

Rescattering effects in doubly heavy baryon decays

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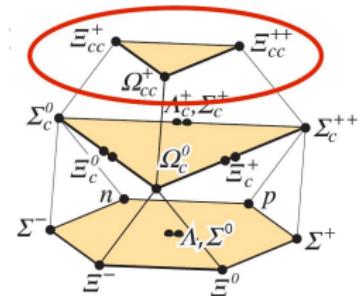
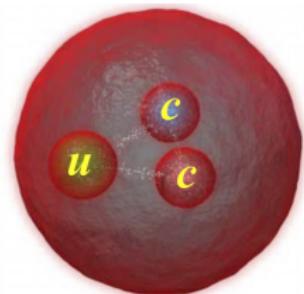
For our next work

Summary

Introduction

- ▶ The elementary structure of doubly heavy baryons
 - ▶ The diquark picture $[QQ'] q$
 - ▶ Description for diquark interaction in NRQCD
 - ▶ The light quark interact with heavy diquark in HQET
- ▶ The spectroscopy of doubly heavy baryons
 - ▶ The prediction in constituent quark model and QCD

Baryons	quarks	$I(J^P)$
$\Xi_{cc}^{++}, \Xi_{bc}^{+}, \Xi_{bb}^0$	ccu/bcu/bbu	$\frac{1}{2}(\frac{1}{2}^+)$
$\Xi_{cc}^+, \Xi_{bc}^0, \Xi_{bb}^-$	ccd/bcd/bbd	$\frac{1}{2}(\frac{1}{2}^+)$
$\Omega_{cc}^+, \Omega_{bc}^0, \Omega_{bb}^-$	ccs/bcs/bbs	$0(\frac{1}{2}^+)$



Introduction

- ▶ The prediction for Ξ_{cc}^{++} decay
 - ▶ We recommend the processes of $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$ and $\Xi_c^+ \pi^+$ as the first priority for experiments to search for the doubly heavy baryons.
- ▶ Study the non-leptonic weak decay of doubly heavy baryons
 - ▶ No satisfactory methods
 - ▶ We develop a theoretical method to calculate these non-leptonic decay modes.
 - ▶ Factorization approach for T, C diagram
 - ▶ Rescattering effects for C, C', E_1, E_2 and B diagram
- ▶ We have calculated all the decay modes of $\mathcal{B}_{cc} \rightarrow \mathcal{B}_c P$.

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Summary

The prediction for Ξ_{cc}^{++} decay

- ▶ The SELEX experiment report they found the doubly charmed baryons Ξ_{cc}^+ via the process of $\Xi_{cc}^+ \rightarrow \Lambda_c^+ K^- \pi^+$, but it have not been confirmed by other experiments.
- ▶ We think Ξ_{cc}^{++} can be easily found
 - ▶ First, the life time of Ξ_{cc}^{++} longer than Ξ_{cc}^+ about three times:

$$\mathcal{R}_\tau = \frac{\tau_{\Xi_{cc}^+}}{\tau_{\Xi_{cc}^{++}}} = 0.25 \sim 0.37 \quad \text{arXiv:1703.09086}$$

then, the branching ratios of Ξ_{cc}^{++} decays larger than Ξ_{cc}^+ about three times.

- ▶ $\Xi_{cc}^{++} \rightarrow \Sigma_c^{++} \bar{K}^{*0} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$ and $\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+$ have a relatively large branching fractions.
- ▶ Next, we develop a theoretical method to compute the non-leptonic two body decay amplitudes of doubly heavy baryons.

