Hidden-charm pentaquark production in three-body baryonic B decays

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Based on arXiv:2409.04951

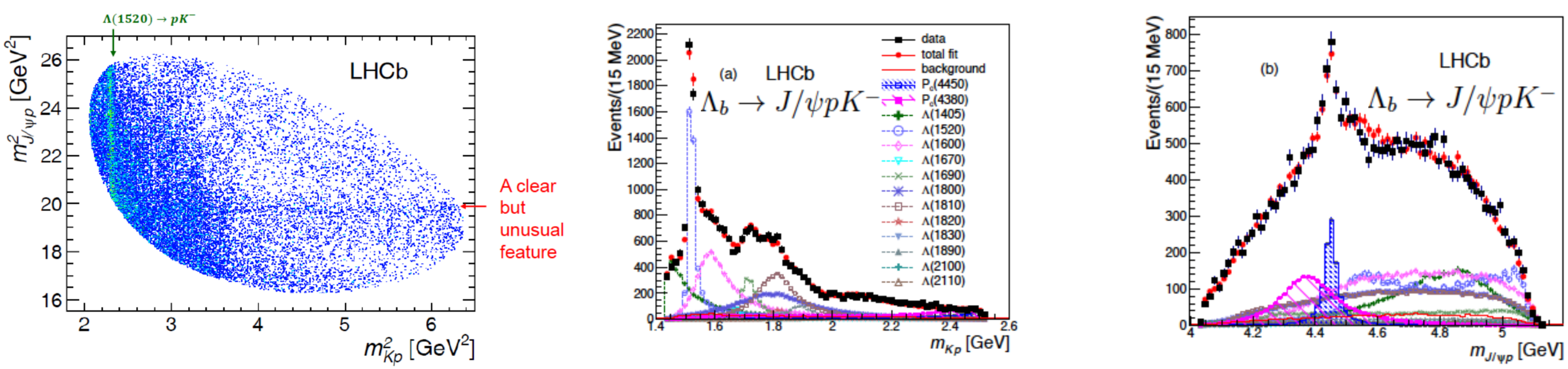
Outline:
1. Introduction
2. Formalism
3. Some results
4. Summary

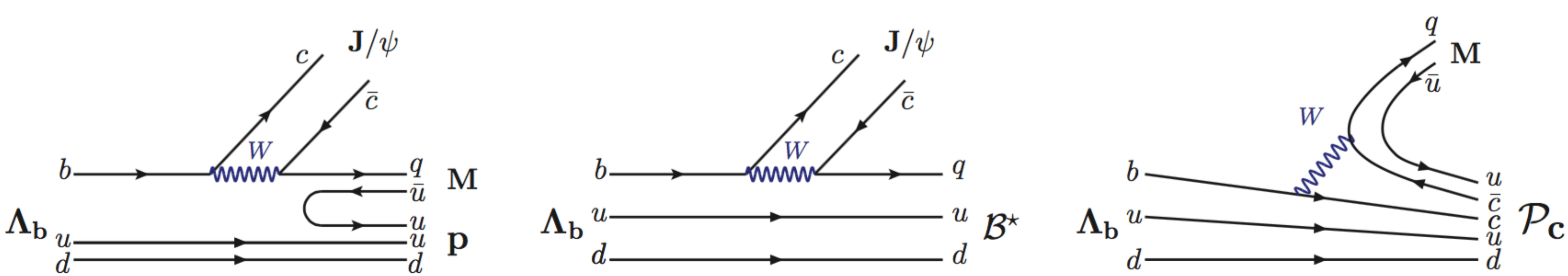
Introduction

- $\mathbf{B}_b \to J/\psi \mathbf{B} M$ plays an important role in exploring $\mathcal{P}_c(c\bar{c}uud)$ and $\mathcal{P}_{cs}(c\bar{c}uds)$ at LHCb

1. PRL115, 072001 (2015), *"Observation of $J/\psi p$ Resonances Consistent with Pentaquark States in $\Lambda_b^0 \to J/\psi K^- p$ Decays,"*

$\mathcal{P}_c(4380, 4450)^+$ was discovered as the 1st pentaquark candidates.





(a) (b) (c)

