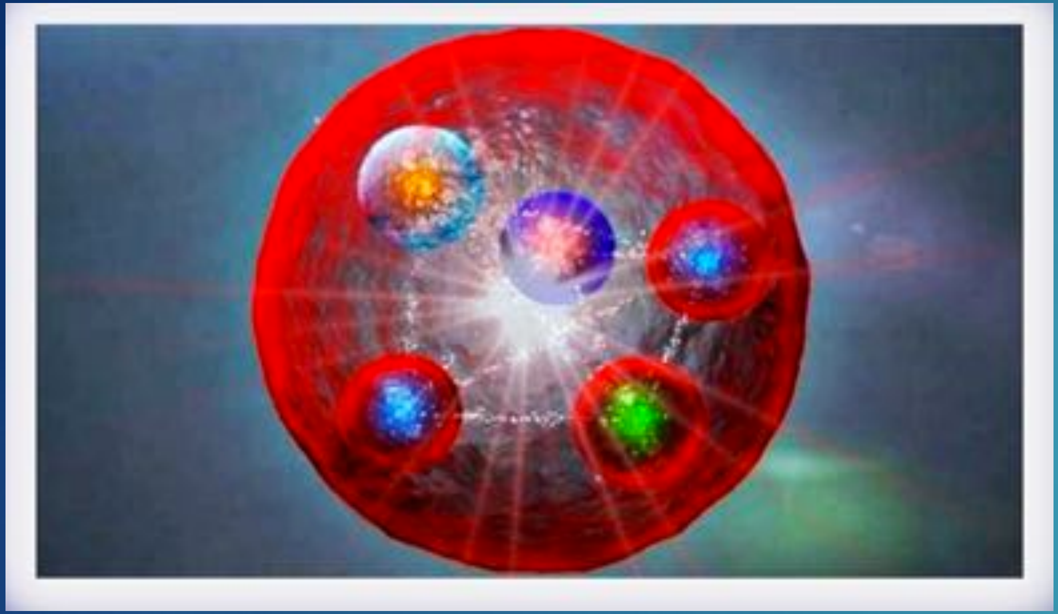
The LHCb observation [1] was further supported by another two articles by the same group [2,3]:


[1] R. Aaij *et al.* [LHCb Collaboration], Phys. Rev. Lett. **115** (2015) 072001

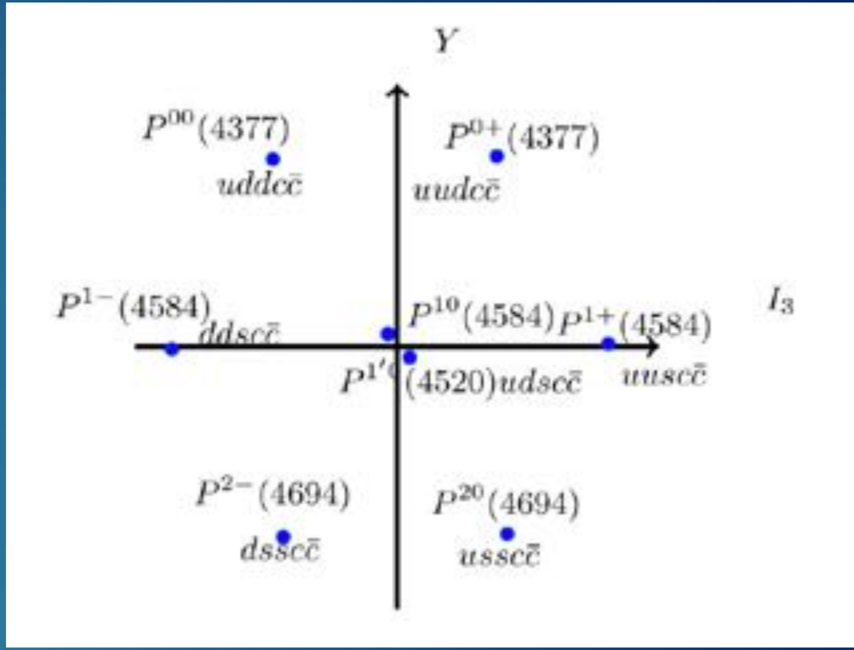
[2] R. Aaij *et al.* [LHCb Collaboration], Phys. Rev. Lett. **117** (2016) no.8, 082002

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

# The pentaquark as a compact five quark state



- Using group theory techniques we found that the compact pentaquark states belong to to an SU(3) flavour octet.
- The masses of the octet pentaquark states were calculated by means of a Gürsey-Radicati mass formula extension.




$$\Gamma_\nu^- = \begin{pmatrix} \gamma_\nu \gamma_5 \\ \gamma_\nu \end{pmatrix}, \qquad \Gamma^- = \begin{pmatrix} \gamma_5 \\ \mathbf{1} \end{pmatrix}.$$

- The partial decay widths were calculated by means of an effective Lagrangian:

| Initial state | Channel | Partial width [MeV] |
|---|---|---|
| $P^{1'0}$ | $\Lambda J/\Psi$ | 7.94 |
| $P^{1-}, P^{10}, P^{1+}$ | $\Sigma J/\Psi$ | 7.21 |
| $P^{2-}, P^{20}$ | $\Xi J/\Psi$ | 6.35 |

$$\mathcal{L}^{3/2^-}_{PNJ/\psi} = i\bar{P}_\mu \left[ \frac{g_1}{2M_N} \Gamma_\nu^- N \right] \psi^{\mu\nu} - i\bar{P}_\mu \left[ \frac{ig_2}{(2M_N)^2} \Gamma^- \partial_\nu N + \frac{ig_3}{(2M_N)^2} \Gamma^- N \partial_\nu \right] \psi^{\mu\nu} + \text{H.c.},$$