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Looking for Ξ_{cc}^{++}

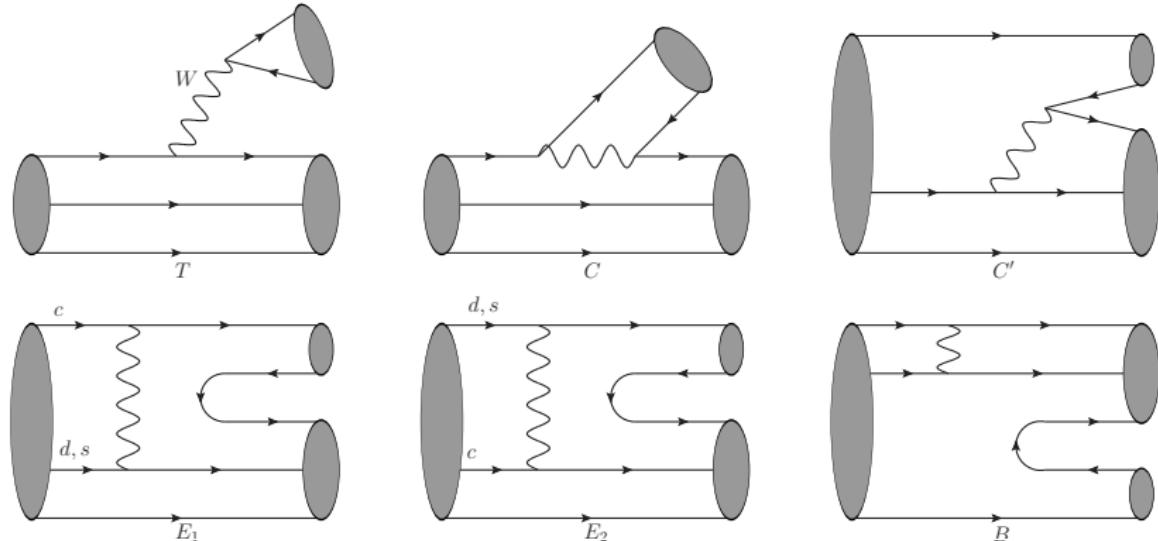
The elementary calculations

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Summary

The analysis of topology classification

- Topologies of two-body non-leptonic charmed baryon decays:



- Hierarchy in heavy quark expansion: Leibovich, Ligeti, Stewart and Wise, PLB 586,337 (2004)
 SCET: $|C/T| \sim |C'/T| \sim |E/T| \sim O(\Lambda_{QCD}/m_Q)$, $|B/E| \sim O(\Lambda_{QCD}/m_Q)$,
 for b decay: $O(\Lambda_{QCD}/m_Q) \sim 0.3$, c decay: $O(\Lambda_{QCD}/m_Q) \sim 1$.

The short distance contributions of T and C

- The weak vertices $M(\mathcal{B}_{cc} \rightarrow B'_c P)$ and $M(\mathcal{B}_{cc} \rightarrow B'_c V)$ via T or C topology decays has been parameterized as

$$\begin{aligned} M(\mathcal{B}_{cc} \rightarrow \mathcal{B}'_c P) &= i \bar{u}_{B'}(A + B\gamma_5)u_B, \\ M(\mathcal{B}_{cc} \rightarrow \mathcal{B}'_c V) &= \epsilon^{*\mu} \bar{u}_{B'}(A_1\gamma_\mu\gamma_5 + A_2\frac{p'_\mu}{M}\gamma_5 + B_1\gamma_\mu + B_2\frac{p'_\mu}{M})u_B \end{aligned} \quad (1)$$

