Photocouplings of hidden charm pentaquarks

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HADRON 2023 (Genoa, Italy)

June 9, 2023

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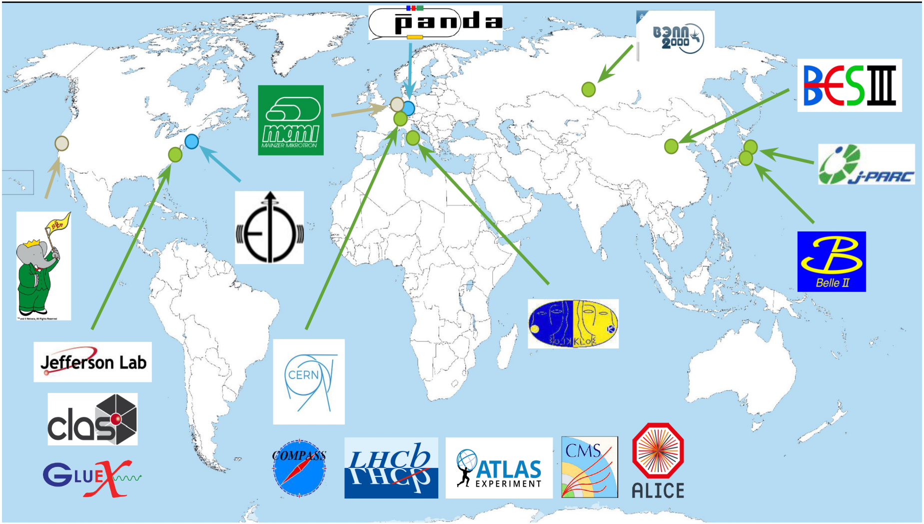
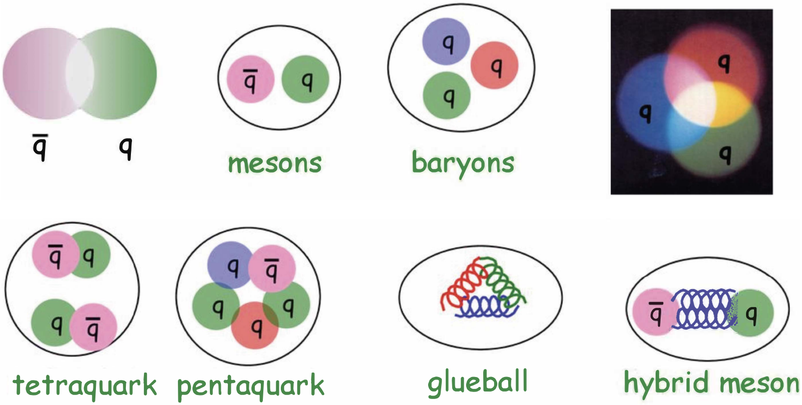


panda
MAMI
MAINZER MIKROTRON
BESIII
J-PARC
Belle II
Jefferson Lab
clas
GlueX
CERN
KLOE
COMPASS
LHCb
ATLAS
EXPERIMENT
CMS
ALICE

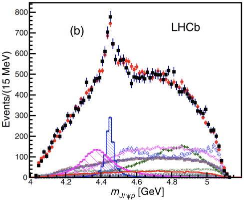
Hadrons

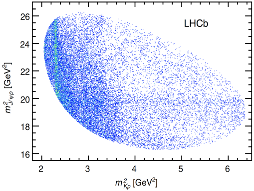


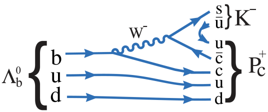
$\bar{q}$
q
mesons
baryons
tetraquark
pentaquark
glueball
hybrid meson

LHCb

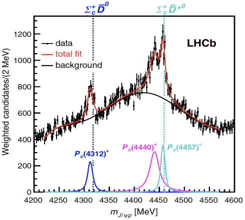
Pentaquarks $P_c(4380)^+$ and $P_c(4450)^+$, with $J^P = 3/2^{\mp}, 5/2^{\pm}$. [1]

