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

Makoto Takizawa(Showa Parmaceutical Univ.), Yasuhiro Yamaguchi(RIKEN),
Atsushi Hosaka(RCNP, Osaka Univ.), Sachiko Takeuchi(Japan. Coll. Social Work),
Hugo Garcia-Tecocoatzi(UNAM), Alesssandro Giachino (Univ. Genova),
Elena Santopinto(Univ. Genova)

Based on: arXiv:1907.04684

ECT*, Trento, Italy, Sept. 26, 2019

Contents

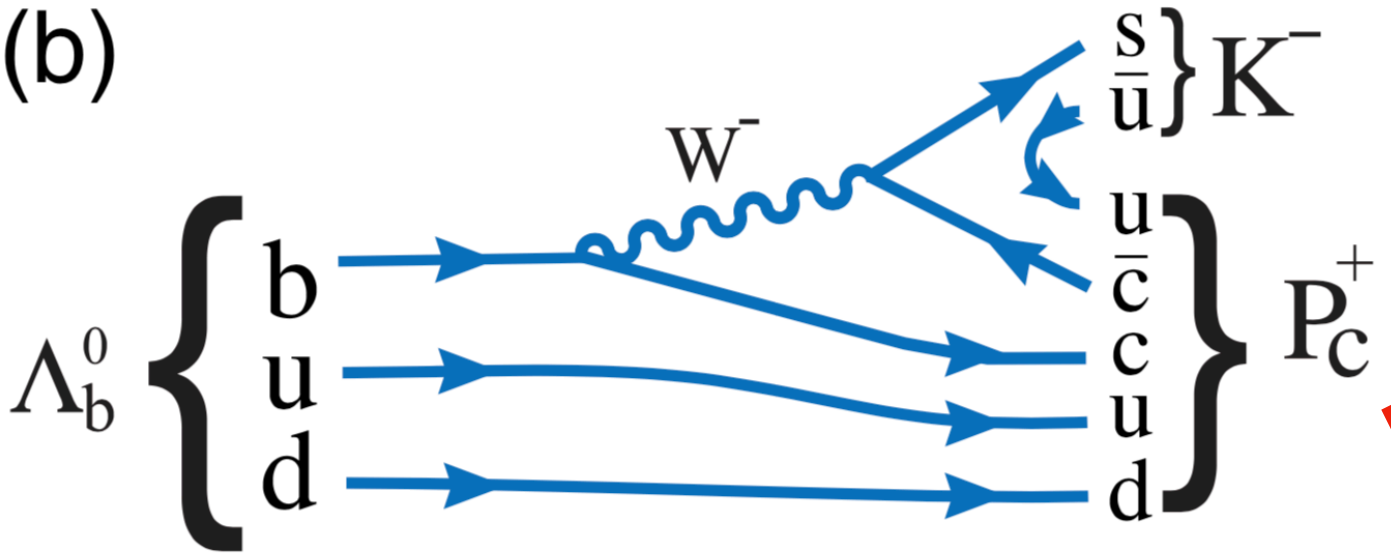
- LHCb experimental results, $P_c(4312)^+$, $P_c(4440)^+$, $P_c(4457)^+$
- $\Sigma_c \bar{D}^{(*)}$ hadronic molecule with coupling to 5-quark compact core states
- Chiral tensor dynamics
- Numerical results
- Summary

LHCb Experimental results:

$P_c(4312)^+$, $P_c(4440)^+$, $P_c(4457)^+$

LHCb, PRL 122, 222001 (2019)

