Weak Decays of Ξ_{cc} — discovery potentials



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2nd workshop on Heavy Quark Physics @ IHEP, 2018.04.23

In collaboration with Hua-Yu Jiang, Run-Hui Li, Ying Li, Cai-Dian Lü, Wei Wang, Zhen-Xing Zhao, Zhi-Tian Zou

Outline

- 1. Introduction
- 2. Theoretical Framework
- 3. Discussions and Results
 - compare all the decay modes
- 4. Summary

LHCb observed E_{cc}^{++} recently





[**FSY**, H.Y.Jiang, R.H.Li, C.D.Lü, W.Wang, Z.X.Zhao, CPC42(2018)05001, [arXiv:1703.09086]]

Doubly Heavy Baryon Decays @ LHCb



Fu-Sheng Yu (于福升)

Lanzhou University

2016.12.26 @ UCAS

Thank Dr. Ji-Bo He to give me this project and push me a lot!

In collaboration with Run-Hui Li, Ying Li, Cai-Dian Lü, Wei Wang, Zhen-Xing Zhao, Zhi-Tian Zou

Talk @ LHCb-China, 2016.12

Weak Decays of \mathcal{Z}_{cc}



Fu-Sheng Yu (于福升)

Lanzhou University

15.03.2017 @ LHCb Charm WG

Thank Ji-Bo and Andrea for invitation to give a talk!

Based on [arXiv:1703.09086]

In collaboration with <u>Hua-Yu</u> Jiang, <u>Run-Hui</u> Li, Ying Li, <u>Cai-Dian</u> Lü, Wei Wang, Zhen-Xing Zhao, Zhi-Tian Zou

Talk @ LHCb-Charm, 2017.03

LHCb spokesperson Passaleva:

A group of Chinese theorists provided fundamental inputs to drive the analysis to the right direction and gave key suggestions to achieve this result. Collaboration between theory and experiment



Searching History

- In experiments
 - The only evidence was found for Ξ_{cc}^+ by SELEX
 - $\Xi_{cc}^+ \rightarrow \Lambda_c^+ K^- \pi^+ \qquad \Xi_{cc}^+ \rightarrow p D^+ K^- \quad \text{[SELEX, 02', 04']}$
 - But not confirmed by other experiments

$$\begin{split} &\Xi_{cc}^{+} \to \Lambda_{c}^{+} K^{-} \pi^{+} \text{ [FOCUS, 02']} \\ &\Xi_{cc}^{+(+)} \to \Xi_{c}^{0} \pi^{+} (\pi^{+}) \text{ and } \Lambda_{c}^{+} K^{-} \pi^{+} (\pi^{+}) \text{ [Babar, 06'; Belle, 13']} \\ &\Xi_{cc}^{+} \to \Lambda_{c}^{+} K^{-} \pi^{+} \text{ [LHCb, 13']} \end{split}$$

cross sections of production @ LHC

$\sigma(\Xi_{cc})$ is close to $\sigma(B_c)$ @ LHC

\Box_{cc}	

-	$\sqrt{S} = 7.0 \text{TeV}$	$\sqrt{S} = 14.0 \text{TeV}$
$[^{3}S_{1}]$	38.11	69.40
$[{}^{1}S_{0}]$	9.362	17.05
Total	47.47	86.45

in unit of nb

 $p_t \ge 4GeV \qquad |y| \le 1.5$

[J.-W. Zhang, X.-G. Wu, T. Zhong, Y. Yu, Z.-Y. Fang, Phys.Rev. D 83, 034026 (2011)]



LHC ($\sqrt{S} = 14.0 \text{ TeV}$) in unit of nb

[C.-H. Chang, C.-F. Qiao, J.-X. Wang, X.-G. Wu, Phys.Rev. D71 (2005) 074012]

 B_c well studied at LHCb,

discovery and establishment of Ξ_{cc} would not be far

The key issue is to select the decaying processes with the largest possibilities of observing doubly charmed baryons

