Charmed baryon semileptonic decays

On the puzzle of $\Xi_c^0 \to \Xi^- \ell^+ \nu_\ell$

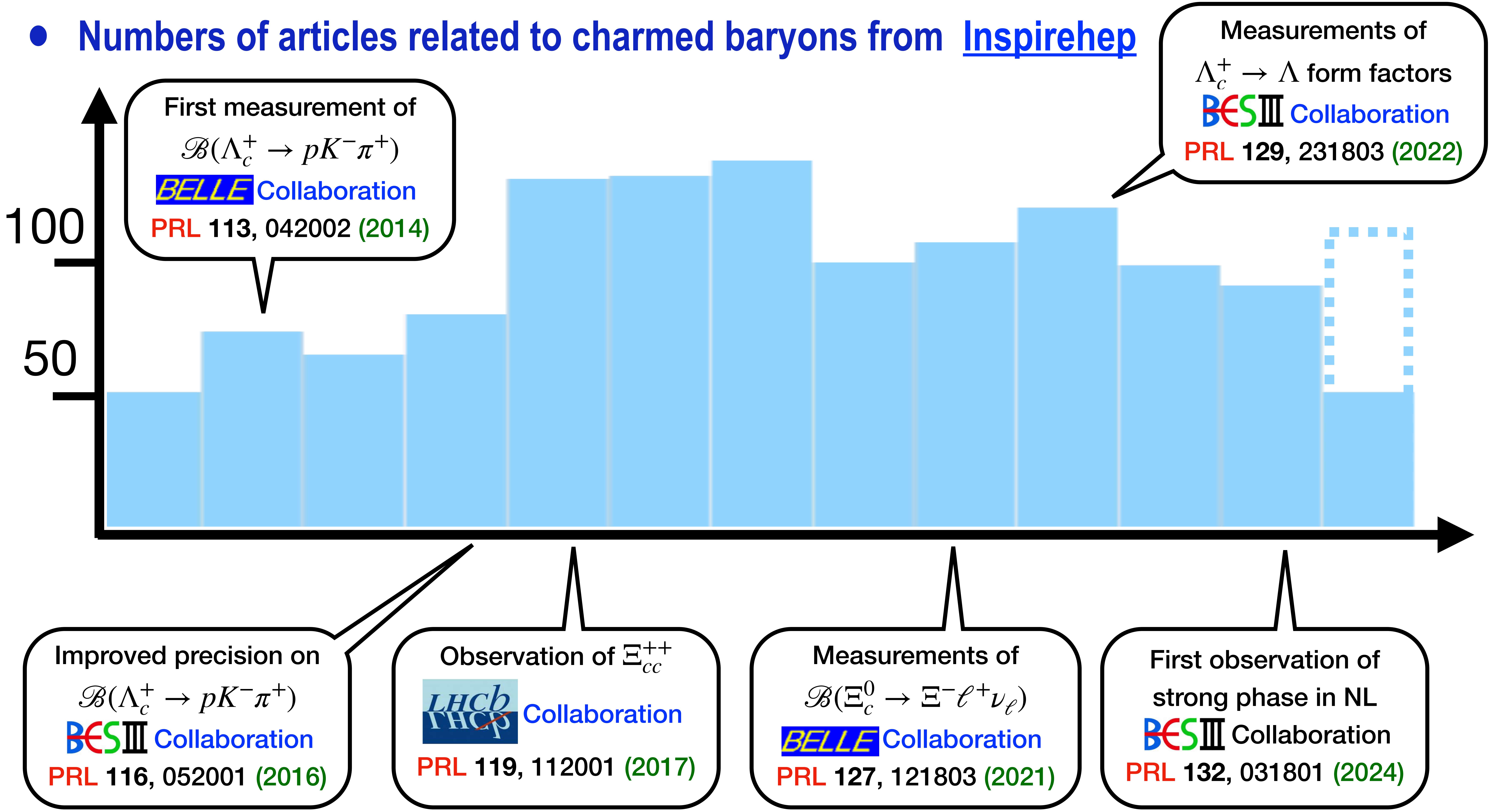
第三届 BESIII Belle II LHCb 粲强子物理联合研讨会

刘 佳 韦

June 28

2025

- Numbers of articles related to charmed baryons from Inspirehep



- Numbers of articles related to charmed baryons from Inspirehep

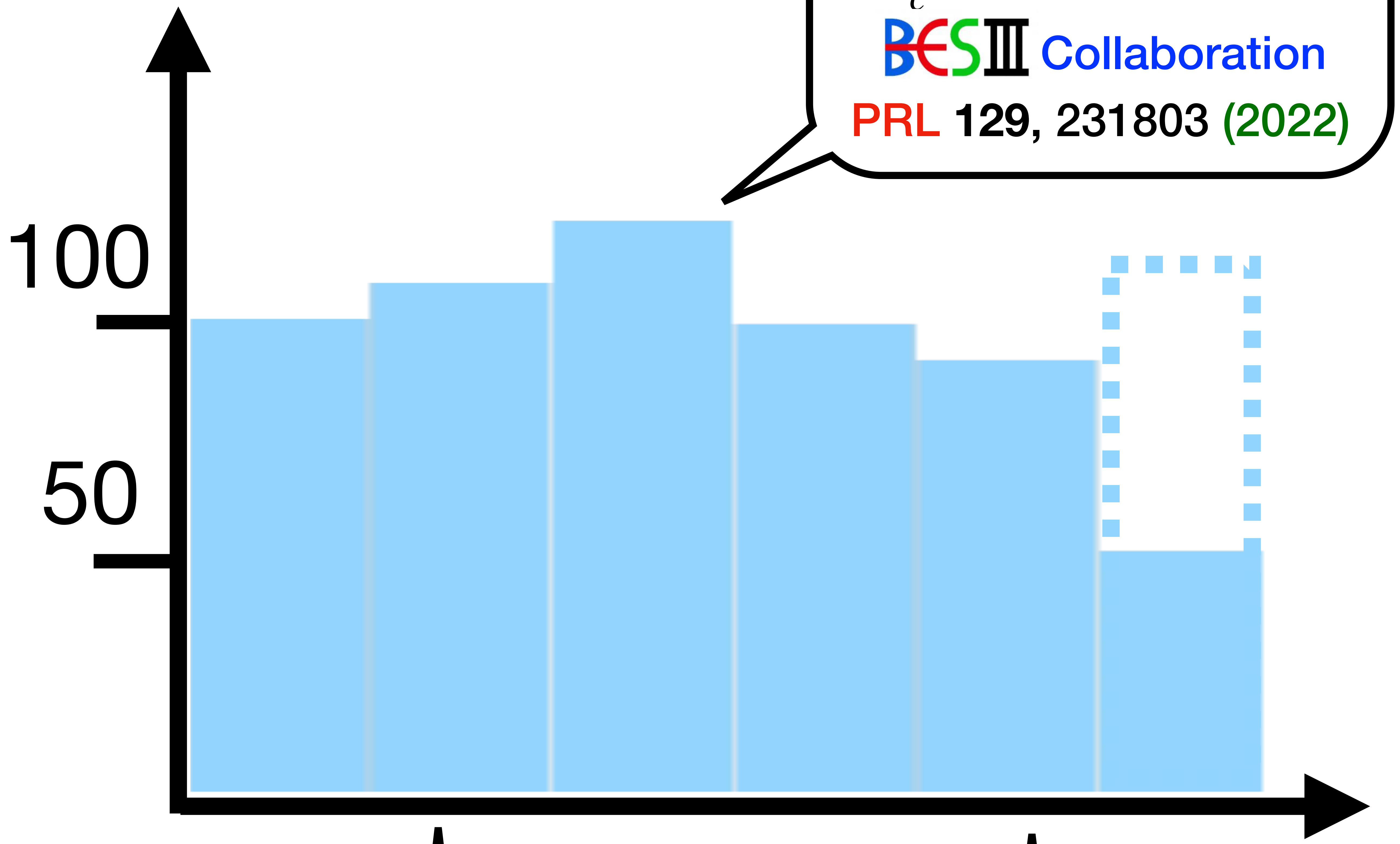
- **Before 2020, studies focus on charmed baryons themselves.**

- **Since 2020, they have been used as tools to examine the standard model !**

In semileptonic decays:
Form factors, Time-reversal asymmetries.