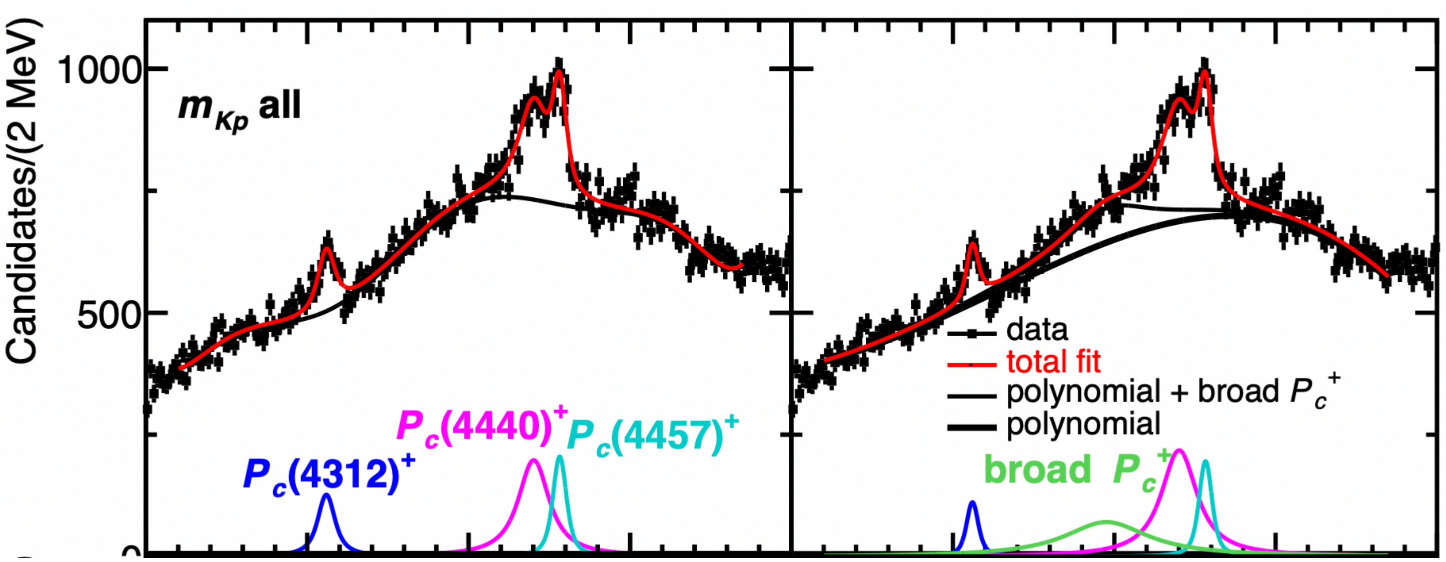
2. PRL122, 222001 (2019),

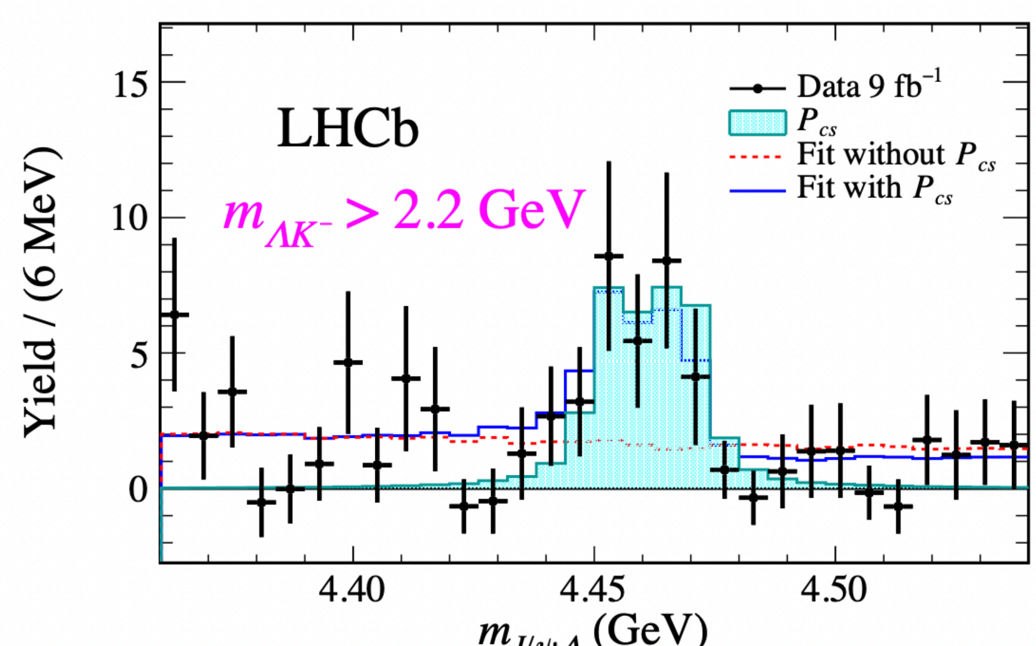
"Observation of a narrow pentaquark state, $P_c(4312)^+$, and of two-peak structure of the $P_c(4450)^+$,"

$\mathcal{P}_c(4312)^+$ was newly discovered; $\mathcal{P}_c(4450)^+$ was split into $\mathcal{P}_c(4440, 4457)^+$; $\mathcal{P}_c(4380)^+$ became obscure.

3. Sci. Bull. **66**, 1278 (2021), *"Evidence of a $J/\psi\Lambda$ structure and observation of excited Ξ^- states in the $\Xi_b^- \to J/\psi\Lambda K^-$ decay,"*

$\mathcal{P}_{cs}(4459)^0$ with strangeness was newly found.





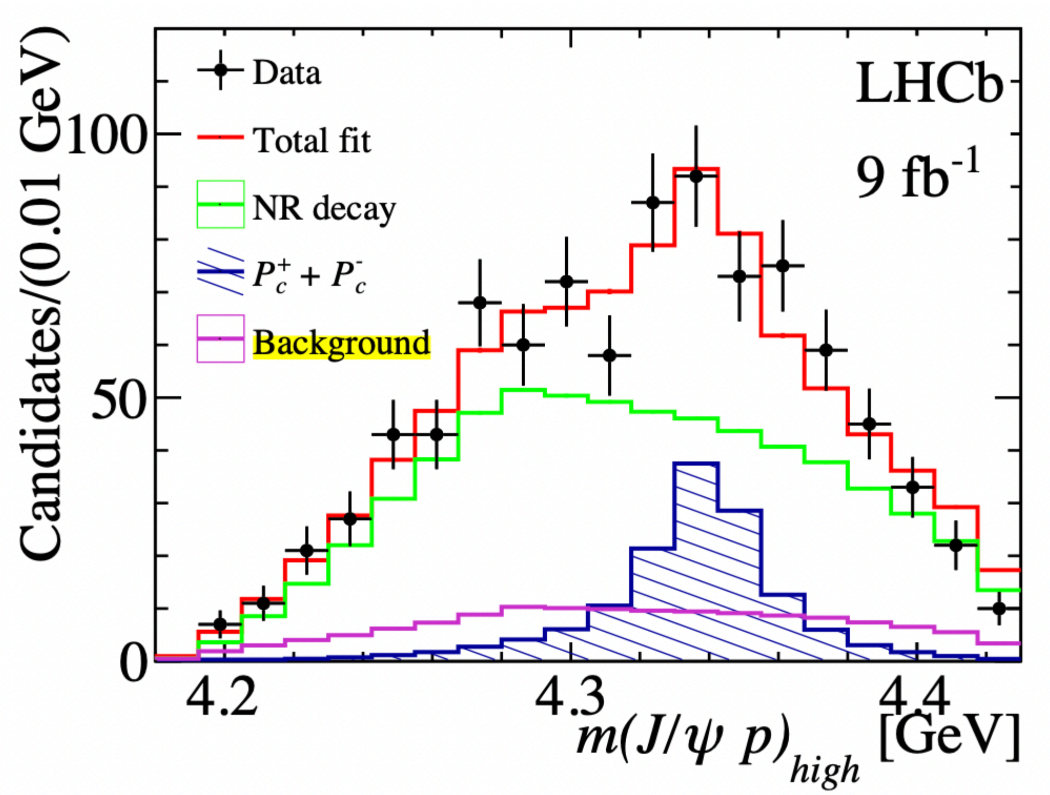
• $B \to J/\psi \mathbf{B}\bar{\mathbf{B}}'$ provides an equally important test bed for studying $\mathcal{P}_{c(s)}$ at LHCb

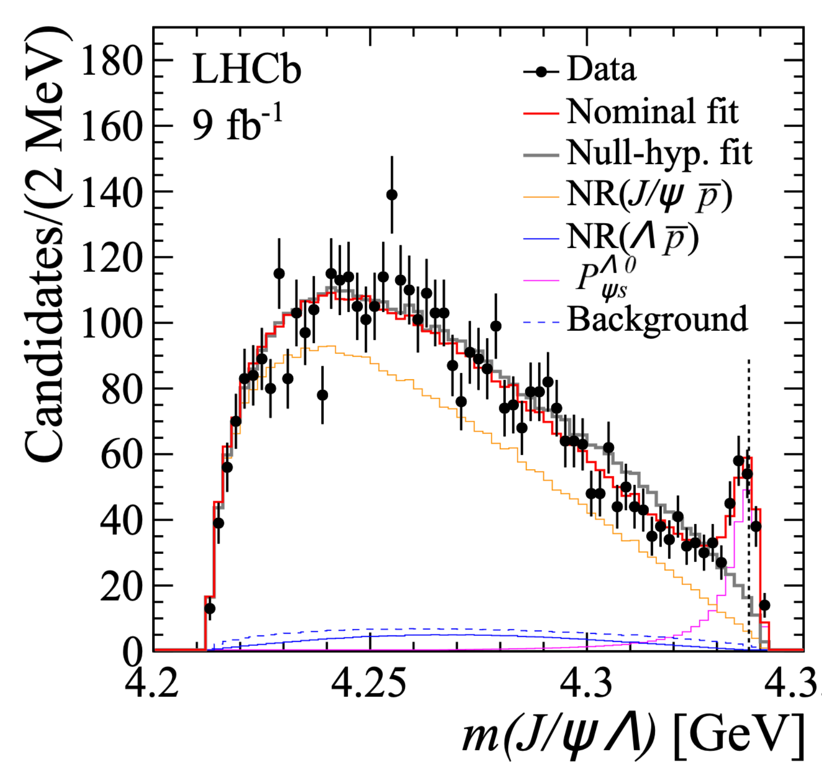
1. PRL128, 062001 (2022), *"Evidence for a new structure in the $J/\psi p$ and $J/\psi \bar{p}$ systems in $B_s^0 \to J/\psi p\bar{p}$ decays,"*

$\mathcal{P}_c^{\pm} \equiv \mathcal{P}_c(4337)^{\pm}$ was observed.

