Charmed baryon decays

Form Factors and CP Violation; Puzzles and Opportunities

第二届重味物理前沿论坛研讨会

華中師範大學
CENTRAL CHINA NORMAL UNIVERSITY

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刘 佳 韦

Sep 13

2025

- **Exclusive semileptonic decays**

  Lattice QCD: $\Xi_c^0 \to \Xi^- \ell^+ \nu_\ell \ldots$

- **Inclusive decays**

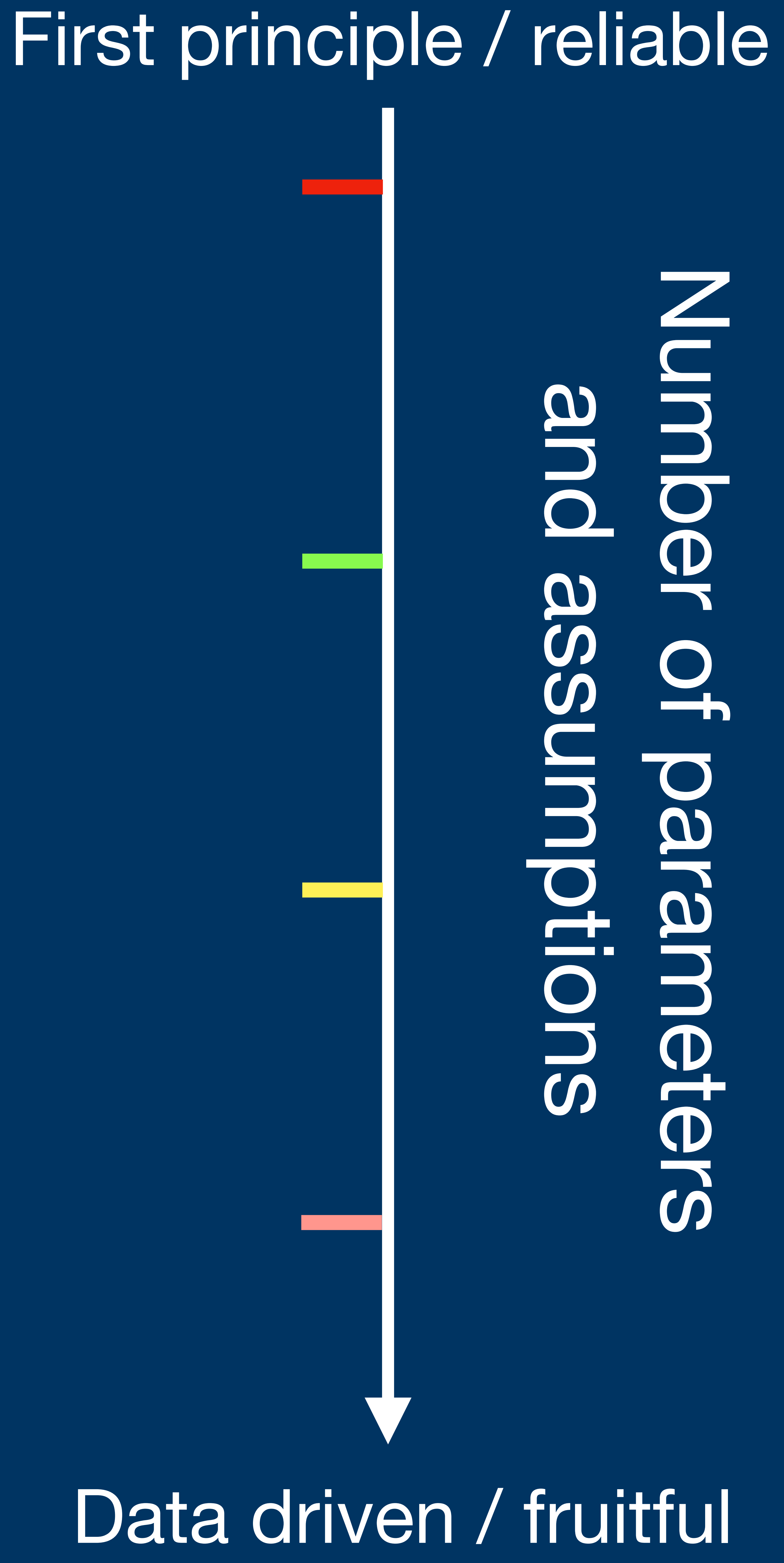
  Heavy quark expansion: $\Lambda_c \to X \ell^+, \tau(\Lambda_c) \ldots$

- **Interactions at hadron level**

  Small released energy, χPT: $\Xi_c^0 \to \Lambda_c^+ \pi^- \ldots$

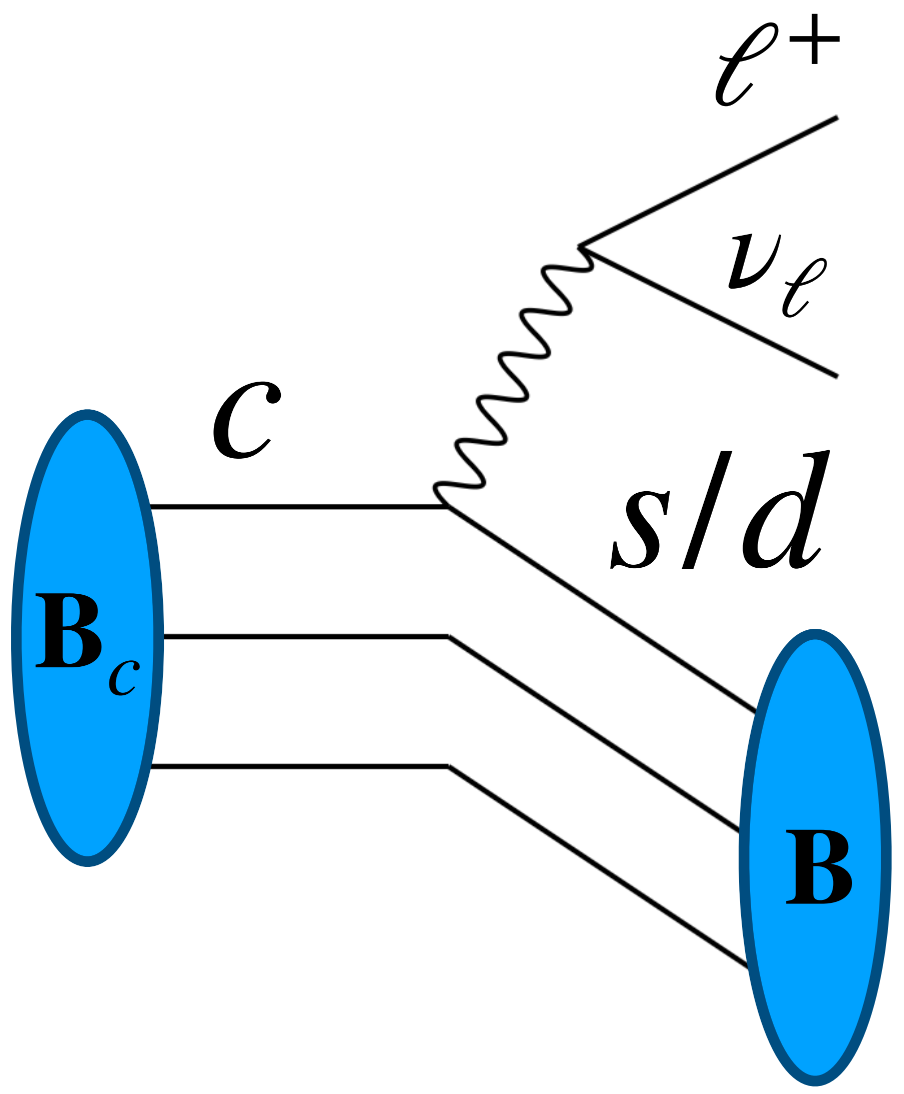
- $SU(3)_F$ **analysis**

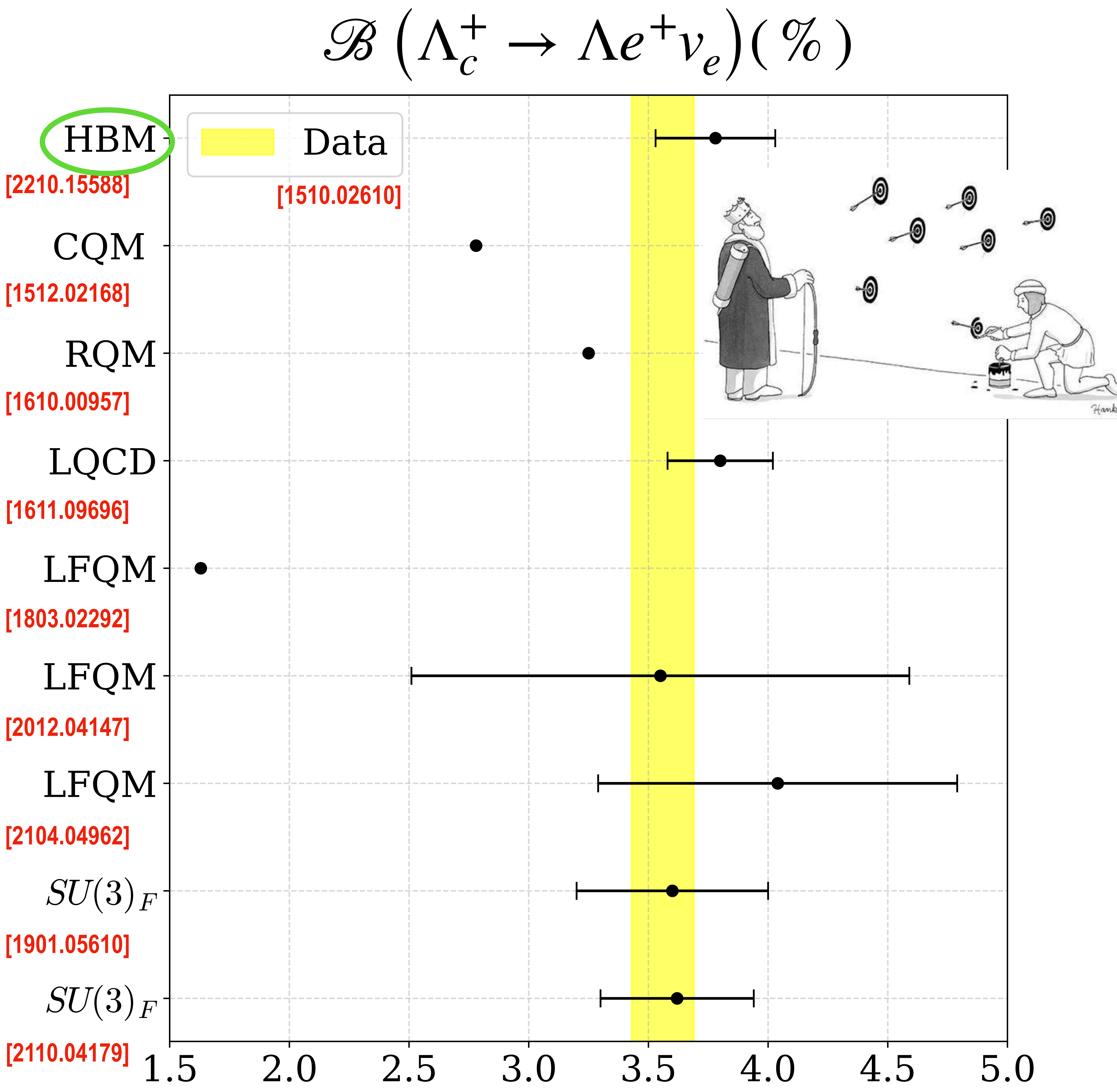
  2-body, 3-body, semileptonic…
  Most general but requires (too) many parameters



Semileptonic decays (exclusive)

- **Theoretical predictions range widely.**
- **Lattice predictions are consistent with data for Λ_c^+ decays.**





