李政道研究所
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Charming ~~CP~~ violation

Chia-Wei Liu

arXiv:2404.19166

Collaborate with Xiao-Gang He

Wuhan, April 26, 2025 — LHCb

Charming physics - CP violation

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

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

PRL **122**, 211803 (2019); PRL **131**, 091802 (2023)

- Short distance predictions are **an order smaller**!
  Data driven approach:

  Factorization with fitted hadron matrix element.

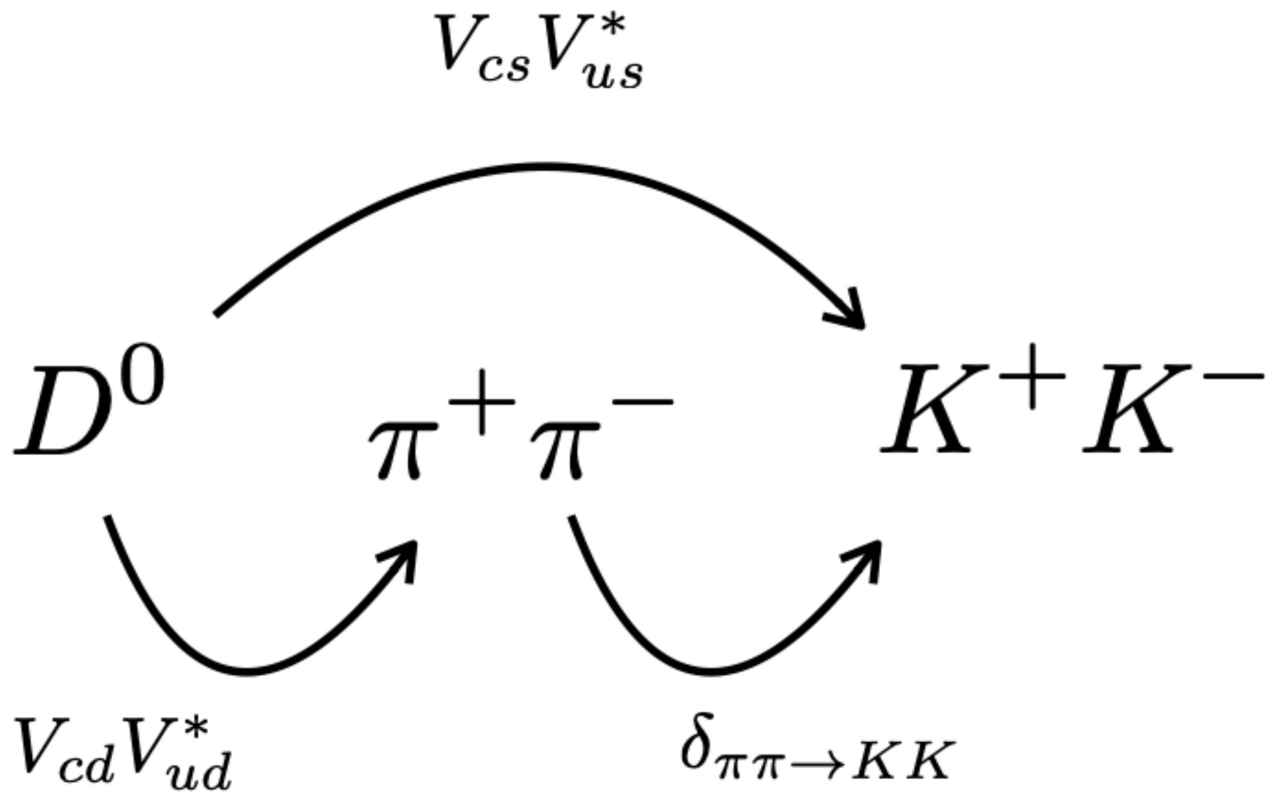
  PRD **86**, 036012 (2012). Fusheng Yu's talk

  Use the relations of final state interactions; $P^{LD} = E$.

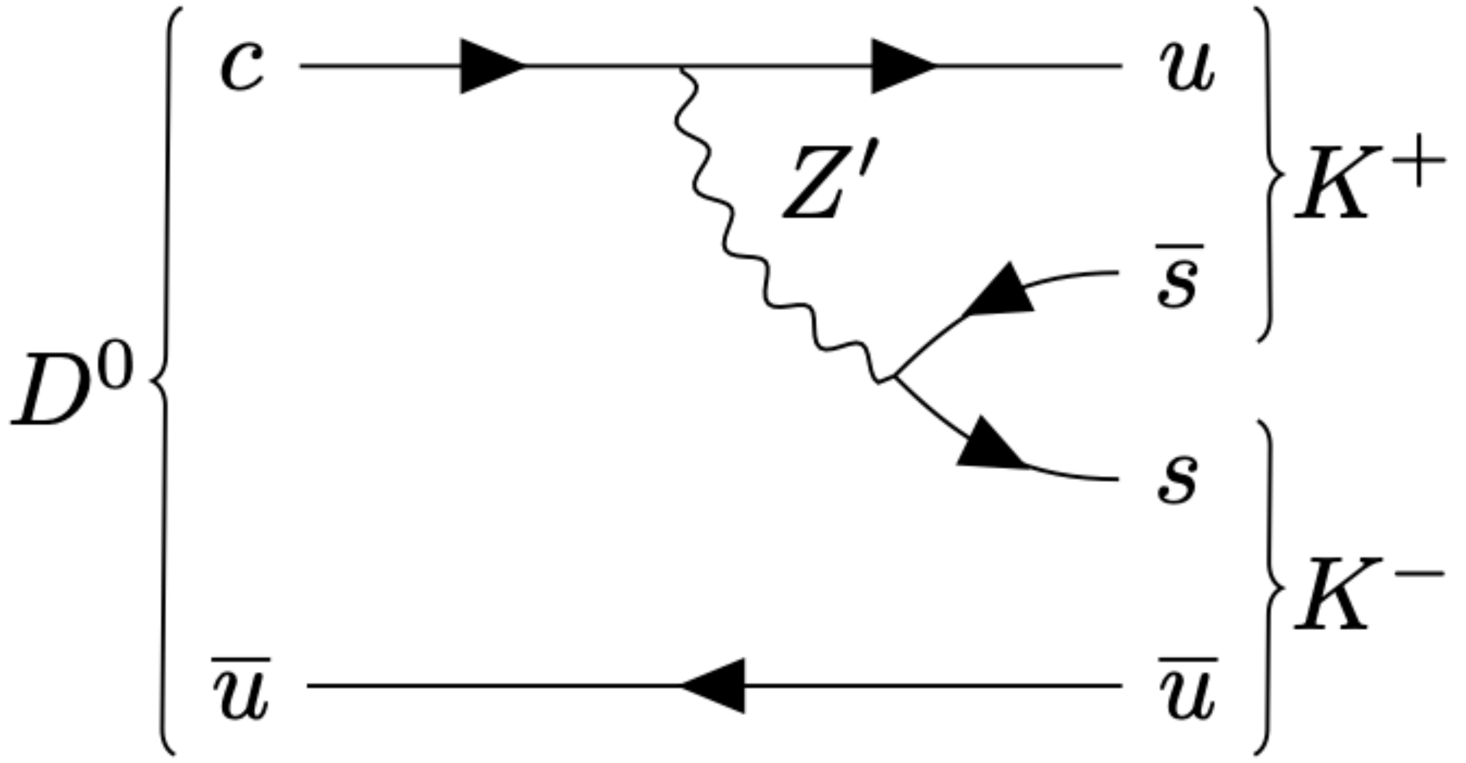
  PRD **86**, 014014 (2012); PRD **109**, 073008 (2024).

  Consider the re-scattering of $\pi\pi \to KK$.

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



- SM ***naively*** predicts $a_{CP}^{\pi\pi} = -\, a_{CP}^{KK}$ but data found opposite!



PRD **108**, 035005 (2023)

● Charming physics - CP violation

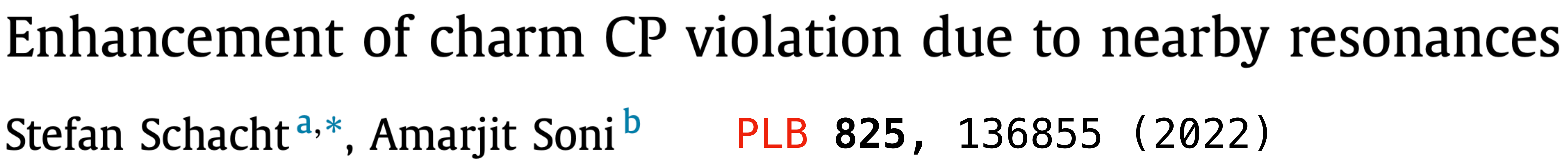
Reasons to go **beyond** charmed mesons:

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

PHYSICAL REVIEW D **81,** 074021 (2010)

Two-body hadronic charmed meson decays

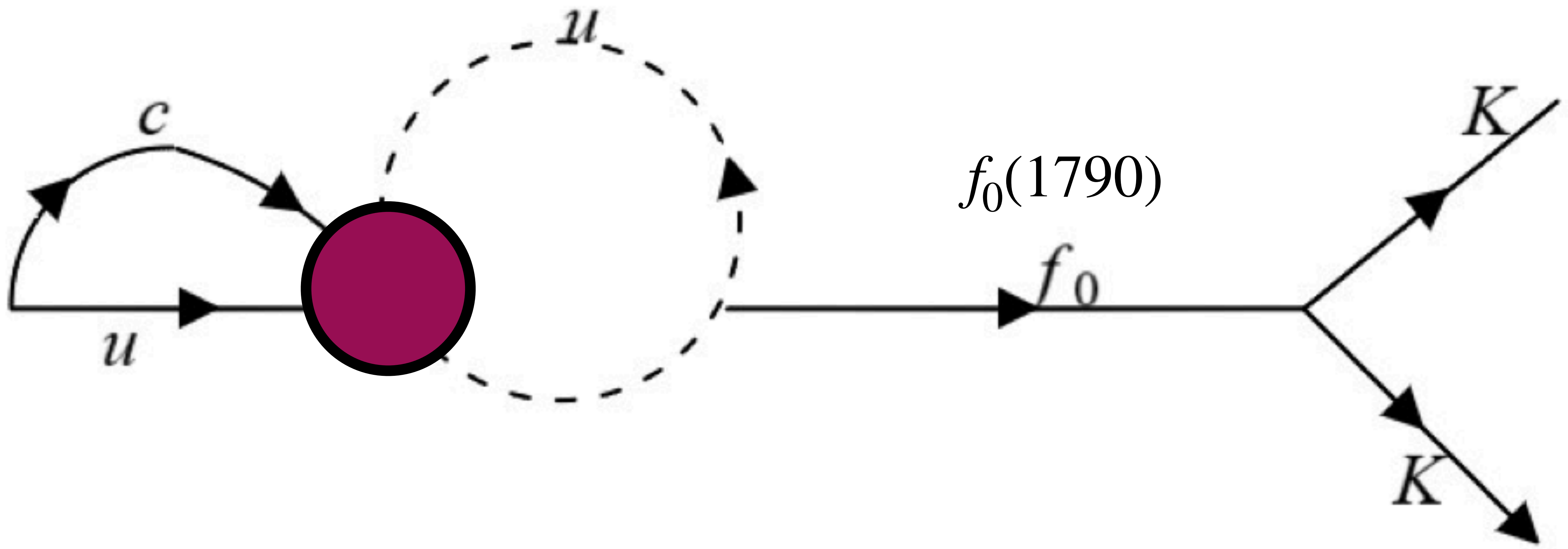
Hai-Yang Cheng[1,2] and Cheng-Wei Chiang[1,3]



Enhancement of charm CP violation due to nearby resonances

Stefan Schacht[a,*], Amarjit Soni[b]

PLB **825,** 136855 (2022)



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

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

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

For D CPV see: PRD **86,** 036012 (2012); PRD **86,** 014014 (2012); PRD **109,** 073008 (2024); PRL **131,** 051802 (2023).

STCF
Super Tau Charm Facility

BESIII

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***!

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.

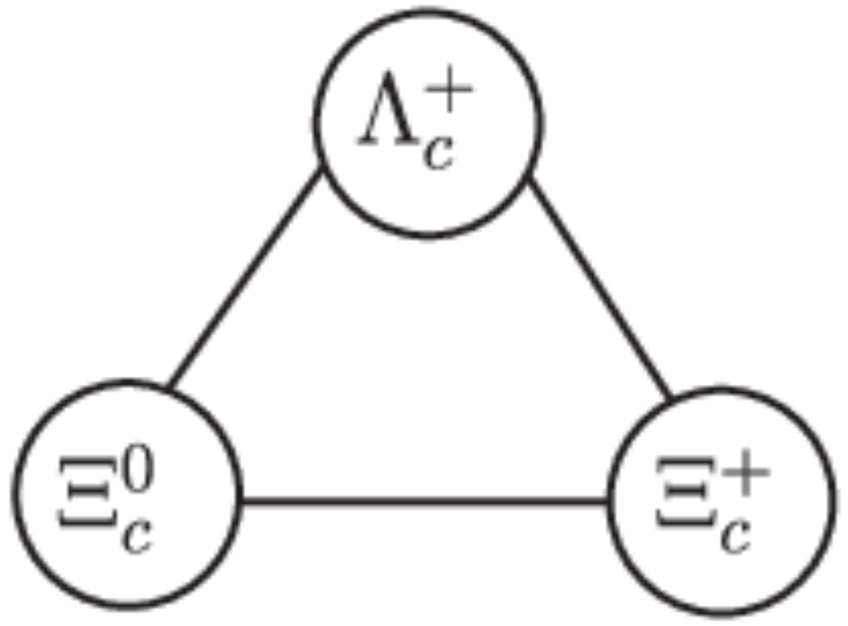
• SU(3) flavor perspective of charmed baryon decays

Murray Gell-Mann 1929-2019

By far, the only ***reliable* (?)** way is the $SU(3)_F$ **symmetry**.

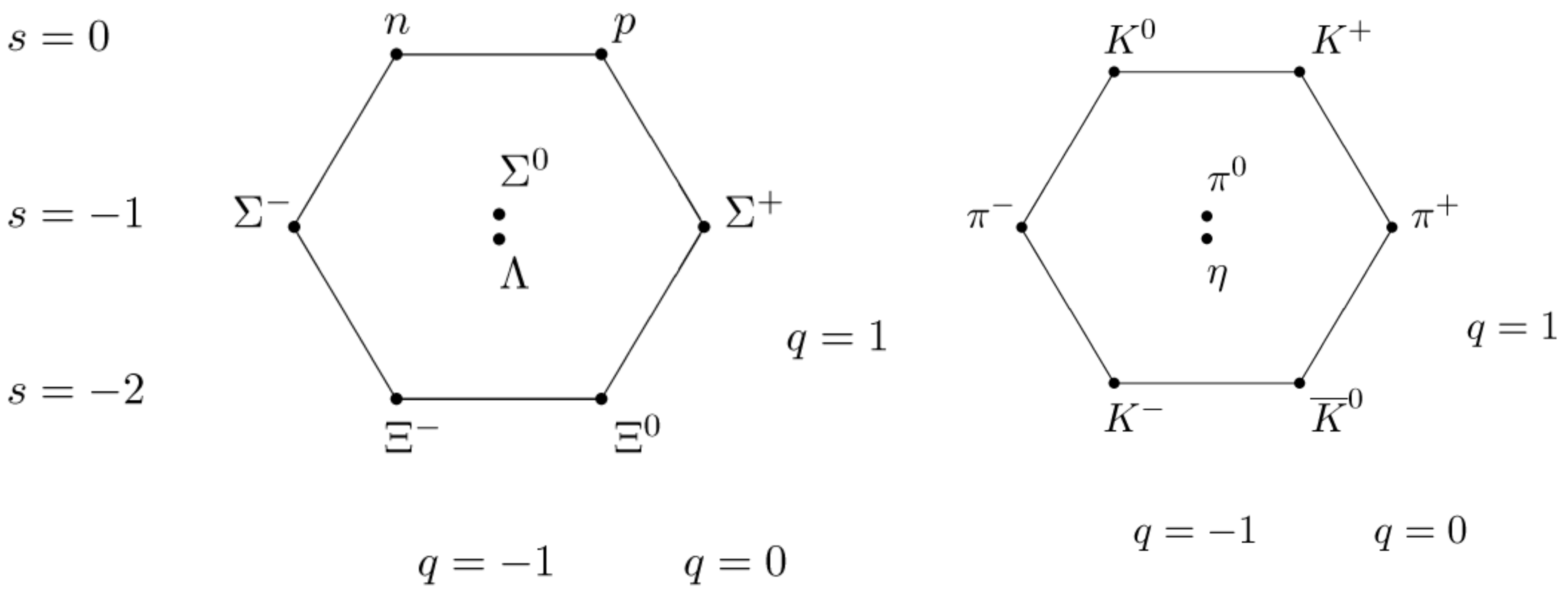
PRD **54**, 2132 (1996), PRD **93**, 056008 (2016), NPB **956**, 115048 (2020)

JHEP **09**, 035 (2022), JHEP **03**, 143 (2022), PRD **109**, 114027 (2024) …



Weak interactions

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



For instance:

$$A_{CP}(\Lambda_b^0 \to p\pi^+K^-\pi^-) = (2.45 \pm 0.46 \pm 0.10)\,\% \longrightarrow A_{CP}\left(\Lambda_b^0 \to p\pi^+\pi^-\pi^-\right) = -\,(12 \pm 3)\,\%\,.$$

LHCb, 2503.16954

X. G. He, **C. W. Liu**, J. Tandean, 2503.16954

SU(3) flavor perspective of charmed baryon decays

- Predicted **direct relations**: PLB **794**, 19(2019)

$$\Gamma(\Lambda_c^+ \to \Sigma^+ K_S^0) = \Gamma(\Lambda_c^+ \to \Sigma^0 K^+) = s_c^2 \Gamma(\Xi_c^0 \to \Xi^0 \pi^0)$$

$\mathscr{B}(\Lambda_c^+ \to \Sigma^+ K_S^0, \Sigma^0 K^+)$ BESIII

$$(4.7 \pm 1.0) \times 10^{-4}$$
$$\approx (4.8 \pm 1.4) \times 10^{-4}$$

PRD **106**, 052003 (2022)

$\mathscr{B}(\Xi_c^0 \to \Xi^0 \pi^0)$ BELLE

$$(7.1 \pm 0.4)_{th} \times 10^{-3}$$
$$(6.9 \pm 1.4)_{exp} \times 10^{-3}$$

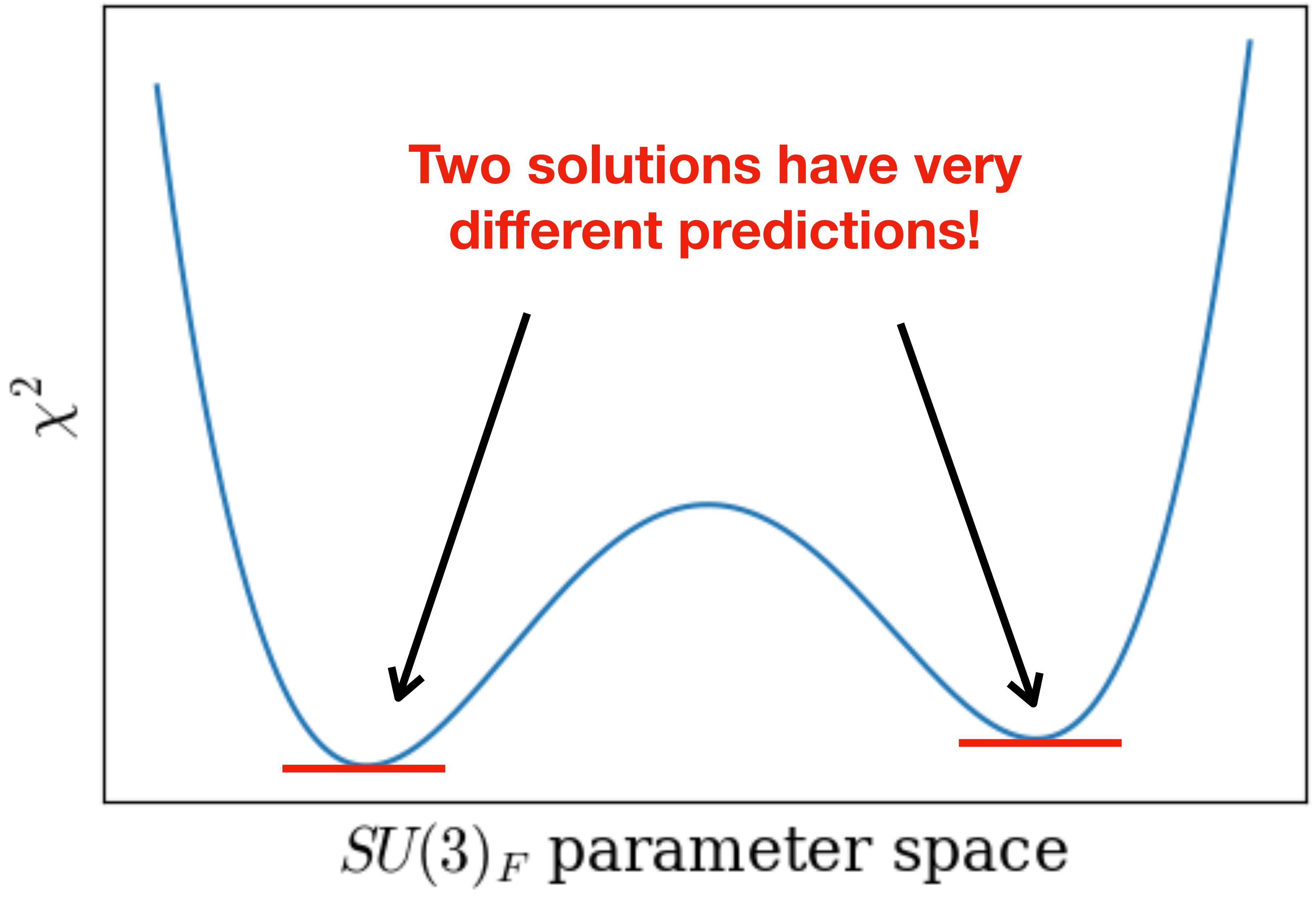
JHEP **10**, 045 (2024)

