

Hybrid and Pentaquark states

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INFN

GGI Florence, 13 march 2018

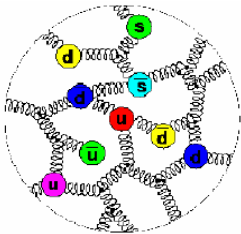
Why Hadron Spectroscopy: laboratory for studying non pQCD & confinement.

Perturbative

High energy
Small distance

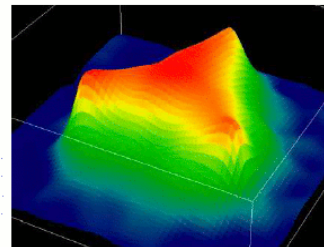
Asymptotic
freedom

pQCD



$\ll 0.1 \text{ fm}$

Transition



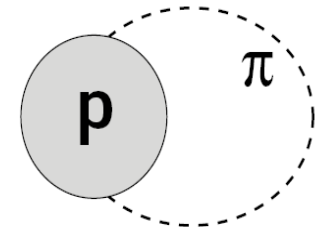
$0.1 - 1 \text{ fm}$

Effective
degrees
of
freedom
(models)

Non- Perturbative

Low energy
Large distance

Confinement



Mesons
&
Baryons

$> 1 \text{ fm}$

Hadron spectroscopy: lab. for QCD@ work

Bulk of mass of hadrons

Confinement

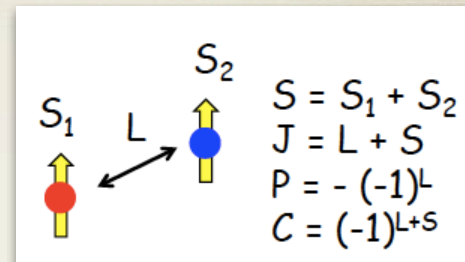
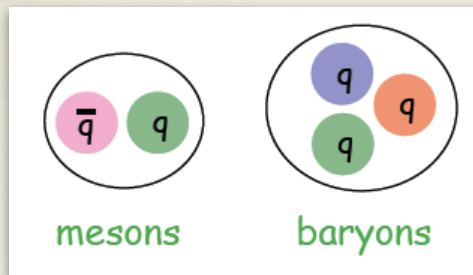
X,Y, Z, etc. new hadron states

- Finally to claim new physics also in other sectors, a precise knowledge of non perturbative QCD observables is necessary if they are involved!

The gluons and the meson spectrum

Neutralize color

... the simple way



... or the “exotic” way



(flavor) exotic

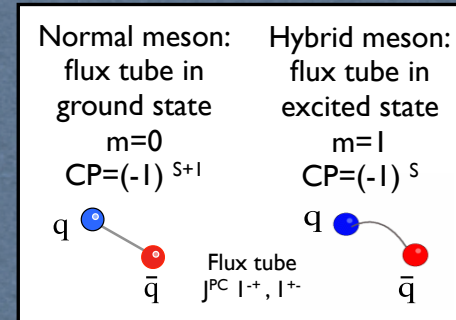
exotic of the II kind

$J^{PC} = 0^{--}, 0^{+-}, 1^{-+}, 2^{+-} \dots$

Gluonic excitation models

Flux tube model

- Gluonic field confined in a tube between q and anti- q
- Linear Regge trajectories
- Hybrid mesons as transverse oscillation of the tube
- Flux-tube breaking give rise to meson decay



Lightest multiplet
 $(0, 1, 2)^{+-}, (0, 1, 2)^{+-}, 1^{-}, 1^{++}$

Bag model

- Quarks confined inside a cavity
- Full relativistic
- Gluonic excitation: gluonic field modes by boundary conditions

Lightest multiplet
 $(0, 1, 2)^{+-}, 1^{-}$

CQM + constituent gluon

- qq + massive transverse quasi-gluon (J_g^{PgCg})
- Gluon adds in relative S-wave to a qq pair is S-wave or P-wave

qq in S-wave +
 $J_g^{PgCg} = 1^{-}$ in S-wave

Lightest multiplet
 $(0, 1, 2)^{++}, 1^{+-}$

qq in P-wave +
 $J_g^{PgCg} = 1^{-}$ in S-wave

Lightest multiplet
 $0^{-+}, (1^{+-})^3, (2^{-+})^2, 3^{-+}, 0^{-+}, 0^{-+}, 1^{-+}, 2^{-+}$

or in Cb gauge QCD :

P.Guo, A.Szczepaniak, Galatà, Vasallo, E.S. , PRD78, 056003 (2008)

- Repulsive 3-body force selects $J_g^{PgCg} = 1^{+-}$ in relative P-wave added to a qq pair is S-wave or P-wave

