scib.2025.05.045

Charming ~~CPV~~

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BESIII, Lanzhou

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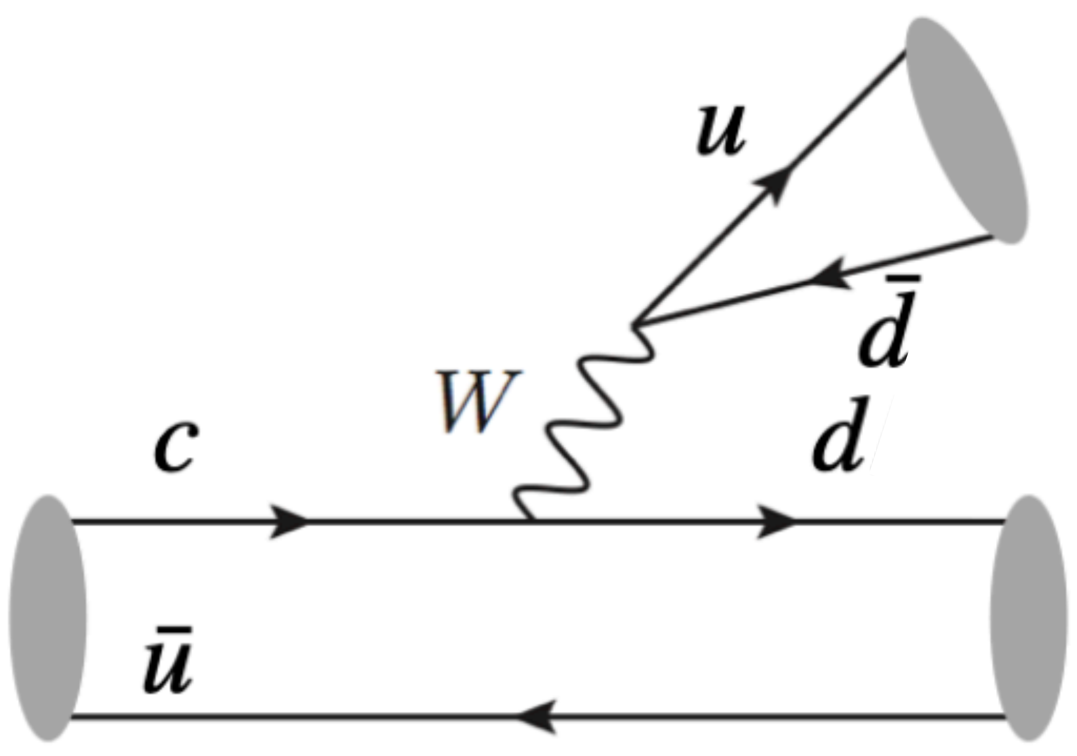
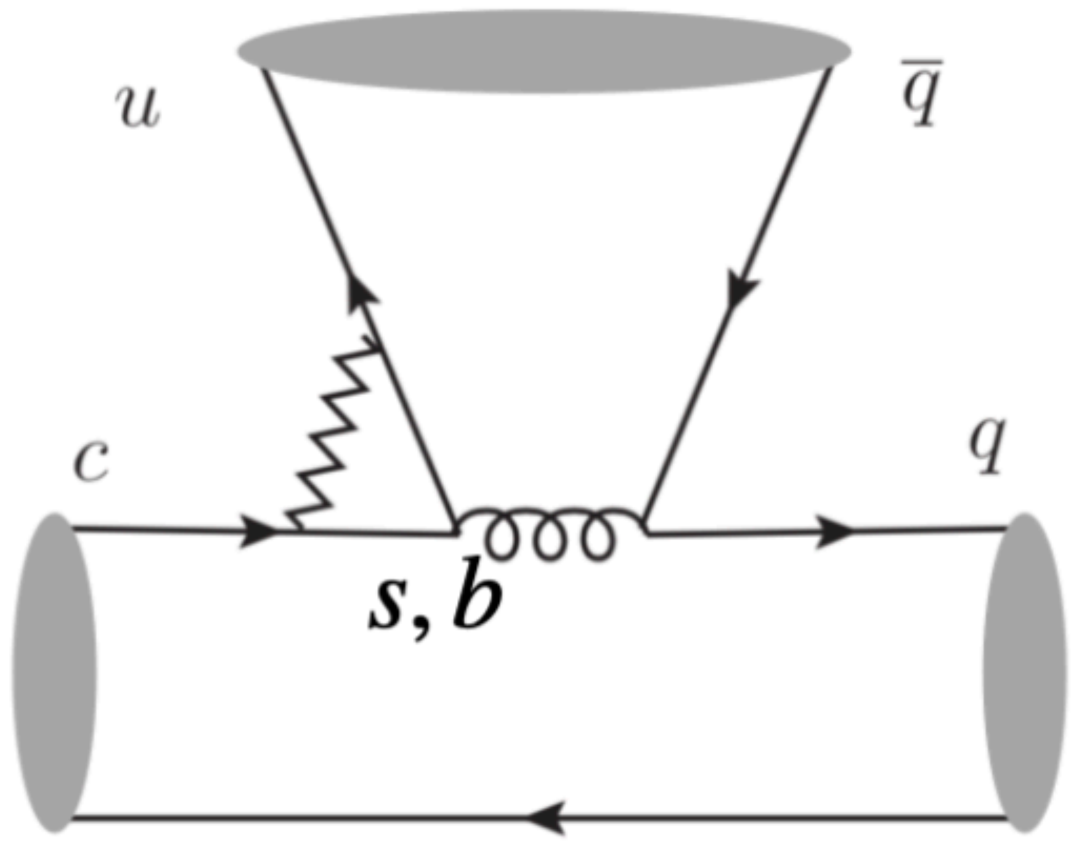
• Charming physics - CP violation

$$a_{CP} \approx 1.5 \times 10^{-3} \times \mathrm{Im}(P/T)$$

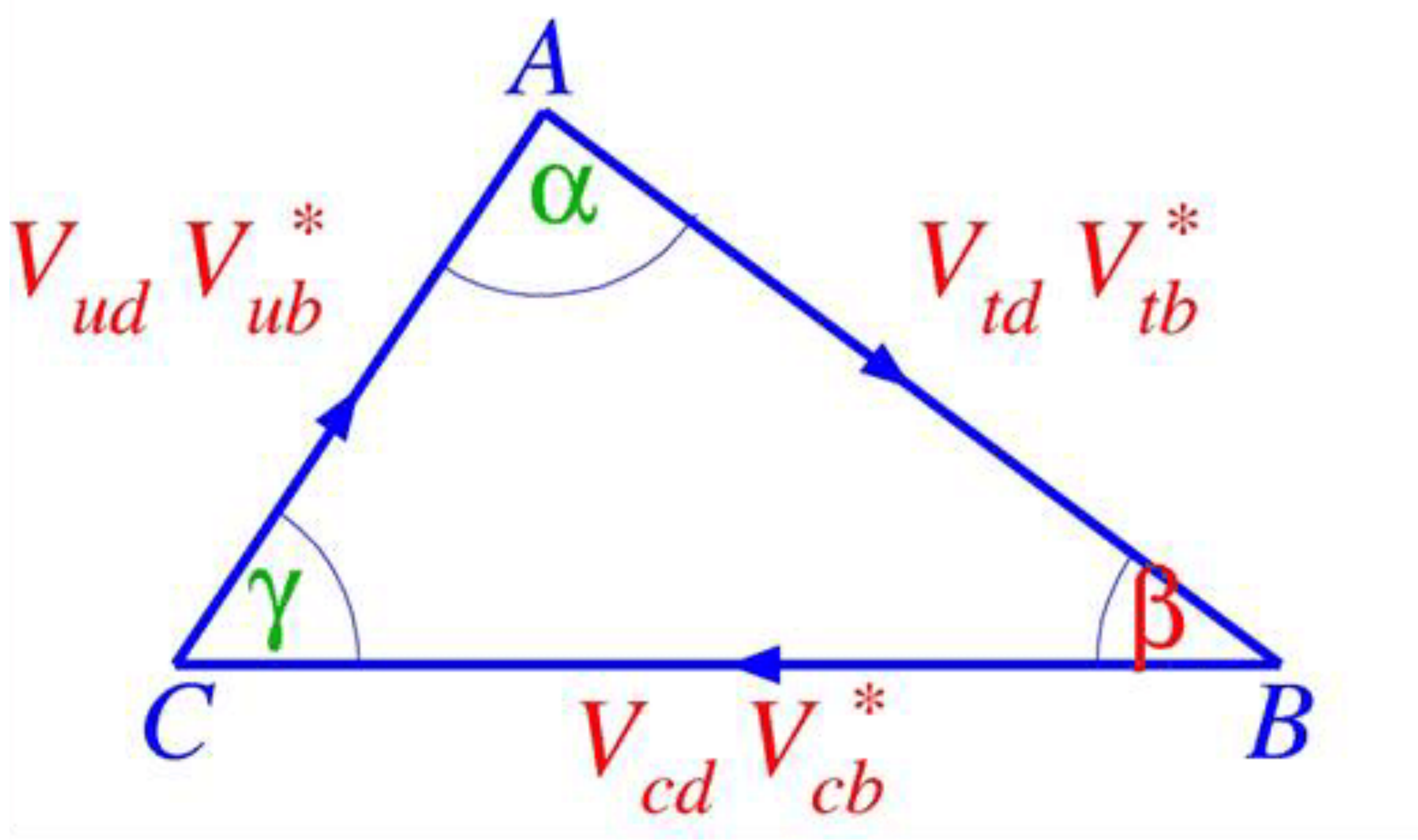
$$A(D^0 \to \pi^+\pi^-) = V_{cd}^* V_{ud}\, T + V_{cb}^* V_{ub}\, P$$



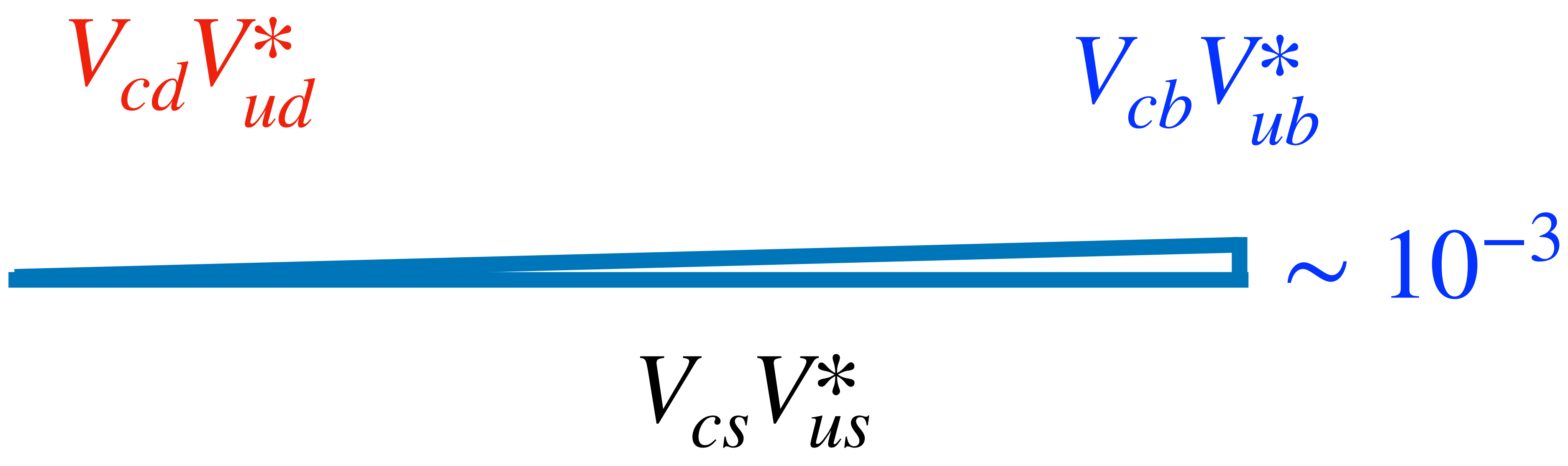
(T)



(P)



CKM triangle for $b \to d$



CKM triangle for $c \to u$

See Fu-Sheng's talk for details.

Charming physics - CP violation

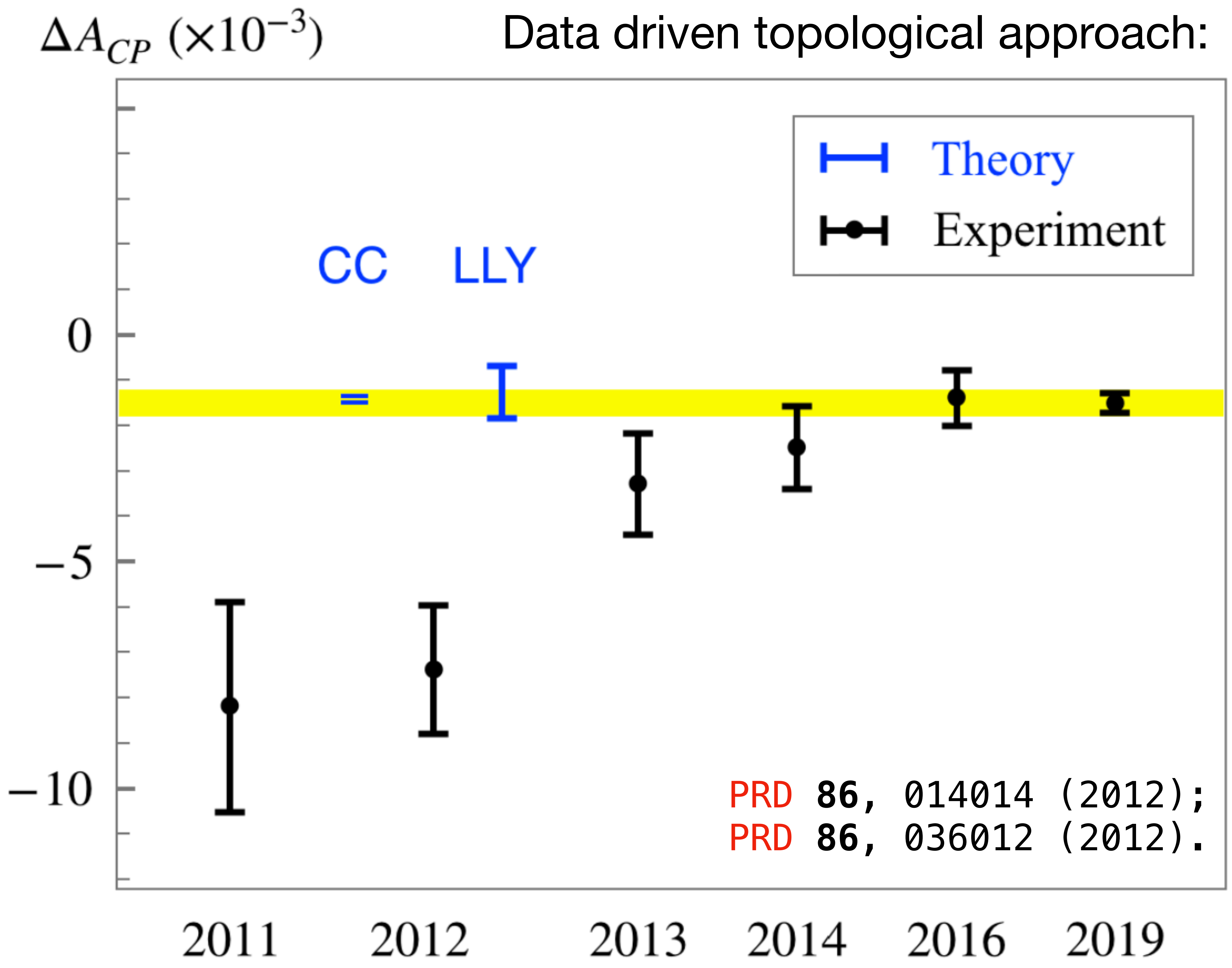
$$a_{CP} \approx 1.5 \times 10^{-3} \times \mathrm{Im}(P/T)$$

