Large CP violation in charmed baryon decays

Based on SU(3) flavor symmetry

arXiv : 2404.19166

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• Experimental status of charmed hadron decays

2019: First evidence of CP violation in charm sector

PRL **122**, 211803 (2019)

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

An order larger than theoretical expectations!

* First evidence of CP violation in charm hadron decays.

2022: 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 violation measurement by far in charmed baryons.

2023: Measurements of strong phases 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!

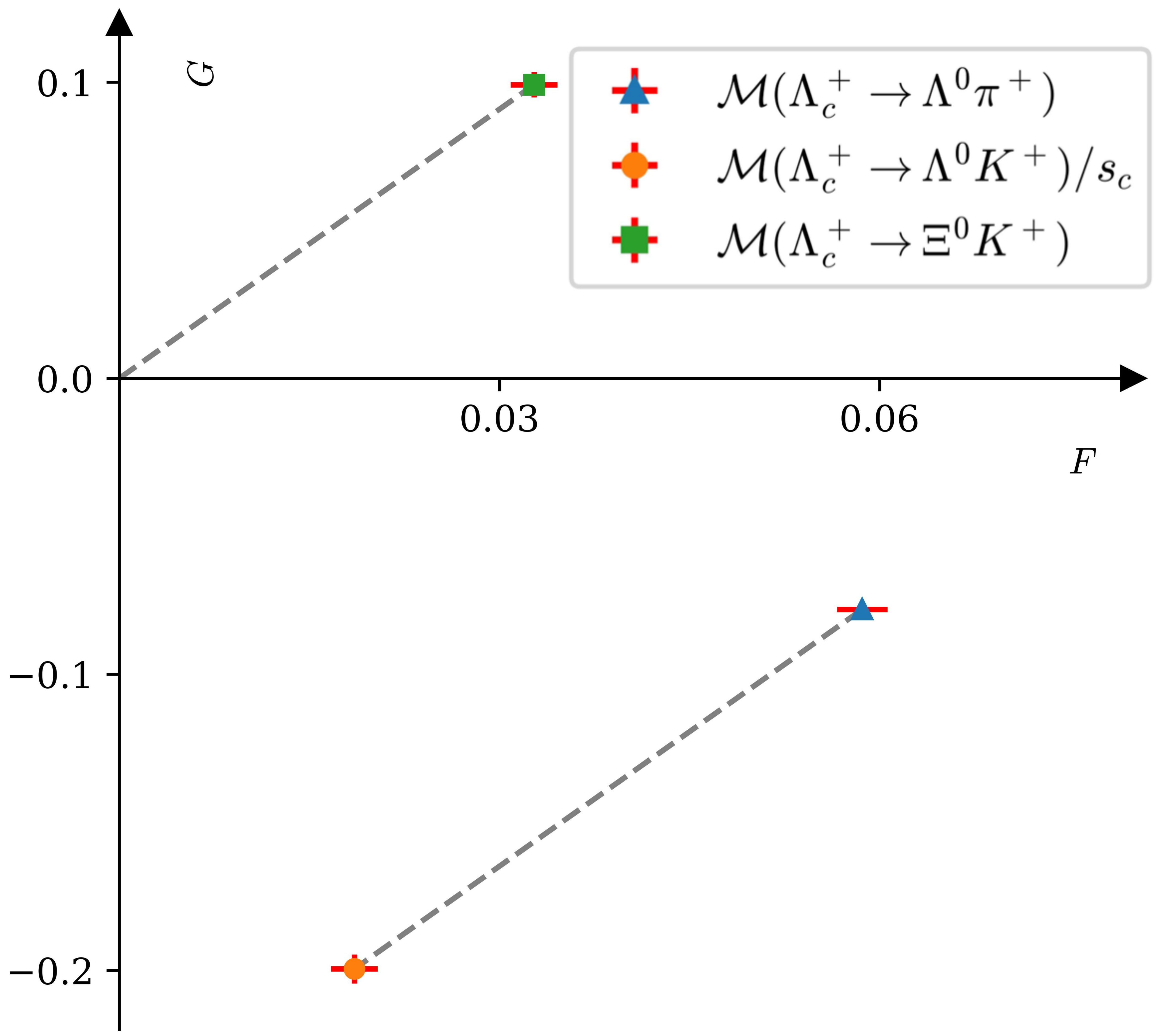
• Experimental status of charmed hadron decays

The SU(3) flavor relation:

$$\Gamma = \frac{p_f}{8\pi}\frac{\left(M_i + M_f\right)^2 - M_P^2}{M_i^2}\left(|F|^2 + \kappa^2|G|^2\right), \quad \alpha = \frac{2\kappa\,\mathrm{Re}\,(F^*G)}{|F|^2 + \kappa^2|G|^2}$$

$$F(\Lambda_c^+ \to \Xi^0 K^+) = \frac{2}{\sqrt{6}}F(\Lambda_c^+ \to \Lambda^0\pi^+) - \frac{1}{s_c}F(\Lambda_c^+ \to \Lambda^0 K^+)$$

If F and G are real, they are solvable from experimental Γ and α!



→ Leads to $|\alpha(\Lambda_c^+ \to \Xi^0 K^+)| \approx 1$

2023: Measurements of strong phases in $\Lambda_c^+ \to \Xi^0 K^+$

PRL **132**, 031801 (2024)

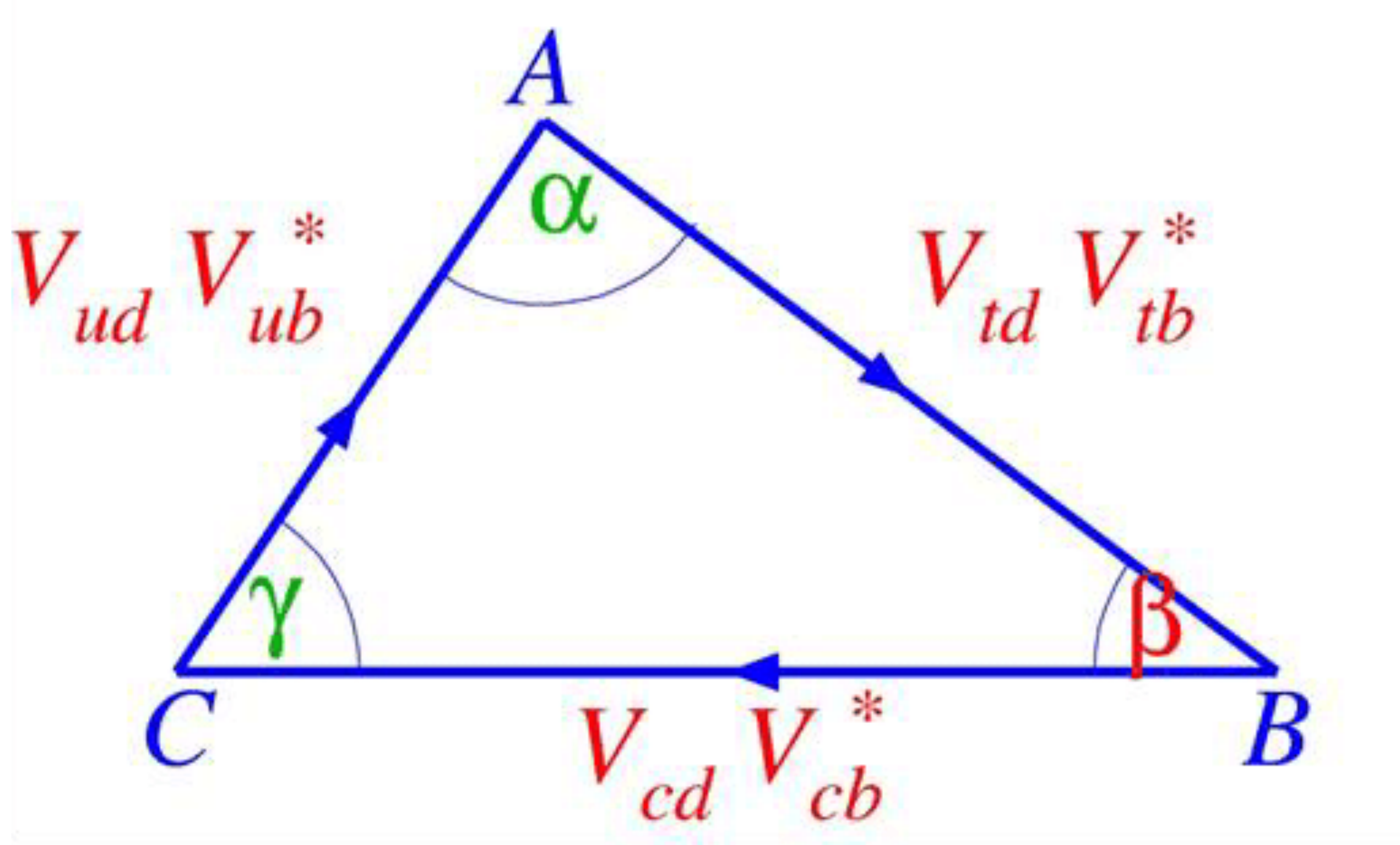
$$\delta_P - \delta_S = -1.55 \pm 0.27 (+\pi), \quad \alpha = 0.01 \pm 0.16$$

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

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

S wave amplitude : $V_{cs}V_{us}^{*}\overbrace{F^{s-d}}^{5\text{ parameters}} + V_{cb}V_{ub}^{*}\overbrace{F^{b}}^{4\text{ parameters}}$

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



CKM triangle for $b \to d$

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

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

CKM triangle for $c \to u$

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

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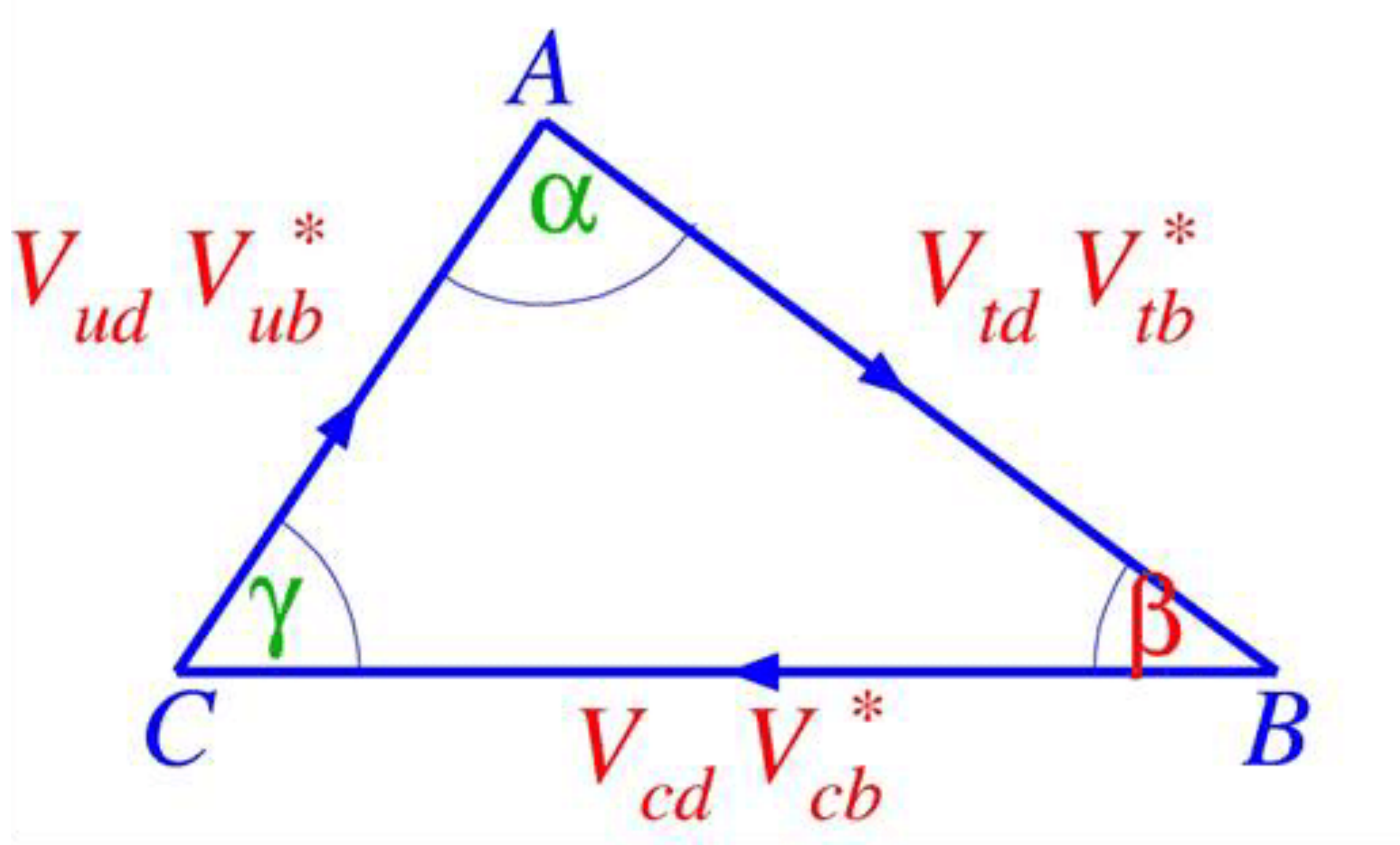
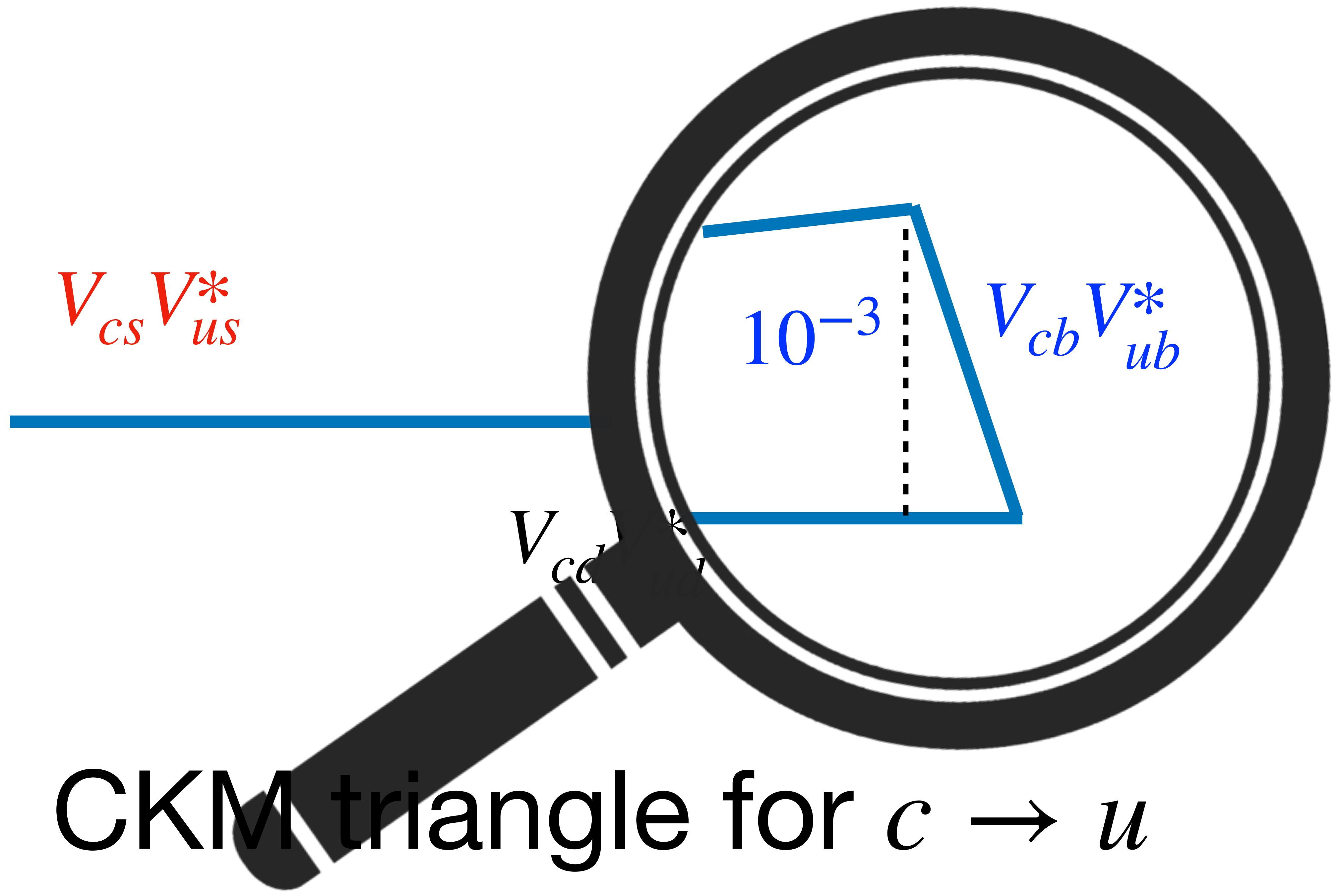


CKM triangle for $b \to d$



CKM triangle for $c \to u$

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

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

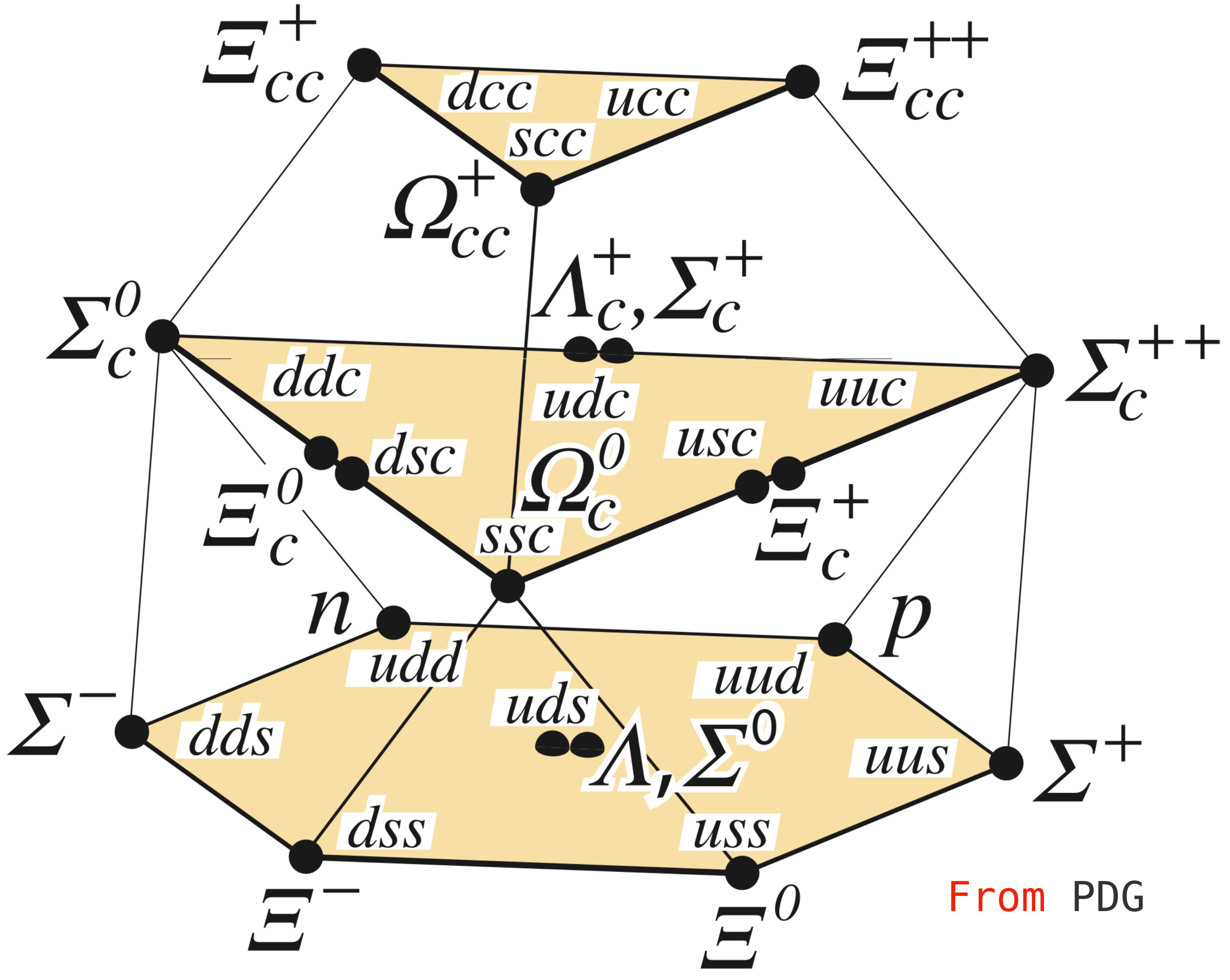
• SU(3) flavor analysis — Tree

SU(3) flavor representations :

