Hybrid and Pentaquark states

E. Santopinto
INFN

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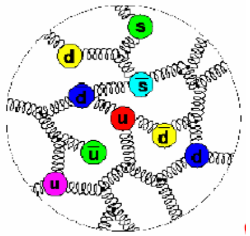
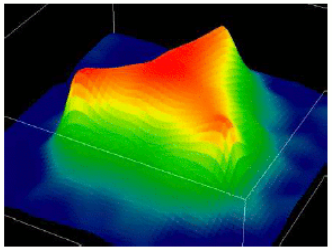
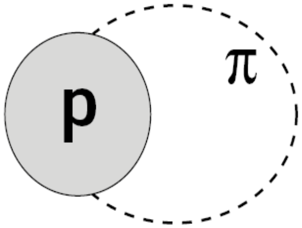
Why Hadron Spectroscopy:

laboratory for studying non pQCD & confinement.

Perturbative	Transition	Non- Perturbative
High energy Small distance Asymptotic freedom	↔	Low energy Large distance Confinement
pQCD 	 Effective degrees of freedom (models)	 Mesons & Baryons
<< 0.1 fm	0.1 – 1 fm	> 1 fm

Hadron spectroscopy: lab. for QCD@ work

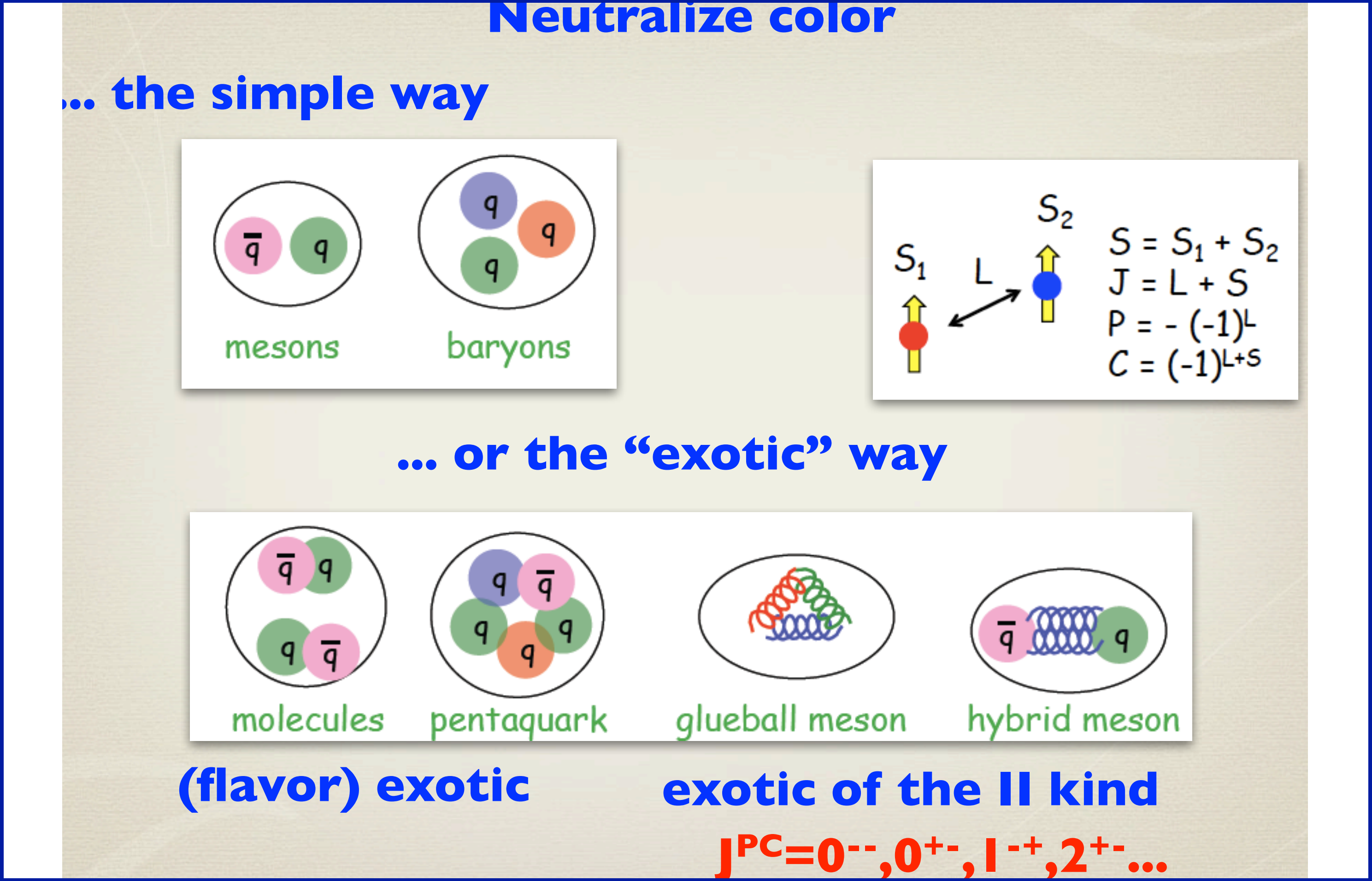
Bulk of mass of hadrons

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

$S = S_1 + S_2$

$J = L + S$

$P = -(-1)^L$

$C = (-1)^{L+S}$

… or the "exotic" way

(flavor) exotic

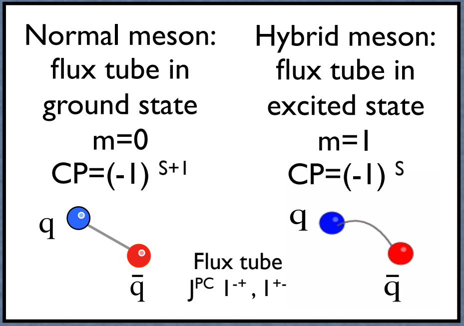
exotic of the II kind

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

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