2. PRL131, 031901 (2023), *"Observation of a $J/\psi\Lambda$ Resonance Consistent with a Strange Pentaquark Candidate in $B^- \to J/\psi\Lambda\bar{p}$ Decays,"*

$\mathcal{P}_{cs}^{0} \equiv \mathcal{P}_{cs}(4338)^{0}$ with strangeness was observed.





• Between $\mathbf{B}_b \to J/\psi \mathbf{B} M$ and $B \to J/\psi \mathbf{B}\bar{\mathbf{B}}'$,

no mutual discoveries of $\mathcal{P}_{c(s)}$ states:

• $\mathcal{P}_c(4312)^+$ vs. $\mathcal{P}_c(4337)^+$

1. Simply identical particles (due to poor statistics)

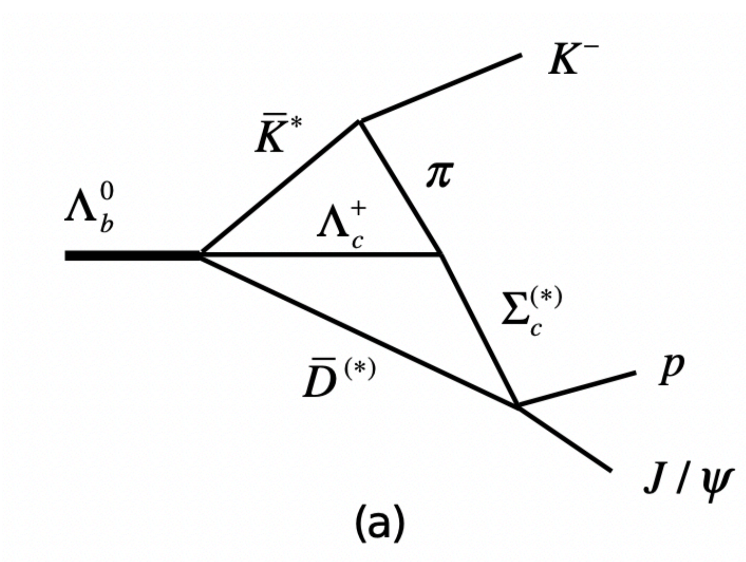
Nakamura, Hosaka, Yamaguchi, PRD104, L091503 (2021)

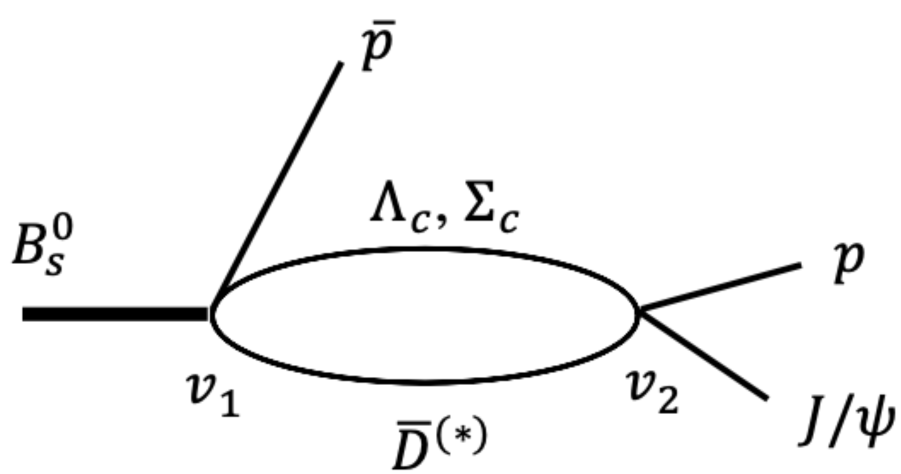
Yan, Peng, Sánchez, Valderrama, EPJC82, 574 (2022)

2. Double triangle mechanism and $\Sigma_c \bar{D}$ one-loop mechanism causing threshold cusps

Nakamura, PRD103, 111503 (2021)

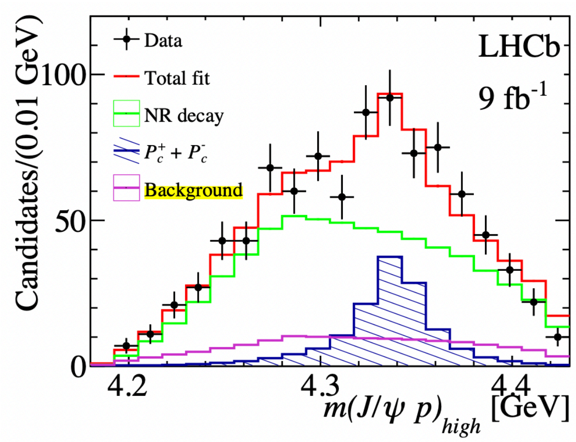
Nakamura, Hosaka, Yamaguchi, PRD104, L091503 (2021)

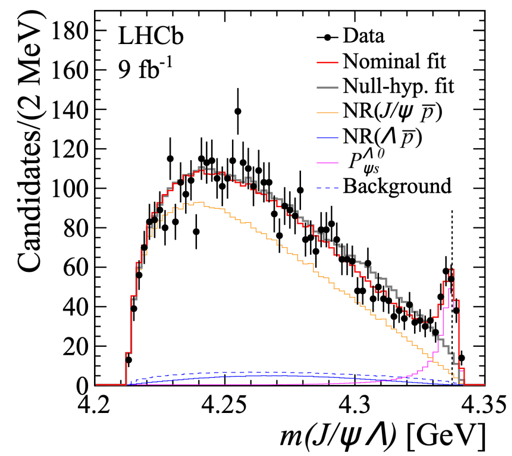




• $\mathcal{P}_c(4440, 4457)^+$ not observed in $\bar{B}_s^0 \to J/\psi p\bar{p}$?

Easy to answer.

