Rescattering effects in doubly heavy baryon decays

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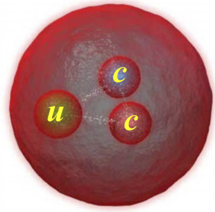
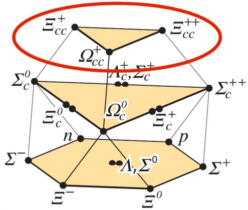
Introduction

- 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

- 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
- The prediction for Ξ_{cc}^{++} decay
  - We recommend the processes of $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ and $\Xi_c^+ \pi^+$ as the first priority for experiments to search for the doubly heavy baryons.
- We have calculated all the decay modes of $\mathcal{B}_{cc} \to \mathcal{B}_c P$.

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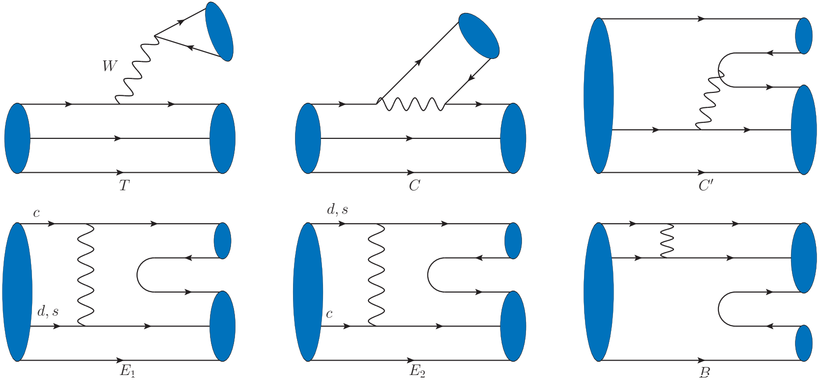
The analysis of topology classification

- 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: $O(\Lambda_{QCD}/m_Q) \sim 0.2$, *c* decay: $O(\Lambda_{QCD}/m_Q) \sim 1$.

The short distance contributions of T and C

The weak amplitudes $M(\mathcal{B}_{cc} \to \mathcal{B}'_c P)$ and $M(\mathcal{B}_{cc} \to \mathcal{B}'_c V)$ generally can be expressed as

$$M(\mathcal{B}_{cc} \to \mathcal{B}'_c P) = i\ \bar{u}_{B'}(A + B\gamma_5)u_B,$$

$$M(\mathcal{B}_{cc} \to \mathcal{B}'_c V) = \epsilon^{*\mu}\bar{u}_{B'}(A_1\gamma_\mu\gamma_5 + A_2\frac{p'_\mu}{M}\gamma_5 + B_1\gamma_\mu + B_2\frac{p'_\mu}{M})u_B$$

for T or C topology decays, these parameters based on factorization hypothesis can be expressed as

$$A = \lambda f_P(M - M')f_1(m^2),\ \ B = \lambda f_P(M + M')g_1(m^2),$$

$$A_1 = -\lambda f_V m(g_1(m^2) + g_2(m^2)\frac{M - M'}{M}),\ A_2 = -2\lambda f_V m g_2(m^2),$$

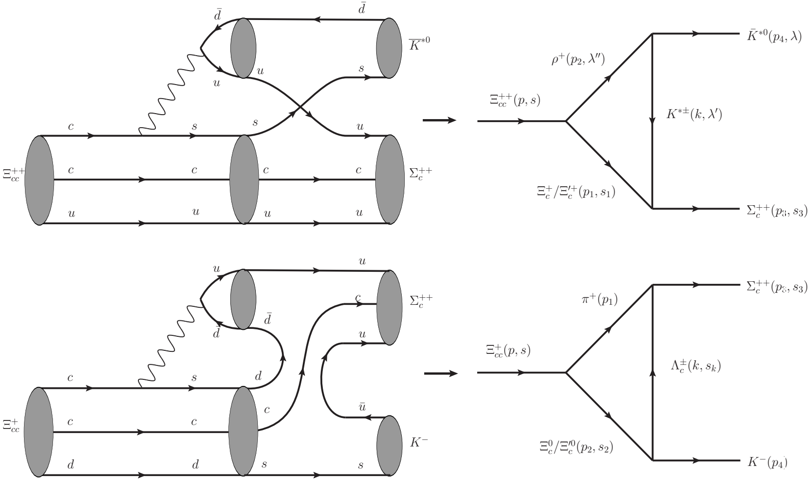
$$B_1 = \lambda f_V m(f_1(m^2) - f_2(m^2)\frac{M + M'}{M}),\ B_2 = 2\lambda f_V m f_2(m^2)$$

