

Production Mechanism of the Hidden-Charm Pentaquark

Samson Clymton

Asia Pacific Center for Theoretical Physics (APCTP)

New Perspective on Exotic and Heavy Hadrons

Inha University, 25–28 August 2026

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Hidden-charm pentaquarks

- Hidden-charm pentaquarks are exotic baryons containing $c\bar{c}$.
 - $P_{c\bar{c}}(qqqc\bar{c})$ in $J/\psi N$ ($I = 3/2$ partner (?))
 $P_{c\bar{c}}(4312)$, $P_{c\bar{c}}(4380)$, $P_{c\bar{c}}(4440)$, $P_{c\bar{c}}(4457)$ [LHCb]
 - $P_{c\bar{c}s}(qqsc\bar{c})$ in $J/\psi \Lambda$ ($I = 1$ partner (?))
 $P_{c\bar{c}s}(4338)$, $P_{c\bar{c}s}(4459)$ [LHCb], $P_{c\bar{c}s}(4472)$ [Belle]
 - $P_{c\bar{c}ss}(qssc\bar{c})$: not yet observed
 - $P_{c\bar{c}sss}(sssc\bar{c})$: not yet observed
- However, GlueX sees no $P_{c\bar{c}}$ signal in $\gamma p \rightarrow J/\psi p$ [PRL123, 072001 (2019)].
- CMS and LHCb searched for $P_{c\bar{c}ss}$ in the $\Lambda_b^0 \rightarrow J/\psi \Xi^- K^+$ and $\Xi_b^0 \rightarrow J/\psi \Xi^- \pi^+$ decays. [EPJC 84, 1062 (2024); EPJC 85, 812 (2025)]
- $\Xi_b^0 \rightarrow J/\psi \Omega^- K^+$ is a promising channel for $P_{c\bar{c}sss}$.
- We study these states in the off-shell coupled-channel formalism, which already succeeded for the axial vector mesons:
 - Molecular nature of the $a_1(1260)$ [PRD106, 114015 (2022)]
 - Two-pole structure of the $b_1(1235)$ [PRD108, 074021 (2023)]
 - Two-pole structure of the $h_1(1415)$: resolving the mass discrepancy [PRD110, 114002 (2024)]

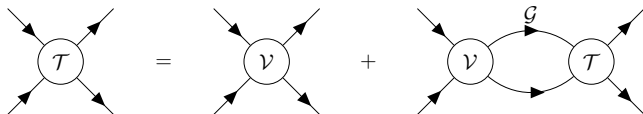
Off-shell coupled-channel formalism

We start from the S matrix,

$$S_{fi} = \delta_{fi} - i(2\pi)^4 \delta^4(P_f - P_i) \mathcal{T}_{fi}$$

The Bethe-Salpeter equation for a two-body system reads

$$\mathcal{T}_{fi}(p', p) = \mathcal{V}_{fi}(p', p) + \frac{1}{(2\pi)^4} \int d^4q \mathcal{V}_{fg}(p', q) \mathcal{G}_g(q) \mathcal{T}_{gi}(q, p)$$



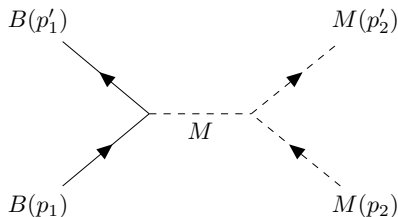
In the Blankenbecler-Sugar scheme, this four-dimensional equation reduces to

$$\mathcal{T}_{fi}(\mathbf{p}, \mathbf{p}') = \mathcal{V}_{fi}(\mathbf{p}, \mathbf{p}') + \frac{1}{(2\pi)^3} \int \frac{d^3q}{2E_{1g}E_{2g}} \mathcal{V}_{fg}(\mathbf{p}, \mathbf{q}) \frac{E_g}{s - E_g^2 + i\varepsilon} \mathcal{T}_{gi}(\mathbf{q}, \mathbf{p}')$$

