Hybrid and Pentaquark states

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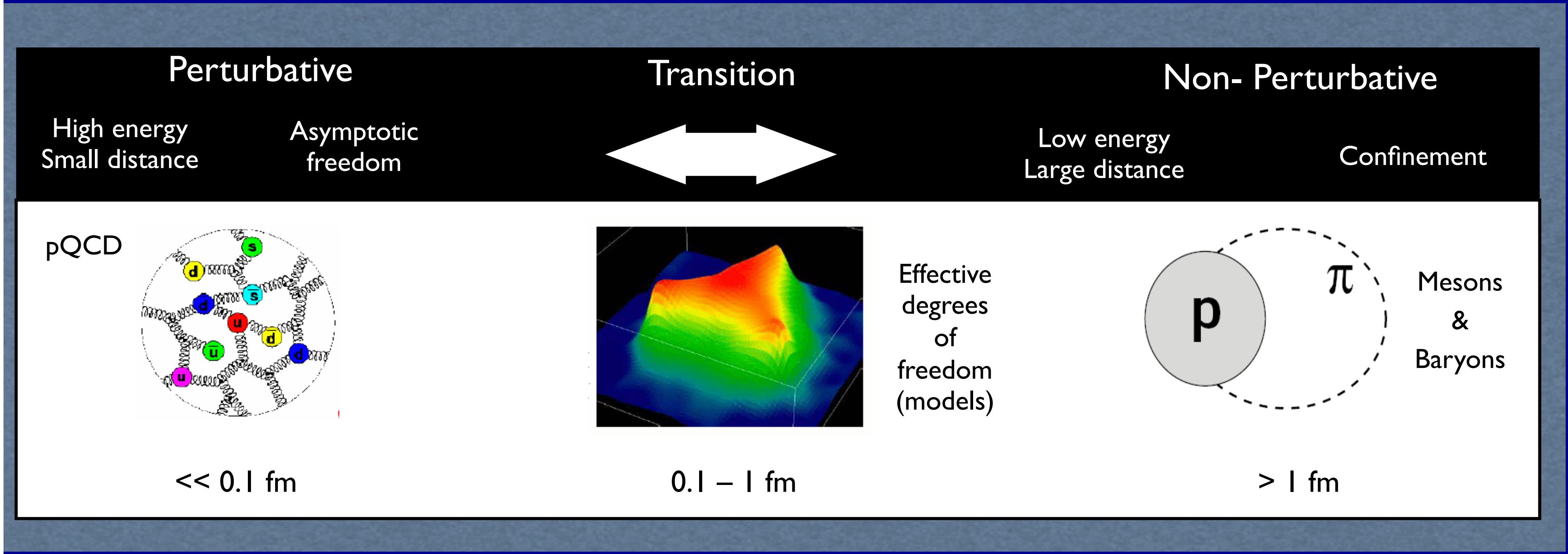
QCD@Work – 25-28 June 2018 **Matera,** 2018

Why Hadron Spectroscopy:

laboratory for studying non pQCD & confinement.



Hadron spectroscopy: lab. for QCD@ work

Bulk of mass of hadrons

Confinement

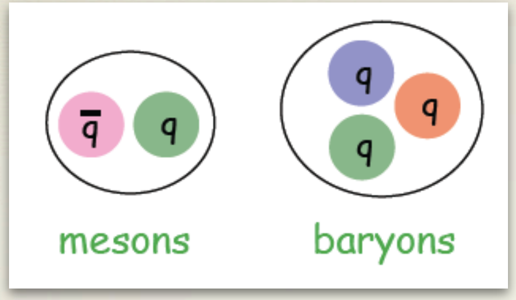
X,Y, Z, etc. new hadron states

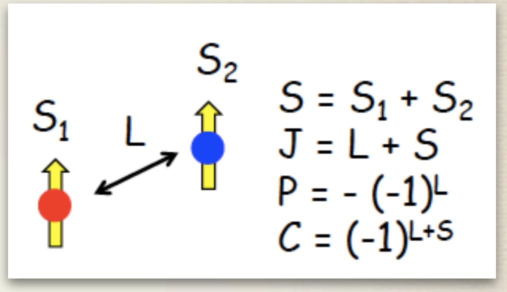
- Finally to claim new physics also in other sectors, a precise knowledge of non perturbative QCD observables is necessary if they are involved!

The gluons and the meson spectrum

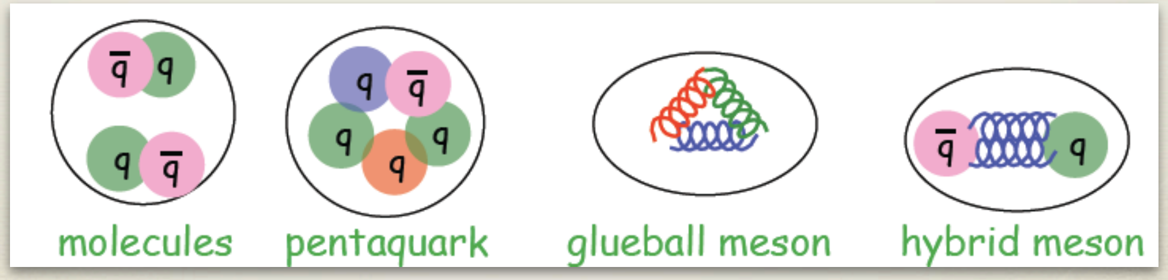
Neutralize color

... the simple way





... or the "exotic" way



(flavor) exotic

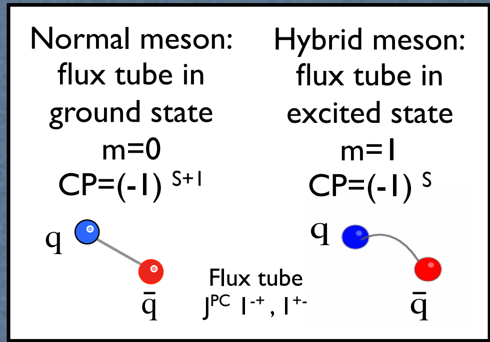
exotic of the II kind

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

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 ($J_g^{P_gC_g}$)
- Gluon adds in relative S-wave to a qq pair is S-wave or P-wave

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

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

qq in P-wave + $J_g^{P_gC_g}=1^{--}$ 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 $J_g^{P_gC_g}=1^{+-}$ in relative P-wave added to a qq pair is S-wave or P-wave

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

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

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

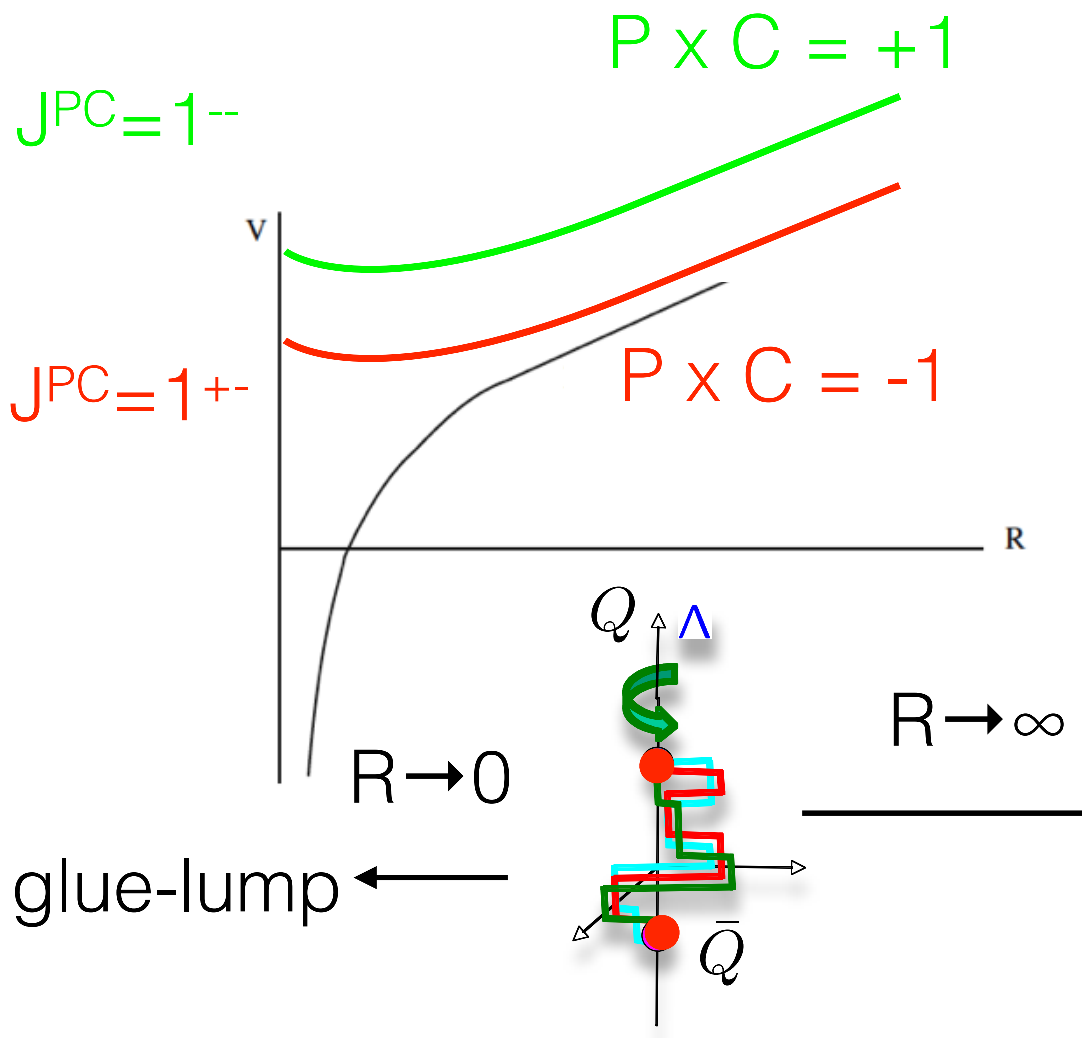
Lightest multiplet
$0^{+-}, (1^{+-})^3, (2^{+-})^2, 3^{+-}, (0,1,2)^{++}$

