EXOTIC SPECTROSCOPY: FROM PENTAQUARKS TO HYBRIDS

V-th Collaboration Meeting of the MPD Experiment at the NICA Facilit, 23-24 April 2020,VBLHEP,JINR,Dubna,Russia

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Hadron spectroscopy: lab. for QCD@ work

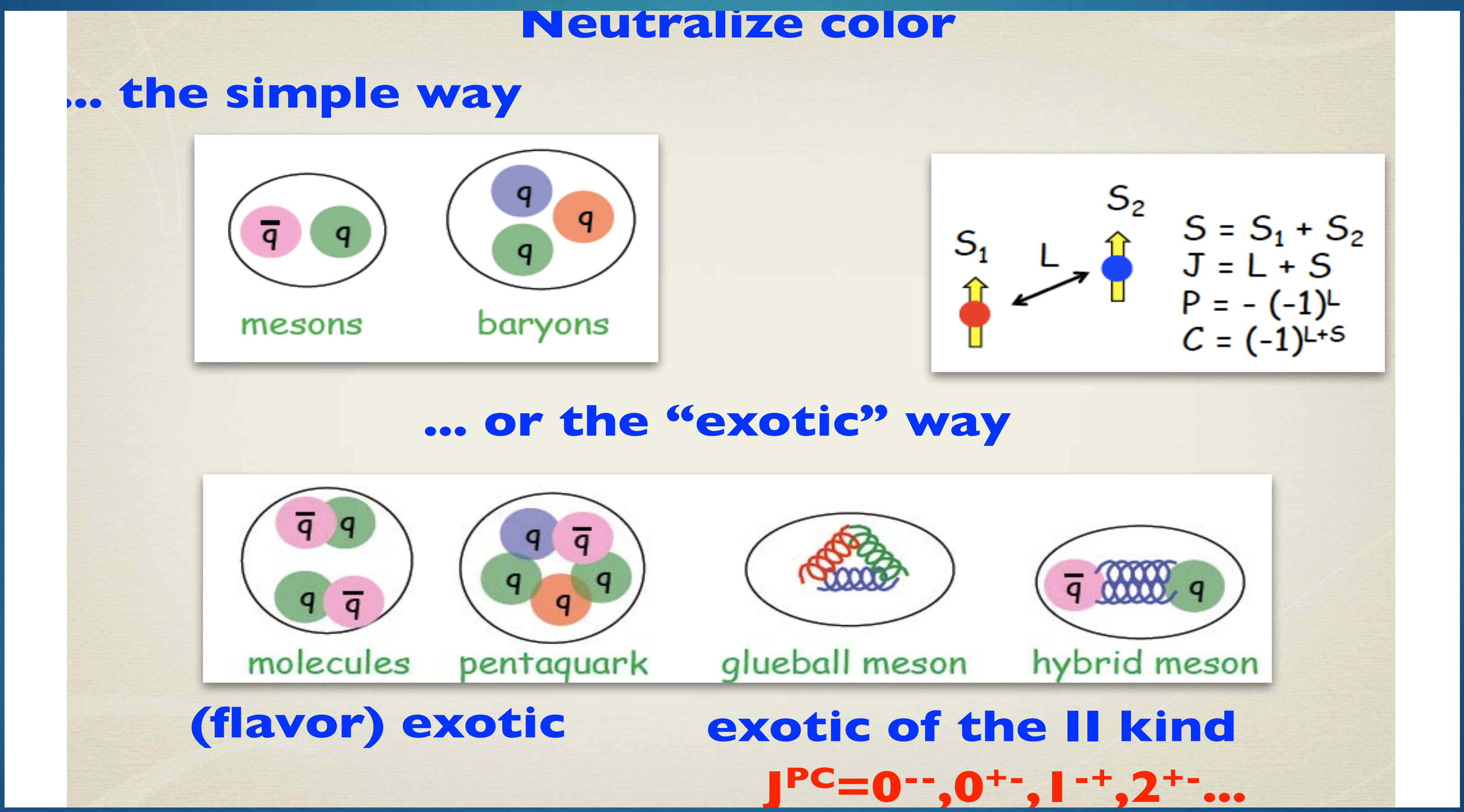
Bulk of mass of hadrons

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

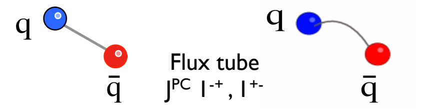


Gluonic excitation models

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 ($J_g^{P_gC_g}$)
- 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^{+-}, $(0,1,2)^{++}$