qq in S-wave +
 $J_g^{PgCg} = 1^{+-}$ in P-wave

Lightest multiplet
 $(0, 1, 2)^{-+}, 1^{-}$

qq in P-wave +
 $J_g^{PgCg} = 1^{+-}$ in P-wave

Lightest multiplet
 $0^{-+}, (1^{+-})^3, (2^{-+})^2, 3^{+-}, (0, 1, 2)^{++}$

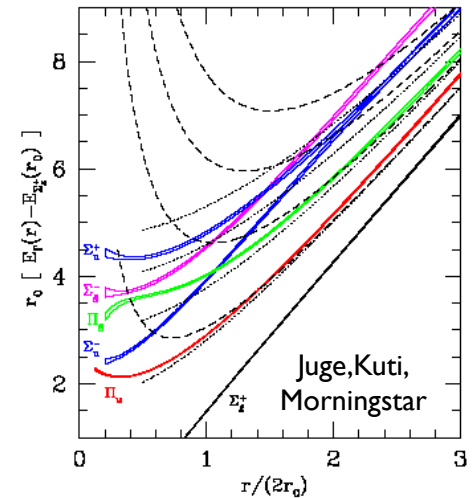
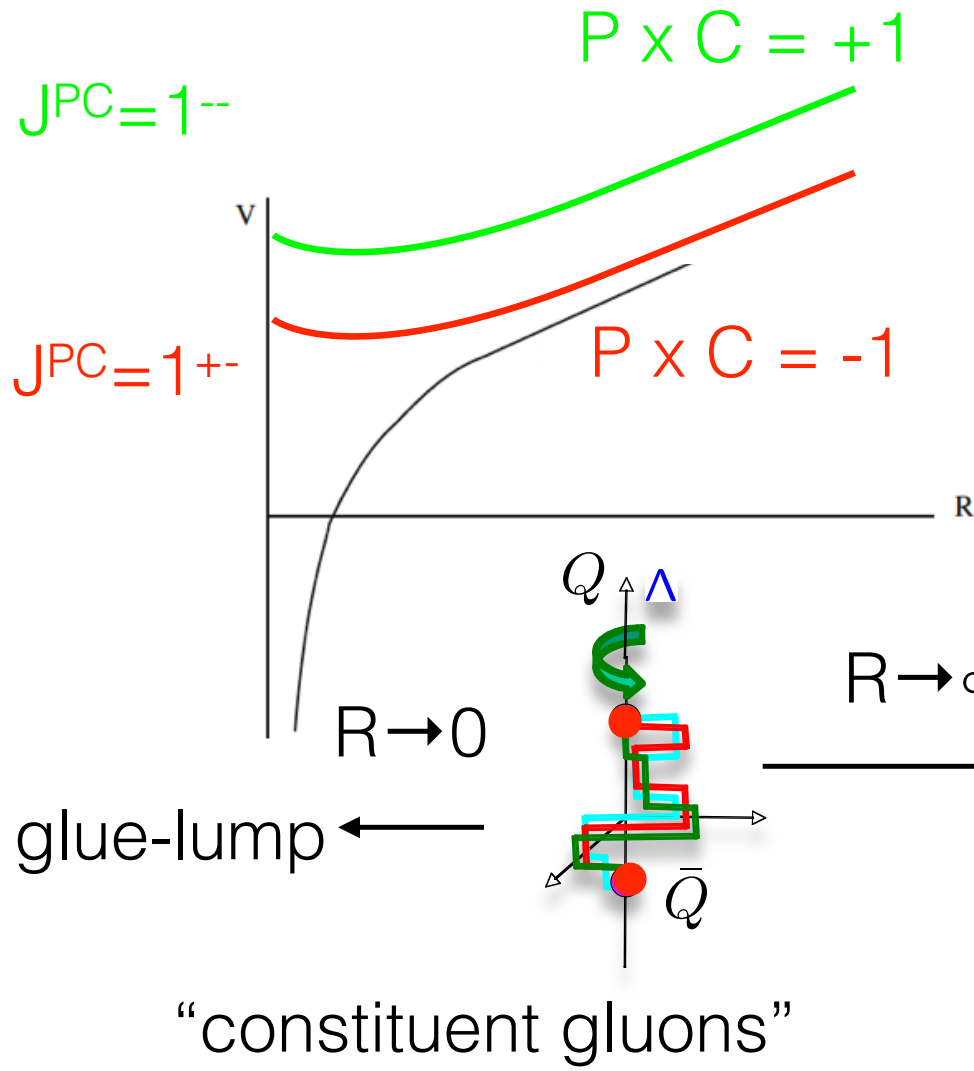
Start from the study of the glue-lamp
(lamp or "grumo" of gluons or " constituent gluon")
as obtained from QCD in physical gauge

Gluelamp in Cb gauge QCD:

P.Guo,A.Szczepaniak,G.Galatà,A. Vassallo, E.S.,PRD78,056003(2008)

it is easy to study the $c\bar{c}$ –gluon system, i.e. the
hybrids (next two slides)

Flux tube and strings



Gluelump

Guo, Szczpaniak, Vassallo, E.S., PRD2008

Greensite e Thorn's chain model

Ostrander, Szczpaniak, Vassallo, E.S., PRD2014

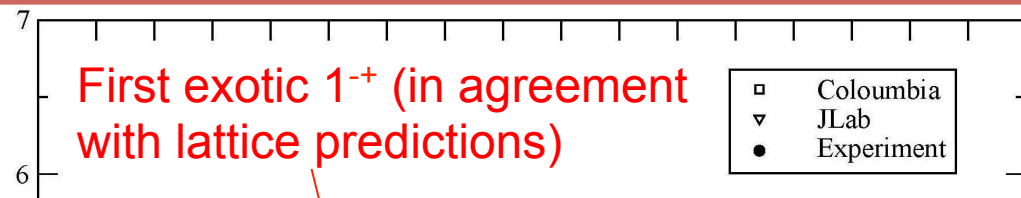
Charmonia (qq bar) & hybrids (qqg)