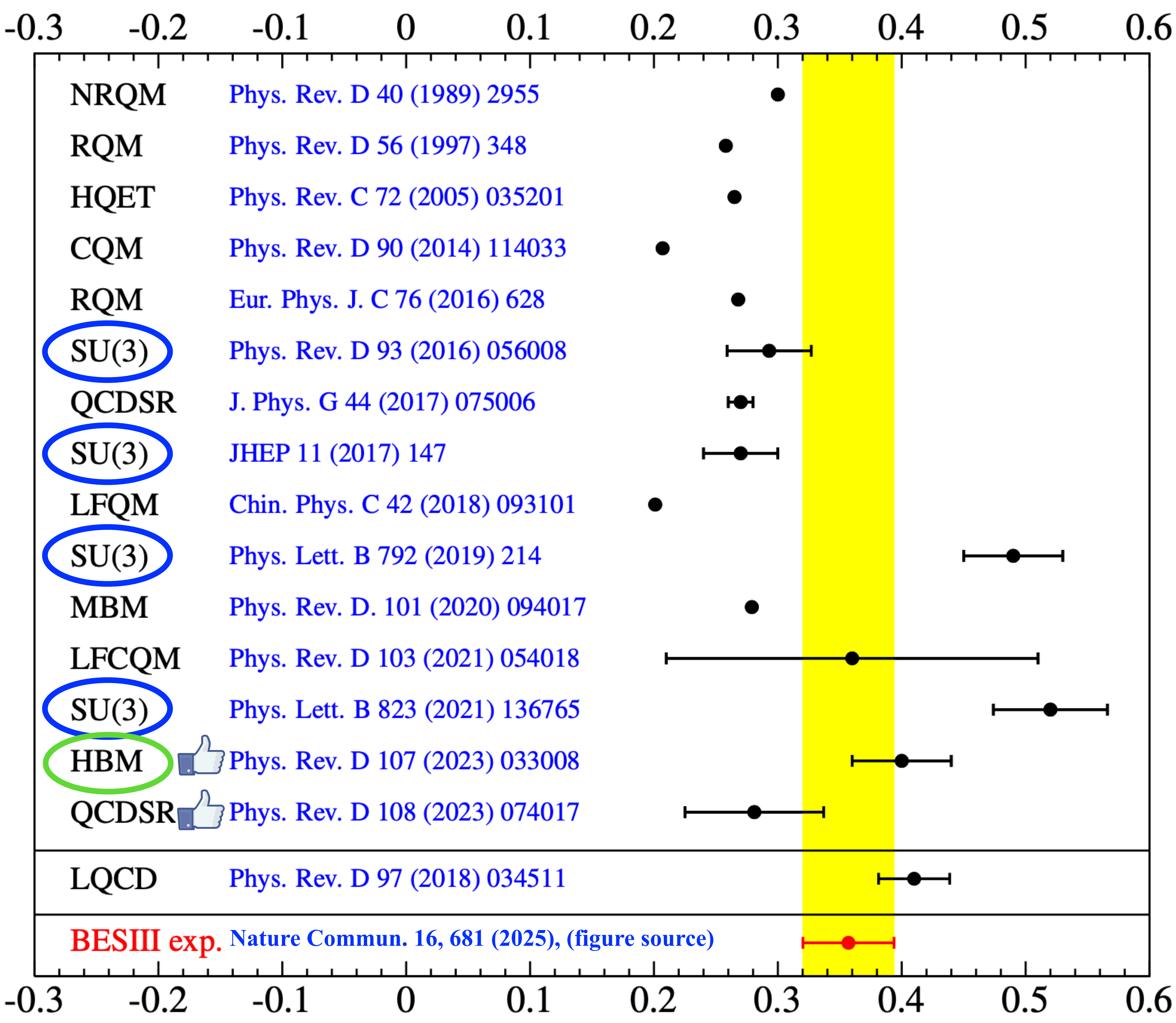
- **Semileptonic decays (exclusive)**

- **Theoretical predictions range widely.**

- **Lattice predictions are consistent with data for Λ_c^+ decays.**

- **Handling of phase space and the running of form factors generate main differences in $SU(3)_F$ analysis.**

$\mathcal{B}\left(\Lambda_c^+ \to n e^+ \nu_e\right)(\%)$



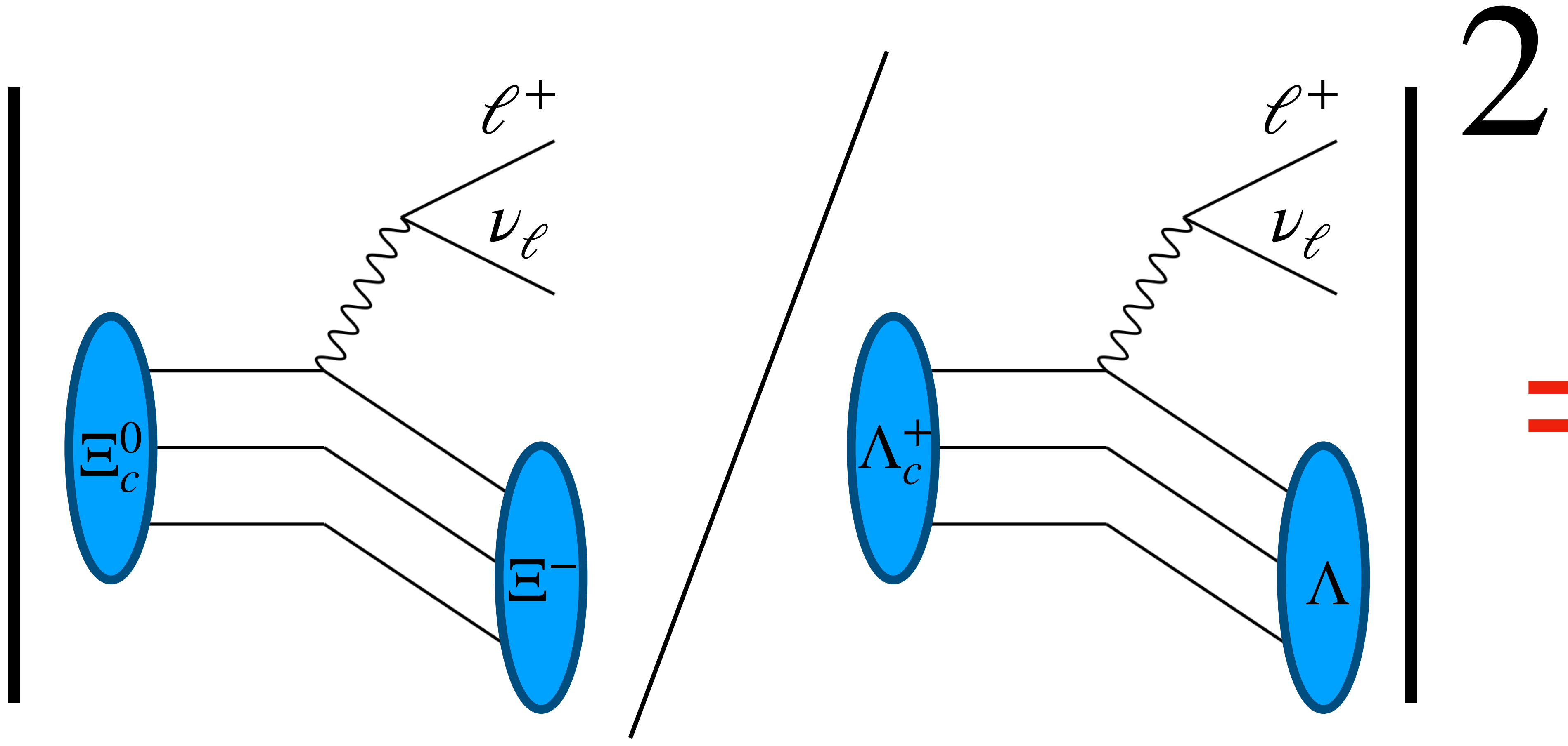
see Dong's talk in this morning

- **Semileptonic decays (exclusive)**

- Use * $\tau_{\Xi_c^0} = 0.15$ ps instead of 0.118 ps.

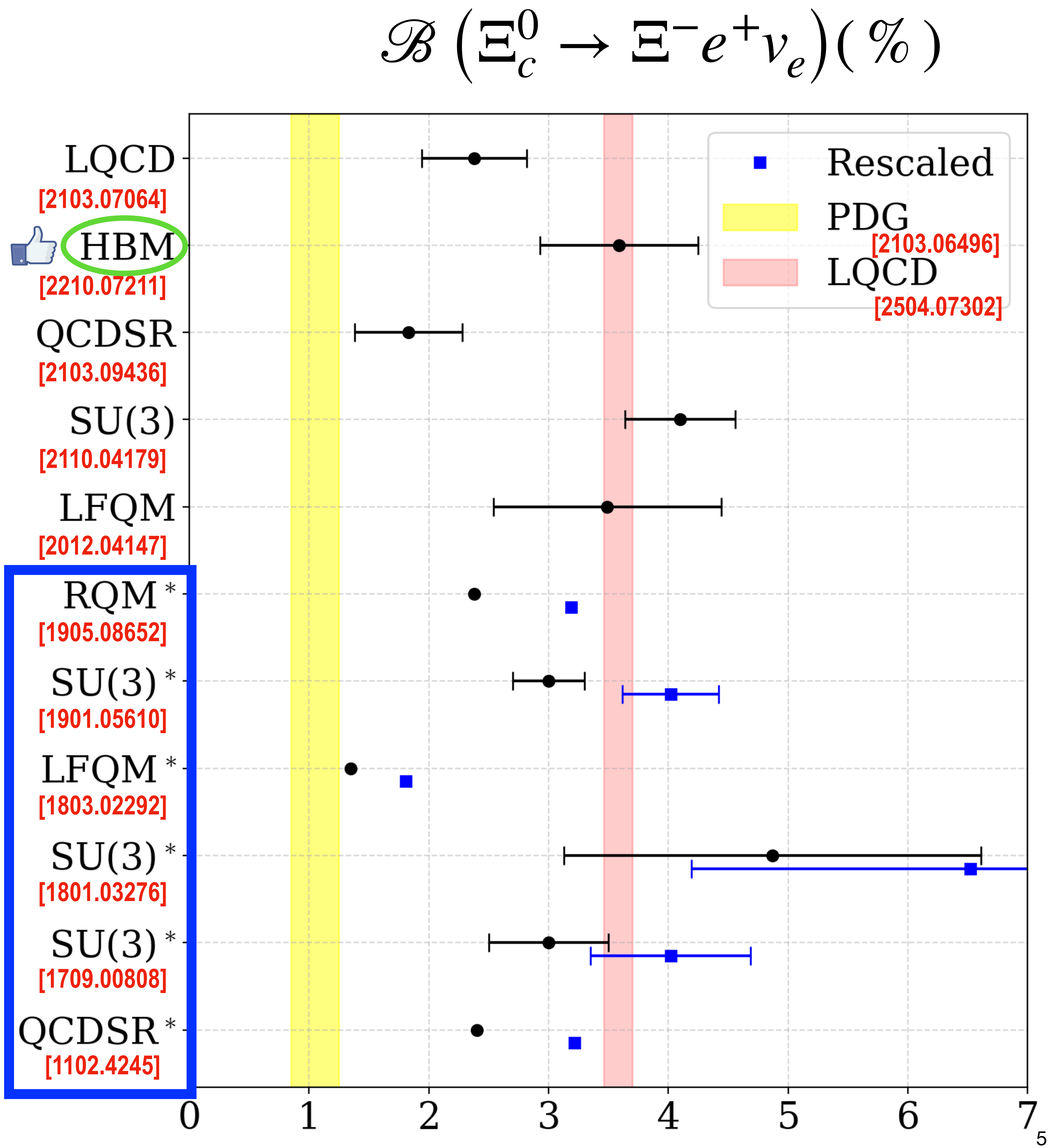
- So far, there is ***no*** literature that can explain satisfactorily the smallness of it.

- What's worse, the $SU(3)_F$ symmetry :



$$= \frac{3}{2}$$

- It is around **0.3** instead! Both are $c \to s$, and large $SU(3)_F$ breaking is unexpected.



