Charming lifetime, mixing and CPV

Puzzles and Opportunities in baryons

Chia-Wei Liu

HIAS

Sep 17 2025

HQL2025 THE 17th INTERNATIONAL CONFERENCE ON HEAVY QUARKS AND LEPTONS
Sept. 15-19, 2025 • Beijing, China

Hosted by Peking University, University of Chinese Academy of Sciences
Supported by State Key Laboratory of Nuclear Physics and Technology,
Center for High Energy Physics, Peking University,
National Natural Science Foundation of China (NSFC)

- **Exclusive (semi)leptonic decays**

  2-, 3-point cor. : $\langle 0|J_\mu|h_c\rangle,\ \langle h|J_\mu|h_c\rangle.$

- **Inclusive decays and mixing** √

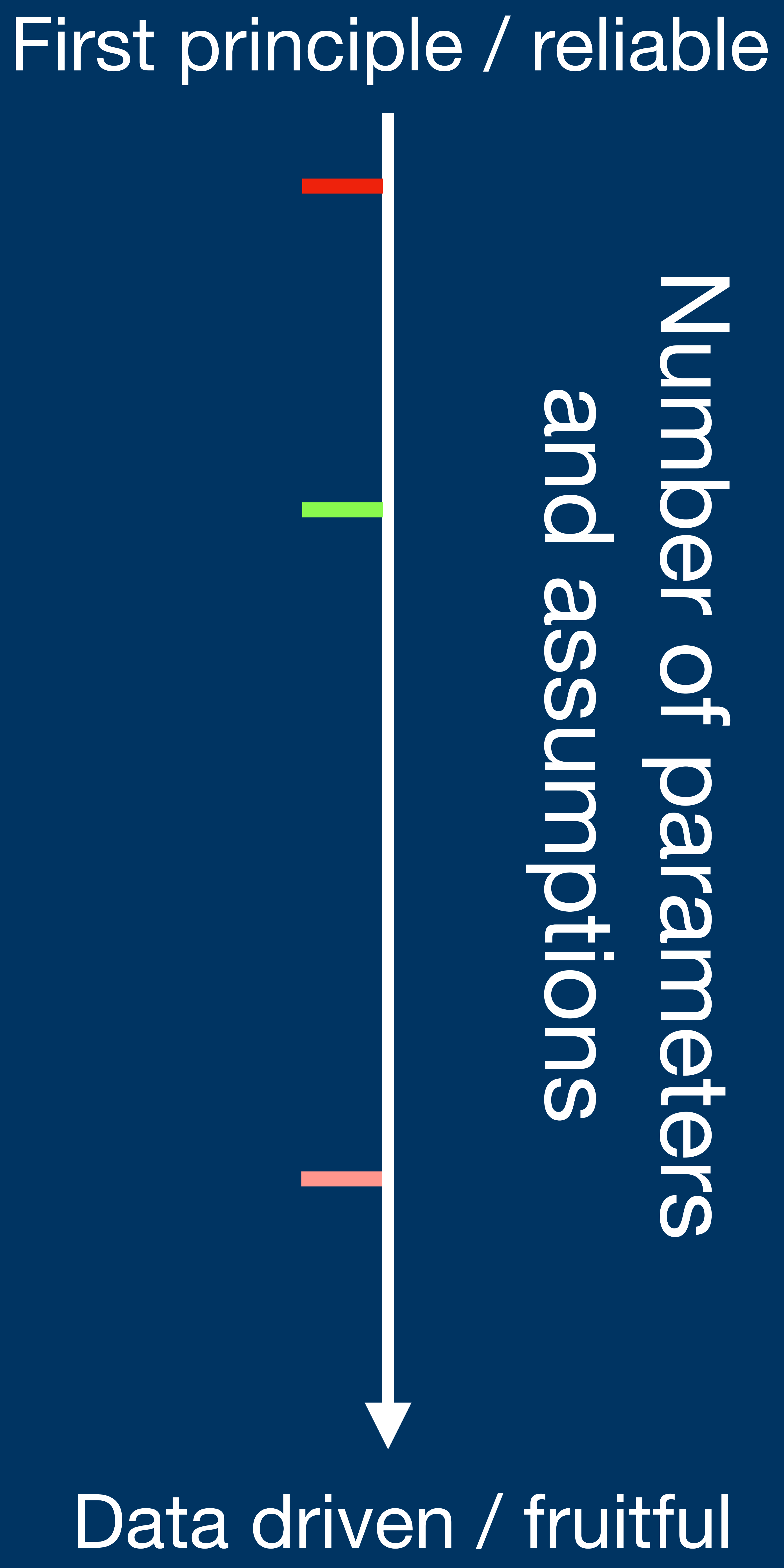
  4-point cor. : $\langle h_c|\mathscr{H}_{eff}(x)\mathscr{H}_{eff}(0)|h_c\rangle$

  $$\Big\downarrow\ m_c \gg \Lambda_{\rm QCD} \quad (?)$$

  3-point cor. : $\sum m_c^n c_n \langle h|\mathcal{O}_n|h_c\rangle$

- **Exclusive nonleptonic decays** √

  4-point cor. : $\langle h_1 h_2|\mathscr{H}_{eff}|h_c\rangle$



First principle / reliable

Number of parameters and assumptions

Data driven / fruitful

- **Inclusive decays; CKM leading $c \to u\bar{d}s$**

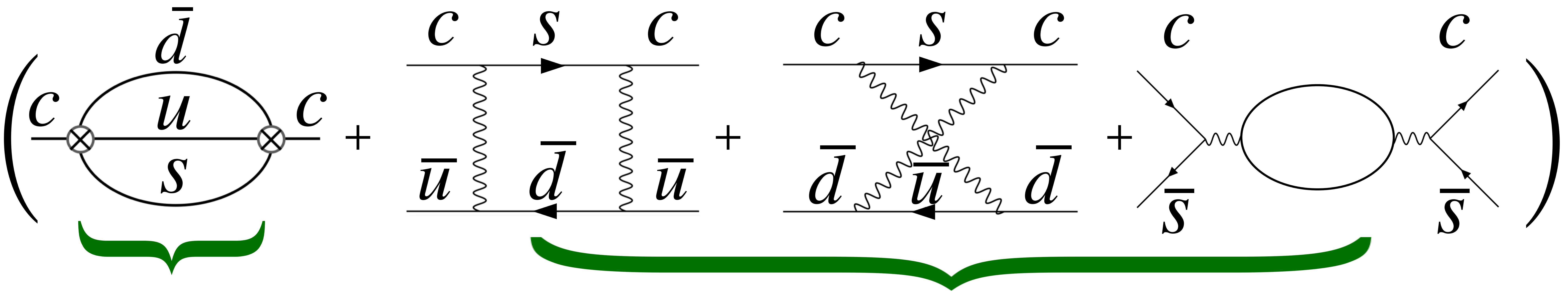
$$i\frac{d}{dt}\begin{pmatrix} D^0 \\ \bar{D}^0 \end{pmatrix} = \left(M - \frac{i}{2}\Gamma\right)\begin{pmatrix} D^0 \\ \bar{D}^0 \end{pmatrix}$$

- $i = j$: lifetimes; $i \neq j$: mixing.

$$\underbrace{\Gamma_{ij}}_{\text{Optical theorem}} = \mathrm{Im}\left(\frac{i}{2m_D}\int T\left\langle \mathcal{H}_{eff}(x)\mathcal{H}_{eff}(0)\right\rangle d^4x\right) \overset{?}{=} \frac{m_c^5}{m_D}\sum_{n=0}\frac{1}{m_c^n}\left\langle D_i \,|\, C_n O_n \,|\, D_j\right\rangle$$

Separating energy scales $\underbrace{M_W}_{\mathcal{H}_{eff}} \gg \underbrace{m_c}_{C_n} \gg \underbrace{\Lambda_{\mathrm{QCD}}}_{\langle O_n \rangle}$

$C_nO_n =$



$\propto m_c^5$

$\propto (4\pi)^2 m_c^2$

Inclusive decays; CKM leading $c \to u\bar{d}s$

$(m_b, m_c, \Lambda_{QCD}) = (4.8, 1.5, 0.3)$ GeV

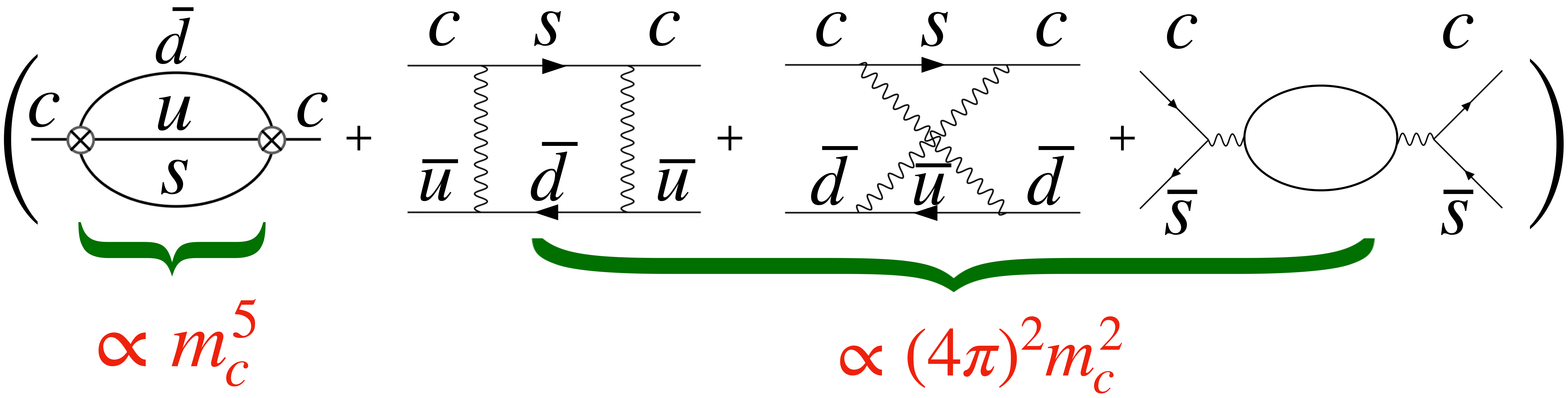
Pole mass, non-perturbative input

[2502.05901]

🤔 $$\left(16\pi^2\left(\frac{\Lambda_{QCD}}{m_b}\right)^3, 16\pi^2\left(\frac{\Lambda_{QCD}}{m_c}\right)^3,\right) \approx \left(\frac{160}{4000}, \frac{160}{125}\right)$$

- The dim-6 operators are of order $\mathcal{O}(10^{-2})$ and $\mathcal{O}(1)$ relative to the dim-3 ones.