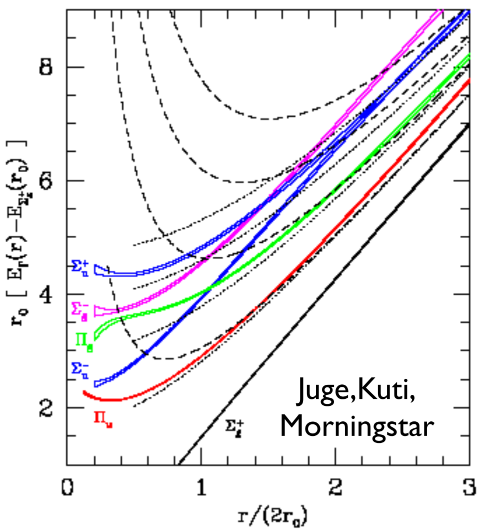
Starting from the study of the glue-lamp (lamp or ”grumo” of gluons or “ constituent gluon”) as obtained from QCD in physical gauge

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

Gluon chain model

Ostrander,Szczpaniak,Vassallo,E.S,PRD2014

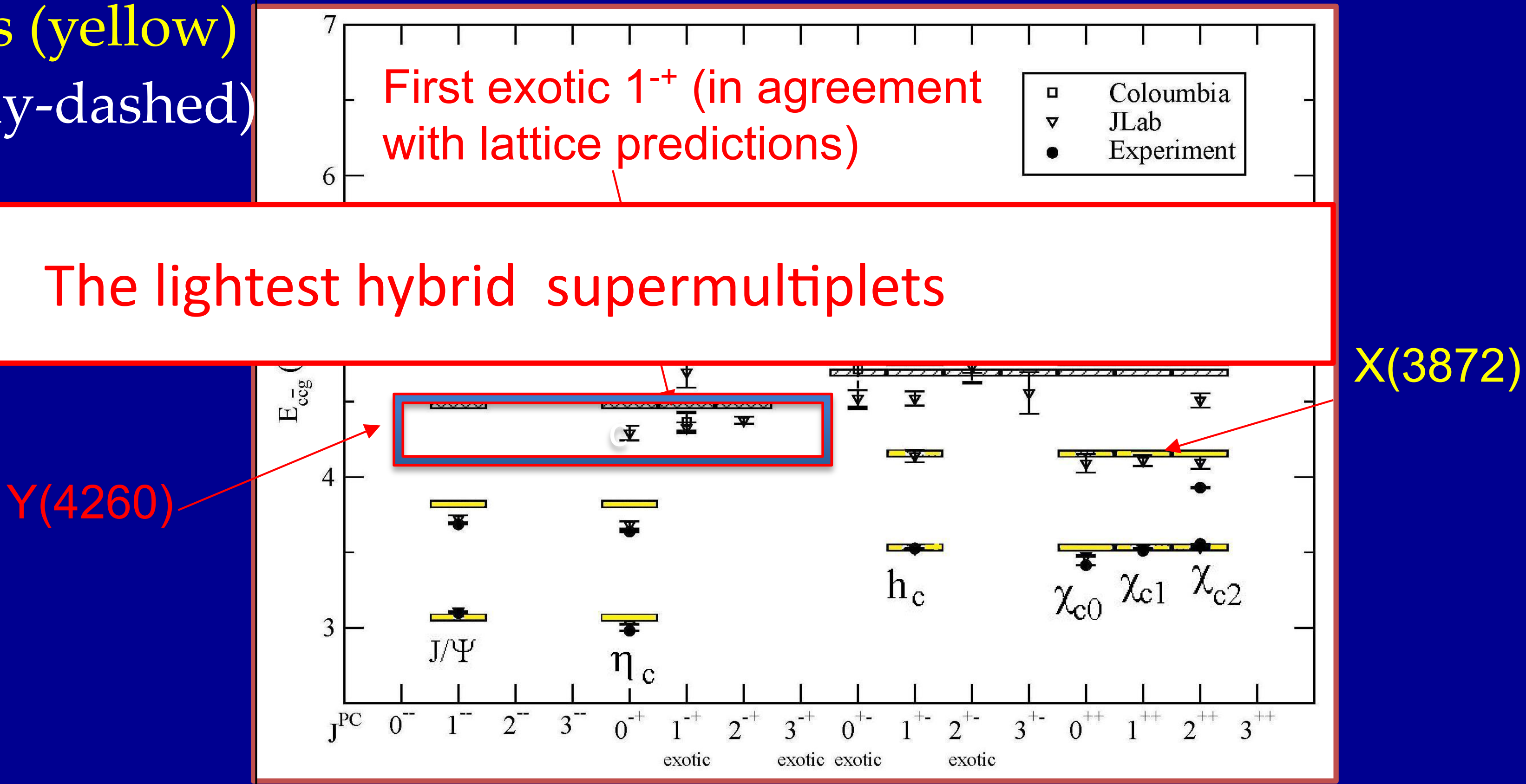
Charmonia (qq bar) & hybrids (qqg)

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

$J_g^{P_g}$	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), [?,?,?]

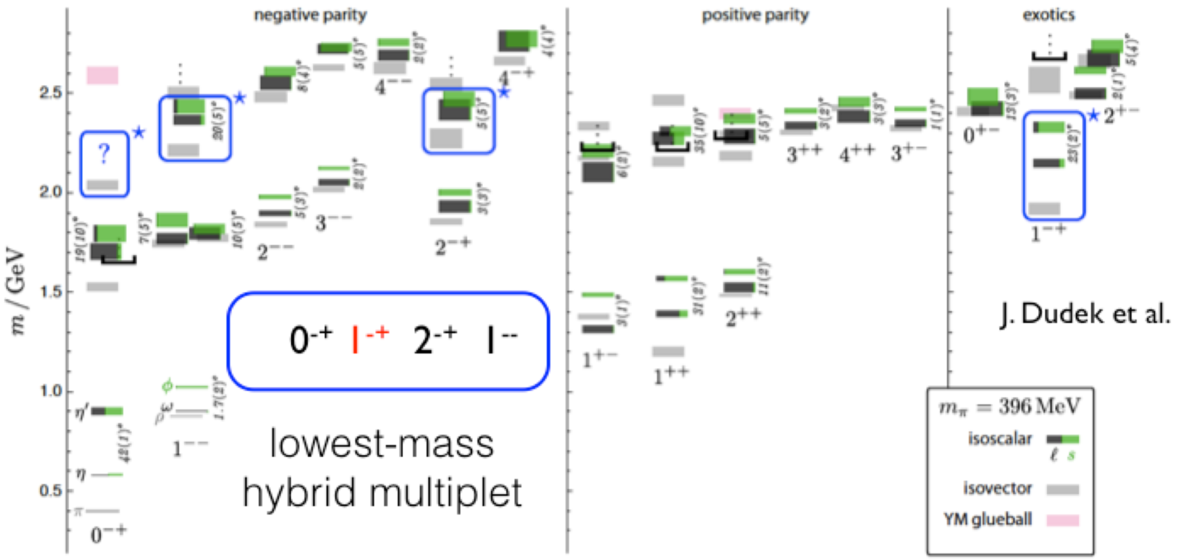
[14]:J. J. Dudek, R. G. Edwards, N. Mathur, and D. G.Richards, Phys. Rev. D 77, 034501 (2008).

