Equivalent $SU(3)_f$ approaches for two-body Anti-triplet charmed baryon decays

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Outline:
1. Introduction
2. Formalism
3. Results
4. Summary

Introduction (IRA and TDA)

• IRA: irreducible $SU(3)_f$ approach (amplitude)

$\mathbf{B}_c$, $\mathbf{B}$, M, and $\mathcal{H}_{eff}$ in the irreducible forms of $SU(3)_f$,

connected as the invariant $SU(3)_f$ amplitudes (a_i)

[Savage, Springer, PRD42, 1527 (1990)]

$\mathcal{H}_{\rm IRA} \sim c_- H(6) + c_+ H(\overline{15})$, $c_- > c_+$

a_1, a_2, a_3, QCD-favored

a_4, a_5, a_6, a_7, QCD-disfavored

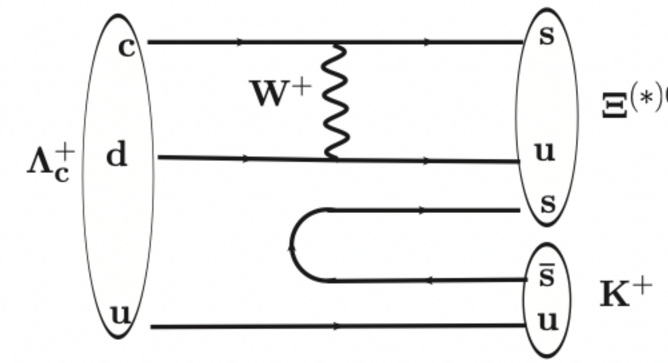
C.D. Lu, W. Wang and F.S. Yu [PRD93, 056008 (2016)],

"Test flavor SU(3) symmetry in exclusive Λ_c decays,"

Geng, Hsiao, Y.H. Lin and L.L. Liu [PLB776, 265 (2017)]

able to explain $\mathcal{B}(\mathbf{B}_c \to \mathbf{B}M)$

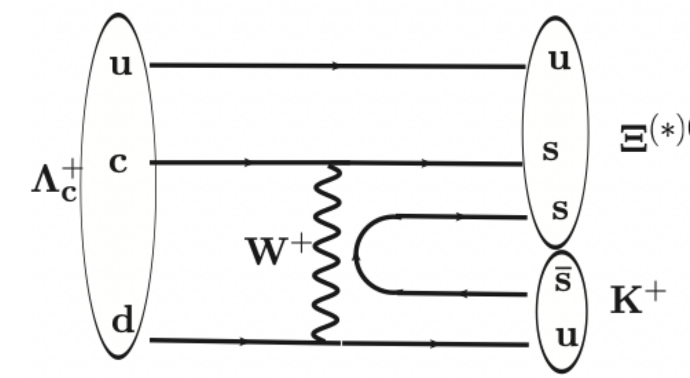
Introduction (IRA and TDA)



• One prefers topological diagrams for the decay: factorizable, non-factorizable, W-boson exchange

BESIII [PLB783, 200 (2018)]

Feynman diagrams of $\Lambda_c^+ \to \Xi^{(*)0} K^+$



IRA: $\mathcal{M}(\Lambda_c^+ \to \Xi^0 K^+) = -2(a_2 - \frac{a_4 + a_7}{2})$

Pole model + current algebra:

J. Zou, F. Xu, G. Meng and H.Y. Cheng, PRD101, 014011 (2020),

"Two-body hadronic weak decays of antitriplet charmed baryons."

Long-distance triangle rescattering:

H.W. Ke and X.Q. Li [PRD102, 113013 (2020)]

"A natural interpretation on the data of $\Lambda_c \to \Sigma\pi$."