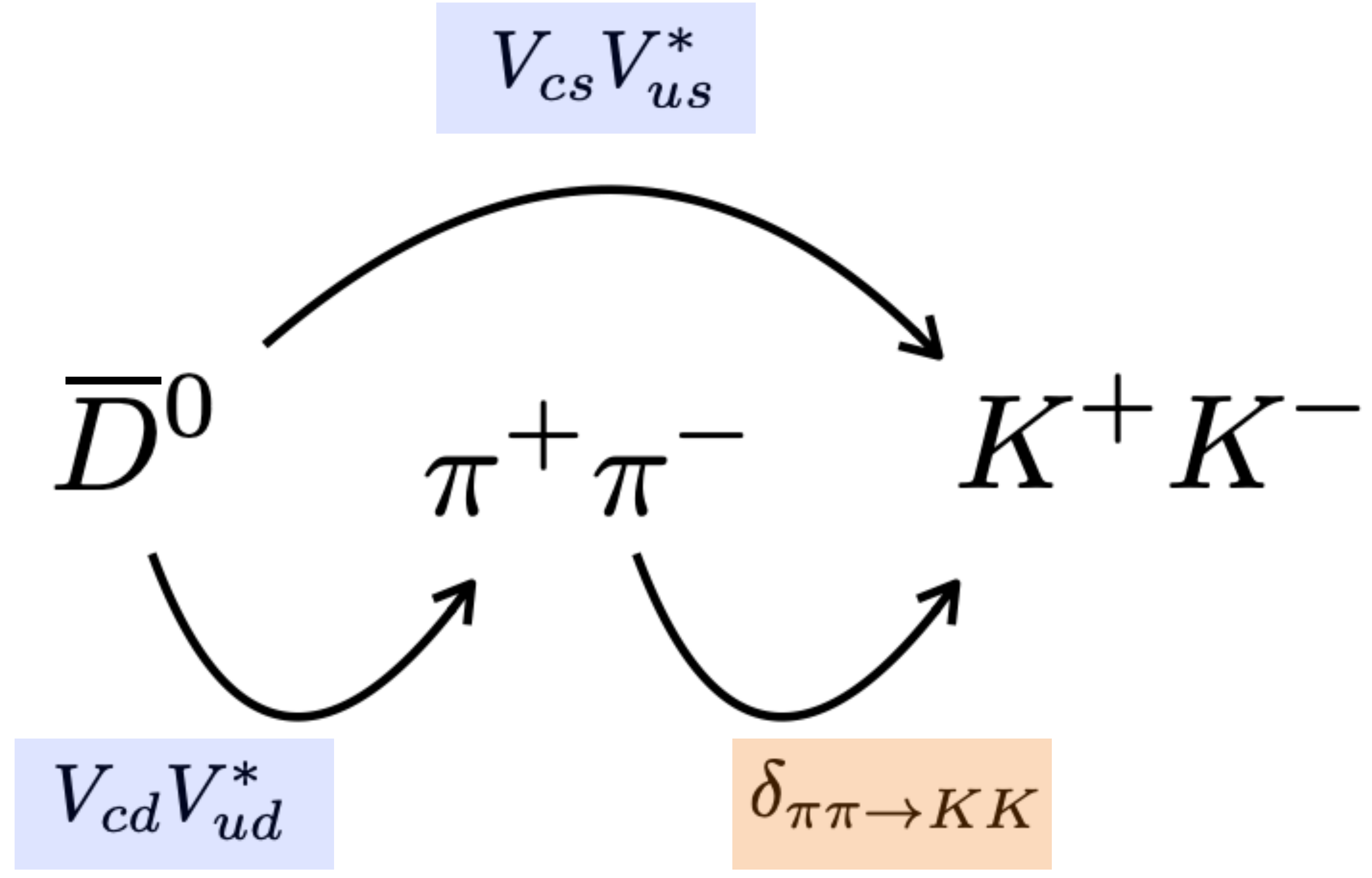
$$a_{CP}(D^0 \to K^+K^-) - a_{CP}(D^0 \to \pi^+\pi^-) = (-1.54 \pm 0.29) \times 10^{-3}$$

PRL **122**, 211803 (2019);

- $|P/T| \approx 1$, **an order larger** than naive expectation!

Data driven topological approach:





$$a_{CP} \propto \sin\delta_{\mathrm{weak}} \sin\delta_{\mathrm{strong}}$$

Two **necessary** and **sufficient** conditions for **CPV:**

CKM phases and **strong phases**.

PRL **131**, 051802 (2023).

Charming physics - CP violation

Cheng and Chiang conjectured $P = E$ in 2012, which was proved in 2021 by Di Wang.

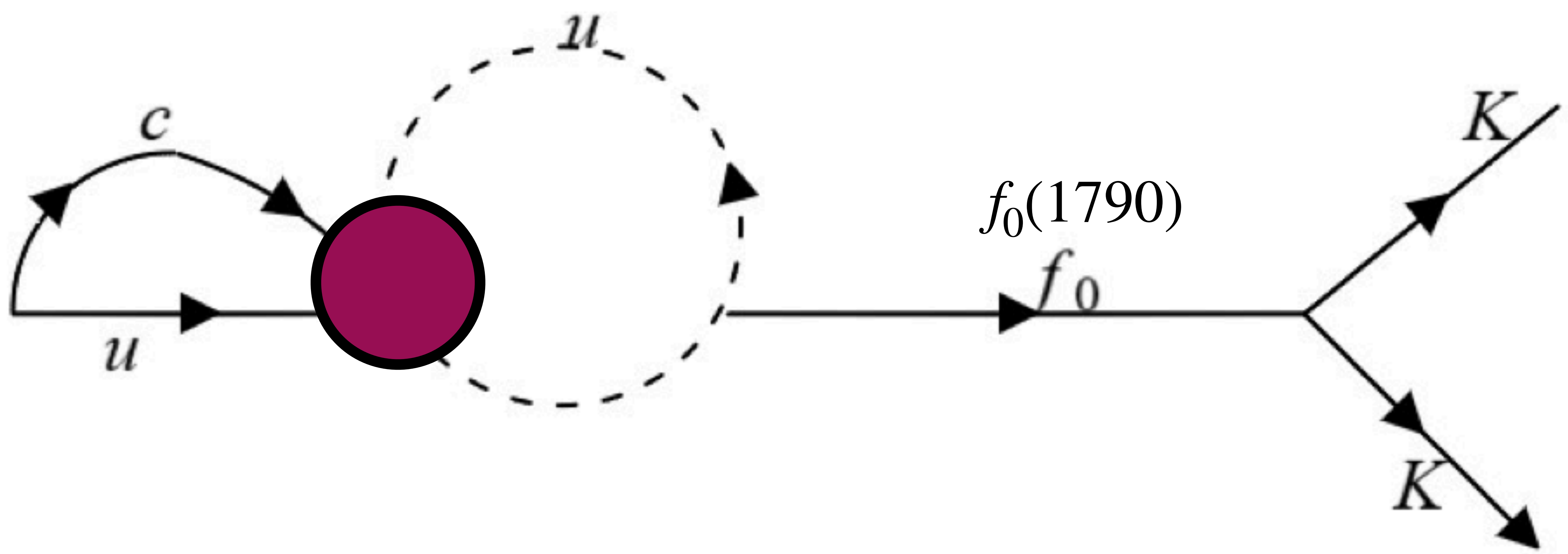
PRD **86**, 014014 (2012), 2111.11201, 2505.07150.

Charming physics - CP violation

Reasons to go **beyond** charmed mesons:

$$a_{CP}^{KK} = (7.7 \pm 5.7) \times 10^{-4}, \quad a_{CP}^{\pi\pi} = (23.2 \pm 6.1) \times 10^{-4}$$

PRL **131**, 091802 (2023)



PRD **81**, 074021 (2010), PLB **825**, 136855 (2022).

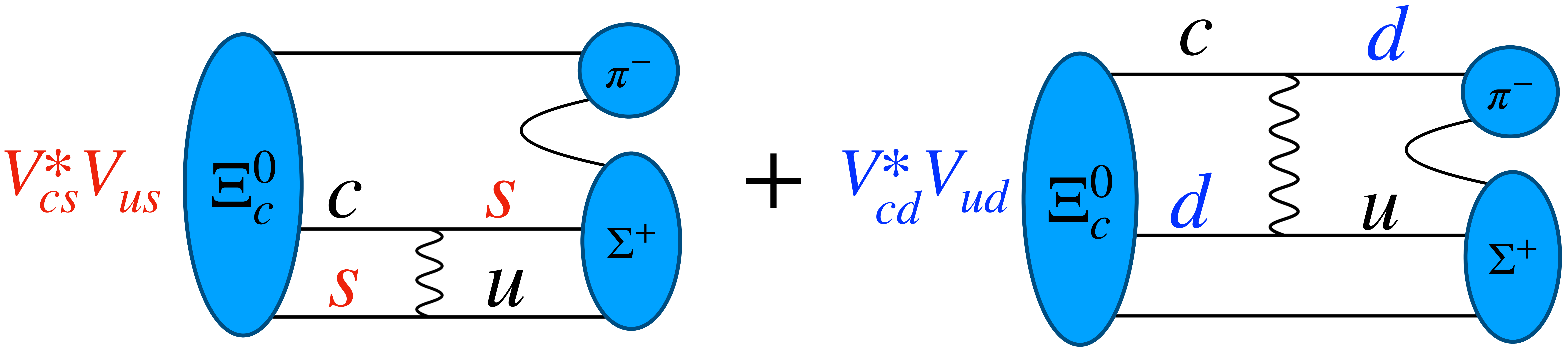
1. Relative sign of a_{CP}^{KK} and $a_{CP}^{\pi\pi}$ **contradicts** to the theoretical expectations.

2. f_0 might be a **glueball** which mainly decays to kaons. Leading order amplitude $\propto m_s$.

3. Its mass is too close to D meson, enhancing **SU(3) breaking** effects from mass splitting.

Charming physics - CP violation

Reasons to go **beyond** charmed mesons:



4. Quark structure provides CKM phase at **tree level**.

5. Unlike $D^0 \to h^+h^-$, CP-even **phase shifts** in baryon decays can be directly measured.

Very important inputs and driven force in the study of charm baryons!

See Pei-Rong's talk.

• Experimental status of charmed baryon decays

2023: The ***first*** measurement of CP violation in charmed baryon two-body decays

Sci. Bull. **68**, 583-592 (2023)

$$A_{CP}(\Lambda_c^+ \to \Lambda K^+) = 0.021 \pm 0.026$$

* The most precise CP asymmetries in branching fractions by far in charmed baryons.

2024: Measurements of the ***strong phase*** in $\Lambda_c^+ \to \Xi^0 K^+$

PRL **132**, 031801 (2024)

$$\delta_P - \delta_S = -1.55 \pm 0.27 (+\pi)\,, \quad \alpha = 0.01 \pm 0.16$$

* CP even and Cabibbo-favored, but very important to studies of ***CP violation***!

See Pei-Rong's talk.

2024: Measurements of ***strong phases*** in $\Lambda_c^+ \to \Lambda\pi^+, \Lambda K^+$

PRL **133**, 261804 (2024)

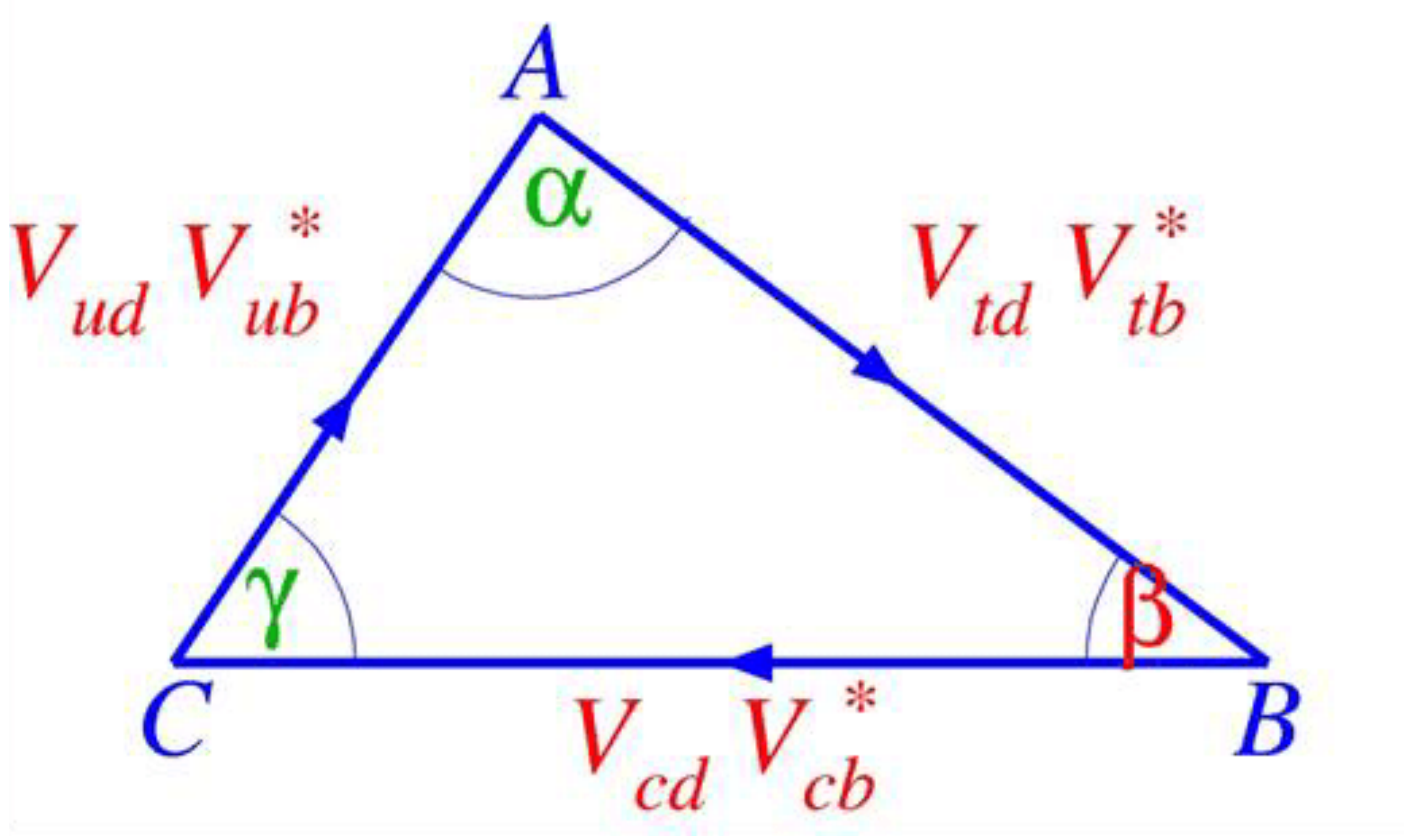
$$(\beta_\pi, \beta_K) = (0.368 \pm 0.019 \pm 0.008\,,\ 0.35 \pm 0.12 \pm 0.04)\,.$$

* Confirmed the discovery of large strong phases in charmed baryon decays.