Kernel amplitudes

$$\mathcal{T}_{fi}(\mathbf{p}, \mathbf{p}') = \mathcal{V}_{fi}(\mathbf{p}, \mathbf{p}') + \frac{1}{(2\pi)^3} \int \frac{d^3q}{2E_{1g}E_{2g}} \mathcal{V}_{fg}(\mathbf{p}, \mathbf{q}) \frac{E_g}{s - E_g^2 + i\varepsilon} \mathcal{T}_{gi}(\mathbf{q}, \mathbf{p}')$$

Each amplitude is modeled by one-meson-exchange diagrams



Each diagram gives

$$\mathcal{A} = IS \times F^2 \times \Gamma_1 \times \mathcal{P} \times \Gamma_2$$

so that $\mathcal{V} = \mathcal{A}_1 + \mathcal{A}_2 + \dots$

The vertices follow from an effective Lagrangian that respects heavy quark spin symmetry, hidden local symmetry, and $SU(3)$ symmetry.

The form factor contains one free parameter $\Lambda = \Lambda_0 + m$, where m is the exchanged meson mass.

After partial-wave decomposition, the BbS equation becomes

$$\mathcal{T}_{\lambda'\lambda}^{fi}(p, p') = \mathcal{V}_{\lambda'\lambda}^{fi}(p, p') + \frac{1}{(2\pi)^3} \sum_{g, \lambda_g} \int \frac{q^2 dq}{2E_{g1}E_{g2}} \mathcal{V}_{\lambda'\lambda_g}^{fg}(p, q) \frac{E_g}{s - E_g^2 + i\epsilon} \mathcal{T}_{\lambda_g\lambda}^{gi}(q, p')$$

where

$$\mathcal{V}_{\lambda'\lambda}^{fi}(p', p) = 2\pi \int d(\cos \theta) d_{\lambda\lambda'}^J(\theta) \mathcal{V}_{\lambda'\lambda}^{fi}(p', p, \theta),$$

Isolating the singularity, we obtain

$$\begin{aligned} \mathcal{T}_{\lambda'\lambda}^{fi}(p, p') = & \mathcal{V}_{\lambda'\lambda}^{fi}(p, p') + \frac{1}{(2\pi)^3} \sum_{g, \lambda_g} \left[\int dE_g \frac{\mathcal{F}(E_g) - \mathcal{F}(\sqrt{s})}{s - E_g^2} \right. \\ & \left. - \frac{\mathcal{F}(\sqrt{s})}{2\sqrt{s}} \left(\ln \left| \frac{\sqrt{s} + E_g^{\text{thr}}}{\sqrt{s} - E_g^{\text{thr}}} \right| + i\pi \right) \right] \end{aligned}$$

with

$$\mathcal{F}(E_g) = \frac{1}{2} q \mathcal{V}_{\lambda'\lambda_g}^{fg}(p, q) \mathcal{T}_{\lambda_g\lambda}^{gi}(p, q),$$

We solve this integral equation by matrix inversion.

Spectrum of Hidden-Charm Pentaquarks

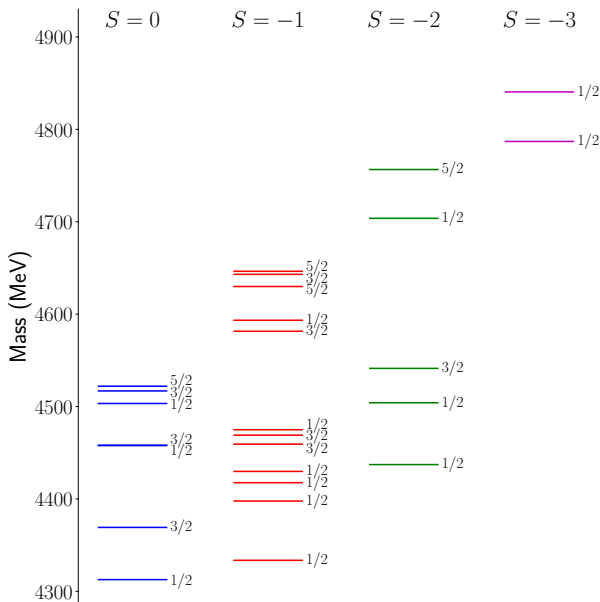
In collaboration with

Prof. Hyun-Chul Kim (Inha University) and Prof. Terry Mart (Universitas Indonesia)

