CP violation in charmed baryon decays with SU(3) flavor symmetry

arXiv : 2310.05491, 2312.xxxxx

全国第二十届重味物理和CP破坏研讨会

劉 佳 韋

TDLI

Dec 17, 2023

Charmed baryons decays

BESIII : $e^+e^- \to \Lambda_c^+\Lambda_c^-$ at 4.6 GeV, providing clean background

Observation of the Singly Cabibbo Suppressed Decay $\Lambda_c^+ \to n\pi^+$

M. Ablikim *et al.* (BESIII Collaboration)
Phys. Rev. Lett. **128**, 142001 – Published 4 April 2022

Belle : e^+e^- collisions at $\Upsilon(4S)$ or $\Upsilon(5S)$

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Science Bulletin www.scibull.com

Article

Search for *CP* violation and measurement of branching fractions and decay asymmetry parameters for $\Lambda_c^+ \to \Lambda h^+$ and $\Lambda_c^+ \to \Sigma^0 h^+$ $(h = K, \pi)$

The Belle Collaboration[1]

LHCb : pp collisions, largest charmed hadron samples

Observation of the Doubly Charmed Baryon Ξ_{cc}^{++}

R. Aaij *et al.* (LHCb Collaboration)
Phys. Rev. Lett. **119**, 112001 – Published 11 September 2017

Physics See Viewpoint: A Doubly Charming Particle

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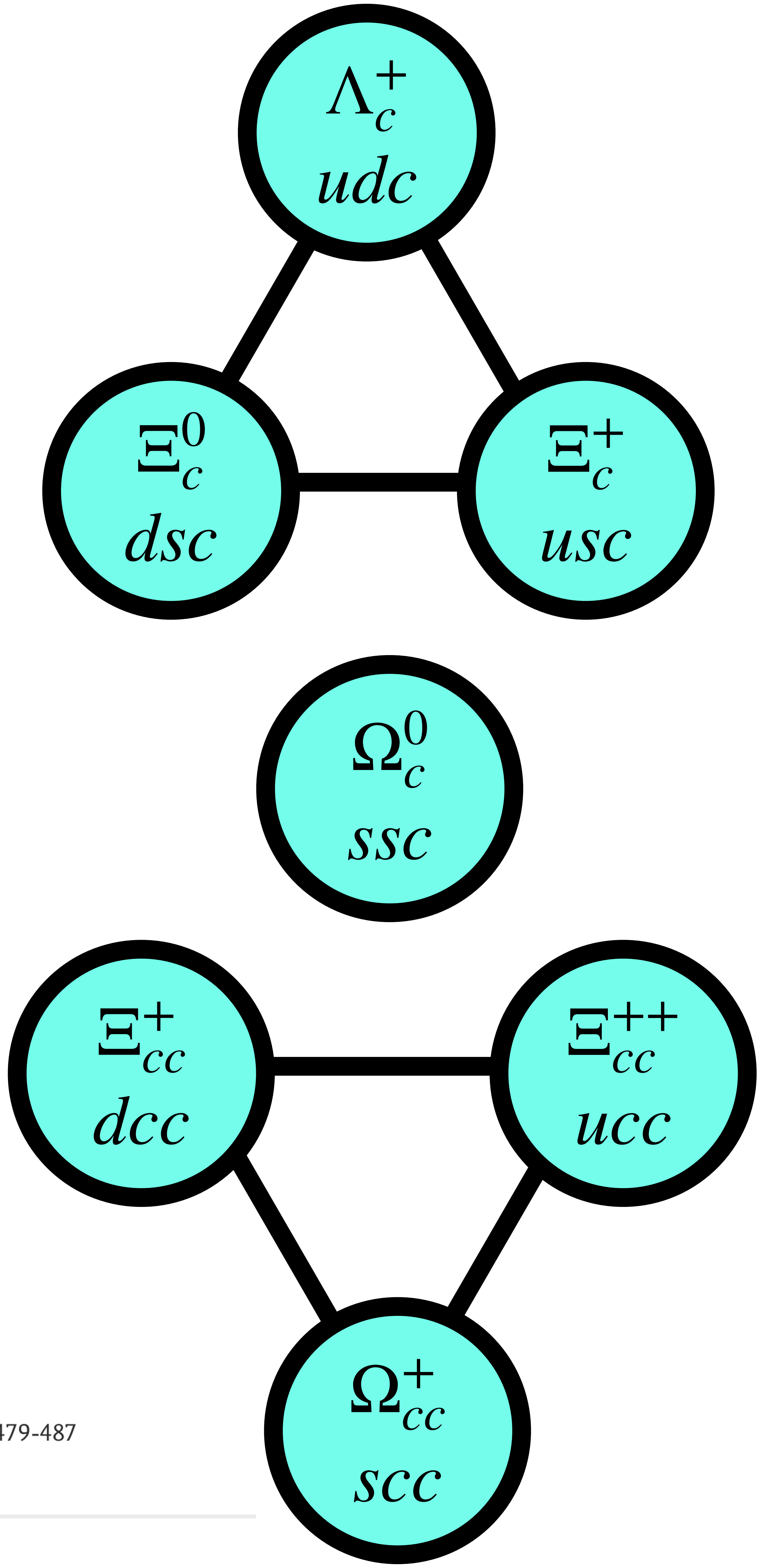
Science Bulletin
Volume 67, Issue 5, 15 March 2022, Pages 479-487

Article

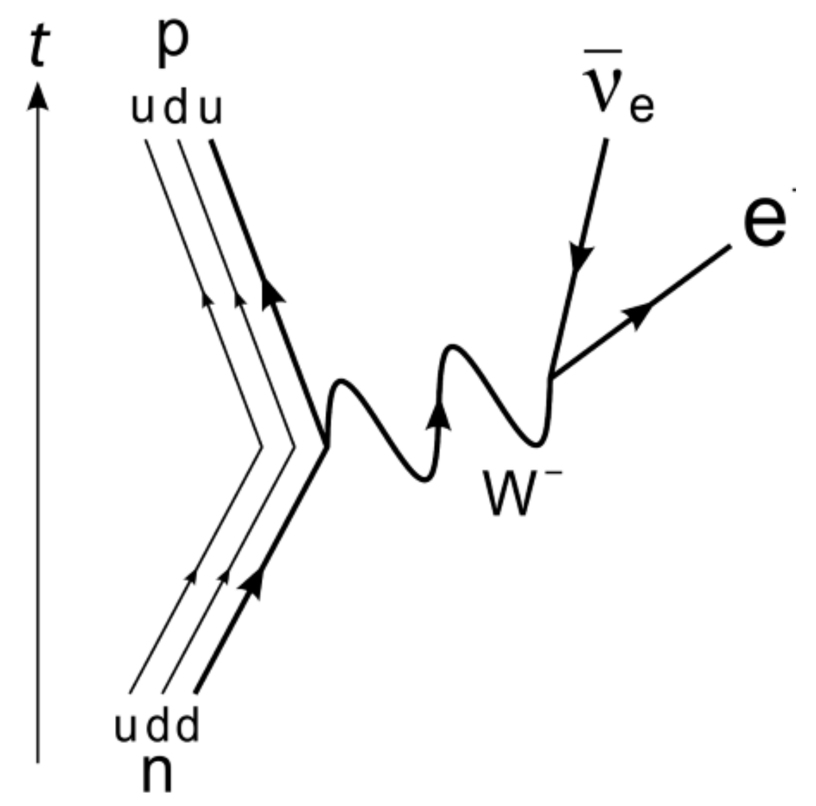
Measurement of the lifetimes of promptly produced Ω_c^0 and Ξ_c^0 baryons

LHCb Collaboration[1]



CP violation in charm - overview

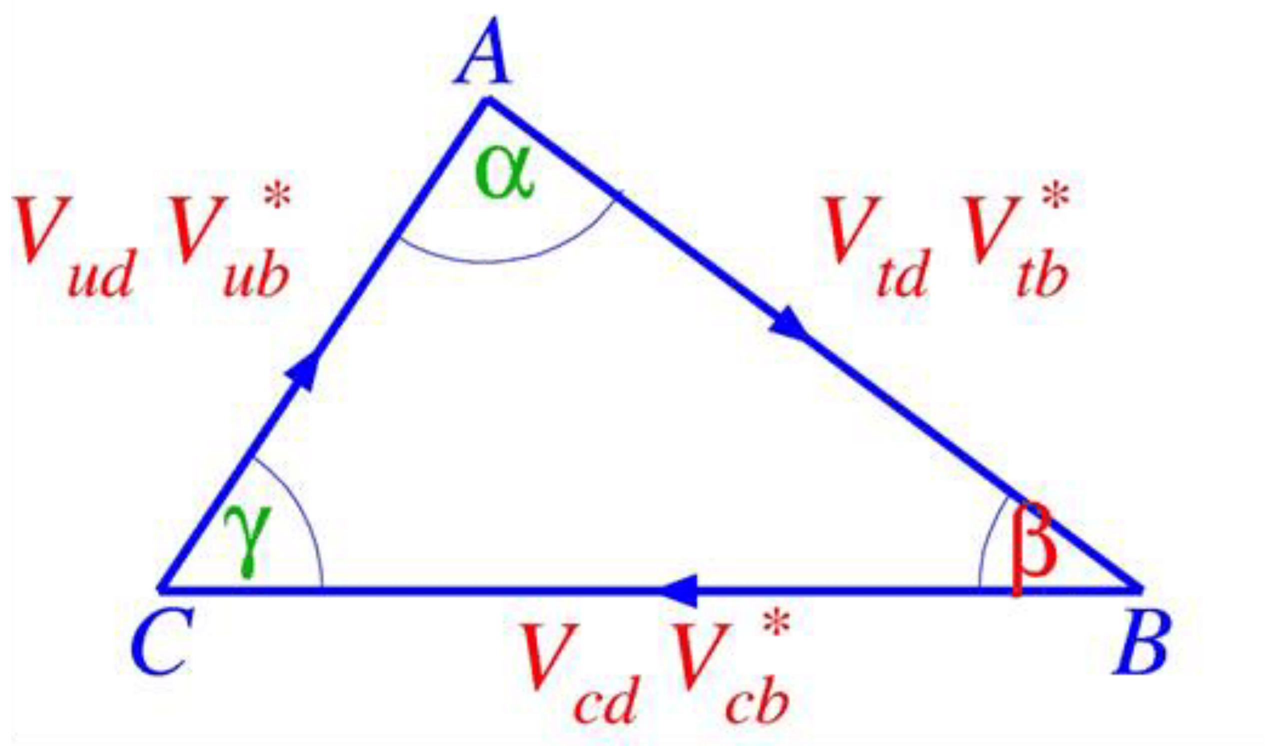
$$V_{\rm CKM} = \begin{bmatrix} V_{\rm ud} & V_{\rm us} & V_{\rm ub} \\ V_{\rm cd} & V_{\rm cs} & V_{\rm cb} \\ V_{\rm td} & V_{\rm ts} & V_{\rm tb} \end{bmatrix} \qquad V_{\rm CKM} V_{\rm CKM}^{\dagger} = 1$$



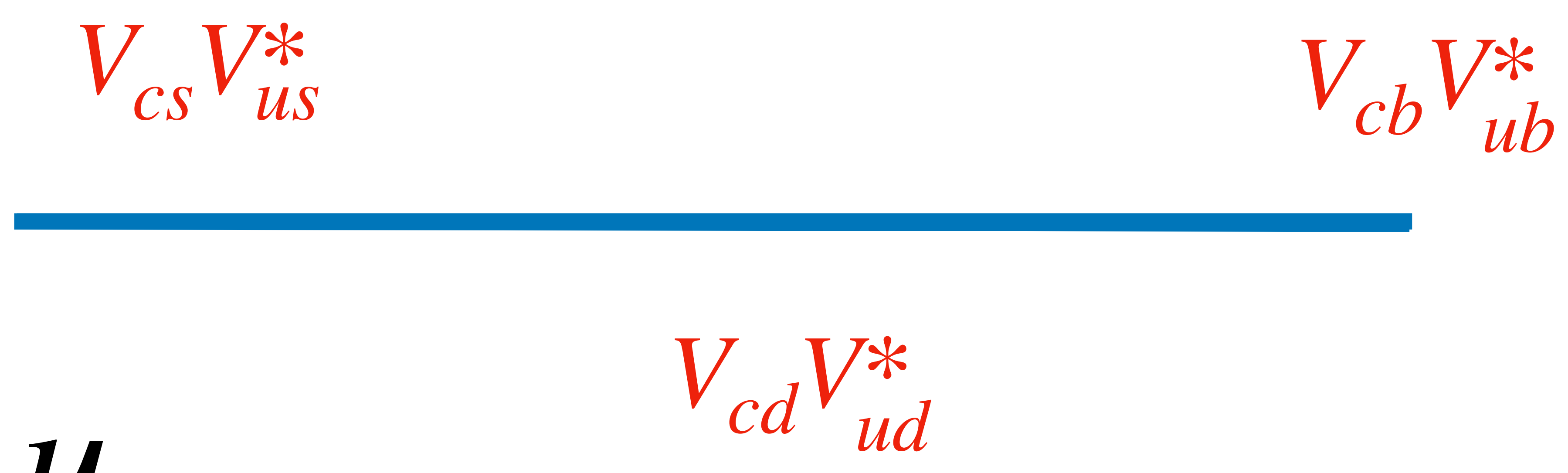
$V_{CKM} \neq V^*_{CKM}$ **under the phase rotations of** $(U_q(1))^6 \rightarrow$ **CP violation.**

$$V_{ud}V^*_{ub} + V_{cd}V^*_{cb} + V_{td}V^*_{tb} = 0 \qquad V_{ud}V^*_{cd} + V_{us}V^*_{cs} + V_{ub}V^*_{cb} = 0$$

$b \rightarrow d$



$c \rightarrow u$



• CP violation in charm - overview

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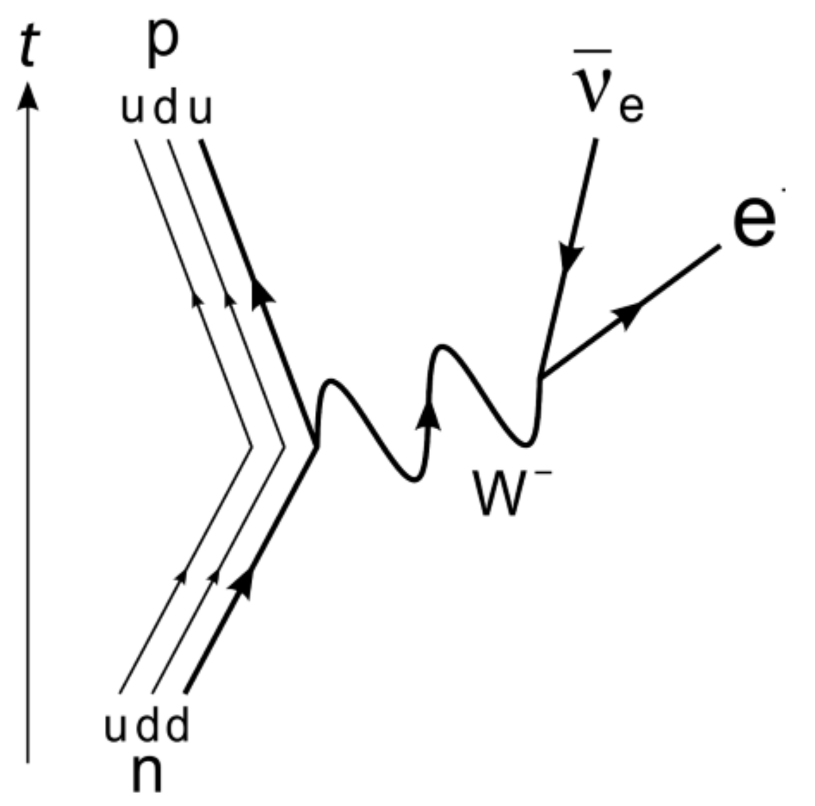