Normal meson:
flux tube in
ground state
m=0
CP=$(-1)^{S+1}$

Hybrid meson:
flux tube in
excited state
m=1
CP=$(-1)^{S}$

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

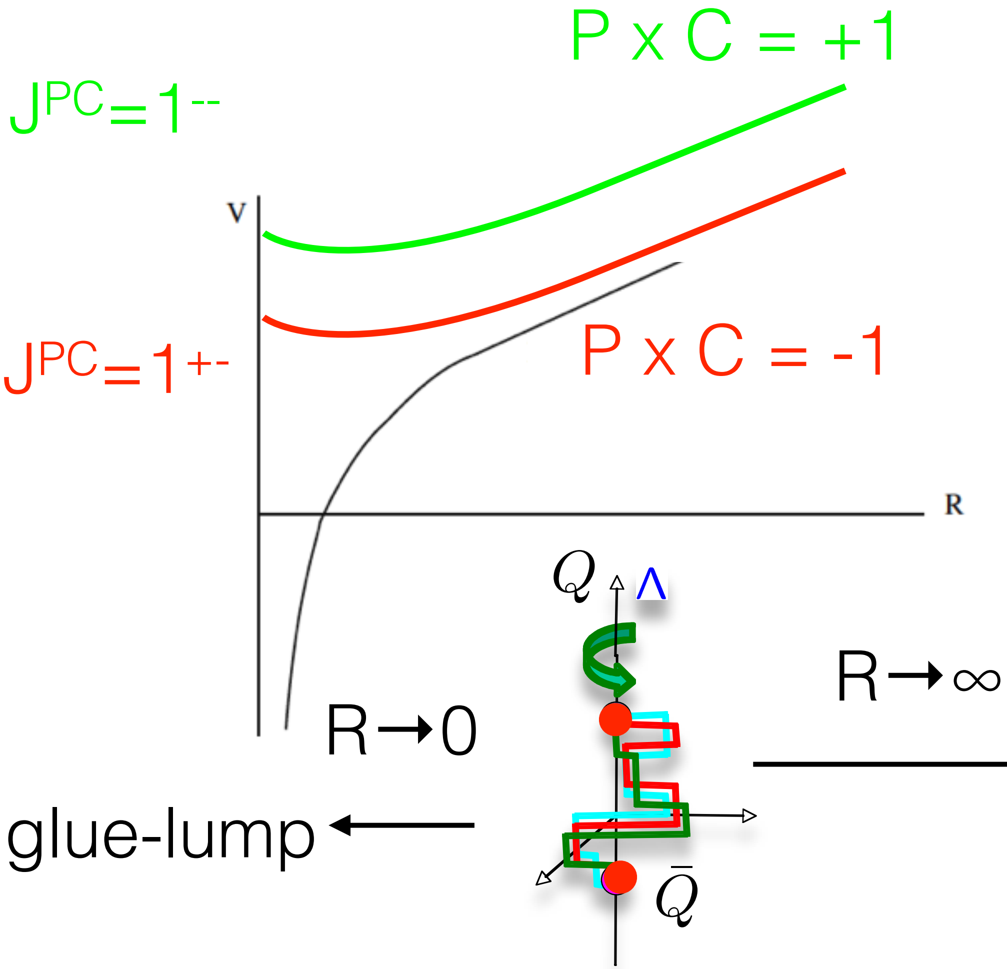
Lightest multiplet
0^{+-},$(1^{+-})^3$,$(2^{+-})^2$,3^{+-}, $(0,1,2)^{++}$

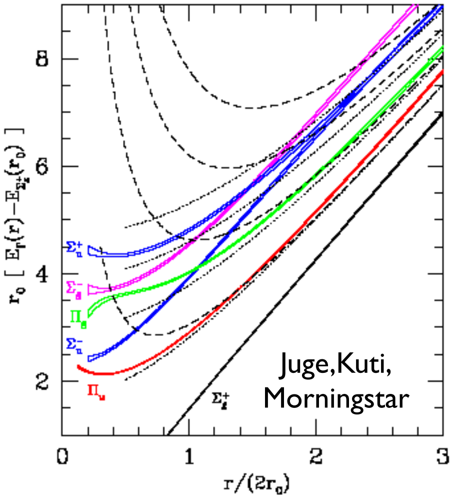
Start from the study of the glue-lamp
(lamp or ”grumo” of gluons or “ constituent gluon”)
as obtained from QCD in physical gauge

Gluelamp in Cb gauge QCD:
P.Guo,A.Szczepaniak,G.Galatà,A. Vassallo, E.S.,PRD78,056003(2008**)**

it is easy to study the ccbar –gluon system, i.e. the hybrids (next two slides)

Flux tube and strings





“constituent gluons”

“gluon chain”

Gluelamp

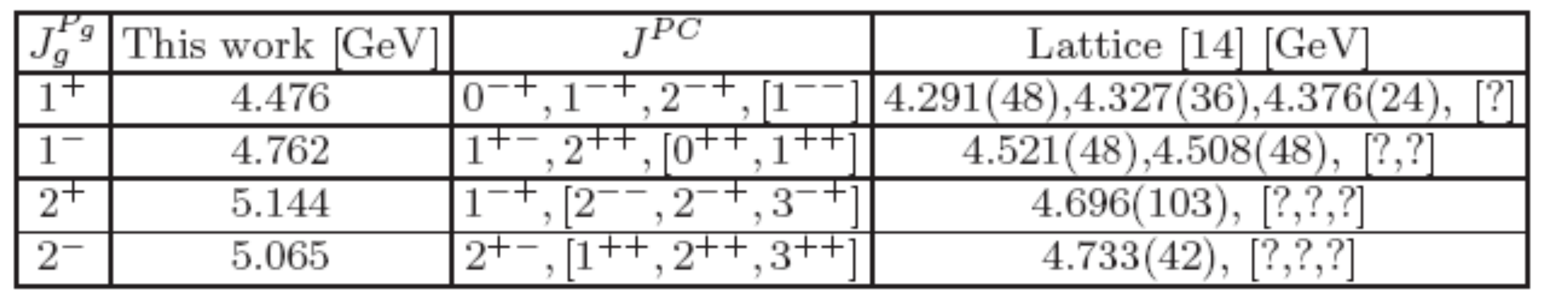
Guo,Szczpaniak,Vassallo, E.S.,PRD2008

Greensite e Thorn’s chain model

Ostrander,Szczpaniak,Vassallo,E.S,PRD2014

Charmonia (qq bar) & hybrids (qqg)

