Triangle singularity in the hidden charm pentaquark decays and a feed-down mechanism at LHCb

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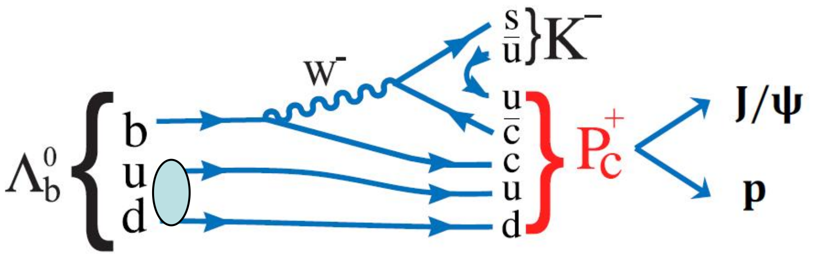
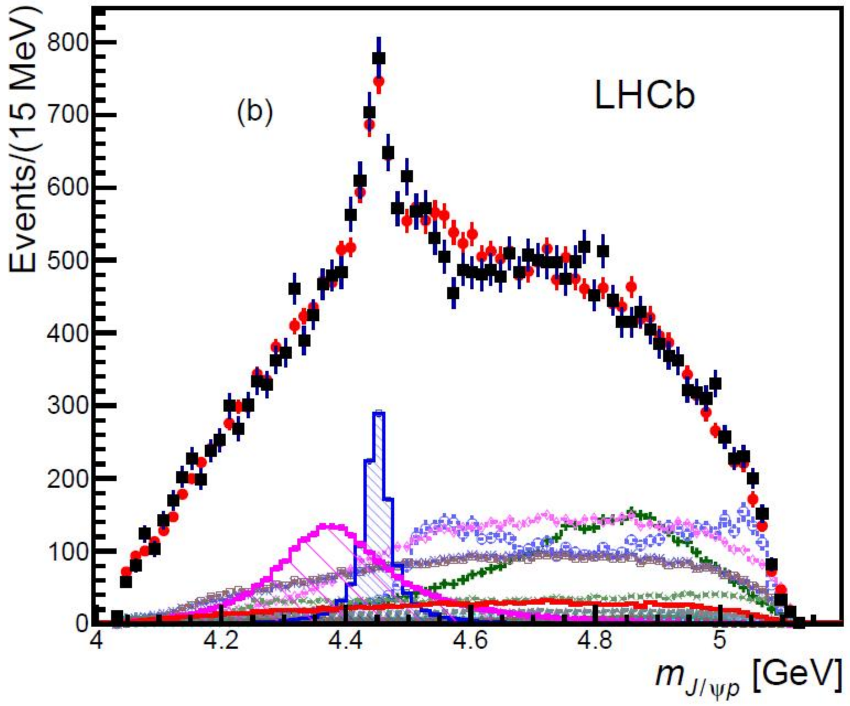
Outline

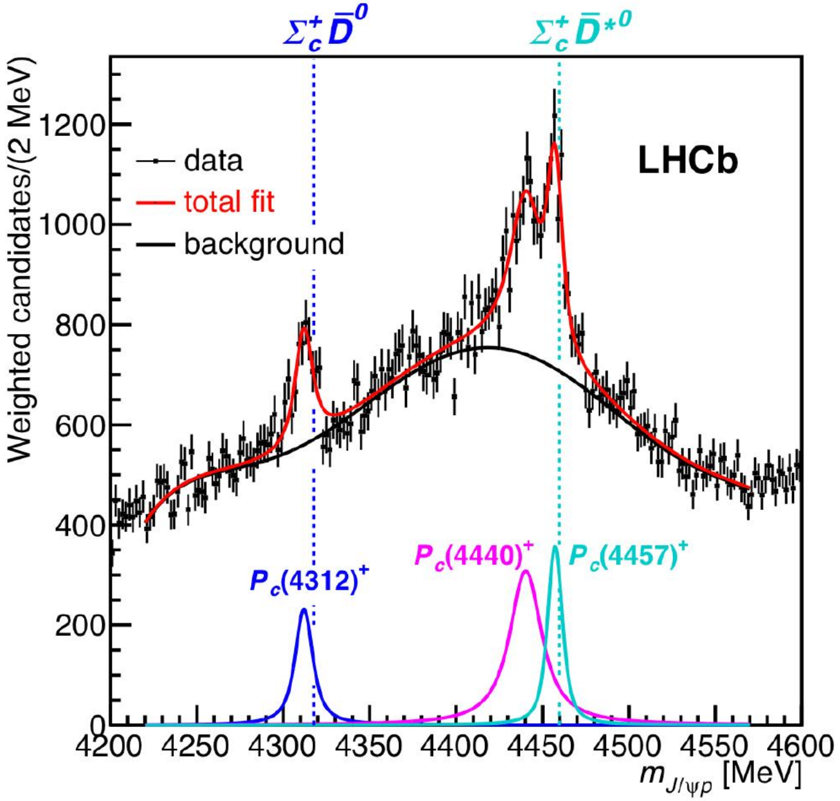
1. A brief review of the Pc's at LHCb
2. Novel phenomena arising from the Pc three-body and four-body decays and a feed-down mechanism into $J/\psi\ p$
3. Comments on the J/psi photoproduction near threshold

1. A brief review of the Pc's at LHCb





Run-I: LHCb, PRL115, 072001 (2015)



Run-II: LHCb, PRL122, 222001 (2019)

The mass positions and the preferred quantum numbers indicate the hadronic molecule nature of these observed enhancements.

Theoretical predictions: [1] J. J. Wu, T. S. H. Lee, and B. S. Zou, PRC 403, 044002 (2012)

[2] Z. C. Yang, Z. F. Sun, J. He, X. Liu, and S. L. Zhu, CPC36, 6 (2012)

Observation of $P_c(4380)$ and $P_c(4450)$ in $\Lambda_b^0 \to J/\psi p \pi$

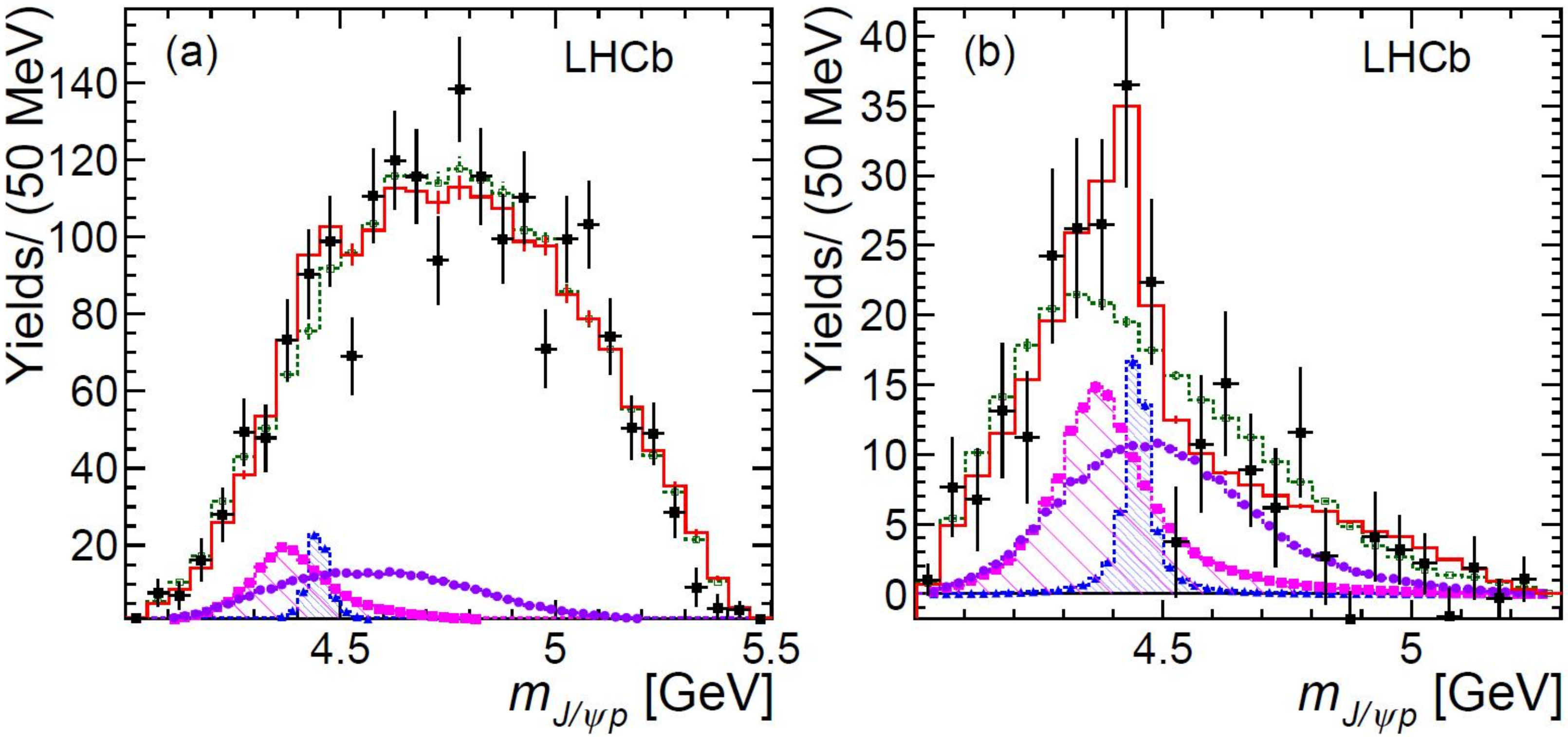


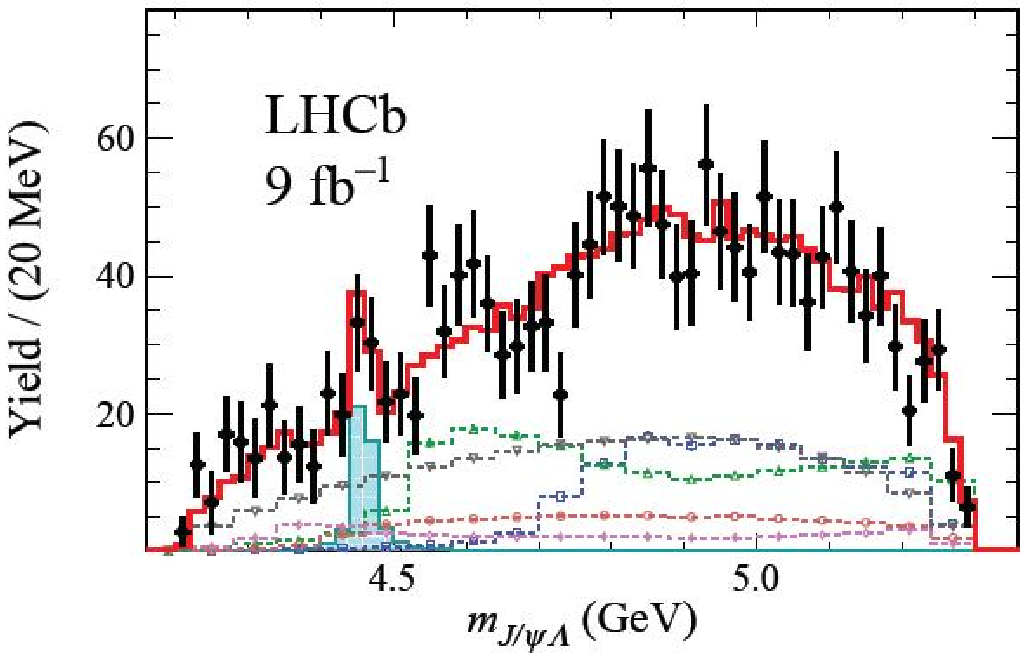
Figure 3: Background-subtracted data and fit projections onto $m_{J/\psi p}$ for (a) all events and (b) the $m_{p\pi} > 1.8$ GeV region. See the legend and caption of Fig. 2 for a description of the components.

LHCb, *Phys.Rev.Lett.* 117 (2016) 8, 082003, *Phys.Rev.Lett.* 117 (2016) 10, 109902 (addendum), *Phys.Rev.Lett.* 118 (2017) 119901 (addendum)

Observation of $P_{\psi_s}^{\Lambda}(4459)$ in $\Xi^- \to J/\psi\Lambda K^-$ and $P_{\psi_s}^{\Lambda}(4338)$ in $B^- \to J/\psi\Lambda\bar{p}$

$M_{P_{cs}} = 4458.8 \pm 2.9^{+4.7}_{-1.1}$ MeV

$\Gamma = 17.3 \pm 6.5^{+8.0}_{-5.7}$ MeV

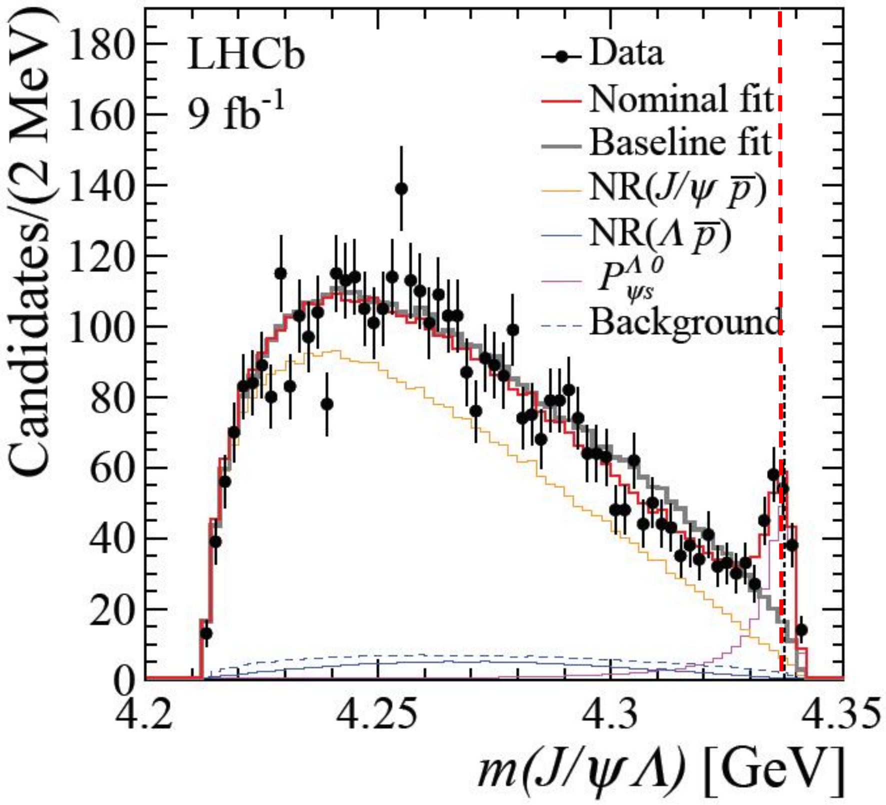


LHCb, Sci.Bull. 66 (2021) 1278-1287

$M_{P_{cs}} = 4338.2 \pm 0.7 \pm 0.4$ MeV

$\Gamma = 7.0 \pm 1.2 \pm 1.3$ MeV

$\Xi_c^+ D^-$ thresh.