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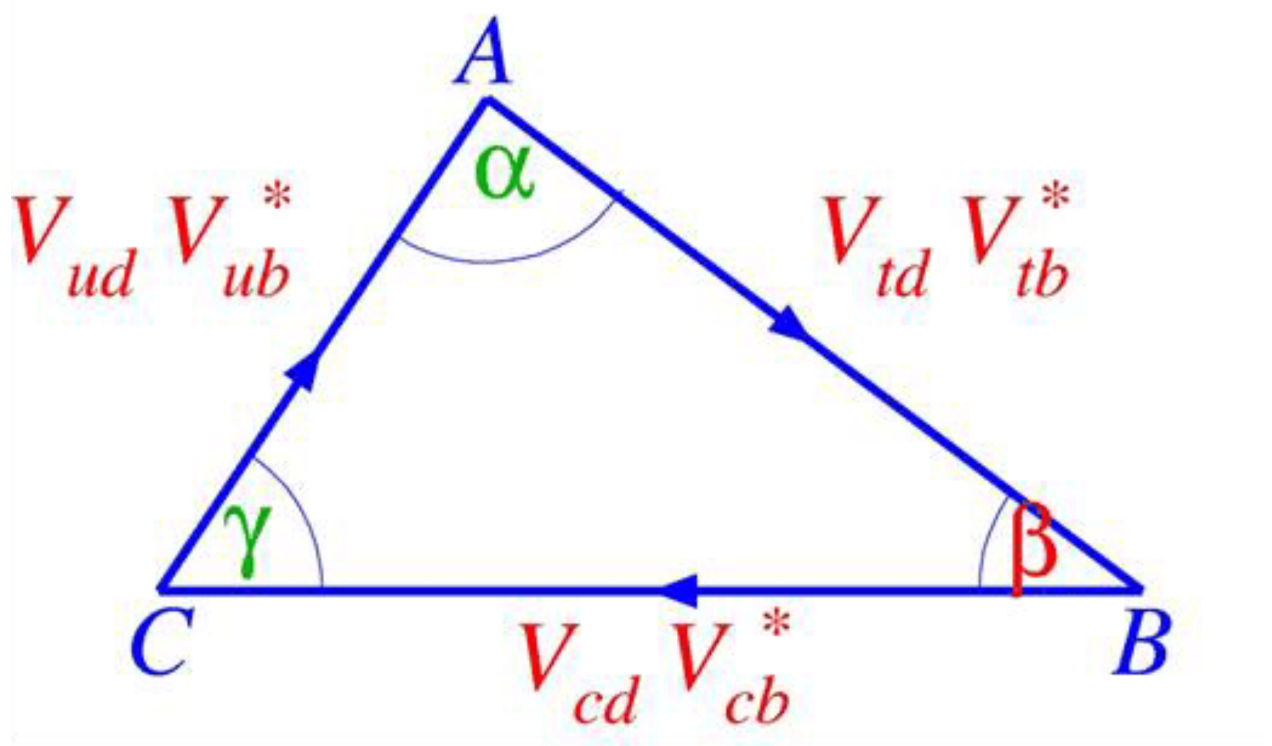
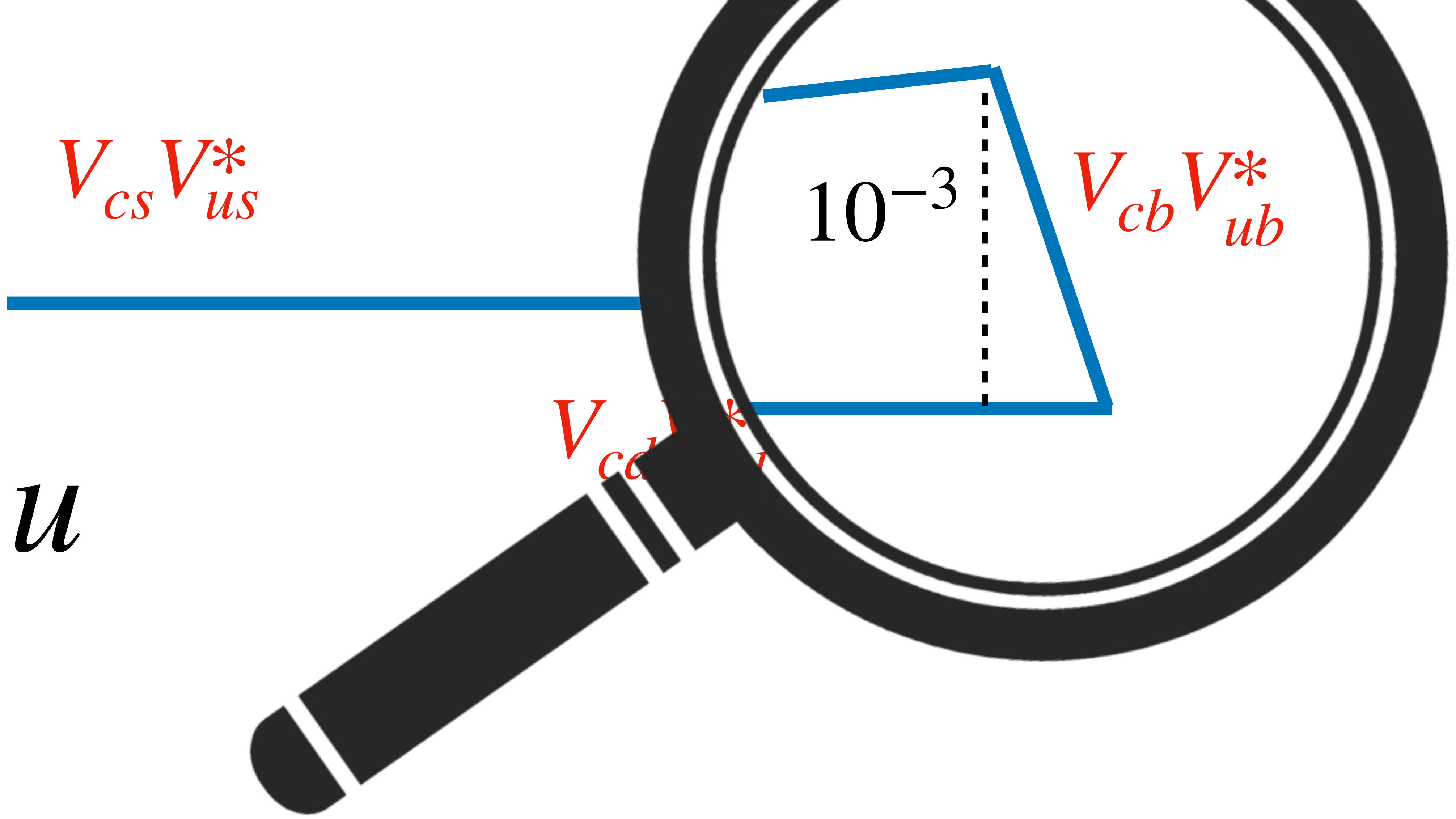


$c \rightarrow u$

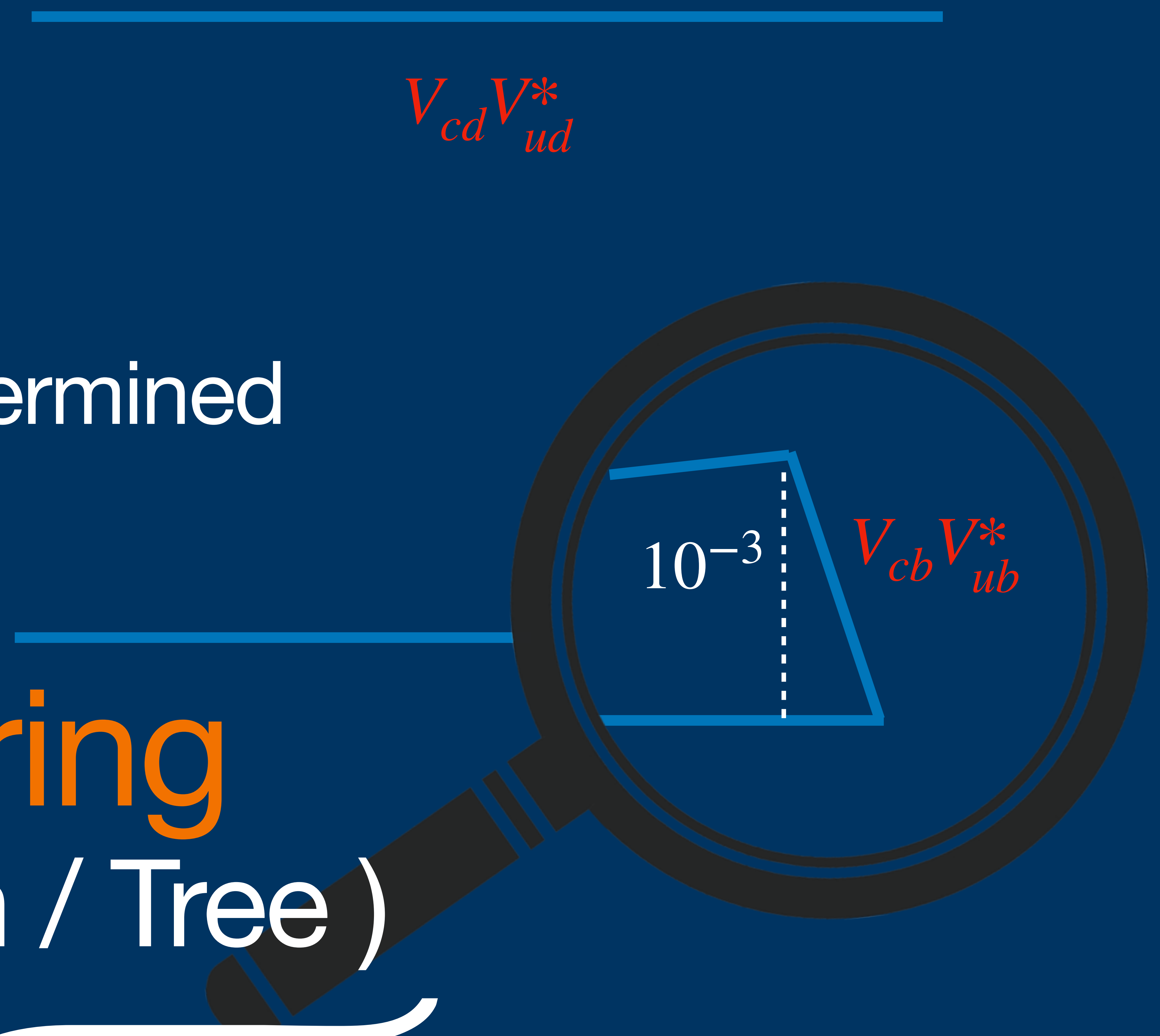


SU(3) flavor analysis

$\lambda_{d,s}$ Tree + $\underbrace{\lambda_b \text{ Penguin}}$

Insensitive to CP-even quantities & undetermined

$\lambda_q = V_{cq}^* V_{uq}$



Pole model + Rescattering

$\lambda_{d,s}$ Tree + λ_b Tree $\times$ $\underbrace{\text{(Penguin / Tree)}}$

Determined by the PM + rescattering

• SU(3) flavor analysis — Tree

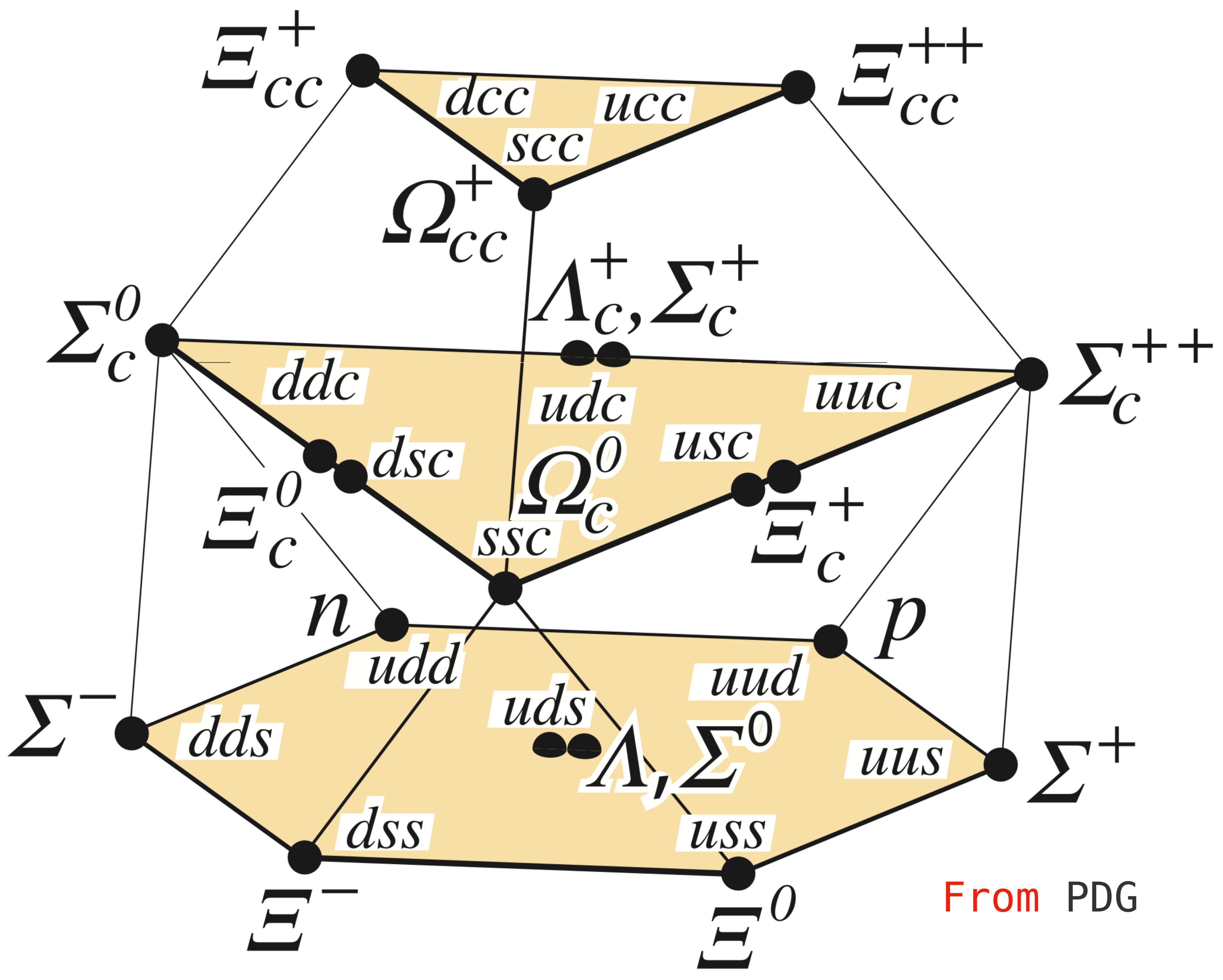
$$\mathscr{M} = \langle \mathbf{B}M; t \to \infty \,|\, \mathscr{H}_{\text{eff}} \,|\, \mathbf{B}_c \rangle = i\bar{u}\left(F - G\gamma_5\right) u_c$$

SU(3) flavor representations :

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

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

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



From PDG

- **SU(3) flavor analysis — Tree**

$$\mathscr{H}_{eff} = \frac{G_F}{\sqrt{2}}\left[\sum_{qq'} V^*_{qc}V_{q'u}\left(C_+O^{qq'}_+ + C_-O^{qq'}_-\right) - \lambda_b \sum_{i=3\sim6} C_iO_i\right]$$

$$\lambda_q = V^*_{cq}V_{uq}$$

$$O^{qq'}_\pm = (\bar{u}q')_{V-A}(\bar{q}c)_{V-A} \pm (\bar{q}q')_{V-A}(\bar{u}c)_{V-A}$$

$$\underbrace{\mathbf{3}\otimes\mathbf{3}\otimes\bar{\mathbf{3}}}_{\mathscr{H}_{eff}} = \underbrace{(\mathbf{15}\oplus\mathbf{3}_+)}_{O_+} \oplus \underbrace{(\bar{\mathbf{6}}\oplus\mathbf{3}_-)}_{O_-}$$

$$\mathcal{H}(\bar{\mathbf{6}}) = \begin{pmatrix} 0 & 0 & 0 \\ 0 & V^*_{cs}V_{ud} & -\lambda_s - \frac{\lambda_b}{2} \\ 0 & -\lambda_s - \frac{\lambda_b}{2} & V^*_{cd}V_{us} \end{pmatrix}$$

$$\mathcal{H}(\mathbf{3}_-) = \lambda_b\left(-\frac{1}{2}, 0, 0\right), \quad \mathcal{H}(\mathbf{3}_+) = \lambda_b\left(-\frac{1}{4}, 0, 0\right),$$

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

$$\lambda_d + \lambda_s + \lambda_b = 0$$

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

SU(3) flavor analysis — Tree

$$\mathcal{H}_{eff} = \frac{G_F}{\sqrt{2}} \left[\sum_{qq'} V^*_{qc} V_{q'u} \left(C_+ O_+^{qq'} + C_- O_-^{qq'} \right) - \lambda_b \sum_{i=3\sim6} C_i O_i \right]$$

$$\langle \mathbf{B} P | \mathcal{H}_{\text{eff}} | \mathbf{B}_c \rangle = i\bar{u} \left(F - G\gamma_5 \right) u_c$$

$$O_\pm^{qq'} = (\bar{u}q')_{V-A}(\bar{q}c)_{V-A} \pm (\bar{q}q')_{V-A}(\bar{u}c)_{V-A}$$

$$\underbrace{\mathbf{3} \otimes \mathbf{3} \otimes \bar{\mathbf{3}}}_{\mathcal{H}_{eff}} = \underbrace{(\mathbf{15} \oplus \cancel{\mathbf{3}_+})}_{O_+} \oplus \underbrace{(\bar{\mathbf{6}} \oplus \cancel{\mathbf{3}_-})}_{O_-}$$

