Charming Opportunities in CP violation

PRD 109, L071302 (2024), arXiv:2404.19166

Collaborators:耿朝强、何小刚、靳湘楠、杨畅

劉 佳 韋

TDLI

Oct. 28, 2024

HFCPV

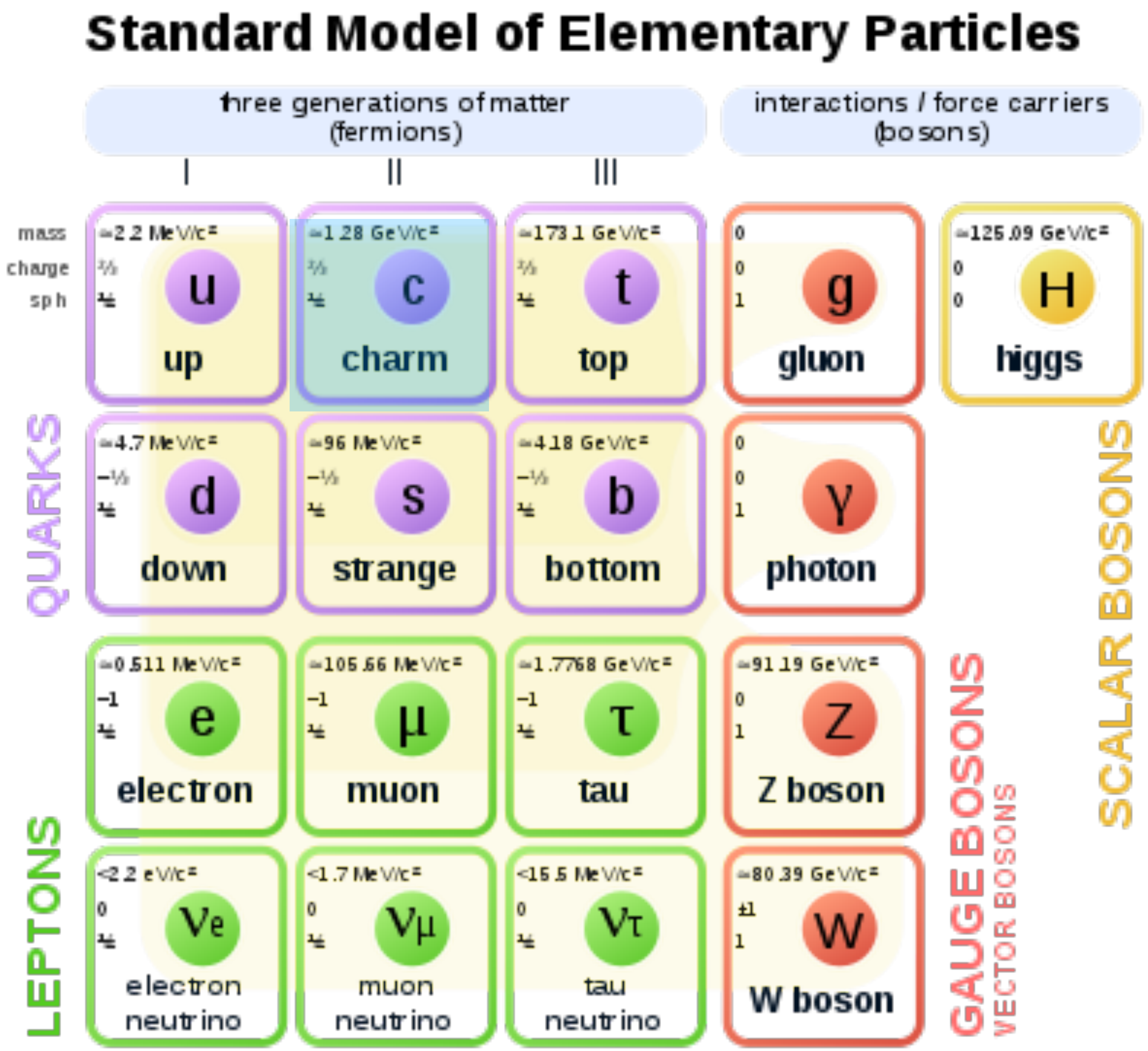
Histories of Charm Quark - November revolution

A discovery of extremely massive, narrow and high pyramid.

Charm

China element

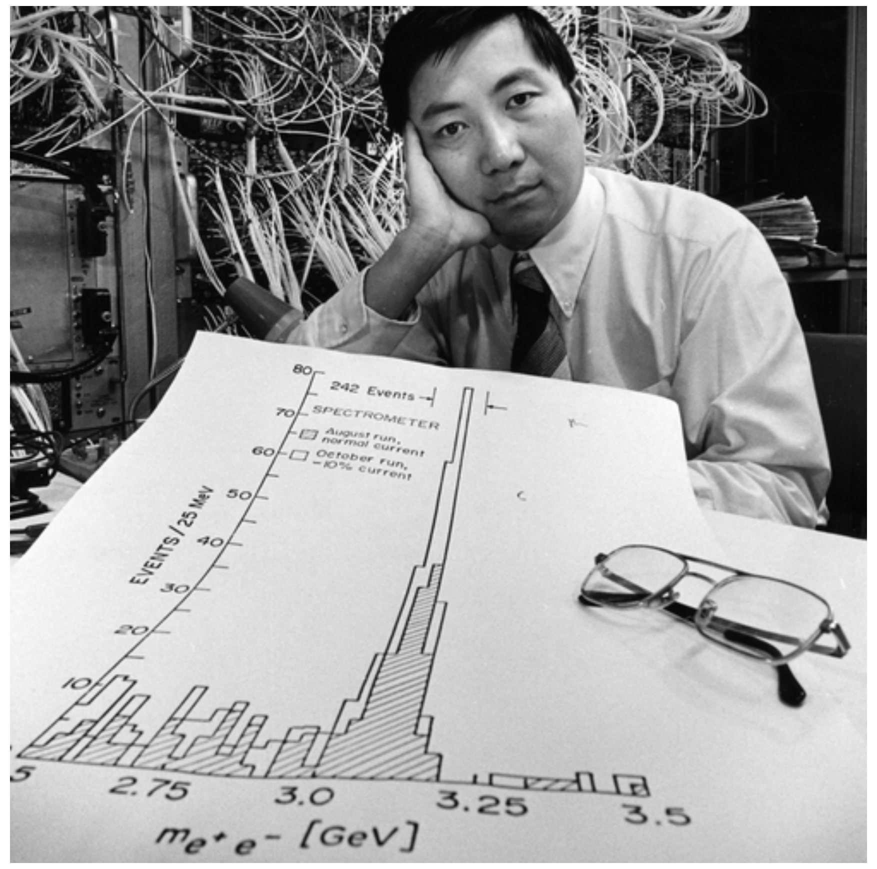
中国元素



A. Khare, ``The November J/ψ revolution: Twenty five years later,''
Curr. Sci. 77, 1210 (1999)

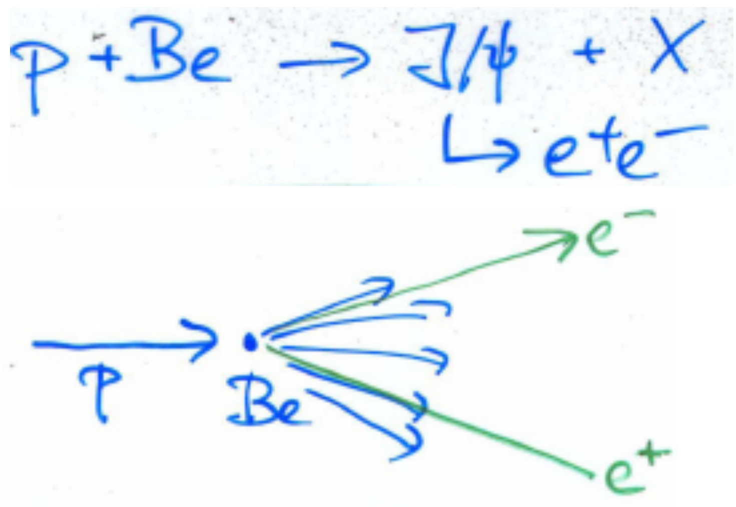
Scanning energies from 2~4 GeV for two weeks Aug. 22, 1974

At the East coast of US: Received by PRL on Nov. 12, 1974



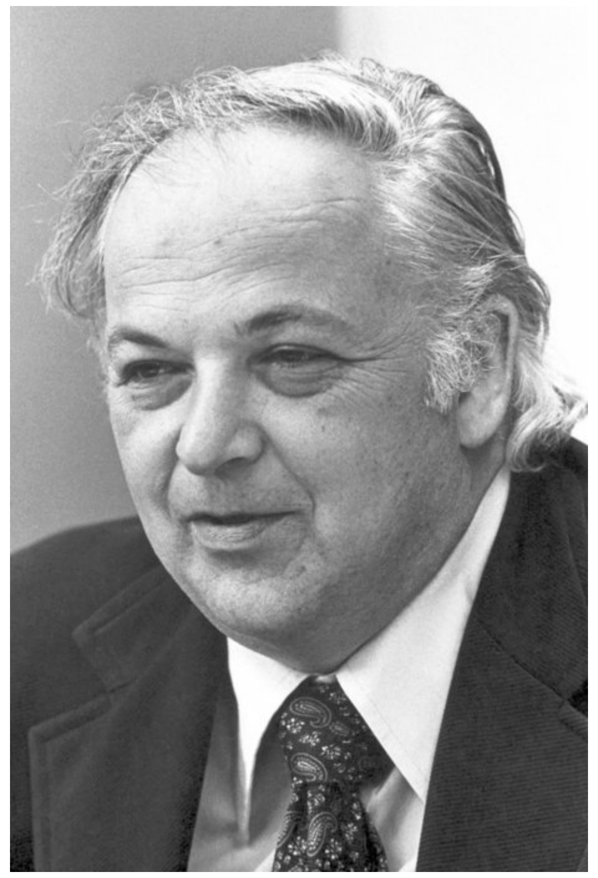
丁肇中

Brookhaven (Proton Synchrotron)



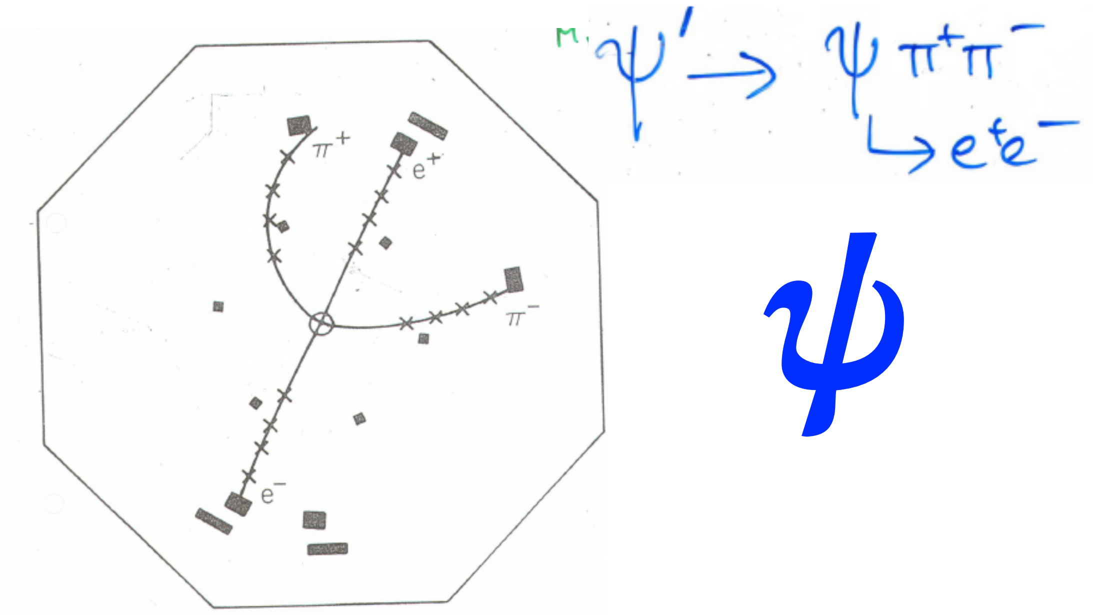
Adjusted the machine to 3.1 GeV Nov. 9, 1974

At the West coast of US: Received by PRL on Nov. 13, 1974



Burton Richter

SLAC (e^+e^- storage ring at 4.5-6 GeV)



Slide from Pro. Chaoqiang Geng


MATTER–ANTIMATTER
IN THE UNIVERSE

Charming physics - CP violation

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

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

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

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

  Factorization with fitted hadron matrix element.

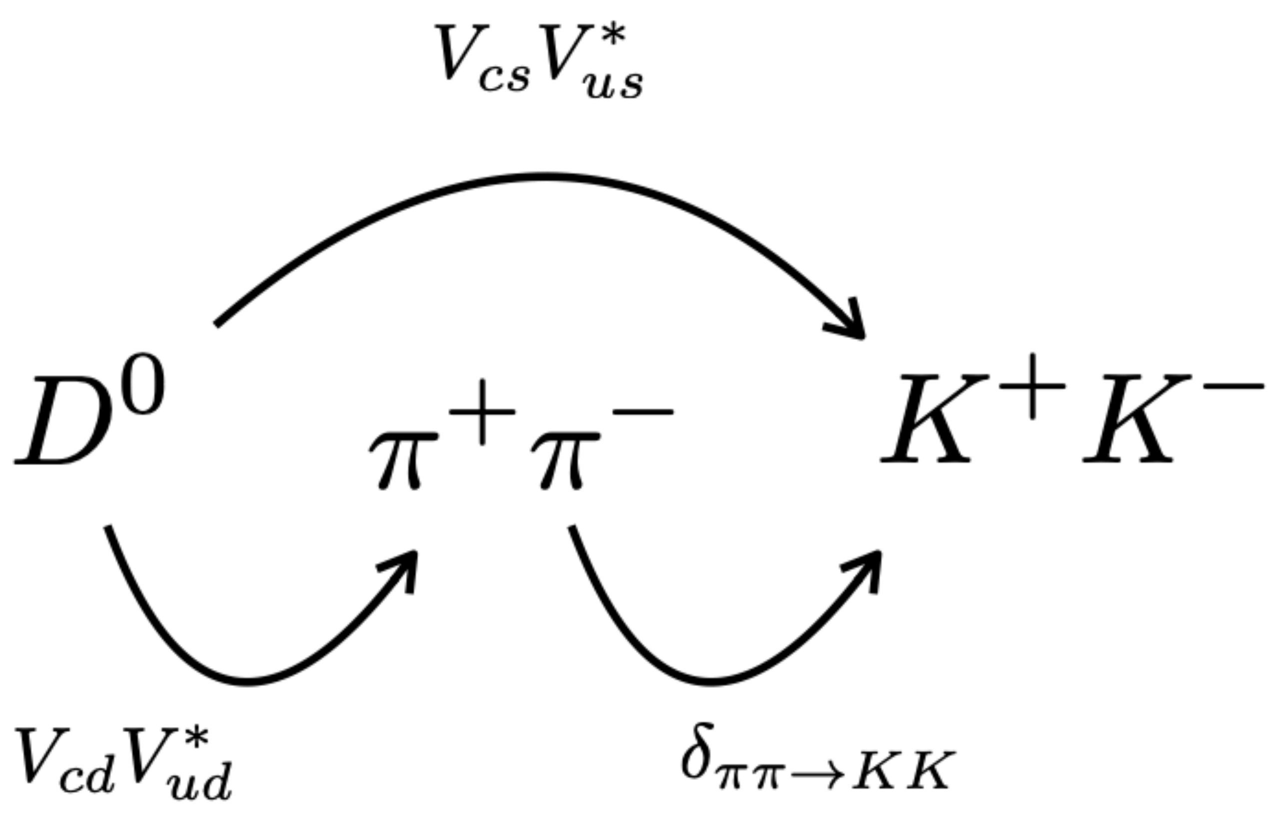
  李湘楠、吕才典、于福升, PRD **86**, 036012 (2012).

