From Topologies to Rescattering Dynamics in the Charmed Baryon Decays

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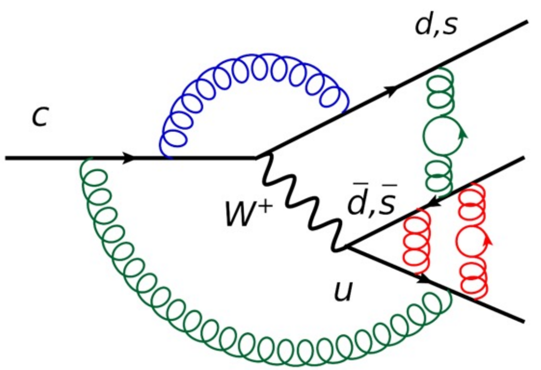
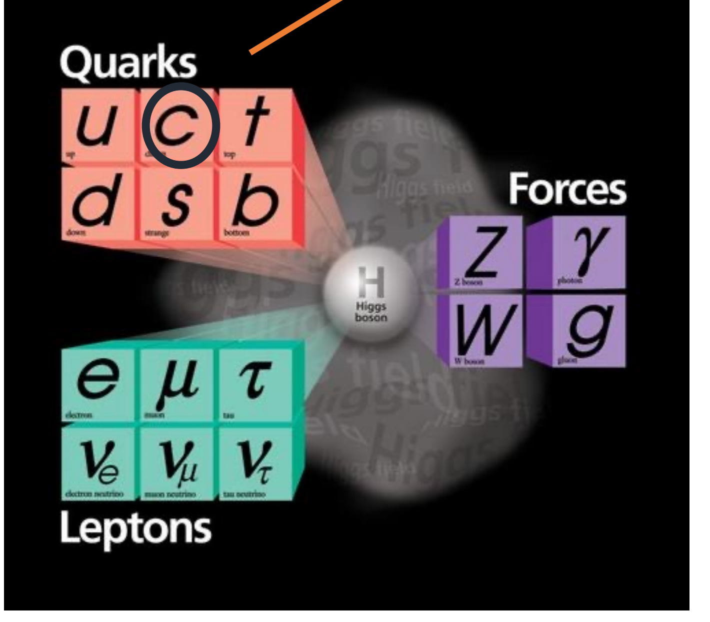
Charmed baryon weak decay

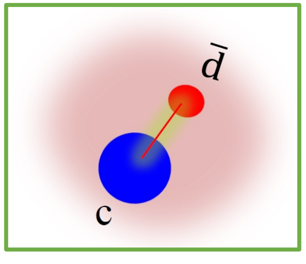
$m_c \simeq 1.3\, GeV$

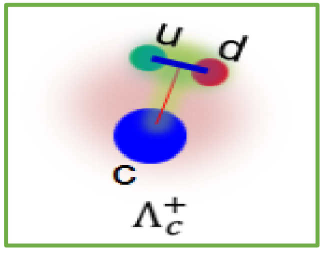
- **Charm physics: test SM and search for NP**
- **Non-perturbative**





- **Three quarks, complex system**





Meson .vs. Baryon

Rescattering Mechanism

- The non-perturbative QCD effects are modeled as an exchange of one particle between the two particles generated from short-distance tree emitted process.

$s - channel$ $t - channel$

- The branching fraction of discovery channel was predicted in the rescattering mechanism in 2017.

F. S. Yu, H. Y. Jiang, R. H. Li, C. D. Lu, W. Wang and Z. X. Zhao, Chin. Phys. C **42**, no. 5, 051001 (2018).

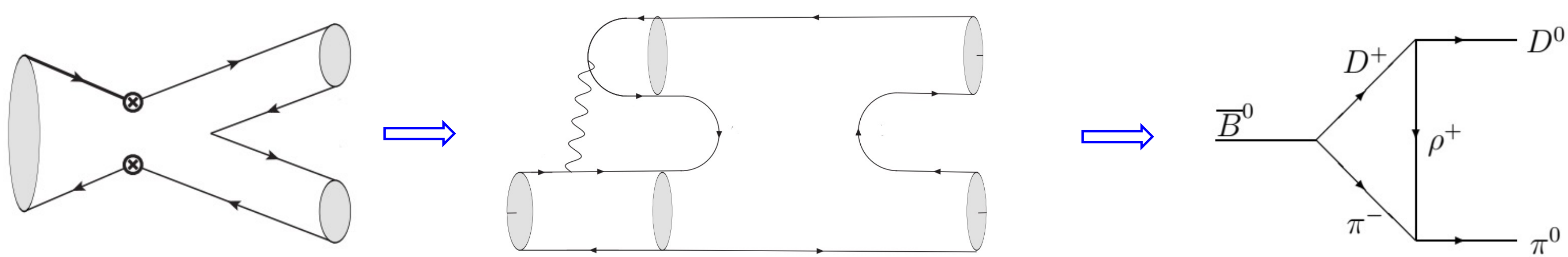
Rescattering Mechanism

- Writing amplitudes Chiral Lagrangian (A)

L. J. Jiang, B. He and R. H. Li, Eur. Phys. J. C 78, no.11, 961 (2018).
J. J. Han, H. Y. Jiang, W. Liu, Z. J. Xiao and F. S. Yu, Chin. Phys. C 45, no.5, 053105 (2021).