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

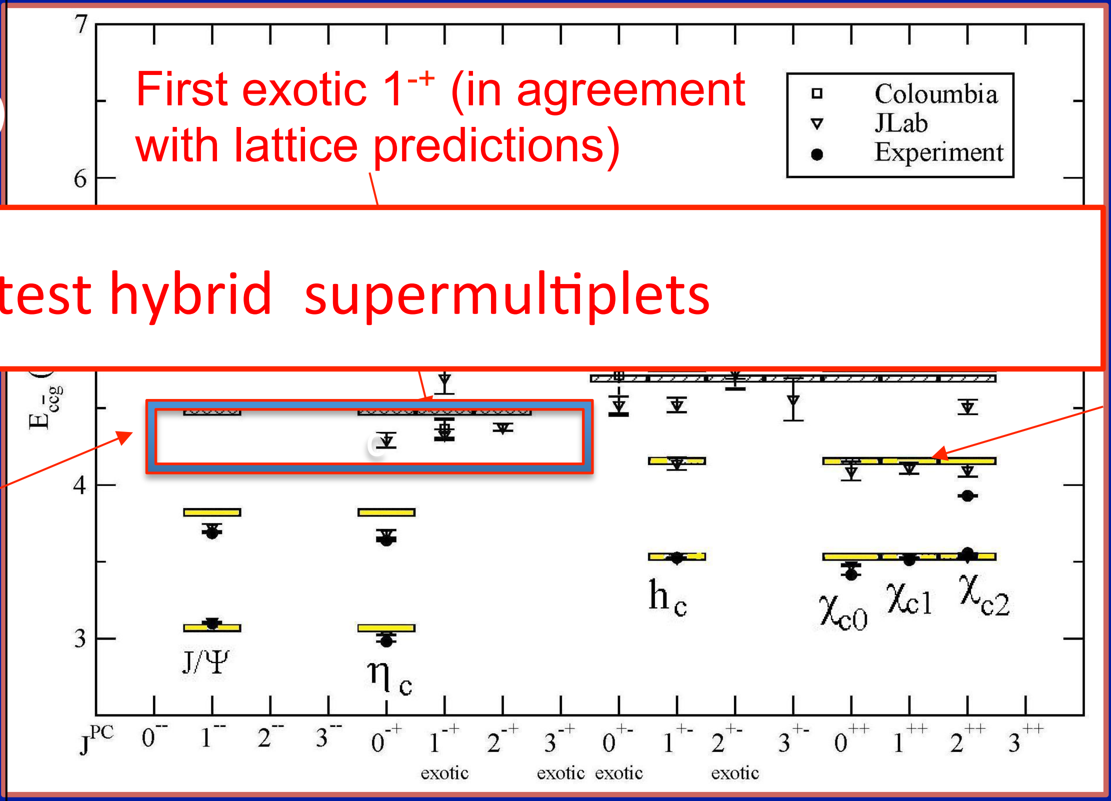


$J_g^{P_g}$	This work [GeV]	J^{PC}	Lattice [14] [GeV]
1^+	4.476	$0^{-+},1^{-+},2^{-+},[1^{--}]$	4.291(48),4.327(36),4.376(24), [?]
1^-	4.762	$1^{+-},2^{++},[0^{++},1^{++}]$	4.521(48),4.508(48), [?,?]
2^+	5.144	$1^{-+},[2^{--},2^{-+},3^{-+}]$	4.696(103), [?,?,?]
2^-	5.065	$2^{+-},[1^{++},2^{++},3^{++}]$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

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

c-cbar states (yellow)

hybrids (gray-dashed)



First exotic 1^{-+} (in agreement with lattice predictions)

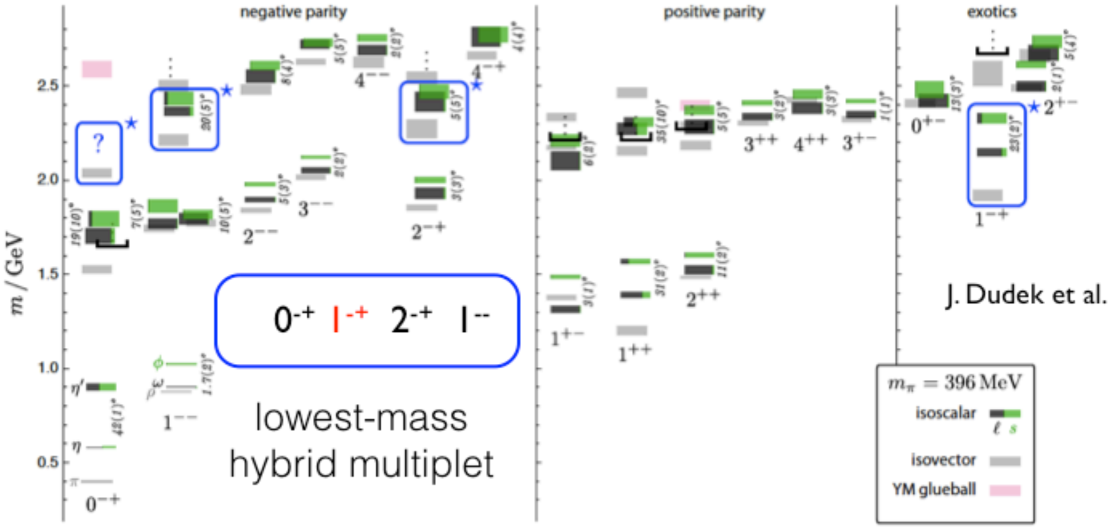
The lightest hybrid supermultiplets

X(3872)

Y(4260)

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

The ligthest 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



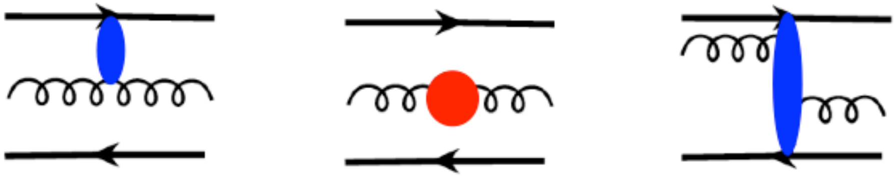
Physical gauge QCD (Hamiltonian)