Coupled channels

$\begin{array}{c c} S \\ \hline I \end{array}$	0	-1	-2	-3
0		$\begin{array}{c} \bar{D}_s \Lambda_c \quad \bar{D} \Xi_c \quad \bar{D}_s^* \Lambda_c \\ \bar{D} \Xi'_c \quad \bar{D}^* \Xi_c \quad \bar{D} \Xi_c^* \\ \bar{D}^* \Xi'_c \quad \bar{D}^* \Xi_c^* \end{array}$		$\begin{array}{c} \bar{D}_s \Omega_c \quad \bar{D}_s \Omega_c^* \\ \bar{D}_s^* \Omega_c \quad \bar{D}_s^* \Omega_c^* \end{array}$
$\frac{1}{2}$	$\begin{array}{c} \bar{D} \Lambda_c \quad \bar{D}^* \Lambda_c \\ \bar{D} \Sigma_c \quad \bar{D} \Sigma_c^* \\ \bar{D}^* \Sigma_c, \bar{D}^* \Sigma_c^* \end{array}$		$\begin{array}{c} \bar{D}_s \Xi_c \quad \bar{D}_s \Xi'_c \quad \bar{D} \Omega_c \\ \bar{D}_s^* \Xi_c \quad \bar{D}_s^* \Xi_c^* \quad \bar{D} \Omega_c^* \\ \bar{D}_s^* \Xi'_c \quad \bar{D}^* \Omega_c \quad \bar{D}_s^* \Xi_c^* \\ \bar{D}^* \Omega_c^* \end{array}$	
1		$\begin{array}{c} \bar{D} \Xi_c \quad \bar{D}_s \Sigma_c \quad \bar{D} \Xi'_c \\ \bar{D}^* \Xi_c \quad \bar{D}_s \Sigma_c^* \quad \bar{D} \Xi_c^* \\ \bar{D}_s^* \Sigma_c \quad \bar{D}^* \Xi'_c \quad \bar{D}_s^* \Sigma_c^* \\ \bar{D}^* \Xi_c^* \end{array}$		
$\frac{3}{2}$	$\begin{array}{c} \bar{D} \Sigma_c \quad \bar{D} \Sigma_c^* \\ \bar{D}^* \Sigma_c \quad \bar{D}^* \Sigma_c^* \end{array}$			

Spectrum of hidden-charm pentaquarks



We find 26 negative-parity resonances with strangeness $S = 0$ to -3 and spin $J = 1/2$ to $5/2$.