For CP-even quantities it is safe to take $\lambda_b \to 0$

$$\begin{aligned}\mathcal{M} = {} & a_{15} \times (T_{c\bar{3}})_i (H_{\overline{15}})^{\{ik\}}_j (\overline{T}_8)^j_k P^l_l + b_{15} \times (T_{c\bar{3}})_i (H_{\overline{15}})^{\{ik\}}_j (\overline{T}_8)^l_k P^j_l + c_{15} \times (T_{c\bar{3}})_i (H_{\overline{15}})^{\{ik\}}_j (\overline{T}_8)^j_l P^l_k \\ & + d_{15} \times (T_{c\bar{3}})_i (H_{\overline{15}})^{\{jk\}}_l (\overline{T}_8)^l_j P^i_k + e_{15} \times (T_{c\bar{3}})_i (H_{\overline{15}})^{\{jk\}}_l (\overline{T}_8)^i_j P^l_k + a_6 \times (T_{c\bar{3}})^{[ik]} (H_{\bar{6}})_{\{ij\}} (\overline{T}_8)^j_k P^l_l \\ & + b_6 \times (T_{c\bar{3}})^{[ik]} (H_{\bar{6}})_{\{ij\}} (\overline{T}_8)^l_k P^j_l + c_6 \times (T_{c\bar{3}})^{[kl]} (H_{\bar{6}})_{\{ij\}} (\overline{T}_8)^j_l P^l_k + d_6 \times (T_{c\bar{3}})^{[ik]} (H_{\bar{6}})_{\{ij\}} (\overline{T}_8)^i_k P^j_l .\end{aligned}$$

To date, there are in total **30** data points but $\mathbf{9} \times 2$(S- & P-waves) $\times\, 2$(complex) $- 1 =$ **35**

- **SU(3) flavor analysis — Tree**

$$\mathscr{H}_{eff} = \frac{G_F}{\sqrt{2}} \left[\sum_{qq'} V^*_{qc} V_{q'u} \left(C_+ O^{qq'}_+ + C_- O^{qq'}_- \right) - \lambda_b \sum_{i=3\sim6} C_i O_i \right]$$

$$\langle \mathbf{B} P | \mathscr{H}_{\text{eff}} | \mathbf{B}_c \rangle = i\bar{u} \left(F - G\gamma_5 \right) u_c$$

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To date, there are in total **30** data points but $\mathbf{9} \times 2$(S- & P-waves) ~~$\times\, 2$(complex) $- 1$~~ $=$ ~~35~~ **5**

In the absence of final state interactions → **18**

- ## SU(3) flavor analysis — Tree

(2019) 16 input, 10 parameters*

(2023) 28 input, 18 parameters

(2023) 28 input, 18 parameters

$$\alpha\left(\Lambda_c^+ \to \Xi^0 K^+\right) = \quad 0.94^{+0.06}_{-0.11} \quad 0.91^{+0.03}_{-0.04} \quad 0.955 \pm 0.018$$

First Measurement of the Decay Asymmetry of pure W-exchange Decay $\Lambda_c^+ \to \Xi^0 K^+$

(Dated: **September 8, 2023**)

Based on 4.4 fb^{-1} of e^+e^- annihilation data collected at the center-of-mass energies between 4.60 and 4.70 GeV with the BESIII detector at the BEPCII collider, the pure W-exchange decay $\Lambda_c^+ \to \Xi^0 K^+$ is studied with a full angular analysis. The corresponding decay asymmetry is measured for the first time to be $\alpha_{\Xi^0 K^+} = 0.01 \pm 0.16(\text{stat.}) \pm 0.03(\text{syst.})$. This result reflects the interference between the S- and P-wave amplitudes. The phase shift between S- and P-wave amplitudes is $\delta_p - \delta_s = -1.55 \pm 0.25(\text{stat.}) \pm 0.05(\text{syst.})$ rad.

To date, there are in total **30** data points but **9** $\times$ 2(S- & P-waves) ~~$\times$ 2(complex) $-$ 1~~ = ~~3~~5

In the absence of final state interactions → **18**

Phys. Lett. B 794, 19-28 (2019) JHEP **02**, 235 (2023) Phys. Rev. D 108, no.5, 053004 (2023)

• SU(3) flavor analysis — Tree

(2019) 16 input,
10 parameters*

$$\alpha\left(\Lambda_c^+ \to \Xi^0 K^+\right) = \quad 0.94^{+0.06}_{-0.11}$$

• Free parameters: 18 →10

$$A_{(\mathbf{B}_c\to\mathbf{B}_n M)} =$$
$$a_0 H(6)_{ij}(\mathbf{B}'_c)^{ik}(\mathbf{B}_n)^j_k(M)^l_l + a_1 H(6)_{ij}(\mathbf{B}'_c)^{ik}(\mathbf{B}_n)^l_k(M)^j_l + a_2 H(6)_{ij}(\mathbf{B}'_c)^{ik}(M)^l_k(\mathbf{B}_n)^j_l +$$
$$a_3 H(6)_{ij}(\mathbf{B}_n)^i_k(M)^j_l(\mathbf{B}'_c)^{kl} + a'_0(\mathbf{B}_n)^i_j(M)^l_l H(\overline{15})^{jk}_i(\mathbf{B}_c)_k + a_4 H(\overline{15})^{li}_k(\mathbf{B}_c)_j(M)^j_i(\mathbf{B}_n)^k_l +$$
$$a_5(\mathbf{B}_n)^i_j(M)^l_i H(\overline{15})^{jk}_l(\mathbf{B}_c)_k + a_6(\mathbf{B}_n)^j_i(M)^m_l H(\overline{15})^{li}_m(\mathbf{B}_c)_j + a_7(\mathbf{B}_n)^l_i(M)^i_j H(\overline{15})^{jk}_l(\mathbf{B}_c)_k,$$

PLB **794**, 19(2019)

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

EXP(2022): $(4.7 \pm 1.0)\times 10^{-4}$ $\quad (4.8 \pm 1.4)\times 10^{-4}$

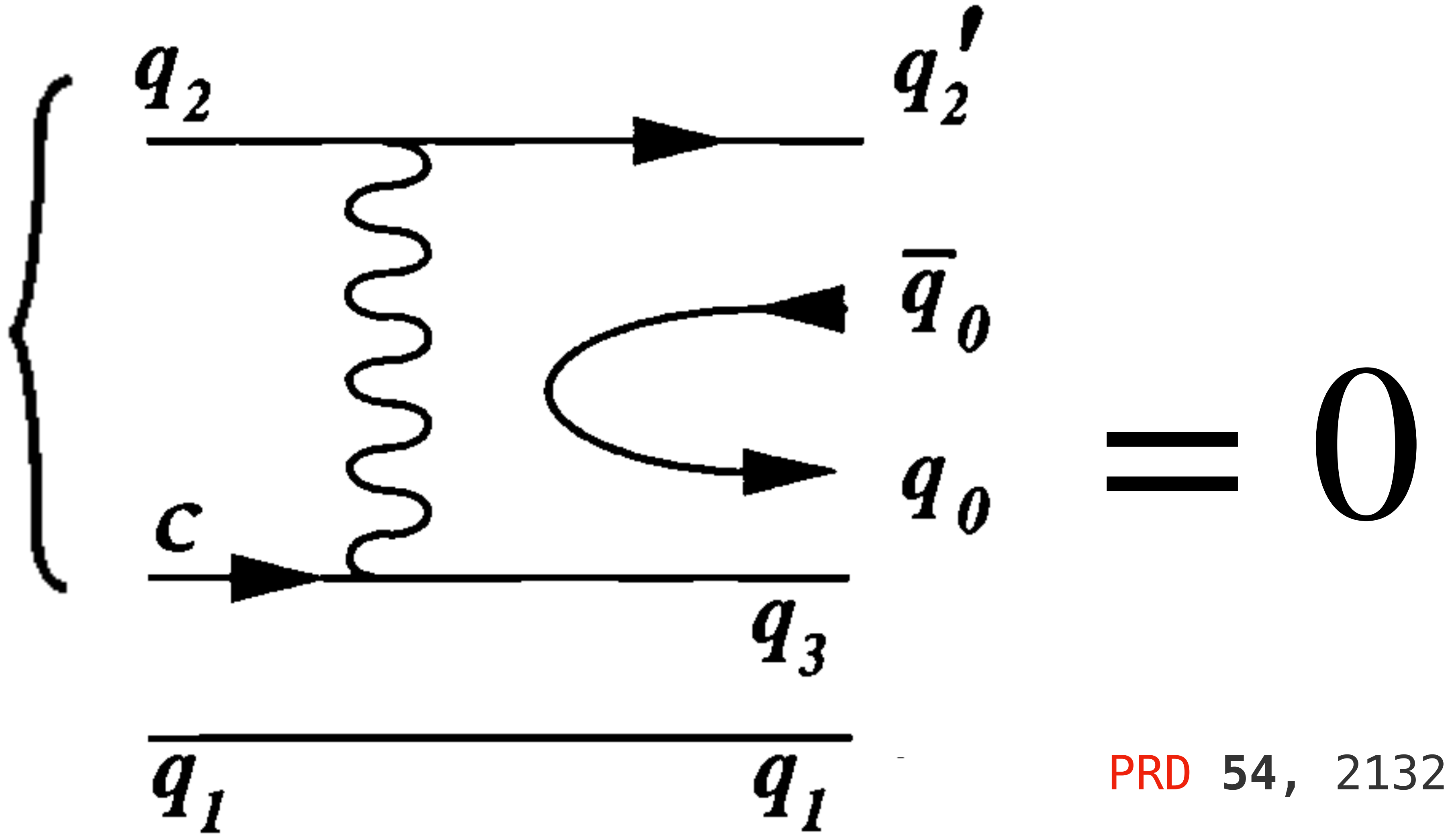
BESIII PRD **106**, no.5, 052003 (2022)

• The Körner-Pati-Woo theorem:

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

Color symmetric   Color singlet

$$O_+^{qq'} = \frac{1}{2}\left[\left(\bar{u}q'\right)_{V-A}\left(\bar{q}c\right)_{V-A} + \left(\bar{q}q'\right)_{V-A}(\bar{u}c)_{V-A}\right],$$



PRD **54**, 2132 (1996)

Chau, Cheng, Tseng

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$0.94^{+0.06}_{-0.11}$	$0.91^{+0.03}_{-0.04}$	0.955 ± 0.018

$$\alpha\left(\Lambda_c^+ \to \Xi^0 K^+\right) =$$

First Measurement of the Decay Asymmetry of pure W-exchange Decay $\Lambda_c^+ \to \Xi^0 K^+$

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Considering the Körner-Pati-Woo theorem: $\to$ **10**

Phys. Lett. B 794, 19-28 (2019) | JHEP **02**, 235 (2023) | Phys. Rev. D 108, no.5, 053004 (2023)

- **SU(3) flavor analysis — Tree**

	(2023) 29 input, 19 parameters*	(2023) 28 input, 18 parameters	(2023) 28 input, 18 parameters
$\alpha\left(\Lambda_c^+ \to \Xi^0 K^+\right) =$	-0.15 ± 0.14	$0.91^{+0.03}_{-0.04}$	0.955 ± 0.018

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Considering the Körner-Pati-Woo theorem: $\rightarrow$ **19**

arXiv:2310.05491 [hep-ph] | JHEP **02**, 235 (2023) | Phys. Rev. D **108**, no.5, 053004 (2023)

• SU(3) flavor analysis — Tree

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

- Sizable strong phases
- KPW + SU(3)

$$\frac{\tau_{\Lambda_c^+}}{\tau_{\Xi_c^0}}\mathcal{B}(\Xi_c^0 \to \Xi^-\pi^+) = \mathcal{B}(\Lambda_c^+ \to \Sigma^0\pi^+) + 3\mathcal{B}(\Lambda_c^+ \to \Lambda\pi^+) - \frac{1}{s_c^2}\mathcal{B}(\Lambda_c^+ \to n\pi^+)$$

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

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

$$\times$$

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

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

$$||$$

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

?

Channels	$\mathcal{B}_{\rm exp}(\%)$	$\alpha_{\rm exp}$	$\mathcal{B}(\%)$	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)
$\Lambda_c^+ \to \Xi^0K^+$	**0.55(7)	0.01(16)	0.40(3)	−0.15(14)	−0.29(22)
$\Lambda_c^+ \to \Lambda^0K^+$	0.064(3)	−0.585(52)	0.063(3)	−0.56(5)	0.82(5)
$\Lambda_c^+ \to \Sigma^0K^+$	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	$\mathcal{R}_X^{\rm exp}$	$\alpha_{\rm exp}$	$\mathcal{R}_X$	α	β
$\Xi_c^0 \to \Lambda^0K_S$	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)
$\Xi_c^0 \to \Sigma^0K_S$	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]

• SU(3) flavor analysis — Tree

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

PDG $> 4\sigma$

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

SU(3)

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

Belle $< 2\sigma$

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

Channels	$\mathcal{B}_{\rm exp}(\%)$	$\alpha_{\rm exp}$	$\mathcal{B}(\%)$	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)
$\Lambda_c^+ \to \Xi^0K^+$	**0.55(7)	0.01(16)	0.40(3)	−0.15(14)	−0.29(22)
$\Lambda_c^+ \to \Lambda^0K^+$	0.064(3)	−0.585(52)	0.063(3)	−0.56(5)	0.82(5)
$\Lambda_c^+ \to \Sigma^0K^+$	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	$\mathcal{R}_X^{\rm exp}$	$\alpha_{\rm exp}$	$\mathcal{R}_X$	α	β
$\Xi_c^0 \to \Lambda^0K_S$	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)
$\Xi_c^0 \to \Sigma^0K_S$	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)

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

$\times$ LQCD, CPC **46**, 011002 (2022)

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

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

$||$

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

arXiv:2310.05491 [hep-ph]

- **SU(3) flavor analysis — Tree**

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

$$CP \propto \tilde{f}^e, \tilde{g}^e$$

$$A^{dir}_{CP} = \frac{\Gamma - \overline{\Gamma}}{\Gamma + \overline{\Gamma}}, \quad \alpha_{CP} = \frac{\alpha + \overline{\alpha}}{2},$$
$$\beta_{CP} = \frac{\beta + \overline{\beta}}{2}, \quad \gamma_{CP} = \frac{\gamma - \overline{\gamma}}{2}.$$

CP-odd quantities $\sim 10^{-4}$

$$a^{\rm dir}_{D\to K^+K^-} - a^{\rm dir}_{D\to\pi^+\pi^-} = (-1.57 \pm 0.29) \times 10^{-3}$$

Channels	$\mathcal{B}(10^{-3})$	$\alpha_{CP}(10^{-3})$	$\beta_{CP}(10^{-3})$	$\gamma_{CP}(10^{-3})$	$A^{dir}_{CP}(10^{-3})$
$\Lambda_c^+ \to p\pi^0$	0.16(2)	−0.61(39)	−0.43(48)	0.53(145)	0.01(1)
$\Lambda_c^+ \to p\eta$	1.45(25)	0.05(17)	0.04(14)	−0.07(22)	−0.03(4)
$\Lambda_c^+ \to p\eta'$	0.52(11)	−0.02(7)	0.01(4)	0.00(4)	0.00(1)
$\Lambda_c^+ \to n\pi^+$	0.67(8)	0.12(20)	0.13(26)	−0.28(40)	−0.01(2)
$\Lambda_c^+ \to \Lambda^0 K^+$	0.63(2)	−0.03(10)	0.03(5)	0.04(24)	0.01(1)
$\Xi_c^+ \to \Sigma^+\pi^0$	2.11(14)	0.06(13)	−0.01(13)	−0.09(42)	−0.07(7)
$\Xi_c^+ \to \Sigma^+\eta$	0.70(32)	−0.10(22)	0.09(73)	0.29(57)	0.01(4)
$\Xi_c^+ \to \Sigma^+\eta'$	1.13(23)	0.03(7)	−0.01(2)	−0.01(4)	−0.01(0)
$\Xi_c^+ \to \Sigma^0\pi^+$	3.04(11)	−0.01(6)	−0.01(11)	0.05(21)	0.05(5)
$\Xi_c^+ \to \Xi^0 K^+$	1.04(13)	0.02(14)	0.13(18)	−0.18(25)	−0.02(2)
$\Xi_c^+ \to \Lambda^0\pi^+$	0.32(9)	0.0(19)	0.36(30)	0.20(19)	0.00(1)
$\Xi_c^0 \to \Sigma^0\pi^0$	0.34(2)	−0.04(12)	0.25(39)	0.12(12)	0.00(1)
$\Xi_c^0 \to \Sigma^0\eta$	0.12(5)	−0.11(22)	0.09(73)	0.29(57)	0.00(1)
$\Xi_c^0 \to \Sigma^0\eta'$	0.19(4)	0.03(7)	−0.01(2)	−0.01(4)	0.00(1)
$\Xi_c^0 \to \Sigma^-\pi^+$	1.83(6)	0.02(7)	−0.09(21)	0.03(12)	0.02(3)
$\Xi_c^0 \to \Xi^- K^+$	1.12(3)	0.02(5)	−0.08(16)	0.02(11)	0.01(1)
$\Xi_c^0 \to \Lambda^0\pi^0$	0.09(1)	0.07(20)	−0.27(25)	−0.15(17)	0.00(1)
$\Xi_c^0 \to \Lambda^0\eta$	0.43(11)	0.06(12)	0.11(14)	−0.01(2)	−0.01(1)
$\Xi_c^0 \to \Lambda^0\eta'$	0.68(13)	0.00(1)	0.00(1)	0.00(1)	0.00(1)