$P_c(4312)^+, P_c(4440)^+, P_c(4457)^+$



$c\bar{c}uud$

exotic

$J/\psi\, p$

$P_c(4312)^+, P_c(4440)^+, P_c(4457)^+$

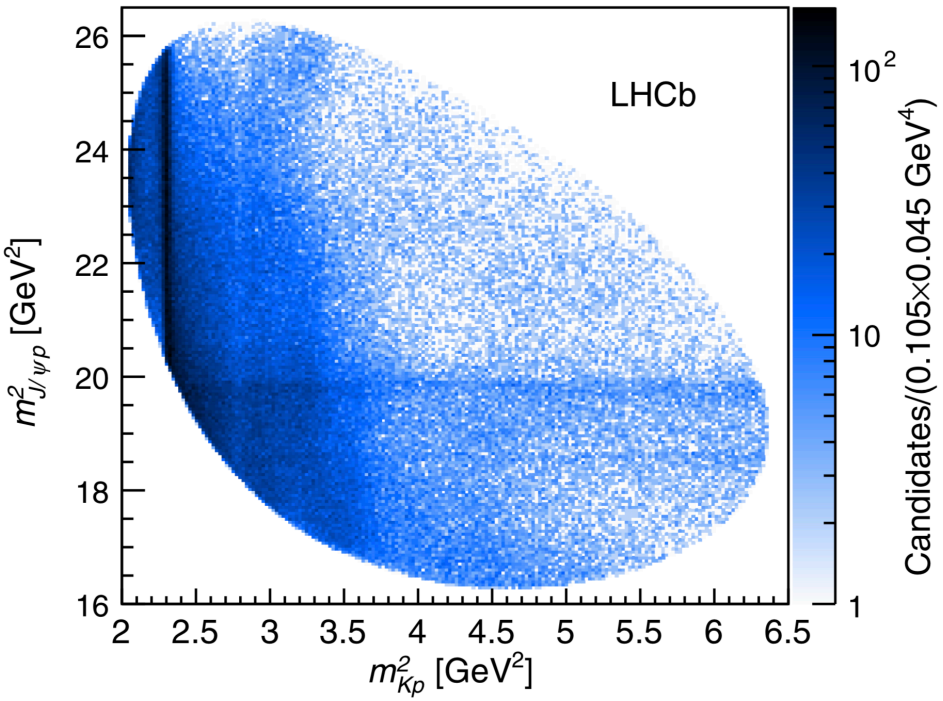


FIG. 2. Dalitz plot of $\Lambda_b^0 \to J/\psi p K^-$ candidates. The data contain 6.4% of non-Λ_b^0 backgrounds, which are distributed smoothly over the phase space. The vertical bands correspond to the Λ^* resonances. The horizontal bands correspond to the $P_c(4312)^+$, $P_c(4440)^+$, and $P_c(4457)^+$ structures at $m^2_{J/\psi p} =$ 18.6, 19.7, and 19.9 GeV^2, respectively.