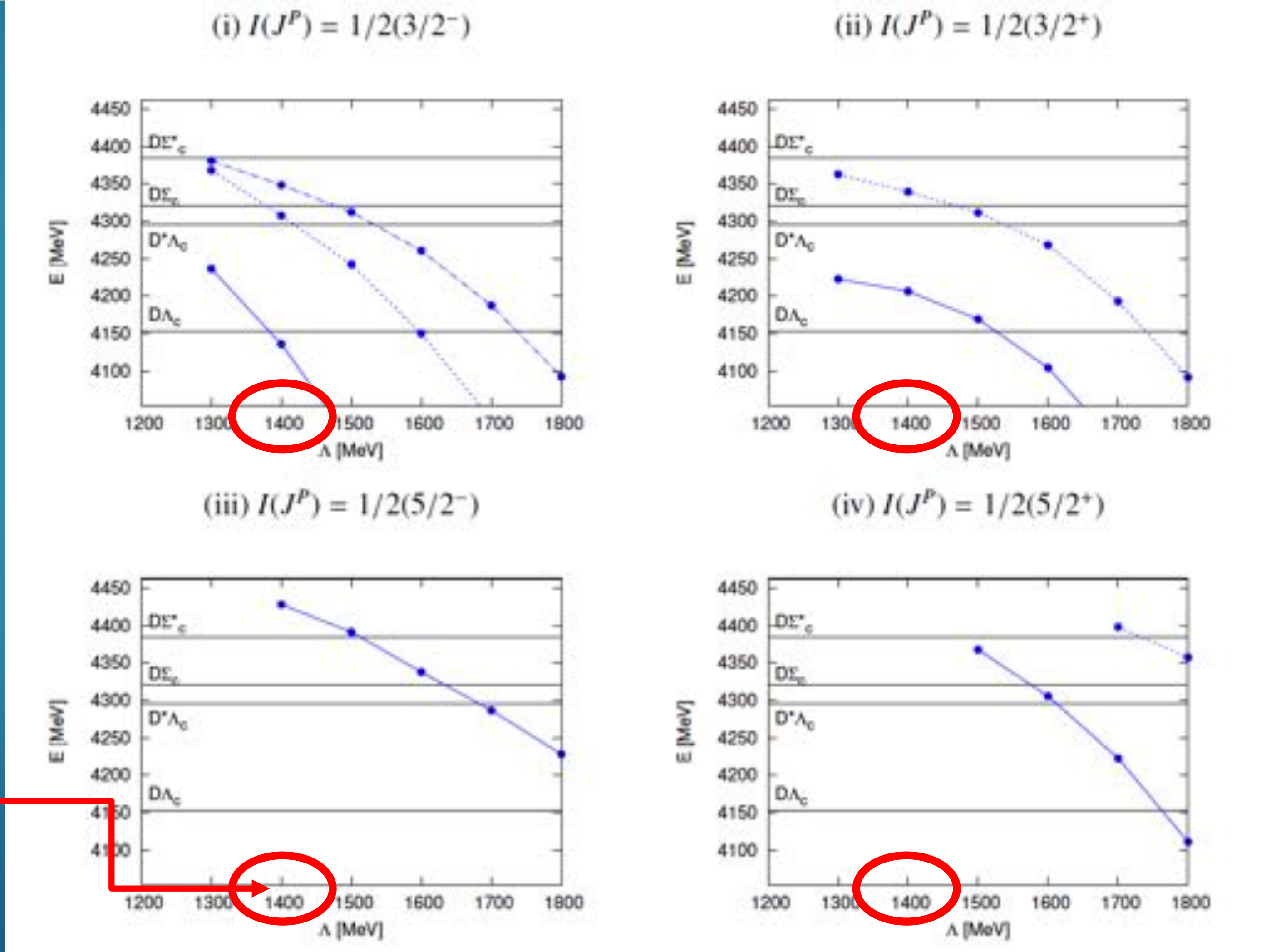
# **The hidden-charm pentaquarks** as meson-baryon molecule with **coupled channel systems for $\bar{D}^* \Lambda_c$ and $\bar{D}^* \Sigma_c^*$**

- Near the thresholds, resonances are expected to have a non trivial structure, like hadronic molecules.
- **The observed pentaquarks are found to be just below the $\bar{D}^* \Sigma_c$ ($P_c^+(4380)$) and the $\bar{D}^* \Sigma_c^*$ ($P_c^+(4450)$) thresholds. Moreover, the $\bar{D}^* \Lambda_c$ threshold is only 25 MeV below the $\bar{D}\, \Sigma_c$ threshold. For this reason, the $\bar{D}\, \Lambda_c$ , $\bar{D}^* \Lambda_c$ channels are not irrelevant in the hidden-charm meson-baryon molecules.**

**In Phys.Rev. D96 (2017) no.1, 014018 Y. Yamaguchi and E.S. considered the hidden-charm pentaquarks** as meson-baryon molecule with **coupled channel systems for $\bar{D}^* \Lambda_c$, $\bar{D}^* \Sigma_c^*$**, i. e. $\Lambda_c$ , $\bar{D}^* \Lambda_c$, $\bar{D}\, \Sigma_c$, $\bar{D}\Sigma_c^*$, **$\bar{D}^* \Sigma_c$ 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).**

# The hidden-charm pentaquarks as meson-baryon molecule with **coupled channel systems for $\bar{D}^* \Lambda_c$ and $\bar{D}^* \Sigma_c^*$**

- In particular the bound and resonant states with $J^P = \frac{3}{2}^+, \frac{3}{2}^-, \frac{5}{2}^+$ and $\frac{5}{2}^-$ with isospin $I = \frac{1}{2}$ are studied by solving the coupled channel equations.
- Free parameter of the model: the cut-off parameter $\Lambda$ ;
- $\Lambda$ is fixed to reproduce the heaviest resonant state $P_c^+(4450)$



# **The hidden-charm pentaquarks** as meson-baryon molecule with **coupled channel systems for $\bar{D}^* \Lambda_c$ and $\bar{D}^* \Sigma_c^*$**

## results

| $\Lambda$ [MeV] | 1300 | 1400 | 1500 | 1600 | 1700 | 1800 |
|---|---|---|---|---|---|---|
| $J^P = 3/2^-$ | $4236.9 - i0.8$ | 4136.0 | 4006.3 | 3848.2 | 3660.0 | 3438.26 |
| | $4381.3 - i11.4$ | $4307.9 - i18.8$ | $4242.6 - i1.4$ | 4150.1 | 4035.2 | 3897.3 |
| | $4368.5 - i64.9$ | $4348.7 - i21.1$ | $4312.7 - i16.0$ | $4261.0 - i7.0$ | $4187.7 - i0.9$ | 4092.5 |
| $J^P = 3/2^+$ | $4223.0 - i97.9$ | $4206.7 - i41.2$ | $4169.3 - i5.3$ | 4104.2 | 3996.7 | 3855.8 |
| | $4363.3 - i57.0$ | $4339.7 - i26.8$ | $4311.8 - i6.6$ | $4268.5 - i1.3$ | $4193.2 - i0.1$ | 4091.6 |
| $J^P = 5/2^-$ | — | $4428.6 - i89.1$ | $4391.7 - i88.8$ | $4338.2 - i56.2$ | $4286.8 - i27.3$ | $4228.3 - i7.4$ |
| $J^P = 5/2^+$ | — | — | $4368.0 - i9.2$ | $4305.8 - i1.9$ | $4222.7 - i1.4$ | 4111.1 |
| | — | — | — | — | $4398.5 - i15.0$ | $4357.8 - i8.2$ |