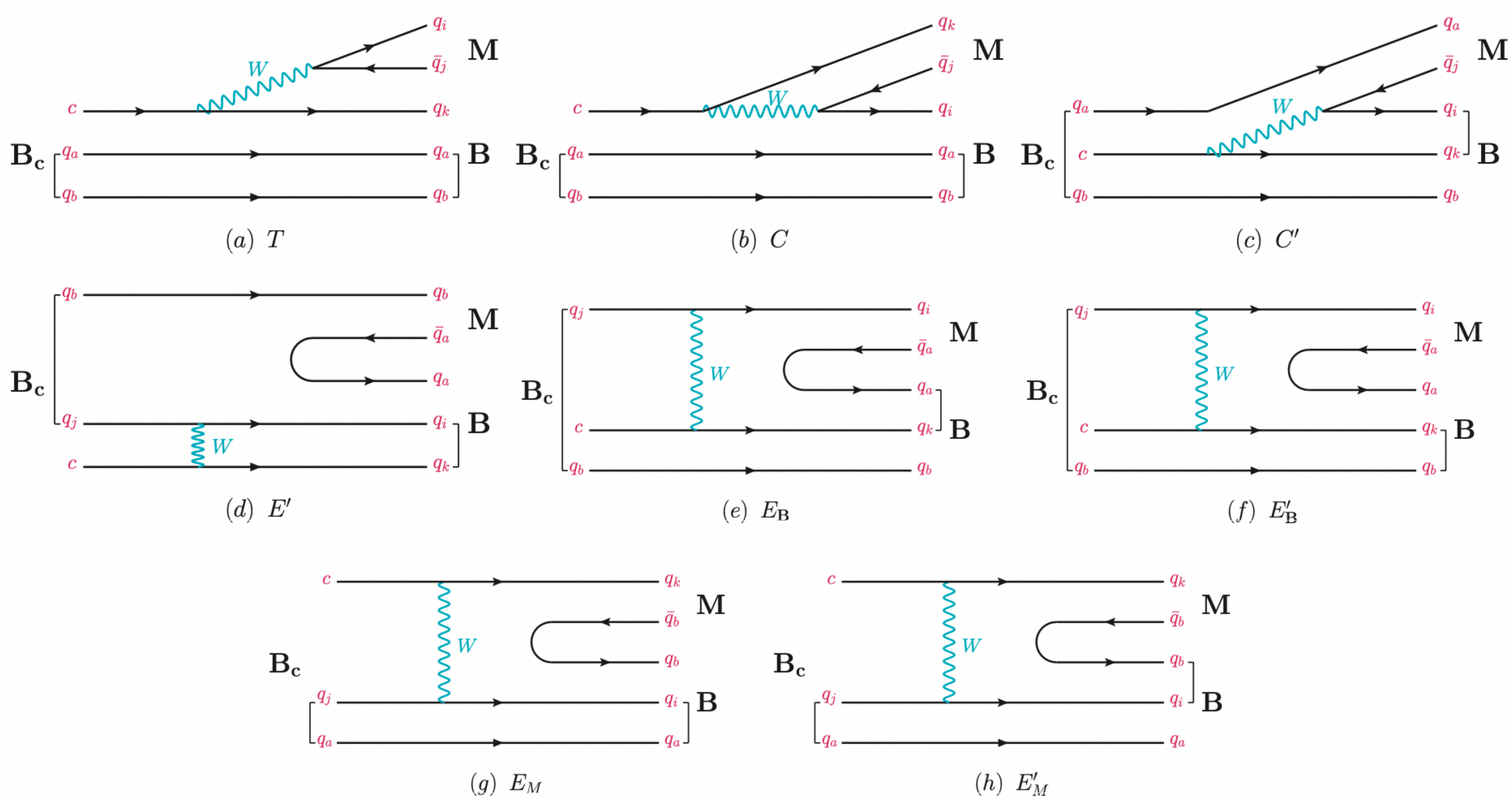
Yu, Hsiao [PLB820, 136586 (2021)]

"Cabibbo-favored $\Lambda_c^+ \to \Lambda a_0(980)^+$ decay in the final state interaction."

• TDA: topological $SU(3)_f$ approach (amplitude)

$SU(3)_f$ symmetry+topological diagrams

more approachable, more information



Ξ_c^0, Ξ_c^+ and Λ_c^+: $(ds-sd)c$, $(su-us)c$ and $(ud-du)c$

$\mathbf{B} \sim (q_a - q_k)q_b\,[(q_i - q_a)q_b]$ for $E_{\mathbf{B}(M)}$, $\mathbf{B} \sim (q_k - q_b)q_a\,[(q_b - q_i)q_a]$ for $E'_{\mathbf{B}(M)}$

• Studies with TDA

Y. Kohara [PRD44, 2799 (1991)]

"Quark diagram analysis of charmed baryon decays,"

L.L. Chau, H.Y. Cheng and B. Tseng [PRD54, 2132 (1996)]

"Analysis of two-body decays of charmed baryons using the quark diagram scheme"

H.J. Zhao, Y.L. Wang, Hsiao and Y. Yu [JHEP02, 165 (2020)]

"A diagrammatic analysis of two-body charmed baryon decays with flavor symmetry."