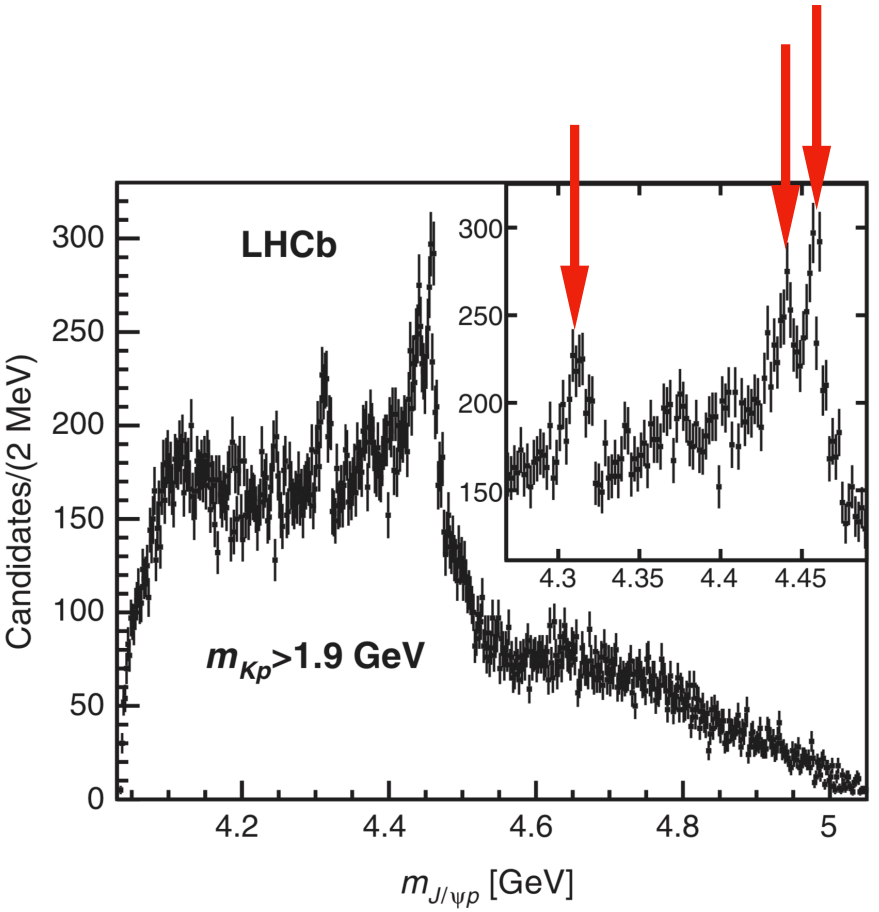
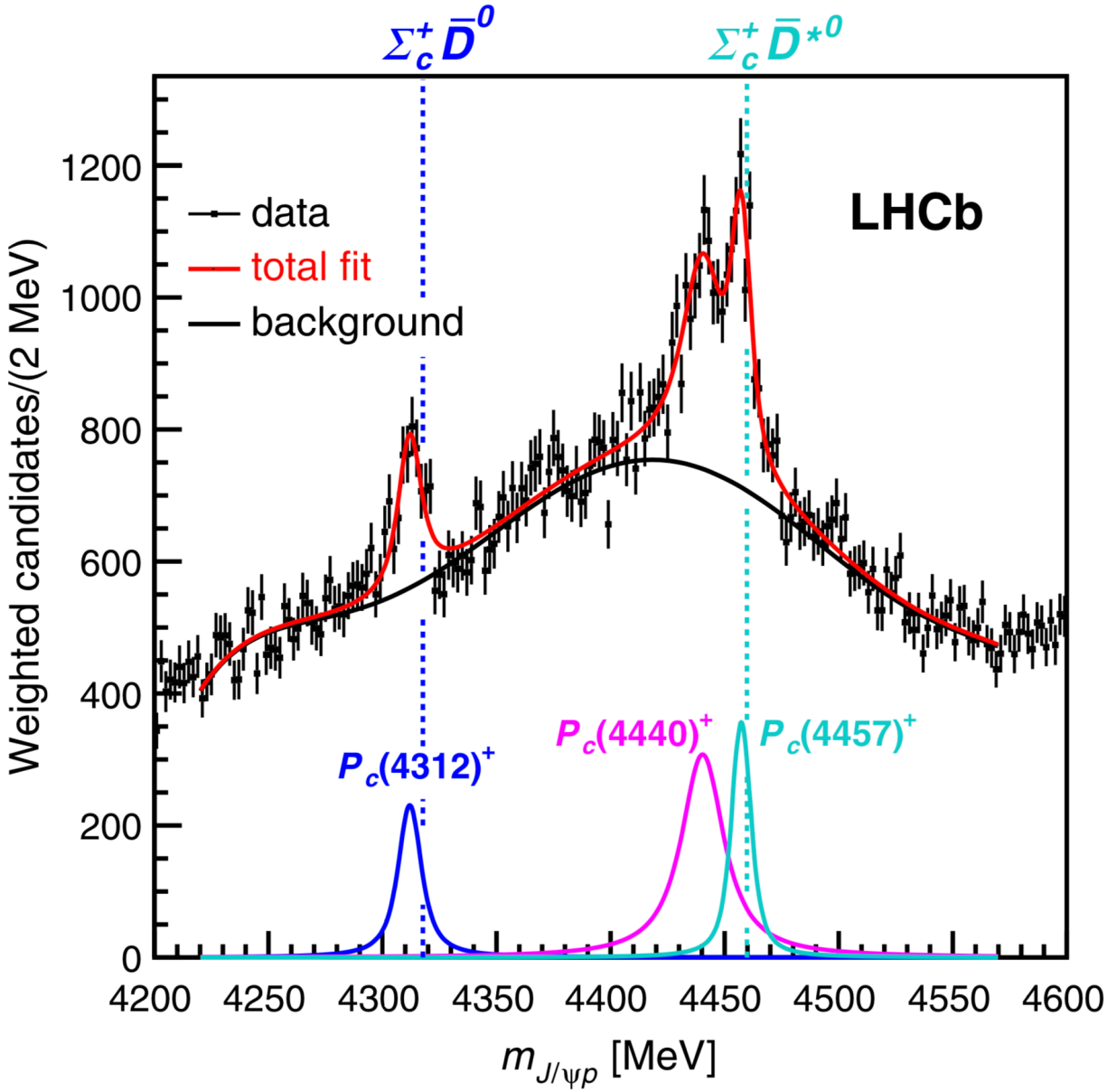


FIG. 3. Distribution of $m_{J/\psi p}$ from $\Lambda_b^0 \to J/\psi p K^-$ candidate after suppression of the dominant $\Lambda^* \to pK^-$ contributions wit the $m_{Kp} > 1.9$ GeV requirement. The inset shows a zoom int the region of the narrow P_c^+ peaks.

$P_c(4312)^+, P_c(4440)^+, P_c(4457)^+$



$P_c(4312)^+, P_c(4440)^+, P_c(4457)^+$

TABLE I. Summary of P_c^+ properties. The central values are based on the fit displayed in Fig. 6.