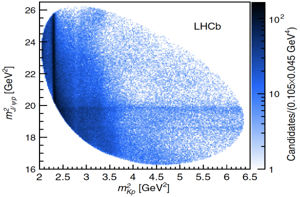


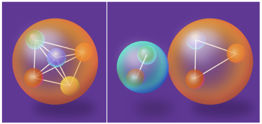




Pentaquarks $P_c(4312)^+$, $P_c(4440)^+$ and $P_c(4457)^+$. [2]







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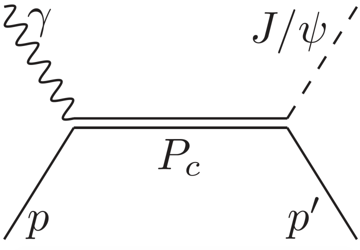
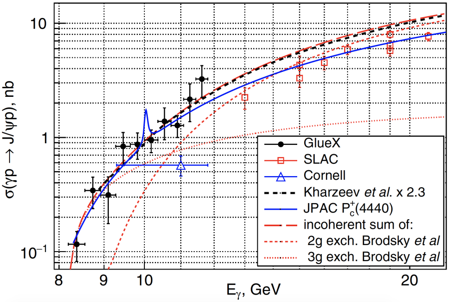
[1] R. Aaij *et al.* (LHCb Collaboration), Phys. Rev. Lett. **115**, 072001 (2015).

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

Jefferson Lab

One of the proposals is to confirm the nature of the pentaquark, through photoproduction.





In 2019, The GlueX Collaboration published their first results, in which it was reported that **they do not see evidence for a pentaquark structure** by J/ψ photoproduction [3]. Where are the pentaquarks?

[3] A. Ali *et al.* (GlueX Collaboration), Phys. Rev. Lett. **123**, 072001 (2019).

Pentaquark wave functions

- Quark Model

Hadrons $\rightarrow$ Multiquark systems$\rightarrow$ Degrees of freedom

$$\psi = \psi^{\rm o}\chi^{\rm s}\phi^{\rm f}\psi^{\rm c}$$

(i) Since quarks are fermions, the total pentaquark wave function should be antisymmetric under any permutation of the three light quarks.

(ii) As all physical states, the pentaquark wave function has to be a color singlet.

The wave functions

- Ground state pentaquarks[4] with $J^P = 3/2^-$ and $L^\pi = 0^+$

$$\psi = \left[\psi^{\rm o}_{A_1} \times \psi^{\rm csf}_{A_2}\right]_{A_2} \quad \Rightarrow \quad \begin{cases} \psi^{\rm csf}_{A_2} = \left[\psi^{\rm c}_{A_2} \times \psi^{\rm sf}_{A_1}\right]_{A_2} \\ \psi^{\rm csf}_{A_2} = \left[\psi^{\rm c}_{E} \times \psi^{\rm sf}_{E}\right]_{A_2} \end{cases}$$

5 configurations

- Pentaquarks with one quantum of orbital excitation $J^P = 3/2^+$ y $L^\pi = 1^-$

$$\begin{array}{l} \psi = \left[\psi^{\rm o}_{A_1} \times \psi^{\rm csf}_{A_2}\right]_{A_2} \\ \\ \psi = \left[\psi^{\rm o}_{E} \times \psi^{\rm csf}_{E}\right]_{A_2} \end{array} \quad \Rightarrow \quad \begin{cases} \psi^{\rm csf}_{A_2} = \left[\psi^{\rm c}_{A_2} \times \psi^{\rm sf}_{A_1}\right]_{A_2} \\ \psi^{\rm csf}_{A_2} = \left[\psi^{\rm c}_{E} \times \psi^{\rm sf}_{E}\right]_{A_2} \\ \psi^{\rm csf}_{E} = \left[\psi^{\rm c}_{A_2} \times \psi^{\rm sf}_{E}\right]_{E} \\ \psi^{\rm csf}_{E} = \left[\psi^{\rm c}_{E} \times \psi^{\rm sf}_{A_2}\right]_{E} \\ \psi^{\rm csf}_{E} = \left[\psi^{\rm c}_{E} \times \psi^{\rm sf}_{A_1}\right]_{E} \\ \psi^{\rm csf}_{E} = \left[\psi^{\rm c}_{E} \times \psi^{\rm sf}_{E}\right]_{E} . \end{cases}$$

19 configurations

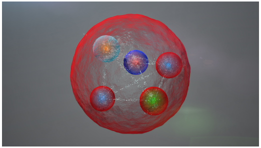
[4] E. Ortiz-Pacheco, R. Bijker, and C. Fernández-Ramírez, J. Phys. G: Nucl. Part. Phys. **46**, 065104 (2019).