- Tests on **predictions** of **global fits** since last year: PRD **109**, 093001; PRD **109**, L071302

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

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 $(F, G) \rightarrow (F^*, G^*)$ 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)

• SU(3) flavor perspective of charmed baryon decays

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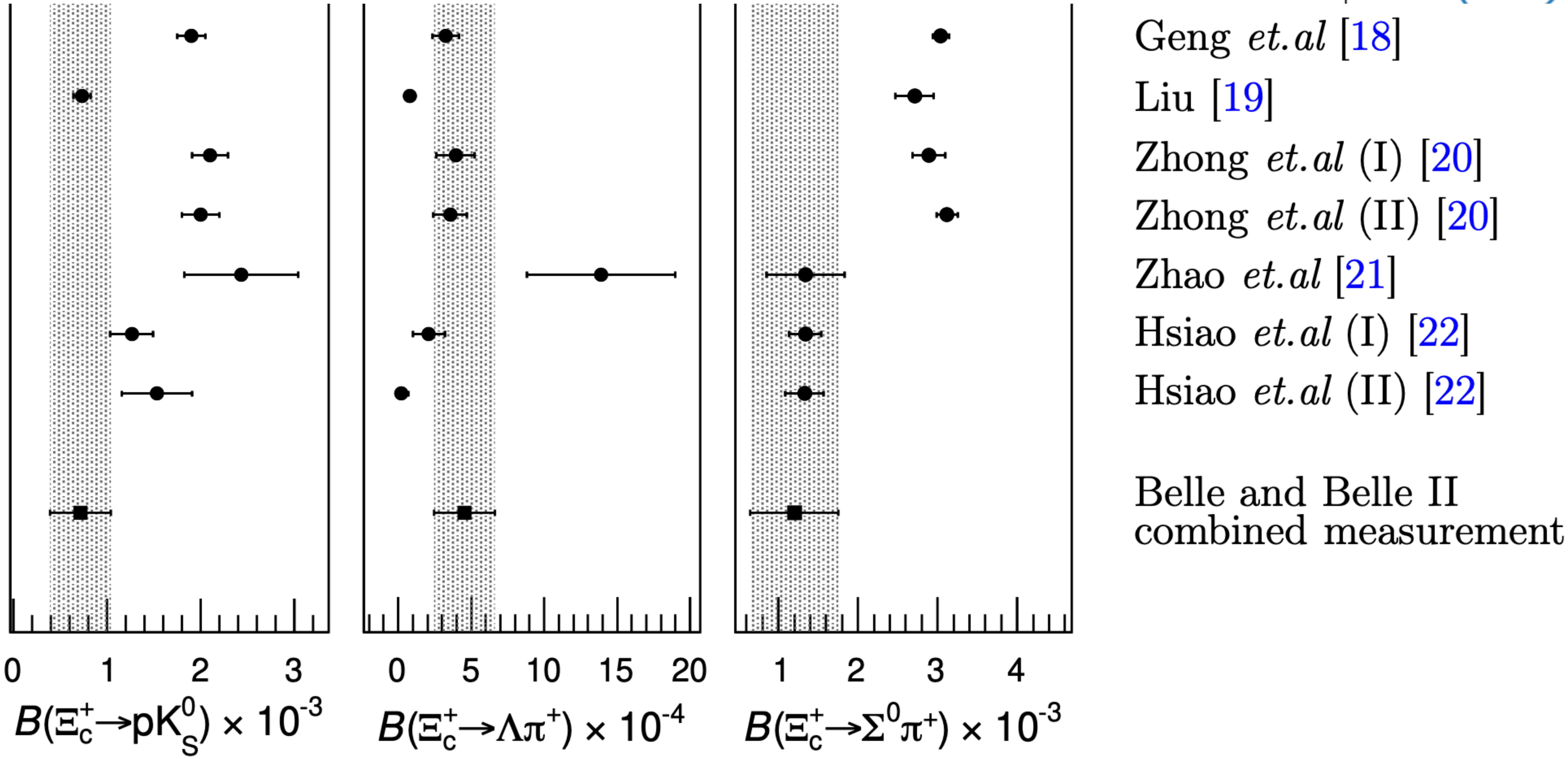
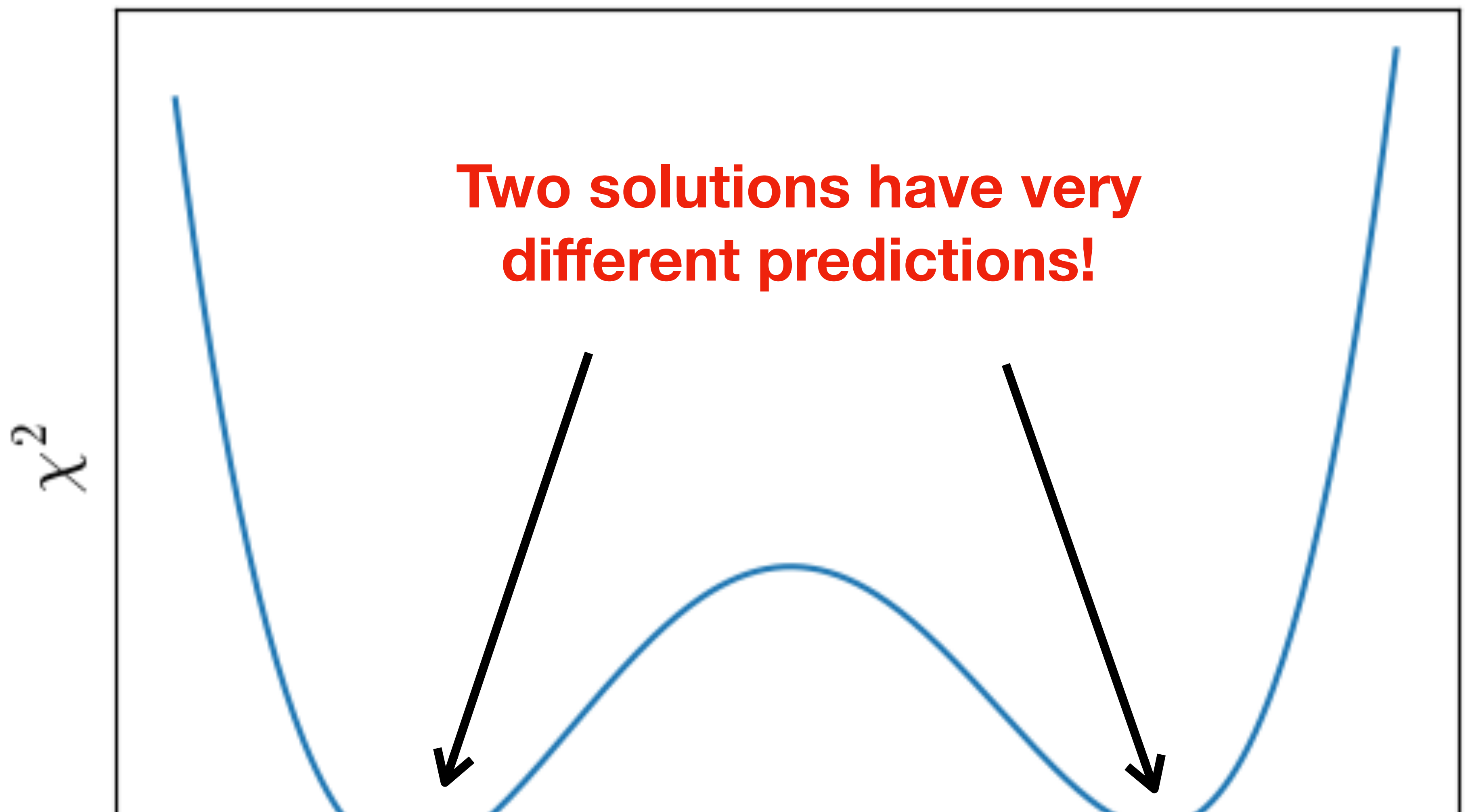




Two solutions have very different predictions!

$)_F$ parameter space

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

nd γ **flip signs**.

ut.

f LHCb work!

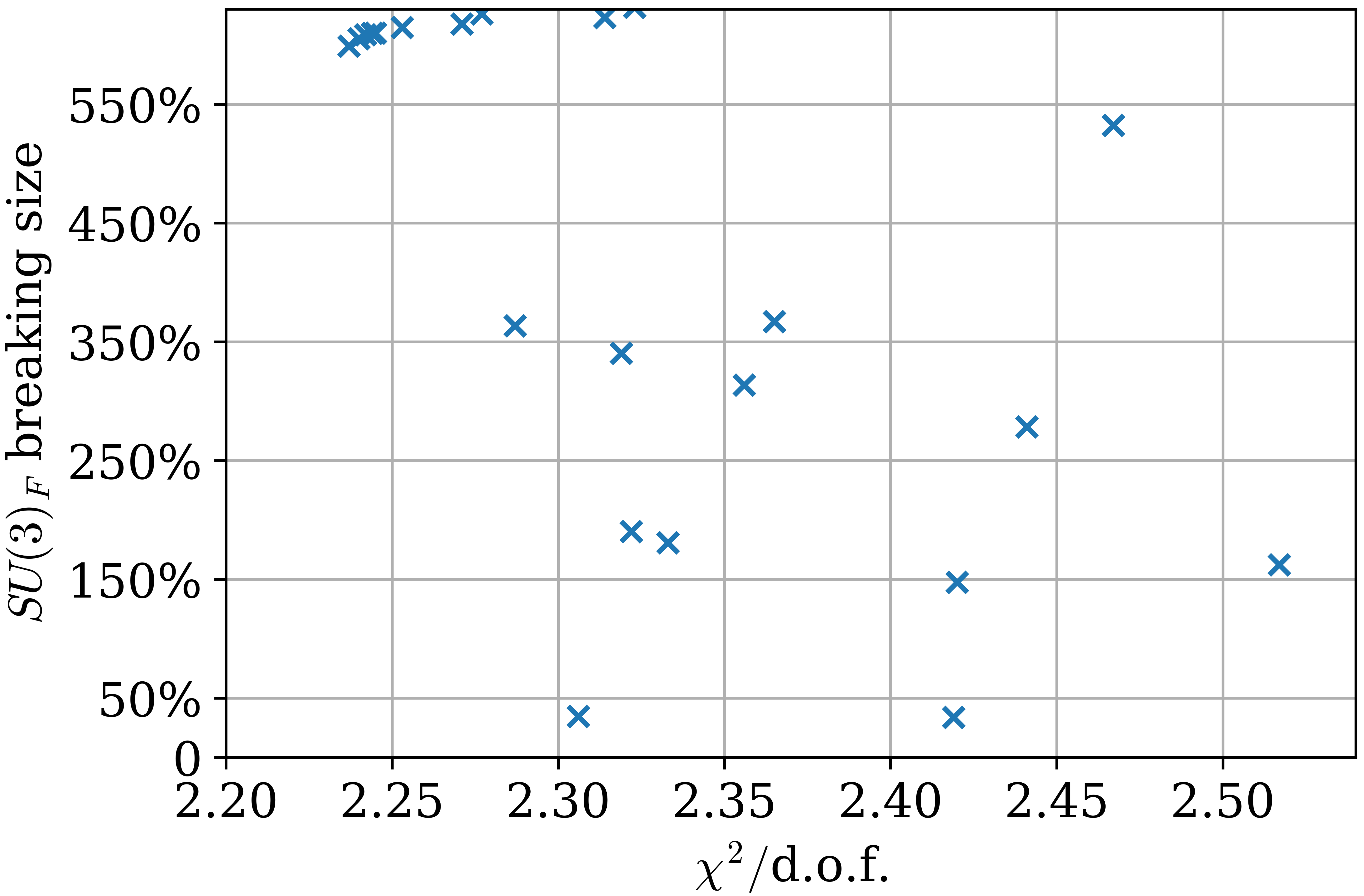
arameters Using $\Lambda_b^0\to\Lambda_c^+h^-$ Decays

PRL **133**, 261804 (2024)

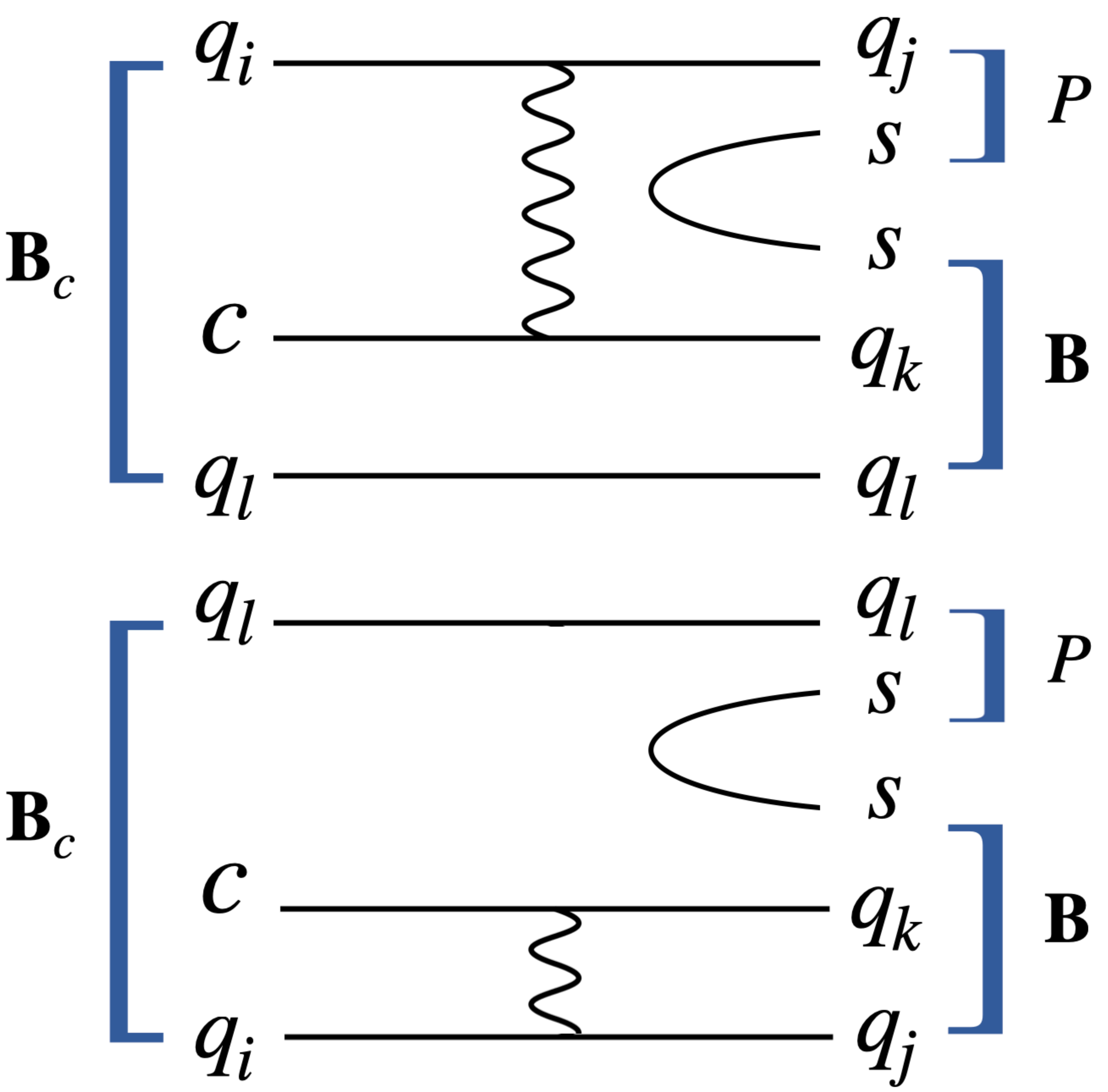
SU(3) flavor perspective of charmed baryon decays

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.



He, Liu, Yang; 2505.XXXX



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

(constituent quark masses)