- # Semileptonic decays (exclusive)

- Use * $\tau_{\Xi_c^0} = 0.15\ \text{ps}$ instead of $0.118\ \text{ps}$.
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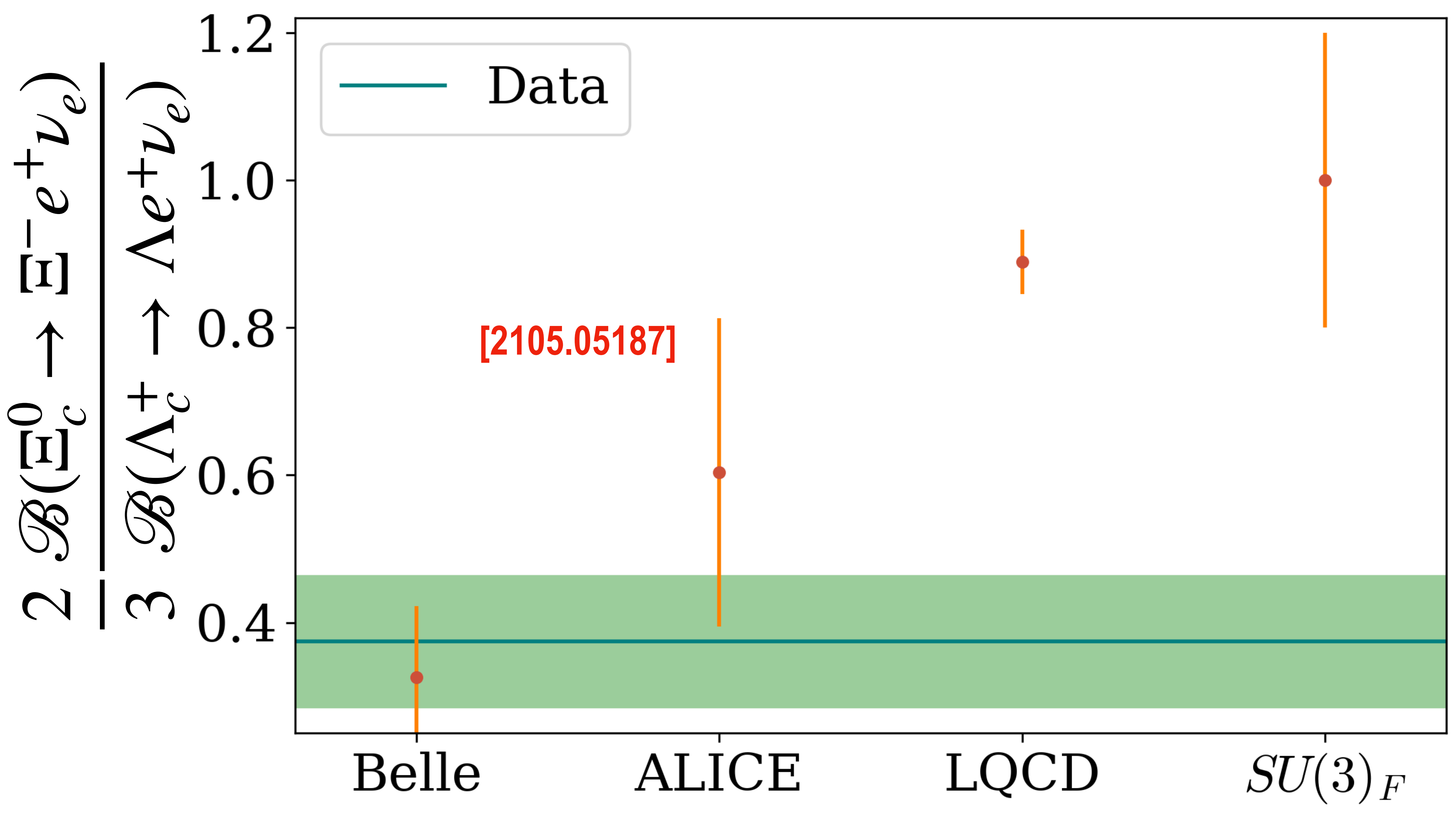
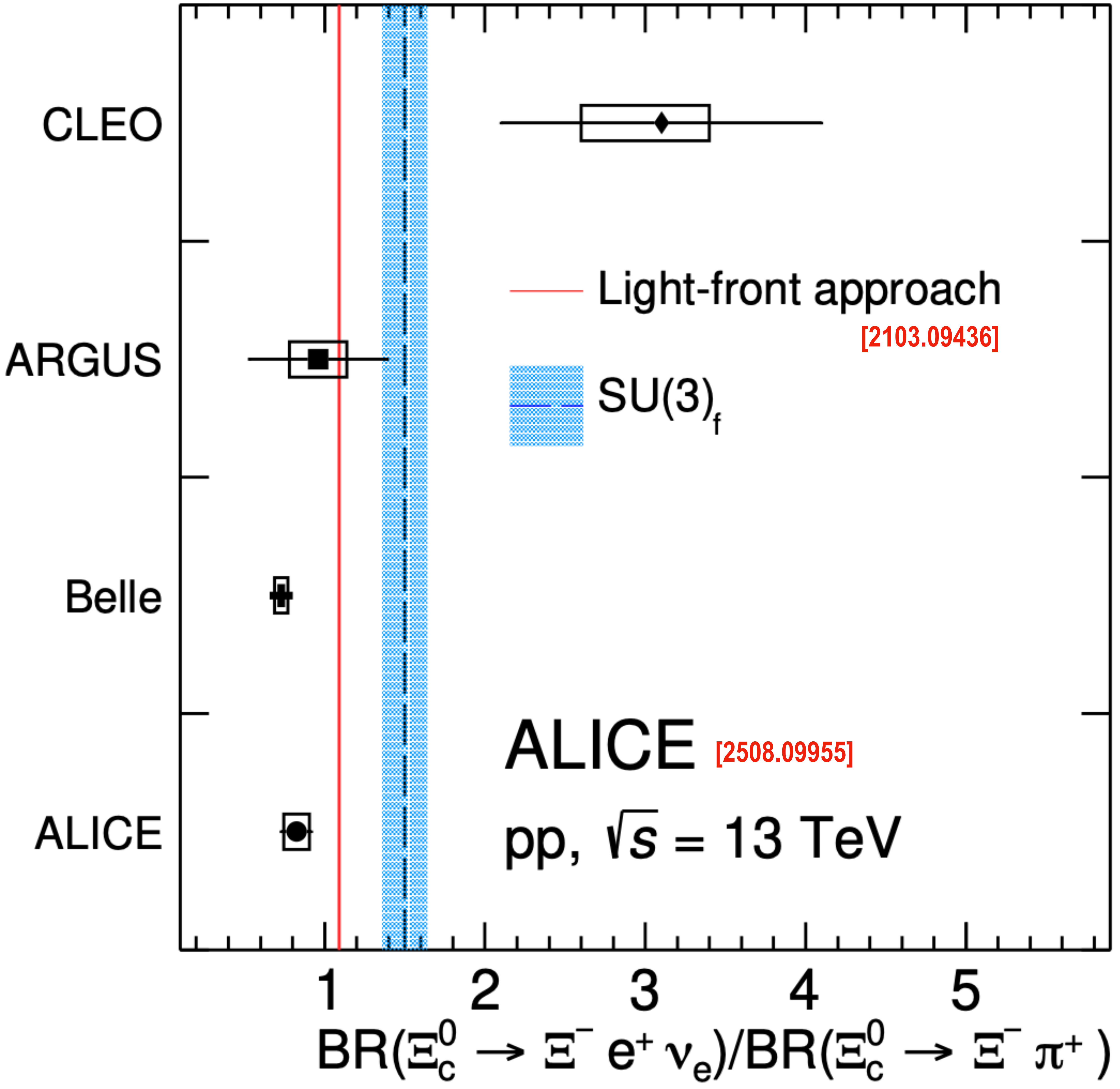


$$\frac{\Gamma(D_s^+ \to \phi e^+ \nu_e)}{\Gamma(D^+ \to \overline{K}^{*0} e^+ \nu_e)} = 0.91 \pm 0.06$$

PDG



• Semileptonic decays (exclusive)

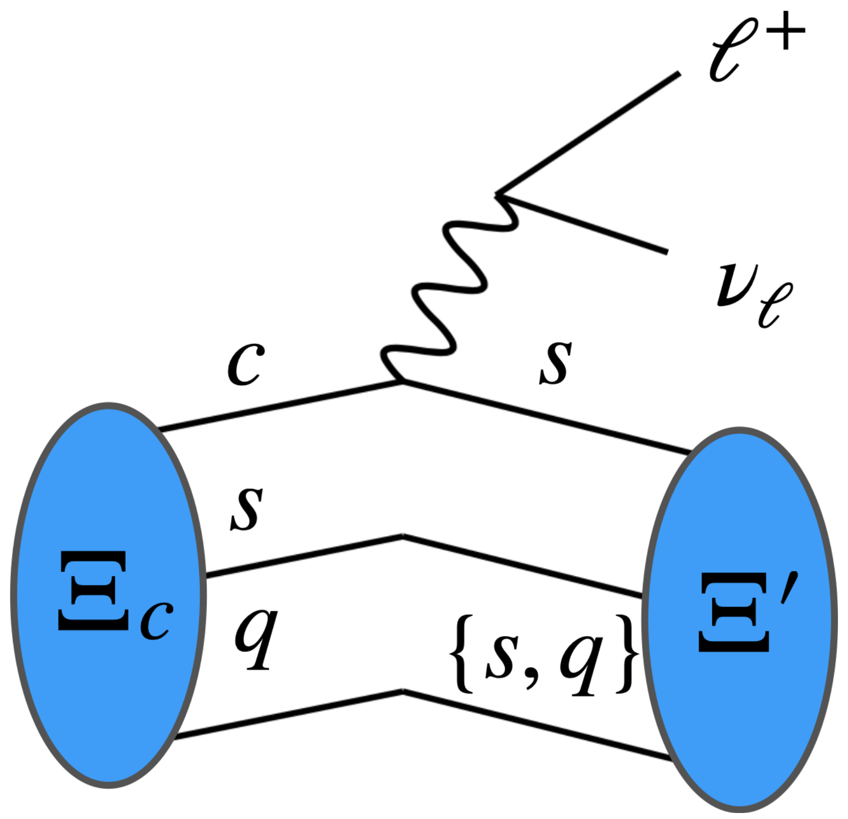
- A possible explanation: [2110.04179]

$$\Xi_c = \cos\theta \; \Xi_c^{\bar{\mathbf{3}}} + \sin\theta \; \Xi_c^{\mathbf{6}}$$

- The form factors of $\Xi_c^{\bar{\mathbf{3}}}$ and $\Xi_c^{\mathbf{6}}$ destructively interfere. With $\theta \approx 25^\circ$, the data can be explained: [2210.07211]

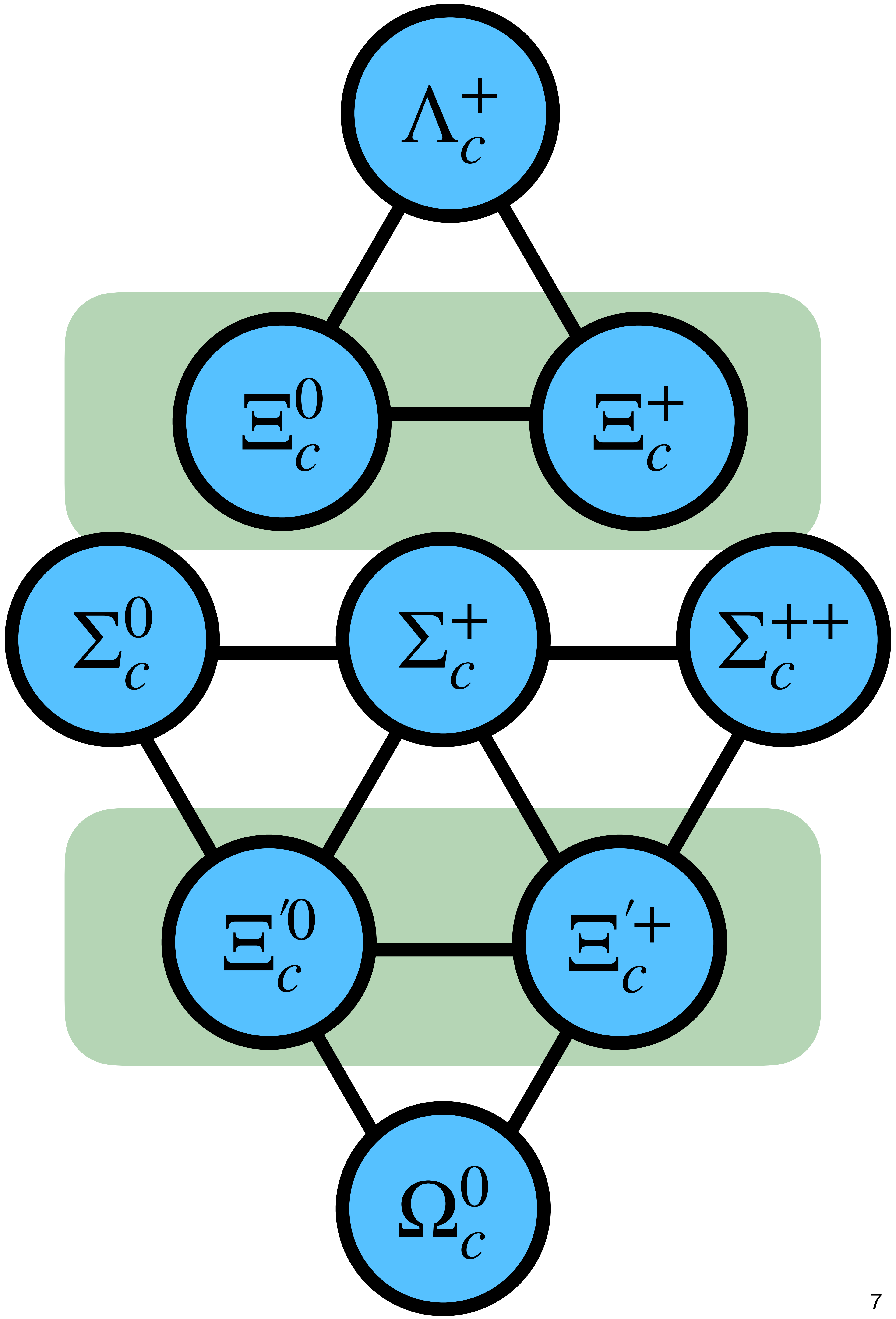
$$\mathscr{B}(\Xi_c^0 \to \Xi'(1520)\ell^+\nu_\ell) \approx 5 \times 10^{-3}$$