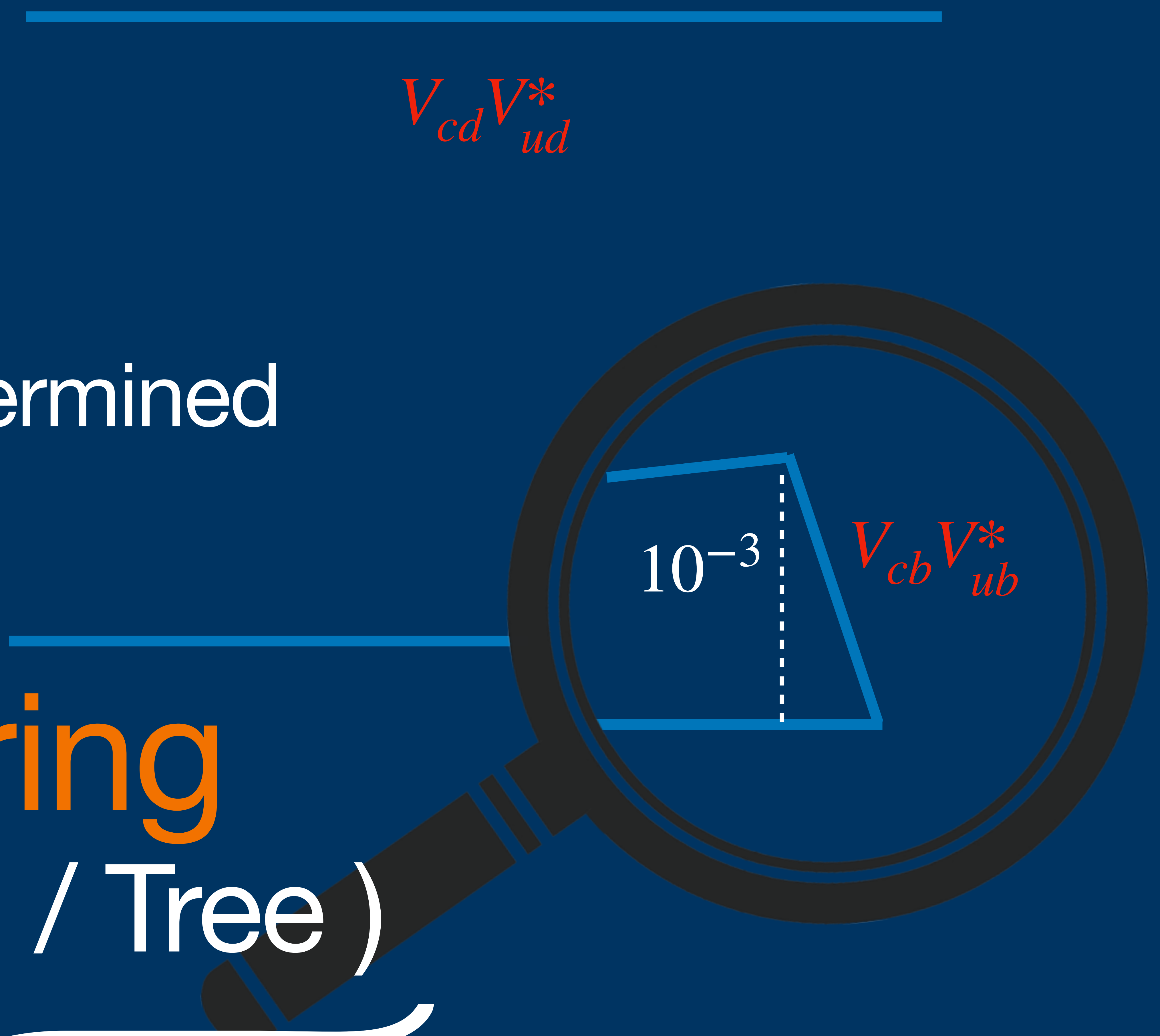
arXiv:2312.xxxx [hep-ph]

SU(3) flavor analysis

$\lambda_{d,s}$ Tree + $\underbrace{\lambda_b \text{ Penguin}}$

Insensitive to CP-even quantities & undetermined

$\lambda_q = V_{cq}^* V_{uq}$



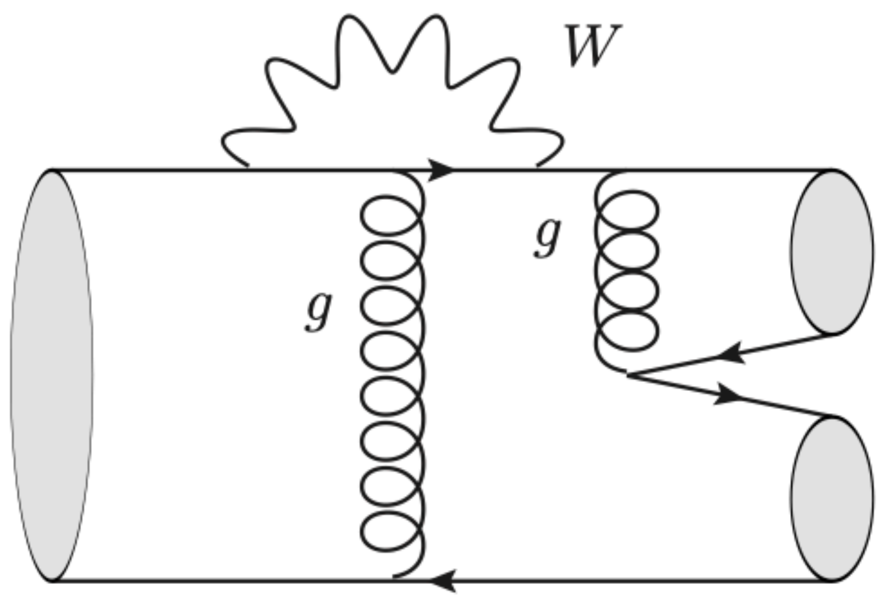
Pole model + Rescattering

$\lambda_{d,s}$ Tree + λ_b Tree × $\underbrace{(\text{ Penguin / Tree })}$

Determined by the PM + rescattering

• Pole model + Rescattering — Penguin / Tree

b – loop is absent!



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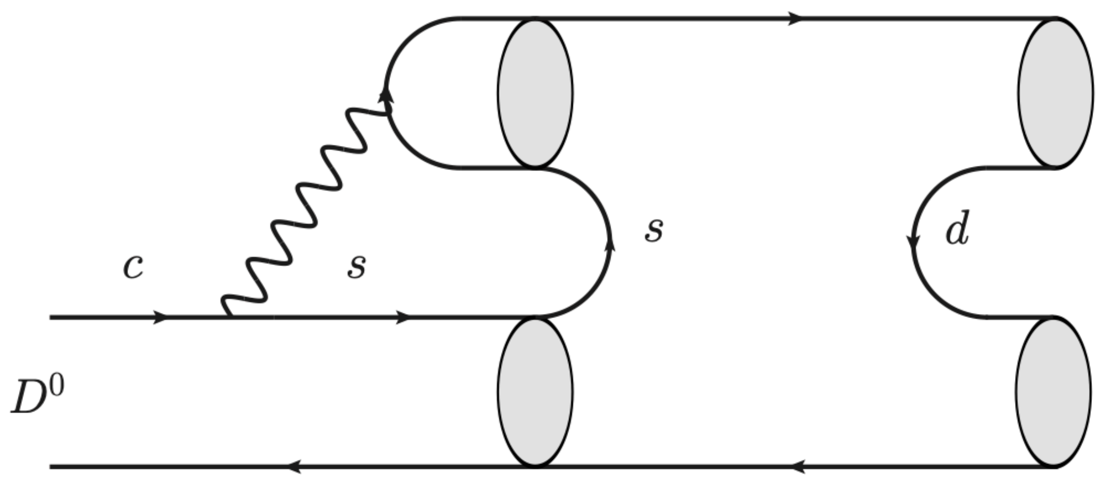

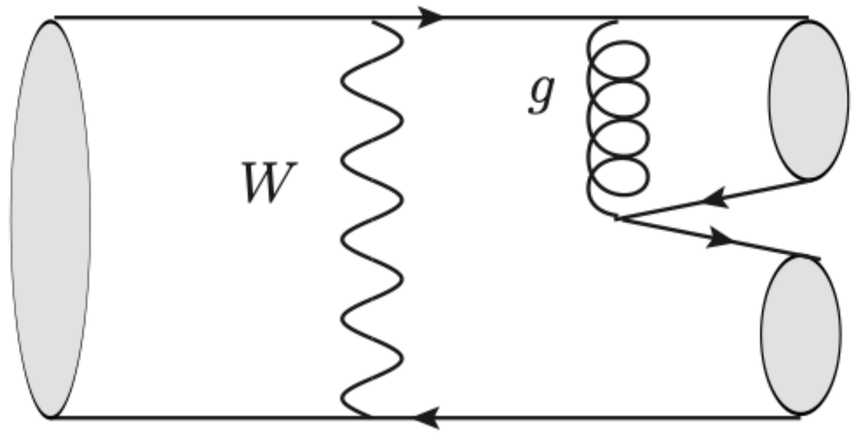

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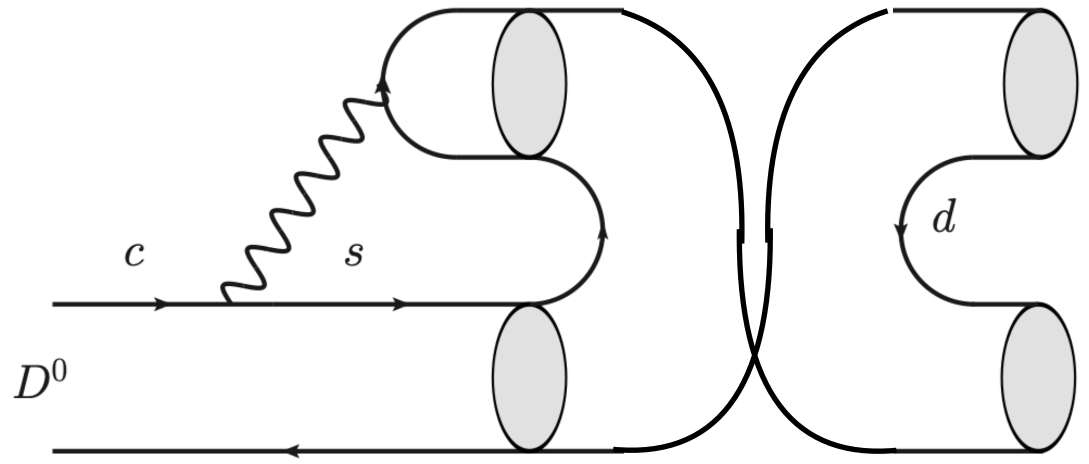
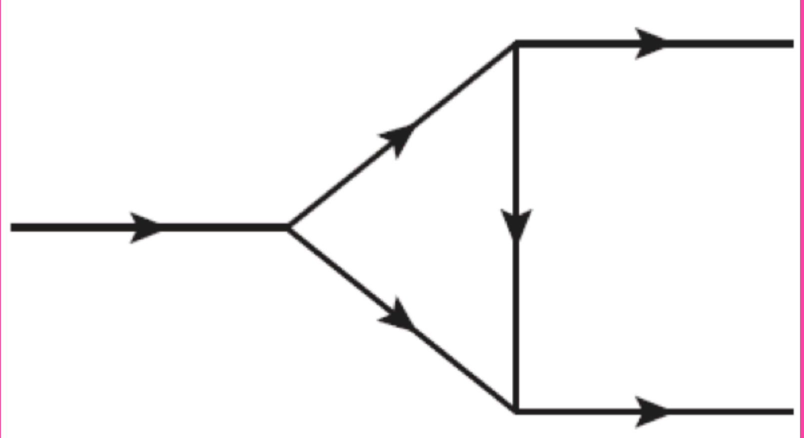
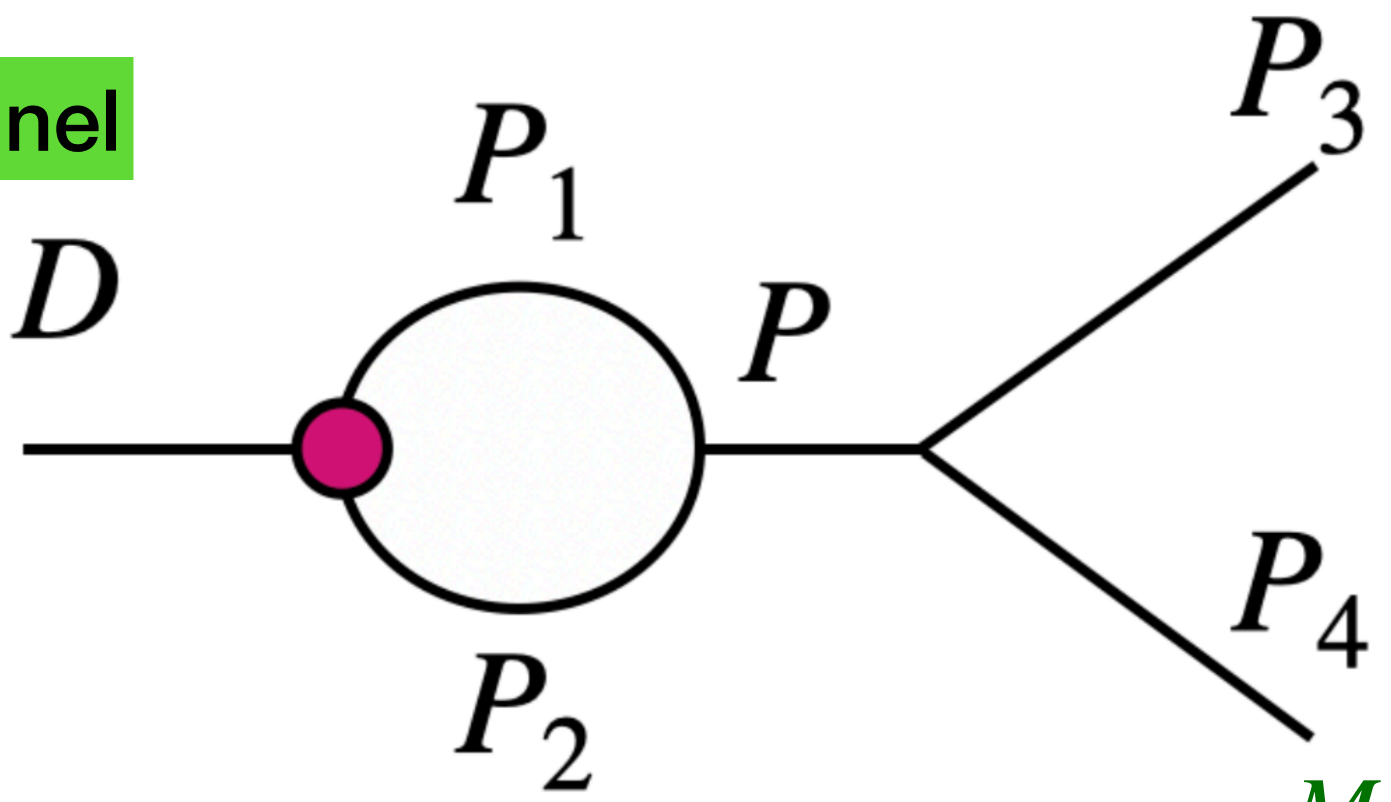