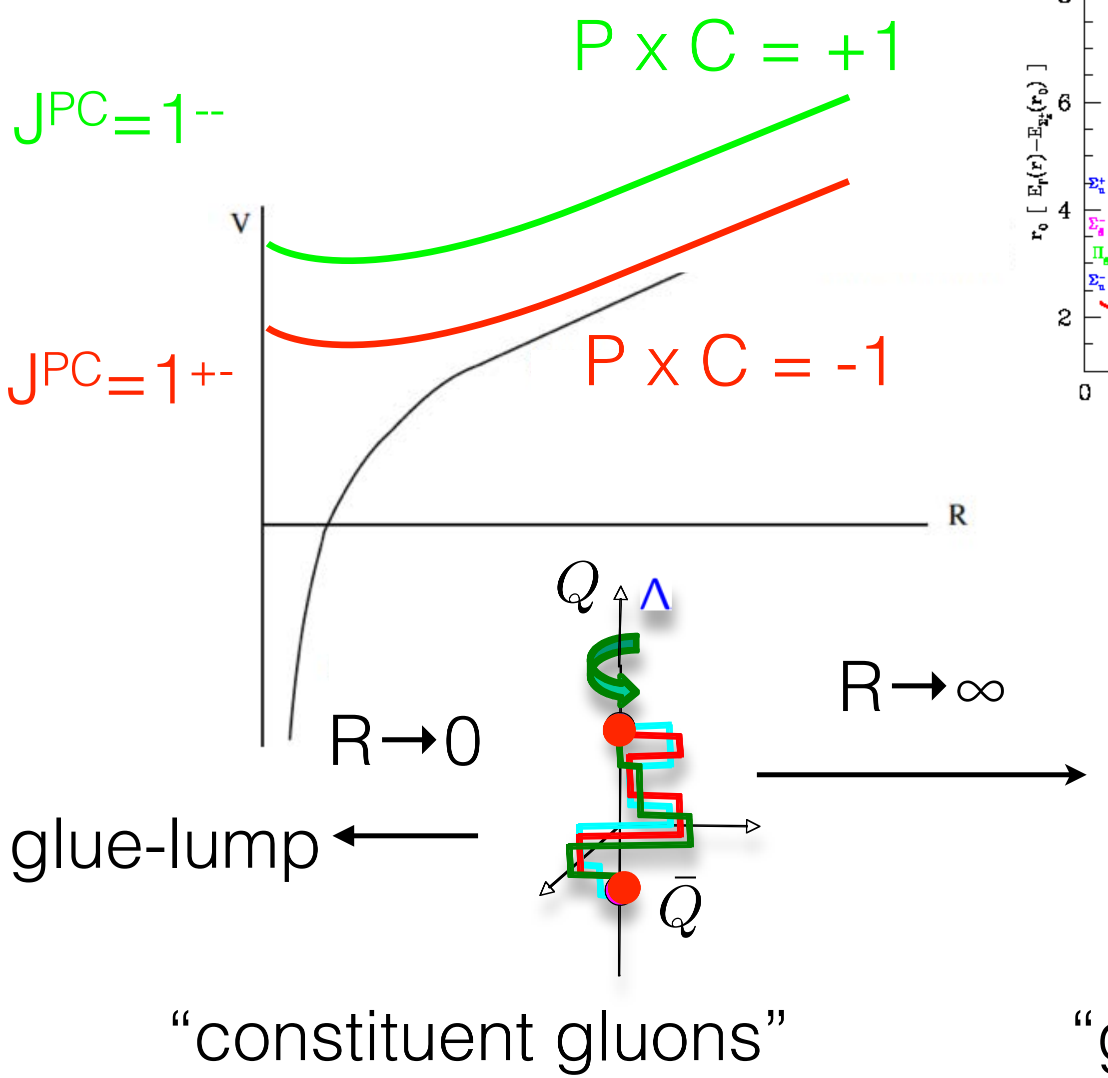
Start from the study of the glue-lamp

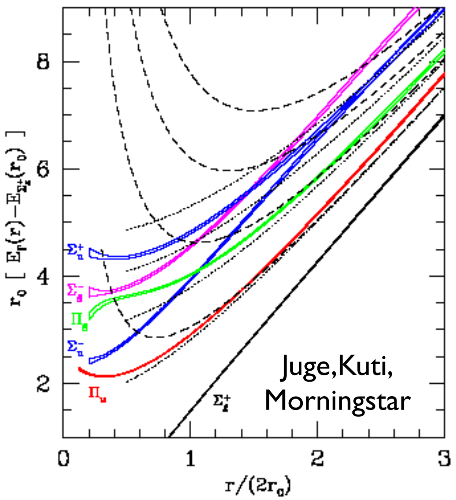
Gluelamp in Cb gauge QCD:
P.Guo,A.Szczepaniak,G.Galatà,A. Vassallo, E.S.,PRD78,056003(2008**)**

gauge

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

Flux tube and strings





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

Greensite e Thorn's chain model
Ostrander,Szczpaniak,Vassallo,E.S,PRD2014

Charmonia (qq bar) & hybrids (qqg)

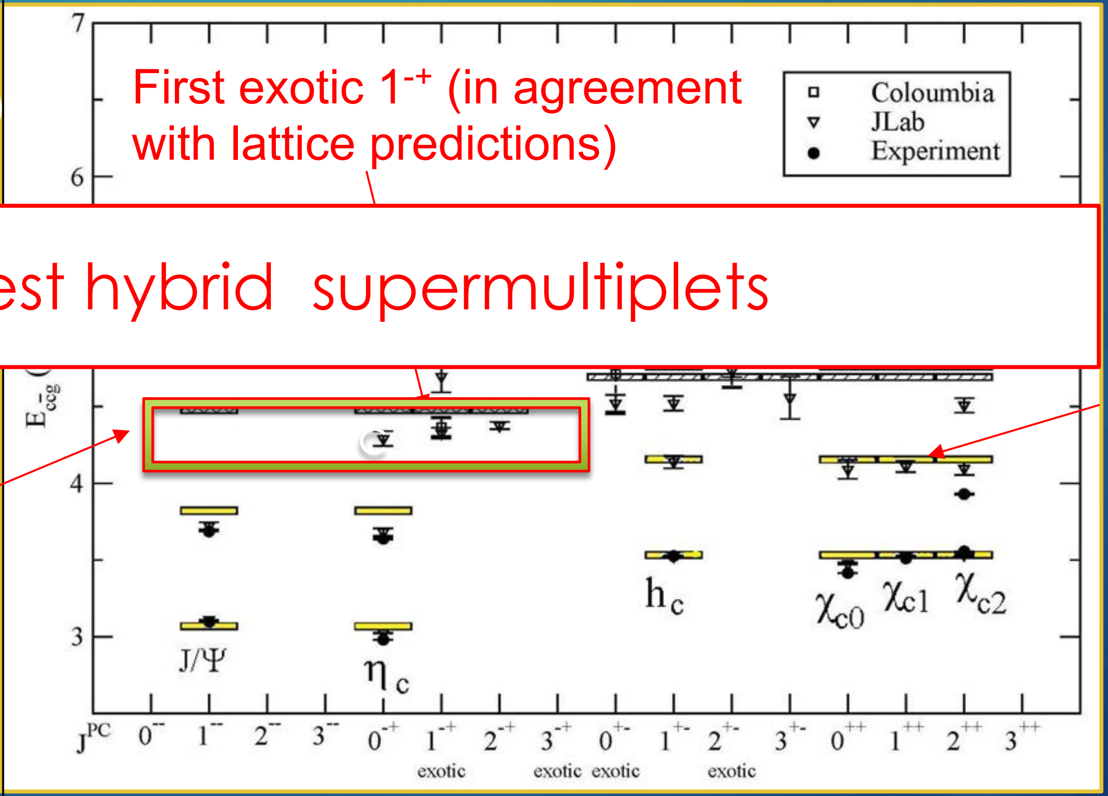
$J_g^{PC} = 1^{+-}, 1^{--}$

$J_g^{P_g}$	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)



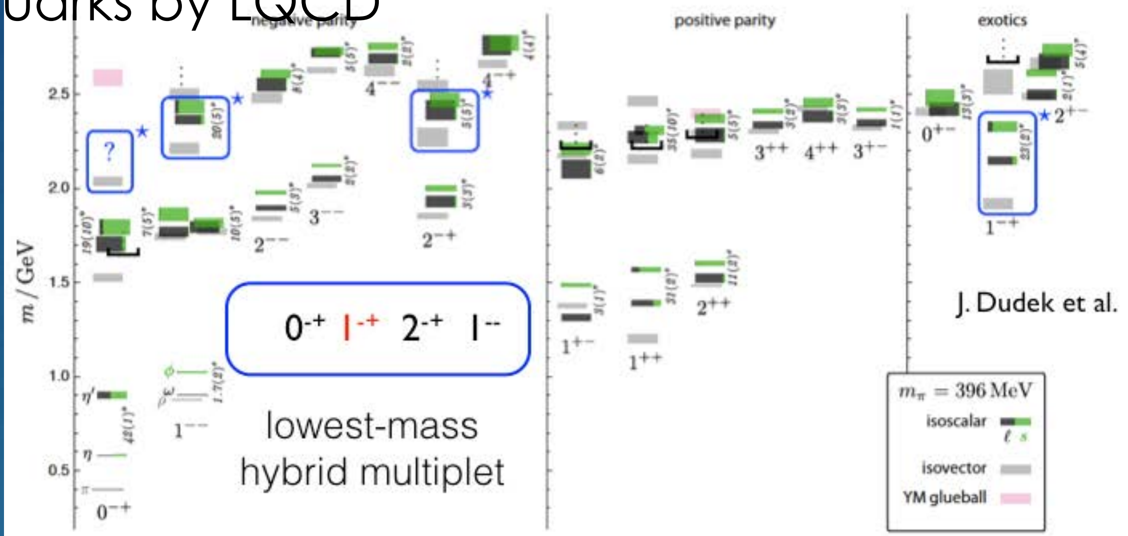
Y(4260)

X(3872)

The lightest hybrid supermultiplets

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



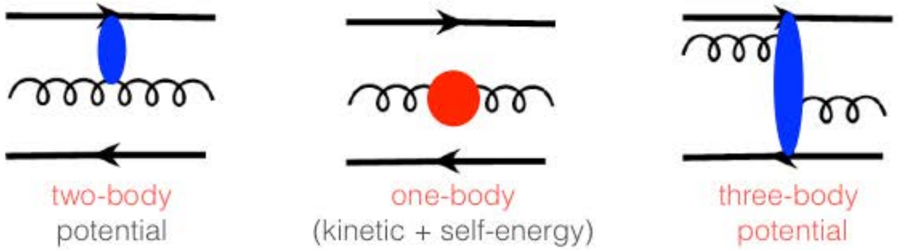
Physical gauge QCD (Hamiltonian)