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, EPJC 77,781, arXiv:1707.02834].

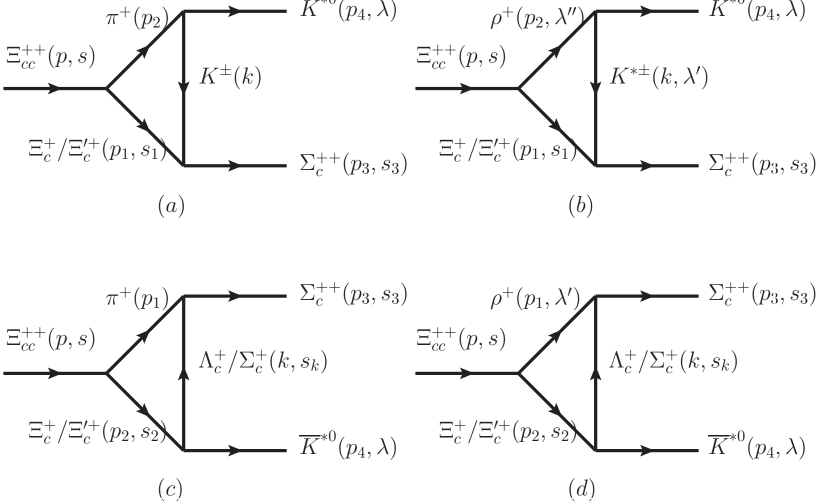
Rescattering mechanism

- Rescattering mechanism, for example for C and E_1

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

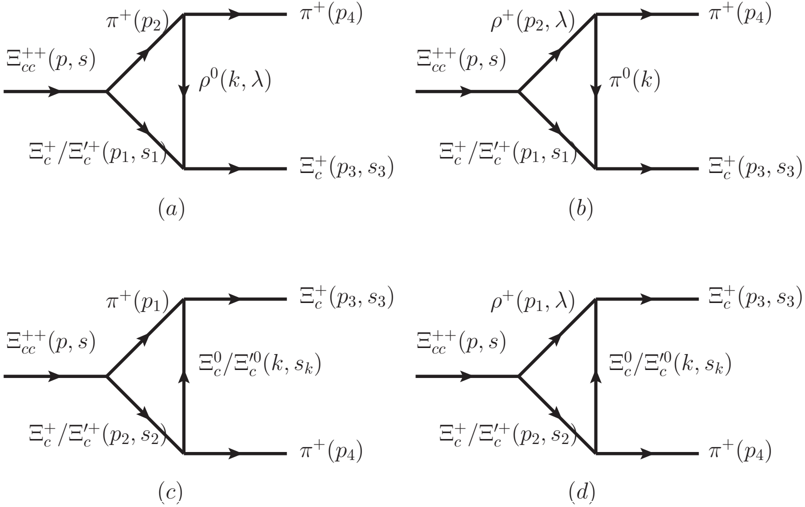


$$\boxed{\Xi_{cc}^{++} \to \Sigma_c^{++}\overline{K}^{*0}} \to \Lambda_c^+ K^- \pi^+ \pi^+ \qquad V_{cs}^* V_{ud}\, C$$