"Hence, it is plausible to assume that PE is of the same order of magnitude as E. We took PE =E."
PRD 100, 093002 (2019)



Proved by Di Wang
JHEP 03, 155 (2022)

For s-channel



$P \sim f(1710)$

$M_D - M_f = 130$

Phys. Rev. D 81, 074021 (2010)

$$\mathcal{H}^{\pm}_{eff} = \frac{G_F}{\sqrt{2}} c_{\pm} (\mathcal{H}^{\pm})^{ij}_{k} (\overline{q}_i q^k)_L (\overline{q}_j c)_L \,,$$

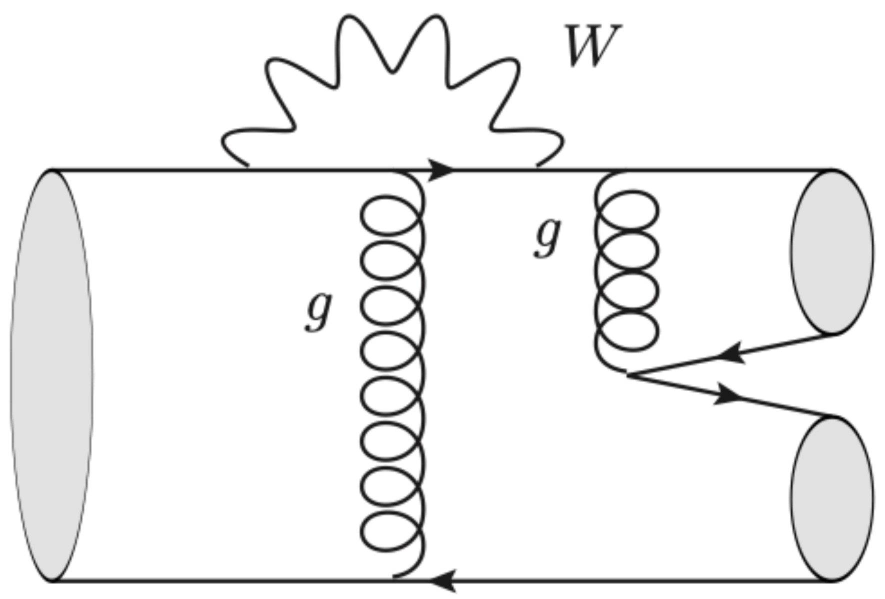
$$\langle P | \mathcal{H}^{\pm}_{eff} | D \rangle = T \sum_{P_1,P_2} \underbrace{D_i (\mathcal{H}^{\pm})^{jk}_{l} (P_1^{\dagger})^{l}_{j} (P_2^{\dagger})^{i}_{k}}_{\text{Weak; } D \to P_1 P_2} \cdot \underbrace{\left((P_1)^m_n (P_2)^n_o (P^{\dagger})^o_m + (P_1)^m_n (P_2)^o_m (P^{\dagger})^n_o \right)}_{\text{Strong; } P_1 P_2 \to P} \,,$$

Penguin / Tree = 1

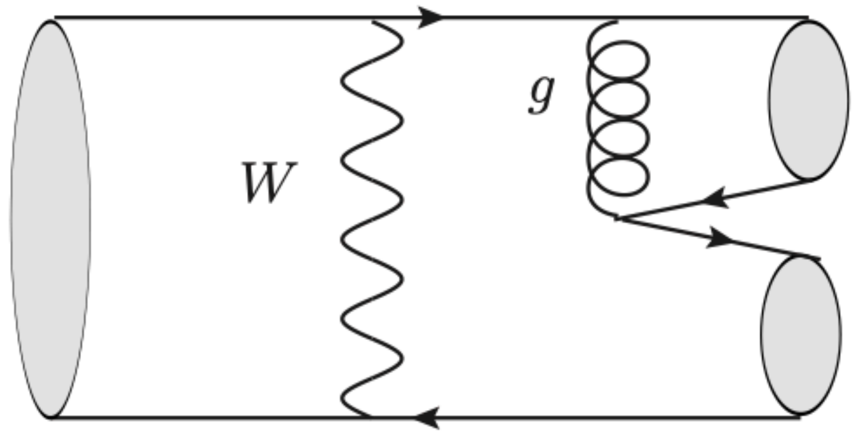
$$= T \left(1 \mp \frac{2}{3} \right) \left(\underbrace{D_i (\mathcal{H}^{\pm})^{jk}_{k} (P^{\dagger})^{i}_{j}}_{P-\text{exchange}} + \underbrace{D_i (\mathcal{H}^{\pm})^{ik}_{j} (P^{\dagger})^{j}_{k}}_{W-\text{exchange}} \right)$$

Completeness relation: $\sum_{\lambda_8} (\lambda_8)^i_j (\lambda_8^{\dagger})^k_l = \delta^i_l \delta^k_j - \frac{1}{3} \delta^i_j \delta^k_l$

- **Pole model + Rescattering — Penguin / Tree**



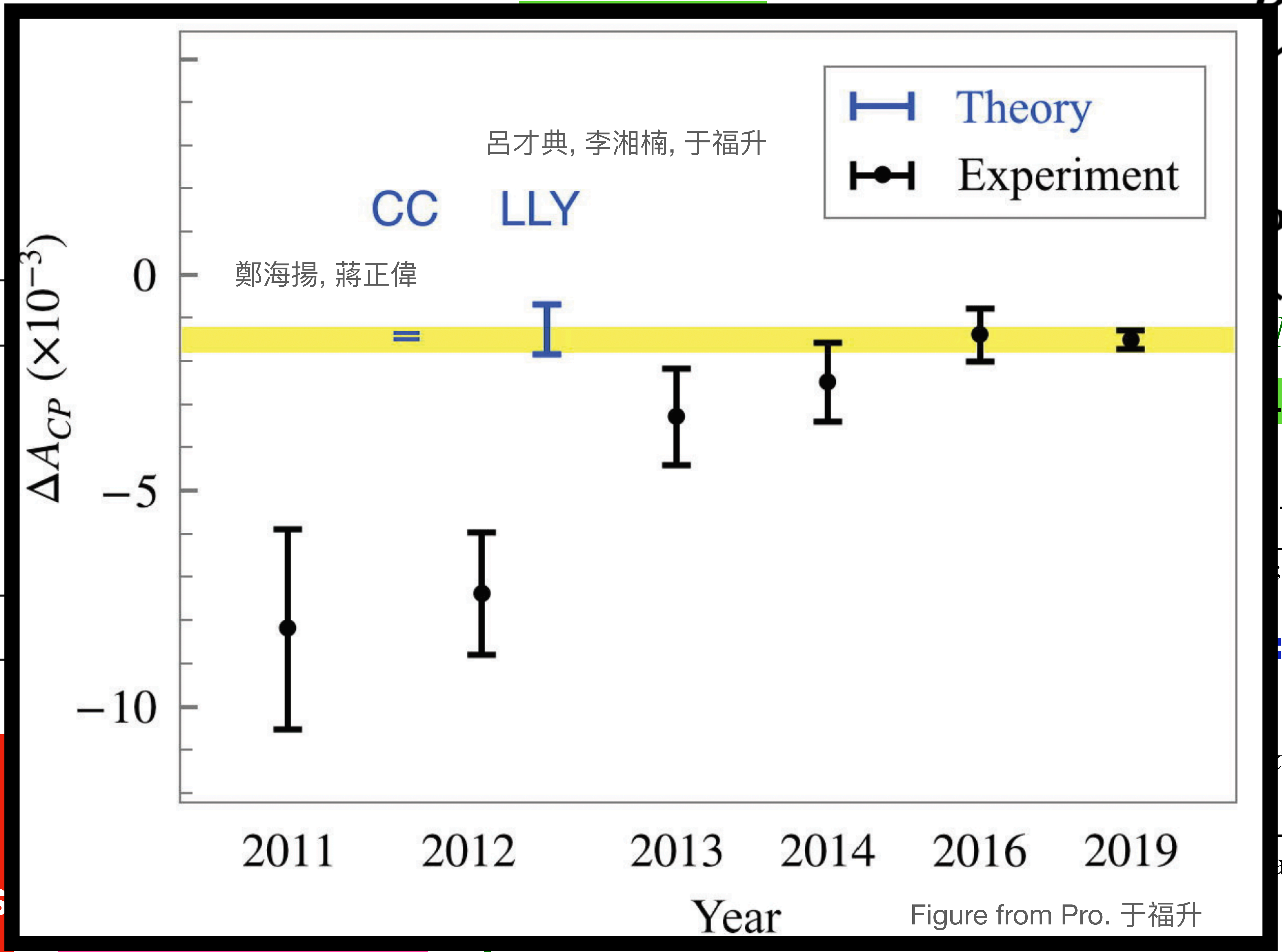
LD



LD

D^0

D^0



"Hence, it is plausible to assume that PE is of the same order of magnitude as E. We took PE =E."
PRD 100, 093002 (2019)

Proved by Di Wang
JHEP 03, 155 (2022)

P_3

P_4

$P \sim f(1710)$

$M_D - M_f = 130$

D 81, 074021 (2010)

$+ (P_1)^m_n (P_2)^o_m (P^\dagger)^n_o)$,

$P_1P_2 \to P$

1

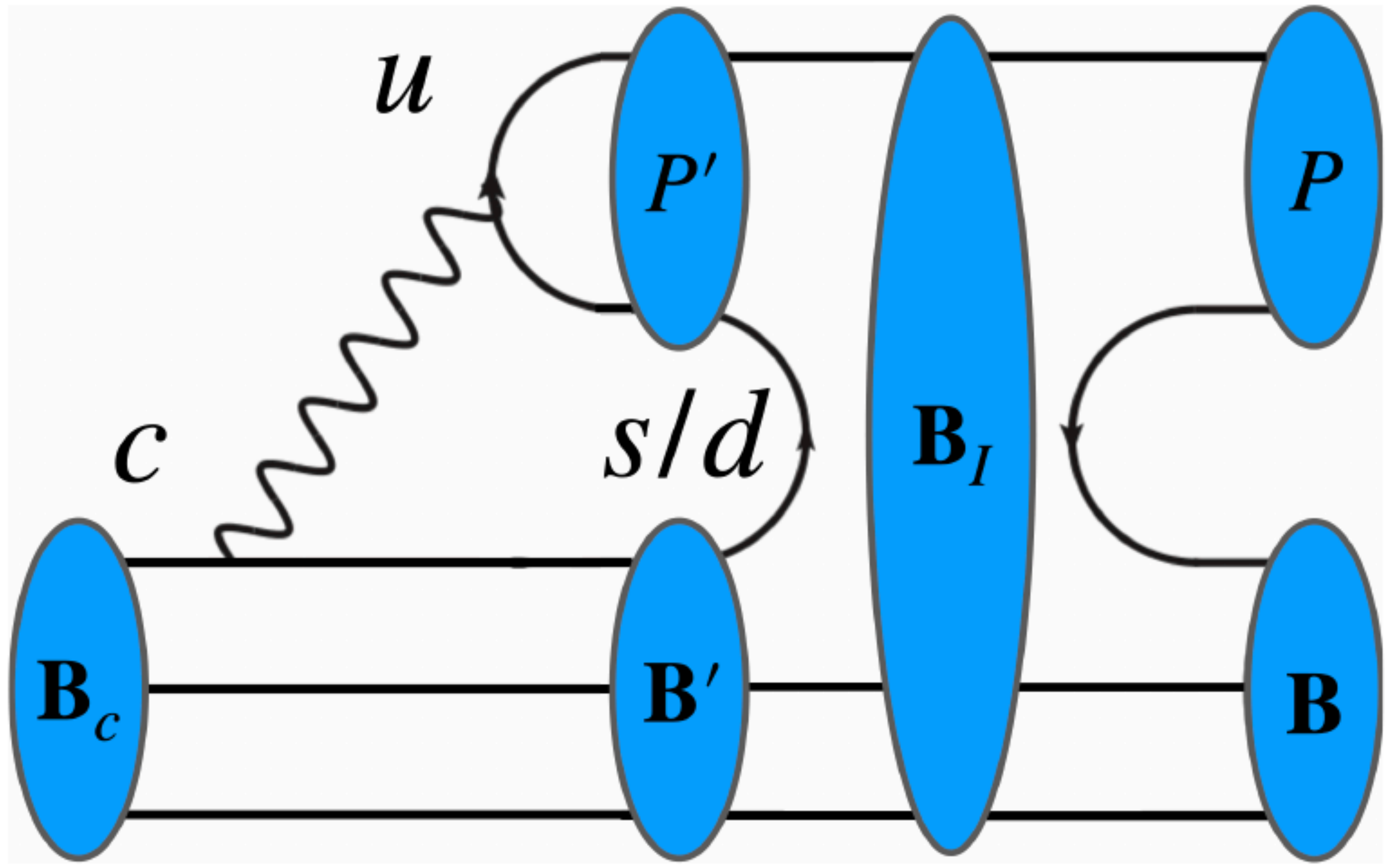
$(P^\dagger)^j_k$

ange

Completeness relation: $\sum_{\lambda_8} (\lambda_8)^i_j (\lambda_8^\dagger)^k_l = \delta^i_l \delta^k_j - \frac{1}{3}\delta^i_j \delta^k_l$

- **Pole model + Rescattering — Penguin / Tree**

b – loop is absent!

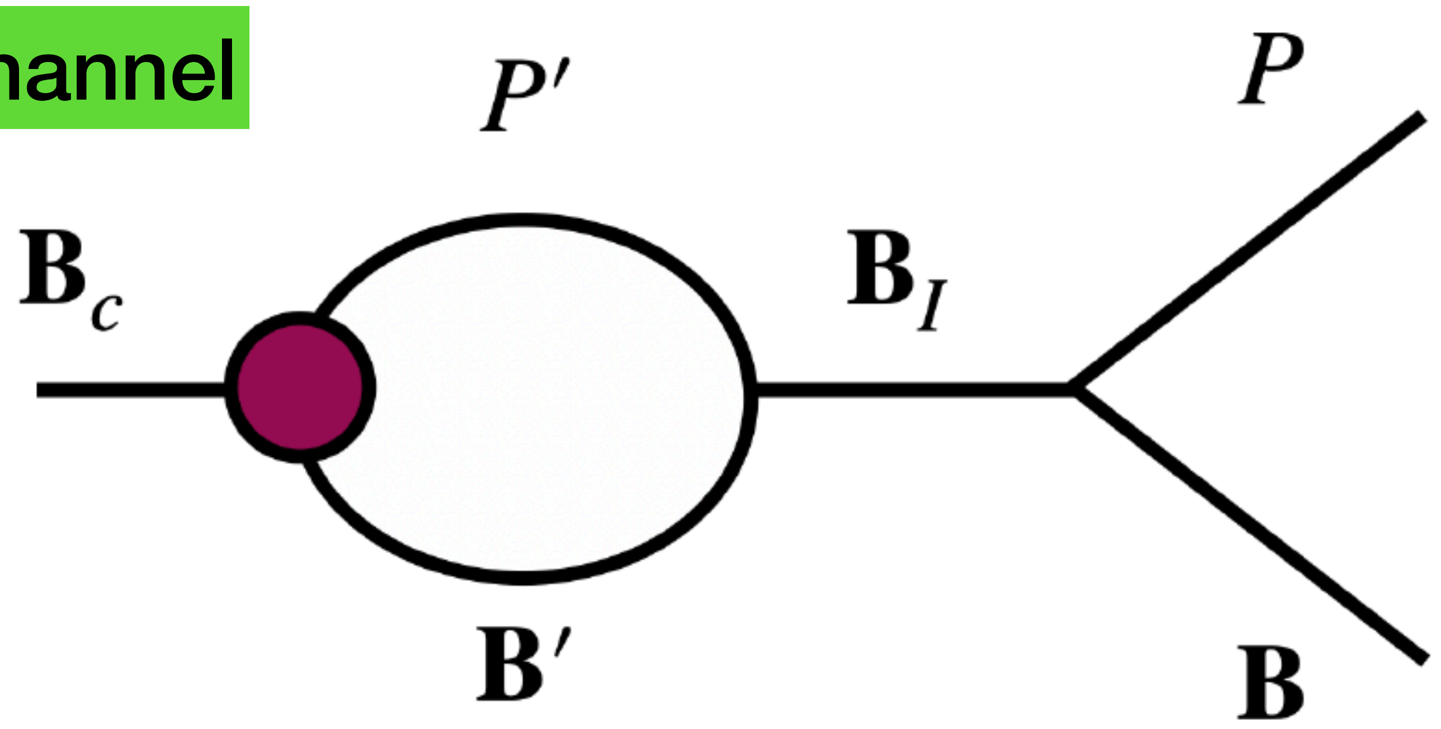


$$F_s^{\rm pole} = \frac{\tilde{E}_s^-}{f_P}\left\{ \frac{1}{\sqrt{2}}\mathcal{H}(\overline{\mathbf{6}})_{kl}(\mathbf{B}_c)^{[ki]}\left((P^\dagger)^l_n(\mathbf{B}^\dagger)^n_i + g_s^-(P^\dagger)^n_i(\mathbf{B}^\dagger)^l_n\right) - \lambda_b\frac{7-2g_s^-}{2+8g_s^-}\Big[(\mathbf{B}_c)_i\mathcal{H}(\overline{\mathbf{3}})^k\left((P^\dagger)^i_j(\mathbf{B}^\dagger)^j_k + g_s^-(P^\dagger)^j_k(\mathbf{B}^\dagger)^i_j\right) - \frac{1+g_s^-}{3}(\mathbf{B}_c)_i\mathcal{H}(\mathbf{3}_-)^i(P^\dagger)^j_k(\mathbf{B}^\dagger)^j_k\Big]\right\}$$