and

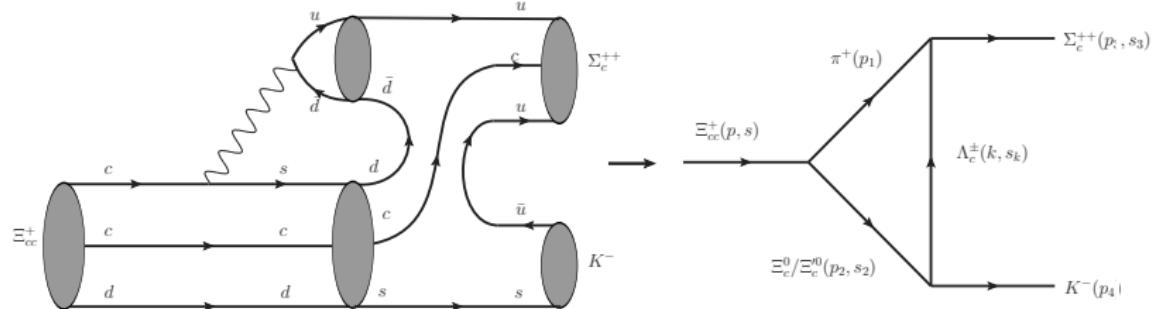
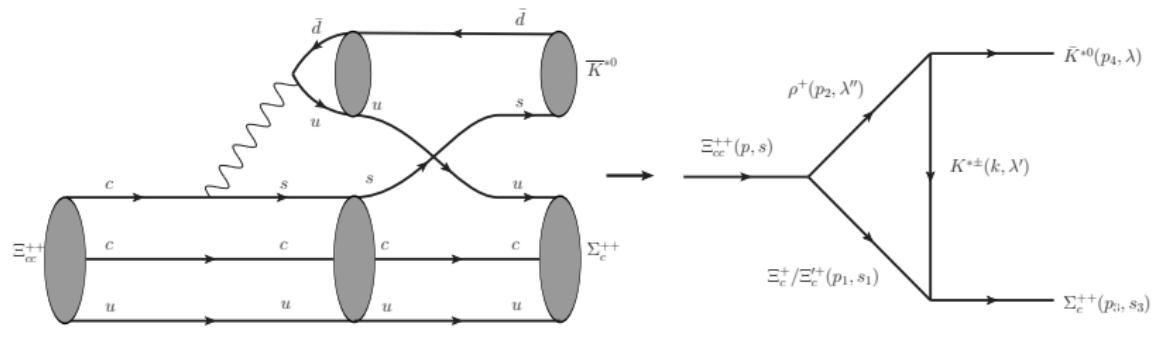
$$\begin{aligned} A &= \lambda f_P(M - M')f_1(m^2), \quad B = \lambda f_P(M + M')g_1(m^2), \\ A_1 &= -\lambda f_V m(g_1(m^2) + g_2(m^2)\frac{M - M'}{M}), \quad A_2 = -2\lambda f_V m g_2(m^2), \\ B_1 &= \lambda f_V m(f_1(m^2) - f_2(m^2)\frac{M + M'}{M}), \quad B_2 = 2\lambda f_V m f_2(m^2) \end{aligned} \quad (2)$$

where $\lambda = \frac{G_F}{\sqrt{2}} V_{CKM} a_1(a_2)$, m is the mass of pseudoscalar or vector meson. ϵ^μ is the polarization vector of the vector meson. We take the form factor from W. Wang, F. S. Yu, Z. X. Zhao, arXiv:1707.02834.

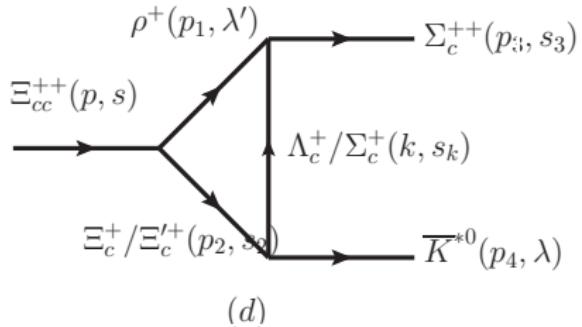
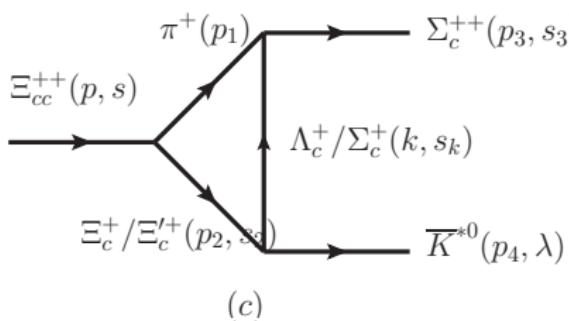
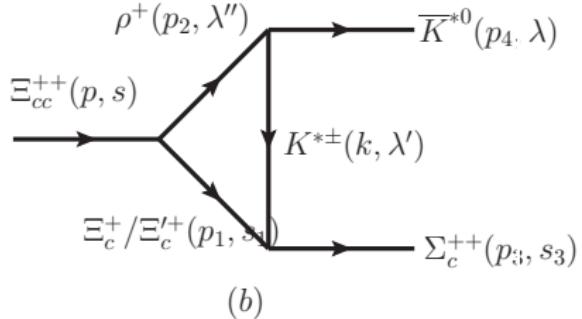
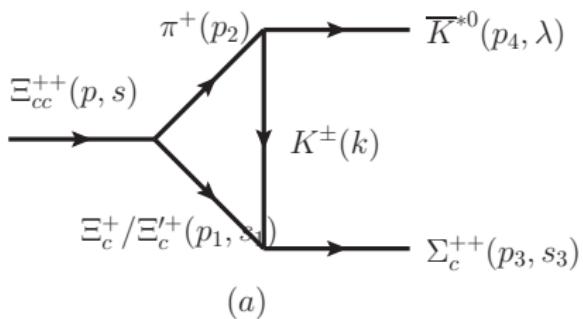
Rescattering mechanism