- Extracting from topological diagram via quark diagram (B)

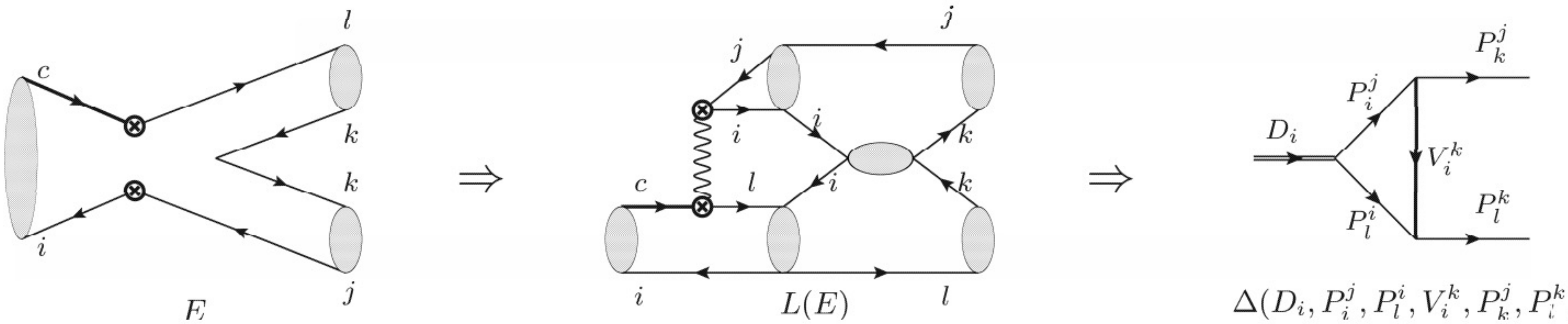
M. Ablikim, D. S. Du and M. Z. Yang, Phys. Lett. B 536, 34-42 (2002).
H. Y. Cheng, C. K. Chua and A. Soni, Phys. Rev. D 71, 014030 (2005).



E $T^{SD} \to E$

$$(A) \stackrel{?}{=} (B)$$

From topology to rescattering – meson decays



$D_i H^{il}_j P^j_k P^k_l$

↳

Propagator, Propagator

Set $H^{pm}_n = H^{il}_j$

$$\boxed{D_q H^{pm}_n P^n_p P^q_m} \cdot \boxed{P^p_n V^k_q P^j_k} \cdot \boxed{P^m_q V^q_k P^k_l} \cdot \boxed{\delta_{ip}\delta_{lm}\delta_{jn}} \cdot \boxed{\delta_{iq}}$$

T diagram, Strong vertex, Strong vertex, Set $D_q = D_i$

Propagator

Completeness

Baryon decays ？

Di Wang, JHEP **03**, 155 (2022).
Di Wang, Phys. Rev. D **105**, no.7, 073002 (2022).

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Topologies of charmed baryon decays

➢ Effective Hamiltonian

$$\mathcal{H}_{\rm eff} = \frac{G_F}{\sqrt{2}}\left[\sum_{q=d,s} V_{cq}^* V_{uq}\left(\sum_{q=1}^{2} C_i(\mu)O_i(\mu)\right) - V_{cb}^* V_{ub}\left(\sum_{i=3}^{6} C_i(\mu)O_i(\mu) + C_{8g}(\mu)O_{8g}(\mu)\right)\right]$$

$$\mathcal{H}_{\rm eff} = \sum_p \sum_{i,j,k=1}^{3} (H^{(p)})_{ij}^k O_{ij}^{(p)k} \qquad O_{ij}^{(p)k} = \frac{G_F}{\sqrt{2}} \sum_{\rm color} \sum_{\rm current} C_p(\bar{q}_i q_k)(\bar{q}_j c)$$

CKM **Operator**

➢ Hadrons

$$|M^\alpha\rangle = (M^\alpha)_j^i |M_j^i\rangle \qquad M^{\pi^0} = \begin{pmatrix} 1/\sqrt{2} & 0 & 0 \\ 0 & -1/\sqrt{2} & 0 \\ 0 & 0 & 0 \end{pmatrix}, \qquad \cdots$$

D. Wang, C. P. Jia and F. S. Yu, JHEP 09, 126 (2021).

Topology ⟷ Invariant Tensor

$$\mathcal{A}(B_{c\bar{3}}^{\gamma} \to B_8^{\alpha} M^{\beta}) = \langle B_8^{\alpha} M^{\beta} | \mathcal{H}_{\rm eff} | B_{c\bar{3}}^{\gamma} \rangle$$

$$= \sum_p \sum_{\rm Per.} \langle B_8^{ijk} M_m^l | O_{np}^q | [B_{c\bar{3}}]_{rs} \rangle \times (B_8^{\alpha})^{ijk} (M^{\beta})_m^l H_{np}^q (B_{c\bar{3}}^{\gamma})_{rs}$$