Harmonic Oscillator

$$H = \frac{{p_1}^2}{2m} + \frac{{p_2}^2}{2m} + \frac{{p_3}^2}{2m} + \frac{{p_4}^2}{2m'} + \frac{{p_5}^2}{2m'} + \frac{1}{2}C\sum_{i<j}^{5}|\vec{r_i} - \vec{r_j}|^2$$

- Jacobi coordinates

$$\begin{cases} \vec{\rho} \equiv \frac{1}{\sqrt{2}}(\vec{r_1} - \vec{r_2}) \\ \vec{\lambda} \equiv \frac{1}{\sqrt{6}}(\vec{r_1} + \vec{r_2} - 2\vec{r_3}) \\ \vec{\eta} \equiv \frac{1}{\sqrt{2}}(\vec{r_4} - \vec{r_5}) \\ \vec{\zeta} \equiv \sqrt{\frac{6}{5}}\left[\frac{1}{3}(\vec{r_1} + \vec{r_2} + \vec{r_3}) - \frac{1}{2}(\vec{r_4} + \vec{r_5})\right] \\ \vec{R} \equiv \frac{m(\vec{r_1}+\vec{r_2}+\vec{r_3})+m'(\vec{r_4}+\vec{r_5})}{3m+2m'} \end{cases}$$



$$H = \frac{P^2}{2M} + \frac{{p_\rho}^2}{2m_\rho} + \frac{{p_\lambda}^2}{2m_\lambda} + \frac{{p_\eta}^2}{2m_\eta} + \frac{{p_\zeta}^2}{2m_\zeta} + \frac{5}{2}C\rho^2 + \frac{5}{2}C\lambda^2 + \frac{5}{2}C\eta^2 + \frac{5}{2}C\zeta^2$$

M=3m+2m', $\quad$ $m_\rho = m_\lambda \equiv m,$ $\quad$ $m_\eta \equiv m',$ $\quad$ $m_\zeta \equiv \frac{5mm'}{3m+2m'},$

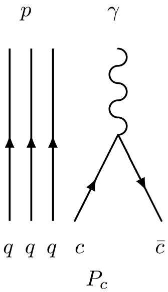
$\alpha_i^2 = (5Cm_i)^{\frac{1}{2}},$ $\quad$ $\omega_i = \sqrt{\frac{5C}{m_i}},$ $\quad$ $i = \{\rho, \lambda, \eta, \zeta\}.$

- The orbital wave function of the pentaquark and the proton

$$\psi_{Pc}(\vec{p_1}, \vec{p_2}, \vec{p_3}, \vec{p_4}, \vec{p_5}) = \delta^3(\vec{P} - \vec{K_{Pc}})\sqrt{5\sqrt{5}}\frac{1}{\pi^{\frac{3}{4}}\alpha_\rho^{\frac{3}{2}}}\frac{1}{\pi^{\frac{3}{4}}\alpha_\lambda^{\frac{3}{2}}}\frac{1}{\pi^{\frac{3}{4}}\alpha_\eta^{\frac{3}{2}}}\frac{1}{\pi^{\frac{3}{4}}\alpha_\zeta^{\frac{3}{2}}}e^{-\frac{1}{2\alpha_\rho^2}p_\rho^2}e^{-\frac{1}{2\alpha_\lambda^2}p_\lambda^2}e^{-\frac{1}{2\alpha_\eta^2}p_\eta^2}e^{-\frac{1}{2\alpha_\zeta^2}p_\zeta^2}$$

$$\psi_p(\vec{p_1}, \vec{p_2}, \vec{p_3}) = \delta^3(\tfrac{3m}{M}\vec{P} + \sqrt{\tfrac{6}{5}}\vec{p_\zeta} - \vec{K_p})\sqrt{3\sqrt{3}}\left(\frac{1}{\pi^{\frac{3}{4}}\beta^{\frac{3}{2}}}\right)^2 e^{-\frac{1}{2\beta^2}(p_\rho^2+p_\lambda^2)}$$