Masses and widths of the two observed pentaquark states; BE AWARE: the mass of the lightest one is a prediction, while the mass of the heaviest is fitted to fix the cut-off parameter $\Lambda$

## Upgrade of the model:
## Hidden-charm and bottom meson-baryon molecules coupled with five-quark states

### The Model

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

**CAN A COUPLE CHANNEL BETWEEN**

**THE MB CHANNELS AND THE CORE CONTRIBUTION IMPROVE THE**

**DESCRIPTION of PENTAQUARK STATES ?**

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

- Thidden-charm pentaquarks as $\bar{D}\,\Lambda_c\,, \bar{D}^*\,\Lambda_c, \bar{D}\,\Sigma_c,$ $\bar{D}^*\,\Sigma_c,\ \bar{D}\Sigma_c^*,\ and\ \bar{D}^*\Sigma_c^*,$ and molecules coupled to the five-quark states

**ADDITION OF THE CORE CONTRIBUTION**

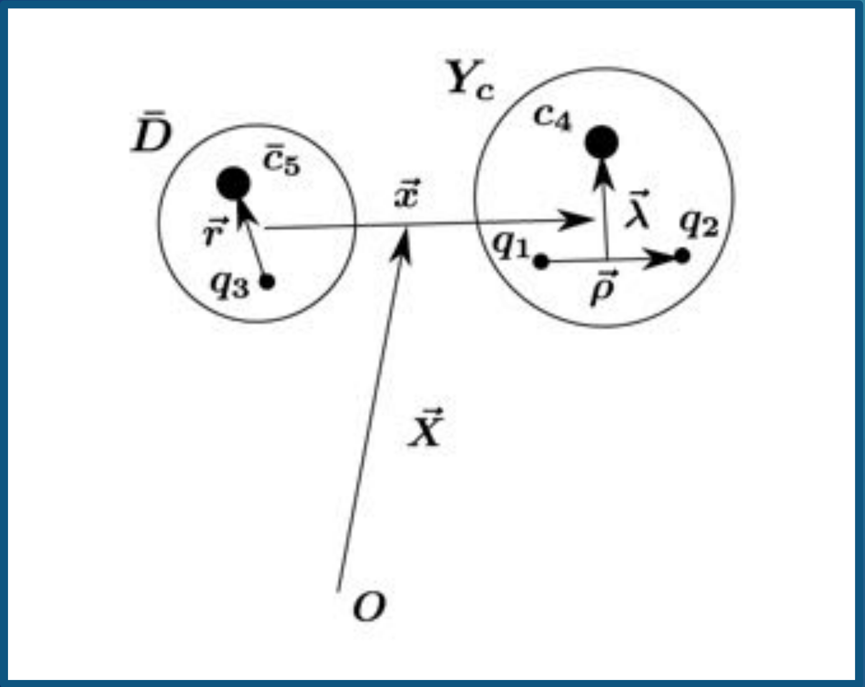
- For the first time some predictions for the hidden bottom pentaquarks as $\bar{D}\,\Lambda_c\,, \bar{D}^*\,\Lambda_c, \bar{D}\,\Sigma_c, \bar{D}^*\,\Sigma_c, \bar{D}\Sigma_c^*$ and $\bar{D}^*\Sigma_c^*$ molecules coupled to the five-quark states are provided.

- In particular, by solving the coupled channel Schr$\ddot{o}$dinger equation, we study the the bound and resonant hidden-charm and hidden-bottom pentaquark states for $J^P = \frac{1}{2}^-, \frac{3}{2}^-, \frac{5}{2}^-$ and isospin $I = \frac{1}{2}$ .

# The Model

## Hidden-charm and bottom meson-baryon molecules coupled with five-quark states

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).




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 $S_i^{\alpha}$:

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

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

# Numerical methods

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

$$\left(K + V^{\pi}(r) + V^{5q}(r)\right)\Psi(r) = E\Psi(r),$$

**This is a very hard task!**

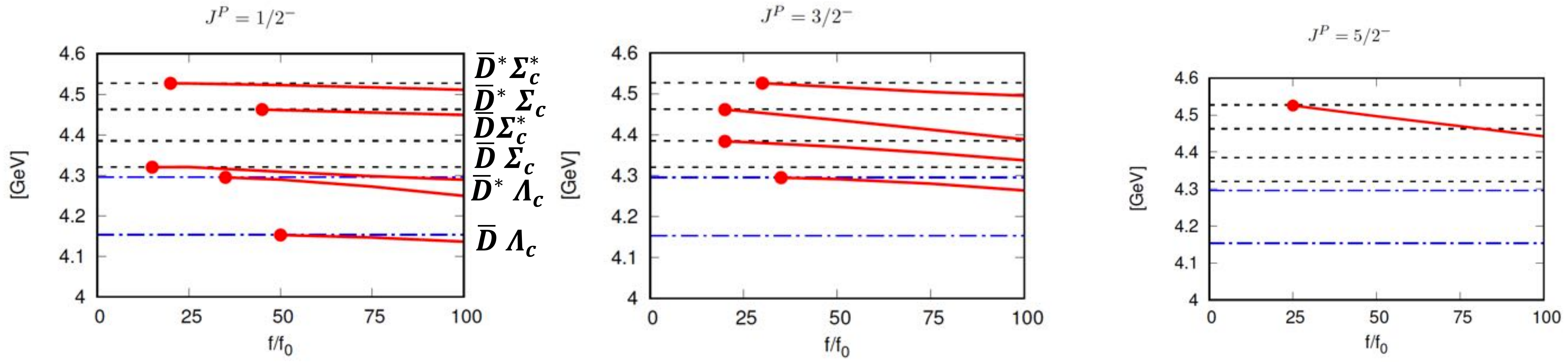
**Powerfull numerical method are needed in order to solve the coupled channel problem.**

# Results for the hidden-charm sector

The lowest threshold $\bar{D}\,\Lambda_c$ is at $4153,46$ MeV and the state whose energy is lower than the threshold is a bound state.