SU(3) flavor perspective of charmed baryon decays

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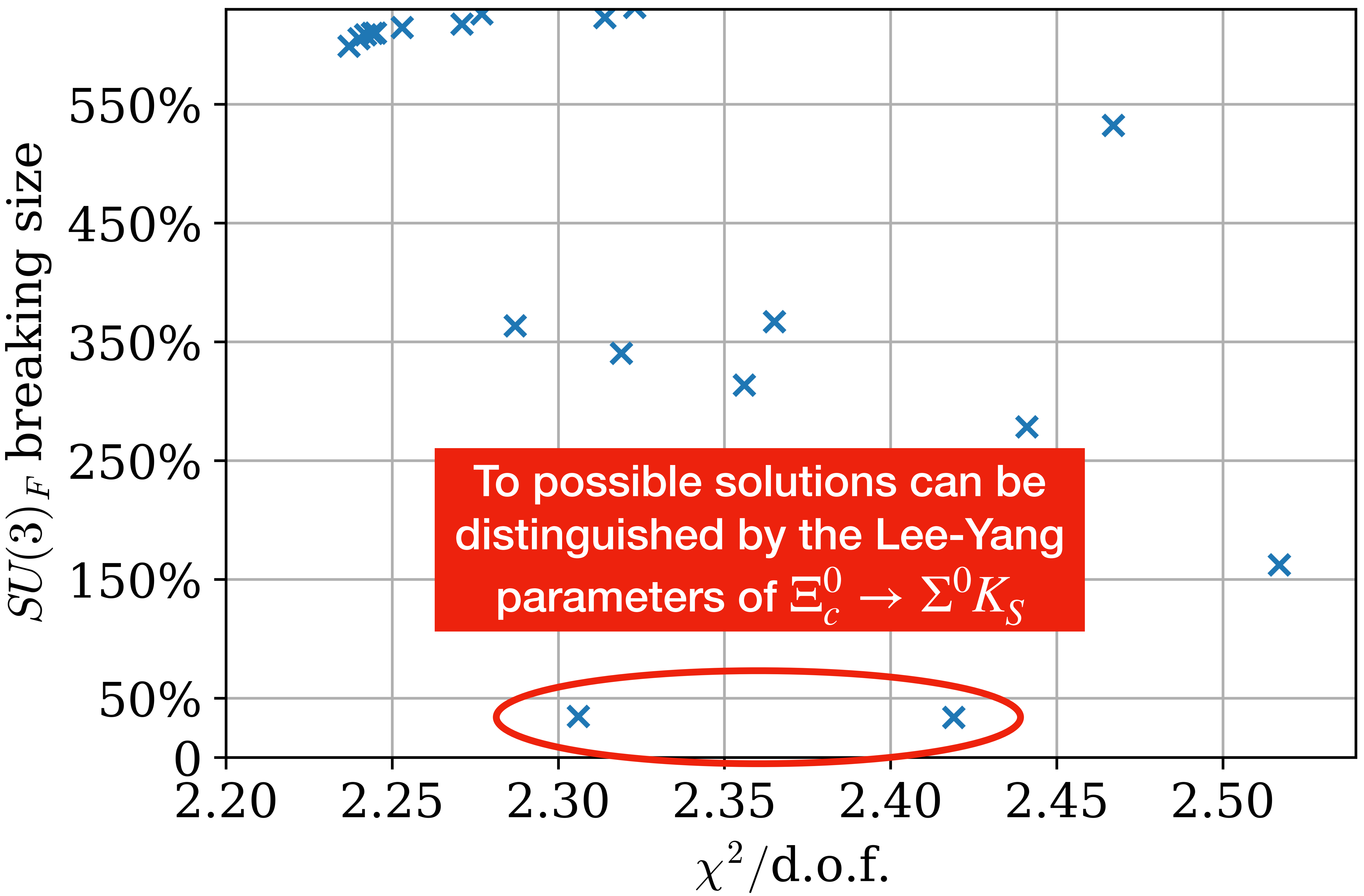
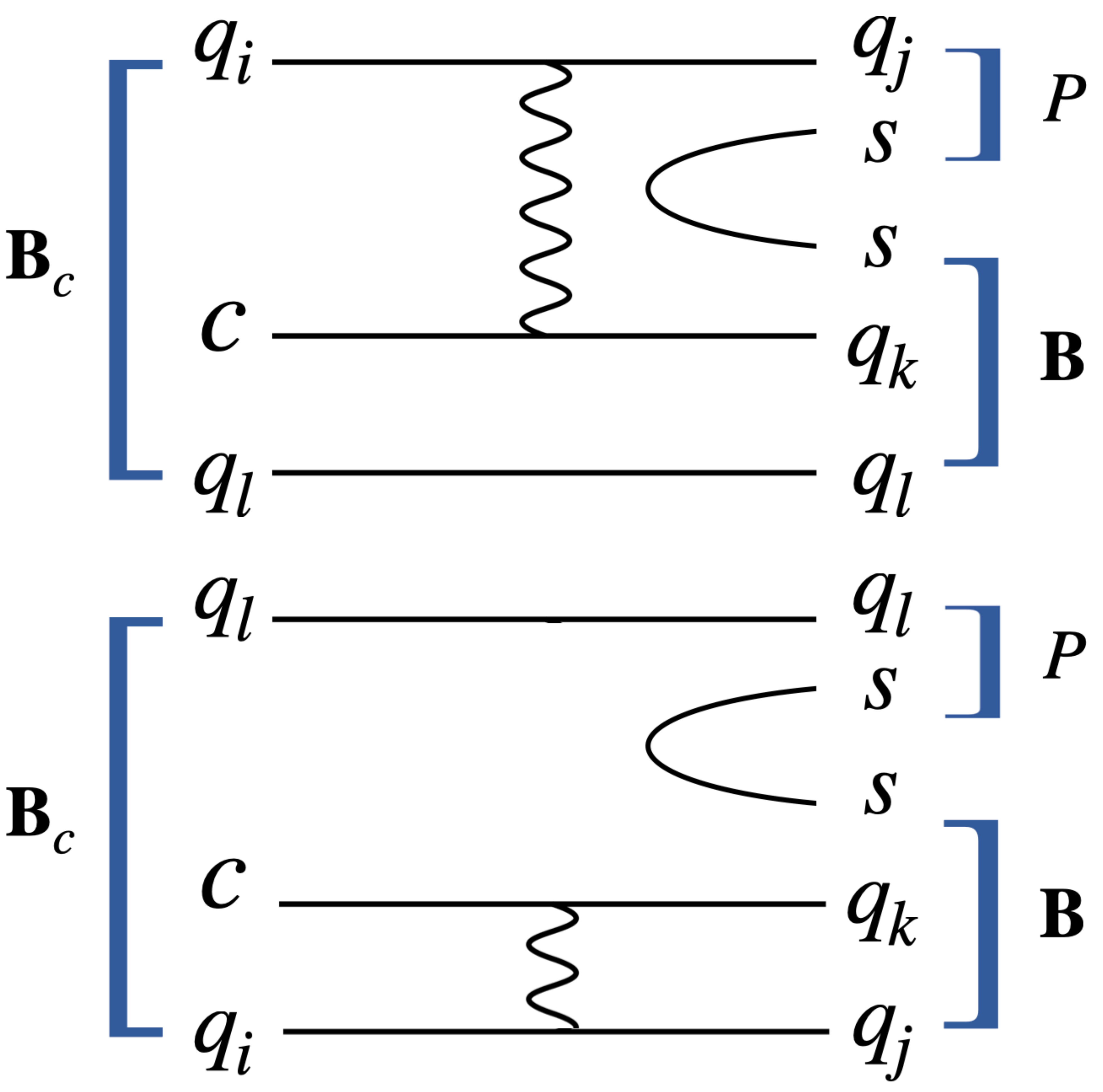


To possible solutions can be distinguished by the Lee-Yang parameters of $\Xi_c^0 \to \Sigma^0 K_S$

He, Liu, Yang; 2505.XXXX



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SU(3) flavor perspective of charmed baryon decays

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

	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	2.90 ± 0.11
$10^2\mathscr{B}(\Xi_c^+ \to \Xi^-\pi^+\pi^+)$	2.9 ± 1.3	6.82 ± 0.36	5.98 ± 0.44

He, **Liu**, Yang; **2505.XXXX**

Both of them are the normalized channels in $\Xi_c^{0,+}$, indicating an possible **underestimation of factor two** in the experimental side.

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

	PDG	$SU(3)_F$	Lattice	Lattice
$10^2\mathscr{B}(\Xi_c^0 \to \Xi^-e^+\nu_e)$	$1.05 \pm 0.20*$	4.10 ± 0.46	2.38 ± 0.44	3.58 ± 0.12
$10^2\mathscr{B}(\Xi_c^0 \to \Xi^-\mu^+\nu_\mu)$	$1.02 \pm 0.21*$	3.98 ± 0.57	2.29 ± 0.42	3.47 ± 0.12
*Using $\mathscr{B}(\Xi_c^0 \to \Xi^-\pi^+) = (1.42 \pm 0.32)\,\%$		**PLB** 823, 136765 (2021)	**CPC** 46, 011002 (2022)	**2504.07302**

SU(3) flavor perspective of charmed baryon decays

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He, **Liu**, Yang; **2505.XXXX**

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

	PDG	$SU(3)_F$	Lattice	Lattice
$10^2\mathscr{B}(\Xi_c^0 \to \Xi^-e^+\nu_e)$	2.12 ± 0.13*	4.10 ± 0.46	2.38 ± 0.44	3.58 ± 0.12
$10^2\mathscr{B}(\Xi_c^0 \to \Xi^-\mu^+\nu_\mu)$	2.05 ± 0.19*	3.98 ± 0.57	2.29 ± 0.42	3.47 ± 0.12
*Using $\mathscr{B}(\Xi_c^0 \to \Xi^-\pi^+) = (2.90 \pm 0.11)\,\%$		**PLB** 823, 136765 (2021)	**CPC** 46, 011002 (2022)	**2504.07302**

SU(3) flavor analysis

$$V_{cs}^{*}V_{us}\,\text{Tree} + \underbrace{\cancel{V_{cb}^{*}V_{ub}\,\text{Penguin}}}_{\text{Insensitive to CP-even quantities \& undetermined}}$$

Final State Rescattering

$$V_{cs}^{*}V_{us}\,\text{Tree} + V_{cb}^{*}V_{ub}\,\text{Tree} \times \underbrace{(\,\text{Penguin / Tree}\,)}_{\text{Determined by the rescattering}}$$

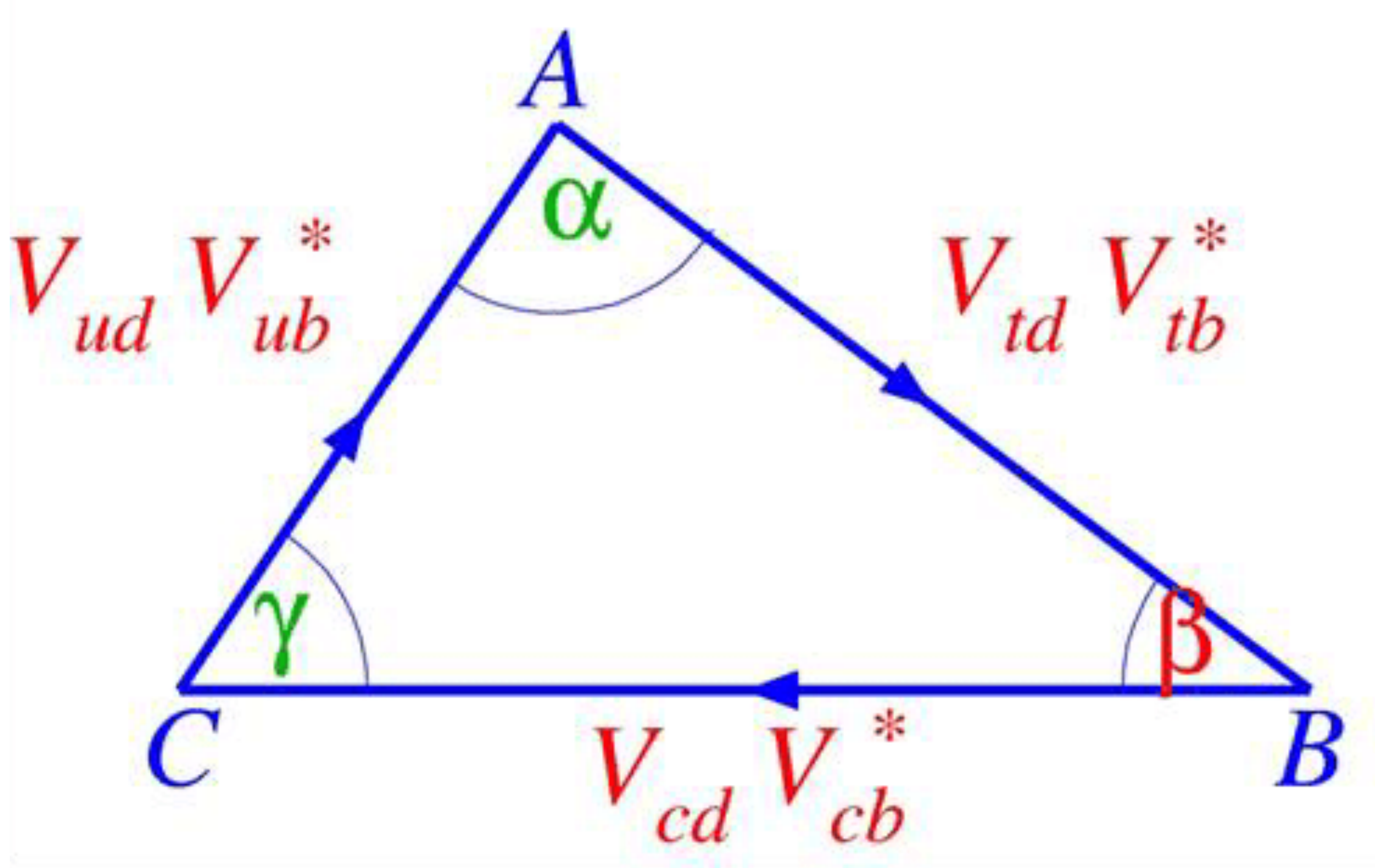
SU(3) flavor perspective of charmed baryon decays

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

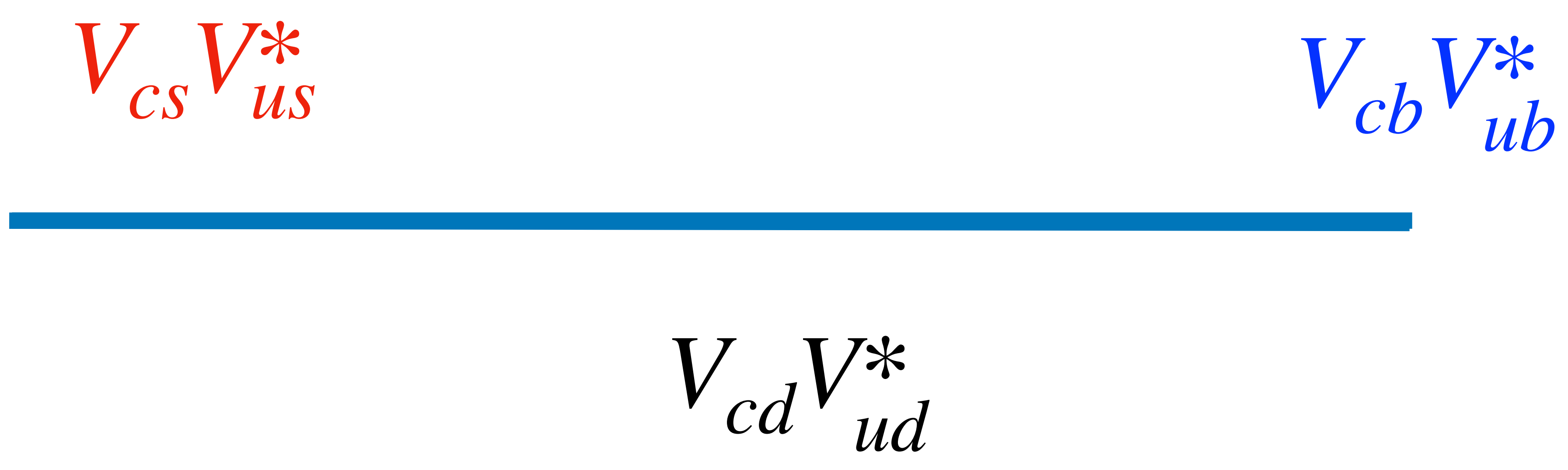
Do not need to consider F^b in studying CP-even quantities.

⟷

F^b cannot be determined with CP-even quantities.



CKM triangle for $b \to d$

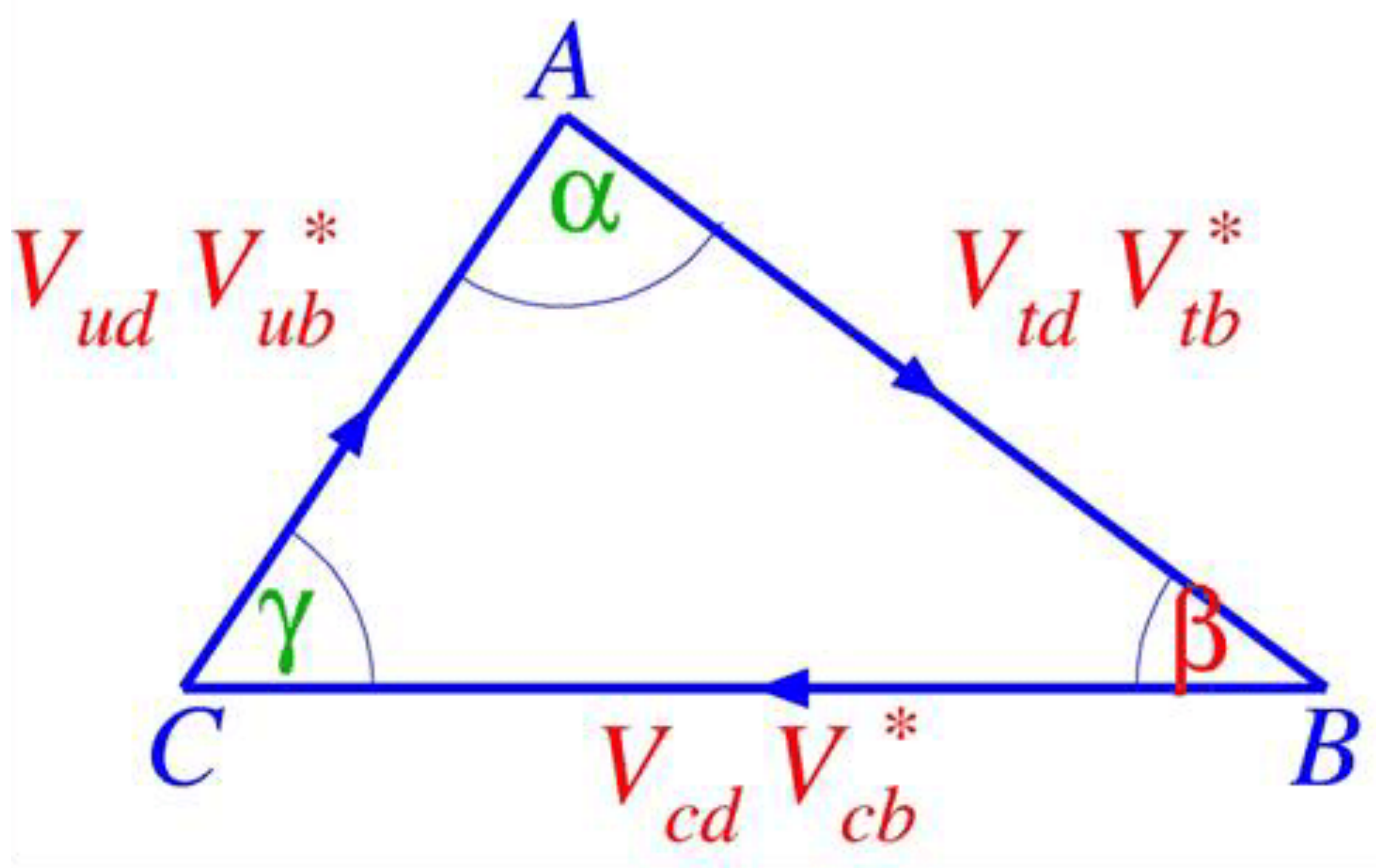


CKM triangle for $c \to u$

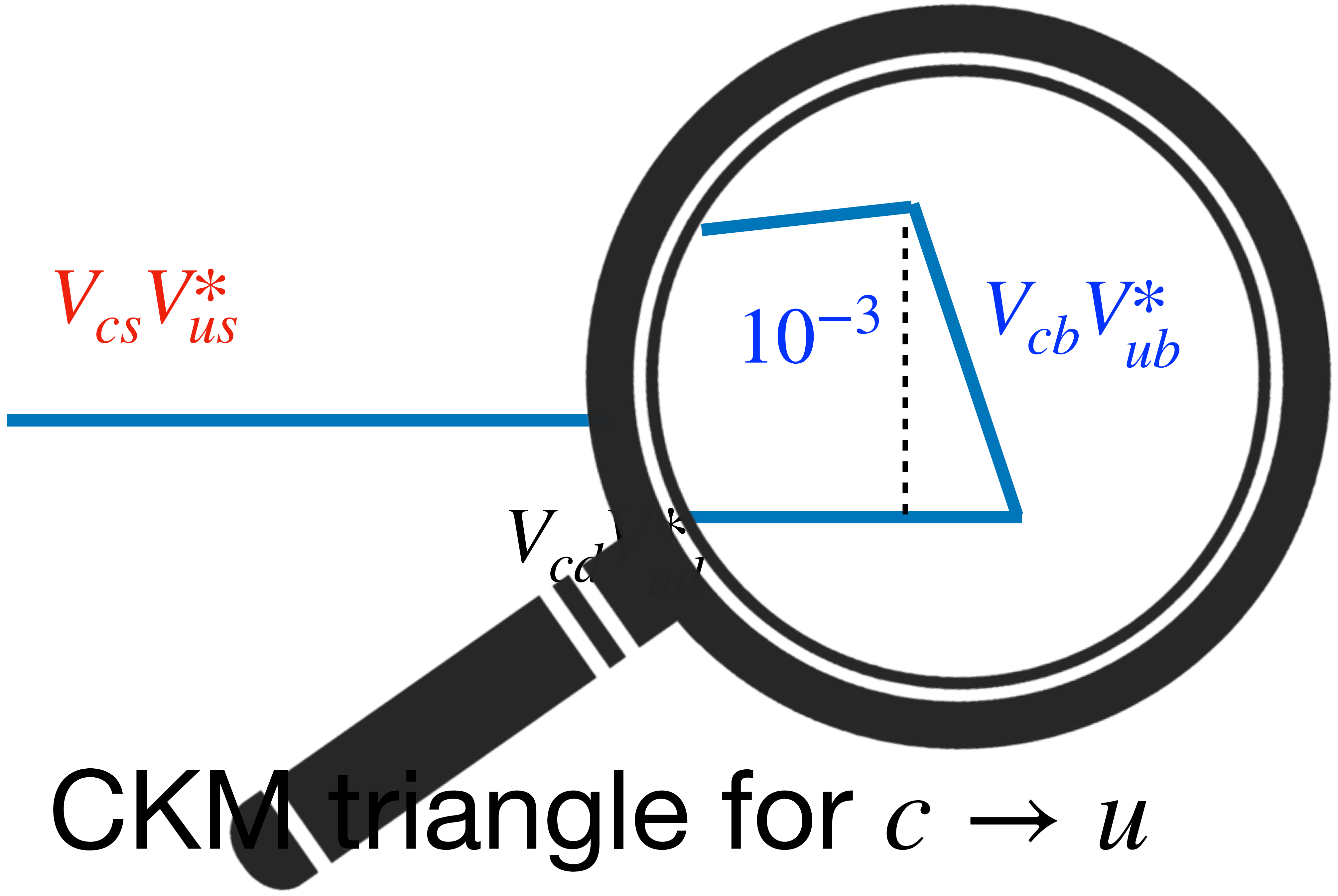
- **SU(3) flavor perspective of charmed baryon decays**