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

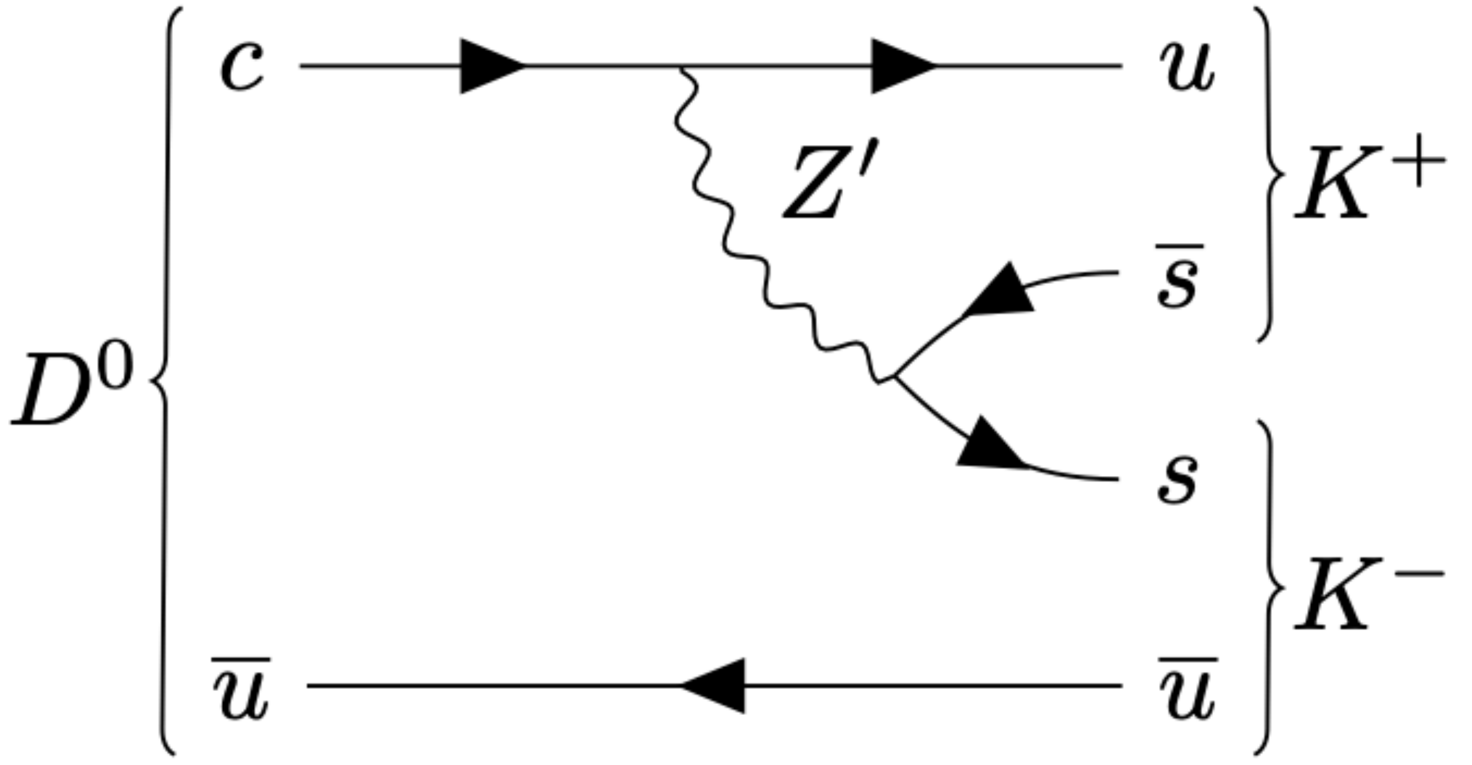
  鄭海揚、蔣正偉, PRD **86**, 014014 (2012); PRD **109**, 073008 (2024).

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

  I. Bediaga et al., PRL **131**, 051802 (2023).



- SM ***naively*** predicts $a_{CP}^{\pi\pi} = -a_{CP}^{KK}$ but two of them are found to be in the same sign !



PRD **108**, 035005 (2023)

• Charming physics - CP violation

Reasons to go **beyond** charmed mesons:

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

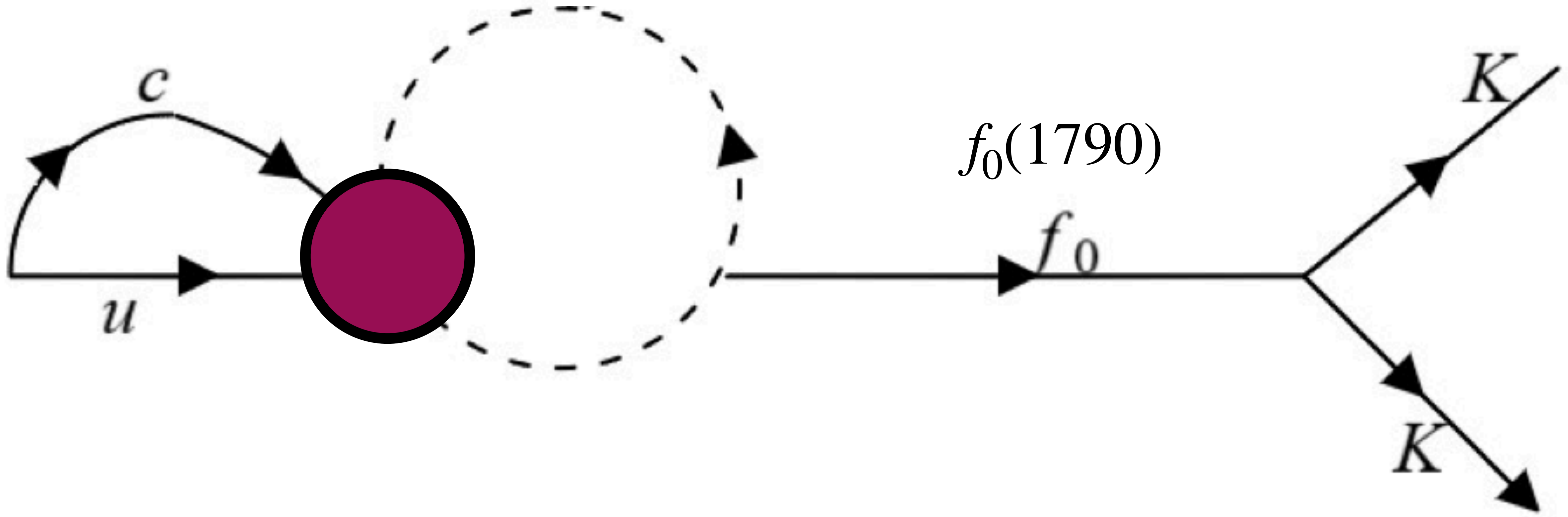
PHYSICAL REVIEW D **81,** 074021 (2010)

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)



$$a_{CP}^{\pi\pi} \sim 2\mathrm{Im}\left(\frac{V_{cs}V_{us}^*}{V_{cd}V_{ud}^*}\right)\left|\frac{\text{Penguin}}{\text{Tree}}\right| \sin\delta_{QCD}$$

1. f_0 might be a **glueball** which mainly decays to kaons. LO amplitude $\propto m_q$.
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.

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***!

Last month: Measurements of ***strong phases*** in $\Lambda_c^+ \to \Lambda\pi^+, \Lambda K^+$ arXiv:2409.02759 [hep-ex]

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

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

• SU(3) flavor perspective of charmed baryon decays

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

To mention a few:

PRD **54**, 2132 (1996), PRD **93**, 056008 (2016), NPB **956**, 115048 (2020)
喬玲麗, 鄭海揚, 曾龍 | 吕才典、王伟、于福升 | 賈彩萍、王迪、于福升

JHEP **09**, 035 (2022), JHEP **03**, 143 (2022), PRD **109**, 114027 (2024)
蕭佑國, Wang, Zhao | 黄飞、邢志鹏、何小刚 | 钟慧玲、徐繁荣、鄭海揚

……

However, there are some ***shortcomings*** in $SU(3)_F$ symmetry approach.

- The CKM-suppressed amplitudes ***cannot*** be determined with CP-even data.

$$\text{Amplitudes}: V_{cs}V_{us}^{*}\, F^{s-d} + V_{cb}V_{ub}^{*}\, F^{b}$$

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

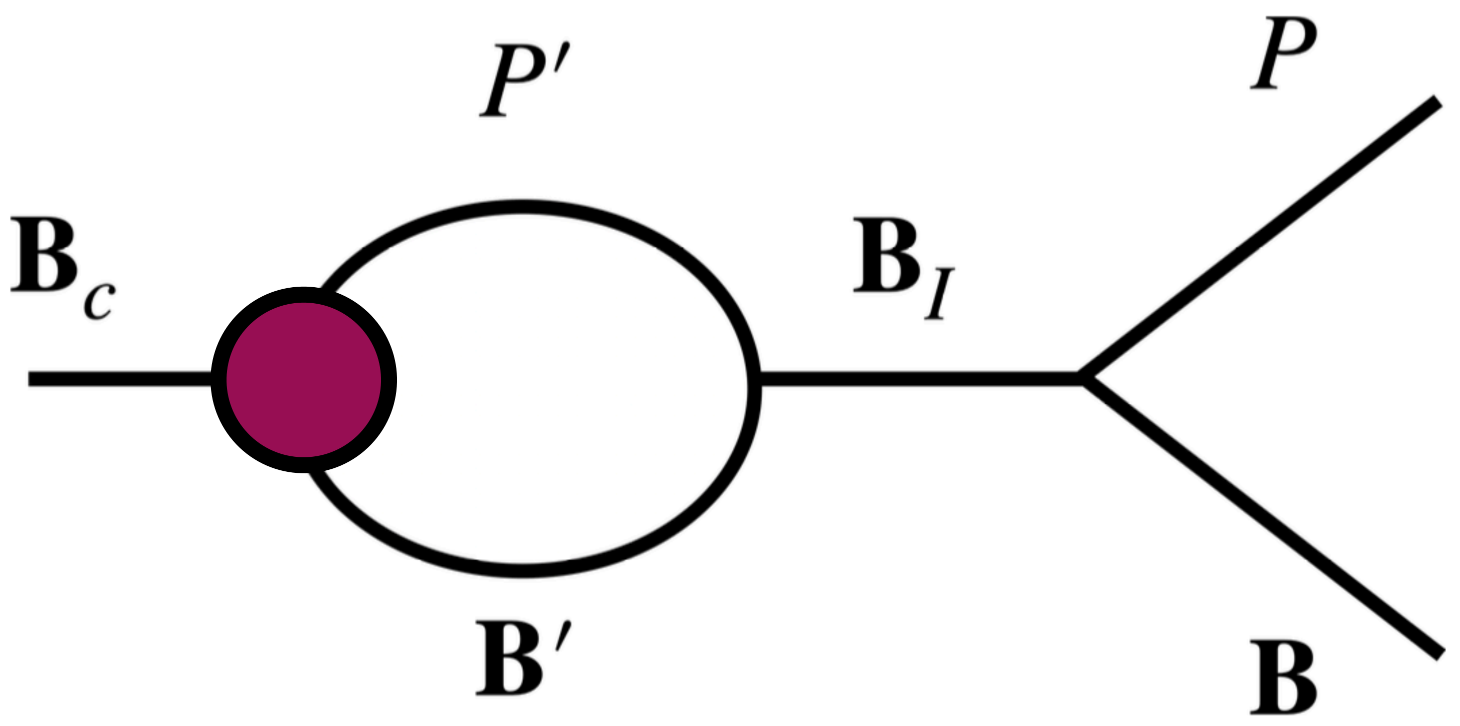
The size of $SU(3)_F$ breaking in F^{s-d} is larger than F^b.

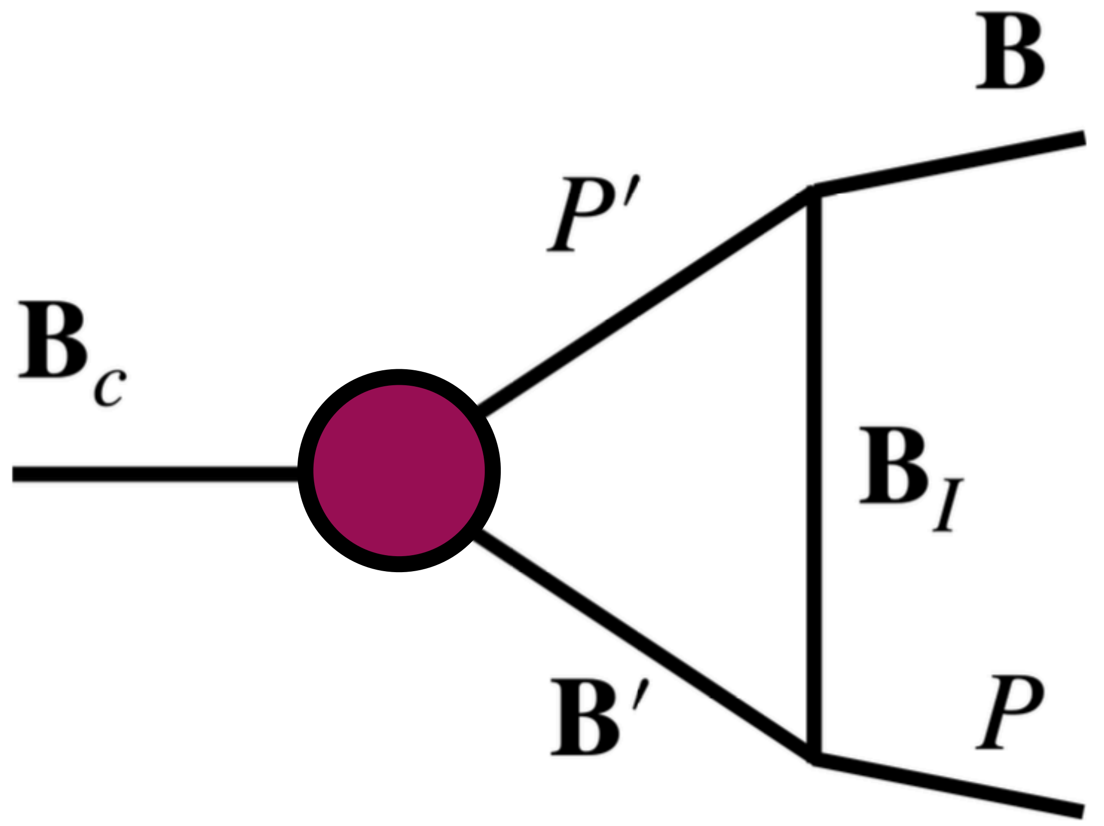
- **SU(3) flavor perspective of charmed baryon decays**

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 arXiv:2408.14959 for direct calculations





$$\text{Amplitudes}: V_{cs}V_{us}^* \, F^{s-d} + V_{cb}V_{ub}^* \, F^b$$

Do not need to consider F^b in studying CP-even quantities. $\xleftrightarrow{FSR}$ F^b ***cannot*** be determined with CP-even quantities.

The size of $SU(3)_F$ breaking in F^{s-d} is larger than F^b.