$$\mathscr{B}(\Xi_c^+ \to \Xi'(1520)\ell^+\nu_\ell) \approx 1.3\,\%$$



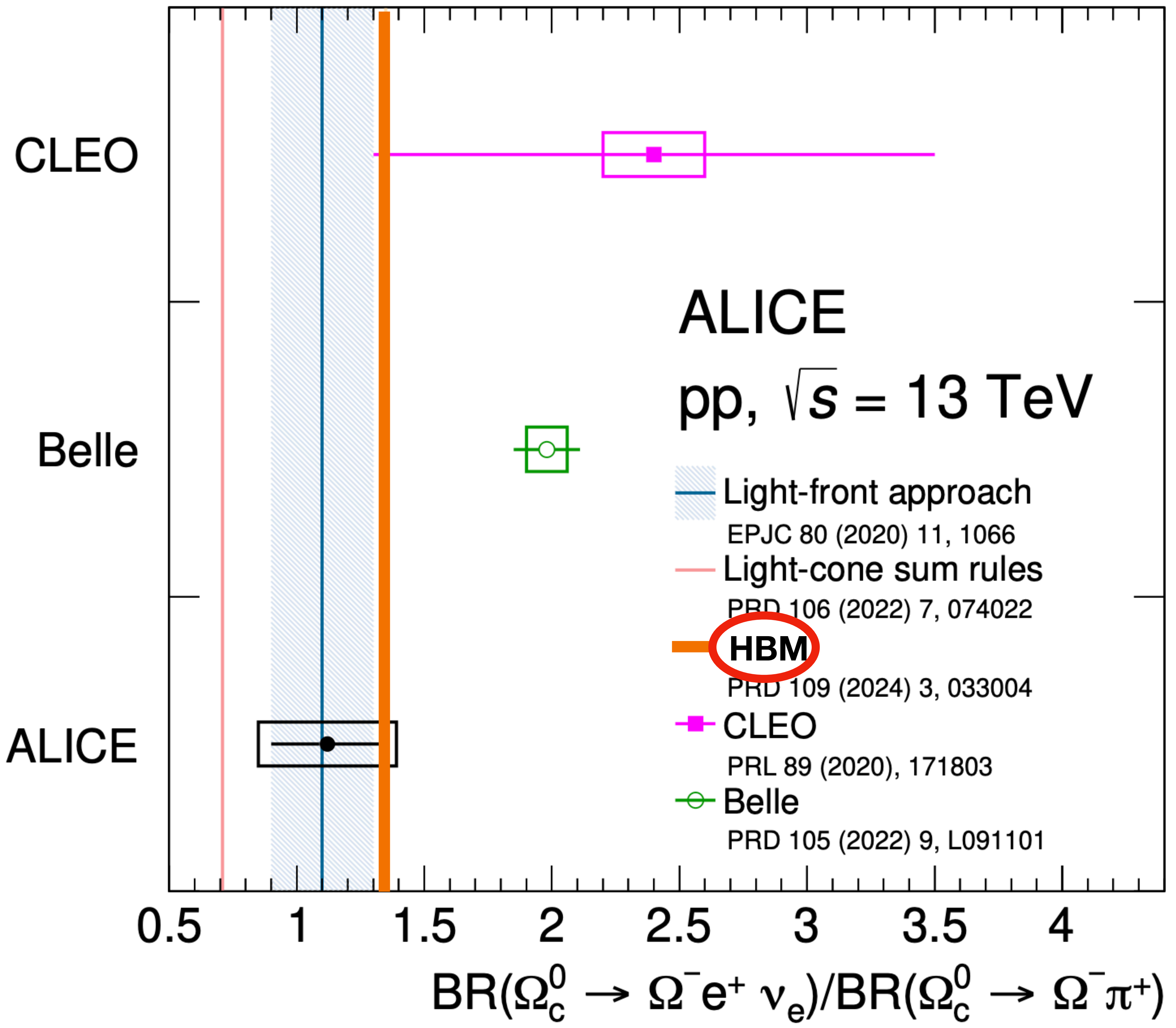
- Unfortunately, it was soon realized from lattice QCD, sum rules and LFQM that the mixing angle is tiny.

[2103.09436, 2303.17865, 2305.08050, 2309.05432, 2309.16386]



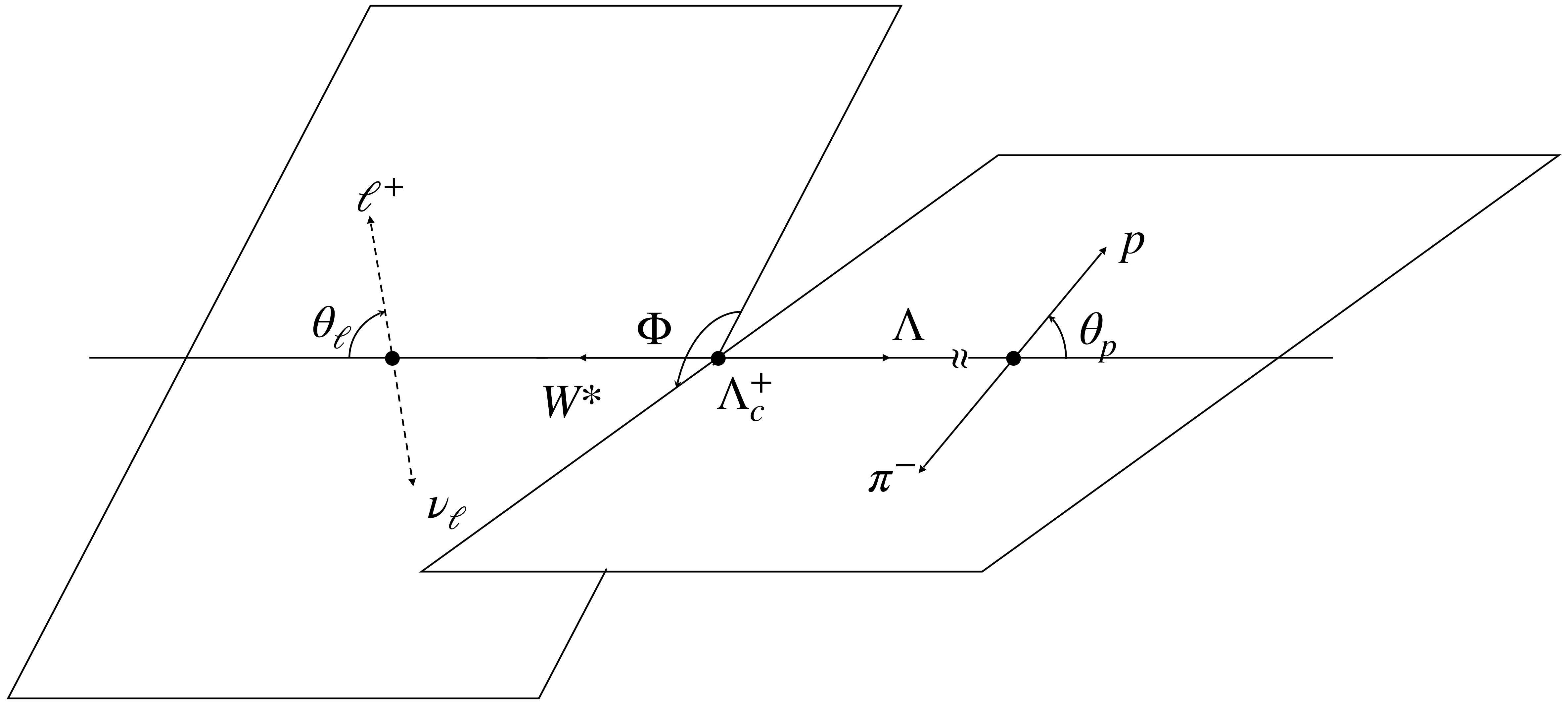
• Semileptonic decays (exclusive): Future aspects

Probing other charmed baryons



[2404.17272]

Triple product asymmetries



Vanish in the SM.

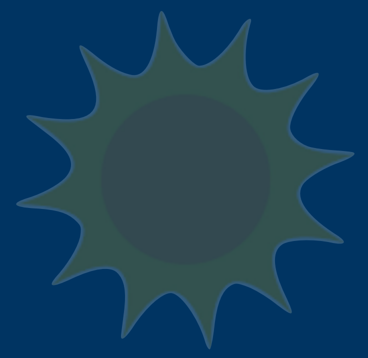
NP unlikely shares the same complex phase with the SM.

$$\mathcal{T}_p(\Lambda_c^+ \to \Lambda e^+ \nu_e) = -0.021 \pm 0.041_{\rm stat} \pm 0.001_{\rm syst}$$
$$\mathcal{T}_p(\Lambda_c^+ \to \Lambda \mu^+ \nu_\mu) = 0.068 \pm 0.055_{\rm stat} \pm 0.002_{\rm syst}.$$

BESIII PRD **108**, L031105 (2023)

- **Inclusive decays**

Heavy quark expansion: $\Lambda_c \to X\ell^+, \tau(\Lambda_c)\ldots$



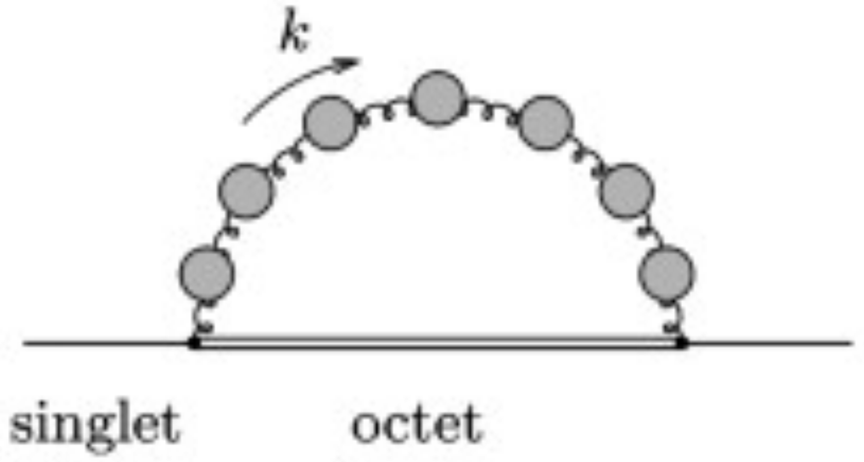
• Inclusive decays - theory

Pole mass, non-perturbative input

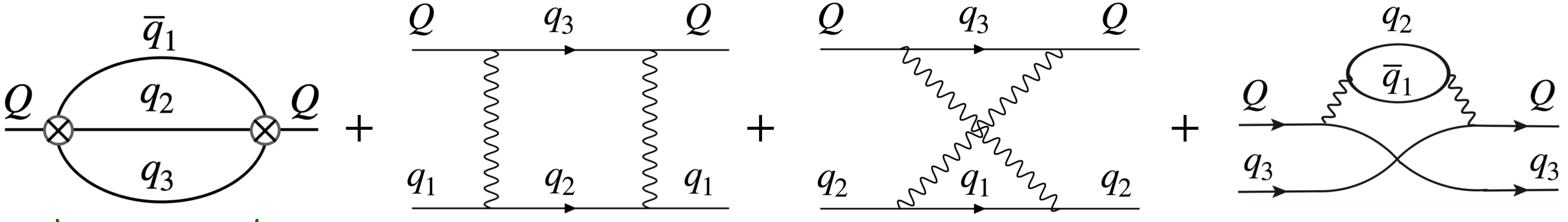
[2502.05901]

$$\frac{1}{m_a}\mathrm{Im}\left(A_{a\to a}\right) = \frac{i}{2m_a}\int\left\langle T\left(\mathcal{H}_{eff}(x)\mathcal{H}_{eff}(0)\right)\right\rangle d^4x = \frac{1}{m_a}\sum_{n\in\mathcal{N}}\frac{m_Q^k}{m_Q^n}\left\langle C_n O_n\right\rangle$$