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

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

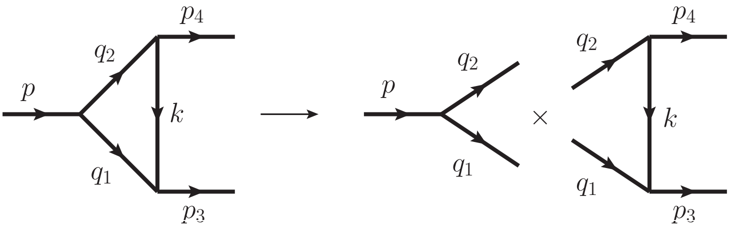


The optical theorem

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

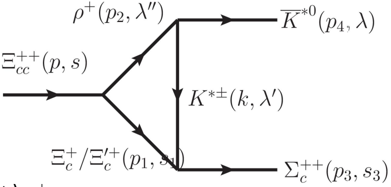
$$\mathrm{Abs}(M(p \to p_3 p_4)) = \frac{1}{2} \sum_j \left(\prod_{k=1}^{j} \int \frac{d^3\vec{q}}{(2\pi)^3 2E_k} \right) (2\pi)^4 \delta^4 (p - \sum_{k=1}^{j} q_k)$$
$$\times M(p \to \{q_k\}) T^*(p_3 p_4 \to \{q_k\}).$$

- Cutkosky cutting rule



Calculation formulism

$$\Xi_{cc}^{++} \to \Sigma_c^{++} \overline{K}^{*0}$$



$$\mathcal{L}_{\rm eff} = \mathcal{L}_{VPP} + \mathcal{L}_{VVV} + \mathcal{L}_{P\mathcal{B}_c\mathcal{B}_c} + \mathcal{L}_{V\mathcal{B}_c\mathcal{B}_c},$$

$$\mathcal{L}_{\rho K^* K^*} = \frac{i}{\sqrt{2}} g_{\rho\rho\rho}\Big[\Big(\partial^\nu K^{*0\mu} K^{*-}_\mu - K^{*0}_\mu \partial^\nu K^{*-\mu}\Big)\rho^+_\nu + \Big(\partial^\nu K^{*-\mu}\rho^+_\mu - K^{*-}_\mu \partial^\nu \rho^{+\mu}\Big) K^{*0}_\nu + \Big(\partial^\nu \rho^{+\mu} K^{*0}_\mu - \rho^+_\mu \partial^\nu K^{*0\mu}\Big) K^{*-}_\nu\Big],$$

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

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

$$\langle \Sigma_c^{++} | i\mathcal{L}_{\Sigma_c\Xi_c K^*} | \Xi_c^+ K^{*+} \rangle = \epsilon^\mu i(k,\lambda)\bar{u}(p_3,s_3)(f_1^{\Sigma_c\Xi_c K^*}\gamma_\mu + \frac{if_2^{\Sigma_c\Xi_c K^*}}{m_{p1} + m_{p3}}\sigma_{\mu\nu}k^\nu)u(p_1,s_1).$$

Calculation formulism

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

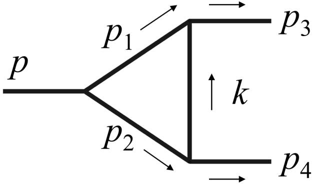
The theoretical uncertainty

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

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

where $\Lambda = m_{exc} + \eta \Lambda_{QCD}$. [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



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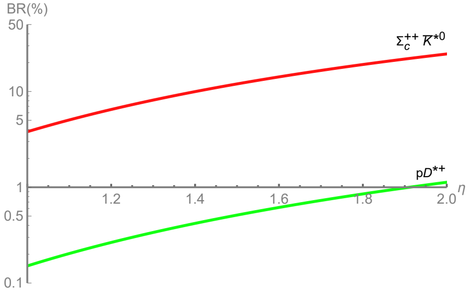
Results analysis

$$\mathcal{B}(\Xi_{cc}^{++} \to \Sigma_c^{++}(2455)\overline{K}^{*0}) = \left(\frac{\tau_{\Xi_{cc}^{++}}}{300\text{ fs}}\right) \times (3.8 \sim 24.6)\%$$