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

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

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

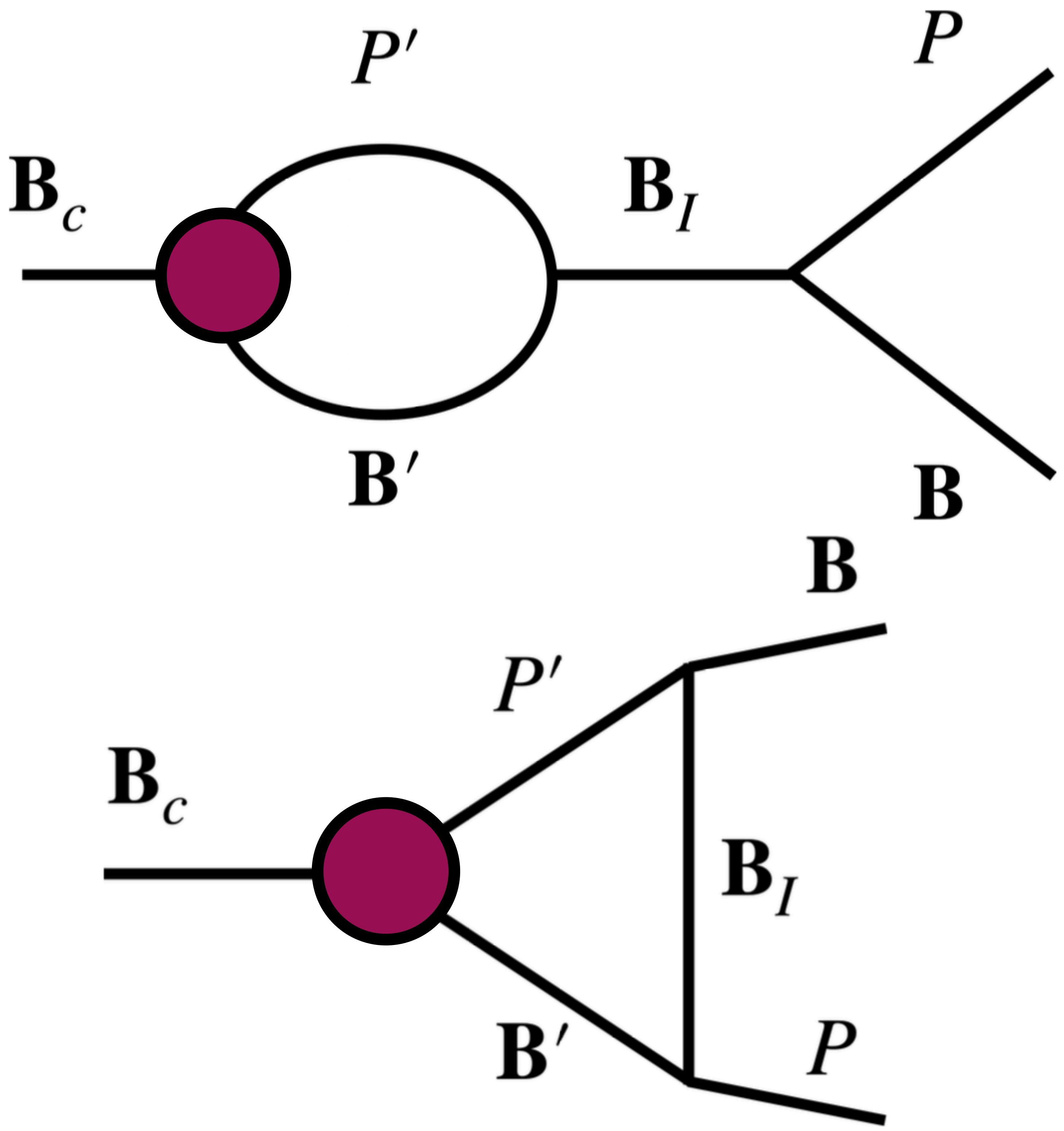
Do not need to consider F^b in studying CP-even quantities. ⟷ F^b cannot be determined with CP-even quantities.

See also the talks of F. S. Yu and Q. Qing.

We analyzed the $SU(3)_F$ structure of final state rescattering.

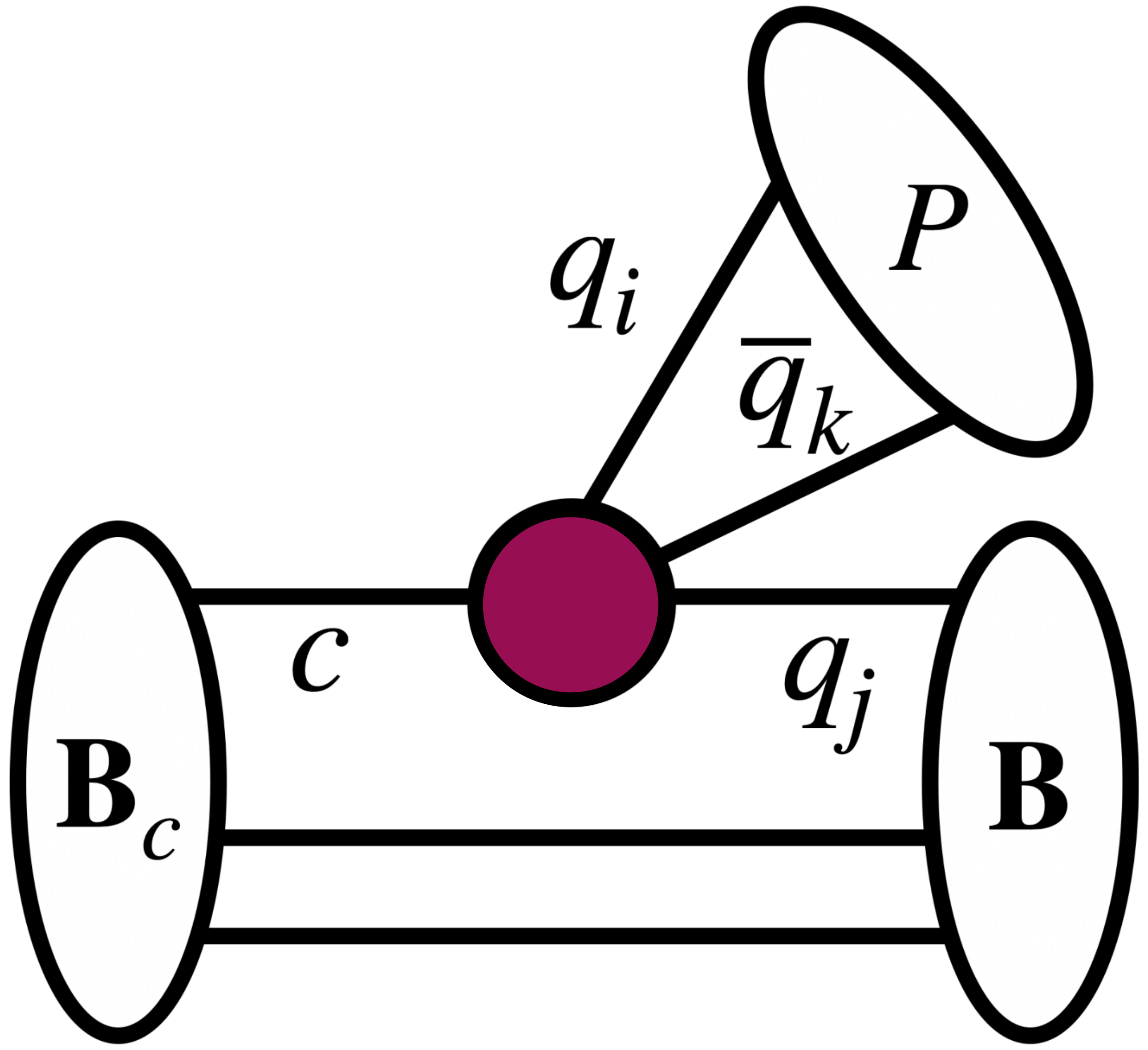
- The $SU(3)_F$ parameters ***acquire*** physical meanings.
- The relation between F^{s-d} and F^b is established.
- One can ***solve*** F^b with the input of F^{s-d}.

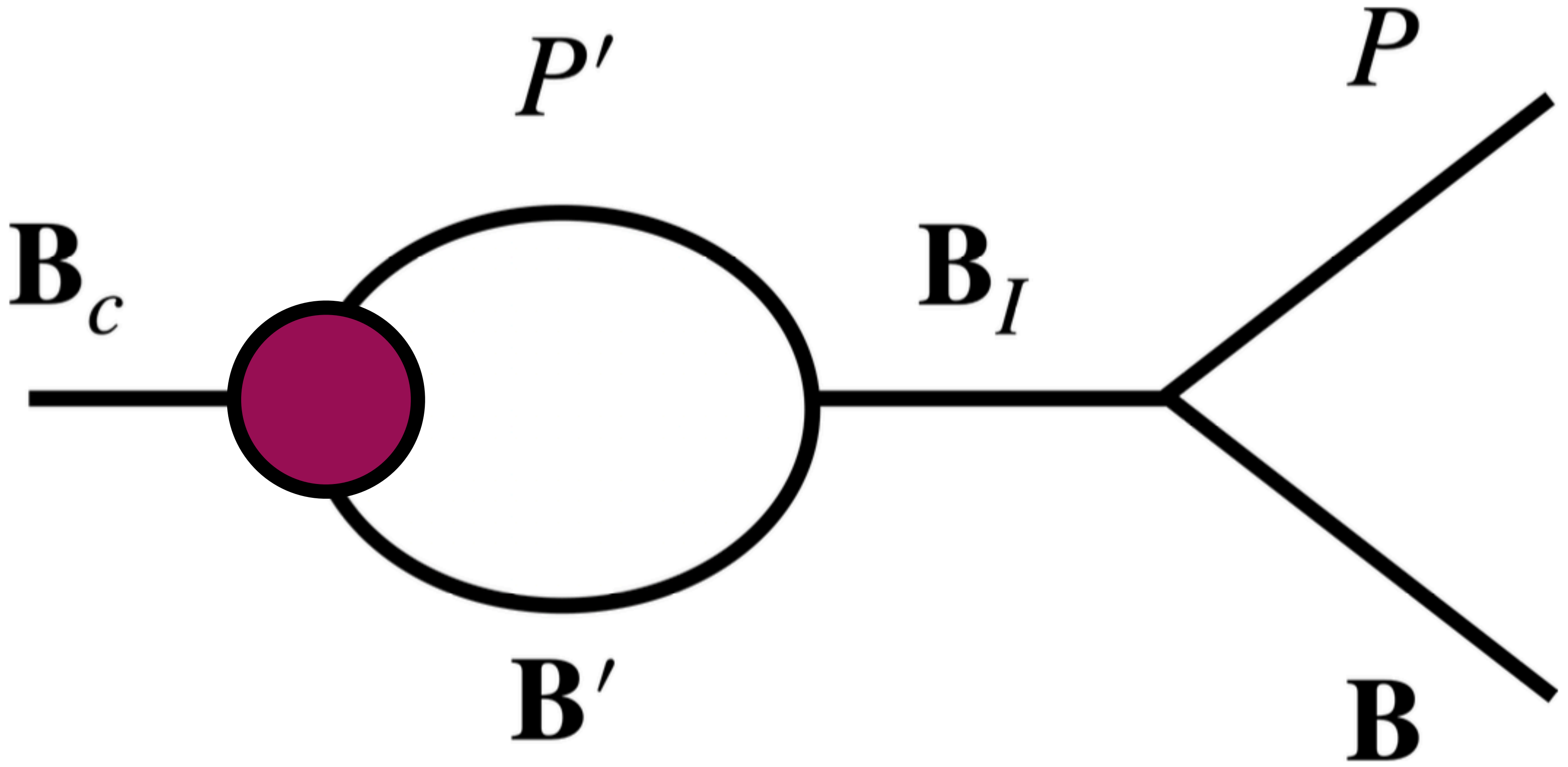
See 2408.14959 for direct calculations

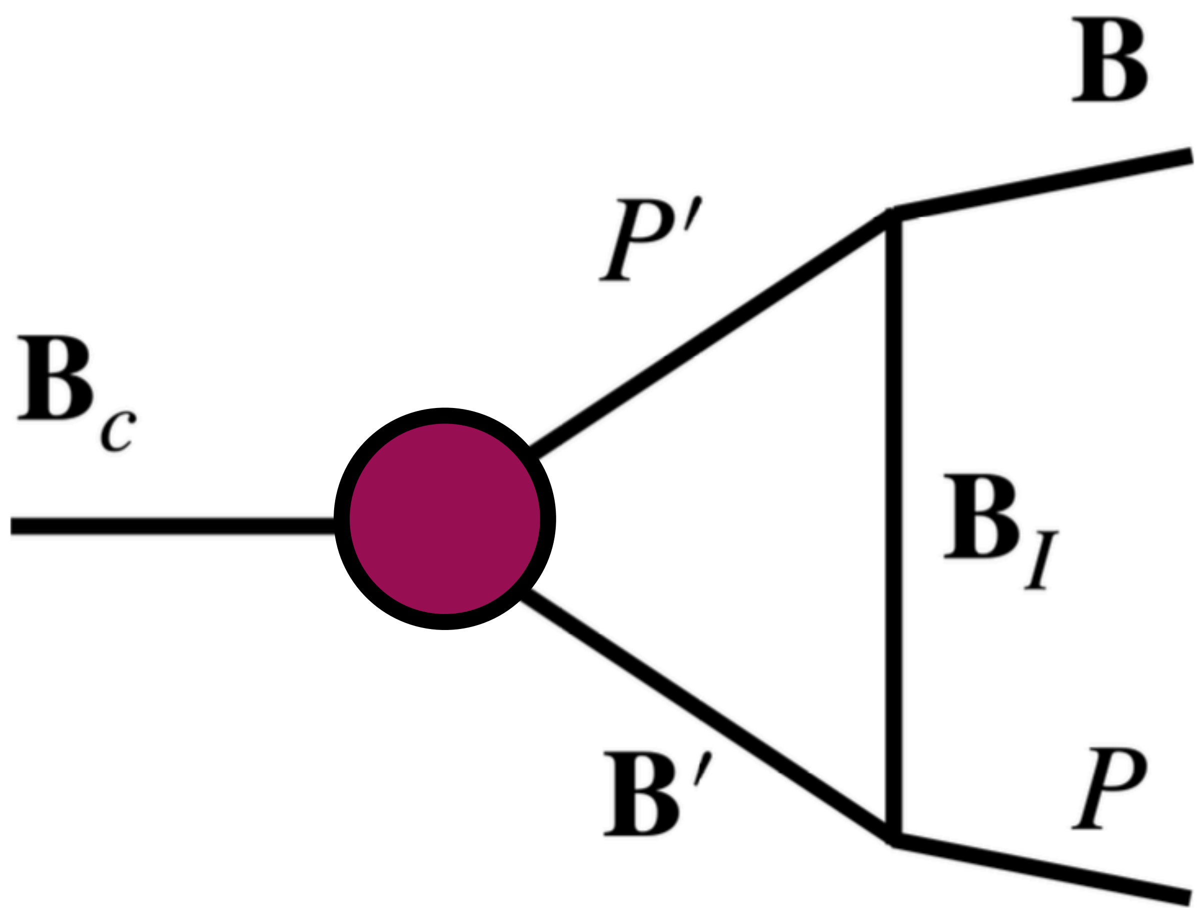


Rescattering, solving penguin/tree

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







Assumptions:

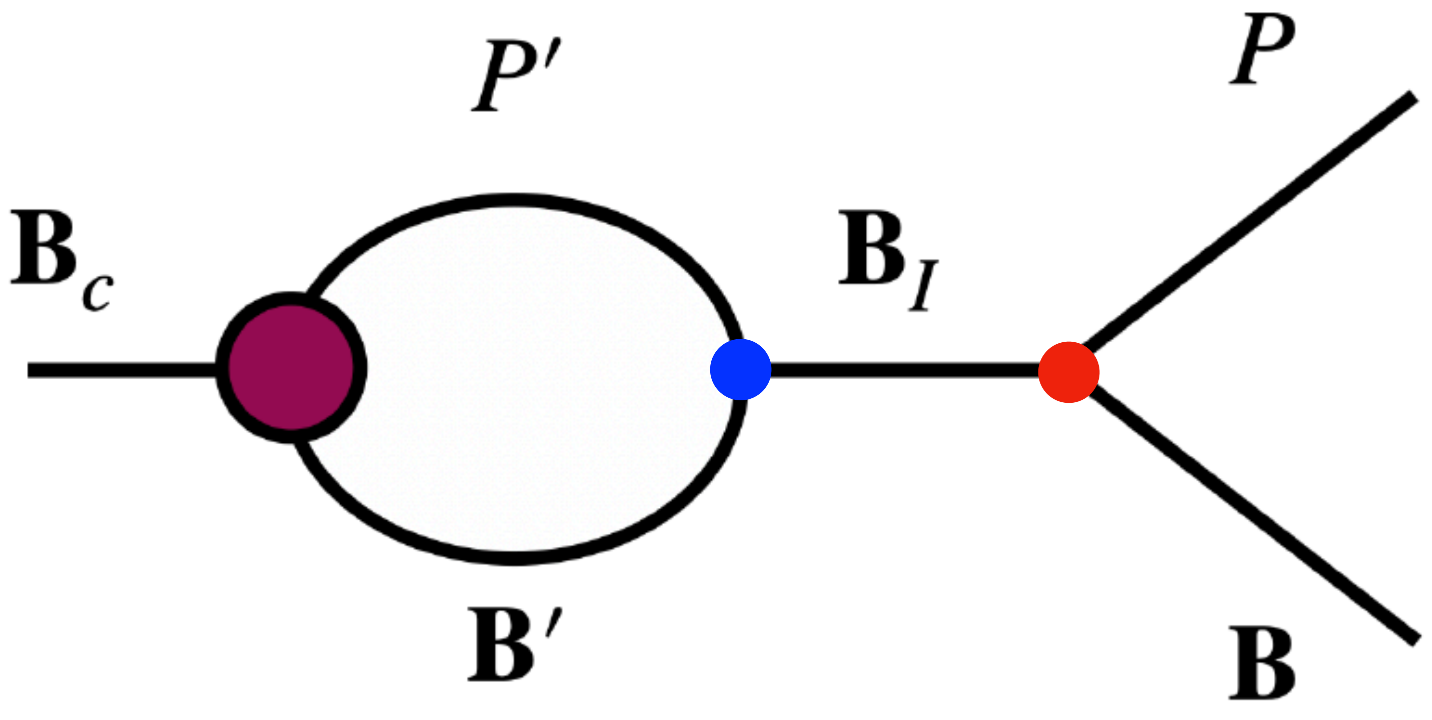
1. Short distance transitions are dominated by the W-emission, including both color-enhanced and color-suppressed.
2. $\mathbf{B}_I \in$ lowest-lying baryons of both parities.
3. The re-scattering is closed, *i.e.* $\mathbf{B}'P'$ belong to the same $SU(3)_F$ group of $\mathbf{B}P$.