No resonant states and no bound states for $\frac{f}{f_0} = 0$

In the hidden-charm sector the OPEP is not enough strong to produce bound and resonant $P_c$ states.



# Hot topic:
# First results for
# the hidden-bottom sector

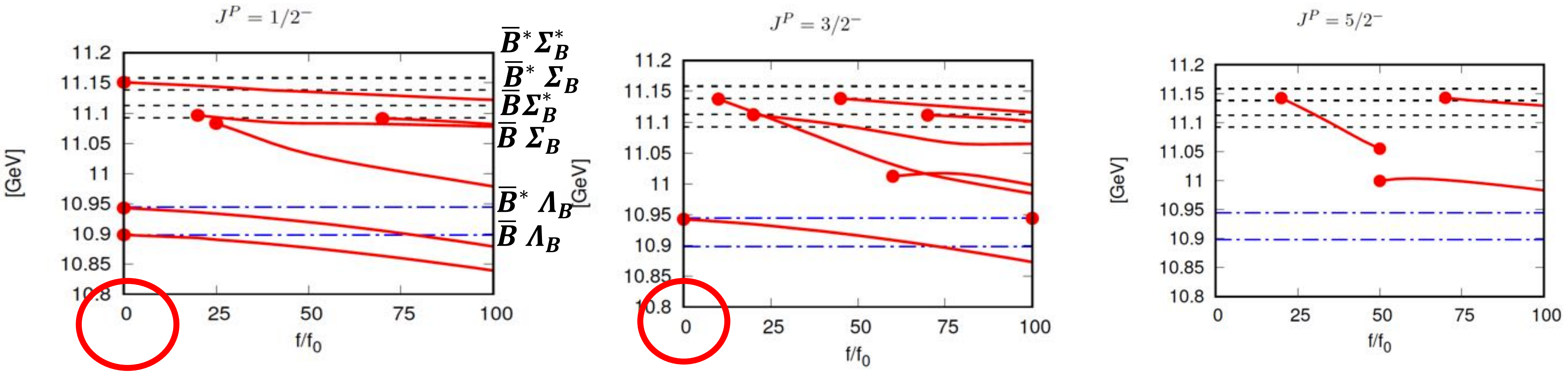
**An important and new result:**

As a matter of fact, we have found that, unlike the charm-sector, in which the five quark potential is needed to produce bound states, in the bottom sector only the OPEP provides sufficiently strong attraction to generate several bound and resonant states.

**Many $\bar{B}\,\Lambda_B$ and $\bar{B}^*\,\Lambda_B$ bound states appear.**

**Some $\bar{B}\,\Lambda_B$ bound states are produced even without introducing the five-quark potential !**

Dot-dashed lines are the $\bar{B}\,\Lambda_B$ and $\bar{B}^*\,\Lambda_B$ thresholds. Dashed lines are the $\bar{B}\,\Sigma_B, \bar{B}\Sigma_B^*$, $\bar{B}^*\,\Sigma_B$ and $\bar{B}^*\Sigma_B^*$ thresholds.



# Hot topic:
# First Results for the hidden-bottom sector

Moreover, many states appear, when the 5q potential is switched on.

As a consequence, the hidden-bottom pentaquarks are more likely to form rather than the hidden-charm pentaquarks.

**The hidden-bottom sector is the more interesting environment to search the pentaquark states**

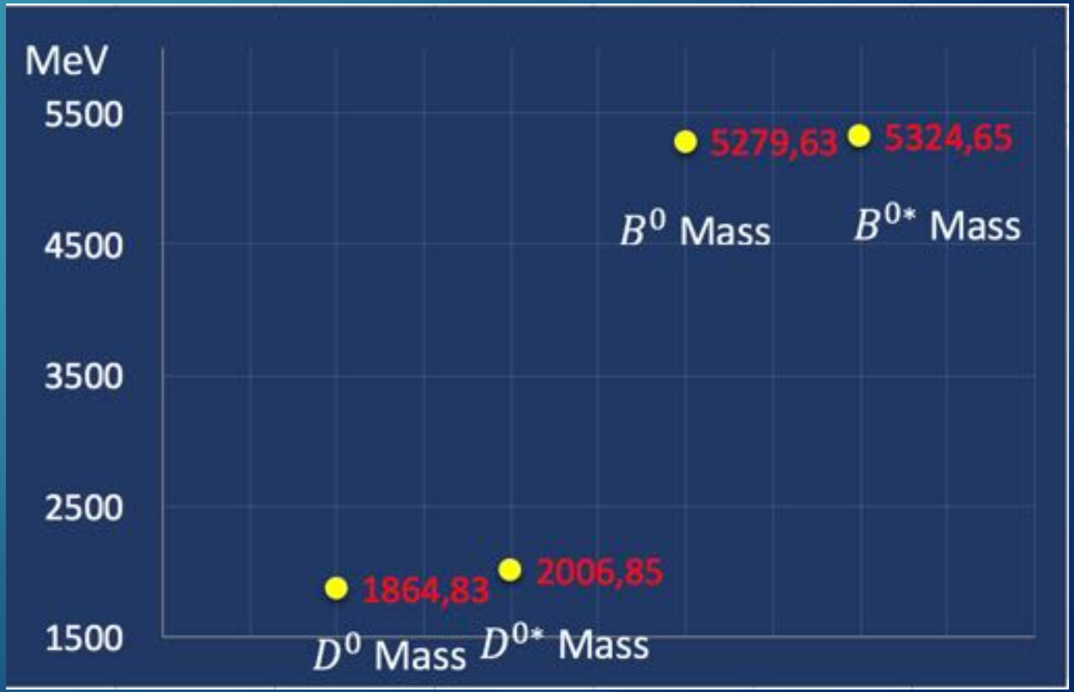
**We suggested to the experimentalists to look for further pentaquark states in the bottom region.**

# Hot topic:
# First results for
# the hidden-bottom sector

- In the hidden bottom sectom, the kinetic energy of the meson-baryon system is suppressed with respect to the charm sector due to the higher reduced mass of the system.