$$J_g^{PC} = 1^{+-}, 1^{--}$$

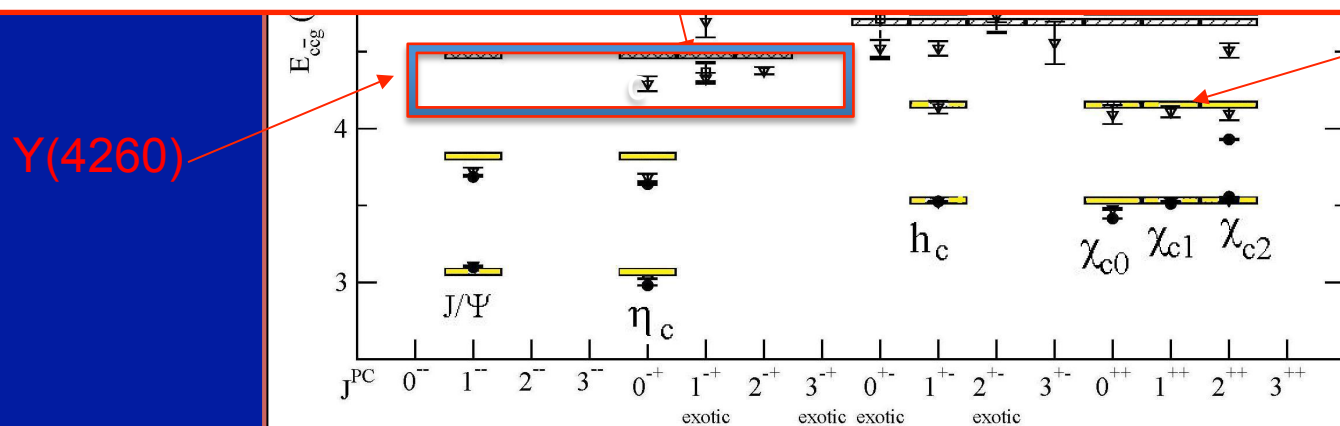
[14]: J. J. Dudek, R. G. Edwards, N. Mathur, and D. G. Richards, Phys. Rev. D 77, 034501 (2008).

J_g^{PC}	This work [GeV]	J^{PC}	Lattice [14] [GeV]
1^+	4.476	$0^{-+}, 1^{-+}, 2^{-+}, [1^{--}]$	4.291(48), 4.327(36), 4.376(24), [?]
1^-	4.762	$1^{+-}, 2^{++}, [0^{++}, 1^{++}]$	4.521(48), 4.508(48), [?, ?]
2^+	5.144	$1^{-+}, [2^{--}, 2^{-+}, 3^{-+}]$	4.696(103), [?, ?, ?]
2^-	5.065	$2^{+-}, [1^{++}, 2^{++}, 3^{++}]$	4.733(42), [?, ?, ?]

c-bar states (yellow)
hybrids (gray-dashed)

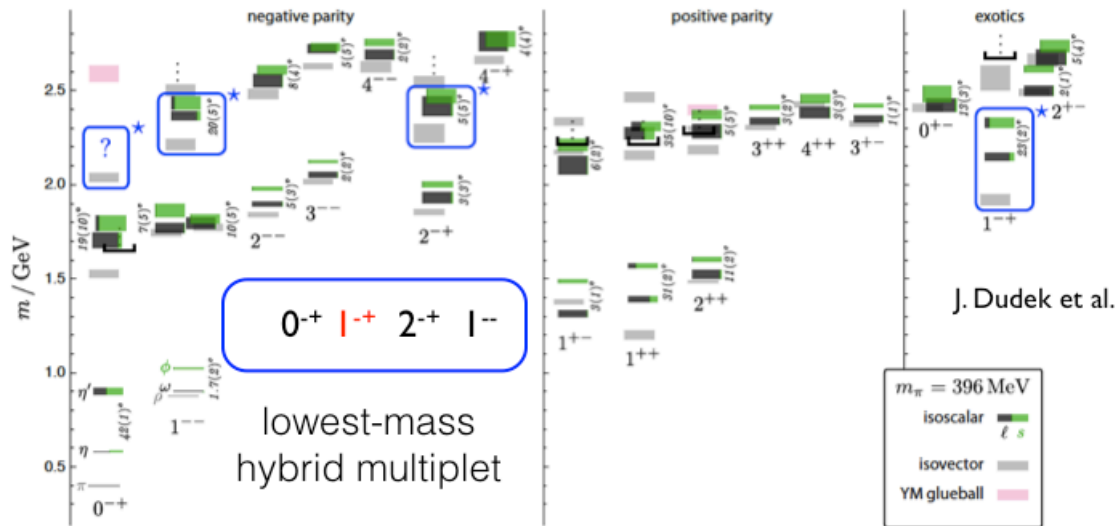


The lightest hybrid supermultiplets



Guo, Szczepaniak, Galatà, Vassallo, E.S., Phys.Rev.D78:056003, 2008.