$C_n O_n =$



$\propto m_c^5$

$\propto (4\pi)^2 m_c^2$

Inclusive decays; CKM leading $c \to u\bar{d}s$

- Dim-6 contributions of D^0 & D_s^+ are proportional to the m_q in the internal loop:

$$(\Gamma_{D^0}, \Gamma_{D_s^+}) = \begin{matrix} \left(1.71^{+0.57}_{-0.59}, 1.71^{+0.66}_{-0.72}\right)_{\text{theory}} \\ \left(2.44 \pm 0.01, 1.88 \pm 0.02\right)_{\text{exp}} \end{matrix}$$

[2204.11935]

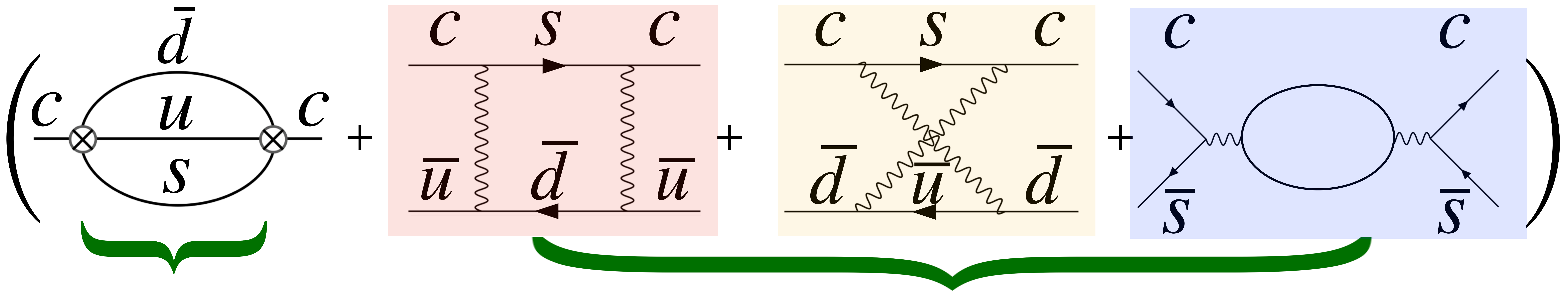
- Nevertheless, it causes disaster in D^+:

$$\Gamma_{D^+} = \left(-0.07^{+0.82}_{-0.71}\right)_{\text{theory}} \quad \left(0.96 \pm 0.01\right)_{\text{exp}}$$ in units of ps^{-1}

- $\Gamma_{D^0} - \Gamma_{D^+}$ is consistent with HQE, suggesting long-distance effects are cancelled.

[1711.02100]

$C_n O_n =$



$\propto m_c^5$

$\propto (4\pi)^2 m_c^2$

Inclusive decays; $D-\bar{D}$ mixing

- Difficulties also encountered in the mixing :

$$\left(\frac{\Delta m}{\Gamma},\frac{\Delta\Gamma}{2\Gamma}\right)=\left(0.405\pm0.043,0.638\pm0.023\right)\%_{\text{HFlAV}}$$

Theory shows $\propto V_{us}^2(m_s/\Lambda_{QCD})^2$, which is round 10^{-6} in HQE due to **GIM** !

- Long distance approach has been considered. Master equation:

$$y=\sum_n(-1)^{ns}\eta_{\mathrm{CP}}\cos\delta_n\sqrt{\mathscr{B}\left(D^0\to n\right)\mathscr{B}\left(D^0\to\bar{n}\right)}\,.$$

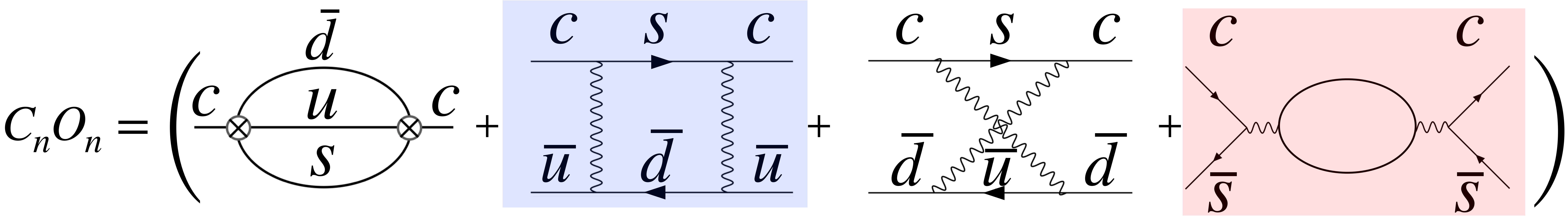
$D\to PP$ and $D\to PV$ take up half of $\Delta\Gamma/(2\Gamma)$. [2401.06316]

- Other nonperturbative methods: lattice QCD, inverse problem, sum rules…

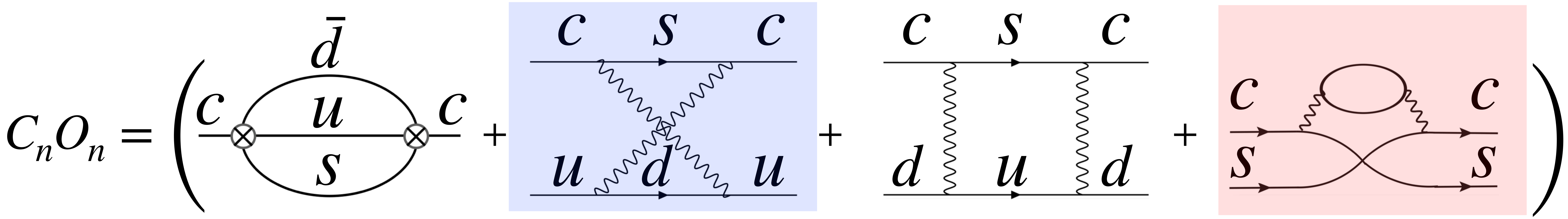
[1706.04622, 2504.16189] [2001.04079] [1711.02100]

Inclusive decays - Charmed baryons

- Does the HQE work in charmed baryons?



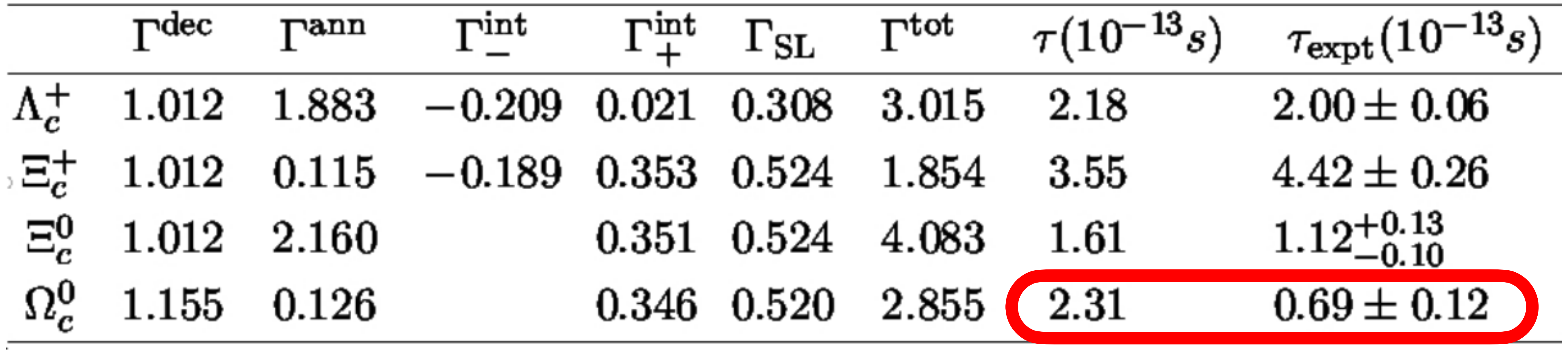
Flipping the initial and final states of fermions



- However, *W*-exchange and *W*-annihilation are no longer subject to helicity suppression!

Inclusive decays - Charmed baryons

Hai-Yang Cheng (LO + NRQM), March 19, 2018



	$\Gamma^{\rm dec}$	$\Gamma^{\rm ann}$	$\Gamma^{\rm int}_{-}$	$\Gamma^{\rm int}_{+}$	$\Gamma_{\rm SL}$	$\Gamma^{\rm tot}$	$\tau(10^{-13}s)$	$\tau_{\rm expt}(10^{-13}s)$
Λ_c^+	1.012	1.883	−0.209	0.021	0.308	3.015	2.18	2.00 ± 0.06
Ξ_c^+	1.012	0.115	−0.189	0.353	0.524	1.854	3.55	4.42 ± 0.26
Ξ_c^0	1.012	2.160		0.351	0.524	4.083	1.61	$1.12^{+0.13}_{-0.10}$
Ω_c^0	1.155	0.126		0.346	0.520	2.855	2.31	0.69 ± 0.12

> By the end of the work, I was very disappointed because […] the predicted Ω_c lifetime […] opposite to the experiment.

LHCb, June 8, 2018

$$\tau(\Omega_c^0) = (2.68 \pm 0.24 \pm 0.10) \times 10^{-13} s$$

Belle II, Aug 17, 2022

$$\tau(\Omega_c^0) = (2.43 \pm 0.58 \pm 0.11) \times 10^{-13} s$$

Shows predictive power of HQE in charm baryon!

The 2nd International Workshop
on High Intensity Electron-Positron Accelerator
@2-7GeV in China
HIEPA

March 19-21, 2018
University of Chinese Academy of Sciences,
Yanqihu Campus, Huairou, Beijing, China,

High Intensity Electron Positron Accelerator (HIEPA) is one of the possible future collider project post BEPCII/BESIII in China.The 2nd international workshop for HIEPA will invite both high energy physicists and accelerator experts to review the physics potentials and the conceptual designs of both detector and accelerators at the HIEPA facility. In addition, we will take this opportunity to discuss the possibilities of worldwide cooperation and formation of an international collaboration.

Supported by
the Collaborative Innovation Center for Elementary Particles and Interactions
USTC and UCAS.
http://cicpi.ustc.edu.cn/hiepa2018/

Inclusive decays - Charmed baryons

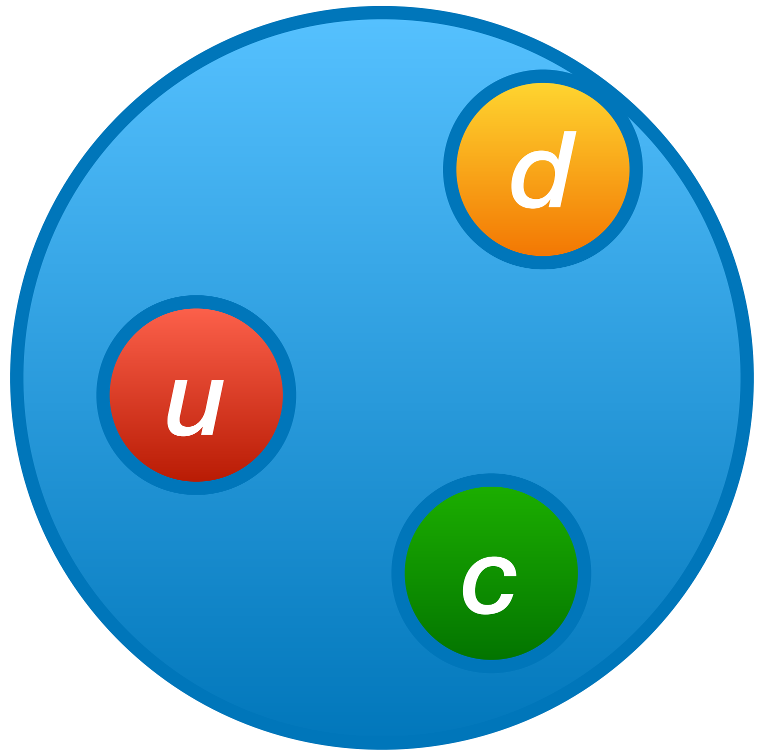
- **From QCD and HQET sum rules** $L^{q_I}_{\Lambda_b} = -3.2 \pm 1.6 \& -2.38 \pm 0.11 \pm 0.34 \pm 0.22$

[9604425] [PLB 387, 371(1996)]

- **The HQE expectation** $\langle O \rangle_c \sim \langle O \rangle_b$ **works poorly in NRQM but well in BM.**

Model	$(\mathcal{B}_Q, q)$	(Λ_b, q_I)	(Ξ_b, q_I)	(Ξ_b, s)	(Ω_b, s)	(Λ_c, q_I)	(Ξ_c, q_I)	(Ξ_c, s)	(Ω_c, s)
BM ^{a}	$L^q_{\mathcal{B}_Q}$	-5.44	-5.15	-5.88	-34.12	-4.83	-4.87	-5.34	-31.63
	$S^q_{\mathcal{B}_Q}$	2.44	2.32	2.74	-5.41	1.96	1.98	2.32	-4.65
	$P^q_{\mathcal{B}_Q}$	-0.27	-0.25	-0.20	-0.62	-0.44	-0.44	-0.34	-1.12
NRQM	$L^q_{\mathcal{B}_Q}$	$-13(5)$	$-14(5)$	$-18(6)$	$-126(60)$	$-5.1(15)$	$-5.4(16)$	$-7.4(22)$	$-46(14)$
	$S^q_{\mathcal{B}_Q}$	$7(2)$	$7(2)$	$9(3)$	$-21(10)$	$2.5(8)$	$2.7(8)$	$3.7(11)$	$-7.7(23)$
	$P^q_{\mathcal{B}_Q}$	0	0	0	0	0	0	0	0

[2305.00665]



Bag is localized and cannot be 3-momentum eigenstate. Underestimate a factor of 2.