$$= \sum_{\omega} X_{\omega}^{(p)} (C_{\omega}^{(p)})_{\alpha\beta\gamma}$$

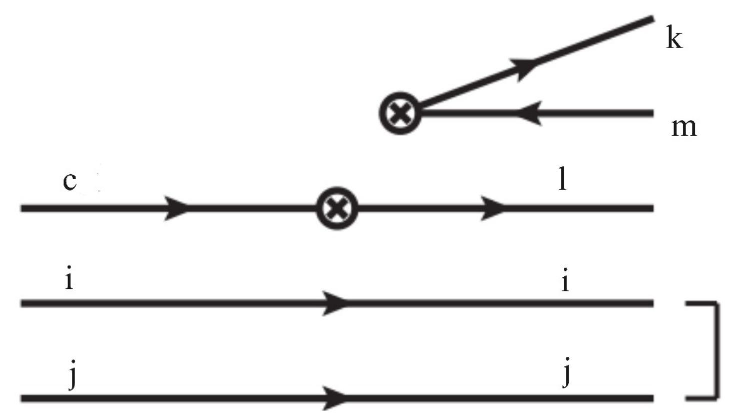
CG coefficient, mode-dependent

Reduced matrix element, mode-independent

Wigner-Eckart theorem

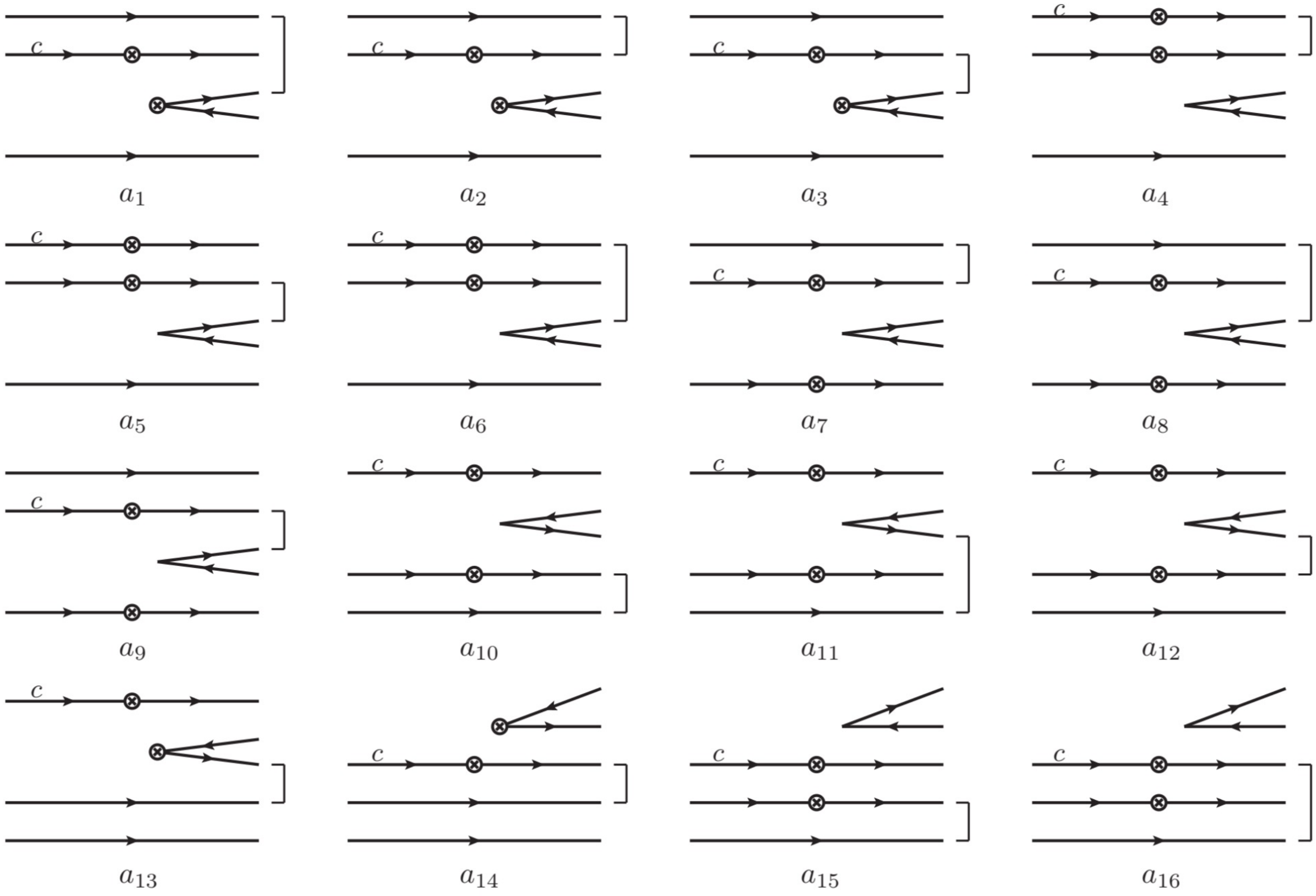
$$\langle jm | T_q^{(k)} | j'm' \rangle = \langle j'm'kq | jm \rangle \langle j | T^{(k)} | j' \rangle$$

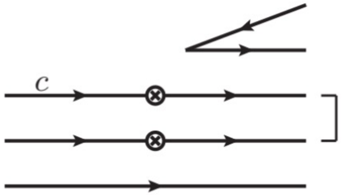
- Index-contraction ⟷ Quark flowing



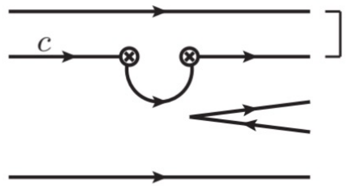
$$(B_{c\bar{3}})_{ij} H_{kl}^m M_m^k (B_8^A)^{ijl}$$