Photoproduction of pentaquarks



- Interaction Hamiltonian [5]

$$H = e\int d^3x\, \underbrace{\bar{q}(\vec{x}) e_q \gamma^\mu q(\vec{x})}_{J^\mu \text{ quark current}} A_\mu(\vec{x})$$

- The helicity amplitude and the form factor

$$A_\nu(k) = \langle \gamma p | H | P_c \rangle = \frac{e}{(2\pi)^{\frac{3}{2}} 2\sqrt{k_0}} \langle \psi_p^{csf} 1/2, \nu - 1 | e_c \sigma_- | \psi_{P_c}^{csf} 3/2, \nu \rangle \underbrace{F(k)}_{\text{Orbital contribution}}$$

[5]

Fotoproduction of pentaquarks

- Decay width $\Gamma(P_c \to p + \gamma) = 2\pi\rho \, \frac{2}{2J+1} \sum_{\nu>0} |A_\nu(k)|^2$

For a frame with the pentaquark at rest:

$$\rho = 4\pi \frac{E_p k^2}{m_{P_c}}, \qquad E_p = \sqrt{m_p^2 + k^2}.$$

The four-momentum $(k_0, \vec{k})$ of the photon is $Q^2 = Q^\mu Q_\mu = k_0^2 - k^2$

$$k^2 = \left(\frac{Q^2 - m_{P_c}^2 - m_p^2}{2m_{P_c}} \right)^2 - m_p^2 \qquad \xrightarrow{Q^2=0} \qquad k = \frac{m_{P_c}^2 - m_p^2}{2m_{P_c}}$$

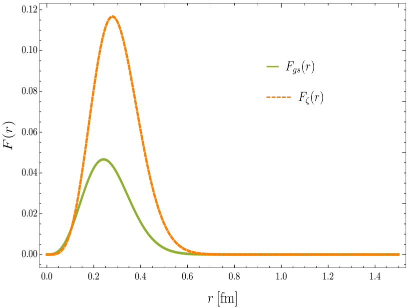
Form factor $F(k)$ in the Harmonic Oscillator

$$\mathsf{F}_{gs}(k) = \left(\frac{\sqrt{5(2a+3)}}{3}\right)^{\frac{3}{4}} \left(\frac{2\alpha_\rho\beta}{\alpha_\rho^2+\beta^2}\right)^3 e^{-\frac{5}{12\alpha_\rho^2}\sqrt{\frac{2a+3}{5a}}k^2}, \qquad a \equiv \frac{m'}{m}, \qquad k = 2.12\ GeV.$$

Parameters

$m = m_u = m_d$	320	MeV
$m' = m_c$	1500	MeV
$\beta = 1/r_p$	1.19	fm

Pentaquark charge radius: $$r^2 = \frac{1}{\alpha_\rho^2}\left(1 + \frac{1}{5}\left(\frac{5a}{3+2a}\right)^{\frac{3}{2}}\right)$$



Why is the the form factor $F(k)$ too small?

Electromagnetic couplings of heavy baryons Ξ_c

- For the first time The Belle Collaboration reported the electromagnetic decays of the **excited charm baryons** $\Xi_c(2790)$ and $\Xi_c(2815)$.[6]

$B_Q \to B'_Q\gamma$	Our work[7]	$ChQM$[8]	DGCB.[9]	$LCQSR$[10]	RQM[11]	Γ^{exp}(KeV)[13]
$\Xi_c^+(2790) \to {}^2\Xi_c^+\gamma$	**7.4**	4.65	249.6±41.9	265(1±0.4)		< 350
$\Xi_c^0(2790) \to {}^2\Xi_c^0\gamma$	**202.5**	263	119.3±21.7	2.7(1±0.3)		800 ± 320
$\Xi_c^+(2815) \to {}^2\Xi_c^+\gamma$	**4.8**	2.80			190 ± 5	< 80
$\Xi_c^0(2815) \to {}^2\Xi_c^0\gamma$	**292.6**	292			497 ± 14	320 ± 45