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



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



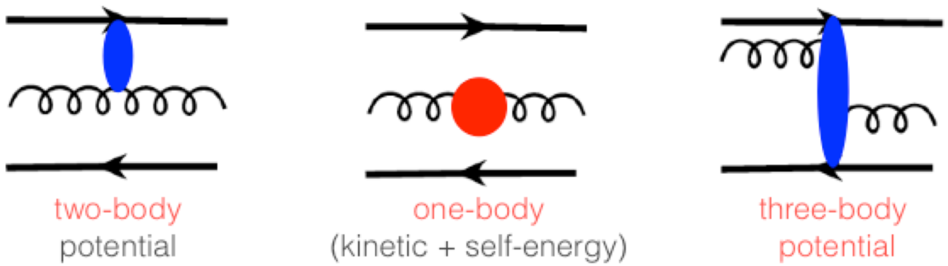
Physical gauge QCD (Hamiltonian)

J^{PC} glue

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

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

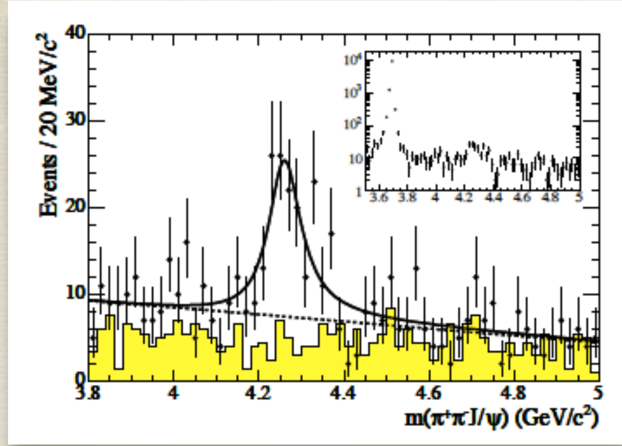
$$1^{+-} \times 1^{--}_{S_{Q\bar{Q}}=1} = \boxed{0^{-+}, 1^{-+}, 2^{-+}}$$

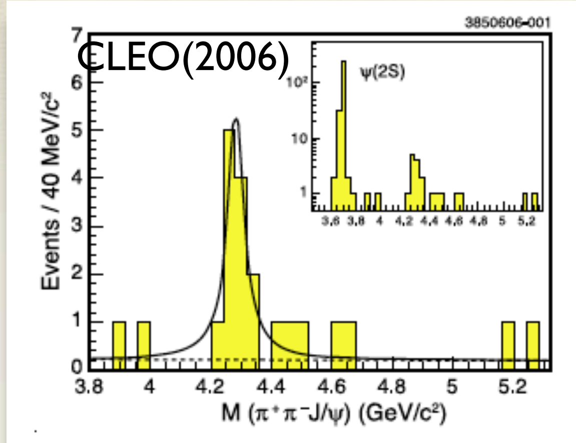


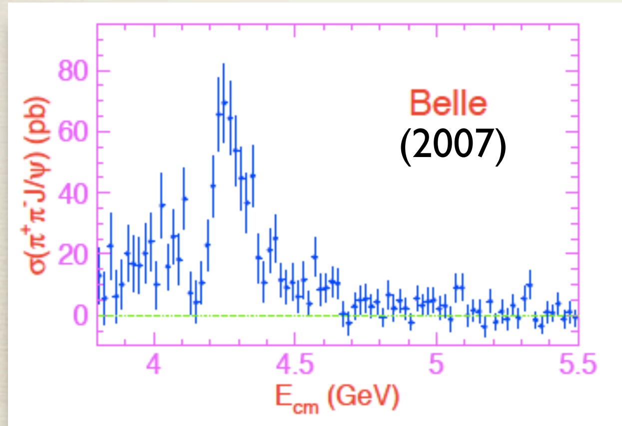
Guo,Szczpaniak,Galatà,Vassallo, E.S.,PRD2008

20XX experimental confirmation - discovery ?

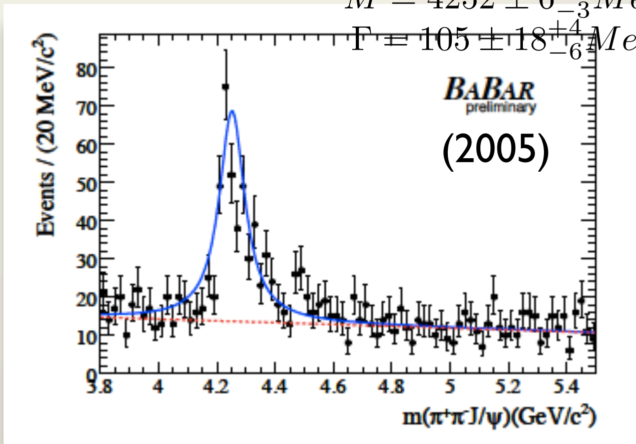
- **Y(4260)** **discovered by BaBar in J/ψ $\pi^+\pi^-$ (2005) confirmed by CLEO,Belle other modes from BaBar**
  $J^{PC}=1^{--}$ (from e^+e^-) width O(100MeV)



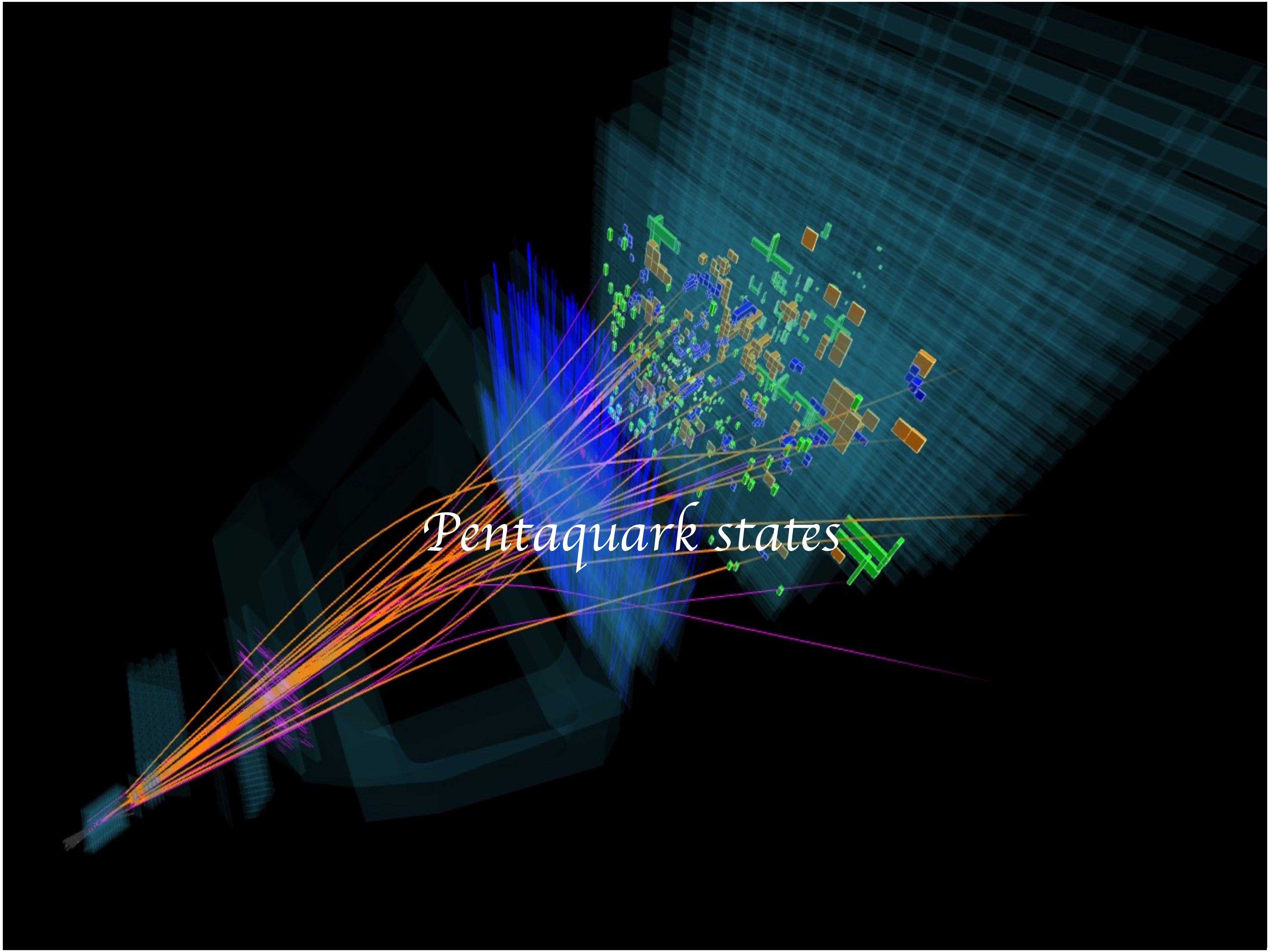




$$M = 4252 \pm 6^{+2}_{-3} MeV$$
$$\Gamma = 105 \pm 18^{+4}_{-6} MeV$$

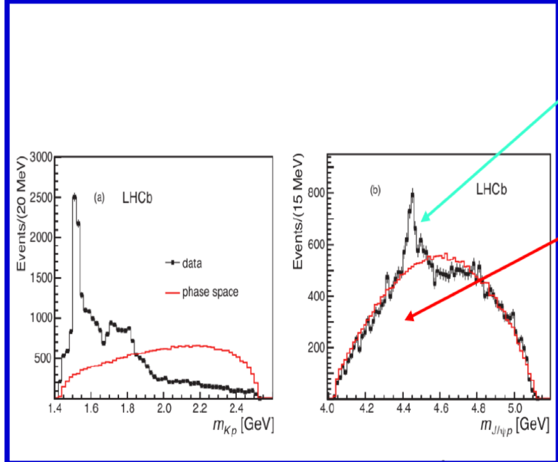


Theory: Hybrid candidate


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

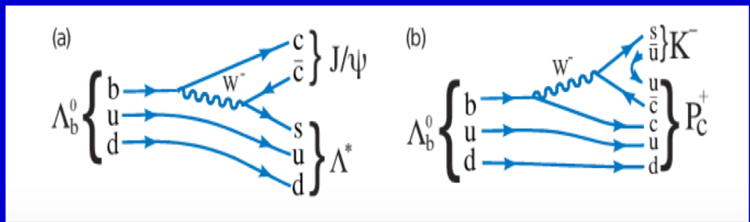
$M_P_c^+(4380) = (4380 \pm 1.7 \pm 2.5)$MeV