Hsiao, Q. Yi, S.T. Cai and H.J. Zhao [EPJC80, 1067 (2020)]

"Two-body charmed baryon decays involving decuplet baryon in the quark-diagram scheme."

Equivalent $SU(3)_f$ approaches for $\mathbf{B}_c \to \mathbf{B}M$

- Both based on $SU(3)_f$ symmetry,

TDA and IRA can be equivalent

X.G. He and W. Wang [CPC42, 103108 (2018)]

"Flavor SU(3) Topological Diagram and

Irreducible Representation Amplitudes

for Heavy Meson Charmless Hadronic Decays: Mismatch and Equivalence,"

X.G. He, Y.J. Shi and W. Wang [EPJC80, 359 (2020)]

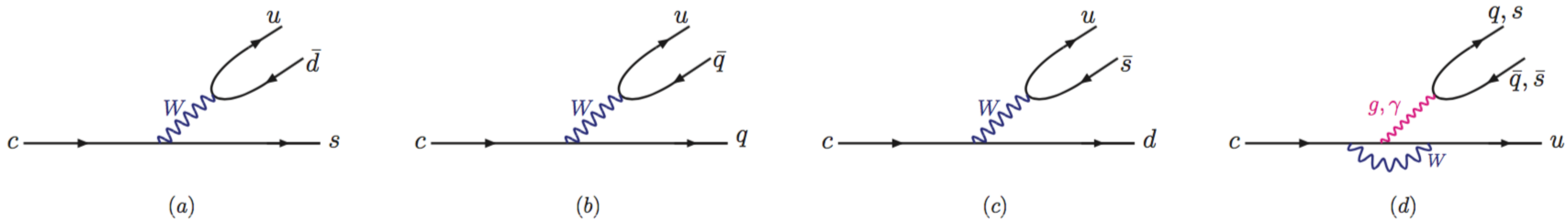
"Unification of Flavor SU(3) Analyses of Heavy Hadron Weak Decays,"

Hsiao, Q. Yi, S.T. Cai and H.J. Zhao [EPJC80, 1067 (2020)]

"Two-body charmed baryon decays involving decuplet baryon

in the quark-diagram scheme."

Formalism



- IRA

$$\mathcal{H}_{\rm IRA} = c_- \frac{\epsilon^{ijl}}{2} H(6)_{lk} + c_+ H(\overline{15})^{ij}_k$$

$$\mathbf{B}_c(\mathbf{B}_{c\,i}) = (\Xi_c^0, -\Xi_c^+, \Lambda_c^+)$$

$$\mathbf{B}^i_j : (n,\ p,\ ,\Sigma^{\pm,0}, \Xi^{-,0},\ \Lambda)$$

$$M^i_j : (\pi^{\pm,0},\ K^{\pm},\ K^0,\ \bar{K}^0,\ \eta)$$

- TDA

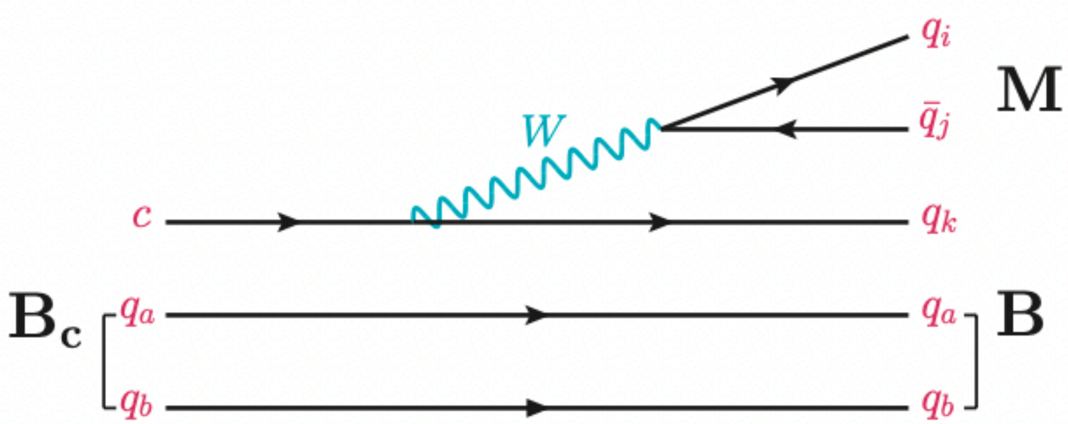
$$\mathcal{H}_{\rm TDA} = H^{ki}_j\ [H^{31}_2 = 1]$$

