Theories on
Weak Decays of Doubly Charm Baryons

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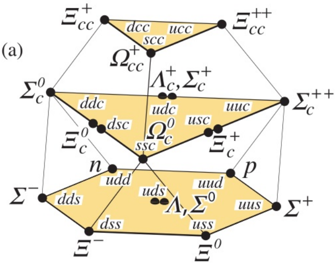
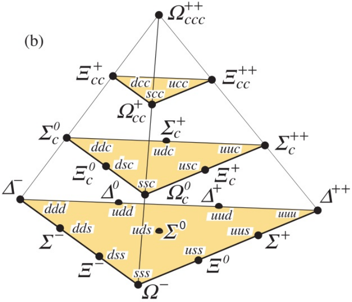
$\mathcal{B}_{cc} \to \mathcal{B}_{c}V$ decays & Discovery potentials of Ξ_{cc}^{+} and Ω_{cc}

Summary

- Doubly charm baryons form two $SU(3)$ triplets, which belongs to two $SU(4)$ 20-plets respectively.



Spin-1/2 states



Spin-3/2 states

- Unestablished in experiments until 2017.
- Necessary to study the weak decays to present some discovery channels.

Properties & production

There is a very very long list of studies on the masses, liftetimes, production, decay constants,......, of the doubly charm baryons.

Weak decays

- Lack of factorization theories; difficult to be calculated
- Form factors of some transitions are studied intensively
- $SU(3)$ analysis

Our work:

Initiated in 2016; aimed at presenting the branching fractions of weak decays

proposals	Available framework?	$\mathcal{BR}$?
★ $SU(3)$ analysis	✓	✗
★ Semileptonic weak decays	✓	✓
★ Nonleptonic weak decays	?	✓

For nonleptonic weak decays, we begin with the simplest case:

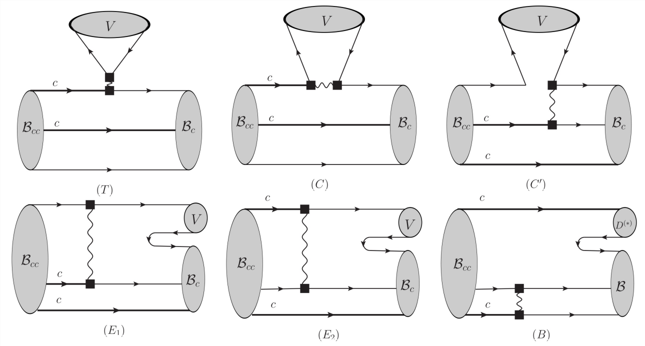
the TWO body nonleptonic decays

Two body nonleptonic weak decays

- Tree level effective Hamiltonian

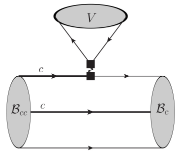
$$\mathcal{H}_{eff} = \frac{G_F}{\sqrt{2}} \sum_{q=d,s} V_{cq}^{*} V_{uD} \Big[C_1(\mu) O_1^q(\mu) + C_2(\mu) O_2^q(\mu) \Big] + \text{h.c.}$$

- Complicated dynamics. Topological classification:



Two body nonleptonic weak decays

- T diagram dominated processes:

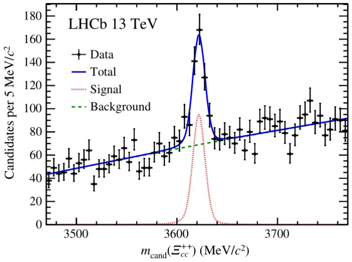


calculated under factorization hypothesis, similar to semileptonic decays.

- *"Semileptonic decays & Decays under Factorization Hypothesis"*

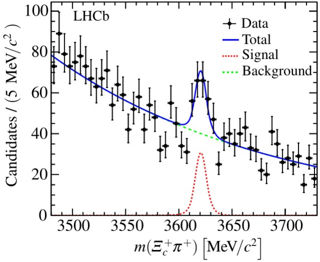
- Other approaches?
  - Similar to B meson decays? — *"A tentative work"*
  - Other systematic ways. — *Final state interactions*
- Two discovery decays are proposed for Ξ_{cc}^{++}:
  $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ & $\Xi_{cc}^{++} \to \Xi_{cc}^+ \pi^+$

In July 2017 LHCb anounced the discovery of Ξ_{cc}^{++} via $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ with its mass of about 3621 MeV, which was confirmed in July 2018 via $\Xi_{cc}^{++} \to \Xi_{cc}^{+} \pi^+$.



Invariant mass distribution of $\Lambda_c^+ K^- \pi^+ \pi^+$

[PRL 119, 112001 (2017)]



Invariant mass distribution of $\Xi_{cc}^{+} \pi^+$

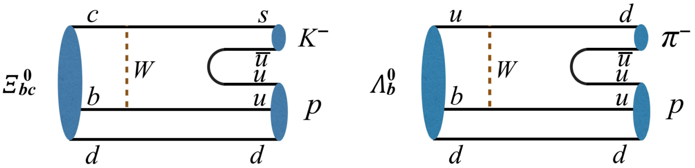
[PRL 121, 162002 (2018)]

A tentative work: $\Xi_{bc}^0 \to pK^-$ & $\Xi_{cc}^+ \to \Sigma_c^{++}K^-$

[R.H. Li, C.D. Lu, W. Wang, F.S. Yu, Z.T. Zou, PLB767(2017)232-235]

Aimed at making some rough estimations of branching fractions.

$\Xi_{bc}^0 \to pK^-$ VS $\Lambda_b^0 \to p\pi^-$

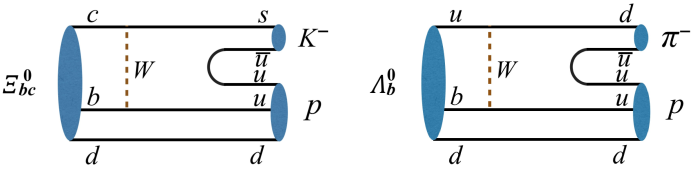


(a) (b)

- $\Xi_{bc}^0 \to pK^-$ has only W exchange contribution as diagram (a).
- Assuming $m_q/m_b \sim m_c/m_b \sim 0$, (a) and (b) have similar values.
- Amplitudes of these two decays can be parameterized as $\mathcal{M} = \bar{u}(p)[f_1 + f_2\gamma_5]u(\Xi_{bc}/\Lambda_b)$.
- The contribution of diagram (b) to $f_{1,2}$ of $\Lambda_b^0 \to p\pi^-$ has been calculated under perturbative QCD as $f_1 = -7.00 \times 10^{-11} + i3.33 \times 10^{-10}$ & $f_2 = 2.21 \times 10^{-10} - i4.04 \times 10^{-11}$. [PRD 80,034001]

Aimed at making some rough estimations of branching fractions.