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

$$\mathbf{B} = \begin{pmatrix} \frac{1}{\sqrt{6}}\Lambda + \frac{1}{\sqrt{2}}\Sigma^0 & \Sigma^+ & p \\ \Sigma^- & \frac{1}{\sqrt{6}}\Lambda - \frac{1}{\sqrt{2}}\Sigma^0 & n \\ \Xi^- & \Xi^0 & -\sqrt{\frac{2}{3}}\Lambda \end{pmatrix},$$

$$P = \begin{pmatrix} \frac{1}{\sqrt{2}}(\pi^0 + c_\phi\eta + s_\phi\eta') & \pi^+ & K^+ \\ \pi^- & \frac{1}{\sqrt{2}}(-\pi^0 + c_\phi\eta + s_\phi\eta') & K^0 \\ K^- & \bar{K}^0 & -s_\phi\eta + c_\phi\eta' \end{pmatrix},$$



From PDG

- **SU(3) flavor analysis — Tree**

*V − A dirac strucutre implied

$$\mathscr{H}_{eff} = \frac{G_F}{\sqrt{2}} \left[\sum_{q=d,s} \lambda_q \left(C_1(\bar{u}q)(\bar{q}c) + C_2(\bar{q}q)(\bar{u}c) \right) + \lambda_b \sum_{i=3\sim6} C_i Q_i \right] + \text{(H.c.)}$$

$$\lambda_q = V^*_{cq} V_{uq} \qquad \lambda_d + \lambda_s + \lambda_b = 0$$

Cabibbo-suppressed decays $(c \to u)$

S wave amplitude : $\dfrac{\lambda_s - \lambda_d}{2} F^{s-d} + \lambda_b F^b$

$$\begin{aligned} \mathcal{H}_{eff} \; = \; & \frac{G_F}{\sqrt{2}} \Big\{ \boxed{\frac{\lambda_s - \lambda_d}{2}} \Big[C_+ \big((\bar{u}s)(\bar{s}c) + (\bar{s}s)(\bar{u}c) - (\bar{d}d)(\bar{u}c) - (\bar{u}d)(\bar{d}c) \big)_{\mathbf{15}} \\ & + C_- \big((\bar{u}s)(\bar{s}c) - (\bar{s}s)(\bar{u}c) + (\bar{d}d)(\bar{u}c) - (\bar{u}d)(\bar{d}c) \big)_{\bar{\mathbf{6}}} \Big] \\ & - \boxed{\frac{\lambda_b}{4}} \Big[C_+ \big((\bar{u}d)(\bar{d}c) + (\bar{d}d)(\bar{u}c) + (\bar{s}s)(\bar{u}c) + (\bar{u}s)(\bar{s}c) - 2(\bar{u}u)(\bar{u}c) \big)_{\mathbf{15}} \\ & + C_+ \sum_{q=u,d,s} \big((\bar{u}q)(\bar{q}c) + (\bar{q}q)(\bar{u}c) \big)_{\mathbf{3}_+} + 2C_- \sum_{q=d,s} \big((\bar{u}q)(\bar{q}c) - (\bar{q}q)(\bar{u}c) \big)_{\mathbf{3}_-} \Big] \Big\} \end{aligned}$$

Leading terms

Provide CP phase

• SU(3) flavor analysis — Tree

S wave amplitude : $\dfrac{\lambda_s - \lambda_d}{2} F^{s-d} + \lambda_b F^b$

Generalized Wigner-Eckart theorem

$\tilde{f}$:Free parameters

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

$$+ \tilde{f}^d \mathcal{H}(\overline{\mathbf{6}}^{\mathbf{C}})_{ij} (\mathbf{B}^\dagger)^i_k (P^\dagger)^j_l (\mathbf{B}_c)^{kl} + \tilde{f}^e (\mathbf{B}^\dagger)^j_i \mathcal{H}(\mathbf{15}^{\mathbf{C}})^{\{ik\}}_l (P^\dagger)^l_k (\mathbf{B}_c)_j \,,$$

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

$$+ \tilde{f}^c_{\mathbf{3}} (\mathbf{B}_c)_i \mathcal{H}(\mathbf{3}^b)^i (\mathbf{B}^\dagger)^j_k (P^\dagger)^k_j + \tilde{f}^d_{\mathbf{3}} (\mathbf{B}_c)_j \mathcal{H}(\mathbf{3}^b)^i (\mathbf{B}^\dagger)^j_k (P^\dagger)^k_i \,,$$

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

arXiv:2310.05491 [hep-ph]

- **SU(3) flavor analysis — Tree**

S wave amplitude : $\frac{\lambda_s - \lambda_d}{2} F^{s-d} + \cancel{\lambda_b F^b}$

Generalized Wigner-Eckart theorem

$\tilde{f}$:Free parameters

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

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

To date, there are in total $\underbrace{\textbf{30}}_{\text{CP-even}}$ data points but $\overset{\mathbf{5}}{\cancel{\mathbf{9}}} \times 2$(S & P waves) $\times\, 2$(complex) $- 1 = \overset{\mathbf{19}}{\cancel{\mathbf{35}}}$

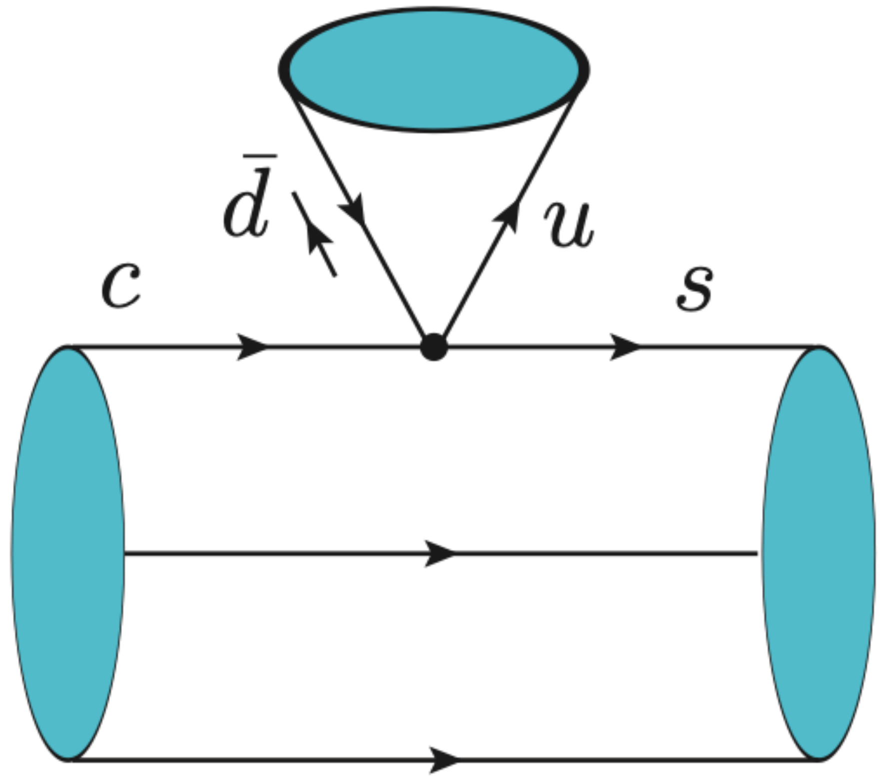
$\tilde{f}^{a,b,c,d,e}, \cancel{\tilde{f}_{\mathbf{3}}^{a,b,c,d}}$

arXiv:2310.05491 [hep-ph]

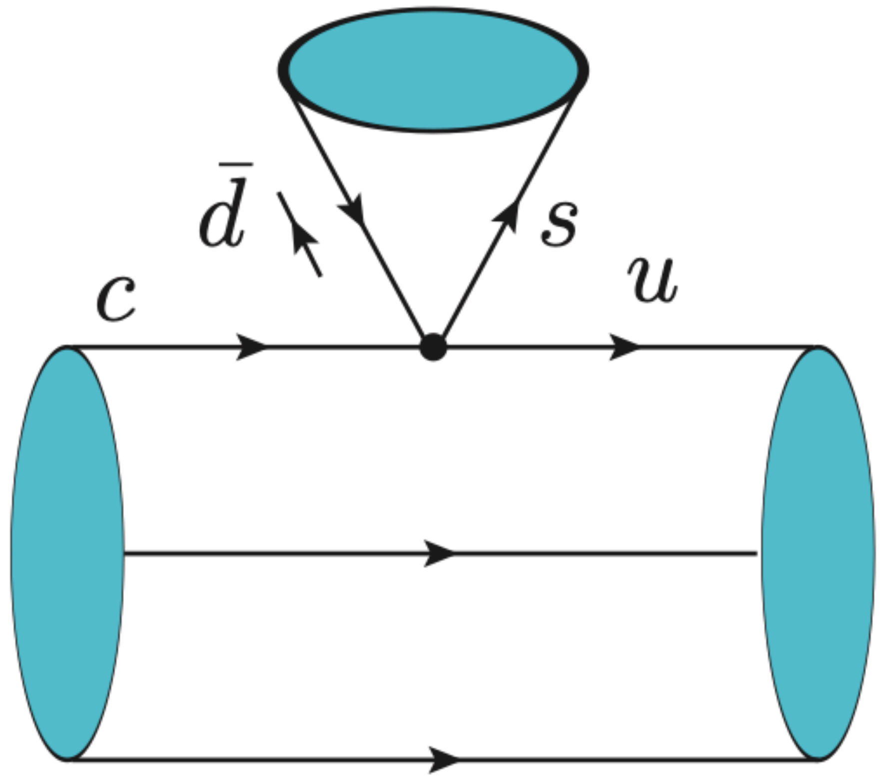
• SU(3) flavor analysis — Tree

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

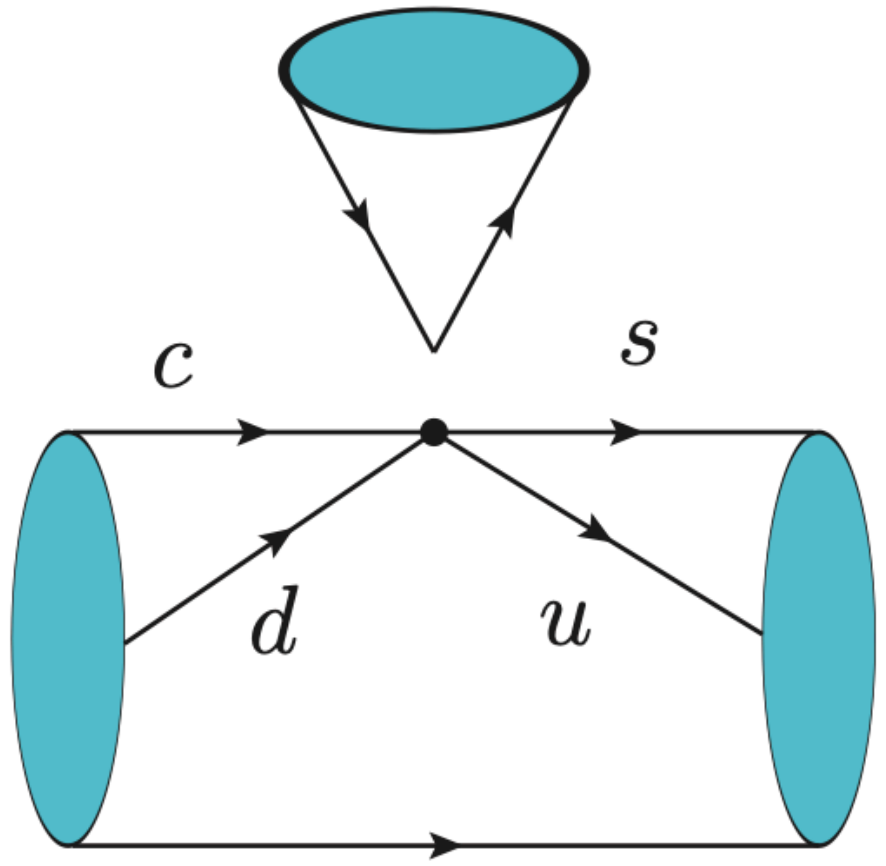
Equivalence to the quark diagrams analysis; see arXiv : 1811.03480, 2404.01350, 2406.14061