SU(3) flavor analysis

$V_{cs}^* V_{us}$ Tree + ~~$V_{cb}^* V_{ub}$ Penguin~~

Insensitive to CP-even quantities & undetermined

Final State Rescattering

$V_{cs}^* V_{us}$ Tree + $V_{cb}^* V_{ub}$ Tree × (Penguin / Tree)

Determined by the rescattering

- **SU(3) flavor analysis — Tree**

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

Generalized Wigner-Eckart theorem

$\tilde{f}$:Free parameters

$$F^{s-d} = \tilde{f}^a (P^\dagger)^l_l \mathcal{H}(\overline{\mathbf{6}}^{\mathbf{C}})_{ij} (\mathbf{B}_c)^{ik} (\mathbf{B}^\dagger)^j_k + \tilde{f}^b \mathcal{H}(\overline{\mathbf{6}}^{\mathbf{C}})_{ij} (\mathbf{B}_c)^{ik} (\mathbf{B}^\dagger)^l_k (P^\dagger)^j_l + \underbrace{\tilde{f}^c \mathcal{H}(\overline{\mathbf{6}}^{\mathbf{C}})_{ij} (\mathbf{B}_c)^{ik} (P^\dagger)^l_k (\mathbf{B}^\dagger)^j_l}_{SU(3)_F \text{ tensors}}$$
$$+ \tilde{f}^d \mathcal{H}(\overline{\mathbf{6}}^{\mathbf{C}})_{ij} (\mathbf{B}^\dagger)^i_k (P^\dagger)^j_l (\mathbf{B}_c)^{kl} + \tilde{f}^e (\mathbf{B}^\dagger)^j_i \mathcal{H}(\mathbf{15}^{\mathbf{C}})^{\{ik\}}_l (P^\dagger)^l_k (\mathbf{B}_c)_j ,$$

$$F^b = \tilde{f}^e (\mathbf{B}^\dagger)^j_i \mathcal{H}(\mathbf{15}^b)^{\{ik\}}_l (P^\dagger)^l_k (\mathbf{B}_c)_j + \tilde{f}^a_{\mathbf{3}} (\mathbf{B}_c)_j \mathcal{H}(\mathbf{3}^b)^i (\mathbf{B}^\dagger)^j_i (P^\dagger)^k_k + \tilde{f}^b_{\mathbf{3}} (\mathbf{B}_c)_k \mathcal{H}(\mathbf{3}^b)^i (\mathbf{B}^\dagger)^j_i (P^\dagger)^k_j$$
$$+ \tilde{f}^c_{\mathbf{3}} (\mathbf{B}_c)_i \mathcal{H}(\mathbf{3}^b)^i (\mathbf{B}^\dagger)^j_k (P^\dagger)^k_j + \tilde{f}^d_{\mathbf{3}} (\mathbf{B}_c)_j \mathcal{H}(\mathbf{3}^b)^i (\mathbf{B}^\dagger)^j_k (P^\dagger)^k_i ,$$

$$\mathcal{H}(\overline{\mathbf{6}}) = \begin{pmatrix} 0 & 0 & 0 \\ 0 & V^*_{cs} V_{ud} & -\lambda_s - \frac{\lambda_b}{2} \\ 0 & -\lambda_s - \frac{\lambda_b}{2} & V^*_{cd} V_{us} \end{pmatrix} \qquad \mathcal{H}(\mathbf{15})^{ij}_k = \left(\begin{pmatrix} \frac{\lambda_b}{2} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}_{ij}, \begin{pmatrix} 0 & -\lambda_s - \frac{3\lambda_b}{4} & V^*_{cs} V_{ud} \\ -\lambda_s - \frac{3\lambda_b}{4} & 0 & 0 \\ V^*_{cs} V_{ud} & 0 & 0 \end{pmatrix}_{ij}, \begin{pmatrix} 0 & V^*_{cd} V_{us} & \lambda_s + \frac{\lambda_b}{4} \\ V^*_{cd} V_{us} & 0 & 0 \\ \lambda_s + \frac{\lambda_b}{4} & 0 & 0 \end{pmatrix}_{ij} \right)_k$$

• SU(3) flavor analysis — Tree

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

Generalized Wigner-Eckart theorem

$\tilde{f}$:Free parameters

$$F^{s-d} = \tilde{f}^a (P^\dagger)^l_l \mathcal{H}(\overline{\mathbf{6}}^{\mathbf{C}})_{ij} (\mathbf{B}_c)^{ik} (\mathbf{B}^\dagger)^j_k + \tilde{f}^b \mathcal{H}(\overline{\mathbf{6}}^{\mathbf{C}})_{ij} (\mathbf{B}_c)^{ik} (\mathbf{B}^\dagger)^l_k (P^\dagger)^j_l + \tilde{f}^c \underbrace{\mathcal{H}(\overline{\mathbf{6}}^{\mathbf{C}})_{ij} (\mathbf{B}_c)^{ik} (P^\dagger)^l_k (\mathbf{B}^\dagger)^j_l}_{SU(3)_F \text{ tensors}}$$
$$+ \tilde{f}^d \mathcal{H}(\overline{\mathbf{6}}^{\mathbf{C}})_{ij} (\mathbf{B}^\dagger)^i_k (P^\dagger)^j_l (\mathbf{B}_c)^{kl} + \tilde{f}^e (\mathbf{B}^\dagger)^j_i \mathcal{H}(\mathbf{15}^{\mathbf{C}})^{\{ik\}}_l (P^\dagger)^l_k (\mathbf{B}_c)_j \,,$$

~~$$F^b = \tilde{f}^e (\mathbf{B}^\dagger)^j_i \mathcal{H}(\mathbf{15}^b)^{\{ik\}}_l (P^\dagger)^l_k (\mathbf{B}_c)_j + \tilde{f}^a_{\mathbf{3}} (\mathbf{B}_c)_j \mathcal{H}(\mathbf{3}^b)^i (\mathbf{B}^\dagger)^j_i (P^\dagger)^k_k + \tilde{f}^b_{\mathbf{3}} (\mathbf{B}_c)_k \mathcal{H}(\mathbf{3}^b)^i (\mathbf{B}^\dagger)^j_i (P^\dagger)^k_j$$~~
~~$$+ \tilde{f}^c_{\mathbf{3}} (\mathbf{B}_c)_i \mathcal{H}(\mathbf{3}^b)^i (\mathbf{B}^\dagger)^j_k (P^\dagger)^k_j + \tilde{f}^d_{\mathbf{3}} (\mathbf{B}_c)_j \mathcal{H}(\mathbf{3}^b)^i (\mathbf{B}^\dagger)^j_k (P^\dagger)^k_i \,,$$~~

To date, there are in total **44** data points but ~~9~~ **5** $\times$ 2(S & P waves) $\times$ 2(complex) $- 1 =$ ~~35~~ **19**

CP-even

$\tilde{f}^{a,b,c,d,e}$, ~~$\tilde{f}^{a,b,c,d}_{\mathbf{3}}$~~

• SU(3) flavor analysis — Tree

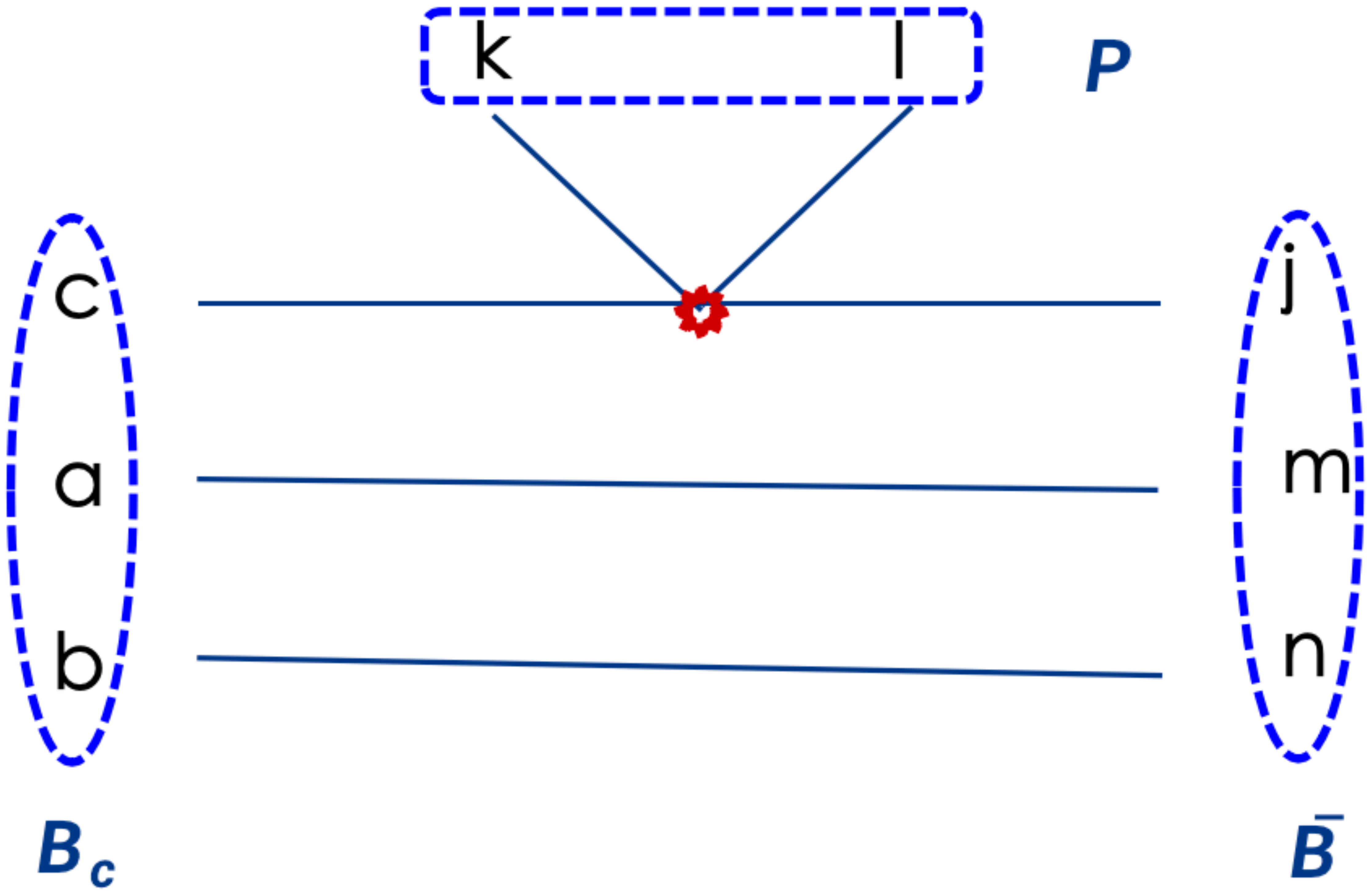
He, Shi, Wang — Zhong, Xu, Cheng — Wang, Luo

Equivalence to the quark diagrams analysis; see arXiv : 1811.03480, 2404.01350, 2406.14061

$$f^e (P)^l_k \bar{B}^i_j H(15)^{jk}_l (B_c)_i$$

$$\downarrow$$

$$f^e (P)^l_k \varepsilon^{mni} (\bar{B})_{mnj} H(15)^{jk}_l \varepsilon_{abi} (B_c)^{ab}$$