The lightest hybrid supermultiplet predicted (and explained) for charmonia by QCD in physical gauge, $1^-(0,1,2)^+$, it is predicted also for light quarks by LQCD



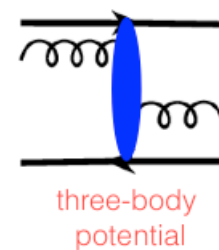
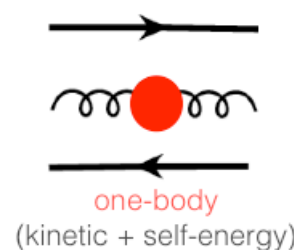
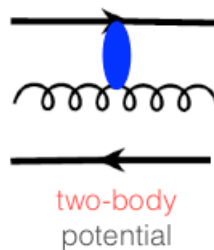
Physical gauge QCD (Hamiltonian)

$J^{PC} \text{ glue}$

$J^{PC} Q\bar{Q}$

$$1^{+-} \times 0_{S_{Q\bar{Q}}}^{-+} = 1^{--}$$

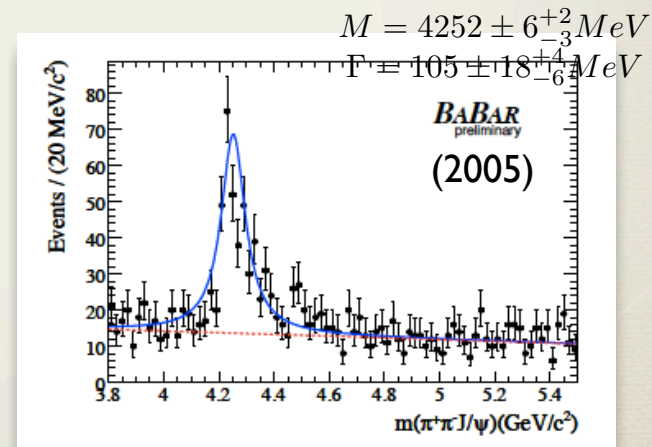
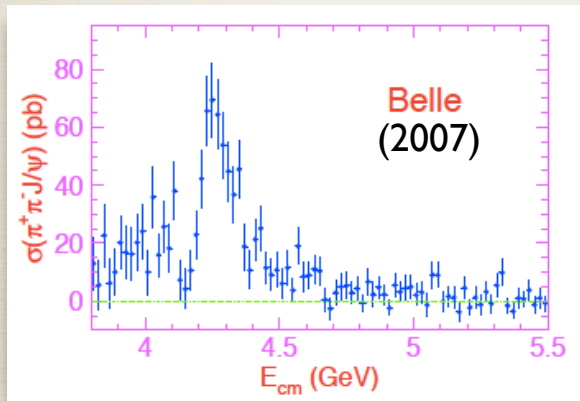
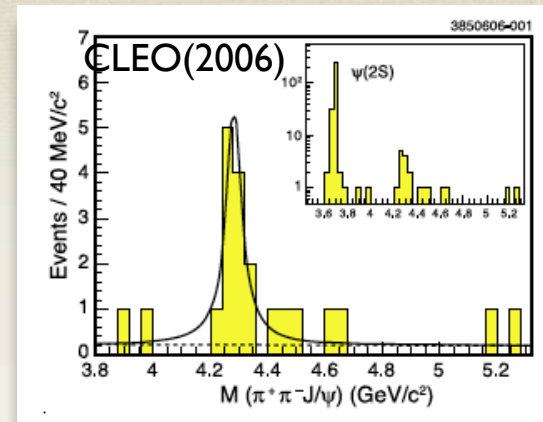
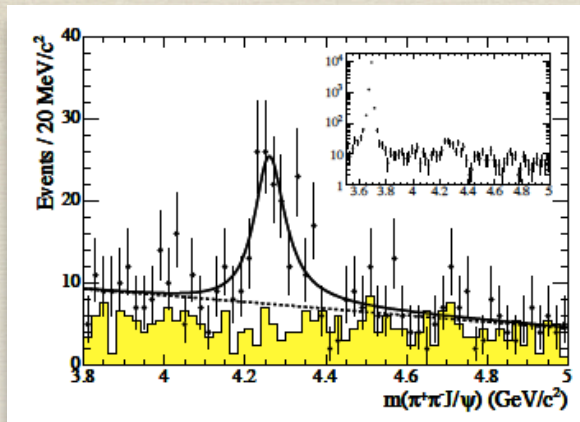
$$1^{+-} \times 1_{S_{Q\bar{Q}}}^{-+} = 0^{-+}, 1^{-+}, 2^{-+}$$