J^{PC} glue

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

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

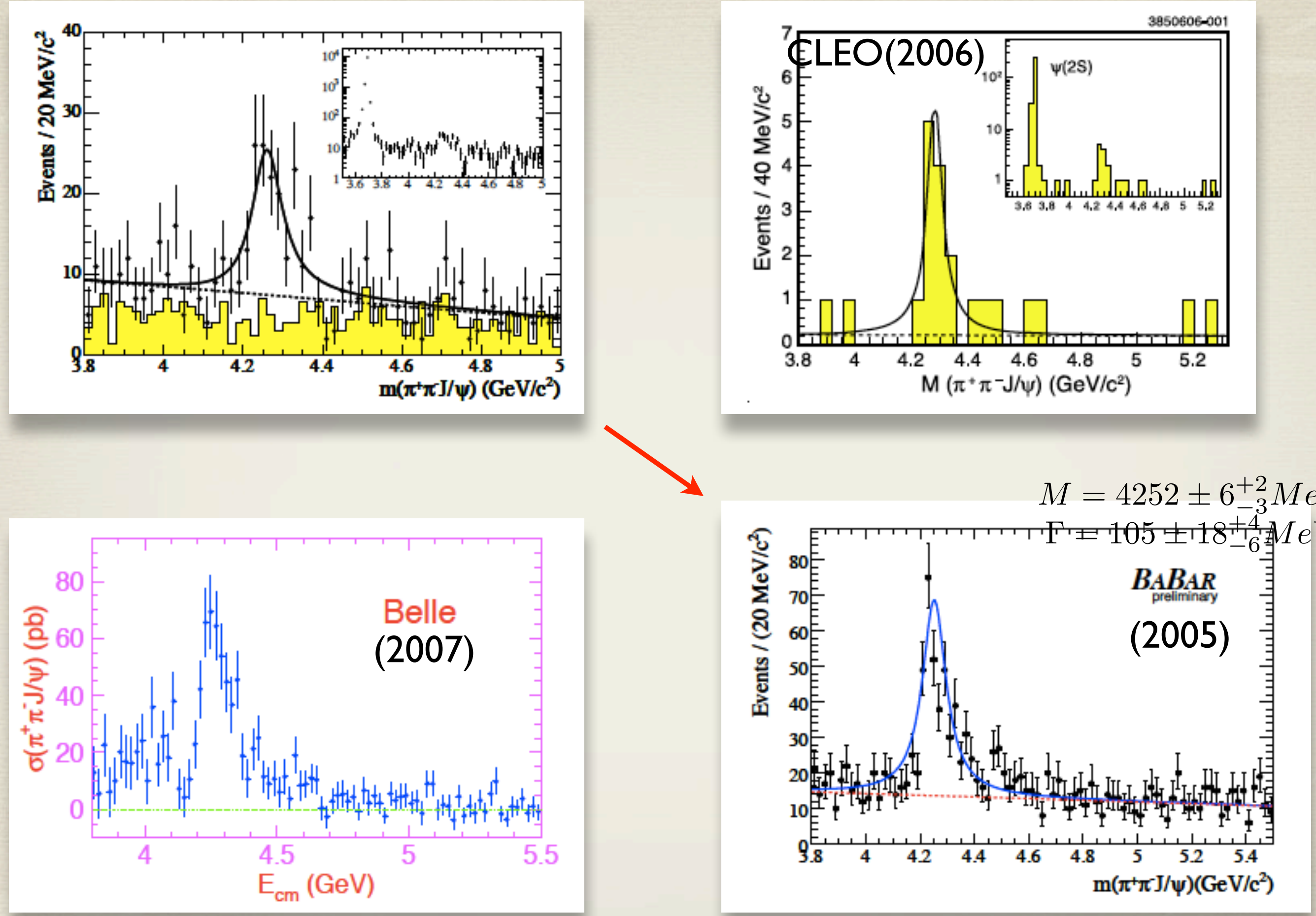
$$1^{+-} \times 1^{--}_{S_{Q\bar{Q}}=1} = \boxed{0^{-+}, 1^{-+}, 2^{-+}}$$



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)