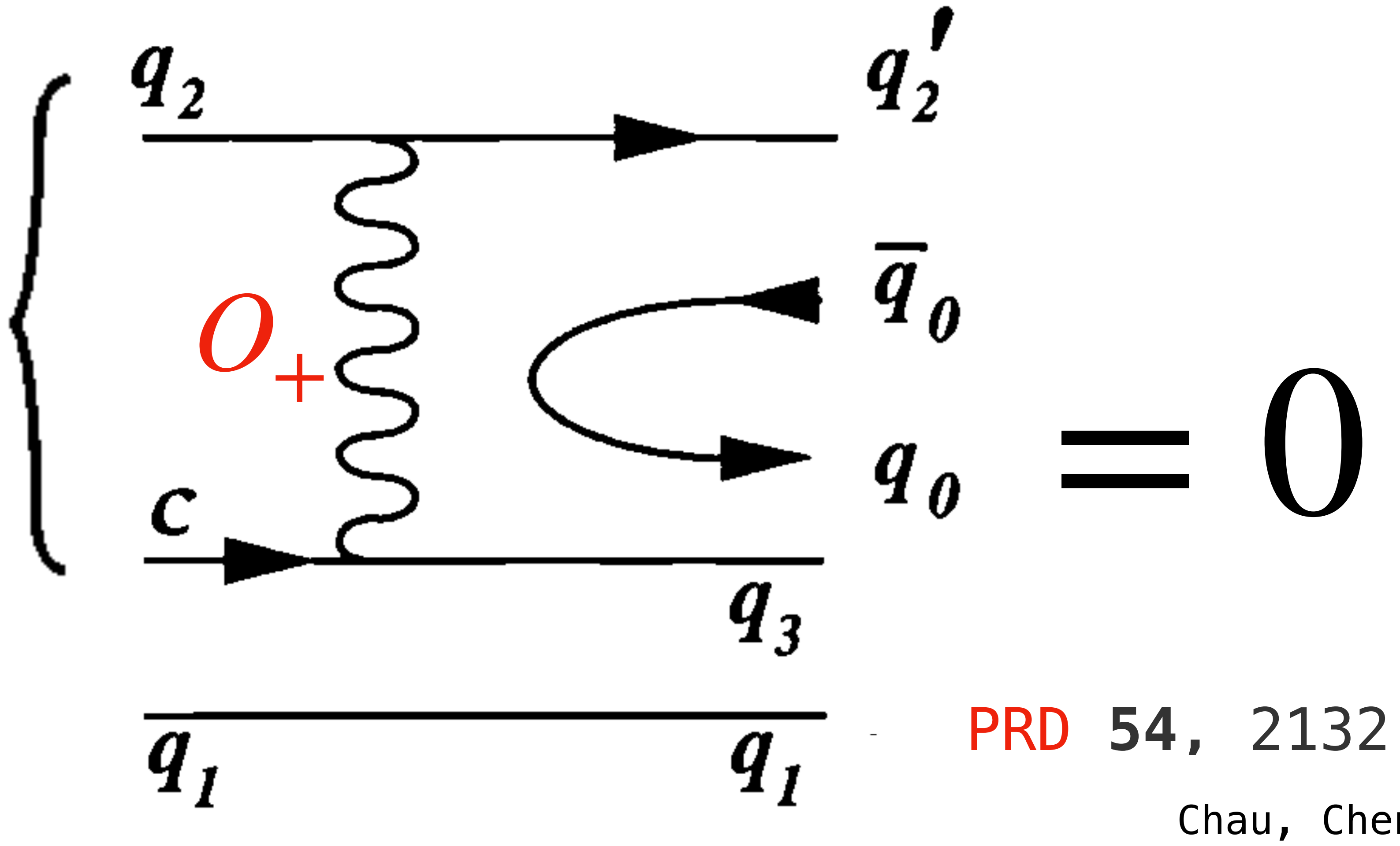


• SU(3) flavor analysis — Tree

- **Körner-Pati-Woo theorem:**

$$\langle q_a q_b q_c | O_+^{qq'} | \mathbf{B}_i \rangle = 0$$

Color symmetric　　Color singlet



PRD **54**, 2132 (1996)
Chau, Cheng, Tseng

- **First employed in PLB 794, 19(2019)**

- **Predicted direct relations:**

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

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

- **Lessons: Results are bad in η and η' but good in others.**

SU(3) flavor analysis

$V_{cs}^{*}V_{us}$ Tree + ~~$V_{cb}^{*}V_{ub}$ Penguin~~

Insensitive to CP-even quantities & undetermined

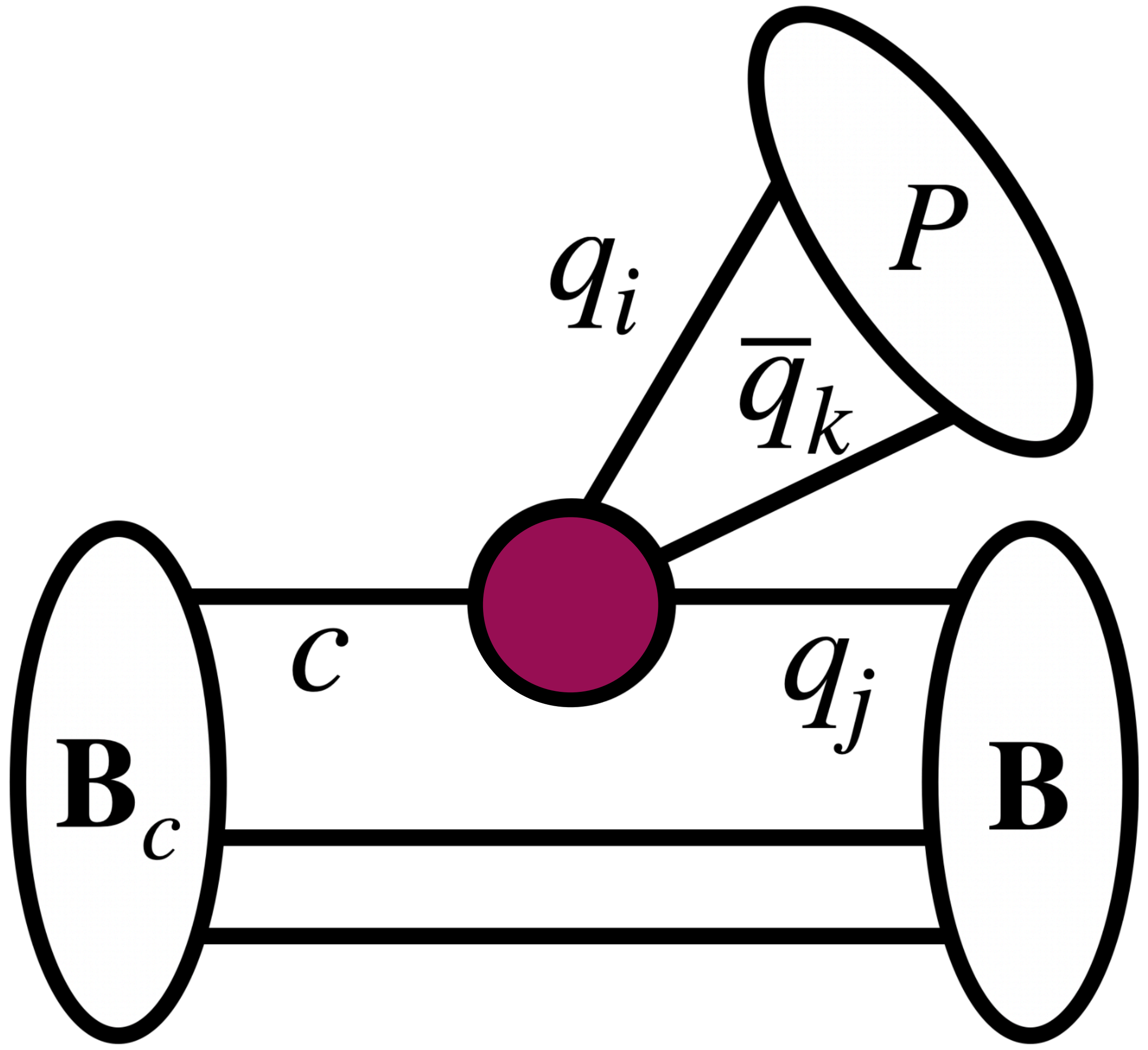
Final State Rescattering

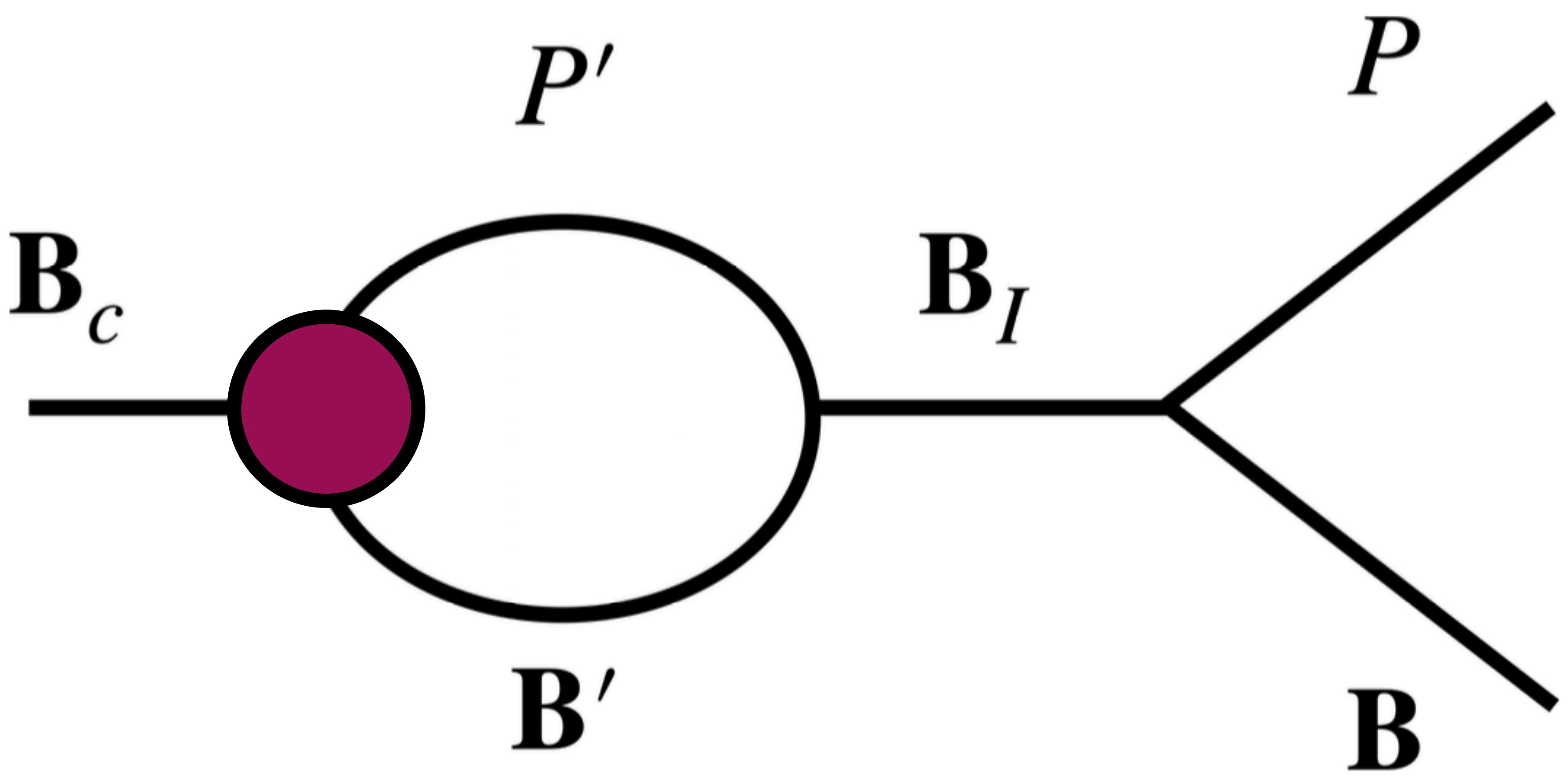
$V_{cs}^{*}V_{us}$ Tree + $V_{cb}^{*}V_{ub}$ Tree × (Penguin / Tree)

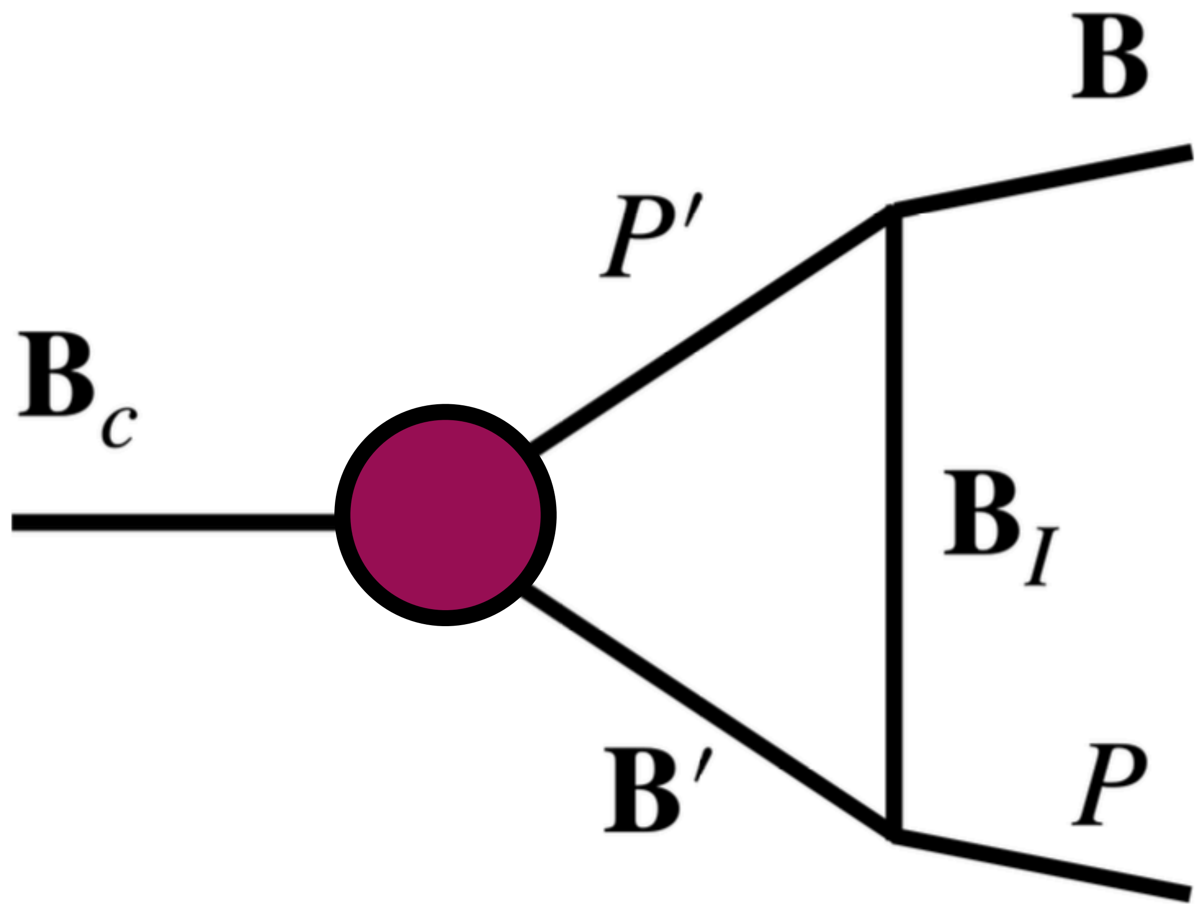
Determined by the rescattering

- **Rescattering, solving penguin/tree**

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





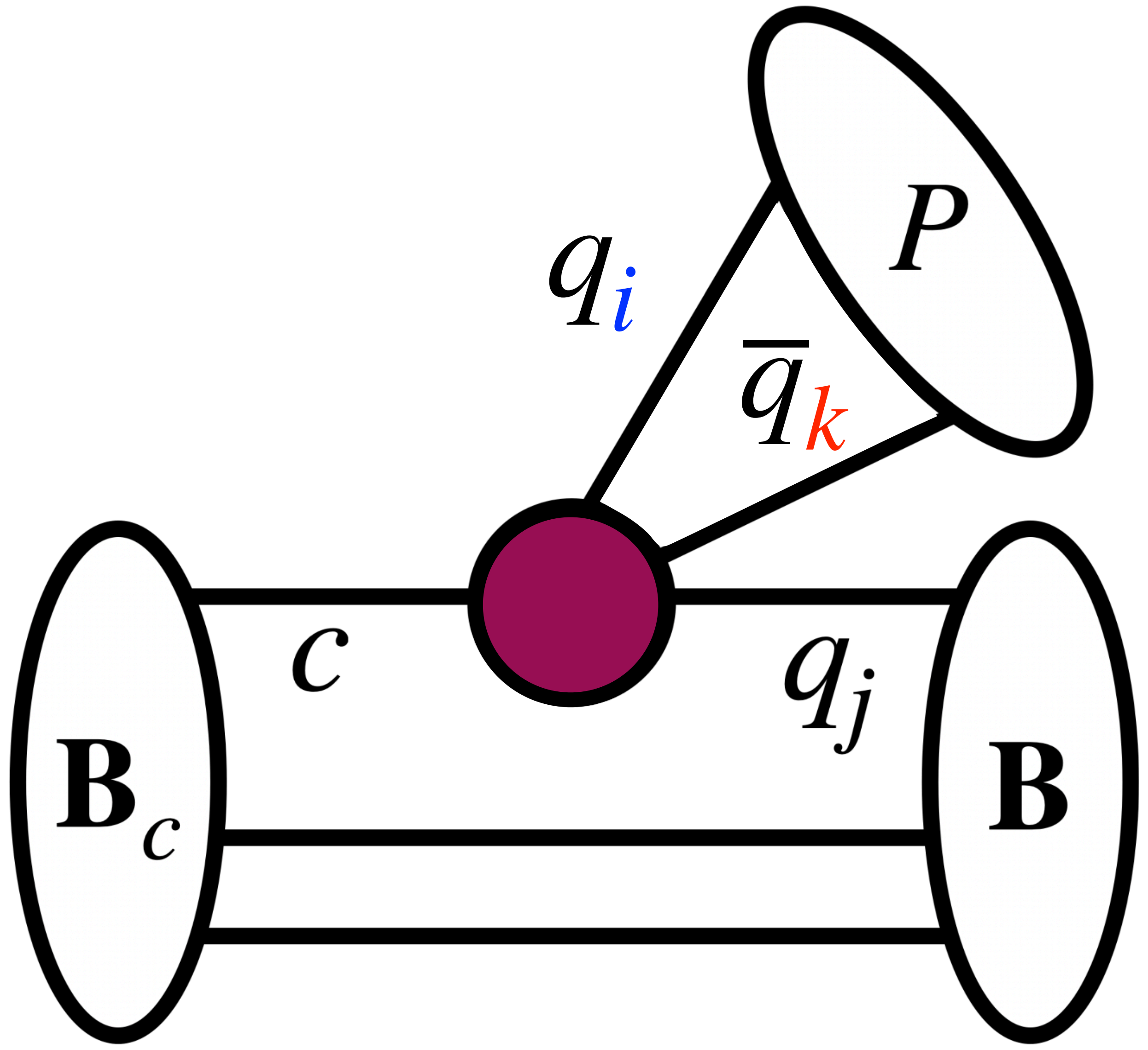


Assumptions:

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

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



From figure, we deduce:

$$\mathscr{L}^{\text{Tree}}_{\mathbf{B}_c\mathbf{B}P} = \left(P^\dagger\right)^k_i (\overline{\mathbf{B}})^l_j \left(\tilde{F}^+_V \left(\mathscr{H}_+\right)^{ij}_k + \tilde{F}^-_V \left(\mathscr{H}_-\right)^{ij}_k \right) \left(\mathbf{B}_c\right)_l$$

where

$$(\mathscr{H}_+)^{ij}_k = \frac{\lambda_s - \lambda_d}{2} \mathscr{H}(\mathbf{15}^{s-d})^{ij}_k + \lambda_b \left(\mathscr{H}(\mathbf{15}^b)^{ij}_k + \mathscr{H}(\mathbf{3}_+)^i \delta^j_k + \mathscr{H}(\mathbf{3}_+)^j \delta^i_k \right)$$

$$(\mathscr{H}_-)^{ij}_k = \frac{\lambda_s - \lambda_d}{2} \mathscr{H}(\overline{\mathbf{6}})_{kl} \epsilon^{lij} + 2\lambda_b \left(\mathscr{H}(\mathbf{3}_-)^i \delta^j_k - \mathscr{H}(\mathbf{3}_-)^j \delta^i_k \right)$$

$$\mathcal{H}(\overline{\mathbf{6}}) = \begin{pmatrix} 0 & 0 & 0 \\ 0 & V^*_{cs}V_{ud} & -\lambda_s - \frac{\lambda_b}{2} \\ 0 & -\lambda_s - \frac{\lambda_b}{2} & V^*_{cd}V_{us} \end{pmatrix} \qquad \mathcal{H}(\mathbf{15})^{ij}_k = \left(\begin{pmatrix} \frac{\lambda_b}{2} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}_{ij}, \begin{pmatrix} 0 & -\lambda_s - \frac{3\lambda_b}{4} & V^*_{cs}V_{ud} \\ -\lambda_s - \frac{3\lambda_b}{4} & 0 & 0 \\ V^*_{cs}V_{ud} & 0 & 0 \end{pmatrix}_{ij}, \begin{pmatrix} 0 & V^*_{cd}V_{us} & \lambda_s + \frac{\lambda_b}{4} \\ V^*_{cd}V_{us} & 0 & 0 \\ \lambda_s + \frac{\lambda_b}{4} & 0 & 0 \end{pmatrix}_{ij} \right)_k$$

It is very important that $\mathbf{15}$, $\overline{\mathbf{6}}$ and $\mathbf{3}$ share ***two*** parameters $\tilde{F}^{\pm}_V$!

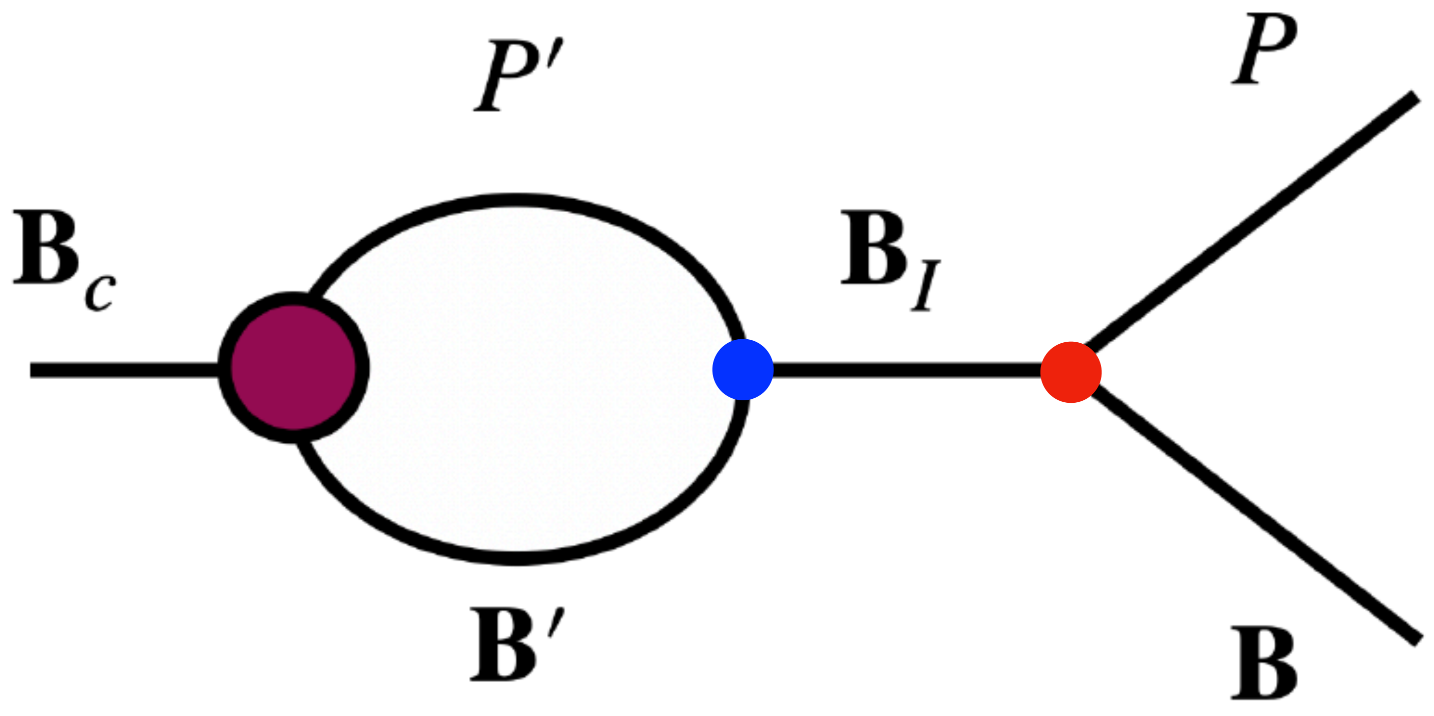
We can ***solve*** $\mathbf{3}$ with $\mathbf{15}$ and $\overline{\mathbf{6}}$!!