Ratio between 3 & $\overline{6}$ is determined

$$CP \propto \overline{\mathbf{6}} \times \mathbf{3}$$

For s-channel



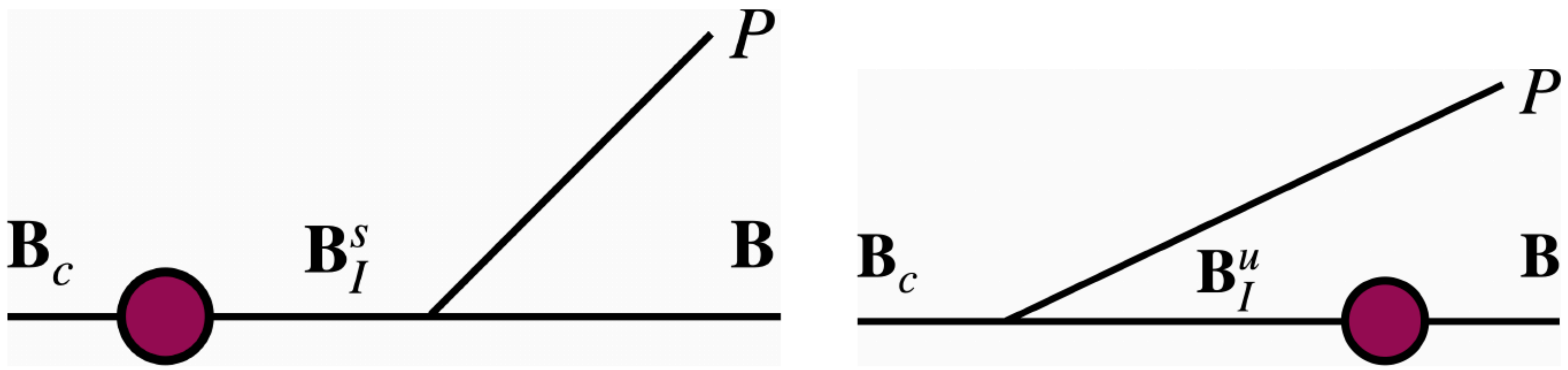
$$a^{RE}_{\mathbf{B}_I\mathbf{B}_c} \propto \sum_{\mathbf{B}',P'} \underbrace{\left((\mathbf{B}_c)_i\mathcal{H}^{jk}_l(\mathbf{B}'^\dagger)^i_j(P'^\dagger)^l_k\right)}_{\text{Weak; } \mathbf{B_c}\to\mathbf{B}'\mathrm{P}'} \cdot \underbrace{(P')^o_m\left(g^{s\pm}_{12}(\mathbf{B}')^m_n(\mathbf{B}_I^\dagger)^n_o + g^{s\pm}_{21}(\mathbf{B}_I^\dagger)^m_n(\mathbf{B}')^n_o\right)}_{\text{Strong; } \mathbf{B}'\mathrm{P}'\to\mathbf{B_I}}$$

$$= \left(\frac{8}{3}g^{s\pm}_{21} + \frac{2}{3}g^{s\pm}_{12}\right)\left(\frac{1}{\sqrt{2}}(\mathbf{B}_c)^{[lj]}\mathcal{H}(\overline{\mathbf{6}})_{kl}(\mathbf{B}_I^\dagger)^k_j - \lambda_b\frac{7-2g_s^\pm}{2+8g_s^\pm}(\mathbf{B}_c)_i\mathcal{H}(\mathbf{3}_-)^k(\mathbf{B}_I^\dagger)^i_k\right),$$

$a^{RE}_{\mathbf{B}_c\mathbf{B}_I}$ becomes complex if $M_{\mathbf{B}_c} > M_{\mathbf{B}'} + M_{P'}$

Completeness relation: $\sum_{\lambda_8}(\lambda_8)^i_j(\lambda_8^\dagger)^k_l = \delta^i_l\delta^k_j - \frac{1}{3}\delta^i_j\delta^k_l$

Pole model + Rescattering — Penguin / Tree



$$\tilde{E}_s^- = (18.0 \pm 0.8) e^{i(-0.271 \pm 0.017)}, \quad \tilde{E}_s^+ = (9.9 \pm 1.2) e^{i(-0.424 \pm 0.144)},$$

$$\tilde{E}_{u\bar{\mathbf{3}}}^- = 22.0 \pm 1.4, \quad \tilde{E}_{u\mathbf{6}}^- = -24.4 \pm 0.7, \quad \tilde{E}_{u\bar{\mathbf{6}}}^+ = -15.0 \pm 1.1,$$

$$a^+ = (0.401 \pm 0.025) e^{i(-0.104 \pm 0.122)}, \quad a^0 = 0.4 e^{-i(164 \pm 7)^\circ}$$

Case in charmed baryons; arXiv: 2312.xxxx

$a^+, T \propto$ **Color-allowed tree** , $a^0, C \propto$ **Color-suppressed tree**

Case in D meson; Phys. Rev. D 100, 093002 (2019)

$$T = 3.113 \pm 0.011, \qquad C = (2.767 \pm 0.029)\, e^{-i(151.3 \pm 0.3)^\circ},$$

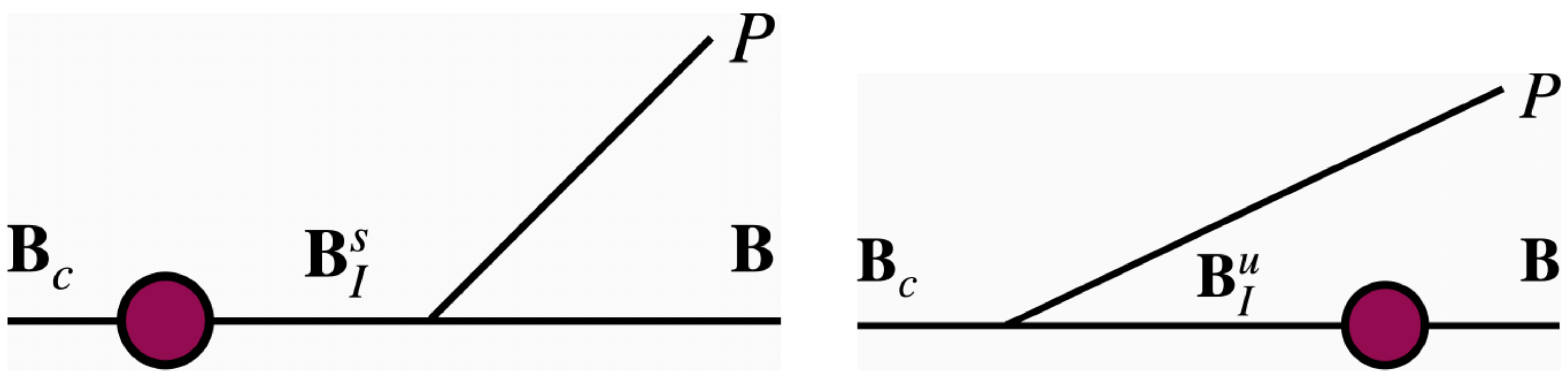
Preliminary results

30 input,
10 parameters

Channels	$\mathcal{B}_{\rm exp}(\%)$	$\alpha_{\rm exp}$	$\mathcal{B}(\%)$	α	β	γ
$\Lambda_c^+ \to pK_S$	1.59(8)	0.18(50)*	1.55(6)	−0.76(2)	−0.11(3)	0.65(3)
$\Lambda_c^+ \to \Lambda\pi^+$	1.30(6)*	−0.755(6)	1.23(5)	−0.75(1)	−0.13(9)	0.64(2)
$\Lambda_c^+ \to \Sigma^0\pi^+$	1.27(6)	−0.466(18)	1.31(5)	−0.47(2)	0.01(5)	0.88(1)
$\Lambda_c^+ \to \Sigma^+\pi^0$	1.25(10)	−0.48(3)	1.31(5)	−0.47(2)	0.01(5)	0.88(1)
$\Lambda_c^+ \to \Xi^0 K^+$	0.55(7)*	0.01(16)**	0.45(3)	−0.31(11)	−0.29(7)	0.91(4)
$\Lambda_c^+ \to \Lambda K^+$	0.064(3)	−0.585(52)	0.062(3)	−0.55(5)	0.10(10)	0.83(3)
$\Lambda_c^+ \to \Sigma^0 K^+$	0.0382(25)*	−0.54(20)	0.0347(22)	−0.61(4)	−0.04(4)	0.79(3)
$\Lambda_c^+ \to n\pi^+$	0.066(13)		0.058(7)	−0.70(11)	−0.29(12)	0.66(7)
$\Lambda_c^+ \to \Sigma^+ K_S$	0.048(14)		0.035(2)	−0.61(4)	−0.04(4)	0.79(3)
$\Lambda_c^+ \to p\pi^0$	0.016(7)		0.017(3)	−0.52(17)	−0.45(13)	0.73(7)
$\Xi_c^+ \to \Xi^0\pi^+$	1.60(80)*		0.54(9)	−0.78(10)	0.09(10)	0.61(13)
$\Xi_c^0 \to \Xi^-\pi^+$	1.43(32)****	−0.64(5)	3.04(9)	−0.68(3)	−0.02(4)	0.73(3)
Channels	$\mathcal{R}_X^{\rm exp}$	$\alpha_{\rm exp}$	$\mathcal{R}_X$	α	β	γ
$\Xi_c^0 \to \Lambda K_S$	0.225(13)**		0.191(6)	−0.68(2)	−0.04(3)	0.74(2)
$\Xi_c^0 \to \Xi^- K^+$	0.0275(57)**		0.0431(8)	−0.71(2)	−0.02(4)	0.71(3)
$\Xi_c^0 \to \Sigma^0 K_S$	0.038(7)		0.041(6)	−0.62(9)	−0.60(11)	0.50(5)
$\Xi_c^0 \to \Sigma^+ K^-$	0.123(12)*		0.135(10)	−0.41(14)	−0.38(9)	0.83(7)

	β	$\delta_p - \delta_s$
Data	-0.64 ± 0.70	-1.55 ± 0.25
Theory	-0.29 ± 0.07	-0.75 ± 0.23

- **Pole model + Rescattering — Penguin / Tree**



$$\tilde{E}_s^- = (18.0 \pm 0.8) e^{i(-0.271 \pm 0.017)}, \quad \tilde{E}_s^+ = (9.9 \pm 1.2) e^{i(-0.424 \pm 0.144)},$$

$$\tilde{E}_{u\mathbf{3}}^- = 22.0 \pm 1.4, \quad \tilde{E}_{u\mathbf{6}}^- = -24.4 \pm 0.7, \quad \tilde{E}_{u\bar{\mathbf{6}}}^+ = -15.0 \pm 1.1,$$

$$a^+ = (0.401 \pm 0.025) e^{i(-0.104 \pm 0.122)}, \quad a^0 = 0.4 e^{-i(164 \pm 7)^\circ}$$

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$$T = 3.113 \pm 0.011, \quad C = (2.767 \pm 0.029)\, e^{-i(151.3 \pm 0.3)^\circ},$$

Channels	$\mathcal{B}(10^{-3})$	$\alpha_{CP}(10^{-3})$	$\beta_{CP}(10^{-3})$	$\gamma_{CP}(10^{-3})$	$A_{CP}^{dir}(10^{-3})$
$\Lambda_c^+ \to \Sigma^+ K_{S/L}$	0.35(2)	0.06(2)	−0.20(2)	0.04(1)	0.27(2)
$\Lambda_c^+ \to \Sigma^0 K^+$	0.35(2)	0.00(1)	−0.01(1)	0.00(1)	0.00(1)
$\Lambda_c^+ \to p\pi^0$	0.17(3)	0.14(39)	0.83(39)	0.62(22)	4.19(33)
$\Lambda_c^+ \to n\pi^+$	0.58(7)	0.30(16)	0.35(28)	0.47(13)	3.30(16)
$\Lambda_c^+ \to \Lambda K^+$	0.62(3)	0.03(5)	−0.06(5)	0.03(4)	0.57(7)
$\Xi_c^+ \to \Sigma^+ \pi^0$	2.70(17)	0.02(2)	0.04(3)	0.02(1)	−0.30(2)
$\Xi_c^+ \to \Sigma^0 \pi^+$	2.57(9)	0.02(1)	0.08(1)	0.01(1)	−0.11(1)
$\Xi_c^+ \to \Xi^0 K^+$	1.19(14)	−0.52(8)	−0.18(14)	−0.80(11)	−2.44(12)
$\Xi_c^+ \to p K_{S/L}$	0.97(7)	−0.07(2)	0.27(3)	−0.07(2)	−0.24(2)
$\Xi_c^+ \to \Lambda \pi^+$	0.51(11)	−0.38(6)	−0.10(18)	−0.55(19)	−1.81(20)
$\Xi_c^0 \to \Sigma^+ \pi^-$	0.35(1)	0.08(13)	−0.28(5)	−0.10(7)	−1.45(6)
$\Xi_c^0 \to \Sigma^0 \pi^0$	0.46(1)	−0.03(1)	0.06(1)	−0.01(1)	0.13(2)
$\Xi_c^0 \to \Sigma^- \pi^+$	1.57(1)	−0.01(1)	0.08(1)	0.00(1)	0.02(2)
$\Xi_c^0 \to \Xi^0 K_{S/L}$	0.34(1)	−0.03(3)	−0.08(4)	−0.02(1)	−0.62(3)
$\Xi_c^0 \to \Xi^- K^+$	1.31(1)	0.00(1)	−0.08(1)	0.00(1)	−0.03(2)
$\Xi_c^0 \to p K^-$	0.23(1)	−0.10(14)	0.32(5)	0.14(10)	1.43(6)
$\Xi_c^0 \to n K_{S/L}$	0.36(1)	0.04(4)	0.12(5)	0.03(2)	0.61(4)
$\Xi_c^0 \to \Lambda \pi^0$	0.11(1)	−0.25(3)	−0.03(13)	−0.37(11)	−1.60(17)