In nonleptonic decays:
CP violation

Measurements of
$\Lambda_c^+ \to \Lambda$ form factors
BESIII Collaboration
PRL **129**, 231803 (2022)



Measurements of
$\mathscr{B}(\Xi_c^0 \to \Xi^- \ell^+ \nu_\ell)$
BELLE Collaboration
PRL **127**, 121803 (2021)

First observation of
strong phase in NL
BESIII Collaboration
PRL **132**, 031801 (2024)

- **Exclusive semileptonic decays**

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

- **Inclusive decays (clue 1)**

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

- **Interactions at hadron level**

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

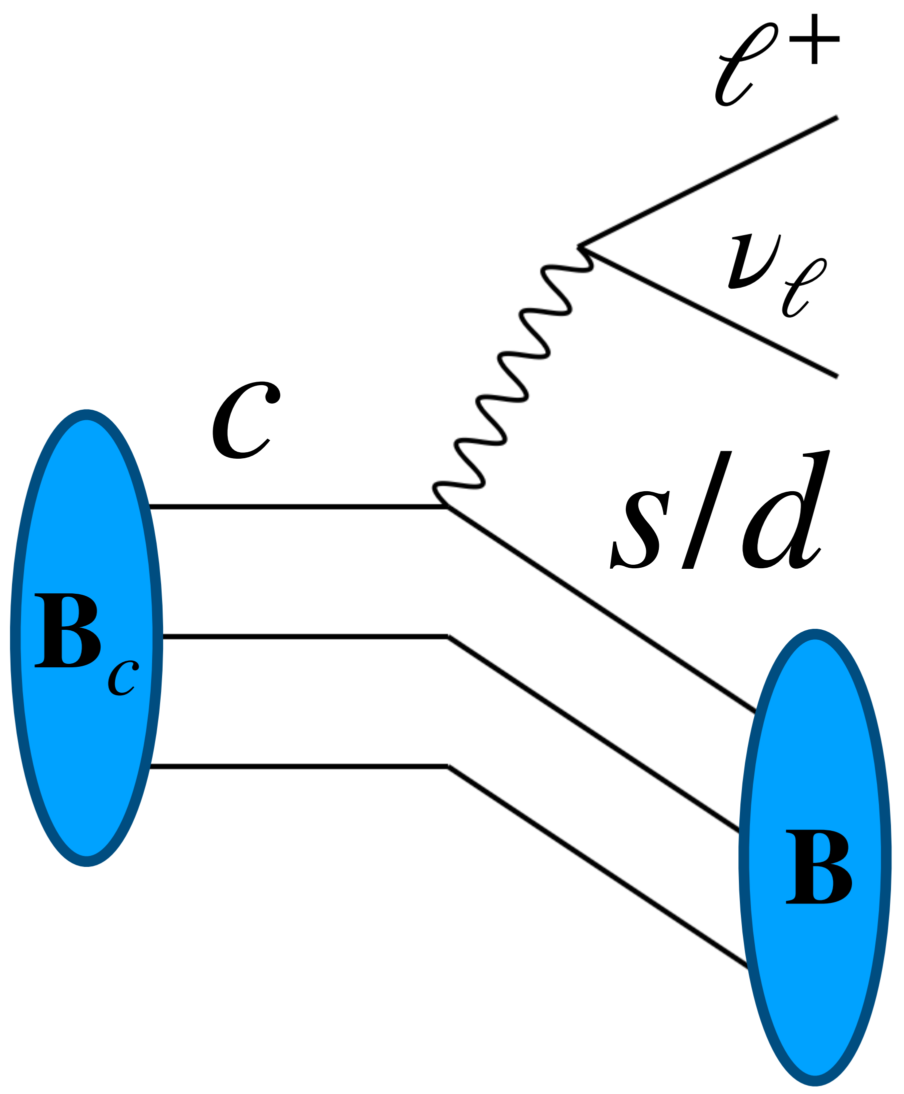
  [2209.00257]

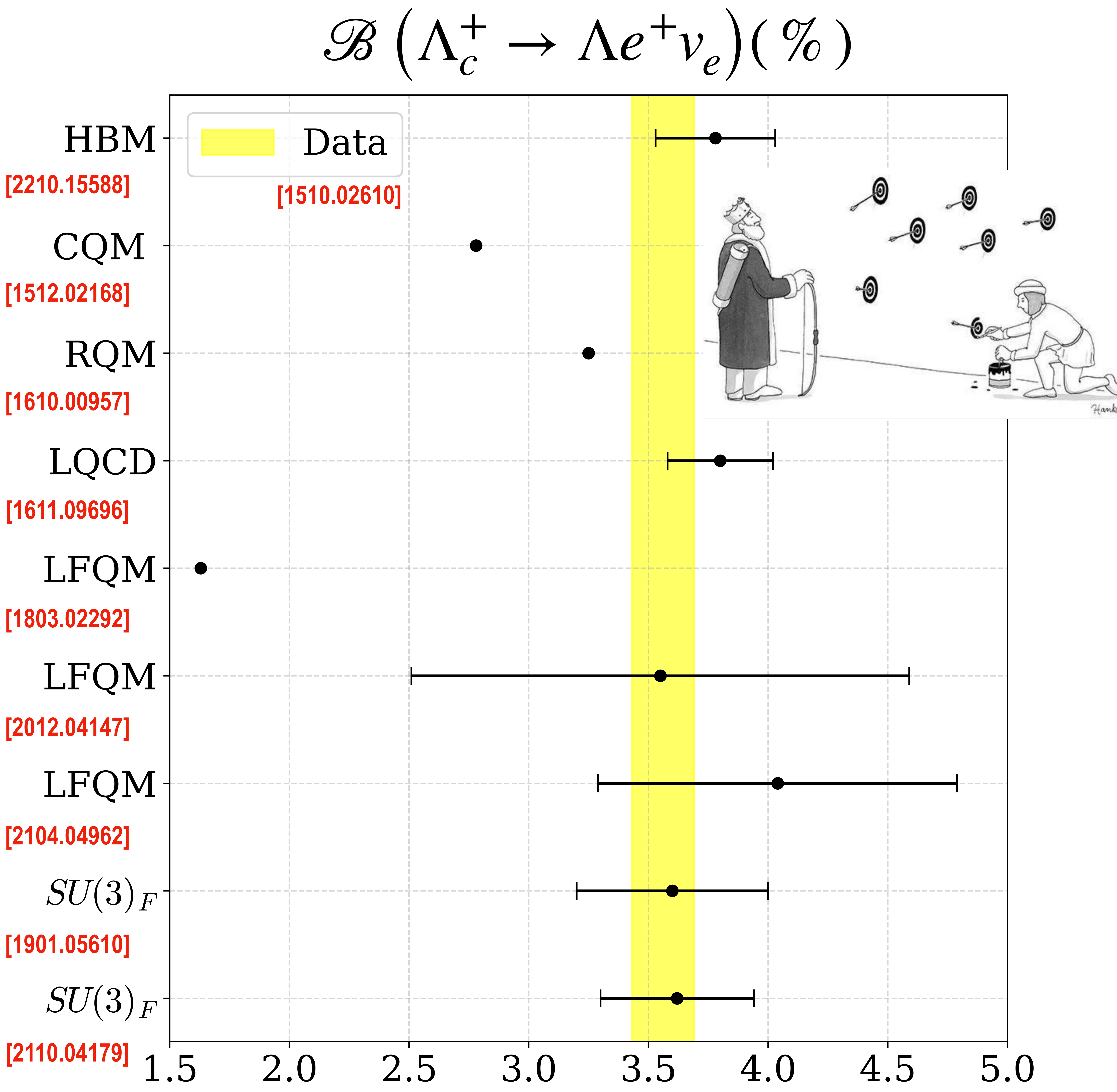
- $SU(3)_F$ **analysis (clue 2)**

  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.