- ## Rescattering, solving penguin/tree

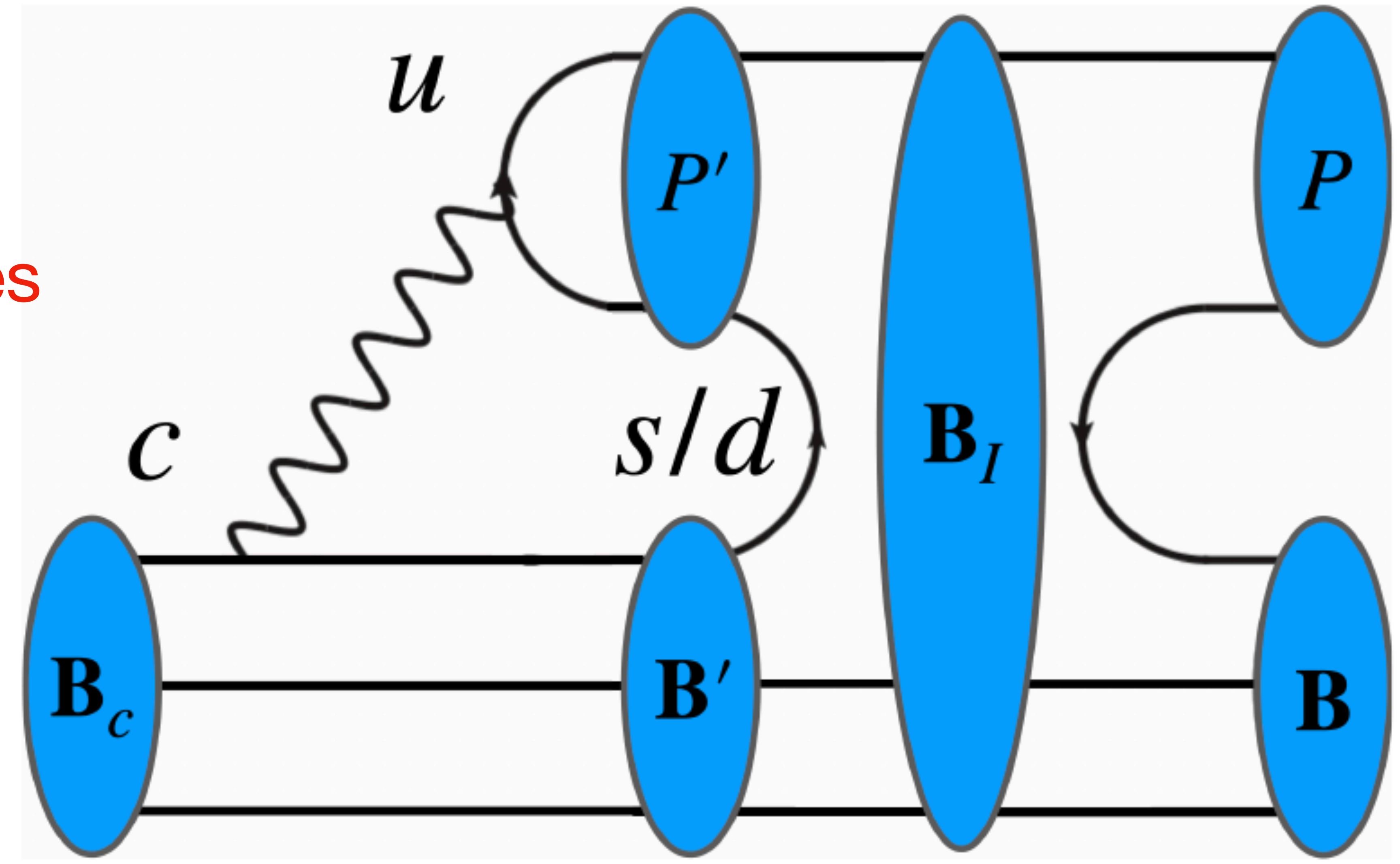
$$\langle \mathscr{L}^{\mathrm{FSR-s}}_{\mathbf{B}_c\mathbf{B}P} \rangle = \sum_{\mathbf{B}_I,\mathbf{B}',P'} \bar{u}_{\mathbf{B}} \left(\int \frac{d^4q}{(2\pi)^4} g_{\mathbf{B}_I\mathbf{B}P} \frac{p^\mu_{\mathbf{B}_c}\gamma_\mu + m_I}{p^2_{\mathbf{B}_c} - m_I^2} g_{\mathbf{B}_I\mathbf{B}'P'} \frac{q^\mu\gamma_\mu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

1. $F^{\mathrm{Tree}}_{\mathbf{B}_c\mathbf{B}'P'}$ 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'.



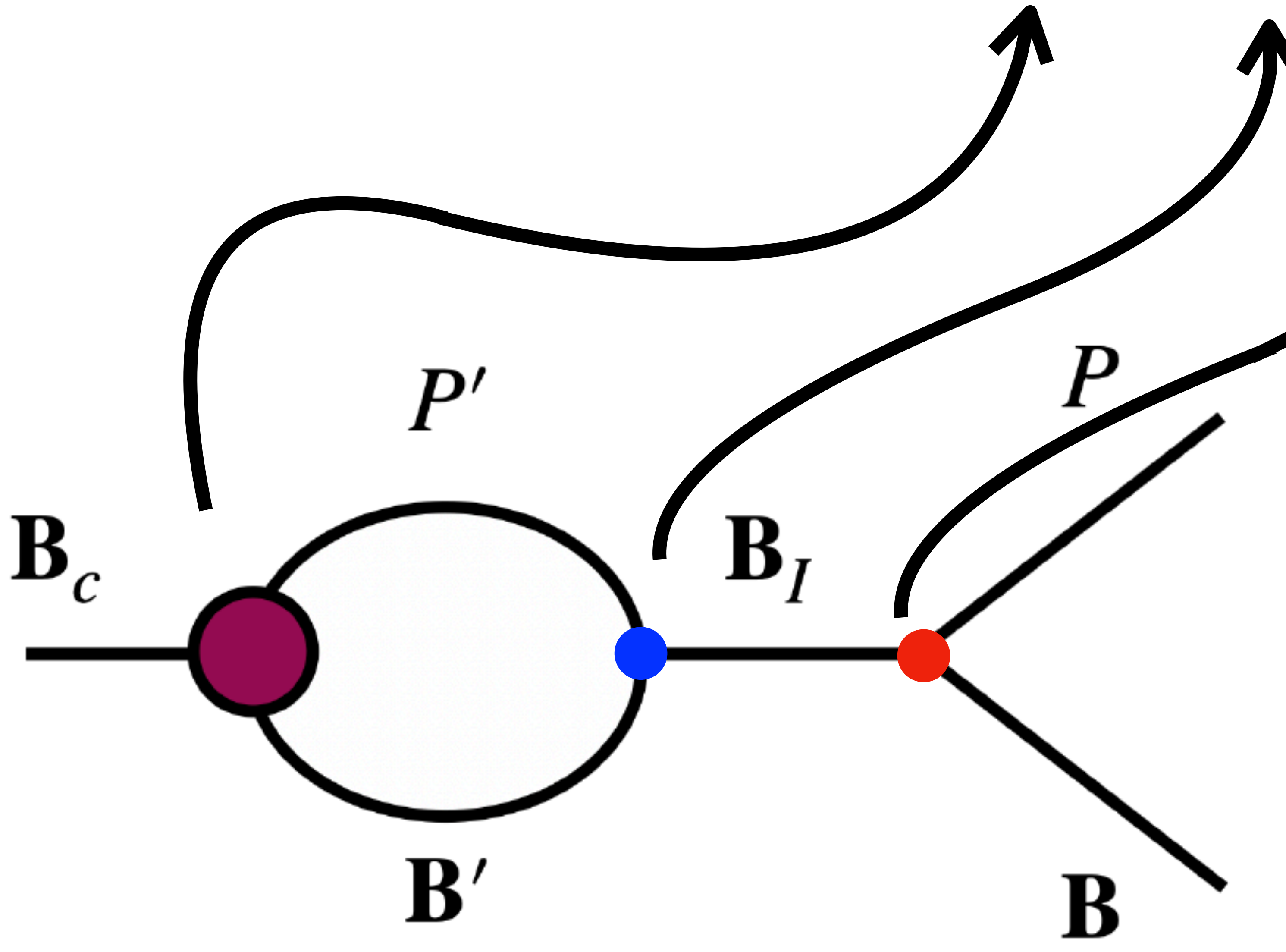
At quark level generates penguin topology



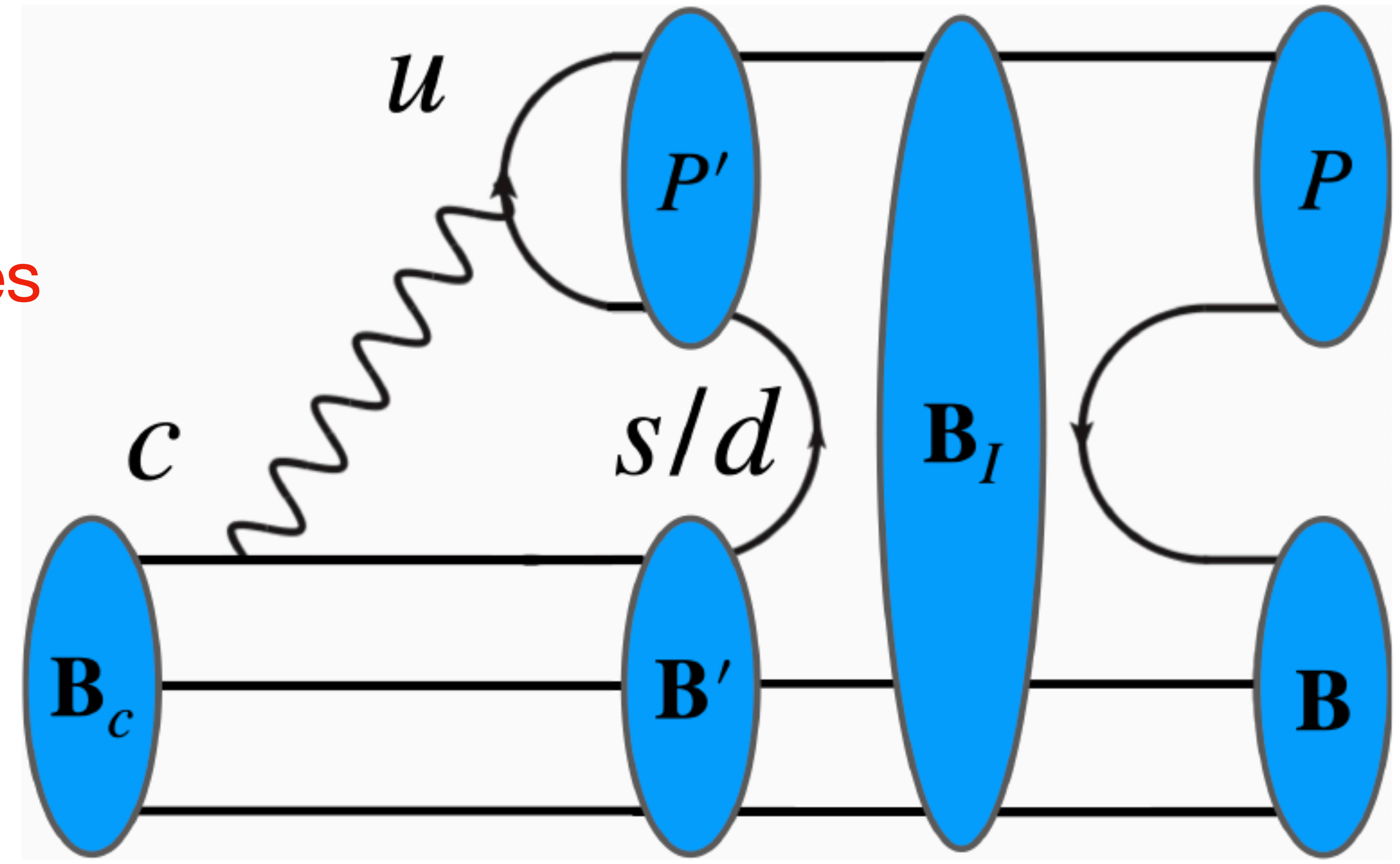
• Rescattering, solving penguin/tree

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

$$= \bar{u}_{\mathbf{B}} \left[\int \frac{d^4q}{(2\pi)^4} \left(\sum_{\mathbf{B}_I,\mathbf{B}',P'} F^{\mathrm{Tree}}_{\mathbf{B}_c\mathbf{B}'P'} g_{\mathbf{B}_I\mathbf{B}'P'} g_{\mathbf{B}_I\mathbf{B}P} \right) I(q^2) \right] u_{\mathbf{B}_c}$$



At quark level generates penguin topology



- **Rescattering, solving penguin/tree**

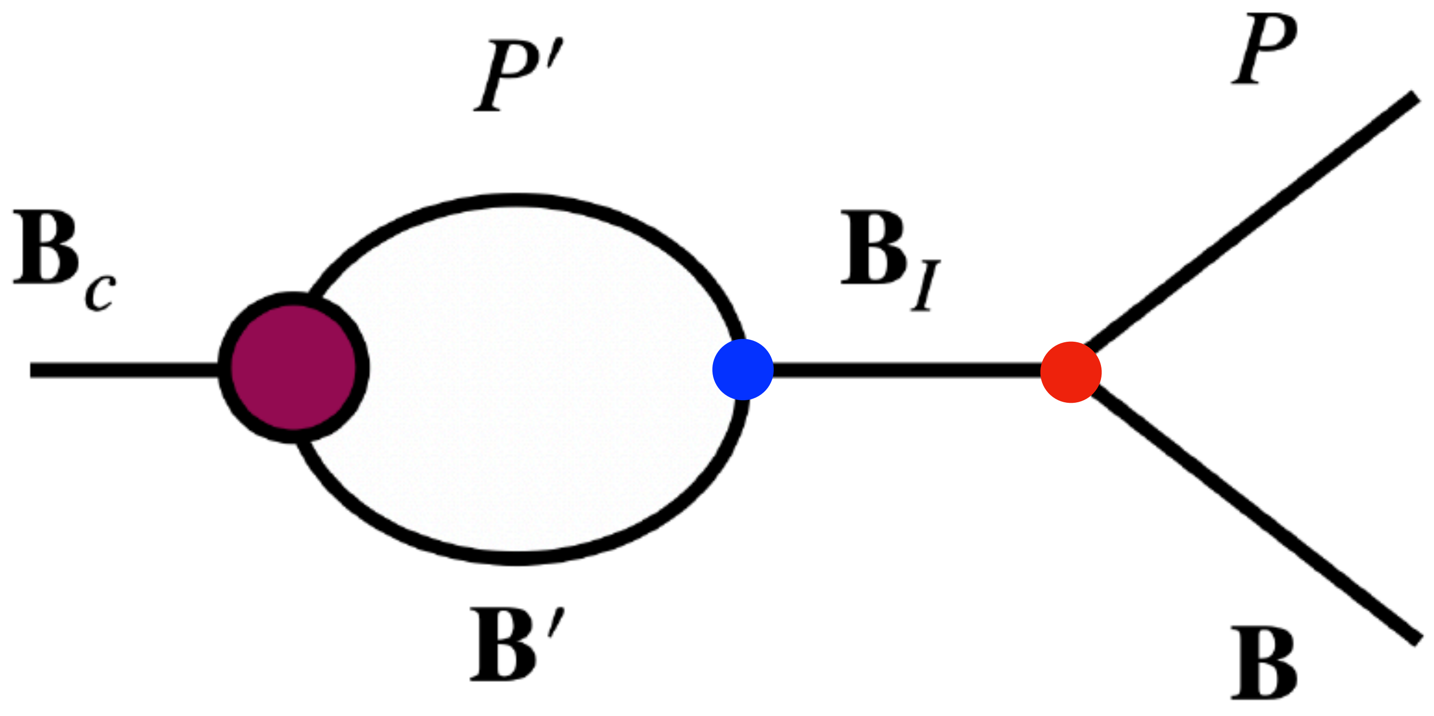
Key of reduction rule: utilizing $\mathbf{B}_I$ belongs to $\mathbf{8}$.