State	M [MeV]	Γ [MeV]	(95% C.L.)	$\mathcal{R}$ [%]
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+3.7}_{-4.5}$	(<27)	$0.30 \pm 0.07^{+0.34}_{-0.09}$
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+8.7}_{-10.1}$	(<49)	$1.11 \pm 0.33^{+0.22}_{-0.10}$
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+5.7}_{-1.9}$	(<20)	$0.53 \pm 0.16^{+0.15}_{-0.13}$

$$\mathcal{R} \equiv \mathcal{B}(\Lambda_b^0 \to P_c^+ K^-)\mathcal{B}(P_c^+ \to J/\psi p)/\mathcal{B}(\Lambda_b^0 \to J/\psi p K^-)$$

$\Sigma_c \bar{D}^{(*)}$ hadronic molecule with coupling to 5-quark compact core states

Y.Yamaguchi, A. Giachino, A. Hosaka, E. Santopinto, S. Takeuchi, M. Takizawa, PRD96(2017)114031

Y.Yamaguchi, H.G-Tecocoatzi, A.Giachino, A.Hosaka, E.Santopinto, S.Takeuchi, M.Takizawa, 1907.04684[hep-ph]

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

- $\Sigma_c^+ \bar{D}^0$ threshold: 4317.4 MeV

  $P_c(4312)^+$ mass: 4311.9 MeV 5.5 MeV bound

  $P_c(4312)^+$ may be $\Sigma_c \bar{D}$ hadronic molecule

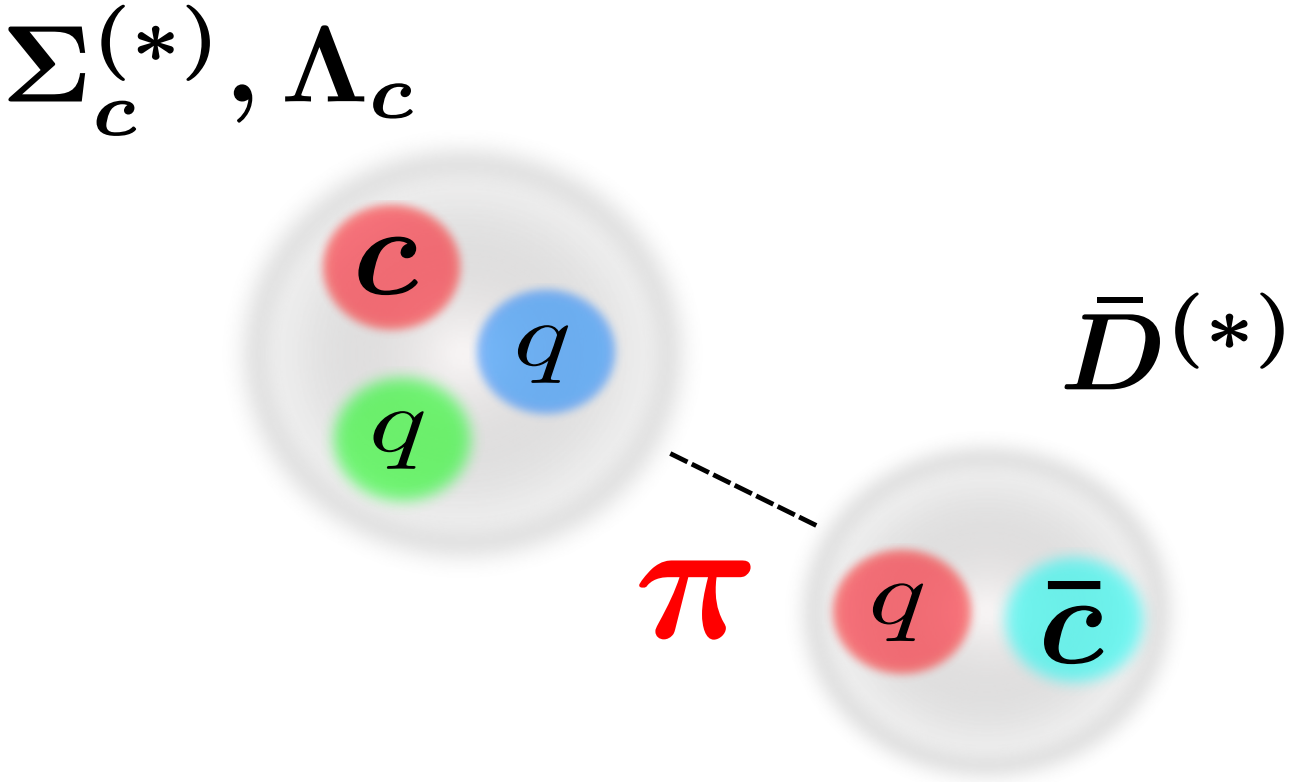
- $\Sigma_c^+ \bar{D}^{*0}$ threshold: 4459.8 MeV