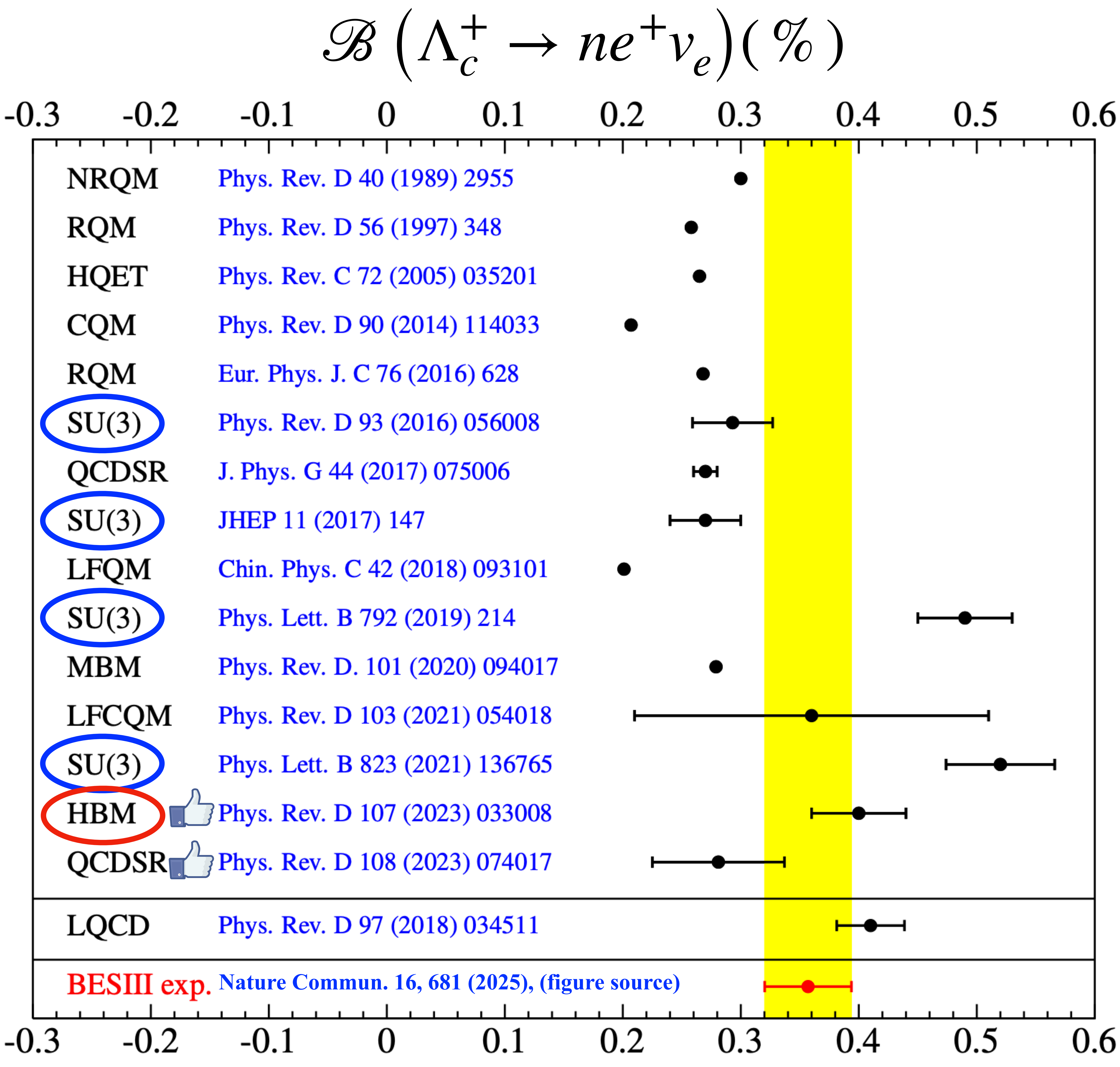
- **Semileptonic decays (exclusive)**

- **Theoretical predictions range widely.**

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

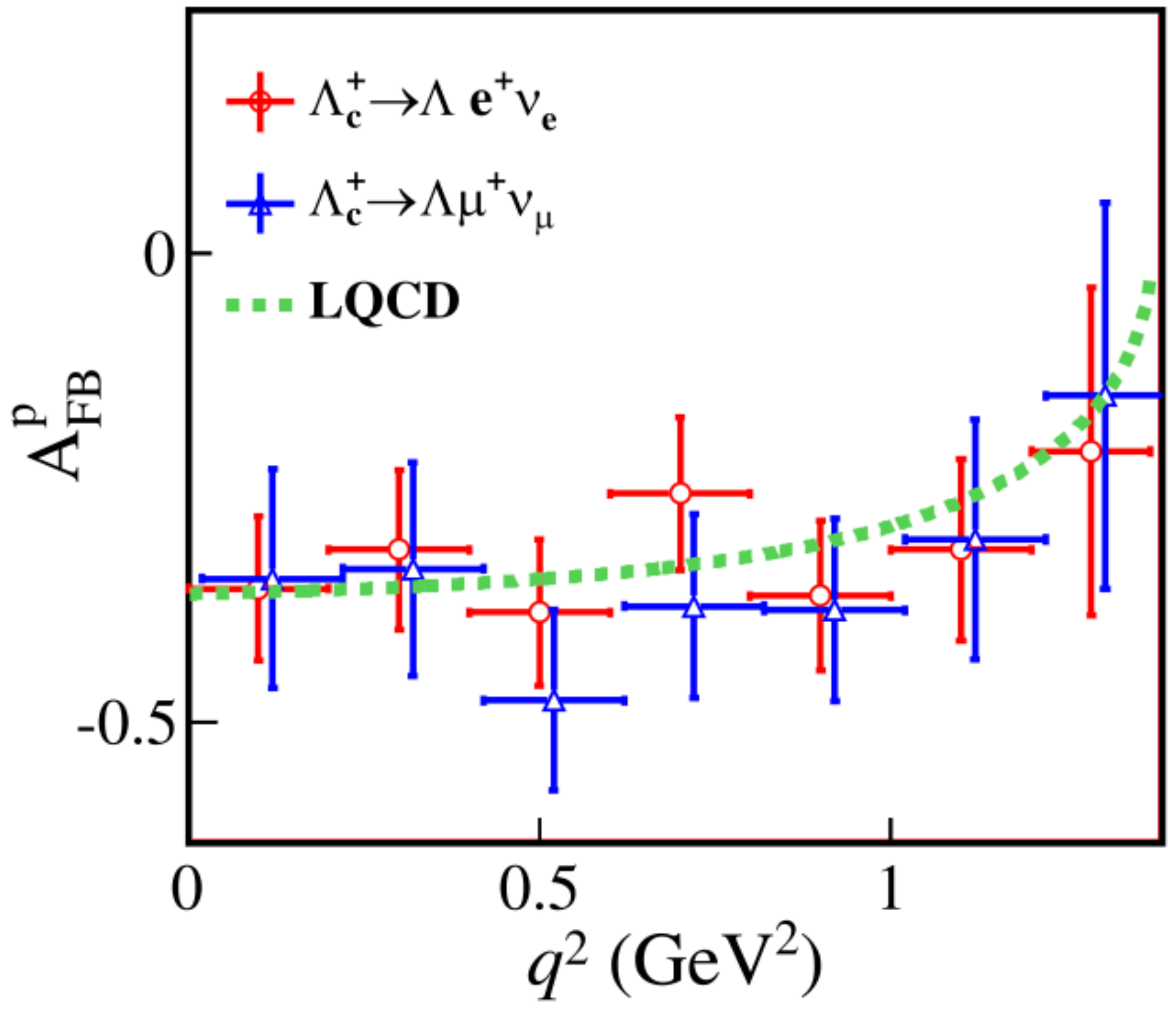
- **Handling of phase space and the running of form factors generate main differences in $SU(3)_F$ analysis.**

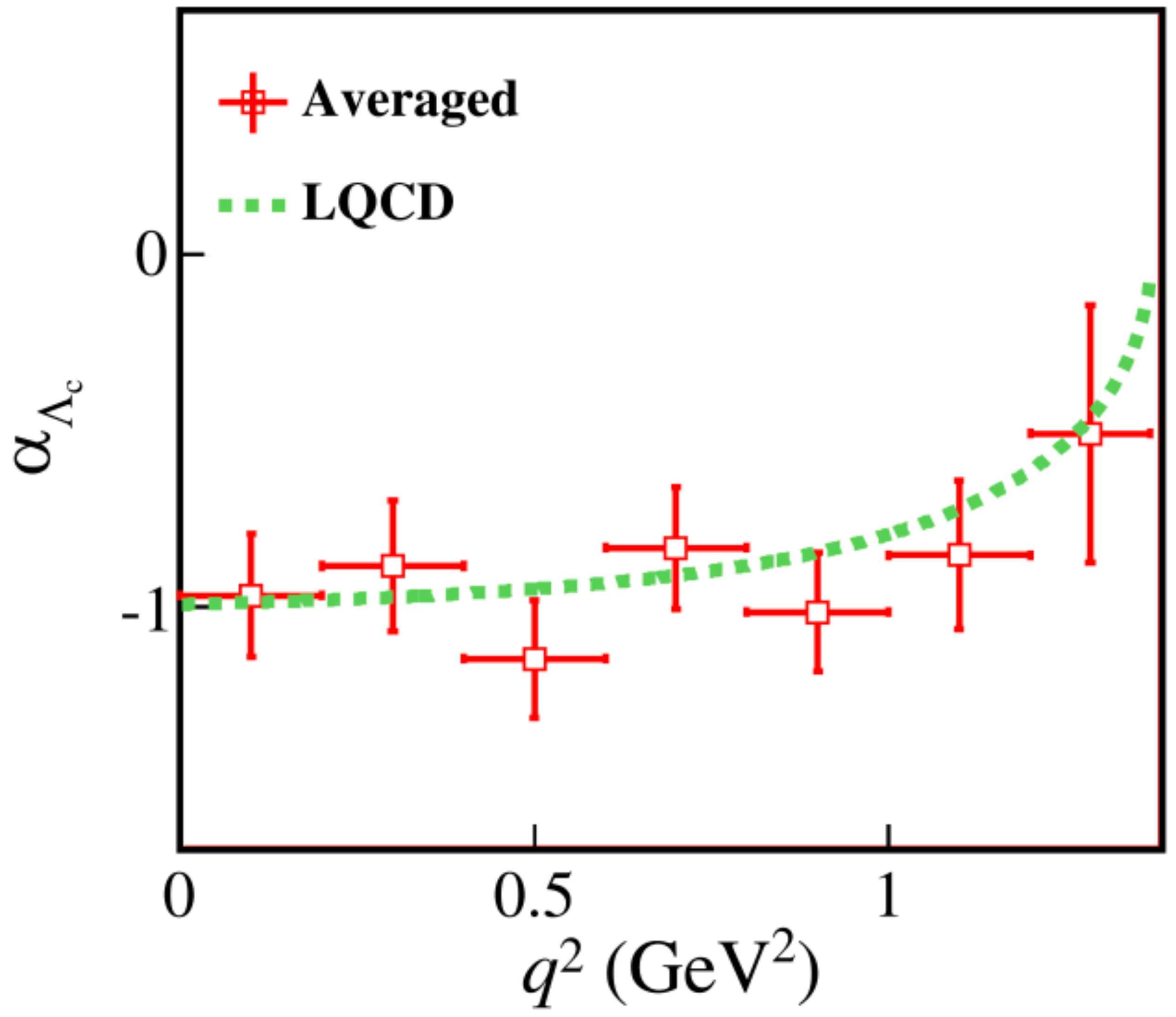
- **$c \to s$ and $c \to d$ can have sizable differences in PS and FFs.**