Lifetimes

Literatures	<i>Ξ_{cc}</i> ++ (fs)	Ξ_{cc} + (fs)
Karliner, Rosner, 2014	185	53
Kiselev, Likhoded, Onishchenko, 1998	430±100	110±10
Kiselev, Likhoded, 2002	460±50	160±50
Chang, Li, Li, Wang, 2007	670	250

But much less ambiguity of ratio of lifetimes

$$\mathcal{R}_{\tau} \equiv \frac{\tau_{\Xi_{cc}^+}}{\tau_{\Xi_{cc}^{++}}} = 0.25 \sim 0.37$$

$$\tau(\Xi_{cc}^{++}) \gg \tau(\Xi_{cc}^{+})$$

Effect of destructive Pauli interference

Longer lifetime of
$$\Xi_{cc}^{++}$$

 $\mathcal{R}_{\tau} \equiv \frac{\tau_{\Xi_{cc}^{+}}}{\tau_{\Xi_{cc}^{++}}} = 0.25 \sim 0.37 \qquad \tau(\Xi_{cc}^{++}) \gg \tau(\Xi_{cc}^{+})$

• Longer lifetime \Rightarrow Larger branching fractions

$$\mathcal{B}_i = \Gamma_i \cdot \tau$$

 Longer lifetime ⇒ Higher efficiency of identification at hadron colliders

We recommend to search for Ξ_{cc}^{++} rather than Ξ_{cc}^{+}



colliders [41–43], the longer lifetime of the Ξ_{cc}^{++} baryon should make it significantly easier to observe than the Ξ_{cc}^{+} baryon in such experiments, due to the use of real-time (online) event-selection requirements designed to reject backgrounds originating from the primary interaction point. [LHCb, PRL119,112001(2017)]

Theory Framework for weak decays of charmed baryons

Short + Long distance contributions

Short-distance contributions

- external W-emission diagrams
- Calculate form factors in light-front quark model
- Calculate amplitudes using factorization approach



Transition form factors (FF) in light-front quark model

- Isospin symmetry relates FF's of Ξ_{cc}^{++} and Ξ_{cc}^{+}
- Flavor SU(3) symmetry relates FF's of $c \rightarrow s$ and $c \rightarrow d$ transitions
- Uncertainties in FFs are *c* mostly cancelled in the relative branching fractions.



