粲重子衰变的末态相互作用研究

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Based on [C.P.Jia, H.Y.Jiang, J.P.Wang, FSY, 2405.xxxxx]

2024年BESIII粲强子物理研讨会 @ 郑州，2024.05.11

Outline

- Introduction
- charmed baryon decays
- Final-state interactions
- Summary

Charmed baryon decays

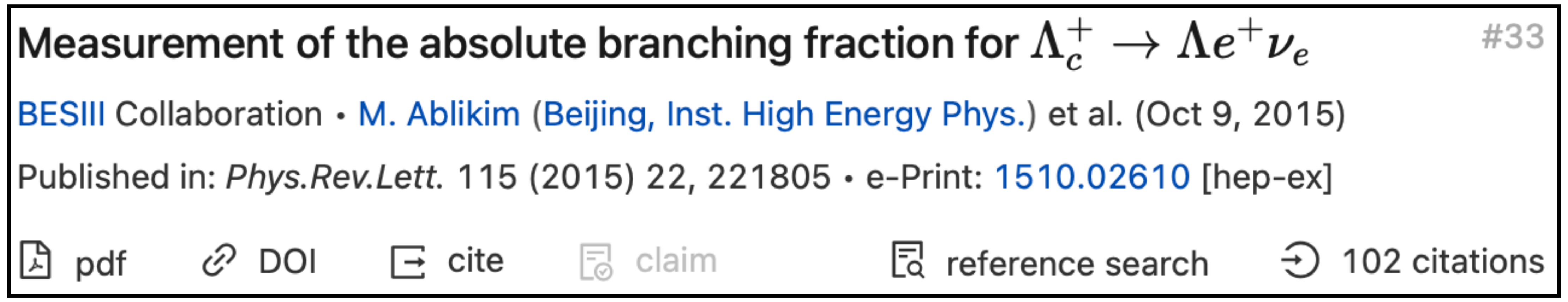
- From 2014, BESIII has studied charmed baryons for ten years! A new period of charm physics has coming.


Measurements of absolute hadronic branching fractions of Λ_c^+ baryon

#16

BESIII Collaboration • M. Ablikim (Beijing, Inst. High Energy Phys.) et al. (Nov 26, 2015)

Published in: *Phys.Rev.Lett.* 116 (2016) 5, 052001 • e-Print: 1511.08380 [hep-ex]


Measurement of the absolute branching fraction for $\Lambda_c^+ \to \Lambda e^+ \nu_e$

#33

BESIII Collaboration • M. Ablikim (Beijing, Inst. High Energy Phys.) et al. (Oct 9, 2015)

Published in: *Phys.Rev.Lett.* 115 (2015) 22, 221805 • e-Print: 1510.02610 [hep-ex]

- 2016, we performed a theoretical study on non-leptonic Λ_c decays in flavor SU(3) symmetry


Test flavor SU(3) symmetry in exclusive Λ_c decays

#3

Cai-Dian Lü (Beijing, Inst. High Energy Phys.), Wei Wang (Shanghai Jiao Tong U. and Shanghai Jiaotong U. and Beijing, Inst. Theor. Phys.), Fu-Sheng Yu (Lanzhou U.) (Jan 16, 2016)

Published in: *Phys.Rev.D* 93 (2016) 5, 056008 • e-Print: 1601.04241 [hep-ph]

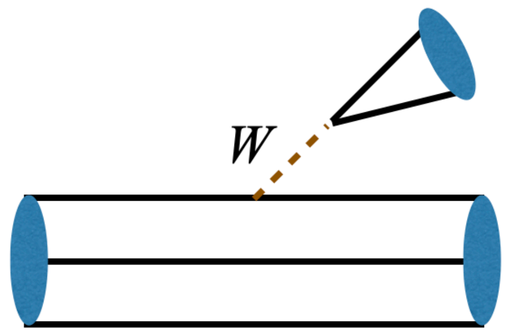
- After that, a lot of experimental results and theoretical studies.
- Exp: BESIII, Belle, LHCb. Th: C.Q.Geng, H.Y.Cheng, F.R.Xu, Y.K.Hsiao, C.W.Liu and so on.

CP violation in baryons

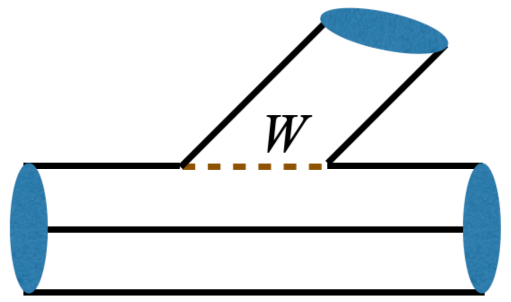
- Sakharov conditions for **Baryogenesis:**
  1) **baryon** number violation
  2) C and **CP violation**
  3) out of thermal equilibrium
- **CPV: SM < BAU. => new source of CPV, NP**
- CPV well established in K, B and D mesons,
  but CPV never established in any baryon
- **Comparison between precise prediction and measurement is helpful to test the SM and search for NP**

Charmed baryon decays

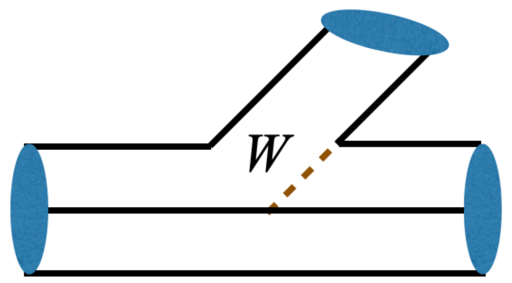
- Charmed baryon decays are the next opportunity and challenge of charm physics
- No any real CPV predictions
- Dynamics are more complicated
  - Many more topological diagrams + more partial waves
  - SU(3) irreducible representations cannot provide information on penguins
  - Final-state interactions (FSI) are necessary



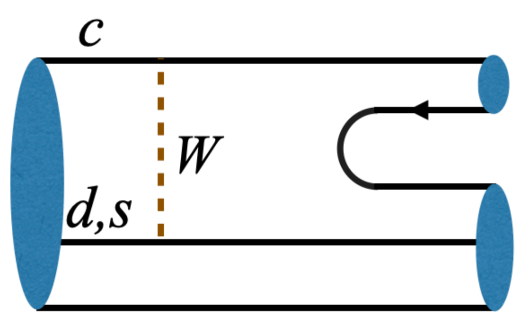
(T)
color-favored tree emitted



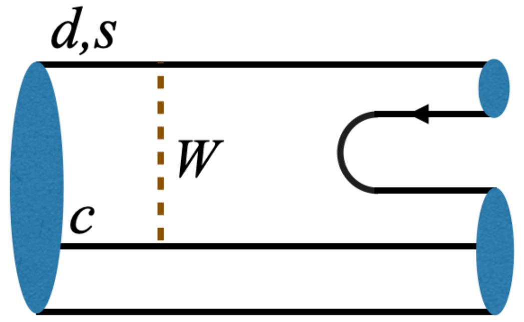
(C)
color-suppressed emitted



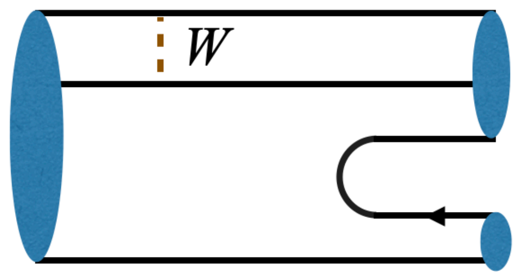
(C′)
color-commensurate



(E_1)
W-exchange 1



(E_2)
W-exchange 2

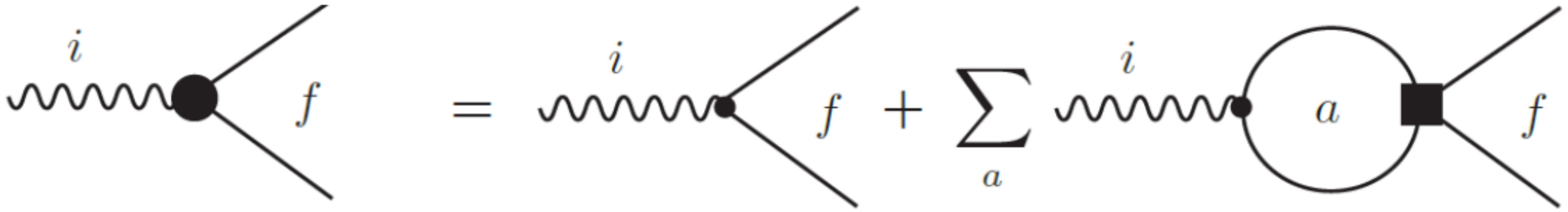


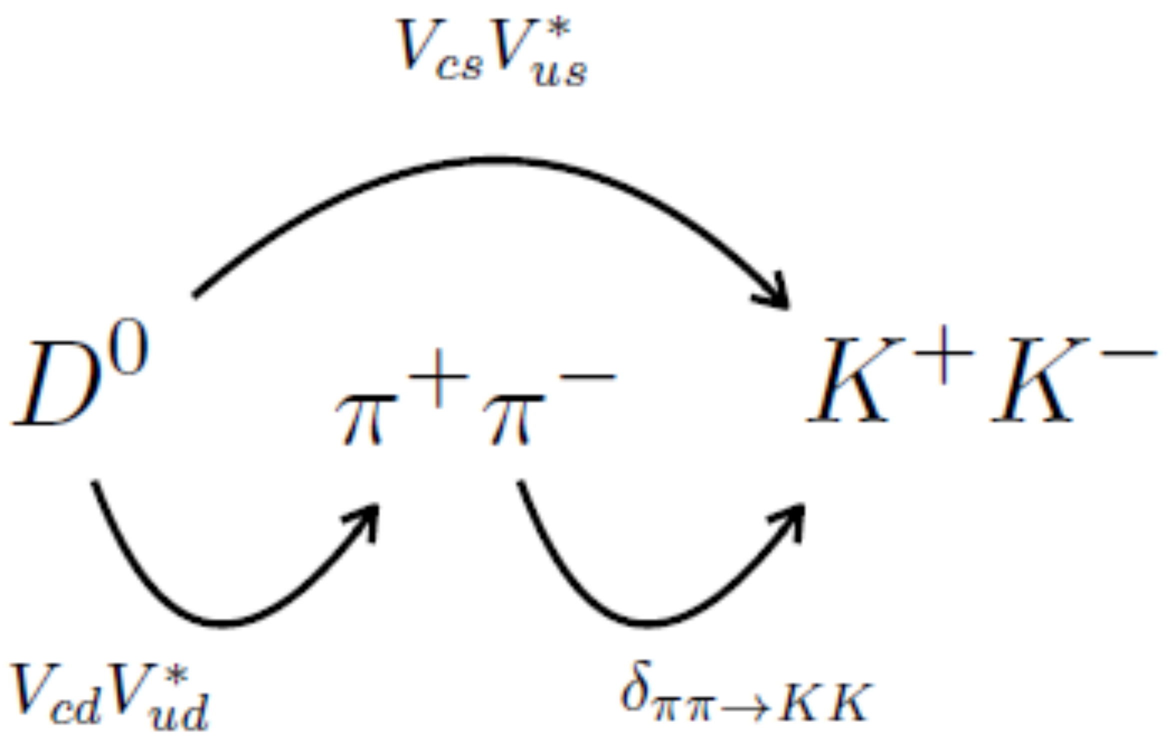
(B)
Bow tie

See topologies in H.Y. Cheng's and F.R.Xu's talk

See FSI in En Wang's and C.W.Liu's talk

Final-state interactions





- Rescattering mechanism for charm CPV [Bediaga, Frederico, Magalhaes, PRL2023; Pich, Solomonidi, Silva, PRD2023]
  - Data-driven extraction of magnitudes and phases of the $\pi\pi \to KK$ scatterings

$$|\Delta A_{CP}^{\text{short-distance}}| < 2 \times 10^{-4} \qquad \text{v.s.} \qquad \Delta A_{CP}^{\text{FSI}} = -(6.4 \pm 1.8) \times 10^{-4}$$

Model-independently manifest on the enhancement of final-state interactions!!!