$\Xi_{bc}^0 \to pK^-$ VS $\Lambda_b^0 \to p\pi^-$



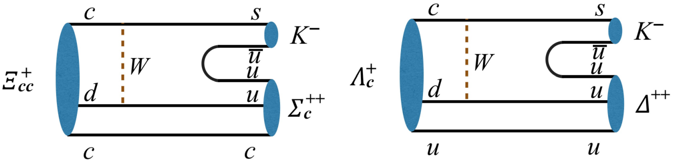
(a) (b)

- Considering the differences of decay constants, lifetimes, CKM and the parameters in wave functions, the coefficients in the amplitude of $\Xi_{bc}^0 \to pK^-$ are given as $f_1 = \left(-2.18 \times 10^{-10} + i1.04 \times 10^{-9}\right)\mathcal{R}_f$ & $f_2 = \left(6.88 \times 10^{-10} - i1.26 \times 10^{-10}\right)\mathcal{R}_f$
- $\mathcal{BR}(\Xi_{bc} \to p^+K^-) \approx 3.21 \times \mathcal{R}_f^2 \times \mathcal{R}_\tau \times 10^{-7}$

A tentative work: $\Xi_{bc}^0 \to pK^-$ & $\Xi_{cc}^+ \to \Sigma_c^{++} K^-$

[R.H. Li, C.D. Lu, W. Wang, F.S. Yu, Z.T. Zou, PLB767(2017)232-235]

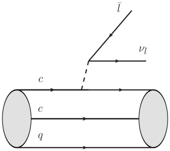
$\Xi_{cc}^+ \to \Sigma_c^{++}(2520) K^-$ vs $\Lambda_c^+ \to \Delta^{++} K^-$



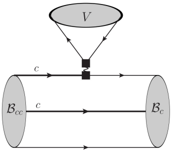
(a) (b)

- Low energy scale; nonperturbative dynamics dominating.
- Twin processes: Pure *W*-exchange decays; similar quark structures; the same polarizations.
- Low energy released, almost static final state; the spectators exchange little energy with the decaying quarks. $\Rightarrow$ similar amplitudes
- $\mathcal{BR}(\Xi_{cc}^+ \to \Sigma_c^{++}(2520) K^-) \in [0.36\%, 1.80\%]$

[W. Wang, F.S. Yu, Z.X. Zhao, EPJC 77(2017)781]



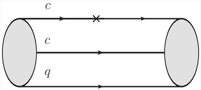
(a) A semileptonic decay



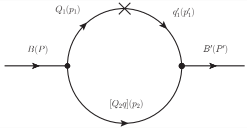
(b) A factorizable two body nonleptonic decay

- (a): factorized as a leptonic part and a hadronic part (form factors);
  $\mathcal{A}(\mathcal{B}_{cc} \to \mathcal{B}_c l^+ \nu) = \lambda \langle l^+ \nu | J^{\mu} | 0 \rangle \langle \mathcal{B}_c(p_f) | J_{\mu}^{\mathrm{w}} | \Xi_{cc}(p_i) \rangle$
- (b): factorized as a decay constant and a hadronic transition (form factors)
  $\mathcal{A}(\mathcal{B}_{cc} \to \mathcal{B}_c M)_{\mathrm{SD}} = \lambda \langle M(q) | J^{\mu} | 0 \rangle \langle \mathcal{B}_c(p_f) | J_{\mu}^{\mathrm{w}} | \Xi_{cc}(p_i) \rangle$
- Key ingredient — form factors;
  can be calculated under the light front quark model, QCD sum rules,.....

Transition under the light front quark model



$\Rightarrow$



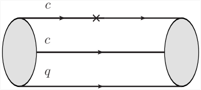
- The transition is parameterized as

$$
\begin{aligned}
&\langle B'(P',S_z')|(V-A)_\mu|B(P,S_z)\rangle \\
=&\bar{u}(P',S_z')\left[\gamma_\mu f_1(q^2)+i\sigma_{\mu\nu}\frac{q^\nu}{M}f_2(q^2)+\frac{q_\mu}{M}f_3(q^2)\right]u(P,S_z), \\
&-\bar{u}(P',S_z')\left[\gamma_\mu g_1(q^2)+i\sigma_{\mu\nu}\frac{q^\nu}{M}g_2(q^2)+\frac{q_\mu}{M}g_3(q^2)\right]\gamma_5 u(P,S_z)
\end{aligned}
$$

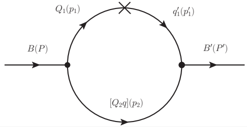
- In the diquark picture, a baryon state can be expanded as

$$
\begin{aligned}
|B(P,S,S_z)\rangle =& \int \{d^3p_1\}\{d^3p_2\}2(2\pi)^3\delta^3(\tilde{P}-\tilde{p}_1-\tilde{p}_2) \\
&\times \sum_{\lambda_1,\lambda_2}\Psi^{SS_z}(\tilde{p}_1,\tilde{p}_2,\lambda_1,\lambda_2)|q_1(p_1,\lambda_1)[di](p_2,\lambda_2)\rangle,
\end{aligned}
$$

Transition under the light front quark model



$\Longrightarrow$



- The transition can be calculated as

$$\langle B'(P', S_z')|(V-A)_\mu|B(P,S_z)\rangle = \int\{d^3p_2\}\frac{\phi'^*(x',k'_\perp)\phi(x,k_\perp)}{2\sqrt{p_1^+p_1'^+(p_1\cdot\bar{P}+m_1M_0)(p_1'\cdot\bar{P}'+m_1'M_0')}}$$
$$\times\,\bar{u}(\bar{P}',S_z')\bar{\Gamma}'(\not{p}_1'+m_1')\gamma_\mu(1-\gamma_5)(\not{p}_1+m_1)\Gamma u(\bar{P},S_z)$$

- The diquark can be either a spin-0 or a spin-1 state.
  The physical transition is a mixture of these two cases.

