The effect of hidden-charm strange pentaquarks P_{cs} on the $K^- p \to J/\psi \Lambda$ reaction

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Motivation

- The LHCb Collaboration[1] found the hidden-charm pentaquark state with strangeness in the analysis of $\Xi_b^- \to J/\psi \Lambda K^-$.

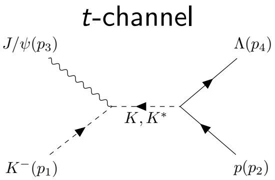
$$M_{P_{cs}} = 4458.8 \pm 2.9^{+4.7}_{-1.1}\,\mathrm{MeV}, \qquad \Gamma_{P_{cs}} = 17.3^{+8.0}_{-5.7}\,\mathrm{MeV}$$

- In principle, the hidden-charm pentaquark states can be produced by meson beams such as the pion and kaon.
- The systematic investigation of $K^- p \to J/\psi\,\Lambda$ production mechanism will provide helpful guidance on possible future experiments and on determining the spin-parity quantum number of P_{cs}.

[1] R. Aaij *et al.* [LHCb Collaboration], [arXiv:2012.10380 [hep-ex]].

Effective Lagrangian Method (Model I)

Background Part



* The coupling constants for vertex $p\Lambda K$ and $p\Lambda K^*$ are taken from the Nijmegen extended-soft-core model (ESC08a)[2].

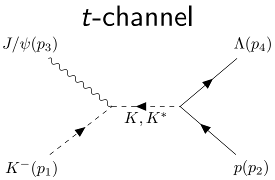
K-exchange:

$$\mathcal{L}_{J/\psi KK} = -ig_{J/\psi KK}\,\psi^\mu\left(K^+\partial_\mu K^- - K^-\partial_\mu K^+\right)$$

$$\mathcal{L}_{\Lambda NK} = -\frac{f_{\Lambda NK}}{m_\pi}\bar{\Lambda}\gamma_\mu\gamma_5 N\partial^\mu K + \mathrm{h.c.}$$

[2] T. A. Rijken *et al.*, Prog. Theor. Phys. Suppl. **185**, 14-71 (2010).

Background Part



* The coupling constants for vertex $p\Lambda K$ and $p\Lambda K^*$ are taken from the Nijmegen extended-soft-core model (ESC08a)[2].

K^*-exchange:

$$\mathcal{L}_{J/\psi KK^*} = -\frac{g_{J/\psi KK^*}}{m_\psi}\varepsilon^{\mu\nu\alpha\beta}\partial_\mu\psi_\nu K\partial_\alpha K^*_\beta,$$

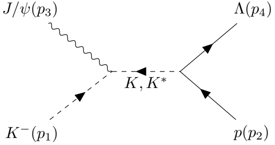
$$\mathcal{L}_{\Lambda NK^*} = -g_{\Lambda NK^*}\bar{\Lambda}\gamma^\mu NK^*_\mu - \frac{f_{\Lambda NK^*}}{4m_N}\bar{\Lambda}\sigma^{\mu\nu}N\left(\partial_\mu K^*_\nu - \partial_\nu K^*_\mu\right) + \mathrm{h.c.}.$$

where $\varepsilon^{\mu\nu\alpha\beta}$ is Levi-Civita symbol and $\sigma^{\mu\nu} = i(\gamma^\mu\gamma^\nu - \gamma^\nu\gamma^\mu)/2$

[2] T. A. Rijken *et al.*, Prog. Theor. Phys. Suppl. **185**, 14-71 (2010).

Background Part

t-channel



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* The coupling constans for $J/\psi KK$ and $J/\psi KK^*$ are calculated by using partial decay width.