J^{PC} glue

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

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

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



two-body potential

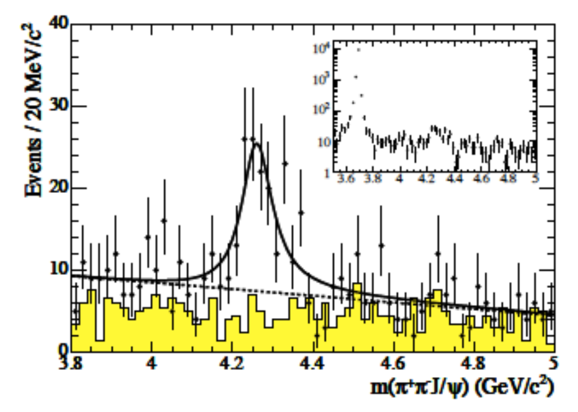
one-body (kinetic + self-energy)

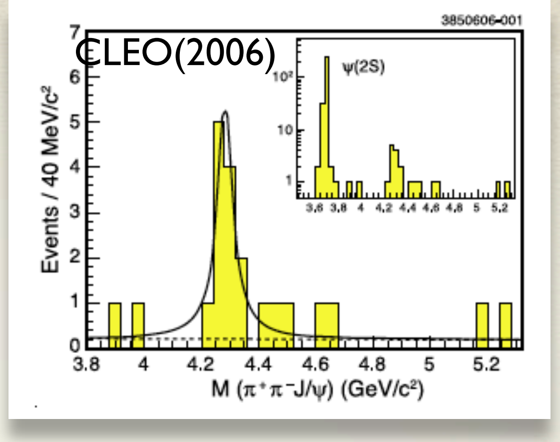
three-body potential

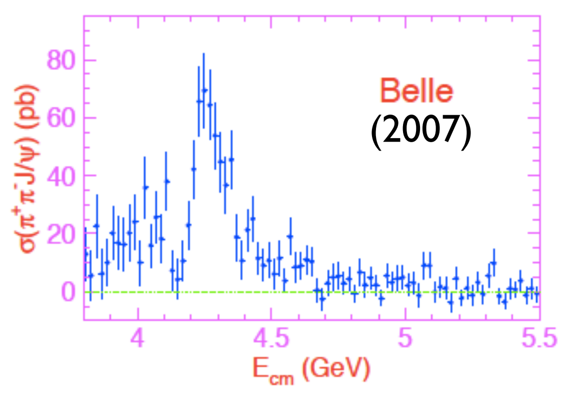
Guo,Szczpaniak,Galatà,Vassallo, E.S.,PRD2008

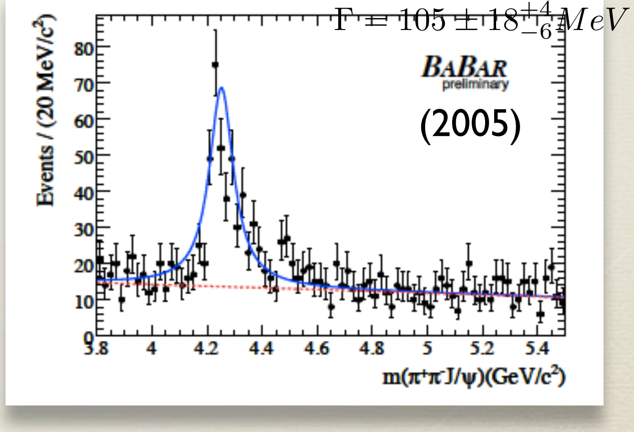
20XX experimental confirmation - discovery ?

- **Y(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(100MeV)