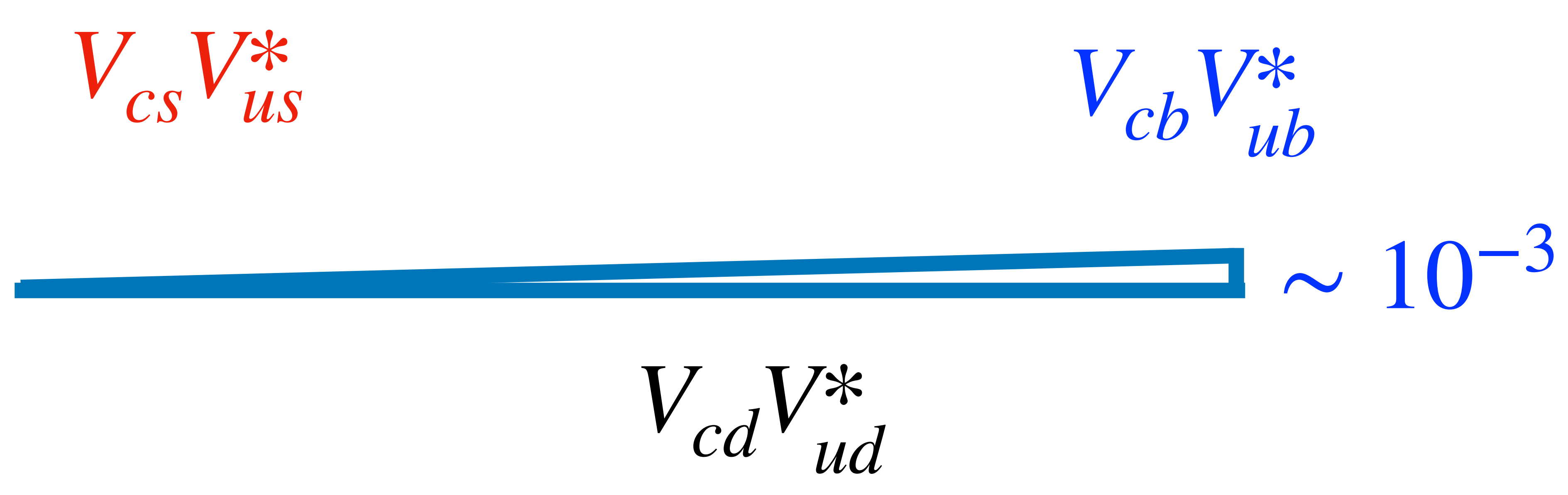
• SU(3) flavor perspective of charmed baryon decays

$$\text{Amplitude}: \underbrace{V_{cs}^{*}V_{us}\, F^{s-d}}_{4\text{ parameters}} + \underbrace{V_{cb}^{*}V_{ub}\, F^{b}}_{3\text{ parameters}}$$

Do not need to consider F^b in studying CP-even quantities. ⟷ F^b cannot be determined with CP-even quantities.



CKM triangle for $b \to d$

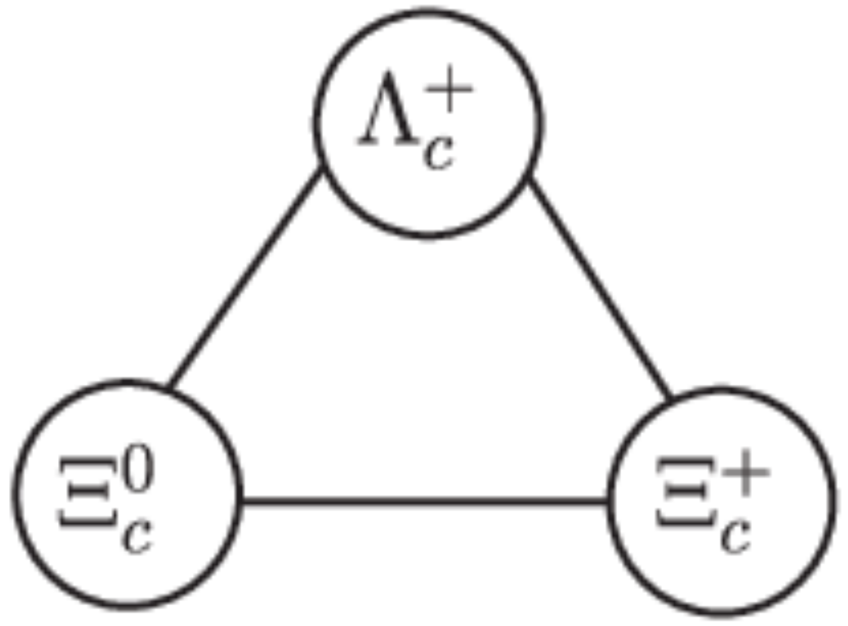


CKM triangle for $c \to u$

SU(3) flavor perspective of charmed baryon decays

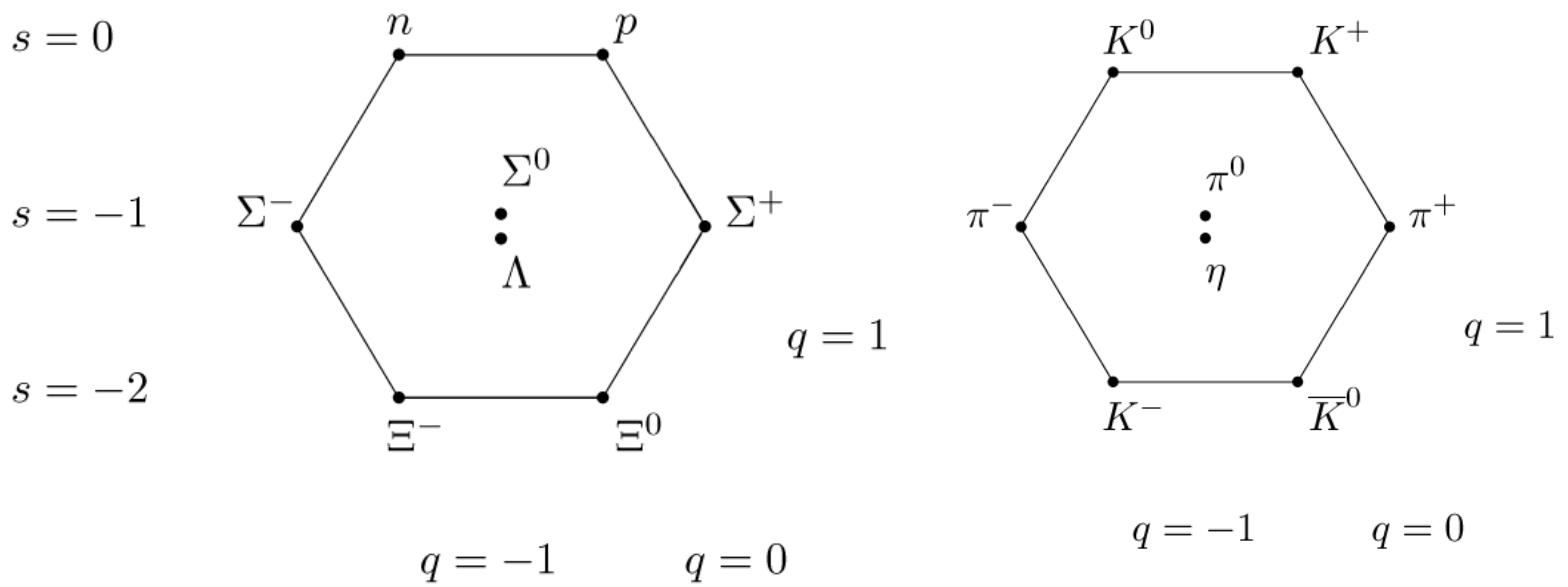
Focus on the leading **CKM** contributions, i.e. $V_{cb}^* V_{ub} = 0$.

PRD **93**, 056008 (2016), NPB **956**, 115048 (2020)
JHEP **09**, 035 (2022), JHEP **03**, 143 (2022) …



Weak interactions

$\mathbf{B}_c \to \mathbf{B}P$



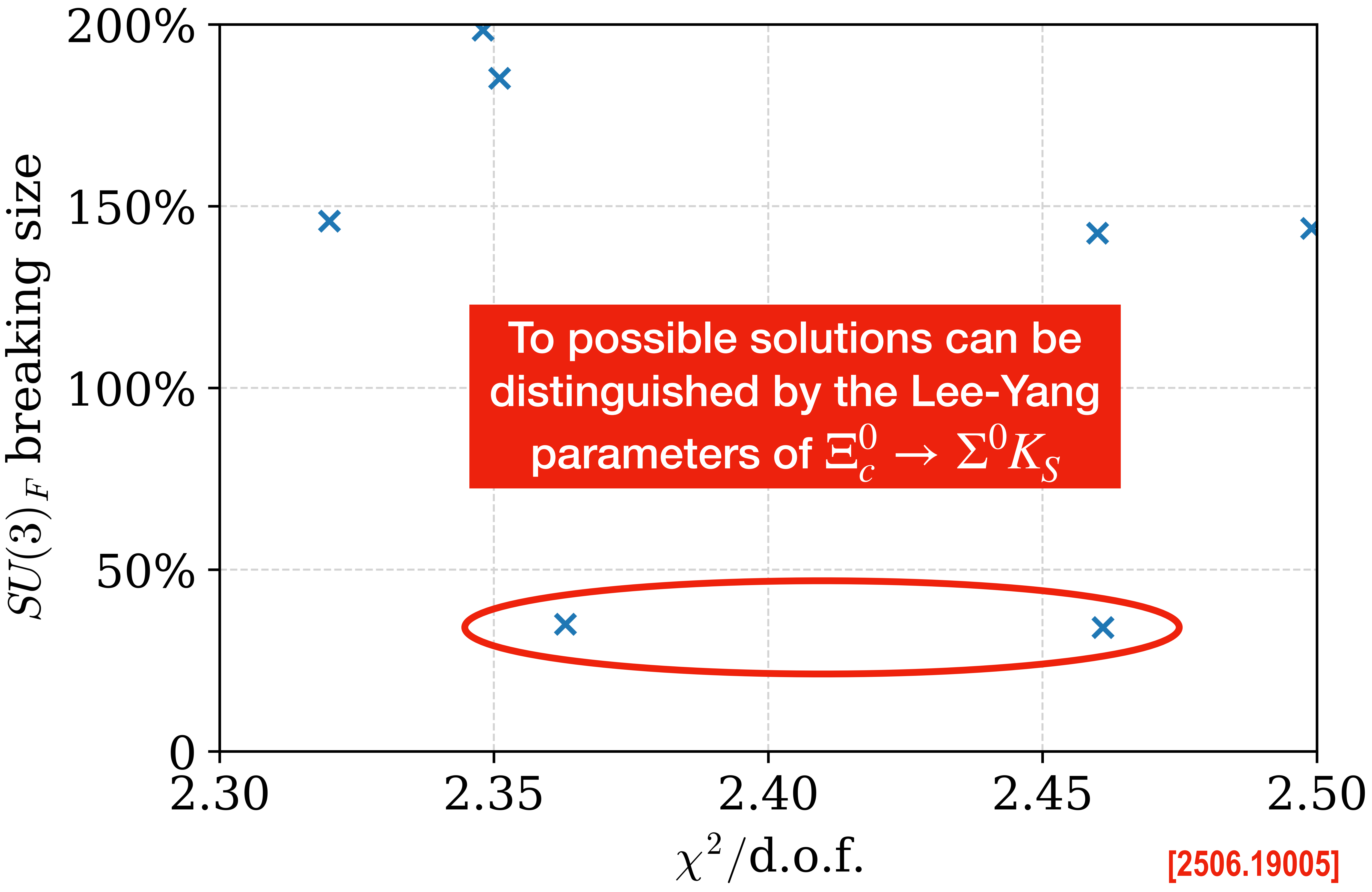
	PDG (2023)	Theory (2023)	Data (2024)	
$\alpha(\Lambda_c^+ \to pK_S^0)$	0.18 ± 0.45	-0.40 ± 0.49	-0.744 ± 0.015	LHCb
$10^4\mathcal{B}(\Lambda_c^+ \to p\pi^0)$	< 0.8	1.6 ± 0.2	1.79 ± 0.41	BESIII
$10^3\mathcal{B}(\Lambda_c^+ \to \Lambda K_S^0 \pi^+)$	None	1.97 ± 0.38	1.73 ± 0.28	BESIII
$10^3\mathcal{B}(\Xi_c^0 \to \Xi^0 \eta)$	None	2.94 ± 0.97	1.6 ± 0.5	BELLE
$10^3\mathcal{B}(\Xi_c^0 \to \Xi^0 \eta')$	None	5.66 ± 0.93	1.2 ± 0.4	BELLE

There are some ***shortcomings*** in $SU(3)_F$ symmetry approach.

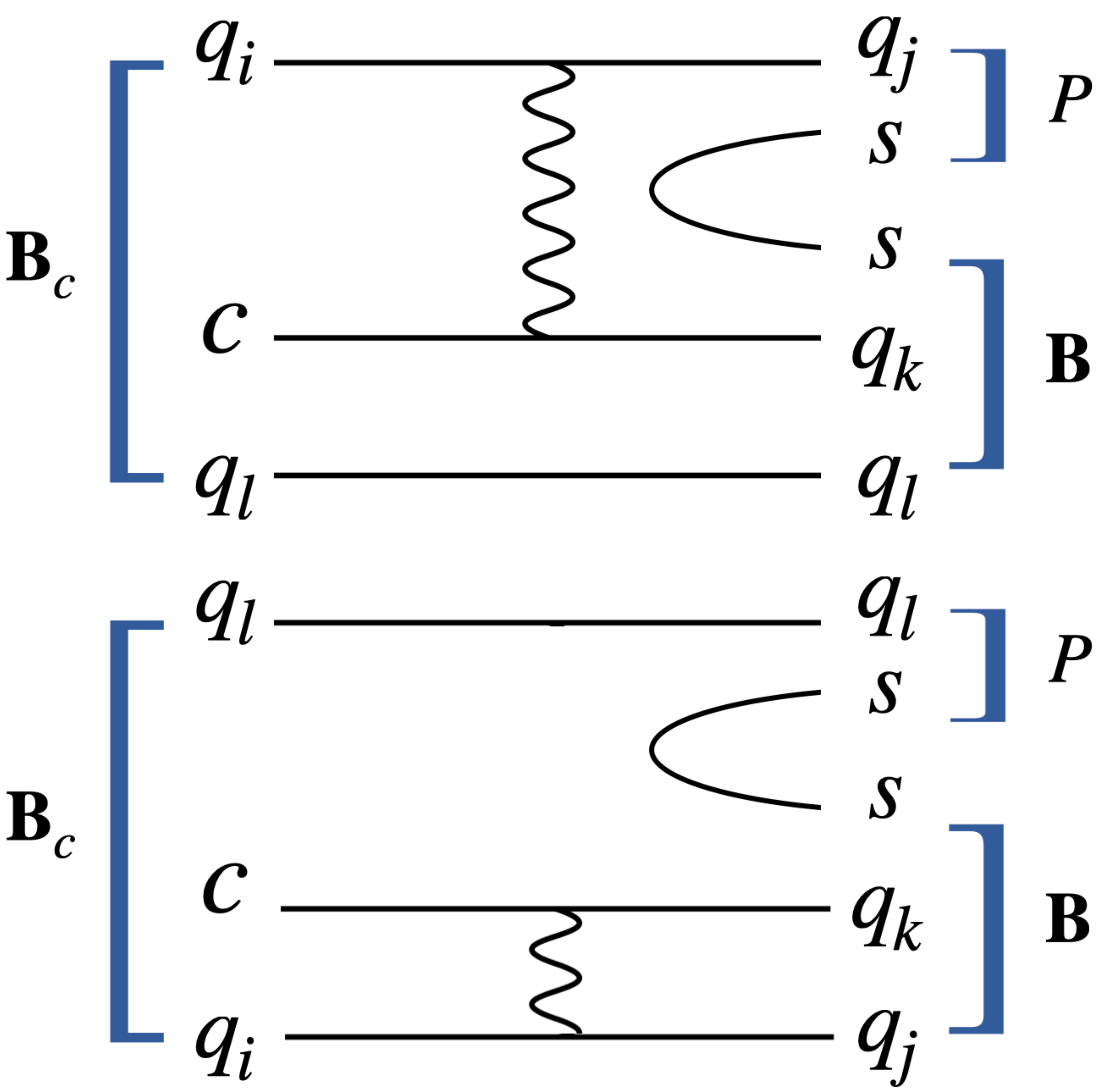
• SU(3) flavor perspective of charmed baryon decays

The $SU(3)_F$ is an approximate symmetry with **errors** in 10^{-1}.