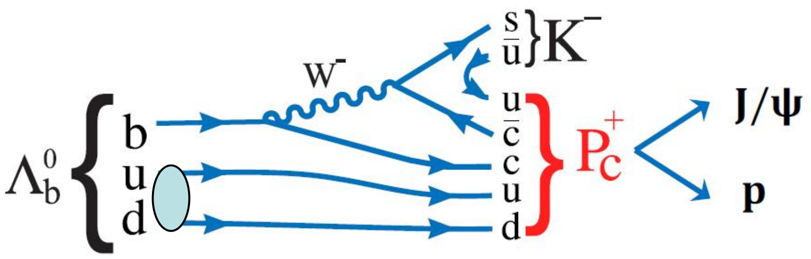


LHCb, Phys.Rev.Lett. 131 (2023) 3, 031901

Crucial issues with the observed Pc pentaquarks

Questions:

- A direct production of Pc's would imply that a pair of $\Lambda_c^{(*)}\bar{D}^{(*)}$ will be created at leading order, while the production of the $\Sigma_c^{(*)}\bar{D}^{(*)}$ pair is via the color-suppressed transitions. What should be the production mechanism for the Pc's as the $\Sigma_c^{(*)}\bar{D}^{(*)}$ molecular states?
- What's the nature of the (ud) diquark?
- How $\Sigma_c\bar{D}$ get bound without pion exchange?
- ……

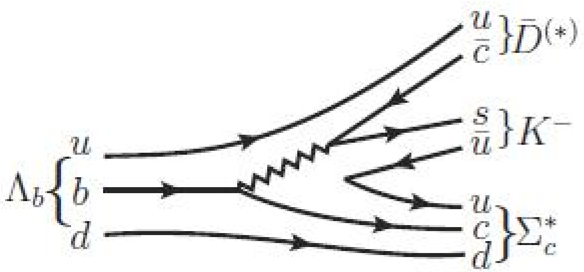


$\boxed{I_{ud} = 0}$

A novel feature that a loosely bound system is driven by the short-ranged interaction in the framework of hidden gauge symmetry dynamics.

[See Wu, Molina, Oset and Zou, PRL (2010).]

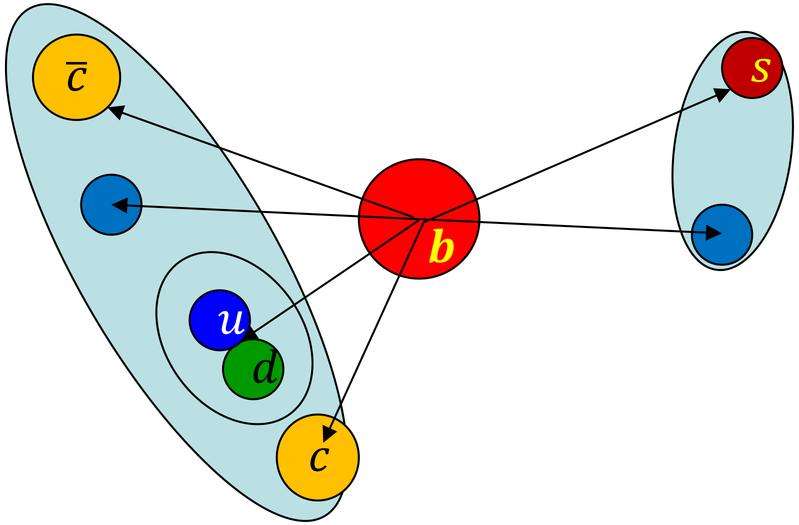
- **The color suppressed diagram may not be so suppressed!**



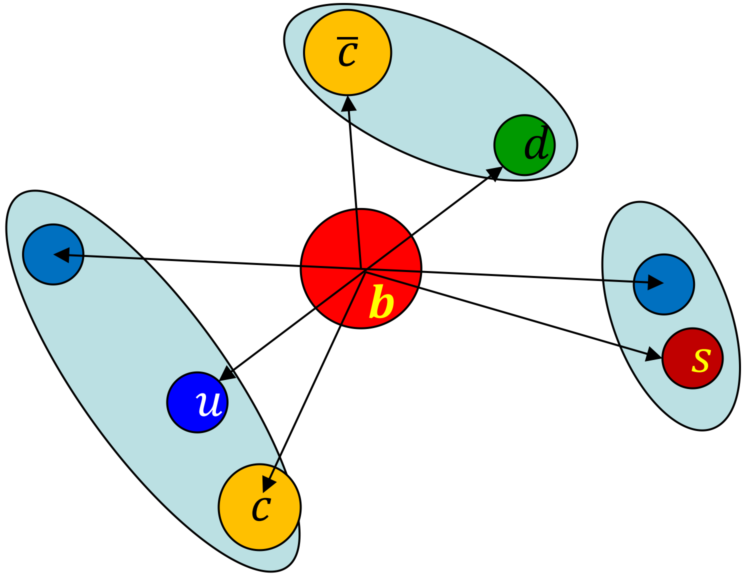
(c)

$$\langle Y_c\bar{K}\bar{D}|\hat{H}_w|\Lambda_b\rangle_{(c)} = \frac{1}{2\sqrt{2}}\left[-\Sigma_c^{++}K^-D^- + \frac{1}{2}\Sigma_c^+\bar{K}^0D^- - \frac{1}{2}\Sigma_c^+K^-\bar{D}^0 + \Sigma_c^0\bar{K}^0\bar{D}^0 + \frac{1}{2}\Lambda_c^+K^-\bar{D}^0 - \frac{1}{2}\Lambda_c^+\bar{K}^0D^-\right]$$

Spatially compact ud diquark



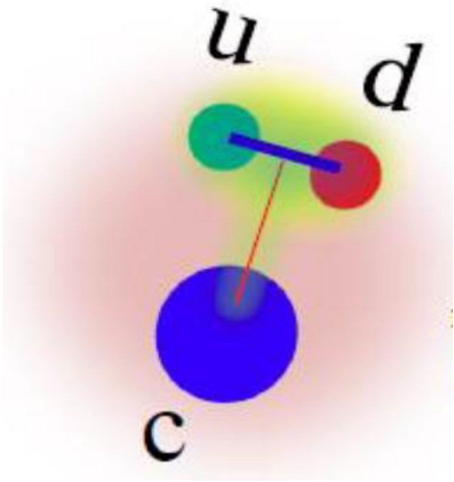
ud diquark with quantum correlation



X.-H. Liu, Q. Wang, and Q. Zhao, PLB(2016); arXiv:1507.05359 [hep-ph]; P.-Y. Niu, J.-M. Richard, Q. Wang, Q. Zhao, Phys. Rev. D 102, 073005 (2020); Chin. Phys. C 45, no.1, 013101 (2021); P.-Y. Niu, Q. Wang and Q. Zhao, Phys. Lett. B 826, 136916 (2022); M.-Y. Barabanov et al., Prog. Part. Nucl. Phys. 116, 103835 (2021)

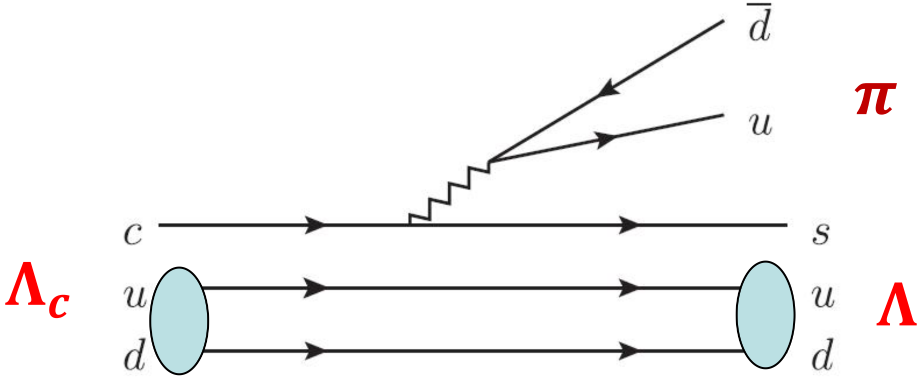
An evidence for the quark correlation:

The hadronic weak decay of Λ_c

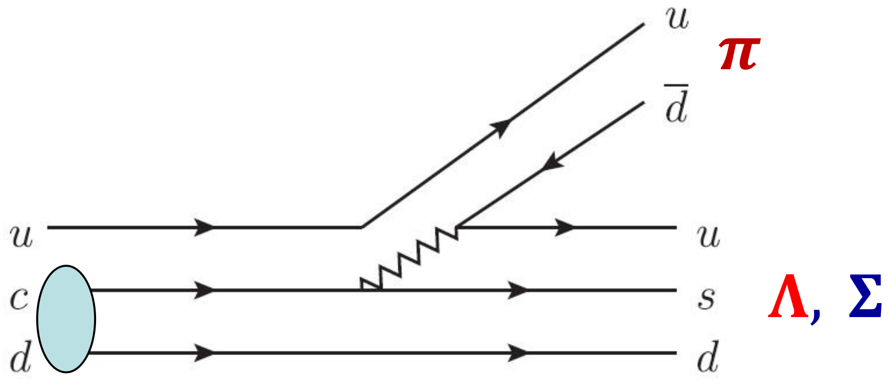


Color SU(3): $3\otimes3\otimes3=(\bar{3}\oplus6)\otimes3=(1\oplus8)\oplus(8\oplus10)$

Quark correlation ≠ compact structure



(a)



(b)

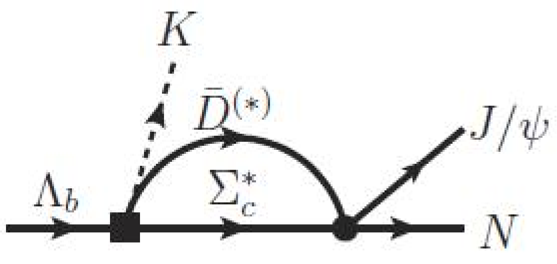
(In %)	$BR(\Lambda_c\to\Lambda\pi^+)$	$BR(\Lambda_c\to\Sigma^0\pi^+)$	$BR(\Lambda_c\to\Sigma^+\pi^0)$
PDG data [24]	1.30 ± 0.07	1.29 ± 0.07	1.24 ± 0.10
BESIII [20]	$1.24\pm0.07\pm0.03$	$1.27\pm0.08\pm0.03$	$1.18\pm0.10\pm0.03$

P.-Y. Niu, J.-M. Richard, Q. Wang, Q. Zhao, Phys. Rev. D 102, 073005 (2020)

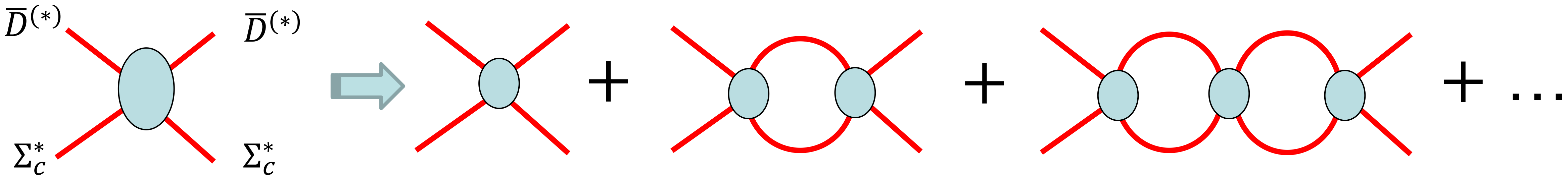
Rescattering to generate a pole?

- **Favored by the molecular picture.**
- **Coupled channel picture?**

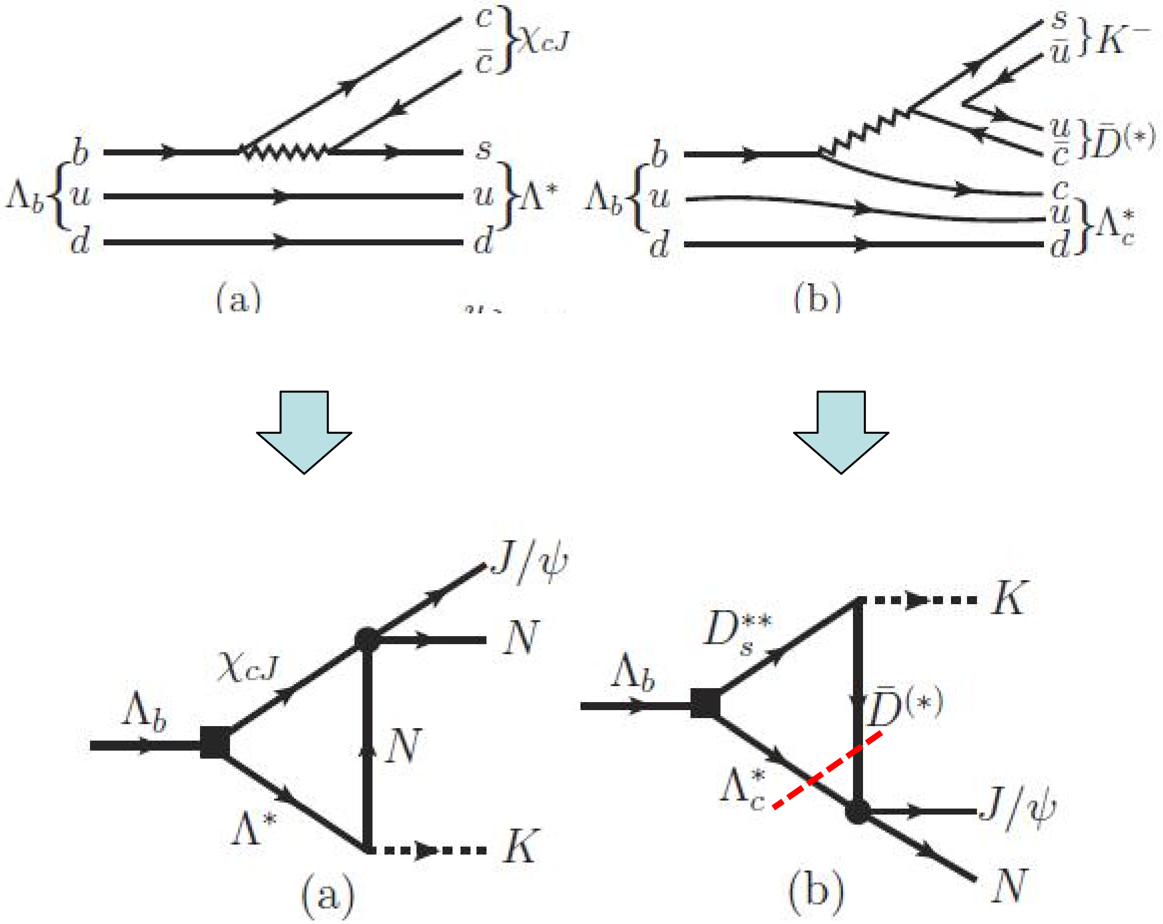
[see Y. Yamaguchi and E. Santopinto, PRD96, 014018 (2017); N. Yalikun et al., PRD104, 094039 (2021)]



(c)



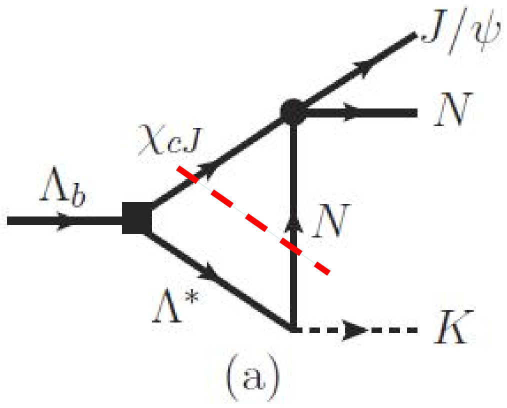
- **Rescatterings via triangle diagrams**