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 $\frac{1}{2}\sum_{\lambda_a} (\lambda_a)^{k_1}_{i_1} (\lambda_a)^{j_2}_{k_2} = \delta^{j_2}_{i_1}\delta^{k_1}_{k_2} - \frac{1}{3}\delta^{k_1}_{i_1}\delta^{j_2}_{k_2}$

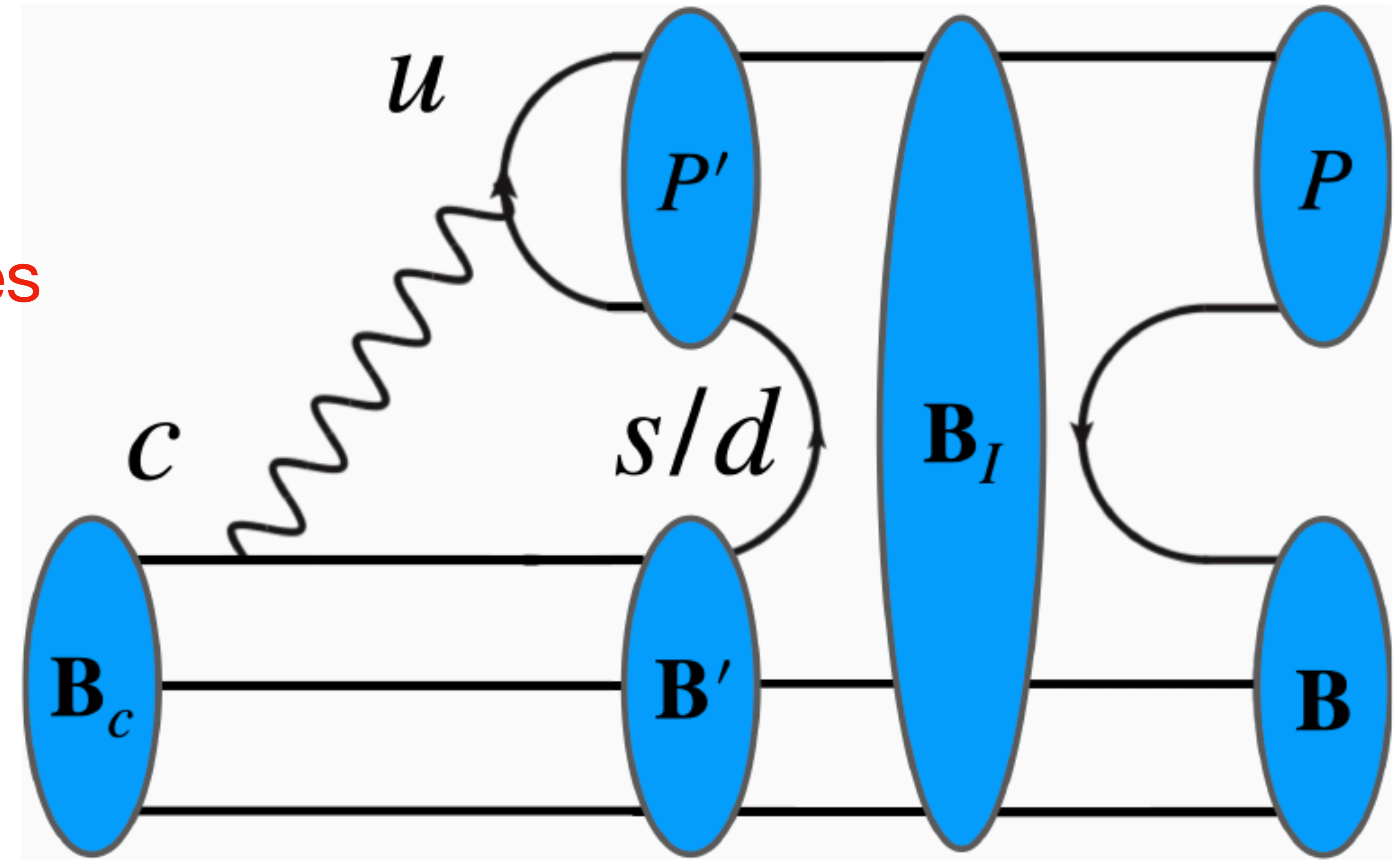
$$\sum_{\mathbf{B}_I,\mathbf{B}',P'} F^{\rm Tree}_{\mathbf{B}_c\mathbf{B}'P'} g_{\mathbf{B}_I\mathbf{B}'P'} g_{\mathbf{B}_I\mathbf{B}P}$$

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

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

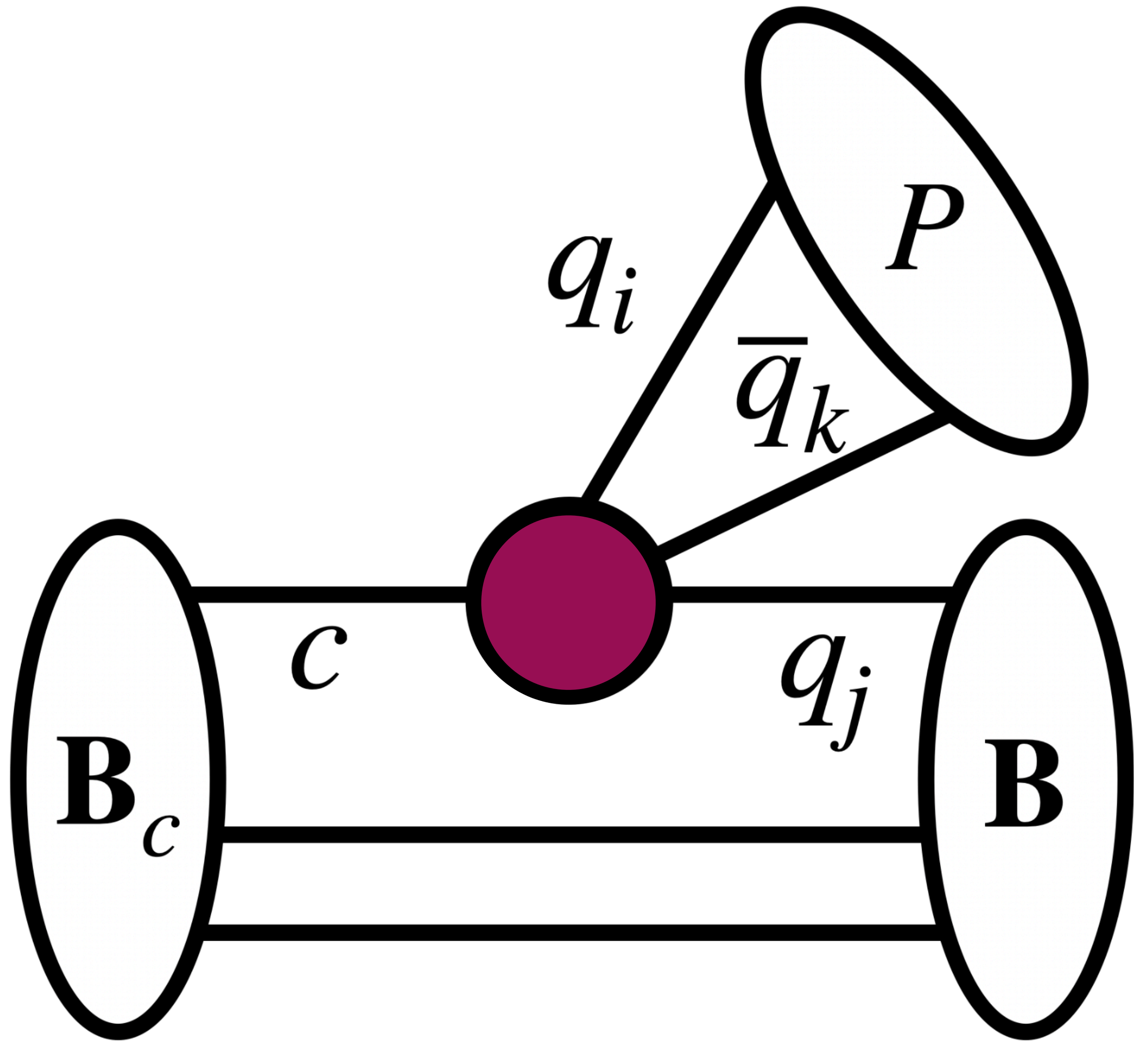


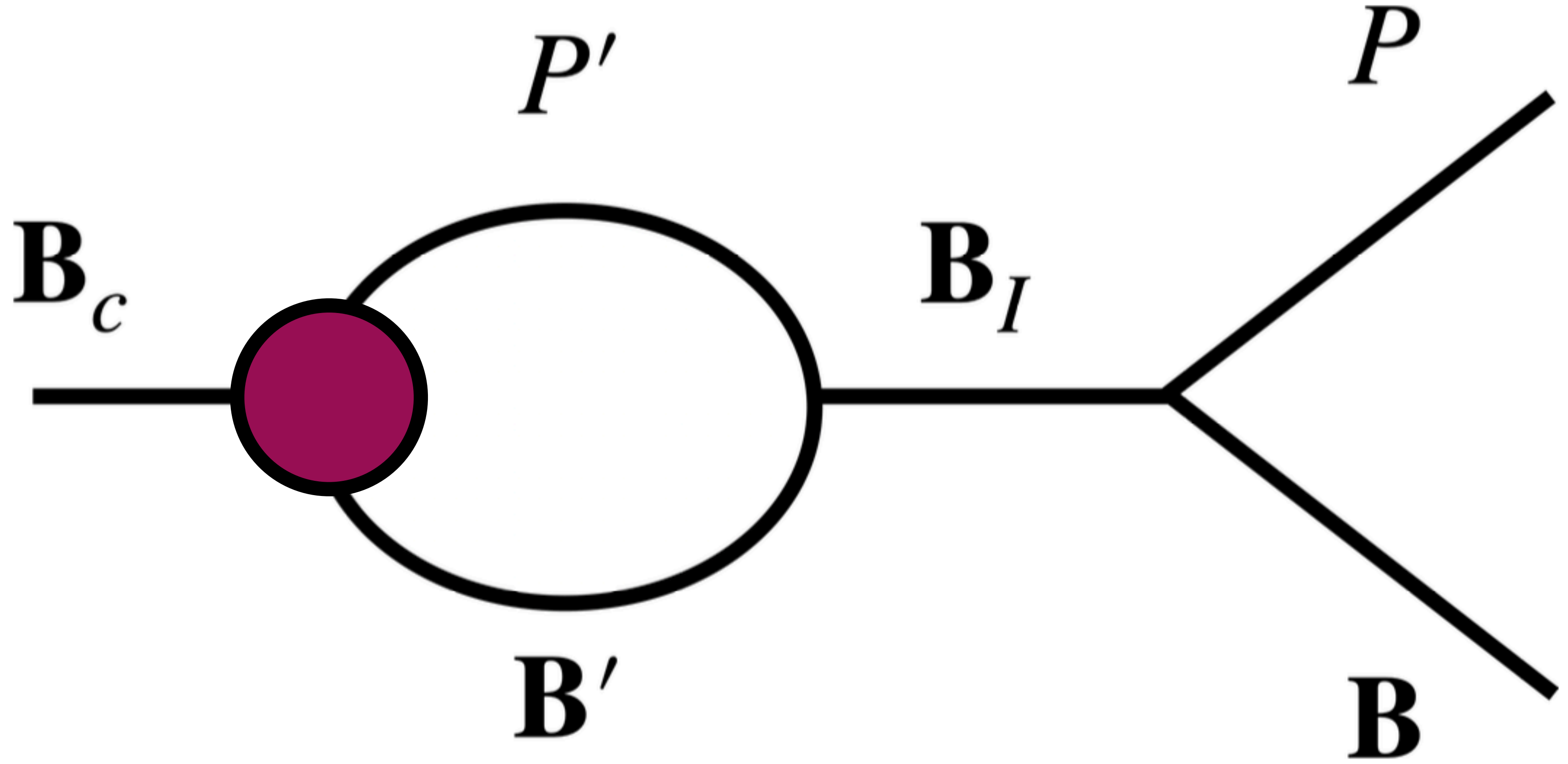
At quark level generates penguin topology

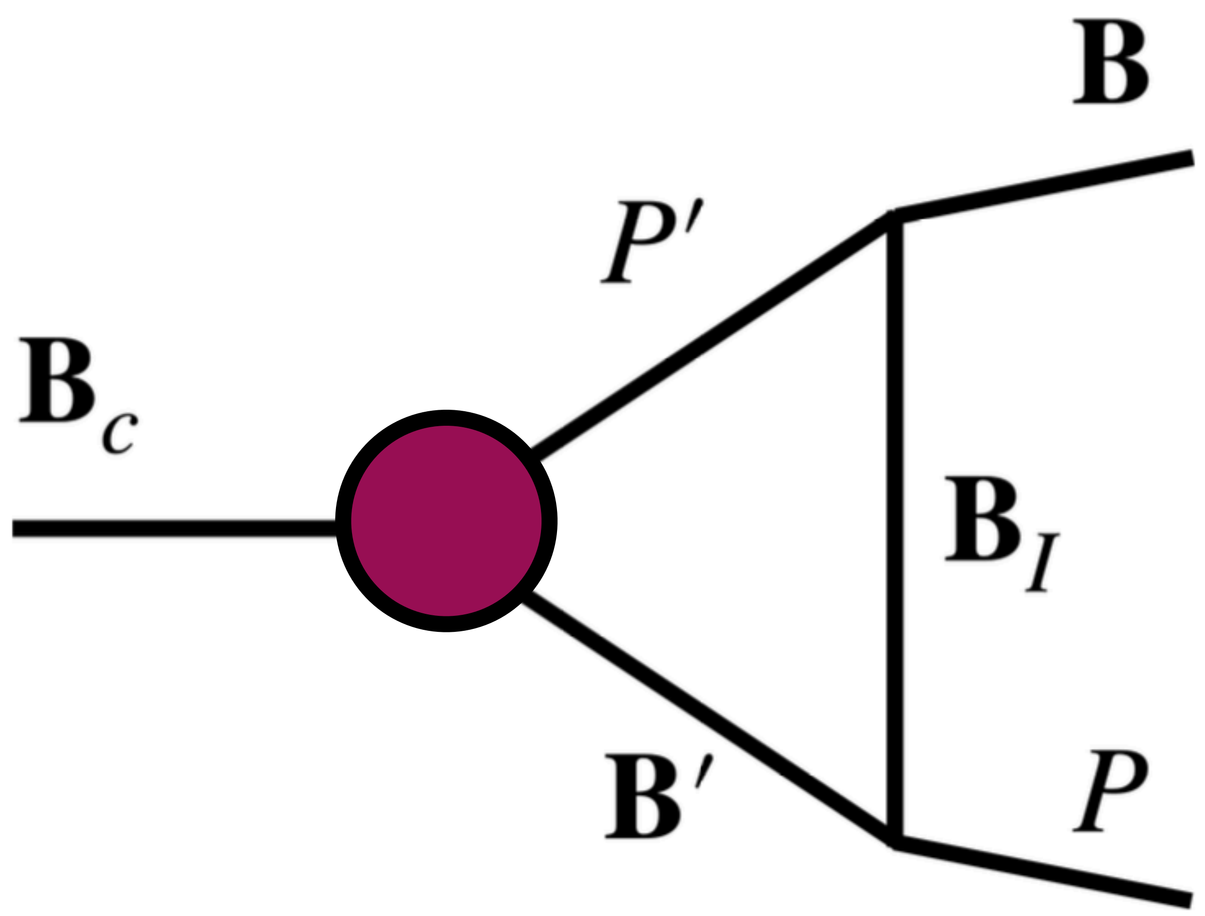


- **Rescattering, solving penguin/tree**

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







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.