- **Rescattering, solving penguin/tree**

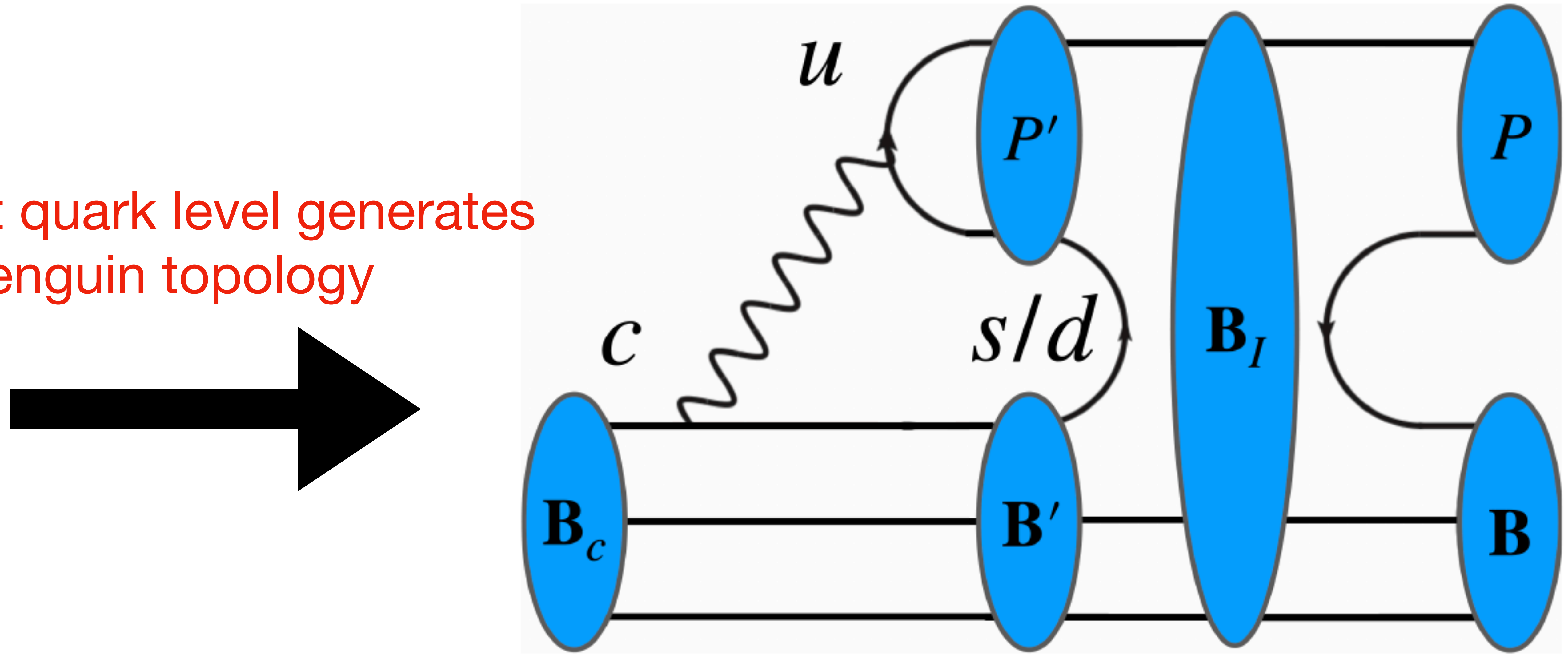
$$\langle \mathscr{L}^{\rm FSR-s}_{\mathbf{B}_c\mathbf{B}P}\rangle = \sum_{\mathbf{B}_I,\mathbf{B}',P'} \bar{u}_{\mathbf{B}} \left(\int \frac{d^4q}{(2\pi)^4}\, g_{\mathbf{B}_I\mathbf{B}P} \frac{p^{\mu}_{\mathbf{B}_c}\gamma_\mu + m_I}{p^2_{\mathbf{B}_c} - m_I^2}\, g_{\mathbf{B}_I\mathbf{B}'P'} \frac{q^\mu\gamma_\mu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

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

2. Sum over the intermediate hadrons $\mathbf{B}_I$, $\mathbf{B}'$ and P'.



At quark level generates penguin topology



Rescattering, solving penguin/tree

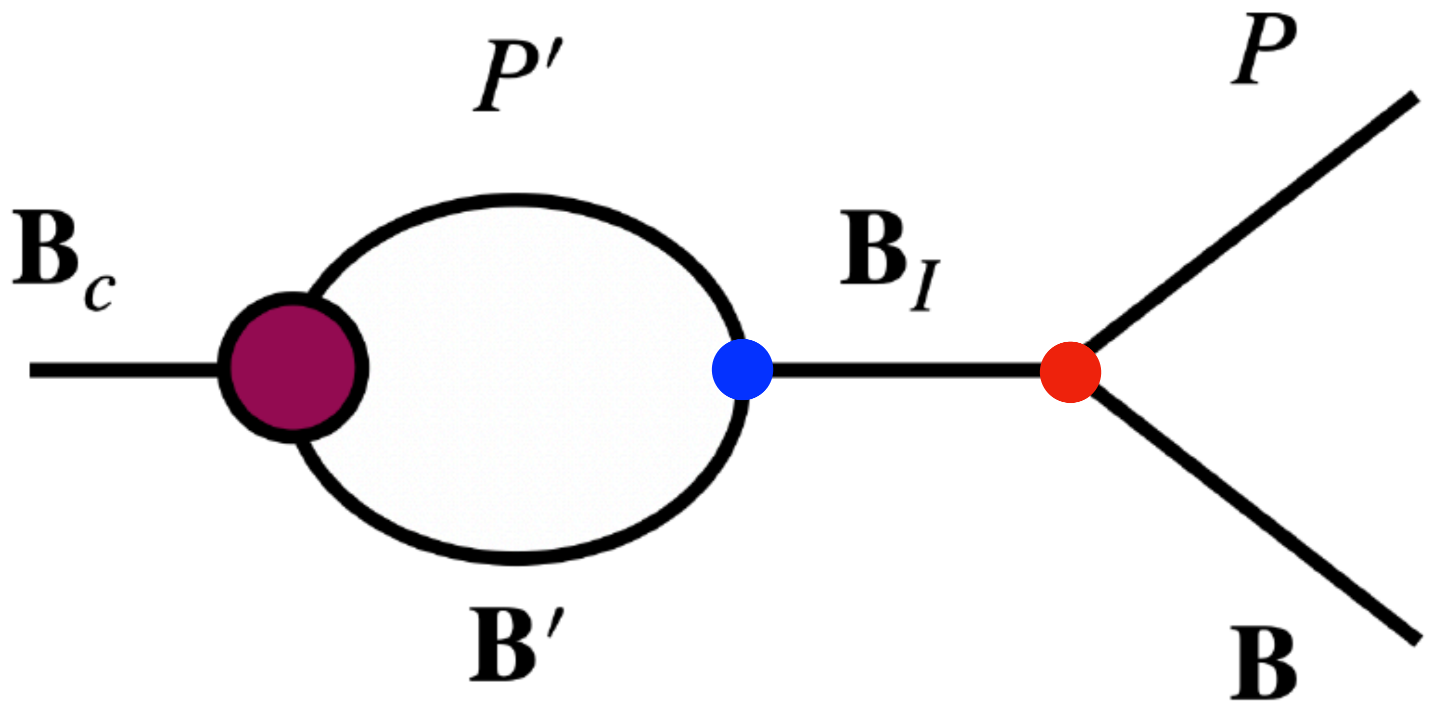
$$\sum_{\mathbf{B}_I,\mathbf{B}',P'} F^{\rm Tree}_{\mathbf{B}_c\mathbf{B}'P'}\, g_{\mathbf{B}_I\mathbf{B}'P'}\, g_{\mathbf{B}_I\mathbf{B}P}$$

Key of reduction rule: utilizing $\mathbf{B}_I$ belongs to $\mathbf{8}$.

Substitute $\sum_{\mathbf{B}_I} \langle\overline{\mathbf{B}}_I\rangle^{k_1}_{i_1}\langle\mathbf{B}_I\rangle^{j_2}_{k_2}$ with $\frac{1}{2}\sum_{\lambda_a}(\lambda_a)^{k_1}_{i_1}(\lambda_a)^{j_2}_{k_2} = \delta^{j_2}_{i_1}\delta^{k_1}_{k_2} - \frac{1}{3}\delta^{k_1}_{i_1}\delta^{j_2}_{k_2}$

$$\propto \sum_{\mathbf{B}_I,\mathbf{B}',P'} \left(\langle P'^{\dagger}\rangle^{k}_{i}\langle\overline{\mathbf{B}}'\rangle^{l}_{j}(\mathscr{H}_-)^{ij}_{k}\langle\mathbf{B}_c\rangle_l\right)\left(\langle P'\rangle^{i_2}_{j_2}\langle\overline{\mathbf{B}}_I\rangle^{j_2}_{k_2}\langle\mathbf{B}'\rangle^{k_2}_{i_2} + r_-\langle P'\rangle^{j_2}_{k_2}\langle\overline{\mathbf{B}}_I\rangle^{i_2}_{j_2}\langle\mathbf{B}'\rangle^{k_2}_{i_2}\right)\left(\langle P^{\dagger}\rangle^{i_3}_{j_3}\langle\overline{\mathbf{B}}\rangle^{j_3}_{k_3}\langle\mathbf{B}_I\rangle^{k_3}_{i_3} + r_-\langle P^{\dagger}\rangle^{j_3}_{k_3}\langle\overline{\mathbf{B}}\rangle^{i_3}_{j_3}\langle\mathbf{B}_I\rangle^{k_3}_{i_3}\right)$$

$$\langle\mathscr{L}^{\rm FSR-s}_{\mathbf{B}_c\mathbf{B}P}\rangle = \tilde{S}^-\left(\langle P^{\dagger}\rangle^{i_1}_{j_1}\langle\overline{\mathbf{B}}\rangle^{j_1}_{k_1} + r_-\langle P^{\dagger}\rangle^{j_1}_{k_1}\langle\overline{\mathbf{B}}\rangle^{i_1}_{j_1}\right)\left(\delta^{k_1}_{i}\delta^{k}_{i_1} - \frac{1}{3}\delta^{k_1}_{i_1}\delta^{k}_{i}\right)\left((\mathscr{H}_-)^{ij}_{k}\langle\mathbf{B}_c\rangle_j + \frac{4r_-+1}{r_-+4}(\mathscr{H}_-)^{ji}_{j}\langle\mathbf{B}_c\rangle_k\right)$$



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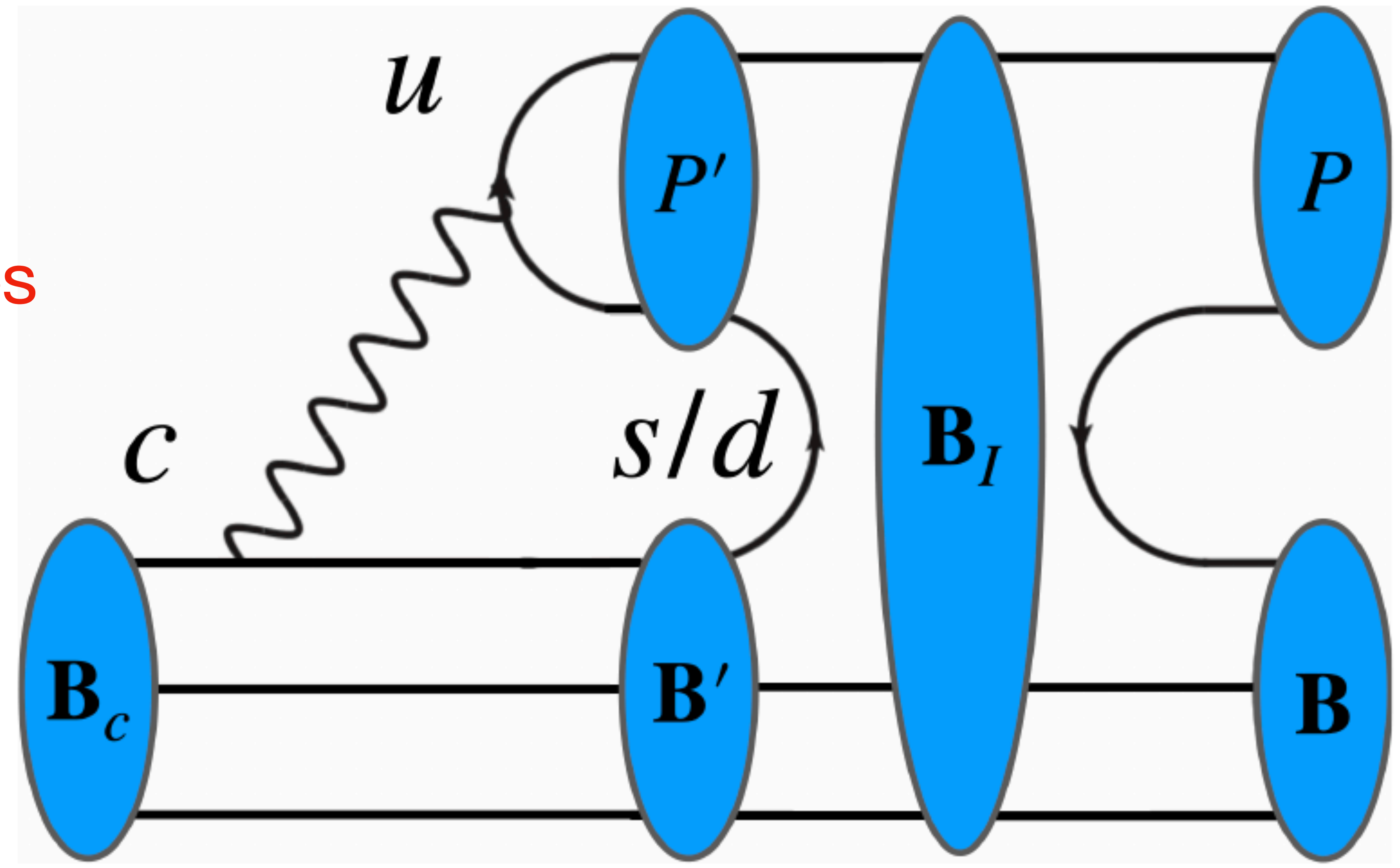
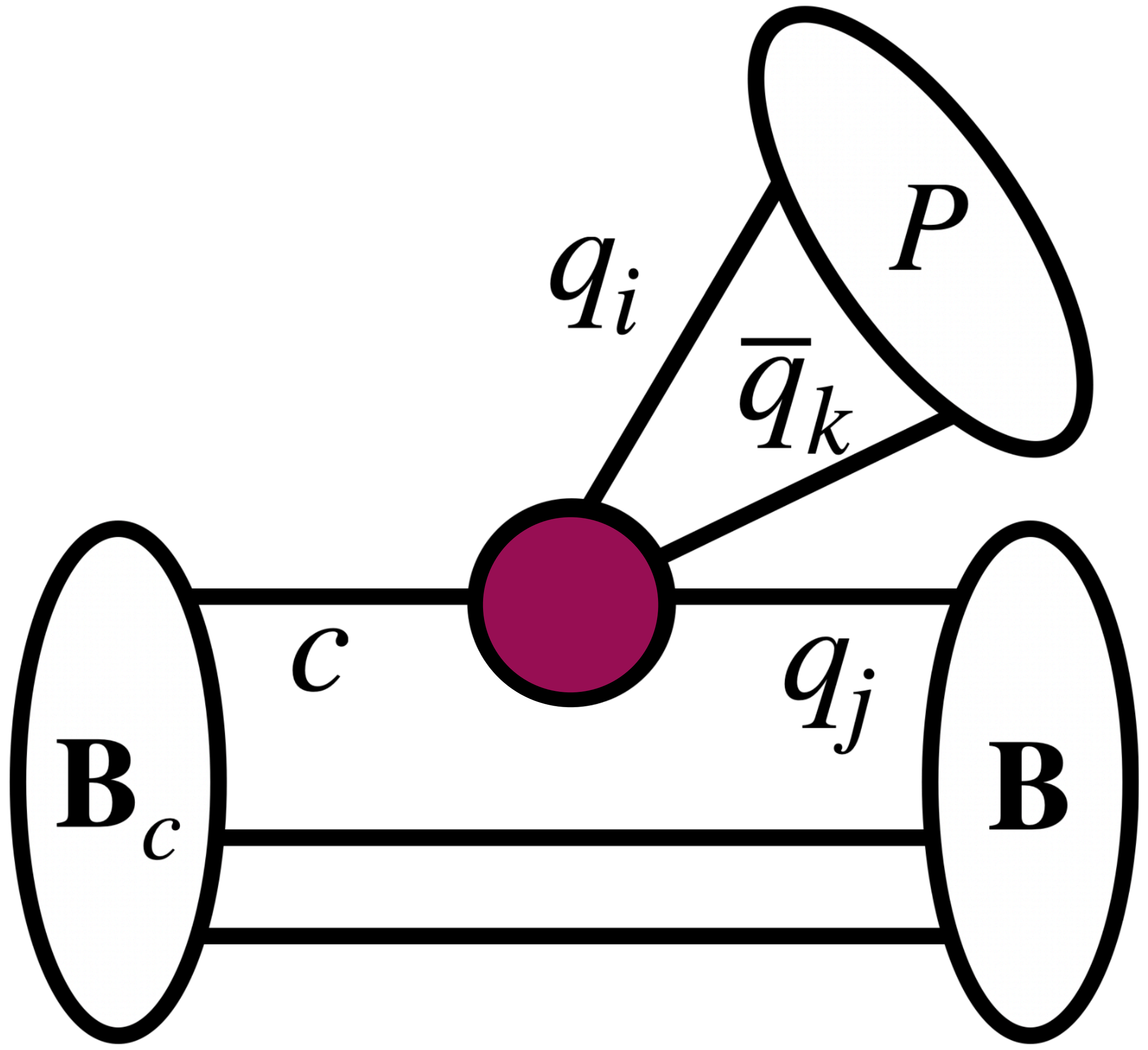
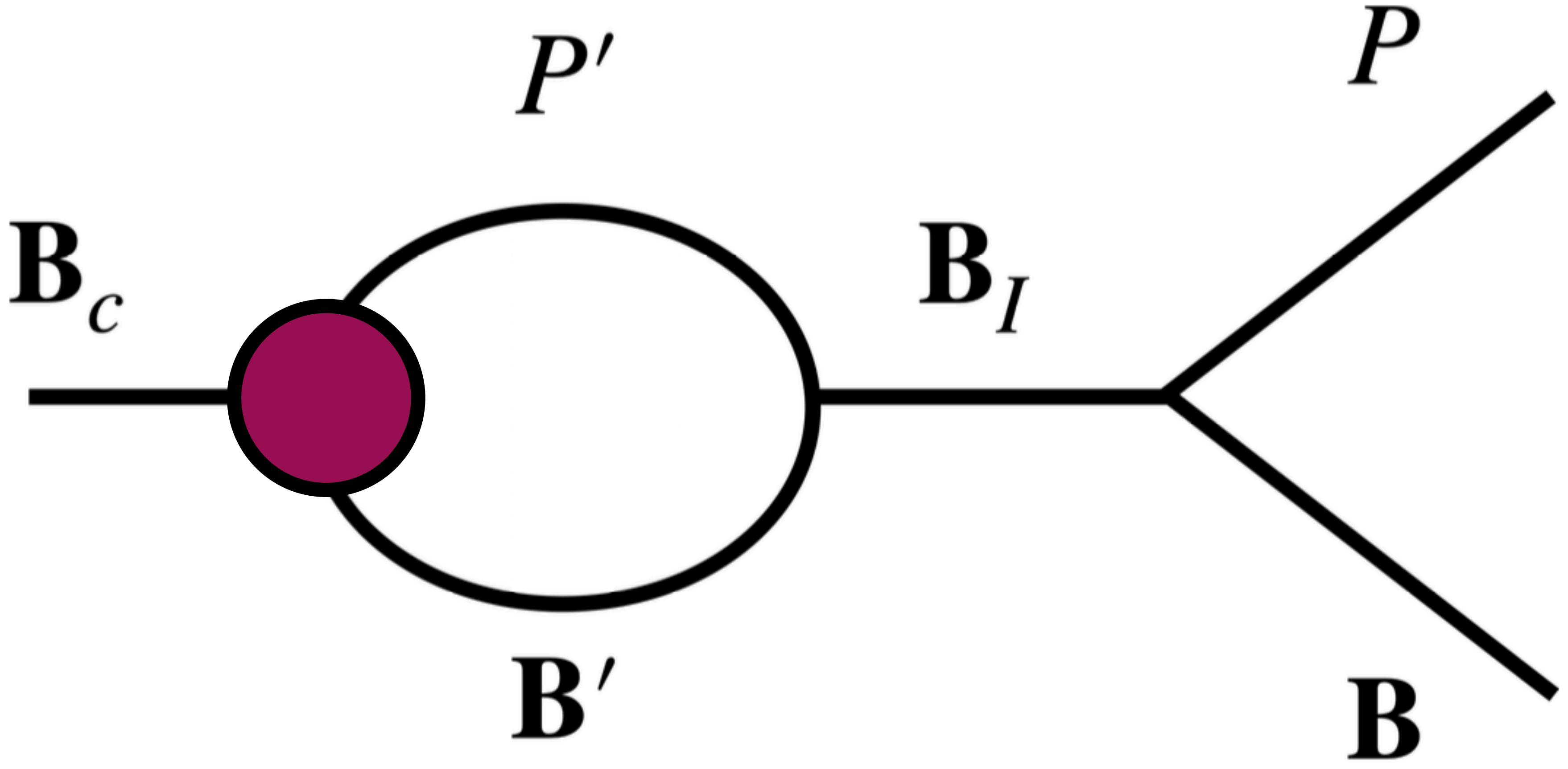
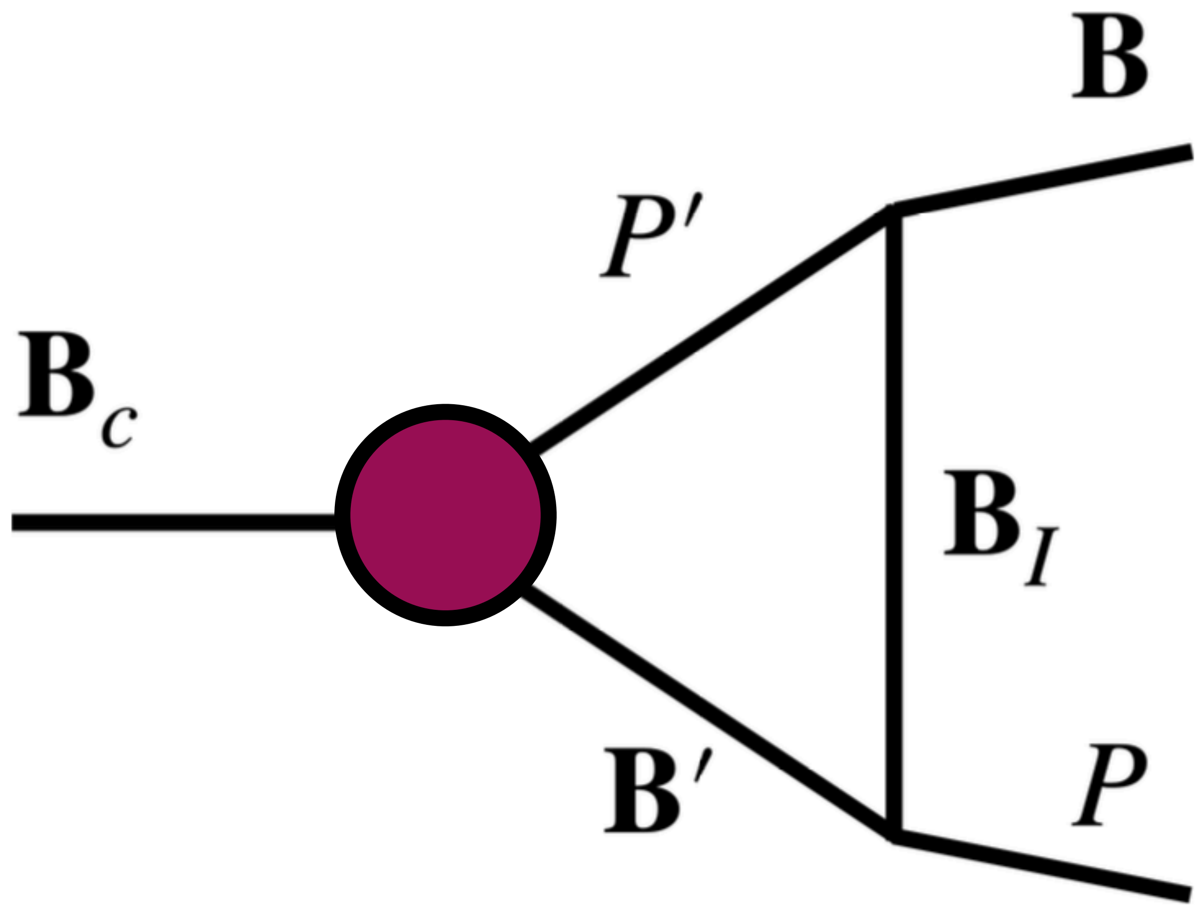


Rescattering, solving penguin/tree

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







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 !