  $P_c(4457)^+$ mass: 4457.3 MeV 2.5 MeV bound

  $P_c(4440)^+$ mass: 4440.3 MeV 19.5 MeV bound

  $P_c(4440)^+$, $P_c(4457)^+$ may be $\Sigma_c \bar{D}^*$ hadronic molecules

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

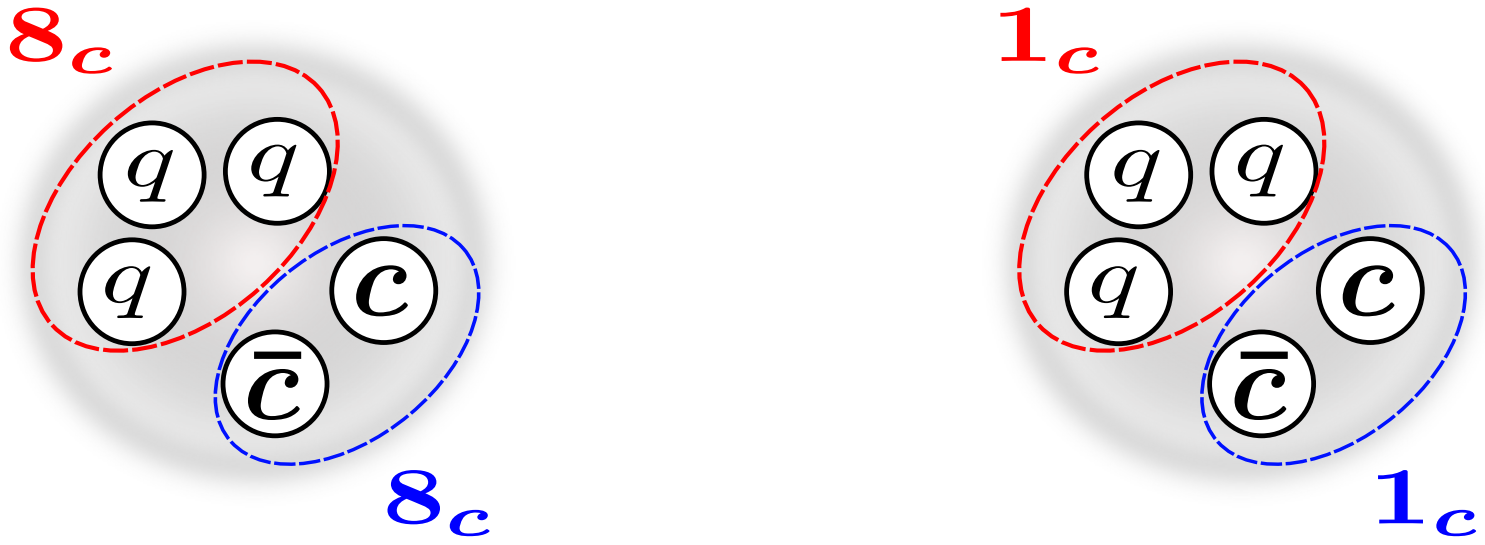


Hadronic molecule

5-quark compact core states

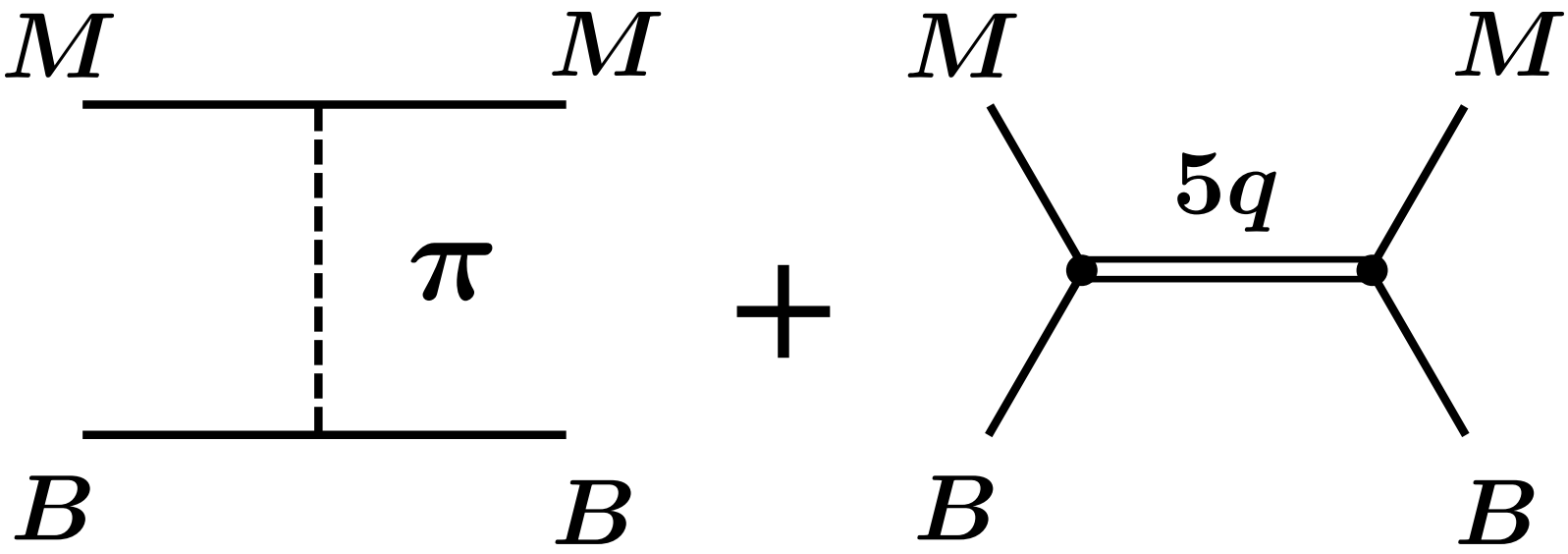
- S. Takeuchi and M. Takizawa, PLB764 (2017) 254-259. Quark cluster model calculations.