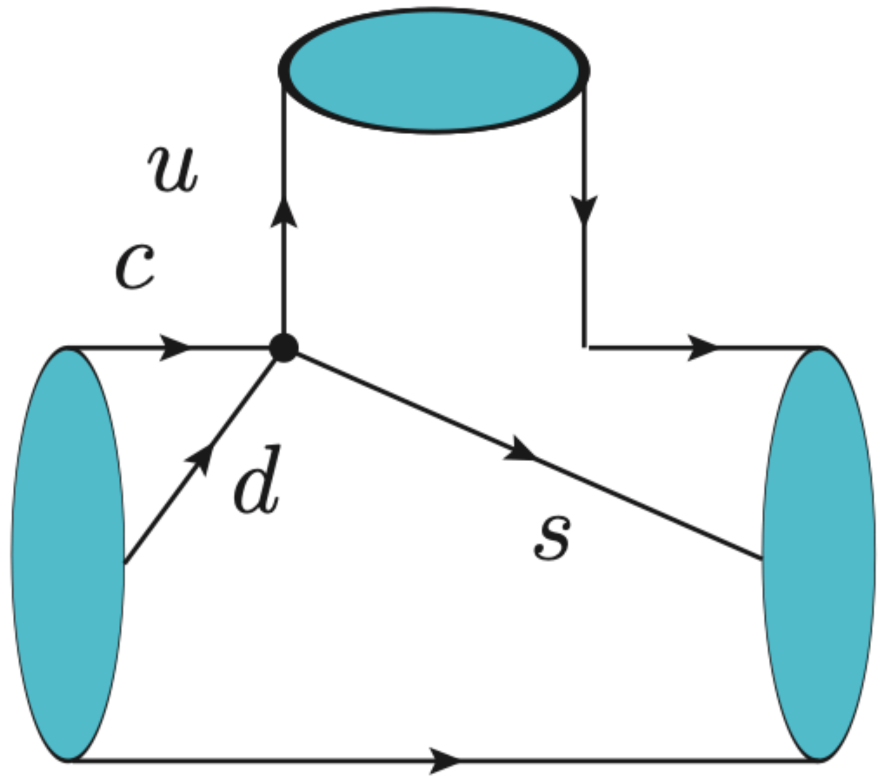
$(\bar{a}_1, \bar{a}_{15})$



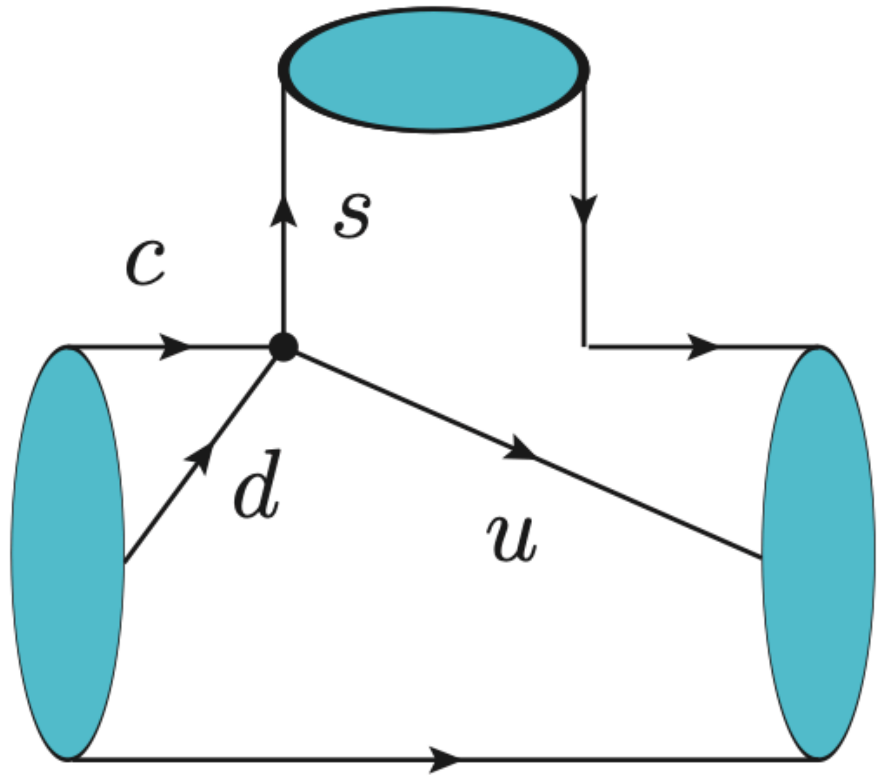
$(\bar{a}_2, \bar{a}_{16})$



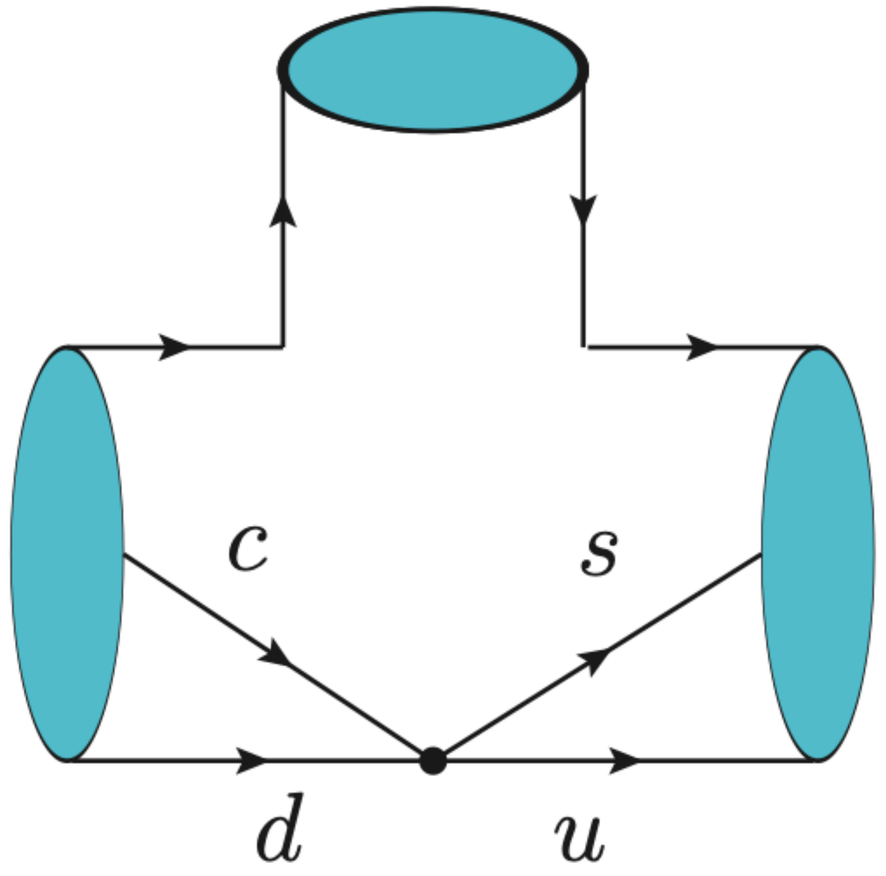
$(\bar{a}_3, \bar{a}_5, \bar{a}_9)$



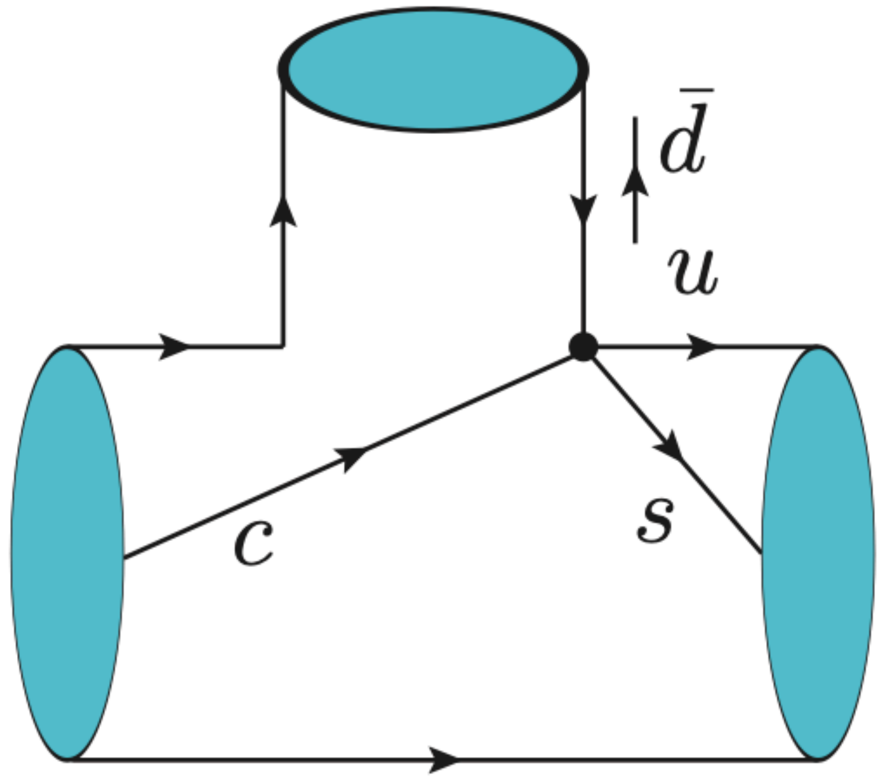
$(\bar{a}_4, \bar{a}_6, \bar{a}_{10})$



$(\bar{a}_7, \bar{a}_8, \bar{a}_{11})$



$(\bar{a}_{12}, \bar{a}_{13}, \bar{a}_{14})$



$(\bar{a}_{17}, \bar{a}_{18}, \bar{a}_{19})$

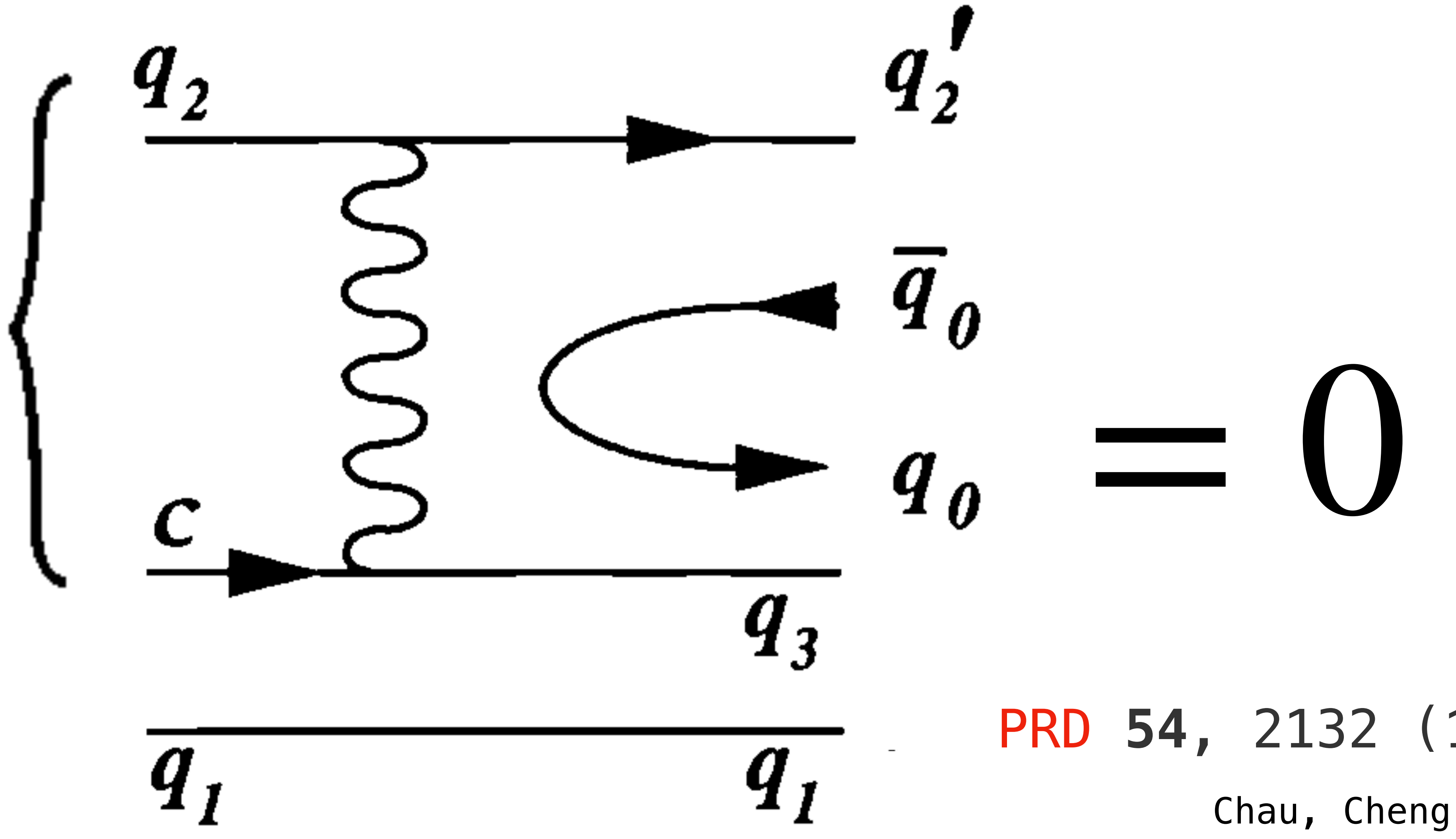
arXiv:2310.05491 [hep-ph]

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

- **Eliminate 4 redundancies in $\mathscr{H}(\mathbf{15})$**

- **Predict direct relations:**

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

PLB **794**, 19(2019)

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

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

arXiv:2406.04642

- **Works without considering color-symmetry**

PRD **93**, 056008 (2016), PRD **97**, 073006 (2018)
Lü, Wang, Yu   Geng, Hsiao, Liu, Tsai

JHEP **09**, 035 (2022), JHEP **03**, 143 (2022), NPB **956**, 115048 (2020)
Hsiao, Wang, Zhao   Huang, Xing, He   Jia, Wang, Yu

Not able to determine both complex phases.

arXiv:2310.05491 [hep-ph]

• SU(3) flavor analysis — Tree

• **Sizable strong phases are found.**

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

LQCD, CPC **46**, 011002 (2022)

$$\times$$

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

PRL **127** 121803 (2021)

$$||$$

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

Values within parentheses represent the backward digit count of uncertainties, such as $1.59(8) = 1.59 \pm 0.08$.

Channels	$\mathcal{B}_{\text{exp}}(\%)$	α_{exp}	$\mathcal{B}(\%)$	α	β
$\Lambda_c^+ \to pK_S$	$1.59(8)$	$^*0.18(45)$	$1.55(7)$	$-0.40(49)$	$0.32(29)$
$\Lambda_c^+ \to n\pi^+$	$0.066(13)$		$0.067(8)$	$-0.78(12)$	$-0.63(15)$
$\Lambda_c^+ \to \Sigma^+ K_S$	$0.048(14)$		$0.036(2)$	$-0.52(10)$	$0.48(24)$
$\Lambda_c^+ \to p\pi^0$	< 0.008		0.016(2)		$-0.82(32)$
$\Lambda_c^+ \to \Sigma^+\eta$	$0.32(4)$	$-0.99(6)$	$0.32(4)$	$-0.93(4)$	$-0.32(16)$
$\Lambda_c^+ \to p\eta$	$0.142(12)$		$0.145(26)$	$-0.42(61)$	$0.64(40)$
$\Lambda_c^+ \to \Sigma^+\eta'$	$0.437(84)$	$-0.46(7)$	$0.420(70)$	$-0.44(25)$	$0.86(6)$
$\Lambda_c^+ \to p\eta'$	$0.0484(91)$		$0.0520(114)$	$-0.59(9)$	$0.76(14)$
$\Xi_c^+ \to \Xi^0\pi^+$	$1.6(8)$		$0.90(16)$	$-0.94(6)$	$0.32(21)$
$\Xi_c^0 \to \Xi^-\pi^+$	$^{****}1.43(32)$	$^* - 0.64(5)$	$2.72(9)$	$-0.71(3)$	$0.36(20)$

29 data points with 10 complex parameters.

arXiv:2310.05491 [hep-ph]

- **SU(3) flavor analysis — Tree**

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

Generalized Wigner-Eckart theorem

$\tilde{f}$:Free parameters

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

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

Naive assumption: $\tilde{f}^{a,b,c,d}_{\mathbf{3}} \to 0$

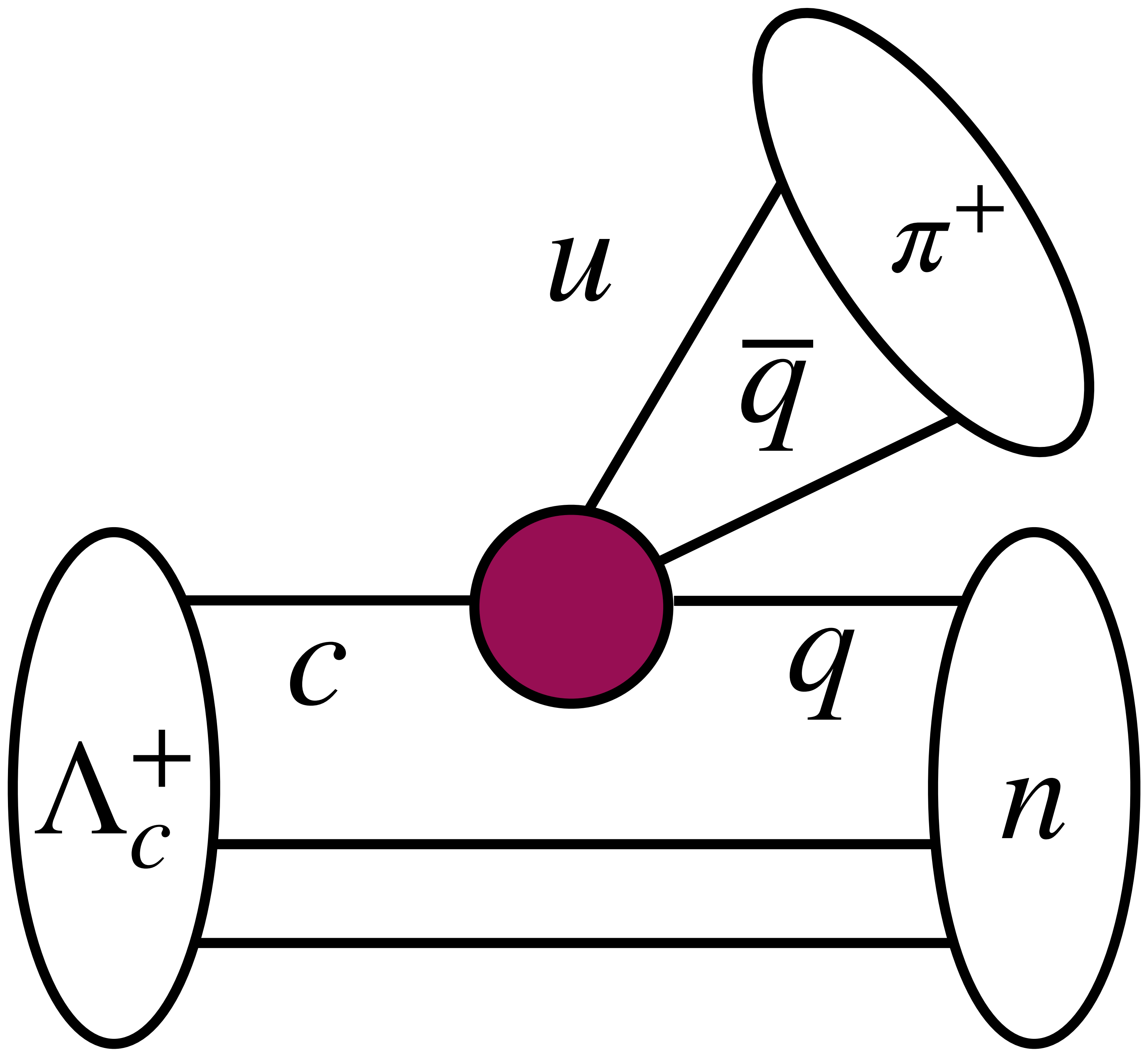
To date, there are in total $\underbrace{\textbf{30}}_{\text{CP-even}}$ data points and $\mathbf{5} \times 2$(S & P waves) $\times\, 2$(complex) $- 1 = \mathbf{19}$

arXiv:2310.05491 [hep-ph]

SU(3) flavor analysis — Tree

$A_{CP}(\Lambda_c^+ \to n\pi^+) \neq 0$, as parts of the tree interaction contain penguin topology.

$$\mathscr{H}_{eff}^{\mathrm{Tree}} = \frac{G_F}{\sqrt{2}}\lambda_b\Bigg(C_+ \sum_{q=u,d,s}((\bar{u}q)(\bar{q}c) + (\bar{q}q)(\bar{u}c)) + 2C_- \sum_{q=d,s}((\bar{u}q)(\bar{q}c) - (\bar{q}q)(\bar{u}c))\Bigg)_{\mathbf{3}} \cdots$$



Too small compared to *D* meson's:

$$A_{CP}^{dir}(D^0 \to K^+K^-) - A_{CP}^{dir}(D^0 \to \pi^+\pi^-)$$

$$= (-1.54 \pm 0.29) \times 10^{-3}$$

Channels	$\mathcal{B}(10^{-3})$	$A_{CP}^{\alpha}(10^{-3})$	$A_{CP}(10^{-3})$
$\Lambda_c^+ \to p\pi^0$	0.16(2)	−0.61(39)	0.42(1.15)
$\Lambda_c^+ \to p\eta$	1.45(25)	0.05(17)	−0.24(26)
$\Lambda_c^+ \to p\eta'$	0.52(11)	−0.02(7)	0.08(2)
$\Lambda_c^+ \to n\pi^+$	0.67(8)	0.12(20)	−0.15(42)
$\Lambda_c^+ \to \Lambda^0 K^+$	0.63(2)	−0.03(10)	0.19(18)

SU(3) flavor analysis

$$V^*_{cs} V_{us} \text{ Tree} + \underbrace{\cancel{V^*_{cb} V_{ub} \text{ Penguin}}}_{}$$

Insensitive to CP-even quantities & undetermined

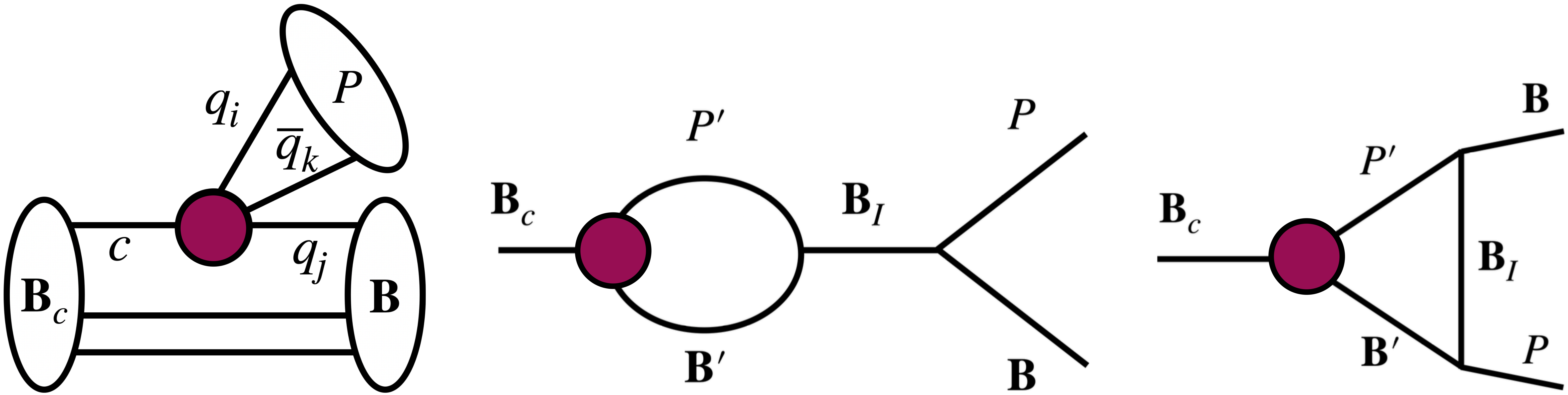
Final State Rescattering

$$V^*_{cs} V_{us} \text{ Tree} + V^*_{cb} V_{ub} \text{ Tree} \times \underbrace{(\text{ Penguin / Tree })}_{}$$