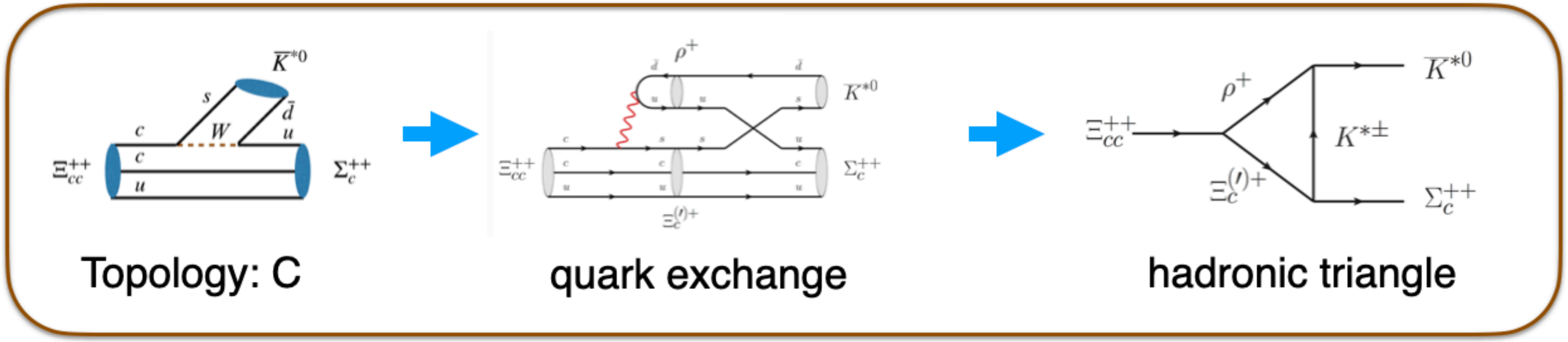
  - Power of predictions is limited due to only few channels of available data

$$\Delta A_{CP}^{\text{exp}} = -(15.4 \pm 2.9) \times 10^{-4}$$

See H.Y.Cheng's talk

Rescattering mechanism

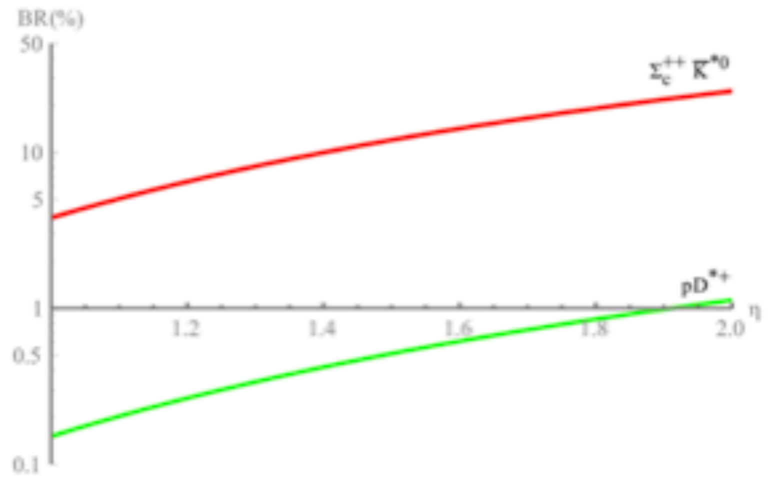
- Rescattering mechanism have been successfully used to predict the discovery channel of $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ [FSY, Jiang, Li, Lu, Wang, Zhao, ’17]



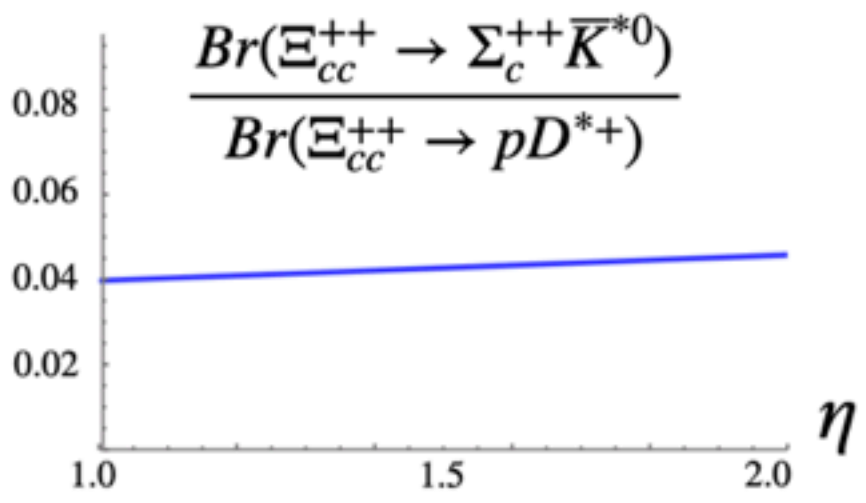
Topology: C

quark exchange

hadronic triangle



- Theoretical uncertainty is under control in the **ratio** of branching fractions of different processes



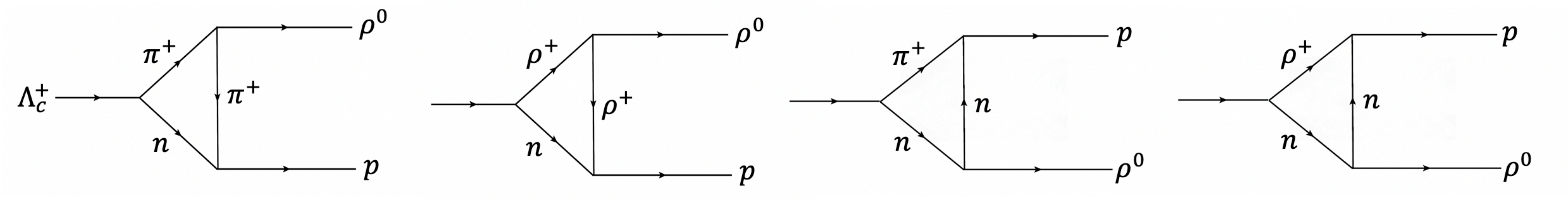
1703.09086
2102.00961

- It deserves to develop the rescattering mechanism to study CPV of charmed baryons

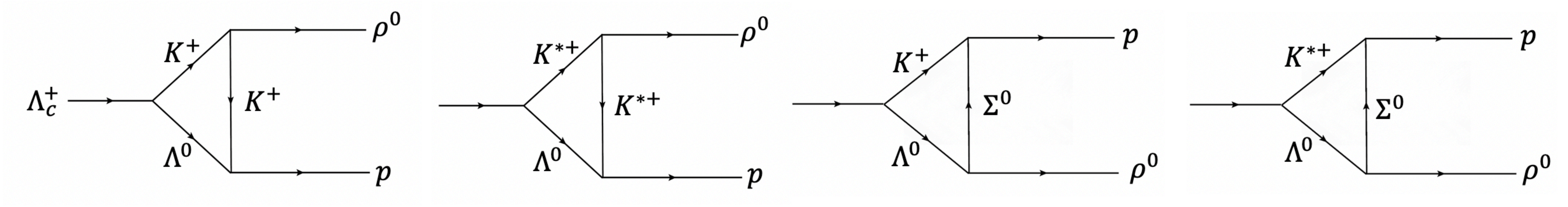
Triangle diagrams

- Much more channels are included in the rescattering mechanism

$V_{ud}V_{cd}^*$



$V_{us}V_{cs}^*$



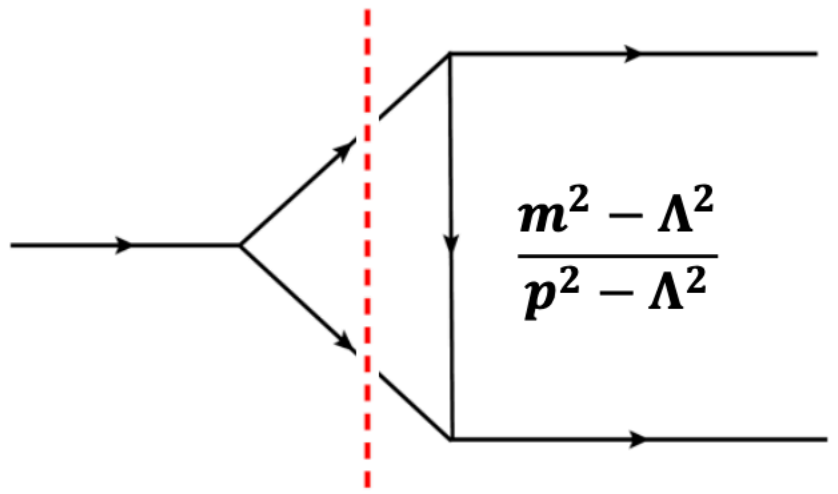
CPV can be easily obtained within the rescattering mechanism

$$\lambda_d\, A_d + \lambda_s\, A_s$$

See C.W.Liu's talk

➢ **Conventional method：** optical theorem + Cutkosky cutting rule

- H. Y. Cheng, C. K. Chua and A. Soni, Phys. Rev. D 71, 014030 (2005)........



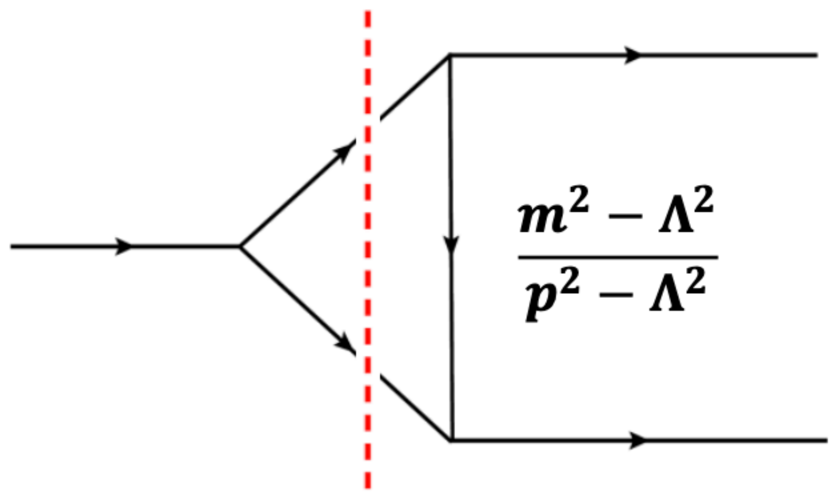
$$\Lambda = m_k + \eta\Lambda_{QCD}$$

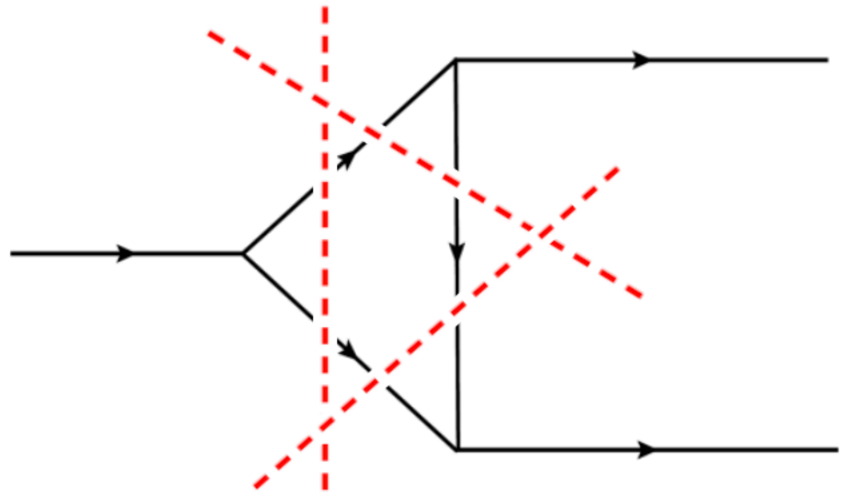
$$\mathcal{A}bs[\mathcal{M}(P_i \to P_3 P_4)]$$
$$= \frac{1}{2}\sum_{\{P_1P_2\}}\int\frac{d^3p_1}{(2\pi)^3 2E_1}\int\frac{d^3p_2}{(2\pi)^3 2E_2}(2\pi)^4\delta^4(p_3+p_4-p_1-p_2)$$
$$\boxed{\cdot\, M(P_i \to \{P_1P_2\})}\boxed{T^*(P_3P_4 \to \{P_1P_2\})}.$$