Spectrum of hidden-charm pentaquarks

S	I	J^P	Name	$\sqrt{s_R}$ [MeV]		Data [MeV]		Collaboration	Reference
				M	Γ	M	Γ		
0	1/2	1/2 ⁻	$P_{c\bar{c}}(4312)$	4312.7	18.0	$4311.9^{+7.0}_{-0.9}$	10 ± 5	LHCb	PRL 122 222001 (2019)
			$P_{c\bar{c}}(4440)$	4457.7	31.8	4440^{+4}_{-5}	21^{+10}_{-11}	LHCb	PRL 122 222001 (2019)
		3/2 ⁻	$P_{c\bar{c}}(4380)$	4369.1	60.0	4380 ± 30	205 ± 90	LHCb	PRL 115 072001 (2015)
			$P_{c\bar{c}}(4457)$	4458.1	6.2	$4457.3^{+4.0}_{-1.8}$	$6.4^{+6.0}_{-2.8}$	LHCb	PRL 122 222001 (2019)
			$P_{c\bar{c}}(4517)$	4516.9	23.4				
		5/2 ⁻	$P_{c\bar{c}}(4522)$	4522.1	7.6				
	3/2	1/2 ⁻	$P_{c\bar{c}}(4503)$	4503.3	48.6				
-1	0	1/2 ⁻	$P_{c\bar{c}s}(4338)$	4333.6	4.6	4338.2 ± 0.8	7.0 ± 1.8	LHCb	PRL 131 031901 (2023)
			$P_{c\bar{c}s}(4398)$	4397.8	0.08				
			$P_{c\bar{c}s}(4430)$	4429.8	20.0				
		3/2 ⁻	$P_{c\bar{c}s}(4472)$	4474.9	28.0	4471.7 ± 4.8	21.9 ± 13.1	Belle	arXiv:2502.09951
			$P_{c\bar{c}s}(4459)$	4459.3	2.0	$4458.8^{+5.5}_{-3.1}$	17^{+10}_{-9}	LHCb	Sci.Bull. 66 1278 (2021)
	1	3/2 ⁻	$P_{c\bar{c}s}(4582)$	4581.5	10.2				
			$P_{c\bar{c}s}(4643)$	4643.1	39.6				
		5/2 ⁻	$P_{c\bar{c}s}(4646)$	4646.4	7.6				
		1/2 ⁻	$P_{c\bar{c}s}(4417)$	4417.5	0.14				
			$P_{c\bar{c}s}(4593)$	4593.4	43.0				
		3/2 ⁻	$P_{c\bar{c}s}(4469)$	4468.9	0.0				
		5/2 ⁻	$P_{c\bar{c}s}(4630)$	4629.8	2.0				
-2	1/2	1/2 ⁻	$P_{c\bar{c}ss}(4437)$	4437.2	0				
			$P_{c\bar{c}ss}(4504)$	4504.1	0.4				
			$P_{c\bar{c}ss}(4704)$	4703.7	21.2				
		3/2 ⁻	$P_{c\bar{c}ss}(4541)$	4541.3	0				
		5/2 ⁻	$P_{c\bar{c}ss}(4756)$	4756.5	3.4				
-3	0	1/2 ⁻	$P_{c\bar{c}sss}(4787)$	4785.9	14.4				
			$P_{c\bar{c}sss}(4840)$	4840.5	85.2				

Search for $P_{c\bar{c}}$ in J/ψ production

- **Photoproduction of J/ψ from proton** ([arXiv:2606.11808](#))

Collaborator:

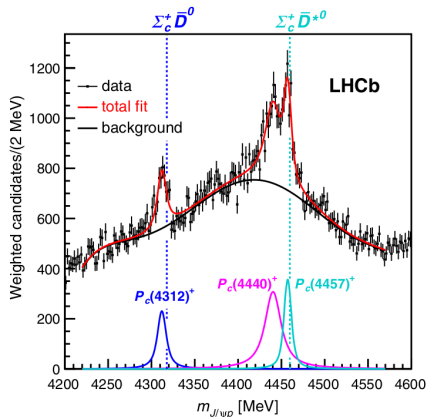
Prof. Hyun-Chul Kim (Inha University) and Dr. Sang-Ho Kim (Soongsil University)

- **Pion-induced J/ψ production** ([arXiv:2605.28285](#))

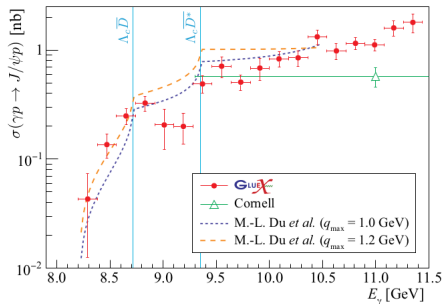
Collaborator:

Prof. Hyun-Chul Kim (Inha University), Prof. Jung-Keun Ahn (Korea University) and Prof. Sun Young Ryu (RCNP)

Search for $P_{c\bar{c}}$ in J/ψ production



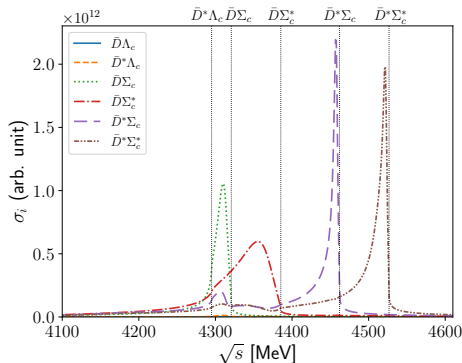
[Source: R.Aaij *et al.* (LHCb), PRL122 222001 (2019)]



[Source: S.Adhikari *et al.* (GlueX), PRC108 025201 (2023)]

How do the $P_{c\bar{c}}$ states disappear in $\gamma p \rightarrow J/\psi p$?

$P_{c\bar{c}}$ in the present model



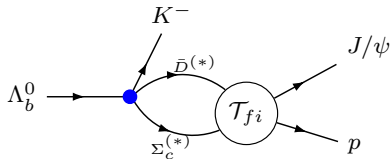
The $P_{c\bar{c}}$ states couple strongly to the $\bar{D}^{(*)}\Sigma_c^{(*)}$ channels:

- $P_{c\bar{c}}(4312) \rightarrow \bar{D}\Sigma_c$
- $P_{c\bar{c}}(4380) \rightarrow \bar{D}\Sigma_c^*$
- $P_{c\bar{c}}(4440)$ and $P_{c\bar{c}}(4457) \rightarrow \bar{D}^*\Sigma_c$

All of them are seen in $\Lambda_b^0 \rightarrow J/\psi p K^-$.

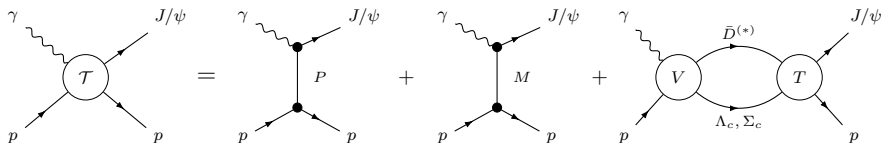
Their observation follows from the rescattering of the $\bar{D}^{(*)}\Sigma_c^{(*)}$ channels.

Why does the same mechanism not work in J/ψ photoproduction?



Photoproduction of J/ψ from the proton

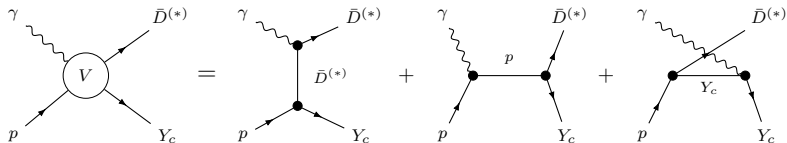
The scattering amplitude for $\gamma + p \rightarrow J/\psi + p$



- We include the rescattering from the $\bar{D}^{(*)}\Lambda_c$ and $\bar{D}^{(*)}\Sigma_c$ channels.
- The Born term is almost negligible, being suppressed by the OZI rule.
- The background comes from Pomeron exchange in the Donnachie-Landshoff model, whose parameters are fitted to the total cross section data of diffractive vector meson photoproduction at high energies.