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

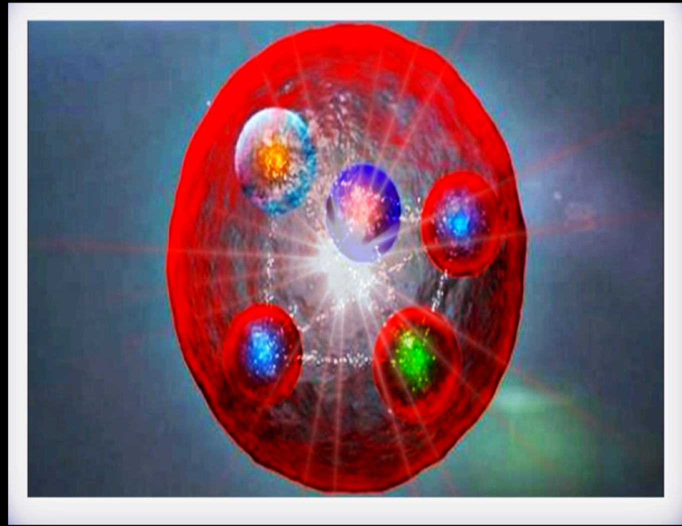
statistic significance greater then 9 sigma !

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

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



Why pentaquark states?



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

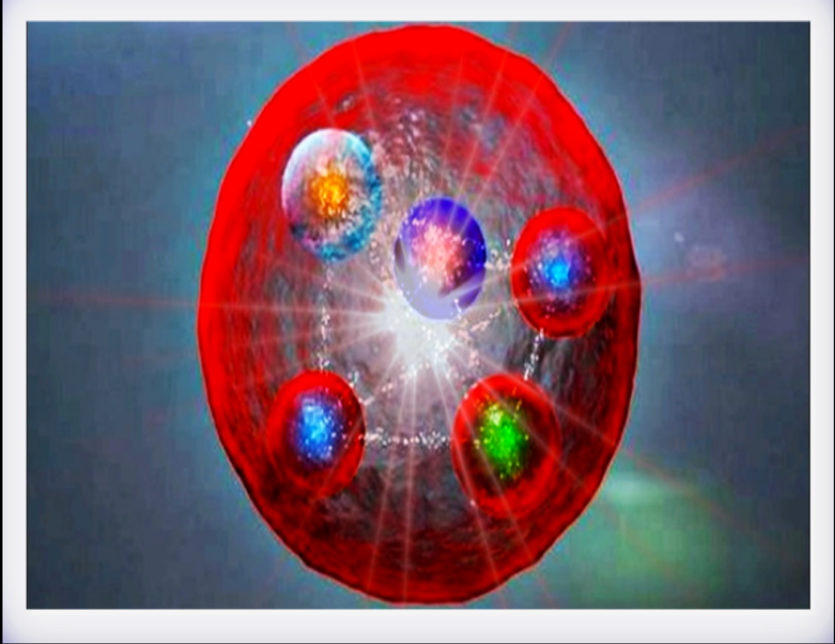
[1] R. Aaij *et al.* [LHCb Collaboration], Phys. Rev. Lett. **115** (2015) 072001

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

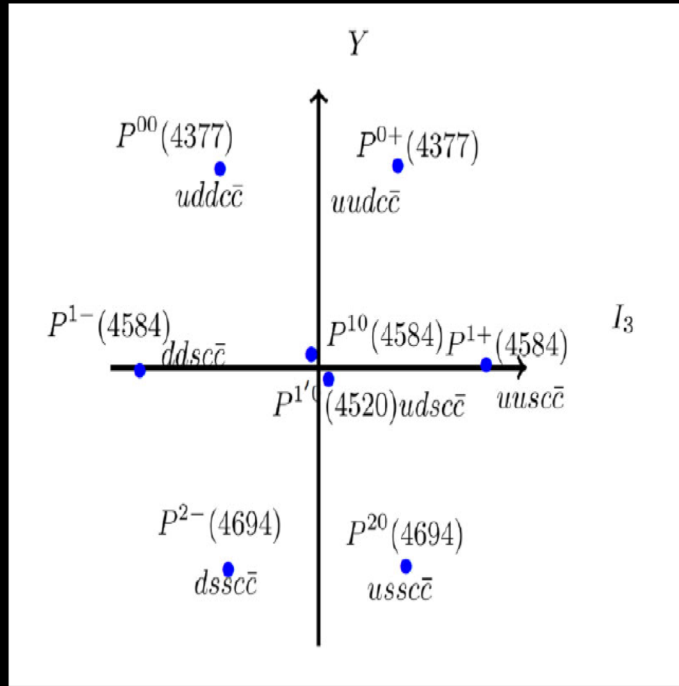
[3] R. Aaij *et al.* [LHCb Collaboration], Phys. Rev. Lett. **117** (2016) no.8, 082003

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.



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

- 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

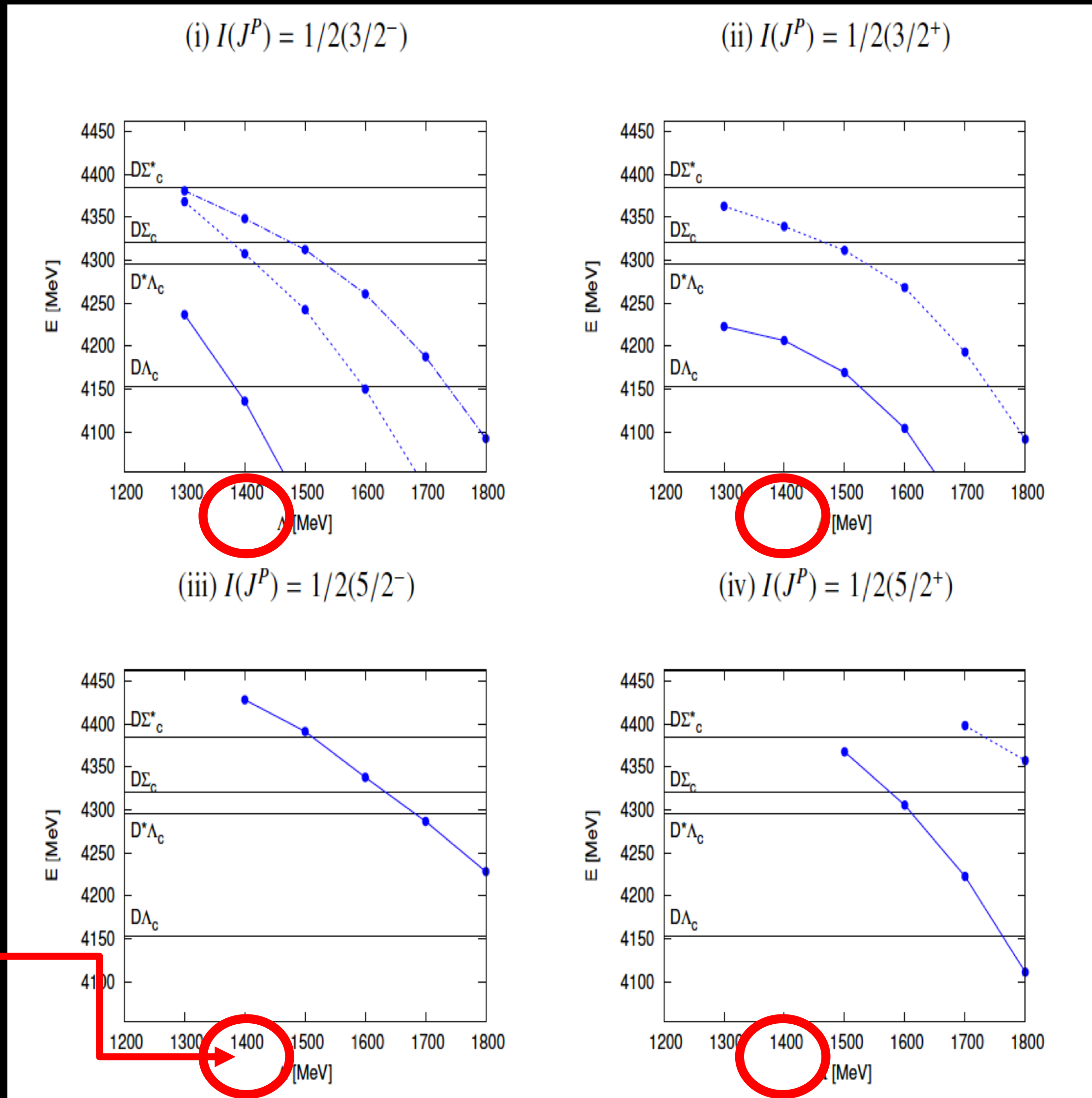
Hidden-charm pentaquarks as a meson-baryon molecule with coupled channels for $\bar{D}^{(*)}\Lambda_c$ and $\bar{D}^{(*)}\Sigma_c$