SU(3) flavor perspective of charmed baryon decays

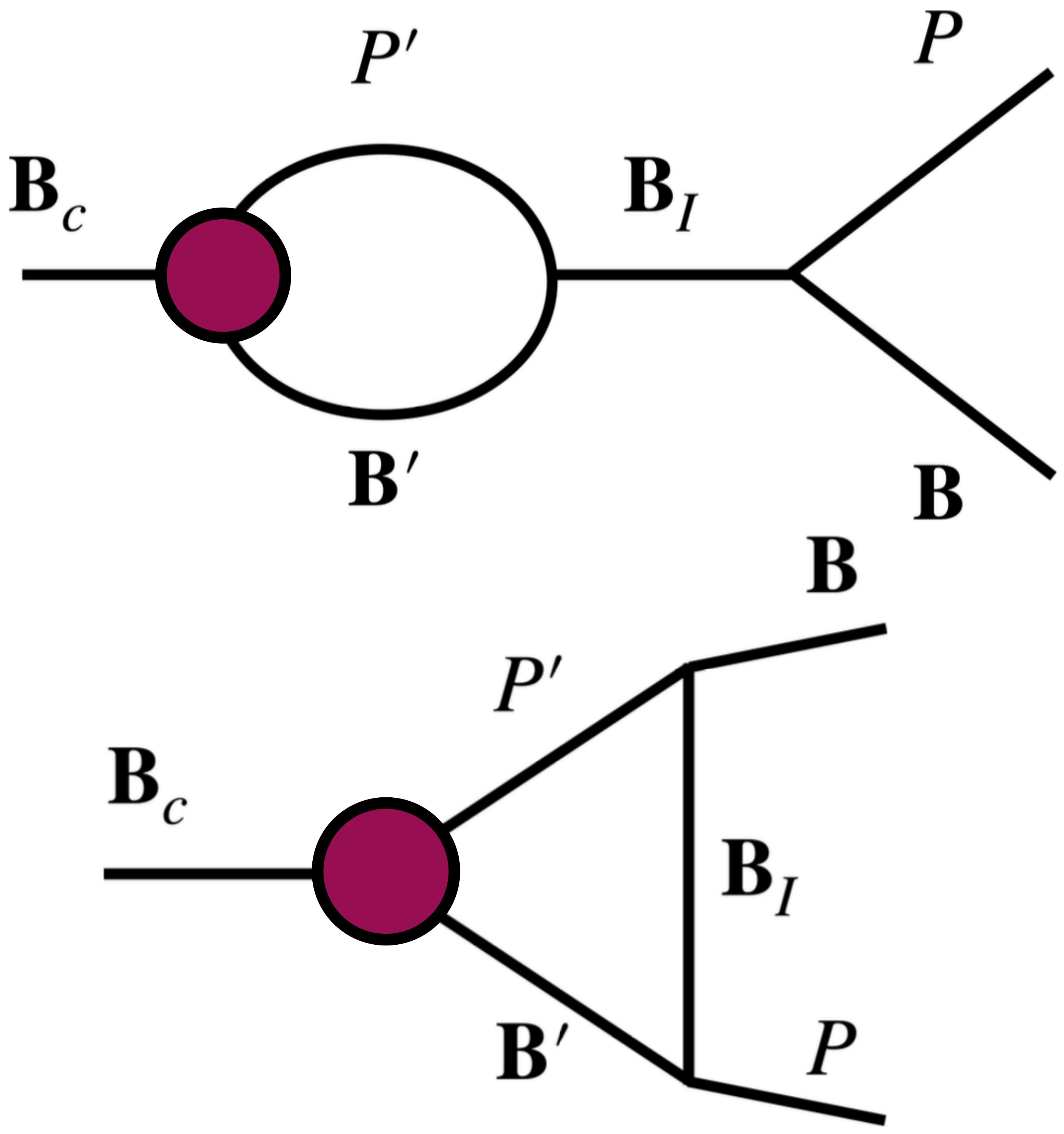
$$\text{Amplitude}: V_{cs}V_{us}^{*}\overbrace{F^{s-d}}^{4\ \text{parameters}}+V_{cb}V_{ub}^{*}\overbrace{F^{b}}^{3\ \text{parameters}}$$

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

We analyzed the $SU(3)_F$ structure of final state rescattering.

- The $SU(3)_F$ parameters ***acquire*** physical meanings.
- The relation between F^{s-d} and F^b is established.
- One can ***solve*** F^b with the input of F^{s-d}.

See 2408.14959 for direct calculations



Rescattering, numerical results

The sizes of CP violation are of the order $\mathcal{O}(10^{-4})$, in accordance with naive expectations.

Channels	$\mathcal{B}(10^{-3})$	$A_{CP}(10^{-3})$	$\alpha_{CP}(10^{-3})$
$\Lambda_c^+ \to \Sigma^+ K_S$	0.37(3)	0.29(3)	−0.22(4)
$\Lambda_c^+ \to \Sigma^0 K^+$	0.37(3)	0.29(3)	−0.22(4)
$\Lambda_c^+ \to p\pi^0$	0.20(3)	0.97(28)	0.99(13)
$\Lambda_c^+ \to n\pi^+$	0.72(7)	−0.21(13)	−0.43(16)
$\Lambda_c^+ \to \Lambda^0 K^+$	0.66(3)	−0.42(12)	0.29(8)
$\Xi_c^+ \to \Sigma^+ \pi^0$	2.34(13)	0.45(6)	−0.02(10)
$\Xi_c^+ \to \Sigma^0 \pi^+$	2.34(18)	0.28(6)	−0.38(10)
$\Xi_c^+ \to \Xi^0 K^+$	1.20(18)	1.11(17)	−0.08(22)
$\Xi_c^+ \to p K_S$	1.61(9)	−0.23(2)	0.19(3)
$\Xi_c^+ \to \Lambda^0 \pi^+$	0.95(12)	−0.35(5)	0.22(6)

Channels	$\mathcal{B}(10^{-3})$	$A_{CP}(10^{-3})$	$\alpha_{CP}(10^{-3})$
$\Xi_c^0 \to \Sigma^+ \pi^-$	0.23(2)	1.78(25)	−0.45(46)
$\Xi_c^0 \to \Sigma^0 \pi^0$	0.46(2)	0.36(9)	−0.39(7)
$\Xi_c^0 \to \Sigma^- \pi^+$	1.62(6)	0.36(3)	−0.09(3)
$\Xi_c^0 \to \Xi^0 K_S$	0.33(5)	0.31(7)	0.43(6)
$\Xi_c^0 \to \Xi^- K^+$	0.86(8)	−0.46(4)	0.03(3)
$\Xi_c^0 \to p K^-$	0.27(3)	−1.50(25)	0.66(39)
$\Xi_c^0 \to n K_S$	0.50(2)	−0.43(4)	0.28(8)
$\Xi_c^0 \to \Lambda^0 \pi^0$	0.16(2)	−0.02(5)	0.40(4)

Large CP violation is found !

$$A_{CP} = \frac{\Gamma - \overline{\Gamma}}{\Gamma + \overline{\Gamma}}\,, \qquad A_{CP}^{\alpha} = \frac{1}{2}\left(\alpha + \overline{\alpha}\right).$$

Rescattering, numerical results

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

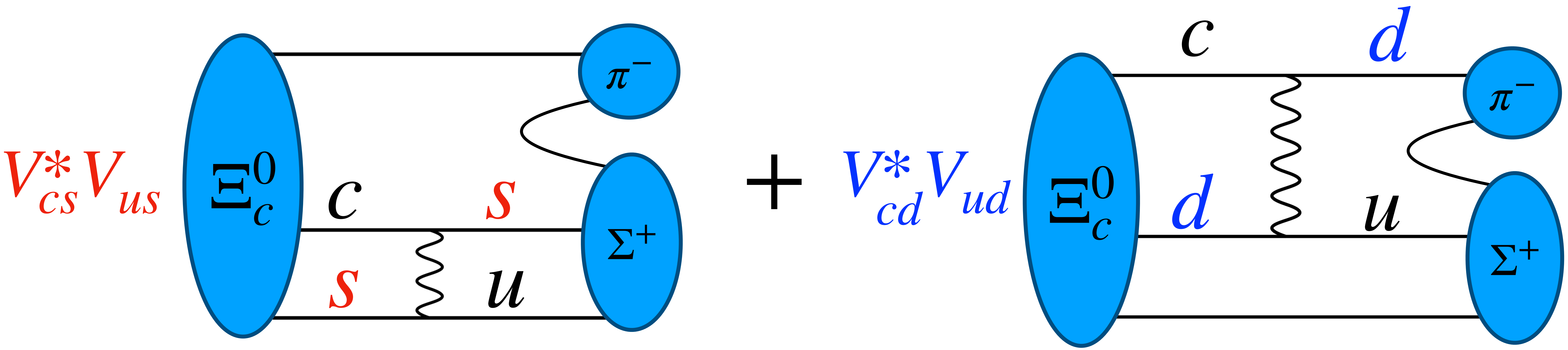
$$A_{CP}\left(\Xi_c^0 \to \Sigma^+\pi^-\right) = (1.78 \pm 0.25) \times 10^{-3}$$

$$A_{CP}\left(\Xi_c^0 \to pK^-\right) = (-1.50 \pm 0.25) \times 10^{-3}$$

- 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 $A_{CP} \sim \left| 2\mathrm{Im}(V_{cs}^* V_{us} / V_{cd}^* V_{ud}) \right| \sim 10^{-3}$.

12th International Workshop on Charm Physics

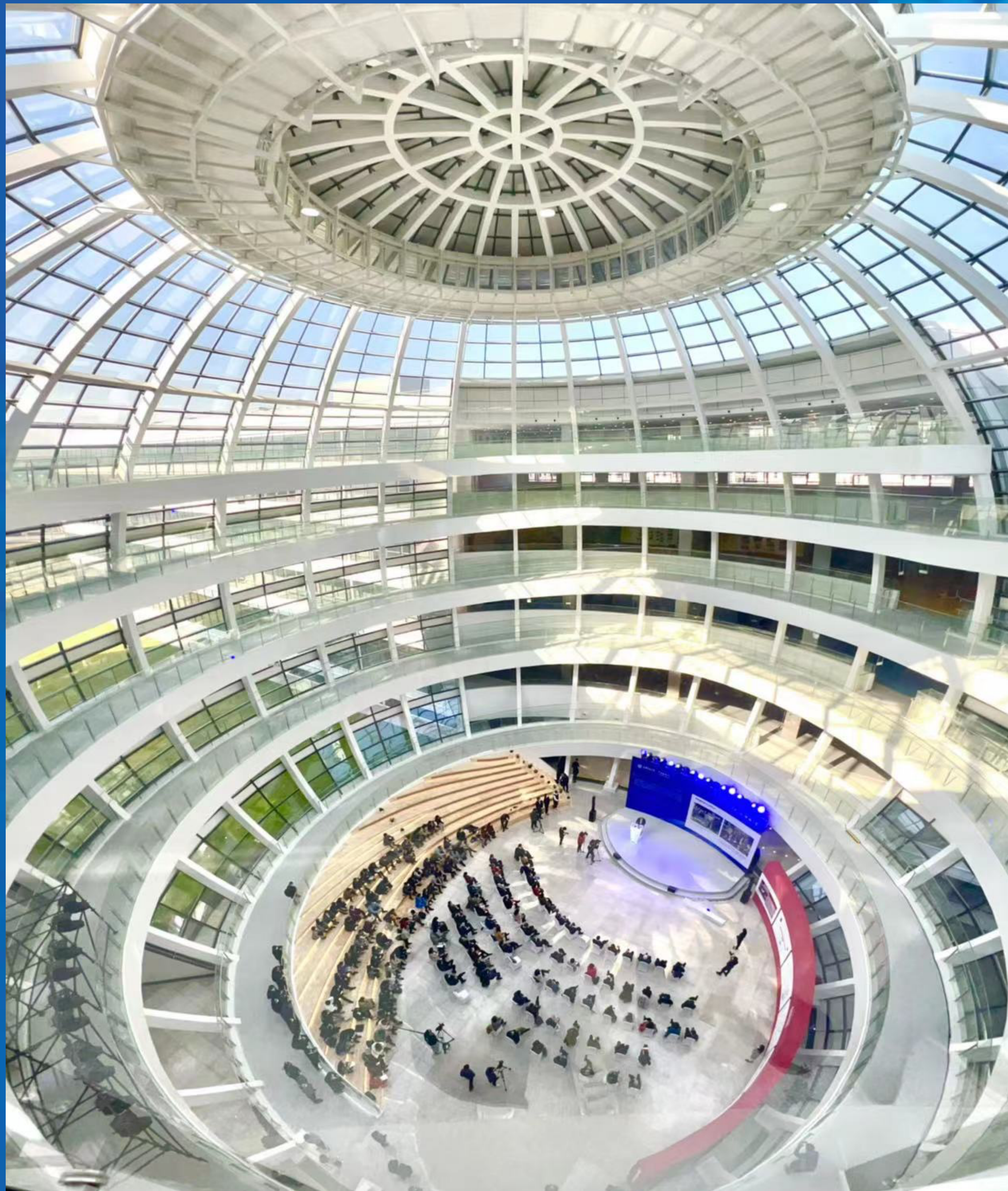
12–16 MAY 2025

TSUNG-DAO LEE INSTITUTE, SHANG HAI

李政道研究所
TSUNG-DAO LEE INSTITUTE

TOPICS:

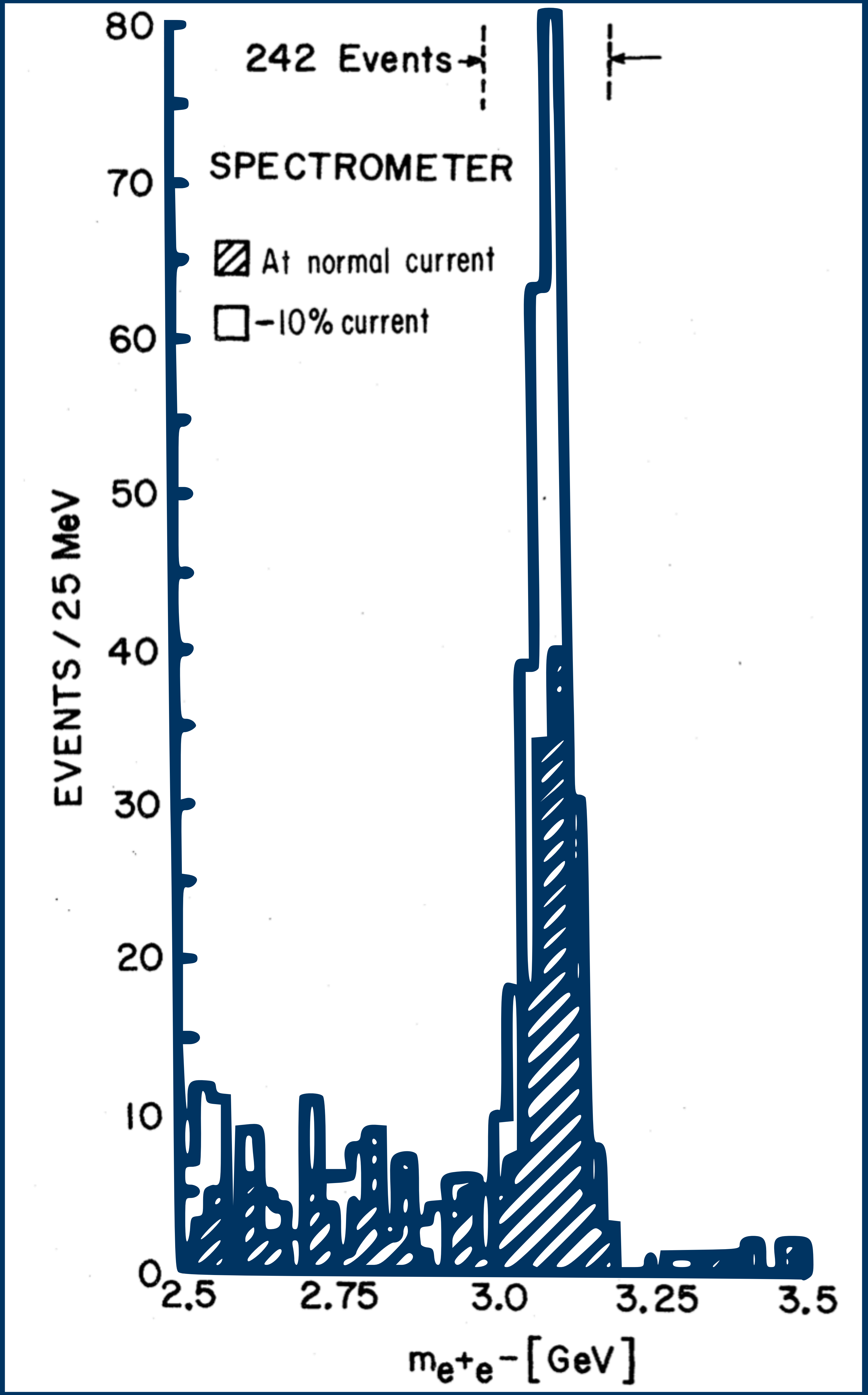
- D mixing and charm hadron lifetime
- Leptonic, semileptonic rare charm decays
- Hadronic charm decays and CP-violation
- Charm hadron spectroscopy and exotic hadrons
- Production of charm and charm in media
- Rare charm decays and new physics
- Charm on the lattice
- Tau lepton physics
- Charm facilities - Status and future