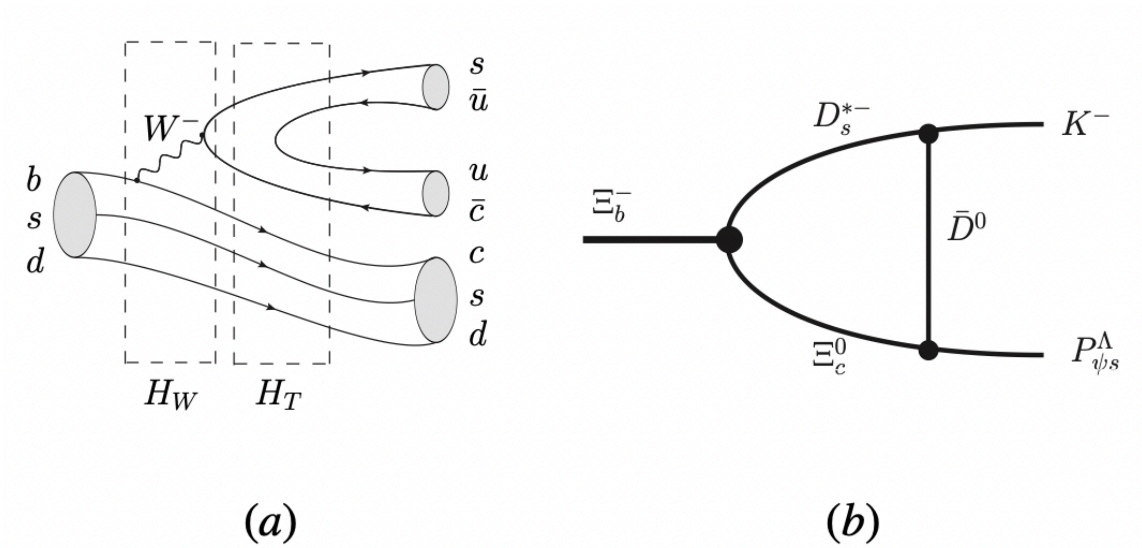


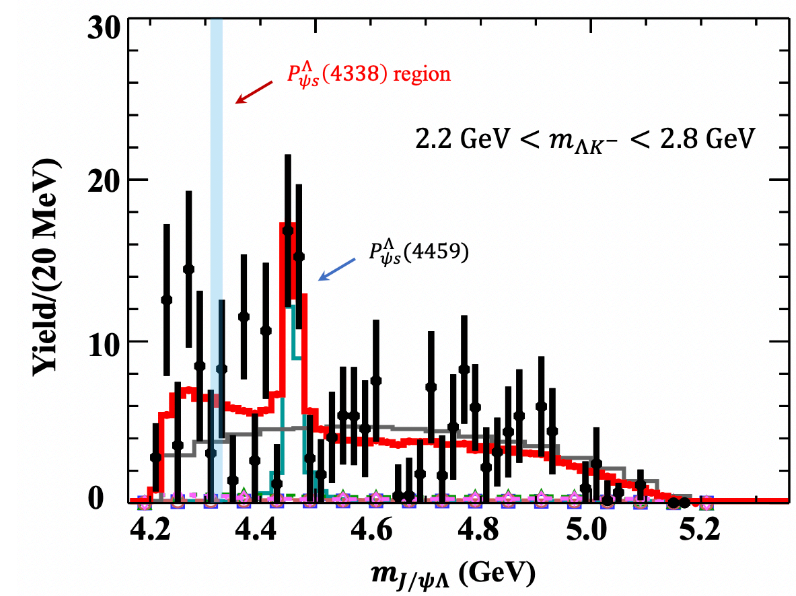


• $\mathcal{P}_{cs}(4459)^0$ vs. $\mathcal{P}_{cs}(4338)^0$

Q. Wu and D. Y. Chen, PRD109, 094003 (2024),

"Production of $P_{\psi s}^{\Lambda}(4338)$ from Ξ_b decay,"





$$\frac{\mathcal{B}(\Xi_b^- \to P_{\psi s}^{\Lambda}(4459)K^- \to J/\psi\Lambda K^-)}{\mathcal{B}(\Xi_b^- \to P_{\psi s}^{\Lambda}(4338)K^- \to J/\psi\Lambda K^-)} = 0.71^{+0.71}_{-0.60}.$$

- Resonant branching fractions:

1. $\mathcal{B}_{\text{res}}(\mathcal{P}_c^{\pm}) \equiv \mathcal{B}(\bar{B}_s^0 \to \bar{p}(\mathcal{P}_c^+ \to)J/\psi p + p(\mathcal{P}_c^- \to)J/\psi\bar{p})$,

$(22.0^{+8.5}_{-4.0} \pm 8.6)\%$ of $\mathcal{B}_{\text{total}}(\bar{B}_s^0 \to J/\psi p\bar{p}) = (3.6 \pm 0.4) \times 10^{-6}$.

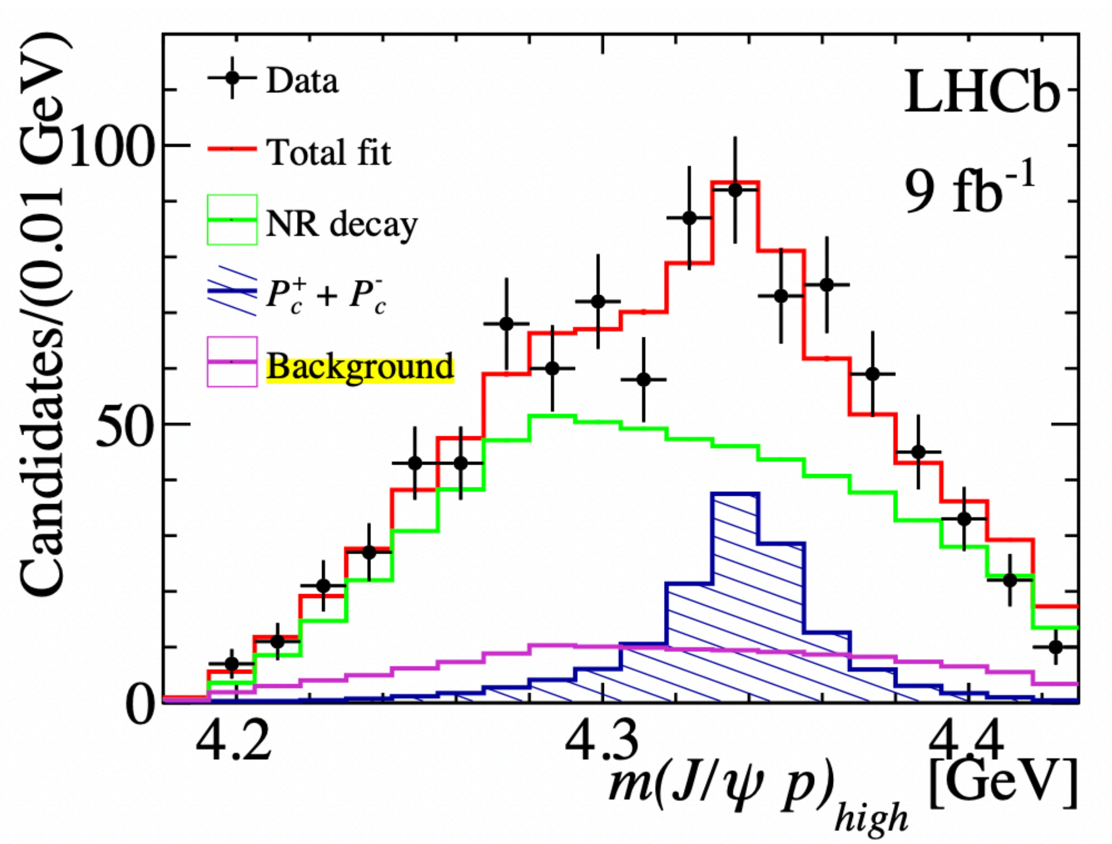
2. $\mathcal{B}_{\text{res}}(\mathcal{P}_{cs}^0) \equiv \mathcal{B}(B^- \to \bar{p}(\mathcal{P}_{cs}^0 \to)J/\psi\Lambda)$,