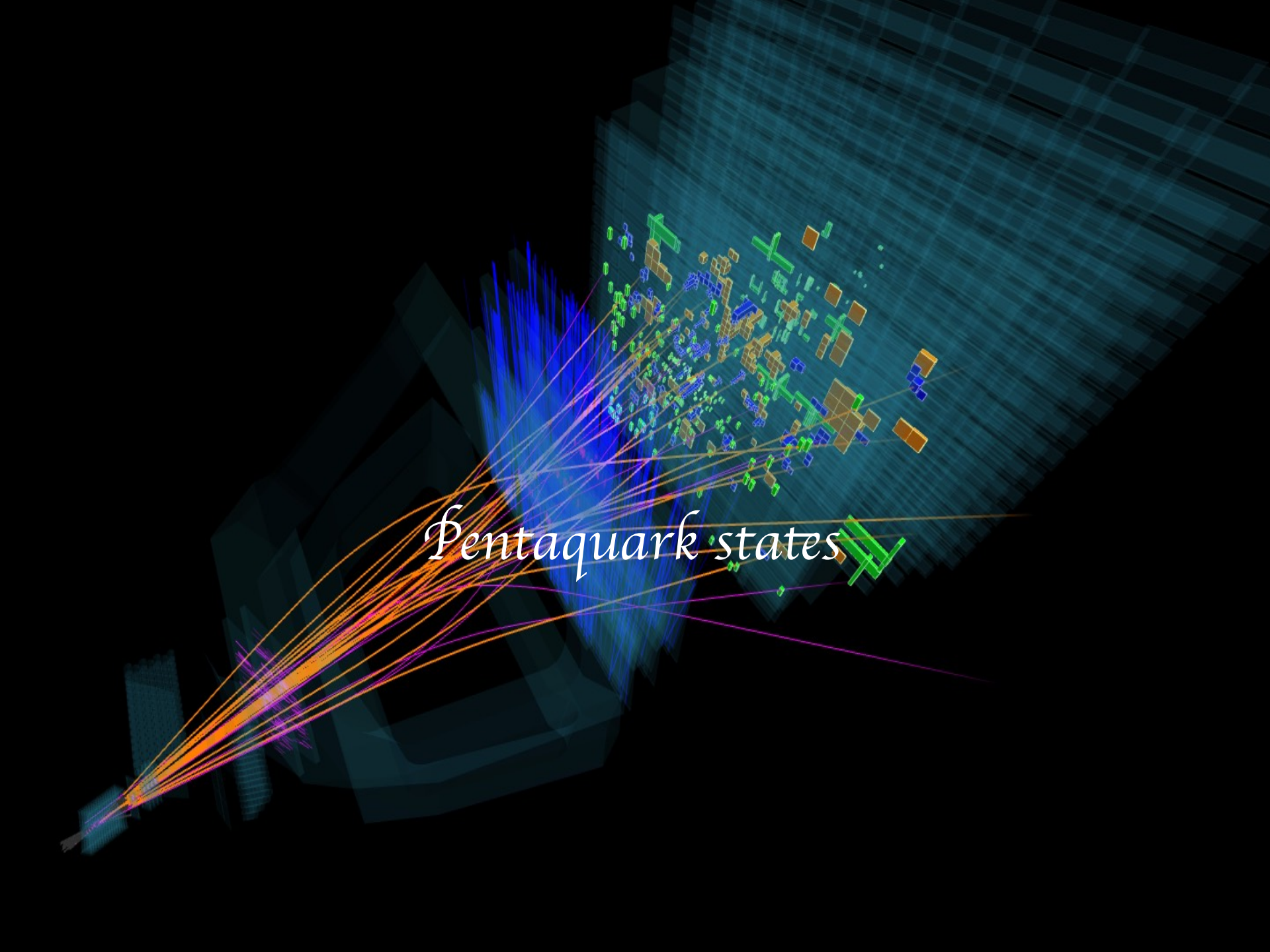
Guo, Szczepaniak, Galatà, Vassallo, E.S., PRD2008

20XX experimental confirmation - discovery ?

- **$\Upsilon(4260)$** discovered by BaBar in $J/\psi \pi^+ \pi^-$ (2005) confirmed by CLEO, Belle other modes from BaBar
 $J^{PC} = 1^{--}$ (from $e^+ e^-$) width $O(100 \text{ MeV})$



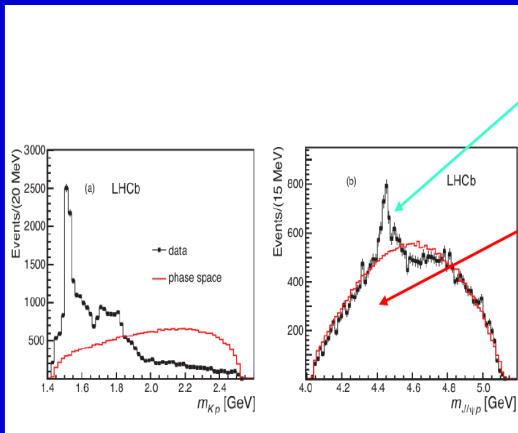
* **Theory: Hybrid candidate**



Pentaquark states

LHCb

Phys. Rev. Lett. 115(2015) 072001



$$M_{P_c^+}(4450) = (4449.8 \pm 8 \pm 29) \text{ MeV}$$

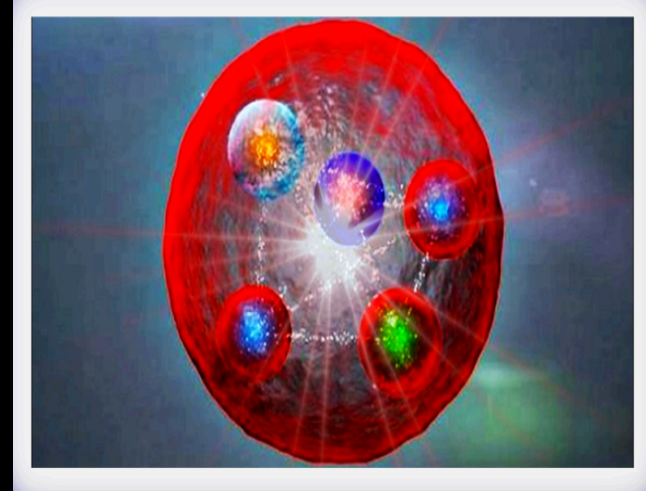
$$\Gamma = (39 \pm 5 \pm 19) \text{ MeV}$$

$$M_{P_c^+}(4380) = (4380 \pm 1.7 \pm 2.5) \text{ MeV}$$

$$\Gamma = (205 \pm 18 \pm 86) \text{ MeV}$$

statistic significance greater
then 9 sigma !