- Rescattering mechanism for C and E_1

$$a_2(\mu = m_c = 1.3 \text{ GeV}) = -0.02 \text{ for } C \text{ short-distance contributions}$$

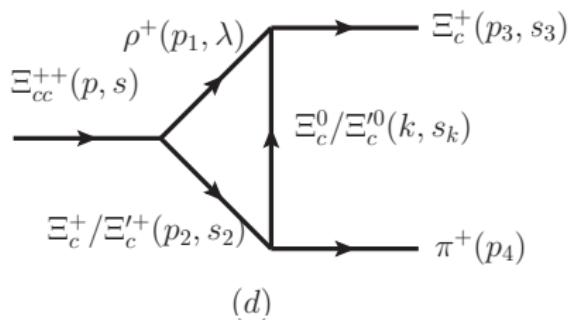
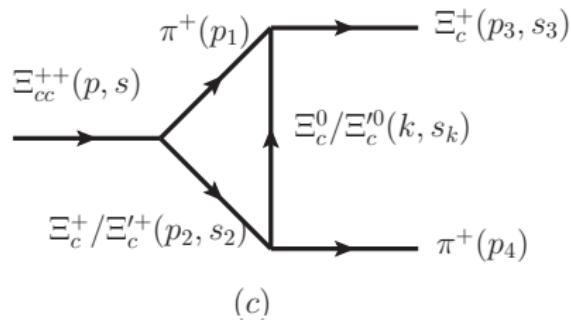
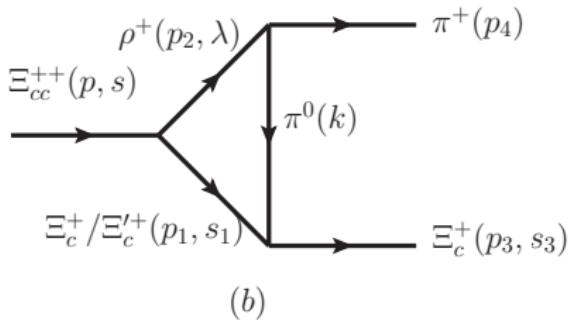
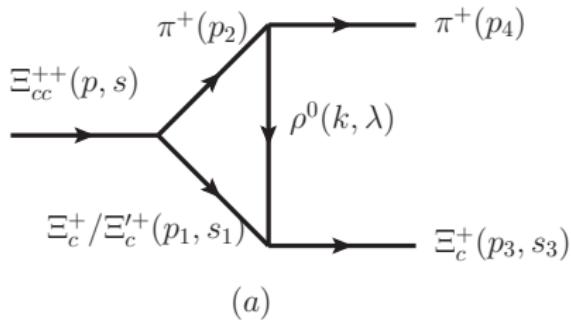


$$\Xi_{cc}^{++} \rightarrow \Sigma_c^{++} \bar{K}^{*0} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+ \quad V_{cs}^* V_{ud} C$$



$$\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+$$

$$V_{cs}^* V_{ud} (T + C')$$

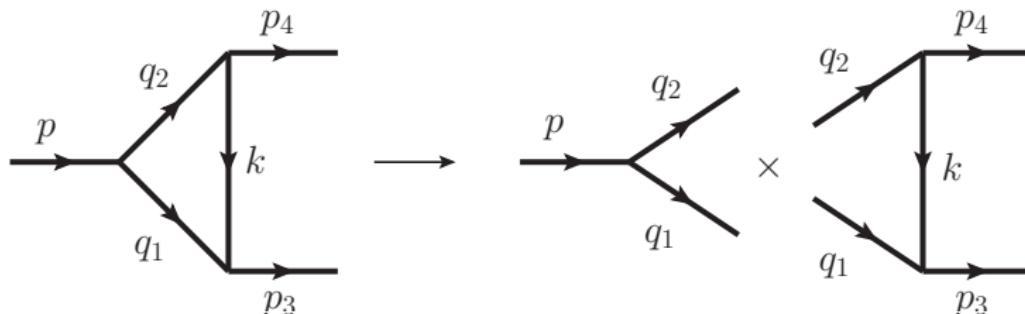


The optical theorem

- For dealing with the divergence, we adopt Optical theorem to calculate the imaginary part of the amplitudes.