Topologies in charmed baryon decays

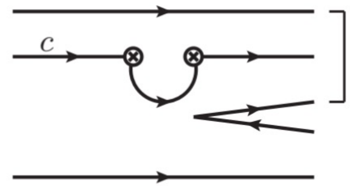




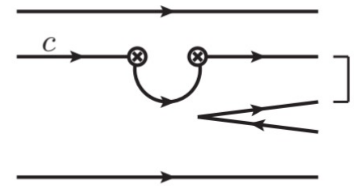
a_{17}



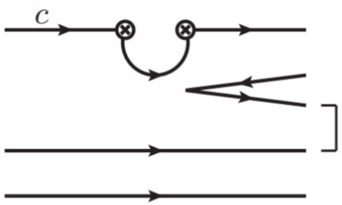
a_{18}



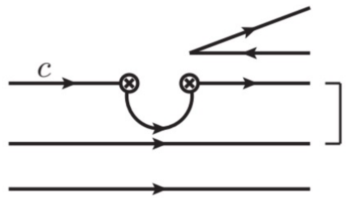
a_{19}



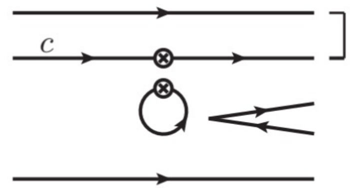
a_{20}



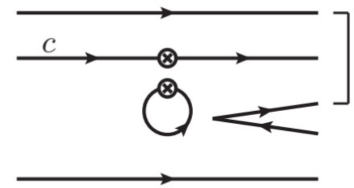
a_{21}



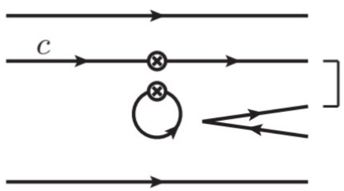
a_{22}



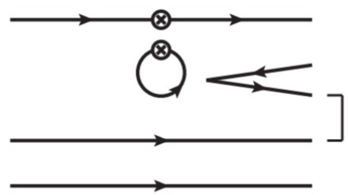
a_{23}

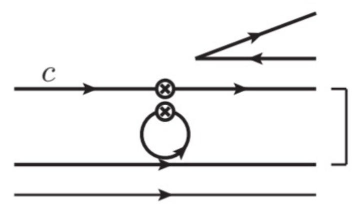


a_{24}

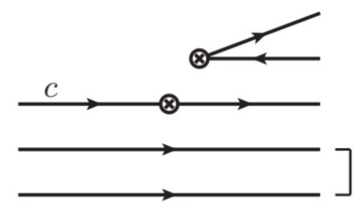


a_{25}

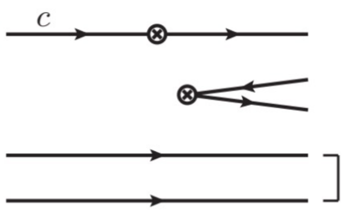

a_{26}



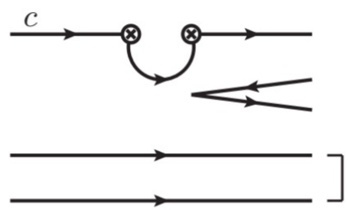
a_{27}



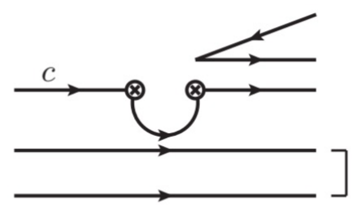
a_{28}



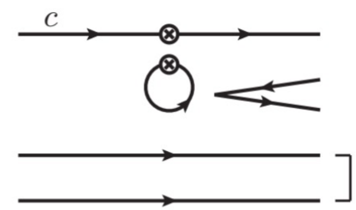
a_{29}



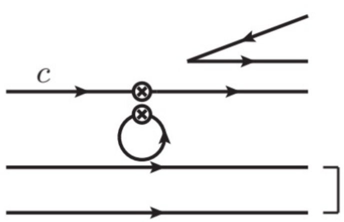
a_{30}



a_{31}



a_{32}



a_{33}

TDA and ChPT

- TDA: constructed via third-rank octet tensors

$$\mathcal{A}^S(B_{c\bar{3}} \to B_8^S M) =$$
$$a_1^S(B_{c\bar{3}})_{ij}H^m_{kl}M^i_m(B_8^S)^{jkl} + a_2^S(B_{c\bar{3}})_{ij}H^m_{kl}M^i_m(B_8^S)^{jlk} + a_3^S(B_{c\bar{3}})_{ij}H^m_{kl}M^i_m(B_8^S)^{klj}$$
$$+ a_4^S(B_{c\bar{3}})_{ij}H^i_{kl}M^j_m(B_8^S)^{klm} + a_5^S(B_{c\bar{3}})_{ij}H^i_{kl}M^j_m(B_8^S)^{kml} + a_6^S(B_{c\bar{3}})_{ij}H^i_{kl}M^j_m(B_8^S)^{lmk}$$
$$+ \quad \ldots$$

?

- ChPT: constructed via second-rank octet tensors

$$\mathcal{L}_{\mathcal{VPP}} = \frac{i}{\sqrt{2}} g_{VPP}\, Tr\,(\mathcal{V}^\mu\,[\mathcal{P}, \partial_\mu \mathcal{P}]),$$
$$\mathcal{L}_{\mathcal{BBP}} = D\, Tr(\overline{\mathcal{B}}\gamma^\mu\gamma_5\,\{\partial_\mu\mathcal{P}, \mathcal{B}\}) + F\, Tr(\overline{\mathcal{B}}\,\gamma^\mu\gamma_5[\partial_\mu\mathcal{P}, \mathcal{B}]),$$
$$\mathcal{L}_{\mathcal{BBV}} = D_V Tr(\overline{\mathcal{B}}\gamma^\mu\{\mathcal{V}_\mu, \mathcal{B}\}) + F_V Tr(\overline{\mathcal{B}}\gamma^\mu\gamma_5[\mathcal{V}_\mu, \mathcal{B}])$$
$$\cdots$$