Decay Amplitude:

$$A_{J/\psi KK} = -\, g_{J/\psi KK}\,(q_K - q'_K)_\mu \epsilon^\mu$$

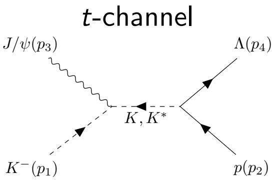
$$A_{J/\psi KK^*} = -\,\frac{g_{J/\psi KK^*}}{m_\psi}\,\varepsilon^{\mu\nu\alpha\beta} q_{\psi\mu}\, q_{K^*\alpha}\, \epsilon_\nu\, \epsilon^*_{K^*\beta}$$

Partial decay width:

$$\Gamma(J/\psi \to MM) = \frac{|\mathrm{k}|}{8\pi M^2_{J/\psi}} \frac{1}{2J+1} \sum_{\lambda_1=-J}^{J} \sum_{\lambda_2,\lambda_3} |A(J/\psi \to MM)|^2$$

[2] T. A. Rijken *et al.*, Prog. Theor. Phys. Suppl. **185**, 14-71 (2010).

Background Part



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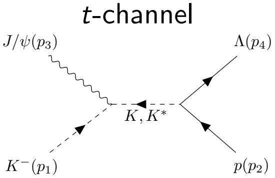
Coupling Constants:

$$f_{\Lambda NK} = -0.2643, \quad g_{\Lambda NK^*} = -1.1983, \quad f_{\Lambda NK^*} = -4.2386\,,$$
$$g_{J/\psi KK} = 7.12 \times 10^{-4}, \quad g_{J/\psi KK^*} = 8.82 \times 10^{-3}.$$

[2] T. A. Rijken *et al.*, Prog. Theor. Phys. Suppl. **185**, 14-71 (2010).

Background Part



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* The coupling constans for $J/\psi KK$ and $J/\psi KK^*$ are calculated by using partial decay width.

K-exchange:

$$\mathcal{M}_K = \frac{g_{J/\psi KK} f_{\Lambda NK}}{m_\pi} \bar{u}(p_4,\lambda_4)\gamma_5 \frac{(2p_1 - p_3)\cdot \epsilon^*(p_3,\lambda_3)}{t - m_K^2} \not{q}_t u(p_2,\lambda_2),$$

K^*-exchange:

$$\mathcal{M}_{K^*} = i\frac{g_{J/\psi KK^*} g_{\Lambda NK^*}}{m_\psi} \bar{u}(p_4,\lambda_4) \frac{\varepsilon_{\mu\nu\alpha\beta} p_3^\mu \epsilon^{*\nu}(p_3,\lambda_3) q_t^\alpha}{t - m_{K^*}^2} \left(-g^{\beta\sigma} + \frac{q_t^\beta q_t^\sigma}{m_{K^*}^2}\right) \times \left(\gamma_\sigma + i\frac{\kappa_{K^*}}{2m_N}\sigma_{\gamma\sigma} q_t^\gamma\right) u(p_2,\lambda_2),$$

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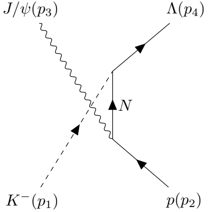
[2] T. A. Rijken *et al.*, Prog. Theor. Phys. Suppl. **185**, 14-71 (2010).

Background Part

u-channel



* The coupling $J/\psi NN$ is taken from the coupling of J/ψ to $N\bar{N}$ value[3]: $g_{J/\psi NN} = 1.62 \times 10^{-3}$

* The tensor coupling is not included in the present work since it is related to the charmed magnetic moment of the nucleon which can be neglected.

N-exchange:

$$\mathcal{L}_{J/\psi NN} = -g_{J/\psi NN}\bar{N}\gamma_\mu\psi^\mu N - \frac{f_{J/\psi NN}}{2M_N}\bar{N}\sigma_{\mu\nu}\psi^{\mu\nu}N + \mathrm{h.c.},$$

$$\mathcal{L}_{\Lambda NK} = -\frac{f_{\Lambda NK}}{m_\pi}\bar{\Lambda}\gamma_\mu\gamma_5 N\partial^\mu K + \mathrm{h.c.},$$

[3] T. Barnes and X. Li, Phys. Rev. D **75**, 054018 (2007).