**Why so more likely to find bound and resonant states in the bottom sector?**

- In the hidden-bottom sector, the OPEP is strong enough to produce resonant or bound states since the suppression of the kinetic energy and also due to the mixing effect enhanced by the small mass splitting between $B, B^*$ and $\Sigma_B, \Sigma_B^*$



# Task for the future

- **What does it happen if one consider a coupled channel MB-core with a OMEP( One Meson Exchange Potential)?**

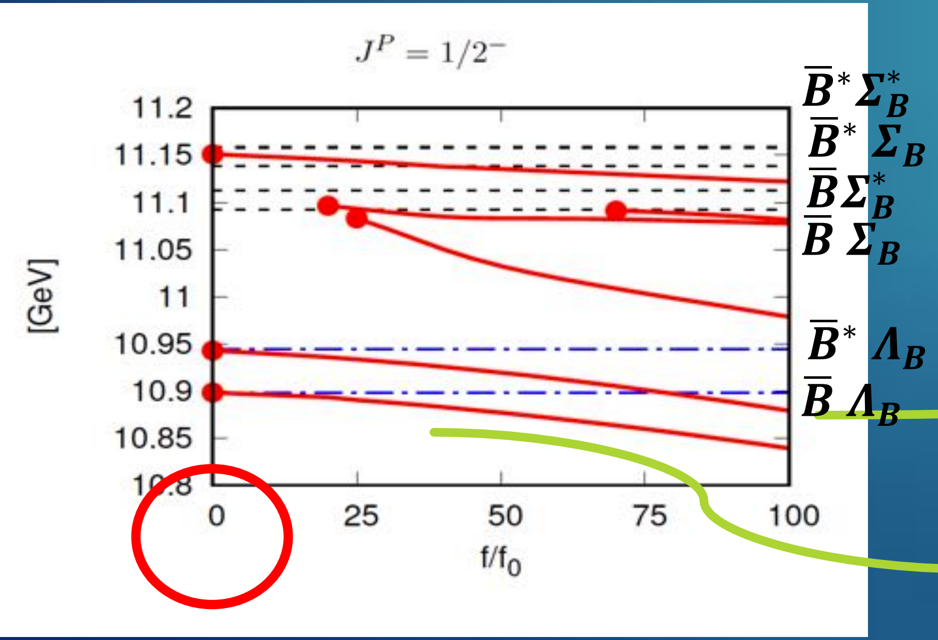
- **So far in our analysis we have studied only the negative parity states dominated by the s-wave configurations. For positive parity states, we need p-wave excitations for both**

**meson-baryon and for 5q states.**

These task require further technical developments which will be a future work.

# Hot topic: Results for the hidden-bottom sector

Example: the $J^p = \frac{1}{2}^-$ state




| SUM | | | | | |
|---|---|---|---|---|---|
| $f/f_0$ | 0 | 25 | 50 | 75 | 100 |
| $E$ [MeV] | 11151 | 11144 | 11135 | 11129 | 11122 |
| $\Gamma/2$ [MeV] | 2.01 | 2.67 | 0.60 | 0.58 | 0.60 |
| $f/f_0$ | 70 | 25 | 50 | 75 | 100 |
| $E$ [MeV] | 11091 | — | — | 11090 | 11082 |
| $\Gamma/2$ [MeV] | 0.36 | — | — | 0.44 | 0.75 |
| $f/f_0$ | 20 | 25 | 50 | 75 | 100 |
| $E$ [MeV] | 11096 | 11093 | 11083 | 11081 | 11078 |
| $\Gamma/2$ [MeV] | 44.69 | 11.35 | 14.15 | 31.45 | 39.32 |
| $f/f_0$ | 25 | 25 | 50 | 75 | 100 |
| $E$ [MeV] | 11083 | 11083 | 11033 | 11003 | 10979 |
| $\Gamma/2$ [MeV] | 78.77 | 78.77 | 40.76 | 14.49 | 4.03 |
| $f/f_0$ | 0 | 25 | 50 | 75 | 100 |
| $E$ [MeV] | 10943 | 10934 | 10920 | 10901 | 10879 |
| $\Gamma/2$ [MeV] | $1.80\times10^{-2}$ | $1.91\times10^{-2}$ | $5.80\times10^{-2}$ | 0.12 | — |
| $f/f_0$ | 0 | 25 | 50 | 75 | 100 |
| $E$ [MeV] | 10898 | 10891 | 10877 | 10860 | 10839 |
| $\Gamma/2$ [MeV] | — | — | — | — | — |

Many $\bar{B}\,\Lambda_B$ and $\bar{B}^*\,\Lambda_B$ bound states appear.

The $\bar{B}\,\Lambda_B$ bound states are pruduced even without introducing the five-quark potential !

# Results for the hidden-charm sector

**Why does the introduction of the core contribution bring about the appearance of bound and resonant states?**

The Meson-Baryon wave function in the coordinate space is given by:

$$\left\langle \vec{\rho},\vec{\lambda},\vec{r},\vec{x}\,\middle|\,\bar{D}Y_c(\vec{p}_i)\right\rangle = \psi_{\bar{D}}^{int}(\vec{r})\psi_{Y_c}^{int}(\vec{\rho},\vec{\lambda})e^{i\vec{p}_i\cdot\vec{x}} \times \phi_{\bar{D}Y_c}(CSF).$$

$$\left\langle \vec{\rho},\vec{\lambda},\vec{r},\vec{x}\,\middle|\,5q\,(\alpha)\right\rangle = \psi_{5q}^{int}(\vec{\rho},\vec{\lambda},\vec{r})\left(\frac{2A}{\pi}\right)^{3/4} e^{-A^2x^2} \times \phi_{5q}(CSF),$$

**$S_i^{\alpha}$ is the spectroscopic factor the transition $\langle\, i|\alpha\,\rangle$**

Assuming that the $\psi_{5q}^{int}$ and $\psi_{\bar{D}}^{int}\psi_{Y_c}^{int}$ are the same, the overlap between the MB configuration and the five quark configuration is given by the color, spin and flavor parts (CSF):

$$\begin{aligned}\langle \bar{D}Y_c(\vec{p}_i)\,|\,5q\,(\alpha)\rangle &= \langle \phi_{\bar{D}Y_c}(CSF)\,|\,\phi_{5q}(CSF)\rangle \int d^3x \left(\frac{2A}{\pi}\right)^{3/4} e^{-Ax^2} e^{i\vec{p}_i\cdot\vec{x}} \\ &= \langle \phi_{\bar{D}Y_c}(CSF)\,|\,\phi_{5q}(CSF)\rangle \left(\frac{2\pi}{A}\right)^{3/4} e^{-p_i^2/4A} \equiv S_i^{\alpha} g(\vec{p}_i),\end{aligned}$$