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



$$\frac{1}{m_a}\mathrm{Im}\Big(\cdots \Big) = \Gamma_{\text{total}}$$



$\propto m_Q^5$ (first diagram); $\propto (4\pi)^2 m_Q^2$ (remaining diagrams)

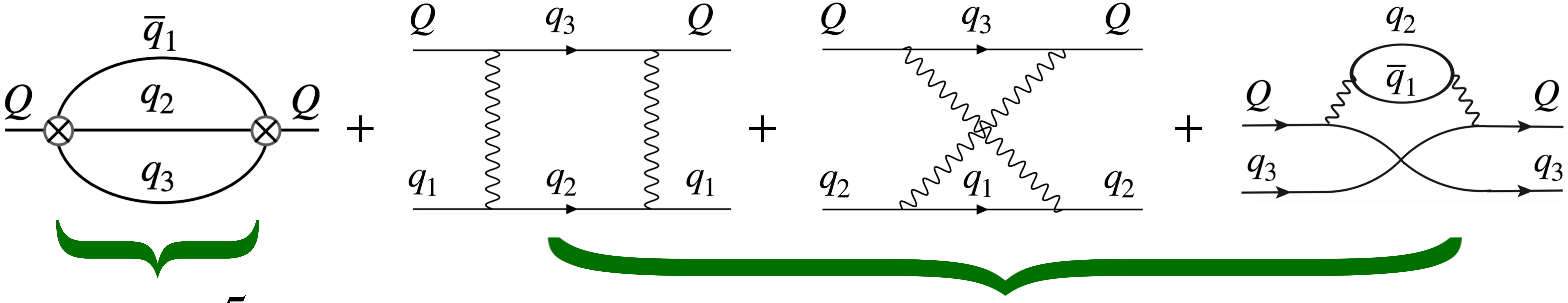
Inclusive decays - theory

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

$$\left(\left(\frac{\Lambda_{QCD}}{m_b}\right)^3, \left(\frac{\Lambda_{QCD}}{m_c}\right)^3, 16\pi^2 \right) \approx \left(\frac{1}{4000}, \frac{1}{125}, 160 \right)$$

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

$$\frac{1}{m_a}\mathrm{Im}\Big($$



$$\Big) = \Gamma_{\text{total}}$$

$\propto m_Q^5$ $\qquad\qquad$ $\propto (4\pi)^2 m_Q^2$

Inclusive decays - theory

- At LO, Ξ_c receives dim-6 corrections but Λ_c^+ does not!

$$\Gamma^{\rm SL}_{\Xi_c} = \Gamma^{\rm SL}_{\Xi_c}(\text{dim-3}) + \Gamma^{\rm SL}_{\Xi_c}(\text{dim-6}) \geq \Gamma^{\rm SL}_{\Lambda_c^+}$$

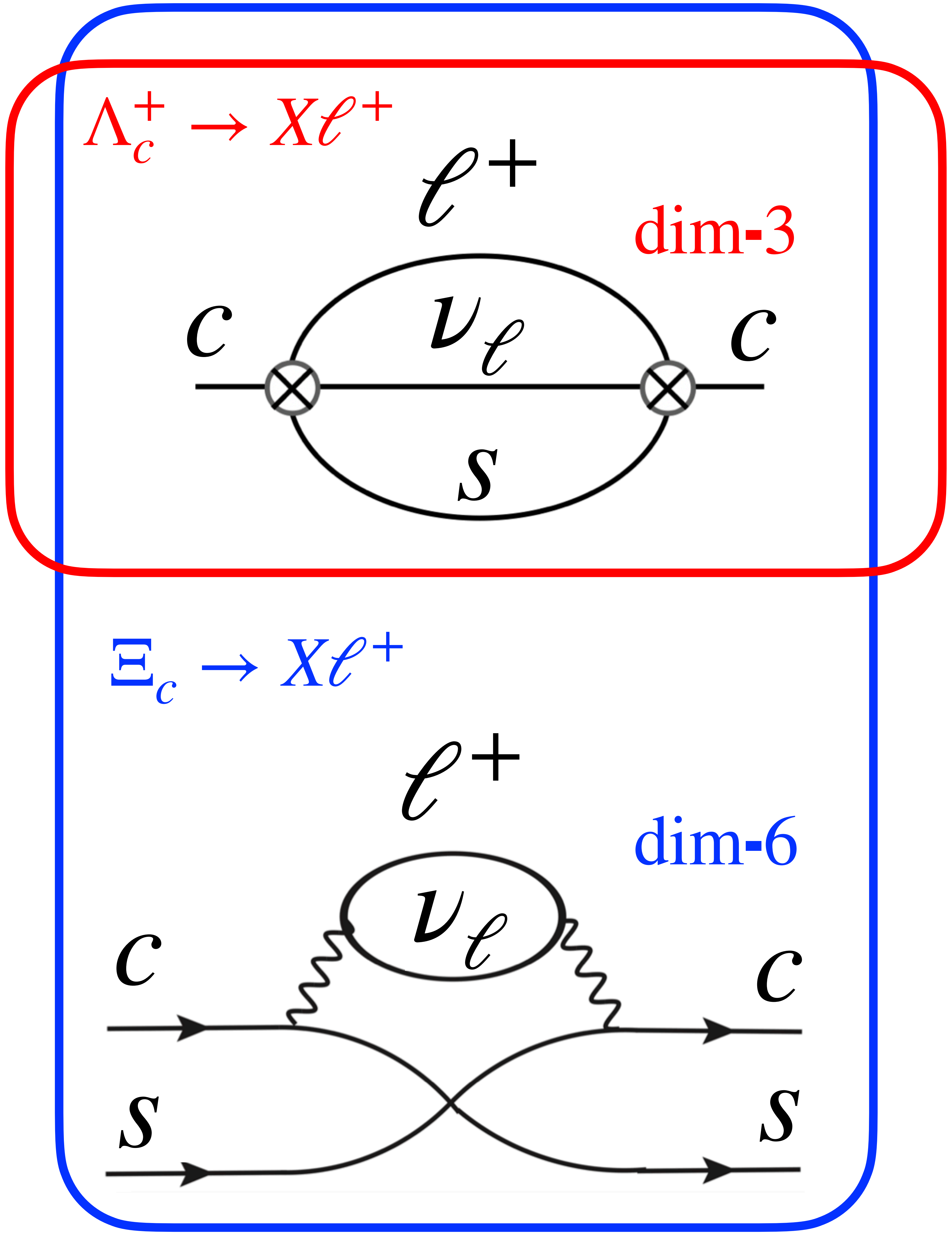
$$\mathscr{B}(\Xi_c^0 \to X e^+) \geq \frac{3}{4}\mathscr{B}(\Lambda_c^+ \to X e^+) \geq 3\,\%$$

- BESIII reveals the 90% saturation of: [2212.03753]

$$\mathscr{B}(\Lambda_c^+ \to X e^+) = (4.06 \pm 13)\,\% \approx 1.1\,\mathscr{B}(\Lambda_c^+ \to \Lambda e^+ \nu_e)$$

- From $\mathscr{B}(\Xi_c^0 \to \Xi^- \ell^+ \nu_\ell) = (1.05 \pm 0.20)\,\%$ we have

$$\frac{\mathscr{B}(\Xi_c^0 \to X e^+)}{\mathscr{B}(\Xi_c^0 \to \Xi^- e^+ \nu_e)} \geq 2$$



Inclusive decays - numerical results

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!

Inclusive decays - numerical results

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

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

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

- We are working on both dim-7 NLO and doubly charmed baryons predictions.

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

$\mathbf{B}_c$		Γ_3^{SL}	Γ_6^{SL}	Γ_7^{SL}	$\mathcal{B}_e^{SL}(\%)$
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]

- **Exclusive semileptonic decays** 

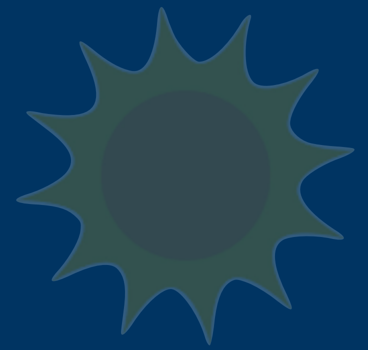
  Lattice QCD: $\Xi_c^0 \to \Xi^- \ell^+ \nu_\ell \dots$

- **Inclusive decays**

  Heavy quark expansion: $\Lambda_c \to X\ell^+, \tau(\Lambda_c) \dots$

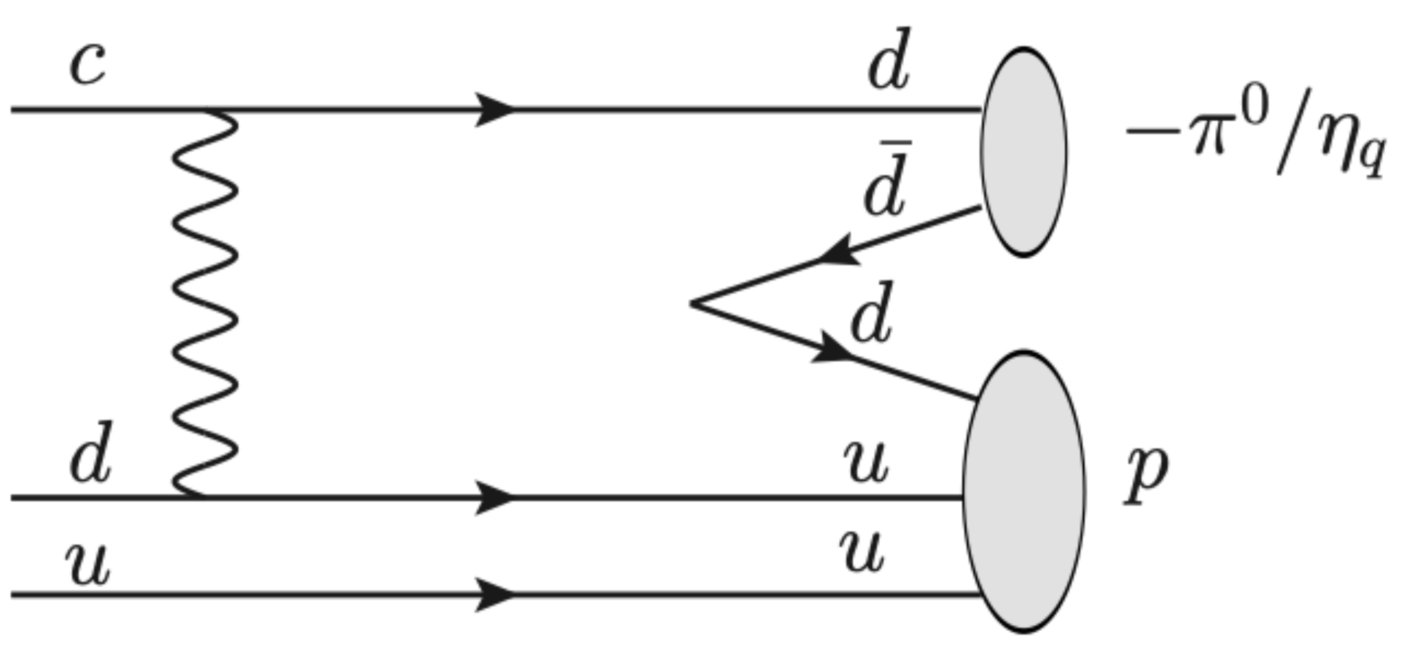
- **Interactions at hadron level**

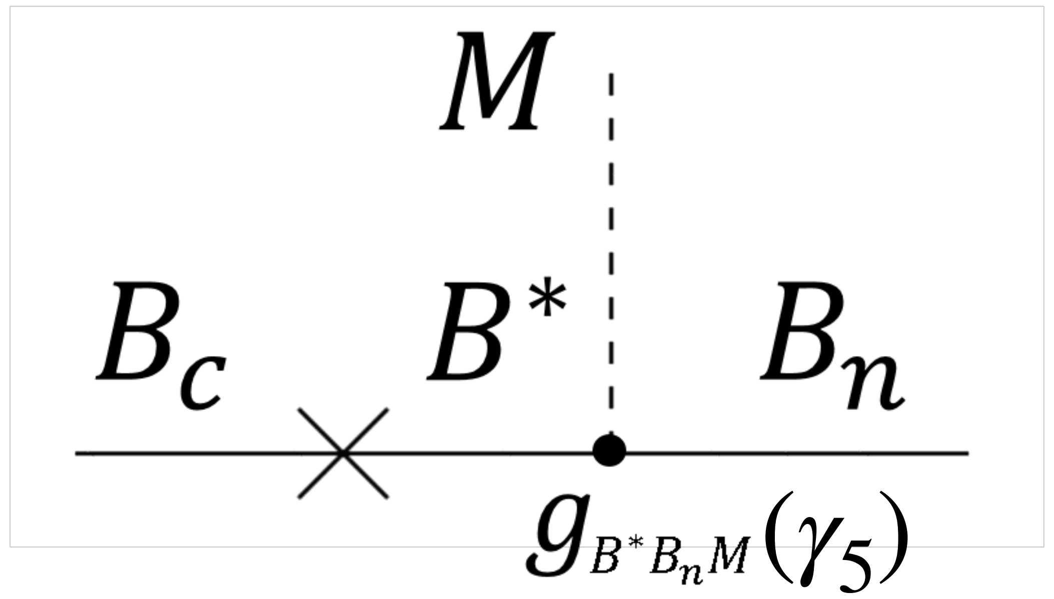
  Small released energy, χPT: $\Xi_c^0 \to \Lambda_c^+ \pi^- \dots$