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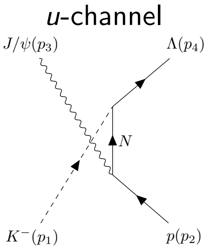

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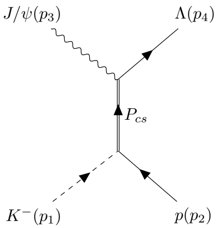
N-exchange:

$$\mathcal{M}_N = -\frac{g_{J/\psi NN} f_{\Lambda NK}}{m_\pi} \bar{u}(p_4,\lambda_4)\gamma_5 \not{p}_1 \frac{\not{q}_u + m_N}{u - m_N^2} \not{\epsilon}^*(p_3,\lambda_3) u(p_2,\lambda_2)$$

[3] T. Barnes and X. Li, Phys. Rev. D **75**, 054018 (2007).

Resonance Part



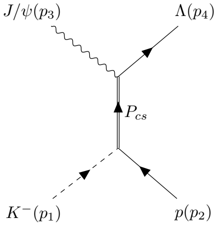
* Since the spin-parity quantum number of P_{cs} is experimentally unknown, we considered six different cases, i.e. $J^P = 1/2^{\pm}$, $J^P = 3/2^{\pm}$, and $J^P = 5/2^{\pm}$.

$P_{cs}(1/2^{\pm})$ exchange:

$$\mathcal{L}^{1/2\pm}_{P\Lambda J/\psi} = -g_{P\Lambda J/\psi}\bar{P}\Gamma^{\mp}_{\mu}\Lambda\psi^{\mu} + \frac{f_{P\Lambda J/\psi}}{2m_{\Lambda}}\bar{P}\sigma_{\mu\nu}\Gamma^{\pm}\Lambda\psi^{\mu\nu} + \mathrm{h.c.},$$

$$\mathcal{L}^{1/2\pm}_{PNK} = -g_{PNK}\bar{P}\Gamma^{\mp}NK + \mathrm{h.c.}$$

Resonance Part



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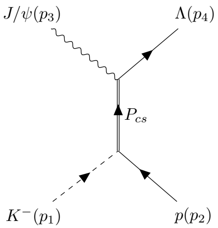
$P_{cs}(3/2^\pm)$ exchange:

$$\mathcal{L}^{3/2\pm}_{P\Lambda J/\psi} = -\frac{g_{P\Lambda J/\psi}}{2m_\Lambda}\bar{P}_\mu\Gamma^\pm_\nu\Lambda\psi^{\mu\nu} - \frac{f_{P\Lambda J/\psi}}{4m_\Lambda^2}\bar{P}_\mu\Gamma^\mp\partial_\nu\Lambda\psi^{\mu\nu} - \frac{h_{P\Lambda J/\psi}}{4m_\Lambda^2}\bar{P}_\mu\Gamma^\mp\Lambda\partial_\nu\psi^{\mu\nu} + \mathrm{h.c.},$$

$$\mathcal{L}^{3/2\pm}_{PNK} = -\frac{g_{PNK}}{M_{P_{cs}}\, m_N}\varepsilon^{\mu\nu\alpha\beta}\partial_\mu\bar{P}_\nu\Gamma^\pm_\alpha N\partial_\beta K + \mathrm{h.c.}$$

Resonance Part



* Since the spin-parity quantum number of P_{cs} is experimentally unknown, we considered six different cases, i.e. $J^P = 1/2^{\pm}$, $J^P = 3/2^{\pm}$, and $J^P = 5/2^{\pm}$.

* Here, the coupling constants for each vertices are unknown. Also, there is no experimental data on branching ratios of P_{cs}.