- $[q^3\, 8_c\, 3/2]$ configuration: color-magnetic int. is attractive!



Hadronic molucule + 5-q compact states

- Interaction between charmed baryons and charmed mesons



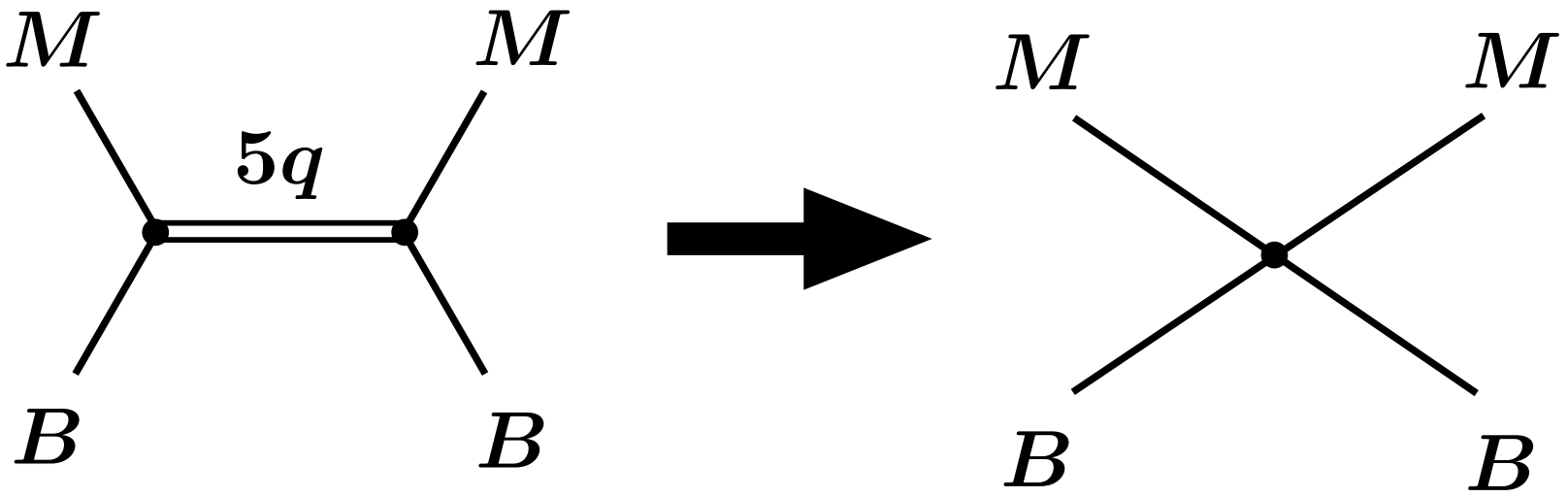
Long range interaction

Short range interaction

Short range interaction

- 5-quark potential -> Local Gaussian

  Pauli blocking + Spectroscopic factors



Chiral Tensor Dymanics

Y.Yamaguchi, H.G-Tecocoatzi, A.Giachino, A.Hosaka, E.Santopinto, S.Takeuchi, M.Takizawa, 1907.04684[hep-ph]

One Pion Exchange Potential (OPEP)

- Heavy hadron molecule -> Long range interaction is important.