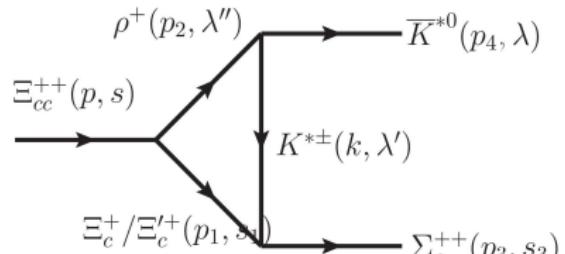
$$\text{Abs}(M(p \rightarrow p_3 p_4)) = \frac{1}{2} \sum_j \left(\prod_{k=1}^j \int \frac{d^3 \vec{q}}{(2\pi)^3 2E_k} \right) (2\pi)^4 \delta^4(p - \sum_{k=1}^j q_k) \times M(p \rightarrow \{q_k\}) T^*(p_3 p_4 \rightarrow \{q_k\}). \quad (3)$$

- Cutkosky cutting rule



Some computational details

$$\Xi_{cc}^{++} \rightarrow \Sigma_c^{++} \bar{K}^{*0}$$



$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{VPP} + \mathcal{L}_{VVV} + \mathcal{L}_{PB_cB_c} + \mathcal{L}_{VB_cB_c},$$

$$\begin{aligned} \mathcal{L}_{\rho K^* K^*} = & \frac{i}{\sqrt{2}} g_{\rho\rho\rho} \left[\left(\partial^\nu K^{*0\mu} K_\mu^{*-} - K_\mu^{*0} \partial^\nu K^{*-\mu} \right) \rho_\nu^+ \right. \\ & \left. + \left(\partial^\nu K^{*-\mu} \rho_\mu^+ - K_\mu^{*-} \partial^\nu \rho^{+\mu} \right) K_\nu^{*0} + \left(\partial^\nu \rho^{+\mu} K_\mu^{*0} - \rho_\mu^+ \partial^\nu K^{*0\mu} \right) K_\nu^{*-} \right], \end{aligned}$$

$$\mathcal{L}_{\Sigma_c \Xi_c K^*} = f_1^{\Sigma_c \Xi_c K^*} \Sigma_c^{++} \gamma_\mu K^{*+\mu} \Xi_c^+ + \frac{f_2^{\Sigma_c \Xi_c K^*}}{m_{\Sigma_c} + m_{\Xi_c}} \Sigma_c^{++} \sigma^{\mu\nu} \partial_\mu K_\nu^{*+} \Xi_c^+,$$

$$\begin{aligned} \langle \bar{K}^{*0} K^{*+} | i \mathcal{L}_{\rho K^* K^*} | \rho^+ \rangle = & -ig_{\rho\rho\rho}/\sqrt{2} \left[\epsilon^{*\mu}(k, \lambda') \epsilon_\mu(p_2, \lambda'') \epsilon_\nu^*(p_4, \lambda) (2p_2^\nu) \right. \\ & \left. + \epsilon^{*\mu}(p_4, \lambda) \epsilon_\mu^*(k, \lambda') \epsilon_\nu(p_2, \lambda'') (2p_4^\nu - p_2^\nu) - \epsilon^{*\mu}(p_4, \lambda) \epsilon_\mu(p_2, \lambda'') \epsilon_\nu^*(k, \lambda') (p_2^\nu + p_4^\nu) \right], \end{aligned}$$

$$\langle \Sigma_c^{++} | i \mathcal{L}_{\Sigma_c \Xi_c K^*} | \Xi_c^+ K^{*+} \rangle = \epsilon^\mu i(k, \lambda) \bar{u}(p_3, s_3) \left(f_1^{\Sigma_c \Xi_c K^*} \gamma_\mu + \frac{if_2^{\Sigma_c \Xi_c K^*}}{m_{\rho 1} + m_{\rho 3}} \sigma_{\mu\nu} k^\nu \right) u(p_1, s_1).$$