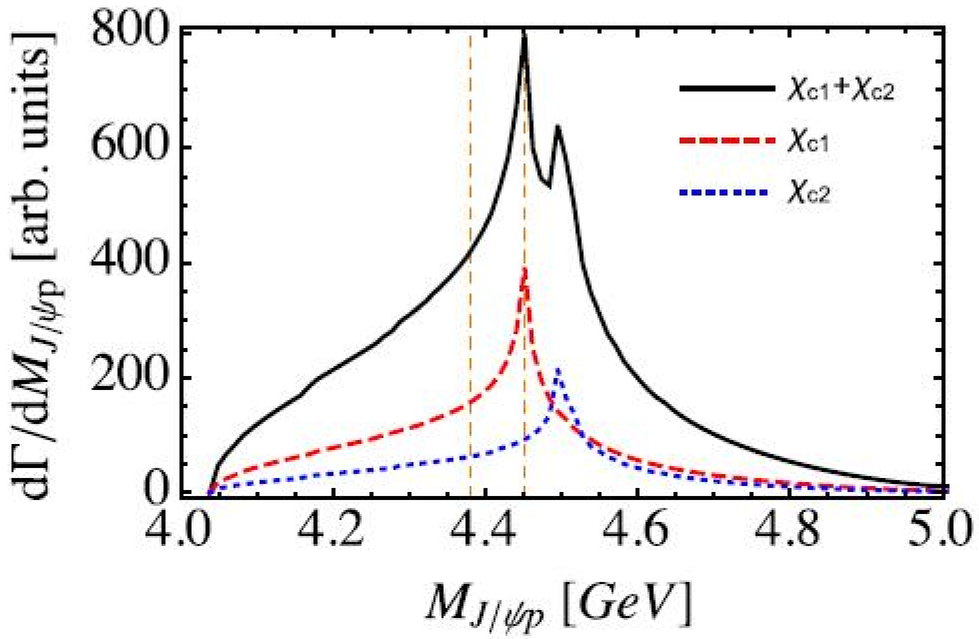


X.-H. Liu, Q. Wang, and Q. Zhao, PLB(2016); arXiv:1507.05359 [hep-ph]
F.K. Guo, U.-G. Meissner, W. Wang and Z. Yang, PRD92, 071502 (2015); arXiv:1507.04950[hep-ph]

Thresholds for χ_{cJ} p

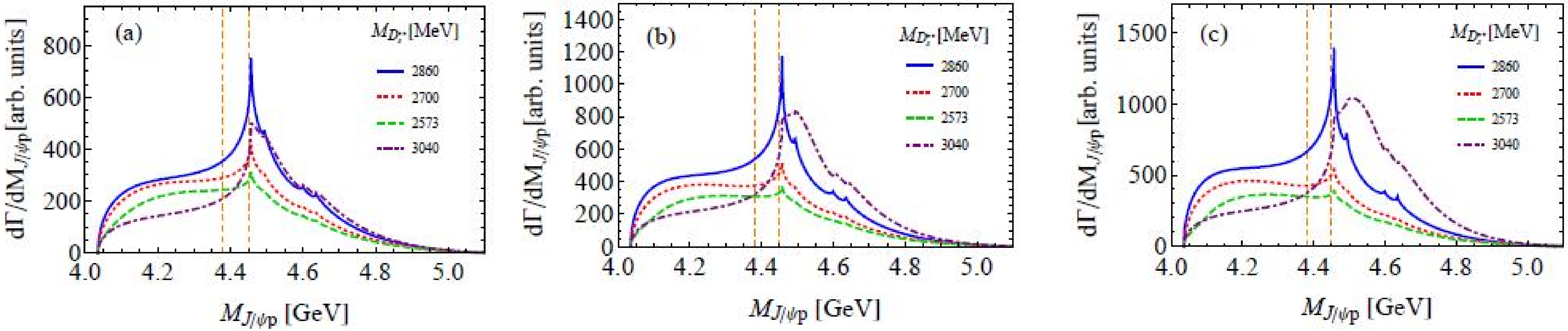
Threshold masses [MeV]	$\chi_{c0}(1P)\ 0^+$	$\chi_{c1}(1P)\ 1^+$	$\chi_{c2}(1P)\ 2^+$
$p\ 1/2^+$	4353	4449	4494



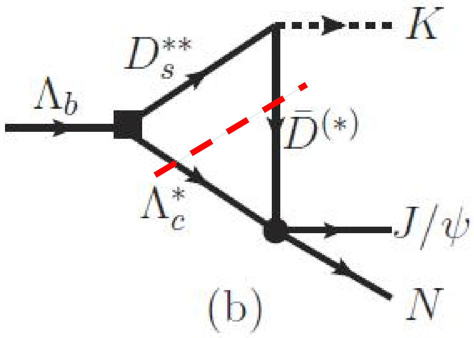


X.-H. Liu, Q. Wang, and Q. Zhao, PLB(2016); arXiv:1507.05359 [hep-ph]

Threshold structures arising from the TS mechanism involving both W emission and color-suppressed trans.



Threshold masses [MeV]	$\Lambda_c(2286)\ 1/2^+$	$\Lambda_c(2595)\ 1/2^-$	$\Lambda_c(2625)\ 3/2^-$	$\Lambda_c(2880)\ 5/2^+$
$\bar{D}_s(1968)\ 0^-$	4254	4563	4593	4848
$\bar{D}_s^*(2112)\ 1^-$	4398	4707	4737	4994
$\bar{D}_{s0}(2317)\ 0^+$	4585	4912	4942	5197
$\bar{D}_{s1}(2460)\ 1^+$	4728	5055	5085	5340
$\bar{D}_{s1}(2536)\ 1^+$	4822	5131	5161	5416
$\bar{D}_{s2}(2573)\ 2^+$	4859	5168	5198	5453
$\bar{D}_{s1}(2700)\ 1^-$	4986	5295	5325	5580
$\bar{D}_{sJ}(2860)\ ?^?$	5146	5455	5485	[5740]
$\bar{D}_{sJ}(3040)\ ?^?$	5331	[5636]	[5672]	[5926]



Threshold masses [GeV]	$\Sigma_c(2455)\ 1/2^+$	$\Sigma_c(2520)\ 3/2^+$	$\Sigma_c(2625)\ ?^?$
$\bar{D}(1865)\ 0^-$	4.321	4.385	4.668
$\bar{D}^*(2007)\ 1^-$	4.463	4.527	4.810
$\bar{D}_1(2420)\ 1^+$	4.875	4.939	5.222
$\bar{D}_2(2460)\ 2^+$	4.917	4.981	5.264

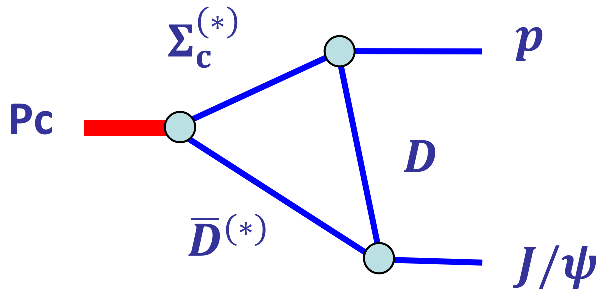
- The TS is not sufficient for explaining the Run-II data. Pole structures are needed for those observed Pc signals.
- Do we have further evidences for understanding the nature of Pc's?

2. Novel phenomena arising from the Pc three-body and four-body decays

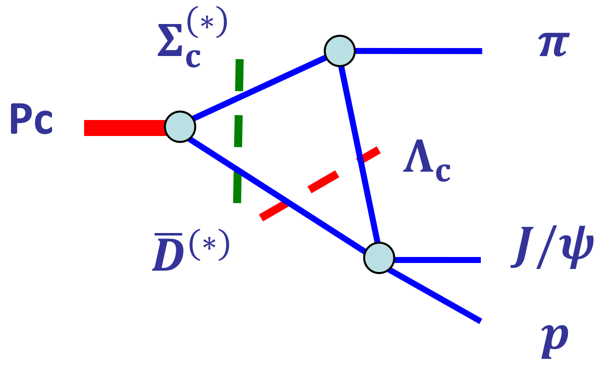
TABLE I. Summary of P_c^+ properties. The central values are based on the fit displayed in Fig. 6.

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)	$0.53 \pm 0.16^{+0.15}_{-0.13}$

Two-body decay:
Hidden charm decays are generally suppressed.



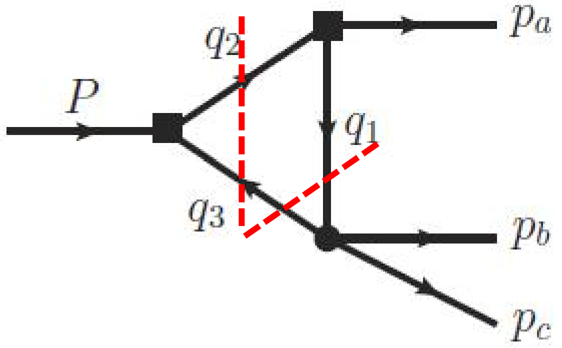
Three-body decay:
Hidden charm decays are further suppressed by the phase space. However, the presence of triangle singularity (TS) or box singularity (BS) may produce unique structures.



Exotics of Type-III:
Peak structures caused by kinematic effects, in particular, by triangle singularity.

$$\Gamma_3(s_1,s_2,s_3) = \frac{1}{i(2\pi)^4}\int \frac{d^4q_1}{(q_1^2-m_1^2+i\epsilon)(q_2^2-m_2^2+i\epsilon)(q_3^2-m_3^2+i\epsilon)}$$
$$= \frac{-1}{16\pi^2}\int_0^1\int_0^1\int_0^1 da_1\,da_2\,da_3\,\frac{\delta(1-a_1-a_2-a_3)}{D-i\epsilon},$$

$$D \equiv \sum_{i,j=1}^{3} a_i a_j Y_{ij},\quad Y_{ij} = \frac{1}{2}\left[m_i^2+m_j^2-(q_i-q_j)^2\right]$$

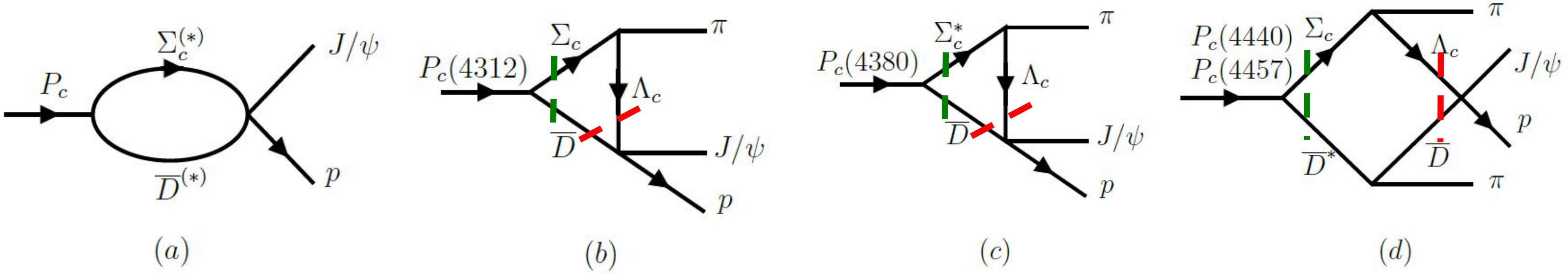


The TS occurs when all the three internal particles can approach their on-shell condition simultaneously:

$\partial D/\partial a_j = 0$ for all j=1,2,3. ⇨ $\det[Y_{ij}] = 0$

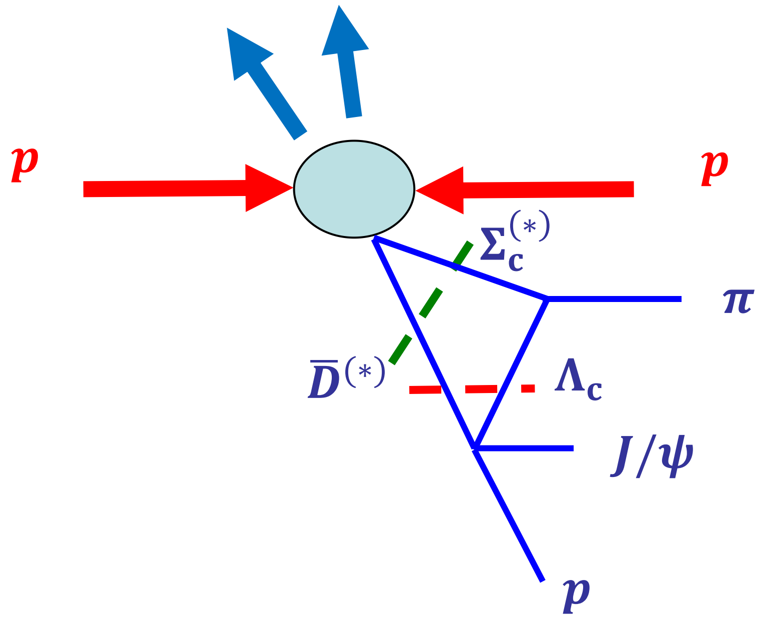
L. D. Landau, Nucl. Phys. 13, 181 (1959);
J.J. Wu, X.-H. Liu, Q. Zhao, B.-S. Zou, Phys. Rev. Lett. 108, 081003 (2012)
Q. Wang, C. Hanhart, Q. Zhao, Phys. Rev. Lett. 111, 132003 (2013); Phys. Lett. B 725, 106 (2013)
X.-H. Liu, M. Oka and Q. Zhao, PLB753, 297(2016)
M.-C. Du and Q. Zhao, Phys.Rev.D 100 (2019) 3, 036005
F.-K. Guo, C. Hanhart, U.-G. Meissner, Q. Wang, Q. Zhao, B.-S. Zou, Rev. Mod. Phys. 90, 015004 (2018)
F.-K. Guo, X.-H. Liu, and S. Sakai, Prog.Part.Nucl.Phys. 112 (2020) 103757

Triangle and box singularity in Pc three and four-body decays



- Although the $\Lambda_c\overline{D}^{(*)}$ interactions would not dynamically generate pole structures, narrow peaks may appear at the thresholds of $\Lambda_c\overline{D}^{(*)}$ due to the TS and BS mechanism.
- Near-threshold $\Sigma_c^{(*)}\overline{D}^{(*)}$ interactions will feed into the TS and BS mechanism and contribute to the $\Lambda_c\overline{D}^{(*)}$ peaks in the $J/\psi p$ invariant mass spectrum.

A feed-down mechanism for producing the enhancements at the $\Lambda_c\bar{D}^{(*)}$ thresholds



Collinear pairs of $\Sigma_c^{(*)}\bar{D}^{(*)}$ produced at LHC may rescatter into the $J/\psi p\pi$ or $J/\psi p\pi\pi$ channel via the TS/BS mechanism, and produce narrow structures at the $\Lambda_c\bar{D}^{(*)}$ thresholds in the $J/\psi p$ or $J/\psi p\pi$ spectra.