# Results for the hidden-charm sector

**Why does the introduction of the core contribution bring about the appearance of bound and resonant states?**

The transition amplitude for the Meson-Baryon channel to the five quark channels is given by:

$$V_{ij}^{5q}(E;r) \sim \sum_{\alpha} S_i^{\alpha} S_j^{\alpha} e^{-Ar^2} \frac{1}{E - E_{5q}^{\alpha}},$$

**From a simple quark model calculation $E_{5q}^{\alpha} \gg M_D + M_{Y_c}$ (this holds even more in the bottom sector), then we may further approximate**

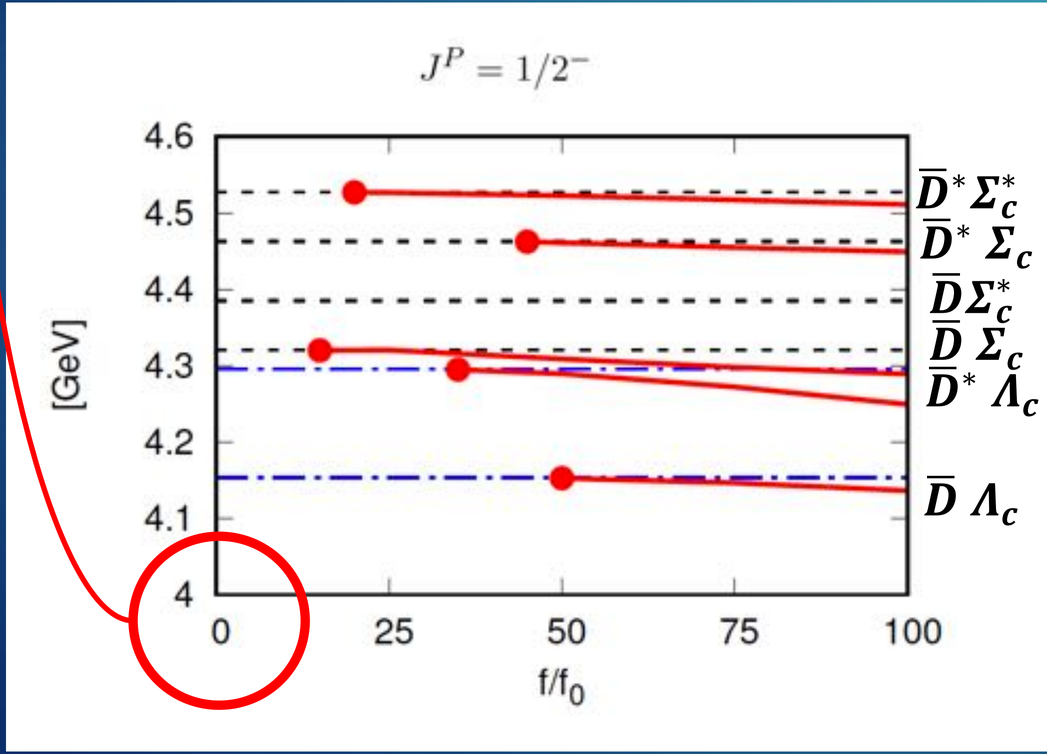
$$V_{ij}^{5q}(r) = -f \sum_{\alpha} S_i^{\alpha} S_j^{\alpha} e^{-Ar^2},$$

This makes the five quark potential attractive for both the hidden-charm and hidden-bottom sectors

# Results for the hidden-charm sector

- **Observations**

No resonant and no bound states without adding the five-quark potential




In the hidden-charm sector we do not obtain any states only with the OPEP, corresponding to the result at $\frac{f}{f_0} = 0$, while the bound and resonant states appear by increasing the strength $f$ of the 5q potential:

**In the charm-sector the OPEP is not enough strong to produce bound and resonant Pc states.**

# Results for the hidden-charm sector

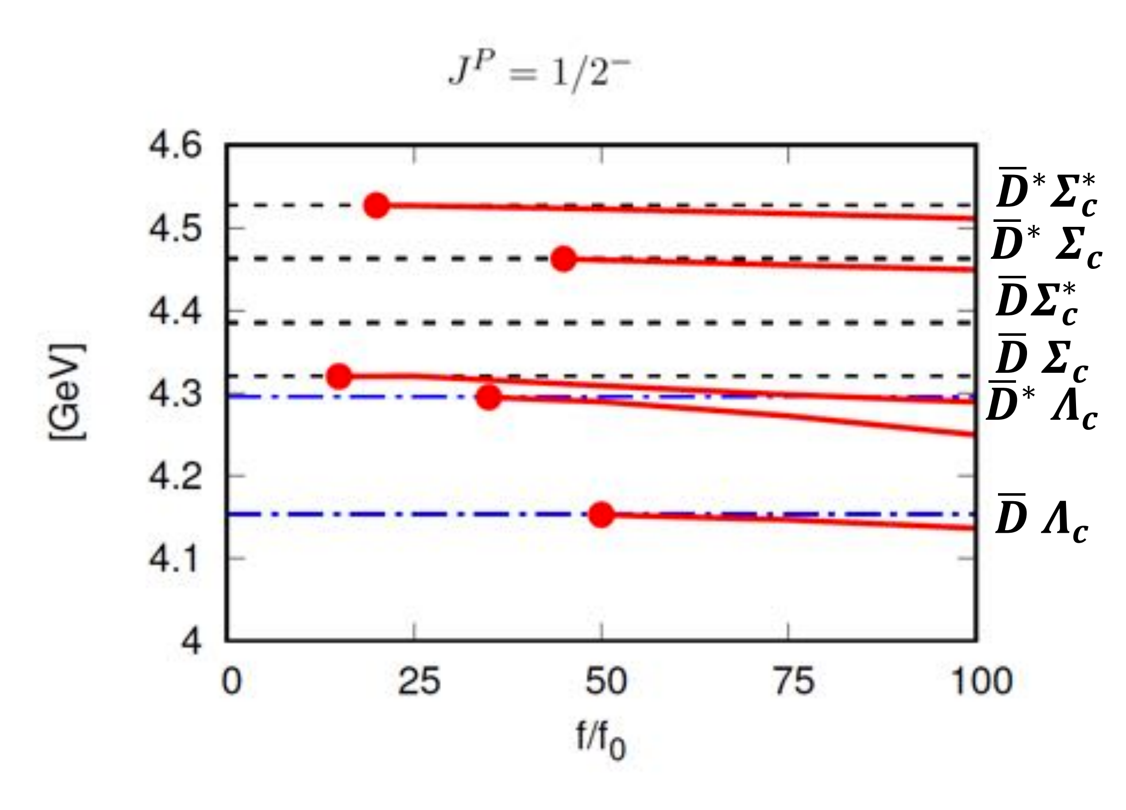
## Comparison with the observed pentaquark states