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

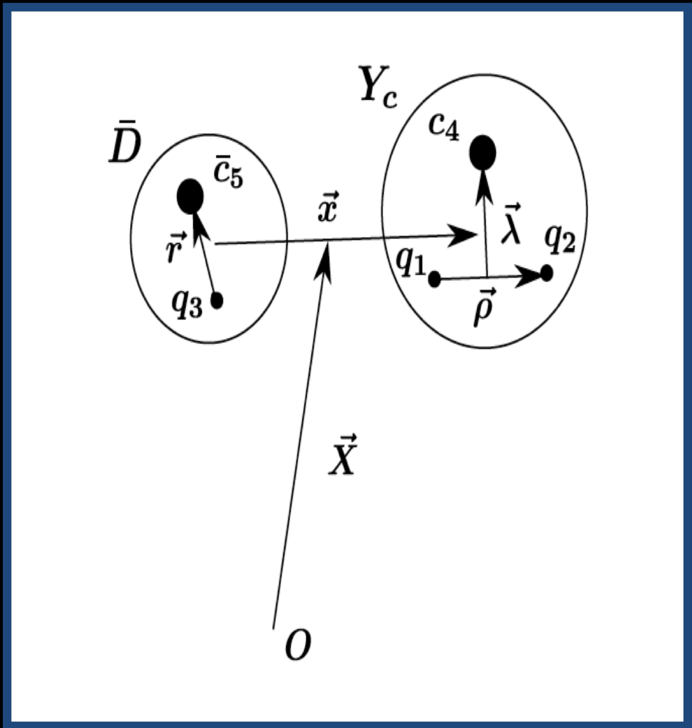
ADDITION OF THE CORE CONTRIBUTION

- 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}:

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

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

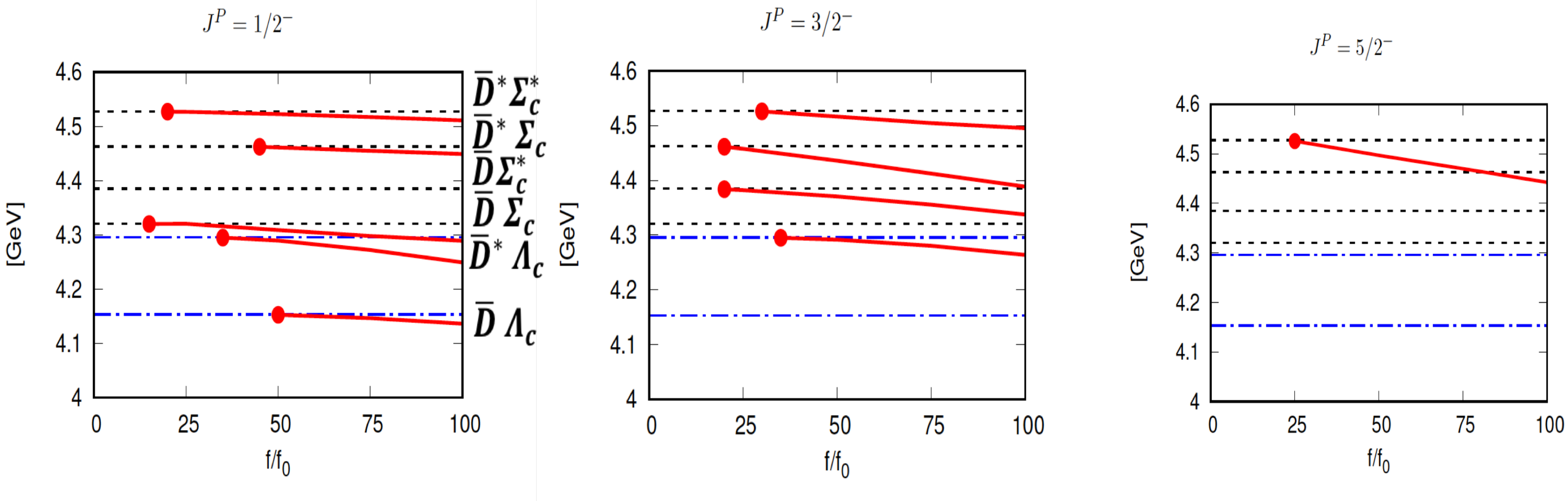
Results for the hidden-charm sector

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.



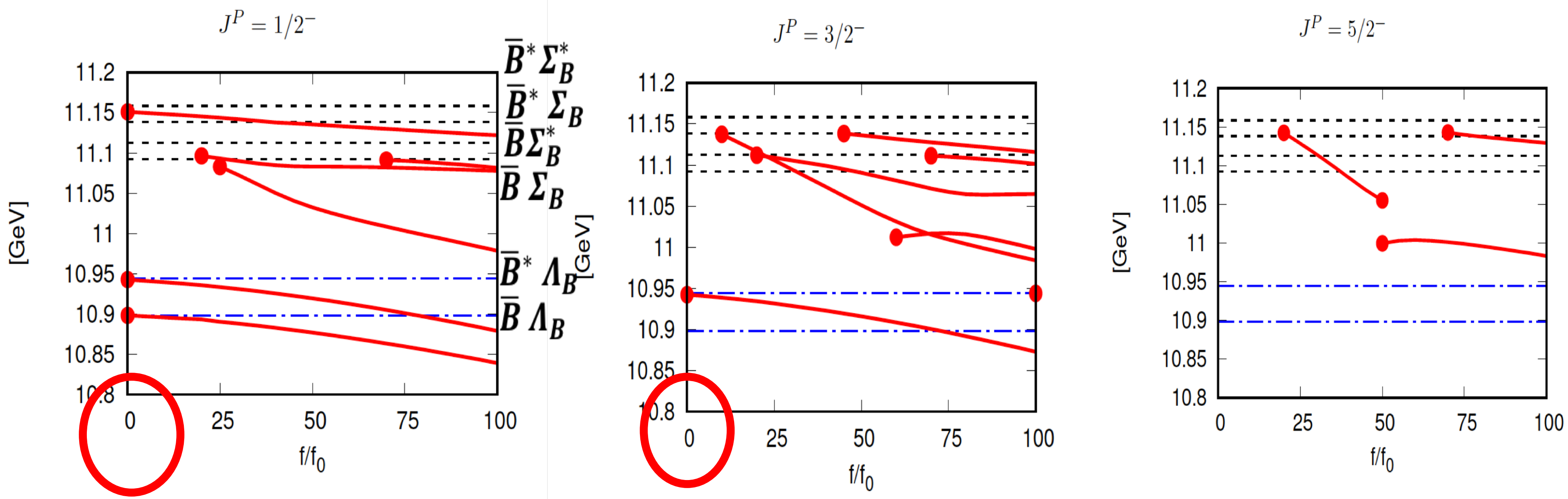
First results for the hidden-bottom sector

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

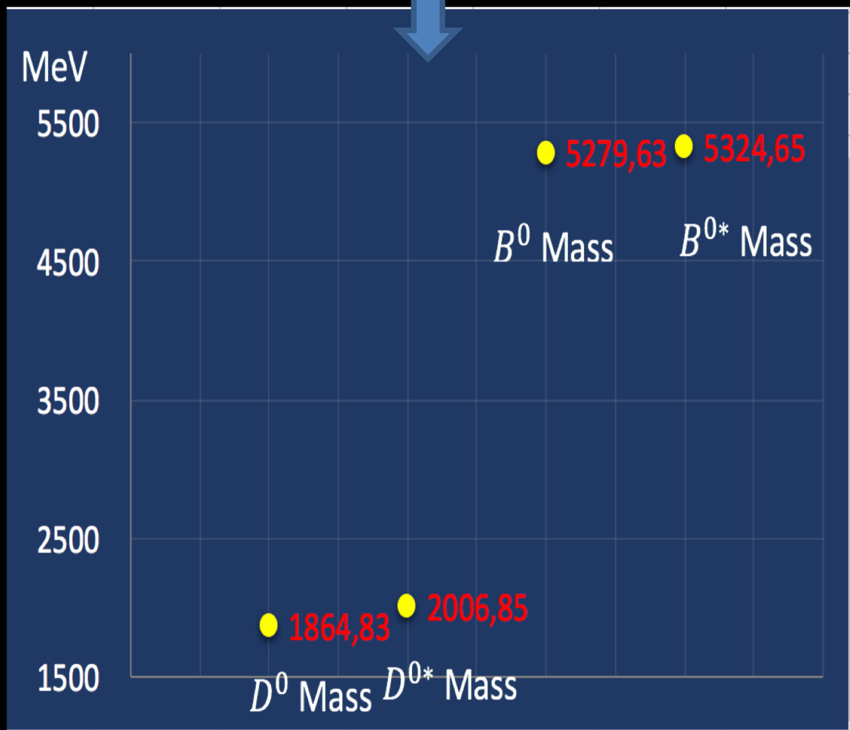
First results for the hidden-bottom sector

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

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^{*}



Task for the future

- **What does it happen if one consider a coupled channel**
  MB-core with a OMEP?

- **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.

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

Unquenching the quark model for the MESONS & Why Unquenching?