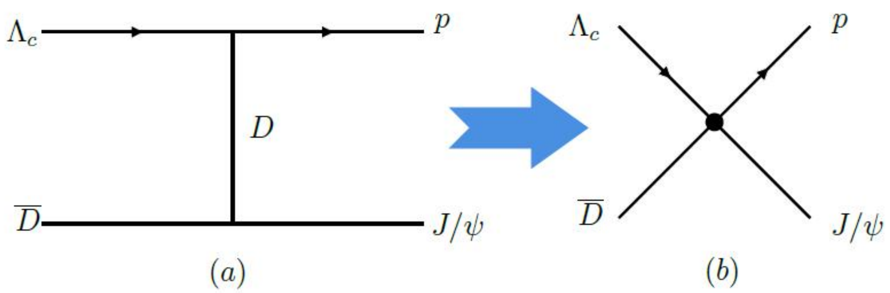
M.-X. Duan, L. Qiu, X.-Z. Ling, and Q. Zhao, PRD 109, L031507 (2024); arXiv:2303.13329 [hep-ph]

Effective Lagrangians for the interaction vertices:

$$\mathcal{L}_{P_c(4312)\Sigma_c\bar{D}} = g_{P_c(4312)}\bar{D}^\dagger\bar{\Sigma}_c P_c,$$
$$\mathcal{L}_{P_c(4380)\Sigma_c^*\bar{D}} = g_{P_c(4380)}\bar{D}^\dagger\bar{\Sigma}_c^* \cdot P_c,$$
$$\mathcal{L}_{P_c(4440)\Sigma_c\bar{D}^*} = g_{P_c(4440)}\bar{D}^{*\mu\dagger}\bar{\Sigma}_c\gamma_5\tilde{\gamma}_\mu(p_A)P_c,$$
$$\mathcal{L}_{P_c(4457)\Sigma_c\bar{D}^*} = g_{P_c(4457)}\bar{\Sigma}_c\bar{D}^{*\dagger} \cdot P_c,$$

The coupling strength is determined by the t-channel scattering with the heavy meson exchange and the Lagrangians are:

$$\mathcal{L}_{\Lambda_c Dp} = ig_{DN\Lambda_c}D^\dagger\bar{N}\gamma_5\Lambda_c,$$
$$\mathcal{L}_{J/\psi D\bar{D}} = g_{J/\psi D\bar{D}}(D\partial_\mu\bar{D} - \partial_\mu D\bar{D})\psi^\mu,$$



M.-X. Duan, L. Qiu, X.-Z. Ling, and Q. Zhao, PRD 109, L031507 (2024); arXiv:2303.13329 [hep-ph]

The triangle loop amplitudes have the following forms:

$$\mathcal{M}^{P_c(4312)\to J/\psi p\pi} = \int \frac{dp_{\Lambda_c}^4}{(2\pi)^4} \bar{u}_p \gamma_5 \gamma_\mu \varepsilon_{J/\psi}^{*\mu} (\not{p}_{\Lambda_c} + m_{\Lambda_c}) \gamma_5 \gamma_\nu p_\pi^\mu (\not{p}_{\Sigma_c} + m_{\Sigma_c}) u_{P_c} \times \frac{g_{P_c(4312)} g_{\Sigma_c \Lambda_c \pi} g_x \mathcal{F}^2(p_{\Lambda_c}^2)}{(p_{\Sigma_c}^2 - m_{\Sigma_c}^2)(p_D^2 - m_D^2)(p_{\Lambda_c}^2 - m_{\Lambda_c}^2)},$$

$$\mathcal{M}^{P_c(4380)\to J/\psi p\pi} = \int \frac{d^4 p_{\Lambda_c}}{(2\pi)^4} \bar{u}_p \gamma_5 \gamma_\mu \varepsilon_{J/\psi}^{*\mu} (\not{p}_{\Lambda_c} + m_{\Lambda_c}) p_{\pi\nu} (\not{p}_{\Sigma_c} + m_{\Sigma_c}) \times [-g^{\nu\alpha} + \frac{1}{3}\gamma^\nu \gamma^\alpha + \frac{1}{3m_{\Sigma_c}}(\gamma^\nu p^\alpha - \gamma^\alpha p^\nu) + \frac{2}{3p_{\Sigma_c}^2} p_{\Sigma_c}^\nu p_{\Sigma_c}^\alpha] \times u_{P_c\alpha} \frac{g_{P_c(4380)} g_{\Sigma_c^* \Lambda_c \pi} g_x \mathcal{F}^2(p_{\Lambda_c}^2)}{(p_{\Sigma_c^*}^2 - m_{\Sigma_c^*}^2)(p_D^2 - m_D^2)(p_{\Lambda_c}^2 - m_{\Lambda_c}^2)},$$

$$\mathcal{M}^{P_c(4440)\to J/\psi p\pi\pi} = \int \frac{d^4 p_D}{(2\pi)^4} (-g^{\alpha\rho} + \frac{p_{D^*}^\alpha p_{D^*}^\rho}{m_{D^*}^2}) p_{\pi\rho} \times \bar{u}_p \gamma_5 \gamma_\mu \varepsilon_{J/\psi}^{*\mu} (\not{p}_{\Lambda_c} + m_{\Lambda_c}) \gamma_5 \gamma_\nu p_\pi^\nu (\not{p}_{\Sigma_c} + m_{\Sigma_c}) \gamma_5 \tilde{\gamma}_\alpha u_{P_c} \times \frac{g_{P_c(4440)} g_{\Sigma_c^* \Lambda_c \pi} g_x g_{D^* D\pi} \mathcal{F}^2(p_{\Lambda_c}^2)}{(p_{\Sigma_c}^2 - m_{\Sigma_c}^2)(p_{D^*}^2 - m_{D^*}^2)(p_{\Lambda_c}^2 - m_{\Lambda_c}^2)(p_D^2 - m_D^2)},$$

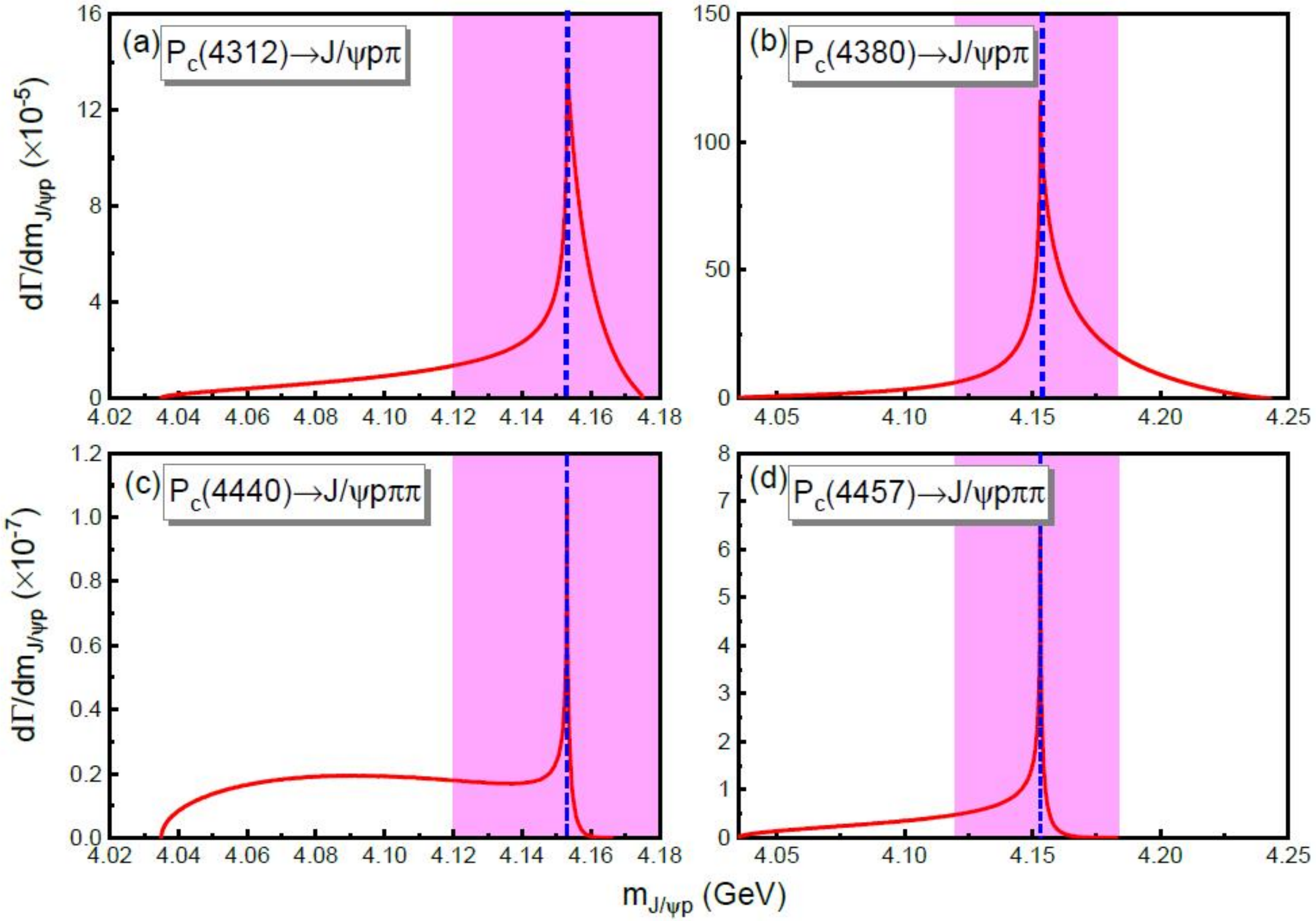
$$\mathcal{M}^{P_c(4457)\to J/\psi p\pi\pi} = \int \frac{d^4 p_D}{(2\pi)^4} \bar{u}_p \gamma_5 \gamma_\mu \varepsilon_{J/\psi}^{*\mu} (\not{p}_{\Lambda_c} + m_{\Lambda_c}) \gamma_5 \gamma_\nu p_\pi^\nu (\not{p}_{\Sigma_c} + m_{\Sigma_c}) u_{P_c\alpha} \times (-g^{\alpha\beta} + \frac{p_{D^*}^\alpha p_{D^*}^\beta}{m_{D^*}^2}) p_{\pi\beta} \times \frac{g_{P_c(4457)} g_{\Sigma_c^* \Lambda_c \pi} g_x g_{D^* D\pi} \mathcal{F}^2(p_{\Lambda_c}^2)}{(p_{\Sigma_c}^2 - m_{\Sigma_c}^2)(p_{D^*}^2 - m_{D^*}^2)(p_{\Lambda_c}^2 - m_{\Lambda_c}^2)(p_D^2 - m_D^2)}.$$

where a monopole form factor is adopted to regularize the UV divergence:

$$\mathcal{F}(q^2) = (\Lambda^2 - m_q^2)/(q^2 - \bar{m}_q^2)$$

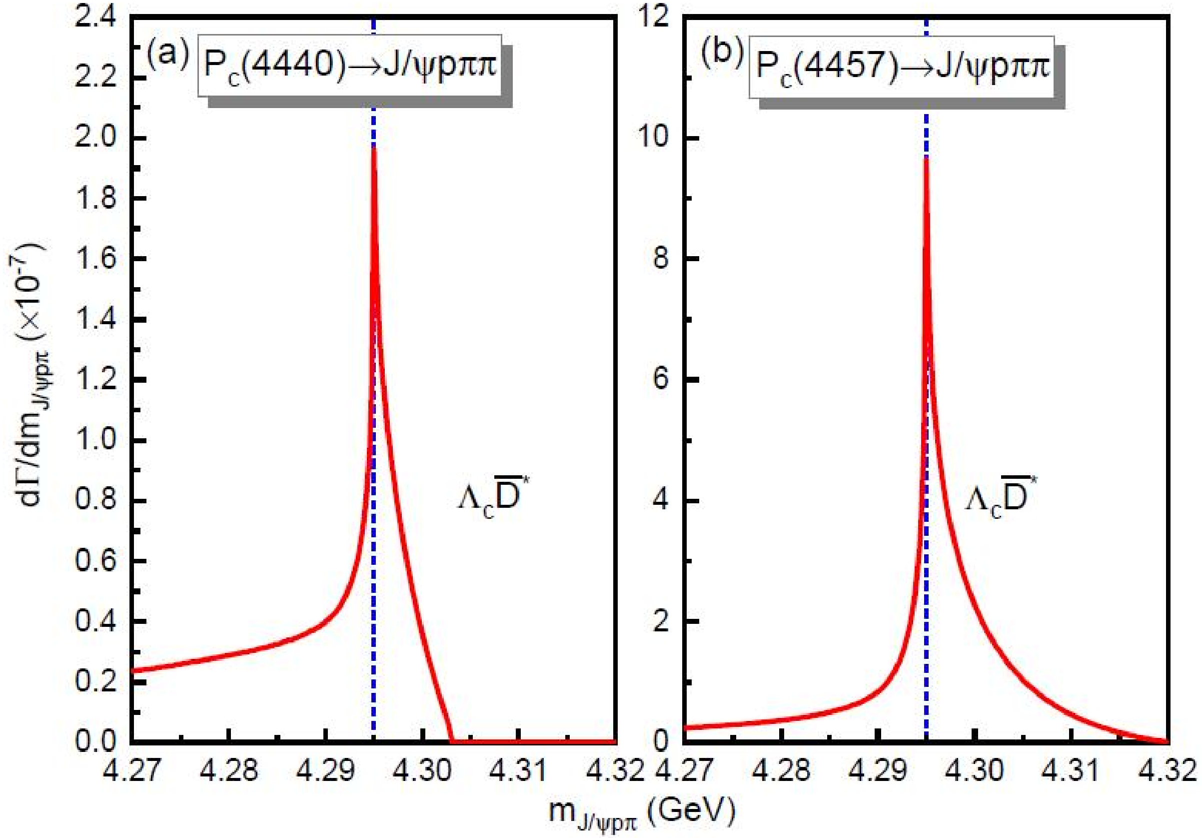
The invariant mass spectra of $J/\psi p$ for the exclusive decays of Pc states into $J/\psi p\pi$ and/or $J/\psi p\pi\pi$ channels.

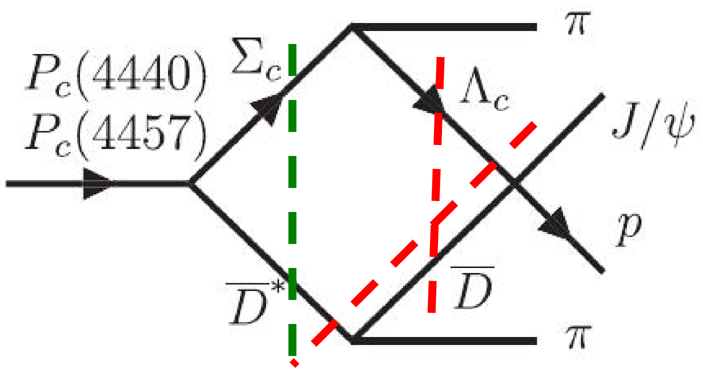
$\Lambda_c\overline{D}$ $\Lambda_c\overline{D}$



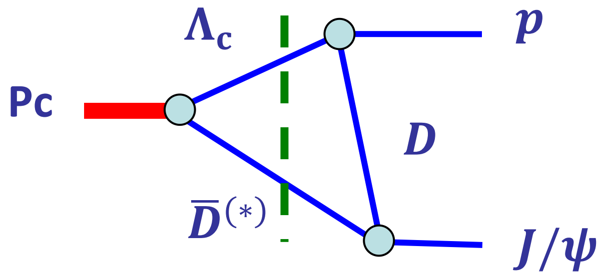
- Relatively large phase space for $\Sigma_c^* \to \Lambda_c\pi$ within the TS kinematic region leads to the strong enhancement in $Pc(4380) \to J/\psi p\pi$.
- Such an effect actually will add additional partial decay widths to the $Pc(4380)$ decay.