$P_{cs}(5/2^{\pm})$ exchange:

$$\mathcal{L}^{5/2\pm}_{P\Lambda J/\psi} = -\frac{g_{P\Lambda J/\psi}}{2m_\Lambda^2}\bar{P}_{\mu\alpha}\Gamma^{\mp}_{\nu}\Lambda\partial^{\alpha}\psi^{\mu\nu} - \frac{f_{P\Lambda J/\psi}}{4m_\Lambda^3}\bar{P}_{\mu\alpha}\Gamma^{\pm}\partial_\nu\Lambda\partial^{\alpha}\psi^{\mu\nu} - \frac{h_{P\Lambda J/\psi}}{4m_\Lambda^3}\bar{P}_{\mu\alpha}\Gamma^{\pm}\Lambda\partial^{\alpha}\partial_{\nu}\psi^{\mu\nu} + \mathrm{h.c.},$$

$$\mathcal{L}^{5/2\pm}_{PNK} = -\frac{g_{PNK}}{M_{P_{cs}}\, m_N^2}\varepsilon^{\mu\nu\alpha\beta}\partial_\mu\bar{P}_{\nu\rho}\Gamma^{\mp}_{\alpha}N\partial^{\rho}\partial_{\beta}K + \mathrm{h.c.}$$

How we determine the coupling constants

P_c in $\pi^- p \to J/\psi n$:

There are several studies[4] [5] which calculated the coupling constants of P_c by estimating the branching ratios of P_c using the upper limit of total cross section data of the $\pi^- p \to J/\psi n$ reaction. They estimated the branching ratio of $P_c \to J/\psi n$ to be about a few percents and $P_c \to \pi^- p$ to be of order 10^{-4}.

[4] S. H. Kim, H. C. Kim and A. Hosaka, Phys. Lett. B **763**, 358 (2016)
[5] X. Y. Wang *et al.*, Phys. Lett. B **797**, 134862 (2019)

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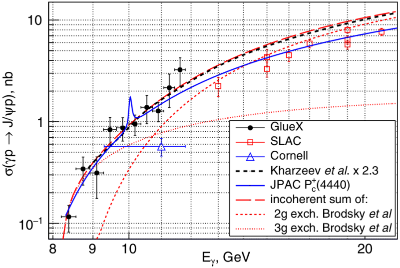
These estimates are in agreement with recent findings from the GlueX Collaboration[6].



[4] S. H. Kim, H. C. Kim and A. Hosaka, Phys. Lett. B **763**, 358 (2016)
[5] X. Y. Wang *et al.*, Phys. Lett. B **797**, 134862 (2019)
[6] A. Ali *et al.* [GlueX],Phys. Rev. Lett. **123**, 072001 (2019)

How we determined the coupling constants

P_{cs} in $K^- p \to J/\psi \Lambda$:

- Is there any experimental data for this reaction?
- We use the same upper limit as in the P_c case.
  - Since the threshold energy of the P_{cs} production is rather high, the effects of the explicit SU(3) symmetry breaking are also suppressed.
  - The magnitude of the total cross section of $K^- p$ scattering is similar to $\pi^- p$ scattering.
  - Based on this, we estimate the upper limit of the total cross section for the $K^- p \to J/\psi \Lambda$ reaction near threshold to be around 1 nb.

How we determined the coupling constants

P_{cs} in $K^- p \to J/\psi\Lambda$:

- Is there any experimental data for this reaction?
- We use the same upper limit as in the P_c case.
- We estimate $B(P_{\rm cs} \to J/\psi\Lambda) = 1\%$ and $B(P_{\rm cs} \to K^- p) = 0.01\%$.
  - This 1% branching ratio of the $P_{cs} \to J/\psi\Lambda$ decay is in line with the molecular picture of P_{cs}[7].
  - Since the $P_{cs} \to K^- p$ decay is the OZI-suppressed process, its branching fraction is very small.

[7] R. Chen, Eur. Phys. J. C **81**, no.2, 122 (2021)

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P_{cs} in $K^- p \to J/\psi\Lambda$:

- Is there any experimental data for this reaction?
- We use the same upper limit as in the P_c case.
- We estimate $B(P_{\rm cs} \to J/\psi\Lambda) = 1\%$ and $B(P_{\rm cs} \to K^- p) = 0.01\%$.