$\Xi_{cc} \to \Xi_c / \Xi_c'(0^+)$		$ = \Xi_{cc} \to \Xi_c / \Xi_c'(1^+) $						
~5	f_1	g_1	f_2	g_2	f_1	g_1	f_2	g_2^*
F(0)	0.75	0.62	-0.78	-0.08	0.74	-0.20	0.80	-0.02
$m_{ m fit}$	1.84	2.16	1.67	1.29	1.58	2.10	1.62	1.62
δ	0.25	0.35	0.30	0.52	0.36	0.21	0.31	1.37
d	$\Xi_{cc} \to \Lambda_c / \Sigma_c(0^+)$		$\Xi_{cc} \to \Lambda_c / \Sigma_c(1^+)$					
<i>→u</i>	f_1	g_1	f_2	g_2	f_1	g_1	f_2	g_2^*
F(0)	0.65	0.53	-0.74	-0.05	0.64	-0.17	0.73	-0.03
$m_{ m fit}$	1.72	2.03	1.56	1.12	1.49	1.99	1.53	2.03
δ	0.27	0.38	0.32	1.10	0.37	0.23	0.32	2.62
	$ \overrightarrow{F(0)} $ $ fft \\ \delta $ $ \overrightarrow{\delta} $ $ F(0) $ $ fft \\ \delta $	$ \begin{array}{c} \bullet S \\ f_1 \\ f_1 \\ \hline f_1 \\ \hline f_1 \\ 0.75 \\ m_{\rm fit} \\ 1.84 \\ \delta \\ 0.25 \\ \hline \bullet d \\ f_1 \\ \hline f_1 \\ F(0) \\ 0.65 \\ m_{\rm fit} \\ 1.72 \\ \delta \\ 0.27 \\ \end{array} $	$ \begin{array}{c} \Xi_{cc} \rightarrow \\ f_1 & g_1 \\ \hline F(0) & 0.75 & 0.62 \\ m_{fit} & 1.84 & 2.16 \\ \delta & 0.25 & 0.35 \\ \hline \delta & 0.25 & 0.35 \\ \hline f_1 & g_1 \\ \hline F(0) & 0.65 & 0.53 \\ m_{fit} & 1.72 & 2.03 \\ \delta & 0.27 & 0.38 \\ \end{array} $	$ \begin{array}{c} \overleftarrow{F(0)} & \Xi_{cc} \rightarrow \Xi_c / \Xi_c' (\\ f_1 & g_1 & f_2 \\ \hline f_1 & g_1 & f_2 \\ \hline F(0) & 0.75 & 0.62 & -0.78 \\ m_{\rm fit} & 1.84 & 2.16 & 1.67 \\ \hline \delta & 0.25 & 0.35 & 0.30 \\ \hline \overrightarrow{\delta} & 0.25 & 0.35 & 0.30 \\ \hline \overrightarrow{F(0)} & 1.84 & g_1 & f_2 \\ \hline F(0) & 0.65 & 0.53 & -0.74 \\ m_{\rm fit} & 1.72 & 2.03 & 1.56 \\ \hline \delta & 0.27 & 0.38 & 0.32 \\ \hline \end{array} $	$ \begin{array}{c c} & \Xi_{cc} \rightarrow \Xi_c / \Xi_c'(0^+) \\ \hline f_1 & g_1 & f_2 & g_2 \\ \hline f(0) & 0.75 & 0.62 & -0.78 & -0.08 \\ m_{\rm fit} & 1.84 & 2.16 & 1.67 & 1.29 \\ \hline \delta & 0.25 & 0.35 & 0.30 & 0.52 \\ \hline \bullet d & \Xi_{cc} \rightarrow \Lambda_c / \Sigma_c(0^+) \\ \hline f_1 & g_1 & f_2 & g_2 \\ \hline f(0) & 0.65 & 0.53 & -0.74 & -0.05 \\ m_{\rm fit} & 1.72 & 2.03 & 1.56 & 1.12 \\ \hline \delta & 0.27 & 0.38 & 0.32 & 1.10 \\ \end{array} $	$ \begin{array}{c cccccccccc} & \Xi_{cc} \to \Xi_{c} / \Xi_{c}' (0^{+}) & \Xi_{cc} \\ \hline f_{1} & g_{1} & f_{2} & g_{2} & f_{1} \\ \hline F(0) & 0.75 & 0.62 & -0.78 & -0.08 & 0.74 \\ m_{\text{fit}} & 1.84 & 2.16 & 1.67 & 1.29 & 1.58 \\ \hline \delta & 0.25 & 0.35 & 0.30 & 0.52 & 0.36 \\ \hline \bullet & & & \\ \hline f_{1} & g_{1} & f_{2} & g_{2} & f_{1} \\ \hline F(0) & 0.65 & 0.53 & -0.74 & -0.05 & 0.64 \\ m_{\text{fit}} & 1.72 & 2.03 & 1.56 & 1.12 & 1.49 \\ \hline \delta & 0.27 & 0.38 & 0.32 & 1.10 & 0.37 \\ \hline \end{array} $	$ \begin{array}{c c c c c c c c c c c c c c c c c c c $	$ \begin{array}{c c c c c c c c c c c c c c c c c c c $

[W.Wang, FSY, Z.X.Zhao, '17]