The $J/\psi p\pi$ invariant mass spectra for $P_c(4440),\ P_c(4457) \to J/\psi p\pi\pi$



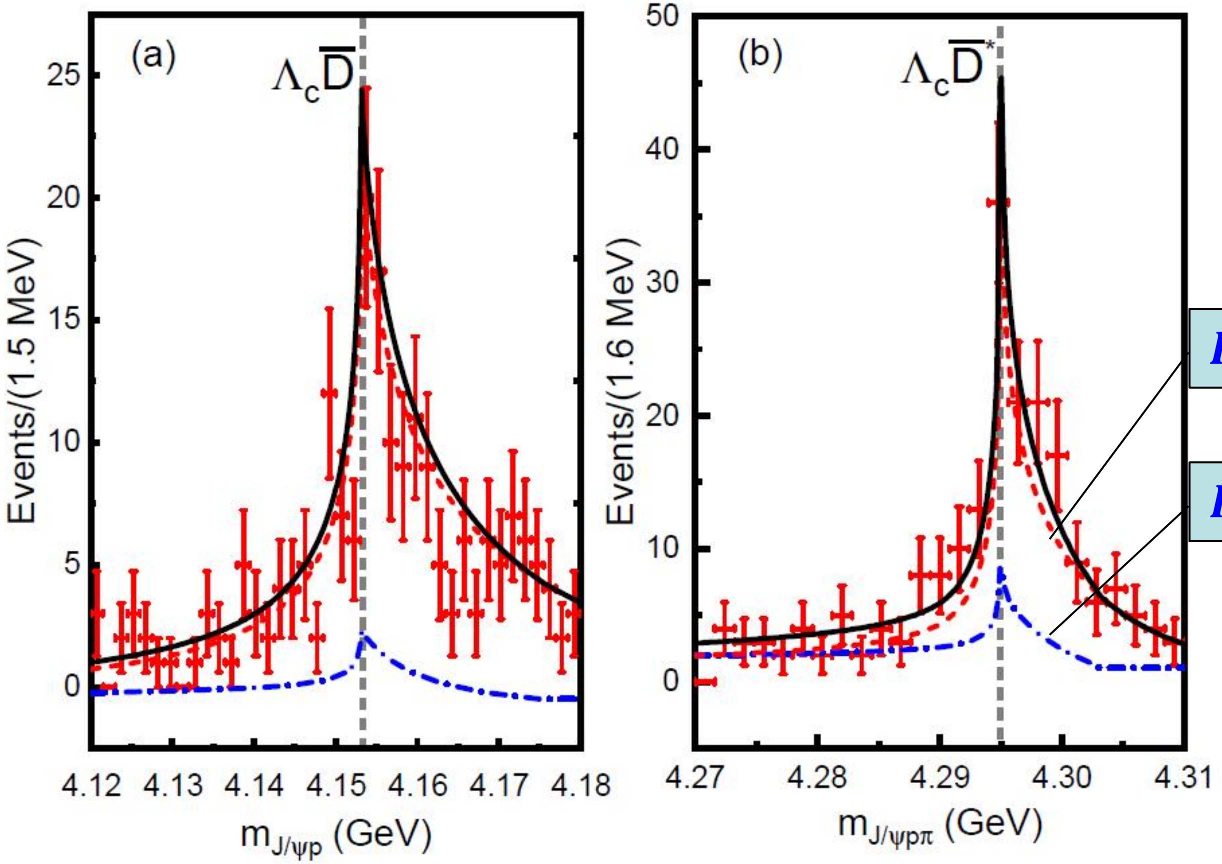


- Note that the $\Lambda_c\bar{D}^{(*)}$ thresholds also appear in $\Lambda_b \to K^- J/\psi p$. However, they only contribute as CUSP structures which is subleading to the TS/BS contributions.
- A narrow structure in the $\Lambda_c\bar{D}^{(*)}$ spectra is a direct evidence for the TS/BS mechanisms.



The accumulated $J/\psi p$ (left) and $J/\psi p\pi$ (right) invariant mass spectra from all different Pc states

$P_c(4380)$ (red dashed) dominant



$P_c(4457)$ (red dashed)

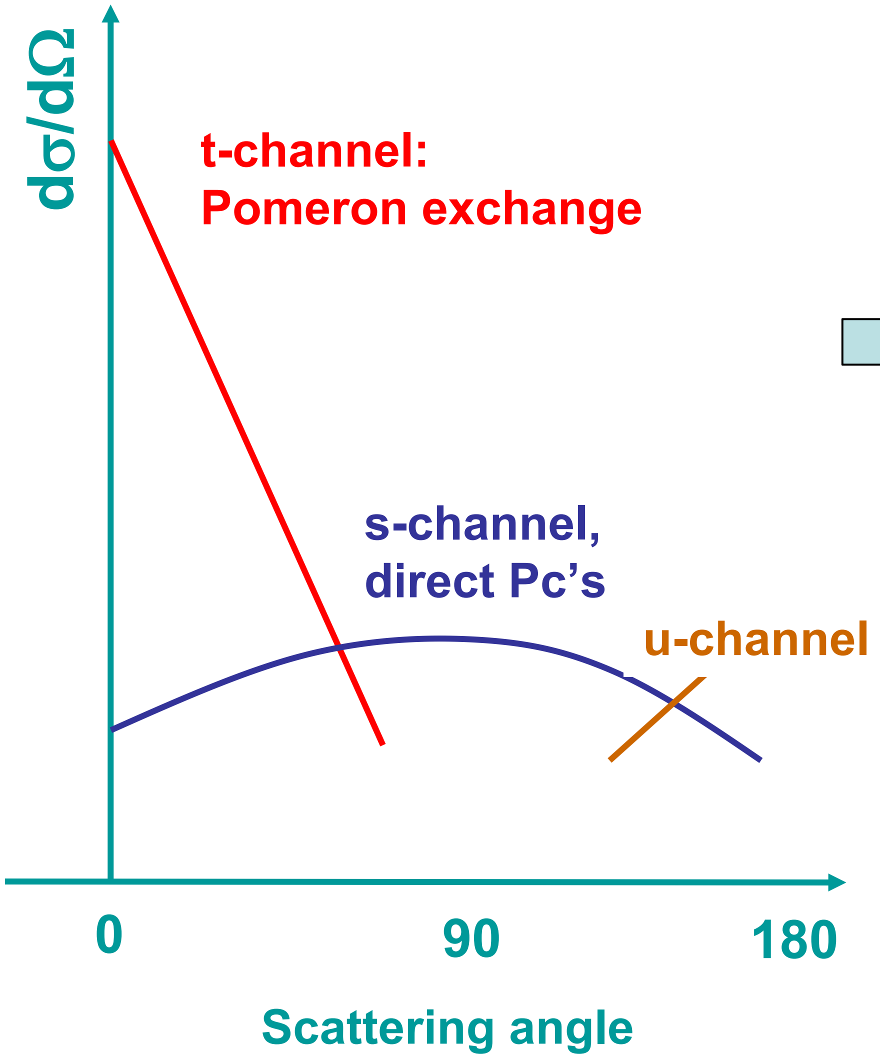
$P_c(4440)$ (blue dot-dashed)

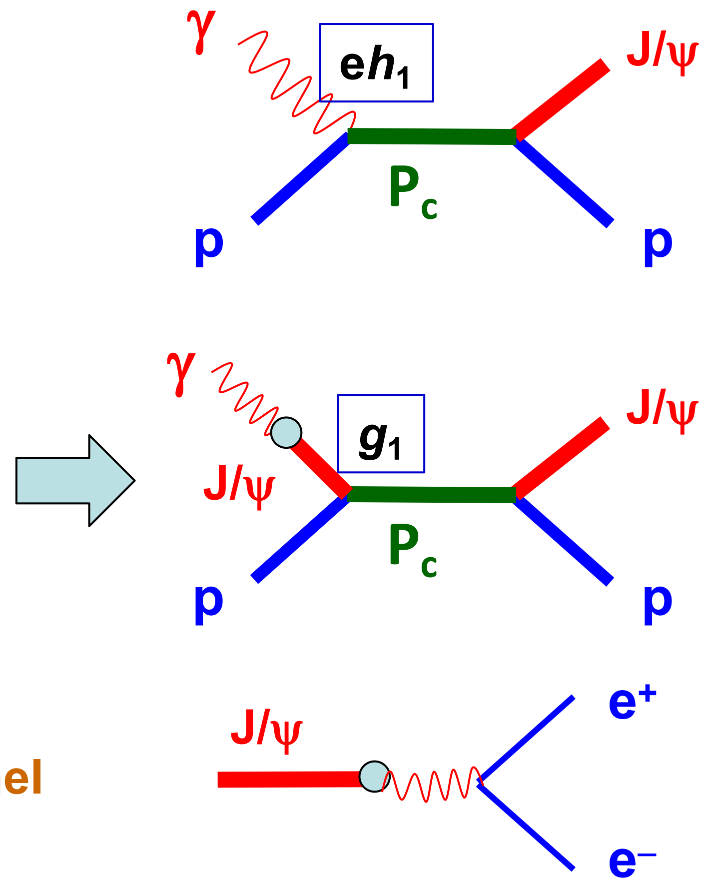
Feed-down mechanism:

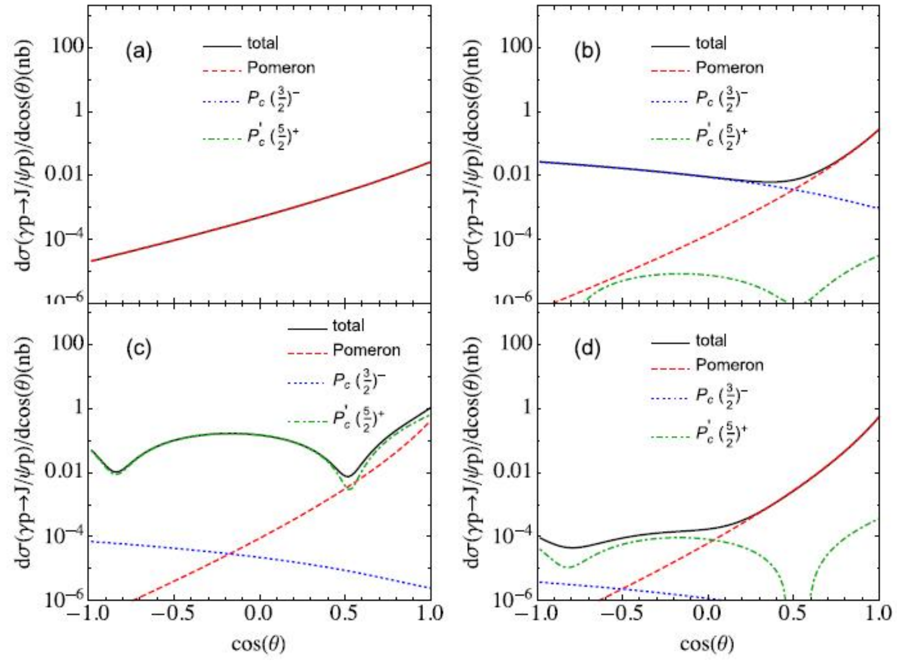
All semi-inclusive $J/\psi\ p$ events in heavy-ion collisions may produce narrow structures at the thresholds of $\Lambda_c\bar{D}$ and $\Lambda_c\bar{D}^*$.