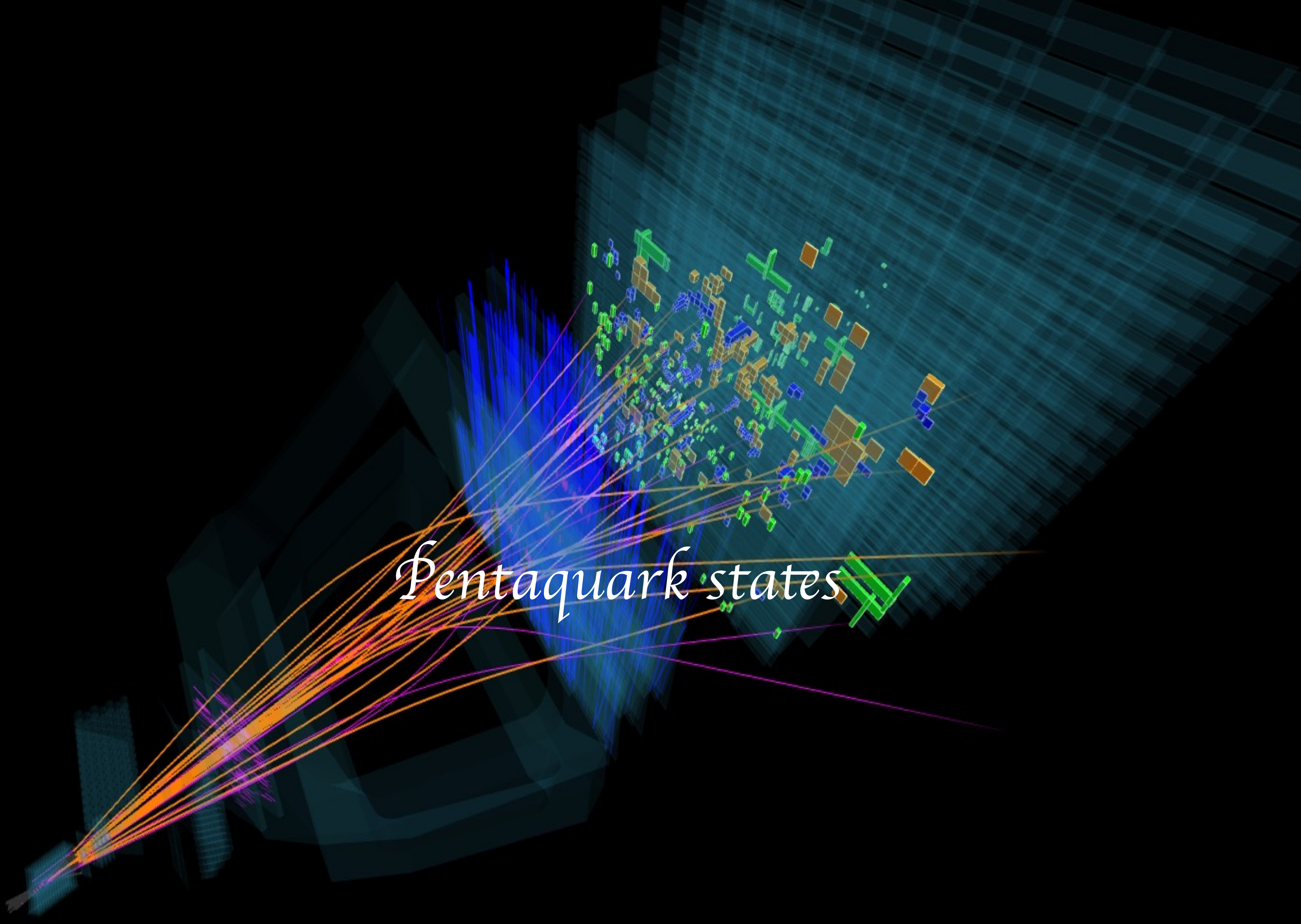

CLEO(2006)


Belle (2007)


$$M = 4252 \pm 6^{+2}_{-3} MeV$$
$$\Gamma = 105 \pm 18^{+4}_{-6} MeV$$
(2005)

✱ **Theory: Hybrid candidate**

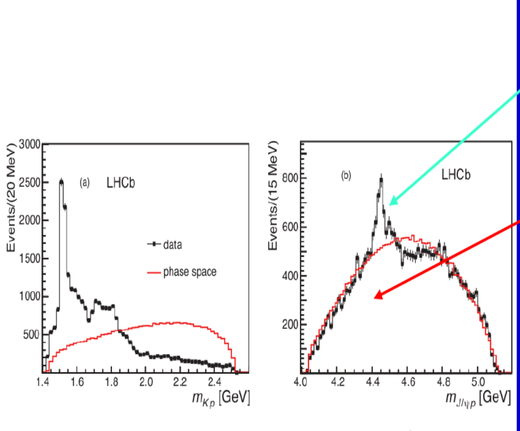
Pentaquark states



LHCb

Phys. Rev. Lett.115(2015) 072001

Why pentaquark states?



M _P_c^+(4450) = (4449.8 ± 8 ± 29)MeV

Γ = (39 ± 5 ± 19) MeV

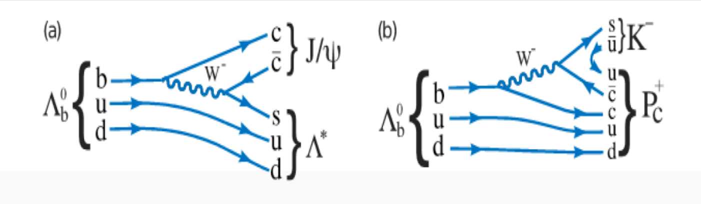
M_P_c^+(4380) = (4380 ± 1.7 ± 2.5)MeV

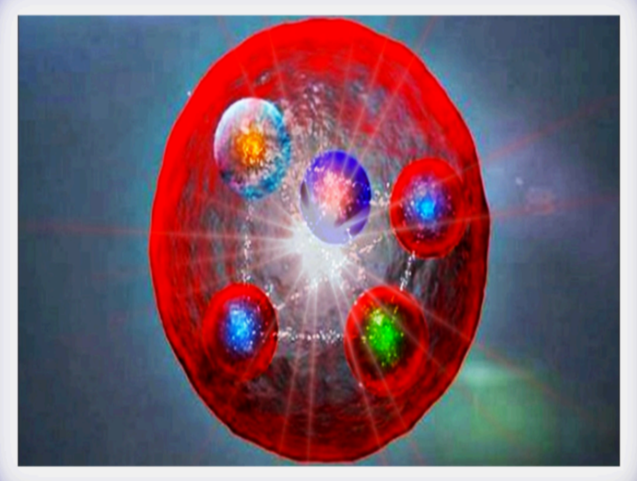
Γ =(205±18±86)MeV

statistic significance greater then 9 sigma !

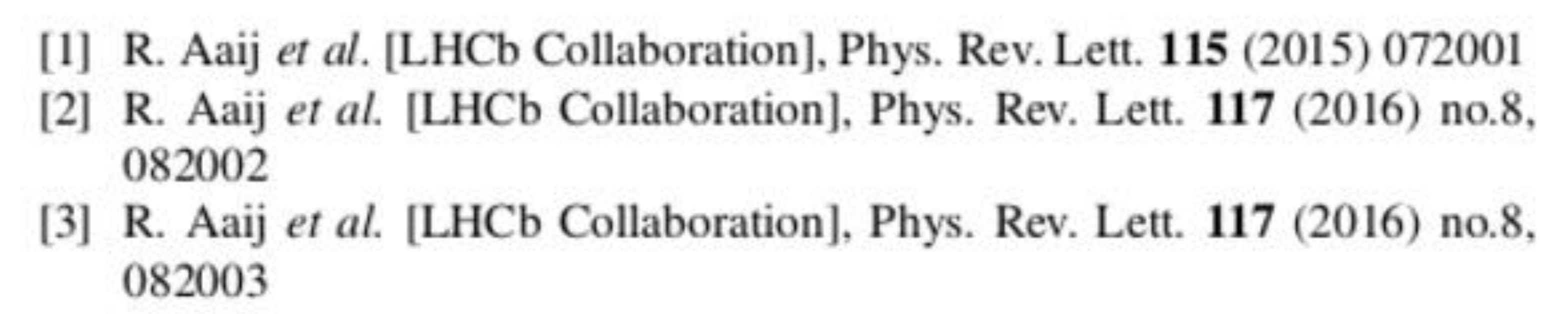
$$\Lambda_b^0 \longrightarrow J/\psi + \Lambda^*, \Lambda^* \longrightarrow K^- + p$$