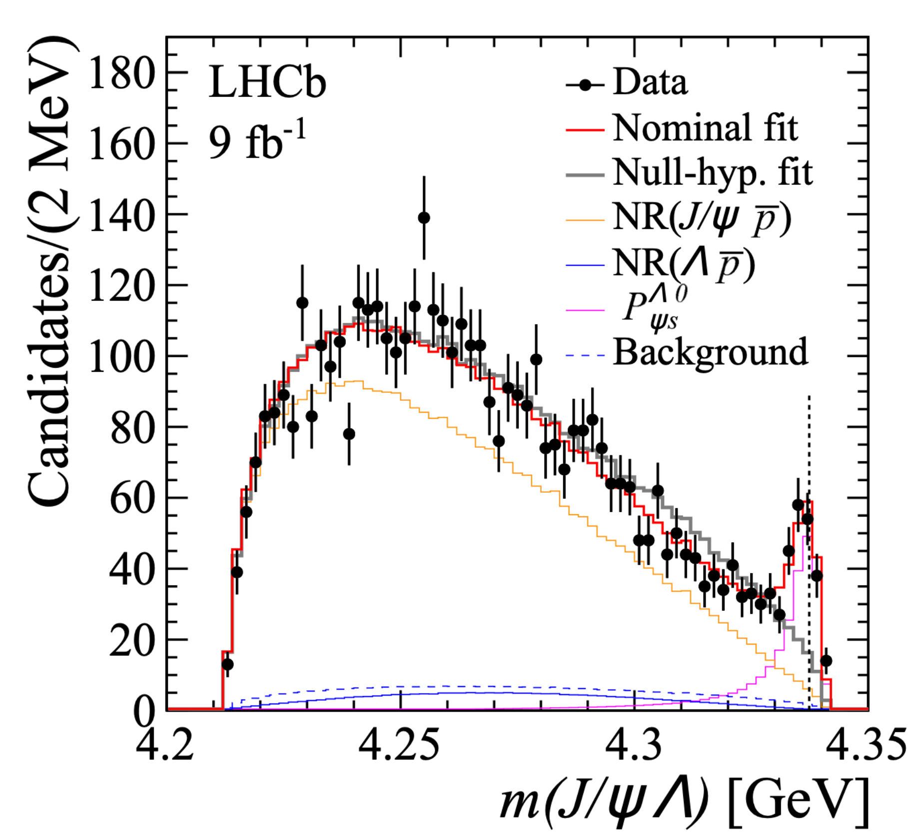
$(12.5 \pm 0.7 \pm 1.9)\%$ of $\mathcal{B}_{\text{total}}(B^- \to J/\psi\Lambda\bar{p}) = (14.6 \pm 1.2) \times 10^{-6}$.

- We thus obtain:

$\mathcal{B}_{\text{res}}(\mathcal{P}_c^{\pm}) = (7.9 \pm 4.4) \times 10^{-7}$,

$\mathcal{B}_{\text{res}}(\mathcal{P}_{cs}^0) = (1.8 \pm 0.3) \times 10^{-6}$.





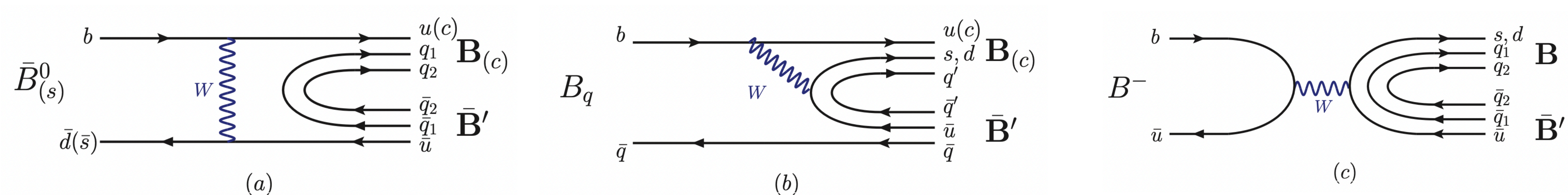
- Explaining $\mathcal{B}_{\rm res}(\mathcal{P}_c^{\pm})$ and $\mathcal{B}_{\rm res}(\mathcal{P}_{cs}^{0})$ helps resolve the confusion.
- Mechanism for $\mathcal{P}_{c(s)}$ production in $B \to \mathcal{P}_{c(s)}\bar{\mathbf{B}}'$
- Short-distance picture: $\bar{B}_s^0 \to \mathcal{P}_c^+\bar{p}$ and $B^- \to \mathcal{P}_{cs}^0\bar{p}$

exotic edition of $\bar{B}_s^0 \to p\bar{p}$ and $B^- \to \Lambda\bar{p}$

with $c\bar{c}$ from intrinsic charm and sea quarks.

- $\mathcal{B}(\bar{B}_s^0 \to \mathcal{P}_c^+\bar{p})$, $\mathcal{B}(B^- \to \mathcal{P}_{cs}^0\bar{p})$ not as small as

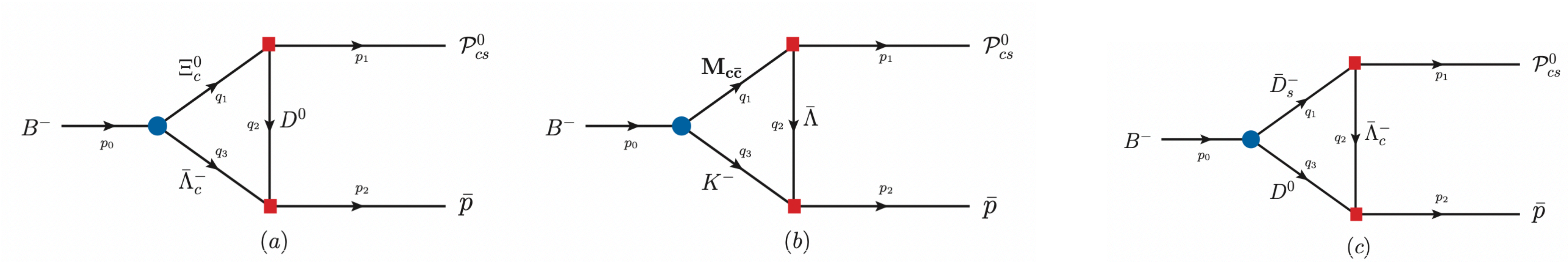
$\mathcal{B}(\bar{B}_s^0 \to p\bar{p}) < 4.4 \times 10^{-9}$, $\mathcal{B}(B^- \to \Lambda\bar{p}) \simeq 2 \times 10^{-7}$.