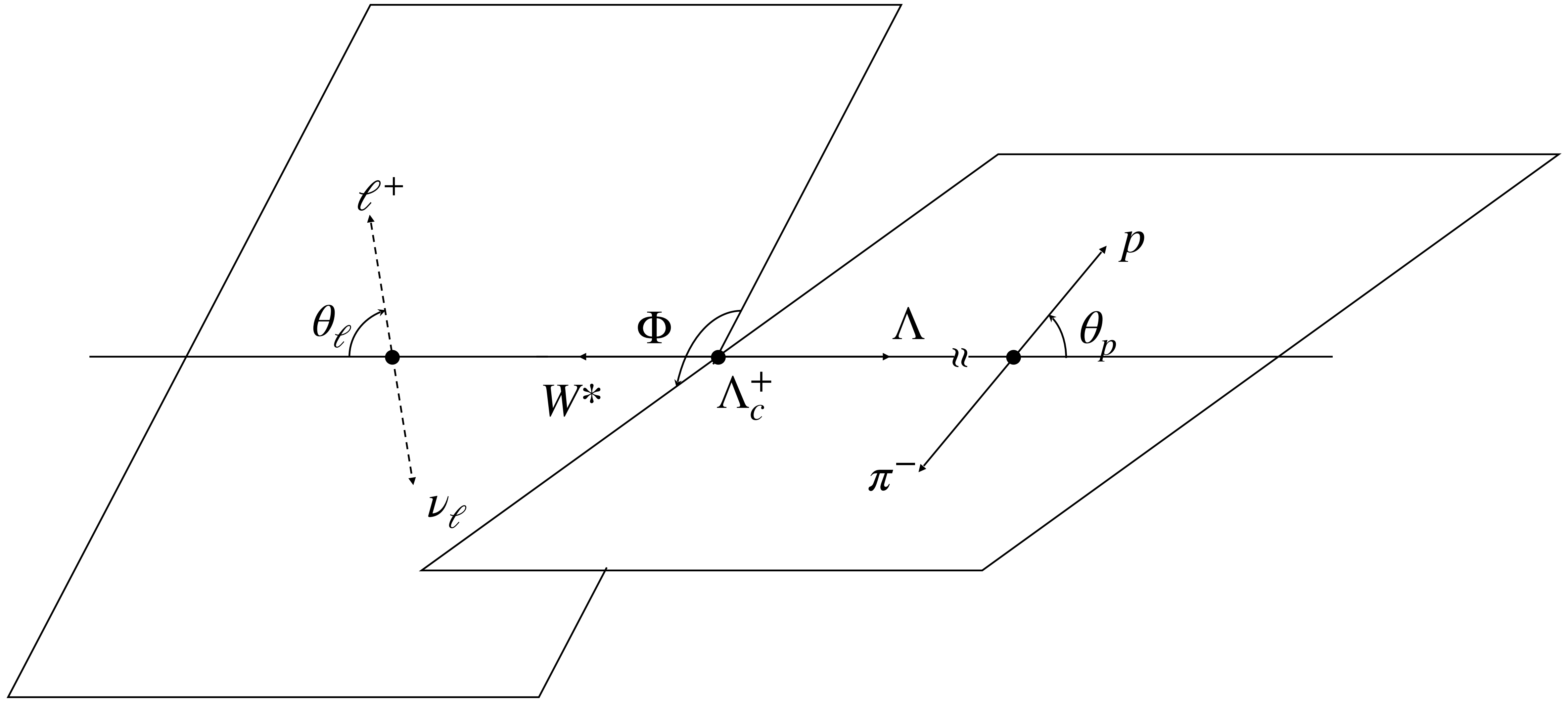


see Dong's talk in this morning

● Semileptonic decays (exclusive)



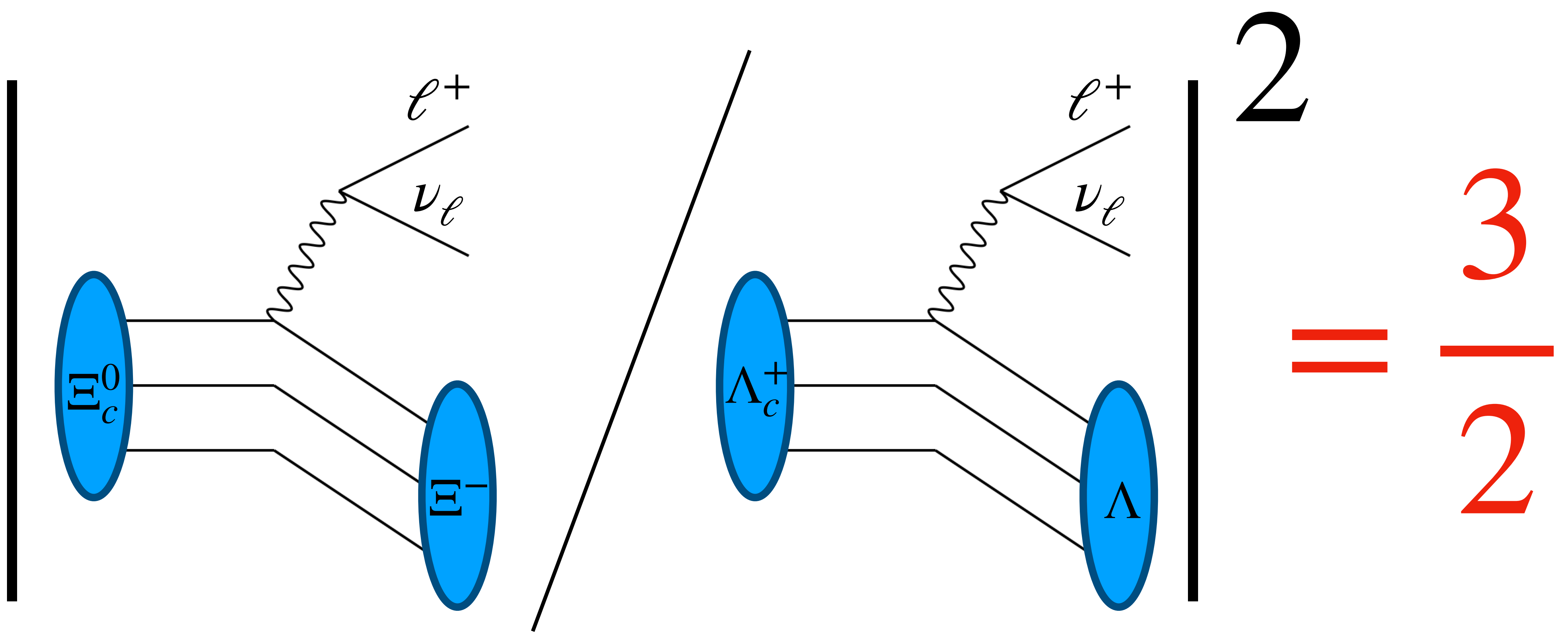




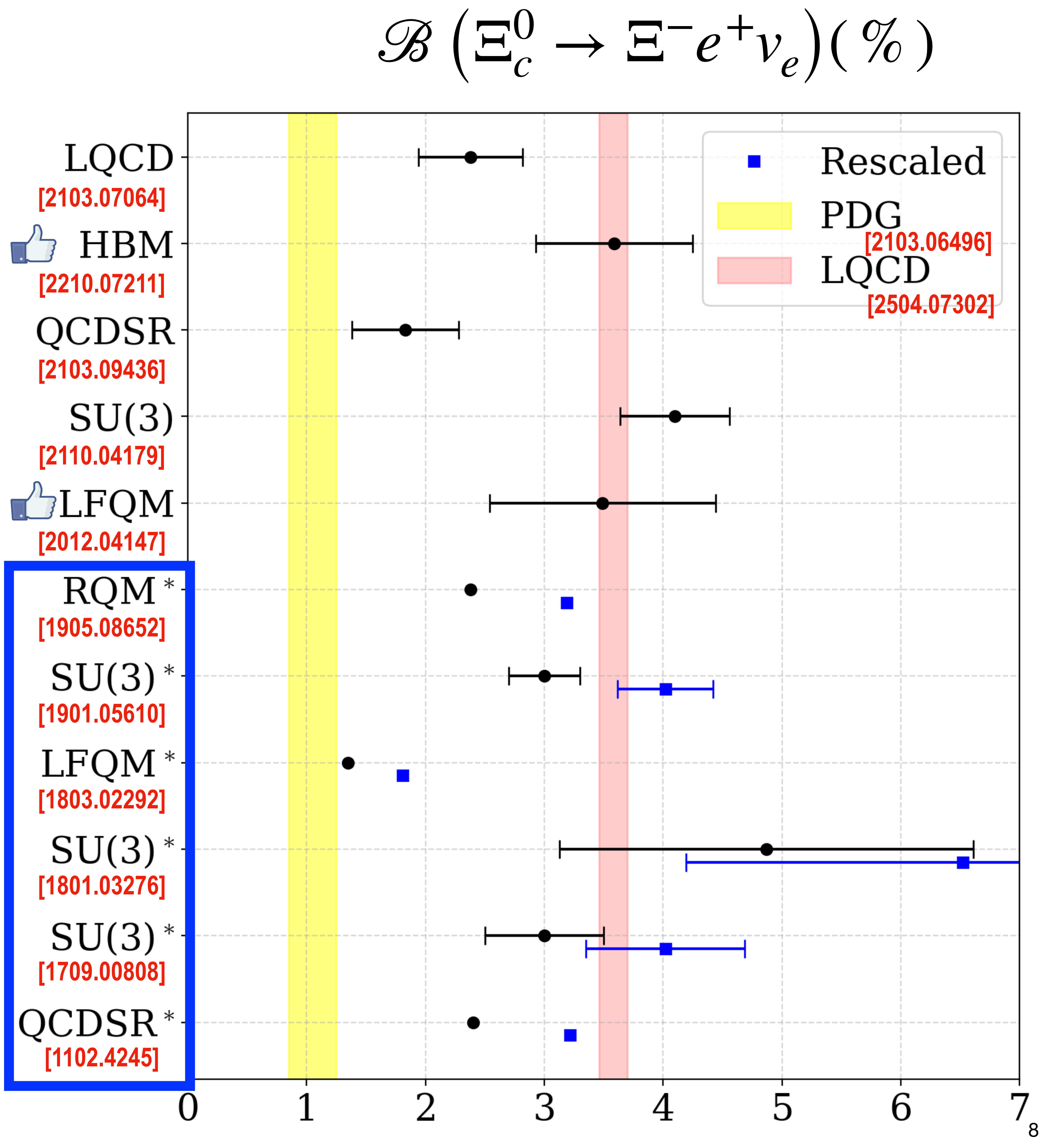
$$\frac{d^4\Gamma}{dq^2 d\cos\theta'_\ell d\cos\theta_p d\chi} = \frac{G_F^2|V_{cs}|^2}{2(2\pi)^4} \cdot \frac{Pq^2(1-m_\ell^2/q^2)^2}{24M_{\Lambda_c}^2} \Big\{ \frac{3}{8}(1-\cos\theta'_\ell)^2|H_{\frac{1}{2}1}|^2(1+\alpha_\Lambda\cos\theta_p)$$
$$+\frac{3}{8}(1+\cos\theta'_\ell)^2|H_{-\frac{1}{2}-1}|^2(1-\alpha_\Lambda\cos\theta_p)$$
$$+\frac{3}{4}\sin^2\theta'_\ell[|H_{\frac{1}{2}0}|^2(1+\alpha_\Lambda\cos\theta_p)+|H_{-\frac{1}{2}0}|^2(1-\alpha_\Lambda\cos\theta_p)]+\frac{3}{2\sqrt{2}}\alpha_\Lambda\cos\chi\sin\theta'_\ell\sin\theta_p$$
$$\times[(1-\cos\theta'_\ell)H_{-\frac{1}{2}0}H_{\frac{1}{2}1}+(1+\cos\theta'_\ell)H_{\frac{1}{2}0}H_{-\frac{1}{2}-1}]+\mathcal{H}_{m_\ell^2}\Big\},$$