Some computational details

$$\begin{aligned}
\text{Abs}(b) = & \frac{1}{2} \sum_{s_1, \lambda', \lambda''} \int \frac{d^3 \vec{p}_1}{(2\pi)^3 2E_1} \frac{d^3 \vec{p}_2}{(2\pi)^3 2E_2} (2\pi)^4 \delta^4(p - p_1 - p_2) i\bar{u}(p_3, s_3) \\
& \times \left(f_1^{\Sigma_c \Xi_c K^*} \gamma_\alpha - \frac{i f_2^{\Sigma_c \Xi_c K^*}}{m_{p_1} + m_{p_3}} \sigma_{\alpha\beta} k^\alpha \right) u(p_1, s_1) \epsilon^\alpha(k, \lambda') \frac{F^2(t, m_{K^*})}{t - m_{K^*}^2} (-i \frac{g_{\rho\rho\rho}}{\sqrt{2}}) \\
& \times \left[\epsilon^{*\mu}(k, \lambda') \epsilon_\mu(p_2, \lambda'') \epsilon_\nu^*(p_4, \lambda) (2p_2^\nu) + \epsilon^{*\mu}(p_4, \lambda) \epsilon_\mu^*(k, \lambda') \epsilon_\nu(p_2, \lambda'') (2p_4^\nu - p_2^\nu) \right. \\
& \quad \left. + \epsilon^{*\mu}(p_4, \lambda) \epsilon_\mu(p_2, \lambda'') \epsilon_\nu^*(k, \lambda') (-p_2^\nu - p_4^\nu) \right] \\
& \times \epsilon^{*\delta}(p_2, \lambda'') \bar{u}(p_1, s_1) (A_1 \gamma_\delta \gamma_5 + A_2 \frac{p_{1\delta}}{m_p} \gamma_5 + B_1 \gamma_\delta + B_2 \frac{p_{1\delta}}{m_p}) u(p, s) \\
= & \int \frac{|\vec{p}| \sin\theta d\theta}{16\pi m_{\Xi_{cc}}} i(-ig_{\rho\rho\rho}) \bar{u}(p_3, s_3) \left(f_1^{\Sigma_c \Xi_c K^*} \gamma_\alpha - \frac{i f_2^{\Sigma_c \Xi_c K^*}}{m_{p_1} + m_{p_3}} \sigma_{\alpha\beta} k^\alpha \right) (\not{p}_1 + m_{p_1}) \\
& \times \left[(-g^{\mu\alpha} + \frac{k^\mu k^\alpha}{m_{K^*}^2}) (-g_{\mu\delta} + \frac{p_{2\mu} p_{2\delta}}{m_p^2}) \epsilon_\nu^*(p_4, \lambda) (2p_2^\nu) + \epsilon_\mu^*(p_4, \lambda) (-g^{\mu\alpha} + \frac{k^\mu k^\alpha}{m_{K^*}^2}) \right. \\
& \quad \left. (-g_{\nu\delta} + \frac{p_{2\nu} p_{2\delta}}{m_p^2}) (2p_4^\nu - p_2^\nu) + \epsilon_\mu^*(p_4, \lambda) (-g^{\nu\alpha} + \frac{k^\nu k^\alpha}{m_{K^*}^2}) (-g_{\mu\delta} + \frac{p_{2\mu} p_{2\delta}}{m_p^2}) \right. \\
& \quad \left. (-p_{2\nu} - p_{4\nu}) \right] (A_1 \gamma^\delta \gamma_5 + A_2 \frac{p_1^\delta}{m_p} + B_1 \gamma^\delta + B_2 \frac{p_1^\delta}{m_p}) u(p, s) \frac{F^2(t, m_{K^*})}{t - m_{K^*}^2}
\end{aligned}$$

The theoretical uncertainty

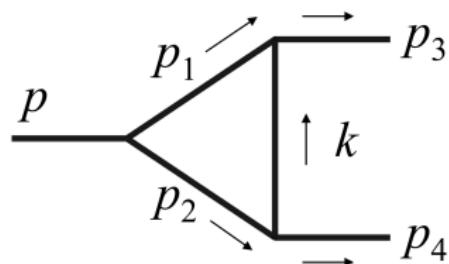
- ▶ Strong couplings between hadrons
 - large ambiguities in literatures refer arXiv:1703.09086
- ▶ off-shell effects of intermediate states

$$F(t, m) = \left(\frac{\Lambda^2 - m^2}{\Lambda^2 - t} \right)^n, \quad t = (p_3 - p_1)^2, \quad n = 1$$

where $\Lambda = m_{\text{exc}} + \eta \Lambda_{QCD}$. Cheng,Chua,Soni,PRD 71, 014030(2005)