Results of the semileptonic decays: $\mathcal{B}_{cc} \to \mathcal{B}_c l^+ \nu_l$

channels	$\Gamma/$ GeV	$\mathcal{B}$	Γ_L/Γ_T
$\Xi_{cc}^{++} \to \Lambda_c^+ l^+ \nu_l$	1.05×10^{-14}	4.81×10^{-3}	8.52
$\Xi_{cc}^{++} \to \Sigma_c^+ l^+ \nu_l$	9.60×10^{-15}	4.38×10^{-3}	1.28
$\Xi_{cc}^{++} \to \Xi_c^+ l^+ \nu_l$	1.15×10^{-13}	5.25×10^{-2}	9.99
$\Xi_{cc}^{++} \to \Xi_c^{\prime +} l^+ \nu_l$	1.28×10^{-13}	5.84×10^{-2}	1.42
$\Xi_{cc}^{+} \to \Sigma_c^0 l^+ \nu_l$	1.91×10^{-14}	2.91×10^{-3}	1.28
$\Xi_{cc}^{+} \to \Xi_c^0 l^+ \nu_l$	1.14×10^{-13}	1.73×10^{-2}	9.99
$\Xi_{cc}^{+} \to \Xi_c^{\prime 0} l^+ \nu_l$	1.27×10^{-13}	1.93×10^{-2}	1.42
$\Omega_{cc}^{+} \to \Xi_c^0 l^+ \nu_l$	8.06×10^{-15}	3.31×10^{-3}	8.84
$\Omega_{cc}^{+} \to \Xi_c^{\prime 0} l^+ \nu_l$	9.34×10^{-15}	3.83×10^{-3}	1.28
$\Omega_{cc}^{+} \to \Omega_c^0 l^+ \nu_l$	2.55×10^{-13}	1.05×10^{-1}	1.42

- Some $\mathcal{BR}$s reach the order of %.
- $\mathcal{B}_{cc} \to \mathcal{B}_{c6} l^+ \nu$ and $\mathcal{B}_{cc} \to \mathcal{B}_{c\bar{3}} l^+ \nu$ have different polarization contributions.

Results of the nonleptonic decays under FA: $\Xi_{cc}^{++} \to \mathcal{B}_c(P, V, A)$

channels	$\mathcal{B}$	channels	$\mathcal{B}$
$\Xi_{cc}^{++} \to \Lambda_c^+ \pi^+$	4.05×10^{-3}	$\Xi_{cc}^{++} \to \Lambda_c^+ \rho^+$	1.06×10^{-2}
$\Xi_{cc}^{++} \to \Lambda_c^+ a_1^+$	4.66×10^{-3}	$\Xi_{cc}^{++} \to \Lambda_c^+ K^+$	3.55×10^{-4}
$\Xi_{cc}^{++} \to \Lambda_c^+ K^{*+}$	4.98×10^{-4}		
$\Xi_{cc}^{++} \to \Sigma_c^+ \pi^+$	2.62×10^{-3}	$\Xi_{cc}^{++} \to \Sigma_c^+ \rho^+$	1.13×10^{-2}
$\Xi_{cc}^{++} \to \Sigma_c^+ K^{*+}$	5.83×10^{-4}	$\Xi_{cc}^{++} \to \Sigma_c^+ K^+$	1.92×10^{-4}
$\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$	7.14×10^{-2}	$\Xi_{cc}^{++} \to \Xi_c^+ \rho^+$	1.38×10^{-1}
$\Xi_{cc}^{++} \to \Xi_c^+ K^{*+}$	5.44×10^{-3}	$\Xi_{cc}^{++} \to \Xi_c^+ K^+$	5.97×10^{-3}
$\Xi_{cc}^{++} \to \Xi_c^{\prime +} \pi^+$	5.00×10^{-2}	$\Xi_{cc}^{++} \to \Xi_c^{\prime +} \rho^+$	1.88×10^{-1}
$\Xi_{cc}^{++} \to \Xi_c^{\prime +} K^{*+}$	8.54×10^{-3}	$\Xi_{cc}^{++} \to \Xi_c^{\prime +} K^+$	3.41×10^{-3}

$\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$ seem easy to be observed in experiments.

Results of the nonleptonic decays under FA: $\Xi_{cc}^{+} \to \mathcal{B}_c(P, V, A)$

channels	$\mathcal{B}$	channels	$\mathcal{B}$
$\Xi_{cc}^{+} \to \Sigma_c^0 \pi^+$	1.74×10^{-3}	$\Xi_{cc}^{+} \to \Sigma_c^0 \rho^+$	7.49×10^{-3}
$\Xi_{cc}^{+} \to \Sigma_c^0 K^{*+}$	3.88×10^{-4}	$\Xi_{cc}^{+} \to \Sigma_c^0 K^+$	1.28×10^{-4}
$\Xi_{cc}^{+} \to \Xi_c^0 \pi^+$	2.36×10^{-2}	$\Xi_{cc}^{+} \to \Xi_c^0 \rho^+$	4.55×10^{-2}
$\Xi_{cc}^{+} \to \Xi_c^0 K^{*+}$	1.79×10^{-3}	$\Xi_{cc}^{+} \to \Xi_c^0 K^+$	1.98×10^{-3}
$\Xi_{cc}^{+} \to \Xi_c^{\prime 0} \pi^+$	1.66×10^{-2}	$\Xi_{cc}^{+} \to \Xi_c^{\prime 0} \rho^+$	6.23×10^{-2}
$\Xi_{cc}^{+} \to \Xi_c^{\prime 0} K^{*+}$	2.82×10^{-3}	$\Xi_{cc}^{+} \to \Xi_c^{\prime 0} K^+$	1.13×10^{-3}

$\Xi_{cc}^{+} \to \Xi_c^0 \pi^+$ seem easy to be observed in experiments.

Results of the nonleptonic decays under FA: $\Omega_{cc} \to \mathcal{B}_c(P, V, A)$

channels	$\mathcal{B}$	channels	$\mathcal{B}$
$\Omega_{cc}^+ \to \Xi_c^0 \pi^+$	3.22×10^{-3}	$\Omega_{cc}^+ \to \Xi_c^0 \rho^+$	7.93×10^{-3}
$\Omega_{cc}^+ \to \Xi_c^0 a_1^+$	1.55×10^{-3}	$\Omega_{cc}^+ \to \Xi_c^0 K^+$	2.82×10^{-4}
$\Omega_{cc}^+ \to \Xi_c^0 K^{*+}$	3.59×10^{-4}		
$\Omega_{cc}^+ \to \Xi_c^{\prime 0} \pi^+$	2.31×10^{-3}	$\Omega_{cc}^+ \to \Xi_c^{\prime 0} \rho^+$	1.00×10^{-2}
$\Omega_{cc}^+ \to \Xi_c^{\prime 0} K^{*+}$	5.18×10^{-4}	$\Omega_{cc}^+ \to \Xi_c^{\prime 0} K^+$	1.70×10^{-4}
$\Omega_{cc}^+ \to \Omega_c^0 \pi^+$	8.95×10^{-2}	$\Omega_{cc}^+ \to \Omega_c^0 \rho^+$	3.39×10^{-1}
$\Omega_{cc}^+ \to \Omega_c^0 K^{*+}$	1.54×10^{-2}	$\Omega_{cc}^+ \to \Omega_c^0 K^+$	6.13×10^{-3}

$\Omega_{cc}^+ \to \Omega_c^0 \pi^+$ seems easy to be observed in experiments.