Kernel amplitude: $\gamma p \rightarrow \bar{D}^{(*)} Y_c$

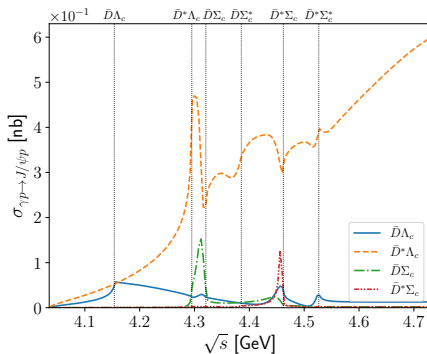
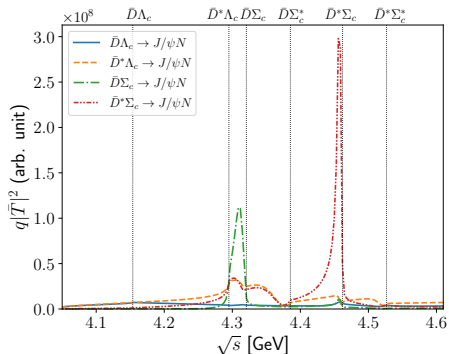
The transition amplitude for $\gamma + p \rightarrow \bar{D}^{(*)} + Y_c$



$$V_{\bar{D}^{(*)}\Lambda_c, \gamma p} = \mathcal{A}_{\bar{D}^{(*)}}^t + \mathcal{A}_p^s + \mathcal{A}_{\Lambda_c}^u, \quad V_{\bar{D}^{(*)}\Sigma_c, \gamma p} = \mathcal{A}_{\bar{D}^{(*)}}^t + \mathcal{A}_p^s + \mathcal{A}_{\Sigma_c}^u$$

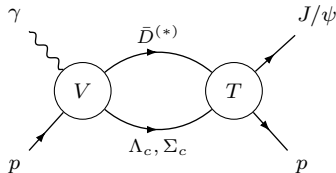
- The amplitude is constructed so that it preserves gauge invariance.
- The coupling $g_{Y_c \bar{D} N}$ sets the overall strength of the amplitude.
- By the SU(4) relation, $g_{\Lambda_c \bar{D} N} \approx 5g_{\Sigma_c \bar{D} N}$, so the $\Sigma_c^{(*)} \bar{D}^{(*)}$ rescattering is suppressed.

$\bar{D}^{(*)}\Sigma_c$ suppression

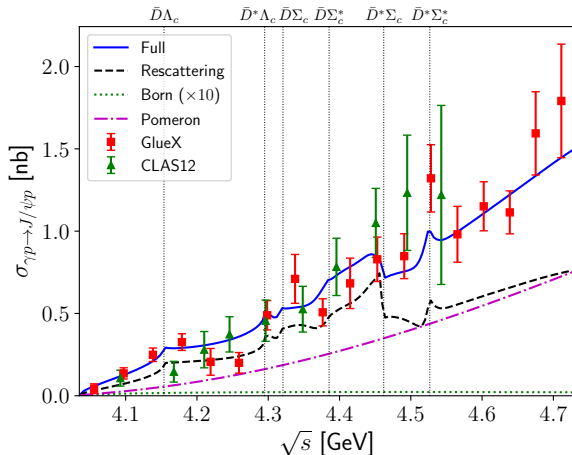


The $\bar{D}\Sigma_c$ and $\bar{D}^*\Sigma_c$ rescattering contributions are smaller than the $\bar{D}^*\Lambda_c$ one.

The suppression is mild, because $\bar{D}\Sigma_c$ has two charge channels ($\bar{D}^0\Sigma_c^+$ and $D^-\Sigma_c^{++}$).