Determined by the rescattering

- **Rescattering, solving penguin/tree**

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

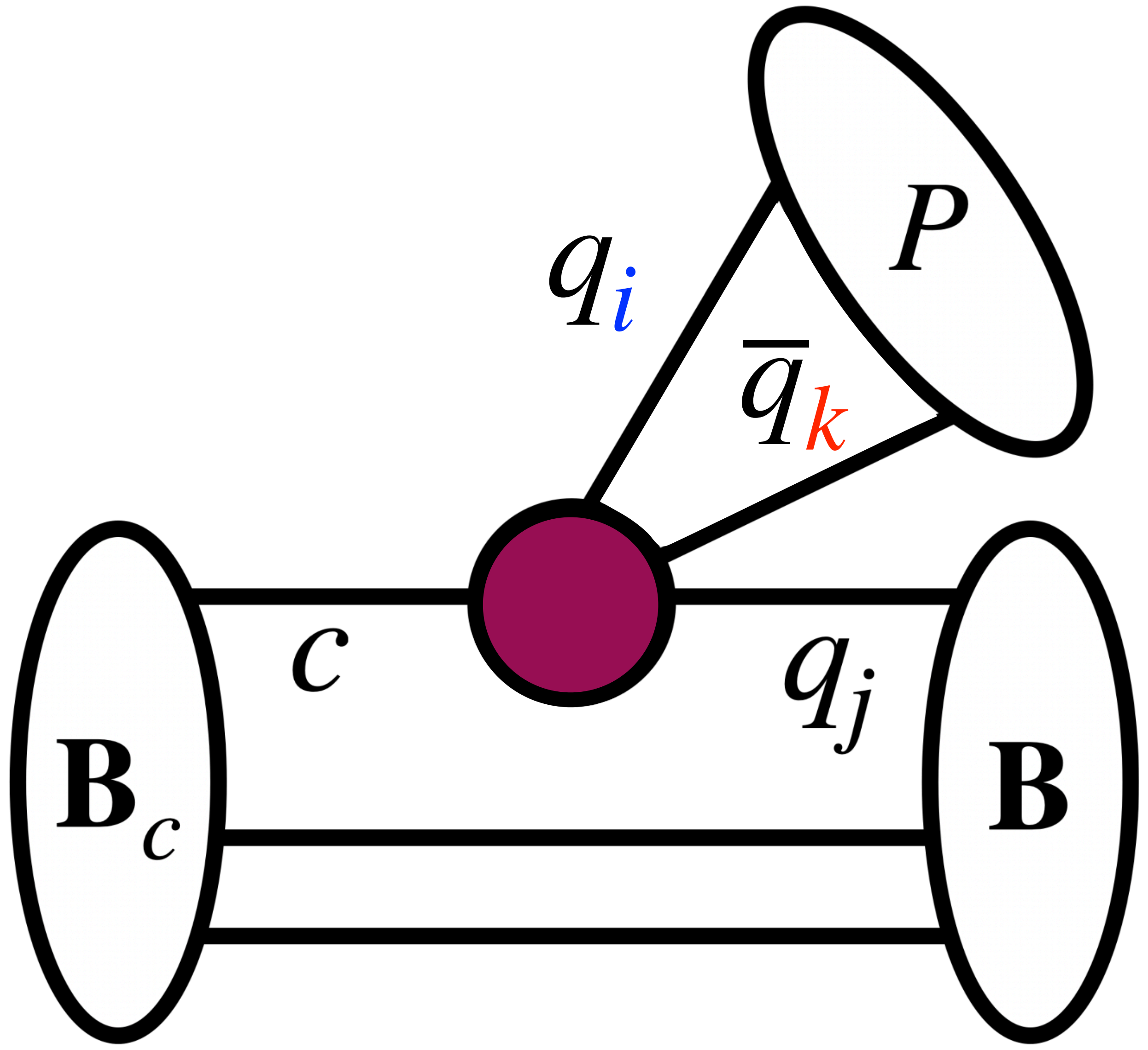


Assumptions:

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

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

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

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

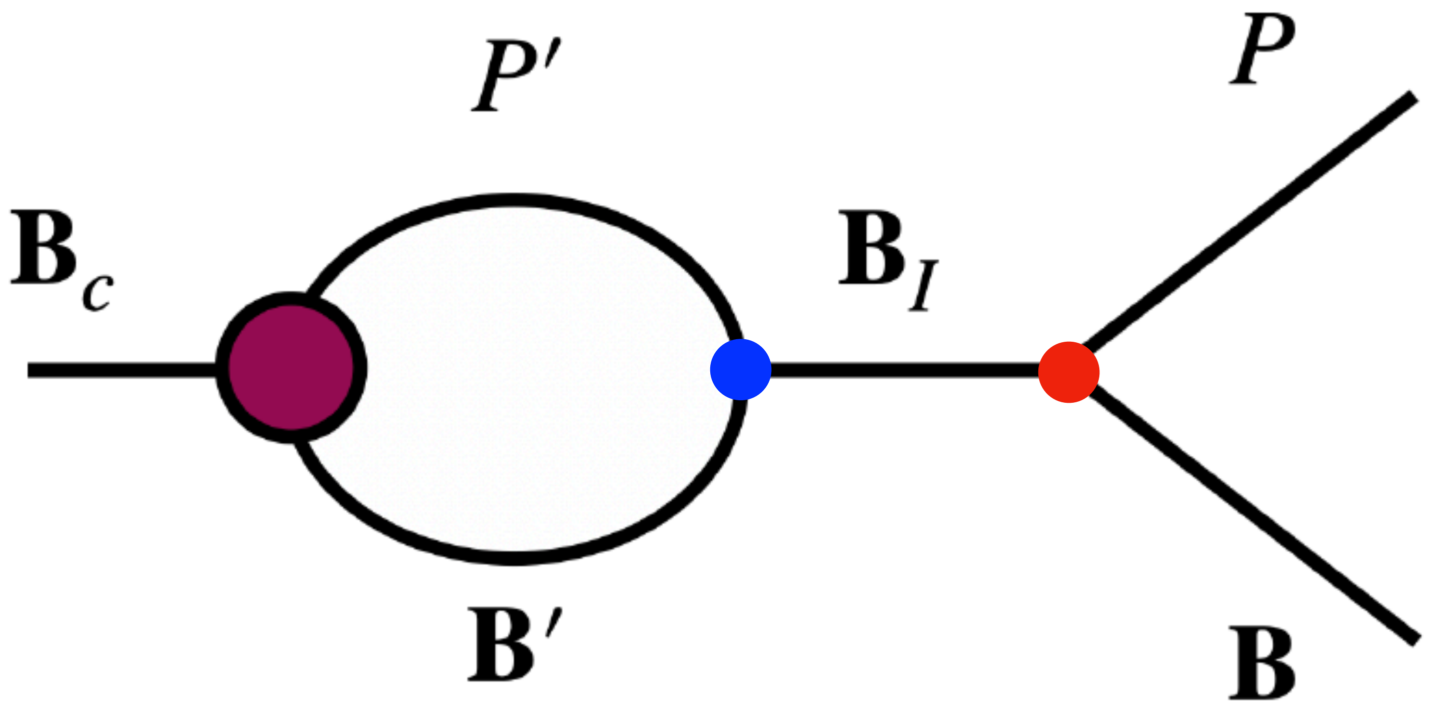
It is very important that $\mathbf{15}$, $\overline{\mathbf{6}}$ and $\mathbf{3}$ share two parameters $\tilde{F}^\pm_V$!

- **Rescattering, solving penguin/tree**

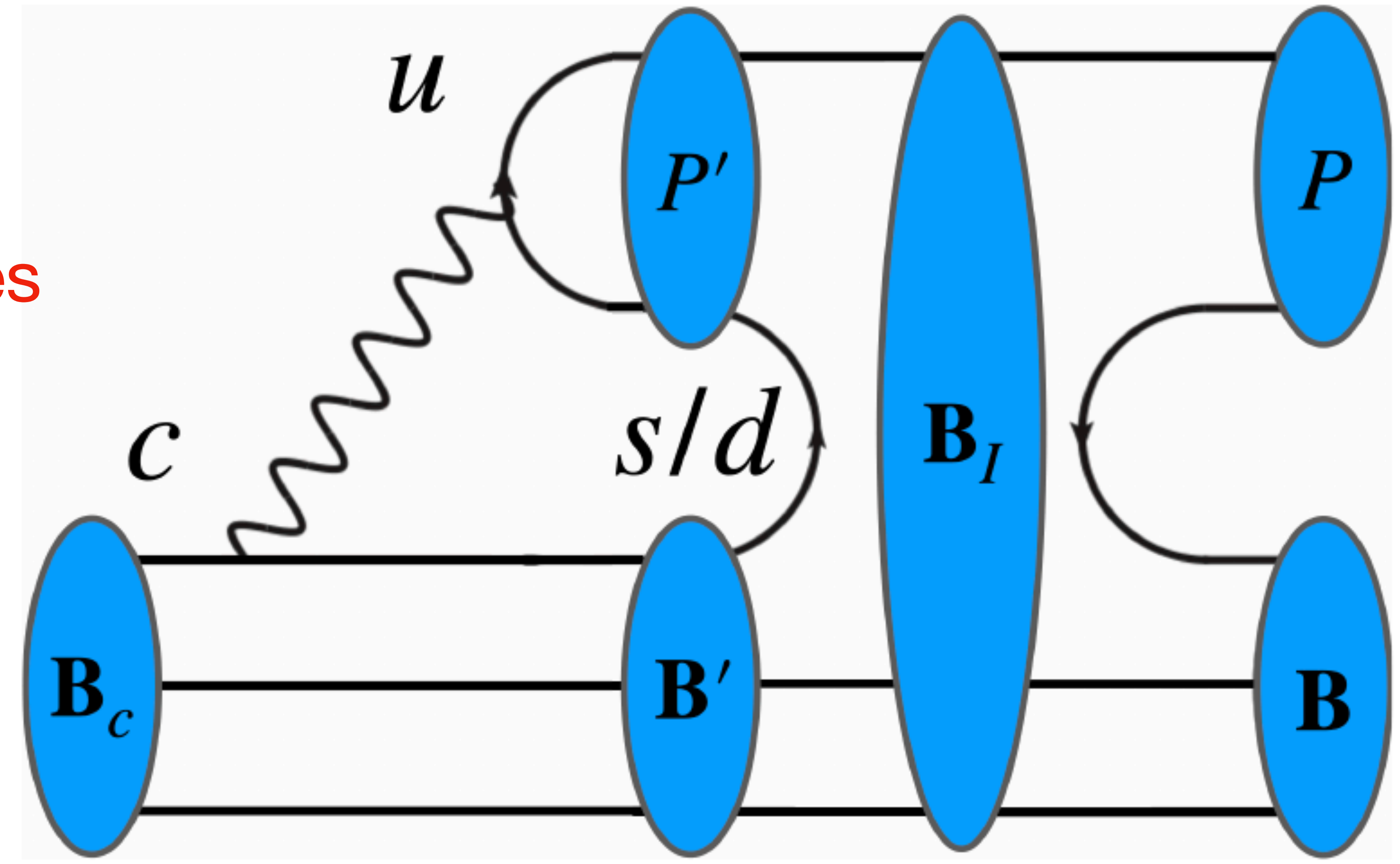
$$\langle \mathscr{L}^{\mathrm{FSR-s}}_{\mathbf{B}_c\mathbf{B}P} \rangle = \sum_{\mathbf{B}_I,\mathbf{B}',P'} \bar{u}_{\mathbf{B}} \left(\int \frac{d^4q}{(2\pi)^4} g_{\mathbf{B}_I\mathbf{B}P} \frac{p^\mu_{\mathbf{B}_c}\gamma_\mu + m_I}{p^2_{\mathbf{B}_c} - m_I^2} g_{\mathbf{B}_I\mathbf{B}'P'} \frac{q^\mu\gamma_\mu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

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'.



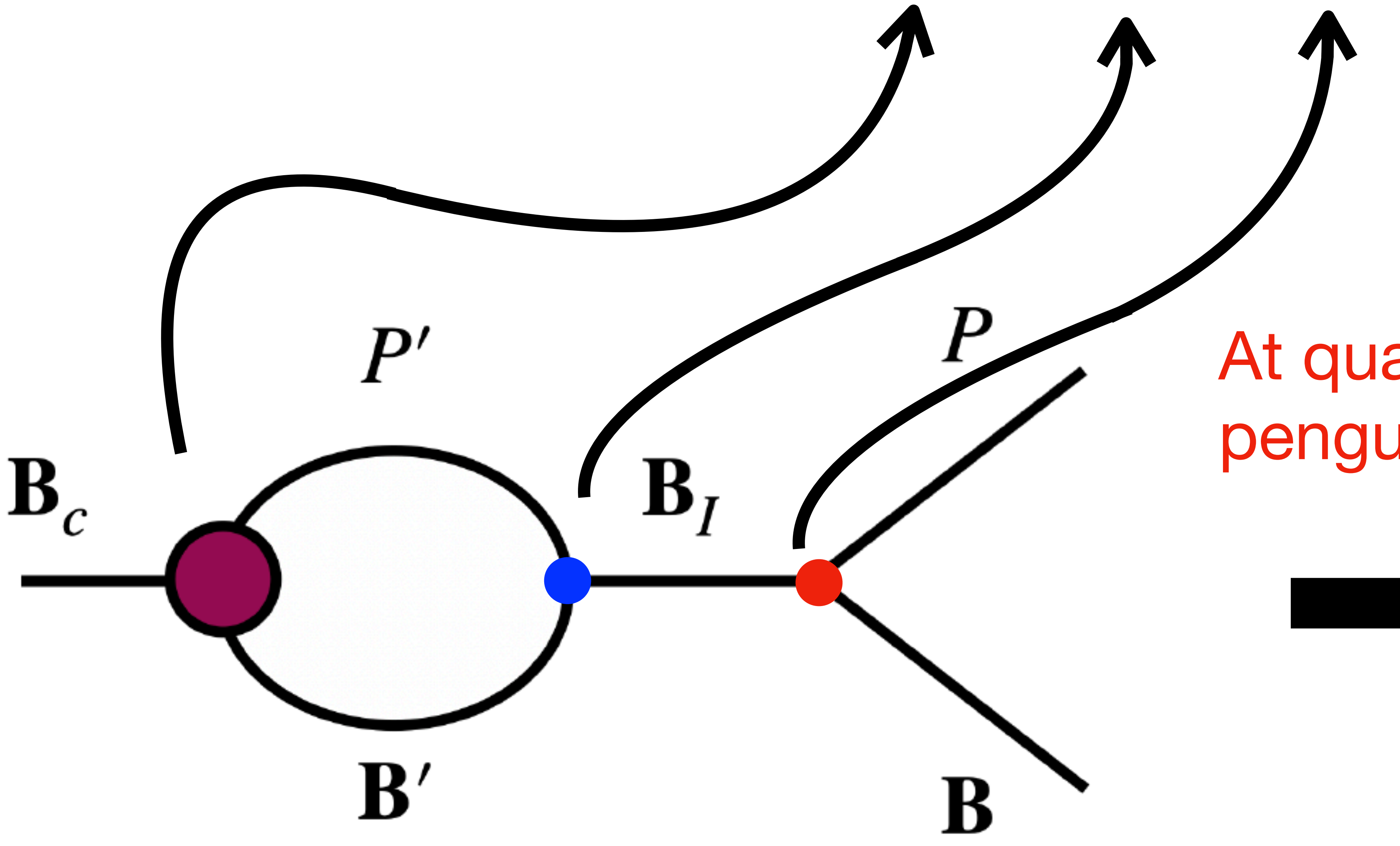
At quark level generates penguin topology



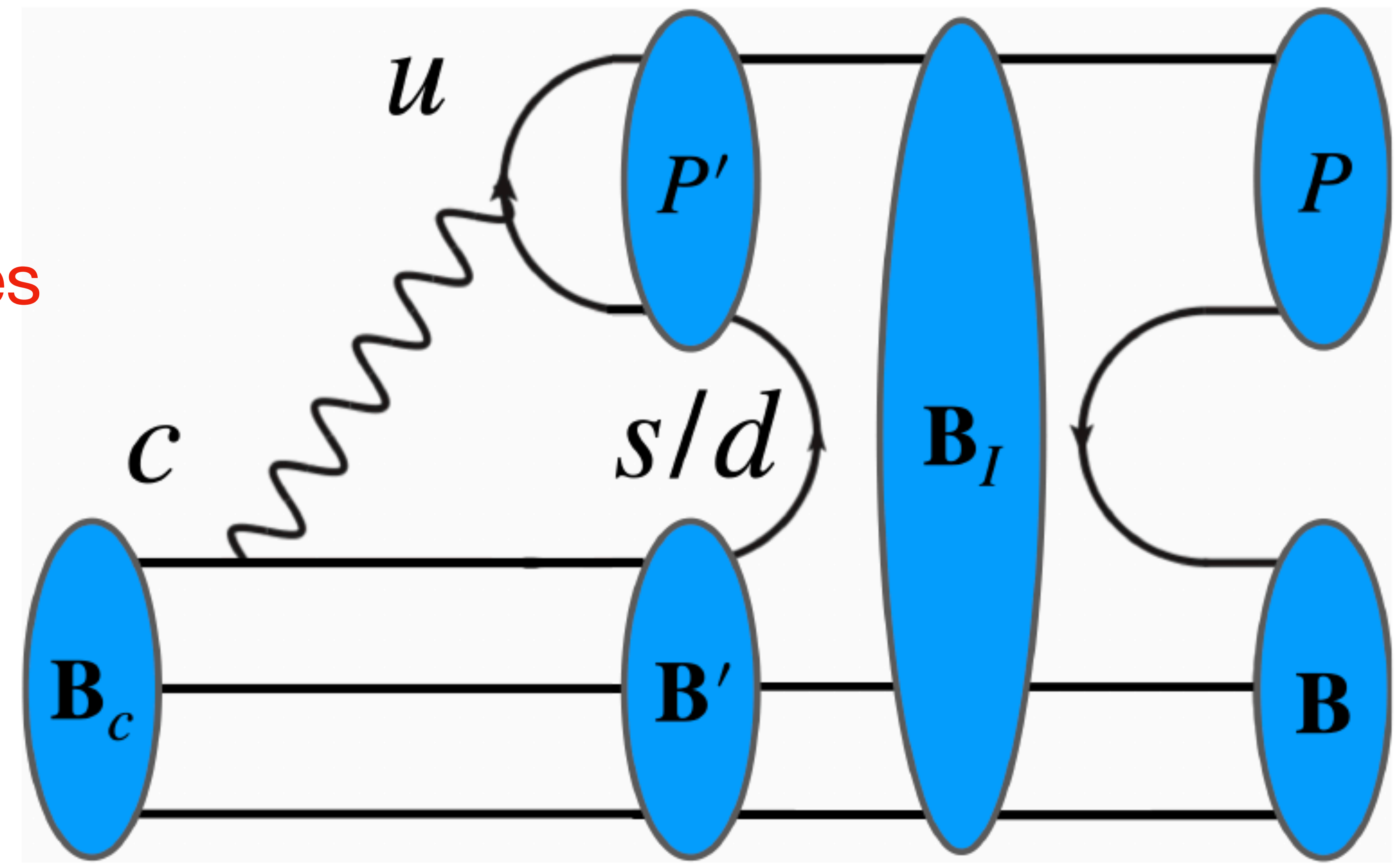
- **Rescattering, solving penguin/tree**