Conclusions

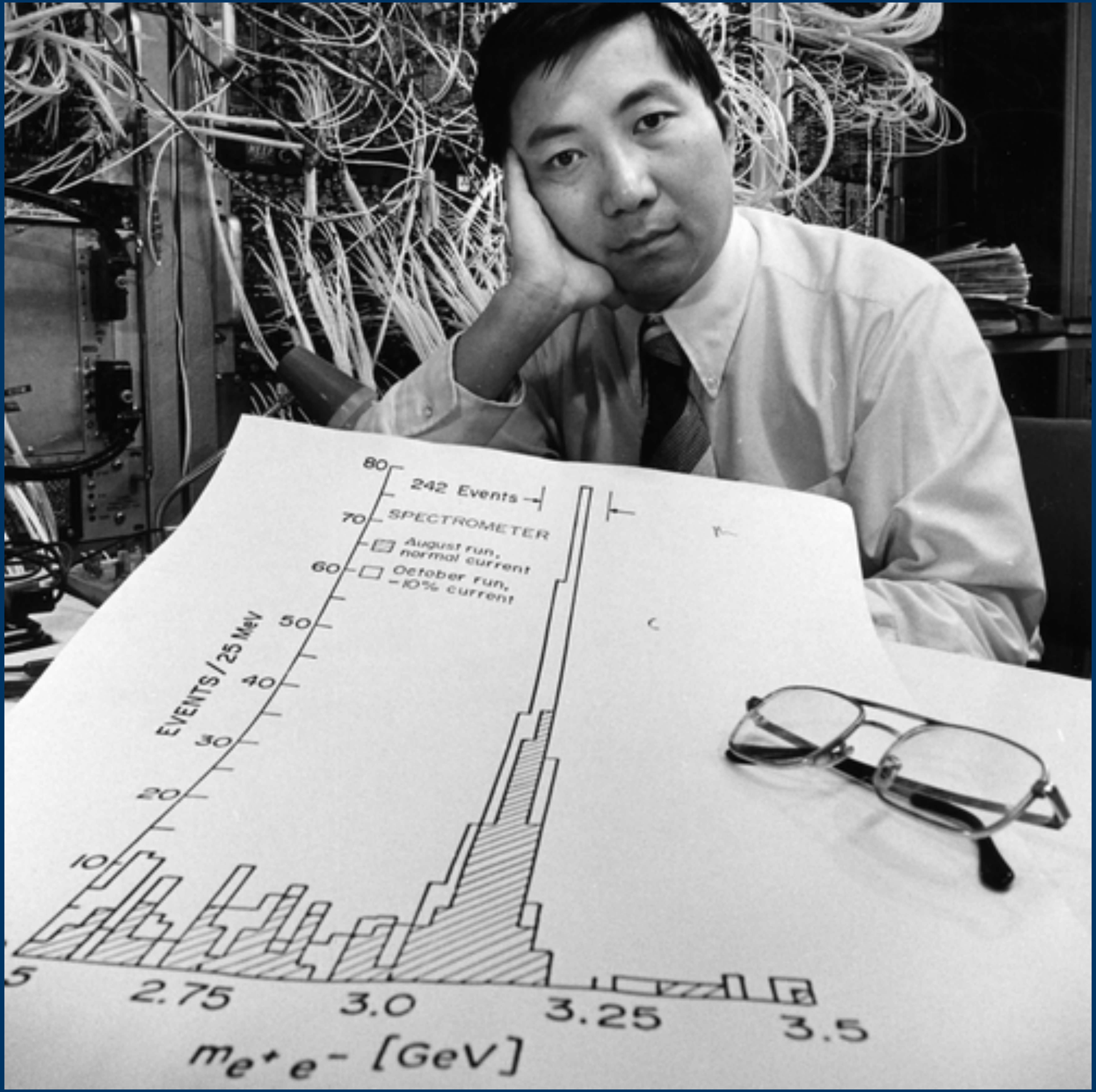
More measurements!

More theoretical studies!



Discovery of J over 50 years

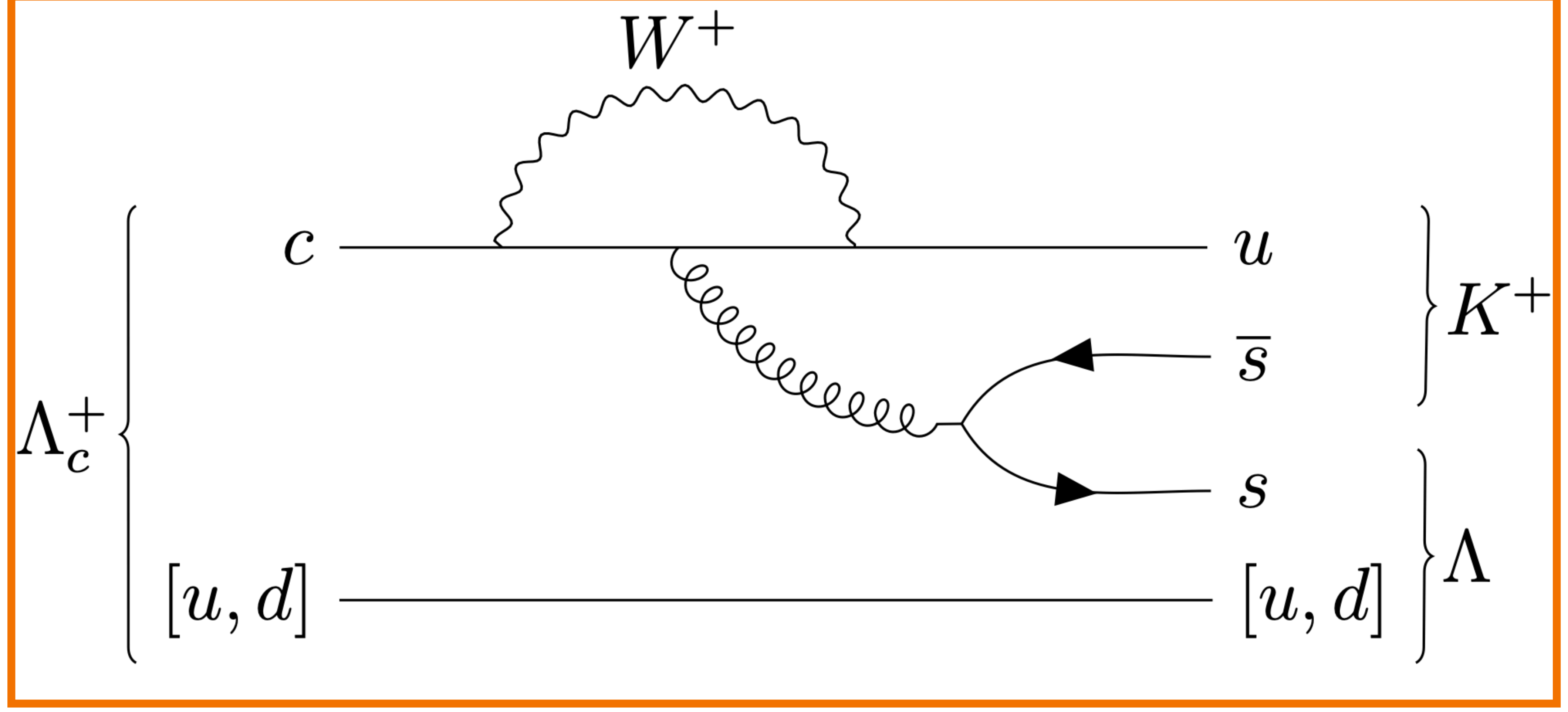
Backup slides



- **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%



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

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

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

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

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

$$\tilde{f}_{\mathbf{3}}^d = \frac{r_-(7r_- - 2)}{8 + 2r_-}\tilde{S}^- - \sum_{\lambda=\pm} \frac{1}{2}(r_\lambda + 1)^2\tilde{T}_\lambda^- - \frac{1}{4}\left(\tilde{F}_V^+ + 2\tilde{F}_V^-\right)$$

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

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

PRD **100**, 093002 (2019)

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

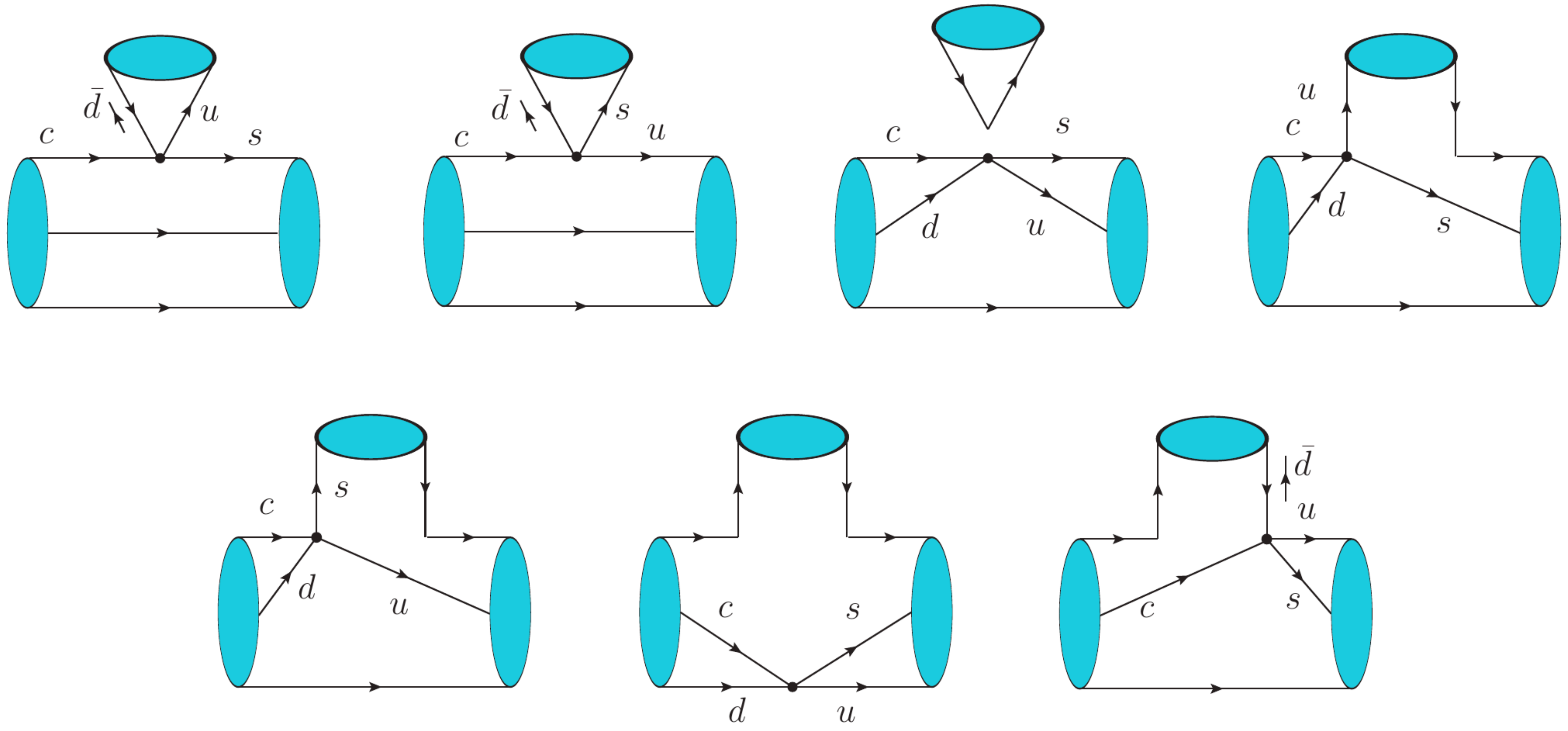
Rescattering, solving penguin/tree

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

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

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

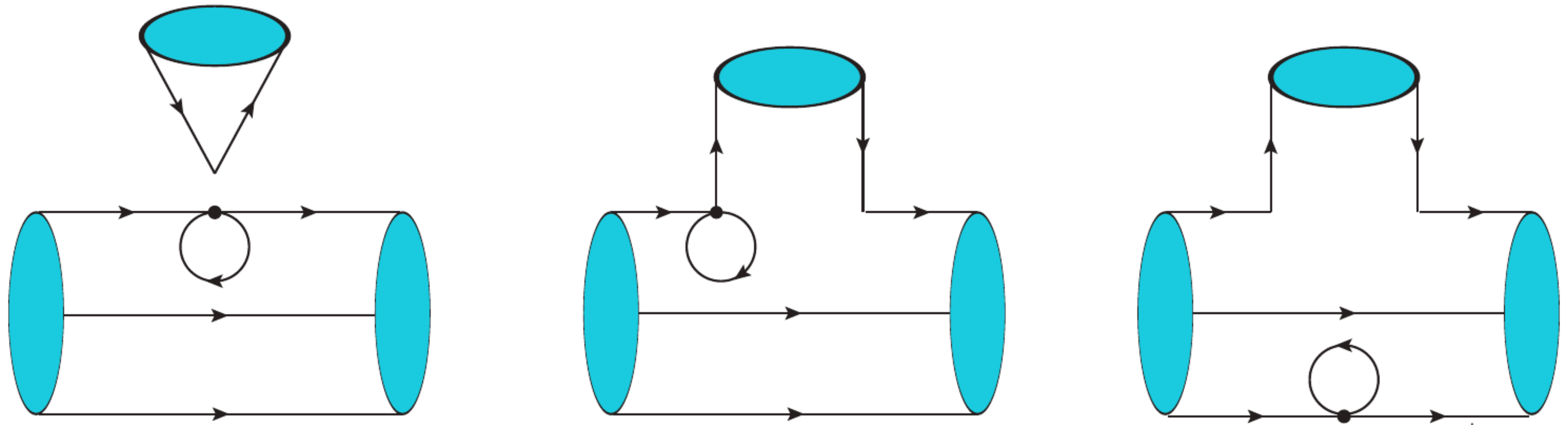
$$\tilde{f}^d = \tilde{F}_V^- + \sum(2r_\lambda^2 - 2r_\lambda - 4)\tilde{T}_\lambda^- \,, \quad \tilde{f}^e = \tilde{F}_V^+$$



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

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

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



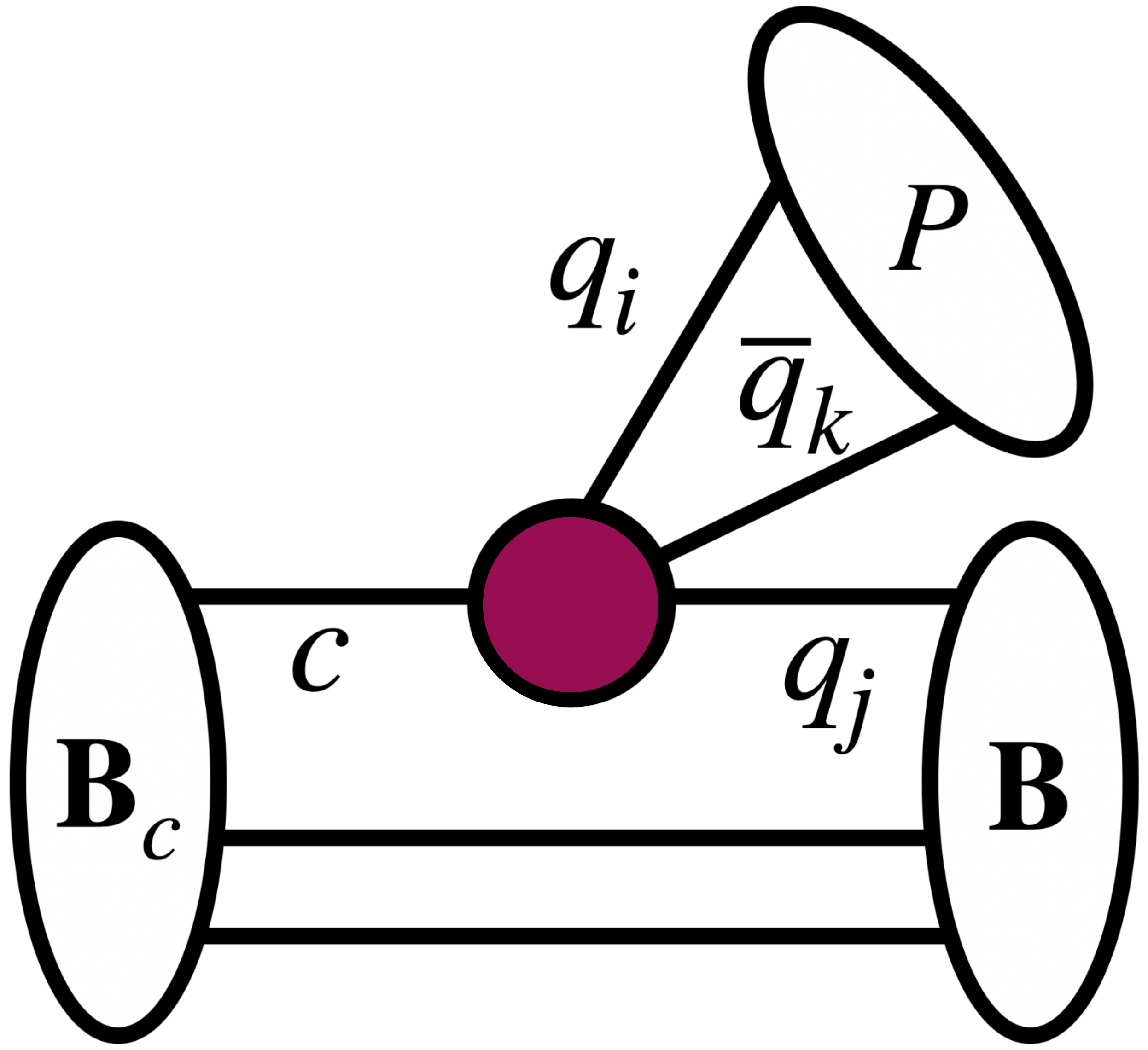
$$\left(\tilde{f}^b, \tilde{f}^c, \tilde{f}^d, \tilde{f}^e\right) \longleftrightarrow \left(\tilde{F}_V^+, \tilde{F}_V^-, \tilde{S}^-, \tilde{T}^-\right) \longrightarrow \left(\tilde{f}_{\mathbf{3}}^b, \tilde{f}_{\mathbf{3}}^c, \tilde{f}_{\mathbf{3}}^d\right)$$

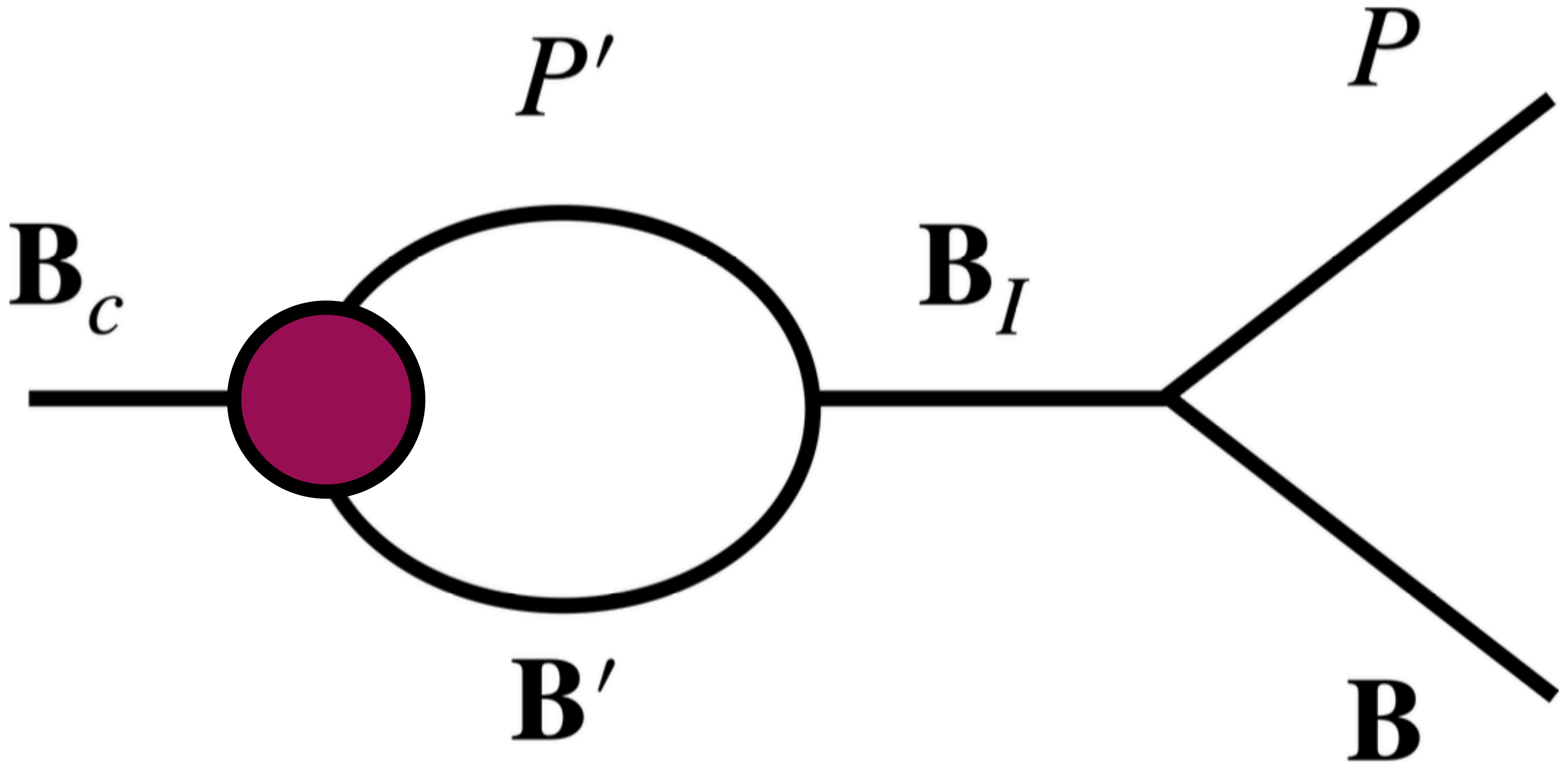
PRD **100**, 093002 (2019)