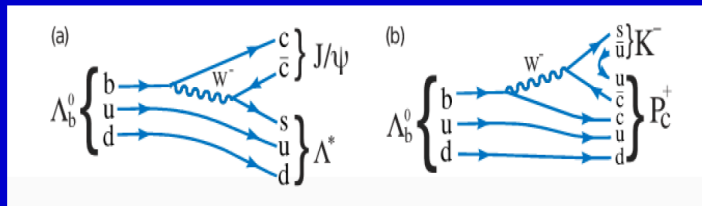
Why pentaquark states?



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

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

$$\Lambda_b^0 \rightarrow P^{0+} + K^-, P^{0+} \rightarrow J/\psi + p$$



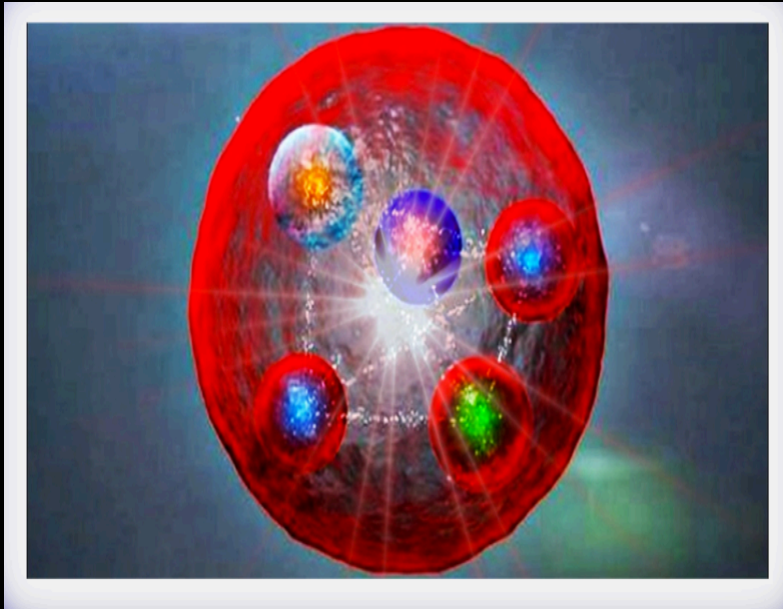
[1] R. Aaij *et al.* [LHCb Collaboration], Phys. Rev. Lett. **115** (2015) 072001

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

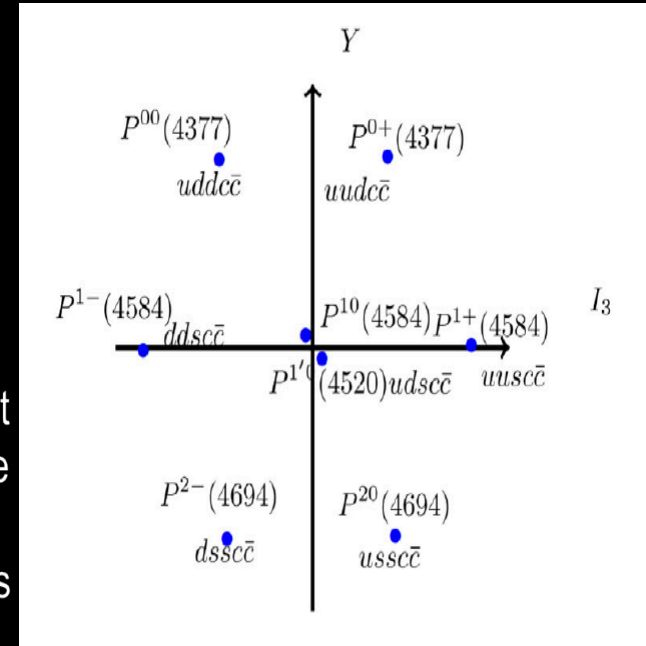
[3] R. Aaij *et al.* [LHCb Collaboration], Phys. Rev. Lett. **117** (2016) no.8, 082003

Pentaquarks as compact five quark states,

E. S., A. Giachino, Phys. Rev. D 96 (2017), 014014



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



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

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

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

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

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

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

- ▶ Near the thresholds, resonances are expected to have an exotic structure, like the 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.**



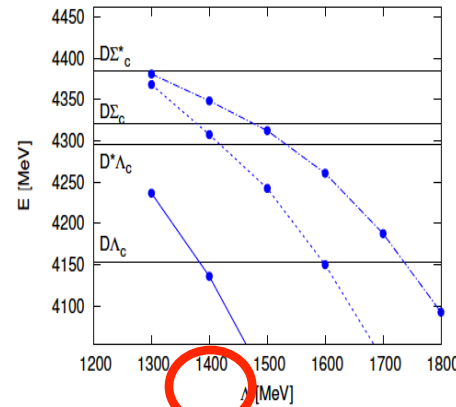
In Phys.Rev. D96 (2017) no.1, 014018 E. Santopinto e Y. Yamaguchi considered the coupled channel systems of $\bar{D} \Lambda_c, \bar{D}^* \Lambda_c, \bar{D} \Sigma_c, \bar{D} \Sigma_c^*, \bar{D}^* \Sigma_c$ and $\bar{D}^* \Sigma_c^*$ to predict the bound and the resonant states in the hidden-charm sector.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

- 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 Schrödinger equations.