3. Comments on the J/psi photoproduction near threshold

Photoproduction will provide crucial evidence for understanding the Pc's nature

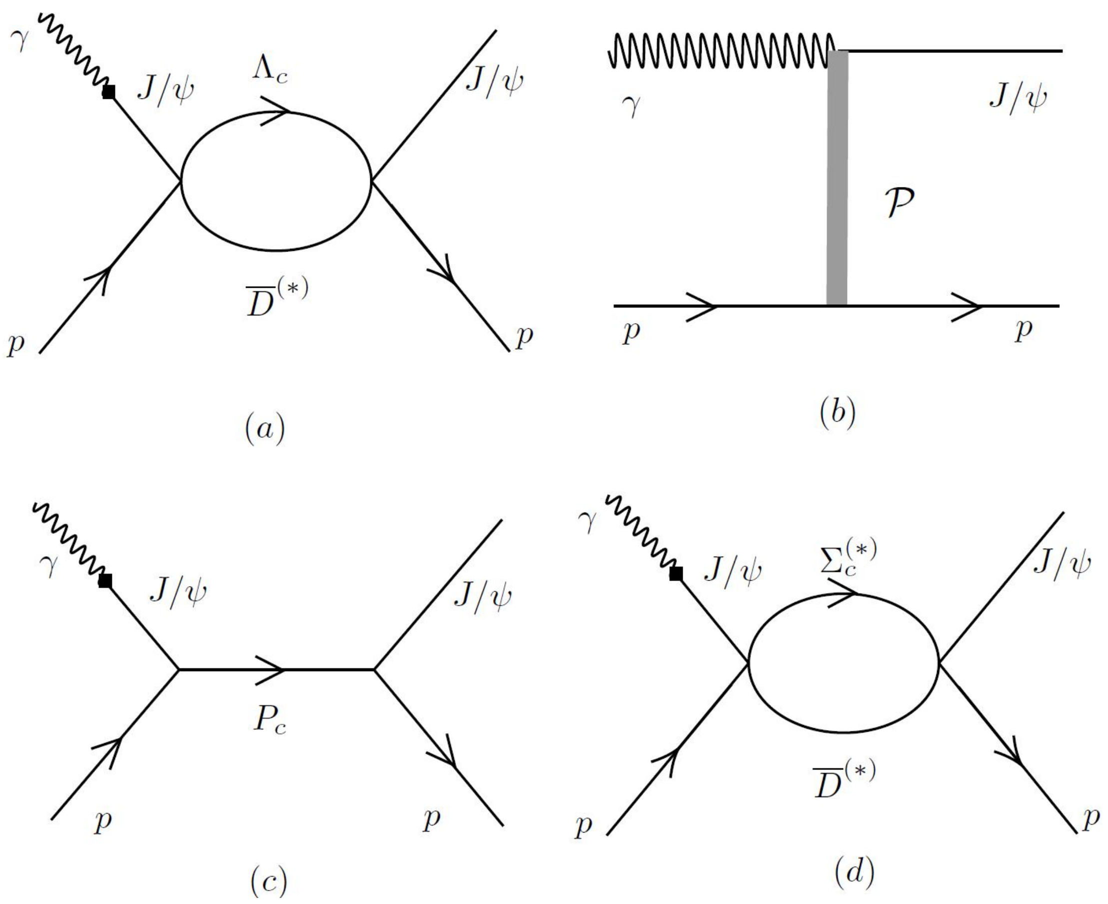


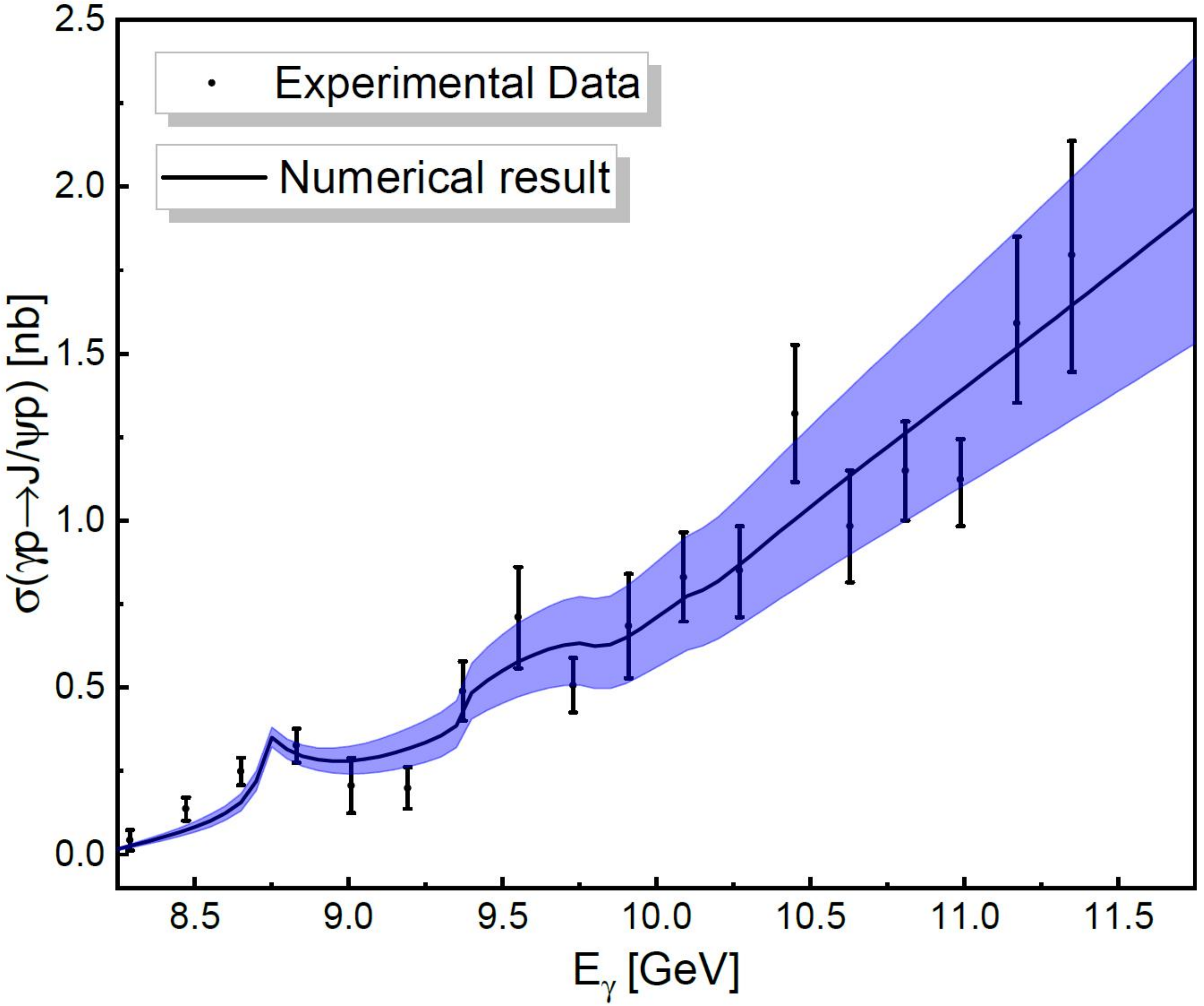




Q. Wang, X.-H. Liu, and Q. Z., PRD92, 034022 (2015); arXiv:1508.00339 [hep-ph]
V. Kubarovsky and M.B. Voloshin, PRD92, 031502 (2015)
M. Karliner and J. Rosner, PLB752, 329 (2016)
M.L. Du et al., Eur.Phys.J.C 80 (2020) 11, 1053

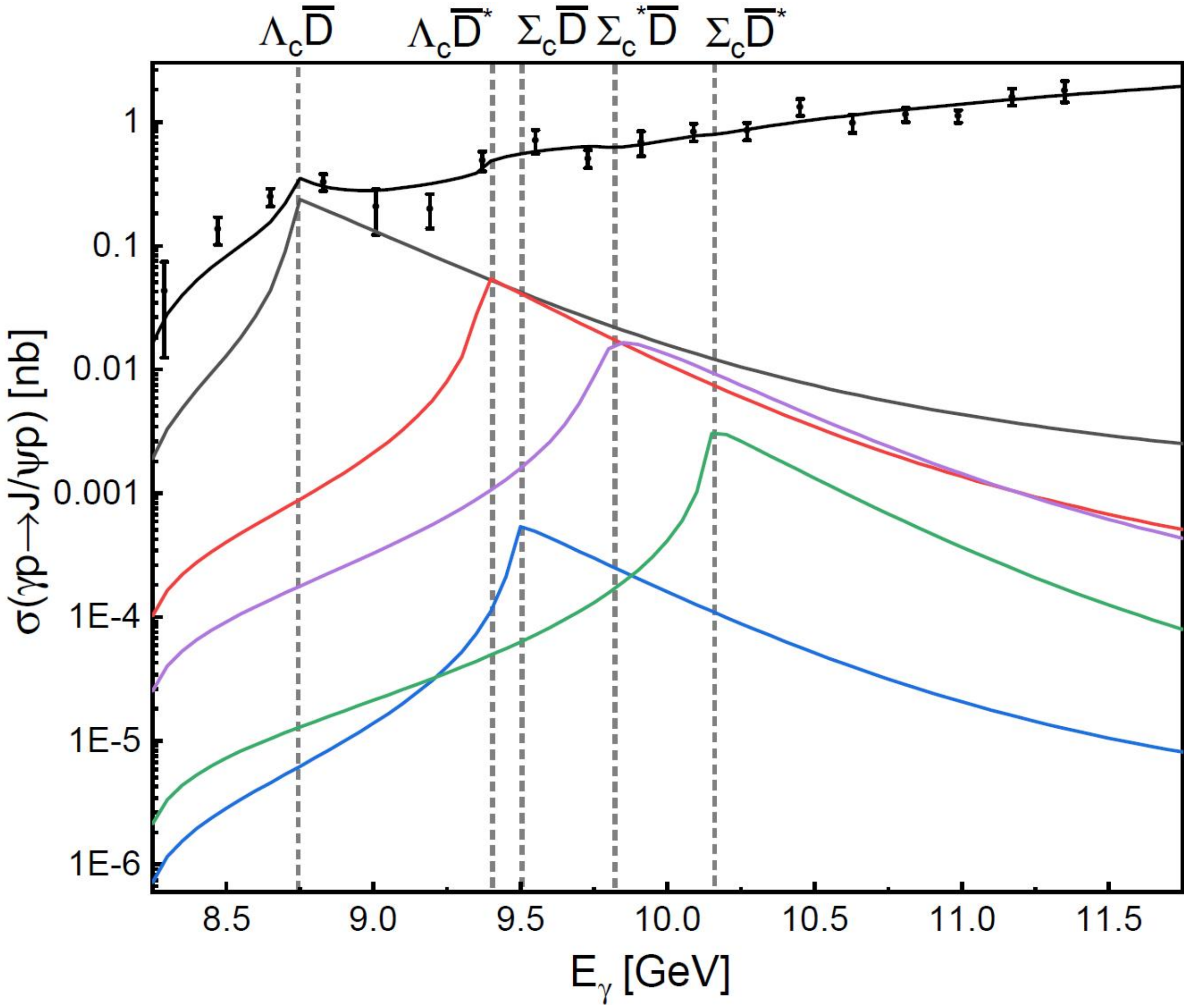
Photoproduction mechanism:





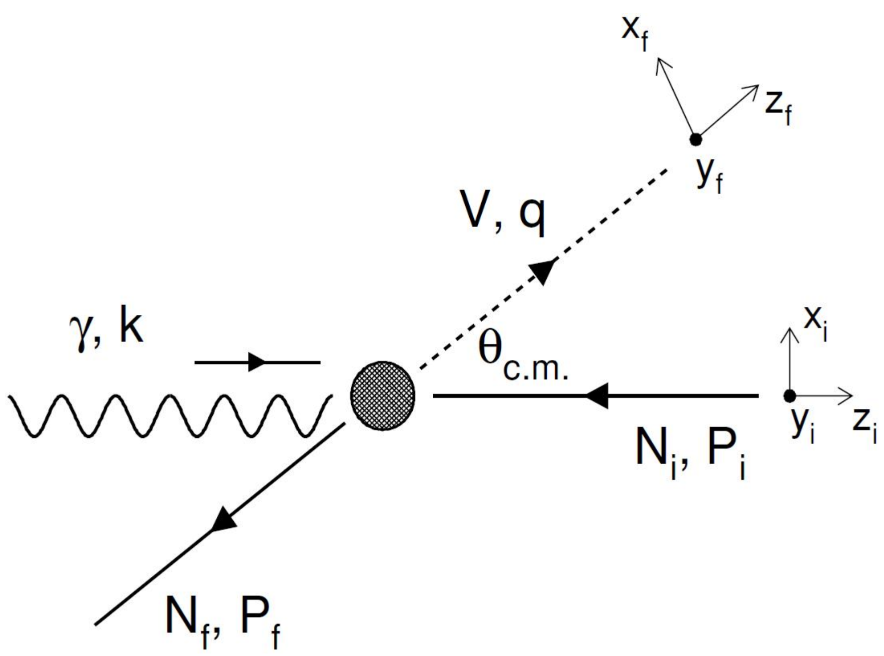
S. Adhikari et al. [GlueX], Phys. Rev. C 108, no.2, 025201 (2023)

Exclusive and inclusive contributions from different open threshold channels



- The photoproduction process will pick up the open threshold first.
- The production of Pc's is relatively suppressed by their small couplings to $J/\psi p$ which means that higher statistics are still needed.
- Processes of $\gamma p \to J/\psi p \pi$ and $J/\psi p \pi\pi$ are useful for further disentangling the role played by the TS/BS though the measurement would be challenging.

Polarized beam asymmetry measurement:



The density matrix elements of the vector meson is defined as:

$$\rho_{\lambda_v\lambda'_v}(V) = \frac{1}{N}\sum_{\lambda_f\lambda_\gamma\lambda_i\lambda'_\gamma} T_{\lambda_v\lambda_f,\lambda_\gamma\lambda_i}\rho_{\lambda_\gamma\lambda'_\gamma}(\gamma)T^*_{\lambda'_v\lambda_f,\lambda'_\gamma\lambda_i}$$

with $N \equiv \frac{1}{2}\sum_{\lambda_v\lambda_f\lambda_\gamma\lambda_i}|T_{\lambda_v\lambda_f,\lambda_\gamma\lambda_i}|^2$ as the normalization factor.

The polarized-photon density matrix element is defined as:

$$\rho(\gamma) = \tfrac{1}{2}(I_\gamma + \boldsymbol{\sigma}\cdot\mathbf{P}_\gamma)$$

$\boldsymbol{P}_\gamma$ determines both the degree of polarization (via its magnitude p_γ) and the polarization direction.

$$\begin{cases} \mathbf{P}_\gamma = P_\gamma(-\cos 2\Phi, -\sin 2\Phi, 0) & \text{for transversely polarized photon} \\ \mathbf{P}_\gamma = P_\gamma(0, 0, \lambda_\gamma) \text{ with } \lambda_\gamma = \pm 1 & \text{for longitudinally polarized photon} \end{cases}$$

The familiar form of the vector meson density matrix elements can be obtained:

$$\rho^0_{\lambda_v \lambda'_v} = \frac{1}{2N} \sum_{\lambda_\gamma \lambda_f \lambda_i} T_{\lambda_v \lambda_f, \lambda_\gamma \lambda_i} T^*_{\lambda'_v \lambda_f, \lambda_\gamma \lambda_i},$$

$$\rho^1_{\lambda_v \lambda'_v} = \frac{1}{2N} \sum_{\lambda_\gamma \lambda_f \lambda_i} T_{\lambda_v \lambda_f, -\lambda_\gamma \lambda_i} T^*_{\lambda'_v \lambda_f, \lambda_\gamma \lambda_i},$$

$$\rho^2_{\lambda_v \lambda'_v} = \frac{i}{2N} \sum_{\lambda_\gamma \lambda_f \lambda_i} \lambda_\gamma T_{\lambda_v \lambda_f, -\lambda_\gamma \lambda_i} T^*_{\lambda'_v \lambda_f, \lambda_\gamma \lambda_i},$$

$$\rho^3_{\lambda_v \lambda'_v} = \frac{i}{2N} \sum_{\lambda_\gamma \lambda_f \lambda_i} \lambda_\gamma T_{\lambda_v \lambda_f, \lambda_\gamma \lambda_i} T^*_{\lambda'_v \lambda_f, \lambda_\gamma \lambda_i}.$$

The decomposition of the vector meson decay distribution
in terms of the initial photon polarizations gives

$$W(\cos\theta_c, \phi_c, \rho) = W^0(\cos\theta_c, \phi_c, \rho^0) + \sum_{\alpha=1}^{3} P^\alpha_\gamma W^\alpha(\cos\theta_c, \phi_c, \rho^\alpha)$$

The polarized beam asymmetry can be expressed as

$$\check{\Sigma} = \frac{\rho^1_{00} + 2\rho^1_{11}}{\rho^0_{00} + 2\rho^0_{11}}$$

Thanks for your attention!

FB23 Website

http://fb23.ihep.ac.cn/

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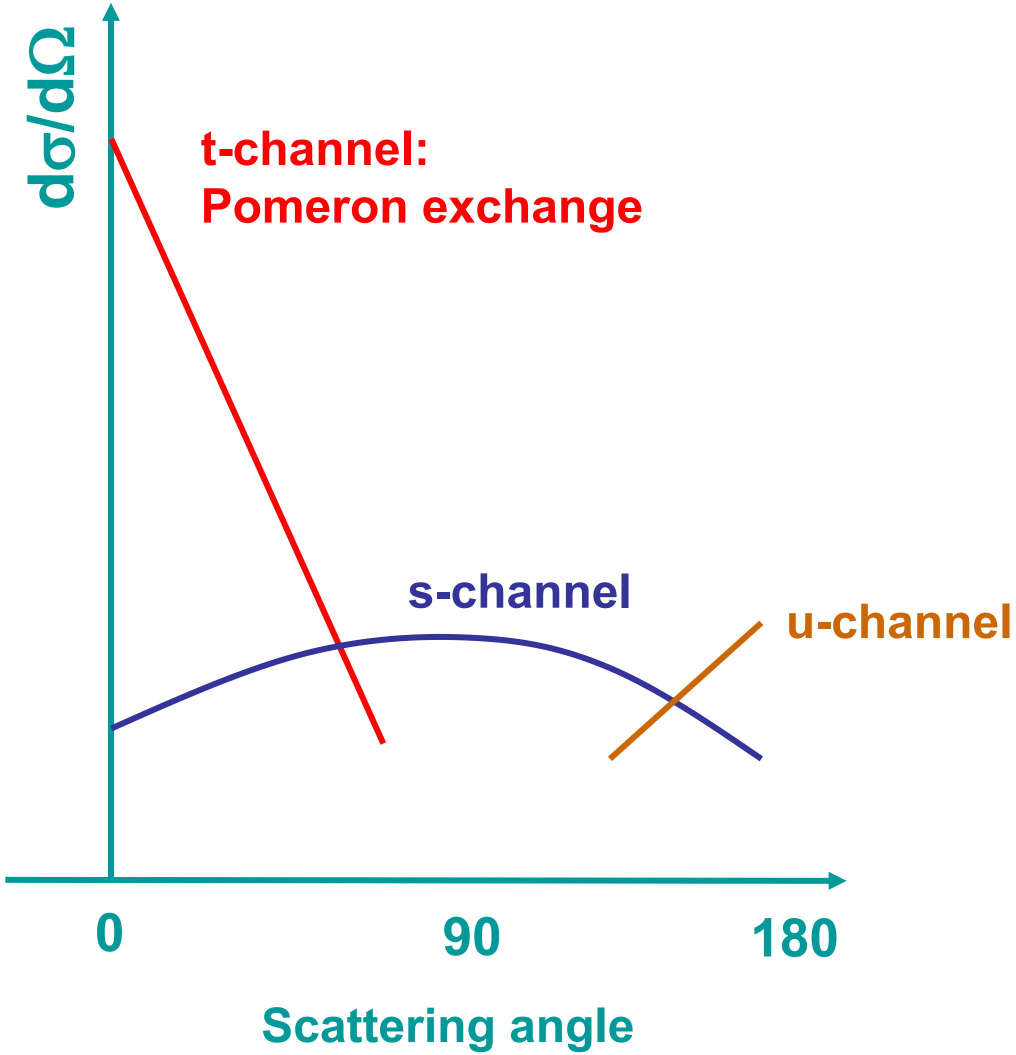
Thanks for your attention!