A phenomenological model of two body nonleptonic weak decays I

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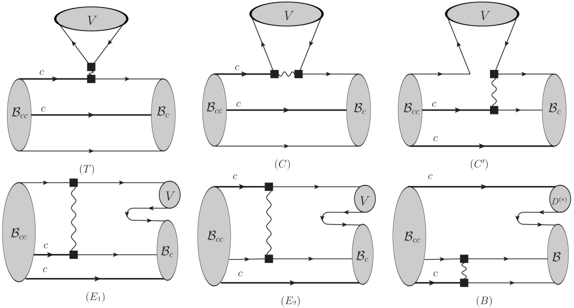


- Factorizable contribution under the factorization hypothesis (short distance)
  - $\mathcal{A}(\mathcal{B}_{cc} \to \mathcal{B}_c M)_{\rm SD} = \lambda \langle M(q)|J^{\mu}|0\rangle \langle \mathcal{B}_c(p_f)|J^{\rm w}_{\mu}|\mathcal{B}_{cc}(p_i)\rangle$
  - Decay constants of pseudoscalar & vector meson:
    $\langle 0|A_\mu|P(q)\rangle = if_P q_\mu \,,\ \langle 0|V_\mu|V(q)\rangle = f_V m_V \epsilon_\mu$

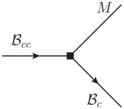
- The transition is parameterized as

$$
\begin{aligned}
& \langle \mathcal{B}_c(p', s_z') | (V-A)_\mu | \mathcal{B}_{cc}(p, s_z) \rangle \\
= \; & \bar{u}(p', s_z') \left[\gamma_\mu f_1(q^2) + i\sigma_{\mu\nu} \frac{q^\nu}{M} f_2(q^2) + \frac{q^\mu}{M} f_3(q^2) \right] u(p, s_z) \\
& - \bar{u}(p', s_z') \left[\gamma_\mu g_1(q^2) + i\sigma_{\mu\nu} \frac{q^\nu}{M} g_2(q^2) + \frac{q^\mu}{M} g_3(q^2) \right] \gamma_5 u(p, s_z).
\end{aligned}
$$

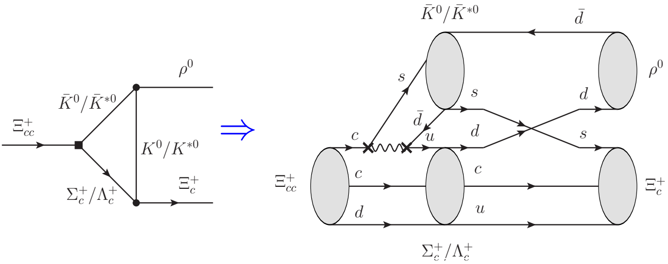
- The amplitudes of T diagram are given as

$$
\begin{aligned}
T_{\mathrm{SD}}(\mathcal{B}_{cc} \to \mathcal{B}_c P) \; = \; & i \frac{G_F}{\sqrt{2}} V_{cq}^* V_{uD} a_1 f_P \bar{u}(p', s_z') \left[(M - M') f_1(m_P^2) + (M + M') g_1(m_P^2) \gamma_5 \right] \\
& \times u(p, s_z) \, , \\
T_{\mathrm{SD}}(\mathcal{B}_{cc} \to \mathcal{B}_c V) \; = \; & \frac{G_F}{\sqrt{2}} V_{cq}^* V_{uD} a_1 f_V \epsilon_\mu^* \bar{u}(p', s_z') \left[\left(f_1(m_V^2) - \frac{M + M'}{M} f_2(m_V^2) \right) \gamma^\mu \right. \\
& + \frac{2}{M} f_2(m_V^2) p'^\mu - \left(g_1(m_V^2) + \frac{M - M'}{M} g_2(m_V^2) \right) \gamma^\mu \gamma_5 \\
& \left. - \frac{2}{M} g_2(m_V^2) p'^\mu \gamma_5 \right] u(p, s_z) \, ,
\end{aligned}
$$

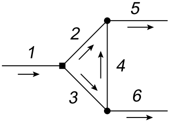
- At hadron level the weak transition can be depicted as



- Nonfactorizable contributions treated as final state interactions (long distance)
  - Nonperturbative dynamics
  - The leading contribution is realized by one particle exchange between two intermediate states, Eg.



- Calculation performed with optical theorem [PRD71,014030]



The absorptive part

$$\mathcal{A}bs\, M(P1 \to P5P6) = \frac{1}{2}\int \frac{d^3p_2 d^3p_3}{(2\pi)^6 4E_2E_3}(2\pi)^4\delta^4(p_5+p_6-p_2-p_3) \times M(p_1 \to p_2p_3)T^*(p_5p_6 \to p_2p_3)$$

The dispersive part can be calculated with the dispersion relation. It suffers from large ambiguities and is usually neglected.

- To render the frmework make sense in the meaning of perturbative calculation, a factor is associated with No. 4 particle to account for its off-shell effect
$$F(t,m) = \left(\frac{\Lambda^2-m^2}{\Lambda^2-t}\right)^n \text{ with } \Lambda = m + \eta\Lambda_{\rm QCD}.$$

An example: $\Xi_{cc}^{+} \to \Xi_c^{+}\rho^0$ [L.J. Jiang, B. He, R.H. Li, EPJC 78 (2018) no.11, 961]

Lagrangian at hadron level:

$$\mathcal{L}_{eff} = \mathcal{L}_{\pi hh} + \mathcal{L}_{\rho hh} + \mathcal{L}_{\pi\mathcal{B}\mathcal{B}} + \mathcal{L}_{\rho\mathcal{B}\mathcal{B}} + \mathcal{L}_{\rho\pi\pi} + \mathcal{L}_{\rho\rho\rho} + \mathcal{L}_{\rho DD} + \mathcal{L}_{\pi D^* D} + \mathcal{L}_{\rho D^* D^*}$$

$$\mathcal{L}_{\pi hh} = g_{\pi\mathcal{B}_6\mathcal{B}_6} Tr[\bar{\mathcal{B}}_6 i\gamma_5 \Pi \mathcal{B}_6] + g_{\pi\mathcal{B}_{\bar{3}}\mathcal{B}_{\bar{3}}} Tr[\bar{\mathcal{B}}_{\bar{3}} i\gamma_5 \Pi \mathcal{B}_{\bar{3}}] + \{g_{\pi\mathcal{B}_6\mathcal{B}_{\bar{3}}} Tr[\bar{\mathcal{B}}_6 i\gamma_5 \Pi \mathcal{B}_{\bar{3}}] + h.c.\}$$