$$\mathbf{B}_c(\mathbf{B}_c{}^{ij}) = \begin{pmatrix} 0 & \Lambda_c^+ & \Xi_c^+ \\ -\Lambda_c^+ & 0 & \Xi_c^0 \\ -\Xi_c^+ & -\Xi_c^0 & 0 \end{pmatrix}$$

$$\mathbf{B}_{ijk} = \epsilon_{ijl}\mathbf{B}^l_k$$

$$M^i_j : (\pi^{\pm,0},\ K^{\pm},\ K^0,\ \bar{K}^0,\ \eta)$$

$$
\begin{aligned}
\mathcal{M}_{\mathrm{IRA}} &= \mathcal{M}_{6} + \mathcal{M}_{\overline{15}}\,, \\
\mathcal{M}_{6} &= a_1 H_{ij}(6) T^{ik} \mathbf{B}^{l}_{k} M^{j}_{l} + a_2 H_{ij}(6) T^{ik} M^{l}_{k} \mathbf{B}^{j}_{l} + a_3 H_{ij}(6) \mathbf{B}^{i}_{k} M^{j}_{l} T^{kl}\,, \\
\mathcal{M}_{\overline{15}} &= a_4 H^{li}_{k}(\overline{15}) \mathbf{B}_{c\,j} M^{j}_{i} \mathbf{B}^{l}_{k} + a_5 \mathbf{B}^{i}_{j} M^{l}_{i} H(\overline{15})^{jk}_{l} \mathbf{B}_{c\,k} \\
&\quad + a_6 \mathbf{B}^{k}_{l} M^{i}_{j} H(\overline{15})^{jl}_{i} \mathbf{B}_{c\,k} + a_7 \mathbf{B}^{l}_{i} M^{i}_{j} H(\overline{15})^{jk}_{l} \mathbf{B}_{c\,k}\,, \\
\mathcal{M}_{\mathrm{TDA}} &= T \mathbf{B}_{c}{}^{ab} H^{ki}_{j} \mathbf{B}_{abk} M^{i}_{j} + C \mathbf{B}_{c}{}^{ab} H^{ki}_{j} \mathbf{B}_{abi} M^{k}_{j} + C' \mathbf{B}_{c}{}^{ab} H^{ki}_{j} \mathbf{B}_{ikb} M^{a}_{j} \\
&\quad + E_{\mathbf{B}} \mathbf{B}_{c}{}^{jb} H^{ki}_{j} \mathbf{B}_{kab} M^{i}_{a} + E'_{\mathbf{B}} \mathbf{B}_{c}{}^{jb} H^{ki}_{j} \mathbf{B}_{kba} M^{i}_{a} \\
&\quad + E_{M} \mathbf{B}_{c}{}^{jb} H^{ki}_{j} \mathbf{B}_{iba} M^{k}_{a} + E'_{M} \mathbf{B}_{c}{}^{jb} H^{ki}_{j} \mathbf{B}_{iab} M^{k}_{a} + E' \mathbf{B}_{c}{}^{jb} H^{ki}_{j} \mathbf{B}_{ika} M^{b}_{a}\,,
\end{aligned}
$$