Inclusive decays - Charmed baryons

- **The prediction of $\Lambda_c^+ \to Xe^+$ is consistent with the data of $(4.06 \pm 0.13)\,\%$. BESIII**

- **$\mathscr{B}(\Xi_c^0 \to Xe^+)$ is consistent with the lattice result of $\mathscr{B}(\Xi_c^0 \to \Xi^- e^+ \nu_e) \approx (3.58 \pm 0.12)\,\%$ together with the lowest bound-state saturation.**

- **For Λ_c^+, Ξ_c the HQE of $\Gamma_3 > \Gamma_6 > \Gamma_7$ holds but not for Ω_c.**

- **We are working on dim-7 NLO.**

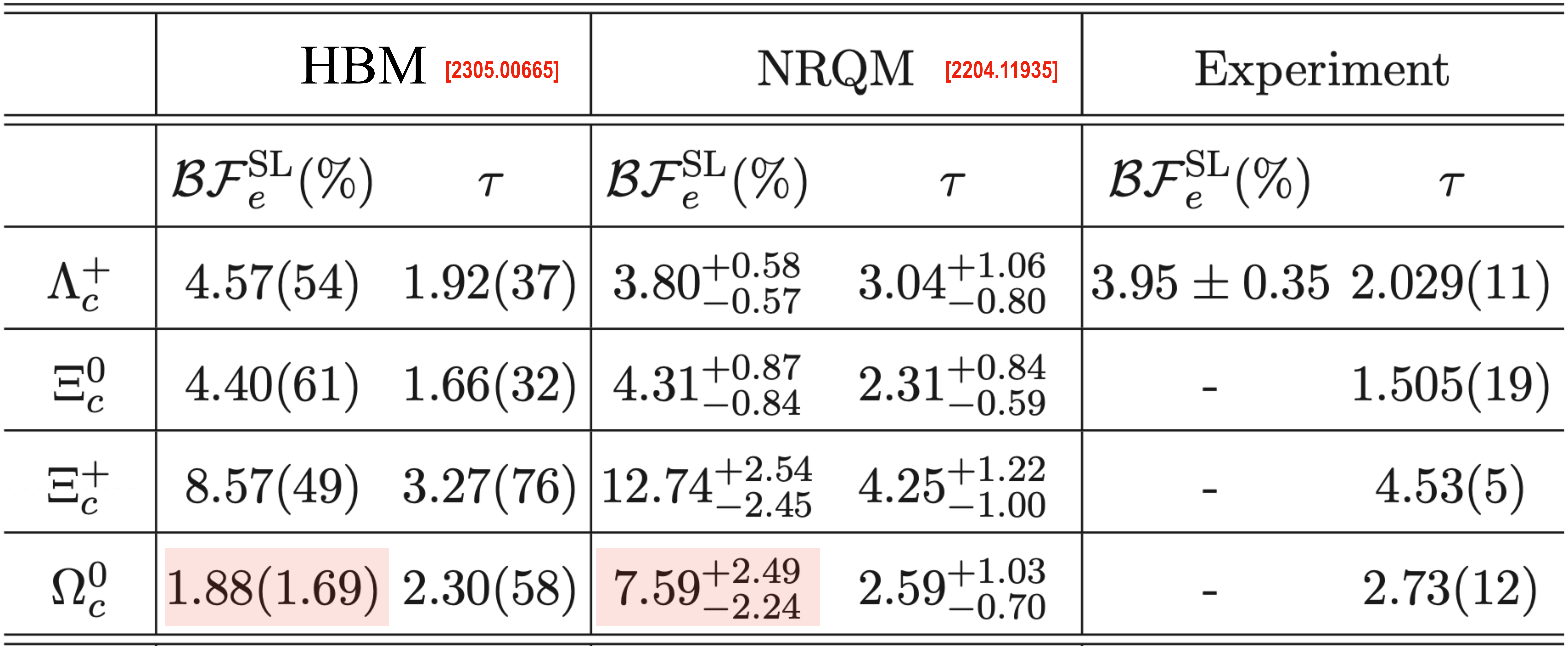
Hai-Yang Cheng, **Chia-Wei Liu** (NLO + HBM), **May 1, 2023**

$\mathbf{B}_c$		Γ_3^{SL}	Γ_6^{SL}	Γ_7^{SL}	$\mathcal{B}_e^{\mathrm{SL}}(\%)$
Λ_c^+	LO	$0.40(13)_m$	0.01	0	$8.25(78)_m(44)_\mu(37)_4(37)_s$
	NLO	$0.35(11)_m$	0.01	-	$4.57(42)_m(24)_\mu(21)_4(13)_s$
Ξ_c^0	LO	$0.40(14)_m$	0.36	-0.15	$8.99(58)_m(29)_\mu(25)_4(43)_s$
	NLO	$0.35(12)_m$	0.18	-	$4.40(45)_m(22)_\mu(19)_4(30)_s$
Ξ_c^+	LO	$0.40(14)_m$	0.35	-0.15	$18.59(26)_m(22)_\mu(19)_4(39)_s$
	NLO	$0.35(12)_m$	0.18	-	$8.57(20)_m(5)_\mu(5)_4(44)_s$
Ω_c^0	LO	$0.42(14)_m$	1.22	-0.83	$13.51(42)_m(10)_\mu(8)_4(23)_s$
	NLO	$0.37(12)_m$	0.61	-	$1.88(1.33)_m(47)_\mu(40)_4(85)_s$

[2305.00665]

Inclusive decays - Charmed baryons

Hai-Yang Cheng, **Chia-Wei Liu** James Gratrex, Blaženka Melić, Ivan Nišandžić



	HBM [2305.00665]		NRQM [2204.11935]		Experiment	
	$\mathcal{BF}_e^{\mathrm{SL}}(\%)$	τ	$\mathcal{BF}_e^{\mathrm{SL}}(\%)$	τ	$\mathcal{BF}_e^{\mathrm{SL}}(\%)$	τ
Λ_c^+	4.57(54)	1.92(37)	$3.80^{+0.58}_{-0.57}$	$3.04^{+1.06}_{-0.80}$	3.95 ± 0.35	2.029(11)
Ξ_c^0	4.40(61)	1.66(32)	$4.31^{+0.87}_{-0.84}$	$2.31^{+0.84}_{-0.59}$	-	1.505(19)
Ξ_c^+	8.57(49)	3.27(76)	$12.74^{+2.54}_{-2.45}$	$4.25^{+1.22}_{-1.00}$	-	4.53(5)
Ω_c^0	1.88(1.69)	2.30(58)	$7.59^{+2.49}_{-2.24}$	$2.59^{+1.03}_{-0.70}$	-	2.73(12)

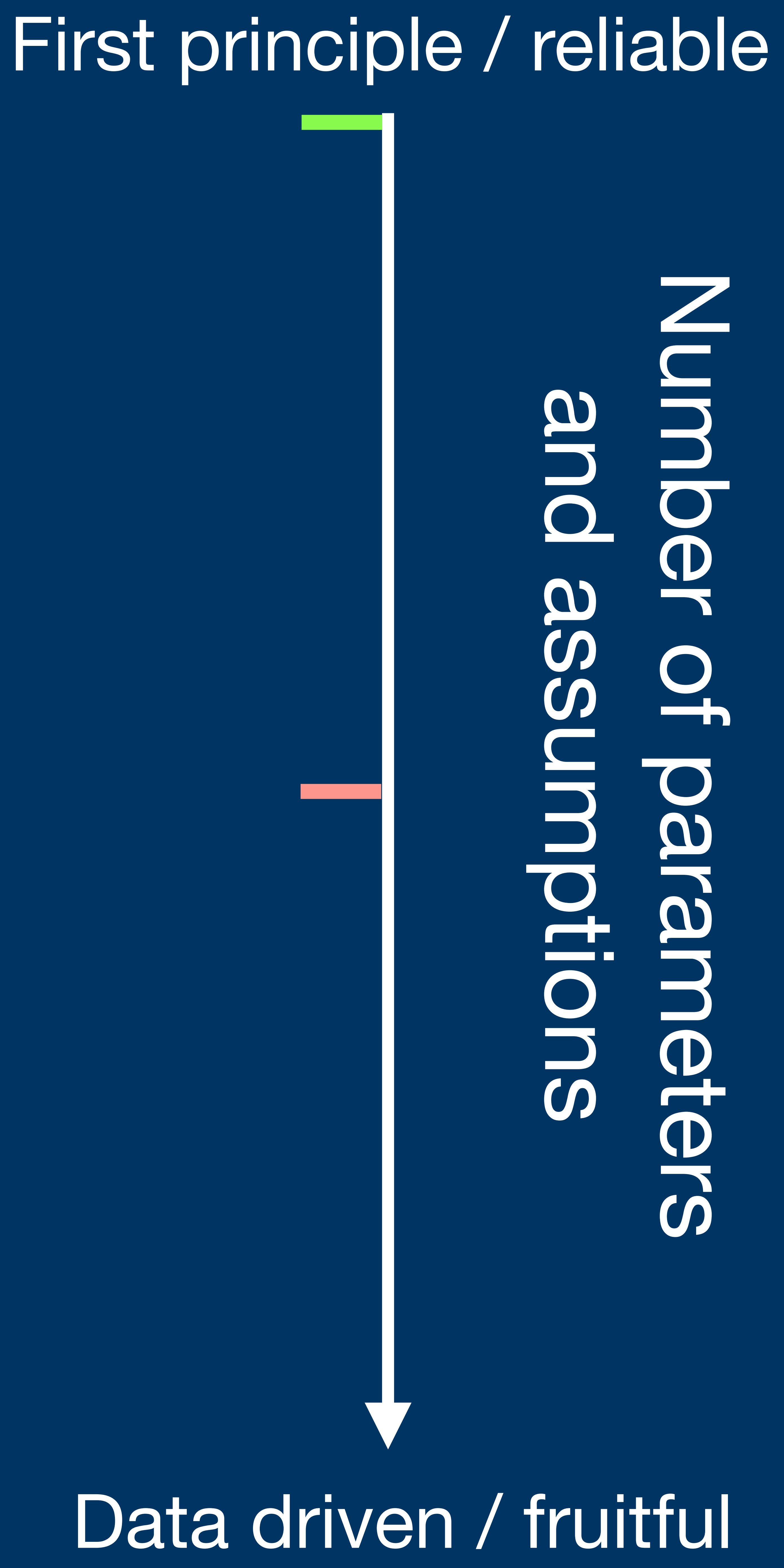
- **Mostly consistent within uncertainties except for $\mathscr{B}^{\mathrm{SL}}(\Omega_c)$ due to dim-7 operators.**

- **Exclusive nonleptonic decays √**

4-point cor. : $\langle h_1 h_2 | \mathscr{H}_{eff} | h_c \rangle$

Lessons from lifetime and mixing:

1. m_c converges slowly.
2. LD is important.
3. GIM cancellation does not exactly hold.