Short-Distance Contributions



• External W-emission processes using factorization approach $A(\Xi_{cc} \rightarrow \mathcal{B}_c M)_{SD}$

$$= \frac{G_F}{\sqrt{2}} V_{cq'}^* V_{uq} a_1(a_2) \langle M | \bar{u} \gamma^\mu (1 - \gamma_5) q | 0 \rangle \langle \mathcal{B}_c | \bar{q}' \gamma_\mu (1 - \gamma_5) | \Xi_{cc} \rangle$$

Relative branching fractions are reliable

$$\begin{aligned} &\mathcal{B}(\Xi_{cc}^{+} \to \Xi_{c}^{0} \pi^{+}) / \mathcal{B}(\Xi_{cc}^{++} \to \Xi_{c}^{+} \pi^{+}) = \mathcal{R}_{\tau} = 0.25 \sim 0.37, \\ &\mathcal{B}(\Xi_{cc}^{++} \to \Lambda_{c}^{+} \pi^{+}) / \mathcal{B}(\Xi_{cc}^{++} \to \Xi_{c}^{+} \pi^{+}) = 0.056, \\ &\mathcal{B}(\Xi_{cc}^{++} \to \Xi_{c}^{+} \ell^{+} \nu) / \mathcal{B}(\Xi_{cc}^{++} \to \Xi_{c}^{+} \pi^{+}) = 0.71, \end{aligned}$$

Uncertainties of form factors are mostly cancelled

 $\mathcal{B}(\Xi_{cc}^{++} \to \Xi_{c}^{+}\pi^{+})$ is the largest one

$\begin{array}{l} \mbox{small lifetime} \\ \mbox{Cabibbo-} \\ \mbox{suppressed} \end{array} \xrightarrow{\begin{subarray}{l} \mathcal{B}(\Xi_{cc}^{++} \to \Xi_{c}^{0}\pi^{+})/\mathcal{B}(\Xi_{cc}^{++} \to \Xi_{c}^{+}\pi^{+}) = \mathcal{R}_{\tau} = 0.25 \sim 0.37, \\ \end{subarray} \xrightarrow{\begin{subarray}{l} \mathcal{B}(\Xi_{cc}^{++} \to \Lambda_{c}^{+}\pi^{+})/\mathcal{B}(\Xi_{cc}^{++} \to \Xi_{c}^{+}\pi^{+}) = 0.056, \\ \end{subarray} \xrightarrow{\begin{subarray}{l} \mathcal{B}(\Xi_{cc}^{++} \to \Xi_{c}^{+}\ell^{+}\nu)/\mathcal{B}(\Xi_{cc}^{++} \to \Xi_{c}^{+}\pi^{+}) = 0.71, \\ \end{subarray} \\ \end{subarray} \\ \end{subarray} \end{array}$

Other processes with large branching fractions, but

either have neutral final-state particles

$$\Xi_c^+ \rho^+ (\to \pi^+ \pi^0) \qquad \qquad \Xi_c'^+ (\to \Xi_c^+ \gamma) \pi^+$$

• or have more tracks $\Xi_c^+ a_1^+ (\to \pi^+ \pi^+ \pi^-)$

 $\Xi_{cc}^{++} \rightarrow \Xi_{c}^{+} \pi^{+}$ is the best one to search for doubly heavy baryons among external W-emission processes

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

Absolute branching fractions:

$$\mathcal{B}(\Xi_{cc}^{++} \to \Xi_{c}^{+} \pi^{+}) = \left(\frac{7 \Xi_{cc}^{++}}{300 \,\mathrm{fs}}\right) \times 3.4\%$$

large enough for measurement

We suggest to measure $\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$ with the reconstruction of $\Xi_c^+ \to p K^- \pi^+$

[FSY, et al, 1703.09086]

 $\mathcal{B}(\Xi_c^+ \to pK^-\pi^+)$ has never been directly measured but predicted to be $(2.2 \pm 0.8)\%$



Branching Ratio of $E_c^+ \rightarrow pK^-\pi^+$

Under U-spin symmetry, $d \leftrightarrow s$

[FSY, *et al*, 1703.09086]