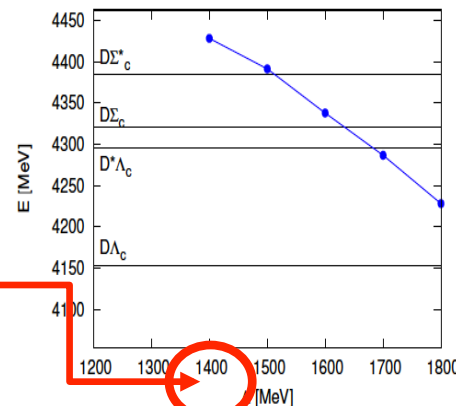
- Free parameter of the model: the cut-off parameter Λ ;

- Λ is fixed to reproduce the heaviest resonant

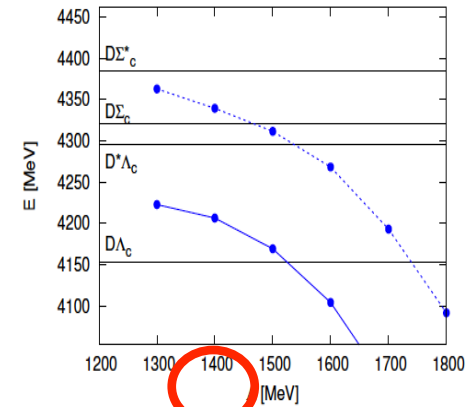
(i) $I(J^P) = 1/2(3/2^-)$



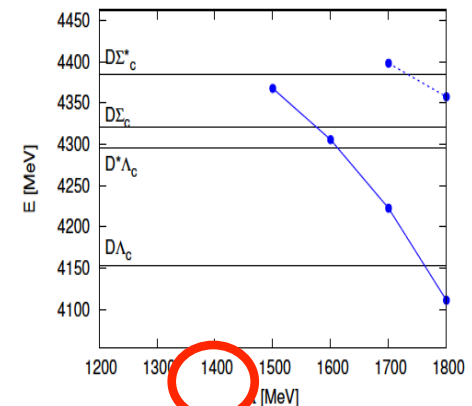
(iii) $I(J^P) = 1/2(5/2^-)$



(ii) $I(J^P) = 1/2(3/2^+)$



(iv) $I(J^P) = 1/2(5/2^+)$



Coupled channel between the meson-baryon states

results

Λ [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
	—	—	—	—	$4398.5 - i15.0$	$4357.8 - i8.2$

Good agreement for the mass and quantum numbers of the lightest pentaquark P_c^+ (4380)

The 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 Λ

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

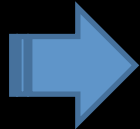
- In the current problem of pentaquark P_c , there are two competing sets of channels: the meson-baryon (MB) channels and the five-quark channels.

**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. Giachino, A. Hosaka, E. S., S. Tacheuchi, M. Takizawa, Phys .Rev. D96 (2017) no.11, 114031

- ▶ Hidden-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

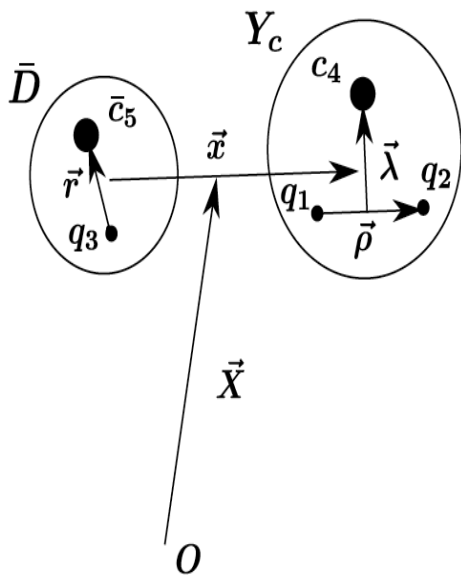


ADDITION OF THE CORE CONTRIBUTION

- ▶ 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 Schrödinger equation, we study the the bound and resonant hidden-charm

The Model

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^α :

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

Kinetic energy and harmonic oscillator potential of the five quark states

Results for the hidden-charm sector

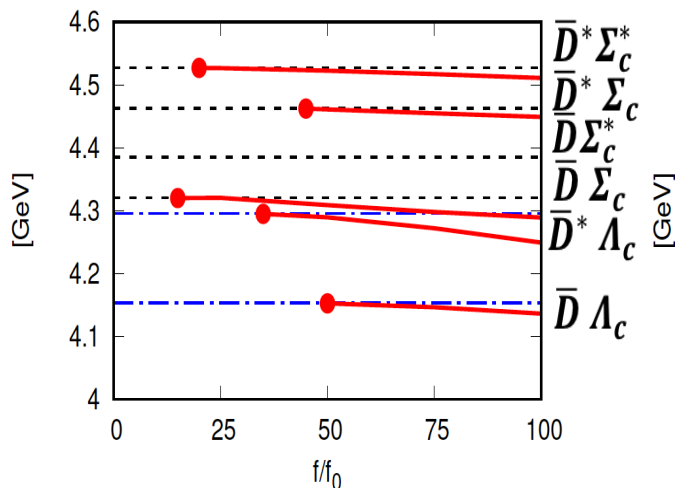
The lowest threshold $\bar{D} \Lambda_c$ is at 4153,46 MeV and the state whose energy is lower than the threshold is a bound state.