- **Strong model-dependent in charmed baryon decay：**

decay mode	Topology diagram	Experiment(%)	Short-distance	η
$\Lambda_c^+ \to \Sigma^+\phi$	E_1	0.39 ± 0.06	-	6.5
$\Lambda_c^+ \to p\omega$	C, C', E_1, E_2, B	0.09 ± 0.04	2.83×10^{-6}	0.65

- **Only a part of the imaginary contribution is included……**

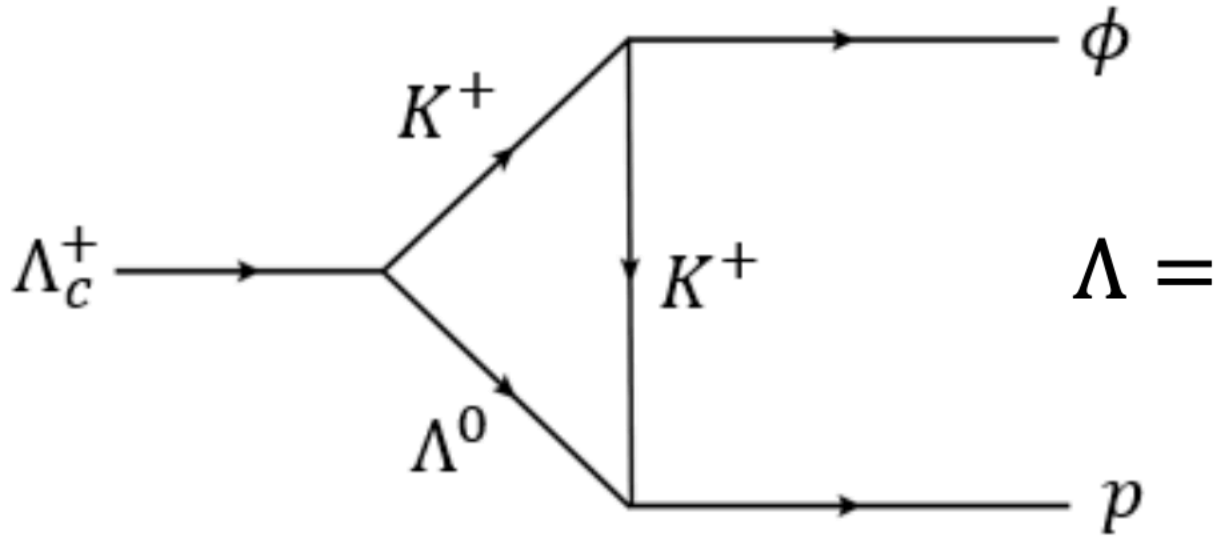




- Off-shell effects
- Lost contribution

- J.J. Han, H.Y. Jiang, W. Liu, Z.J. Xiao, and F.S. Yu, ” Chin. Phys. C 45, 053105 (2021).

➢ Improving method： Loop integral



$\Lambda = m_k + \eta\Lambda_{QCD}$

$$
\begin{aligned}
&\mathcal{M}[P,B;V] \\
&= -i\int \frac{d^4p_1}{(2\pi)^4} g_{BBP}\, g_{VPP}\, \bar{u}(p_4,s_4)\gamma_5(\not{p}_2+m_2)(A+B\gamma_5)u(p,s)\epsilon^{\star}_{\mu}(p_3,\lambda_3)(p_1+k)^{\mu} \\
&\quad\times \frac{1}{(p_1^2-m_1^2+i\epsilon)(p_2^2-m_2^2+i\epsilon)(k^2-m_k^2+i\epsilon)} \boxed{\left(\frac{\Lambda_1^2-m_1^2}{\Lambda_1^2-p_1^2}\right)\left(\frac{\Lambda_2^2-m_2^2}{\Lambda_2^2-p_2^2}\right)\left(\frac{\Lambda_k^2-m_k^2}{\Lambda_k^2-k^2}\right)}
\end{aligned}
$$

- The complete amplitudes with real part and strong phase

$$
\begin{pmatrix}
\{0.,\ 0.,\ -1.57956\times10^{-7}+6.40596\times10^{-8}\,i\} & \{4.65132\times10^{-7}+1.10998\times10^{-6}\,i,\ 0.,\ 0.\} \\
\{0.,\ \underline{-1.00635\times10^{-6}+1.46048\times10^{-7}\,i},\ 0.\} & \{0.,\ 0.,\ 4.56956\times10^{-7}-2.83047\times10^{-7}\,i\}
\end{pmatrix}
$$

- The process dependence of the parameters is greatly reduced

The contribution of the real part is on the same order as the contribution of the imaginary part!

Branching Ratios

Only one parameter explains all the 8 experimental data!

$$BR(\Lambda_c^+ \to p\pi^+\pi^-) = (4.60 \pm 0.26) \times 10^{-3}$$

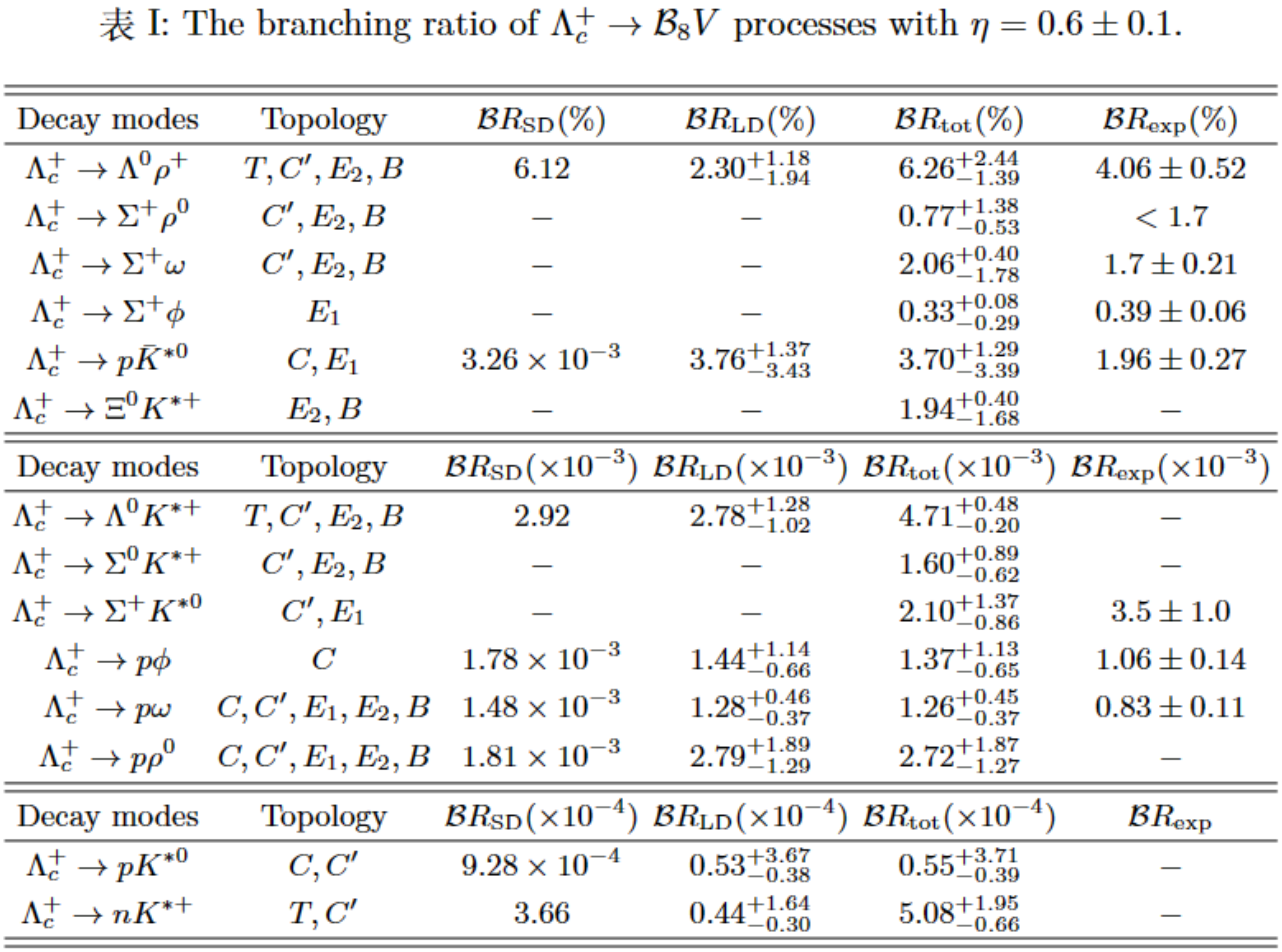


表 I: The branching ratio of $\Lambda_c^+ \to \mathcal{B}_8 V$ processes with $\eta = 0.6 \pm 0.1$.

Decay modes	Topology	$\mathcal{B}R_{\rm SD}(\%)$	$\mathcal{B}R_{\rm LD}(\%)$	$\mathcal{B}R_{\rm tot}(\%)$	$\mathcal{B}R_{\rm exp}(\%)$
$\Lambda_c^+ \to \Lambda^0\rho^+$	T, C', E_2, B	6.12	$2.30^{+1.18}_{-1.94}$	$6.26^{+2.44}_{-1.39}$	4.06 ± 0.52
$\Lambda_c^+ \to \Sigma^+\rho^0$	C', E_2, B	–	–	$0.77^{+1.38}_{-0.53}$	< 1.7
$\Lambda_c^+ \to \Sigma^+\omega$	C', E_2, B	–	–	$2.06^{+0.40}_{-1.78}$	1.7 ± 0.21
$\Lambda_c^+ \to \Sigma^+\phi$	E_1	–	–	$0.33^{+0.08}_{-0.29}$	0.39 ± 0.06
$\Lambda_c^+ \to p\bar{K}^{*0}$	C, E_1	3.26×10^{-3}	$3.76^{+1.37}_{-3.43}$	$3.70^{+1.29}_{-3.39}$	1.96 ± 0.27
$\Lambda_c^+ \to \Xi^0 K^{*+}$	E_2, B	–	–	$1.94^{+0.40}_{-1.68}$	–

Decay modes	Topology	$\mathcal{B}R_{\rm SD}(\times 10^{-3})$	$\mathcal{B}R_{\rm LD}(\times 10^{-3})$	$\mathcal{B}R_{\rm tot}(\times 10^{-3})$	$\mathcal{B}R_{\rm exp}(\times 10^{-3})$
$\Lambda_c^+ \to \Lambda^0 K^{*+}$	T, C', E_2, B	2.92	$2.78^{+1.28}_{-1.02}$	$4.71^{+0.48}_{-0.20}$	–
$\Lambda_c^+ \to \Sigma^0 K^{*+}$	C', E_2, B	–	–	$1.60^{+0.89}_{-0.62}$	–
$\Lambda_c^+ \to \Sigma^+ K^{*0}$	C', E_1	–	–	$2.10^{+1.37}_{-0.86}$	3.5 ± 1.0
$\Lambda_c^+ \to p\phi$	C	1.78×10^{-3}	$1.44^{+1.14}_{-0.66}$	$1.37^{+1.13}_{-0.65}$	1.06 ± 0.14
$\Lambda_c^+ \to p\omega$	C, C', E_1, E_2, B	1.48×10^{-3}	$1.28^{+0.46}_{-0.37}$	$1.26^{+0.45}_{-0.37}$	0.83 ± 0.11
$\Lambda_c^+ \to p\rho^0$	C, C', E_1, E_2, B	1.81×10^{-3}	$2.79^{+1.89}_{-1.29}$	$2.72^{+1.87}_{-1.27}$	–