- ▶ Results are very sensitive to the value of η

- ▶ No first-principle calculations for η
- ▶ We take η from 1.0 to 2.0



Results analysis

$$\mathcal{B}(\Xi_{cc}^{++} \rightarrow \Sigma_c^{++}(2455)\bar{K}^{*0}) = \left(\frac{\tau_{\Xi_{cc}^{++}}}{300 \text{ fs}} \right) \times (3.3 \sim 20.6)\%$$

Branching fractions of Ξ_{cc}^{++} and Ξ_{cc}^+ decays with the long-distance contributions, relative to that of $\Xi_{cc}^{++} \rightarrow \Sigma_c^{++}(2455)\bar{K}^{*0}$.

Baryons	Modes	amplitudes	\mathcal{B}_{LD}
$\Xi_{cc}^{++}(ccu)$	$\Sigma_c^{++}(2455)\bar{K}^{*0}$	$\lambda_{sd} C$	defined as 1
	pD^{*+}	$\lambda_d C'$	0.04
	pD^+	$\lambda_d C'$	0.0008
$\Xi_{cc}^+(ccd)$	$\Lambda_c^+ \bar{K}^{*0}$	$\lambda_{sd}(C + E_1)$	$(\mathcal{R}_\tau/0.3) \times 0.22$
	$\Sigma_c^{++}(2455)K^-$	$\lambda_{sd} E_1$	$(\mathcal{R}_\tau/0.3) \times 0.008$
	$\Xi_c^+ \rho^0$	$\frac{1}{\sqrt{2}} \lambda_{sd}(C' - E_2)$	$(\mathcal{R}_\tau/0.3) \times 0.04$
	ΛD^+	$\lambda_{sd}(C' + B)$	$(\mathcal{R}_\tau/0.3) \times 0.004$
	pD^0	$\lambda_d B$	$(\mathcal{R}_\tau/0.3) \times 0.002$

Ξ_{cc}^{++} and Ξ_{cc}^+ decays

Branching ratios for the Ξ_{cc}^{++} and $\Xi_{cc}^+ \rightarrow \mathcal{B}_c P$ decays in units of 10^{-3} .

Par	Modes	$\mathcal{B}(\text{LD})$	$\mathcal{B}(\text{SD})$	Modes	$\mathcal{B}(\text{LD})$	$\mathcal{B}(\text{SD})$
Ξ_{cc}^{++}	$\Lambda_c^+ \pi^+$	$3.96 \sim 4.30$	3.86	$\Sigma_c^+ \pi^+$	$2.44 \sim 2.61$	2.48
	$\Xi_c^+ \pi^+$	$71.5 \sim 107$	67.6	$\Xi_c'^+ \pi^+$	$47.4 \sim 51.9$	47.1
	$\Lambda_c^+ K^+$	$0.33 \sim 0.34$	0.32	$\Sigma_c^+ K^+$	$0.18 \sim 0.22$	0.17
	$\Xi_c^+ K^+$	$5.35 \sim 5.83$	5.38	$\Xi_c'^+ K^+$	$3.05 \sim 3.23$	3.03
	$\Sigma_c^{++} \bar{K}^0$	$4.05 \sim 27.5$	0.015	$\Sigma_c^{++} K^0$	$0.011 \sim 0.088$	4.4×10^{-5}
Ξ_{cc}^+	$\Sigma_c^{++} \pi^0$	$0.25 \sim 1.89$	6.3×10^{-4}	$\Sigma_c^+ \pi^0$	$0.137 \sim 0.88$	2.1×10^{-4}
	$\Xi_c^+ \pi^0$	$11.5 \sim 74.4$		$\Xi_c'^+ \pi^0$	$1.08 \sim 6.42$	
	$\Lambda_c^+ K^0$	$0.012 \sim 0.10$	2.7×10^{-5}	$\Sigma_c^+ K^0$	$0.020 \sim 0.16$	1.9×10^{-5}
	$\Lambda_c^+ \bar{K}^0$	$1.18 \sim 8.81$	0.0096	$\Sigma_c^+ \bar{K}^0$	$5.46 \sim 37.0$	0.0051
	$\Xi_c^+ K^0$	$0.10 \sim 0.65$		$\Xi_c'^+ K^0$	$0.044 \sim 0.30$	
	$\Xi_c^0 \pi^+$	$26.0 \sim 39.1$	22.4	$\Xi_c'^0 \pi^+$	$15.5 \sim 15.7$	15.6
	$\Sigma_c^0 \pi^+$	$1.86 \sim 2.57$	1.65	$\Sigma_c^0 K^+$		0.115
	$\Xi_c^0 K^+$	$1.79 \sim 1.83$	1.78	$\Xi_c'^0 K^+$	$1.04 \sim 1.21$	1.00
	$\Omega_c^0 K^+$	$0.16 \sim 0.94$		$\Sigma_c^{++} \pi^-$	$0.014 \sim 0.088$	
	$\Sigma_c^{++} K^-$	$0.30 \sim 2.12$				