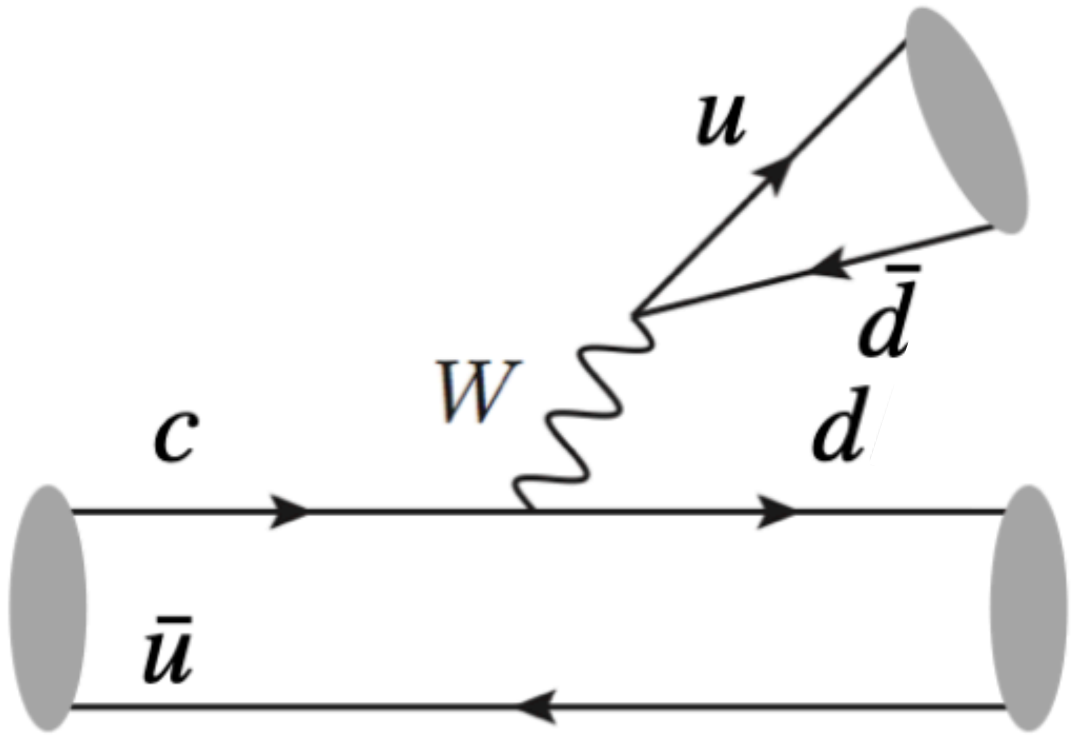

First principle / reliable

Number of parameters and assumptions

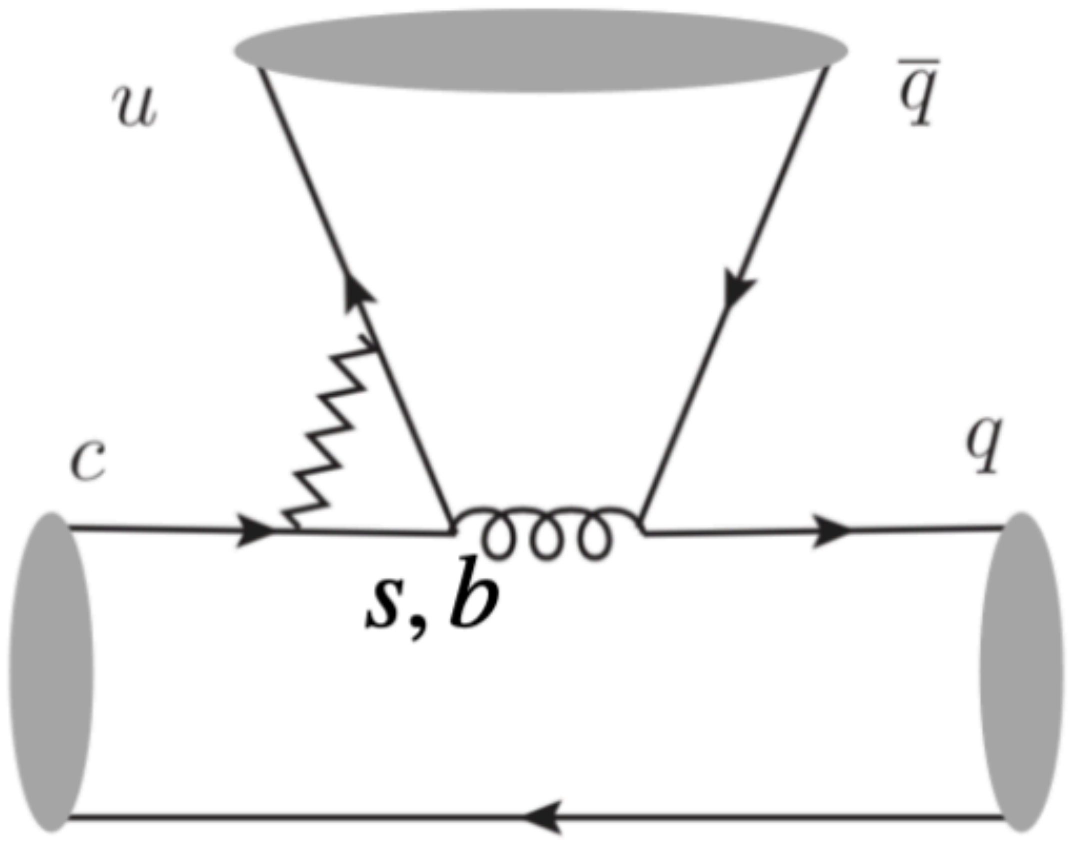
Data driven / fruitful

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

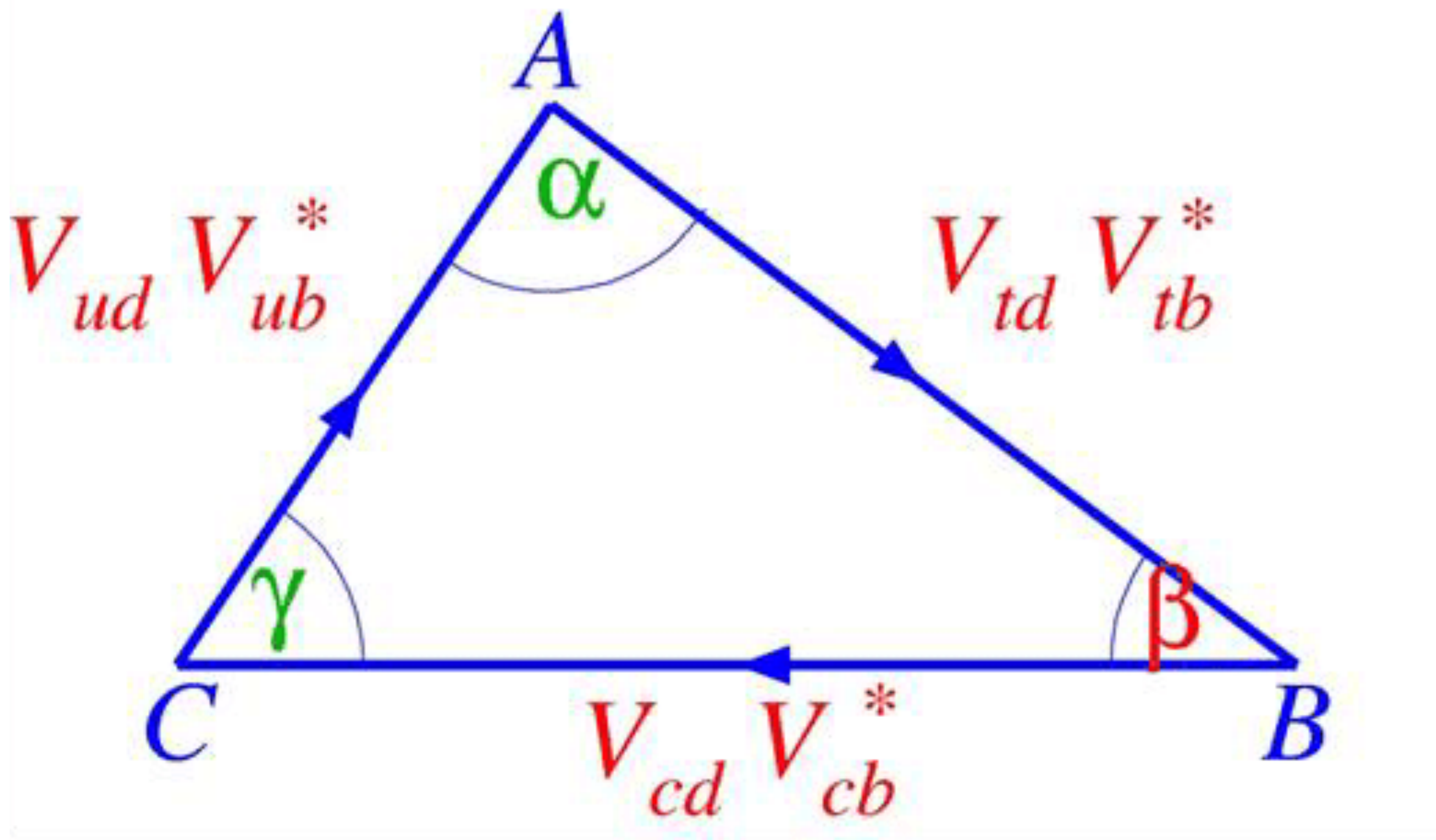
$$A(D^0 \to \pi^+\pi^-) = V_{cd}^* V_{ud}\ T + V_{cb}^* V_{ub}\ P$$