Welcome to Beijing!

Kinematic features of the production mechanism

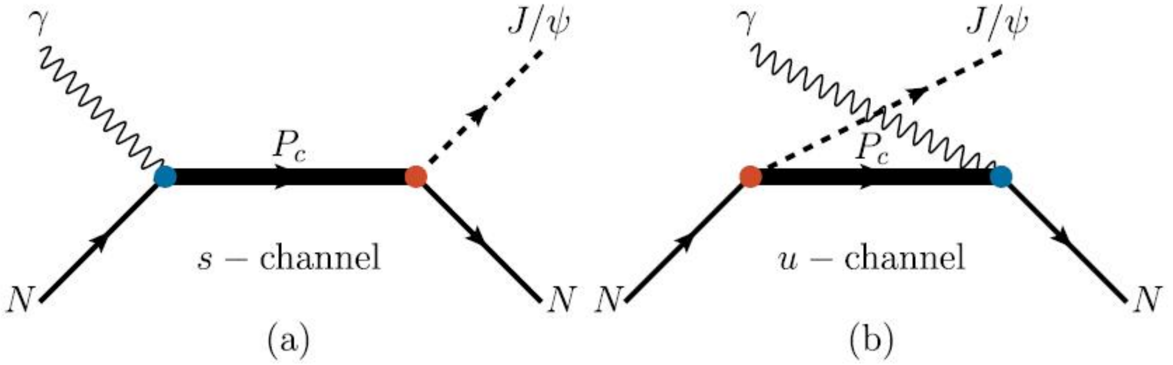


1) Forward angle peaking is predominant due to the diffractive process, i.e. Pomeron exchanges.
2) S-channel resonance excitations contribute to the cross sections at middle and backward angles.
3) U-channel contributes to backward angles.

Interferences from different transition mechanisms

Q. Wang, X.-H. Liu, and Q. Z., PRD92, 034022 (2015); arXiv:1508.00339 [hep-ph]

s and *u*-channel pentaquark production



Coupling vertices for γNP_c:

$$\mathcal{L}^{3/2^\pm}_{\gamma NP_c} = \frac{ieh_1}{2M_N}\bar{N}\Gamma^{(\pm)}_\nu F^{\mu\nu}P_{c\mu} - \frac{eh_2}{(2M_N)^2}\partial_\nu\bar{N}\Gamma^{(\pm)}F^{\mu\nu}P_{c\mu} + \text{H.c.},$$

$$\mathcal{L}^{5/2^\pm}_{\gamma NP_c} = \frac{eh_1}{(2M_N)^2}\bar{N}\Gamma^{(\mp)}_\nu\partial^\alpha F^{\mu\nu}P_{c\mu\alpha} - \frac{ieh_2}{(2M_N)^3}\partial_\nu\bar{N}\Gamma^{(\mp)}_\nu\partial^\alpha F^{\mu\nu}P_{c\mu\alpha} + \text{H.c.},$$

$$\Gamma^{(\pm)}_\mu \equiv \begin{pmatrix}\gamma_\mu\gamma_5\\ \gamma_\mu\end{pmatrix}, \qquad \Gamma^{(\pm)} \equiv \begin{pmatrix}\gamma_5\\ \mathbf{1}\end{pmatrix},$$

S. H. Kim, S. i. Nam, Y. Oh and H. C. Kim, PRD 84, 114023 (2011)
Q. Wang, X.-H. Liu, and Q. Zhao, PRD92 (2015) 034022; arXiv:1508.00339 [hep-ph]

Coupling vertices for $J/\psi NP_c$:

$$
\begin{aligned}
\mathcal{L}_{P_cN\psi}^{3/2^\pm} &= -\frac{ig_1}{2M_N}\bar{N}\Gamma_\nu^{(\pm)}\psi^{\mu\nu}P_{c\mu} - \frac{g_2}{(2M_N)^2}\partial_\nu\bar{N}\Gamma^{(\pm)}\psi^{\mu\nu}P_{c\mu} + \frac{g_3}{(2M_N)^2}\bar{N}\Gamma^{(\pm)}\partial_\nu\psi^{\mu\nu}P_{c\mu} + H.c.\ , \\
\mathcal{L}_{P_cN\psi}^{5/2^\pm} &= \frac{g_1}{(2M_N)^2}\bar{N}\Gamma_\nu^{(\mp)}\partial^\alpha\psi^{\mu\nu}P_{c\mu\alpha} - \frac{ig_2}{(2M_N)^3}\partial_\nu\bar{N}\Gamma^{(\mp)}\partial^\alpha\psi^{\mu\nu}P_{c\mu\alpha} + \frac{ig_3}{(2M_N)^3}\bar{N}\Gamma^{(\mp)}\partial^\alpha\partial_\nu\psi^{\mu\nu}P_{c\mu\alpha} + H.c.
\end{aligned}
$$

Leading transition matrix elements:

$$
\begin{aligned}
\mathcal{M}^{3/2^\pm} &= \frac{1}{s-M_{P_c}^2}\frac{eh_1g_1}{(2M_N)2}\epsilon_{\psi\nu}^*\bar{u}_N\Gamma_\sigma^{(\pm)}\Delta_{\beta\alpha}(P_c,k+p)\Gamma_\delta^{(\pm)}(k^\alpha g^{\mu\delta}-k^\delta g^{\alpha\mu})u_N\epsilon_{\gamma\mu}\ , \\
\mathcal{M}^{5/2^\pm} &= \frac{1}{s-M_{P_c}^2}\frac{eh_1g_1}{(2M_N)4}\epsilon_{\psi\nu}^*\bar{u}_Nq^\sigma(q^\rho g^{\nu\delta}-q^\delta g^{\nu\rho})\Delta_{\rho\sigma;\ \alpha\beta}(P_c,k+p)\Gamma_\lambda^{(\mp)}k^\beta(k^\alpha g^{\mu\lambda}-k^\lambda g^{\alpha\mu})u_N\epsilon_{\gamma\mu}
\end{aligned}
$$

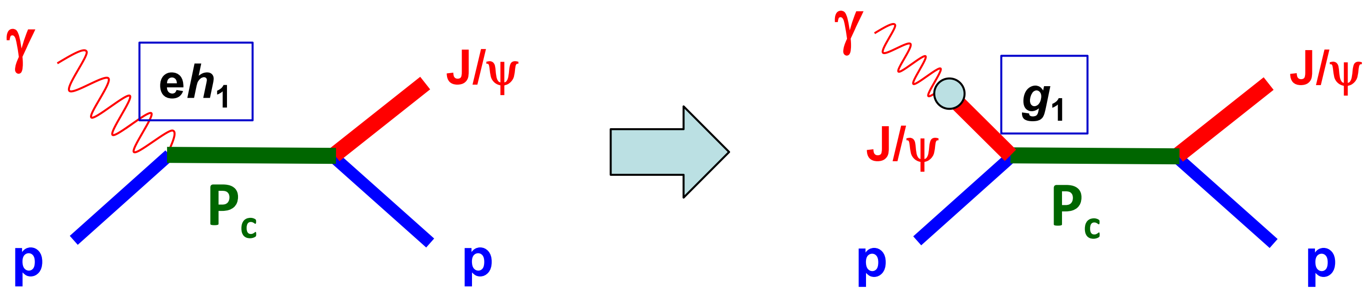
Rarita-Schwinger spin projections:

$$
\begin{aligned}
\Delta_{\beta\alpha}(B,p) &= (\not{p}+M_B)\left[-g_{\beta\alpha}+\frac{1}{3}\gamma_\beta\gamma_\alpha+\frac{1}{3M_B}(\gamma_\beta p_\alpha-\gamma_\alpha p_\beta)+\frac{2}{3M_B^2}p_\beta p_\alpha\right]\ , \\
\Delta_{\rho\sigma;\ \alpha\beta}(B,p) &= (\not{p}+M_B)\left[\frac{1}{2}(\bar{g}_{\rho\alpha}\bar{g}_{\sigma\beta}+\bar{g}_{\rho\beta}\bar{g}_{\sigma\alpha})-\frac{1}{5}\bar{g}_{\rho\sigma}\bar{g}_{\alpha\beta}-\frac{1}{10}(\bar{\gamma}_\rho\bar{\gamma}_\alpha\bar{g}_{\sigma\beta}+\bar{\gamma}_\rho\bar{\gamma}_\beta\bar{g}_{\sigma\alpha}+\bar{\gamma}_\sigma\bar{\gamma}_\alpha\bar{g}_{\rho\beta}+\bar{\gamma}_\sigma\bar{\gamma}_\beta\bar{g}_{\rho\alpha})\right]
\end{aligned}
$$

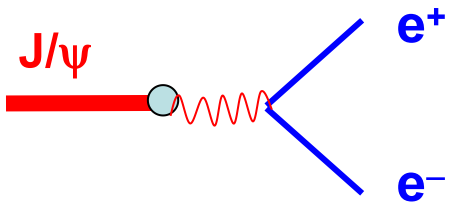
with

$$
\left\{
\begin{aligned}
\bar{g}_{\alpha\beta} &= g_{\alpha\beta}-\frac{p_\alpha p_\beta}{M_B^2}\ , \\
\bar{\gamma}_\alpha &= \gamma_\alpha-\frac{p_\alpha}{M_B^2}\not{p}\ .
\end{aligned}
\right.
$$

Vector meson dominance



$$\boxed{\mathcal{L}_{V\gamma} = \sum_V \frac{eM_V^2}{f_V} V_\mu A^\mu}$$



$$eh_1 = -\frac{eM_{J/\psi}^2}{f_{J/\psi}} \frac{ig_1}{k^2 - M_{J/\psi}^2} = i\frac{e}{f_{J/\psi}} g_1$$

By assuming that the J/ψ p saturate the decay widths of the Pc states, we have

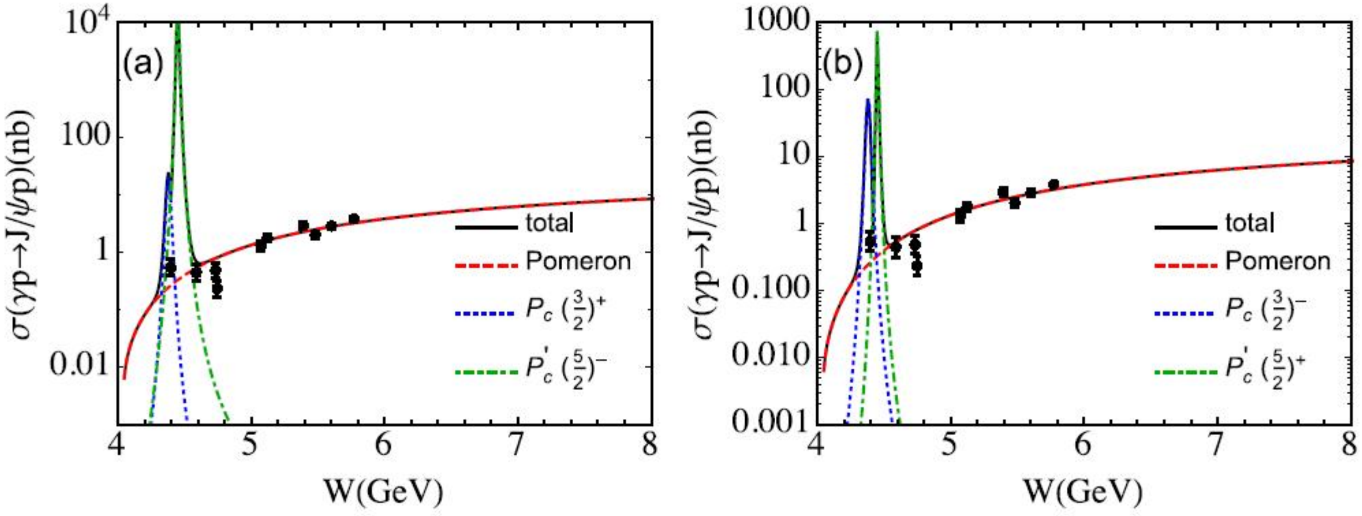
$$g_{\frac{3}{2}^+} = 1.07, \quad g_{\frac{3}{2}^-} = 1.40, \quad g_{\frac{5}{2}^+} = 2.56, \quad g_{\frac{5}{2}^-} = 5.58\ ,$$

A form factor is included:

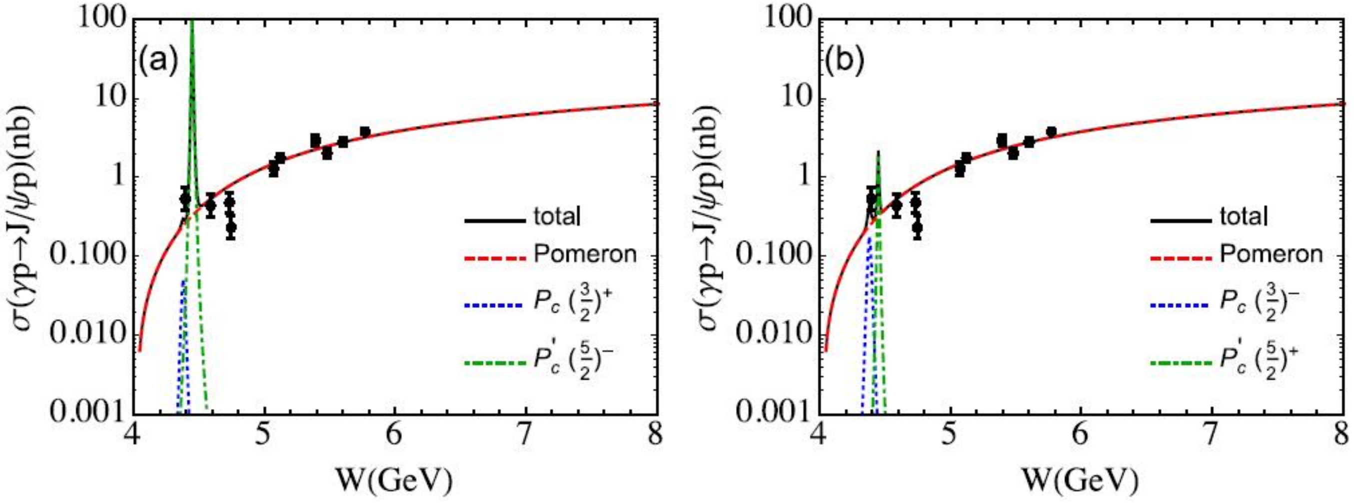
$$\mathcal{F}(p^2) = \frac{\Lambda^4}{\Lambda^4 + (p^2 - M_{P_c}^2)^2}$$