Long-distance contributions

- final-state interacting (FSI) effects

- significantly large in charm decays
- Calculate rescattering effects



Short-distance v.s. Long-distance Contributions





Br=3.4%

short-distance branching fractions

Br=0.003%

external W-emissioninternal W-emissioncolor-favoredcolor-suppressed $a_1(\mu_c)=1.07$ $a_2(\mu_c)=-0.02$

But long-distance contributions are significantly enhanced in charmed hadron decays

Indication from pure internal W-emission





Short-distance v.s. Lo

Long-distance

Br(SD)=10⁻⁶ $la_2(\mu_c)l=0.02$

 $Br(exp)=(1.04\pm0.21)\times10^{-3}$

 $la_2^{eff}(\mu_c) = 0.7$

large-N_c limit

Understanding long-distance contributions is essential to find a best process for the searches for doubly heavy baryons

 Λ_c^+



Relative Branching Fractions with long-distance contributions

Baryons	Modes	$\mathcal{B}_{ ext{LD}}$
$\Xi_{cc}^{++}(ccu)$	$\Sigma_c^{++}(2455)\overline{K}^{*0}$	defined as 1
Largest	pD^{*+}	0.04
	pD^+	0.0008
$\Xi_{cc}^+(ccd)$	$\Lambda_c^+ \overline{K}^{*0}$	$(\mathcal{R}_{\tau}/0.3) \times 0.22$
	$\Sigma_{c}^{++}(2455)K^{-}$	$(\mathcal{R}_{ au}/0.3) imes 0.008$
	$\Xi_c^+ ho^0$	$(\mathcal{R}_{\tau}/0.3) \times 0.04$
	ΛD^+	$(\mathcal{R}_{\tau}/0.3) \times 0.004$
	pD^0	$(\mathcal{R}_{\tau}/0.3) \times 0.002$

Uncertainties of the relative branching fractions induced by the parameter of η are less than 10%



 $\mathcal{B}(\Xi_{cc}^{++} \to \Xi_{c}^{+} \pi^{+}) = 3.4\%$ $\mathcal{B}(\Xi_{cc}^{++} \to \Xi_{c}^{+} \rho^{+}) = 6.3\%$ $\mathcal{B}(\Xi_{cc}^{++} \to \Xi_{c}^{\prime+} \pi^{+}) = 2.4\%$ $\mathcal{B}(\Xi_{cc}^{++} \to \Xi_{c}^{\prime+} \rho^{+}) = 8.7\%$

$$\mathcal{B}(\Xi_{cc}^{++} \to \Sigma_{c}^{++} \overline{K}^{*0}) = (3.8 \sim 24.6)\%$$

$$\times \frac{\tau_{\Xi_{cc}^{++}}}{300 \,\mathrm{fs}}$$

 $\eta = 1.0 \sim 2.0$

Large enough for measurements

 $\rightarrow \Lambda_{a}^{+}K^{-}\pi^{+}\pi^{+}$



$$\Xi_{cc}^{++} \to \Sigma_c^{++} (2455) \overline{K}^{*0}$$

is actually a four-body decay

 $\Sigma_{c}^{++}(2455)$ or $\Sigma_{c}^{++}(2520)$

In charmed hadron decays, final-state particles are not energetic, and easily located in the momentum range of resonances $\mathcal{B}(\Xi_{cc}^{++} \to \Sigma_{c}^{++}(2455)\overline{K}^{*0}) = \left(\frac{\tau_{\Xi_{cc}^{++}}}{300 \,\mathrm{fs}}\right) \times (3.8 \sim 24.6)\%$

It would be expected to be as large as O(10%)

$$\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+ \text{ V.S. } \Xi_{cc}^+ \rightarrow \Lambda_c^+ K^- \pi^+$$
SELEX's discovery channe
LHCb measured