$$\begin{aligned}\mathcal{L}_{\rho hh} = & f_{1\rho\mathcal{B}_6\mathcal{B}_6} Tr[\bar{\mathcal{B}}_6 \gamma_\mu V^\mu \mathcal{B}_6] + \frac{f_{2\rho\mathcal{B}_6\mathcal{B}_6}}{2m_6} Tr[\bar{\mathcal{B}}_6 \sigma_{\mu\nu} \partial^\mu V^\nu \mathcal{B}_6] \\ & + f_{1\rho\mathcal{B}_{\bar{3}}\mathcal{B}_{\bar{3}}} Tr[\bar{\mathcal{B}}_{\bar{3}} \gamma_\mu V^\mu \mathcal{B}_{\bar{3}}] + \frac{f_{2\rho\mathcal{B}_{\bar{3}}\mathcal{B}_{\bar{3}}}}{2m_{\bar{3}}} Tr[\bar{\mathcal{B}}_{\bar{3}} \sigma_{\mu\nu} \partial^\mu V^\nu \mathcal{B}_{\bar{3}}] \\ & + \{f_{1\rho\mathcal{B}_6\mathcal{B}_{\bar{3}}} Tr[\bar{\mathcal{B}}_6 \gamma_\mu V^\mu \mathcal{B}_{\bar{3}}] + \frac{f_{2\rho\mathcal{B}_6\mathcal{B}_{\bar{3}}}}{m_6 + m_{\bar{3}}} Tr[\bar{\mathcal{B}}_6 \sigma_{\mu\nu} \partial^\mu V^\nu \mathcal{B}_{\bar{3}}] + h.c.\}\end{aligned}$$

$$\mathcal{L}_{\pi\mathcal{B}\mathcal{B}} = g_{\pi\mathcal{B}\mathcal{B}} Tr[\bar{\mathcal{B}} i\gamma_5 \Pi \mathcal{B}]$$

$$\mathcal{L}_{\rho\mathcal{B}\mathcal{B}} = f_{1\rho\mathcal{B}\mathcal{B}} Tr[\bar{\mathcal{B}} \gamma_\mu V^\mu \mathcal{B}] + \frac{f_{2\rho\mathcal{B}\mathcal{B}}}{2m_{\mathcal{B}}} Tr[\bar{\mathcal{B}} \sigma_{\mu\nu} \partial^\mu V^\nu \mathcal{B}]$$

$$\mathcal{L}_{\rho\pi\pi} = \frac{ig_{\rho\pi\pi}}{\sqrt{2}} Tr[V^\mu [\Pi, \partial_\mu \Pi]]$$

$$\mathcal{L}_{\rho\rho\rho} = \frac{ig_{\rho\rho\rho}}{\sqrt{2}} Tr[(\partial_\nu V_\mu - \partial_\mu V_\nu) V^\mu V^\nu] = \frac{ig_{\rho\rho\rho}}{\sqrt{2}} Tr[(\partial_\nu V_\mu V^\mu - V^\mu \partial_\nu V_\mu) V^\nu]$$

An example: $\Xi_{cc}^{+} \to \Xi_c^{+}\rho^0$ [L.J. Jiang, B. He, R.H. Li, EPJC 78 (2018) no.11, 961]

Multiplets of particles:

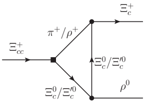
$$\Pi = \begin{pmatrix} \frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & \pi^+ & K^+ \\ \pi^- & -\frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & K^0 \\ K^- & \bar{K}^0 & -\sqrt{\frac{2}{3}}\eta \end{pmatrix}, \mathcal{B}_6 = \begin{pmatrix} \Sigma_c^{++} & \frac{1}{\sqrt{2}}\Sigma_c^{+} & \frac{1}{\sqrt{2}}\Xi_c^{\prime +} \\ \frac{1}{\sqrt{2}}\Sigma_c^{+} & \Sigma_c^{0} & \frac{1}{\sqrt{2}}\Xi_c^{\prime 0} \\ \frac{1}{\sqrt{2}}\Xi_c^{\prime +} & \frac{1}{\sqrt{2}}\Xi_c^{\prime 0} & \Omega_c \end{pmatrix},$$

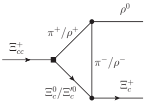
$$V = \begin{pmatrix} \frac{\rho^0}{\sqrt{2}} + \frac{\omega}{\sqrt{2}} & \rho^+ & K^{*+} \\ \rho^- & -\frac{\rho^0}{\sqrt{2}} + \frac{\omega}{\sqrt{2}} & K^{*0} \\ K^{*-} & \bar{K}^{*0} & \phi \end{pmatrix}, \quad \mathcal{B}_{\bar{3}} = \begin{pmatrix} 0 & \Lambda_c^{+} & \Xi_c^{+} \\ -\Lambda_c^{+} & 0 & \Xi_c^{0} \\ -\Xi_c^{+} & -\Xi_c^{0} & 0 \end{pmatrix},$$

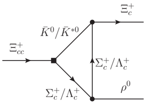
$$\mathcal{B} = \begin{pmatrix} \frac{\Sigma^0}{\sqrt{2}} + \frac{\Lambda}{\sqrt{6}} & \Sigma^+ & p \\ \Sigma^- & -\frac{\Sigma^0}{\sqrt{2}} + \frac{\Lambda}{\sqrt{6}} & n \\ \Xi^- & \Xi^0 & -\frac{2}{\sqrt{6}}\Lambda \end{pmatrix}. \qquad (1)$$

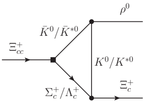
A phenomenological model III

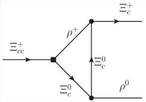
An example: $\Xi_{cc}^{+} \to \Xi_c^{+}\rho^0$ [L.J. Jiang, B. He, R.H. Li, EPJC 78 (2018) no.11, 961]

$\mathcal{M}(\Xi_{cc}^{+} \to \Xi_c^{+}\rho^0) =$ 

$+$ 

$+$ 

$+$ 

$\mathcal{A}bs$ 

$$= -\int \frac{|\vec{p}_2|\sin\theta\, d\theta\, d\varphi}{32\pi^2 m_{\Xi_{cc}^+}} \frac{G_F}{\sqrt{2}} V_{cs}^* V_{ud}\, a_1 f_\rho \frac{F^2(t, m_{\Xi_c^0})}{t - m^2_{\Xi_c^0}} \left(-g^{\beta\nu} + \frac{p_2^\beta p_2^\nu}{m_\rho^2}\right)\epsilon_6^{*\alpha}$$

$$\times \bar{u}(p_5, s_z') \left[f_{1\Xi_c^+\Xi_c^0\rho^+}\gamma_\nu - i\frac{f_{2\Xi_c^+\Xi_c^0\rho^+}}{m_{\Xi_c^+} + m_{\Xi_c^0}}\sigma_{\mu\nu} p_2^\mu \right] (\not{p}_4 + m_{\Xi_c^0}) \left[f_{1\Xi_c^0\Xi_c^0\rho^0}\gamma_\alpha + i\frac{f_{2\Xi_c^0\Xi_c^0\rho^0}}{2m_{\Xi_c^0}}\sigma_{\rho\alpha} p_6^\rho \right]$$

$$\times (\not{p}_3 + m_{\Xi_c^0}) \left[\left(f_1(m_\rho^2) - \frac{m_{\Xi_{cc}^+} + m_{\Xi_c^0}}{m_{\Xi_{cc}^+}} f_2(m_\rho^2) \right)\gamma_\sigma + \frac{2}{m_{\Xi_{cc}^+}} f_2(m_\rho^2) p_{3\sigma} \right.$$

$$\left. - \left(g_1(m_\rho^2) + \frac{m_{\Xi_{cc}^+} - m_{\Xi_c^0}}{m_{\Xi_{cc}^+}} g_2(m_\rho^2) \right)\gamma_\sigma\gamma_5 - \frac{2}{m_{\Xi_{cc}^+}} g_2(m_\rho^2) p_{3\sigma}\gamma_5 \right] u(p_1, s_z)$$