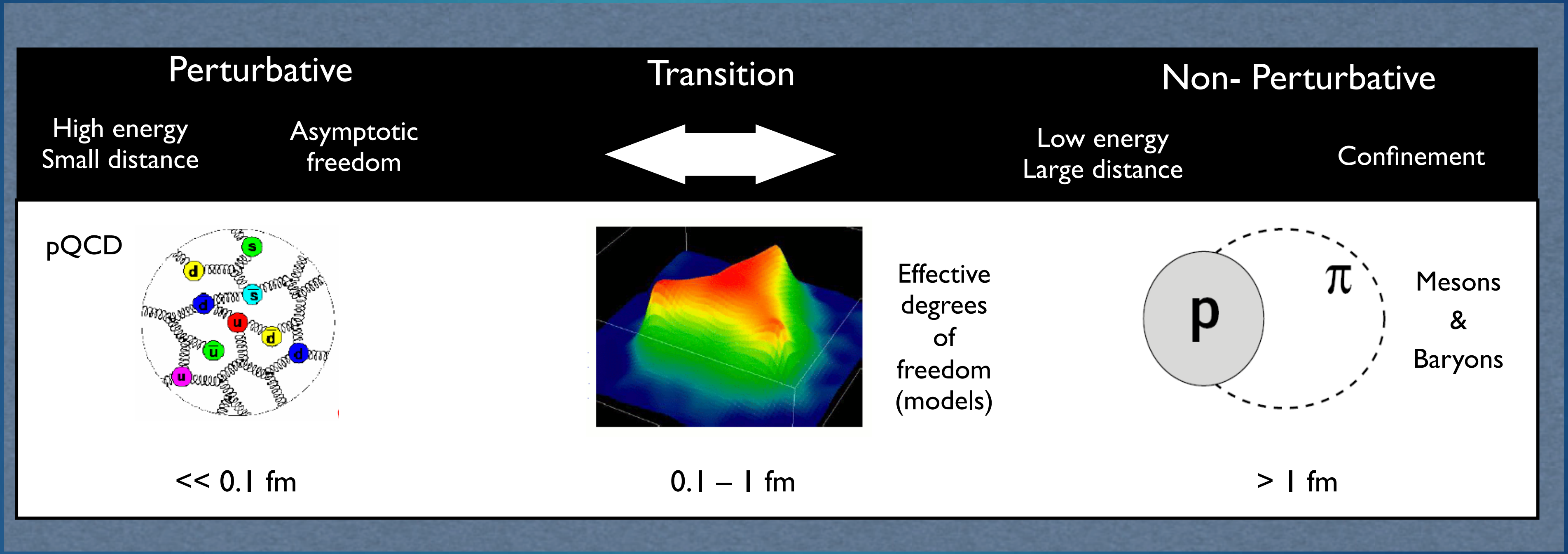


$$M = 4252 \pm 6^{+2}_{-3} MeV$$
$$\Gamma = 105 \pm 18^{+4}_{-6} MeV$$

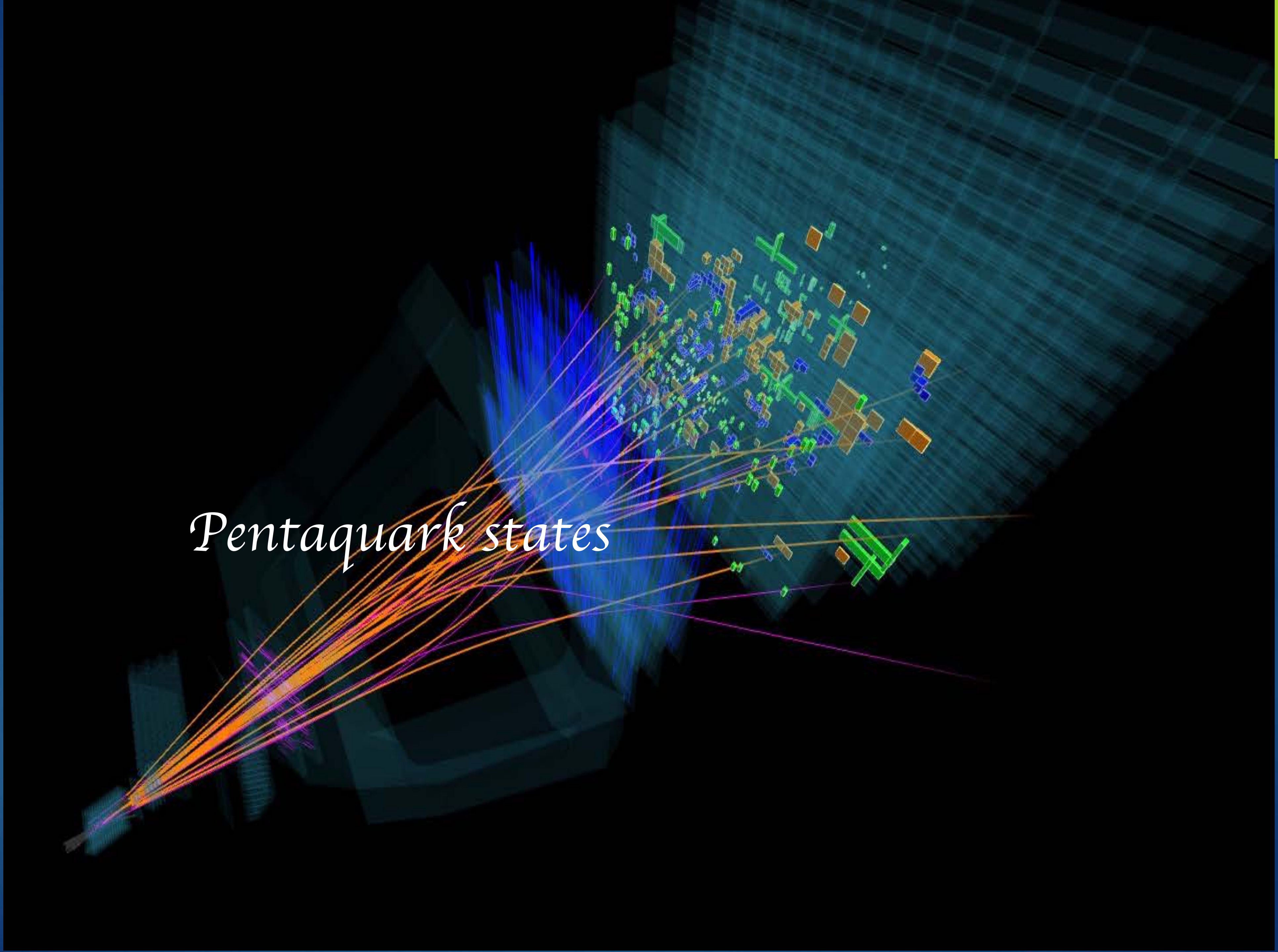
✱ **Theory: Hybrid candidate**

- If
Q
S
2
O

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



Pentaquark states



▶ Pentaquark states based on

[1] E. Santopinto, **A. Giachino**, **Phys. Rev. D 96, 014014 (2017);**

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

[3] Y. Yamaguchi**,** H. Garcia-Tecocoatzi, **A. Giachino,** A. Hosaka, E. Santopinto**,** S. Takeuchi and M. Takizawa, **Few-Body Systems, DOI: 10.1007/978-3-030-32357-8_98 (2019)**

[4] Y. Yamaguchi, H. Garcia-Tecocoatzi, **A. Giachino**, A. Hosaka, E. Santopinto, S. Takeuchi and M. Takizawa arXiv:1907.04684**, it will be submitted to Phys. Rev. D in the next days**

Part 1: Pentaquark states

- **The pentaquark as a compact five quark state [1]**
- **The penataquark states as meson baryon molecuies [2]**
- **Hidden-charm and -bottom meson baryon molecules coupled with five-quark states [3], [4]**
- **Heavy quark spin symmetry with chiral tensor dynamics in lights of the recent LHCb Pentaquarks [5]**

[1] E. Santopinto, A. Giachino, **Phys. Rev. D 96, 014014 (2017);**
[2] Y. Yamaguchi, E. Santopinto, **Phys. Rev. D Phys.Rev. D96 (2017) no.1, 014018**

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

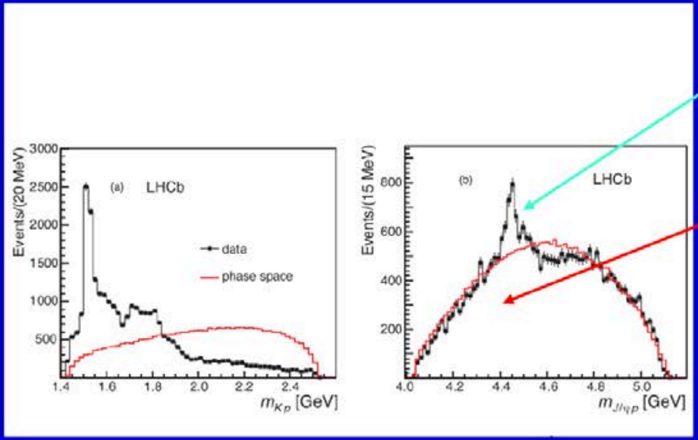
[4] Y. Yamaguchi, H. Garcia-Tecocoatzi, A. Giachino, A. Hosaka, E. Santopinto, S. Takeuchi and M. Takizawa, **Few-Body Systems, DOI: 10.1007/978-3-030-32357-8_98 (2019)**

[5] Y. Yamaguchi, H. Garcia-Tecocoatzi, A. Giachino, A. Hosaka, E. Santopinto, S. Takeuchi and M. Takizawa arXiv:1907.04684**, accepted as Physical Review D Rapid Communication, April 2020**

Why pentaquark states?