Three indices → Two indices

- Reducing indices by Levi-Civita tensor

$$(B_{c\bar{3}})_{ij} = \epsilon_{ijk}(B_{c\bar{3}})^k$$

$$(B_8^A)^{ijk} = \epsilon^{ijl}(B_8)_l^k$$

$$(B_8^S)^{ijk} = \epsilon^{kil}(B_8)_l^j + \epsilon^{kjl}(B_8)_l^i$$

$$\begin{aligned}
&\mathcal{A}(B_{c\bar{3}} \to B_8 M) = \\
&\quad A_1(B_{c\bar{3}})^i H_{kl}^j M_i^l (B_8)_j^k + A_2(B_{c\bar{3}})^i H_{lk}^j M_j^l (B_8)_i^k + A_3(B_{c\bar{3}})^i H_{lk}^j M_i^l (B_8)_j^k \\
&+ A_4(B_{c\bar{3}})^i H_{kl}^j M_j^l (B_8)_i^k + A_5(B_{c\bar{3}})^i H_{ik}^j M_j^l (B_8)_l^k + A_6(B_{c\bar{3}})^i H_{il}^j M_k^l (B_8)_j^k \\
&+ A_7(\mathcal{B}_{c\bar{3}})^i H_{ki}^j M_j^l (B_8)_l^k + A_8(B_{c\bar{3}})^i H_{li}^j M_k^l (B_8)_j^k + +A_9(B_{c\bar{3}})^i H_{ik}^j M_l^l (B_8)_j^k \\
&+ A_{10}(B_{c\bar{3}})^i H_{ki}^j M_l^l (B_8)_j^k + A_{11}(B_{c\bar{3}})^i H_{kj}^j M_j^l (B_8)_i^k + A_{12}(B_{c\bar{3}})^i H_{lj}^j M_k^l (B_8)_i^k \\
&+ A_{13}(B_{c\bar{3}})^i H_{kj}^j M_l^l (B_8)_i^k + A_{14}(B_{c\bar{3}})^i H_{ij}^j M_k^l (B_8)_l^k + A_{15}(B_{c\bar{3}})^i H_{jl}^j M_k^l (B_8)_i^k \\
&+ A_{16}(B_{c\bar{3}})^i H_{jk}^j M_l^l (B_8)_i^k + A_{17}(B_{c\bar{3}})^i H_{jk}^j M_i^l (B_8)_l^k + A_{18}(B_{c\bar{3}})^i H_{ji}^j M_k^l (B_8)_l^k
\end{aligned}$$

Relations between 3- and 2-rank amplitudes

- Relation between third- and second-rank octets

$$(B_{c\bar{3}})_{ij} = \epsilon_{ijk}(B_{c\bar{3}})^k$$

$$(B_8^S)^{ijk} = \epsilon^{kil}(B_8)^j_l + \epsilon^{kjl}(B_8)^i_l$$

- Example

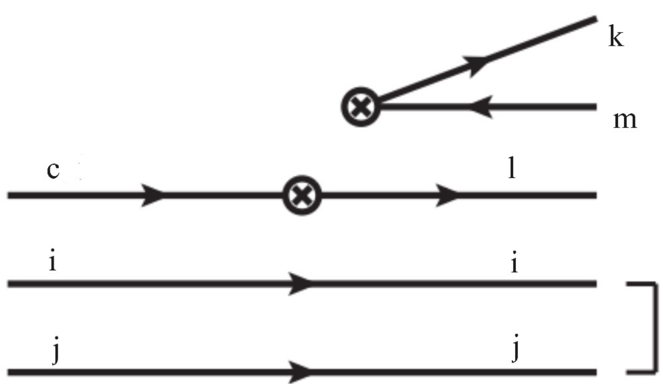
$$
\begin{aligned}
&a_1^S(B_{c\bar{3}})_{ij}H^m_{kl}M^i_m(B_8^S)^{jkl} = \\
&a_1^S\epsilon_{ijp}(B_{c\bar{3}})^p H^m_{kl}M^i_m\epsilon^{qlj}(B_8)^k_q + a_1^S\epsilon_{ijp}(B_{c\bar{3}})^p H^m_{kl}M^i_m\epsilon^{qlk}(B_8)^j_q \\
&= -a_1^S\,(B_{c\bar{3}})^i H^j_{lk}M^l_j(B_8)^k_i + 2a_1^S\,(B_{c\bar{3}})^i H^j_{kl}M^l_j(B_8)^k_i \\
&\quad + a_1^S\,(B_{c\bar{3}})^i H^j_{ik}M^l_j(B_8)^k_l - 2a_1^S\,(B_{c\bar{3}})^i H^j_{ki}M^l_j(B_8)^k_l
\end{aligned}
$$

$$\longrightarrow \quad A_2 = -\sqrt{6}\,a_1^S + ..., \qquad A_4 = 2\sqrt{6}\,a_1^S + ...,$$

$$A_5 = \sqrt{6}\,a_1^S + ..., \qquad A_7 = -2\sqrt{6}\,a_1^S + ...$$

Relations between 3- and 2-rank amplitudes

$$
\begin{aligned}
A_1 =& \sqrt{2}(a_6^A + a_{11}^A + a_{12}^A) - \sqrt{6}(a_4^S - a_5^S + 2a_{10}^S - a_{11}^S - a_{12}^S), \\
A_2 =& \sqrt{2}(-a_1^A + a_3^A - a_5^A - a_8^A - a_9^A + a_{14}^A + 2a_{28}^A) \\
& - \sqrt{6}(a_1^S - 2a_2^S + a_3^S - a_4^S + a_6^S - 2a_7^S + a_8^S + a_9^S + 3a_{14}^S), \\
A_3 =& \sqrt{2}(a_5^A + a_8^A + a_9^A) - \sqrt{6}(a_4^S - a_6^S + 2a_7^S - a_8^S - a_9^S), \\
& \cdots \\
A_{18} =& \sqrt{2}(-a_4^A + a_{23}^A - a_{25}^A) - \sqrt{6}(-a_5^S + a_6^S - a_{23}^S + 2a_{24}^S - a_{25}^S).
\end{aligned}
$$