Santopinto, Galatà, Ferretti,Vassallo

UQM: Meson Self Energies & couple channels

- Hamiltonian:

$$H = H_0 + V$$

- H_0 act only in the bare meson space and it is chosen the Godfray and Isgur model
- V couples |A> to the continuum |BC>
- Dispersive equation

$$\Sigma(E_a) = \sum_{BC} \int_0^{\infty} q^2 dq \frac{|V_{a,bc}(q)|^2}{E_a - E_{bc}}$$

- from non-relativistic Schrödinger equation
- Bare energy E_a (H_0 eigenvalue) satisfies:

$$M_a = E_a + \Sigma(E_a)$$

- M_a = physical mass of meson A
- $\Sigma(E_a)$ = self energy of meson A

UQM: Meson Self Energies -- UQM I

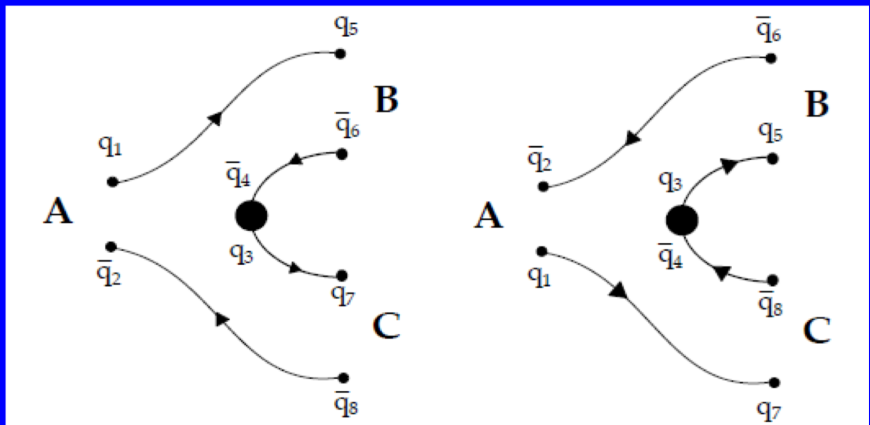
- Coupling $V_{a,bc}(q)$ in $\Sigma(E_a)$ calculated as:

$$V_{a,bc}(q) = \sum_{\ell J} \langle BC\vec{q}\ell J | T^\dagger | A \rangle$$

Sum over a complete set of accesible ground state (1S) mesons

Coupling calculated in the $^3P_0$ model

- Two possible diagrams contribute:



- Self energy in the UQM:

$$\Sigma(E_a) = \sum_{BC\ell J} \int_0^\infty q^2 dq \frac{|\langle BC\vec{q}\ell J | T^\dagger | A \rangle|^2}{E_a - E_b - E_c}$$

Godrey and Isgur model as bare mass

- Bare energies E_a calculated in the relativized G.I.Model for mesons
- Hamiltonian:

$$H = \sqrt{q^2 + m_1^2} + \sqrt{q^2 + m_2^2} + V_{\text{conf}} + V_{\text{hyp}} + V_{\text{so}}$$

- Confining potential:

$$V_{\text{conf}} = -\left(\frac{3}{4}c + \frac{3}{4}br - \frac{\alpha_s(r)}{r}\right)\vec{F}_1 \cdot \vec{F}_2$$

- Hyperfine interaction:

$$\begin{aligned} V_{\text{hyp}} &= -\frac{\alpha_s(r)}{m_1 m_2}\left[\frac{8\pi}{3}\vec{S}_1 \cdot \vec{S}_2\, \delta^3(\vec{r}) \right. \\ &\left. + \frac{1}{r^3}\left(\frac{3\, \vec{S}_1 \cdot \vec{r}\, \vec{S}_2 \cdot \vec{r}}{r^2} - \vec{S}_1 \cdot \vec{S}_2\right)\right] \vec{F}_i \cdot \vec{F}_j \end{aligned}$$

- Spin-orb. :

$$\begin{aligned} V_{\text{so,cm}} &= -\frac{\alpha_s(r)}{r^3}\left(\frac{1}{m_i} + \frac{1}{m_j}\right) \\ &\left(\frac{\vec{S}_i}{m_i} + \frac{\vec{S}_j}{m_j}\right) \cdot \vec{L}\ \ \vec{F}_i \cdot \vec{F}_j \end{aligned}$$

$$V_{\text{so,tp}} = -\frac{1}{2r}\frac{\partial H_{ij}^{conf}}{\partial r}\left(\frac{\vec{S}_i}{m_i^2} + \frac{\vec{S}_j}{m_j^2}\right) \cdot \vec{L}$$

UQM or couple channel Quark Model

- Parameters of the relativized QM fitted to

$$M_a = E_a + \Sigma(E_a)$$

- Recursive fitting procedure

- M_a = calculated physical masses of q bar-q mesons → reproduce experimental spectrum [PDG]

- Intrinsic error of QM/UQM calculations: 30-50 MeV

UQM: charmonium with self-energy corr.

- Parameters of the UQM ($^3P_0$ vertices)

Parameter	Value
γ_0	0.510
α	0.500 GeV
r_q	0.335 fm
m_n	0.330 GeV
m_s	0.550 GeV
m_c	1.50 GeV

- fitted to:

State	DD	DD^*	D^*D^*	D_sD_s	$D_sD_s^*$	$D_s^*D_s^*$	Total	Exp.
$\eta_c(3^1S_0)$	–	38.8	52.3	–	–	–	91.1	–
$\Psi(4040)(3^3S_1)$	0.2	37.2	39.6	3.3	–	–	80.3	80 ± 10
$h_c(2^1P_1)$	–	64.6	–	–	–	–	64.6	–
$\chi_{c0}(2^3P_0)$	97.7	–	–	–	–	–	97.7	–
$\chi_{c2}(2^3P_2)$	27.2	9.8	–	–	–	–	37.0	–
$\Psi(3770)(1^3D_1)$	27.7	–	–	–	–	–	27.7	27.2 ± 1.0
$c\bar{c}(1^3D_3)$	1.7	–	–	–	–	–	1.7	–
$c\bar{c}(2^1D_2)$	–	62.7	46.4	–	8.8	–	117.9	–
$\Psi(4160)(2^3D_1)$	11.2	0.4	39.4	2.1	5.6	–	58.7	103 ± 8
$c\bar{c}(2^3D_2)$	–	43.5	49.3	–	11.3	–	104.1	–
$c\bar{c}(2^3D_3)$	17.2	58.3	48.1	3.6	2.6	–	129.8	–

UQM: charmonium spectrum with self-energy corr.

Ferretti, Galata' and Santopinto, Phys. Rev. C 88, 015207 (2013)

State	J^{PC}	$D\bar{D}$	$\bar{D}D^*$ $D\bar{D}^*$	$\bar{D}^*D^*$	$D_s\bar{D}_s$	$D_s\bar{D}_s^*$ $\bar{D}_sD_s^*$	$D_s^*\bar{D}_s^*$	$\eta_c\eta_c$	η_cJ/Ψ	$J/\Psi J/\Psi$	$\Sigma(E_a)$	E_a	M_a	$M_{exp.}$
$\eta_c(1^1S_0)$	0^{-+}	–	-34	-31	–	-8	-8	–	–	-2	-83	3062	2979	2980
$J/\Psi(1^3S_1)$	1^{--}	-8	-27	-41	-2	-6	-10	–	-2	–	-96	3233	3137	3097
$\eta_c(2^1S_0)$	0^{-+}	–	-52	-41	–	-9	-8	–	–	-1	-111	3699	3588	3637
$\Psi(2^3S_1)$	1^{--}	-18	-42	-54	-2	-7	-10	–	-1	–	-134	3774	3640	3686
$h_c(1^1P_1)$	1^{+-}	–	-59	-48	–	-11	-10	–	-2	–	-130	3631	3501	3525
$\chi_{c0}(1^3P_0)$	0^{++}	-31	–	-72	-4	–	-15	0	–	-3	-125	3555	3430	3415
$\chi_{c1}(1^3P_1)$	1^{++}	–	-54	-53	–	-9	-11	–	–	-2	-129	3623	3494	3511
$\chi_{c2}(1^3P_2)$	2^{++}	-17	-40	-57	-3	-8	-10	0	–	-2	-137	3664	3527	3556
$h_c(2^1P_1)$	1^{+-}	–	-55	-76	–	-12	-8	–	-1	–	-152	4029	3877	–
$\chi_{c0}(2^3P_0)$	0^{++}	-23	–	-86	-1	–	-13	0	–	-1	-124	3987	3863	–
$\chi_{c1}(2^3P_1)$	1^{++}	–	-30	-66	–	-11	-9	–	–	-1	-117	4025	3908	3872
$\chi_{c2}(2^3P_2)$	2^{++}	-2	-42	-54	-4	-8	-10	0	–	-1	-121	4053	3932	3927
$c\bar{c}(1^1D_2)$	2^{-+}	–	-99	-62	–	-12	-10	–		[illegible]	[illegible]	[illegible]	[illegible]	
$\Psi(3770)(1^3D_1)$	1^{--}	-11	-40	-84	-4	-2	-16	–						
$c\bar{c}(1^3D_2)$	2^{--}	–	-106	-61	–	-11	-11	–						
$c\bar{c}(1^3D_3)$	3^{--}	-25	-49	-88	-4	-8	-10	–						