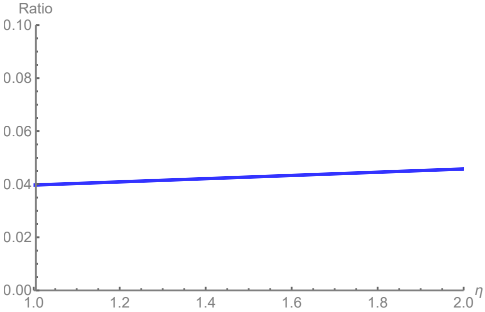
Baryons	Modes	amplitudes	$\mathcal{B}_{LD}$
$\Xi_{cc}^{++}(ccu)$	$\Sigma_c^{++}(2455)\overline{K}^{*0}$	$\lambda_{sd} C$	defined as 1
	pD^{*+}	$\lambda_d C'$	0.04
	pD^{+}	$\lambda_d C'$	0.0008
$\Xi_{cc}^{+}(ccd)$	$\Lambda_c^{+}\overline{K}^{*0}$	$\lambda_{sd}(C+E_1)$	$(\mathcal{R}_\tau/0.3) \times 0.22$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

$$\mathcal{B}(\Xi_{cc}^{++} \to \Sigma_c^{++}\overline{K}^{*0} \to \Lambda_c^{+}K^{-}\pi^{+}\pi^{+}) \sim \mathcal{O}(10\%)$$

- The branching fractions of $\Xi_{cc}^{++} \to \Sigma_c^{++}\overline{K}^{*0}$ and pD^{*+} vary with η.



- The ratio $\frac{\mathcal{B}(\Xi_{cc}^{++} \to pD^{*+})}{\mathcal{B}(\Xi_{cc}^{++} \to \Sigma_c^{++}\overline{K}^{*0})}$ vary with η.



Ξ_{cc}^{++} and Ξ_{cc}^{+} decays

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

Par	Modes	$\mathcal{B}$(LD+SD)	$\mathcal{B}$(SD)	Modes	$\mathcal{B}$(LD+SD)	$\mathcal{B}$(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
	$\Sigma_c^{++}\overline{K}^0$	$4.05 \sim 27.5$	0.015	$\Sigma_c^{++}K^0$	$0.011 \sim 0.088$	4.4×10^{-5}
	$\Sigma_c^{++}\pi^0$	$0.25 \sim 1.89$	6.3×10^{-4}			
Ξ_{cc}^{+}	$\Lambda_c^+\pi^0$	$0.05 \sim 0.34$	3.3×10^{-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}
	$\Lambda_c^+\overline{K}^0$	$1.18 \sim 8.81$	0.0096	$\Sigma_c^+\overline{K}^0$	$5.46 \sim 37.0$	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	$\Sigma_c^0K^+$		0.115
	$\Xi_c^0K^+$	$1.79 \sim 1.83$	1.78	$\Xi_c'^0K^+$	$1.04 \sim 1.21$	1.00
	$\Omega_c^0K^+$	$0.16 \sim 0.94$		$\Sigma_c^{++}\pi^-$	$0.014 \sim 0.088$	
	$\Sigma_c^{++}K^-$	$0.30 \sim 2.12$				

Ω_{cc}^{+} decays

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

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

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For our next work

- 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 $\mathcal{B}_{cc} \to \mathcal{B}_c V$
  - all $\mathcal{B}_{cc} \to \mathcal{B} D/D^*$
- 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 perturbative and non-perturbative QCD dynamics.

OUTLINE

Brief Summary

- We have developed a theoretical method to calculate the branching fractions of some processes of Ξ_{cc}decays.
  - Factorization approach for T, C diagram
  - Rescattering effects for C, C', E_1, E_2 and B diagram
- We have calculated many decay channels, and the branching ratios of these channel have a relative large value and can be used to find Ξ_{cc}^{++}.

$$\mathcal{B}(\Xi_{cc}^{++} \to \Sigma_c^{++}(2455)\overline{K}^{*0} \to \Lambda_c^+ K^- \pi^+ \pi^+) \sim O(10\%),$$
$$\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^+ \pi^+) = (7.1 \sim 10.7)\%.$$

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

Thank you for your attention!