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

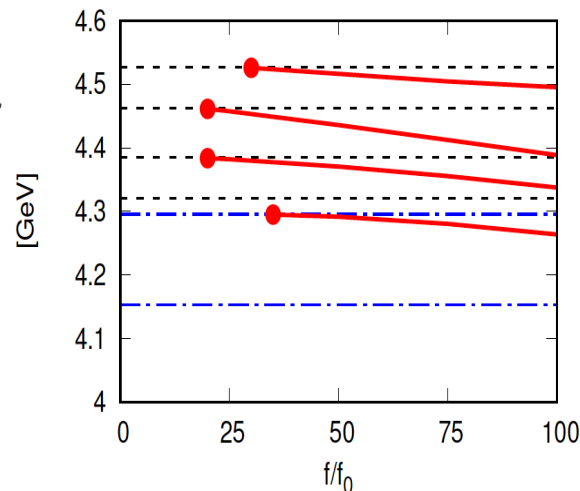


In the hidden-charm sector the OPEP is not enough strong to produce bound and resonant P_c states.

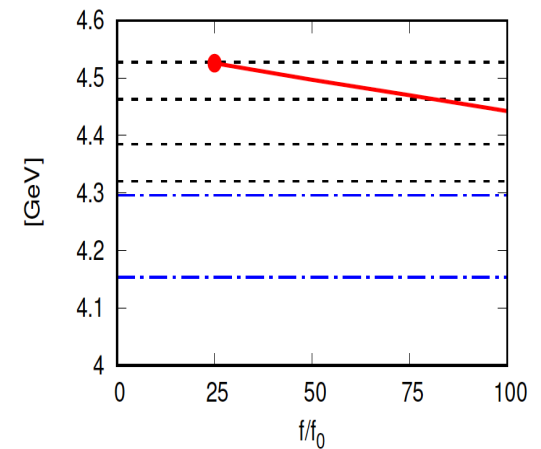
$J^P = 1/2^-$



$J^P = 3/2^-$



$J^P = 5/2^-$



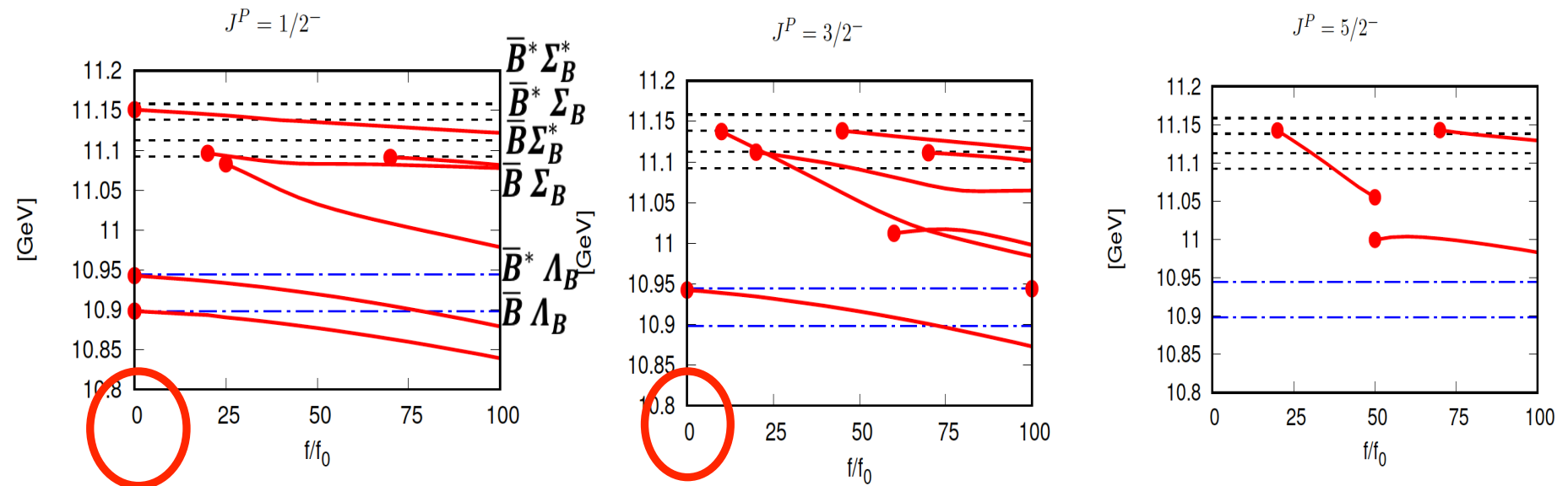
First results for the **hidden-bottom sector**

We found that, unlike the charm-sector, in which the five quark potential is needed to produce bound states, in the bottom sector 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.



First Results for the **hidden-bottom sector**

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

the hidden-bottom pentaquarks are more likely to form than the hidden-charm pentaquarks



The hidden-bottom sector is an interesting environment to search for pentaquark states

First results for the hidden-bottom sector

Why bound and resonant states are more likely to be found in the bottom sector?

- In the hidden-bottom sector, the OPEP is strong enough to produce states due to the mixing effect enhanced by the small mass splitting between B, B^* and Σ_B, Σ_B^*

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