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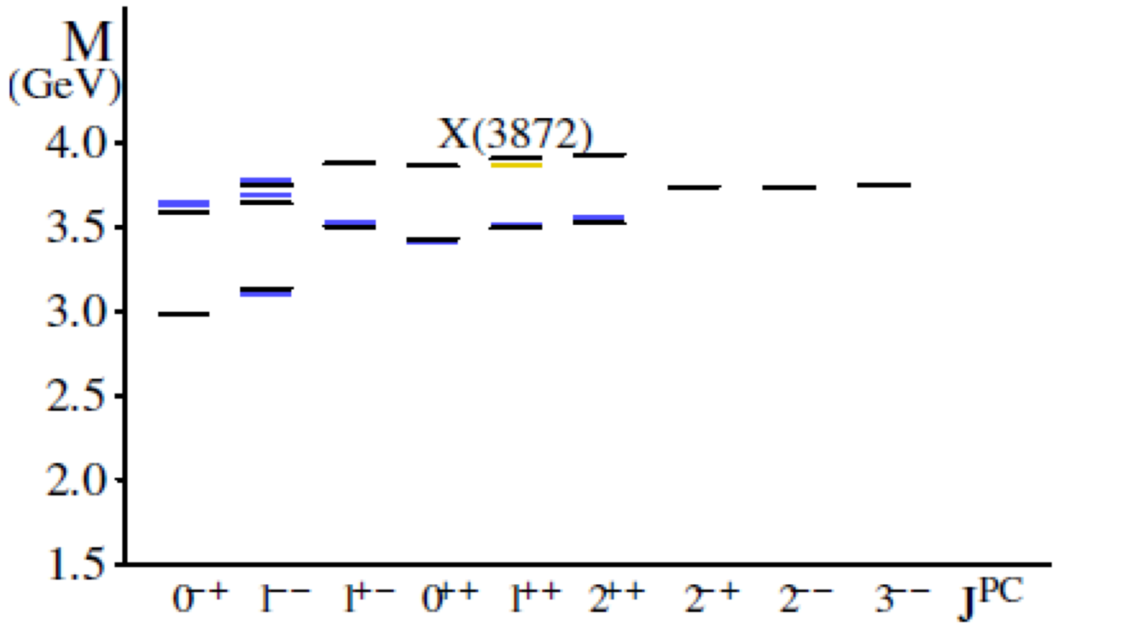


M [X(3872); UQM] = 3908 MeV

UQM: charmonium with self-energy corr.

Ferretti, Galatà, Santopinto, Phys. Rev. C 88, 015207 (2013)

- Experimental mass: 3871.68 ± 0.17 MeV [PDG]
- Several predictions for X(3872)'s mass. Here: c bar-c + continuum effects

$\chi_{c1}(2^3P_1)$'s mass (MeV)	Reference
3908	This paper
4007.5	[2]
3990	[3]
3920.5	[4]
3896	[5]

- [1] Ferretti, Galata' and Santopinto, Phys. Rev. C **88**, 015207 (2013);
- [2] Eichten et al., Phys. Rev. D 69,(2004)
- [3] Kalashnikova, Phys. Rev. D 72, 034010 (2005)
- [4] Eichten et al., Phys. Rev. D 73, 014014 (2008)
- [5] Pennington and Wilson, Phys. Rev. D 76, 077502 (2007)

Interpretation of the X(3872) as a charmonium state plus an extra component due to the coupling to the meson-meson continuum

Ferretti,Galatà, Santopinto, **Phys. Rev. C88 (2013) 1, 015207**

- UCQM results used to study the problem of the **X(3872)** mass, meson with $J^{PC} = 1^{++}$, 2^3P_1 quantum numbers
- Experimental mass: 3871.68 ± 0.17 MeV [PDG]
- X(3872) very close to D bar-D* decay threshold
- Possible importance of continuum coupling effects?
- Several interpretations: pure c bar-c
- D bar-D* molecule
- tetraquark
- c bar-c + continuum effects

nessary to study strong and radiative decays to uderstand the situation

Radiative decays

Ferretti,Galatà,Santopinto,Phys.Rev. D90 (2014) 5, 054010

Transition	E_γ [MeV]	$\Gamma_{c\bar{c}}$ [KeV] present paper	$\Gamma_{D\bar{D}^*}$ [KeV] Ref. [7]	$\Gamma_{D\bar{D}^*}$ [KeV] Ref. [9]	$\Gamma_{D\bar{D}^*}$ [KeV] Ref. [59]	$\Gamma_{c\bar{c}+D\bar{D}^*}$ [KeV] Ref. [60]	$\Gamma_{exp.}$ [KeV] PDG [43]
$X(3872) \to J/\Psi\gamma$	697	11	8	64 – 190	125 – 251	2 – 17	≈ 7
$X(3872) \to \Psi(2S)\gamma$	181	70	0.03			7 – 59	≈ 36
$X(3872) \to \Psi(3770)\gamma$	101	4.0	0				
$X(3872) \to \Psi_2(1^3D_2)\gamma$	34	0.35	0				

[7] Swanson: molecular interpretation
[9] Oset: moleacular interpretation
[59]-[60] Faessler : molecular ; ccbar +molecular

The Molecular model does not predict radiative decays into Ψ(3770) and $\Psi_2(1^3D_2)$-→ Possible way to distinguish between the two interpretations

Bottomonium spectrum (in couple channel calculations)

Ferretti, Santopintio, Phys.Rev. D90, 094022 (2014)

- Parameters of the UQM ($^3P_0$ vertices)

Parameter	Value
γ_0	0.732
α	0.500 GeV
r_q	0.335 fm
m_n	0.330 GeV
m_s	0.550 GeV
m_c	1.50 GeV
m_b	4.70 GeV

- Pair-creation strength γ_0 fitted to:

$$\begin{aligned}\Gamma_{\Upsilon(4S)\to B\bar{B}} &= 2\Phi_{A\to BC}\left|\langle BC\vec{q}_0\,\ell J|T^\dagger|A\rangle\right|^2 \\ &= 2\Phi_{\Upsilon(4S)\to B\bar{B}} \\ &\quad \left|\langle B\bar{B}\vec{q}_0\,11|T^\dagger|\Upsilon(4S)\rangle\right|^2 \\ &= 21\ \text{MeV}\ ,\end{aligned}$$

Bottomonium Strong Decays

Ferretti, Santopinto, Phys.Rev. D90 094022 (2014)

State	Mass [MeV]	J^{PC}	BB	BB^* $\bar{B}B^*$	B^*B^*	B_sB_s	$B_sB_s^*$ $\bar{B}_sB_s^*$	$B_s^*B_s^*$
$\Upsilon(4^3S_1)$	10.595 $10579.4 \pm 1.2^\dagger$	1^{--}	21	–	–	–	–	–
$\chi_{b2}(2^3F_2)$	10585	2^{++}	34	–	–	–	–	–
$\Upsilon(3^3D_1)$	10661	1^{--}	23	4	15	–	–	–
$\Upsilon_2(3^3D_2)$	10667	2^{--}	–	37	30	–	–	–
$\Upsilon_2(3^1D_2)$	10668	2^{-+}	–	55	57	–	–	–
$\Upsilon_3(3^3D_3)$	10673	3^{--}	15	56	113	–	–	–
$\chi_{b0}(4^3P_0)$	10726	0^{++}	26	–	24	–	–	–
$\Upsilon_3(2^3G_3)$	10727	3^{--}	3	43	39	–	–	–
$\chi_{b1}(4^3P_1)$	10740	1^{++}	–	20	1	–	–	–
$h_b(4^1P_1)$	10744	1^{+-}	–	33	5	–	–	–
$\chi_{b2}(4^3P_2)$	10751	2^{++}	10	28	5	1	–	–
$\chi_{b2}(3^3F_2)$	10800	2^{++}	5	26	53	2	2	–
$\Upsilon_3(3^1F_3)$	10803	3^{+-}	–	28	46	–	3	–
$\Upsilon(10860)$	$10876 \pm 11^\dagger$	1^{--}	1	21	45	0	3	1
$\Upsilon_2(4^3D_2)$	10876	2^{--}	–	28	36	–	4	4
$\Upsilon_2(4^1D_2)$	10877	2^{-+}	–	22	37	–	4	3
$\Upsilon_3(4^3D_3)$	10881	3^{--}	1	4	49	0	1	2
$\Upsilon_3(3^3G_3)$	10926	3^{--}	7	0	13	2	0	5
$\Upsilon(11020)$	$11019 \pm 8^\dagger$	1^{--}	0	8	26	0	0	2

Bottomonium spectrum (in couple channel calcu

a)