Baryons	Modes	$\mathcal{B}_{ ext{LD}}$	
$\overline{\Xi_{cc}^{++}(ccu)}$	$\Sigma_c^{++}(2455)\overline{K}^{*0}$	defined as 1	$\Lambda_{c}^{+}K^{-}\pi^{+}\pi^{+}$
$\tau \times (\sim 3)$	pD^{*+}	0.04	$r \sim 5$
	pD^+	0.0008	
$\Xi_{cc}^+(ccd)$	$\Lambda_c^+ \overline{K}^{*0}$	$(\mathcal{R}_{\tau}/0.3) \times 0.22$	$\wedge + \tau z +$
	$\Sigma_{c}^{++}(2455)K^{-}$	$(\mathcal{R}_{\tau}/0.3) \times 0.008$	$\Lambda_c \Lambda \pi'$
	$\Xi_c^+ ho^0$	$(\mathcal{R}_{\tau}/0.3) \times 0.04$	
	ΛD^+	$(\mathcal{R}_{\tau}/0.3) \times 0.004$	
	pD^0	$(\mathcal{R}_{\tau}/0.3) \times 0.002$	

 $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$ has more signal yields around one more order than $\Xi_{cc}^+ \rightarrow \Lambda_c^+ K^- \pi^+$

$$\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+ \text{ V.S. } \Xi_{cc}^+ \to pD^+ K^-$$

SELEX's discovery channel

Baryons	Modes	$\mathcal{B}_{ ext{LD}}$	
$\Xi_{cc}^{++}(ccu)$	$\Sigma_c^{++}(2455)\overline{K}^{*0}$	defined as 1	$\Lambda_c^+ K^- \pi^+ \pi^+$
	pD^{*+}	0.04	C
	pD^+	0.0008	
$\Xi_{cc}^+(ccd)$	$\Lambda_c^+ \overline{K}^{*0}$	$(\mathcal{R}_{\tau}/0.3) \times 0.22$	Λ is below
	$\Sigma_{c}^{++}(2455)K^{-}$	$(\mathcal{R}_{ au}/0.3) imes 0.008$	pK threshold
	$\Xi_c^+ ho^0$	$(\mathcal{R}_{\tau}/0.3) \times 0.04$	-
	ΛD^+	$(\mathcal{R}_{ au}/0.3) imes 0.004$	pD^+K^-
	pD^0	$(\mathcal{R}_{\tau}/0.3) \times 0.002$	

We recommend to measure $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$ to search for doubly heavy baryons

[FSY, et al, 1703.09086]

Summary

- We systematically study the weak decays of doubly charmed baryons
- By comparing all the decay modes, we recommend to measure the following processes to search for doubly heavy baryons

$$\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+ \qquad \Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+$$

- And LHCb observed it via the first process.
- Outlook: similar analysis to search for other particles.

Outlook

Prospect



- > Study \mathcal{Z}_{cc}^{++} in more channels?
- ➢ lifetime?
- $\succ \Xi_{cc}^+$?
- $> J^P = 1/2^+?$
- > Semi-leptonic decay modes?
- > CP Violation?
- **>** ...

A long long list…

[W. Wang's talk @ Implication of LHCb, 2017]

Thank you !