An example: $\Xi_{cc}^{+} \to \Xi_c^{+} \rho^0$ [L.J. Jiang, B. He, R.H. Li, EPJC 78 (2018) no.11, 961]

$$
\begin{aligned}
& \mathcal{A}(\Xi_{cc} \to \Xi_c^{+} \rho^0) \\
= \quad & i\mathcal{A}bs \Big[M_b(\pi^+; \Xi_c^0; \Xi_c^0) + M_b(\rho^+; \Xi_c^0; \Xi_c^0) + M_b(\pi^+; \Xi_c^0; \Xi_c^{\prime 0}) + M_b(\rho^+; \Xi_c^0; \Xi_c^{\prime 0}) \\
& + M_b(\pi^+; \Xi_c^{\prime 0}; \Xi_c^0) + M_b(\rho^+; \Xi_c^{\prime 0}; \Xi_c^0) + M_b(\pi^+; \Xi_c^{\prime 0}; \Xi_c^{\prime 0}) + M_b(\rho^+; \Xi_c^{\prime 0}; \Xi_c^{\prime 0}) \\
& + M_c(\pi^+; \Xi_c^0; \pi^-) + M_c(\rho^+; \Xi_c^0; \rho^-) + M_c(\pi^+; \Xi_c^{\prime 0}; \pi^-) + M_c(\rho^+; \Xi_c^{\prime 0}; \rho^-) \\
& + M_e(\overline{K}^0; \Sigma_c^+; \Lambda_c^+) + M_e(\overline{K}^{*0}; \Sigma_c^+; \Lambda_c^+) + M_e(\overline{K}^0; \Lambda_c^+; \Sigma_c^+) + M_e(\overline{K}^{*0}; \Lambda_c^+; \Sigma_c^+) \\
& + M_f(\overline{K}^0; \Lambda_c^+; K^0) + M_f(\overline{K}^{*0}; \Lambda_c^+; K^{*0}) + M_f(\overline{K}^0; \Sigma_c^+; K^0) + M_f(\overline{K}^{*0}; \Sigma_c^+; K^{*0}) \Big]
\end{aligned}
$$

[F.S. Yu, H.Y. Jiang, R.H. Li, C.D. Lu, W. Wang, Z.X. Zhao, CPC42(2018)051001; arXiv:1703.09086]

Aimed at presenting ideal discovery decays of Ξ_{cc}^{++}

Short-distance contribution dominated processes

$$\mathcal{B}(\Xi_{cc}^{+} \to \Xi_c^0 \pi^+)/\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^+ \pi^+) = \mathcal{R}_\tau = 0.25 \sim 0.37$$

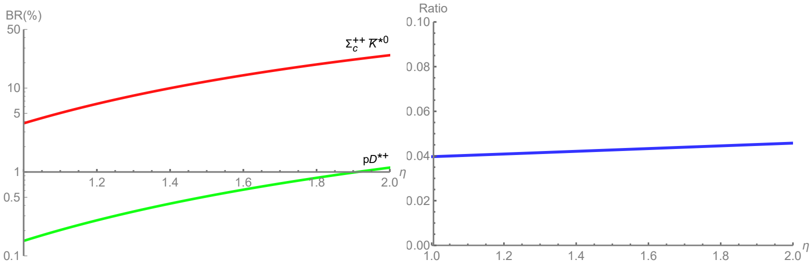
$$\mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+ \pi^+)/\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^+ \pi^+) = 0.056$$

$$\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^+ \ell^+ \nu)/\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^+ \pi^+) = 0.71$$

Long-distance contribution dominated processes

Baryons	Modes	$\mathcal{B}_{\rm LD}$
$\Xi_{cc}^{++}(ccu)$	$\Sigma_c^{++}(2455)\overline{K}^{*0}$	defined as 1
	pD^{*+}	0.04
	pD^+	0.0008
$\Xi_{cc}^{+}(ccd)$	$\Lambda_c^+\overline{K}^{*0}$	$(\mathcal{R}_\tau/0.3) \times 0.22$
	$\Sigma_c^{++}(2455)K^-$	$(\mathcal{R}_\tau/0.3) \times 0.01$
	$\Xi_c^+\rho^0$	$(\mathcal{R}_\tau/0.3) \times 0.04$
	ΛD^+	$(\mathcal{R}_\tau/0.3) \times 0.004$
	pD^0	$(\mathcal{R}_\tau/0.3) \times 0.001$

Sensitivity of observables to η:



A mathematica package "*triangle*"

- Motivation: Massive calculation in $\mathcal{B}_{cc} \to \mathcal{B}_c V$ decays.
- Aimed at the automatic calculation of *our triangle diagram*.
- Now it is used like this

```
In[1]:= << Lirh`triangle`;

This package is developped by Run–Hui Li @ Inner
    Mongolia University. Questions and debug reports are welcomed to lirh@imu.edu.cn.

In[2]:= TriDiagram[{"bd0001", "mp0003", "bc3002", "mp0006", "mv0008", "bc6001"}, {1, 3, 1}]
Out[2]= (-1.3369 × 10^-7 + 1.11077 × 10^-25 i)
```

- Still in development.