30 input,
10 parameters

Preliminary results

What have been done

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

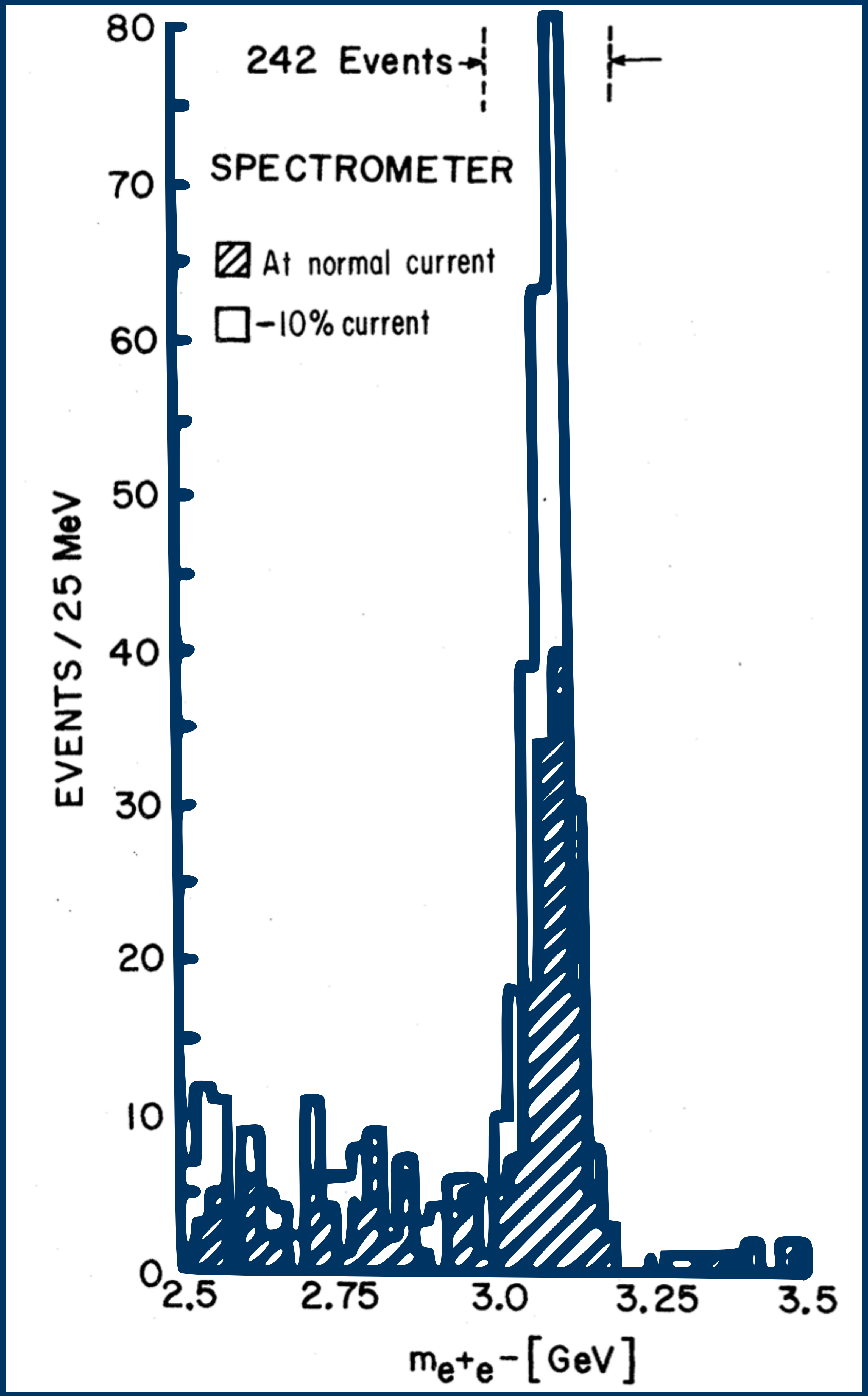
SU(3) flavor symmetry

PM & Rescattering

What we need

Measurements of β and γ in near future

Measurements of A_{CP} in STCF

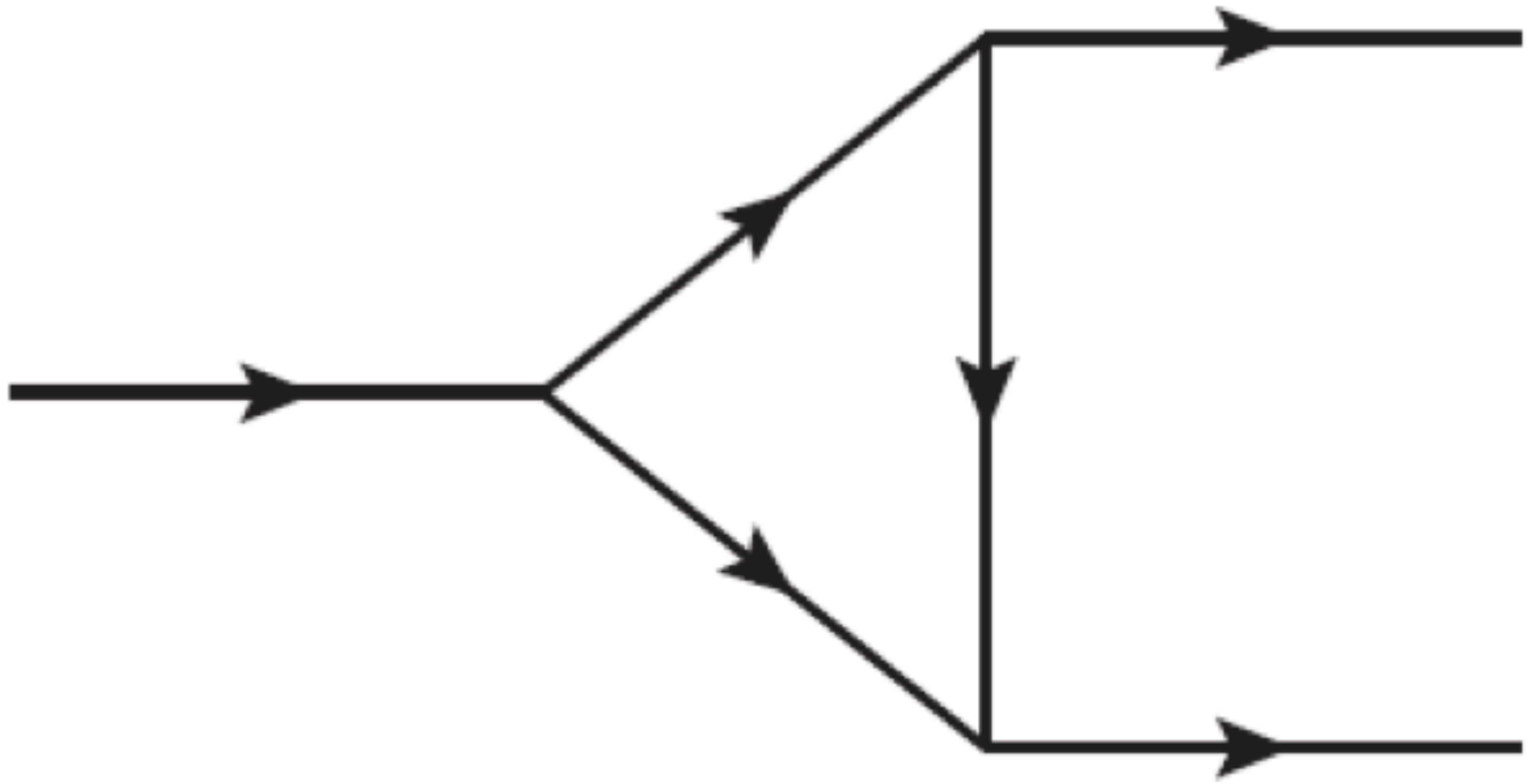


Pole model + Rescattering

PLB **794**, 19(2019) $\mathscr{B}(\Lambda_c^+ \to \Sigma^0 K^+) = \mathscr{B}(\Lambda_c^+ \to \Sigma^+ K_S^0)$

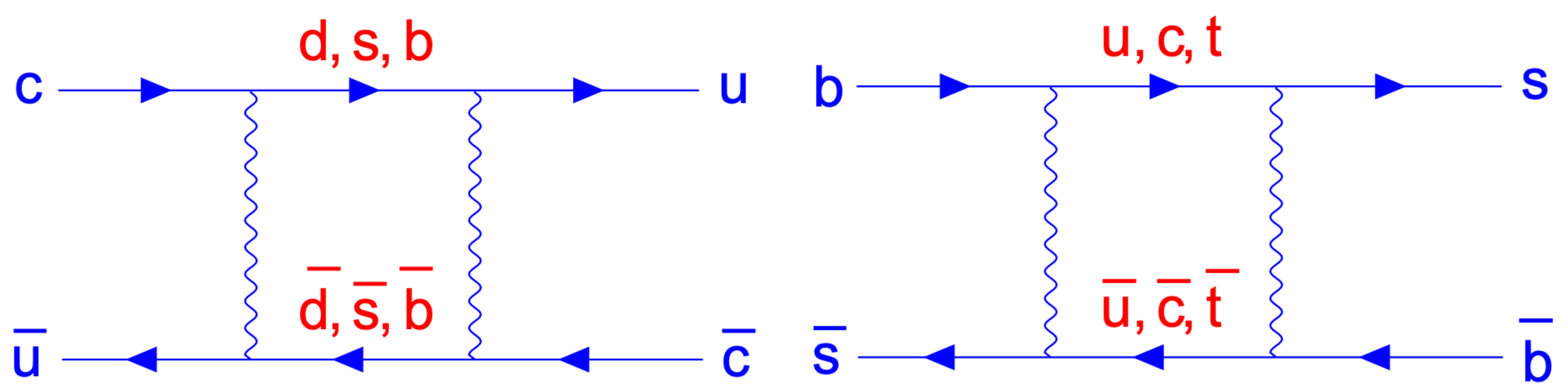
$(4.7 \pm 1.0) \times 10^{-4}$ $\quad$ $(4.8 \pm 1.4) \times 10^{-4}$

BESIII PRD **106**, no.5, 052003 (2022)



$$\mathcal{M} = a_{15} \times (T_{c\bar{3}})_i (H_{\overline{15}})_j^{\{ik\}} (\overline{T_8})_k^j P_l^l + b_{15} \times (T_{c\bar{3}})_i (H_{\overline{15}})_j^{\{ik\}} (\overline{T_8})_k^l P_l^j + c_{15} \times (T_{c\bar{3}})_i (H_{\overline{15}})_j^{\{ik\}} (\overline{T_8})_l^j P_k^l$$
$$+ d_{15} \times (T_{c\bar{3}})_i (H_{\overline{15}})_l^{\{jk\}} (\overline{T_8})_j^l P_k^i + e_{15} \times (T_{c\bar{3}})_i (H_{\overline{15}})_l^{\{jk\}} (\overline{T_8})_j^i P_k^l + a_6 \times (T_{c\bar{3}})^{[ik]} (H_{\bar{6}})_{\{ij\}} (\overline{T_8})_k^j P_l^l$$
$$+ b_6 \times (T_{c\bar{3}})^{[ik]} (H_{\bar{6}})_{\{ij\}} (\overline{T_8})_k^l P_l^j + c_6 \times (T_{c\bar{3}})^{[kl]} (H_{\bar{6}})_{\{ij\}} (\overline{T_8})_l^j P_k^i + d_6 \times (T_{c\bar{3}})^{[ik]} (H_{\bar{6}})_{\{ij\}} (\overline{T_8})_k^i P_l^j.$$

- ## CP violation in charm - overview

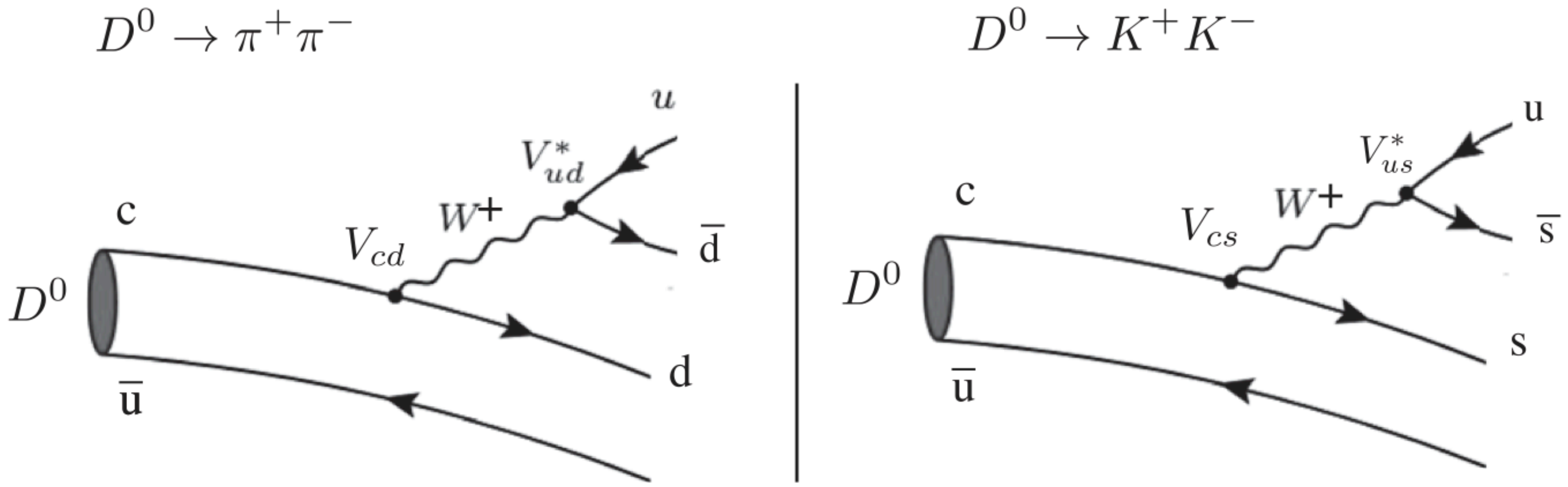


Ann. Rev. Nucl. Part. Sci. **71**, 59-85 (2021)

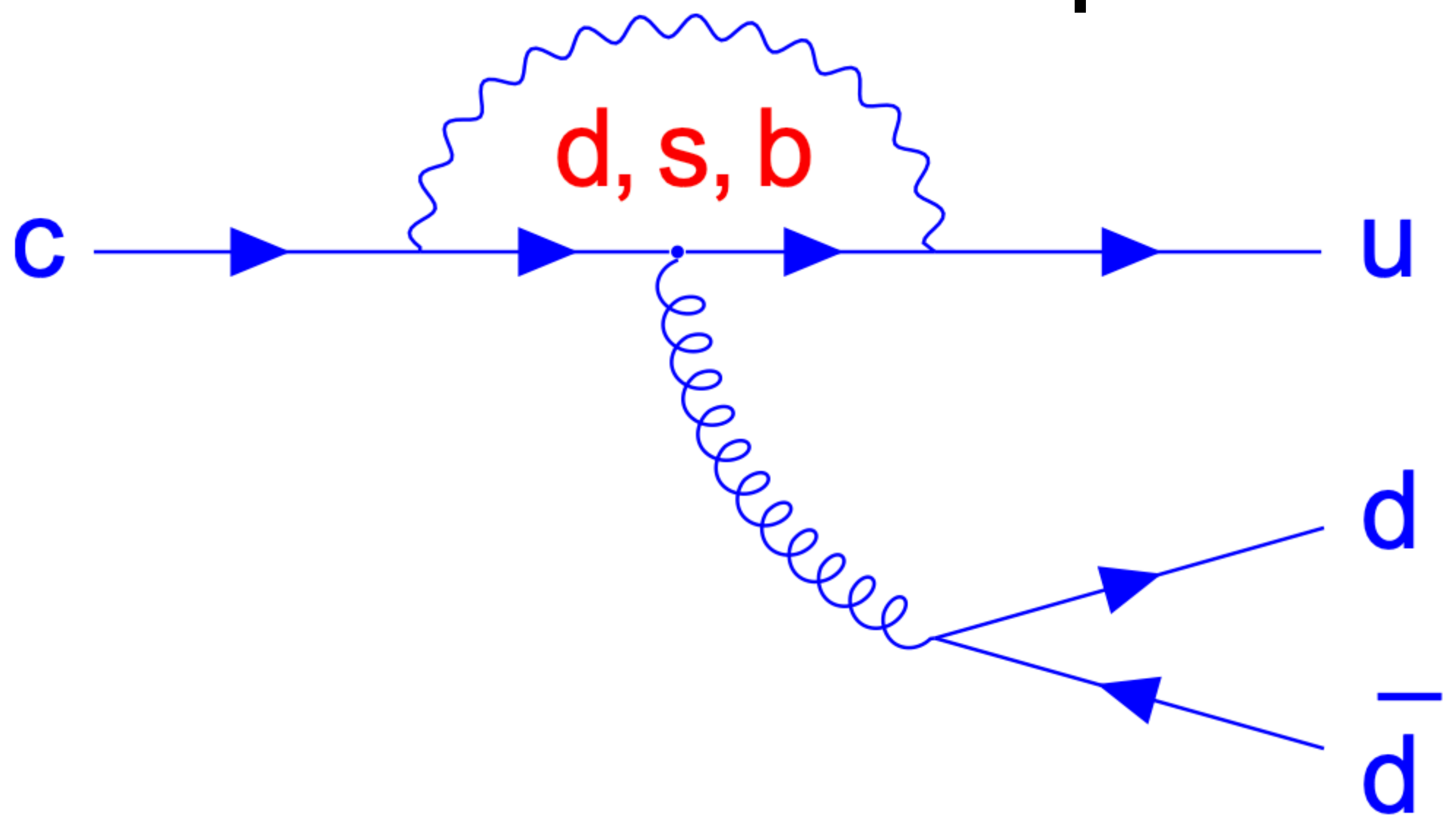
$$A_{CP}(f;t) \equiv \frac{\Gamma\left(D^0(t)\to f\right) - \Gamma\left(\bar{D}^0(t)\to f\right)}{\Gamma\left(D^0(t)\to f\right) + \Gamma\left(\bar{D}^0(t)\to f\right)} \approx a_f^{\mathrm{dir}} + \frac{t}{\tau_{D^0}}\Delta Y_f$$

$$\left|\Delta a_{CP}^{SD}\right| \leq 2.6 \times 10^{-4}$$

JHEP 07 (2019) 161



$\otimes$



$$\Delta a_{CP}^{\mathrm{dir}} = a_{K^+K^-}^{\mathrm{dir}} - a_{\pi^+\pi^-}^{\mathrm{dir}} = (-1.57 \pm 0.29) \times 10^{-3}$$