- Long range interaction
  -> one pion exchange potential (OPEP)

- OPEPs between heavy hadrons are enhanced by the heavy quark spin symmetry.
  -> $\bar{D}(0^-) - \bar{D}^*(1^-)$, $\Sigma_c(1/2^+) - \Sigma_c^*(3/2^-)$ mixing

- **Tensor term by OPEP gives strong attraction through S-D mixing. (like Deuteron case)**
  -> chiral tensor dynamics

Numerical results

Y.Yamaguchi, H.G-Tecocoatzi, A.Giachino, A.Hosaka, E.Santopinto, S.Takeuchi, M.Takizawa, 1907.04684[hep-ph]

Numerical results

- We have solved coupled-channel Schrödinger equation for $\Lambda_c\bar{D}$, $\Lambda_c\bar{D}^*$, $\Sigma_c\bar{D}$, $\Sigma_c\bar{D}^*$, $\Sigma_c^*\bar{D}$, $\Sigma_c^*\bar{D}^*$ (6 MB components).

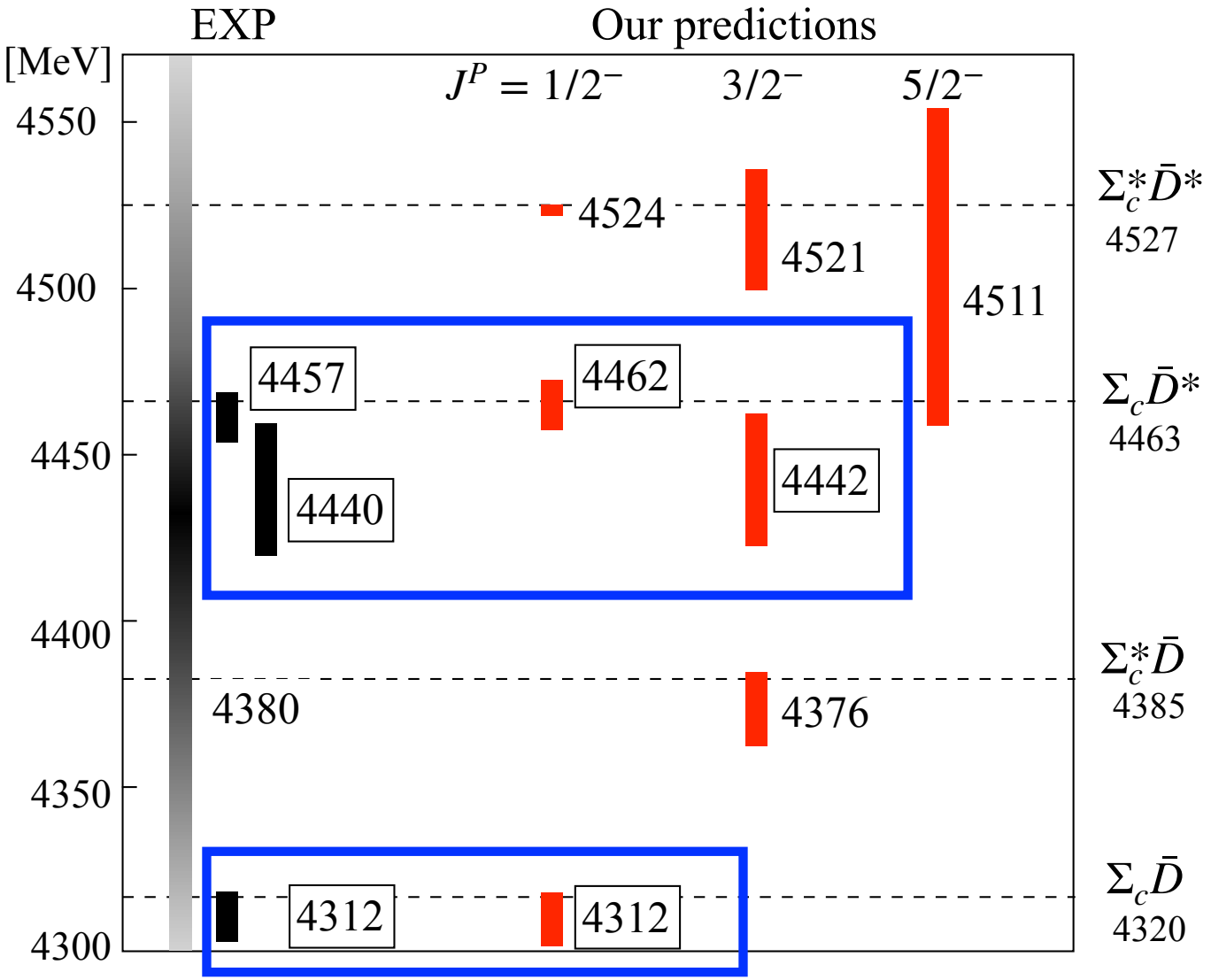
- For $J^P = 1/2^-, 3/2^-, 5/2^-$ (relative S and D wave states)

- OPEP parameters have been determined by D^* decay and deuteron.