- Long-distance picture: avoid threshold and chiral suppressions.

• The triangle rescattering mechanism

as the LD final state interaction



• Diagrams similar to Figs. (a, c), once proposed to induce triangle singularity

Burns, Swanson, PLB838, 137715 (2023)

• $B^- \to \mathcal{P}_{cs}^0 \bar{p}$ for illustration

due to available $\mathcal{P}_{cs}^0 \to \Xi_c^0 \bar{D}^0, (\eta_c \Lambda, J/\psi \Lambda), \Lambda_c^+ \bar{D}_s^-$ strong decays:

S1: Ortega, Entem, Fernandez, PLB838, 137747 (2023)

S2: Azizi, Sarac, Sundu, PRD108, 074010 (2023)

S3: Wang and Z. G. Wang, PRD110, 014008 (2024)

• Initial weak decays with $\mathcal{B} \simeq 10^{-3} - 10^{-2}$:

$\mathcal{B}(B^- \to \Xi_c^0 \bar{\Lambda}_c^-) = (7.8^{+2.3}_{-2.0}) \times 10^{-4}$

$\mathcal{B}(B^- \to J/\psi K^-) = (1.020 \pm 0.019) \times 10^{-3}$

$\mathcal{B}(B^- \to \eta_c K^-) = (1.10 \pm 0.07) \times 10^{-3}$

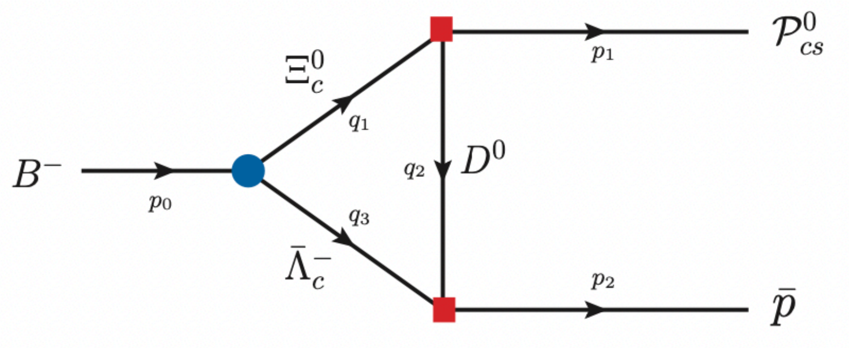
$\mathcal{B}(B^- \to D^0 \bar{D}_s^-) = (9.0 \pm 0.9) \times 10^{-3}$

• Strong decays of $\Lambda_c^+ \to p D^0$ and $\Lambda \to p K^-$:

Duan, Qiu, Ling, Q. Zhao, PRD109, L031507 (2024),

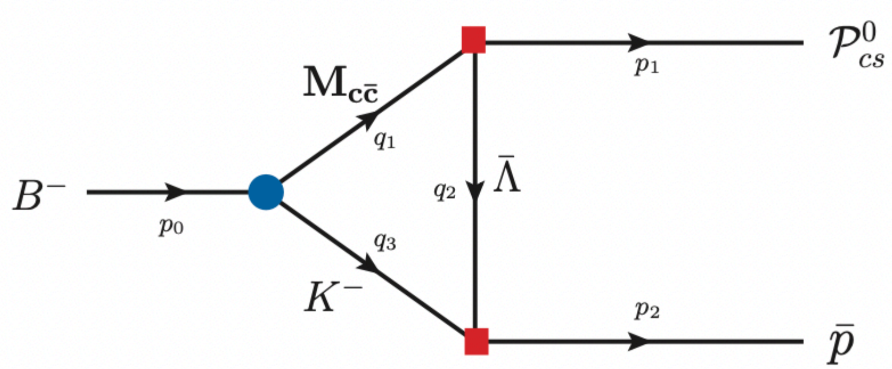
Yang, H. C. Kim, PLB785, 434 (2018)

- **Rescattering amplitudes**



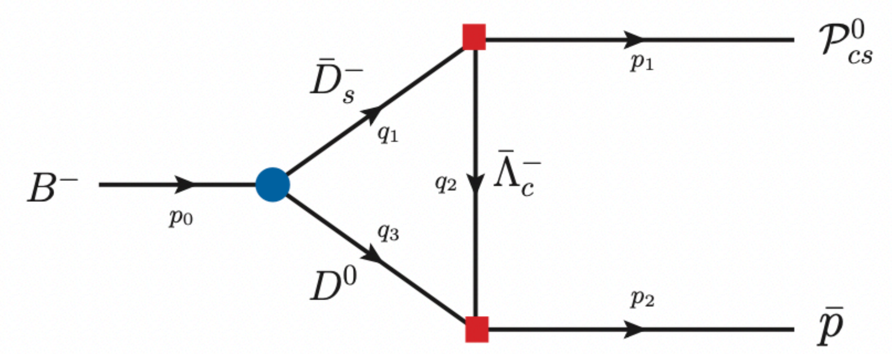
(a)

$$\mathcal{M}_{a1} \equiv \mathcal{M}(B^- \to \Xi_c^0 \bar{\Lambda}_c^-) = \frac{G_F}{\sqrt{2}} V_{cb} V_{cs}^* \bar{u}_{\Xi_c}(F - G\gamma_5) v_{\bar{\Lambda}_c} \,,$$
$$\mathcal{M}_{a2} \equiv \mathcal{M}(\Xi_c^0 \to \mathcal{P}_{cs}^0 D^0) = f_{\Xi_c D} \bar{u}_{\mathcal{P}_{cs}} u_{\Xi_c} \,,$$
$$\mathcal{M}_{a3} \equiv \mathcal{M}(\bar{\Lambda}_c^- \to \bar{p} \bar{D}^0) = g_{pD} \bar{v}_{\bar{\Lambda}_c} \gamma_5 v_{\bar{p}} \,.$$



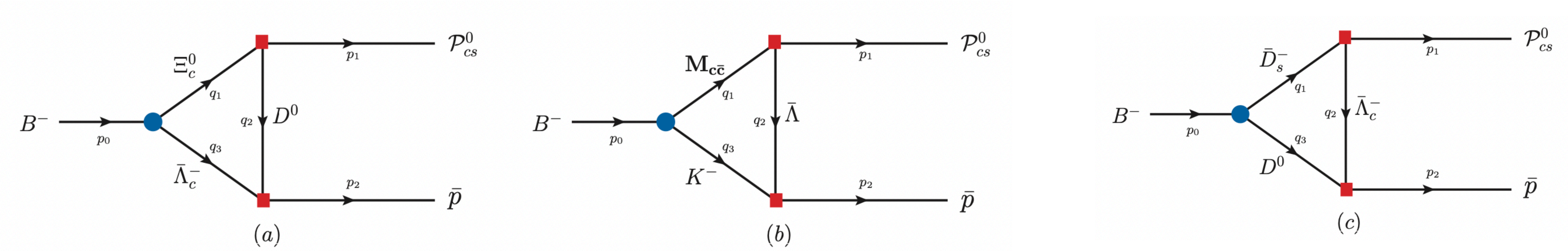
(b)