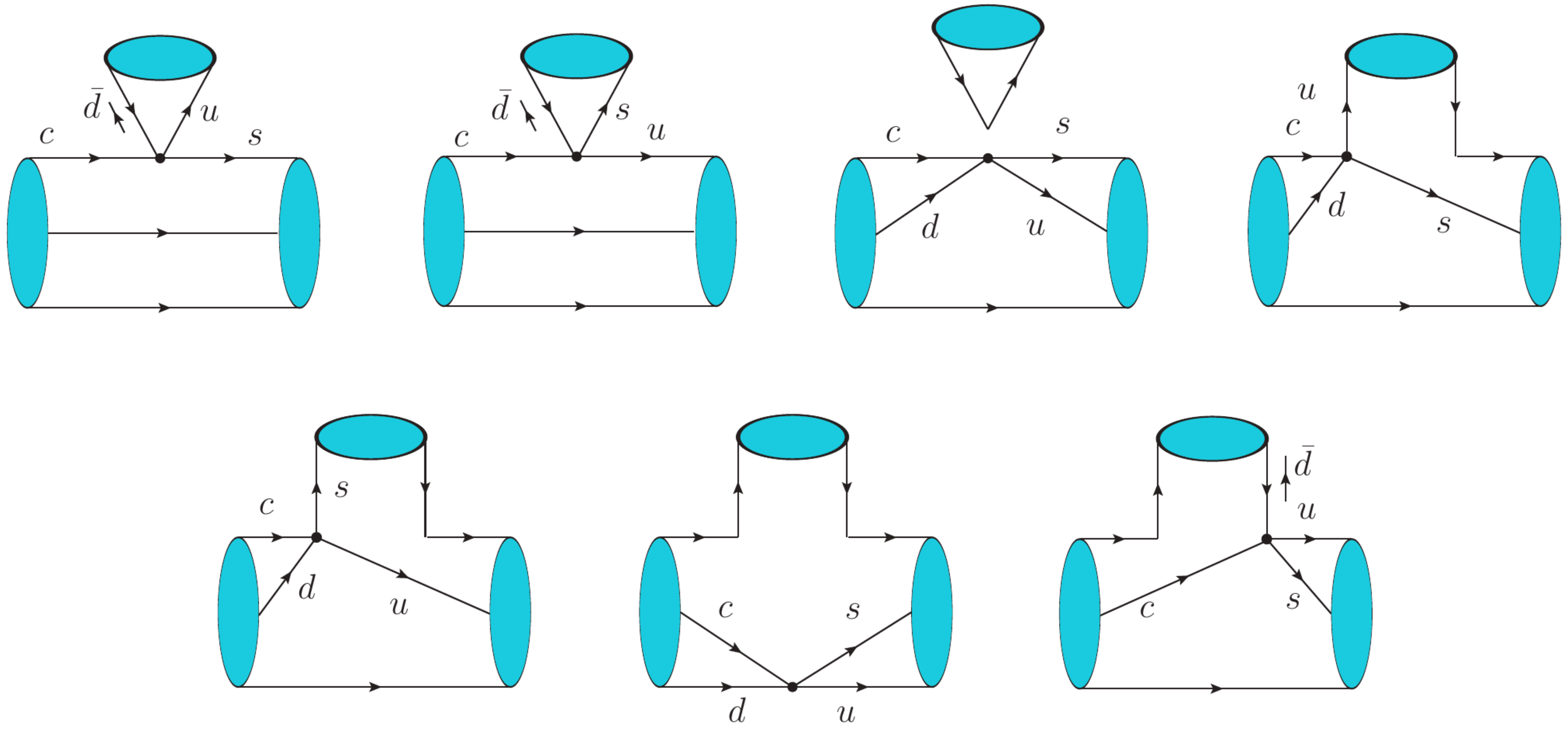
- **Rescattering, solving penguin/tree**

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

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

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

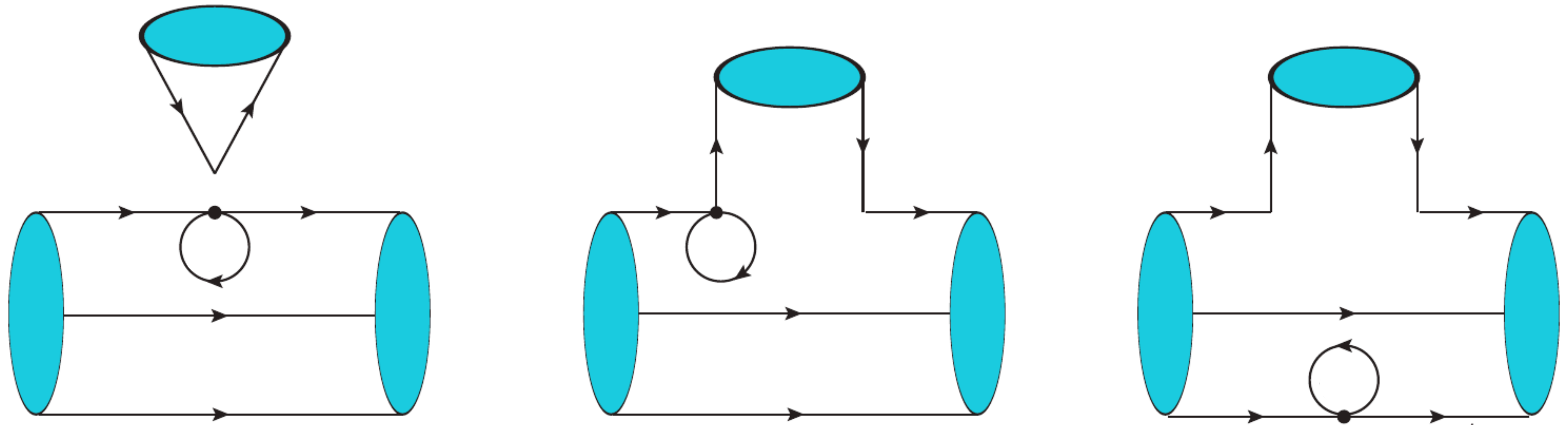
$$\tilde{f}^d = \tilde{F}_V^- + \sum(2r_\lambda^2 - 2r_\lambda - 4)\tilde{T}_\lambda^- \,, \quad \tilde{f}^e = \tilde{F}_V^+$$



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

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

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



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

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

PRD **100**, 093002 (2019)

- ## Rescattering, numerical results

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

Channels	$10^3\mathcal{B}$	$10^3A^{\alpha}_{CP}$	10^3A_{CP}	Channels	$10^3\mathcal{B}$	$10^3A^{\alpha}_{CP}$	10^3A_{CP}
$\Lambda_c^+\to p\pi^0$	0.19(3)	−0.08(21)(3)	−0.12(13)(28)	$\Xi_c^0\to\Sigma^+\pi^-$	0.23(2)	−0.54(17)(5)	1.86(10)(15)
$\Lambda_c^+\to n\pi^+$	0.69(8)	0.02(16)(5)	−0.02(11)(37)	$\Xi_c^0\to\Sigma^0\pi^0$	0.38(4)	−0.01(17)(1)	0.65(9)(23)
$\Lambda_c^+\to\Lambda^0K^+$	0.65(3)	0.00(13)(5)	−0.61(12)(26)	$\Xi_c^0\to\Sigma^-\pi^+$	1.67(4)	0.10(4)(2)	0.35(5)(2)
$\Xi_c^+\to\Sigma^+\pi^0$	2.83(13)	−0.08(7)(5)	0.24(5)(18)	$\Xi_c^0\to\Xi^0K_{S/L}$	0.46(2)	−0.07(3)(2)	0.41(3)(11)
$\Xi_c^+\to\Sigma^0\pi^+$	2.81(8)	0.02(9)(2)	0.31(7)(18)	$\Xi_c^0\to\Xi^-K^+$	1.37(3)	−0.10(5)(2)	−0.37(6)(2)
$\Xi_c^+\to\Xi^0K^+$	1.25(14)	−0.02(11)(2)	0.03(7)(43)	$\Xi_c^0\to pK^-$	0.23(2)	0.63(19)(5)	−1.82(11)(15)
$\Xi_c^+\to\Lambda^0\pi^+$	0.21(7)	0.13(35)(19)	−0.60(29)(74)	$\Xi_c^0\to nK_{S/L}$	0.50(2)	0.09(5)(3)	−0.44(3)(12)
$\Xi_c^+\to pK_s$	1.18(7)	−0.02(2)(1)	−0.33(2)(10)	$\Xi_c^0\to\Lambda^0\pi^0$	0.06(2)	0.00(10)(1)	−0.62(9)(48)

Large CP violation is found ! $A_{CP}=\frac{\Gamma-\overline{\Gamma}}{\Gamma+\overline{\Gamma}}\,,\qquad A^{\alpha}_{CP}=\frac{1}{2}(\alpha+\overline{\alpha})\,.$

44 data points with 10 complex parameters.

Rescattering, numerical results

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

$$A_{CP}\left(\Xi_c^0 \to \Sigma^+\pi^-\right) = (1.86 \pm 0.18) \times 10^{-3}$$

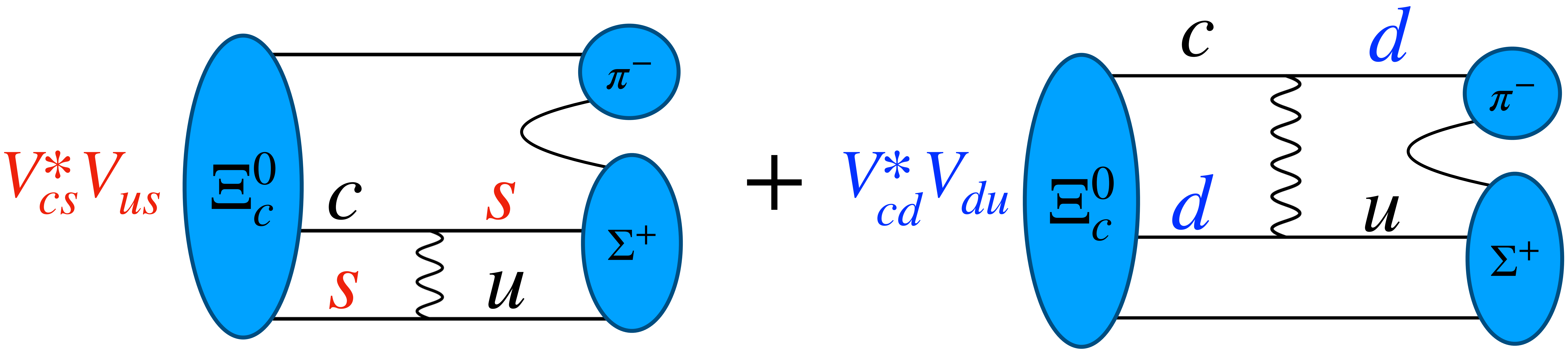
$$A_{CP}\left(\Xi_c^0 \to pK^-\right) = (-1.82 \pm 0.18) \times 10^{-3}$$

- In the U-spin limit, we have that

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

Hence it is reasonable to measure :

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



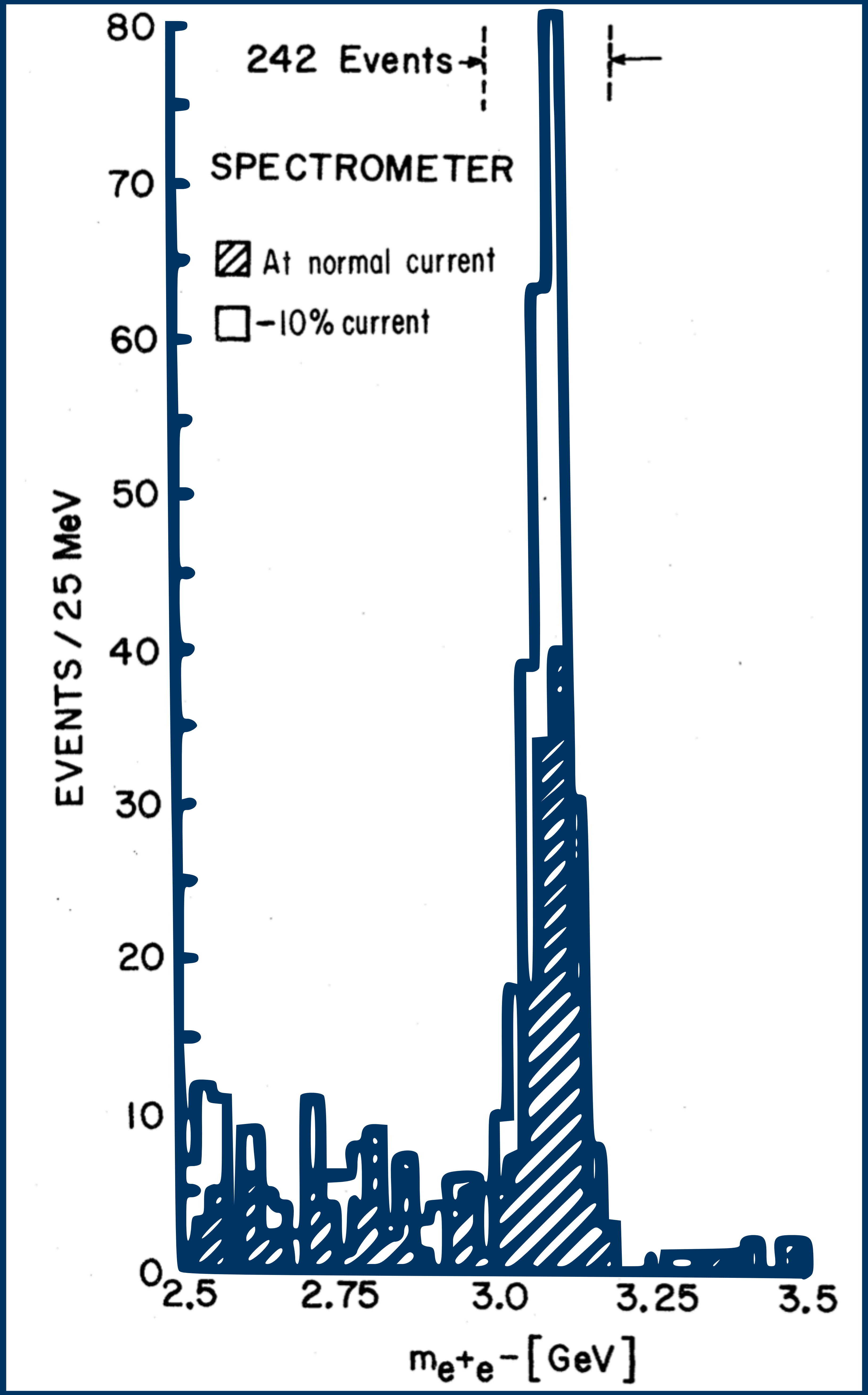
Two topological diagrams are in the same size, leads to $A_{CP} \sim \left| 2\mathrm{Im}(V_{cs}^* V_{us} / V_{cd}^* V_{ud}) \right| \sim 10^{-3}$.

Conclusions

CP violation in charm is a powerful probe for NP!

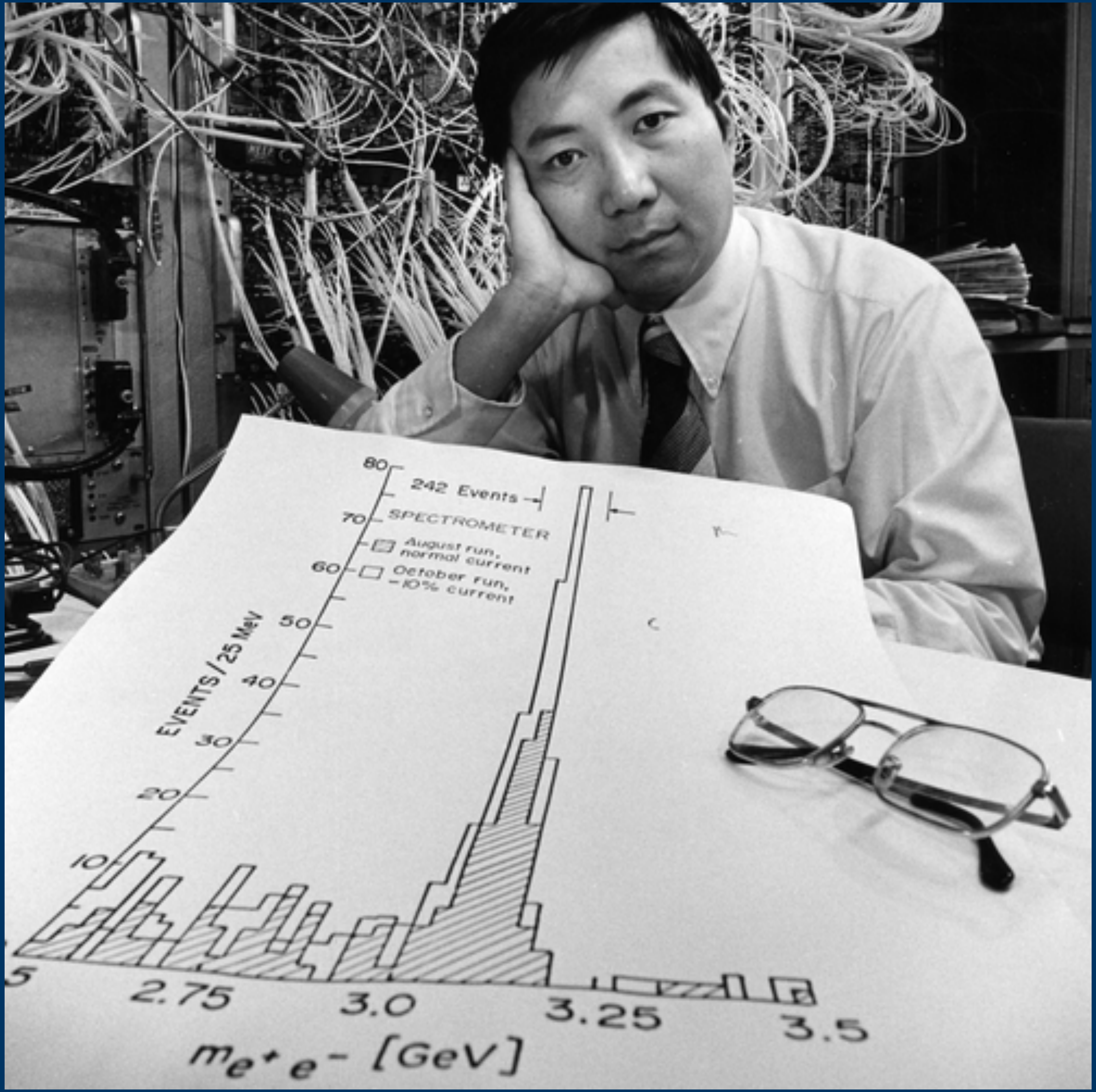
More measurements!