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

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



At quark level generates penguin topology



Rescattering, solving penguin/tree

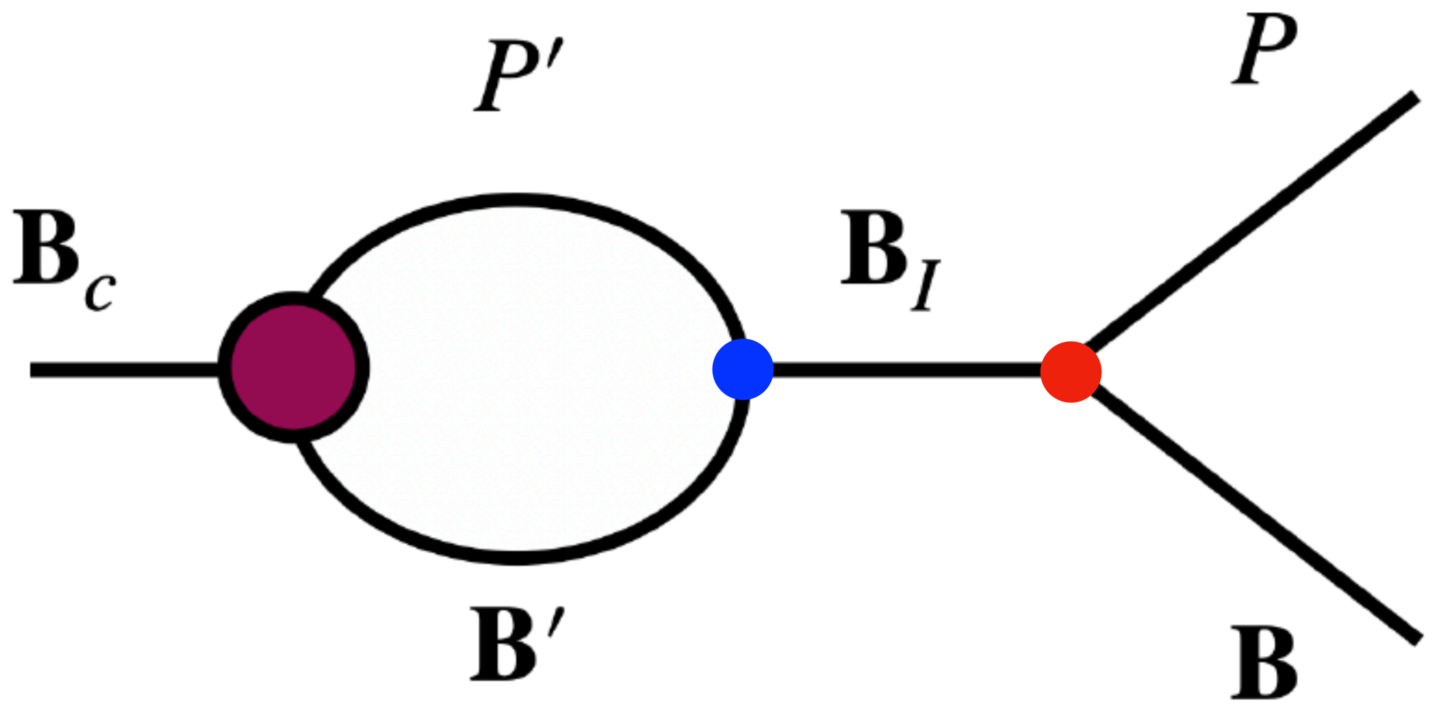
$$\sum_{\mathbf{B}_I,\mathbf{B}',P'} F^{\rm Tree}_{\mathbf{B}_c\mathbf{B}'P'}\, g_{\mathbf{B}_I\mathbf{B}'P'}\, g_{\mathbf{B}_I\mathbf{B}P}$$

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

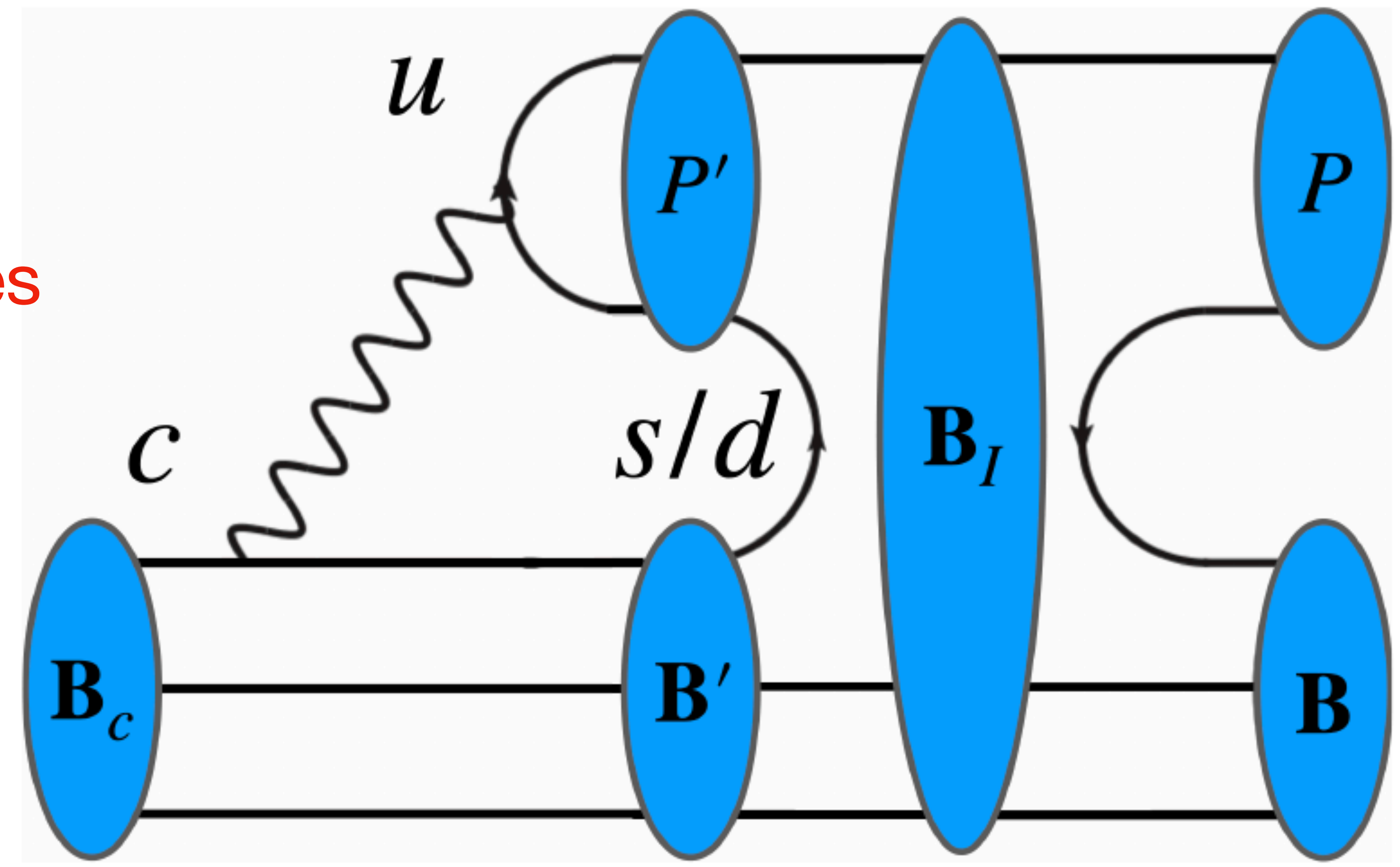
Substitute $\sum_{\mathbf{B}_I} \langle \overline{\mathbf{B}}_I\rangle^{k_1}_{i_1}\langle \mathbf{B}_I\rangle^{j_2}_{k_2}$ with $\frac{1}{2}\sum_{\lambda_a}(\lambda_a)^{k_1}_{i_1}(\lambda_a)^{j_2}_{k_2} = \delta^{j_2}_{i_1}\delta^{k_1}_{k_2} - \frac{1}{3}\delta^{k_1}_{i_1}\delta^{j_2}_{k_2}$

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

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

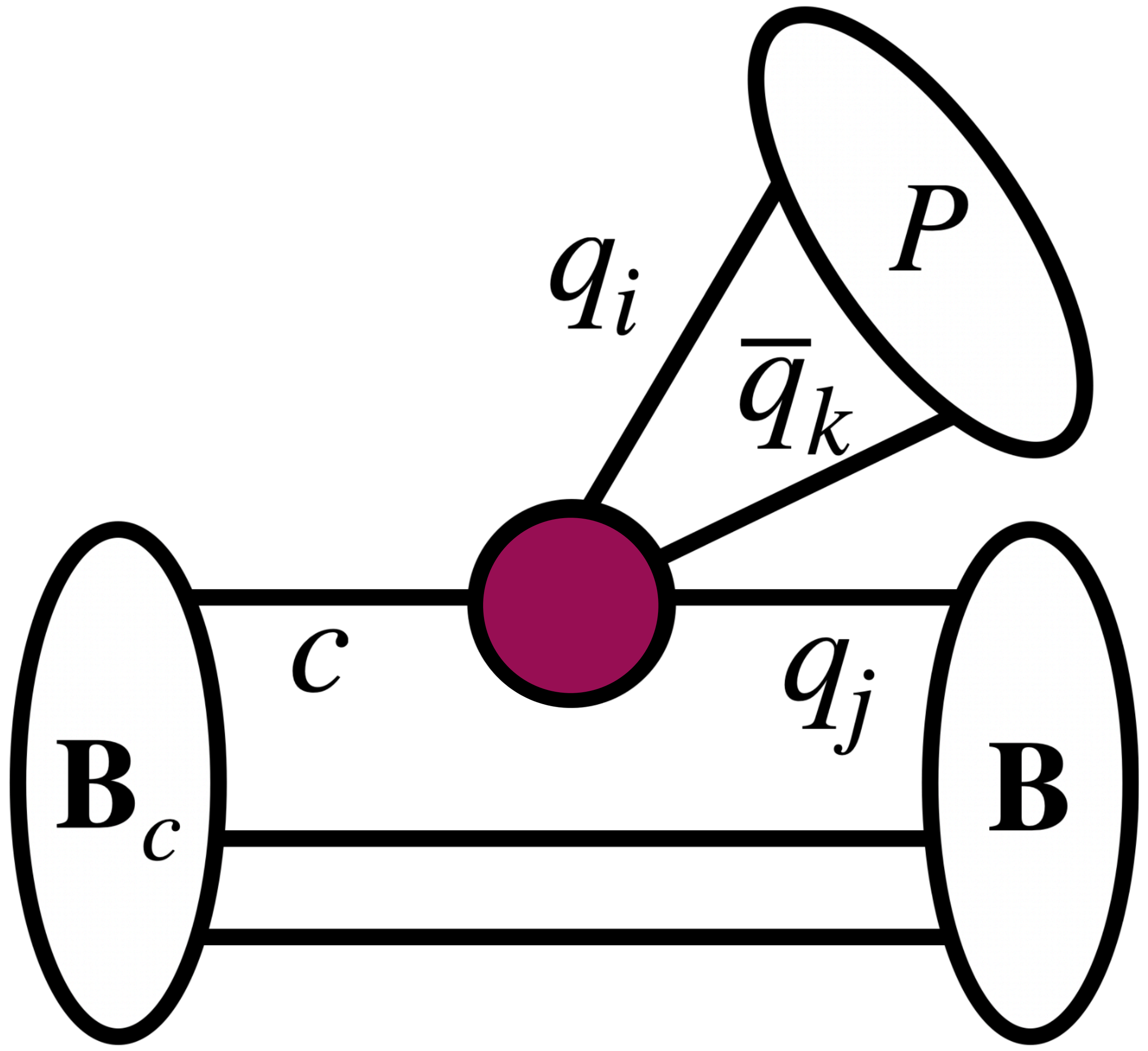


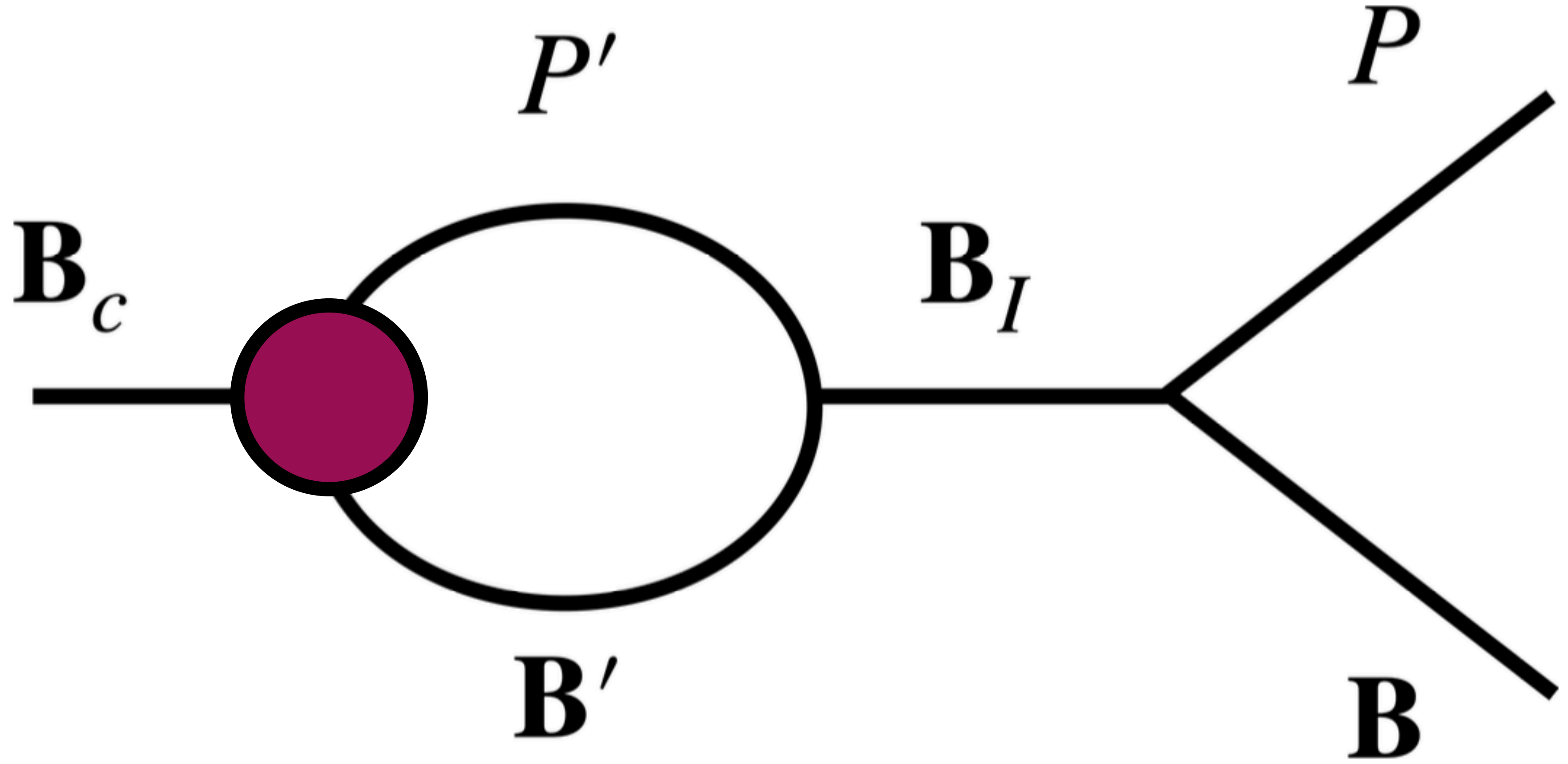
At quark level generates penguin topology

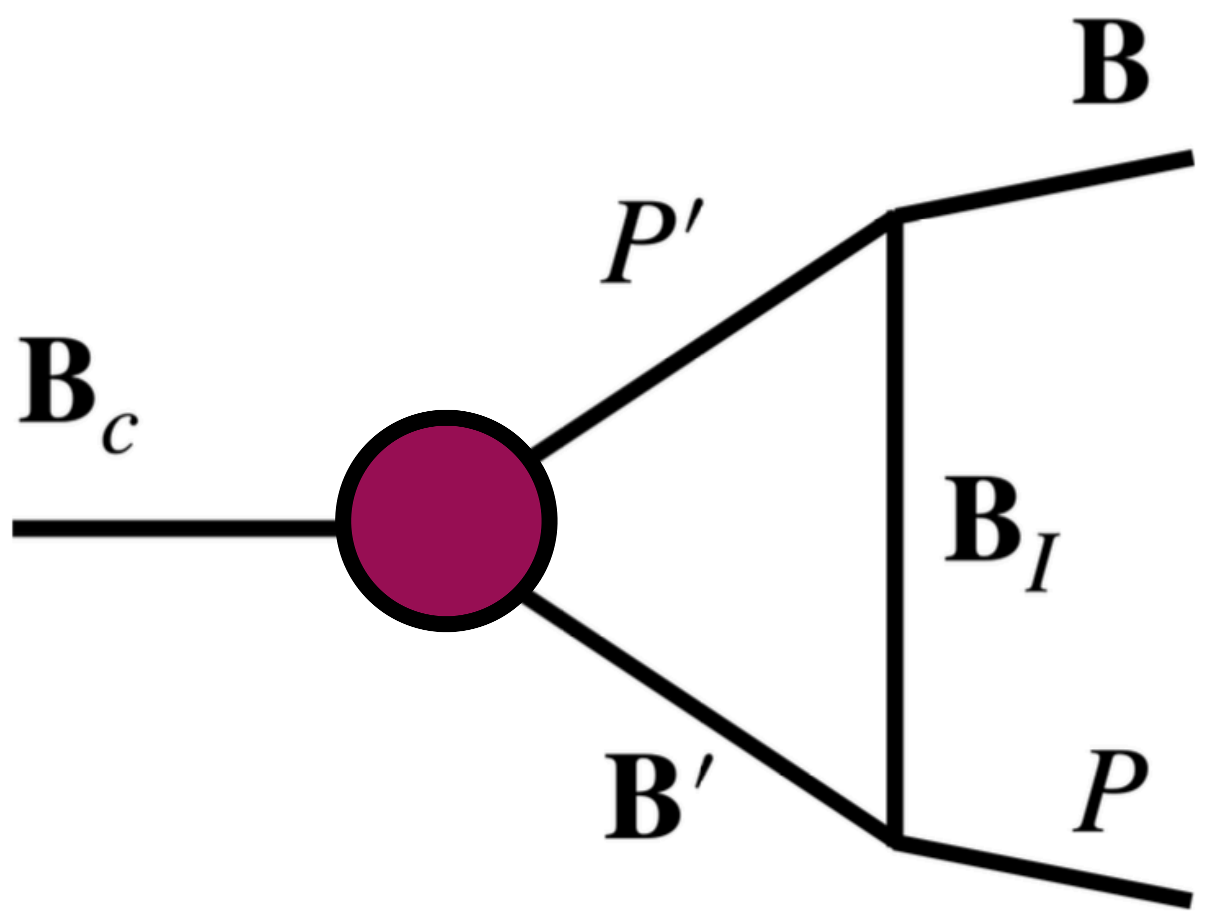


Rescattering, solving penguin/tree

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







Induce two parameters:

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

Induce one parameter:

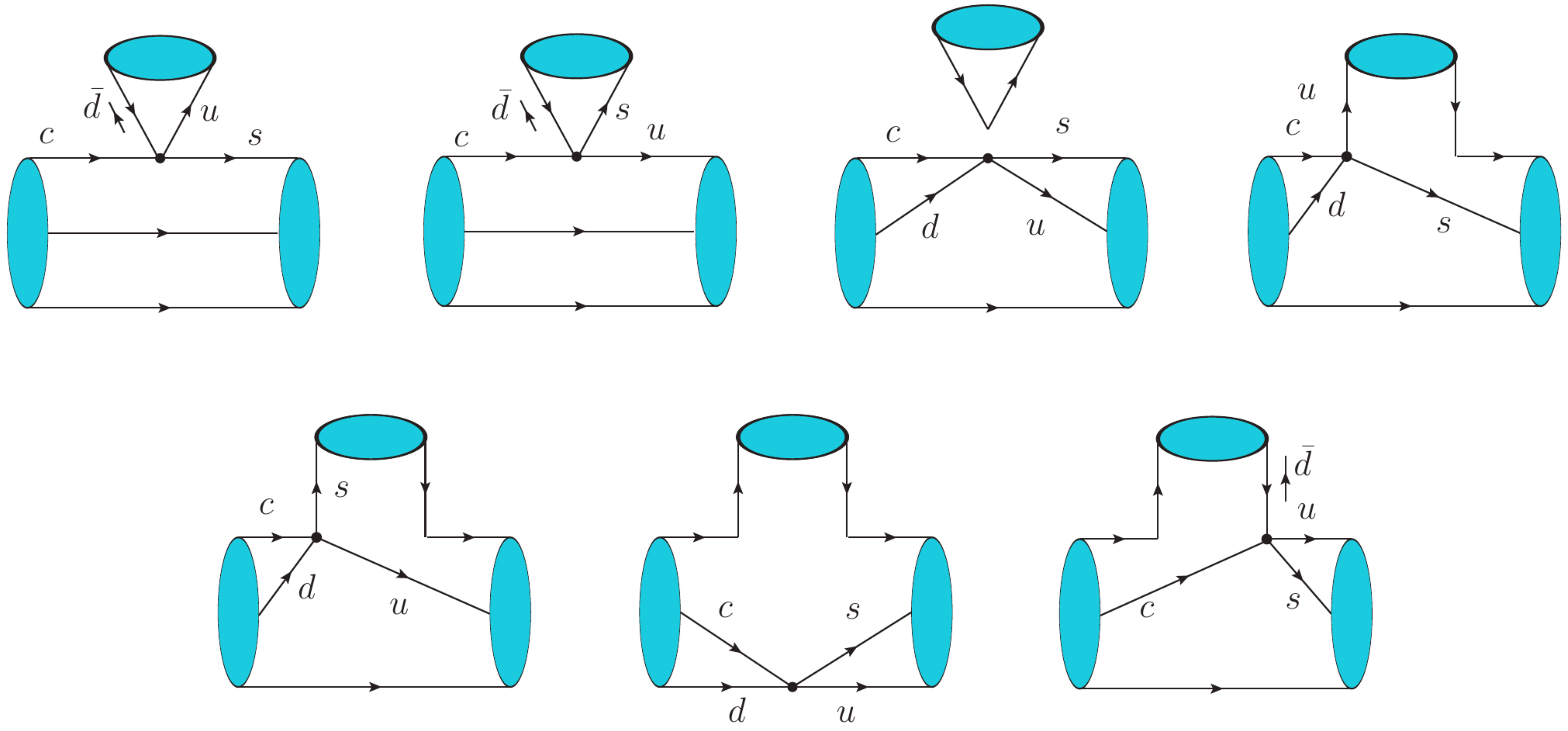
$\tilde{S}^{-}$, containing the q^2 dependencies of couplings.

Induce one parameter:

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

• Rescattering, solving penguin/tree

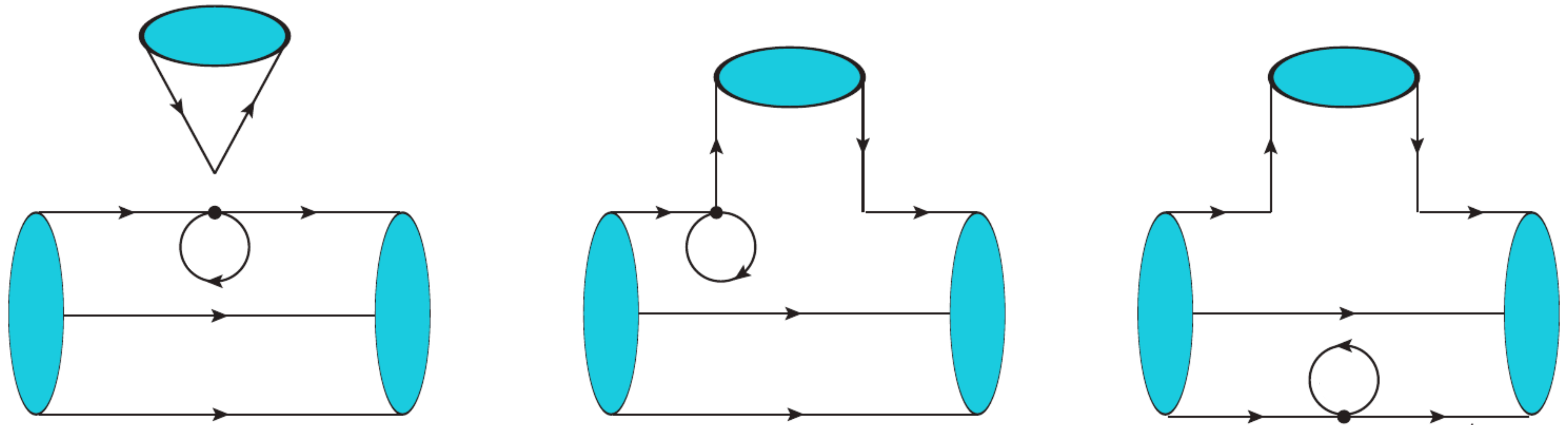
Amplitudes $\sim \dfrac{\lambda_s - \lambda_d}{2}\tilde{f} + \lambda_b \tilde{f}_{\mathbf{3}}$



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

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

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



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

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

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

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

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

PRD **100**, 093002 (2019)

Rescattering, solving penguin/tree

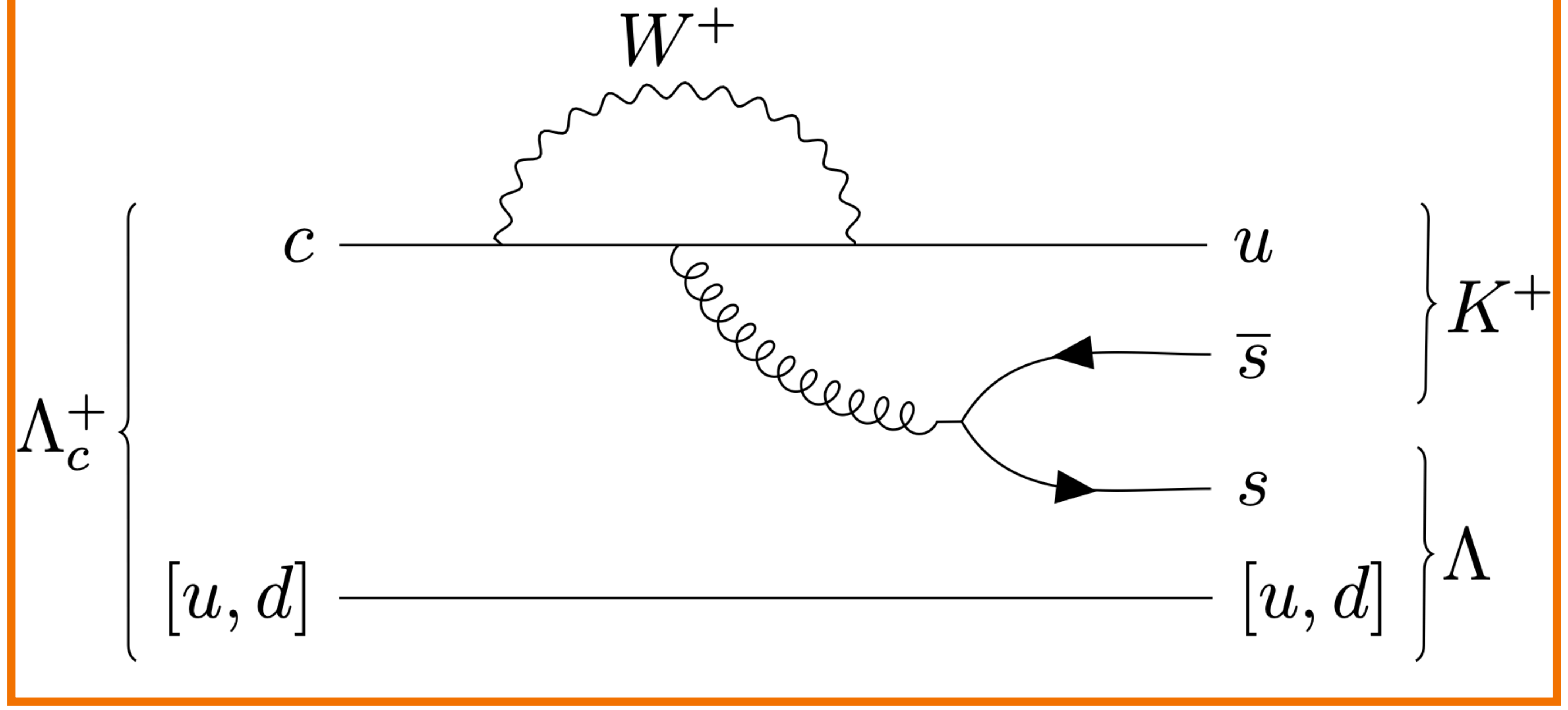
Amplitudes $\sim \dfrac{\lambda_s - \lambda_d}{2}\tilde{f} + \lambda_b \tilde{f}_{\mathbf{3}}$

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

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

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

Corrections to A_{CP} are around 10%



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

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

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

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

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

PRD **100**, 093002 (2019)

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

- **Rescattering, numerical results**

1. A_{CP} in the same size with the ones in D meson! If confirmed, it suggests the natural sizes of A_{CP} are around 10^{-3}.
   No need of NP to explain data !

2. 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

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

3. The main uncertainties are from strong phases.
   Measurement on β can greatly improve!

$$\Delta A_{CP} = (1.75 \pm 0.53) \cdot 10^{-3}$$

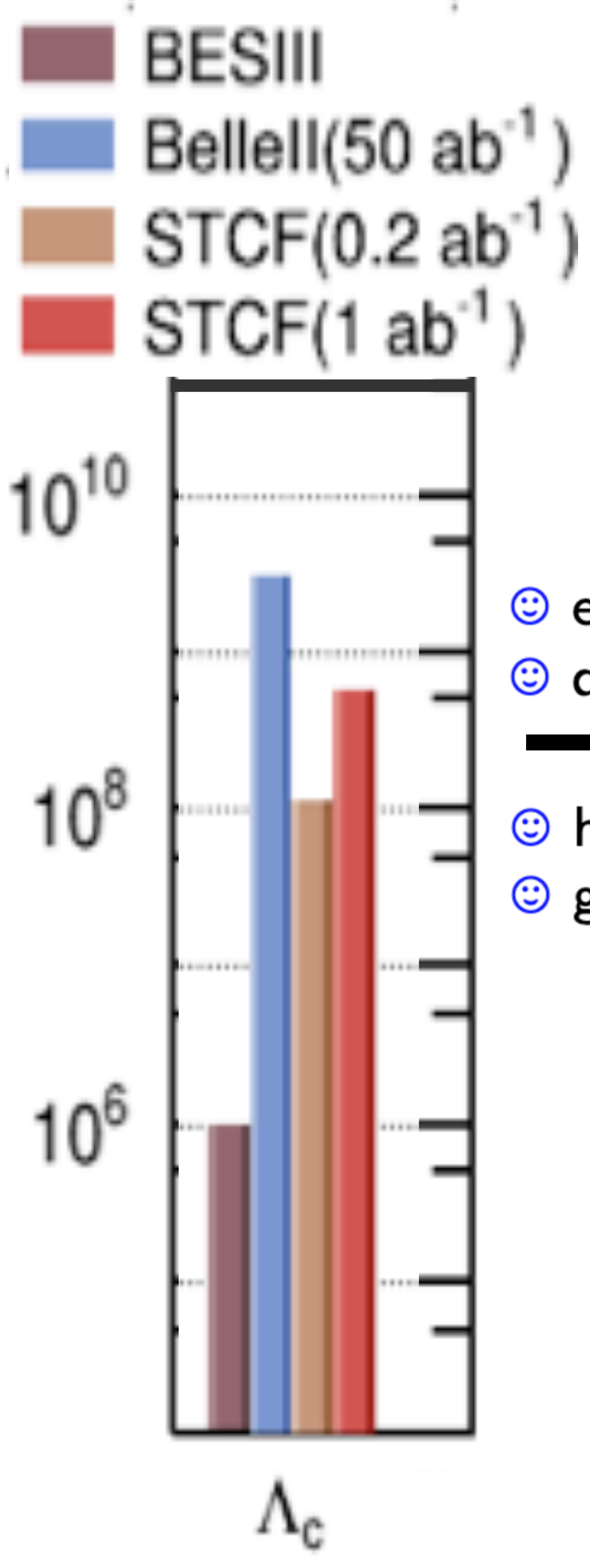
Channels	$\mathcal{B}$	A_{CP}^{α}	A_{CP}
$\Xi_c^0 \to \Sigma^+\pi^-$	0.21(2)	0	0
		2.13(21)	−0.81(23)
$\Xi_c^0 \to pK^-$	0.20(2)	0	0
		−2.51(33)	0.94(30)
$\Lambda_c^+ \to p\pi^0$	0.16(2)	−0.61(39)	0.42(1.15)
		−1.95(61)	0.53(95)
$\Lambda_c^+ \to n\pi^+$	0.67(8)	0.12(20)	−0.15(42)
		−0.68(69)	0.71(54)
$\Lambda_c^+ \to \Lambda^0 K^+$	0.63(2)	−0.03(10)	0.19(18)
		−0.49(12)	0.02(21)

29 data points with 10 complex parameters.

arXiv:2404.19166 [hep-ph]

• Wish list on future experiments

*Rough estimate from statistics only



A_{CP} at $\mathcal{O}(10^{-3})$

☺ extremely clean environment
☺ quantum coherence

A_{CP} at $\mathcal{O}(10^{-3})$

Upgrade

A_{CP} at $\mathcal{O}(10^{-4})$

☺ very large production cross-section
☺ large boost, excellent time resolution

☺ high-efficiency detection of neutrals
☺ good trigger efficiency

☺ extremely clean environment
☺ quantum coherence

Belle : A_{CP} at $\mathcal{O}(10^{-2})$

Upgrade

Belle II : A_{CP} at $\mathcal{O}(10^{-3})$

Measurements on β and γ extract important information of strong phases !

Diagram from 周小蓉

Special thanks to 李龙科

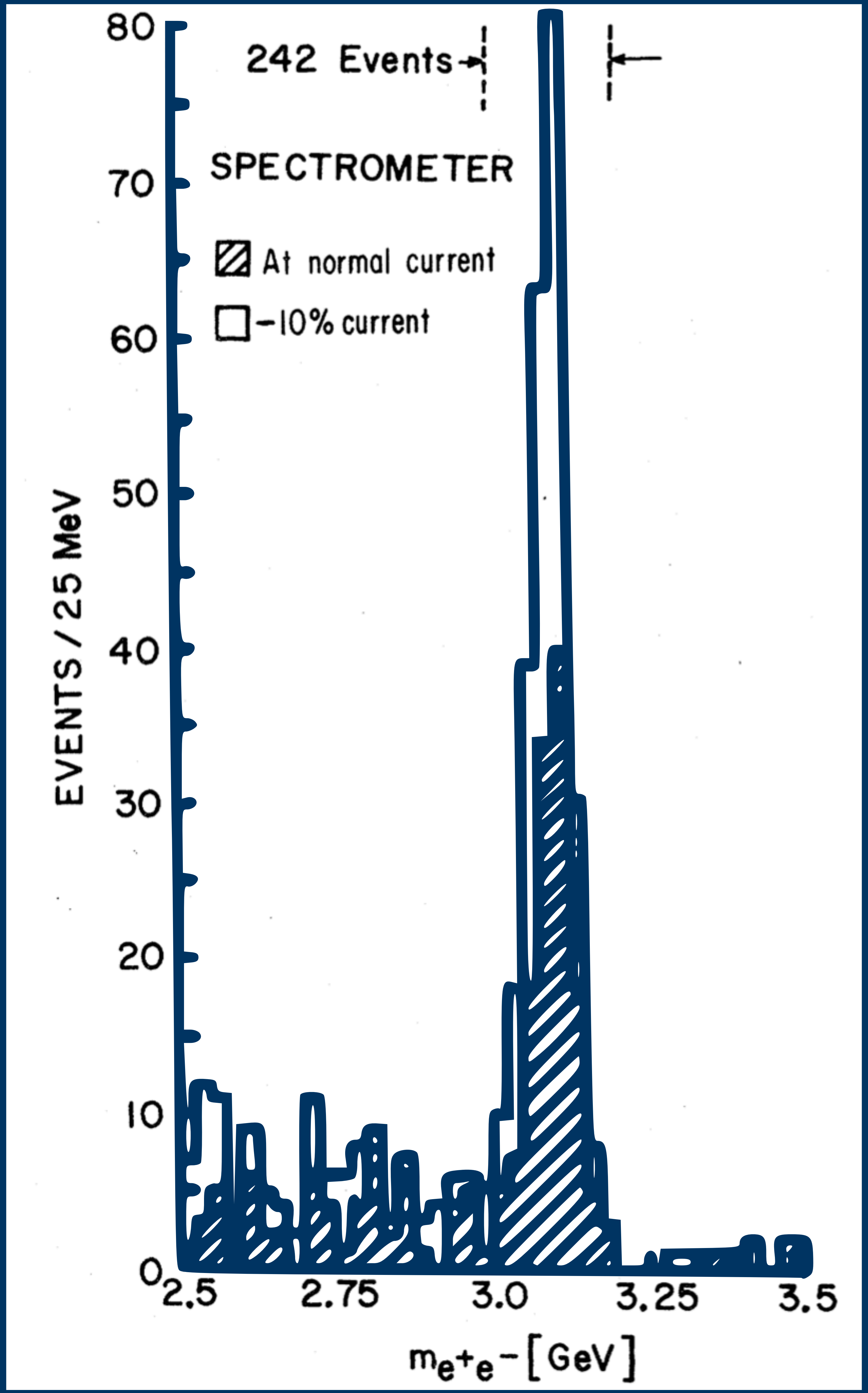
What have been done

$$\underbrace{\text{Tree}}_{\text{SU(3) flavor symmetry}}[\,\lambda_{d,s} + \lambda_b\,\underbrace{(\,\text{Penguin / Tree}\,)}_{\text{Rescattering}}\,]$$