$$A_2 \to A_i$$

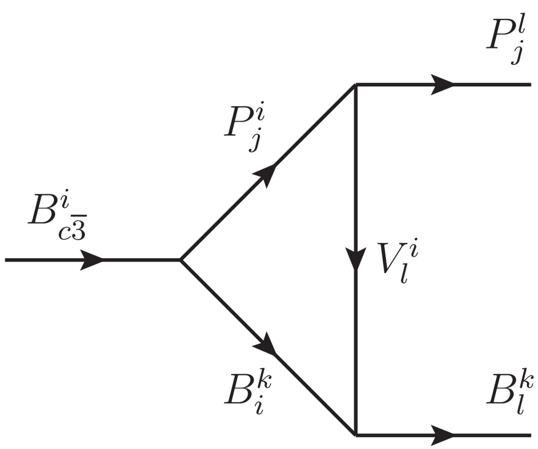
From topologies to re-scattering

➢ **S- and T-channels**

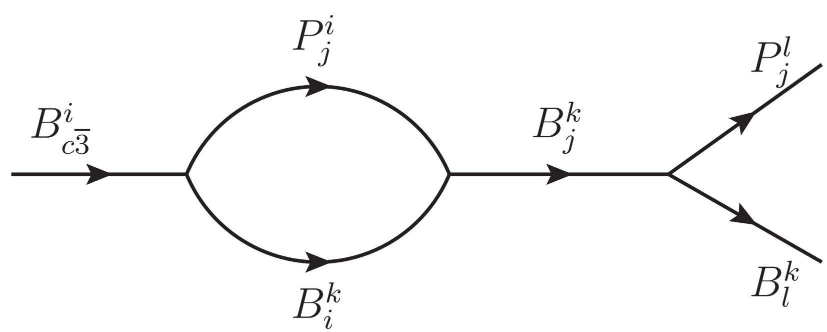
$$B^i_{c\bar{3}} H^j_{ik} P^l_j B^k_l$$

$$S(A_5)[i,j,k,l] = B^q_{c\bar{3}} H^n_{pm} P^p_n B^m_q \cdot P^n_p B^q_m B^m_n \cdot B^j_k P^l_j B^k_l \cdot \delta_{ip}\delta_{km}\delta_{jn} \cdot \delta_{iq},$$

$$T(A_5)[i,j,k,l] = B^q_{c\bar{3}} H^n_{pm} P^p_n B^m_q \cdot P^n_p V^q_l P^l_j \cdot B^q_m V^l_q B^k_l \cdot \delta_{ip}\delta_{km}\delta_{jn} \cdot \delta_{iq}.$$



$\Delta(B^i_{c\bar{3}}, P^i_j, B^k_i, V^i_l, P^l_j, B^k_l)$



$\Theta(B^i_{c\bar{3}}, P^i_j, B^k_i, B^k_j, P^l_j, B^k_l)$

Strong coupling

- **Strong coupling in tensor**

$$\mathcal{A}_{VPP} = \alpha^+ \, P_i^j V_k^i P_j^k + \alpha^- \, P_i^j V_j^k P_k^i,$$
$$\mathcal{A}_{BBP} = \beta^+ \, B_i^j P_k^i B_j^k + \beta^- \, B_i^j P_j^k B_k^i,$$
$$\mathcal{A}_{BBV} = \gamma^+ B_i^j V_k^i B_j^k + \gamma^- B_i^j V_j^k B_k^i.$$

- **Chiral Lagrangian**

$$\mathcal{L}_{\mathcal{VPP}} = \frac{i}{\sqrt{2}} g_{VPP} Tr\left(\mathcal{V}^\mu \left[\mathcal{P}, \partial_\mu \mathcal{P}\right]\right),$$
$$\mathcal{L}_{\mathcal{BBP}} = D\, Tr(\overline{\mathcal{B}}\gamma^\mu\gamma_5 \{\partial_\mu \mathcal{P}, \mathcal{B}\}) + F\, Tr(\overline{\mathcal{B}}\,\gamma^\mu\gamma_5[\partial_\mu \mathcal{P}, \mathcal{B}]),$$
$$\mathcal{L}_{\mathcal{BBV}} = D_V Tr(\overline{\mathcal{B}}\gamma^\mu\{\mathcal{V}_\mu, \mathcal{B}\}) + F_V Tr(\overline{\mathcal{B}}\gamma^\mu\gamma_5[\mathcal{V}_\mu, \mathcal{B}]).$$

$$\alpha^+ = -\alpha^- = \frac{i g_{VPP}}{\sqrt{2}} V^\mu P \partial_\mu P,$$

➡

$$\beta^+ = (D+F)\,\overline{B}\gamma^\mu\gamma_5\partial_\mu P B, \qquad \beta^- = (D-F)\,\overline{B}\gamma^\mu\gamma_5 B\partial_\mu P,$$
$$\gamma^+ = (D_V+F_V)\,\overline{B}\gamma^\mu V_\mu B, \qquad \gamma^- = (D_V-F_V)\,\overline{B}\gamma^\mu B V_\mu.$$

Contents

Examples

- $\Xi_c \to \Xi\pi$ system

$$\mathcal{A}(\Xi_c^0 \to \Xi^- \pi^+) = A_2 + A_5$$

$$\begin{aligned}
T(A_2)[u,d,s,u] &= \frac{1}{2}\Delta_{\alpha^+,\gamma^-}(\Xi_c^0, \pi^+, \Xi^-, \rho^0, \pi^+, \Xi^-) \\
&\quad - \frac{1}{2}\Delta_{\alpha^+,\gamma^-}(\Xi_c^0, \pi^+, \Xi^-, \omega, \pi^+, \Xi^-), \\
T(A_5)[u,d,s,u] &= \frac{1}{2}\Delta_{\alpha^+,\gamma^-}(\Xi_c^0, \pi^+, \Xi^-, \rho^0, \pi^+, \Xi^-) \\
&\quad + \frac{1}{2}\Delta_{\alpha^+,\gamma^-}(\Xi_c^0, \pi^+, \Xi^-, \omega, \pi^+, \Xi^-), \\
S(A_5)[u,d,s,u] &= \Theta_{\beta^-,\beta^-}(\Xi_c^0, \pi^+, \Xi^-, \Xi^0, \pi^+, \Xi^-).
\end{aligned}$$

- The $\omega\pi\pi$ coupling cancel each other.
- Consistent with C. P. Jia, H. Y. Jiang, J. P. Wang and F. S. Yu, [arXiv:2408.14959 [hep-ph]].