Decay modes	Topology	$\mathcal{B}R_{\rm SD}(\times 10^{-4})$	$\mathcal{B}R_{\rm LD}(\times 10^{-4})$	$\mathcal{B}R_{\rm tot}(\times 10^{-4})$	$\mathcal{B}R_{\rm exp}$
$\Lambda_c^+ \to pK^{*0}$	C, C'	9.28×10^{-4}	$0.53^{+3.67}_{-0.38}$	$0.55^{+3.71}_{-0.39}$	–
$\Lambda_c^+ \to nK^{*+}$	T, C'	3.66	$0.44^{+1.64}_{-0.30}$	$5.08^{+1.95}_{-0.66}$	–

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Decay Asymmetries

$$\alpha=\frac{\left|H_{1,\frac{1}{2}}\right|^2-\left|H_{-1,-\frac{1}{2}}\right|^2}{\left|H_{1,\frac{1}{2}}\right|^2+\left|H_{-1,-\frac{1}{2}}\right|^2},\quad \beta=\frac{\left|H_{0,\frac{1}{2}}\right|^2-\left|H_{0,-\frac{1}{2}}\right|^2}{\left|H_{0,\frac{1}{2}}\right|^2+\left|H_{0,-\frac{1}{2}}\right|^2},\quad \gamma=\frac{\left|H_{1,\frac{1}{2}}\right|^2+\left|H_{-1,-\frac{1}{2}}\right|^2}{\left|H_{0,\frac{1}{2}}\right|^2+\left|H_{0,-\frac{1}{2}}\right|^2},$$

$$P_L=\frac{\left|H_{1,\frac{1}{2}}\right|^2-\left|H_{-1,-\frac{1}{2}}\right|^2+\left|H_{0,\frac{1}{2}}\right|^2-\left|H_{0,-\frac{1}{2}}\right|^2}{\left|H_{1,\frac{1}{2}}\right|^2+\left|H_{-1,-\frac{1}{2}}\right|^2+\left|H_{0,\frac{1}{2}}\right|^2+\left|H_{0,-\frac{1}{2}}\right|^2}$$

$\alpha = -0.58;$

$\beta = -0.88;$

$\gamma = 0.63;$

$P_L = -0.76 \pm 0.07;$

BSEIII,2022,JHEP

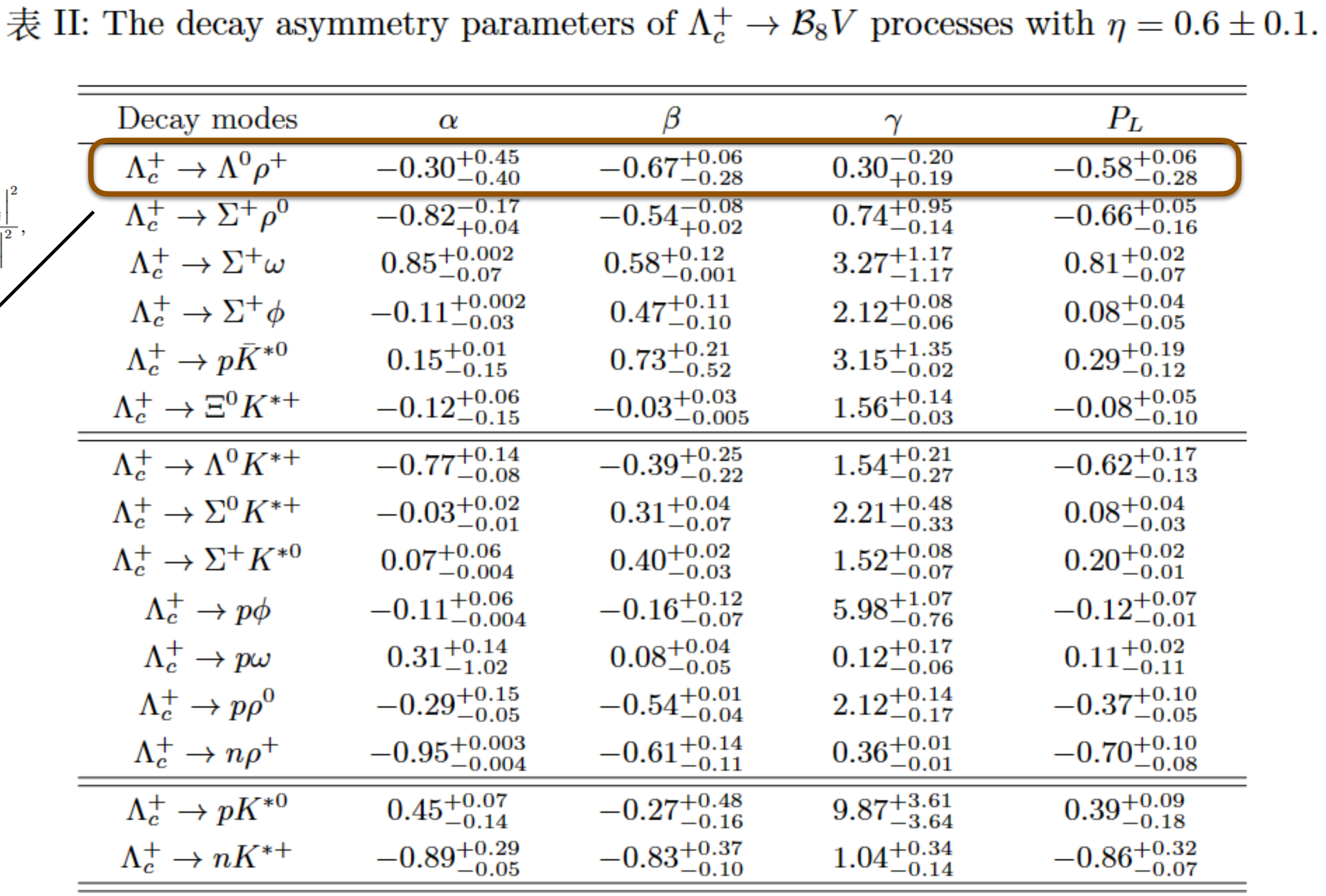

表 II: The decay asymmetry parameters of $\Lambda_c^+ \to \mathcal{B}_8 V$ processes with $\eta = 0.6 \pm 0.1$.

Decay modes	α	β	γ	P_L
$\Lambda_c^+ \to \Lambda^0\rho^+$	$-0.30^{+0.45}_{-0.40}$	$-0.67^{+0.06}_{-0.28}$	$0.30^{-0.20}_{+0.19}$	$-0.58^{+0.06}_{-0.28}$
$\Lambda_c^+ \to \Sigma^+\rho^0$	$-0.82^{-0.17}_{+0.04}$	$-0.54^{-0.08}_{+0.02}$	$0.74^{+0.95}_{-0.14}$	$-0.66^{+0.05}_{-0.16}$
$\Lambda_c^+ \to \Sigma^+\omega$	$0.85^{+0.002}_{-0.07}$	$0.58^{+0.12}_{-0.001}$	$3.27^{+1.17}_{-1.17}$	$0.81^{+0.02}_{-0.07}$
$\Lambda_c^+ \to \Sigma^+\phi$	$-0.11^{+0.002}_{-0.03}$	$0.47^{+0.11}_{-0.10}$	$2.12^{+0.08}_{-0.06}$	$0.08^{+0.04}_{-0.05}$
$\Lambda_c^+ \to p\bar{K}^{*0}$	$0.15^{+0.01}_{-0.15}$	$0.73^{+0.21}_{-0.52}$	$3.15^{+1.35}_{-0.02}$	$0.29^{+0.19}_{-0.12}$
$\Lambda_c^+ \to \Xi^0K^{*+}$	$-0.12^{+0.06}_{-0.15}$	$-0.03^{+0.03}_{-0.005}$	$1.56^{+0.14}_{-0.03}$	$-0.08^{+0.05}_{-0.10}$
$\Lambda_c^+ \to \Lambda^0K^{*+}$	$-0.77^{+0.14}_{-0.08}$	$-0.39^{+0.25}_{-0.22}$	$1.54^{+0.21}_{-0.27}$	$-0.62^{+0.17}_{-0.13}$
$\Lambda_c^+ \to \Sigma^0K^{*+}$	$-0.03^{+0.02}_{-0.01}$	$0.31^{+0.04}_{-0.07}$	$2.21^{+0.48}_{-0.33}$	$0.08^{+0.04}_{-0.03}$
$\Lambda_c^+ \to \Sigma^+K^{*0}$	$0.07^{+0.06}_{-0.004}$	$0.40^{+0.02}_{-0.03}$	$1.52^{+0.08}_{-0.07}$	$0.20^{+0.02}_{-0.01}$
$\Lambda_c^+ \to p\phi$	$-0.11^{+0.06}_{-0.004}$	$-0.16^{+0.12}_{-0.07}$	$5.98^{+1.07}_{-0.76}$	$-0.12^{+0.07}_{-0.01}$
$\Lambda_c^+ \to p\omega$	$0.31^{+0.14}_{-1.02}$	$0.08^{+0.04}_{-0.05}$	$0.12^{+0.17}_{-0.06}$	$0.11^{+0.02}_{-0.11}$
$\Lambda_c^+ \to p\rho^0$	$-0.29^{+0.15}_{-0.05}$	$-0.54^{+0.01}_{-0.04}$	$2.12^{+0.14}_{-0.17}$	$-0.37^{+0.10}_{-0.05}$
$\Lambda_c^+ \to n\rho^+$	$-0.95^{+0.003}_{-0.004}$	$-0.61^{+0.14}_{-0.11}$	$0.36^{+0.01}_{-0.01}$	$-0.70^{+0.10}_{-0.08}$
$\Lambda_c^+ \to pK^{*0}$	$0.45^{+0.07}_{-0.14}$	$-0.27^{+0.48}_{-0.16}$	$9.87^{+3.61}_{-3.64}$	$0.39^{+0.09}_{-0.18}$
$\Lambda_c^+ \to nK^{*+}$	$-0.89^{+0.29}_{-0.05}$	$-0.83^{+0.37}_{-0.10}$	$1.04^{+0.34}_{-0.14}$	$-0.86^{+0.32}_{-0.07}$

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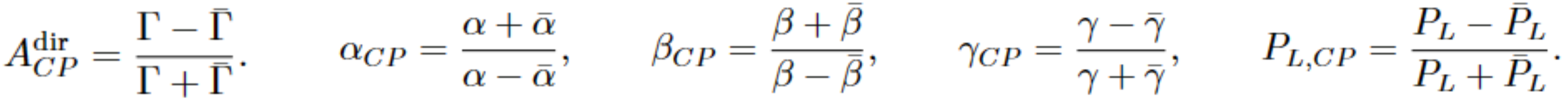
CP violation



$$A_{CP}^{\rm dir} = \frac{\Gamma - \bar{\Gamma}}{\Gamma + \bar{\Gamma}}, \qquad \alpha_{CP} = \frac{\alpha + \bar{\alpha}}{\alpha - \bar{\alpha}}, \qquad \beta_{CP} = \frac{\beta + \bar{\beta}}{\beta - \bar{\beta}}, \qquad \gamma_{CP} = \frac{\gamma - \bar{\gamma}}{\gamma + \bar{\gamma}}, \qquad P_{L,CP} = \frac{P_L - \bar{P}_L}{P_L + \bar{P}_L}.$$