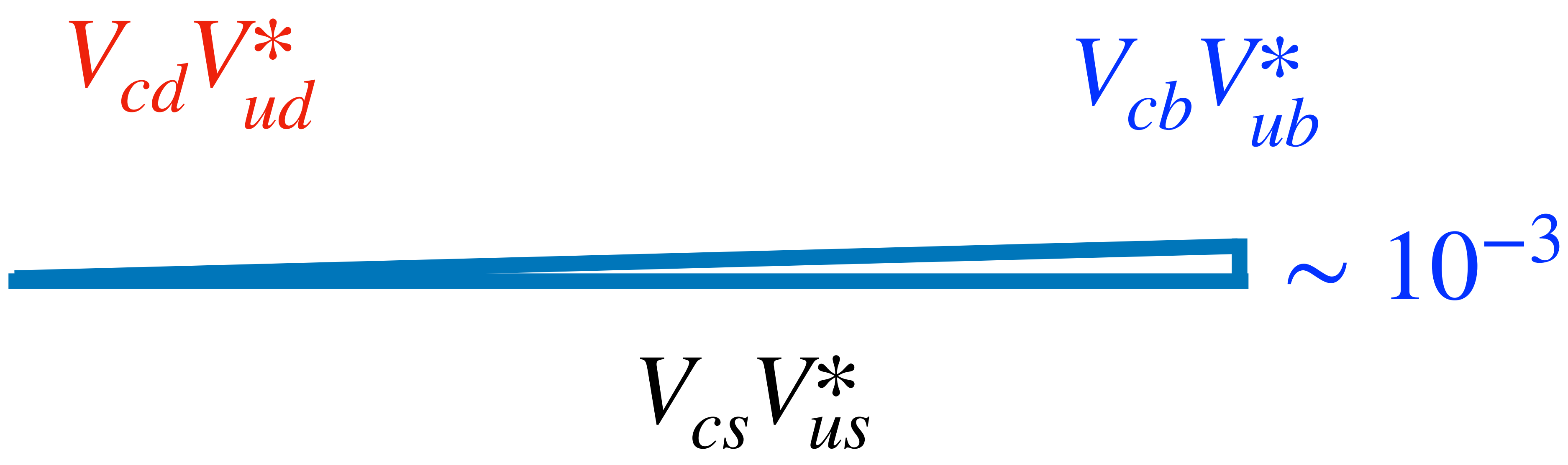
(T) **Solvable** from $\mathscr{B}$.



(P) **Indeterminate** from $\mathscr{B}$.



CKM triangle for $b \to d$



CKM triangle for $c \to u$

Charming physics - CP violation

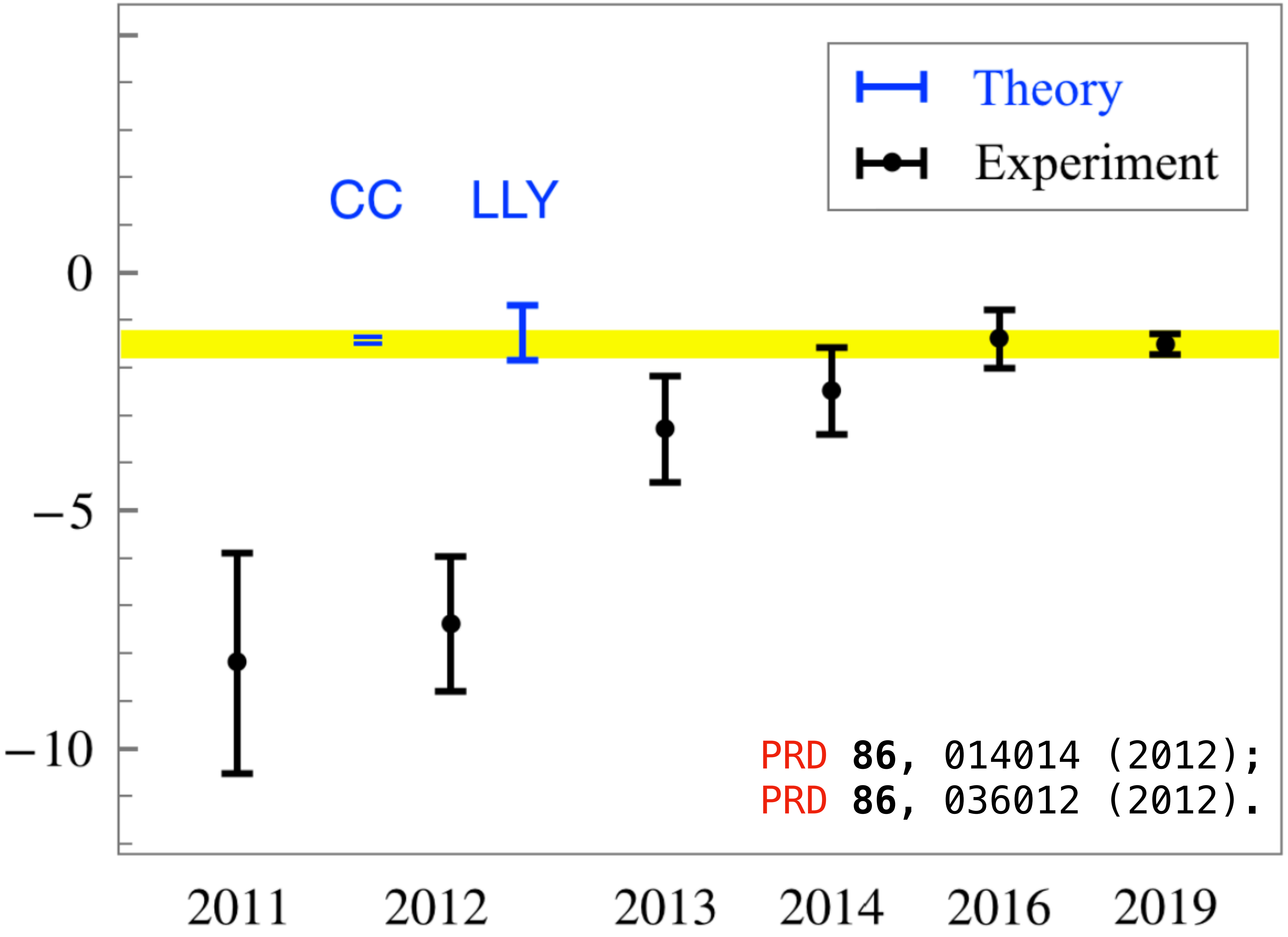
$$a_{CP} \approx 1.5 \times 10^{-3} \times \mathrm{Im}(P/T)$$

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

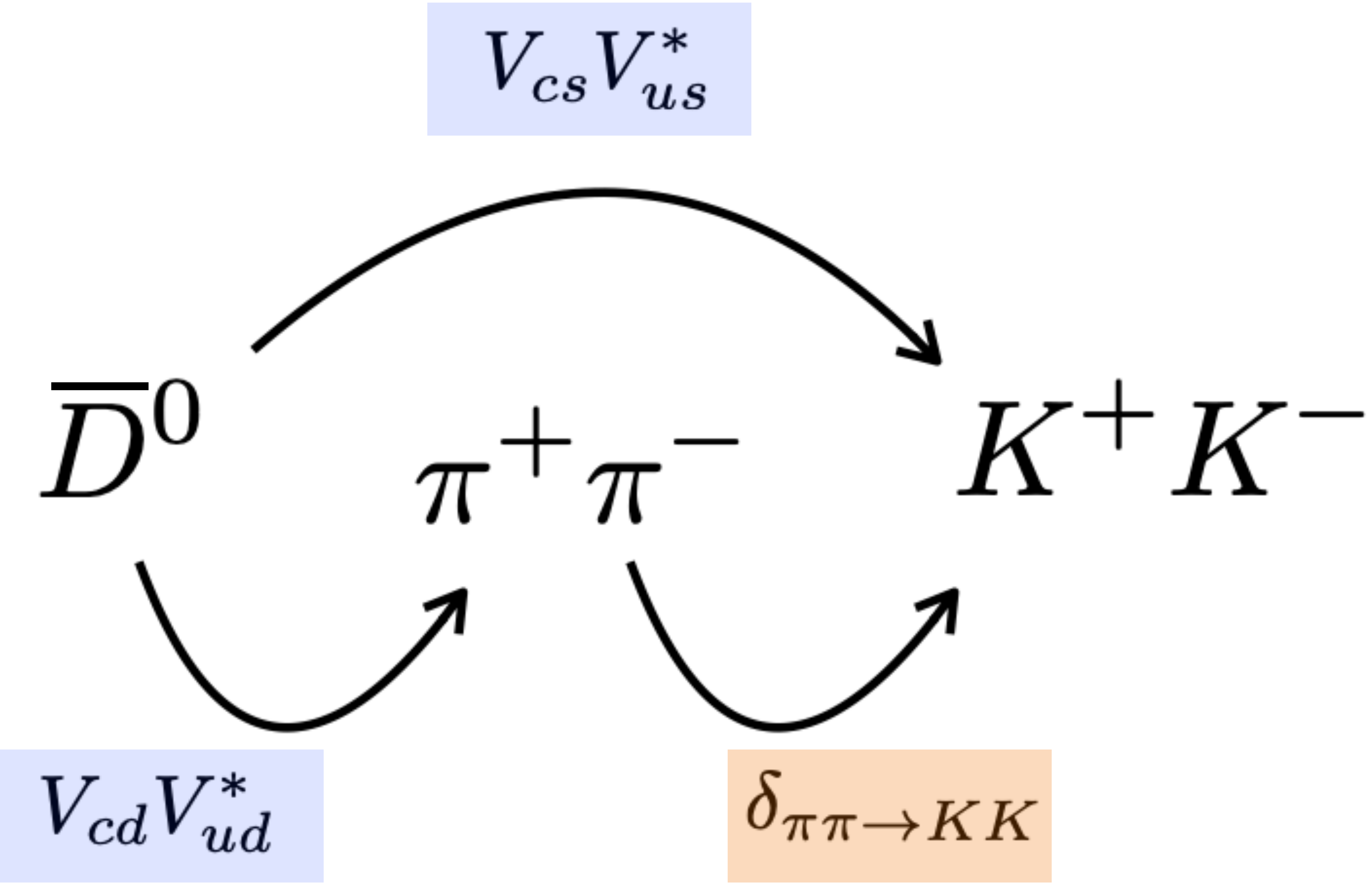
PRL **122**, 211803 (2019);

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

Topological & $SU(3)_F$ approach:



PRD **86**, 014014 (2012);
PRD **86**, 036012 (2012).



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

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

CKM phases and **strong phases**.

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

Charming physics - CP violation

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

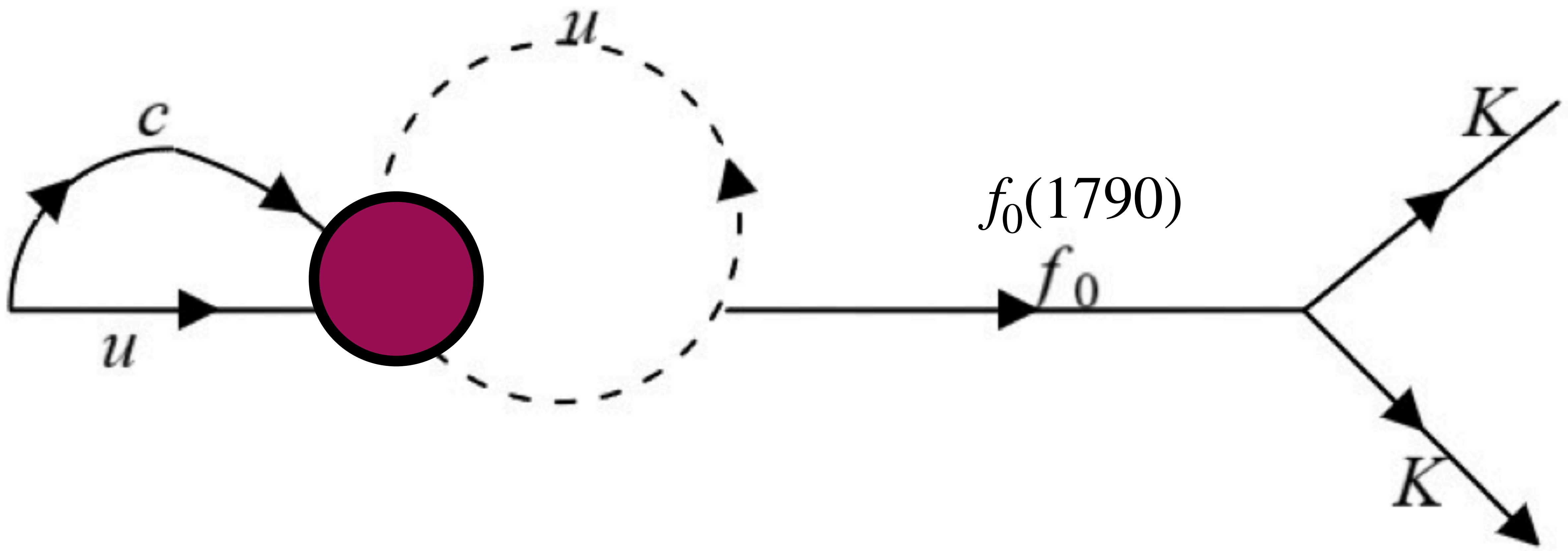
PRD **86**, 014014 (2012), 2111.11201, 2505.07150.