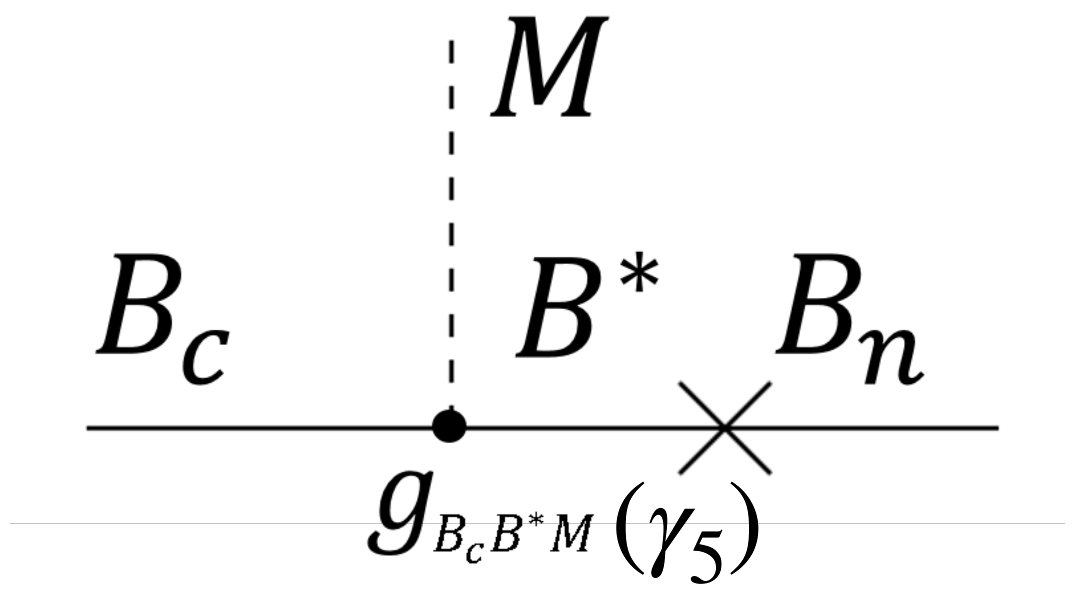
- $SU(3)_F$ **analysis** 

  2-body, 3-body, semileptonic…
  Most general but requires (too) many parameters

- **Exclusive decays - pole model**







$\langle B^*_- | \mathscr{H}_{eff} | B_c \rangle = i b_c \bar{u}^* u_c$

$J^P(B^*_-) = \frac{1}{2}^- \rightarrow$ parity violated $\quad b_c \frac{g_{B^*_-B_nM}}{m_c - m^*} + b_n^* \frac{g_{B_cB^*_-M}}{m_n - m^*}$

$\langle B^*_+ | \mathscr{H}^{PC}_{eff} | B_c \rangle = a_c \bar{u}^* u_c$

$J^P(B^*_+) = \frac{1}{2}^+ \rightarrow$ parity conserved $\quad \left(a_c \frac{g_{B^*_+B_nM}}{m_c - m^*} + a_n^* \frac{g_{B_cB^*_+M}}{m_n - m^*} \right) \gamma_5$

• Exclusive decays - pole model

Pole model :

Heavy flavor conserving decays

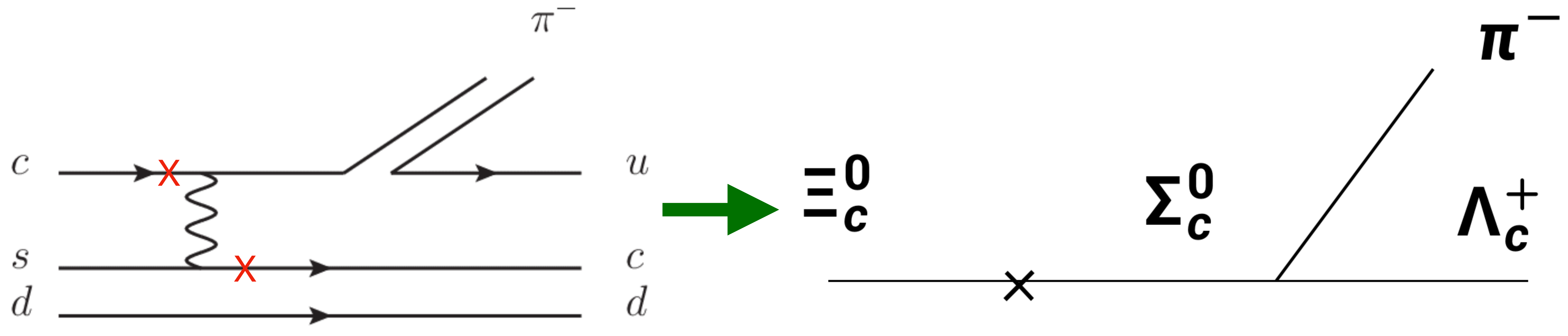
Chiral limit $m_{\Xi_Q} \approx m_{\Sigma_Q}$ holds excellently!

$$\bar{u}_n \left(b_c \frac{g_{B^*_- B_n M}}{m_c - m^*} + b^*_n \frac{g_{B_c B^*_- M}}{m_n - m^*} \right) u_c \overbrace{=} - \frac{1}{f_\pi} \bar{u}_n \left(b_c g_{B^* B_n} - b^*_n g_{B_c B^*} \right) u_c = - \frac{1}{f_\pi} \langle B_n | [Q_5, \mathscr{H}^{PV}_{eff}] | B_c \rangle$$

• Pole contributions are expected to be dominated. ✔

• Soft pion limit is reliable. ✔

$$\frac{1}{\underbrace{M_{\Xi_c} - M_{\Sigma_c}}_{14\text{ MeV}} + i\frac{\Gamma_{\Sigma_c}}{2}}$$



Both $(\bar{d}c)(\bar{c}s)$ and $(\bar{d}u)(\bar{u}s)$ contribute

P. Y. Niu, Q. Wang and Q. Zhao, PLB **826**, 136916 (2022);
S. Groote and J. G. Körner, EPJC **82** 297 (2022).

Branching fractions in units of 10^{-3}

Mode	$(\mathrm{CLY})^2$	Faller	Gronau	Voloshin	Niu	HYC	This work	Exp
	[1512.01276]	[1503.06088]	[1603.07309]	[1911.05730]	[2111.14111]	[2204.03149]	[2209.00257]	
$\Xi_c^0 \to \Lambda_c^+ \pi^-$	0.17	< 3.9	$0.18^{+0.23}_{-0.13}$	$> 0.25 \pm 0.15$	5.8 ± 2.1	$1.76^{+0.18}_{-0.12}$	7.7 ± 1.2	5.4 ± 1.1
			1.34 ± 0.53 [a]					[2007.12096]
$\Xi_c^+ \to \Lambda_c^+ \pi^0$	0.11	< 6.1	< 0.2	–	11.1 ± 4.0	$3.03^{+0.29}_{-0.22}$	15.8 ± 1.6	–
			2.01 ± 0.80 [a]					
$\Xi_b^- \to \Lambda_b^0 \pi^-$	7.0	$1.9 - 7.6$	6.4 ± 4.3	8 ± 3	1.4 ± 0.7	$4.67^{+2.29}_{-1.83}$	9.4 ± 1.3	8.9 ± 3.1
								[2307.09427]
$\Xi_b^0 \to \Lambda_b^0 \pi^0$	2.5	$0.9 - 3.7$	3.2 ± 2.1	–	0.17 ± 0.15	$2.87^{+1.20}_{-0.99}$	5.8 ± 0.7	–

Without charm-exchange

$$\mathscr{B}(\Xi_c^0 \to \Lambda_c^+ \pi^-)/\mathscr{B}(\Xi_c^0 \to \Xi^- \pi^+) = 0.38 \pm 0.06$$

Phase space+**CKM** gives 6×10^{-3} suppression! 50 times larger than naive.

• Exclusive decays - pole model

Reliability is not guaranteed in $\Delta c = -1$ transitions and it yields no complex phases which ***contradicts*** the data:

2024: Measurements of the ***strong phase*** in $\Lambda_c^+ \to \Xi^0 K^+$

PRL **132**, 031801 (2024)

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

* CP even and Cabibbo-favored.

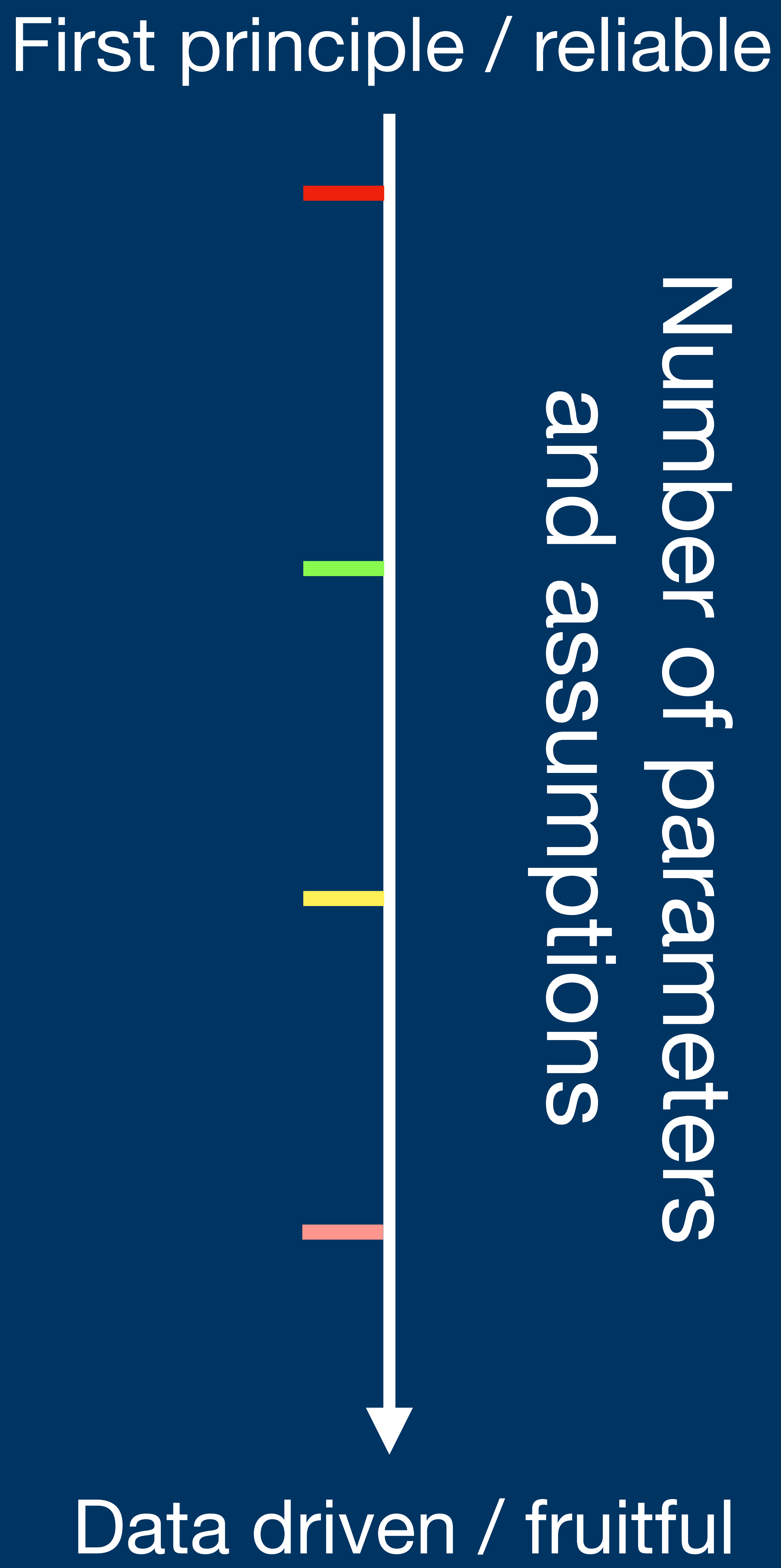
2024: Measurements of ***strong phases*** in $\Lambda_c^+ \to \Lambda\pi^+, \Lambda K^+$