LHCb

Phys. Rev. Lett.115(2015) 072001



M _P_c^+(4450) = (4449.8 ± 8 ± 29)MeV

Γ = (39 ± 5 ± 19) MeV

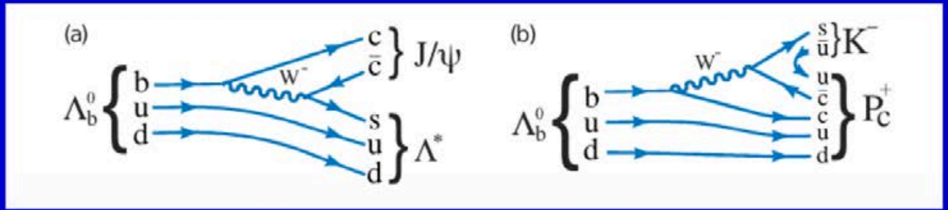
M_P_c^+(4380) = (4380 ± 1.7 ± 2.5)MeV

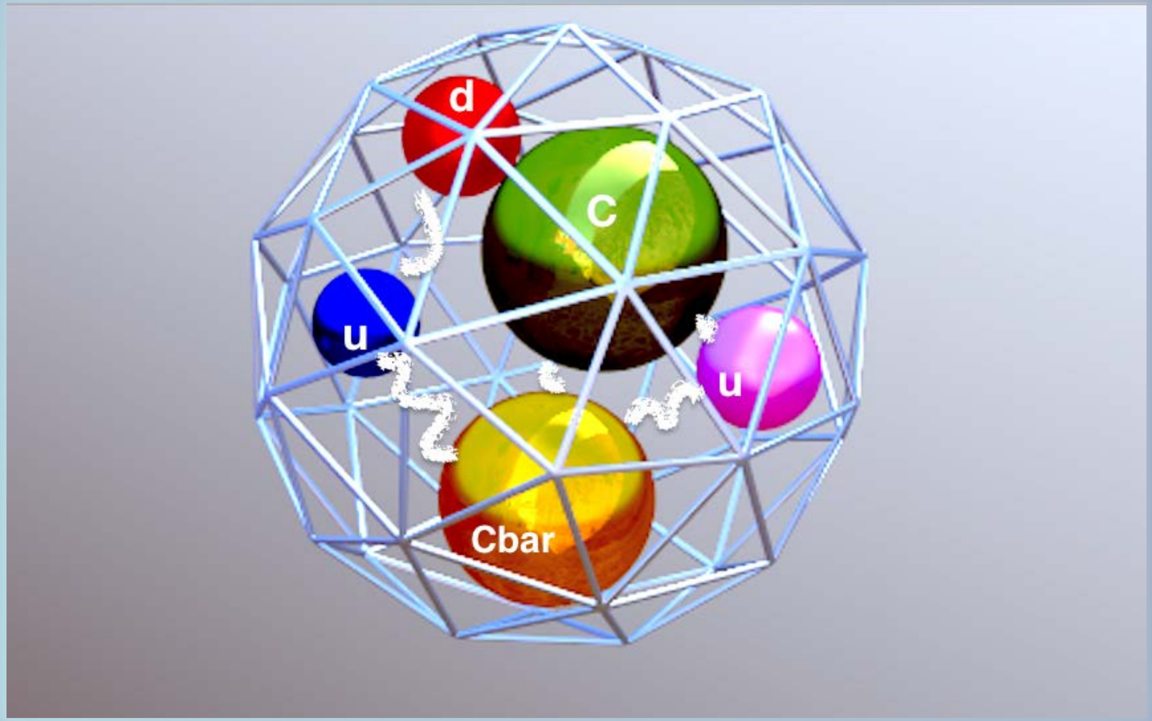
Γ =(205±18±86)MeV

statistic significance greater then 9 sigma !

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

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





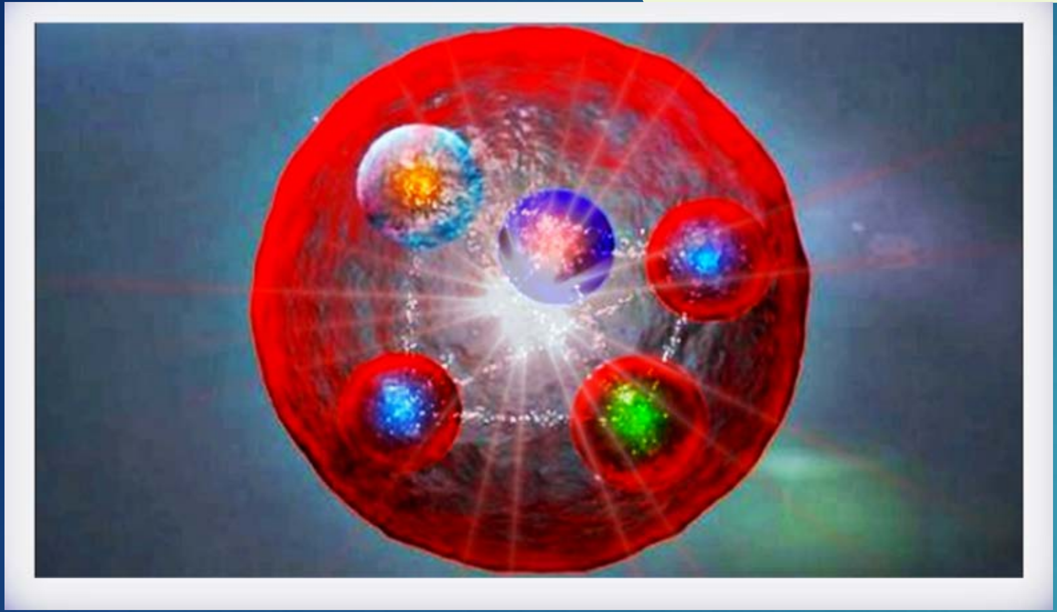
The LHCb observation [1] was further supported by another two articles by the same group [2,3]:

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

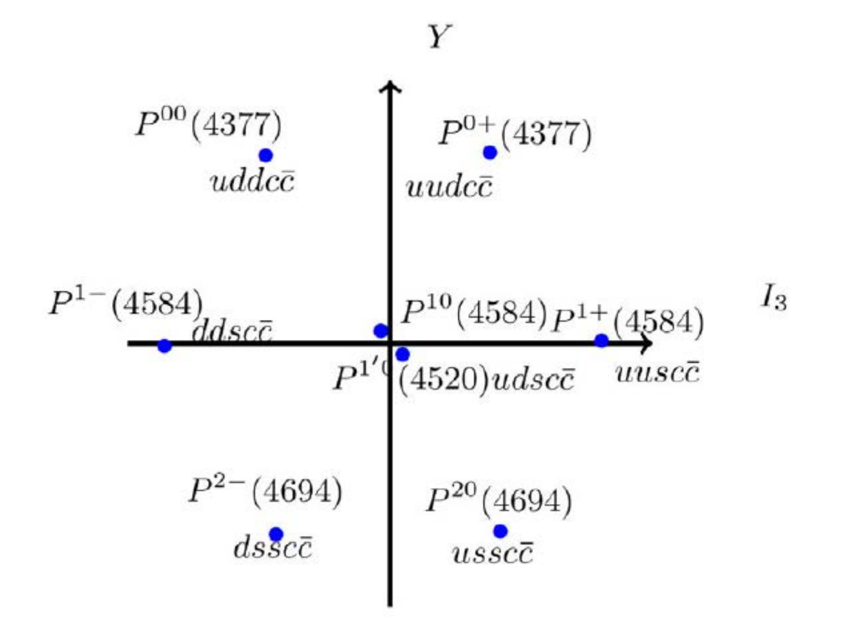
[2] R. Aaij *et al.* [LHCb Collaboration], Phys. Rev. Lett. **117** (2016) no.8, 082002

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

The pentaquark as a compact five quark state [1]



- 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.



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

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

where:

$$\Gamma^{\pm}_{\nu} = \begin{pmatrix} \gamma_{\nu}\gamma_5 \\ \gamma_{\nu} \end{pmatrix}, \Gamma^{\pm} = \begin{pmatrix} \gamma_5 \\ 1 \end{pmatrix}$$

Taking the $J^P = \frac{3}{2}^{-}$ case in the effective lagrangian, we obtained the following partial decay widths:

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

[1] E. Santopinto, A. Giachino, **PHYSICAL REVIEW D 96, 014014 (2017);**

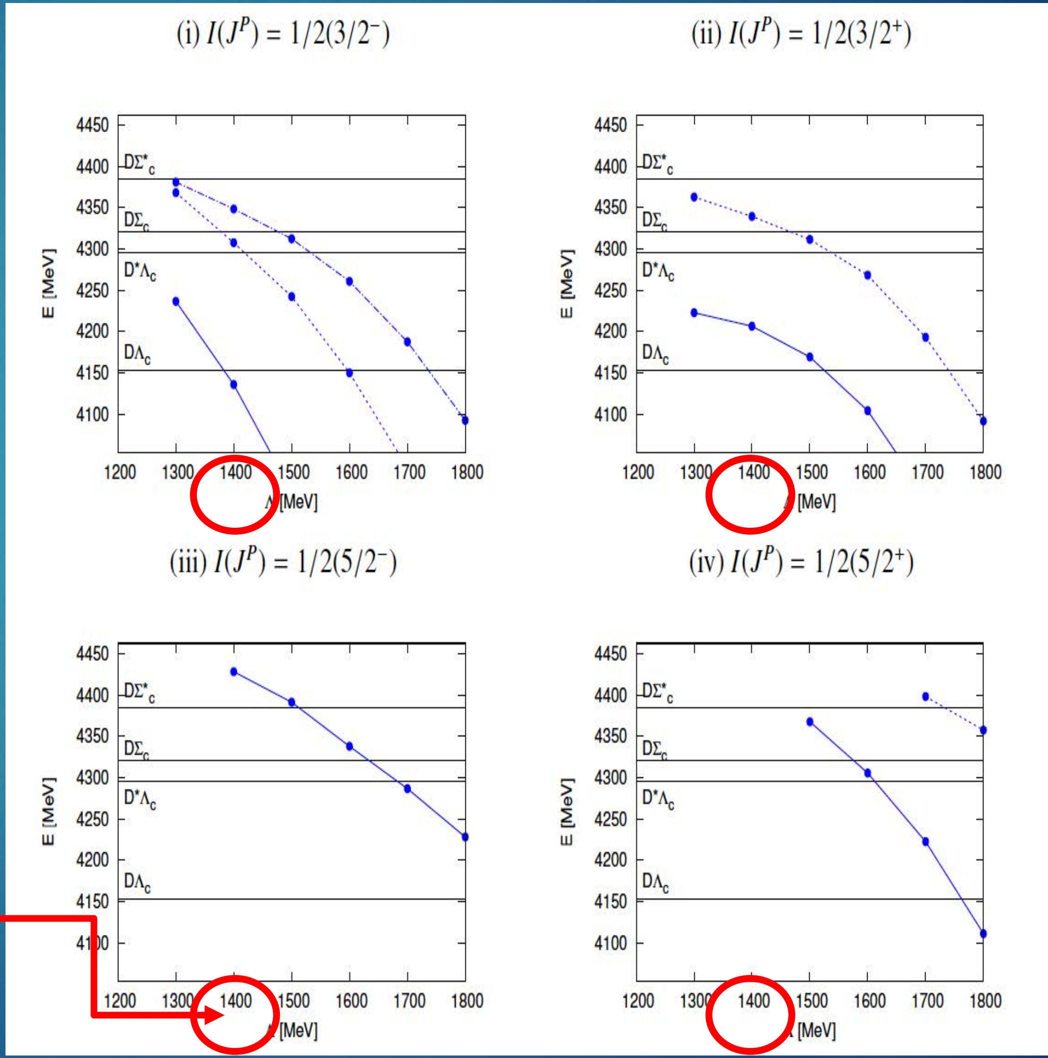
Hidden-charm pentaquarks as a meson-baryon molecule with coupled channels for $\bar{D}^{(*)}\Lambda_c$ and $\bar{D}^{(*)}\Sigma_c$

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**

- 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

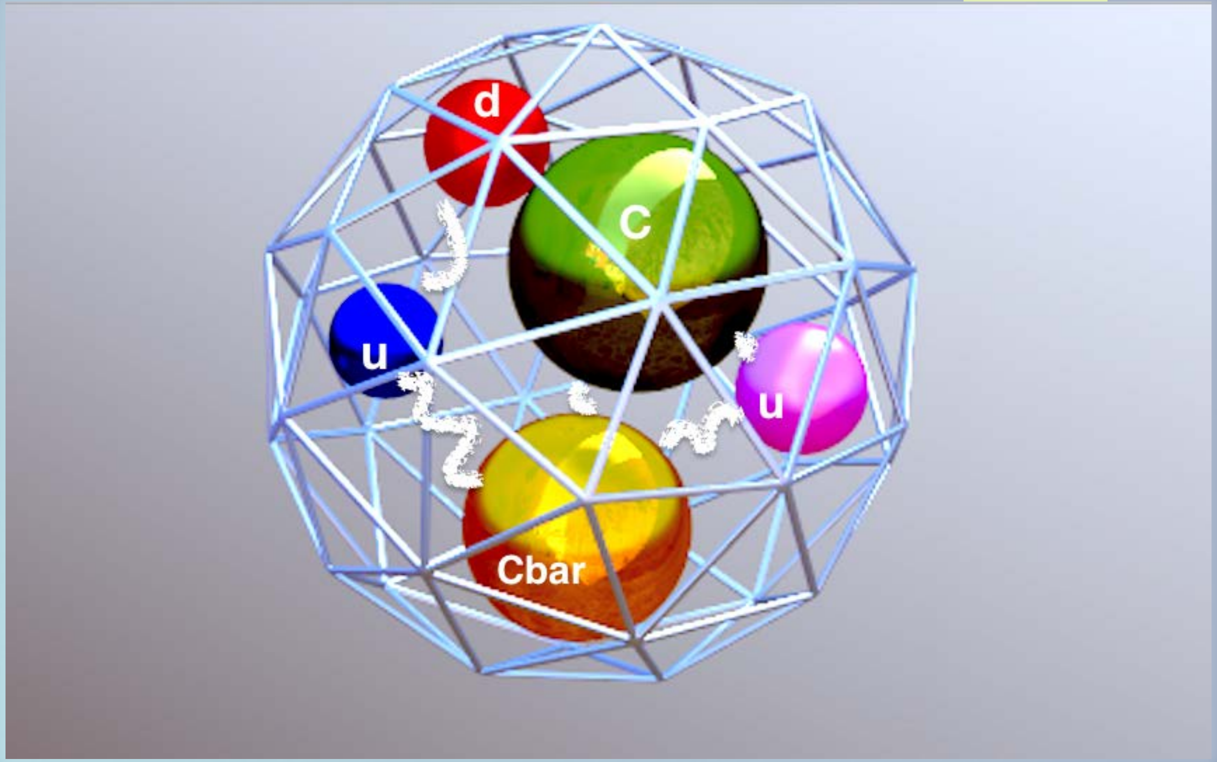
ADDITION OF THE CORE CONTRIBUTION

- 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

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).