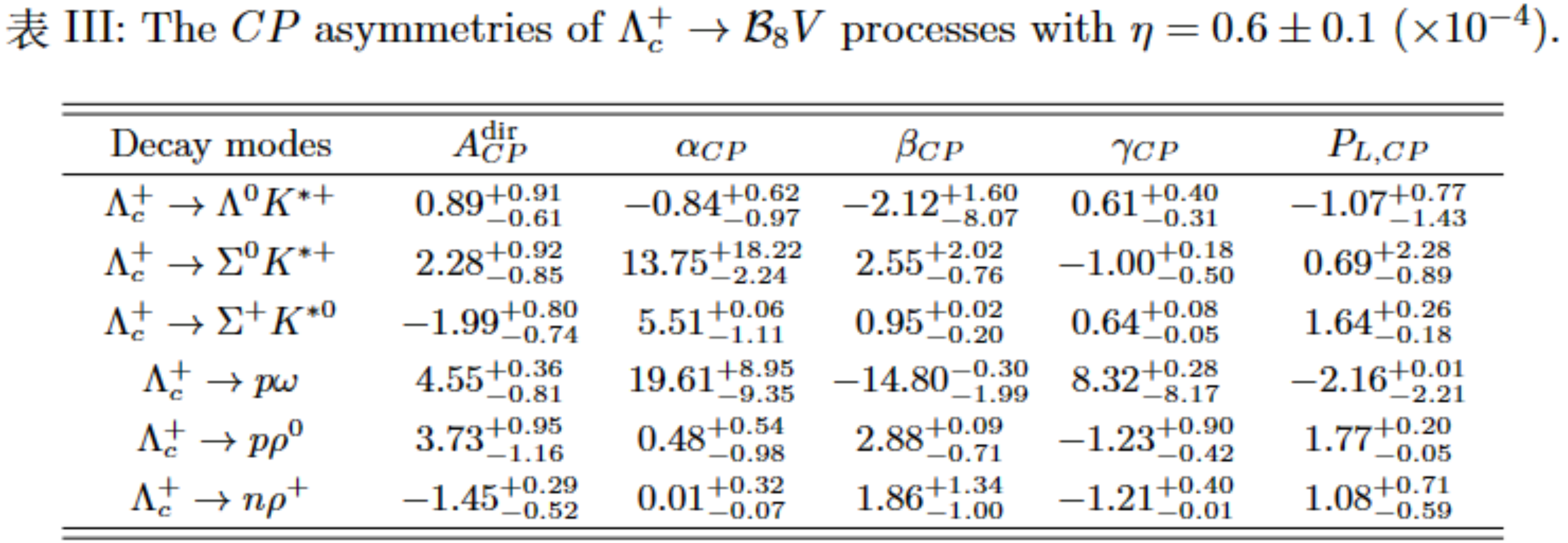


表 III: The CP asymmetries of $\Lambda_c^+ \to \mathcal{B}_8 V$ processes with $\eta = 0.6 \pm 0.1$ $(\times 10^{-4})$.

Decay modes	$A_{CP}^{\rm dir}$	α_{CP}	β_{CP}	γ_{CP}	$P_{L,CP}$
$\Lambda_c^+ \to \Lambda^0 K^{*+}$	$0.89^{+0.91}_{-0.61}$	$-0.84^{+0.62}_{-0.97}$	$-2.12^{+1.60}_{-8.07}$	$0.61^{+0.40}_{-0.31}$	$-1.07^{+0.77}_{-1.43}$
$\Lambda_c^+ \to \Sigma^0 K^{*+}$	$2.28^{+0.92}_{-0.85}$	$13.75^{+18.22}_{-2.24}$	$2.55^{+2.02}_{-0.76}$	$-1.00^{+0.18}_{-0.50}$	$0.69^{+2.28}_{-0.89}$
$\Lambda_c^+ \to \Sigma^+ K^{*0}$	$-1.99^{+0.80}_{-0.74}$	$5.51^{+0.06}_{-1.11}$	$0.95^{+0.02}_{-0.20}$	$0.64^{+0.08}_{-0.05}$	$1.64^{+0.26}_{-0.18}$
$\Lambda_c^+ \to p\omega$	$4.55^{+0.36}_{-0.81}$	$19.61^{+8.95}_{-9.35}$	$-14.80^{-0.30}_{-1.99}$	$8.32^{+0.28}_{-8.17}$	$-2.16^{+0.01}_{-2.21}$
$\Lambda_c^+ \to p\rho^0$	$3.73^{+0.95}_{-1.16}$	$0.48^{+0.54}_{-0.98}$	$2.88^{+0.09}_{-0.71}$	$-1.23^{+0.90}_{-0.42}$	$1.77^{+0.20}_{-0.05}$
$\Lambda_c^+ \to n\rho^+$	$-1.45^{+0.29}_{-0.52}$	$0.01^{+0.32}_{-0.07}$	$1.86^{+1.34}_{-1.00}$	$-1.21^{+0.40}_{-0.01}$	$1.08^{+0.71}_{-0.59}$

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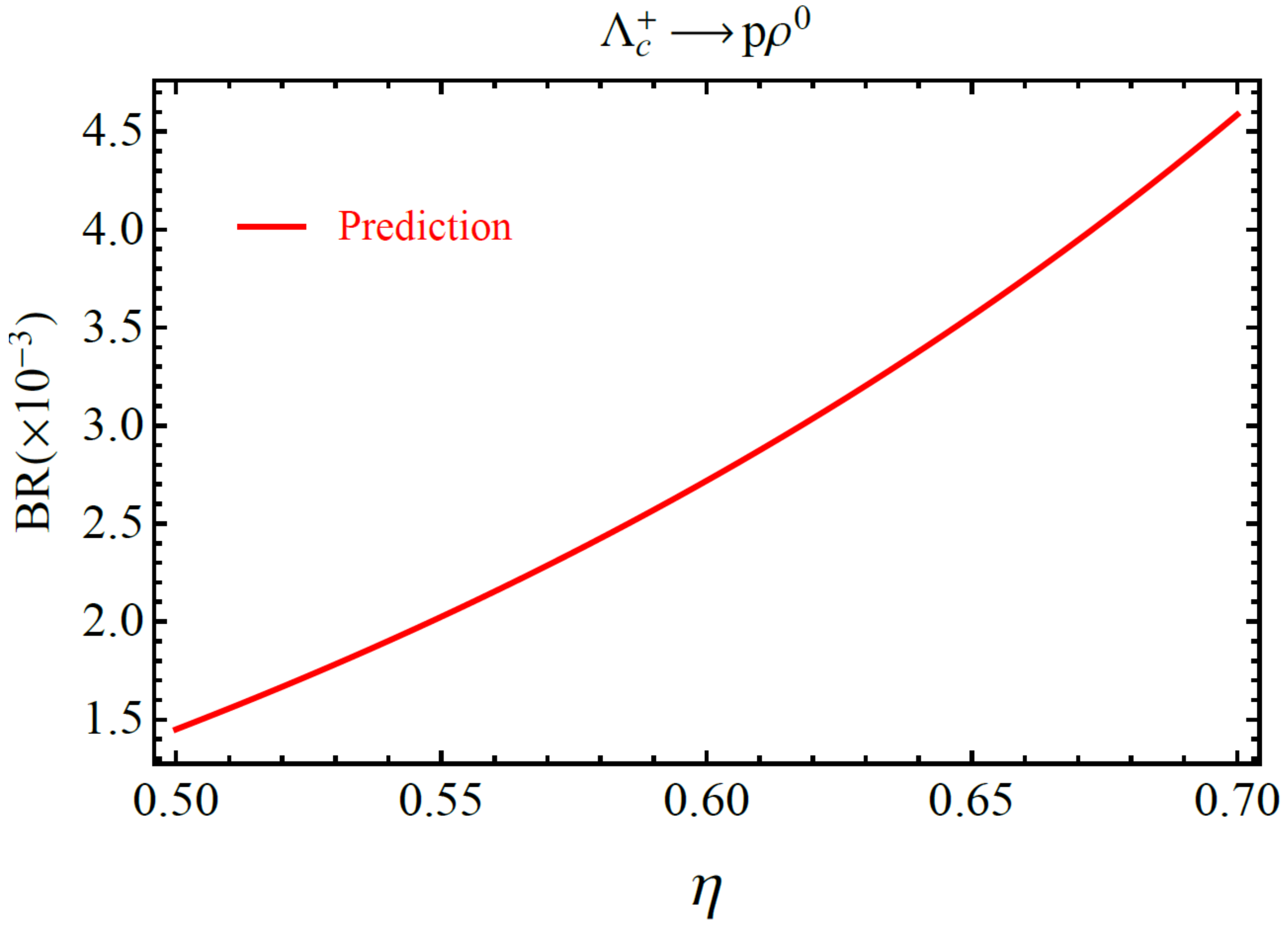
Dependence on η