PRL **133**, 261804 (2024)

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

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

See works from Fanrong and Hai-Yang : **1801.08625, 1910.13626, 2212.12983...**



- $SU(3)_F$ **analysis**

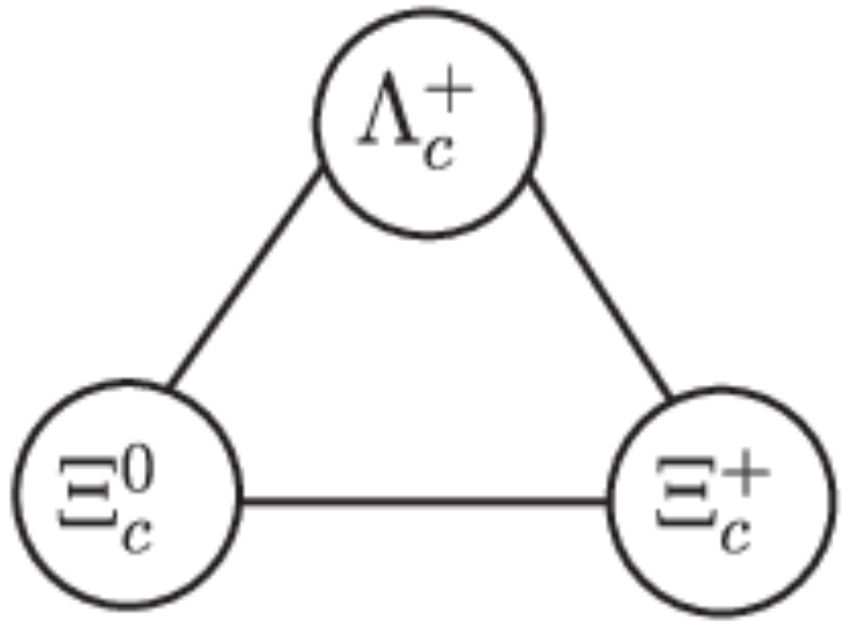
2-body, 3-body, semileptonic…
Most general but requires (too) many parameters

• SU(3) flavor perspective of charmed baryon decays

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

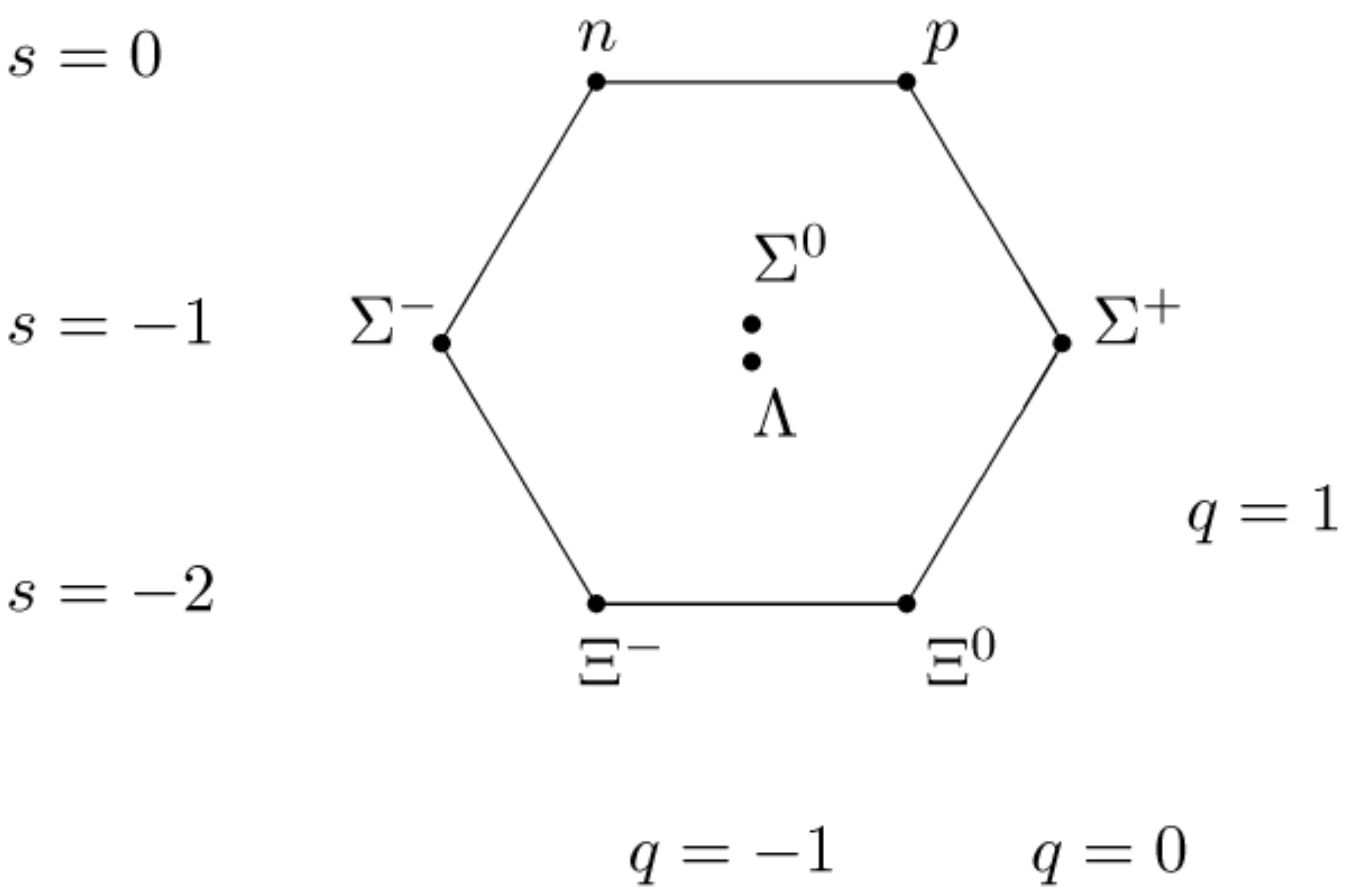
PRD **54**, 2132 (1996), PRD **93**, 056008 (2016), NPB **956**, 115048 (2020)

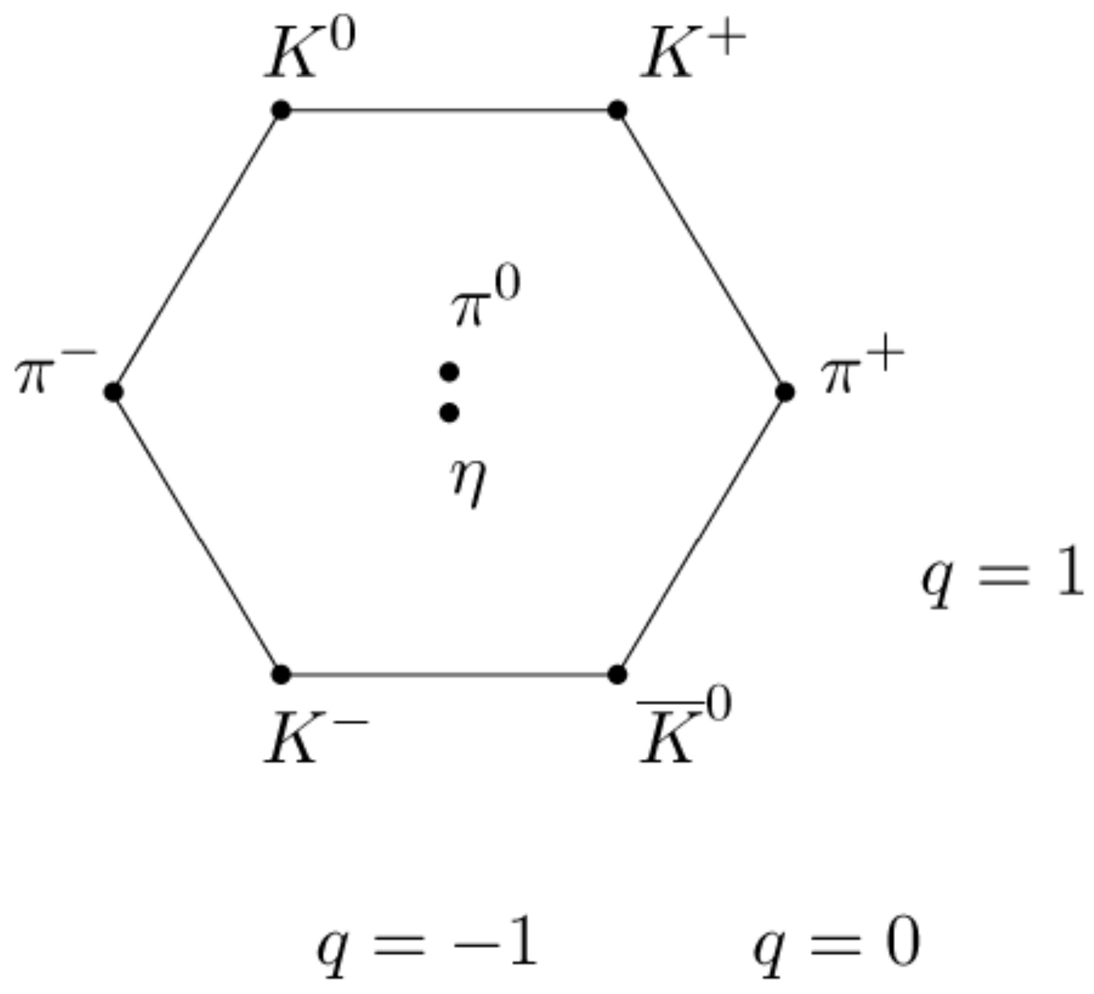
JHEP **09**, 035 (2022), JHEP **03**, 143 (2022), PRD **109**, 114027 (2024) …



Weak interactions

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





SU(3) flavor perspective of charmed baryon decays

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

	PDG	$SU(3)_F$ conserved	$SU(3)_F$ broken [2506.19005]
$10^2\mathcal{B}(\Xi_c^0 \to \Xi^-\pi^+)$	1.43 ± 0.32	2.72 ± 0.09	2.9 ± 0.1
$10^2\mathcal{B}(\Xi_c^+ \to \Xi^-\pi^+\pi^+)$	2.9 ± 1.3	6.82 ± 0.36	6.0 ± 0.4

Both of them are the normalized channels in $\Xi_c^{0,+}$!