Total cross section: $\gamma p \rightarrow J/\psi p$

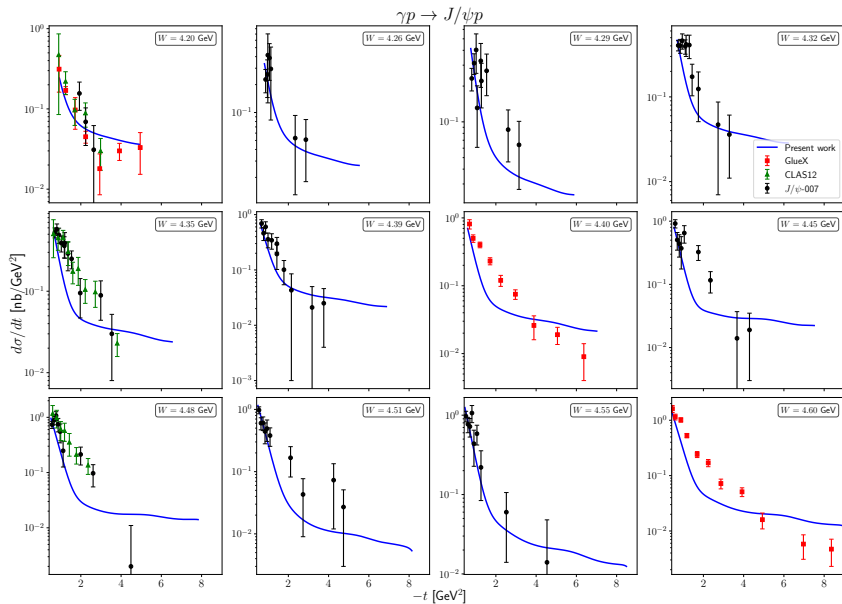


The present model reproduces both the GlueX and CLAS12 data well.

No clear $P_{c\bar{c}}$ signal remains.

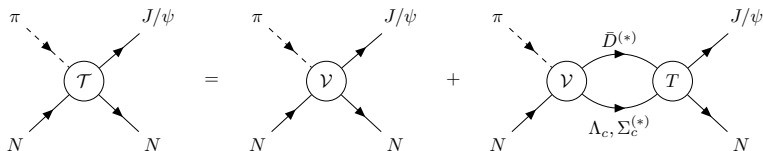
The $P_{c\bar{c}}$ peaks are washed out by destructive interference between the $\bar{D}^*\Lambda_c$ and $\bar{D}\Sigma_c$ rescattering contributions.

Differential cross section: $\gamma p \rightarrow J/\psi p$



Production of J/ψ using a pion beam

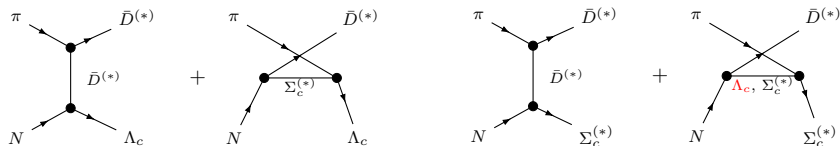
- The hidden-charm pentaquark is hard to observe in J/ψ photoproduction.
- A pion beam may offer a different production mechanism for $P_{c\bar{c}}$.
- The experimental prospect of the $\pi^- p \rightarrow J/\psi n$ reaction at J-PARC will be presented by Sun-Young Ryu (RCNP) in tomorrow's session, 10:15 AM.
- As in photoproduction, the scattering amplitude for $\pi N \rightarrow J/\psi N$ reads



- The Born amplitude follows from tree-level meson exchange and is negligible.
- We include the rescattering from the $\bar{D}^{(*)} \Lambda_c$ and $\bar{D}^{(*)} \Sigma_c^{(*)}$ channels.

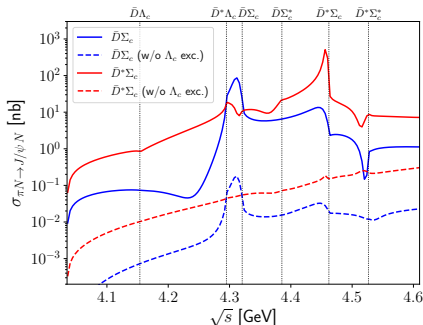
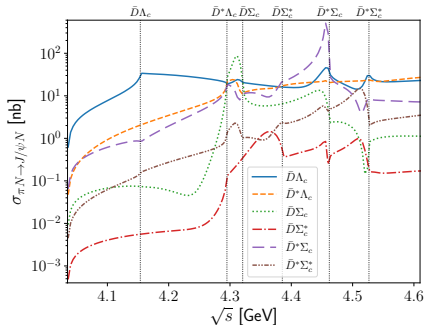
Kernel amplitude: $\pi N \rightarrow \bar{D}^{(*)} Y_c$