- **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 for $c \to s$ indicates:



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



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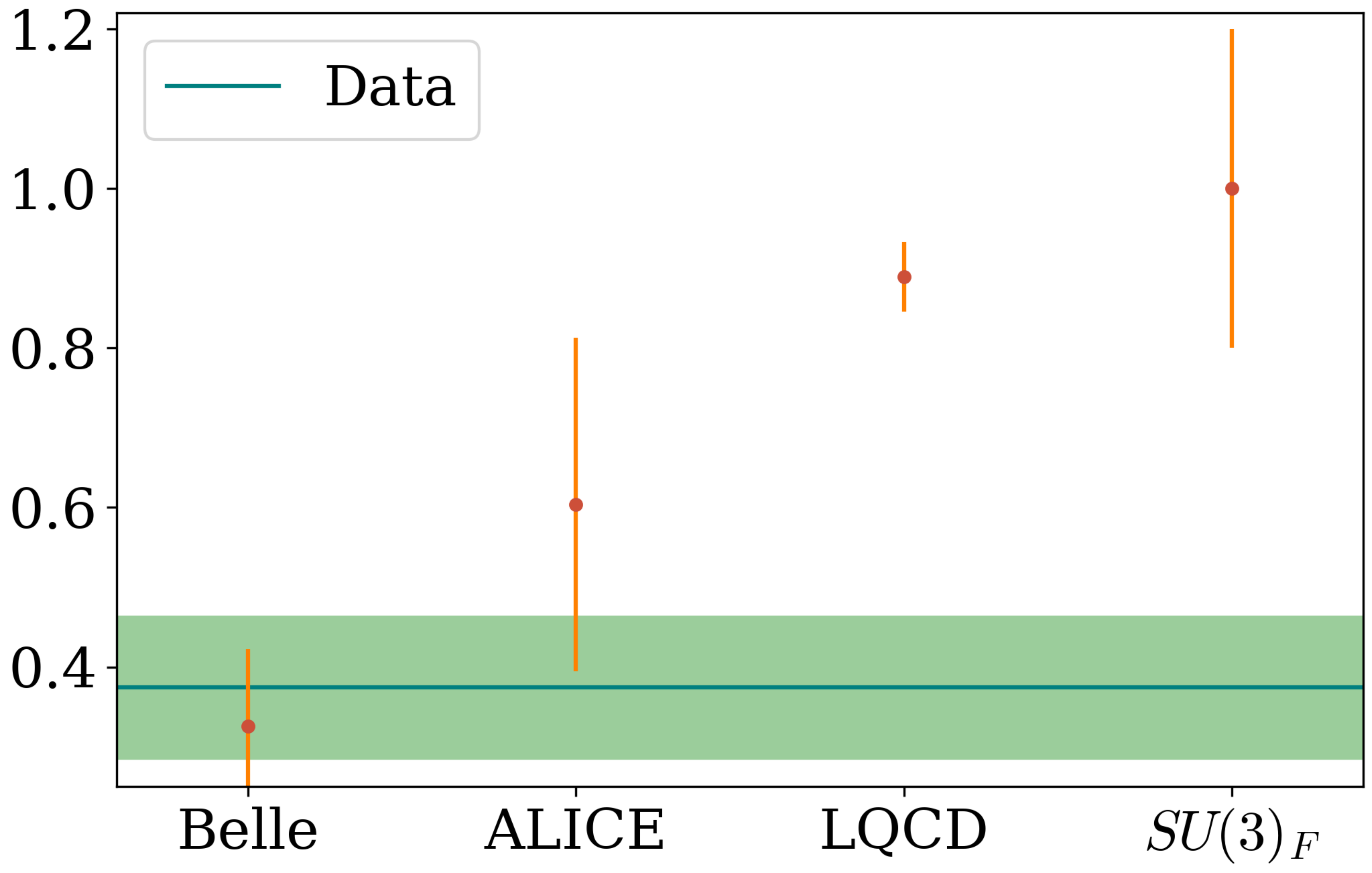
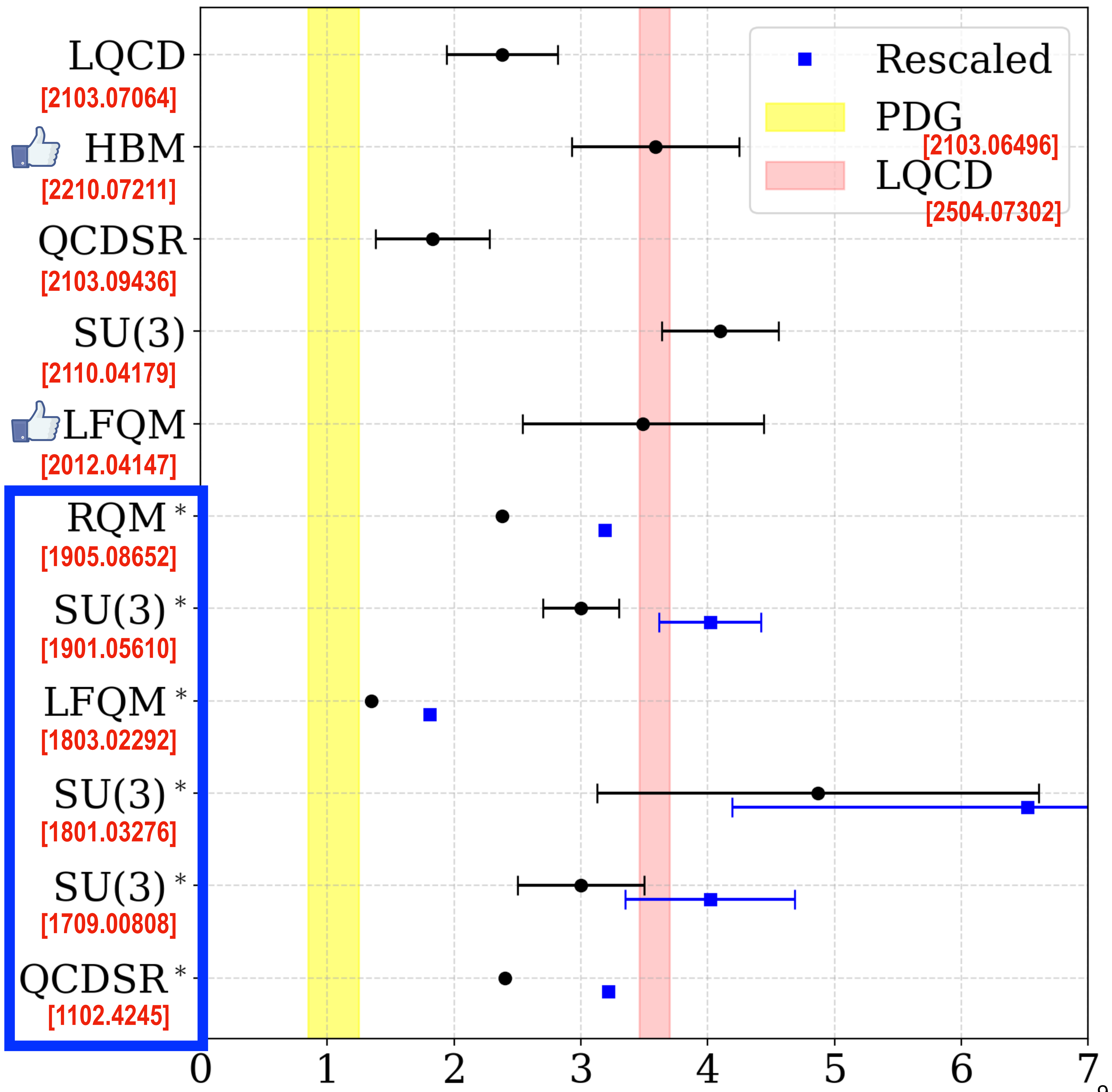


$$\frac{\Gamma(D_s^+ \to \phi e^+ \nu_e)}{\Gamma(D^+ \to \overline{K}^{*0} e^+ \nu_e)} = 0.91 \pm 0.06$$ PDG