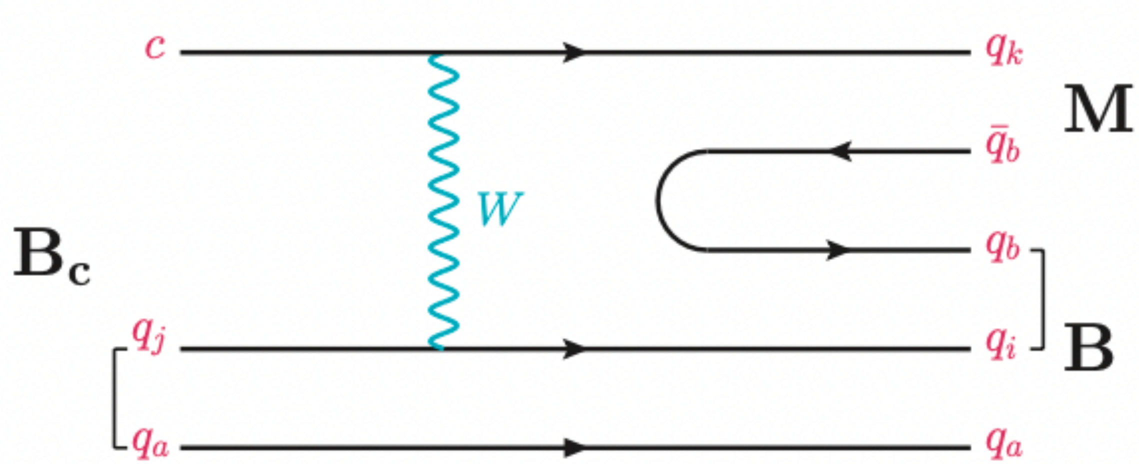


$(a)\ T$

$$T^{ij} \equiv \mathbf{B}_{c\,k} \epsilon^{ijk}$$

Decay mode	$M_{\rm TDA}$	$M_{\rm IRA}$
$\Lambda_c^+ \to \Lambda^0\pi^+$	$-\frac{1}{\sqrt{6}}(4T+C'-E_{\mathbf{B}}-E')$	$-\frac{\sqrt{6}}{3}(a_1+a_2+a_3-\frac{a_5-2a_6+a_7}{2})$
$\Lambda_c^+ \to \Sigma^0\pi^+$	$\frac{1}{\sqrt{2}}(C'+E_{\mathbf{B}}-E')$	$-\sqrt{2}(a_1-a_2-a_3-\frac{a_5-a_7}{2})$
$\Lambda_c^+ \to \Sigma^+\pi^0$	$-\frac{1}{\sqrt{2}}(C'+E_{\mathbf{B}}-E')$	$\sqrt{2}(a_1-a_2-a_3-\frac{a_5-a_7}{2})$
$\Lambda_c^+ \to \Xi^0 K^+$	$E'^{(s)}$	$-2(a_2-\frac{a_4+a_7}{2})$
$\Lambda_c^+ \to p\bar{K}^0$	$2C-E'_M$	$-2(a_1-\frac{a_5+a_6}{2})$
$\Lambda_c^+ \to \Sigma^+\eta$	$[\frac{1}{\sqrt{2}}(C'-E_{\mathbf{B}}+E')c\phi-E'^{(s)}_M s\phi]$	$\sqrt{2}c\phi(-a_1-a_2+a_3+\frac{a_5+a_7}{2})-s\phi a_4$
$\Xi_c^+ \to \Sigma^+\bar{K}^0$	$-2C+C'$	$2(a_3-\frac{a_4+a_6}{2})$
$\Xi_c^+ \to \Xi^0\pi^+$	$-2T-C'$	$2(a_3+\frac{a_4+a_6}{2})$
$\Xi_c^0 \to \Lambda^0\bar{K}^0$	$\frac{1}{\sqrt{6}}(2C+C'-E_M-2E'_M-E')$	$-\frac{\sqrt{6}}{3}(2a_1-a_2-a_3+\frac{2a_5-a_6-a_7}{2})$
$\Xi_c^0 \to \Sigma^0\bar{K}^0$	$\frac{1}{\sqrt{2}}(2C-C'+E_M+E')$	$-\sqrt{2}(a_2+a_3-\frac{a_6-a_7}{2})$
$\Xi_c^0 \to \Sigma^+K^-$	$-E_M-E'$	$2(a_2+\frac{a_4+a_7}{2})$
$\Xi_c^0 \to \Xi^0\pi^0$	$\frac{1}{\sqrt{2}}(E_{\mathbf{B}}+C')$	$-\sqrt{2}(a_1-a_3-\frac{a_4-a_5}{2})$
$\Xi_c^0 \to \Xi^-\pi^+$	$2T-E_{\mathbf{B}}$	$2(a_1+\frac{a_5+a_6}{2})$
$\Xi_c^0 \to \Xi^0\eta$	$[\frac{1}{\sqrt{2}}(E_{\mathbf{B}}-C')c\phi+(E^{(s)}_M+E'^{(s)}_M+E'^{(s)})s\phi]$	$\sqrt{2}c\phi(a_1-a_3+\frac{a_4+a_5}{2})\ -2s\phi(a_2+\frac{a_7}{2})$