• Charming physics - CP violation

Reasons to go **beyond** charmed mesons:

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

PRL **131**, 091802 (2023)



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

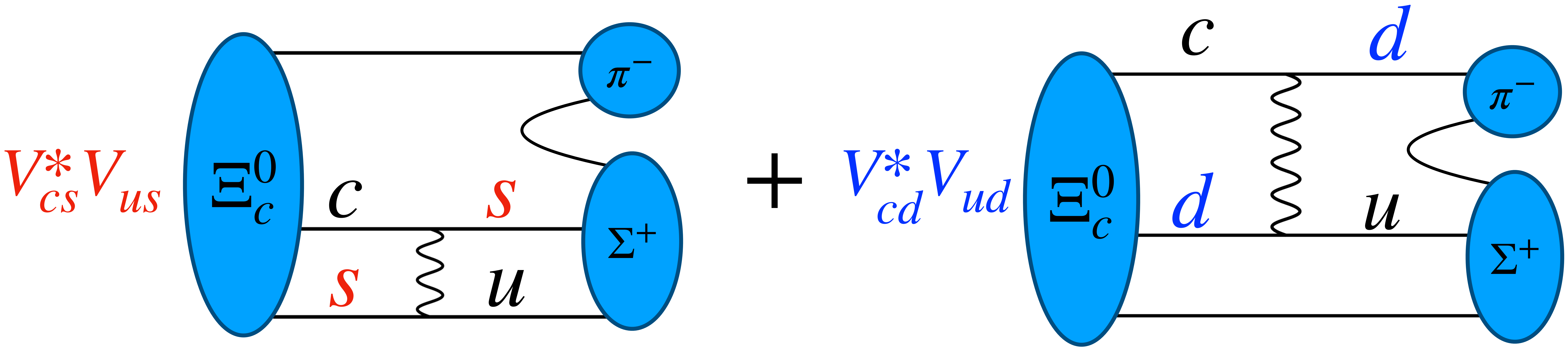
1. Relative sign of a_{CP}^{KK} and $a_{CP}^{\pi\pi}$ **contradicts** to the theoretical expectations.

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

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

Charming physics - CP violation

Reasons to go **beyond** charmed mesons:



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

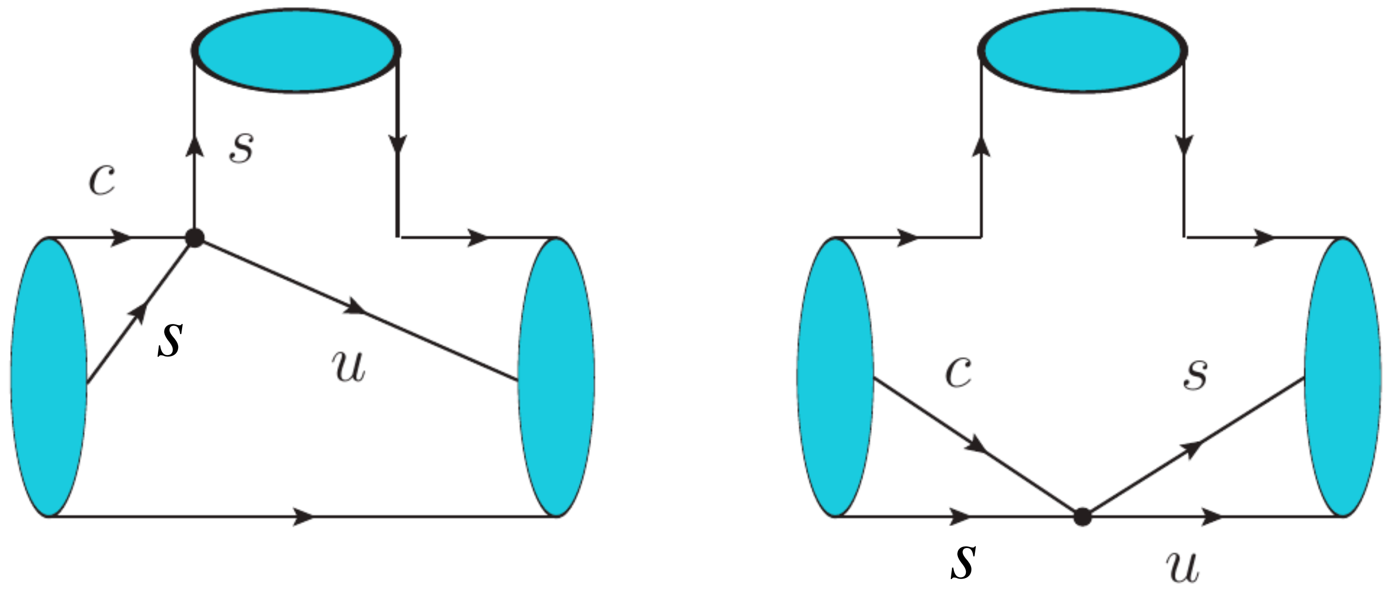
5. Unlike $D^0 \to h^+h^-$, CP-even **phase shifts** in baryon decays can be directly measured.

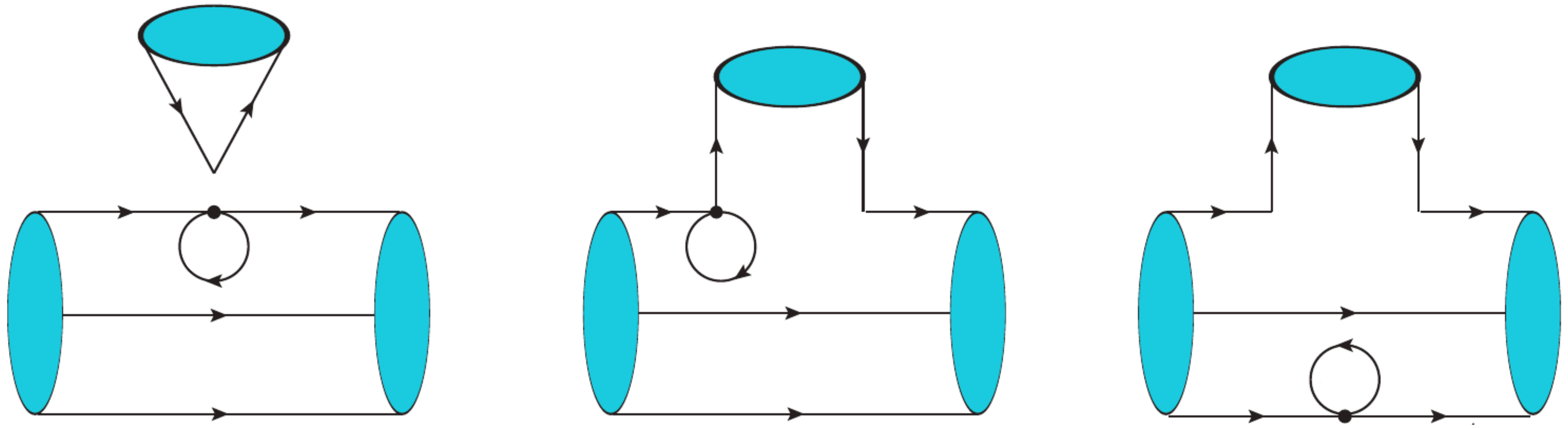
Very important inputs and driven force in the study of charmed baryons!

Final state rescattering

X. G. He and **C. W. Liu** [Sci.Bull. **70** (2025) 2598]:

FIG from PRD **100**, 093002 (2019).



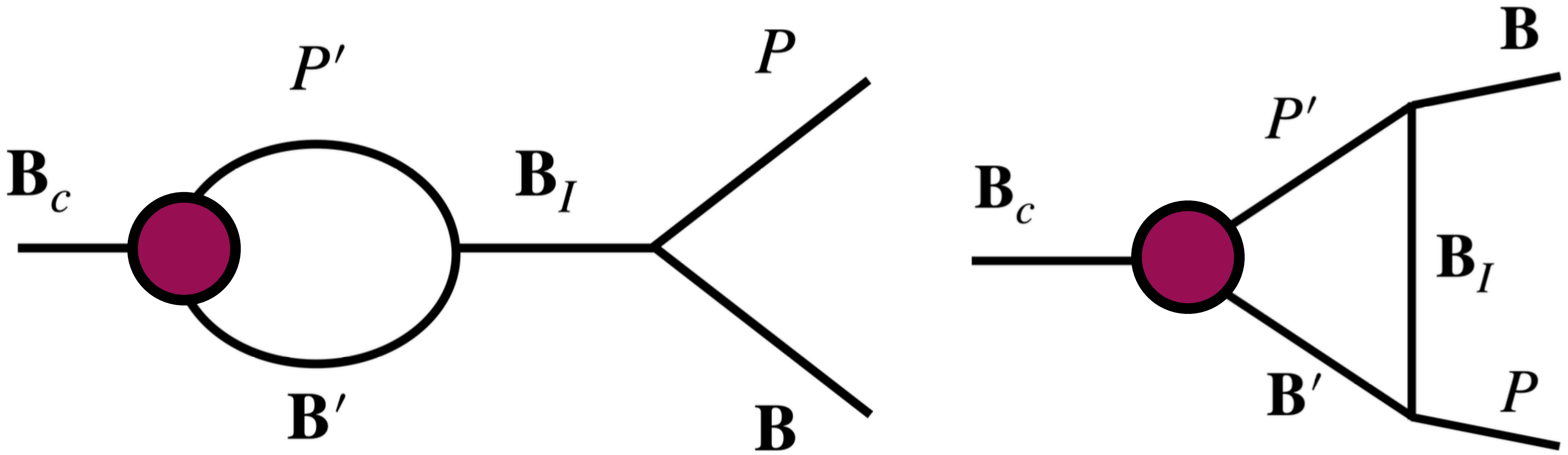


CKM leading $\propto V_{us}V_{cs}^* \sim 10^{-1}$

Solved by experimental data.