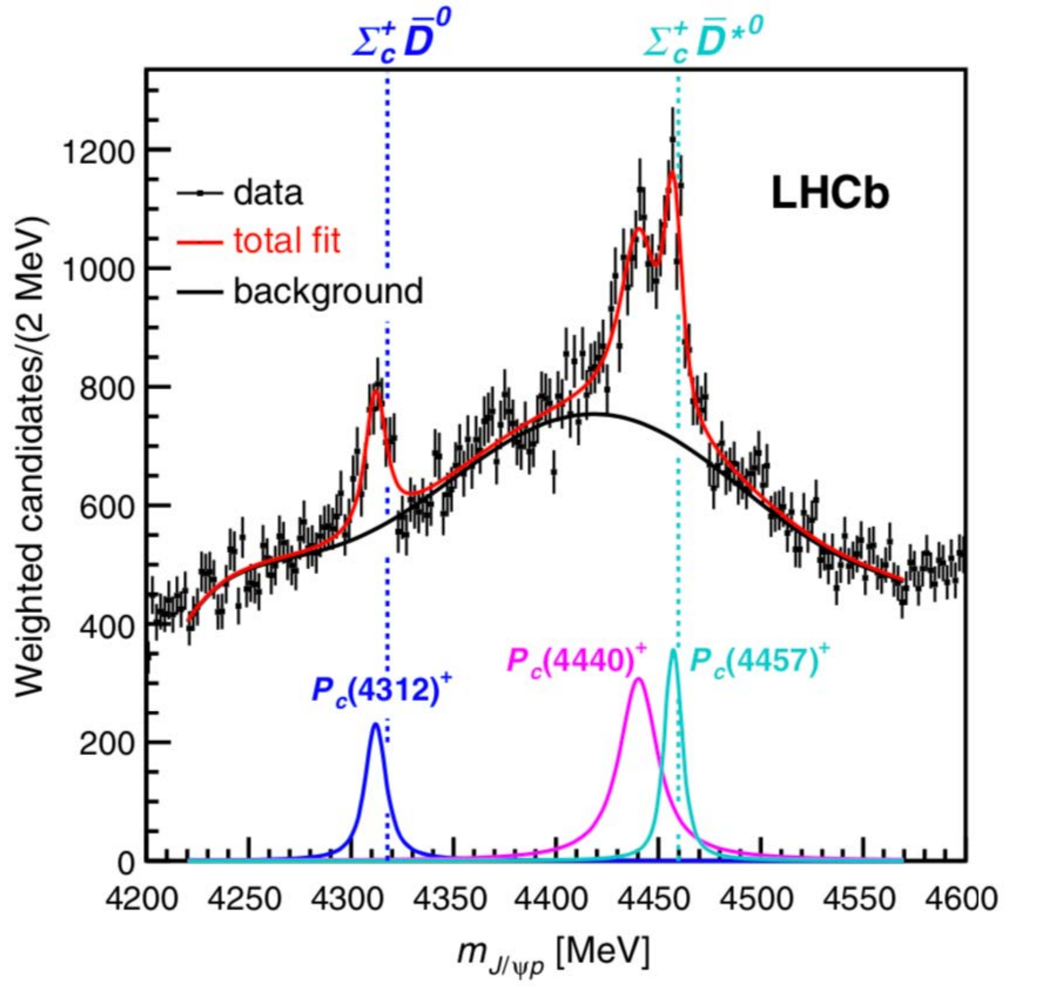
Why pentaquark states?

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]	Γ [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.

Hidden-charm and bottom meson-baryon molecules coupled with five-quark states [3], [4]

- In Refs. [3] , [4] 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.

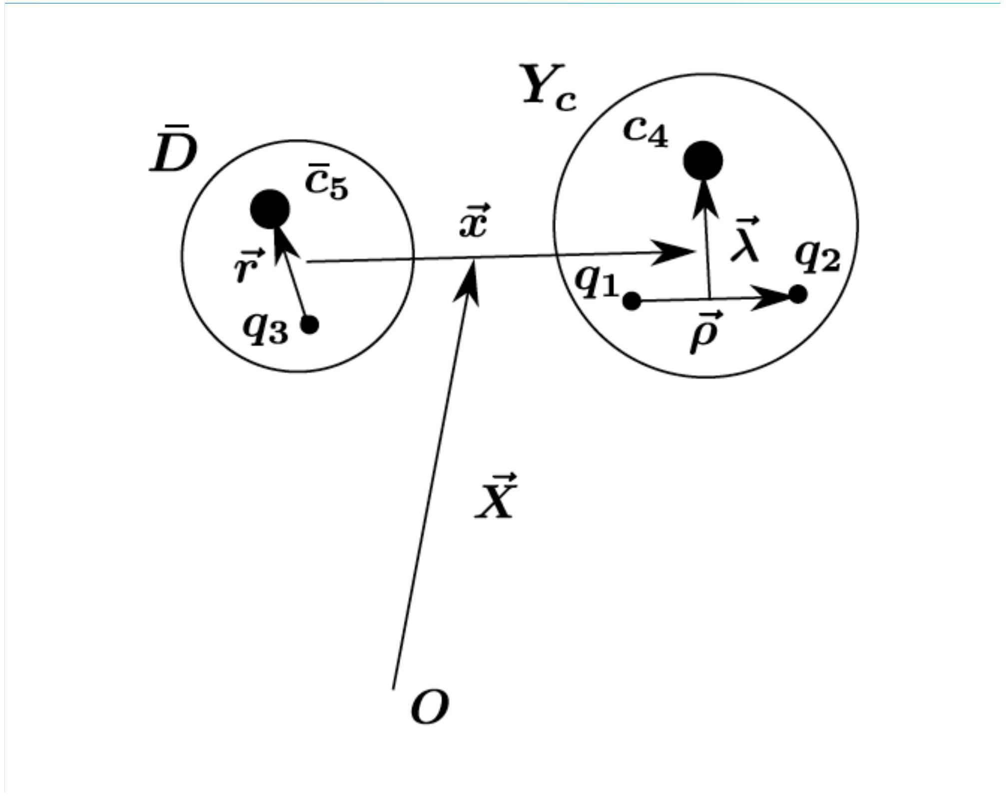
We predicted the three pentaquark states, $P_c(4312), P_c(4440)$ and $P_c(4457)$ two years before the experimental observation by LHCb

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

[4] Y. Yamaguchi, H. Garcia-Tecocoatzi, A. Giachino, A. Hosaka, E. Santopinto, S. Takeuchi and M. Takizawa, **Few-Body Systems, DOI: 10.1007/978-3-030-32357-8_98 (2019)**

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^{α}:

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

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

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

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

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

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

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

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 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).

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The Model in brief

the key ingredients

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

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

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

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

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

[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).

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Heavy Quark Spin Symmetry with Chiral Tensor Dynamics in the Light of the Recent LHCb Pentaquarks [4]

Based on the new LHCb results [*], in Ref. [4] 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:

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

[*]

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

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

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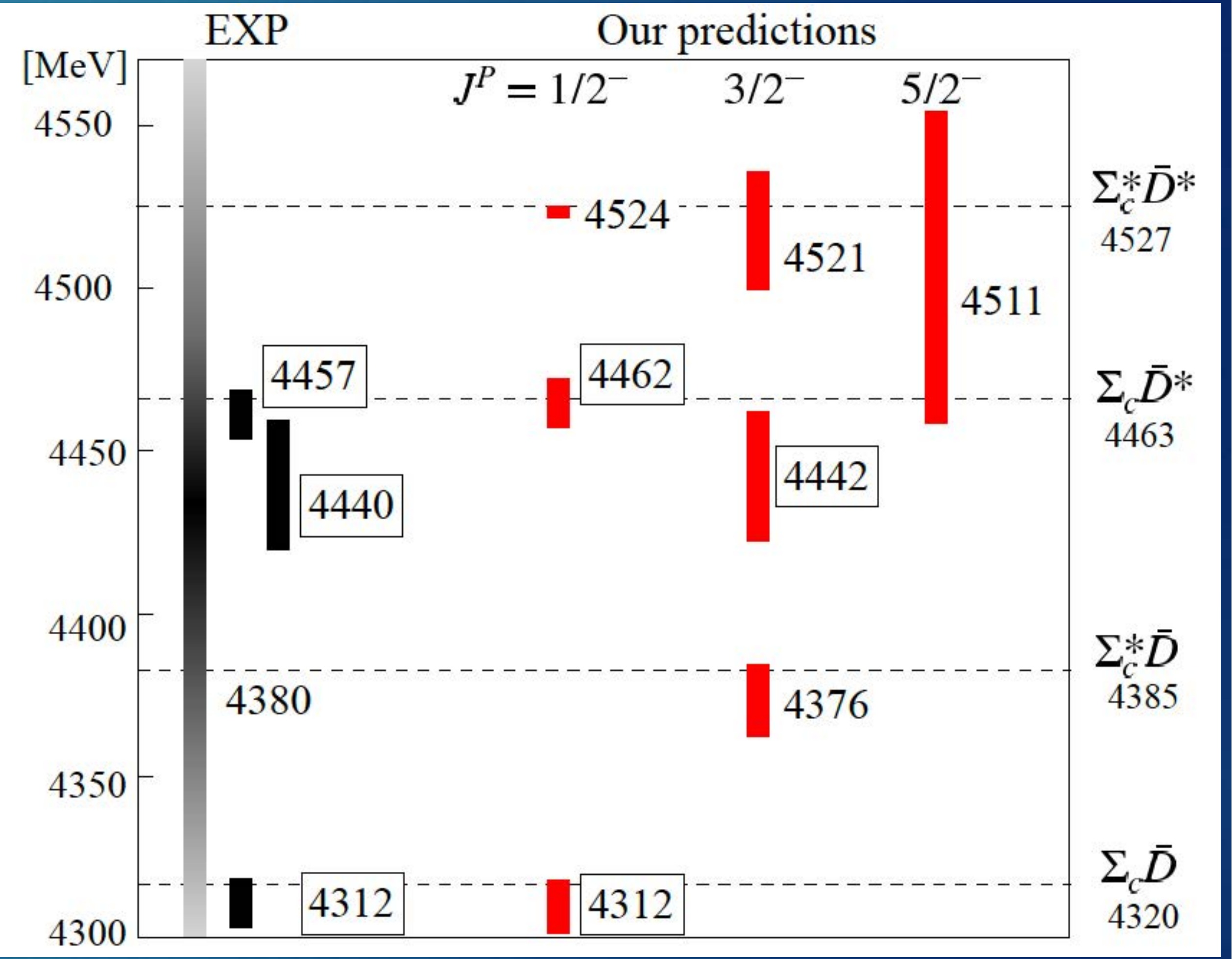
results