E'^{s}_M for $g \to s\bar{s}$



$(h)\ E'_M$

Using $\mathcal{M}_{\mathbf{IRA}} = \mathcal{M}_{\mathbf{TDA}}$

$$(T, C, C') = (a_1 + \tfrac{a_4+a_6}{2}, -a_1 + \tfrac{a_4+a_6}{2}, -2a_1 + 2a_3)$$

$$(E_{\mathbf{B}}, E_M, E') = (a_4, -2a_4 - 2a_7, -2a_2 + a_4 + a_7)$$

$$E'_M = E_{\mathbf{B}}$$

$$(a_1, a_2, a_3) = (\tfrac{T-C}{2}, -\tfrac{E_M+2E'}{4}, \tfrac{T-C+C'}{2})$$

$$(a_4, a_5, a_6, a_7) = (E_{\mathbf{B}}, 0, T + C - E_{\mathbf{B}}, -E_{\mathbf{B}} - \tfrac{E_M}{2})$$

such that we "topologize" the $SU(3)_f$ invariant amplitudes.

Explain the data

- $\Xi_c^0 \to \Xi^- K^+$ and $\Xi_c^0 \to \Xi^- \pi^+$

data: $\mathcal{B}(\Xi_c^0 \to \Xi^- K^+)/\mathcal{B}(\Xi_c^0 \to \Xi^- \pi^+)$=0.02

theory: $\mathcal{B}(\Xi_c^0 \to \Xi^- K^+)/\mathcal{B}(\Xi_c^0 \to \Xi^- \pi^+) \simeq (-\sin\theta_c)^2 \simeq 0.05$

$\Rightarrow SU(3)_f$ symmetry breaking

IRA: at least 3 new parameters for breaking.

Savage [PLB257, 414 (1991)]

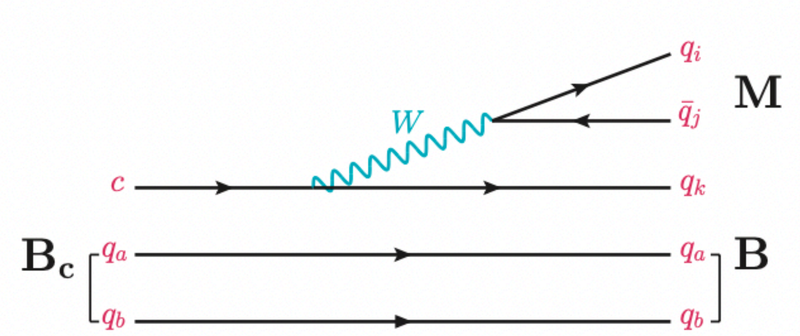
"SU(3) violations in the nonleptonic decay of charmed hadrons,"

Geng, Hsiao, C.W. Liu and T.H. Tsai [EPJC78, 593 (2018)]

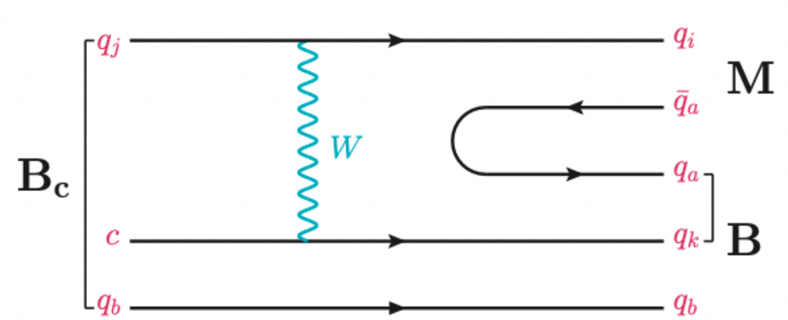
"SU(3) symmetry breaking in charmed baryon decays."