Examples

$$\mathcal{A}(\Xi_c^0 \to \Xi^0\pi^0) = (A_3 - A_5)/\sqrt{2}$$

$$\begin{aligned}
&\mathcal{A}_L(\Xi_c^0 \to \Xi^0\pi^0)\\
=&\frac{1}{\sqrt{2}}\{T(A_3)[u,d,s,u] - T(A_5)[u,d,s,d] - S(A_5)[u,d,s,u]\}\\
=&-\sqrt{2}\Delta_{\alpha^+,\gamma^-}(\Xi_c^0,\pi^+,\Xi^-,\rho^+,\pi^0,\Xi^0) + \frac{1}{\sqrt{2}}\Delta_{\beta^-,\beta^-}(\Xi_c^0,\pi^+,\Xi^-,\Xi^+,\Xi^0,\pi^0)\\
&-\Theta_{\beta^-,\beta^-}(\Xi_c^0,\pi^+,\Xi^-,\Xi^0,\pi^0,\Xi^0).
\end{aligned}$$

$$\mathcal{A}(\Xi_c^+ \to \Xi^0\pi^+) = -(A_2 + A_3)$$

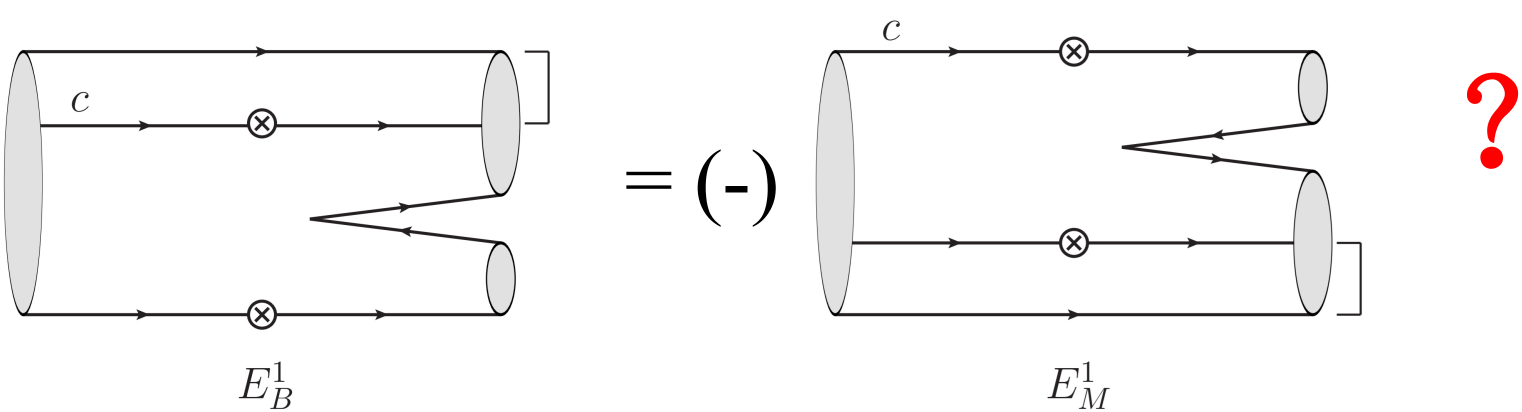
$$\begin{aligned}
&\mathcal{A}_L(\Xi_c^+ \to \Xi^0\pi^+)\\
=&-T(A_2)[u,d,s,u] - T(A_3)[d,d,s,u]\\
=&\Delta_{\alpha^+,\gamma^-}(\Xi_c^+,\pi^+,\Xi^0,\rho^0,\pi^+,\Xi^0) - \Delta_{\beta^-,\beta^-}(\Xi_c^+,\pi^+,\Xi^0,\Xi^+,\Xi^0,\pi^+).
\end{aligned}$$

Isospin: $\mathcal{A}(\Xi_c^0 \to \Xi^-\pi^+) + \sqrt{2}\mathcal{A}(\Xi_c^0 \to \Xi^0\pi^0) + \mathcal{A}(\Xi_c^+ \to \Xi^0\pi^+) = 0$

The Korner-Pati-Woo theorem

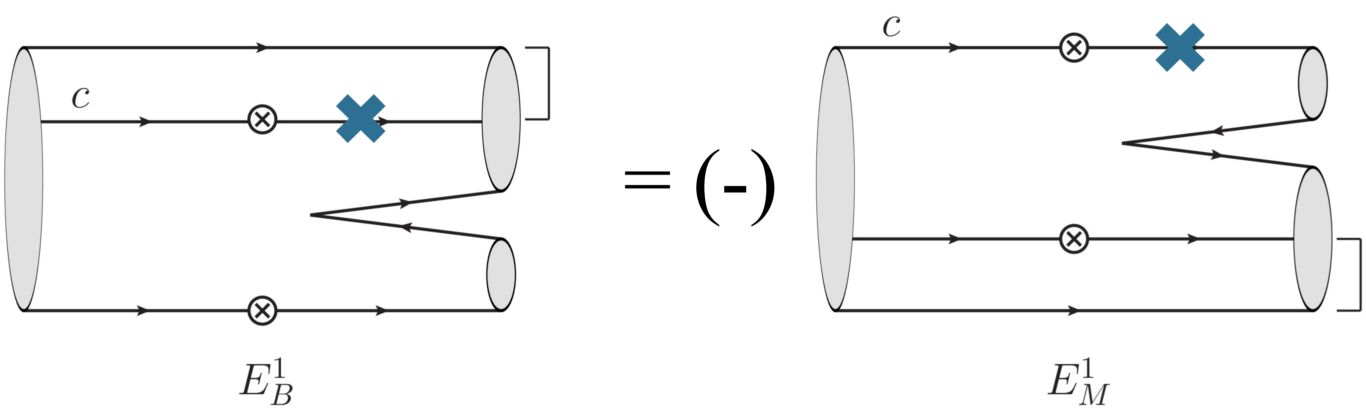
- If two quarks produced by weak operators enter a baryon, they are anti-symmetric in flavor