We propose a new scenario that incorporates the $SU(3)_F$ **breaking** of strange quark pair production from the vacuum.



[2506.19005]



$$m_s^{-2} : m_d^{-2} \approx 1 : 2$$

(constituent quark masses)

SU(3) flavor perspective of charmed baryon decays

The large χ^2 is mainly contributed by two channels:

[2506.19005]

	PDG	$SU(3)_F$ conserved	$SU(3)_F$ broken
$10^2\mathscr{B}(\Xi_c^0 \to \Xi^-\pi^+)$	1.43 ± 0.32	2.72 ± 0.09	2.9 ± 0.1
$10^2\mathscr{B}(\Xi_c^+ \to \Xi^-\pi^+\pi^+)$	2.9 ± 1.3	6.82 ± 0.36	6.0 ± 0.4

Both of them are the normalized channels in $\Xi_c^{0,+}$! It is important for a second group to crosscheck. BESIII

Same **underestimations** occurs in $\Xi_c^0 \to \Xi^-\ell^+\nu_\ell$.

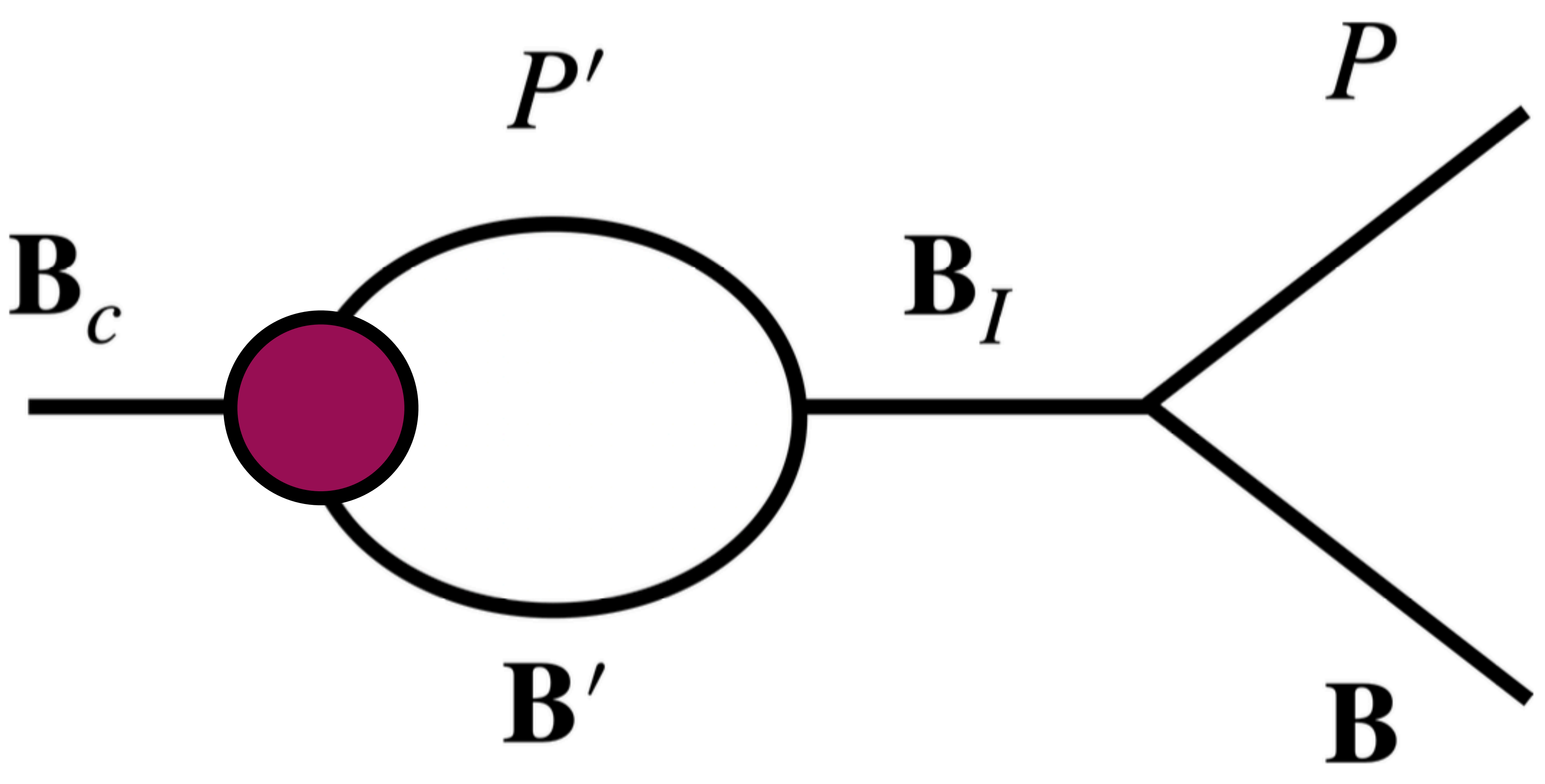
	PDG	$SU(3)_F$	Lattice	Lattice
$10^2\mathscr{B}(\Xi_c^0 \to \Xi^-e^+\nu_e)$	1.05 ± 0.20 2.12 ± 0.13*	4.10 ± 0.46	2.38 ± 0.44	3.58 ± 0.12
		[2110.04179]	[2103.07064]	[2504.07302]

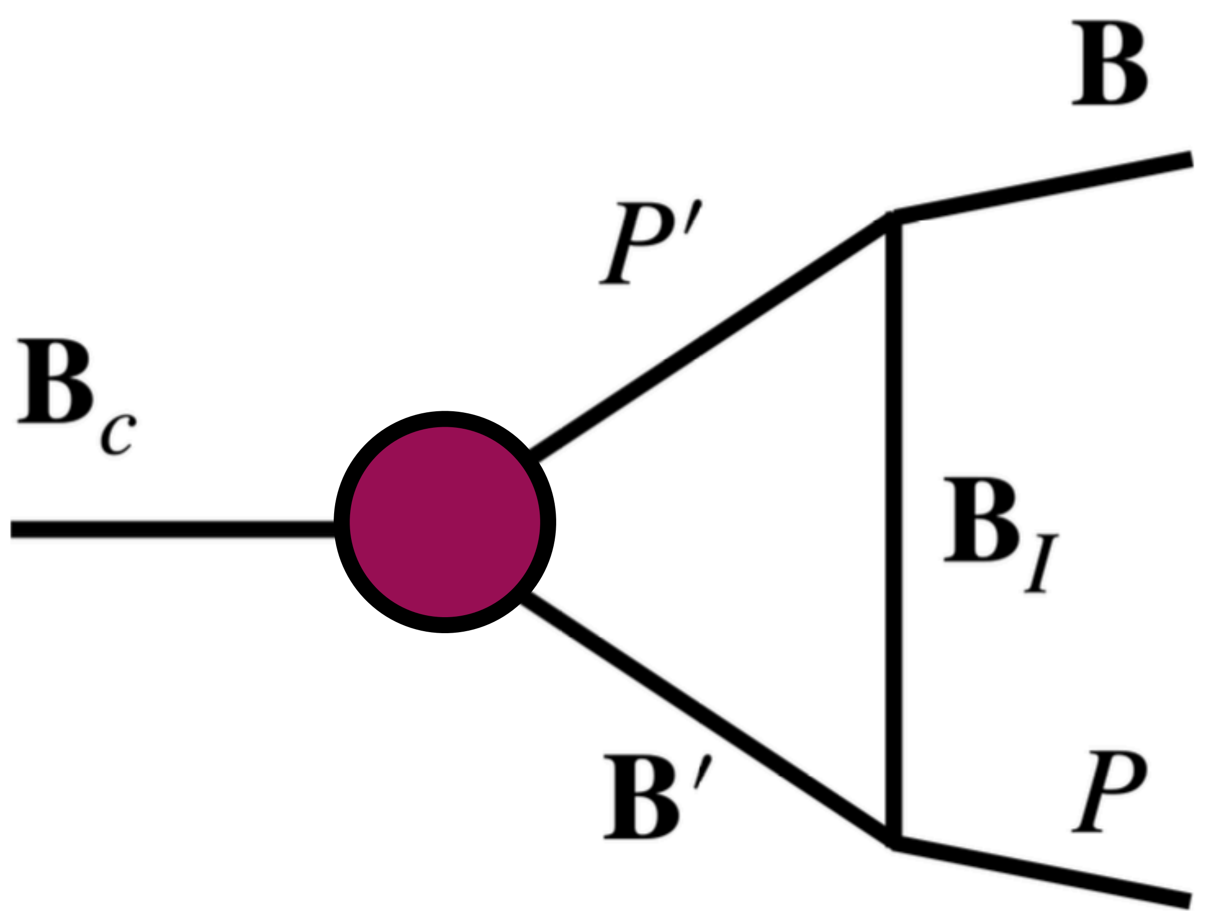
*Using $\mathscr{B}(\Xi_c^0 \to \Xi^-\pi^+) = (2.9 \pm 0.1)\,\%$

• SU(3) flavor perspective of charmed baryon decays

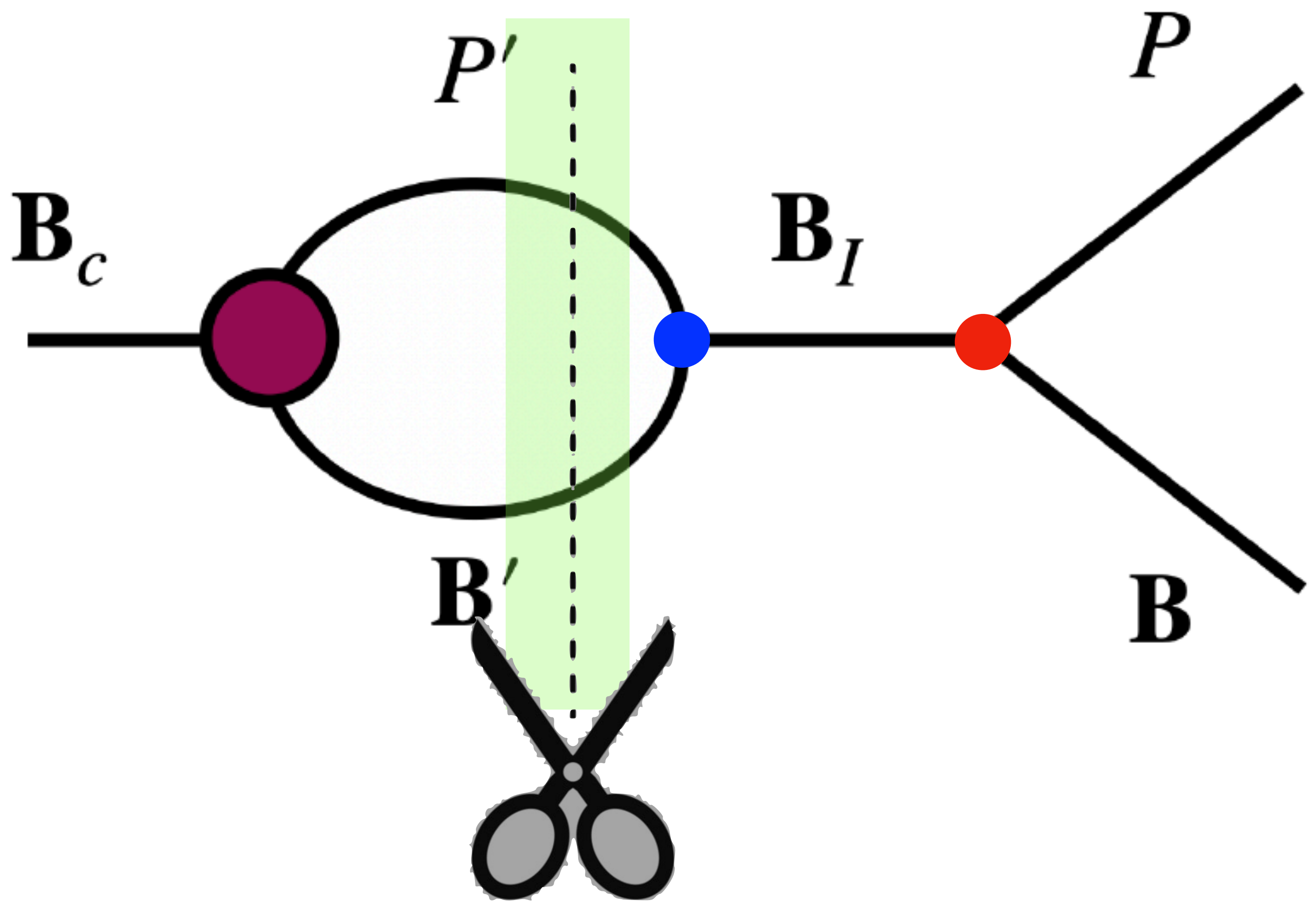
$$\text{Amplitude}: V_{cs}^{*}V_{us}\overbrace{F^{s-d}}^{\text{4 parameters}} + V_{cb}^{*}V_{ub}\overbrace{F^{b}}^{\text{3 parameters}}$$

Four parameters **have been extracted** from the CP-even data. ⟷ Three parameters **need to be determined** with **models**.