Effective Lagrangian

$$\begin{split} \mathcal{L}_{\text{eff}} =& i \frac{g_{VPP}}{\sqrt{2}} Tr\{V^{\mu}[P,\partial_{\mu}P]\} + i \frac{g_{VVV}}{\sqrt{2}} Tr\{(\partial_{\nu}V_{\mu} - \partial_{\mu}V_{\nu})V^{\mu}V^{\nu}\} - ig_{DDV}(D_{i}\partial_{\mu}D^{j\dagger} - \partial_{\mu}D_{i}D^{j\dagger})(V^{\mu})_{j}^{i} \\ &+ ig_{VD^{*}D^{*}}(D_{i}^{*\nu}\partial_{\mu}D_{\nu}^{*j\dagger} - \partial_{\mu}D_{i}^{*\nu}D_{\nu}^{*j\dagger})(V^{\mu})_{j}^{i} + 4if_{VD^{*}D^{*}D^{*}}D_{i\mu}^{*\dagger}(\partial^{\mu}V^{\nu} - \partial^{\nu}V^{\mu})_{j}^{i}D_{\nu}^{*j} \\ &- ig_{PDD^{*}}(D^{i}\partial^{\mu}P_{ij}D_{\mu}^{*j\dagger} - h.c.) + g_{PBB}Tr[\overline{B}i\gamma_{5}PB] + g_{1VBB}Tr[\overline{B}\gamma_{\mu}V^{\mu}B] + \frac{g_{2VBB}}{2m_{B}}Tr[\overline{B}\sigma_{\mu\nu}\partial^{\mu}V^{\nu}B] \\ &+ \{g_{PB_{c\bar{3}}B_{c\bar{3}}}Tr[\overline{B}_{c\bar{3}}i\gamma_{5}PB_{c\bar{3}}] + (B_{c\bar{3}} \rightarrow B_{c\bar{6}})\} + \{g_{PB_{c\bar{6}}B_{c\bar{3}}}Tr[\overline{B}_{c\bar{6}}i\gamma_{5}PB_{c\bar{3}}] + h.c.\}, \\ &+ \{g_{1VB_{c\bar{3}}B_{c\bar{3}}}Tr[\overline{B}_{c\bar{3}}\gamma_{\mu}V^{\mu}B_{c\bar{3}}] + \frac{g_{2VB_{c\bar{3}}B_{c\bar{3}}}}{2m_{c\bar{3}}}Tr[\overline{B}_{c\bar{5}}\sigma_{\mu\nu}\partial^{\mu}V^{\mu}B_{c\bar{3}}] + (B_{c\bar{3}} \rightarrow B_{c\bar{6}})\} \\ &+ \{g_{1VB_{c\bar{6}}B_{c\bar{3}}}Tr[\overline{B}_{c\bar{6}}\gamma_{\mu}V^{\mu}B_{c\bar{3}}] + \frac{g_{2VB_{c\bar{6}}B_{c\bar{3}}}}{2m_{c\bar{3}}}Tr[\overline{B}_{c\bar{6}}\sigma_{\mu\nu}\partial^{\mu}V^{\mu}B_{c\bar{3}}] + h.c.\} + g_{\Lambda_{c}(\Sigma_{c})ND_{q}}\{\overline{\Lambda_{c}}(\overline{\Sigma_{c}})i\gamma_{5}D_{q}N + h.c.\} \\ &+ g_{1\Lambda_{c}(\Sigma_{c})ND_{q}^{*}}\{\overline{\Lambda_{c}}(\overline{\Sigma_{c}})\gamma_{\mu}D_{q}^{*\mu}N + h.c.\} + \frac{g_{2\Lambda_{c}(\Sigma_{c})ND_{q}^{*}}}{m_{\Lambda_{c}(\Sigma_{c})}+m_{N}}\{\overline{\Lambda_{c}}(\overline{\Sigma_{c}})\sigma_{\mu\nu}\partial^{\mu}D_{q}^{*\nu}N + h.c.\} \end{split}$$

Hadronic coupling constants are related under the flavor SU(3) symmetry and the chiral and heavy quark symmetries

Uncertainties are mostly cancelled in relative Br's

[Yan, *et al*, PRD46,1148(1992)] [Casalbuoni, *et al*, Phys.Rept.281,145(1997)] [Meissner, Phys.Rept.161,213(1988)]

Theoretical Uncertainties

- Transition form factors —cancelled in relative Br's
- Hadronic coupling constants —cancelled in relative Br's

 $\Lambda = m_{\rm exc} + \eta \Lambda_{\rm OCD}$

Off-shell effects of intermediate states

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

[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





























