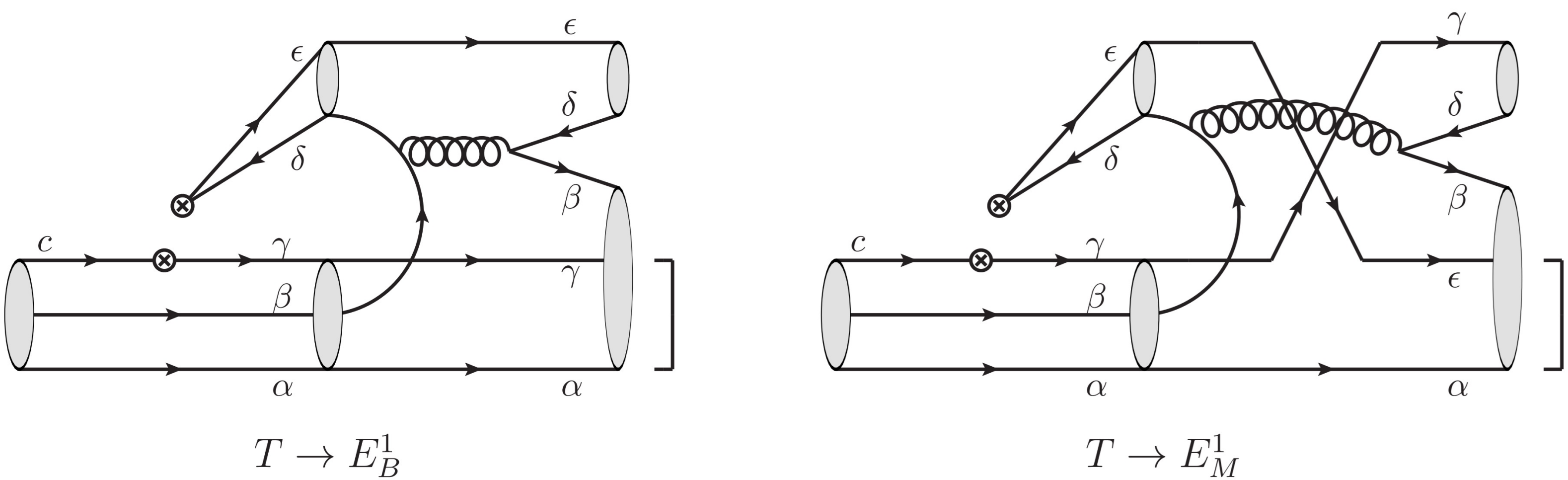
J. G. Korner, Nucl. Phys. B 25, 282-290 (1971). J. C. Pati and C. H. Woo, Phys. Rev. D 3, 2920-2922 (1971).



L. L. Chau, H. Y. Cheng and B. Tseng, Phys. Rev. D 54, 2132 (1996);
C. Q. Geng, C. W. Liu, T. H. Tsai and Y. Yu, Phys. Rev. D 99, no.11, 114022 (2019);
S. Groote and J. G. Körner, Eur. Phys. J. C 82, no.4, 297 (2022);
……

The KPW theorem is broken by FSI





$\delta = \epsilon$ ≠ $\gamma = \delta = \epsilon$

Test the Korner-Pati-Woo theorem

- Isospin symmetry + KPW theorem

$$\mathcal{A}(\Lambda_c^+ \to \Sigma^+ K_S^0) = \mathcal{A}(\Lambda_c^+ \to \Sigma^0 K^+)$$

C. Q. Geng, C. W. Liu and T. H. Tsai, Phys. Lett. B **794**, 19-28 (2019).

$$\mathcal{B}r(\Lambda_c^+ \to \Sigma^+ K_S^0) = (4.8 \pm 1.5) \times 10^{-4}, \qquad \mathcal{B}r(\Lambda_c^+ \to \Sigma^0 K^+) = (4.7 \pm 1.0) \times 10^{-4}.$$

M. Ablikim et al. [BESIII], Phys. Rev. D **106**, no.5, 052003 (2022).

- Other Λ_c^+ decay modes

$$\sqrt{\frac{3}{2}}\mathcal{A}(\Lambda_c^+ \to \Delta^+ \pi^0) = \sqrt{3}\mathcal{A}(\Lambda_c^+ \to \Delta^0 \pi^+) = -\mathcal{A}(\Lambda_c^+ \to \Delta^{++} \pi^-),$$

$$\mathcal{A}(\Lambda_c^+ \to \Sigma^{*+} K^0) = -\sqrt{2}\mathcal{A}(\Lambda_c^+ \to \Sigma^{*0} K^+).$$

D. Wang,,Phys. Lett. B **858**, 139039 (2024).

Contents

Summary

- The correlation between topologies at quark level and rescattering at hadron level in the charmed baryon decays is studied.
- The rescattering amplitudes derived from topological diagrams are consistent with those derived from the ChPT.
- The Korner-Pati-Woo theorem is violated by FSI.

Thanks for your attention!