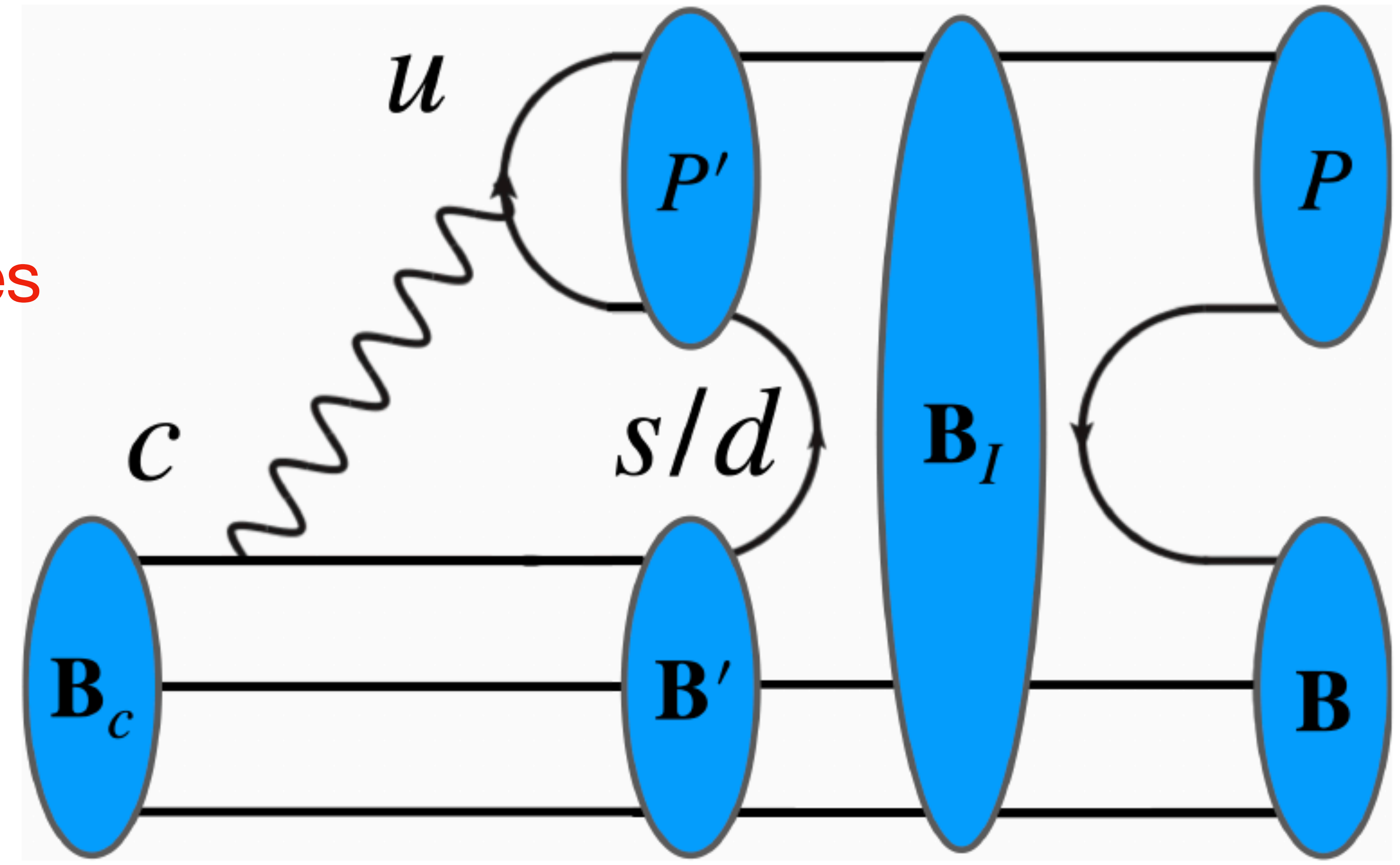


• Rescattering, solving penguin/tree



Generate necessary strong phase!

At quark level generates penguin topology

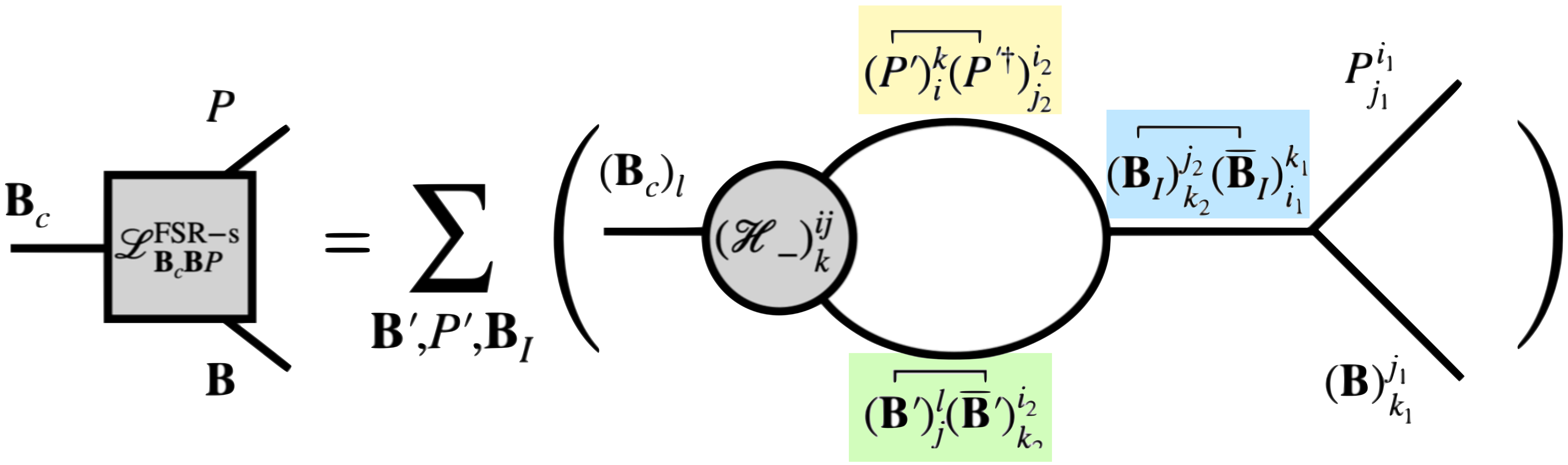


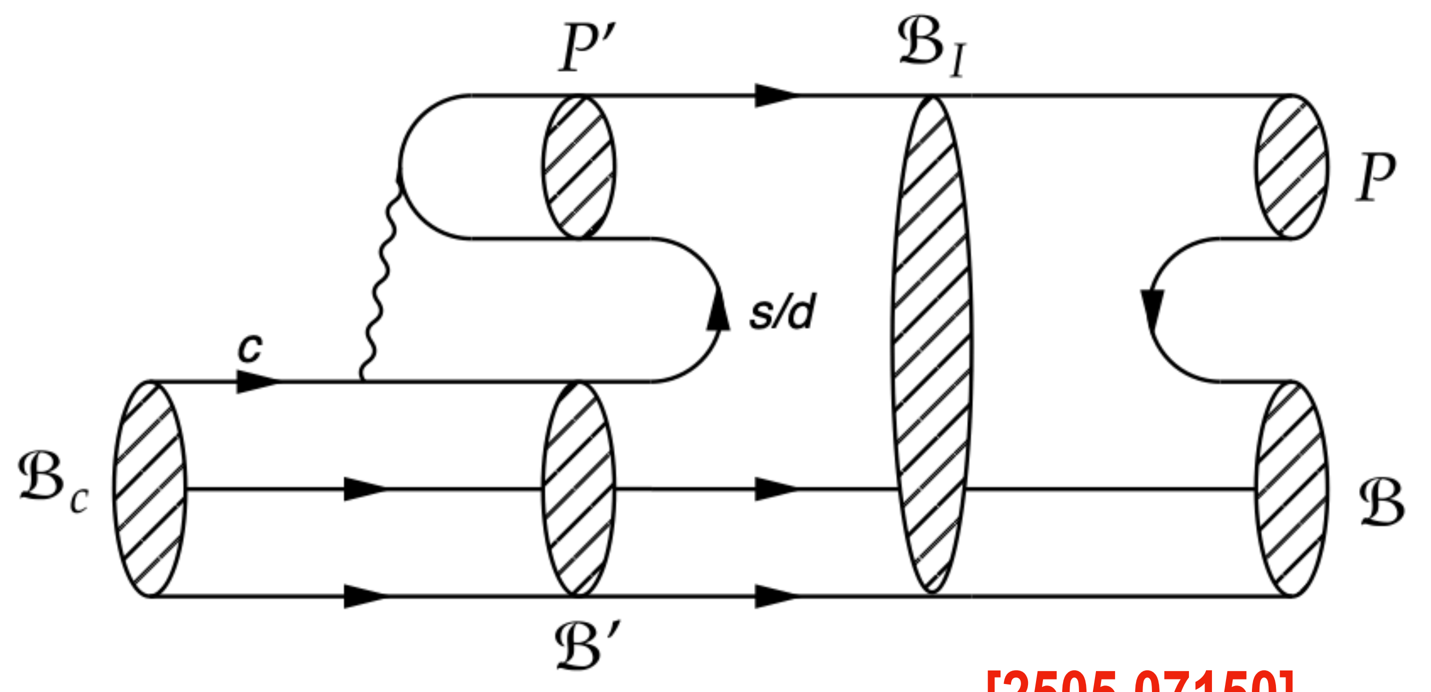
$$\langle \mathscr{L}^{\rm FSR-s}_{\mathbf{B}_c\mathbf{B}P} \rangle = \sum_{\mathbf{B}_I,\mathbf{B}',P'} \bar{u}_{\mathbf{B}} \left(\int \frac{d^4q}{(2\pi)^4} g_{\mathbf{B}_I\mathbf{B}P} \frac{p^{\mu}_{\mathbf{B}_c}\gamma_\mu + m_I}{p^2_{\mathbf{B}_c} - m_I^2} g_{\mathbf{B}_I\mathbf{B}'P'} \frac{q^\mu\gamma_\mu + m_{\mathbf{B}'}}{q^2 - m^2_{\mathbf{B}'}} \frac{1}{(q-p_{\mathbf{B}_c})^2 - m^2_{P'}} F^{\rm Tree}_{\mathbf{B}_c\mathbf{B}'P'} \right) u_{\mathbf{B}_c}$$

$F^{\rm Tree}_{\mathbf{B}_c\mathbf{B}'P'}$ **and** $g_{\mathbf{B}_I\mathbf{B}'P'}$ **depend on** q^2 **otherwise a cut-off has to be introduced.**

See also [2408.14959] and Fu-Sheng's talk

• Rescattering, solving penguin/tree





[2505.07150]

$$\sum_{P'}(P')^k_i(P'^\dagger)^{i_2}_{j_2} \propto \delta^k_{j_2}\delta^{i_2}_i - \frac{1}{3}\delta^k_i\delta^{i_2}_{j_2}$$

$$\sum_{\mathbf{B}'}(\mathbf{B}')^l_j(\overline{\mathbf{B}}')^{i_2}_{k_2} \propto \delta^l_{k_2}\delta^{i_2}_j - \frac{1}{3}\delta^l_j\delta^{i_2}_{k_2}$$

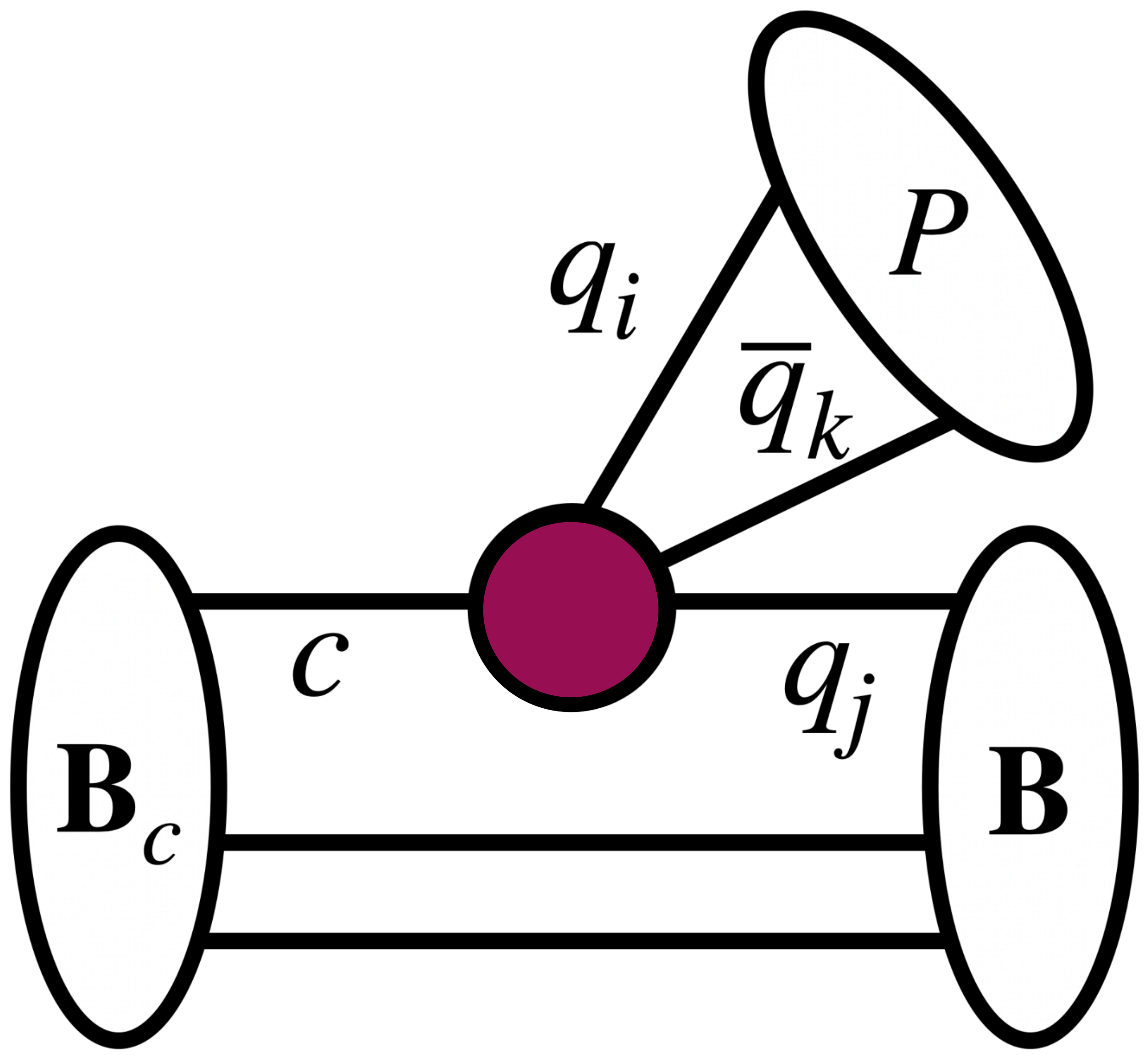
$$\sum_{\mathbf{B}_I}(\mathbf{B}_I)^l_j(\overline{\mathbf{B}}')^{i_2}_{k_2} \propto \delta^l_{k_2}\delta^{i_2}_j - \frac{1}{3}\delta^l_j\delta^{i_2}_{k_2}$$

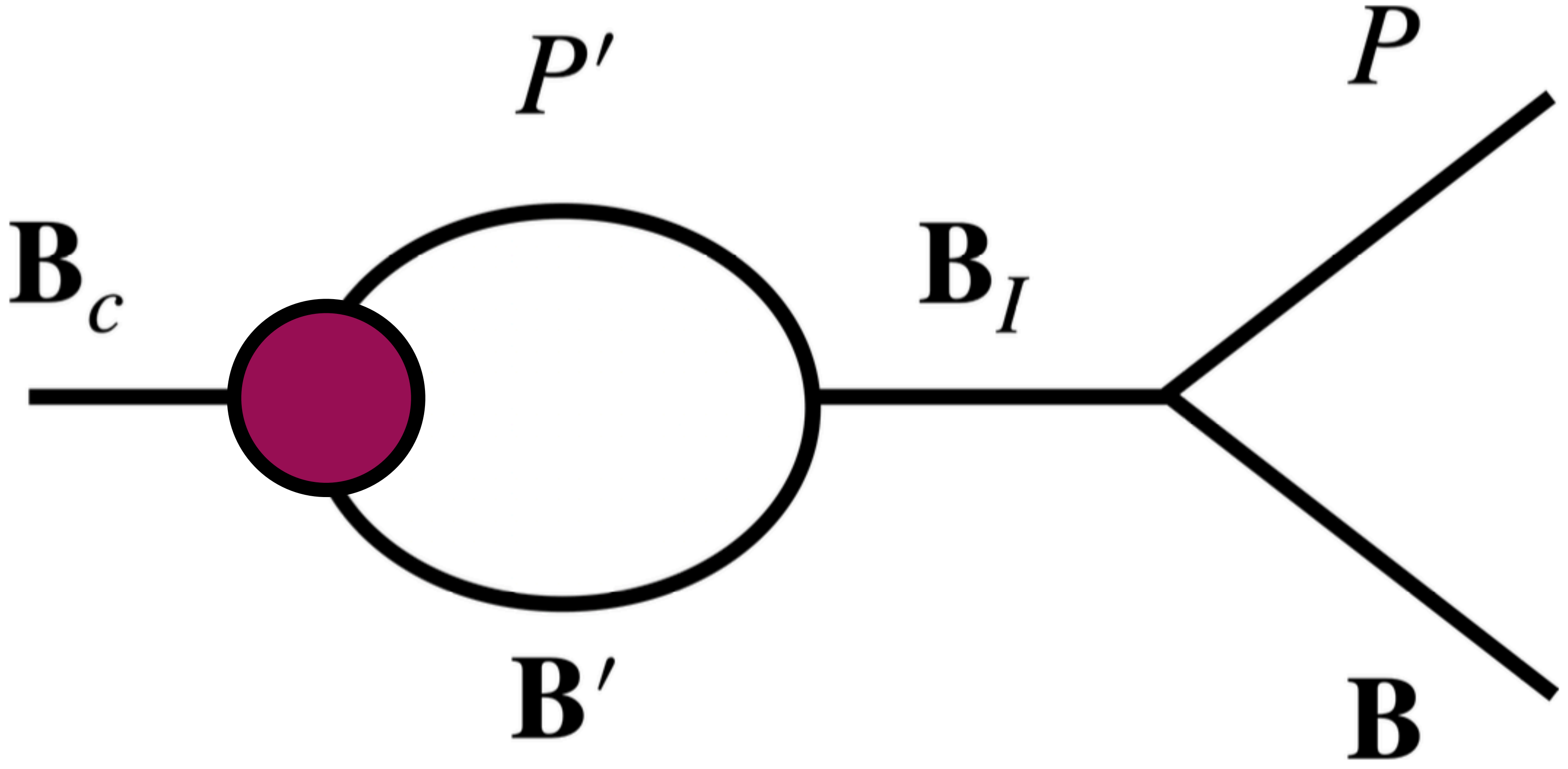
Assumptions:

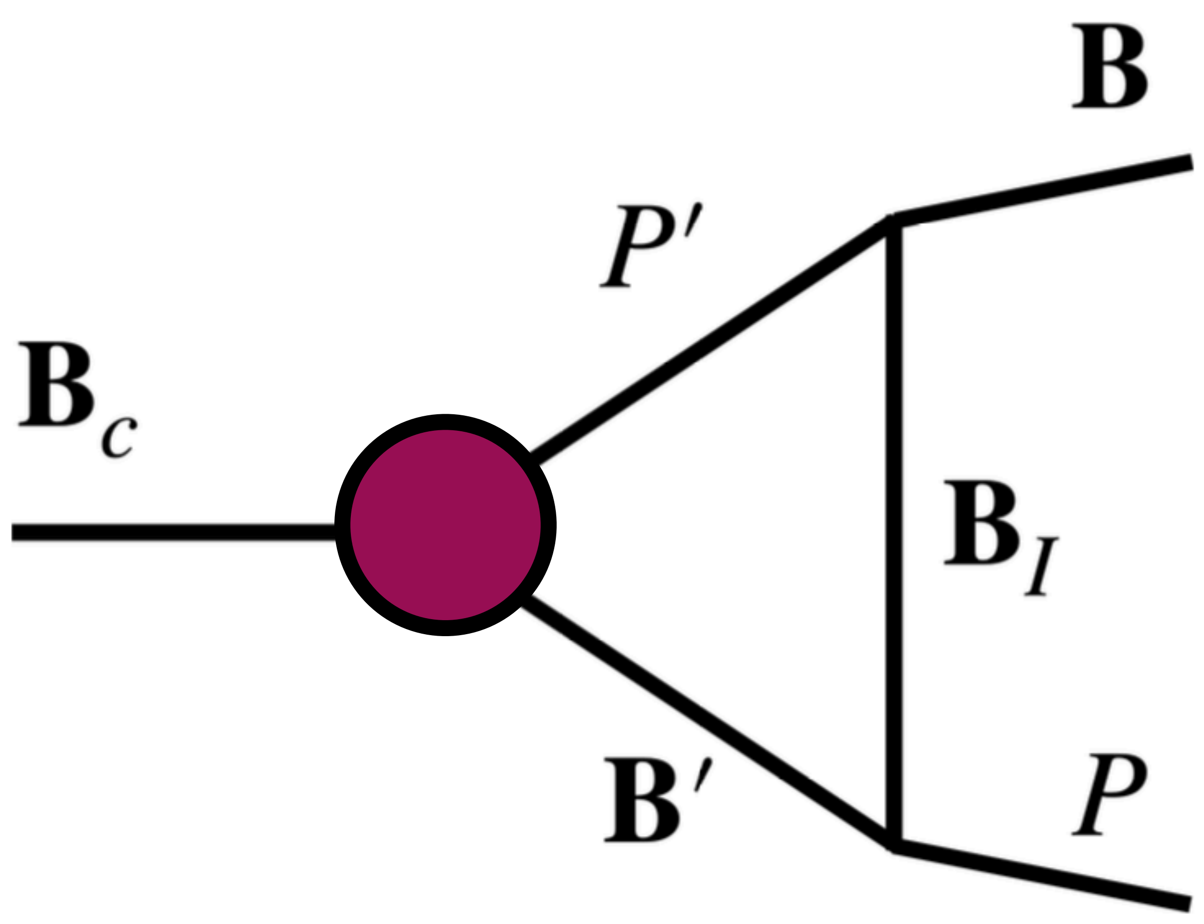
1. $\mathbf{B}_I \in$ lowest-lying baryons of **both parities**.
2. The rescattering is **closed**, *i.e.* $\mathbf{B}'P'$ belong to the same $SU(3)_F$ group of $\mathbf{B}P$.

- **Rescattering, solving penguin/tree**

$$\mathscr{L}_{\mathbf{B}_c\mathbf{B}P} = \mathscr{L}^{\mathrm{Tree}}_{\mathbf{B}_c\mathbf{B}P} + \mathscr{L}^{\mathrm{FSR-s}}_{\mathbf{B}_c\mathbf{B}P} + \mathscr{L}^{\mathrm{FSR-t}}_{\mathbf{B}_c\mathbf{B}P}$$







Induce two parameters:
$F_V^{\pm}$, including effective color number and form factors.

Induce one parameter:
$\tilde{S}^{-}$, containing the q^2 dependencies of couplings.

Induce one parameter:
$\tilde{T}^{-}$, containing the q^2 dependencies of couplings.

Described by 4 complex parameters, having the same number of parameters with the $SU(3)_F$ analysis !

Rescattering, solving penguin/tree

Amplitudes : $\frac{\lambda_s - \lambda_d}{2} \tilde{f}^{b,c,d,e} + \lambda_b \, \tilde{f}_{\mathbf{3}}^{b,c,d}$

SU(3) leading → rescattering parameters → SU(3) suppressed

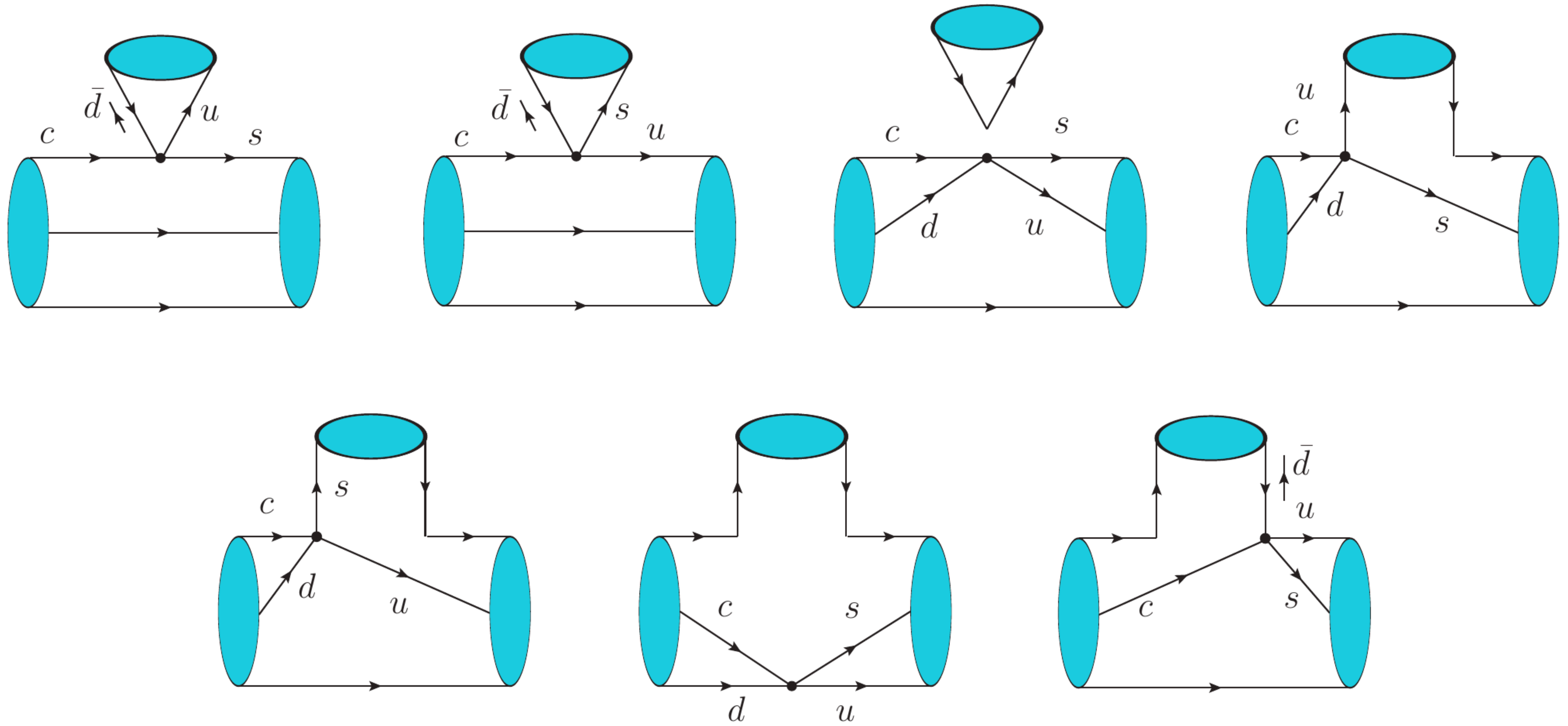
PRD **100**, 093002 (2019)

$$(\tilde{f}^b, \tilde{f}^c, \tilde{f}^d, \tilde{f}^e) \longrightarrow (\tilde{F}_V^+, \tilde{F}_V^-, \tilde{S}^-, \tilde{T}^-) \longrightarrow (\tilde{f}_{\mathbf{3}}^b, \tilde{f}_{\mathbf{3}}^c, \tilde{f}_{\mathbf{3}}^d)$$

$$\tilde{f}^b = \tilde{F}_V^- - (r_- + 4)\tilde{S}^- + \sum_{\lambda=\pm} (2r_\lambda^2 - r_\lambda)\tilde{T}_\lambda^- \,,$$

$$\tilde{f}^c = -r_-(r_- + 4)\tilde{S}^- + \sum_{\lambda=\pm} (r_\lambda^2 - 2r_\lambda + 3)\tilde{T}_\lambda^- \,,$$

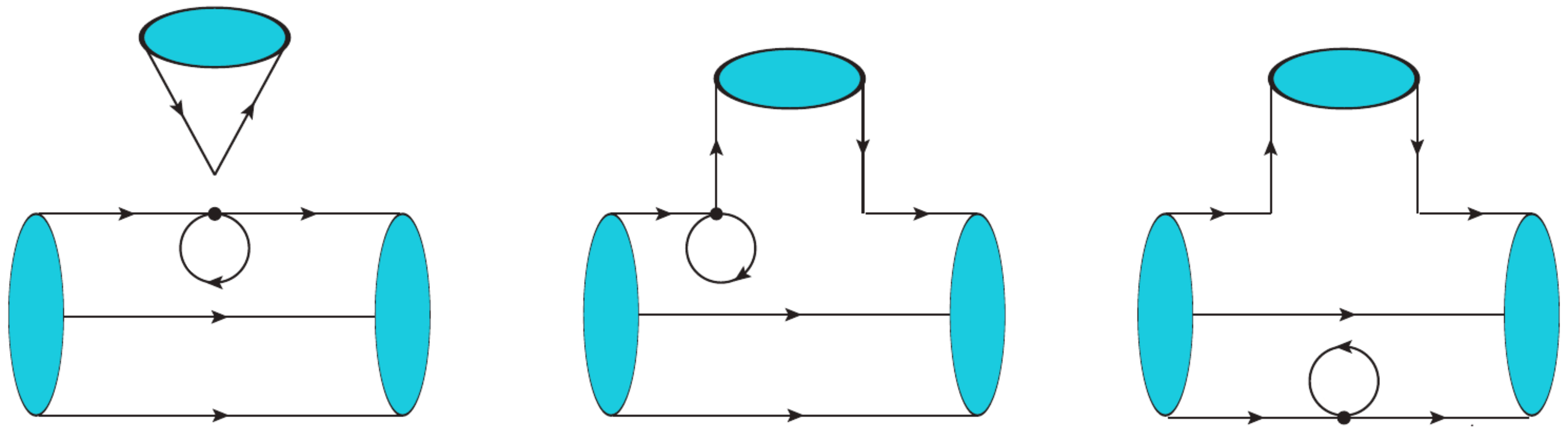
$$\tilde{f}^d = \tilde{F}_V^- + \sum (2r_\lambda^2 - 2r_\lambda - 4)\tilde{T}_\lambda^- \,, \qquad \tilde{f}^e = \tilde{F}_V^+$$



$$\tilde{f}_{\mathbf{3}}^b = (1 - \frac{7r_-}{2})\tilde{S}^- + \sum_{\lambda=\pm} (r_\lambda^2 - 5r_\lambda/2 + 1)\tilde{T}_\lambda^- \,,$$

$$\tilde{f}_{\mathbf{3}}^c = \frac{(r_- + 1)(7r_- - 2)}{6}\tilde{S}^- - \sum_{\lambda=\pm} \frac{r_\lambda^2 + 11r_\lambda + 1}{6}\tilde{T}_\lambda^- \,,$$

$$\tilde{f}_{\mathbf{3}}^d = \frac{2r_- - 7r_-^2}{2}\tilde{S}^- + \sum \frac{(r_\lambda + 1)^2}{2}\tilde{T}_\lambda^- - \frac{\tilde{F}_V^+ + 2\tilde{F}_V^-}{4} .$$



Much more complicated compared to $P^{LD} = E$ in D mesons !

Rescattering, numerical results

- A_{CP} in the same size with the ones in *D* meson!