$\Xi_{cc}^{++} \to \mathcal{B}_c V$ branching fractions

Channels	$\mathcal{BR}(\%)$	Contributions	CKM	Channels	$\mathcal{BR}(\%)$	Contributions	CKM
$\Xi_{cc}^{++} \to \Sigma_c^{++}\bar{K}^{*0}$	$5.40^{+5.59}_{-3.66}$	$C_{\rm SD}$, C	CF	$\Xi_{cc}^{++} \to \Xi_c^{+}\rho^{+}$	$15.98^{+5.33}_{-3.35}$	$T_{\rm SD}$, T, C'	CF
$\Xi_{cc}^{++} \to \Xi_c^{'+}\rho^{+}$	$16.54^{+1.25}_{-0.72}$	$T_{\rm SD}$, T, C'	CF	$\Xi_{cc}^{++} \to \Sigma_c^{+}\rho^{+}$	$1.05^{+0.08}_{-0.06}$	$T_{\rm SD}$, T, C'	SCS
$\Xi_{cc}^{++} \to \Lambda_c^{+}\rho^{+}$	$0.95^{+0.04}_{-0.03}$	$T_{\rm SD}$, T, C'	SCS	$\Xi_{cc}^{++} \to \Sigma_c^{++}\rho^{0}$	$0.45^{+0.51}_{-0.31}$	$C_{\rm SD}$, C	SCS
$\Xi_{cc}^{++} \to \Sigma_c^{++}\omega$	$0.14^{+0.16}_{-0.09}$	$C_{\rm SD}$, C	SCS	$\Xi_{cc}^{++} \to \Sigma_c^{++}\phi$	$0.09^{+0.08}_{-0.06}$	$C_{\rm SD}$, C	SCS
$\Xi_{cc}^{++} \to \Xi_c^{+}K^{*+}$	$0.59^{+0.16}_{-0.09}$	$T_{\rm SD}$, T, C'	SCS	$\Xi_{cc}^{++} \to \Xi_c^{'+}K^{*+}$	$0.80^{+0.10}_{-0.05}$	$T_{\rm SD}$, T, C'	SCS
$\Xi_{cc}^{++} \to \Sigma_c^{+}K^{*+}$	$0.06^{+0.00}_{-0.01}$	$T_{\rm SD}$, T, C'	DCS	$\Xi_{cc}^{++} \to \Lambda_c^{+}K^{*+}$	$0.05^{+0.00}_{-0.00}$	$T_{\rm SD}$, T, C'	DCS
$\Xi_{cc}^{++} \to \Sigma_c^{++}K^{*0}$	$0.02^{+0.02}_{-0.01}$	$C_{\rm SD}$, C	DCS				

- Confirm that $\Xi_{cc}^{++} \to \Sigma_c^{++}\bar{K}^{*0}$ has the largest branching fraction in this mode.
- Confirm that T is the dominating contribution when it appears.
- Confirm the branching fractions in Ref. [EPJC 77(2017)781].

$\Xi_{cc}^{++} \to \mathcal{B}_c V$ (decay widths)

Channels	Γ/GeV	CKM	Channels	Γ/GeV	CKM
$\Xi_{cc}^{+} \to \Sigma_c^{+}\overline{K}^{*0}$	$(8.42^{+8.87}_{-5.74}) * 10^{-14}$	CF	$\Xi_{cc}^{+} \to \Lambda_c^{+}\overline{K}^{*0}$	$(7.06^{+7.68}_{-4.86}) * 10^{-14}$	CF
$\Xi_{cc}^{+} \to \Xi_c^{0}\rho^{+}$	$(3.83^{+0.47}_{-0.37}) * 10^{-13}$	CF	$\Xi_{cc}^{+} \to \Xi_c^{\prime 0}\rho^{+}$	$(4.77^{+0.31}_{-0.24}) * 10^{-13}$	CF
$\Xi_{cc}^{+} \to \Xi_c^{+}\rho^{0}$	$(1.82^{+1.85}_{-1.22}) * 10^{-13}$	CF	$\Xi_{cc}^{+} \to \Xi_c^{\prime +}\rho^{0}$	$(6.13^{+6.23}_{-4.14}) * 10^{-14}$	CF
$\Xi_{cc}^{+} \to \Xi_c^{+}\omega$	$(1.63^{+1.87}_{-1.14}) * 10^{-14}$	CF	$\Xi_{cc}^{+} \to \Xi_c^{\prime +}\omega$	$(2.47^{+2.71}_{-1.70}) * 10^{-15}$	CF
$\Xi_{cc}^{+} \to \Sigma_c^{++}K^{*-}$	$(7.38^{+7.83}_{-5.02}) * 10^{-16}$	CF	$\Xi_{cc}^{+} \to \Xi_c^{+}\phi$	$(5.12^{+5.59}_{-3.52}) * 10^{-15}$	CF
$\Xi_{cc}^{+} \to \Xi_c^{\prime +}\phi$	$(9.90^{+10.24}_{-6.72}) * 10^{-17}$	CF	$\Xi_{cc}^{+} \to \Omega_c^{0}K^{*+}$	$(2.33^{+2.16}_{-1.54}) * 10^{-14}$	CF
$\Xi_{cc}^{+} \to \Sigma_c^{+}\rho^{0}$	$(1.31^{+1.50}_{-0.91}) * 10^{-14}$	SCS	$\Xi_{cc}^{+} \to \Lambda_c^{+}\rho^{0}$	$(3.36^{+3.95}_{-2.35}) * 10^{-15}$	SCS
$\Xi_{cc}^{+} \to \Sigma_c^{+}\omega$	$(2.21^{+2.37}_{-1.52}) * 10^{-15}$	SCS	$\Xi_{cc}^{+} \to \Lambda_c^{+}\omega$	$(1.01^{+1.12}_{-0.70}) * 10^{-15}$	SCS
$\Xi_{cc}^{+} \to \Sigma_c^{0}\rho^{+}$	$(6.01^{+0.57}_{-0.43}) * 10^{-14}$	SCS	$\Xi_{cc}^{+} \to \Sigma_c^{+}\phi$	$(1.54^{+1.40}_{-1.01}) * 10^{-15}$	SCS
$\Xi_{cc}^{+} \to \Lambda_c^{+}\phi$	$(2.61^{+2.67}_{-1.76}) * 10^{-15}$	SCS	$\Xi_{cc}^{+} \to \Xi_c^{0}K^{*+}$	$(1.30^{+0.00}_{-0.00}) * 10^{-14}$	SCS
$\Xi_{cc}^{+} \to \Xi_c^{\prime 0}K^{*+}$	$(2.19^{+0.19}_{-0.10}) * 10^{-14}$	SCS	$\Xi_{cc}^{+} \to \Xi_c^{+}K^{*0}$	$(1.00^{+0.86}_{-0.64}) * 10^{-15}$	SCS
$\Xi_{cc}^{+} \to \Xi_c^{\prime +}K^{*0}$	$(1.53^{+1.47}_{-1.01}) * 10^{-15}$	SCS	$\Xi_{cc}^{+} \to \Sigma_c^{++}\rho^{-}$	$(9.08^{+9.39}_{-6.14}) * 10^{-17}$	SCS
$\Xi_{cc}^{+} \to \Sigma_c^{+}K^{*0}$	$(4.87^{+5.02}_{-3.29}) * 10^{-16}$	DCS	$\Xi_{cc}^{+} \to \Lambda_c^{+}K^{*0}$	$(2.54^{+2.86}_{-1.76}) * 10^{-16}$	DCS
$\Xi_{cc}^{+} \to \Sigma_c^{0}K^{*+}$	$(2.88^{+0.00}_{-0.00}) * 10^{-15}$	DCS			

Estimated with $\tau_{\Xi_{cc}^{+}} = 45fs$, $\mathcal{BR}(\Xi_{cc}^{+} \to \Xi_c^{0}\rho^{+}) \in [2.4\%, 2.9\%]$,
$\mathcal{BR}(\Xi_{cc}^{+} \to \Xi_c^{\prime 0}\rho^{+}) \in [3.1\%, 3.5\%]$, $\mathcal{BR}(\Xi_{cc}^{+} \to \Xi_c^{+}\rho^{0}) \in [0.4\%, 2.5\%]$.