Decay amplitude for $P\Lambda J/\psi$ vertex:

$$\begin{aligned} A^{1/2\pm}_{P\Lambda J/\psi} &= -\, g_{P\Lambda J/\psi}\, \bar{u}_P\, \Gamma^{\mp}_{\mu}\, \epsilon^{\mu}\, u_{\Lambda}, \\ A^{3/2\pm}_{P\Lambda J/\psi} &= i\frac{g_{P\Lambda J/\psi}}{2m_{\Lambda}}\, \bar{u}_{P\mu}\, \Gamma^{\pm}_{\nu}\, (q^{\mu}_{\psi}\epsilon^{\nu} - q^{\nu}_{\psi}\epsilon^{\mu})\, u_{\Lambda}, \\ A^{5/2\pm}_{P\Lambda J/\psi} &= \frac{g_{P\Lambda J/\psi}}{2m^2_{\Lambda}}\, \bar{u}_{P\mu\alpha}\, \Gamma^{\mp}_{\nu}\, (q^{\mu}_{\psi}\epsilon^{\nu} - q^{\nu}_{\psi}\epsilon^{\mu})\, q^{\alpha}_{\psi}\, u_{\Lambda}. \end{aligned}$$

Spinor for $s \geq 3/2$:

$$u^{n+1/2}_{\mu_1\cdots\mu_{n-1}\mu}(p,s) \equiv \sum_{r,m} (n+1/2, s|1, r; n-1/2, m)\, u^{n-1/2}_{\mu_1\cdots\mu_{n-1}}(p,m)\varepsilon^{r}_{\mu}(p).$$

How we determined the coupling constants

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- We use the same upper limit as in the P_c case.
- We estimate $B(P_{\rm cs} \to J/\psi\Lambda) = 1\%$ and $B(P_{\rm cs} \to K^- p) = 0.01\%$.

Decay amplitude for PNK vertex:

$$A^{1/2\pm}_{PNK} = -\, g_{PNK}\, \bar{u}_P\, \Gamma^{\mp}\, u_N,$$
$$A^{3/2\pm}_{PNK} = -\, \frac{g_{PNK}}{M_{P_{cs}}\, m_N} \varepsilon_{\mu\nu\alpha\beta}\, \bar{u}^{\nu}_P\, q^{\mu}_P\, \Gamma^{\alpha}_{\pm}\, q^{\beta}_K\, u_N,$$
$$A^{5/2\pm}_{PNK} = i\, \frac{g_{PNK}}{M_{P_{cs}}\, m_N^2} \varepsilon_{\mu\nu\alpha\beta}\, \bar{u}^{\nu\rho}_P\, q^{\mu}_P\, \Gamma^{\alpha}_{\mp}\, q^{\beta}_K\, q_{K\rho}\, u_N.$$

Partial decay width:

$$\Gamma(P_{cs} \to MB) = \frac{|\mathrm{k}|}{8\pi M^2_{P_{cs}}} \frac{1}{2J+1} \sum_{\lambda_1=-J}^{J} \sum_{\lambda_2,\lambda_3} |A(P_{cs} \to MB)|^2.$$

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Coupling constants:

$g_{P_{cs}MB}(J^P)$	$P_{cs}\, J/\psi\, \Lambda$	$P_{cs}\, K\, p$
$1/2^+$	1.26×10^{-1}	5.82×10^{-3}
$1/2^-$	4.41×10^{-2}	3.77×10^{-3}
$3/2^+$	1.48×10^{-1}	2.06×10^{-3}
$3/2^-$	5.46×10^{-2}	3.18×10^{-3}
$5/2^+$	1.33×10^{-1}	1.84×10^{-3}
$5/2^-$	3.83×10^{-1}	1.19×10^{-3}

Hadronic Form Factor

Since hadrons have finite sizes and structures, it is essential to consider form factors at each vertex. We use the form factors which are most used in reaction calculations.