Ω_{cc}^+ decays

Branching ratios for the $\Omega_{cc}^+ \rightarrow \mathcal{B}_c P$ decays in units of 10^{-3} .

Modes	$\mathcal{B}(\text{LD})$	$\mathcal{B}(\text{SD})$	Modes	$\mathcal{B}(\text{LD})$	$\mathcal{B}(\text{SD})$
$\Lambda_c^+ \pi^0$	$5.7(10^{-4}) \sim 0.0042$		$\Sigma_c^+ \pi^0$	$2.2(10^{-4}) \sim 0.0015$	
$\Xi_c^+ \pi^0$	$0.11 \sim 0.63$		$\Xi_c'^+ \pi^0$	$0.015 \sim 0.14$	
$\Lambda_c^+ \bar{K}^0$	$0.015 \sim 0.099$		$\Sigma_c^+ \bar{K}^0$	$0.006 \sim 0.037$	
$\Xi_c^+ K^0$	$0.0027 \sim 0.020$	$2.1(10^{-5})$	$\Xi_c'^+ K^0$	$0.03 \sim 0.2$	$1.2(10^{-5})$
$\Xi_c^+ \bar{K}^0$	$2.0 \sim 12.4$	0.00725	$\Xi_c'^+ \bar{K}^0$	$3.1 \sim 18.8$	0.00416
$\Xi_c^0 \pi^+$	$0.99 \sim 1.04$	0.98	$\Xi_c'^0 \pi^+$	$0.73 \sim 0.92$	0.69
$\Sigma_c^0 \pi^+$	$3.9(10^{-4}) \sim 0.003$		$\Omega_c^0 \pi^+$		26.0
$\Xi_c^0 K^+$	$0.082 \sim 0.084$	0.081	$\Xi_c'^0 K^+$	$0.047 \sim 0.048$	0.047
$\Omega_c^0 K^+$	$1.68 \sim 2.07$	1.61	$\Sigma_c^{++} \pi^-$	$5.6(10^{-4}) \sim 0.0042$	
$\Sigma_c^{++} K^-$	$0.0072 \sim 0.052$				

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- ▶ To calculate all the final states of non-leptonic two-body decays of the doubly charmed baryon \mathcal{B}_{cc} in our theoretical method.
 - ▶ all $\mathcal{B}_{cc} \rightarrow \mathcal{B}_c V$
 - ▶ all $\mathcal{B}_{cc} \rightarrow \mathcal{B}D/D^*$
- ▶ To study \mathcal{B}_{bc} and \mathcal{B}_{bb} decays, and calculate their non-leptonic two-body decays. So that we can help the experiment looking for these particles.
- ▶ Try to develop a more credible theoretical method to study and calculate the singly and doubly charmed baryon decays, that can promote our further understanding of the non-perturbative QCD dynamics.

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Brief Summary

- ▶ We develop a theoretical method to calculate the branching fractions of some processes of Ξ_{cc} decays.
- ▶ We suggest to measure the following processes with the largest possibilities to be observed.

$$\mathcal{B}(\Xi_{cc}^{++} \rightarrow \Sigma_c^{++}(2455) \bar{K}^{*0} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+) \sim O(10\%),$$

$$\mathcal{B}(\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+) = (7.1 \sim 10.7)\%.$$

- ▶ Ξ_{cc}^{++} has been discovered by LHCb, through the first channel

$$\Xi_{cc}^{++} \rightarrow \Sigma_c^{++}(2455) \bar{K}^{*0} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$$
- ▶ Next, we will calculate the non-leptonic decays of \mathcal{B}_{bc} and \mathcal{B}_{bb} .

Thank you for your attention!