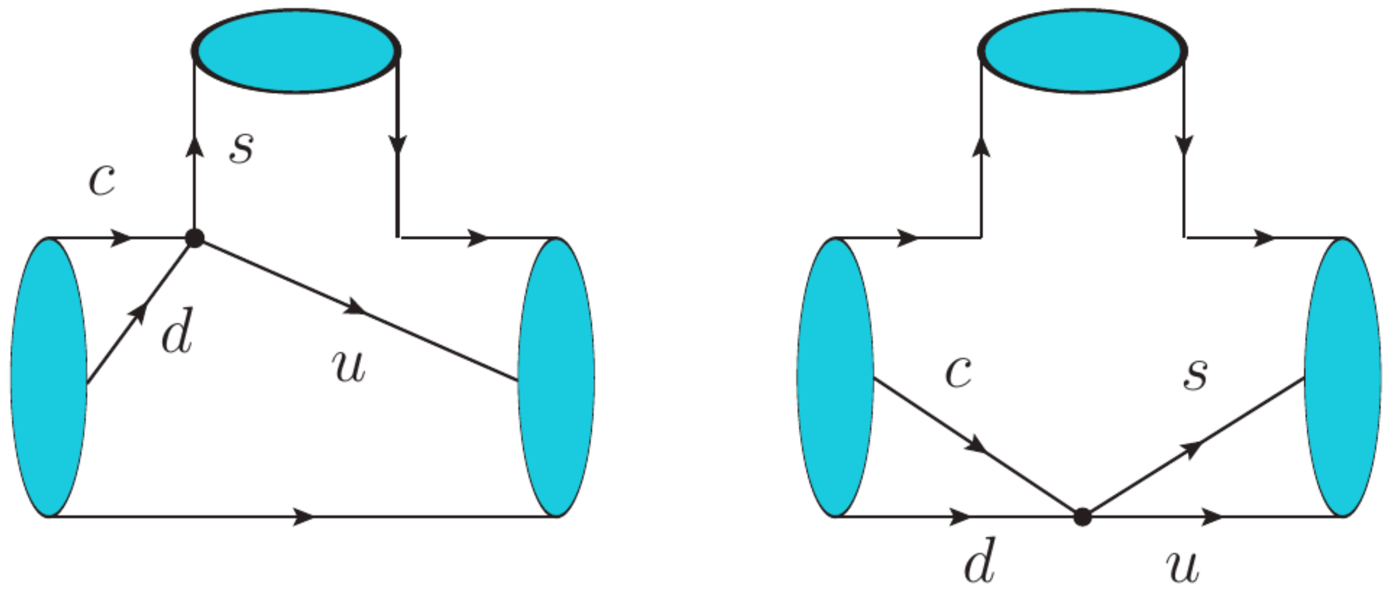
Same **underestimations** occurs in $\Xi_c^0 \to \Xi^- e^+ \nu_e$.

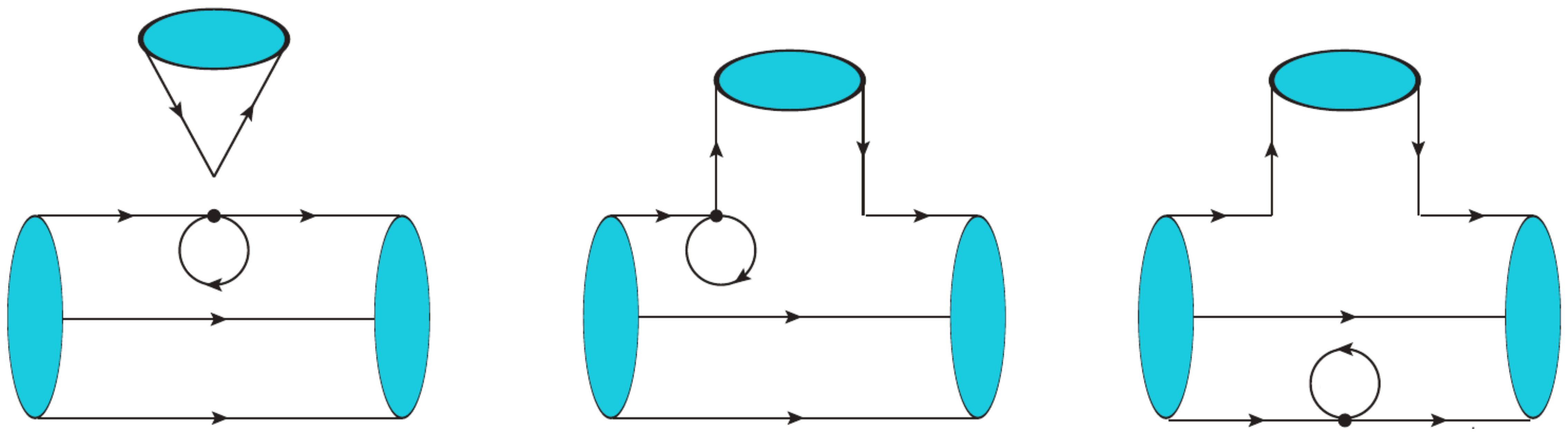
	PDG	$SU(3)_F$	Lattice	Lattice
$10^2\mathcal{B}(\Xi_c^0 \to \Xi^- e^+ \nu_e)$	1.05 ± 0.20 2.12 ± 0.13*	4.10 ± 0.46	2.38 ± 0.44	3.58 ± 0.12
		[2110.04179]	[2103.07064]	[2504.07302]

*Using $\mathcal{B}(\Xi_c^0 \to \Xi^-\pi^+) = (2.9 \pm 0.1)\,\%$

Final state rescattering

Strategy in 2404.19166 :





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

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

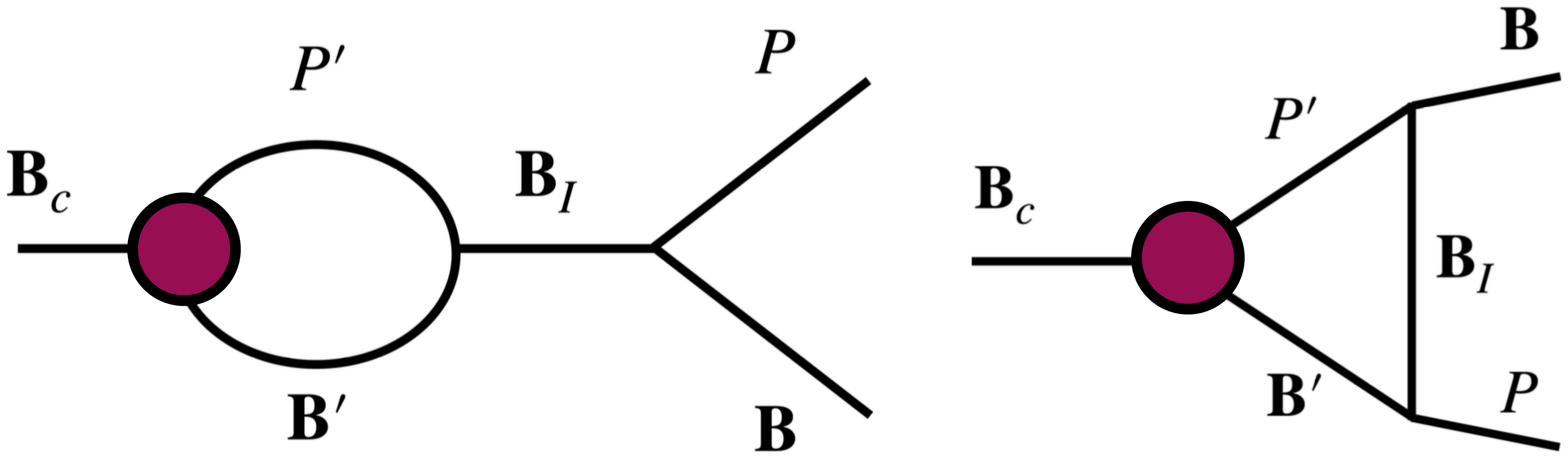


FIG from PRD **100**, 093002 (2019).

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

Final state rescattering

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

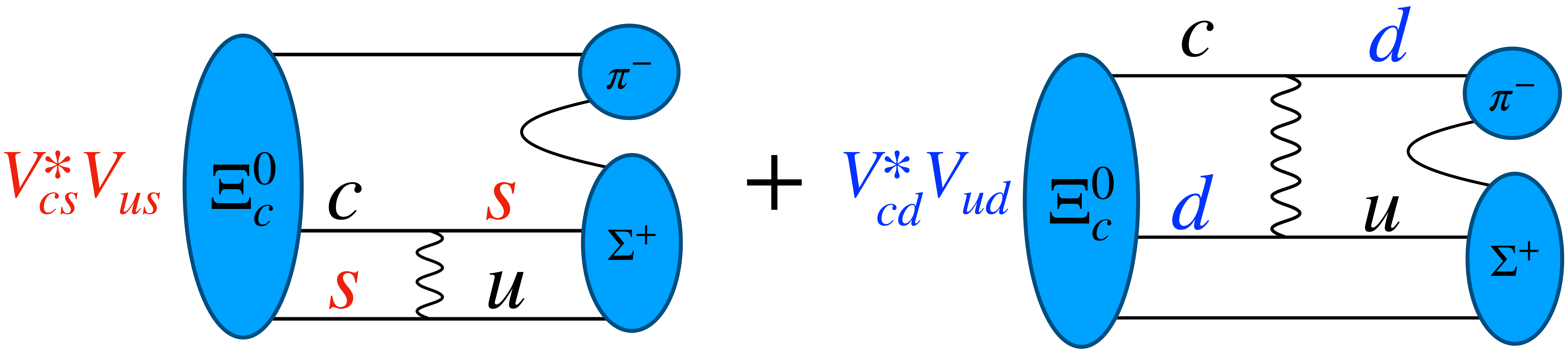
$$A_{CP}\left(\Xi_c^0 \to \Sigma^+\pi^-\right) = (0.71 \pm 0.16) \times 10^{-3}$$

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

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

See Fanrong's talk for details.

Final state rescattering

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

Theory : NLO of dim-7 operators.

Exclusive decays:

Exp : $\Xi_c^0 \to \Xi^-\pi^+$, CPV.

Theory: LD physics and CPV.

Inclusive decays - numerical results

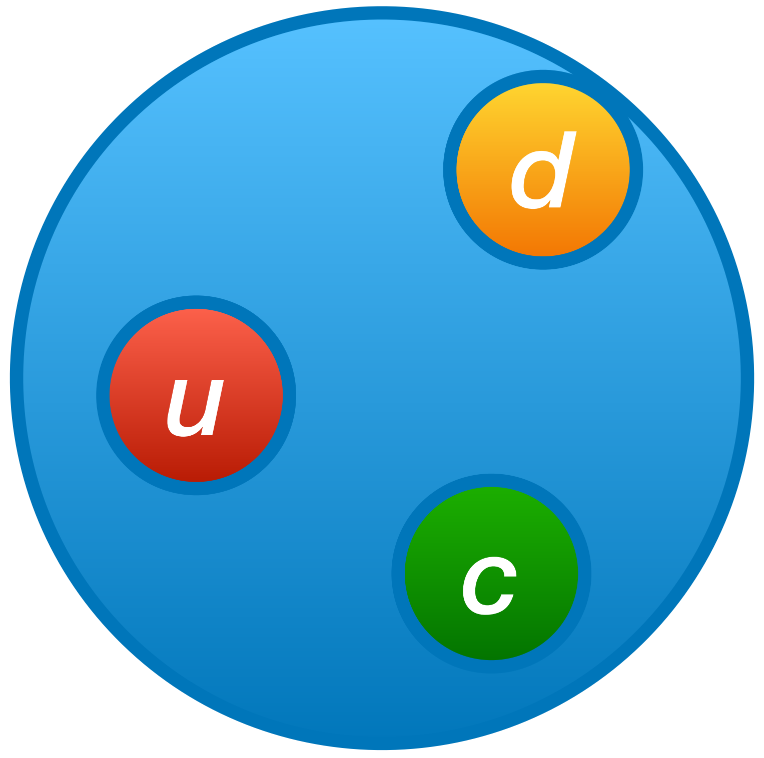
$$L_{\Lambda_b}^{q_I} = -3.2 \pm 1.6 \& -2.38 \pm 0.11 \pm 0.34 \pm 0.22$$

From QCD and HQET sum rules

[2305.00665] [PLB 387, 371(1996)]

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)
	$L^q_{\mathcal{B}_Q}$	-5.44	-5.15	-5.88	-34.12	-4.83	-4.87	-5.34	-31.63
BM [a]	$S^q_{\mathcal{B}_Q}$	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
	$L^q_{\mathcal{B}_Q}$	$-13(5)$	$-14(5)$	$-18(6)$	$-126(60)$	$-5.1(15)$	$-5.4(16)$	$-7.4(22)$	$-46(14)$
NRQM	$S^q_{\mathcal{B}_Q}$	$7(2)$	$7(2)$	$9(3)$	$-21(10)$	$2.5(8)$	$2.7(8)$	$3.7(11)$	$-7.7(23)$
	$P^q_{\mathcal{B}_Q}$	0	0	0	0	0	0	0	0

[2305.00665]



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