$$F_s(q^2) = \frac{\Lambda^4}{\Lambda^4 + (s - m^2)^2},$$

$$F_t(q_t^2) = \frac{\Lambda^2 - m^2}{\Lambda^2 - t},$$

$$F_u(q_u^2) = \frac{\Lambda^2 - m^2}{\Lambda^2 - u}.$$

where we use the following values for cut-off parameter

$$\Lambda_{P_{cs}} = 5.0\,\mathrm{GeV}, \quad \Lambda_K = 1.0\,\mathrm{GeV}, \quad \Lambda_{K^*} = 1.4\,\mathrm{GeV}, \quad \Lambda_N = 1.5\,\mathrm{GeV}$$

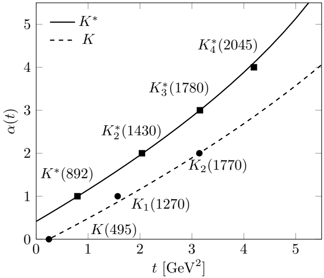
Regge Approach (Model II)

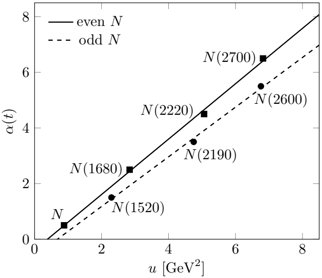
Hybridized Regge Approach

- The effective Lagrangian method is known to describe well the hadronic productions in the vicinity of the threshold energy. However, at the high energy it fail to explain the diffractive behavior of hadronic reactions.
- On the other hand, the Regge approach explains the general high-energy behavior of the hadronic reactions but only qualitatively.
- To overcome this disadvantage, a hybridized Regge approach was proposed in an attempt to improve the Regge approach quantitatively.

$$\frac{1}{t - m_X^2} \longrightarrow \mathcal{P}^{\pm}_{\mathrm{Regge}} = -\Gamma\left(-\alpha_X(t)\right)\xi_X^{\pm}\alpha'_X\left(\frac{s}{s_0}\right)^{\alpha_X(t)}$$

Regge Trajectory





We use the non-linear Regge trajectory for K and K^* reggeon exchange[7]

$$\alpha_{K(K^*)}(t) = \alpha_{K(K^*)}(0) + \gamma\left(\sqrt{T_{K(K^*)}} - \sqrt{T_{K(K^*)} - t}\right).$$

For the nucleon, we use linear Regge trajectory[8]

$$\alpha_N(u) = \alpha_N(0) + \alpha'_N u.$$

[7] M. M. Brisudova *et al.* Phys. Rev. D **61**, 054013 (2000)

[8] J. K. Storrow, Phys. Rept. **103**, 317 (1984).

Scattering Amplitude

We employ here a hybridized Regge method, in which the Feynman propagators are replaced by the Regge propagators[9]

$$\mathcal{M}^R_K(s,t) = -\mathcal{M}_K(s,t)\begin{Bmatrix} 1 \\ e^{-i\pi\alpha_K(t)} \end{Bmatrix}\Gamma(-\alpha_K(t))\alpha'_K(m_K^2)\left(\frac{s}{s_0}\right)^{\alpha_K(t)}\left(t-m_K^2\right),$$

$$\mathcal{M}^R_{K^*}(s,t) = -\mathcal{M}_{K^*}(s,t)\begin{Bmatrix} 1 \\ e^{-i\pi\alpha_{K^*}(t)} \end{Bmatrix}\Gamma(1-\alpha_{K^*}(t))\alpha'_{K^*}(m_{K^*}^2)\left(\frac{s}{s_0}\right)^{\alpha_{K^*}(t)-1}\left(t-m_{K^*}^2\right),$$

$$\mathcal{M}^R_N(s,u) = -\mathcal{M}_N(s,u)\frac{1+e^{-i\pi\alpha_N(u)}}{2}\Gamma(0.5-\alpha_N(u))\alpha'_N\left(\frac{s}{s_0}\right)^{\alpha_N(u)-0.5}\left(u-m_N^2\right).$$

- In the first two equation, we consider degenerate signature and choose constant phase (1).
- The energy scale parameter s_0 is obtained by comparing the amplitude with that of Model I.