6 J. Yelton *et al.* (The Belle Collaboration), Phys. Rev. D, **102**, 071103 (2020).

7 E. Ortiz-Pacheco, R. Bijker (2023 submitted).

8 K.-L. Wang, Y.-X. Yao, X.-H. Zhong, and Q. Zhao, Phys. Rev. D, **96**, 116016 (2017).

9 D. Gamermann, C. E. Jiménez-Tejero, and A. Ramos, Phys. Rev. D, **83**, 074018 (2011).

10 T. M. Aliev, K. Azizi, and A. Ozpineci, Phys. Rev. D, **79**, 056005 (2009).

11 M. A. Ivanov, J. G. Körner, V. E. Lyubovitskij, and A. G. Rusetsky, Phys. Rev. D **60**, 094002 (1999).

Hypercentral Model

$$T = \frac{1}{2m}({p_1}^2 + {p_2}^2 + {p_3}^2) + \frac{1}{2m'}({p_4}^2 + {p_5}^2)$$

- Hamiltonian with the hyper-Coulomb potential plus a linear term (**confining potential**)

$$H = \frac{P^2}{2M_5} + \frac{1}{\mu}({p_\rho}^2 + {p_\lambda}^2 + {p_\eta}^2 + {p_\zeta}^2) - \frac{\tau}{\sqrt{\rho^2+\lambda^2+\eta^2+\zeta^2}} + \epsilon\sqrt{\rho^2+\lambda^2+\eta^2+\zeta^2}$$

$$\begin{cases} \vec{\rho} = \vec{r_2} - \vec{r_1} \\ \vec{\lambda} = \frac{1}{\sqrt{N_\lambda}}\left(\vec{r_3} - \frac{\vec{r_1}+\vec{r_2}}{2}\right) \\ \vec{\eta} = \frac{1}{\sqrt{N_\eta}}\left(\vec{r_4} - \frac{\vec{r_1}+\vec{r_2}+\vec{r_3}}{3}\right) \\ \vec{\zeta} = \frac{1}{\sqrt{N_\zeta}}\left(\vec{r_5} - \frac{m(\vec{r_1}+\vec{r_2}+\vec{r_3})+m'\vec{r_4}}{3m+m'}\right) \\ \vec{R} = \frac{m(\vec{r_1}+\vec{r_2}+\vec{r_3})+m'(\vec{r_4}+\vec{r_5})}{3m+2m'} \end{cases} \Rightarrow \begin{cases} x = \sqrt{\rho^2+\lambda^2+\eta^2+\zeta^2} \\ \xi_1 = \arctan\left(\frac{\rho}{\lambda}\right),\ \xi_2 = \arctan\left(\frac{\eta}{\zeta}\right) \\ \xi = \arctan\left(\sqrt{\frac{\rho^2+\lambda^2}{\eta^2+\zeta^2}}\right), \\ \Omega_\rho = (\theta_\rho, \phi_\rho),\ \Omega_\lambda = (\theta_\lambda, \phi_\lambda), \\ \Omega_\eta = (\theta_\eta, \phi_\eta),\ \Omega_\zeta = (\theta_\zeta, \phi_\zeta). \end{cases}$$

Hyper-radial: $\left[-\frac{1}{2\mu}\left(\frac{\partial^2}{\partial x^2} + \frac{11}{x}\frac{\partial}{\partial x} - \frac{\gamma(\gamma+10)}{x^2}\right) - \frac{\tau}{x}\right] R_{\omega\gamma}(x) = E R_{\omega\gamma}(x)$

Hyper-angular: $\left[-\frac{1}{(\cos\xi)^5(\sin\xi)^5}\frac{\partial}{\partial\xi}\left((\cos\xi)^5(\sin\xi)^5\frac{\partial}{\partial\xi}\right) + \frac{\Lambda_2^2(\Omega_2)}{(\cos\xi)^2} + \frac{\Lambda_1^2(\Omega_1)}{(\sin\xi)^2}\right] Y_{[\gamma]}(\Omega) = \gamma(\gamma+10)Y_{[\gamma]}(\Omega).$