$$\mathcal{M}_{b1} \equiv \mathcal{M}(B^- \to M_{c\bar{c}} K^-) = \frac{G_F}{\sqrt{2}} V_{cb} V_{cs}^* a_2^{M_{c\bar{c}}} \langle M_{c\bar{c}} | (\bar{c}c) | 0 \rangle \langle K^- | (\bar{s}b) | B^- \rangle \,,$$
$$\mathcal{M}_{b2} \equiv \mathcal{M}(\eta_c \to \mathcal{P}_{cs}^0 \bar{\Lambda}) = f_{\Lambda \eta_c} \bar{u}_{\mathcal{P}_{cs}} v_{\bar{\Lambda}} \,,$$
$$\mathcal{M}'_{b2} \equiv \mathcal{M}(J/\psi \to \mathcal{P}_{cs}^0 \bar{\Lambda}) = \epsilon_\mu \bar{u}_{\mathcal{P}_{cs}} \left[g_{\Lambda J} \gamma^\mu - i \frac{h_{\Lambda J}}{(m_{\mathcal{P}_{cs}} + m_\Lambda)} \sigma^{\mu\nu} q_\nu \right] \gamma_5 v_{\bar{\Lambda}} \,,$$
$$\mathcal{M}_{b3} \equiv \mathcal{M}(\bar{\Lambda} \to \bar{p} K^+) = g_{pK} \bar{v}_{\bar{\Lambda}} \gamma_5 v_{\bar{p}} \,,$$



(c)

$$\mathcal{M}_{c1} \equiv \mathcal{M}(B^- \to D^0 \bar{D}_s^-) = \frac{G_F}{\sqrt{2}} V_{cb} V_{cs}^* a_1^D \langle \bar{D}_s^- | (\bar{s}c) | 0 \rangle \langle D^0 | (\bar{c}b) | B^- \rangle \,,$$
$$\mathcal{M}_{c2} \equiv \mathcal{M}(\bar{D}_s^- \to \mathcal{P}_{cs}^0 \bar{\Lambda}_c^-) = f_{\Lambda_c D_s} \bar{u}_{\mathcal{P}_{cs}} v_{\bar{\Lambda}_c} \,,$$
$$\mathcal{M}_{c3} = \mathcal{M}_{a3} \,,$$



$$\mathcal{M}_i^{(\prime)} = \int \frac{d^4 q_1}{(2\pi)^4} \frac{\mathcal{M}_{i1}\mathcal{M}_{i2}^{(\prime)}\mathcal{M}_{i3}F_i(q_{i2}^2)}{(q_1^2 - m_1{}^2)[(q_1-p_1)^2 - m_2^2][(q_1-p_0)^2 - m_3^2]},$$

- Rescattering amplitudes

$\mathcal{M}_a = \mathcal{M}(B^- \to \Xi_c^0 \bar{\Lambda}_c^- \to \mathcal{P}_{cs}\bar{p}),$

$\mathcal{M}_b = \mathcal{M}(B^- \to \eta_c K^- \to \mathcal{P}_{cs}\bar{p}),$

$\mathcal{M}_b' = \mathcal{M}(B^- \to J/\psi K^- \to \mathcal{P}_{cs}\bar{p}),$

$\mathcal{M}_c = \mathcal{M}(B^- \to D^0 \bar{D}_s^- \to \mathcal{P}_{cs}\bar{p}),$

$F_i(q_2^2) \equiv (\Lambda_{\rm cut}^2 - m_2^2)/(\Lambda_{\rm cut}^2 - q_2^2),$

with $\Lambda_{\rm cut}$ as a universal cutoff parameter.

• Strong decays of $\mathcal{P}_{cs}^0 \to \Xi_c^0 \bar{D}^0, (\eta_c\Lambda, J/\psi\Lambda), \Lambda_c^+ \bar{D}_s^-$

	S1 (Ortega)	S2 (Azizi)	S3 (Wang)
$\Gamma_{\Xi_c D}, f_{\Xi_c D}$	$1.1,\ 0.29^*$	—	—
$\Gamma_{\eta_c\Lambda}, f_{\eta_c\Lambda}$	$1.2,\ 0.15^*$	$3.18 \pm 0.74,\ 0.11 \pm 0.02$	$0.95 \pm 0.05,\ 0.184 \pm 0.048$
$\Gamma_{J\Lambda}, g_{J\Lambda}, h_{J\Lambda}$	$0.6,\ 0.23^*,\ 0.23^*$	$7.22 \pm 1.78,\ (-4.71 \pm 0.52) \times 10^{-5},\ 0.61 \pm 0.07$	$5.21^{+8.00}_{-5.21},\ 0.371 \pm 0.107,\ 0.135 \pm 0.042$
$\Gamma_{\Lambda_c D_s}, f_{\Lambda_c D_s}$	$11.0,\ 0.41^*$	—	—
$\mathcal{B}_{J\Lambda}, \mathcal{B}_{\eta_c\Lambda}$	$(4.3, 8.6) \times 10^{-2}$	$(69 \pm 21, 31 \pm 9) \times 10^{-2}$	$(85, 15) \times 10^{-2}$

S1: quark model approach, $\mathcal{P}_{cs}^0$: 45% of $\Lambda_c \bar{D}_s^-$, 28% of $\Lambda_c \bar{D}_s^{*-}$

$\Gamma_{\rm th} = 13.9$ MeV$\simeq 2\Gamma_{\rm ex} = (7.0 \pm 1.2 \pm 1.3)$ MeV

assuming $g_{J\Lambda} = h_{J\Lambda}$

S2: QCD sum rules, $\mathcal{P}_{cs}^0$: $\Xi_c \bar{D}$ molecule

$\Gamma_{\rm th} \simeq \Gamma_{\eta_c\Lambda} + \Gamma_{J\Lambda} = (10.40 \pm 1.93)$ MeV

$h_{J\Lambda} \gg g_{J\Lambda} \simeq 0$

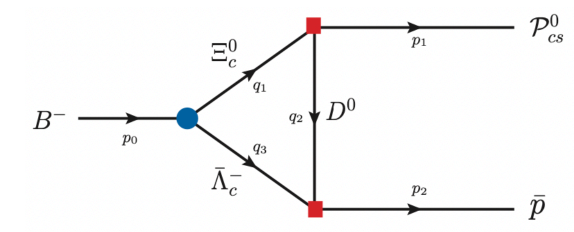
S3: QCD sum rules, $\Xi_c \bar{D}$ molecule