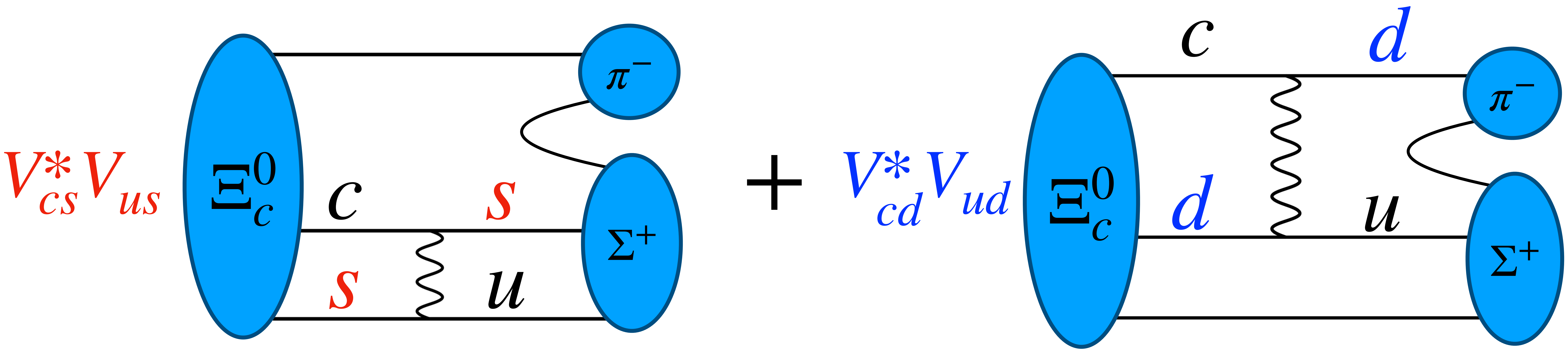
$$A_{CP}\left(\Xi_c^0 \to \Sigma^+\pi^-\right) = (0.71 \pm 0.16) \times 10^{-3}$$

$$A_{CP}\left(\Xi_c^0 \to pK^-\right) = (-0.73 \pm 0.19) \times 10^{-3}$$

- In the U-spin limit, we have that

$$A_{CP}\left(\Xi_c^0 \to \Sigma^+\pi^-\right) = -A_{CP}\left(\Xi_c^0 \to pK^-\right).$$

EPJC 79, 429 (2019)



Two topological diagrams are in the same size, leads to $A_{CP} \sim \left|2\mathrm{Im}(V_{cs}^*V_{us}/V_{cd}^*V_{ud})\right| \sim 10^{-3}$.

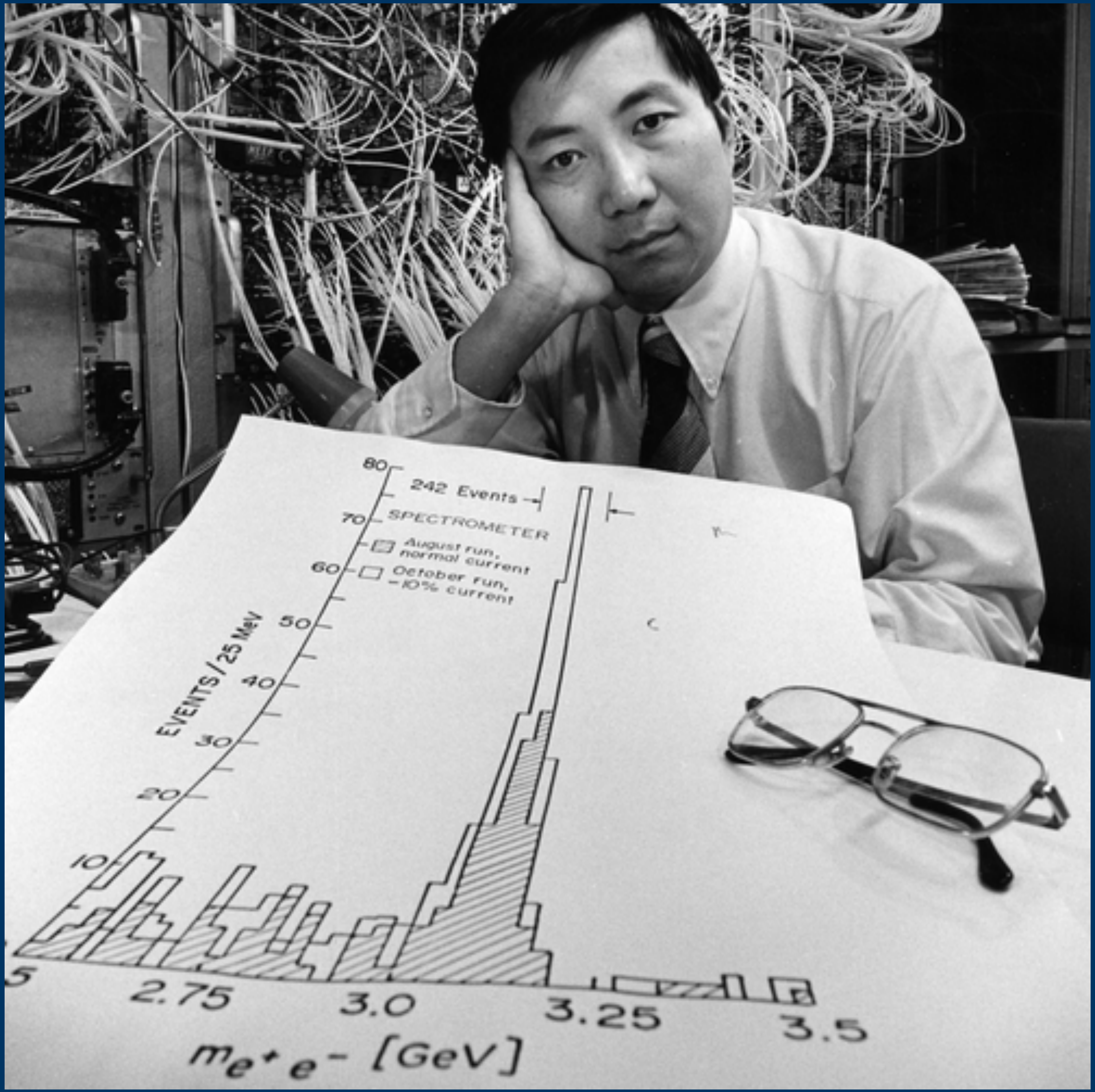
Rescattering, numerical results

Channels	$\mathcal{B}$	A_{CP}	A_{CP}^{α}	Channels	$\mathcal{B}$	A_{CP}	A_{CP}^{α}
$\Lambda_c^+ \to p\pi^0$	0.18(2)	−0.01(7) 0.01(15)(45)	−0.15(13) 0.55(20)(61)	$\Xi_c^0 \to \Sigma^+\pi^-$	0.26(2)	0 0.71(15)(6)	0 −1.83(10)(15)
$\Lambda_c^+ \to n\pi^+$	0.68(6)	0.0(1) −0.02(7)(28)	0.03(2) 0.30(13)(41)	$\Xi_c^0 \to \Sigma^0\pi^0$	0.34(3)	−0.02(4) 0.44(24)(17)	0.01(1) −0.43(31)(16)
$\Lambda_c^+ \to \Lambda K^+$	0.62(3)	0.00(2) −0.15(13)(9)	0.03(2) 0.50(9)(21)	$\Xi_c^0 \to \Sigma^-\pi^+$	1.76(5)	0.01(1) 0.12(6)(2)	−0.01(1) −0.22(5)(21)
$\Xi_c^+ \to \Sigma^+\pi^0$	2.69(14)	−0.02(6) 0.05(7)(8)	0.07(4) −0.23(3)(15)	$\Xi_c^0 \to \Xi^0 K_{S/L}$	0.38(1)	0 0.18(3)(5)	0 −0.38(2)(11)
$\Xi_c^+ \to \Sigma^0\pi^+$	3.14(10)	0.00(1) 0.05(8)(7)	−0.02(1) −0.24(6)(13)	$\Xi_c^0 \to \Xi^- K^+$	1.26(4)	0.00(1) −0.12(5)(2)	0.01(1) 0.21(4)(2)
$\Xi_c^+ \to \Xi^0 K^+$	1.30(10)	0.00(0) 0.01(6)(17)	−0.02(1) −0.23(9)(52)	$\Xi_c^0 \to pK^-$	0.31(2)	0 −0.73(18)(6)	0 1.74(11)(14)
$\Xi_c^+ \to \Lambda\pi^+$	0.18(3)	−0.01(2) −0.31(21)(13)	0.0(0) 0.96(25)(44)	$\Xi_c^0 \to nK_{S/L}$	0.86(3)	0 −0.14(3)(4)	0 0.27(2)(7)
$\Xi_c^+ \to pK_s$	1.55(7)	0 −0.13(3)(4)	0 0.22(3)(7)	$\Xi_c^0 \to \Lambda\pi^0$	0.06(2)	0.02(3) −0.12(18)(10)	0.0(1) 0.69(8)(43)

Quantitative change

leads to

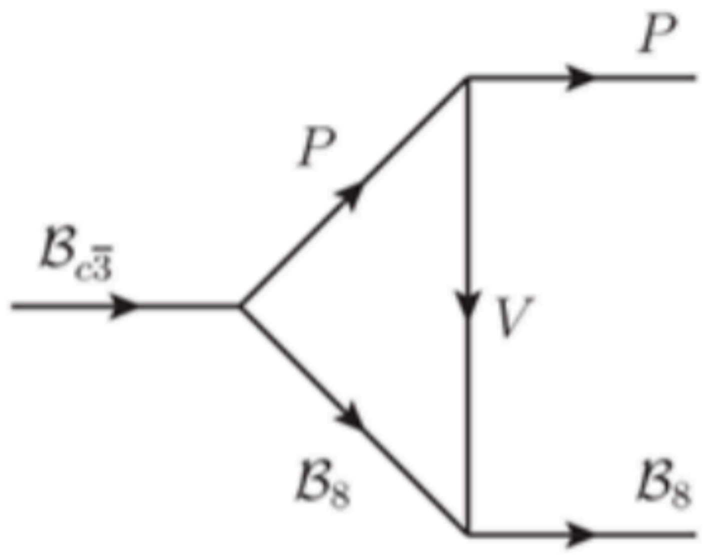
qualitative change.



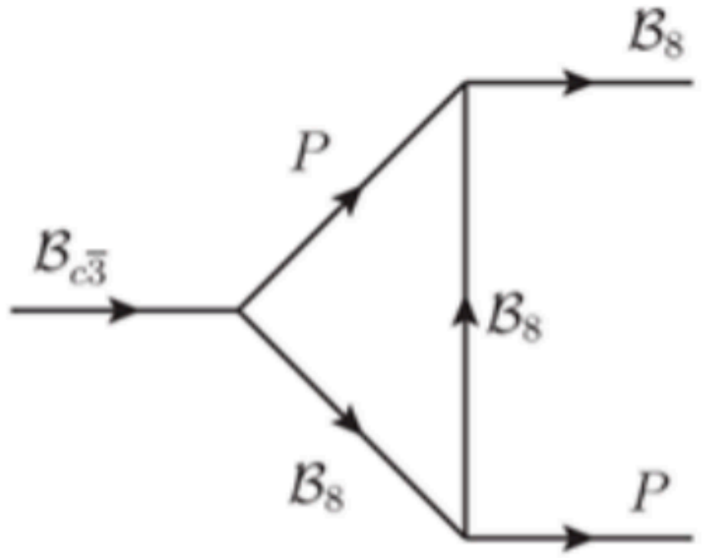
Final-state rescattering

Wang's Slide

$$\mathcal{A}_L(\Lambda_c^+ \to \Sigma^0 K^+) = \boxed{\frac{1}{\sqrt{2}}\lambda_d \Delta_{\alpha^+,\gamma^-}(\Lambda_c^+, \pi^+, n, \overline{K}^{*0}, K^+, \Sigma^0)}$$
$$+ \frac{1}{\sqrt{2}}\lambda_d \Delta_{(\beta^+-\beta^-),\beta^-}(\Lambda_c^+, \pi^+, n, \Sigma^-, \Sigma^0, K^+)$$
$$\cdots$$
$$\mathcal{A}_L(\Lambda_c^+ \to \Sigma^+ K^0) = \boxed{\frac{1}{2}\lambda_d \Delta_{(\beta^++\beta^-),(2\beta^+-\beta^-)}(\Lambda_c^+, \pi^+, n, \Lambda^0, \Sigma^+, K^0)}$$
$$+ \frac{1}{2}\lambda_d \Delta_{(\beta^+-\beta^-),\beta^-}(\Lambda_c^+, \pi^+, n, \Sigma^0, \Sigma^+, K^0)$$
$$\cdots$$



$\Delta(\mathcal{B}_{c\bar{3}}, P, \mathcal{B}_8, V, P, \mathcal{B}_8)$



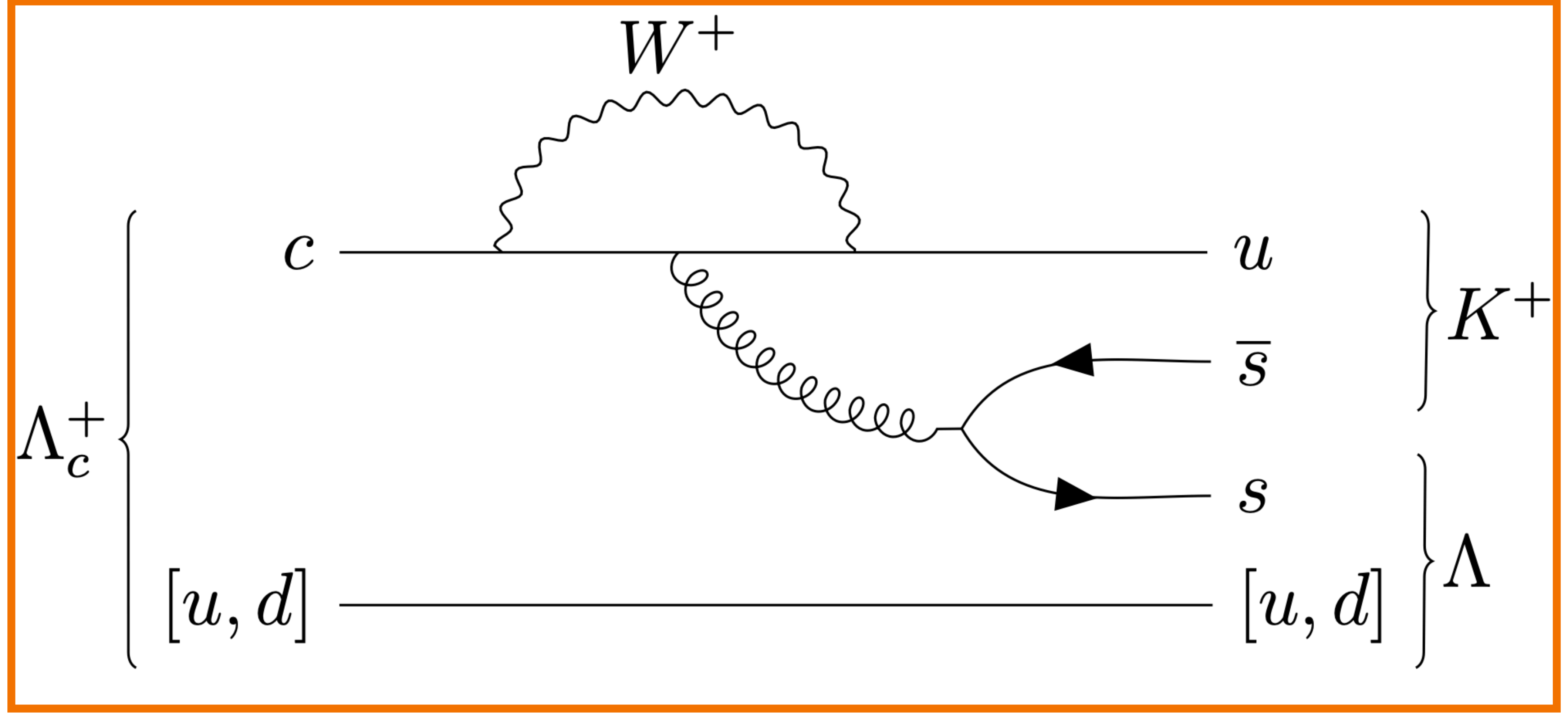
$\Delta(\mathcal{B}_{c\bar{3}}, P, \mathcal{B}_8, \mathcal{B}_8, \mathcal{B}_8, P)$

arXiv:2507.06914.