State	Mass	Width	Our pred. (M,J^P,Γ)
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+3.7}_{-4.5}$	(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

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 →

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

OPE Potential

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

Central part

Tensor operator:

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

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

Dipole form factor

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

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 ^2S, ^4D

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

Notation ^{2S+1}L e.g. ^2S means Σ_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

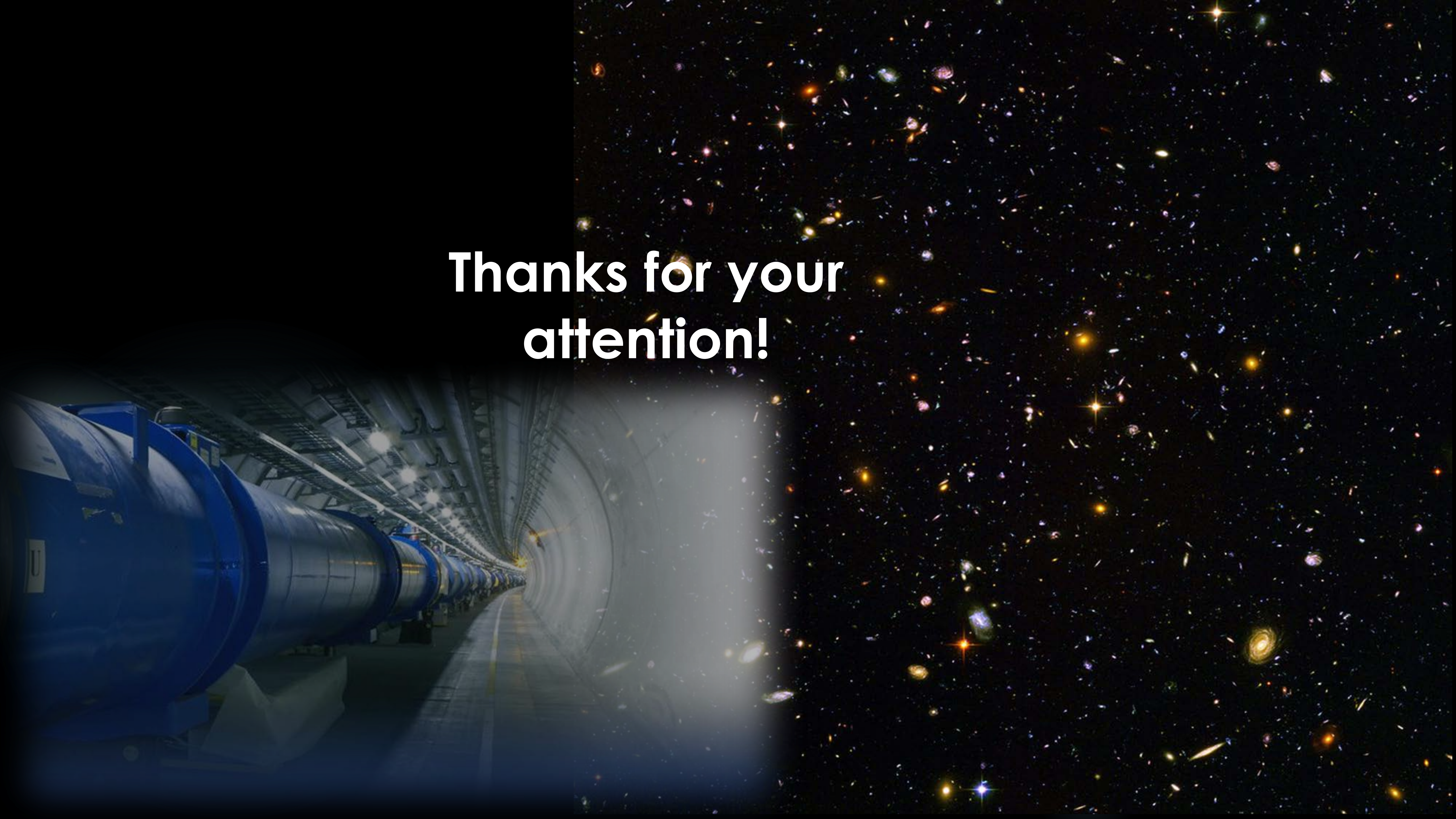
Since the obtained mass difference between $P_c(4440)$ **and** $P_c(4457)$ is 20 MeV the remaining 9 MeV is considered to come from the the short range interaction in our model.

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!

Thanks for your attention!



QCD symmetries – Quark models

$$\mathcal{L}^0_{\text{QCD}} = \sum_{l=u,d,s} \left(\bar{q}_{R,l} i \not{D}\, q_{R,l} + \bar{q}_{L,l} i \not{D}\, q_{L,l}\right) - \frac{1}{4}\mathcal{G}_{\mu\nu,a}\mathcal{G}^{\mu\nu}_a . \qquad \text{(D.50)}$$

As one can see from Eq. D.50, in the chiral limit the QCD Lagrangian possesses an $\mathrm{SU}(3)_L \times \mathrm{SU}(3)_R \times \mathrm{U}(1)_V$ symmetry. For this reason, one would expect that hadrons organize themselves into approximately degenerate multiplets fitting the dimensionalities of irreducible representations of the group $\mathrm{SU}(3)_L \times \mathrm{SU}(3)_R \times \mathrm{U}(1)_V$. The $\mathrm{U}(1)_V$ symmetry results in baryon number conservation and leads to a classification of hadrons into mesons ($B = 0$) and baryons ($B = 1$).

$$P_R = \frac{1}{2}(1+\gamma_5) = P_R^\dagger, \quad P_L = \frac{1}{2}(1-\gamma_5) = P_L^\dagger,$$

$$\bar{q}_R = \bar{q} P_L \text{ and } \bar{q}_L = \bar{q} P_R.$$

where the indices R and L refer to right-handed and left-handed, respectively,

The non-existence of degenerate multiplets of opposite parity points to the fact that SU(3) instead of SU(3)L SU(3)R is approximately realized as a symmetry of the hadrons.

The SU(3) flavor symmetry and the SU(3) color symmetry (hadron are colorless) are the symmetries implemented by the quark models to incorporate QCD.