$\Gamma_{\rm th} \simeq \Gamma_{\eta_c\Lambda} + \Gamma_{J\Lambda} = 6.16$ MeV

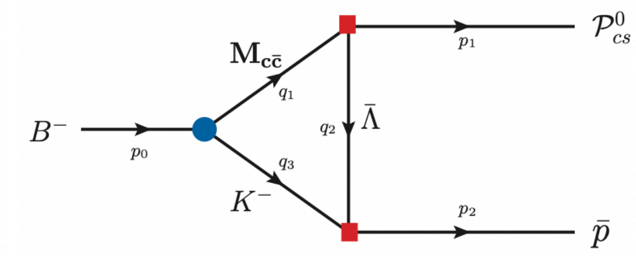
$g_{J\Lambda} \simeq 3h_{J\Lambda}$

• Resonant branching fractions

	S1 (Ortega) [32]	S2 (Azizi) [33]	S3 (Wang) [34]
$\mathcal{B}(B^- \to \Xi_c^0 \bar{\Lambda}_c^- \to \mathcal{P}_{cs}^0 \bar{p})$	$(2.9 \pm 0.8^{+1.1}_{-0.4}) \times 10^{-8}$	—	—
$\mathcal{B}(B^- \to \eta_c K^- \to \mathcal{P}_{cs}^0 \bar{p})$	$(5.2 \pm 0.3^{+0.2}_{-0.3}) \times 10^{-9}$	$(2.8^{+1.1+0.1}_{-0.9-0.2}) \times 10^{-9}$	$(7.8^{+4.6+0.3}_{-3.5-0.4}) \times 10^{-9}$
$\mathcal{B}(B^- \to J/\psi K^- \to \mathcal{P}_{cs}^0 \bar{p})$	$(5.9 \pm 0.1^{+1.7}_{-0.6}) \times 10^{-7}$	$(1.5 \pm 0.3^{+0.5}_{-1.1}) \times 10^{-7}$	$(1.9^{+1.3+0.6}_{-0.9-0.1}) \times 10^{-6}$
$\mathcal{B}(B^- \to D^0 \bar{D}_s^- \to \mathcal{P}_{cs}^0 \bar{p})$	$(6.9 \pm 0.7^{+1.0}_{-1.2}) \times 10^{-6}$	—	—
$\mathcal{B}(B^- \to \mathcal{P}_{cs}^0 \bar{p})$	$(7.5 \pm 0.7^{+1.0}_{-1.2}) \times 10^{-6}$	$(1.5 \pm 0.3^{+0.5}_{-1.1}) \times 10^{-7}$	$(2.0^{+1.3+0.6}_{-0.9-0.1}) \times 10^{-6}$
$\mathcal{B}(B^- \to \mathcal{P}_{cs}^0 \bar{p}, \mathcal{P}_{cs}^0 \to J/\psi\Lambda)$	$(3.2^{+0.5}_{-0.6}) \times 10^{-7}$	$(1.1^{+0.5}_{-0.8}) \times 10^{-7}$	$(1.7^{+1.2}_{-0.8}) \times 10^{-6}$
$\mathcal{B}(B^- \to \mathcal{P}_{cs}^0 \bar{p}, \mathcal{P}_{cs}^0 \to \eta_c\Lambda)$	$(6.5^{+1.1}_{-1.2}) \times 10^{-7}$	$(4.7^{+2.3}_{-3.7}) \times 10^{-8}$	$(3.0^{+2.1}_{-1.4}) \times 10^{-7}$

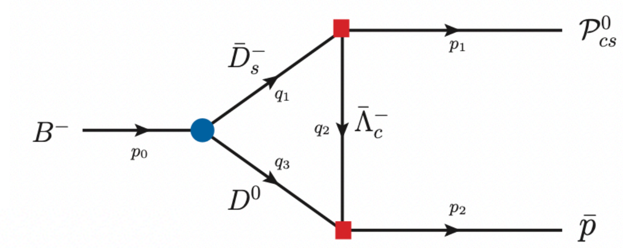


(a)



(b)

$$\mathcal{B}(B^- \to \mathcal{P}_{cs}^0 \bar{p}, \mathcal{P}_{cs}^0 \to M_{c\bar{c}}\Lambda) \simeq \mathcal{B}(B^- \to \mathcal{P}_{cs}^0 \bar{p}) \times \mathcal{B}(\mathcal{P}_{cs}^0 \to M_{c\bar{c}}\Lambda)$$



(c)

• Dominant contribution

S1: $\mathcal{B}(B^- \to D^0 \bar{D}_s^- \to \mathcal{P}_{cs}^0 \bar{p}) = (6.9 \pm 0.7^{+1.0}_{-1.2}) \times 10^{-6}$.

S2: $\mathcal{B}(B^- \to J/\psi K^- \to \mathcal{P}_{cs}^0 \bar{p}) = (1.5 \pm 0.3^{+0.5}_{-1.1}) \times 10^{-7}$.

S3: $\mathcal{B}(B^- \to J/\psi K^- \to \mathcal{P}_{cs}^0 \bar{p}) = (1.9^{+1.3+0.6}_{-0.9-0.1}) \times 10^{-6}$,

leading to $\mathcal{B}(B^- \to \bar{p}(\mathcal{P}_{cs}^0 \to) J/\psi\Lambda) = (1.7^{+1.2}_{-0.8}) \times 10^{-6}$

to interpret the data: $\mathcal{B}(B^- \to \bar{p}(\mathcal{P}_{cs}^0 \to) J/\psi\Lambda) = (1.8 \pm 0.3) \times 10^{-6}$

- The feasibility of these models that studies pentaquarks depends on whether the predicted cousin pentaquarks can be discovered in future measurements.
- In our new findings, potential triangle rescattering effects can also be used to test models.
- The approach of QCD sum rules in S3 (Wang) appears to provide suitable information.

Summary

• We investigated $B^- \to \mathcal{P}^0_{cs}\bar{p}, \mathcal{P}^0_{cs} \to J/\psi\Lambda$, with $\mathcal{P}^0_{cs} \equiv \mathcal{P}_{cs}(4338)^0$

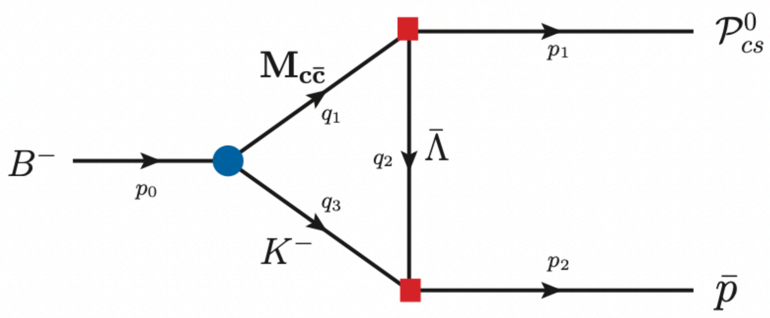
a hidden charm pentaquark candidate.

• By interpreting $\mathcal{P}^0_{cs}$ as the $\Xi_c\bar{D}$ molecule

strongly decaying into $J/\psi\Lambda$ and $\eta_c\Lambda$,

we discover a dominant triangle rescattering effect.

$M_{c\bar{c}} = J/\psi$



(b)

•We thus calculated

$\mathcal{B}(B^- \to \mathcal{P}^0_{cs}\bar{p}, \mathcal{P}^0_{cs} \to J/\psi\Lambda) = (1.7^{+1.2}_{-0.8}) \times 10^{-6}$,

consistent with the measured data.

Thank You