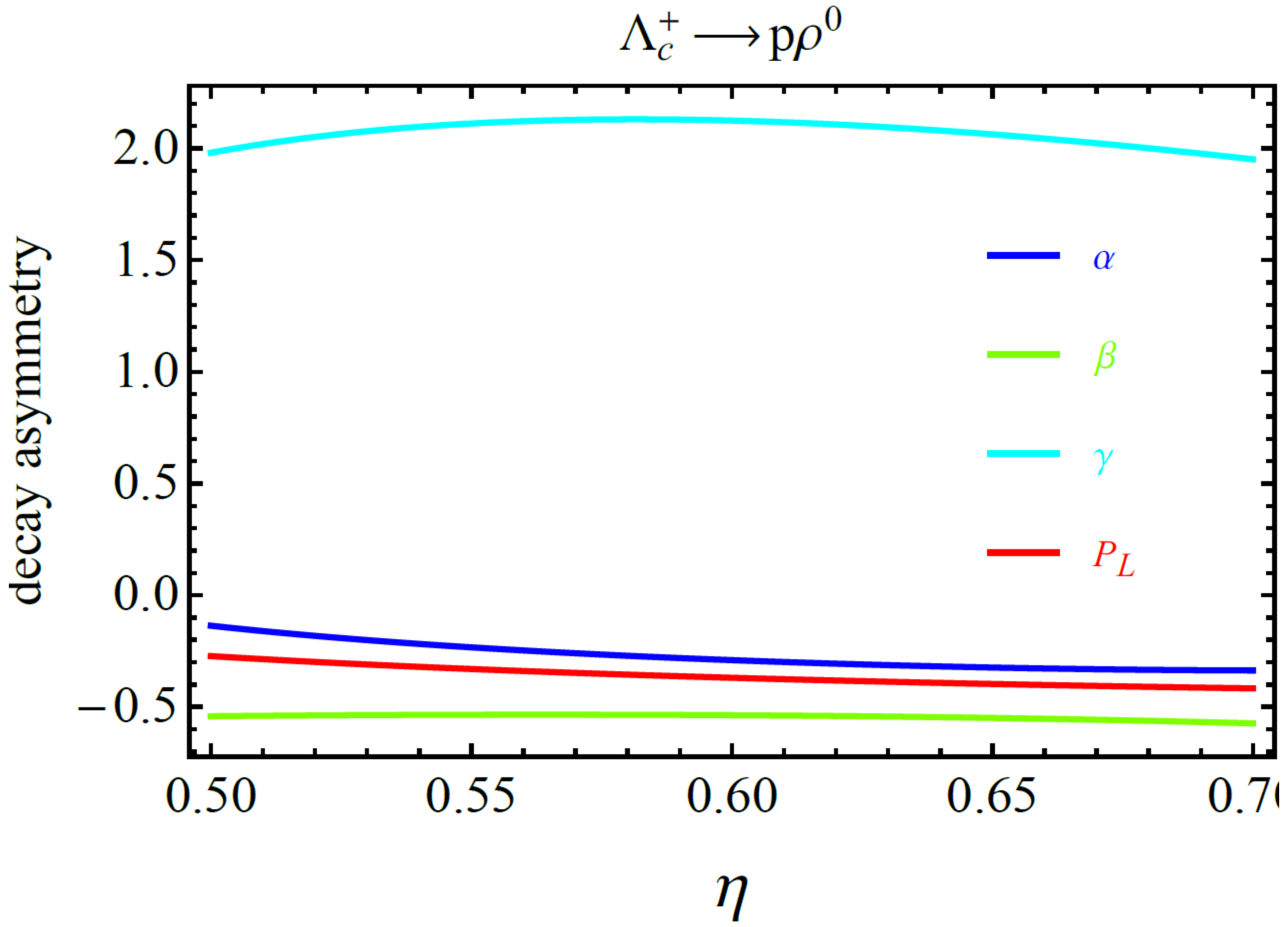
Branching fractions



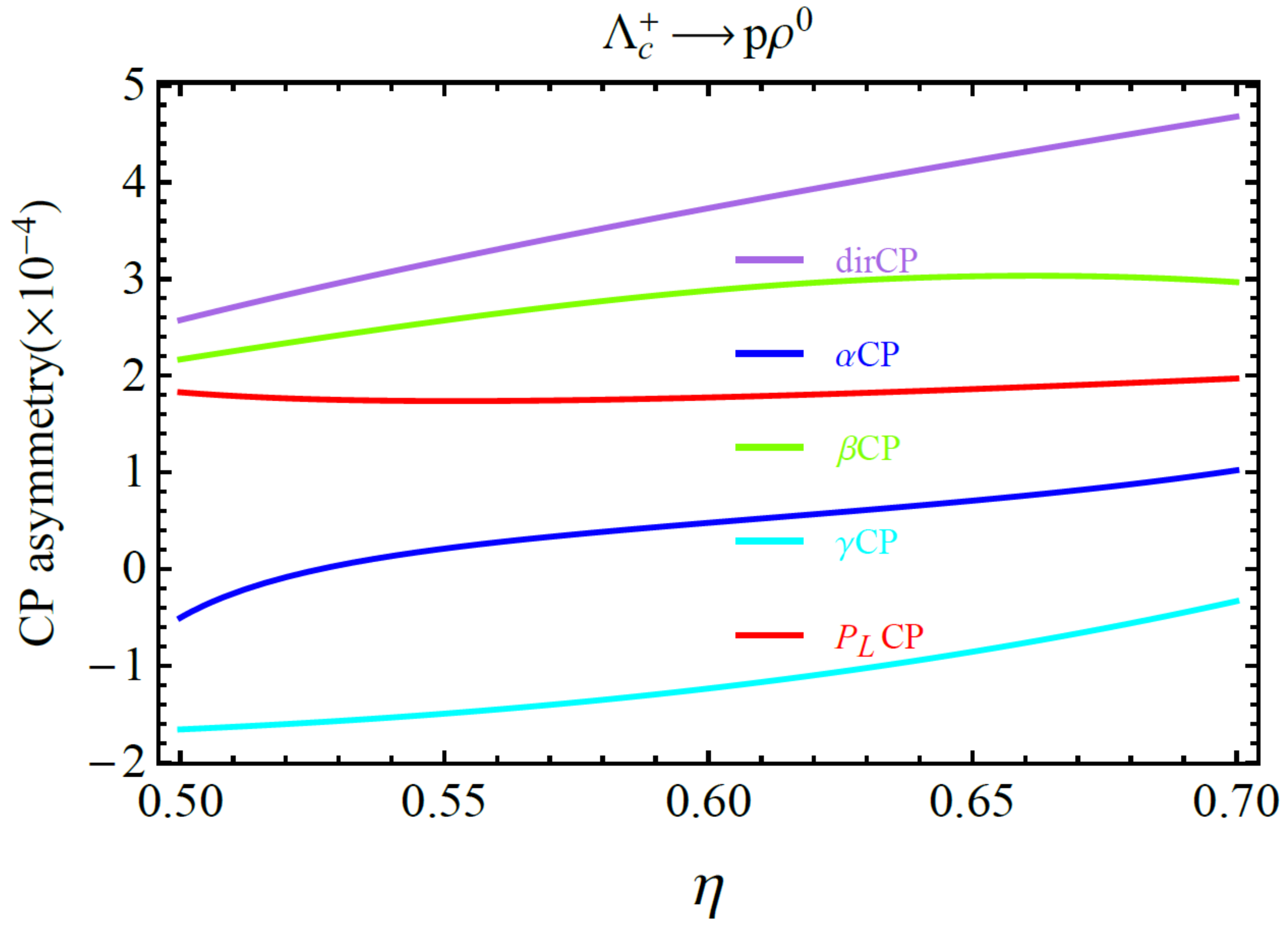
- Branching fractions are very sensitive to η

$$\Gamma \propto 2(|S|^2 + |P_2^2|) + \frac{E_V^2}{m_V^2}(|S+D|^2 + |P_1|^2)$$

Decay asymmetries



CP violations



- The decay asymmetries and CPV are insensitive to η, whose dependences are mostly cancelled by the ratios

$$\alpha = \frac{\left|H_{1,\frac{1}{2}}\right|^2 - \left|H_{-1,-\frac{1}{2}}\right|^2}{\left|H_{1,\frac{1}{2}}\right|^2 + \left|H_{-1,-\frac{1}{2}}\right|^2}$$

$$A_{CP} = \frac{\Gamma - \bar{\Gamma}}{\Gamma + \bar{\Gamma}}$$

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Summary

- Final-State-Interaction (FSI) is a physical picture of long-distance effect.
- Improved FSI method is develop to successfully study charm-baryon decays
- Using only one parameter, it could explain almost all the experimental data.
- It has reasonable strong phases, thus can predict CP violation.
- Theoretical uncertainties can be lowered down in the decay asymmetries and CPV by the ratios.

Outlooks

- We will next study psuedoscalar modes.
- The current uncertainty comes from the form factor. How many? What order? Or what formula?
- Our current formula can contribute strong phase. We are testing some other formula without strong phases.
- BESIII has measured the decay asymmetries of $\Lambda_c^+ \to \Lambda^0 \rho^+$. More processes are required to measure the decay asymmetries. They could tell something about strong phases, so tell what model is better. Like $\Lambda_c^+ \to \Xi^0 K^+$

$$\mathcal{F} = \left(\frac{m^2 \pm \Lambda^2}{p^2 \pm \Lambda^2} \right)^n ,$$

$$\Lambda = m + \eta \Lambda_{QCD} .$$

$$\alpha \propto Re(S^* P)$$

$$\beta \propto Im(S^* P)$$

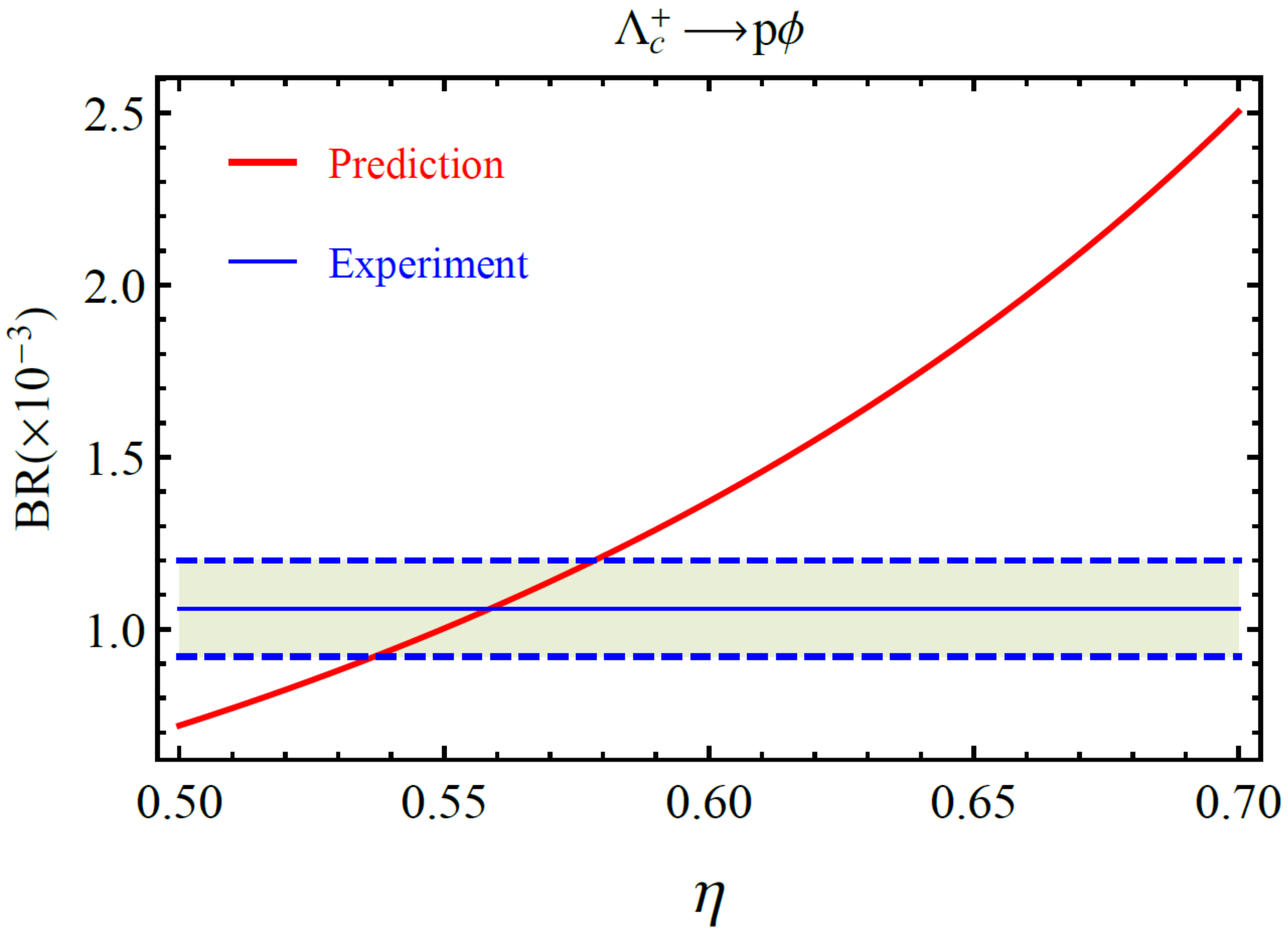
Outlooks

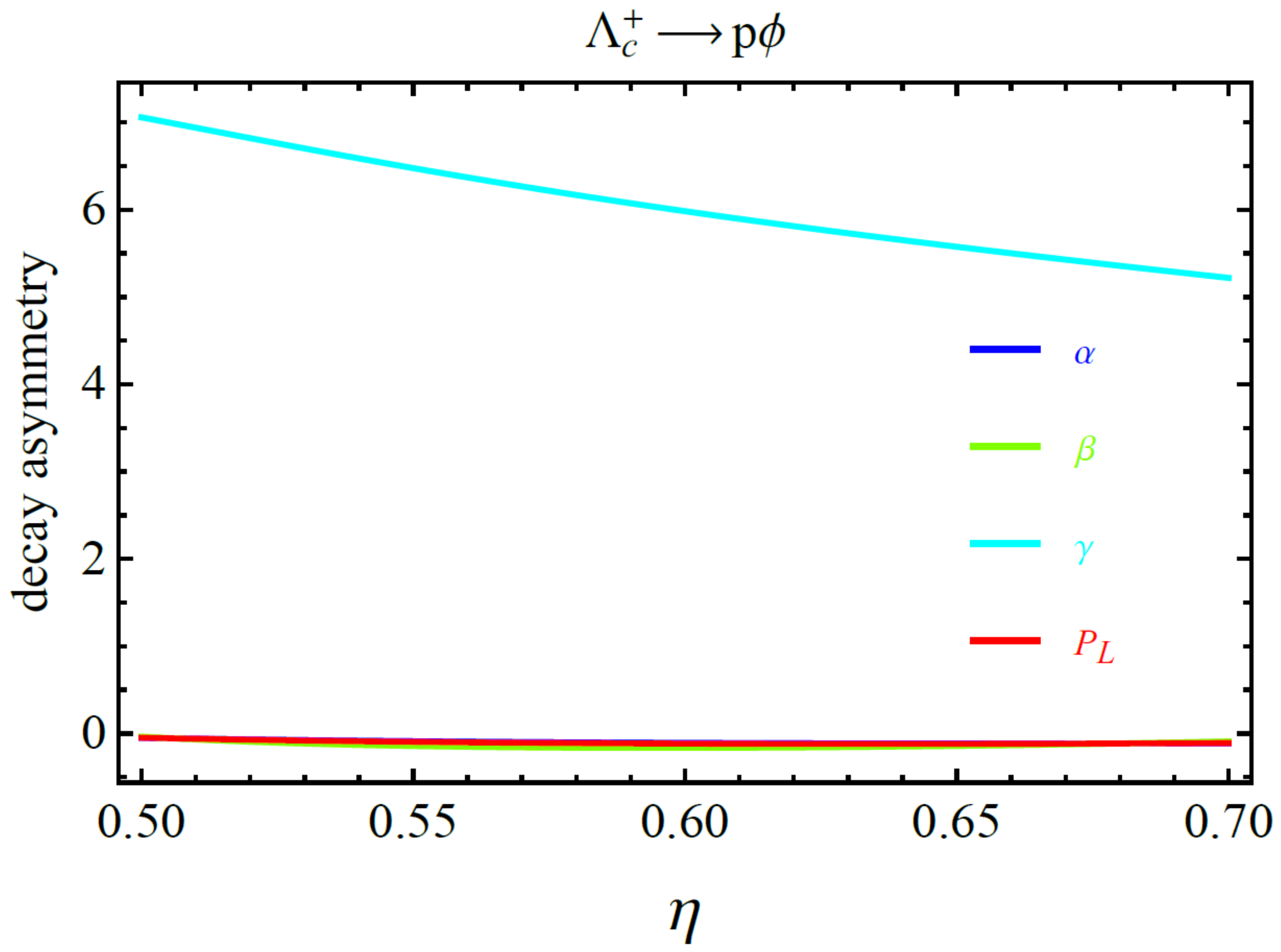
- What opportunities in charm physics?
- CPV is most important one. Dynamics is required for predictions. Branching fractions and decay asymmetries to be measured by BESIII. [See H.Y.Cheng's, F.Xu's, C.W.Liu's talks]
- Lifetimes have not been well predicted. Non-perturbative matrix elements can be extracted from inclusive decays [See Q.Qin's talk] or by Lattice QCD [See W.Wang's talk].
- Spectroscopy in multi-body decays of D and Λ_c [See Y.K.Hsiao's, E.Wang's, C.W.Xiao's, S.Cheng's talks]
- FCNC for searching new physics. Long-distance dominant, but difficult in theory. Local operators from Lattice QCD [See Z.F.Liu's talk]

Thank you very much!