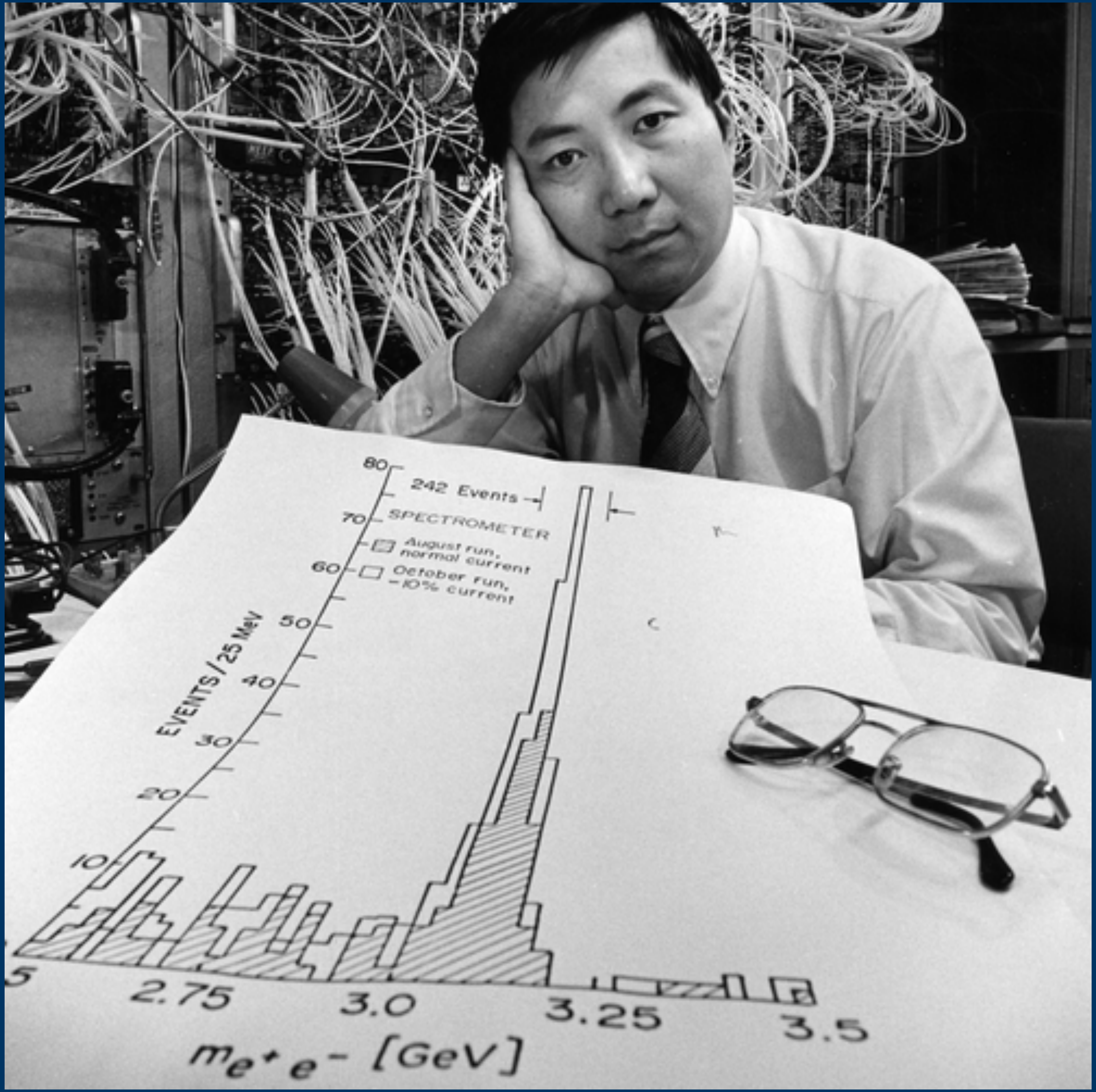
What we need

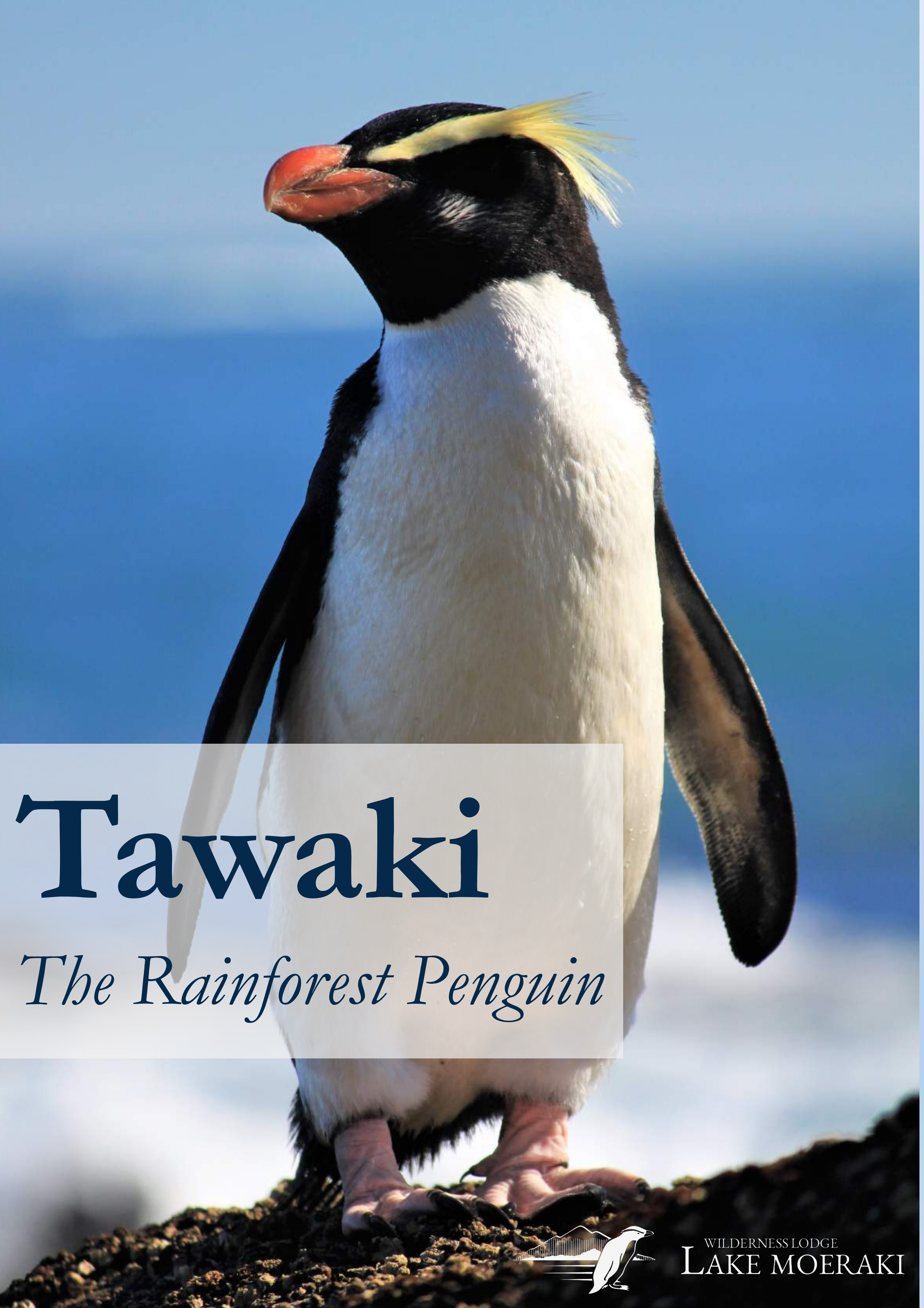
Measurements of β and γ in near future

Measurements of A_{CP} in STCF, Belle II, LHCb



Backup slides





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

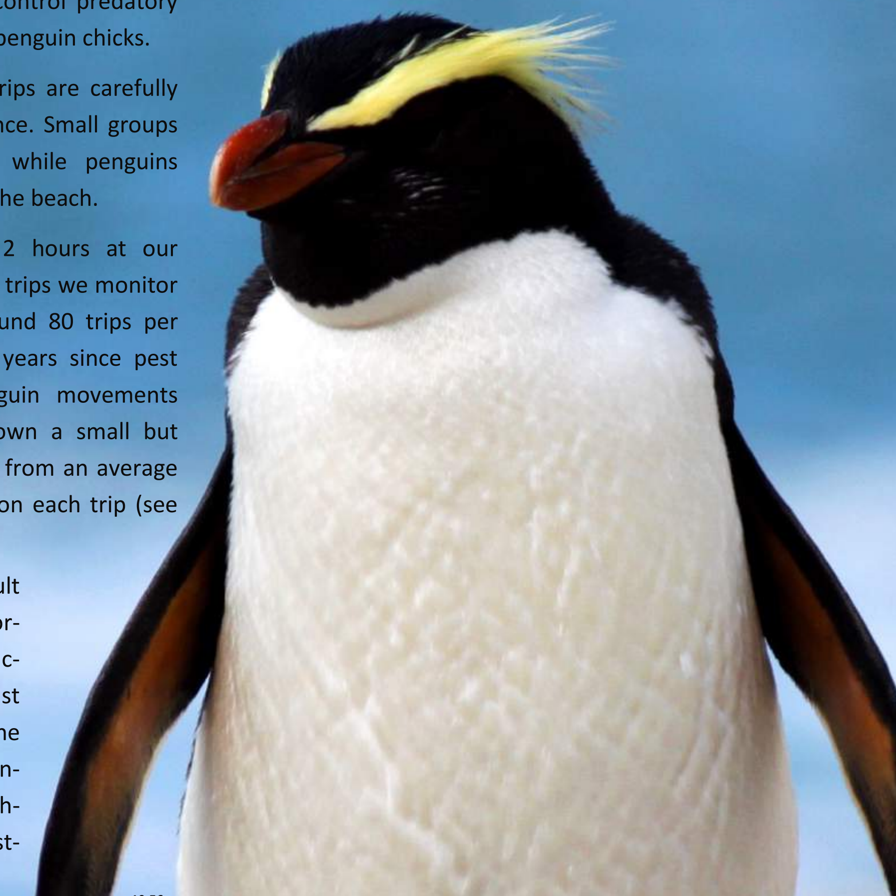
Wilderness Lodge has worked to conserve Tawaki. We campaigned to establish and enforce a Wildlife
e penguins to stop people taking dogs into the colonies where they would attack and kill penguins.

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-



• Backup slide

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

Two-body hadronic charmed meson decays

Hai-Yang Cheng[1,2] and Cheng-Wei Chiang[1,3]
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(Received 8 January 2010; published 22 April 2010)

Enhancement of charm CP violation due to nearby resonances

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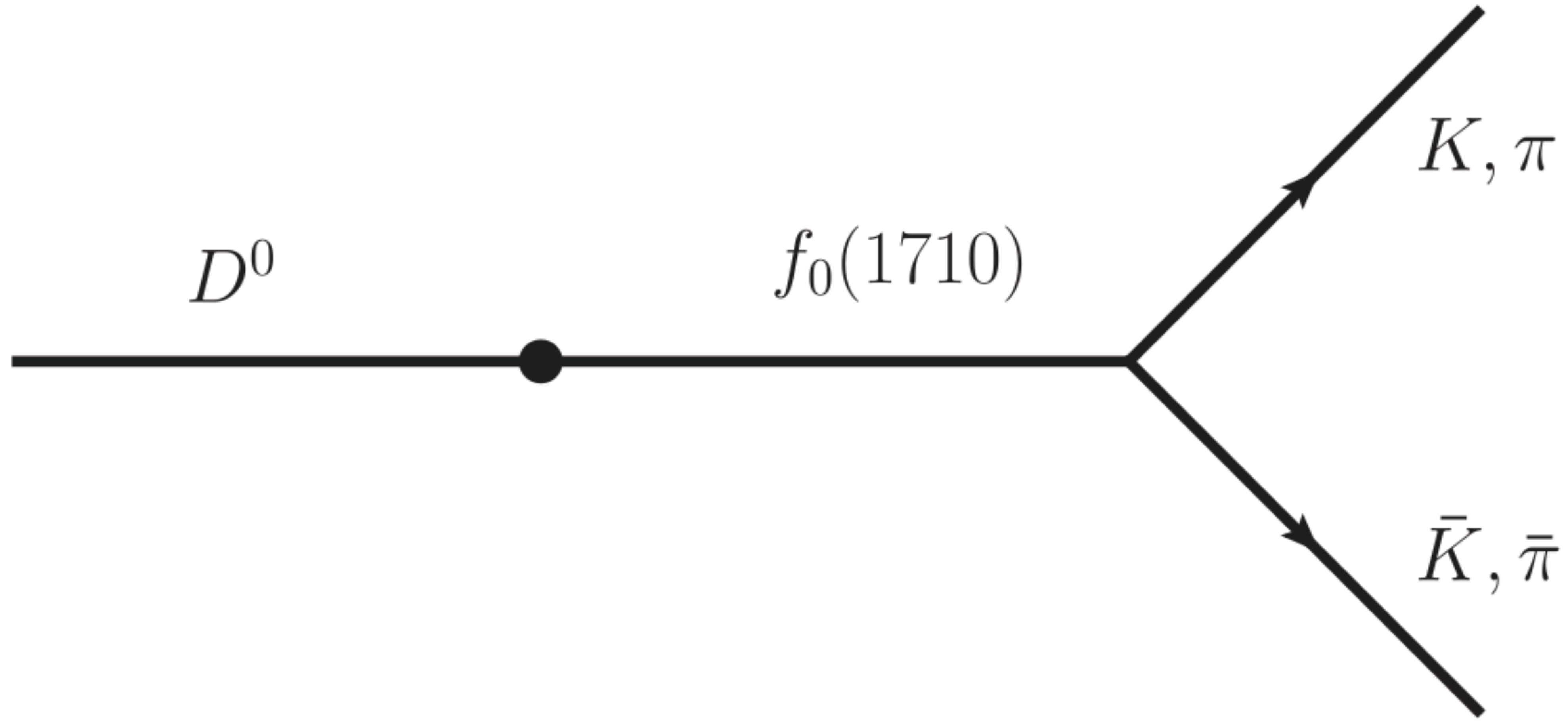
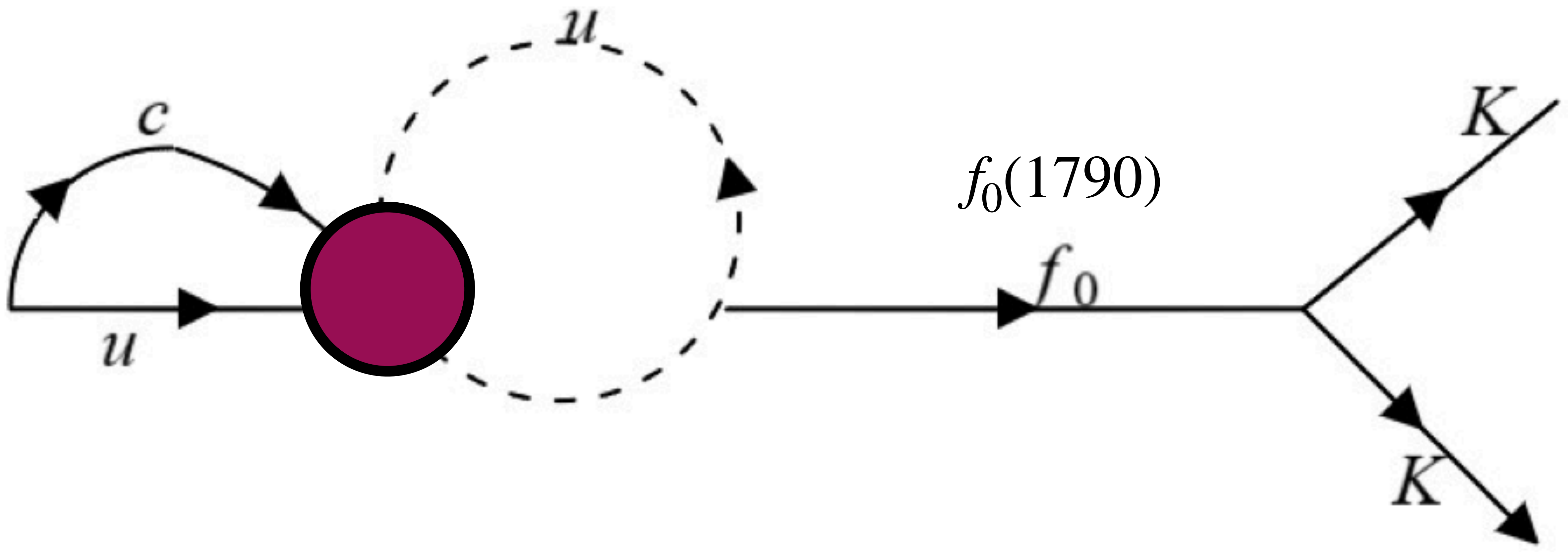




1. f_0 might be a glueball which mainly decays to KK.