Total cross sections predicted:

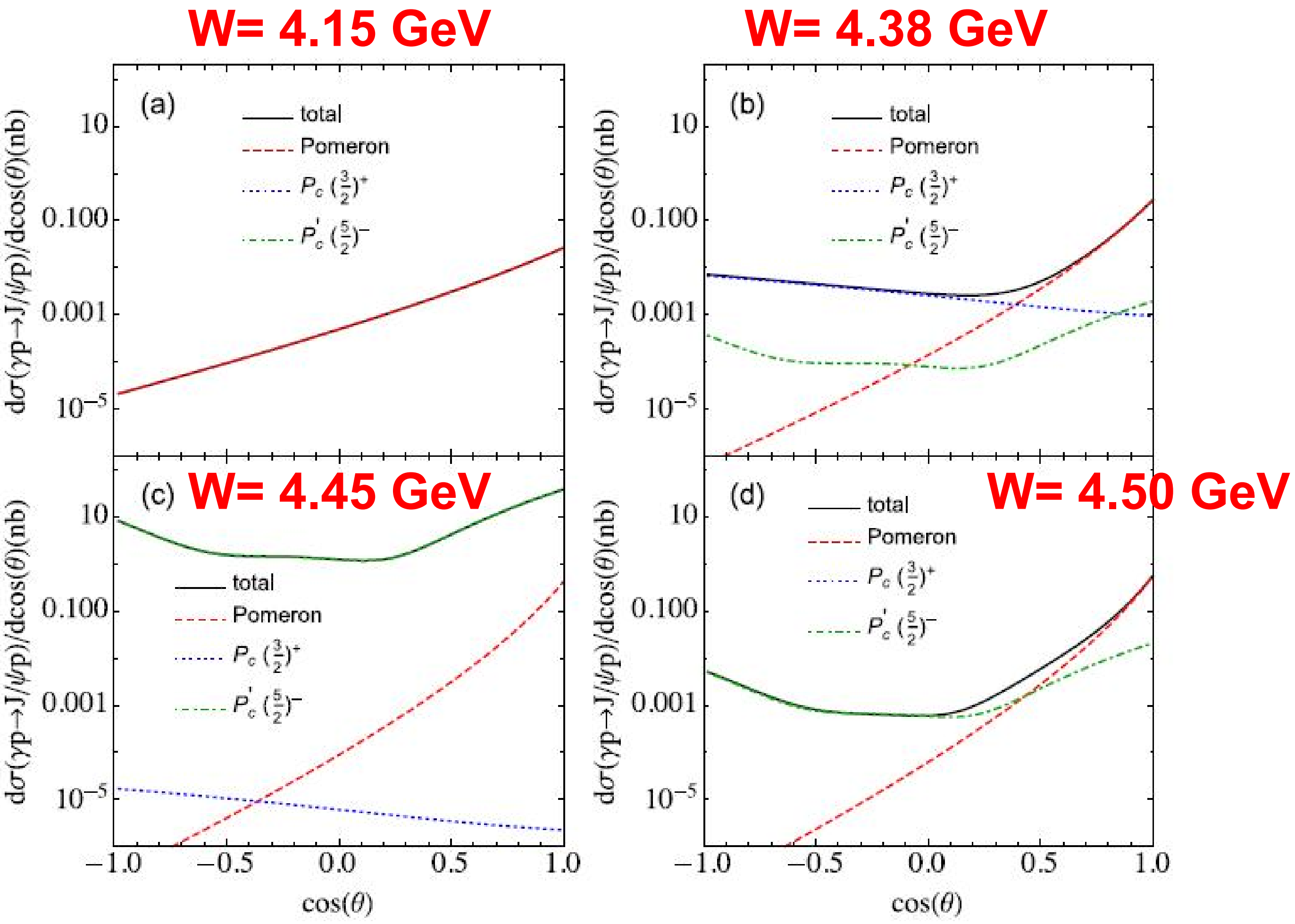
Full width prediction



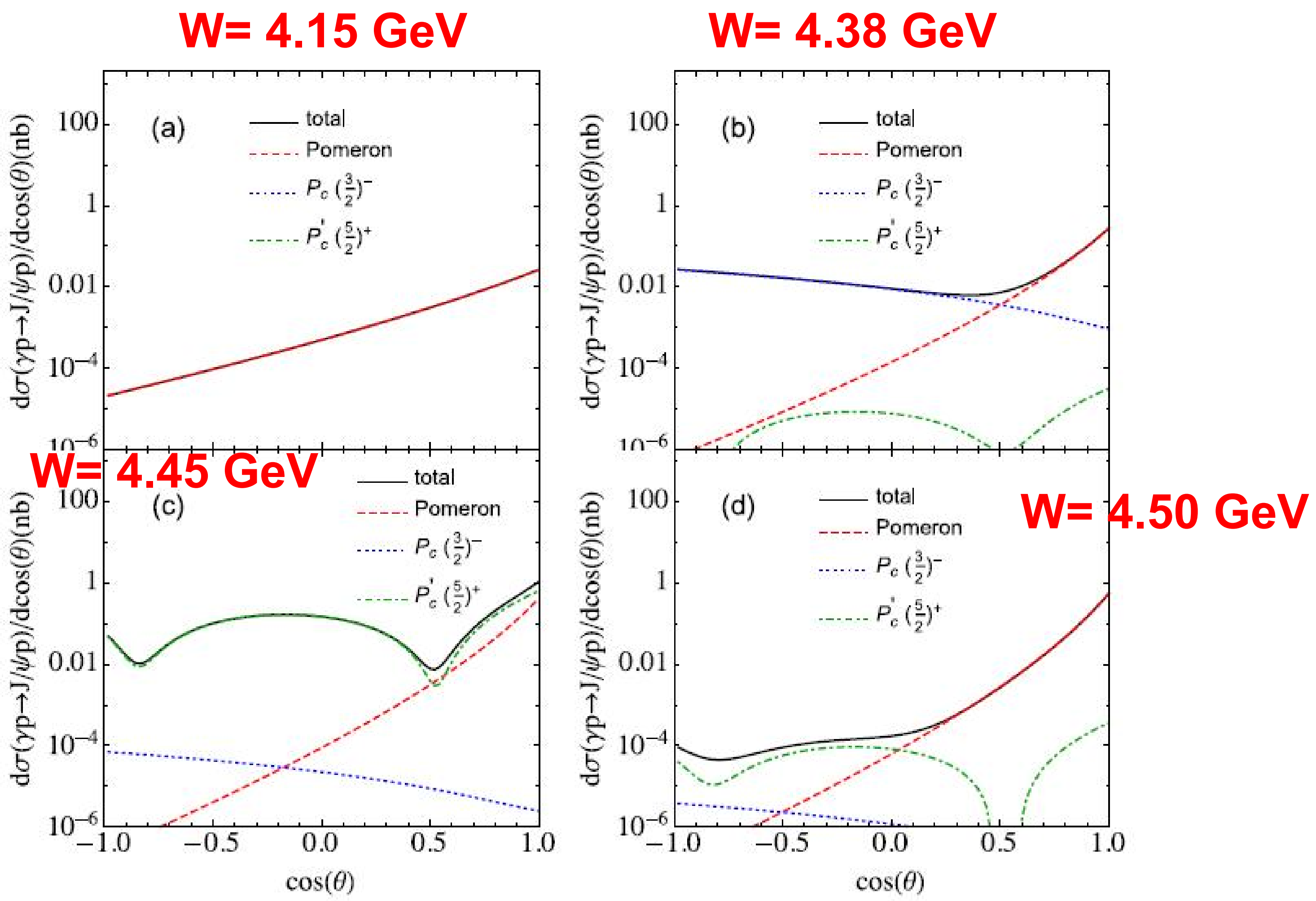
Prediction with 5% of b.r. to J/ψ p:



Predicted differential cross sections at different energies:



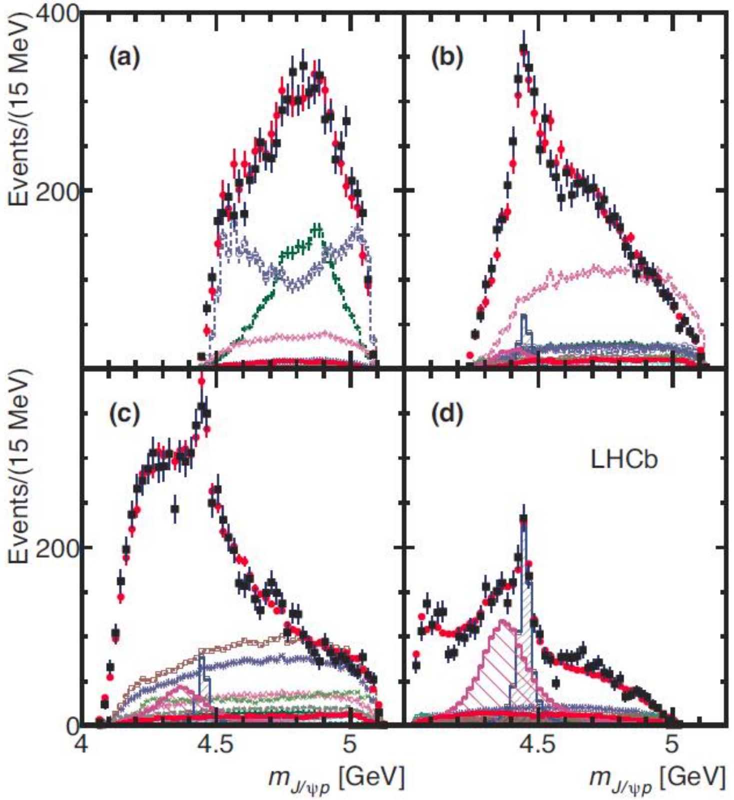
Predicted differential cross sections at different energies:

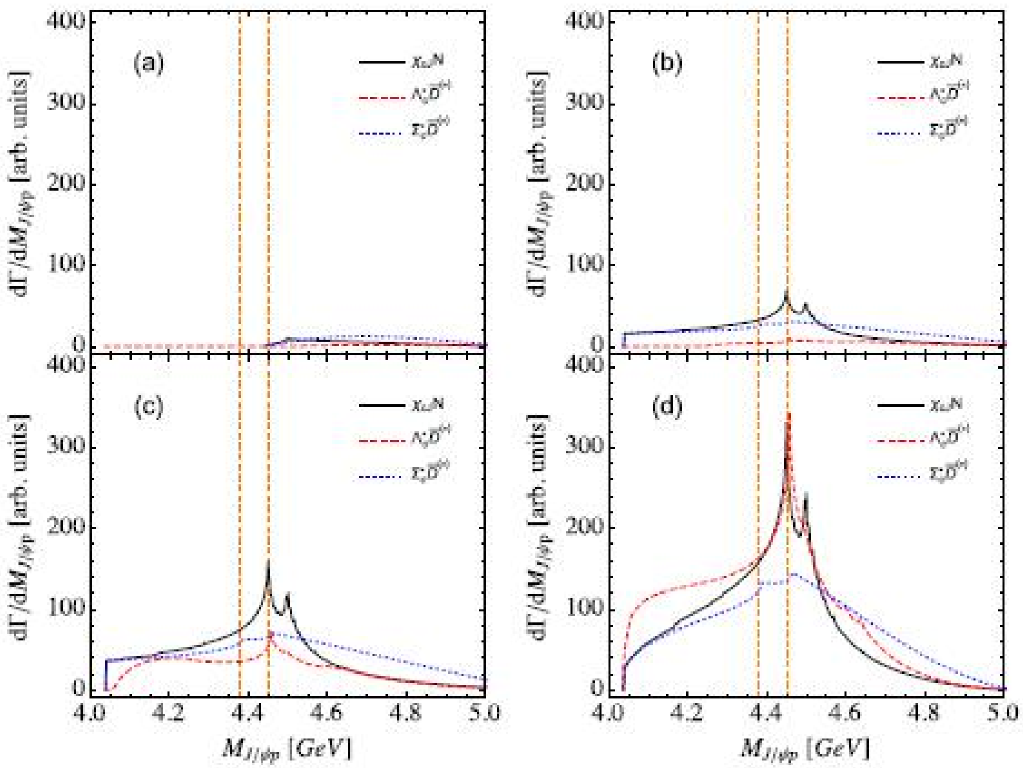


Invariant mass distribution of J/ψ p with different K⁻p momentum cuts

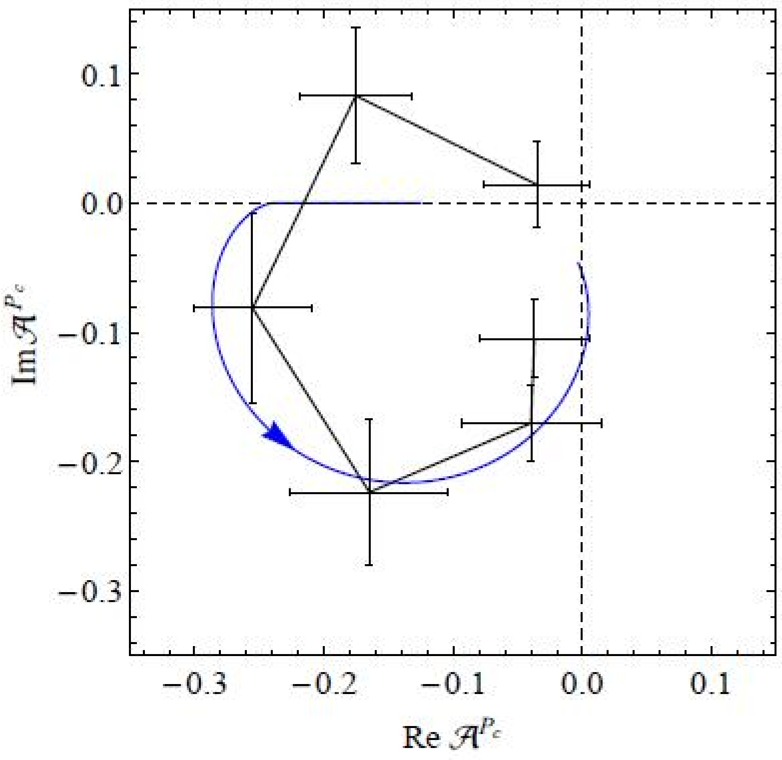
(a) $m_{Kp} < 1.55$ GeV,(b) 1.55 GeV $< m_{Kp} <$ 1.07 GeV,

(c) 1.07 GeV $< m_{Kp} <$ 12.0 GeV, (d) $m_{Kp} > 2.0$ GeV.





The ATS can mimic a resonance behavior in certain cases



F.K. Guo, U.-G. Meissner, W. Wang and Z. Yang, PRD92, 071502 (2015); arXiv:1507.04950[hep-ph]