Backups

The dependence on η





- The branching ratio is sensitive to the parameter η.
- The decay asymmetries are not sensitive to the parameter η.

The dependence on heavy to light form factor

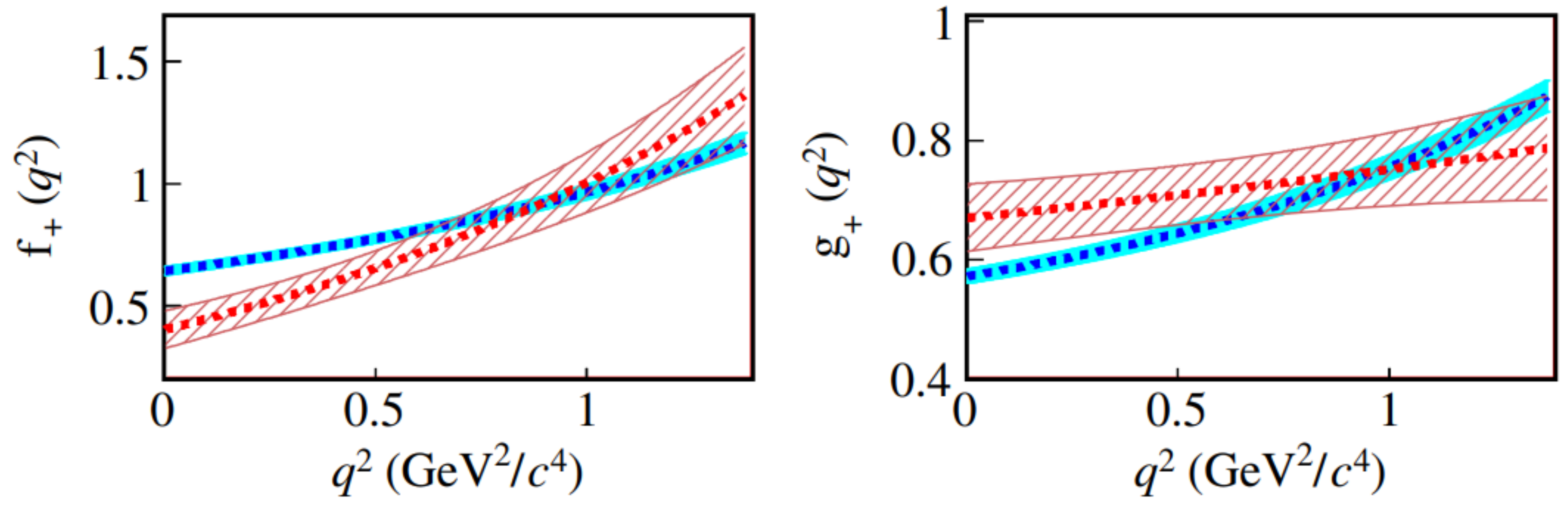
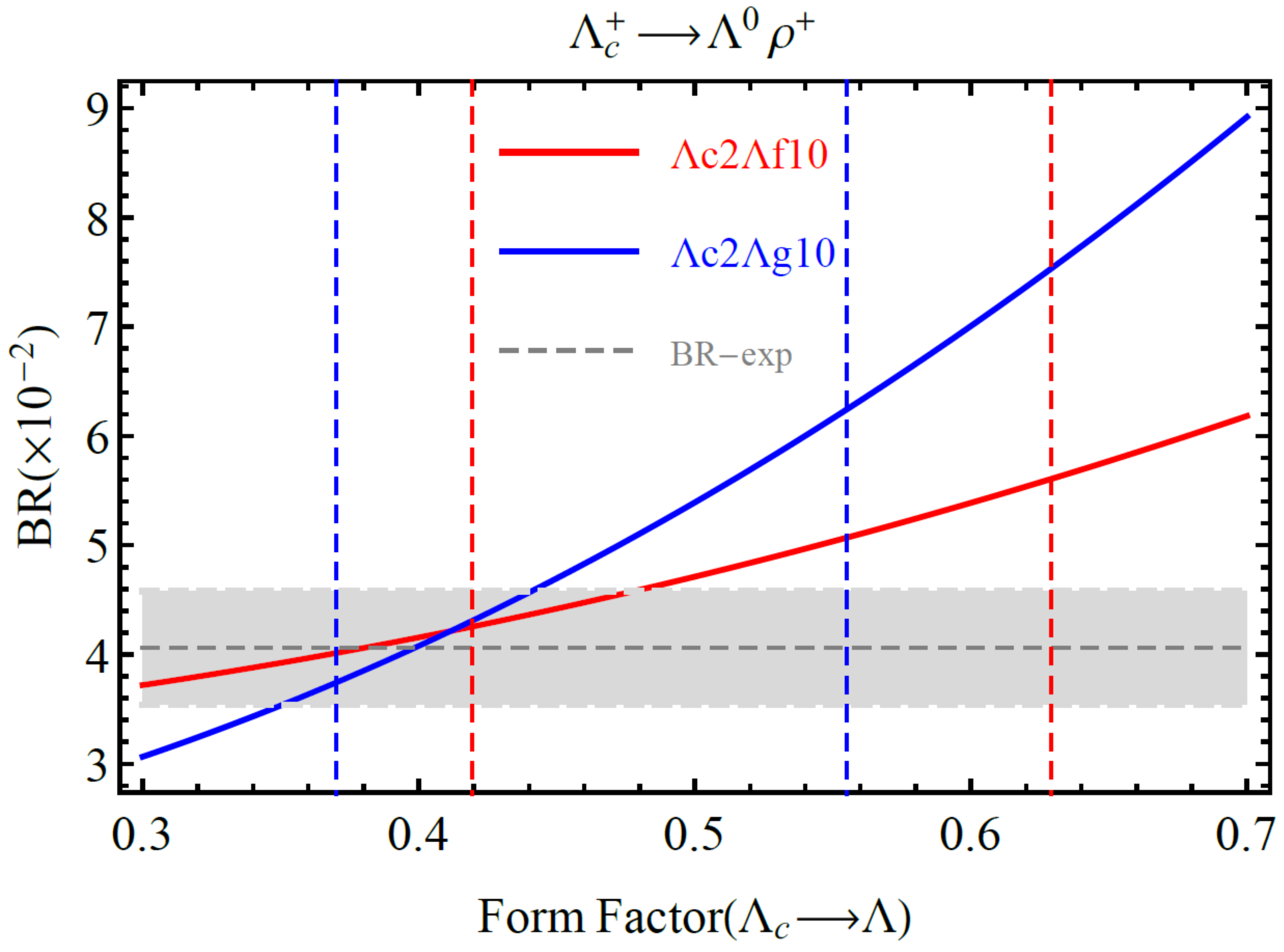
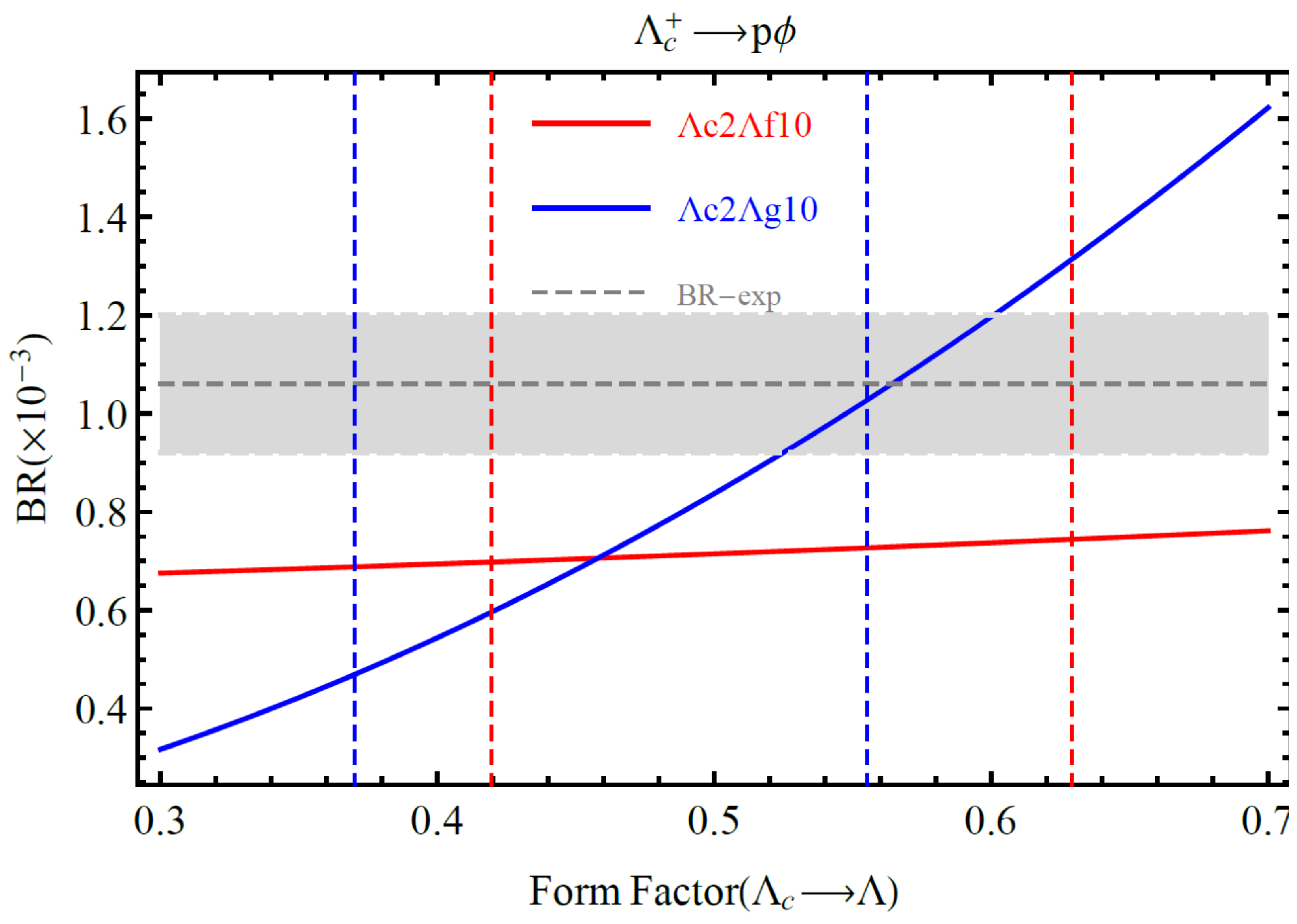


FIG. 3. Comparison of form factors with LQCD calculations. The bands show the total uncertainties.