Phys. Rev. Lett. 122, 211803 (2019)

$$a_{K^+K^-}^{\mathrm{dir}} = (7.7 \pm 5.7) \times 10^{-4}, \qquad a_{\pi^+\pi^-}^{\mathrm{dir}} = (23.2 \pm 6.1) \times 10^{-4}.$$

Phys. Rev. Lett. 131, 091802 (2023)

Backup slide

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

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

- **Pole model + Rescattering — Penguin / Tree**

$$\mathcal{H}_{eff} = \frac{G_F}{\sqrt{2}}\left[\sum_{qq'} V^*_{qc}V_{q'u}\left(C_+O_+^{qq'} + C_-O_-^{qq'}\right) - \lambda_b \sum_{i=3\sim6} C_iO_i\right]$$

$$\langle \mathbf{B}P|\mathcal{H}_{\text{eff}}|\mathbf{B}_c\rangle = i\bar{u}\left(F - G\gamma_5\right)u_c$$

$$O_\pm^{qq'} = (\bar{u}q')_{V-A}(\bar{q}c)_{V-A} \pm (\bar{q}q')_{V-A}(\bar{u}c)_{V-A}$$

$$\underbrace{\mathbf{3}\otimes\mathbf{3}\otimes\bar{\mathbf{3}}}_{\mathcal{H}_{eff}} = \underbrace{(\mathbf{15}\oplus\mathbf{3}_+)}_{O_+}\oplus\underbrace{(\bar{\mathbf{6}}\oplus\mathbf{3}_-)}_{O_-}$$

$$\begin{aligned} F \ =\ & \tilde{f}^a(P^\dagger)^l_l\mathcal{H}(\bar{\mathbf{6}})_{ij}(\mathbf{B}_c)^{ik}(\mathbf{B}^\dagger)^j_k + \tilde{f}^b\mathcal{H}(\bar{\mathbf{6}})_{ij}(\mathbf{B}_c)^{ik}(\mathbf{B}^\dagger)^l_k(P^\dagger)^j_l + \tilde{f}^c\mathcal{H}(\bar{\mathbf{6}})_{ij}(\mathbf{B}_c)^{ik}(P^\dagger)^l_k(\mathbf{B}^\dagger)^j_l \\ & + \tilde{f}^d\mathcal{H}(\bar{\mathbf{6}})_{ij}(\mathbf{B}^\dagger)^i_k(P^\dagger)^j_l(\mathbf{B}_c)^{kl} + \tilde{f}^e(\mathbf{B}^\dagger)^j_i\mathcal{H}(\mathbf{15})^{\{ik\}}_l(P^\dagger)^l_k(\mathbf{B}_c)_j + \lambda_b F_{\mathbf{3}}\,, \end{aligned}$$

Sensitive to CP-odd
Insensitive to CP-even

$$\begin{aligned} F_{\mathbf{3}} \ =\ & \tilde{f}^a_{\mathbf{3}}(\mathbf{B}_c)_j\mathcal{H}(\mathbf{3})^i(\mathbf{B}^\dagger)^j_i(P^\dagger)^k_k + \tilde{f}^b_{\mathbf{3}}(\mathbf{B}_c)_k\mathcal{H}(\mathbf{3})^i(\mathbf{B}^\dagger)^j_i(P^\dagger)^k_j + \tilde{f}^c_{\mathbf{3}}(\mathbf{B}_c)_i\mathcal{H}(\mathbf{3})^i(\mathbf{B}^\dagger)^j_k(P^\dagger)^k_j \\ & + \tilde{f}^d_{\mathbf{3}}(\mathbf{B}_c)_j\mathcal{H}(\mathbf{3})^i(\mathbf{B}^\dagger)^j_k(P^\dagger)^k_i\,, \end{aligned}$$

$SU(3)_F$ breaking effects are expected to be much larger than F_3!

To date, there are in total **30** data points

$(4 + 1 + 4) \times 2$(S- & P-waves) $\times 2$(complex) $- 1 =$ **35**

- **Pole model + Rescattering — Penguin / Tree**

$$\mathcal{H}_{eff} = \frac{G_F}{\sqrt{2}}\left[\sum_{qq'} V^*_{qc}V_{q'u}\left(C_+O_+^{qq'} + C_-O_-^{qq'}\right) - \lambda_b \sum_{i=3\sim6} C_i O_i\right]$$

$$\langle \mathbf{B}P | \mathcal{H}_{\text{eff}} | \mathbf{B}_c\rangle = i\bar{u}\left(F - G\gamma_5\right)u_c$$

$$O_\pm^{qq'} = (\bar{u}q')_{V-A}(\bar{q}c)_{V-A} \pm (\bar{q}q')_{V-A}(\bar{u}c)_{V-A}$$

$$\underbrace{\mathbf{3}\otimes\mathbf{3}\otimes\bar{\mathbf{3}}}_{\mathcal{H}_{eff}} = \underbrace{(\mathbf{15}\oplus \not{\mathbf{3}}_+)}_{O_+} \oplus \underbrace{(\bar{\mathbf{6}}\oplus\not{\mathbf{3}}_-)}_{O_-}$$

$$F = \tilde{f}^a(P^\dagger)^l_l\mathcal{H}(\bar{\mathbf{6}})_{ij}(\mathbf{B}_c)^{ik}(\mathbf{B}^\dagger)^j_k + \tilde{f}^b\mathcal{H}(\bar{\mathbf{6}})_{ij}(\mathbf{B}_c)^{ik}(\mathbf{B}^\dagger)^l_k(P^\dagger)^j_l + \tilde{f}^c\mathcal{H}(\bar{\mathbf{6}})_{ij}(\mathbf{B}_c)^{ik}(P^\dagger)^l_k(\mathbf{B}^\dagger)^j_l$$
$$+\tilde{f}^d\mathcal{H}(\bar{\mathbf{6}})_{ij}(\mathbf{B}^\dagger)^i_k(P^\dagger)^j_l(\mathbf{B}_c)^{kl} + \tilde{f}^e(\mathbf{B}^\dagger)^j_i\mathcal{H}(\mathbf{15})^{\{ik\}}_l(P^\dagger)^l_k(\mathbf{B}_c)_j + \lambda_b \not{F}_{\mathbf{3}},$$

$$\mathcal{H}(\bar{\mathbf{6}}) = \begin{pmatrix} 0 & 0 & 0 \\ 0 & V^*_{cs}V_{ud} & -\lambda_s - \frac{\lambda_b}{2} \\ 0 & -\lambda_s - \frac{\lambda_b}{2} & V^*_{cd}V_{us}\end{pmatrix}$$

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

To date, there are in total **30** data points

$(\,4 + 1 + \not{4}\,) \times 2$(S- & P-waves) $\times\, 2$(complex) $- 1 =$ ~~35~~ **19**

• Pole model + Rescattering — Penguin / Tree

$$F = \tilde{f}^a (P^\dagger)^l_l \mathcal{H}(\overline{\mathbf{6}})_{ij} (\mathbf{B}_c)^{ik} (\mathbf{B}^\dagger)^j_k + \tilde{f}^b \mathcal{H}(\overline{\mathbf{6}})_{ij} (\mathbf{B}_c)^{ik} (\mathbf{B}^\dagger)^l_k (P^\dagger)^j_l + \tilde{f}^c \mathcal{H}(\overline{\mathbf{6}})_{ij} (\mathbf{B}_c)^{ik} (P^\dagger)^l_k (\mathbf{B}^\dagger)^j_l$$
$$+ \tilde{f}^d \mathcal{H}(\overline{\mathbf{6}})_{ij} (\mathbf{B}^\dagger)^i_k (P^\dagger)^j_l (\mathbf{B}_c)^{kl} + \tilde{f}^e (\mathbf{B}^\dagger)^j_i \mathcal{H}(\mathbf{15})^{\{ik\}}_l (P^\dagger)^l_k (\mathbf{B}_c)_j + \lambda_b F_3 ,$$

$$CP \propto \tilde{f}^e, \tilde{g}^e$$

$$A^{dir}_{CP} = \frac{\Gamma - \overline{\Gamma}}{\Gamma + \overline{\Gamma}}, \quad \alpha_{CP} = \frac{\alpha + \overline{\alpha}}{2},$$
$$\beta_{CP} = \frac{\beta + \overline{\beta}}{2}, \quad \gamma_{CP} = \frac{\gamma - \overline{\gamma}}{2}.$$

$$f^x = 1.80(35), 0.91(30), 0.96(5), 0.31(31), 0.55(63),$$
$$\delta^x_f = 1.66(31), 0, -2.20(39), -0.57(31), -0.58(50),$$

$$g^x = 6.11(1.67), 7.01(29), 0.69(43), 1.31(39), 1.62(1.34),$$
$$\delta^x_g = -1.77(34), 2.60(0.37), 2.03(0.43), 2.39(0.74), 1.98(1.03)$$

Channels	$\mathcal{B}(10^{-3})$	$\alpha_{CP}(10^{-3})$	$\beta_{CP}(10^{-3})$	$\gamma_{CP}(10^{-3})$	$A^{dir}_{CP}(10^{-3})$
$\Lambda_c^+ \to p\pi^0$	0.16(2)	−0.61(39)	−0.43(48)	0.53(145)	0.01(1)
$\Lambda_c^+ \to p\eta$	1.45(25)	0.05(17)	0.04(14)	−0.07(22)	−0.03(4)
$\Lambda_c^+ \to p\eta'$	0.52(11)	−0.02(7)	0.01(4)	0.00(4)	0.00(1)
$\Lambda_c^+ \to n\pi^+$	0.67(8)	0.12(20)	0.13(26)	−0.28(40)	−0.01(2)
$\Lambda_c^+ \to \Lambda^0 K^+$	0.63(2)	−0.03(10)	0.03(5)	0.04(24)	0.01(1)
$\Xi_c^+ \to \Sigma^+\pi^0$	2.11(14)	0.06(13)	−0.01(13)	−0.09(42)	−0.07(7)
$\Xi_c^+ \to \Sigma^+\eta$	0.70(32)	−0.10(22)	0.09(73)	0.29(57)	0.01(4)
$\Xi_c^+ \to \Sigma^+\eta'$	1.13(23)	0.03(7)	−0.01(2)	−0.01(4)	−0.01(0)
$\Xi_c^+ \to \Sigma^0\pi^+$	3.04(11)	−0.01(6)	−0.01(11)	0.05(21)	0.05(5)
$\Xi_c^+ \to \Xi^0 K^+$	1.04(13)	0.02(14)	0.13(18)	−0.18(25)	−0.02(2)
$\Xi_c^+ \to \Lambda^0\pi^+$	0.32(9)	0.0(19)	0.36(30)	0.20(19)	0.00(1)
$\Xi_c^0 \to \Sigma^0\pi^0$	0.34(2)	−0.04(12)	0.25(39)	0.12(12)	0.00(1)
$\Xi_c^0 \to \Sigma^0\eta$	0.12(5)	−0.11(22)	0.09(73)	0.29(57)	0.00(1)
$\Xi_c^0 \to \Sigma^0\eta'$	0.19(4)	0.03(7)	−0.01(2)	−0.01(4)	0.00(1)
$\Xi_c^0 \to \Sigma^-\pi^+$	1.83(6)	0.02(7)	−0.09(21)	0.03(12)	0.02(3)
$\Xi_c^0 \to \Xi^- K^+$	1.12(3)	0.02(5)	−0.08(16)	0.02(11)	0.01(1)
$\Xi_c^0 \to \Lambda^0\pi^0$	0.09(1)	0.07(20)	−0.27(25)	−0.15(17)	0.00(1)
$\Xi_c^0 \to \Lambda^0\eta$	0.43(11)	0.06(12)	0.11(14)	−0.01(2)	−0.01(1)
$\Xi_c^0 \to \Lambda^0\eta'$	0.68(13)	0.00(1)	0.00(1)	0.00(1)	0.00(1)

CP-odd quantities $\sim 10^{-4}$

$$a^{dir}_{D\to K^+K^-} - a^{dir}_{D\to\pi^+\pi^-} = (-1.57 \pm 0.29) \times 10^{-3}$$

arXiv:2312.xxxx [hep-ph]

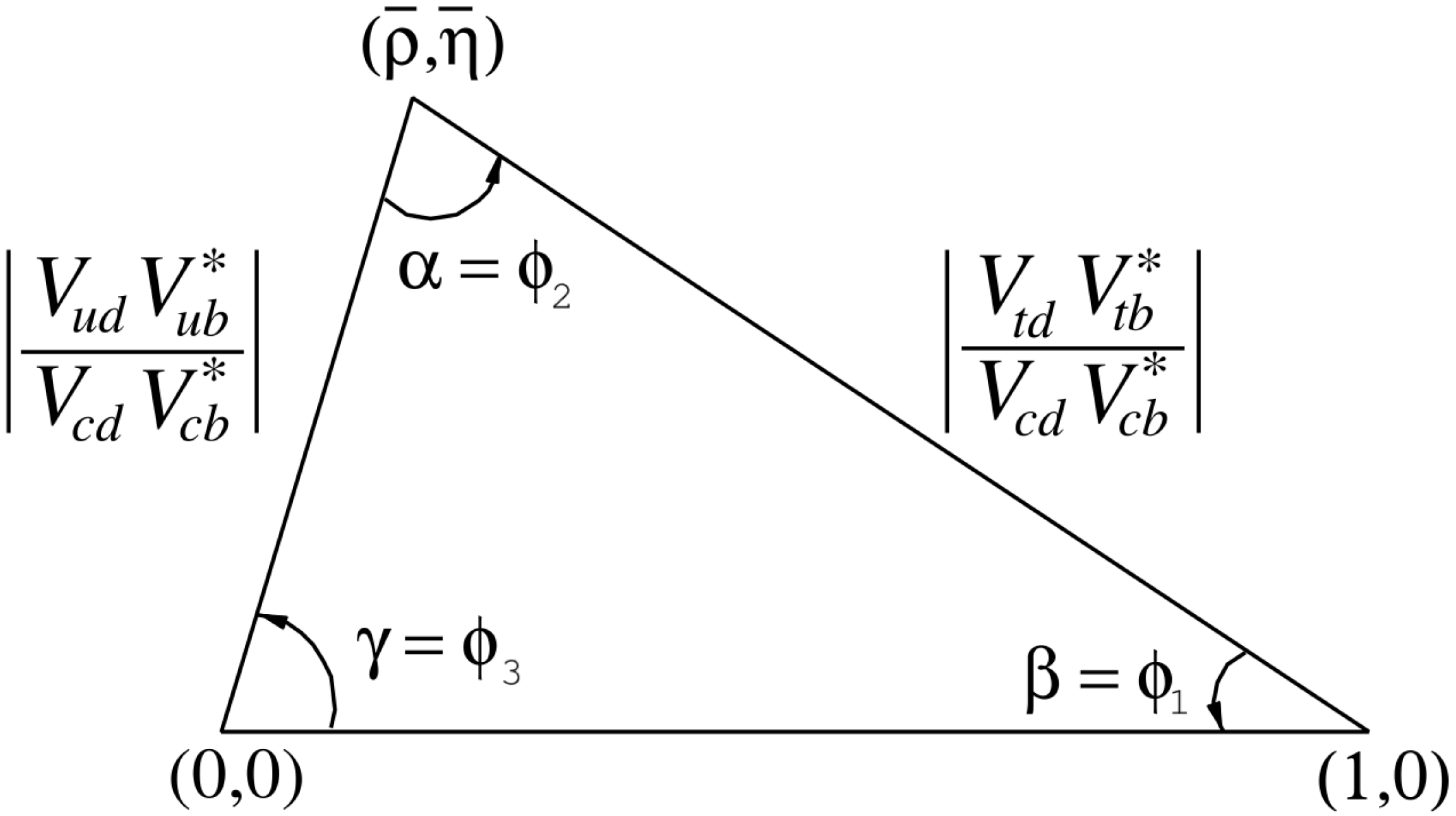


Figure 11.1: Sketch of the unitarity triangle.

The CKM matrix elements are fundamental parameters of the SM, so their precise determination is important. The unitarity of the CKM matrix imposes $\sum_i V_{ij}V_{ik}^* = \delta_{jk}$ and $\sum_j V_{ij}V_{kj}^* = \delta_{ik}$. The six vanishing combinations can be represented as triangles in a complex plane, of which the ones obtained by taking scalar products of neighboring rows or columns are nearly degenerate. The areas of all triangles are the same, half of the Jarlskog invariant, J [7], which is a phase-convention independent measure of CP violation, $\mathrm{Im}\left[V_{ij}V_{kl}V_{il}^*V_{kj}^*\right] = J\sum_{m,n}\varepsilon_{ikm}\varepsilon_{jln}$.