The kernel amplitudes are built from tree-level diagrams



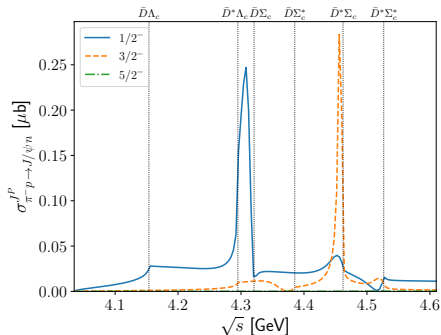
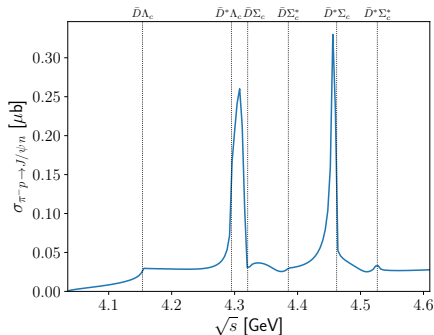
- We use the same coupling constants as in J/ψ photoproduction, so there is no free parameter.
- In the $\pi N \rightarrow \bar{D}^{(*)} \Sigma_c^{(*)}$ kernel, the vertex $\bar{D}^{(*)} N \Lambda_c$ enters and enhances the $\bar{D}^{(*)} \Sigma_c^{(*)}$ rescattering.
- In the $\pi N \rightarrow \bar{D}^{(*)} \Lambda_c$ kernel, there is no Λ_c exchange, due to isospin symmetry.

Individual contribution



- The Λ_c exchange greatly enhances the $\bar{D}^{(*)}\Sigma_c$ rescattering.
- This is not the case for the $\bar{D}^{(*)}\Sigma_c^*$ channels.
- There, $\pi N \rightarrow \bar{D}^{(*)}\Sigma_c^*$ at $J = 3/2$ is suppressed by the spin mismatch between the exchanged spin-1/2 Λ_c and the external spin-3/2 Σ_c^* .

Total cross section: $\pi^- p \rightarrow J/\psi n$



- $P_{c\bar{c}}(4312)$ and $P_{c\bar{c}}(4457)$ appear clearly in $\pi^- p \rightarrow J/\psi n$.
- $P_{c\bar{c}}(4380)$ gives no clear signal, since $\pi N \rightarrow \bar{D}\Sigma_c^*$ is suppressed at $J = 3/2$.
- $P_{c\bar{c}}(4440)$ shows up weakly in the partial-wave cross section at $J^P = 1/2^-$.
- The $J^P = 5/2^-$ states contribute only marginally.
- In short, there is a good chance to see a $P_{c\bar{c}}$ signal in $\pi^- p \rightarrow J/\psi n$ at J-PARC.

Summary and Conclusion

- We investigated hidden-charm pentaquark states with all possible isospin and strangeness quantum numbers.
- Besides the well-known isodoublet $P_{c\bar{c}}$ and isosinglet $P_{c\bar{c}s}$ states, we find one $P_{c\bar{c}}$ state with $I = 3/2$ and four $P_{c\bar{c}s}$ states with $I = 1$.
- $P_{c\bar{c}}(4312)$ disappears in J/ψ photoproduction because the $\bar{D}\Sigma_c$ channel couples to γN more weakly than the $\bar{D}^{(*)}\Lambda_c$ channel does.
- $P_{c\bar{c}}(4312)$ and $P_{c\bar{c}}(4457)$ may be observable in pion-induced J/ψ production.

Thank You