TDA: $\mathcal{R}(\Xi_c^0) \equiv \frac{\mathcal{B}(\Xi_c^0 \to \Xi^- K^+)}{\mathcal{B}(\Xi_c^0 \to \Xi^- \pi^+)} = s_c^2 \frac{(2T - E_{\mathbf{B}}^{(s)})^2}{(2T - E_{\mathbf{B}})^2}$

$E_{\mathbf{B}}^s$ for $g \to s\bar{s}$



(a) T



(e) $E_{\mathbf{B}}$

	TDA (S1)	TDA (S2)
χ^2	4.5	5.7
$n.d.f$	5	4
$\|T\|$	0.23 ± 0.02	0.24 ± 0.02
$\|C\|$	0.26 ± 0.01	0.23 ± 0.02
$\|C'\|$	0.34 ± 0.02	0.32 ± 0.03
$\|E_{\mathbf{B}}\|$	0.22 ± 0.03	0.22 ± 0.05
$\|E_{\mathbf{B}}^s\|$		0.37 ± 0.06
$\|E_M\|$	0.40 ± 0.03	0.38 ± 0.03
$\|E'\|$	0.24 ± 0.02	0.23 ± 0.02
δ_C	$(183.2 \pm 9.6)^\circ$	$(179.5 \pm 12.9)^\circ$
$\delta_{C'}$	$(163.7 \pm 5.0)^\circ$	$(149.7 \pm 6.7)^\circ$
$\delta_{E_{\mathbf{B}}}$	$(-100.3 \pm 7.1)^\circ$	$(-93.6 \pm 8.2)^\circ$
$\delta_{E_{\mathbf{B}}^s}$		$(43.3 \pm 8.0)^\circ$
δ_{E_M}	$(100.3 \pm 8.0)^\circ$	$(113.2 \pm 10.7)^\circ$
$\delta_{E'}$	$(-71.1 \pm 6.7)^\circ$	$(-50.1 \pm 12.3)^\circ$

$$\mathcal{B}_{\mathrm{S1}}(\Xi_c^0 \to \Xi^- K^+) = (11.8 \pm 1.8) \times 10^{-4}$$

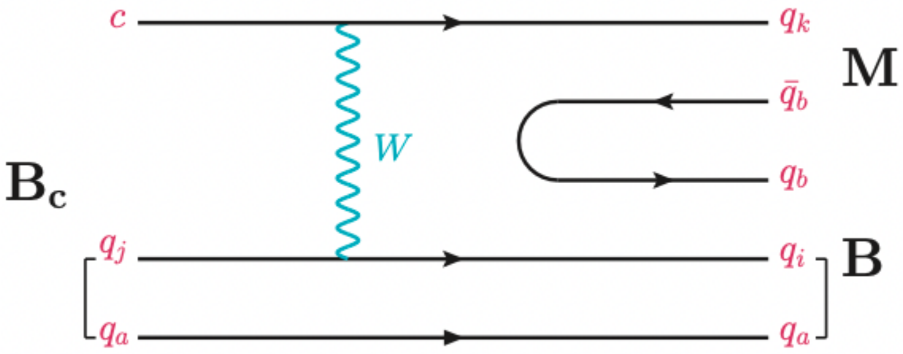
$$\mathcal{B}_{\mathrm{S2}}(\Xi_c^0 \to \Xi^- K^+) = (4.1 \pm 2.8) \times 10^{-4}$$

$$\mathcal{B}_{ex}(\Xi_c^0 \to \Xi^- K^+) = (3.9 \pm 1.2) \times 10^{-4}$$

$$E_{\mathbf{B}}^s = |n_q| e^{i\delta_{n_q}} E_{\mathbf{B}}$$

$$|n_q| = 1.2 \pm 0.4,\ \delta_{n_q} = (50.3 \pm 11.5)^\circ$$

Explain the data



(g) E_M

- CA $\Xi_c^0 \to \mathbf{B}M$

$\mathcal{B}_{ex}(\Xi_c^0 \to \Lambda^0 \bar{K}^0, \Sigma^0 \bar{K}^0, \Sigma^+ K^-)$

$= (8.24 \pm 2.44, 1.38 \pm 0.48, 2.21 \pm 0.68) \times 10^{-3}$

Belle [PRD105, L011102 (2022)]