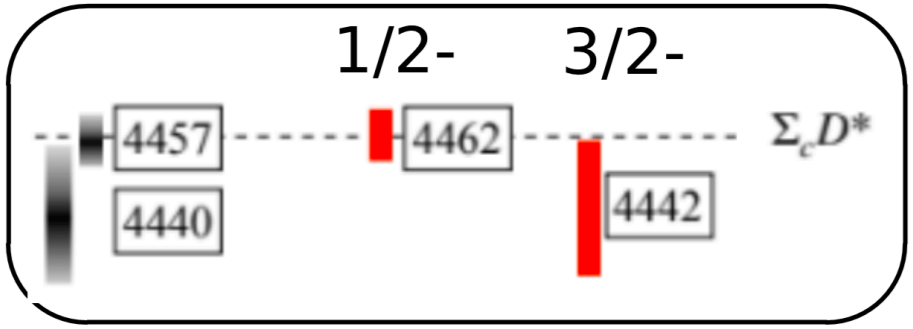
- Overall strength of the 5-quark interaction f has been fixed by $P_c(4312)$ mass.

Pc: Masses and widths

- All observed masses and widths are well reproduced.



Tensor term contribution to $P_c(4440)$ and $P_c(4457)$



▷ J^P assignment

$P_c(4440) : 3/2^-$

$P_c(4457) : 1/2^-$

$\Rightarrow$ **$E(1/2^-) > E(3/2^-)$**

- OPEP of the $\bar{D}^*\Sigma_c$ channel

$1/2^- : {}^2S,\quad {}^4D$

$$\begin{pmatrix} 4C & \mathbf{2\sqrt{2}T} \\ \mathbf{2\sqrt{2}T} & -2C+4T \end{pmatrix}$$

$3/2^- : {}^4S,\quad {}^2D,\quad {}^4D$

$$\begin{pmatrix} -2C & \mathbf{-2T} & \mathbf{-4T} \\ \mathbf{-2T} & 4C & \mathbf{2T} \\ \mathbf{-4T} & \mathbf{2T} & -2C \end{pmatrix}$$

$*$ C: Central force, T: Tensor force

- $S-D$, $D-D$ couplings producing the attraction from the tensor force

$1/2^- : {}^2S - {}^4D$ $\qquad$ $3/2^- : {}^4S - {}^2D, {}^4S - {}^4D, {}^2D - {}^4D$

many channels-> more attraction 11MeV

Pauli blocking and Spectroscopic factor contribution to $P_c(4440)$ and $P_c(4457)$

- For $\Sigma_c \bar{D}^* 3/2^-$ channel, Norm is 23/18

  -> Strongly attractive

- For $\Sigma_c \bar{D}^* 1/2^-$ channel, Norm is 17/18

  -> Slightly repulsive

- $E(1/2^-) - E(3/2^-) = 9$ MeV from Pauli blocking with Spectroscopic factor

Color-magnetic contribution to $P_c(4440)$ and $P_c(4457)$

- Color-magnetic interaction is not included in the present model.
- Color-magnetic interaction gives $E(3/2^-) > E(1/2^-)$
- For larger norm case in baryon-baryon systems,
  Pauli blocking effects overcome color-magnetic interaction.
- Quark cluster model study with Pauli blocking effects and color-magnetic interaction gives attraction for $3/2^-$ but not for $1/2^-$ in $\Sigma_c \bar{D}^*$ channels. (PLB764 (2017) 254-259)

Summary

- OPEP + 5-quark compact core

- Masses and widths of $P_c(4312)^+$, $P_c(4440)^+$, and $P_c(4457)^+$ are reproduced well.

- Spin and parity

  $P_c(4312)^+ : 1/2^-$ $P_c(4440)^+ : 3/2^-$ $P_c(4457)^+ : 1/2^-$

- Mass difference between $P_c(4440)^+$ and $P_c(4457)^+$

  Tensor term : 11 MeV

  Pauli blocking : 9 MeV

- Tensor term contribution is important for heavy hadron molecular states
  -> **chiral tensor dynamics**

- **First example: tensor force can be compared with two partner states.**

- Experimental determination of spin and parity of P_c states are important.