$\mathscr{B}\left(\Xi_c^0 \to \Xi^- e^+ \nu_e\right)(\%)$



Semileptonic decays (exclusive)

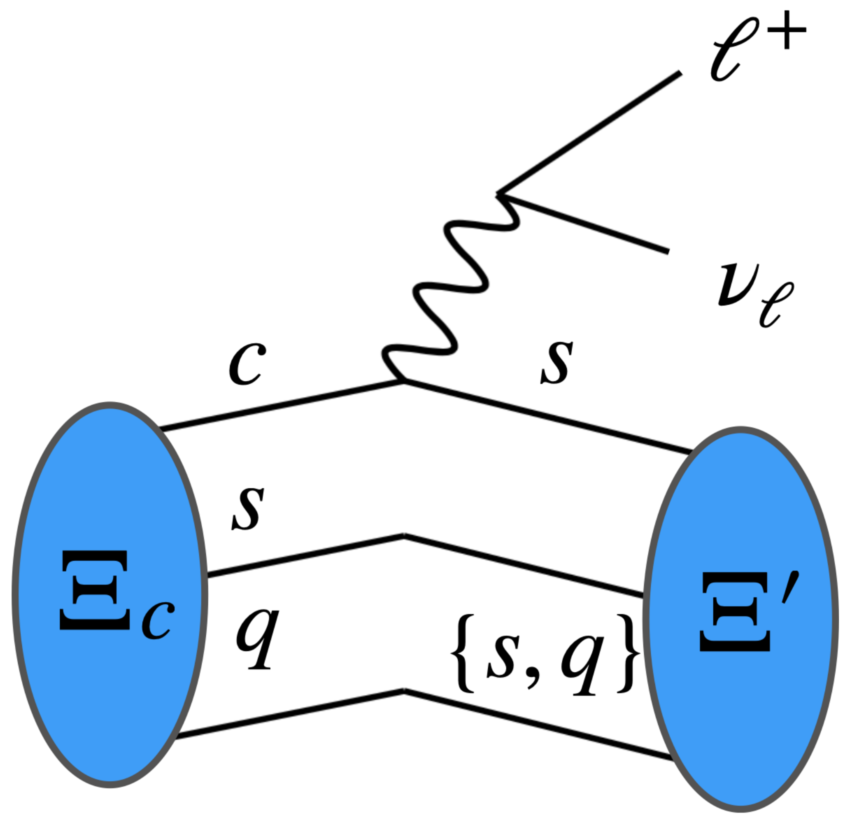
- **Difficult to explain the data with NP with the meson sector unaffected.**
- **A possible explanation:** [2110.04179]

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

- **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]

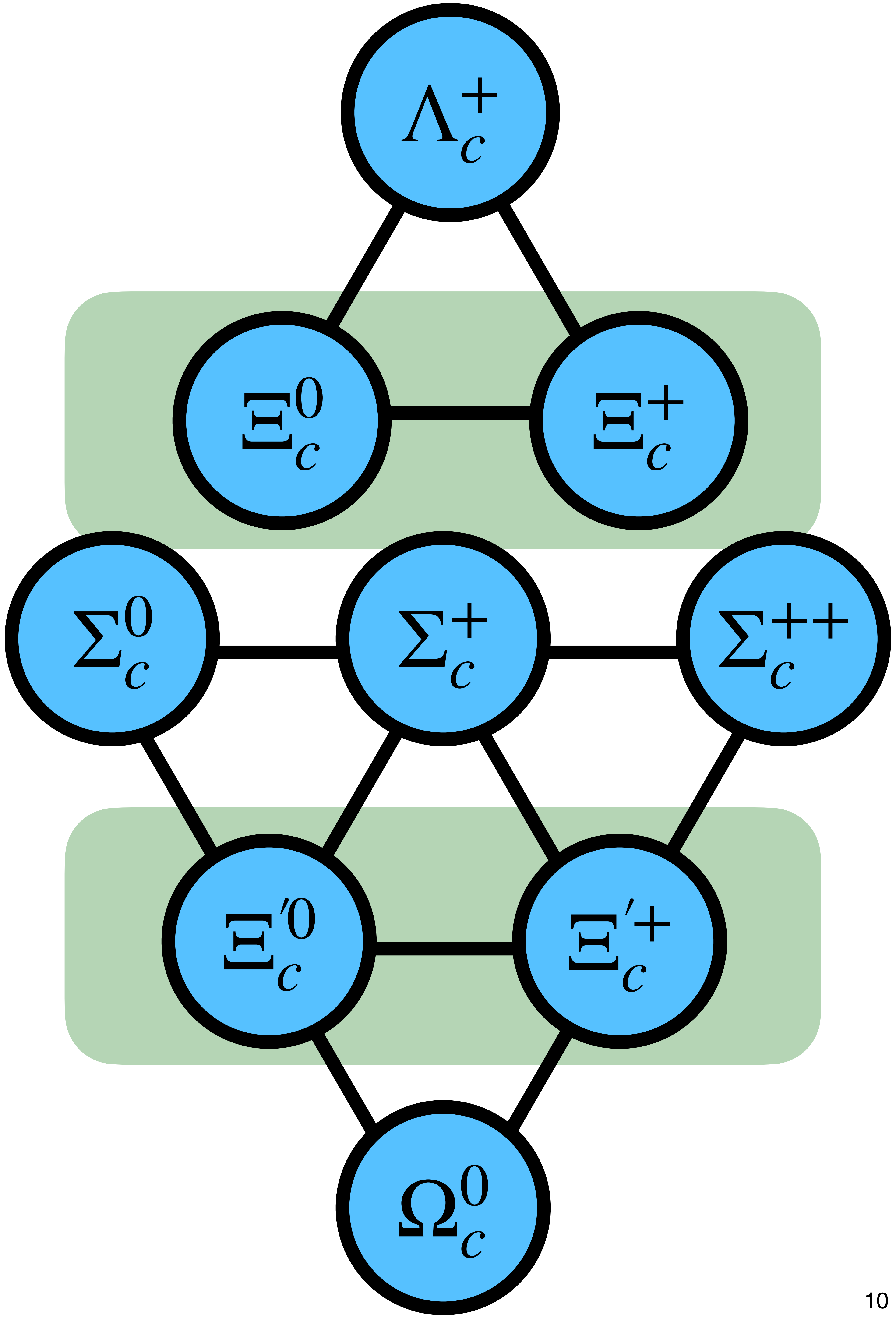
$$\mathscr{B}(\Xi_c^0 \to \Xi'(1520)\ell^+\nu_\ell) \approx 5 \times 10^{-3}$$

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



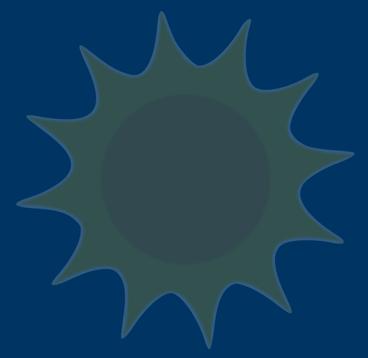
- **Unfortunately, it was soon realized from lattice QCD, sum rules and LFQM that the mixing angle is tiny.**

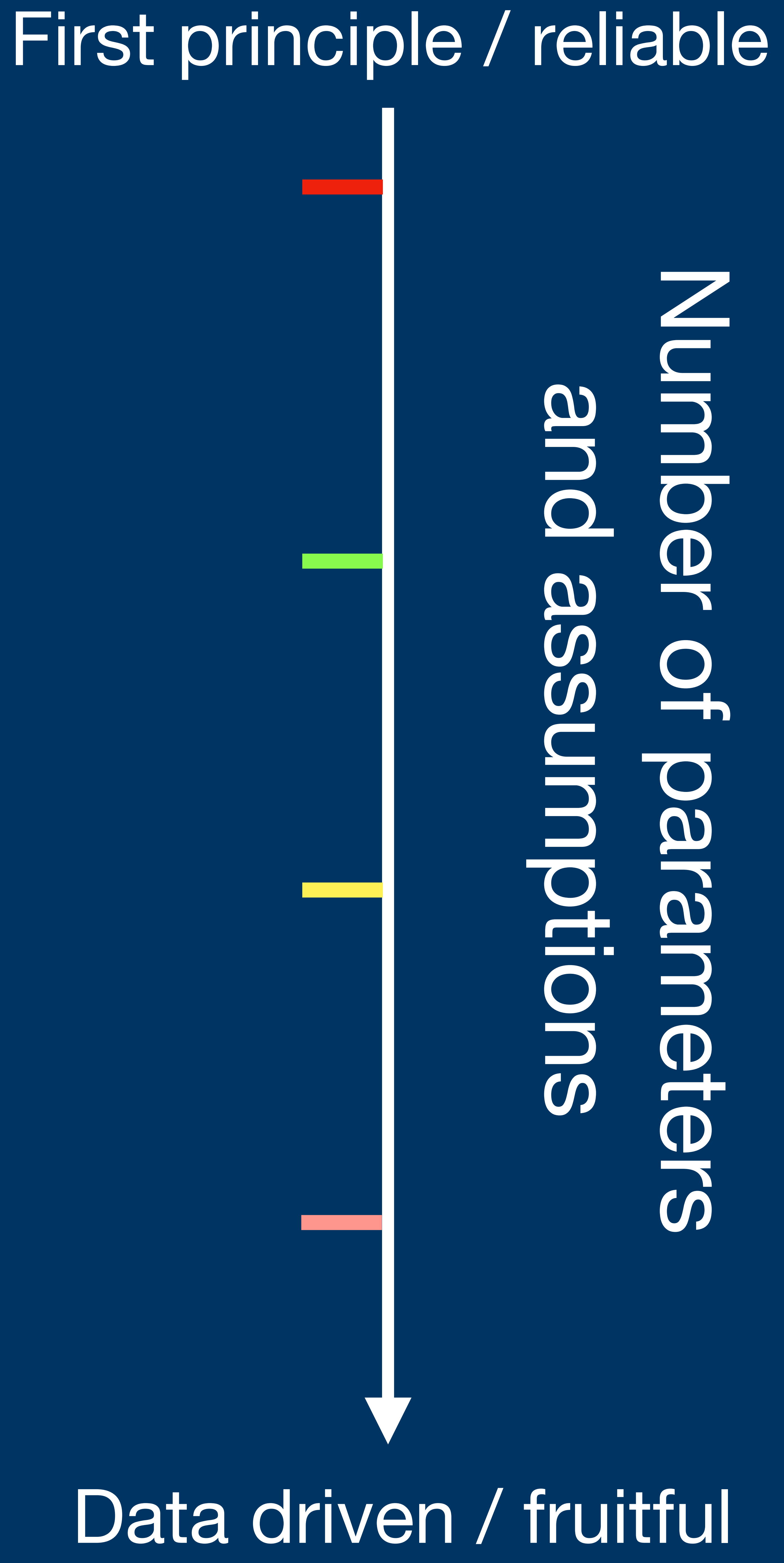
[2103.09436, 2303.17865, 2305.08050, 2309.05432, 2309.16386]