TDA: $\mathcal{M}(\Xi_c^0 \to \Lambda^0 \bar{K}^0, \Sigma^0 \bar{K}^0, \Sigma^+ K^-) = \frac{1}{\sqrt{6}}(2C + C' - E_M - 2E'_M - E'),$
$\frac{1}{\sqrt{2}}(2C - C' + E_M + E'),\ -E_M - E'$

E_M only appearing in $\Xi_c^0 \to \mathbf{B}M$, instead of $\Xi_c^+, \Lambda_c^+ \to \mathbf{B}M$,
cannot be neglected $(E_M = -2a_4 - 2a_7)$.

$\mathcal{B}_{\mathrm{S1}}(\Xi_c^0 \to \Lambda^0 \bar{K}^0, \Sigma^0 \bar{K}^0, \Sigma^+ K^-)$

$= (9.85 \pm 2.26, 1.48^{+1.27}_{-0.92}, 2.21^{+0.37}_{-0.16}) \times 10^{-3}$

$\mathcal{B}_{\mathrm{S2}}(\Xi_c^0 \to \Lambda^0 \bar{K}^0, \Sigma^0 \bar{K}^0, \Sigma^+ K^-)$

$= (10.0 \pm 2.9, 1.46^{+1.57}_{-1.09}, 2.25^{+1.8}_{-1.1}) \times 10^{-3}$

Explain the data

- $\Lambda_c^+ \to p\pi^0$ and $\Lambda_c^+ \to n\pi^+$

$\mathcal{B}_{ex}(\Lambda_c^+ \to p\pi^0) > 3 \times 10^{-4}$, BESIII [PRD95, 111102 (2017)]

$\mathcal{B}_{ex}(\Lambda_c^+ \to p\pi^0) > 0.8 \times 10^{-4}$, Belle [PRD103, 072004 (2021)]

$\mathcal{B}_{ex}(\Lambda_c^+ \to n\pi^+) = (6.6 \pm 1.3) \times 10^{-4}$, BESIII [PRL128, 142001 (2022)]

- $\mathcal{B}_{ex}(\Lambda_c^+ \to n\pi^+) \gg \mathcal{B}_{ex}(\Lambda_c^+ \to p\pi^0)$

IRA: $\mathcal{M}(\Lambda_c^+ \to n\pi^+, p\pi^0) \sim A + B, (A - B)/\sqrt{2}$

$(A, B) = (a_2 + a_3 - a_7/2, a_6/2)$

Causing the constructive and destructive interferences.

- Theoretical results

$\mathcal{B}_{\rm S1,S2}(\Lambda_c^+ \to p\pi^0) = (0.3^{+1.0}_{-0.3}, 0.4^{+1.7}_{-0.4}) \times 10^{-4}$

$\mathcal{B}_{\rm S1,S2}(\Lambda_c^+ \to n\pi^+) = (7.6 \pm 1.7, 8.3 \pm 2.6) \times 10^{-4}$

Consistent with the analyses with IRA

Partly restoring the QCD-disfavored parameters

Geng, C.W. Liu and T.H. Tsai [PLB794, 19 (2019)]

With all parameters

C.P. Jia, D. Wang and F.S. Yu [NPB956, 115048 (2020)]

F. Huang, Z.P. Xing and X.G. He [JHEP **03**, 143 (2022)]

With all parameters+$SU(3)_f$ breaking

H. Zhong, F. Xu, Q. Wen and Y. Gu [JHEP02, 235 (2023)]

Summary

- We demonstrated that IRA and TDA for $\mathbf{B}_c \to \mathbf{B}M$ Equivalent $SU(3)_f$ approaches.
- We explained $\mathcal{B}(\Lambda_c^+ \to \Xi^0 K^+, \Xi^0 \pi^+)$ with $SU(3)_f$ symmetry breaking.
- $\mathcal{B}(\Lambda_c^+ \to p\pi^0)$ and $\mathcal{B}(\Lambda_c^+ \to n\pi^+)$ receive the contributions from the destructive and constructive interfering effects, respectively.
- The exchange topology E_M plays a key role in the $\Xi_c^0 \to \Lambda^0 \bar{K}^0, \Sigma^0 \bar{K}^0, \Sigma^+ K^-$ decays.

Thank You