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





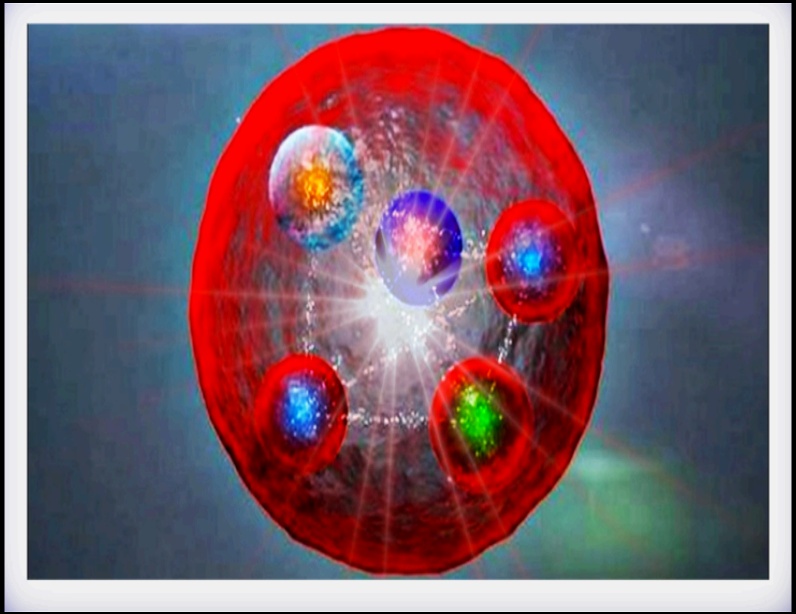
The LHCb observation [1] was further supported by another two articles by the same group [2,3]:



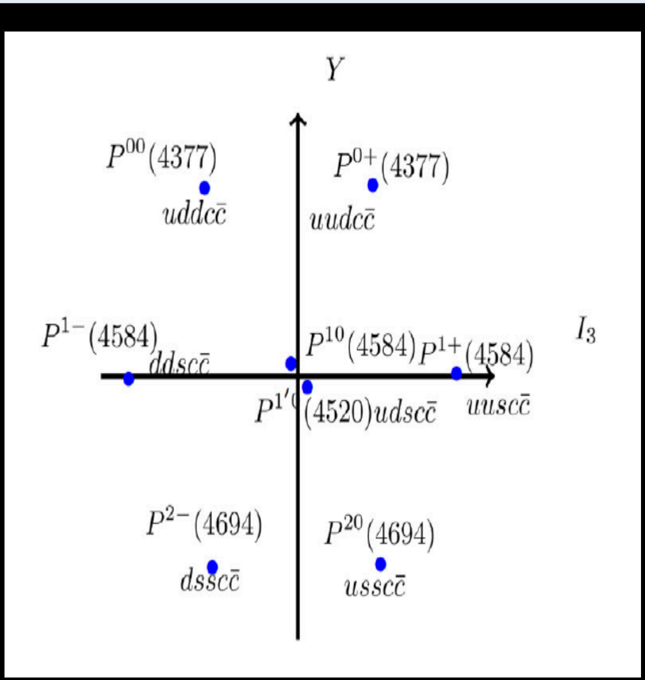
[1] R. Aaij *et al.* [LHCb Collaboration], Phys. Rev. Lett. **115** (2015) 072001
[2] R. Aaij *et al.* [LHCb Collaboration], Phys. Rev. Lett. **117** (2016) no.8, 082002
[3] R. Aaij *et al.* [LHCb Collaboration], Phys. Rev. Lett. **117** (2016) no.8, 082003

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 to an SU(3) flavour octet.
- The masses of the octet pentaquark states were calculated by means of a Gürsey-Radicati mass formula extension.



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

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

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

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 $\bar{D}^{(*)}\Sigma_c$

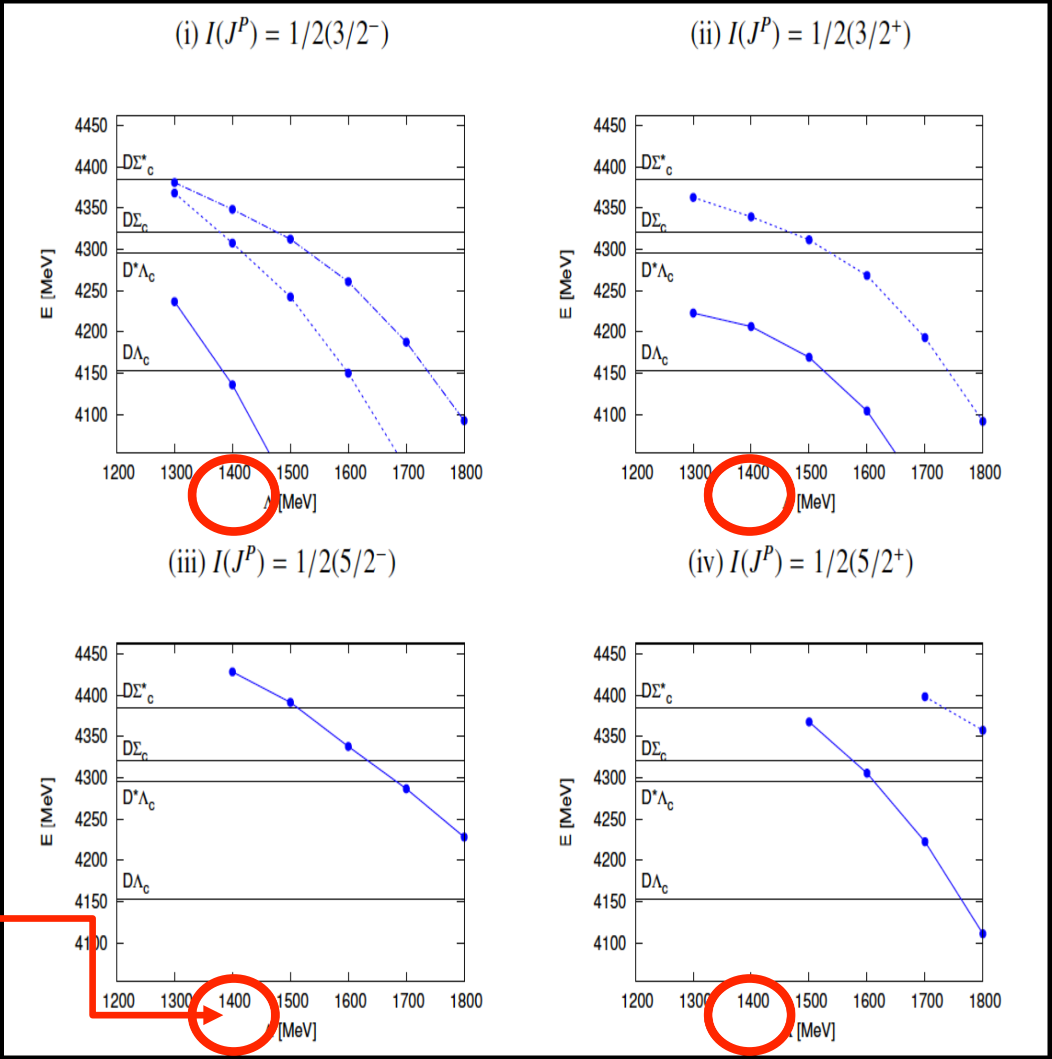
Y. Yamaguchi, E. S., Phys. Rev. D Phys.Rev. D96 (2017) no.1, 014018