• Rescattering, solving penguin/tree

Amplitudes : $\frac{\lambda_s - \lambda_d}{2} F^{s-d} + \lambda_b F^b$

Corrections to A_{CP} are around 10%



$$\tilde f^b = \tilde F_V^- + \tilde S^- - \sum_{\lambda=\pm}(2r_\lambda^2 - r_\lambda)\tilde T_\lambda^- ,$$

$$\tilde f^c = r_- \tilde S^- - \sum_{\lambda=\pm}(r_\lambda^2 - 2r_\lambda + 3)\tilde T_\lambda^- ,$$

$$\tilde f^d = \tilde F_V^- - \sum_{\lambda=\pm}(2r_\lambda^2 - 2r_\lambda - 4)\tilde T_\lambda^- , \quad \tilde f^e = \tilde F_V^+ ,$$

$$\tilde f_{\mathbf{3}}^b = \frac{7r_- - 2}{8+2r_-}\tilde S^- - \sum_{\lambda=\pm}(r_\lambda^2 - 5r_\lambda/2 + 1)\tilde T_\lambda^- ,$$

$$\tilde f_{\mathbf{3}}^c = \frac{(r_- + 1)(2 - 7r_-)}{24 + 6r_-}\tilde S^- + \sum_{\lambda=\pm}\frac{1}{6}(r_\lambda^2 + 11 r_\lambda + 1)\tilde T_\lambda^- ,$$

$$\tilde f_{\mathbf{3}}^d = \frac{r_-(7r_- - 2)}{8+2r_-}\tilde S^- - \sum_{\lambda=\pm}\frac{1}{2}(r_\lambda + 1)^2 \tilde T_\lambda^- - \frac{1}{4}\left(\tilde F_V^+ + 2\tilde F_V^-\right)$$

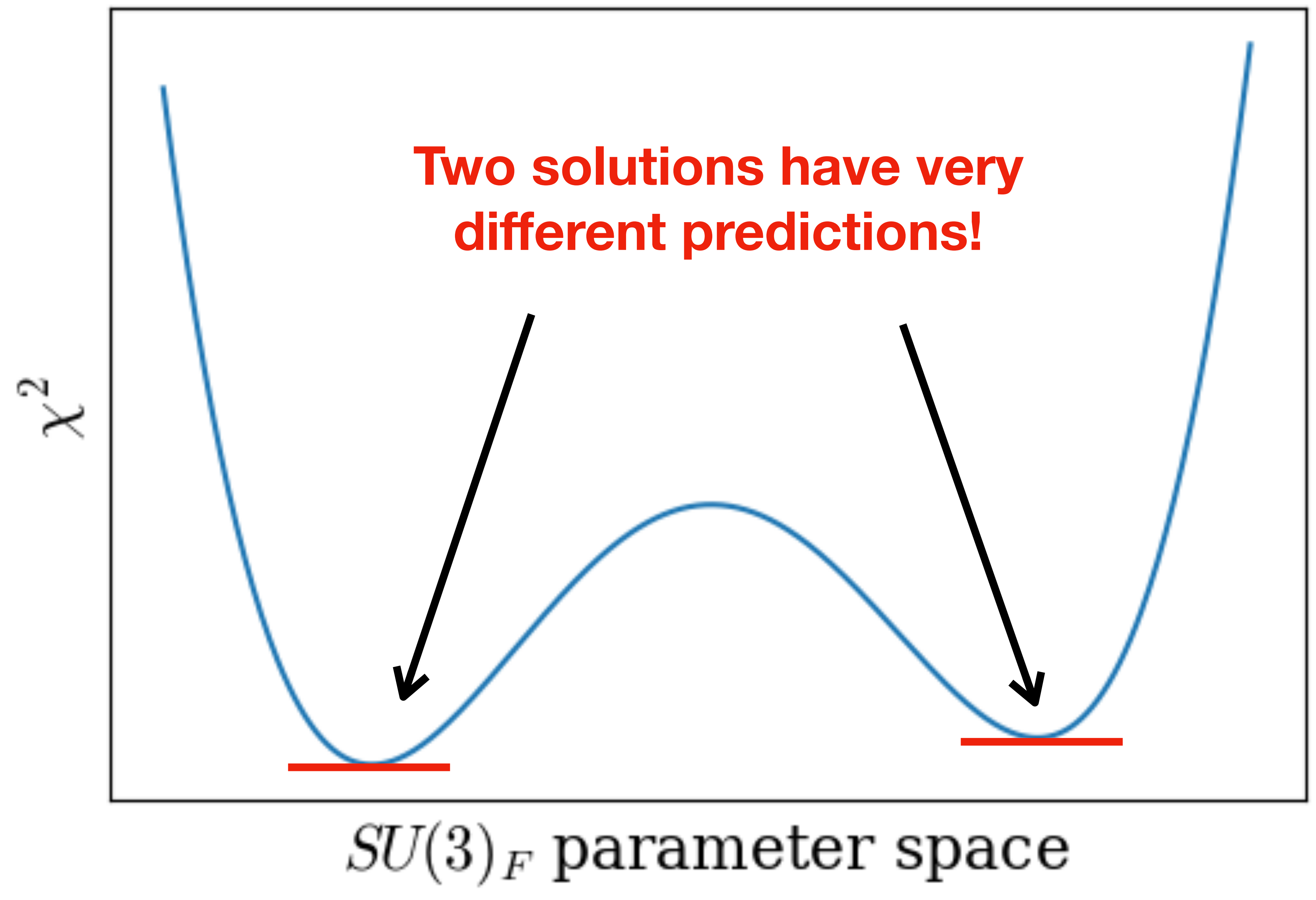
$$\left(1 + \frac{(3C_4 + C_3)\, m_c - \frac{2m_K^2}{m_s + m_u}(3C_6 + C_5)}{(C_+ + C_-)m_c}\right)$$

$$\left(\tilde f^b, \tilde f^c, \tilde f^d, \tilde f^e\right) \longleftrightarrow \left(\tilde F_V^+, \tilde F_V^-, \tilde S^-, \tilde T^-\right) \longrightarrow \left(\tilde f_{\mathbf{3}}^b, \tilde f_{\mathbf{3}}^c, \tilde f_{\mathbf{3}}^d\right)$$

PRD **100**, 093002 (2019)

Much more complicated compared to $P^{LD} = E$ in D mesons !

• SU(3) flavor perspective of charmed baryon decays



The $SU(3)_F$ is an approximate symmetry with **errors** in 10^{-1}.

There exhibits Z_2 **ambiguities**:

$$\Gamma \propto |F^2| + \kappa^2 |G^2|, \quad \alpha = \frac{2\kappa \mathrm{Re}(F^*G)}{|F^2| + \kappa^2 |G^2|}, \quad \beta = \frac{2\kappa \mathrm{Im}(F^*G)}{|F^2| + \kappa^2 |G^2|}, \quad \gamma = \frac{|F^2| - \kappa^2 |G^2|}{|F^2| + \kappa^2 |G^2|}.$$

Γ and α are **invariant** under $(F, G) \to (F^*, G^*)$ and $F \leftrightarrow \kappa G^*$ but β and γ **flip signs**.
In general, the amplitudes cannot be fully reconstructed without β and γ as input.

Precise β and γ data can break the ambiguities, highlighting the importance of LHCb work!

Nevertheless, there are ***still*** a few **ambiguities**.

Measurement of Λ_b^0, Λ_c^+, and Λ Decay Parameters Using $\Lambda_b^0 \to \Lambda_c^+ h^-$ Decays
PRL **133**, 261804 (2024)

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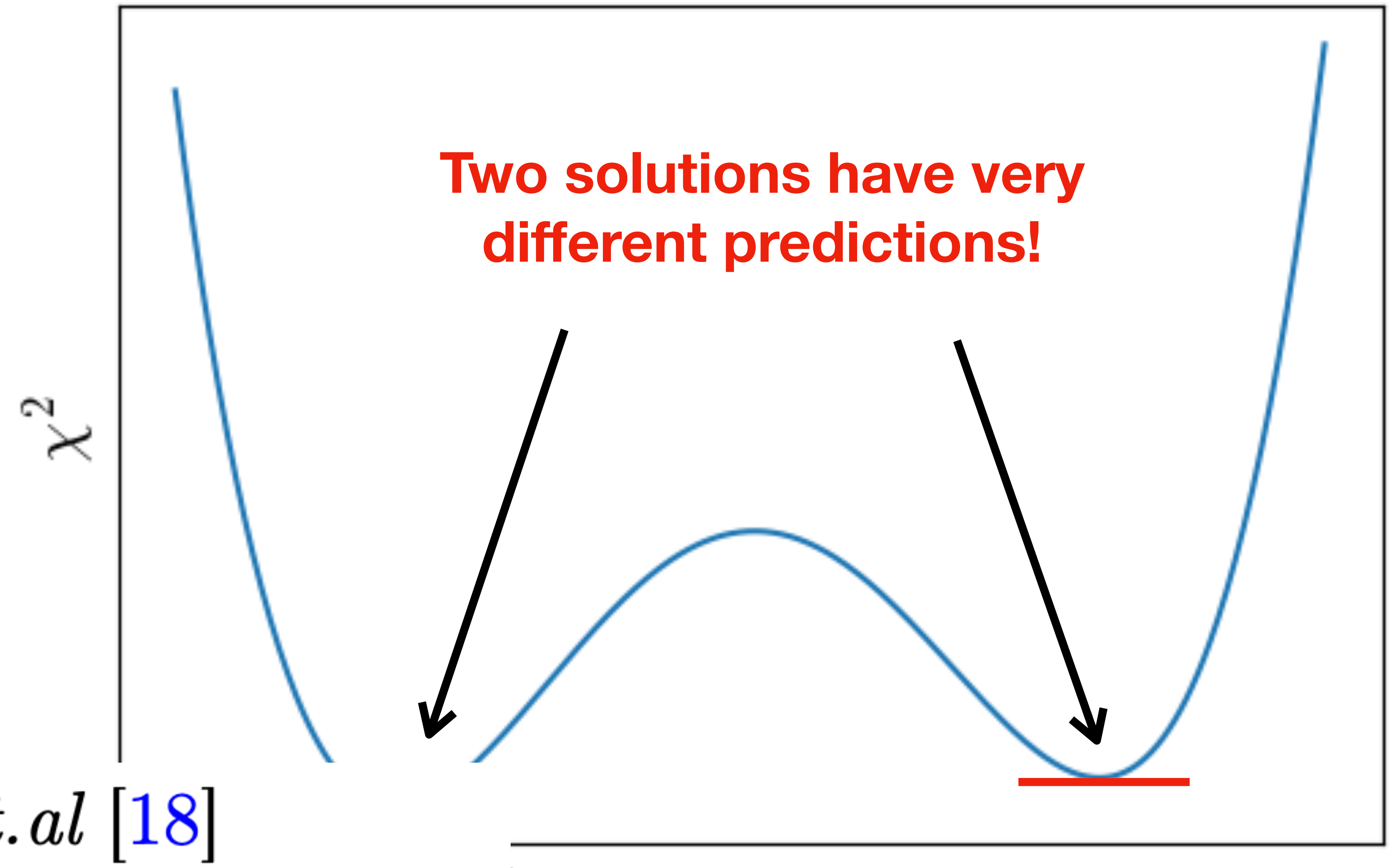

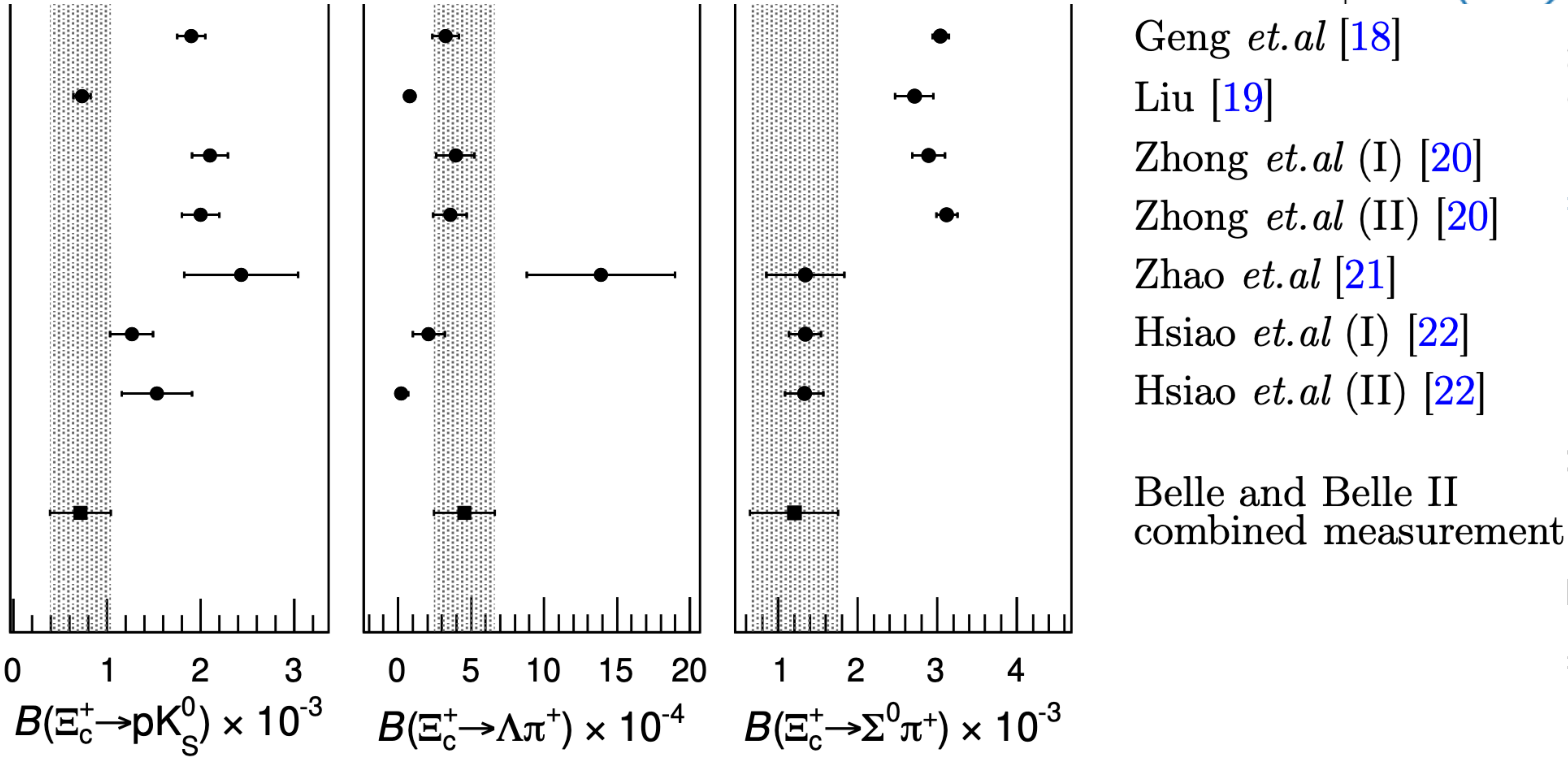

$)_F$ parameter space

$$= \frac{|F^2| - \kappa^2 |G^2|}{|F^2| + \kappa^2 |G^2|}.$$

nd γ **flip signs**.

ut.

f LHCb work!

Parameters Using $\Lambda_b^0 \to \Lambda_c^+ h^-$ Decays

PRL **133**, 261804 (2024)

- **Rescattering, solving penguin/tree**

$$\mathscr{L}_{\mathbf{B}_c\mathbf{B}P} = \mathscr{L}^{\mathrm{Tree}}_{\mathbf{B}_c\mathbf{B}P} + \mathscr{L}^{\mathrm{FSR-s}}_{\mathbf{B}_c\mathbf{B}P} + \mathscr{L}^{\mathrm{FSR-t}}_{\mathbf{B}_c\mathbf{B}P} + \mathscr{L}^{\mathrm{FSR-u}}_{\mathbf{B}_c\mathbf{B}P} + \ldots (?)$$