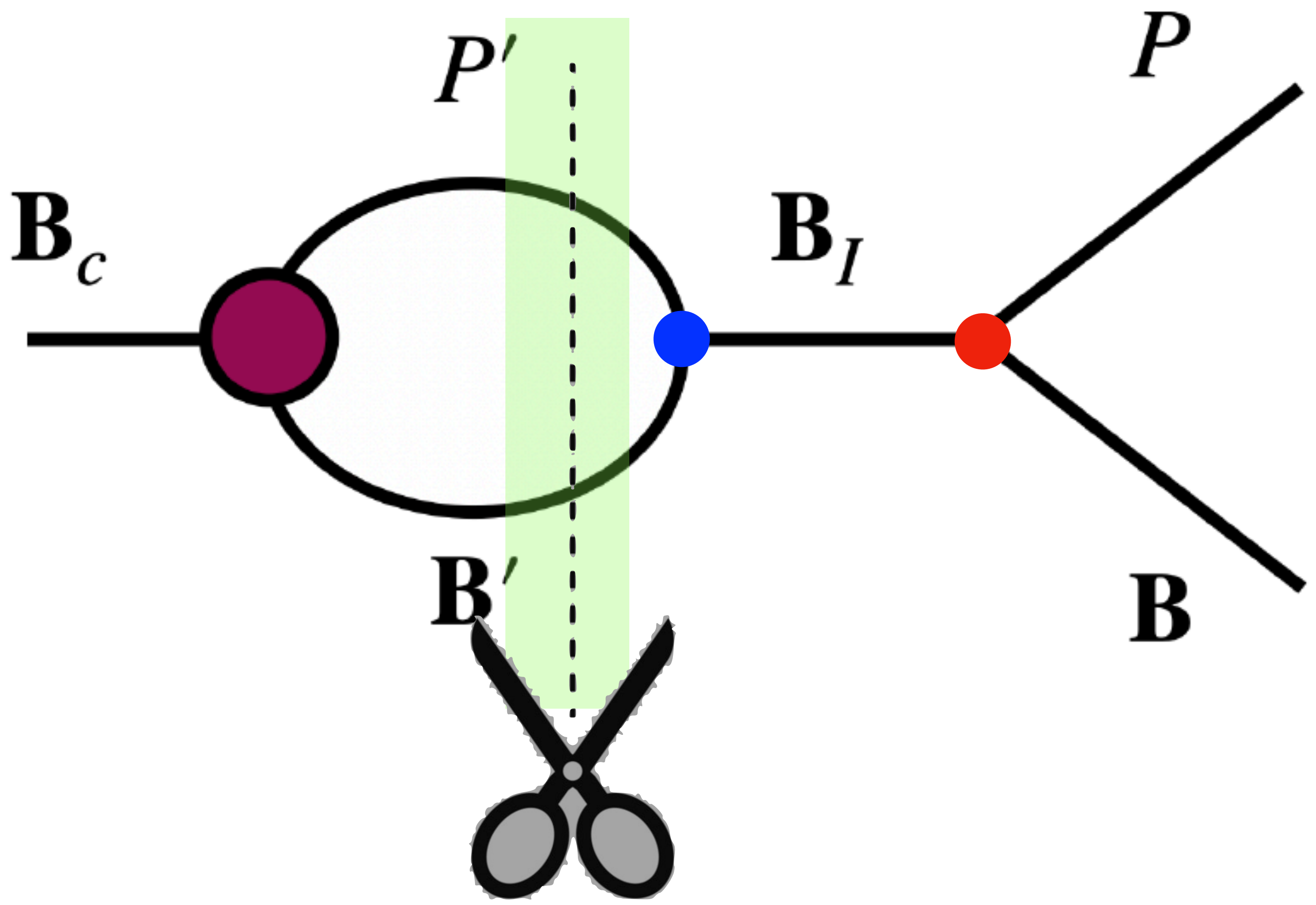
CKM subleading $\propto V_{ub}V_{cb}^* \sim 10^{-4}$

Unsolved!



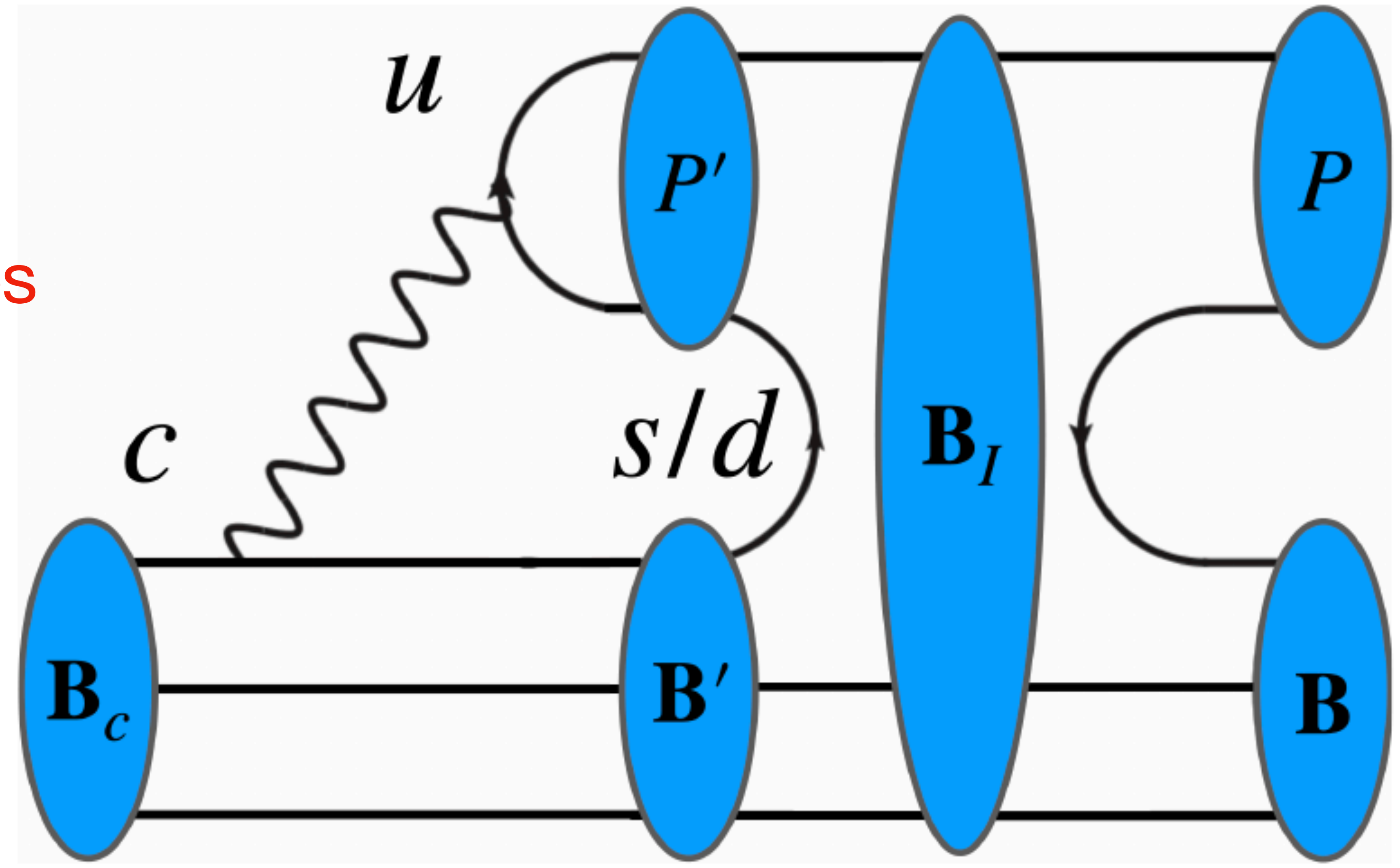
$\mathbf{B}_c \to \mathbf{B}V$ are calculated directly 2408.14959

• Final state rescattering



Generate necessary strong phase!