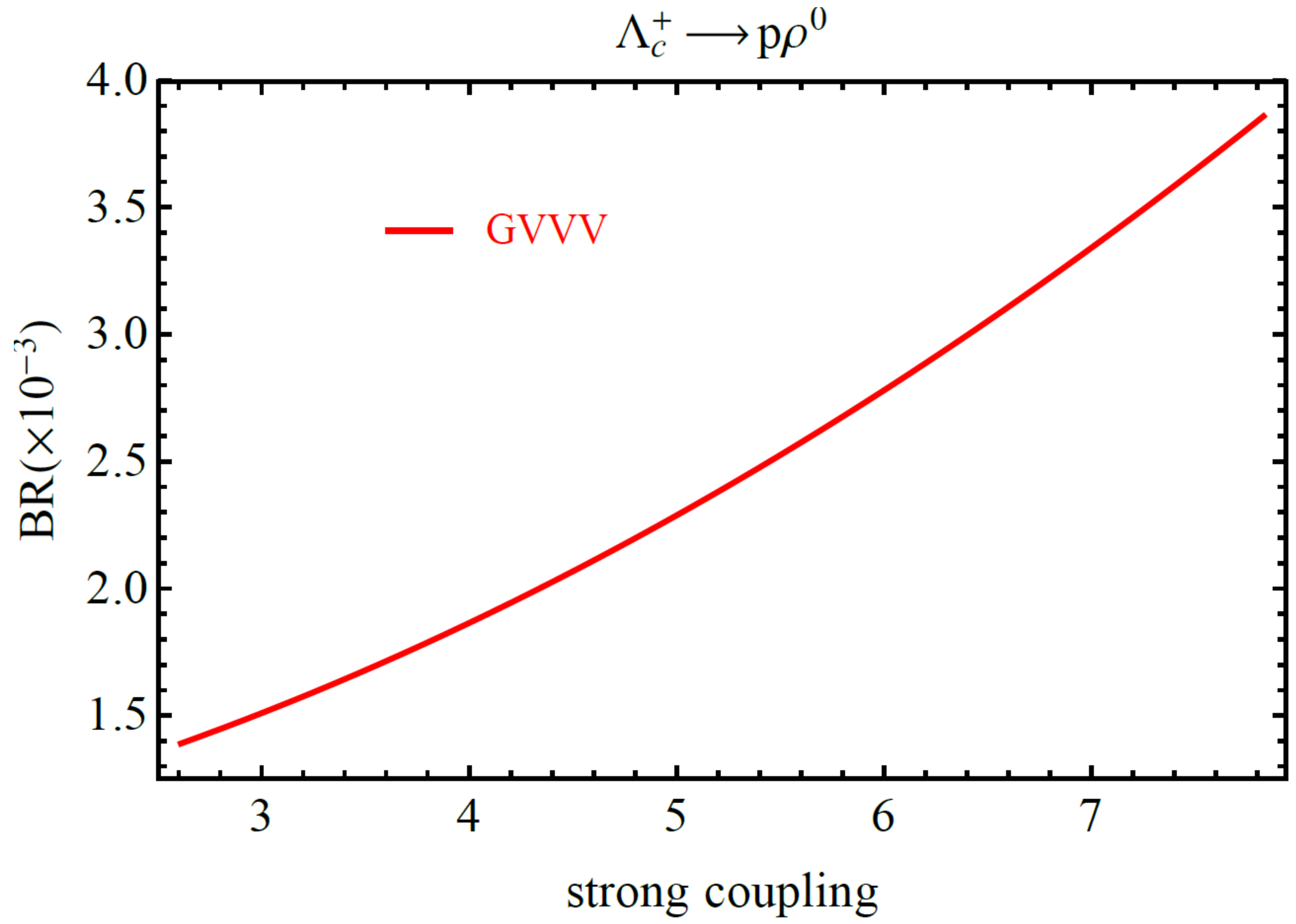
$$f_1(q^2) = \frac{(m_i + m_f)^2 f_+(q^2) - q^2 f_\perp(q^2)}{s_+},$$
$$g_1(q^2) = \frac{(m_i - m_f)^2 g_+(q^2) - q^2 g_\perp(q^2)}{s_-},$$

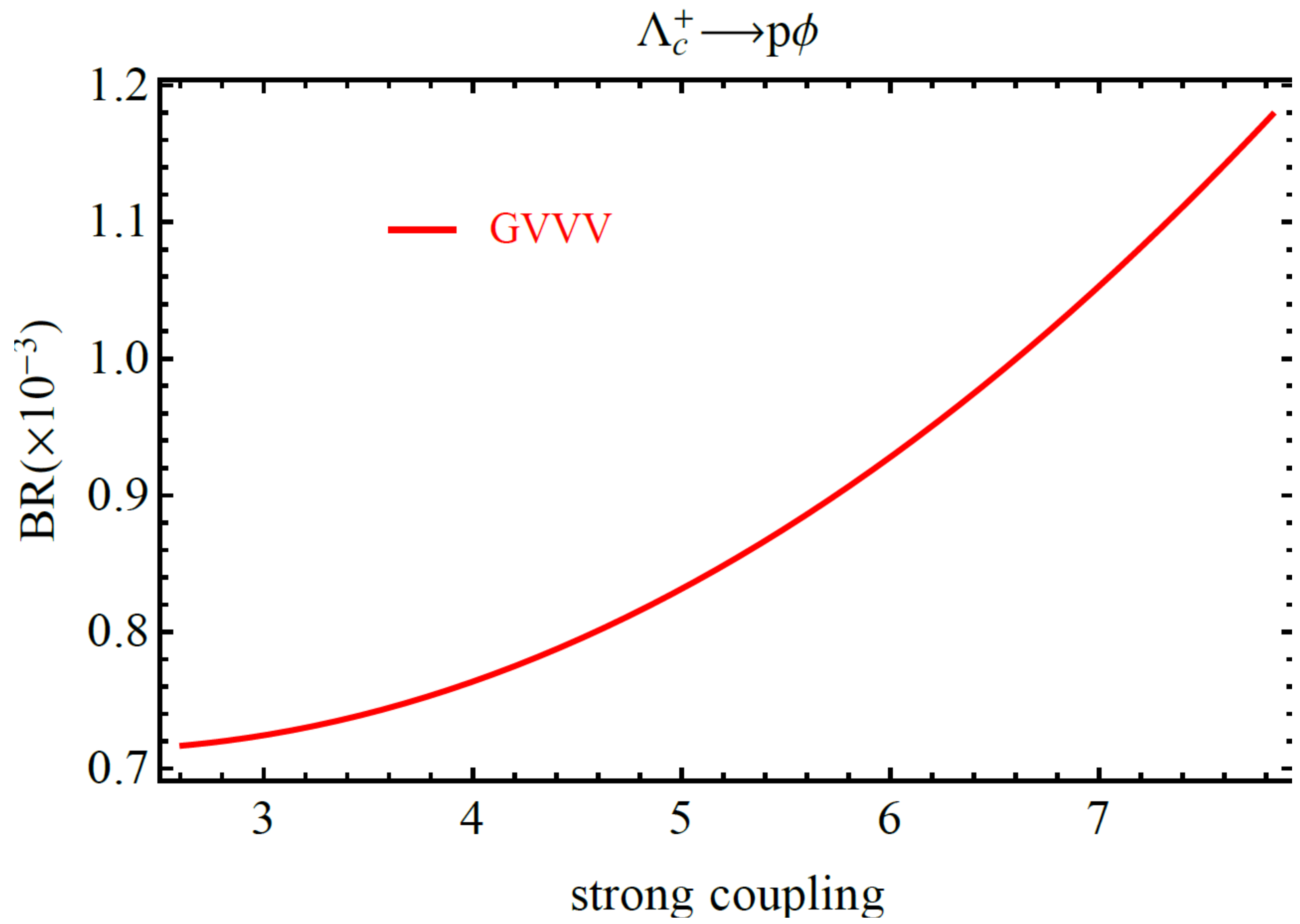


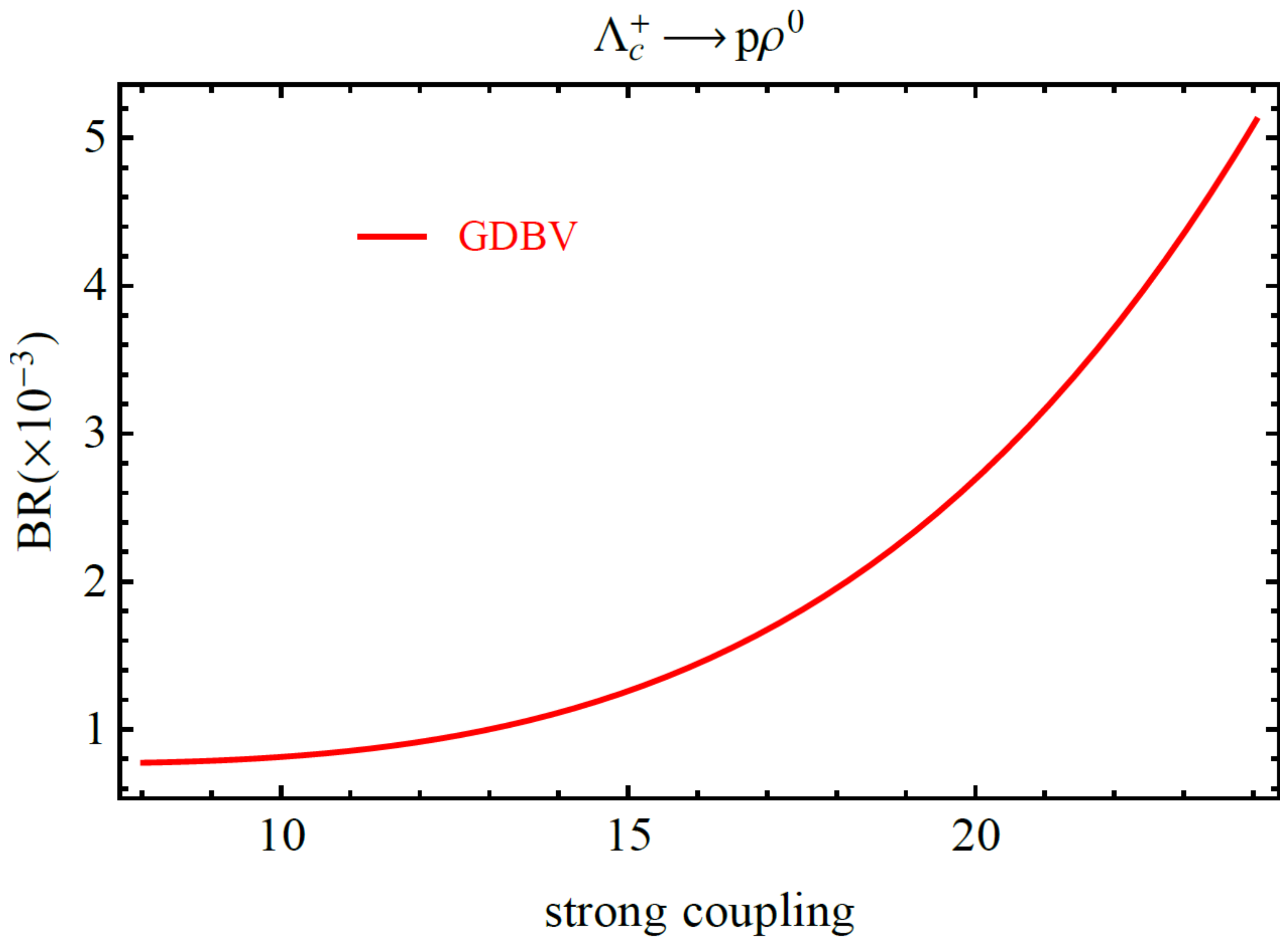


- The branching ratio is sensitive to the value of heavy to light form factor.
- The decay asymmetries and CP asymmetries are not sensitive to FF.

The dependence on strong coupling constants







- The branching ratio is sensitive to the value of strong coupling.
- The decay asymmetries and CP asymmetries are not sensitive to strong coupling.