- For the $J^P = \frac{3}{2}^-$ state, close to the $\bar{D}^* \Sigma_c$ threshold, we predict a mass of around 4460 MeV and a width of 20 MeV; these values are in good agreement with the observed heaviest pentaquark, while the spin-parity of the obtained state is not the one suggested by the LHCb collaboration.

- For the $J^P = \frac{5}{2}^-$ state, close to the $\bar{D}\Sigma_c^*$ threshold, the obtained mass of 4380 MeV is in agreement with the mass reported by LHCb, However, the obtained width around 6 MeV is rather different from the reported width of 205 MeV.

# Results for the hidden-charm sector

**Bound and resonant state energies of the hidden-charm molecules (solid lines) with various coupling constants f.** Dot-dashed lines are the $\bar{D}\,\Lambda_c$ and $\bar{D}^*\,\Lambda_c$ thresholds. Dashed lines are the $\bar{D}\,\Sigma_c, \bar{D}\Sigma_c^*, \bar{D}^*\,\Sigma_c$ and $\bar{D}^*\Sigma_c^*$ thresholds.




Filled circle is the starting point where the states appear.

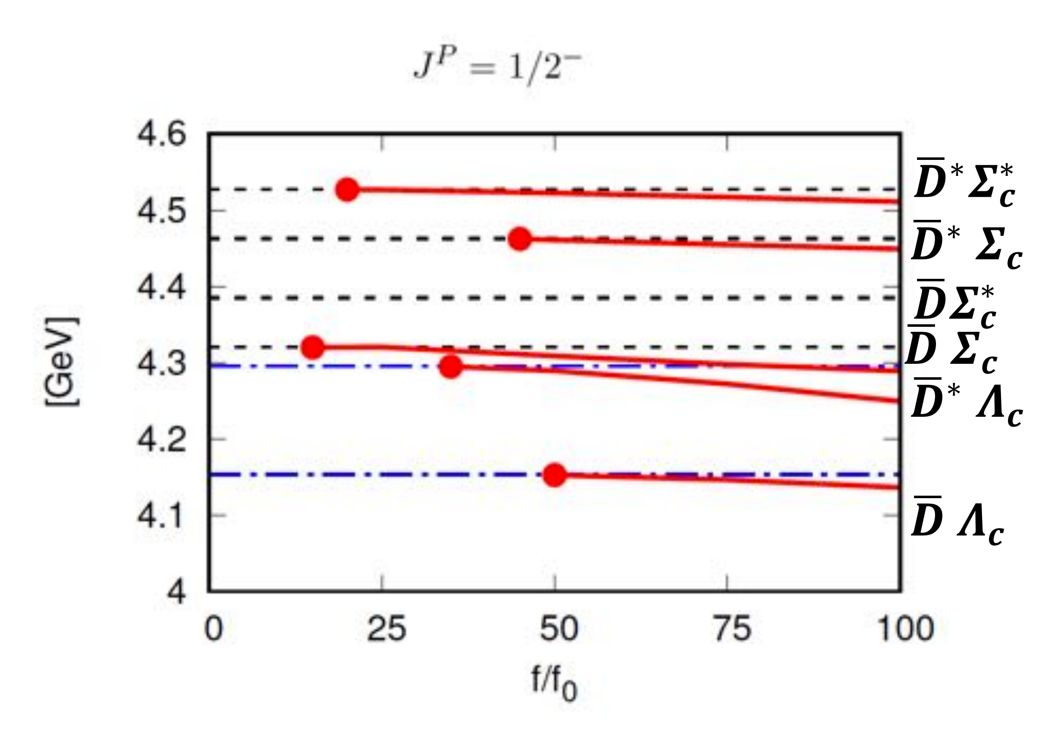
The overall strength f is a free parameter while $f_0$ was fixed from the $\bar{D}^*\,\Sigma_c$ diagonal term of the OPEP:

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

$$f_0 = \left|C^{\pi}_{\bar{D}^*\Sigma_c}(r=0)\right| \sim 6\ \text{MeV},$$

# Results for the hidden-charm sector

## Example: the $J^P = \frac{1}{2}^-$ state

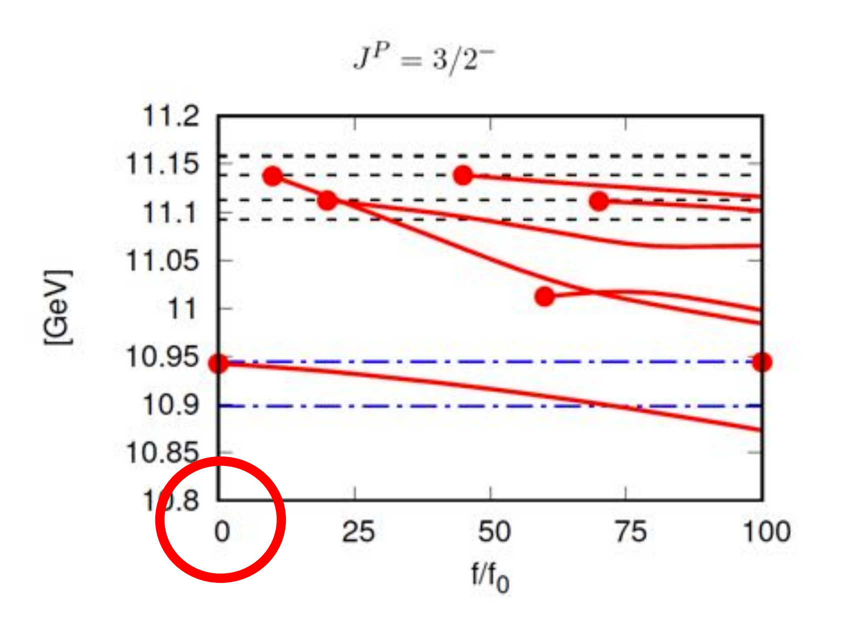



The lowest threshold $\bar{D}\,\Lambda_c$ is at $4153{,}46$ MeV and the state whose energy is lower than the threshold is a bound state.