$\mathcal{B}_{cc} \to \mathcal{B}_c V$ decays & Discovery potentials of Ξ_{cc}^+ and Ω_{cc}

[L.J. Jiang, B. He, R.H. Li, EPJC 78 (2018) no.11, 961]

$\Omega_{cc}^{++} \to \mathcal{B}_c V$ (decay widths)

Channels	Γ/GeV	CKM	Channels	Γ/GeV	CKM
$\Omega_{cc}^+ \to \Xi_c^+ \overline{K}^{*0}$	$(1.38^{+1.49}_{-0.95}) * 10^{-13}$	CF	$\Omega_{cc}^+ \to \Xi_c^{\prime +} \overline{K}^{*0}$	$(2.64^{+2.72}_{-1.79}) * 10^{-13}$	CF
$\Omega_{cc}^+ \to \Omega_c^0 \rho^+$	$(8.75^{+0.00}_{-0.00}) * 10^{-13}$	CF	$\Omega_{cc}^+ \to \Sigma_c^+ \overline{K}^{*0}$	$(1.35^{+1.53}_{-0.96}) * 10^{-15}$	SCS
$\Omega_{cc}^+ \to \Lambda_c^+ \overline{K}^{*0}$	$(1.00^{+1.16}_{-0.70}) * 10^{-15}$	SCS	$\Omega_{cc}^+ \to \Xi_c^+ \rho^0$	$(4.28^{+4.78}_{-2.96}) * 10^{-14}$	SCS
$\Omega_{cc}^+ \to \Xi_c^{\prime +} \rho^0$	$(8.58^{+9.88}_{-5.98}) * 10^{-15}$	SCS	$\Omega_{cc}^+ \to \Xi_c^+ \omega$	$(8.22^{+9.60}_{-5.77}) * 10^{-15}$	SCS
$\Omega_{cc}^+ \to \Xi_c^{\prime +} \omega$	$(6.09^{+6.52}_{-4.18}) * 10^{-15}$	SCS	$\Omega_{cc}^+ \to \Xi_c^0 \rho^+$	$(2.87^{+0.69}_{-0.49}) * 10^{-14}$	SCS
$\Omega_{cc}^+ \to \Xi_c^{\prime 0} \rho^+$	$(2.85^{+0.19}_{-0.14}) * 10^{-14}$	SCS	$\Omega_{cc}^+ \to \Xi_c^+ \phi$	$(1.86^{+1.74}_{-1.23}) * 10^{-15}$	SCS
$\Omega_{cc}^+ \to \Xi_c^{\prime +} \phi$	$(9.45^{+8.84}_{-6.23}) * 10^{-15}$	SCS	$\Omega_{cc}^+ \to \Omega_c^0 K^{*+}$	$(4.18^{+0.02}_{-0.01}) * 10^{-14}$	SCS
$\Omega_{cc}^+ \to \Sigma_c^{++} K^{*-}$	$(1.63^{+2.06}_{-1.16}) * 10^{-17}$	SCS	$\Omega_{cc}^+ \to \Xi_c^{\prime +} K^{*0}$	$(4.77^{+5.07}_{-3.26}) * 10^{-16}$	DCS
$\Omega_{cc}^+ \to \Sigma_c^+ \phi$	$(8.45^{+9.15}_{-5.81}) * 10^{-17}$	DCS	$\Omega_{cc}^+ \to \Lambda_c^+ \phi$	$(4.25^{+4.64}_{-2.93}) * 10^{-17}$	DCS
$\Omega_{cc}^+ \to \Xi_c^0 K^{*+}$	$(1.00^{+0.01}_{-0.00}) * 10^{-15}$	DCS	$\Omega_{cc}^+ \to \Xi_c^{\prime 0} K^{*+}$	$(1.12^{+1.22}_{-0.77}) * 10^{-16}$	DCS
$\Omega_{cc}^+ \to \Xi_c^+ K^{*0}$	$(6.24^{+6.49}_{-4.23}) * 10^{-16}$	DCS	$\Omega_{cc}^+ \to \Sigma_c^{++} \rho^-$	$(1.20^{+1.38}_{-0.84}) * 10^{-17}$	DCS
$\Omega_{cc}^+ \to \Sigma_c^+ \rho^0$	$(4.27^{+4.87}_{-2.98}) * 10^{-17}$	DCS	$\Omega_{cc}^+ \to \Lambda_c^+ \rho^0$	$(4.10^{+4.74}_{-2.87}) * 10^{-17}$	DCS
$\Omega_{cc}^+ \to \Sigma_c^+ \omega$	$(1.74^{+2.05}_{-1.23}) * 10^{-17}$	DCS	$\Omega_{cc}^+ \to \Lambda_c^+ \omega$	$(1.76^{+2.23}_{-1.27}) * 10^{-17}$	DCS
$\Omega_{cc}^+ \to \Sigma_c^0 \rho^+$	$(1.39^{+1.62}_{-0.97}) * 10^{-16}$	DCS			

Estimated with $\tau_{\Omega_{cc}^+} = 75fs$, $\mathcal{BR}(\Omega_{cc}^+ \to \Xi_c^+ \overline{K}^{*0}) \in [0.5\%, 3.3\%]$,
$\mathcal{BR}(\Omega_{cc}^+ \to \Xi_c^{\prime +} \overline{K}^{*0}) \in [1.0\%, 6.1\%]$, $\mathcal{BR}(\Omega_{cc}^+ \to \Omega_c^0 \rho^+) \approx 10.0\%$.

Summary

- Theories on weak decays of doubly charmed baryons: the $SU(3)$ analysis, the light front quark model, the FSIs,......
- The form factors of a doubly heavy baryon to a singly heavy baryon are investigated, as well as the semileptonic decays and short distance dominated two body nonleptonic weak decays
- Based on the current results, the potential discovery channel for Ξ_{cc}^{+} are $\Xi_{cc}^{+} \to \Xi_{c}^{+}\rho^{0}$ and $\Xi_{cc}^{+} \to \Xi_{c}^{0}\pi^{+}$, those for Ω_{cc} are $\Omega_{cc}^{+} \to \Omega_{c}^{0}\pi^{+}$ and $\Omega_{cc}^{+} \to \Xi_{c}^{+}\overline{K}^{*0}$.
- There is still a long way to go.