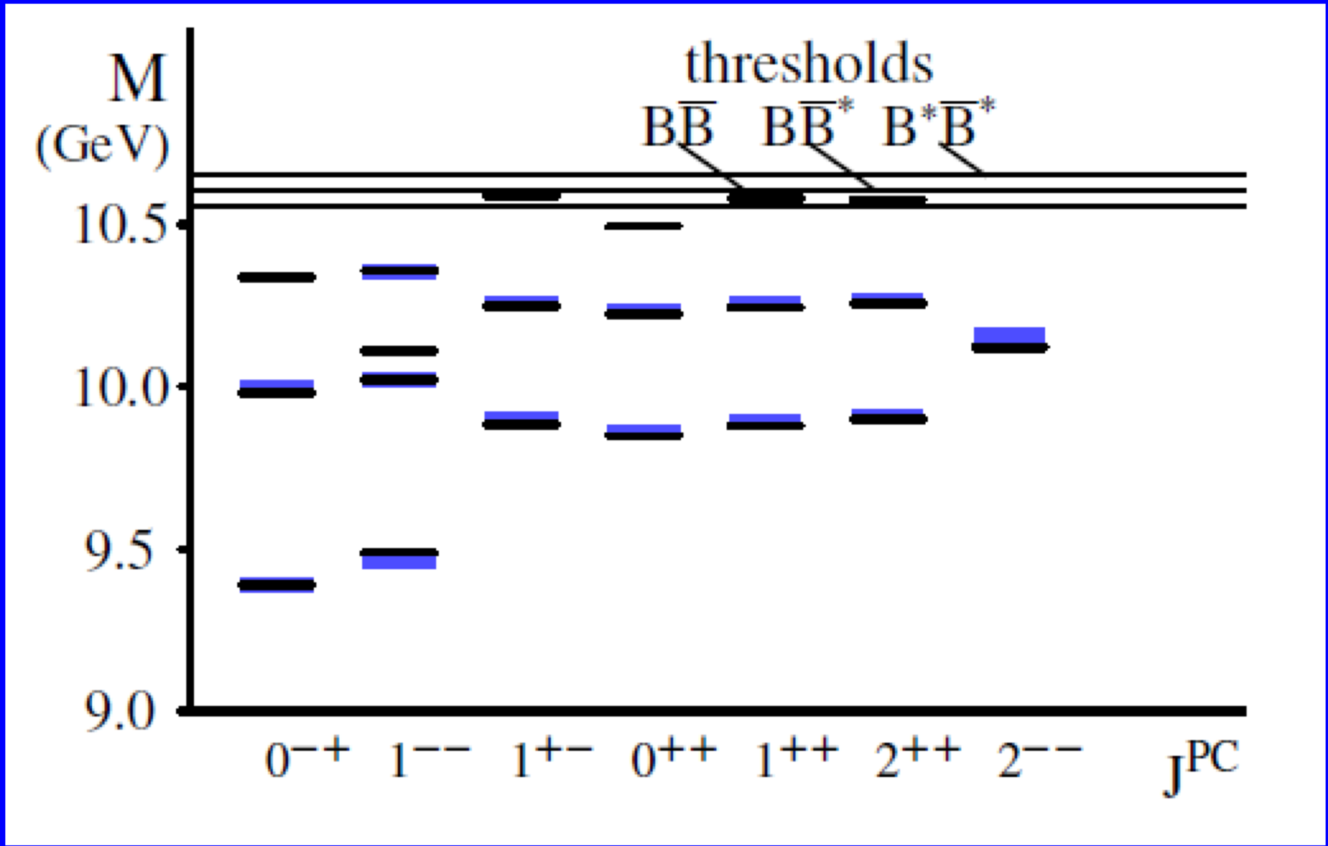
Ferretti, Santopintio, Phys.Rev. D90, 094022 (2014)

State	J^{PC}	BB	$B\bar{B}^*$ $\bar{B}B^*$	B^*B^*	B_sB_s	$B_sB_s^*$ $\bar{B}_sB_s^*$	$B_s^*B_s^*$	B_cB_c	$B_cB_c^*$ $\bar{B}_cB_c^*$	$B_c^*B_c^*$	$\eta_b\eta_b$	$\eta_b\Upsilon$	$\Upsilon\Upsilon$	$\Sigma(E_a)$	E_a	M_a	$M_{exp.}$
$\eta_b(1^1S_0)$	0^{-+}	–	-26	-26	–	-5	-5	–	-1	-1	–	–	0	-64	9455	9391	9391
$\Upsilon(1^3S_1)$	1^{--}	-5	-19	-32	-1	-4	-7	0	0	-1	–	0	–	-69	9558	9489	9460
$\eta_b(2^1S_0)$	0^{-+}	–	-43	-41	–	-8	-7	–	-1	-1	–	–	0	-101	10081	9980	9999
$\Upsilon(2^3S_1)$	1^{--}	-8	-31	-51	-2	-6	-9	0	0	-1	–	0	–	-108	10130	10022	10023
$\eta_b(3^1S_0)$	0^{-+}	–	-59	-52	–	-8	-8	–	-1	-1	–	–	0	-129	10467	10338	–
$\Upsilon(3^3S_1)$	1^{--}	-14	-45	-68	-2	-6	-10	0	0	-1	–	0	–	-146	10504	10358	10355
$h_b(1^1P_1)$	1^{+-}	–	-49	-47	–	-9	-8	–	-1	-1	–	0	–	-115	10000	9885	9899
$\chi_{b0}(1^3P_0)$	0^{++}	-22	–	-69	-3	–	-13	0	–	-1	0	–	0	-108	9957	9849	9859
$\chi_{b1}(1^3P_1)$	1^{++}	–	-46	-49	–	-8	-9	–	-1	-1	–	–	0	-114	9993	9879	9893
$\chi_{b2}(1^3P_2)$	2^{++}	-11	-32	-55	-2	-6	-9	0	-1	-1	0	–	0	-117	10017	9900	9912
$h_b(2^1P_1)$	1^{+-}	–	-66	-59	–	-10	-9	–	-1	-1	–	0	–	-146	10393	10247	10260
$\chi_{b0}(2^3P_0)$	0^{++}	-33	–	-85	-4	–	-14	0	–	-1	0	–	0	-137	10363	10226	10233
$\chi_{b1}(2^3P_1)$	1^{++}	–	-63	-60	–	-9	-10	–	-1	-1	–	–	0	-144	10388	10244	10255
$\chi_{b2}(2^3P_2)$	2^{++}	-16	-42	-72	-2	-6	-10	0	0	-1	0	–	0	-149	10406	10257	10269
$h_b(3^1P_1)$	1^{+-}	–	-18	-73	–	-11	-10	–	-1	-1	–	0	–	-114	10705	10591	–
$\chi_{b0}(3^3P_0)$	0^{++}	-4	–	-160	-6	–	-15	0	–	-1	0	–	0	-186	10681	10495	–
$\chi_{b1}(3^3P_1)$	1^{++}	–	-25	-74	–	-11	-10	–	0	-1	–	–	0	-121	10701	10580	–
$\chi_{b2}(3^3P_2)$	2^{++}	-19	-16	-79	-3	-8	-12	0	0	-1	0	–	0	-138	10716	10578	–
$\Upsilon_2(1^1D_2)$	2^{-+}	–	-72	-66	–	-11	-10	–	-1	-1	–	–	0	-161	10283	10122	–
$\Upsilon(1^3D_1)$	1^{--}	-24	-22	-90	-3	-3	-16	0	0	-1	–	0	–	-159	10271	10112	–
$\Upsilon_2(1^3D_2)$	2^{--}	–	-70	-68	–	-10	-11	–	-1	-1	–	0	–	-161	10282	10121	10164
$\Upsilon_3(1^3D_3)$	3^{--}	-18	-43	-78	-3	-8	-11	0	-1	-1	–	0	–	-163	10290	10127	–

Bottomonium

Ferretti, Santopintio, Phys.Rev. D90 (2014) 9, 094022

- Results:



Couple Channels corrections to Bottomonium, the $\chi_b(3P)$ system

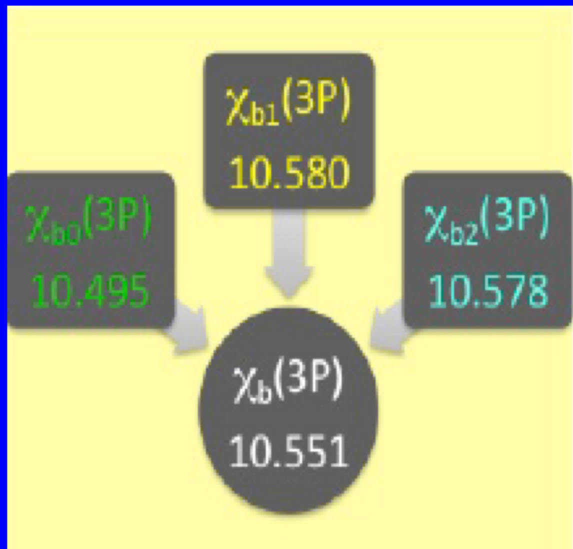
Ferretti, Santopintio, Phys.Rev. D90 (2014) 9, 094022 : 1306.2874

- Results used to study some properties of the $\chi_b(3P)$ system, meson multiplet with N=3, L=1 quantum numbers
- $\chi_b(3P)$ states close to first open bottom decay thresholds
- Possible importance of continuum coupling effects?
- Pure c bar-c and c bar-c + continuum effects interpretations
- Necessary to study decays (strong, e.m., hadronic, ...) to confirm one interpretation
-

Couple Channels corrections to Bottomonium , the $\chi_b(3P)$ system

Ferretti, Santopintio, Phys.Rev. D90 (2014) 9, 094022

- Some experimental results for the mass barycenter of the system:
- $M[\chi_b(3P)] = 10.530 \pm 0.005$ (stat.) ± 0.009 (syst.) GeV
- Aad et al. [ATLAS Coll.], Phys. Rev. Lett. **108**, 152001 (2012)
- $M[\chi_b(3P)] = 10.551 \pm 0.014$ (stat.) ± 0.017 (syst.) GeV
- Abazov et al. [D0 Coll.], Phys. Rev. D 86, 031103 (2012)
- Mass barycenter in the UQM:



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