At quark level generates penguin topology

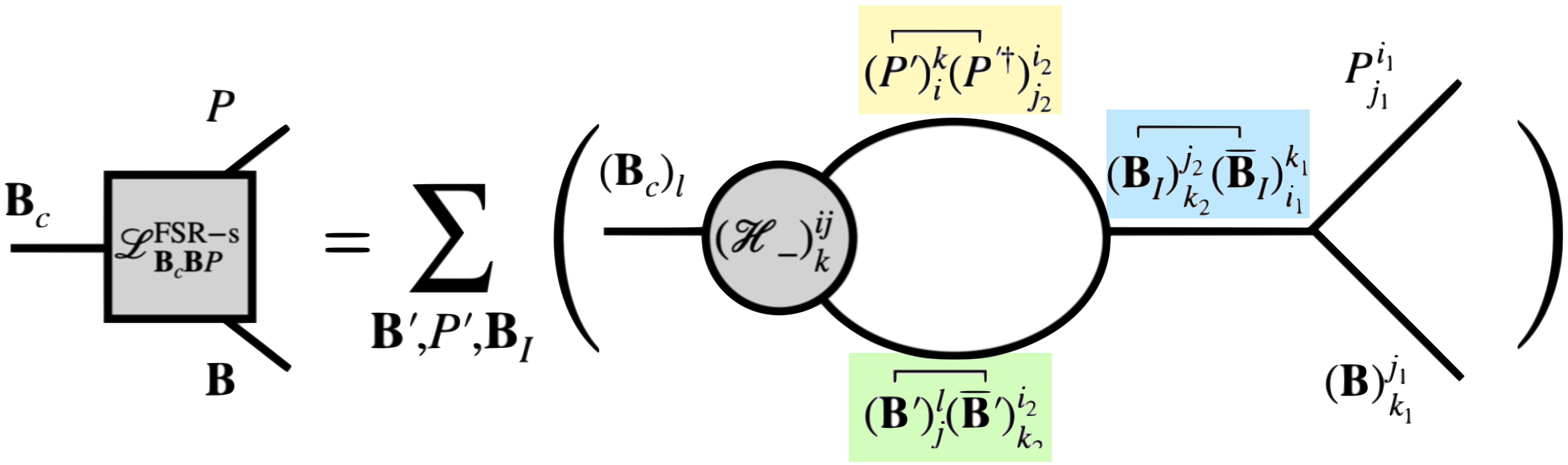


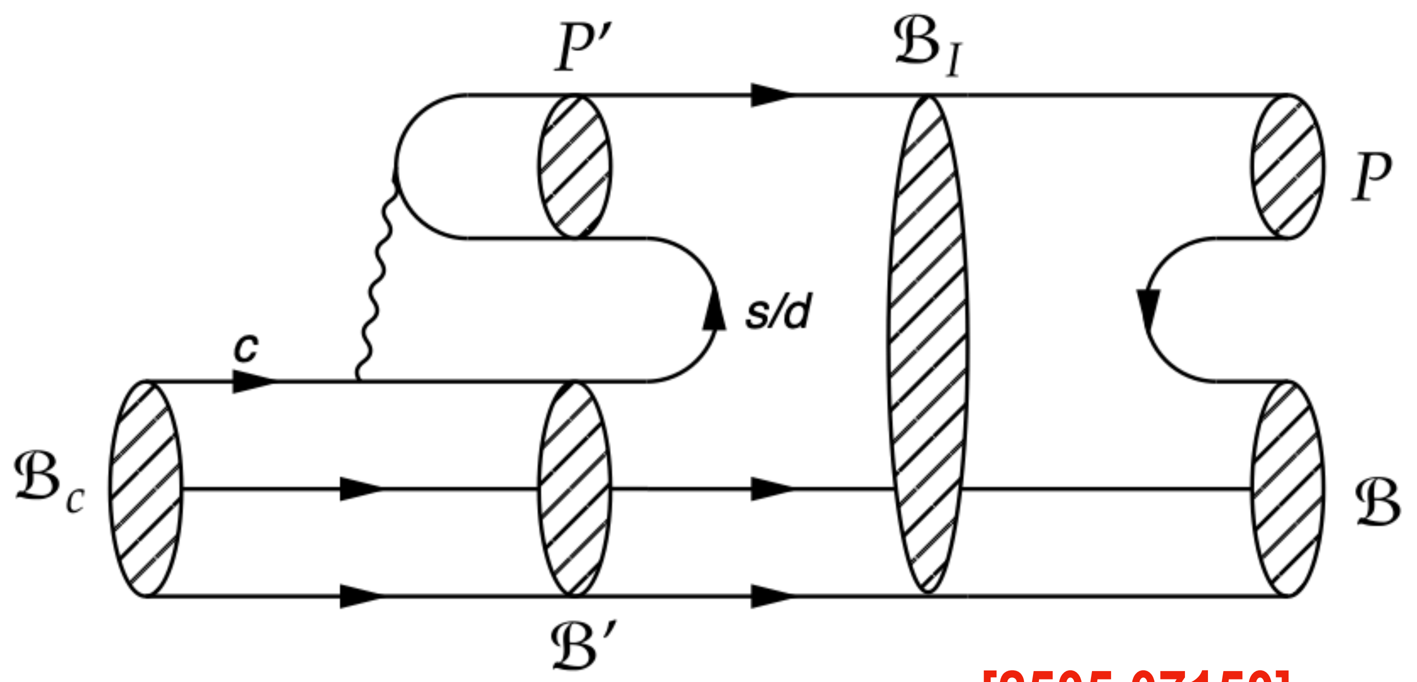
$$\langle \mathscr{L}^{\rm FSR-s}_{\mathbf{B}_c\mathbf{B}P}\rangle = \sum_{\mathbf{B}_I,\mathbf{B}',P'} \bar{u}_{\mathbf{B}} \left(\int \frac{d^4q}{(2\pi)^4} g_{\mathbf{B}_I\mathbf{B}P} \frac{p^{\mu}_{\mathbf{B}_c}\gamma_\mu + m_I}{p^2_{\mathbf{B}_c} - m_I^2} g_{\mathbf{B}_I\mathbf{B}'P'} \frac{q^\mu\gamma_\mu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

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

See also [2408.14959]

Final state rescattering





[2505.07150]

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

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

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

Approximations:

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

Final state rescattering

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

CKM leading → rescattering parameters → CKM suppressed

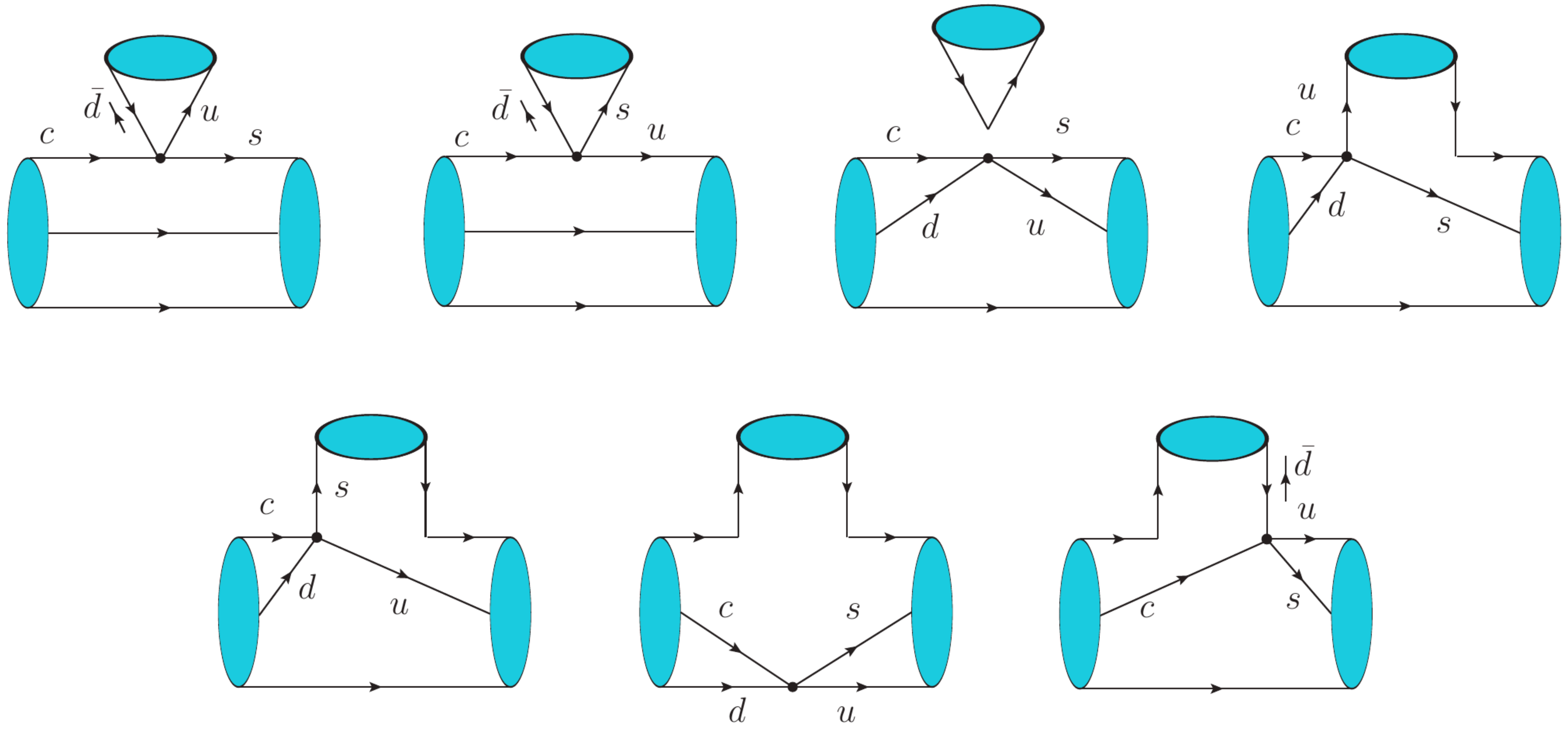
PRD **100**, 093002 (2019)

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

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

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

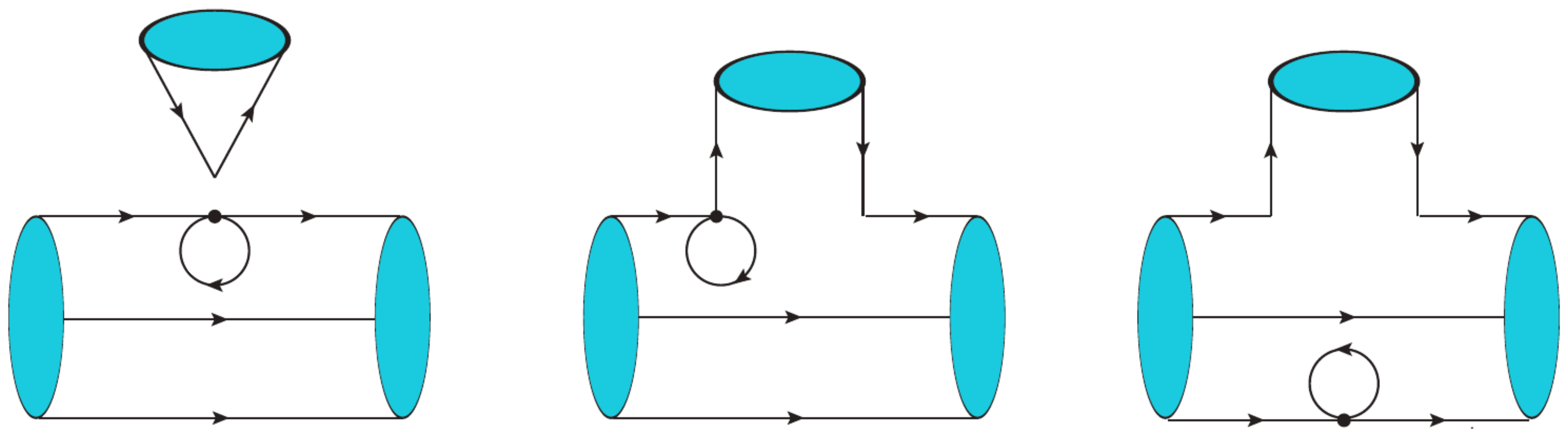
$$\tilde{f}^d = \tilde{F}^-_V + \sum (2r_\lambda^2 - 2r_\lambda - 4)\tilde{T}^-_\lambda \,, \quad \tilde{f}^e = \tilde{F}^+_V$$



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

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

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



Much more complicated than *D* mesons !

Final state rescattering

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

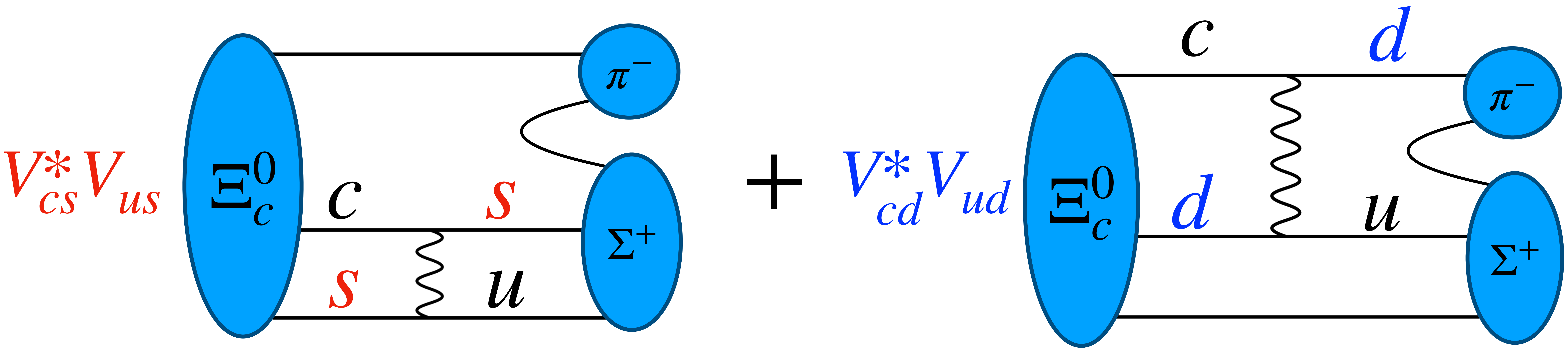
$$A_{CP}\left(\Xi_c^0 \to \Sigma^+\pi^-\right) = (0.71 \pm 0.16) \times 10^{-3}$$

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

- In the U-spin limit, we have that

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

EPJC 79, 429 (2019)



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

- **Final state rescattering**

Branching fractions and CP asymmetries in units of 10^{-3}

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

Charming puzzles and opportunities await!

Inclusive decays:

Exp : $\Omega_c^0 \to X\ell^+\nu_\ell.$

Theory : LD physics and NLO of dim-7.

Exclusive decays:

Exp : CPV and more data.

Theory: LD physics and CPV.