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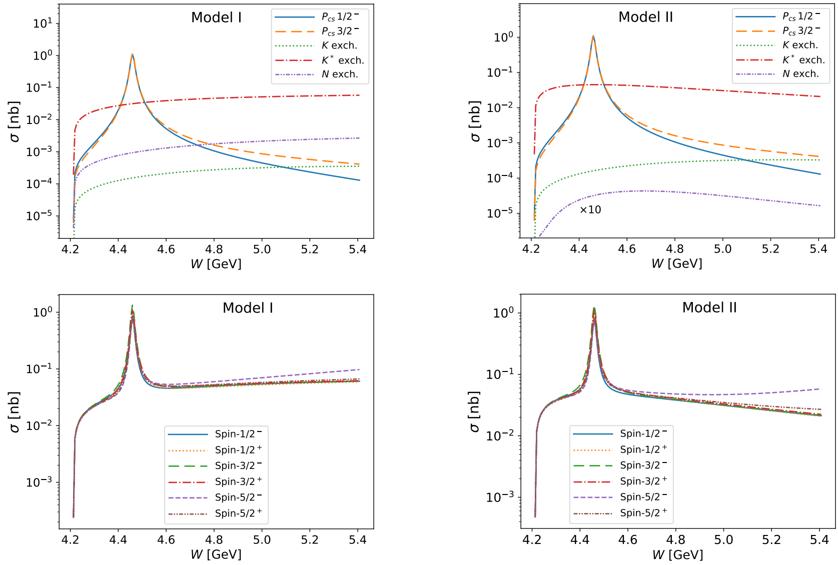
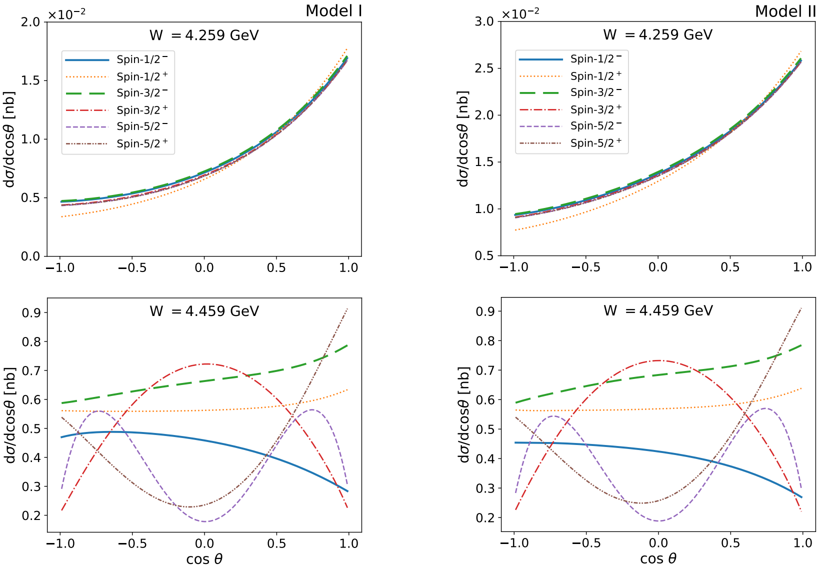
[9] S. H. Kim, H. C. Kim and A. Hosaka, Phys. Rev. D **94**, 094025 (2016)

Results and Discussion

Total Cross Section



Differential Cross Section



Summary and Conclusion

- We investigated the production of $P_{cs}^0(4459)$ in the $K^- p \to J/\psi\Lambda^0$ reaction by employing two theoretical frameworks, i.e. the effective Lagrangian method and the Regge approach.
- The coupling constant for the $P_{cs} J/\psi \Lambda$ and $P_{cs} KN$ vertex are calculated by assuming the branching ratio of P_{cs} to respective decays.
- We presented the total cross section distribution from each theorethical framework and showed the distinct difference between the spin-parity assignment of $P_{\rm cs}$ in angular distribution of differential cross section, especially in the vicinity of resonance mass.
- The present results may be used as a theoretical guide for possible future experiments for findings of the hidden-charm pentaquarks with strangeness.