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

3. There do not have known intermediate baryons play the same rule (?)

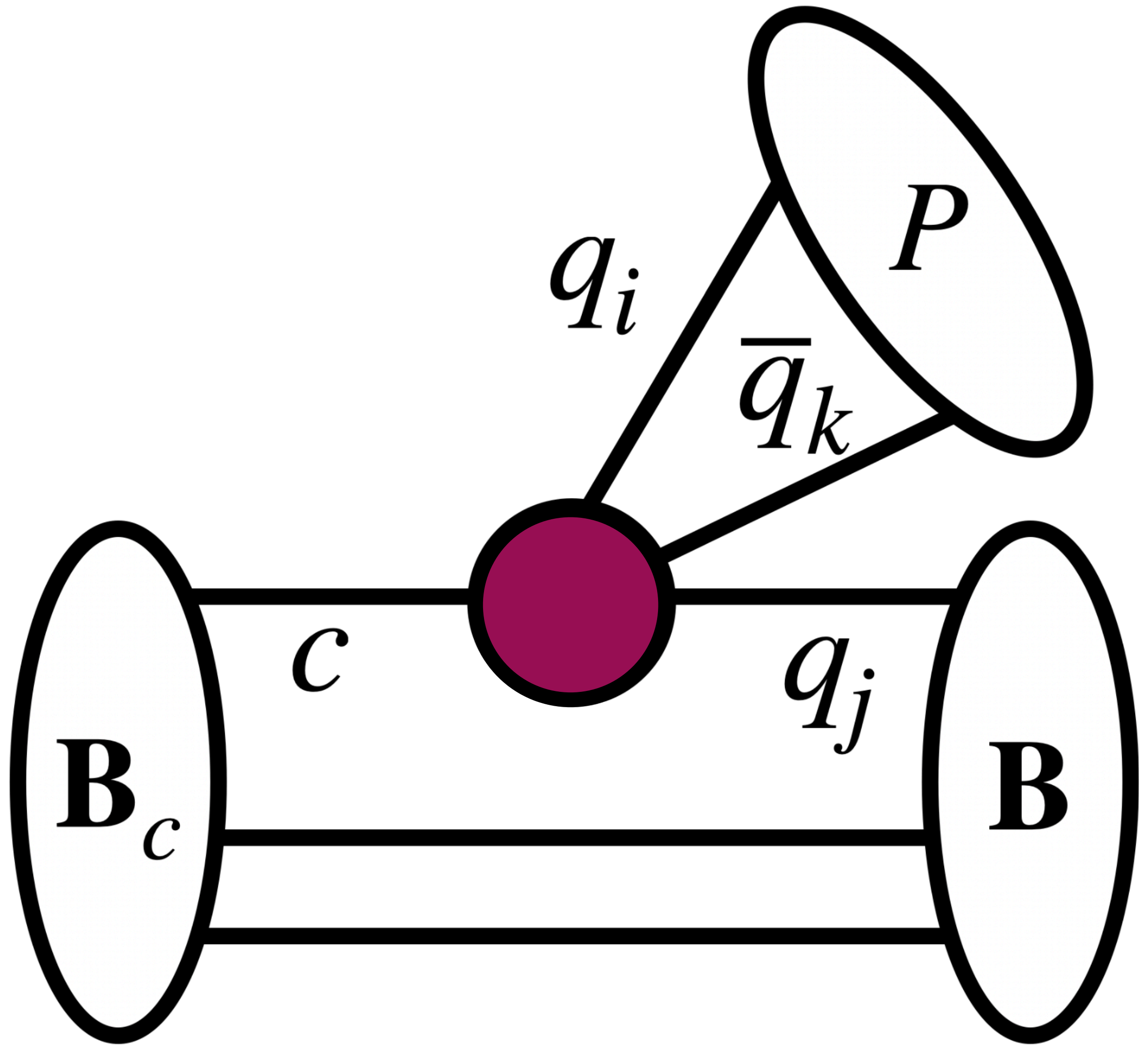
- **Backup slide**

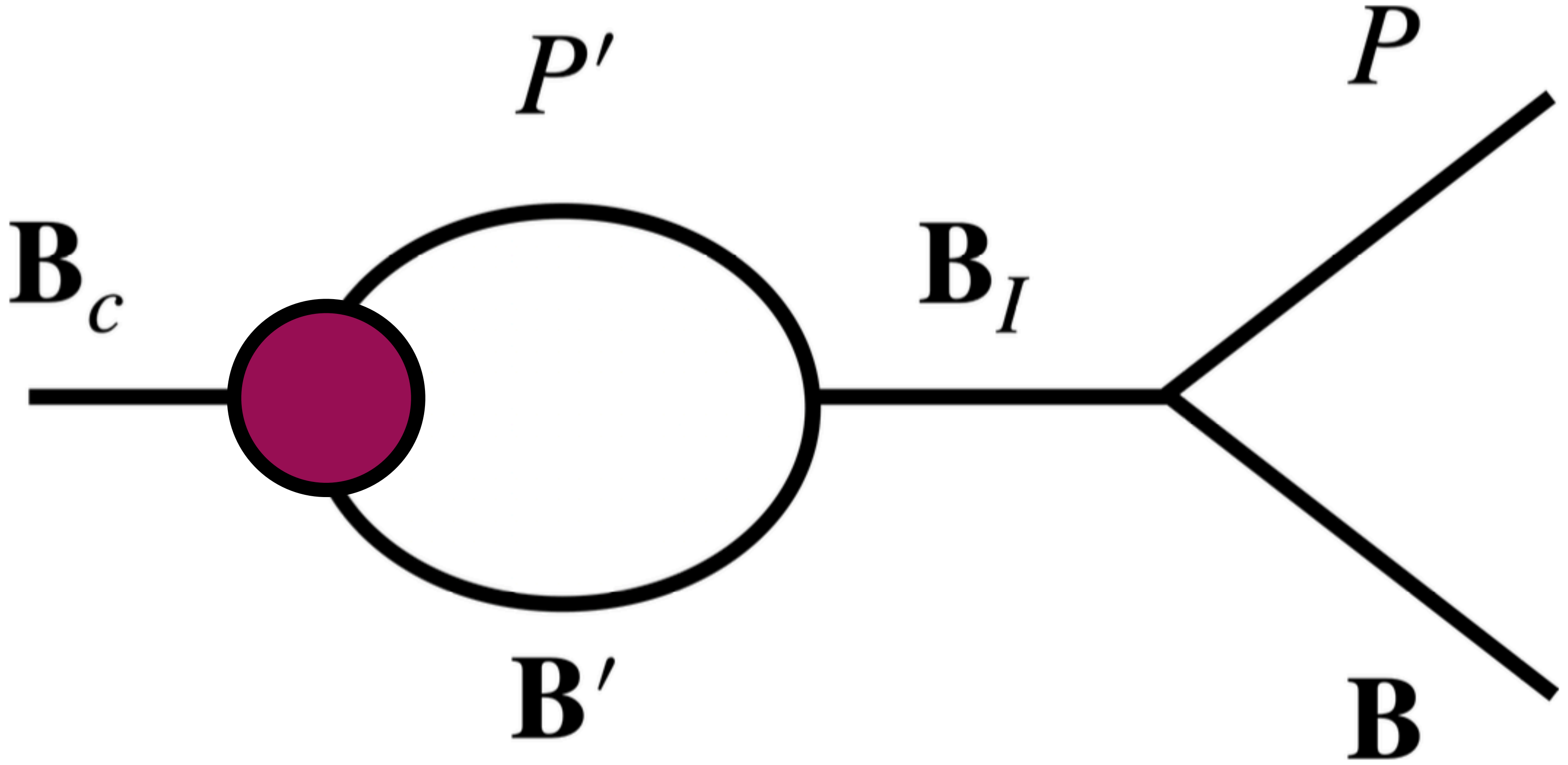
$$g^-_{n\Sigma^- K^-} : g^-_{pN\pi^-} : g^-_{p\Lambda K^-} : g^-_{\Sigma^-\Lambda\pi^+} : g^-_{\Sigma^-\Sigma^0\pi^+} : g^-_{\Lambda\Sigma^0\pi^0}$$
$$= 1 : g_s^- : \frac{1}{\sqrt{6}}\left(1 - 2g_s^-\right) : \frac{1}{\sqrt{6}}\left(1 + g_s^-\right) : \frac{1}{\sqrt{2}}(g_s^- - 1) : \frac{1}{\sqrt{6}}(1 + g_s^-).$$

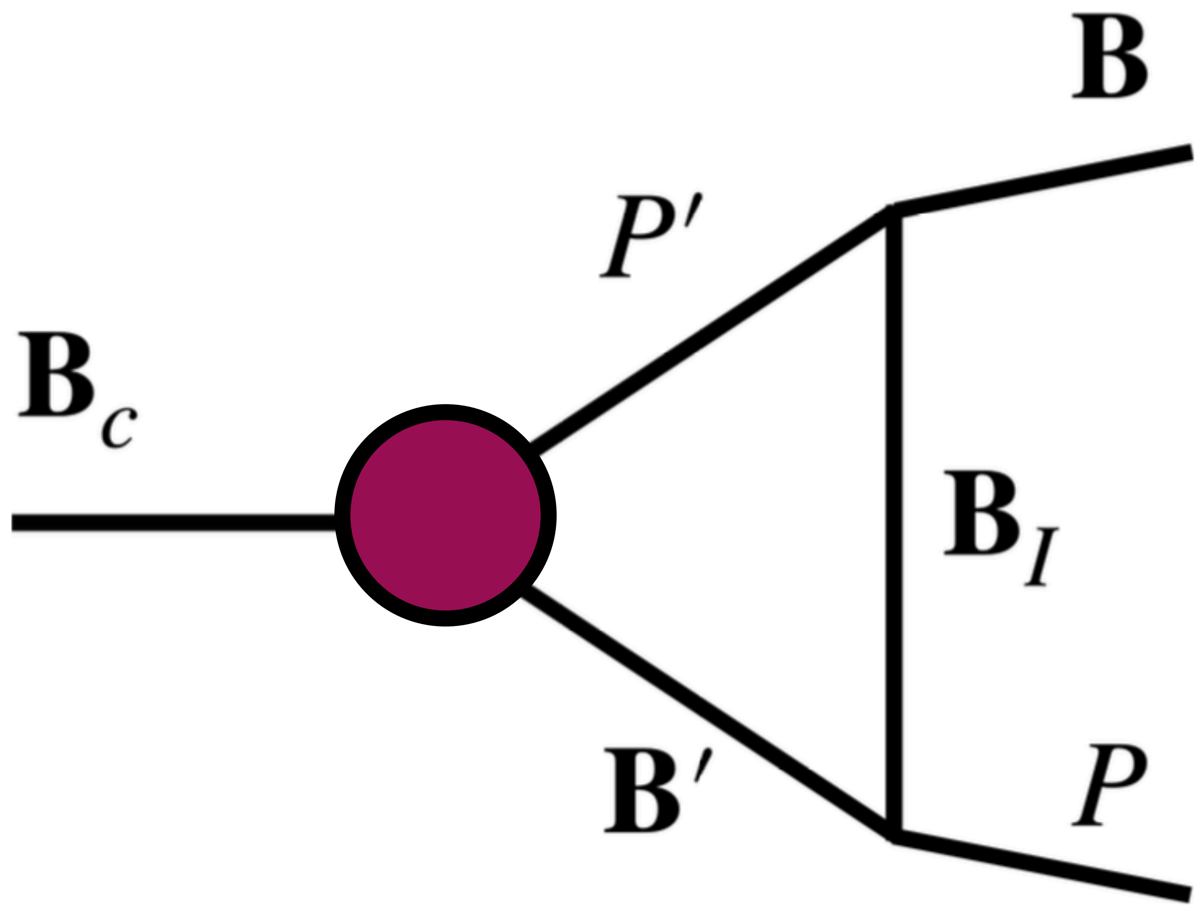
$$\Gamma^{N\pi}_{N(1535)} : \Gamma^{\Lambda\pi}_{\Sigma(1620)} : \Gamma^{\Sigma\pi}_{\Sigma(1620)} : \Gamma^{N\overline{K}}_{\Sigma(1620)} : \Gamma^{N\overline{K}}_{\Lambda(1670)} : \Gamma^{\Sigma\pi}_{\Lambda(1670)}$$
$$= 44.1 \pm 14.8 : 3.51 \pm 1.53 : 6.63 \pm 2.70 : 13.7 \pm 10.5 : 8.0 \pm 1.9 : 12.8 \pm 5.1\,,$$

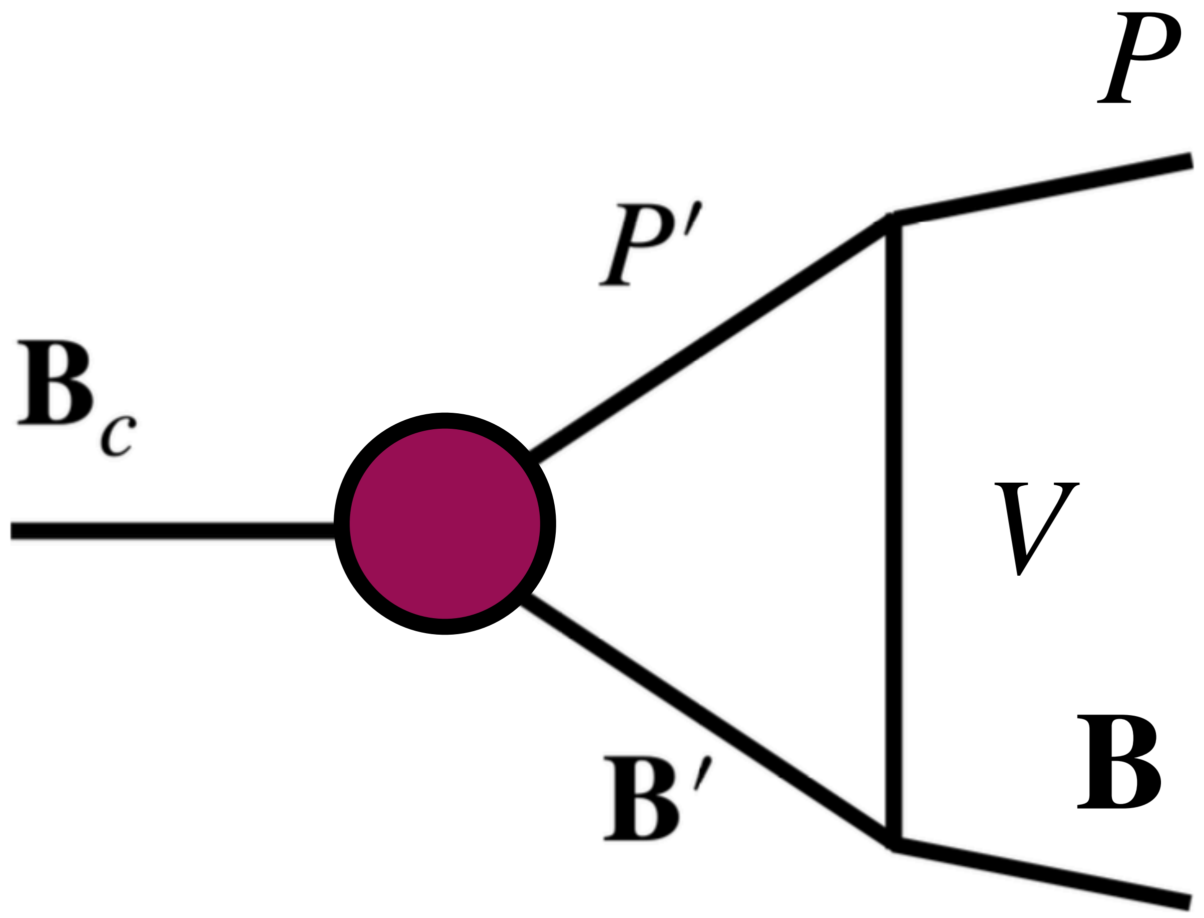
- **Rescattering, solving penguin/tree**

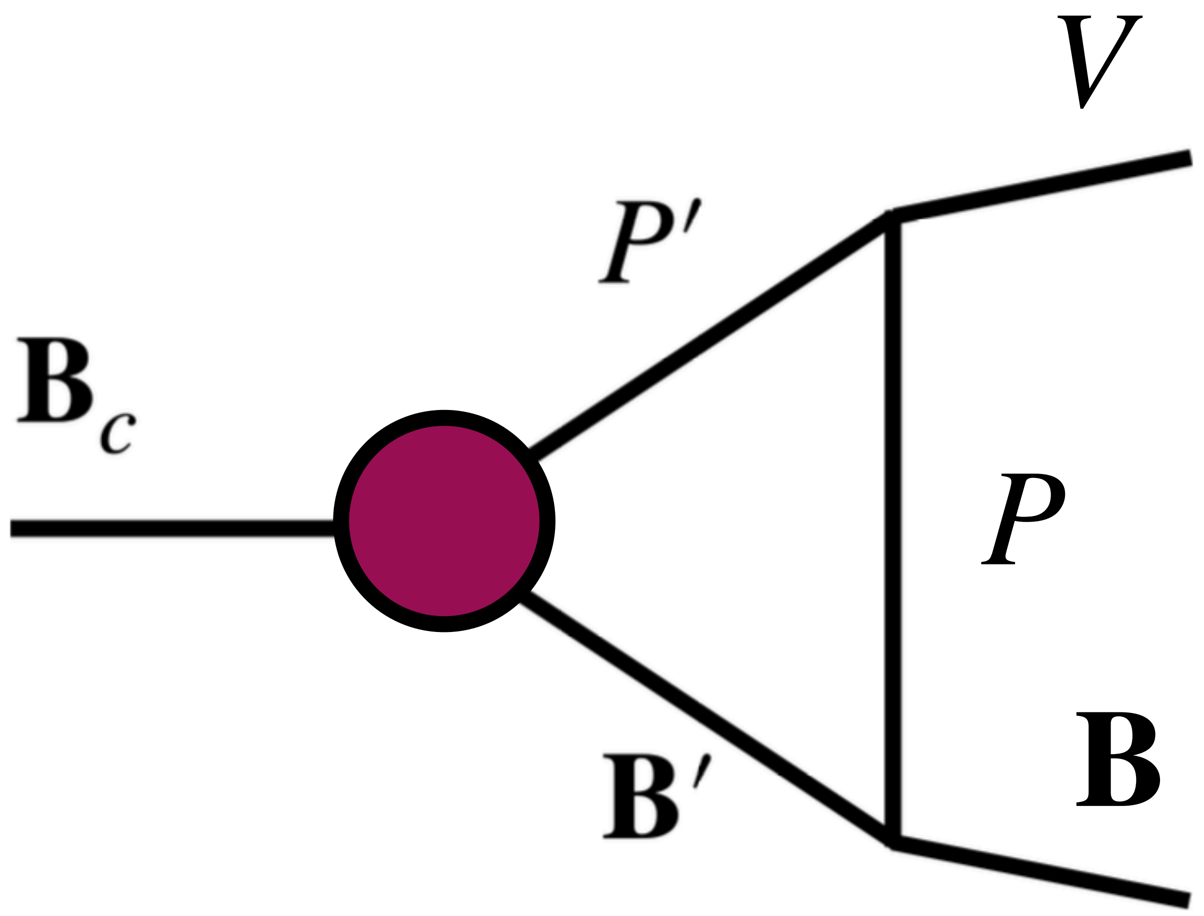
$$\mathscr{L}_{\mathbf{B}_c\mathbf{B}P} = \mathscr{L}^{\mathrm{Tree}}_{\mathbf{B}_c\mathbf{B}P} + \mathscr{L}^{\mathrm{FSR-s}}_{\mathbf{B}_c\mathbf{B}P} + \mathscr{L}^{\mathrm{FSR-t}}_{\mathbf{B}_c\mathbf{B}P} + \mathscr{L}^{\mathrm{FSR-u}}_{\mathbf{B}_c\mathbf{B}P} + \ldots(?)$$











$\ldots(?)$

Why are there matters?

Where are antimatters?