| | | | | | | |
|---|---|---|---|---|---|---|
| SUM | $f/f_0$ | 20 | 25 | 50 | 75 | 100 |
| | $E$ [MeV] | 4527 | 4526 | 4523 | 4517 | 4511 |
| | $\Gamma/2$ [MeV] | 0.63 | 0.85 | 2.00 | 2.79 | 3.33 |
| | $f/f_0$ | 45 | 25 | 50 | 75 | 100 |
| | $E$ [MeV] | 4462 | — | 4461 | 4455 | 4449 |
| | $\Gamma/2$ [MeV] | 3.27 | — | 3.93 | 6.54 | 8.66 |
| | $f/f_0$ | 15 | 25 | 50 | 75 | 100 |
| | $E$ [MeV] | 4320 | 4320 | 4309 | 4298 | 4289 |
| | $\Gamma/2$ [MeV] | 0.45 | 1.70 | 3.40 | 2.34 | $2.57\times10^{-2}$ |
| | $f/f_0$ | 35 | 25 | 50 | 75 | 100 |
| | $E$ [MeV] | 4295 | — | 4290 | 4272 | 4249 |
| | $\Gamma/2$ [MeV] | $2.01\times10^{-2}$ | — | $6.17\times10^{-2}$ | $9.23\times10^{-2}$ | $7.93\times10^{-2}$ |
| | $f/f_0$ | 50 | 25 | 50 | 75 | 100 |
| | $E$ [MeV] | 4153 | — | 4153 | 4147 | 4136 |
| | $\Gamma/2$ [MeV] | | — | — | — | — |

# Hot topic: Numerical results for the hidden-bottom sector

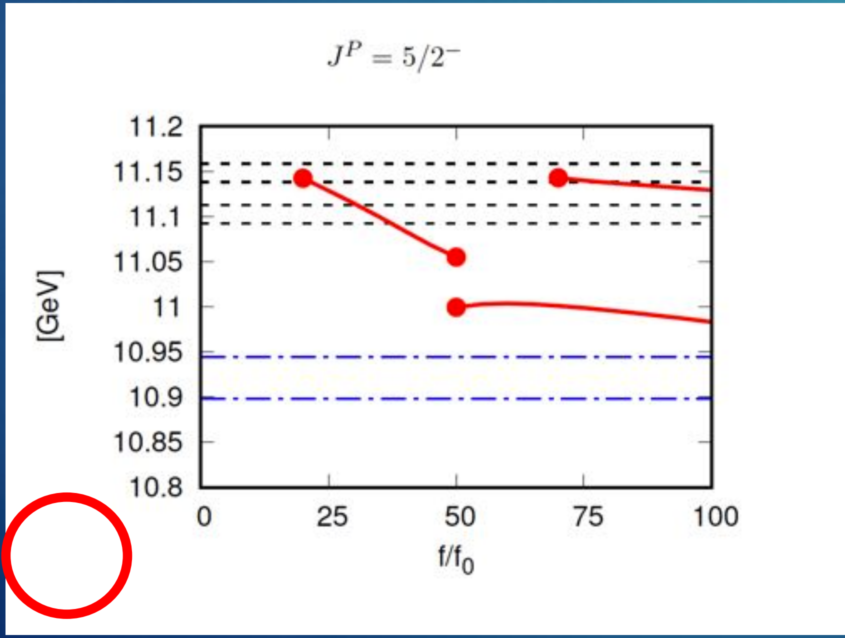
Example: the $J^p = \frac{3}{2}^-$ state




| | | | | | | |
|---|---|---|---|---|---|---|
| SUM | $f/f_0$ | 45 | 25 | 50 | 75 | 100 |
| | $E$ [MeV] | 11138 | — | 11136 | 11126 | 11116 |
| | $\Gamma/2$ [MeV] | 5.13 | — | 5.71 | 3.78 | 1.94 |
| | $f/f_0$ | 70 | 25 | 50 | 75 | 100 |
| | $E$ [MeV] | 11111 | — | — | 11110 | 11101 |
| | $\Gamma/2$ [MeV] | 0.27 | — | — | 0.35 | 0.70 |
| | $f/f_0$ | 20 | 25 | 50 | 75 | 100 |
| | $E$ [MeV] | 11112 | 11109 | 11091 | 11067 | 11065 |
| | $\Gamma/2$ [MeV] | 4.40 | 5.57 | 11.82 | 28.88 | 51.60 |
| | $f/f_0$ | 60 | 25 | 50 | 75 | 100 |
| | $E$ [MeV] | 11012 | — | — | 11017 | 10998 |
| | $\Gamma/2$ [MeV] | 53.76 | — | — | 37.95 | 10.85 |

# Hot topic: Numerical results for the hidden-bottom sector

Example: the $J^p = \frac{5}{2}^-$ state




| | | | | | | |
|---|---|---|---|---|---|---|
| (1,3/2) | $f/f_0$ | 70 | 25 | 50 | 75 | 100 |
| | $E$ [MeV] | 11142.84 | — | — | 11139.85 | 11129.35 |
| | $\Gamma/2$ [MeV] | 15.89 | — | — | 12.66 | 5.15 |
| | $f/f_0$ | 20 | 25 | 50 | 75 | 100 |
| | $E$ [MeV] | 11142.42 | 11128.79 | 11055.16 | — | — |
| | $\Gamma/2$ [MeV] | 123.11 | 125.94 | 153.98 | — | — |
| | $f/f_0$ | 50 | 25 | 50 | 75 | 100 |
| | $E$ [MeV] | 10999.46 | — | 10999.46 | 10998.89 | 10983.33 |
| | $\Gamma/2$ [MeV] | 71.82 | — | 71.82 | 36.75 | 17.97 |

# The Model

$f$ is the only free parameter of the model: we use make the approximation (reasonable) that the off diagonal terms of the coupled channel Hamiltonian are proportional to the spectroscopic factors between the Meson-Baryon channel $i$ and the five quark channel $\alpha$:

$$\langle i \,|\, V \,|\, \alpha \rangle = f \,\langle i \,|\, \alpha \rangle$$