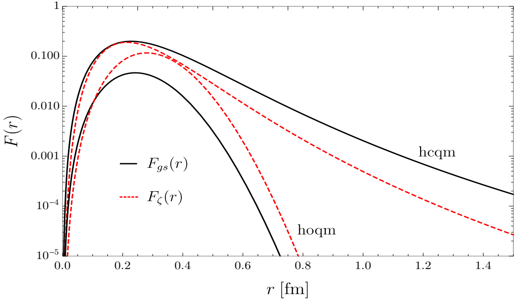
$$\psi_{P_c}(\vec{r_1},\vec{r_2},\vec{r_3},\vec{r_4},\vec{r_5}) = \left[\frac{(2g_0)^{12}}{11!}\right]^{\frac{1}{2}} \frac{2\sqrt{15}}{\pi^3} e^{-g_0 x} \left(\frac{M_2^4 m_3 m_4 m_5}{m_1^3 m_2^3 M_5}\right)^{\frac{3}{4}} \frac{1}{(2\pi)^{\frac{3}{2}}} e^{-i\vec{K}_{P_c}\cdot\vec{R}}.$$

Form factor $F(k)$ in the Hypercentral Model

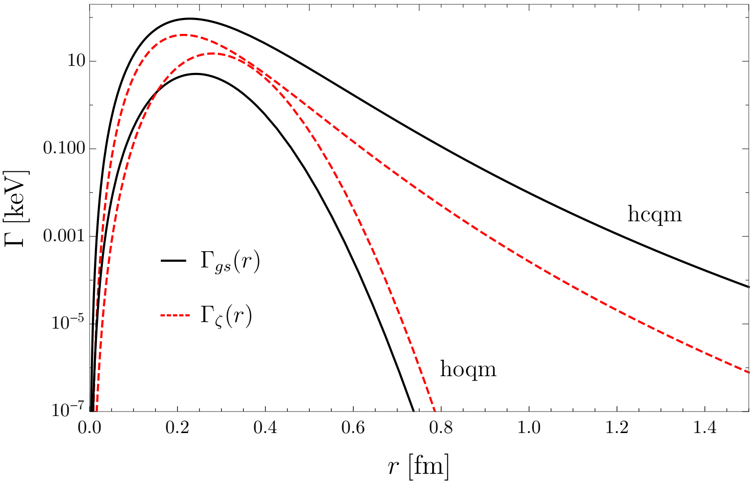
$$\begin{aligned} F_{gs}(k) &= \left(\tfrac{2a+3}{3a^2}\right)^{\frac{3}{4}} \left(\frac{a(a+3)}{2a+3}\right)^{\frac{3}{2}} (4\pi)^3 \left[\frac{(2g_3)^6(2g_0)^{12}}{5!11!}\right]^{\frac{1}{2}} \frac{1}{\pi^{\frac{3}{2}}} \frac{2\sqrt{15}}{\pi^3} \\ & \int d\rho d\lambda d\eta \rho^2\lambda^2\eta^2 j_0\left(-\tfrac{1}{\sqrt{2}}\sqrt{\frac{a+3}{3a}}k\eta\right) e^{-g_3\sqrt{\rho^2+\lambda^2}} e^{-g_0\sqrt{\rho^2+\lambda^2+\left(\frac{2(3+a)}{3+2a}\right)\eta^2}} \end{aligned}$$

with $a \equiv \frac{m'}{m}$, y $k = 2.12\ GeV$. Parameters: $g_3 = \frac{\tau_3\mu}{\sqrt{2}\frac{5}{2}}$ y $g_0 = \frac{\mu\tau}{\sqrt{2}\frac{11}{2}}$.

Pentaquark charge radius: $r^2 = \frac{13}{4}\left(\frac{\frac{11}{2}\sqrt{2}}{\tau\mu}\right)^2 \frac{3(1+a)}{3+2a}e.$



Comparison of both models



Conclusions

Pentaquarks

- It was found that from a large number of considered pentaquark states, 5 for ground states and 19 for radially excited states, in the end, by selection rules, **there are only 2 possible pentaquark states contributing to the photoproduction; 1 ground state, and 1 radially excited state.**

- By calculating the decay width of the photoproduction of pentaquark, in the HO and HC models, one finds that the channel $p + \gamma \rightarrow P_c(uudc\bar{c})$ **gives a maximum contribution $\sim$100 keV only around a pentaquark charge radius of 0.3 fm.**

- Further analysis on our side is needed in order to determine the upper limits of the decay width for $P_c \rightarrow J/\psi + p$. Moreover, search for possible additional ways to coupling P_c and their possible contribution the photoproduction.

Thanks!