More theoretical studies!



Discovery of J over 50 years

Backup slides



• Rescattering, solving penguin/tree

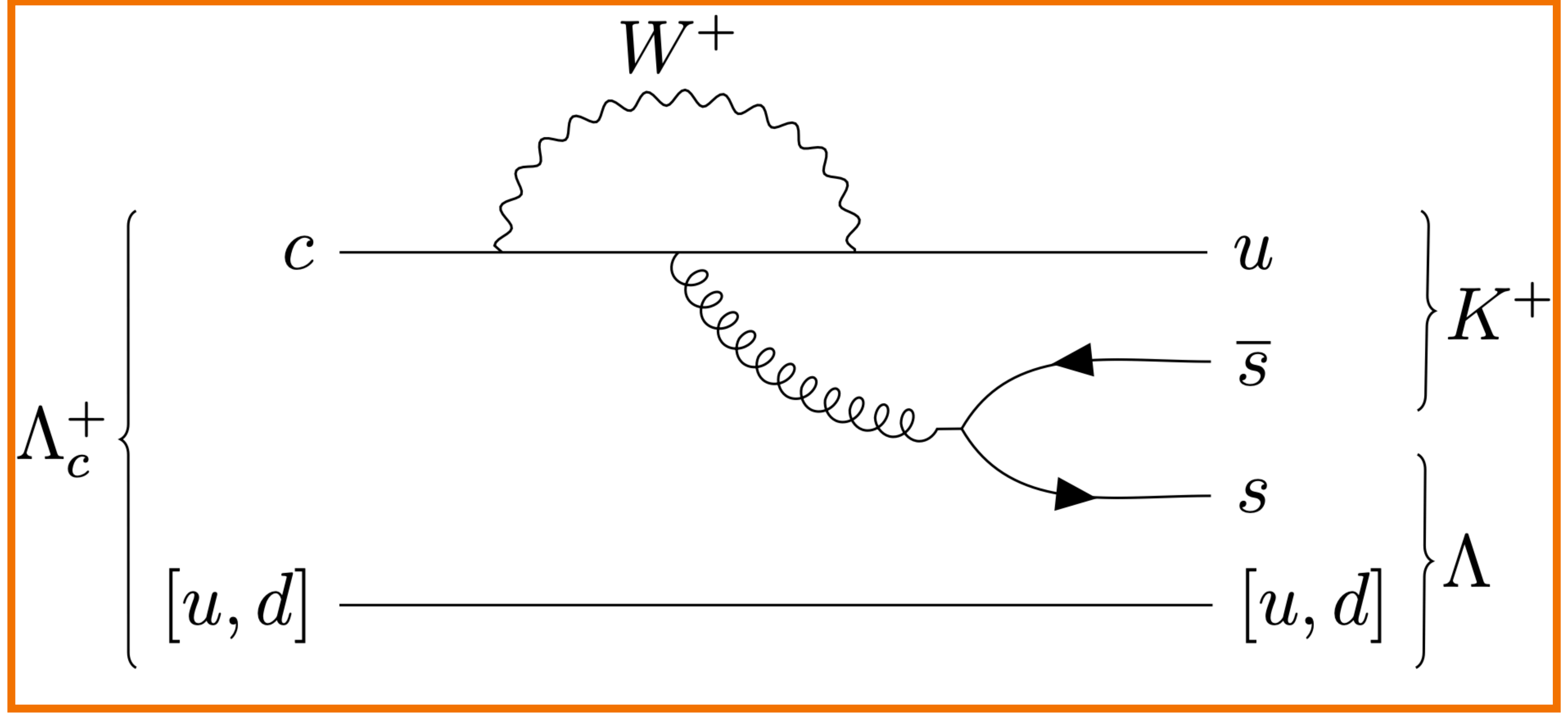
Amplitudes : $\frac{\lambda_s - \lambda_d}{2} F^{s-d} + \lambda_b F^b$

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

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

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

Corrections to A_{CP} are around 10%



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

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

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

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

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

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

PRD **100**, 093002 (2019)

- **SU(3) flavor analysis — Tree**

PDG $> 4\sigma$

$(1.43 \pm 0.32)\,\%$

SU(3)

$(2.72 \pm 0.09)\,\%$

Belle $< 2\sigma$

$(1.80 \pm 0.52)\,\%$

$\mathscr{B}(\Xi_c^0 \to \Xi^- e^+ \nu_e) = (2.38 \pm 0.44)\,\%$

$\times$

LQCD, CPC **46**, 011002 (2022); also Wang's talk in this morning.

$$\frac{\mathscr{B}(\Xi_c^0 \to \Xi^- \pi^+)}{\mathscr{B}(\Xi_c^0 \to \Xi^- e^+ \nu_e)} = 1.37 \pm 0.08$$

Belle, PRL **127** 121803 (2021)

||

$\mathscr{B}(\Xi_c^0 \to \Xi^- \pi^+) = (3.26 \pm 0.63)\,\%$

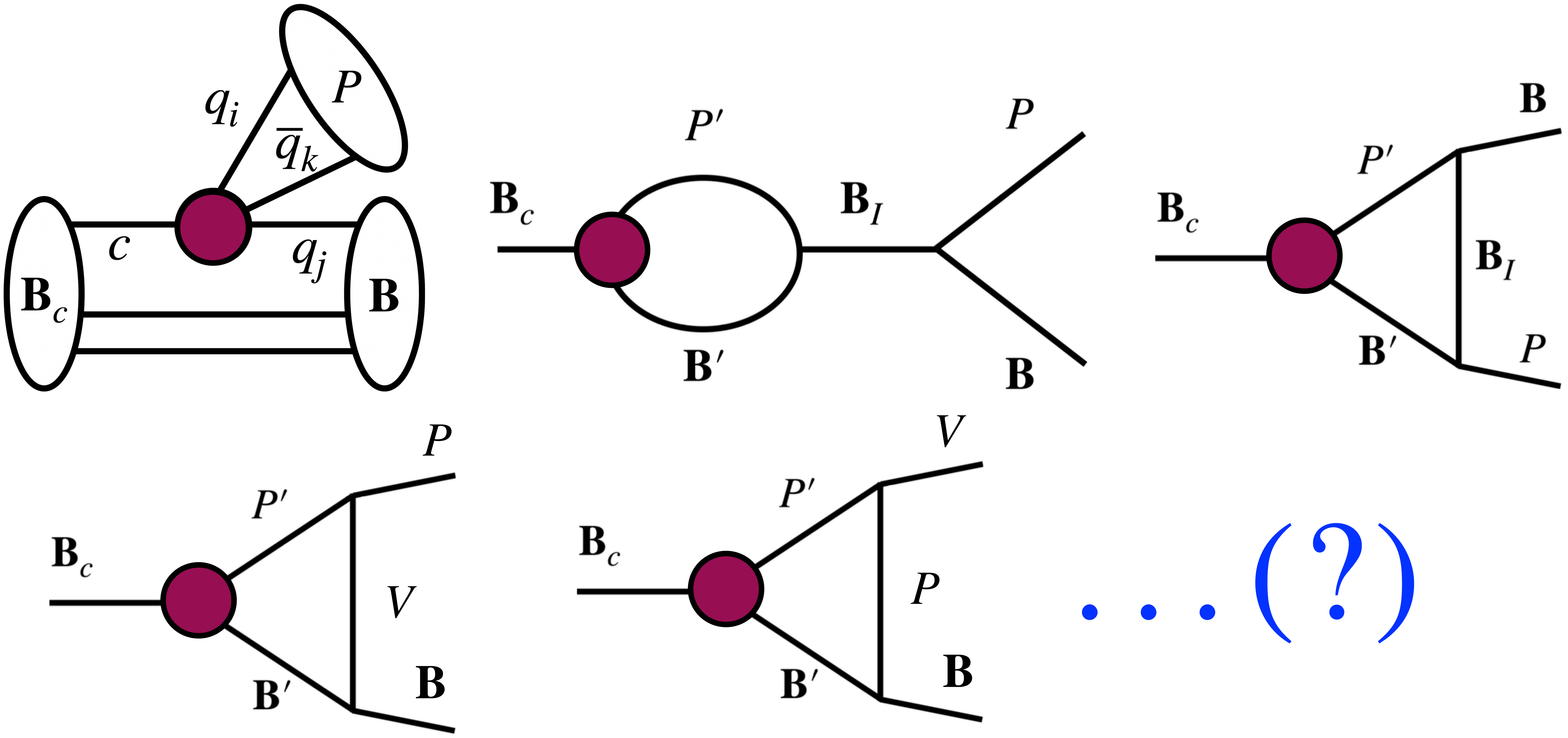
$$\beta = \frac{2\,\mathrm{Im}\,(S^*P)}{|S|^2 + |P|^2}$$

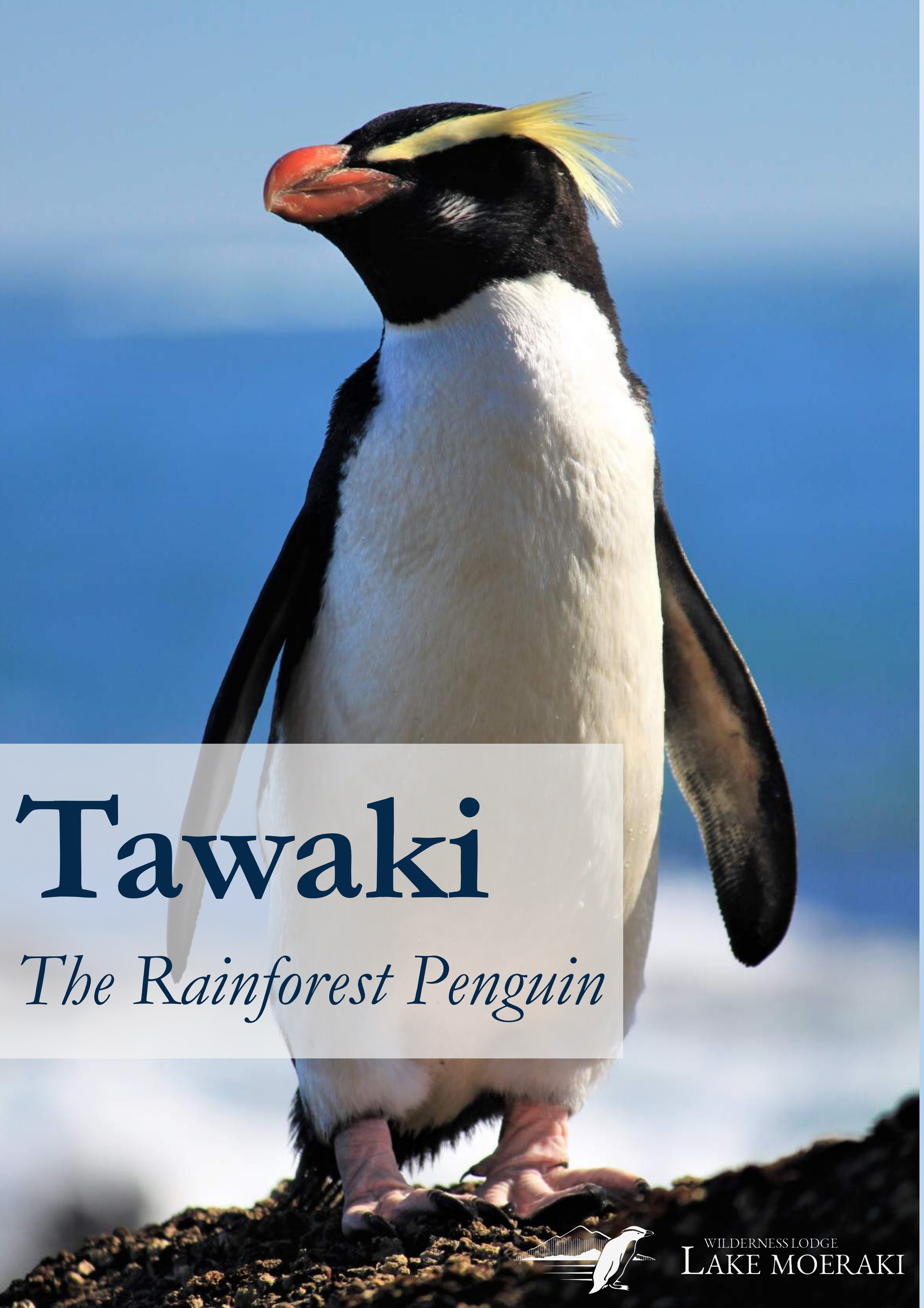
Channels	$\mathcal{B}_{exp}(\%)$	α_{exp}	$\mathcal{B}(\%)$	α	β
$\Lambda_c^+ \to pK_S$	1.59(8)	*0.18(45)	1.55(7)	−0.40(49)	0.32(29)
$\Lambda_c^+ \to \Lambda^0\pi^+$	1.30(6)	−0.755(6)	1.29(5)	−0.75(1)	−0.13(19)
$\Lambda_c^+ \to \Sigma^0\pi^+$	1.27(6)	−0.466(18)	1.27(5)	−0.47(2)	0.88(2)
$\Lambda_c^+ \to \Sigma^+\pi^0$	1.25(10)	−0.48(3)	1.27(5)	−0.47(2)	0.88(2)
$\Lambda_c^+ \to \Xi^0 K^+$	**0.55(7)	0.01(16)	0.40(3)	−0.15(14)	−0.29(22)
$\Lambda_c^+ \to \Lambda^0 K^+$	0.064(3)	−0.585(52)	0.063(3)	−0.56(5)	0.82(5)
$\Lambda_c^+ \to \Sigma^0 K^+$	0.0382(25)	−0.54(20)	0.0365(21)	−0.52(10)	0.48(24)
$\Lambda_c^+ \to n\pi^+$	0.066(13)		0.067(8)	−0.78(12)	−0.63(15)
$\Lambda_c^+ \to \Sigma^+ K_S$	0.048(14)		0.036(2)	−0.52(10)	0.48(24)
$\Lambda_c^+ \to p\pi^0$	< 0.008		0.02(1)		−0.82(32)
$\Lambda_c^+ \to \Sigma^+\eta$	0.32(4)	−0.99(6)	0.32(4)	−0.93(4)	−0.32(16)
$\Lambda_c^+ \to p\eta$	0.142(12)		0.145(26)	−0.42(61)	0.64(40)
$\Lambda_c^+ \to \Sigma^+\eta'$	0.437(84)	−0.46(7)	0.420(70)	−0.44(25)	0.86(6)
$\Lambda_c^+ \to p\eta'$	0.0484(91)		0.0520(114)	−0.59(9)	0.76(14)
$\Xi_c^+ \to \Xi^0\pi^+$	1.6(8)		0.90(16)	−0.94(6)	0.32(21)
$\Xi_c^0 \to \Xi^-\pi^+$	****1.43(32)	* − 0.64(5)	2.72(9)	−0.71(3)	0.36(20)
Channels	$\mathcal{R}_X^{exp}$	α_{exp}	$\mathcal{R}_X$	α	β
$\Xi_c^0 \to \Lambda^0 K_S$	0.225(13)		0.233(9)	−0.47(29)	0.66(20)
$\Xi_c^0 \to \Xi^- K^+$	**0.0275(57)		0.0410(4)	−0.75(4)	0.38(20)
$\Xi_c^0 \to \Sigma^0 K_S$	0.038(7)		0.038(7)	−0.07(117)	−0.83(28)
$\Xi_c^0 \to \Sigma^+ K^-$	0.123(12)		0.132(11)	−0.21(18)	−0.39(29)

arXiv:2310.05491 [hep-ph]

- **Rescattering, solving penguin/tree**

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





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.

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-