- 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.**

↓

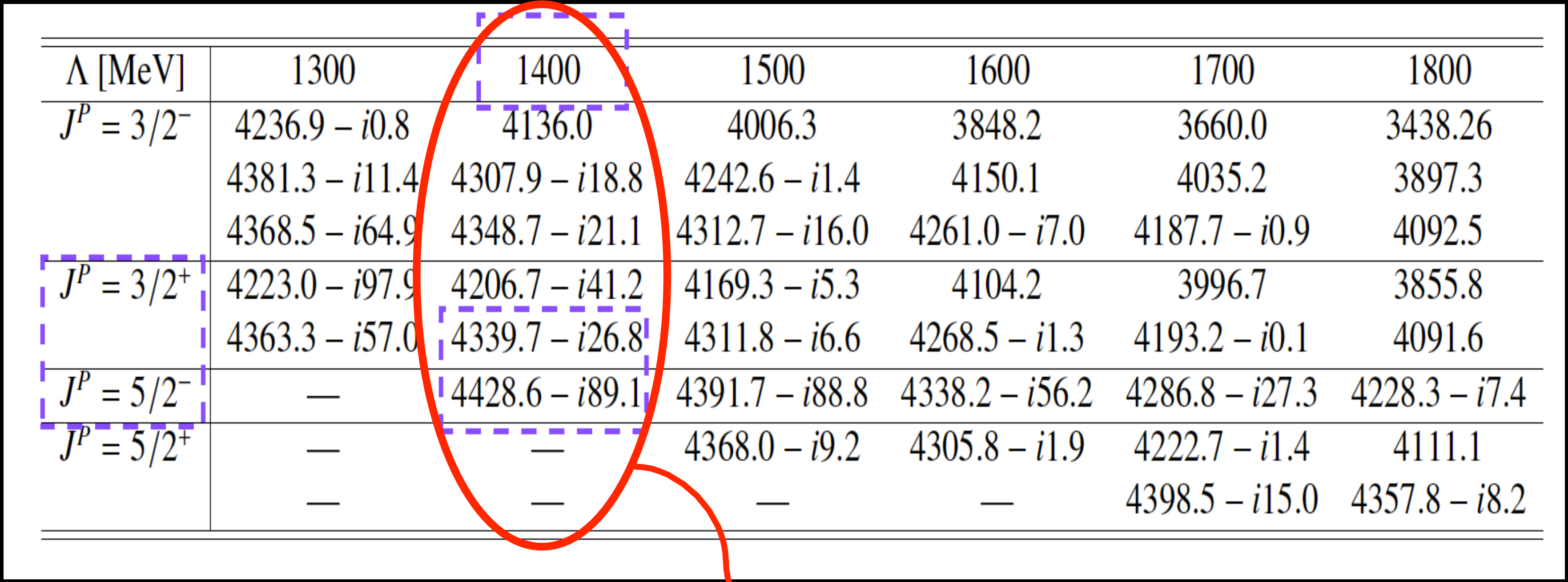
In Phys.Rev. D96 (2017) no.1, 014018 E. Santopinto e Y. Yamaguchi considered the coupled channel systems of $\bar{D}\,\Lambda_c$,$\bar{D}^*\,\Lambda_c$, $\bar{D}\,\Sigma_c$, $\bar{D}\Sigma_c^*$, $\bar{D}^*\,\Sigma_c$ and $\bar{D}^*\Sigma_c^*$ to predict the bound and the resonant states in the hidden-charm 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



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**

- 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

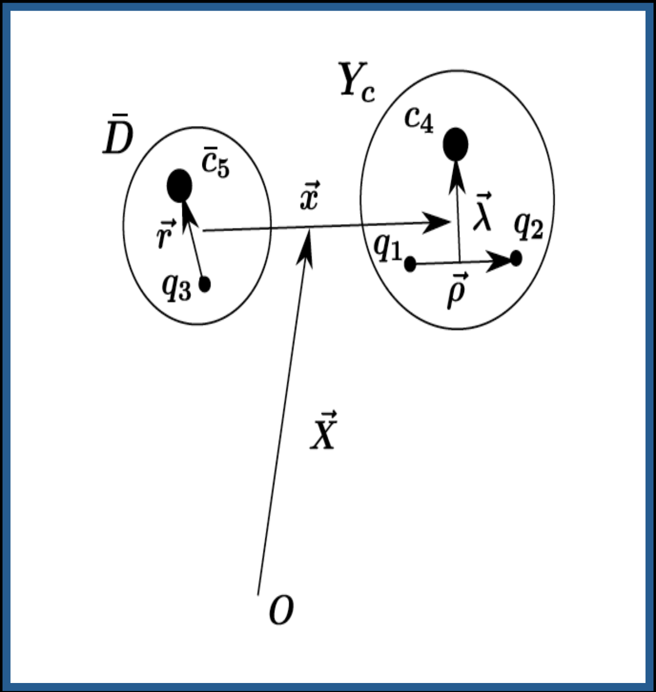
ADDITION OF THE CORE CONTRIBUTION

- 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 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}:

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

Kinetic energy and harmonic oscillator potential of the five quark

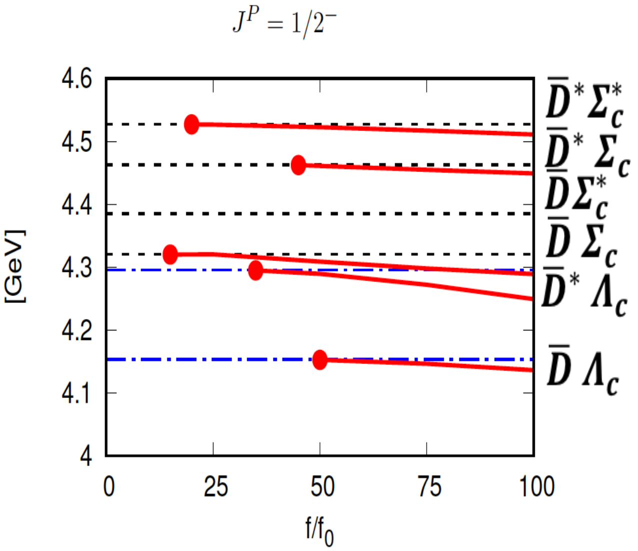
Results for the hidden-charm sector

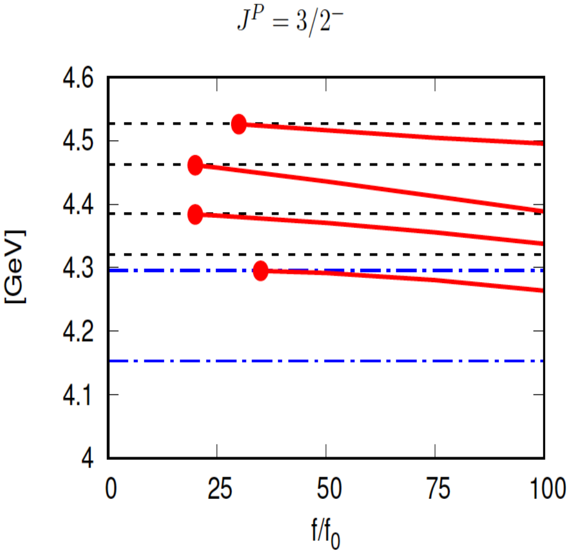
The lowest threshold $\bar{D}\,\Lambda_c$ is at $4153,46$ MeV and the state whose energy is lower than the threshold is a bound state.

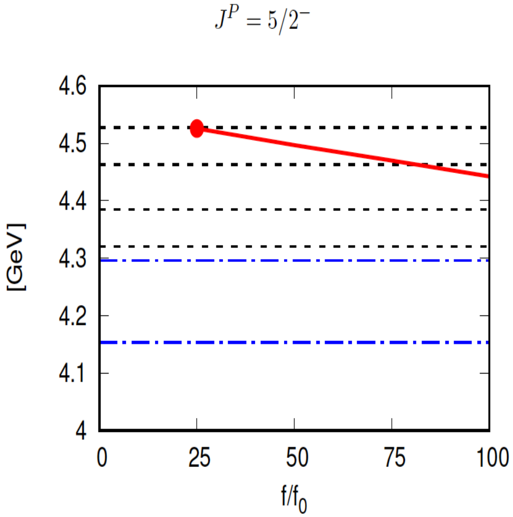
No resonant states and no bound states for $\frac{f}{f_0} = 0$

⇩

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







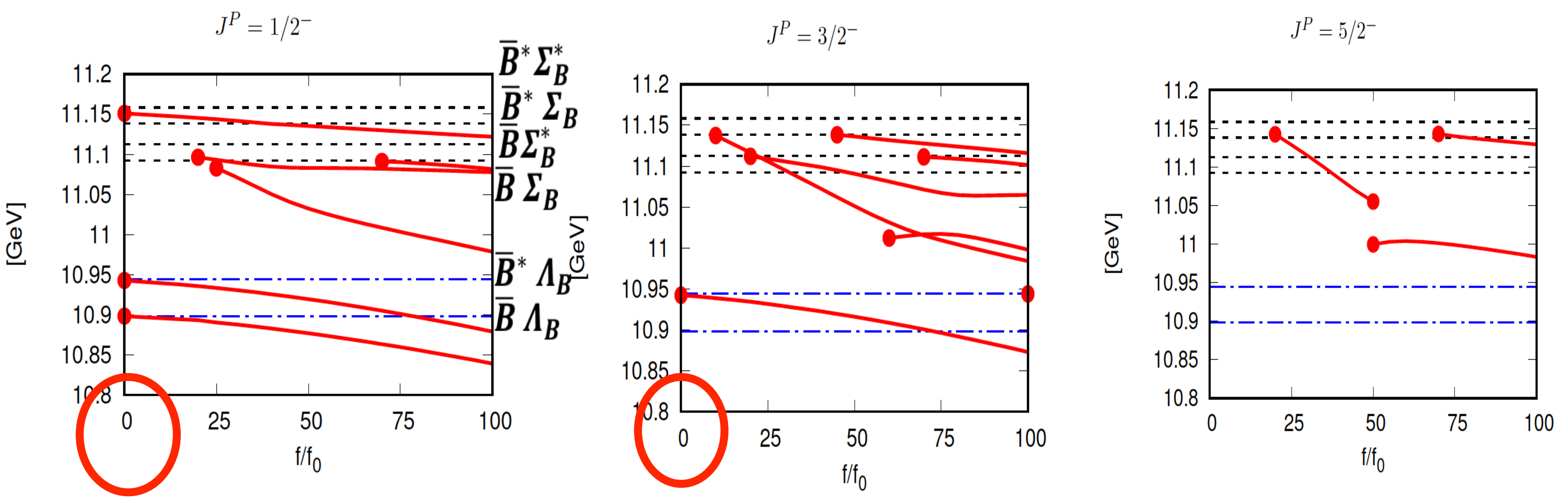
First results for the **hidden-bottom sector**

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

- 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^*