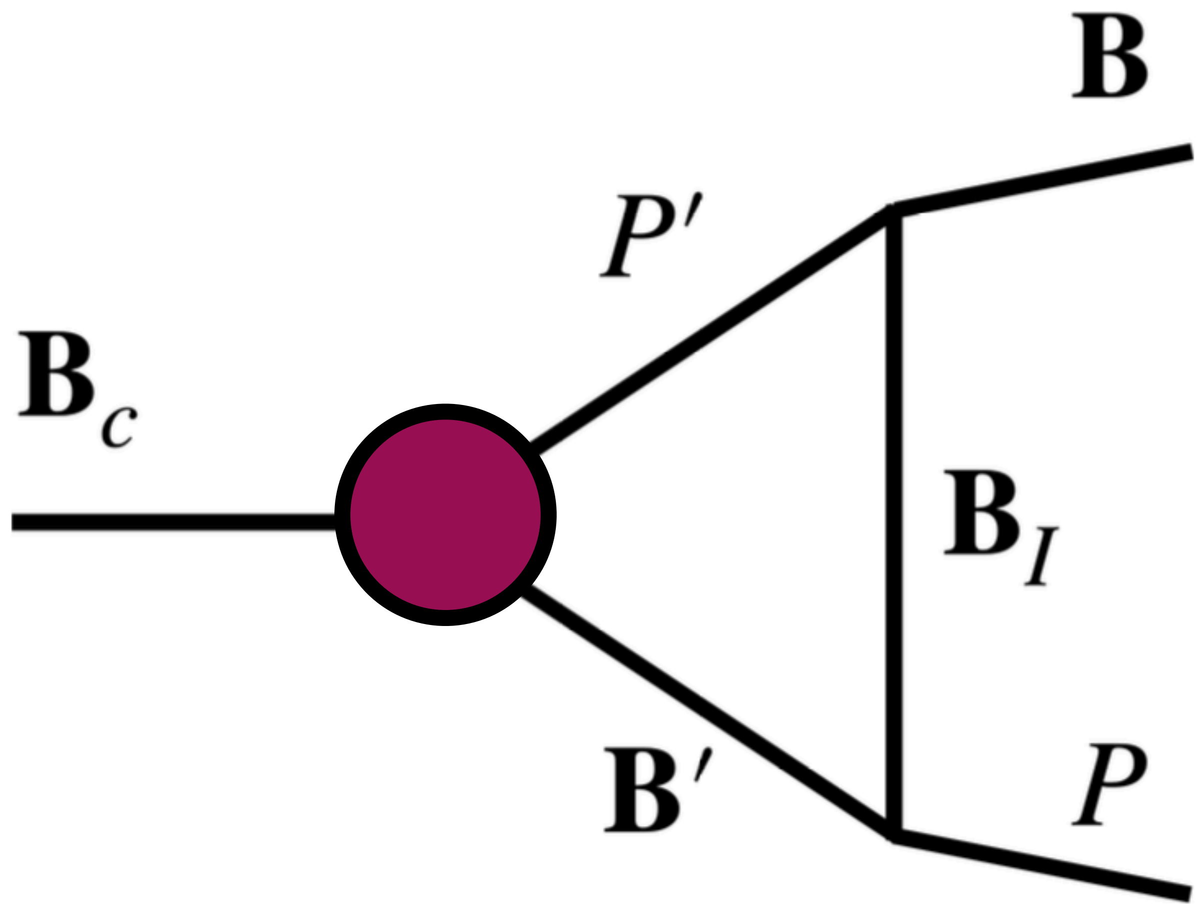
Much more complicated compared to $P^{LD} = E$ in *D* mesons !

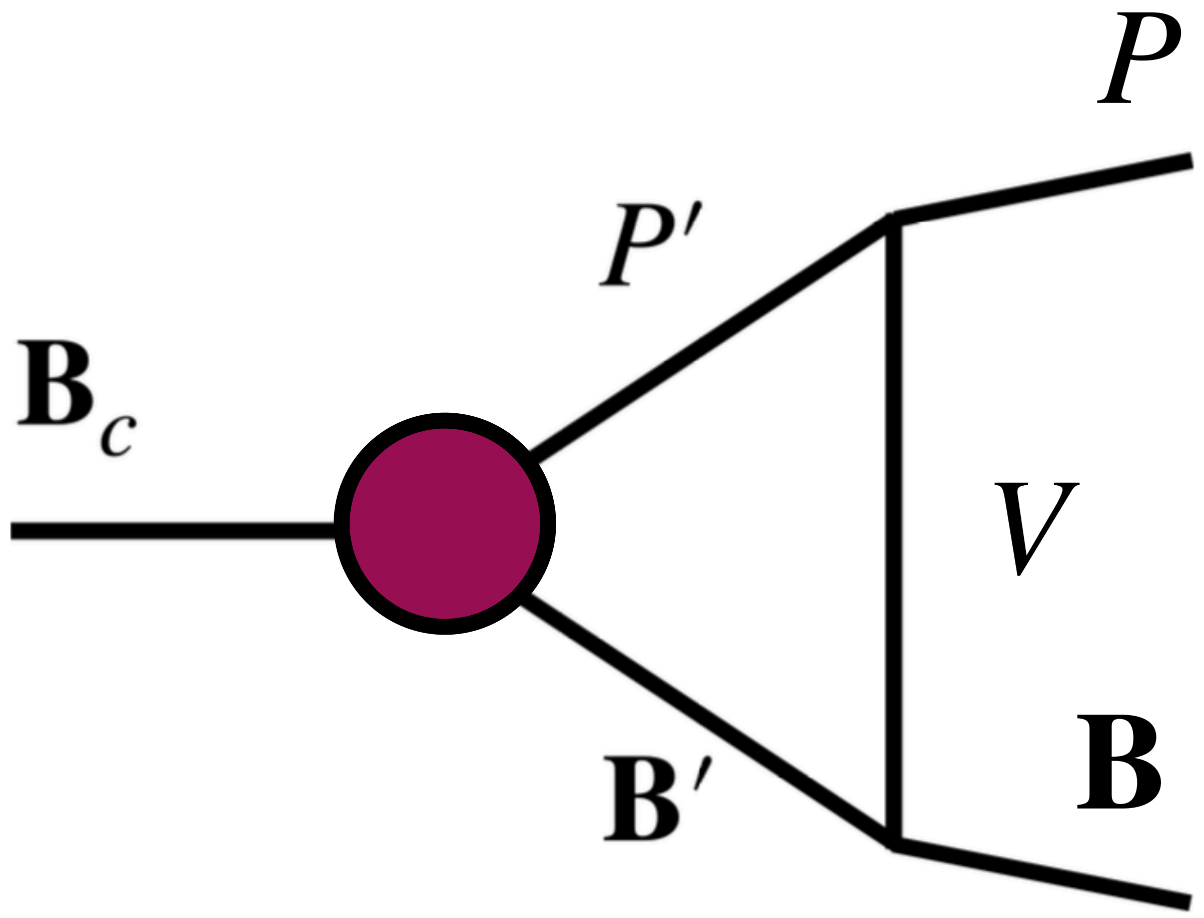
- **Rescattering, solving penguin/tree**

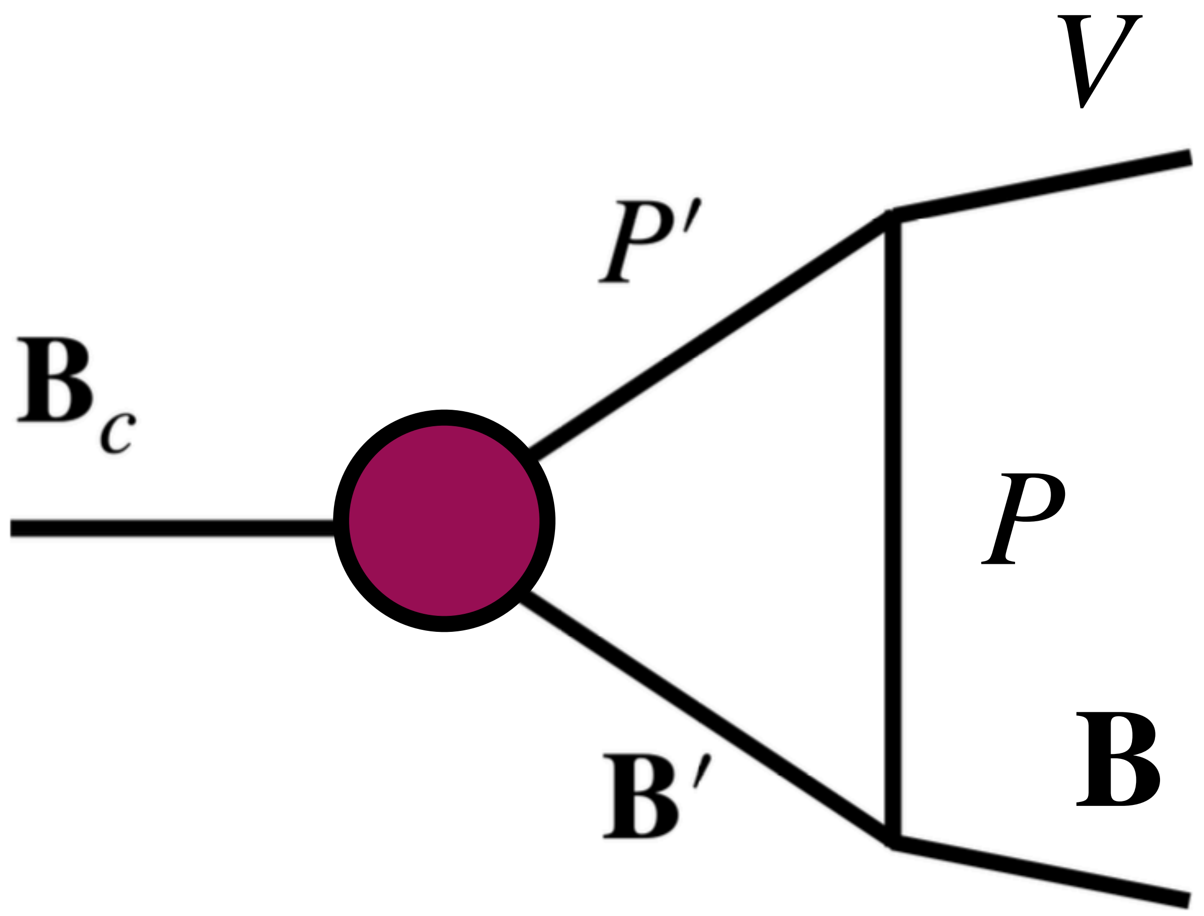
$$\mathscr{L}_{\mathbf{B}_c\mathbf{B}P} = \mathscr{L}^{\mathrm{Tree}}_{\mathbf{B}_c\mathbf{B}P} + \mathscr{L}^{\mathrm{FSR-s}}_{\mathbf{B}_c\mathbf{B}P} + \mathscr{L}^{\mathrm{FSR-t}}_{\mathbf{B}_c\mathbf{B}P} + \mathscr{L}^{\mathrm{FSR-u}}_{\mathbf{B}_c\mathbf{B}P} + \ldots(?)$$



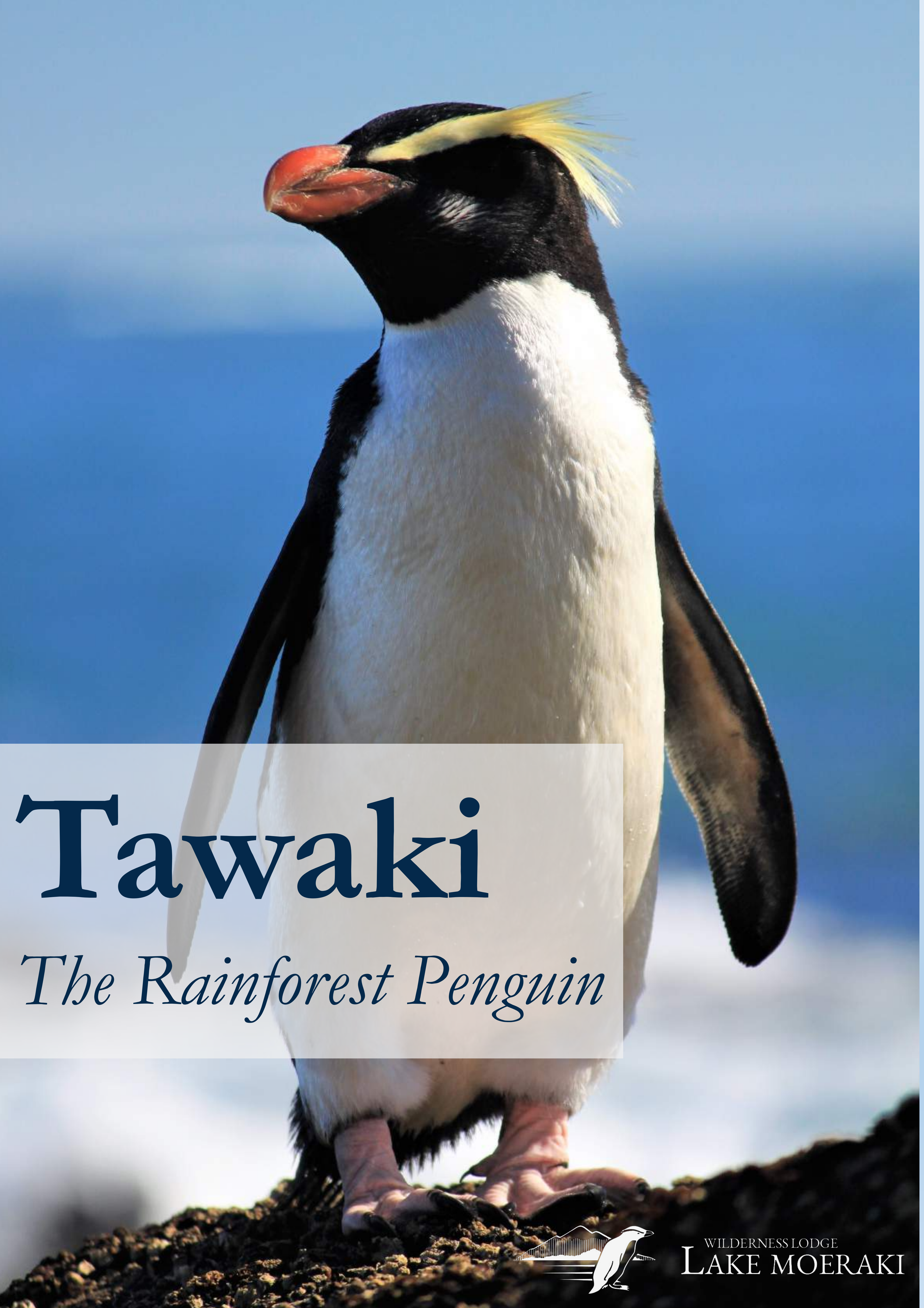








$\ldots(?)$



Tawaki

The Rainforest Penguin

WILDERNESS LODGE
LAKE MOERAKI

WILDERNESS LODGE
LAKE MOERAKI

Tawaki: A Wildlife Treasure

Tawaki breed in jungle-like temperate rainforest along the rugged Lake Moeraki coastline. To see tawaki on wilderness beaches is one of New Zealand's great wildlife experiences.

The Rainforest Penguin

Tawaki, or the Fiordland Crested Penguin (*Eudyptes pachyrhynchus*), are unique among penguins.

They breed in temperate rainforest, only in the southwest corner of New Zealand. During the July to December breeding season they are most easily seen along the Lake Moeraki coastline.

Tawaki build their nests beneath logs and boulders. These will be deep in the forest, often hundreds of metres inland and up steep hillsides.

Adults must negotiate the pounding surf, wild beaches and dense undergrowth as they make their way between the Tasman Sea and their rainforest nests.

Guided Penguin Trips

Since 1989 Wilderness Lodge Lake Moeraki has taken guests to see tawaki under a special license from the Department of Conservation.

Our guides are experts in penguin ecology and delight in sharing this once in a lifetime experience with guests.

Hike through lush rainforest to a wilderness beach then sit quietly as penguins emerge from the surf and make their way across the beach and into the rainforest.

Guided penguin trips last about 3 hours, include light refreshments and require a low to moderate level of fitness. Group sizes are always kept small.

wildernesslodge.co.nz

Tawaki Facts

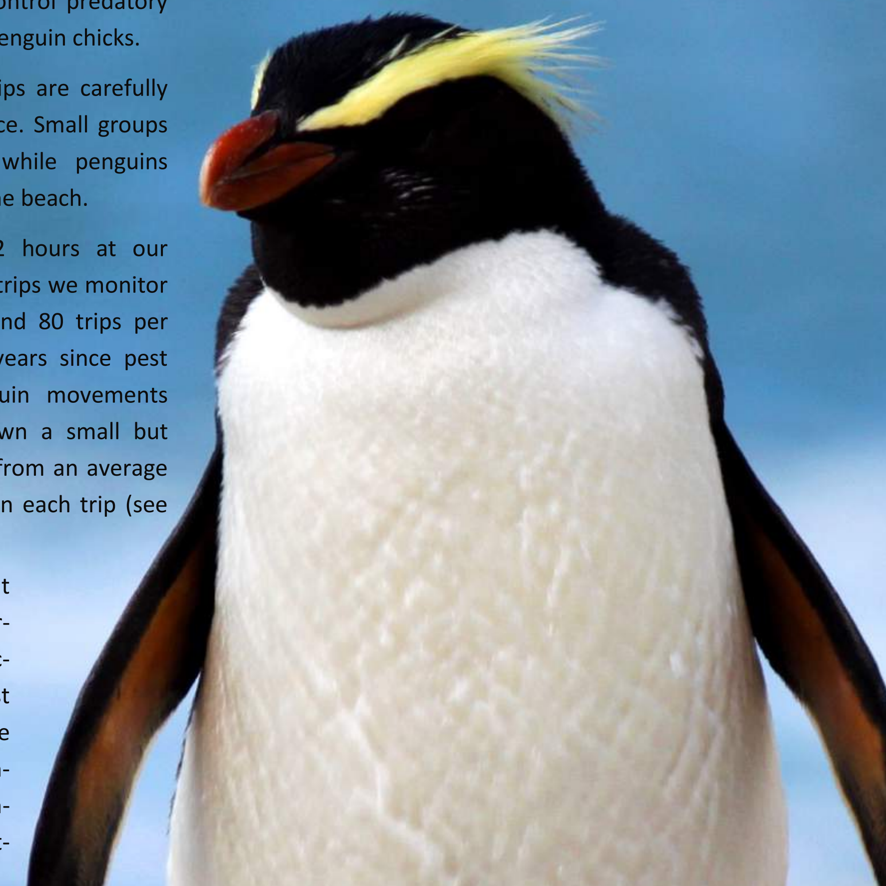
- Tawaki are the world's only penguin to breed in temperate rainforest.
- They stand 60cm tall (2 ft) and weigh approx. 4kg.
- Females lay two eggs each year but only chick is ever feed. This chick grows quickly while the other generally won't survive more than a few days.
- The breeding season runs between July and early December. Outside of this period tawaki are at sea, fishing and sleeping on the surface of the ocean.
- The main threats to tawaki are domestic dogs, introduced stoats (weasel family) and disturbance.

WILDERNESS LODGE
LAKE MOERAKI

Tawaki Conservation

Wilderness Lodge has worked to conserve Tawaki. We campaigned to establish and enforce a Wildlife e penguins to stop people taking dogs into the colonies where they would attack and kill penguins.

e have championed extensive aerial pest control programme by the Conservation Department on the coastline to control predatory s that also kill penguin chicks.



ded penguin trips are carefully avoid disturbance. Small groups nd discreetly while penguins turally across the beach.

ends around 2 hours at our As part of our trips we monitor bers with around 80 trips per r the last 20 years since pest ed here, penguin movements each have shown a small but rease growing from an average enguins seen on each trip (see

couraging result g term monitor- ki breeding suc- n stark contrast strophic decline Yellow Eyed pen- on on the south- h Island coast-