- **Inclusive decays (clue 1)** 

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





• Inclusive decays - theory

Hai-Yang Cheng, March 19, 2018, see the first talk in this morning

	$\Gamma^{\rm dec}$	$\Gamma^{\rm ann}$	$\Gamma^{\rm int}_{-}$	$\Gamma^{\rm int}_{+}$	$\Gamma_{\rm SL}$	$\Gamma^{\rm tot}$	$\tau(10^{-13}s)$	$\tau_{\rm expt}(10^{-13}s)$
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 although the lifetime of Ξ_c^+ as well as its ratio to Λ_c^+ lifetime were largely improved by including dim-7 effects, the predicted Ω_c lifetime becomes the longest one, opposite to the experiment.

LHCb, June 8, 2018

	$\tau(\Xi_c^+)$	$\tau(\Lambda_c^+)$	$\tau(\Xi_c^0)$	$\tau(\Omega_c^0)$
PDG (2004-2018) [10]	442 ± 26	200 ± 6	112^{+13}_{-10}	69 ± 12
LHCb (2018) [12]				268 ± 26
LHCb (2019) [14]	457 ± 6	203.5 ± 2.2	154.5 ± 2.6	
PDG (2020) [11]	456 ± 5	202.4 ± 3.1	153 ± 6	268 ± 26
LHCb (2021) [15]			148.0 ± 3.2	276.5 ± 14.1
World average (2021)	456 ± 5	202.4 ± 3.1	152.0 ± 2.0	274.5 ± 12.4

(The Belle II Collaboration)

We report on a measurement of the Ω_c^0 lifetime using $\Omega_c^0 \to \Omega^- \pi^+$ decays reconstructed in $e^+e^- \to c\bar{c}$ data collected by the Belle II experiment and corresponding to 207 fb^{-1} of integrated luminosity. The result, $\tau(\Omega_c^0) = 243 \pm 48\,(\text{stat}) \pm 11\,(\text{syst})$ fs, agrees with recent measurements indicating that the Ω_c^0 is not the shortest-lived weakly decaying charmed baryon.

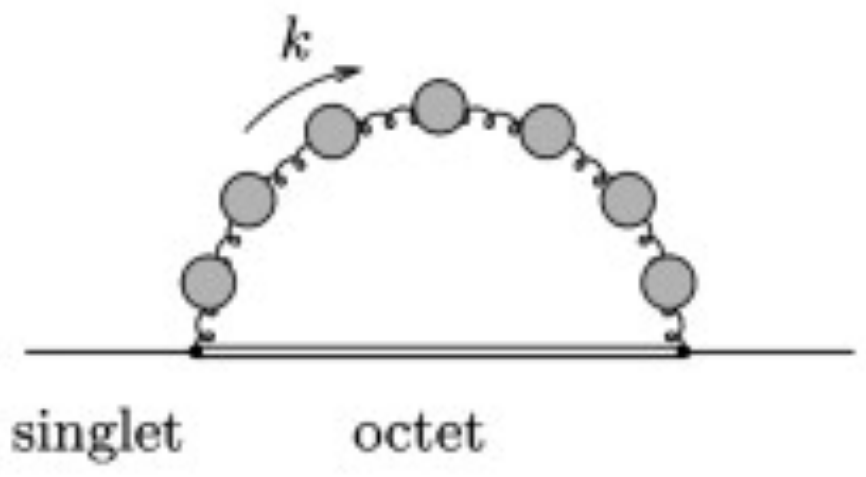
• Inclusive decays - theory

Pole mass, non-perturbative input

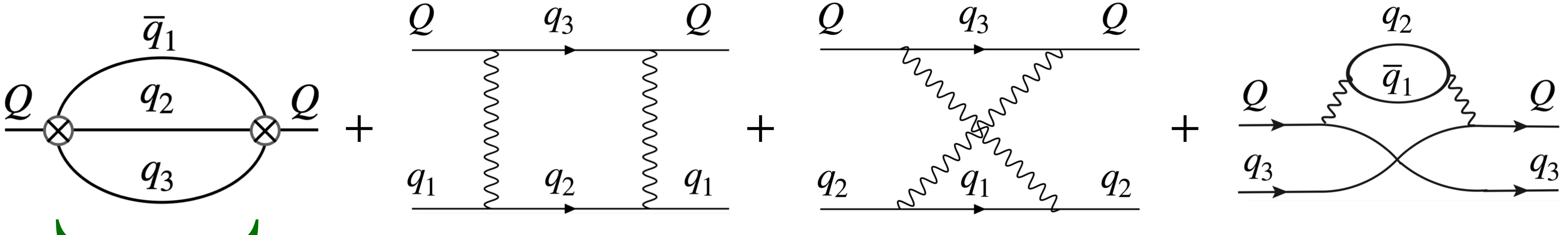
[2502.05901]

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

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



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



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

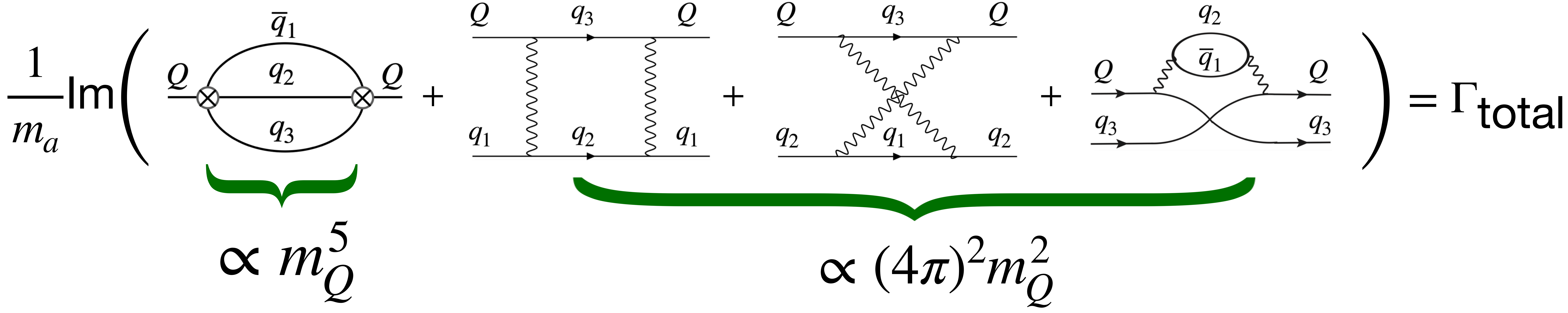
$\propto m_Q^5$ (first diagram) ; $\propto (4\pi)^2 m_Q^2$ (remaining diagrams)

- ## 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.**



Inclusive decays - theory

- Symbolically, the transition operators read:

$$\frac{G_F^2 m_Q^5}{192\pi^3}\xi\left(c_{3,Q}\bar{Q}Q + \frac{c_{5,Q}}{m_Q^2}\bar{Q}\sigma\cdot GQ + \frac{c_{6,Q}}{m_Q^3}T_6 + \frac{c_{7,Q}}{m_Q^4}T_7 + \cdots\right)$$

- In Cabibbo-favored decays, Ξ_c receive dim-6 operators contributions but Λ_c^+ does not!
- Since dim-3 and dim-6 SL operators are in the same sign:

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

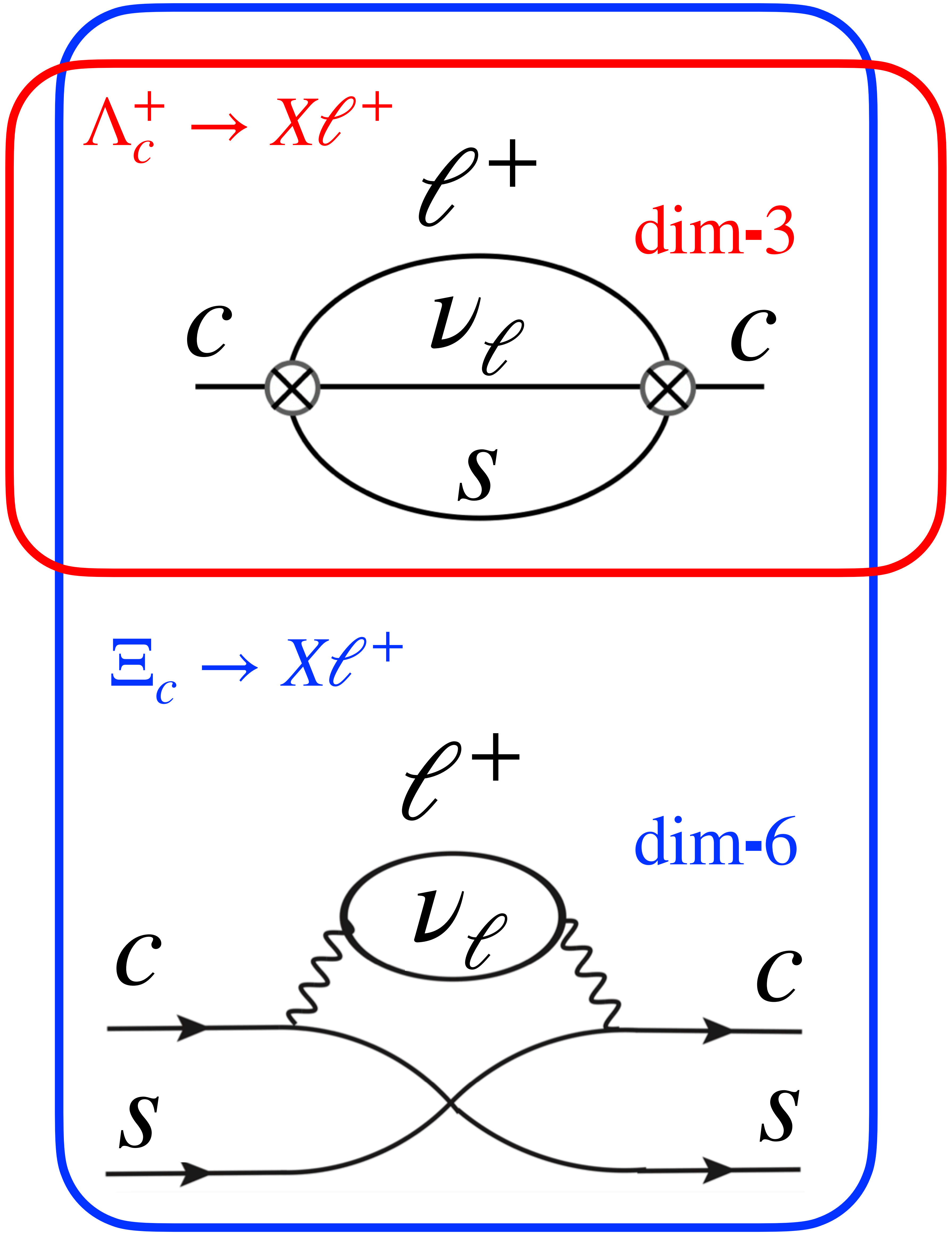
- BESIII reveals the 90% saturation of: [2212.03753]

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

$$\mathcal{B}(\Xi_c^0 \to X\ell^+\nu_\ell) \geq 2.6\,\%$$

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

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



Inclusive decays - numerical results

$$L^q_{\mathcal{B}_Q} \equiv \left\langle \left(Q^\dagger_\alpha L^\mu q_\alpha\right)\left(q^\dagger_\beta L_\mu Q_\beta\right)\right\rangle_{\mathcal{B}_Q}, \qquad \tilde{L}^q_{\mathcal{B}_Q} \equiv \left\langle \left(Q^\dagger_\alpha L^\mu q_\beta\right)\left(q^\dagger_\beta L_\mu Q_\alpha\right)\right\rangle_{\mathcal{B}_Q}$$

$$S^q_{\mathcal{B}_Q} \equiv \left\langle \left(\overline{Q}_\alpha q_\alpha\right)\left(\overline{q}_\beta Q_\beta\right)\right\rangle_{\mathcal{B}_Q}, \qquad \tilde{S}^q_{\mathcal{B}_Q} \equiv \left\langle \left(\overline{Q}_\alpha q_\beta\right)\left(\overline{q}_\beta Q_\alpha\right)\right\rangle_{\mathcal{B}_Q},$$

$$P^q_{\mathcal{B}_Q} \equiv \left\langle \left(\overline{Q}_\alpha \gamma_5 q_\alpha\right)\left(\overline{q}_\beta \gamma_5 Q_\beta\right)\right\rangle_{\mathcal{B}_Q}, \qquad \tilde{P}^q_{\mathcal{B}_Q} \equiv \left\langle \left(\overline{Q}_\alpha \gamma_5 q_\beta\right)\left(\overline{q}_\beta \gamma_5 Q_\alpha\right)\right\rangle_{\mathcal{B}_Q},$$

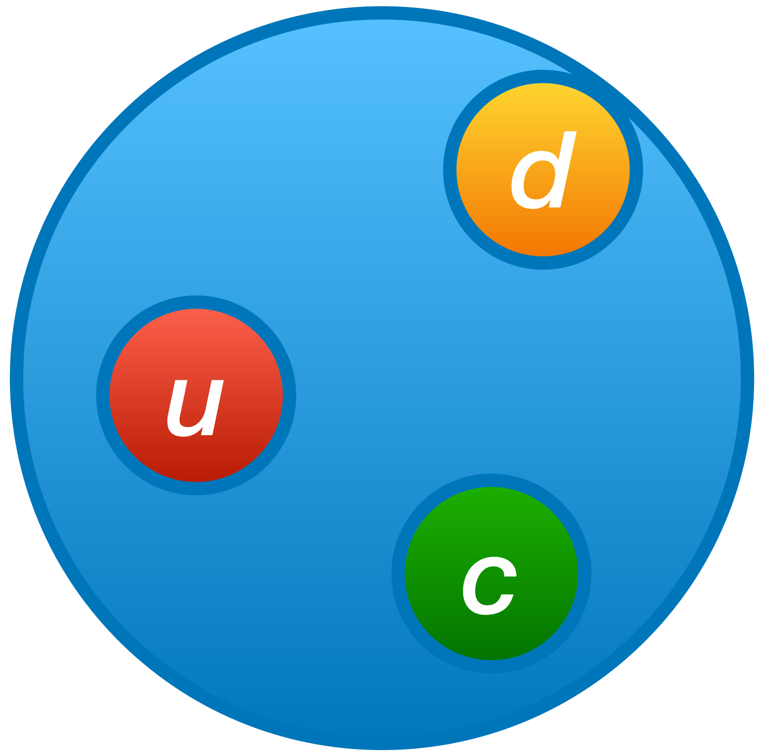
$$L^{q_I}_{\Lambda_b} = -3.2 \pm 1.6 \,\&\, -2.38 \pm 0.11 \pm 0.34 \pm 0.22$$

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 it cannot be 3-momentum eigenstate. Underestimate the 4-quark operator by 2.

• Inclusive decays - numerical results

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

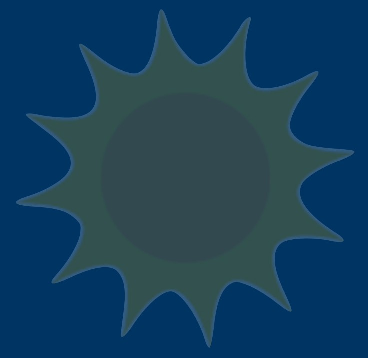
- For Λ_c^+, Ξ_c the **HQE** of $\Gamma_3 > \Gamma_6 > \Gamma_7$ holds but not true for Ω_c.

- The prediction of $\mathscr{B}(\Xi_c^0 \to Xe^+)$ 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 ansatz of **lowest bound-state saturation**.

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

$\mathbf{B}_c$		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]



- $SU(3)_F$ **analysis (clue 2)**

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

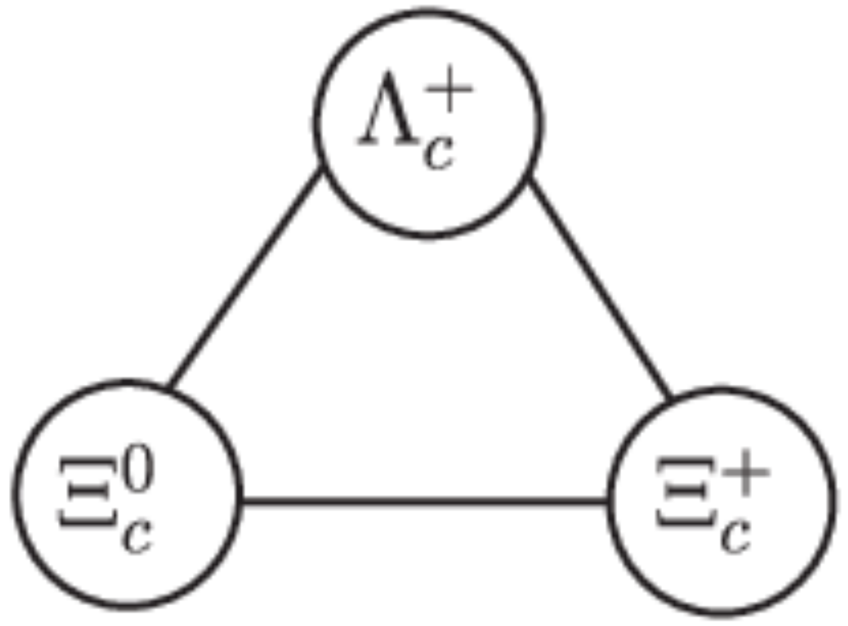
• SU(3) flavor perspective of charmed baryon decays

Murray Gell-Mann 1929-2019

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

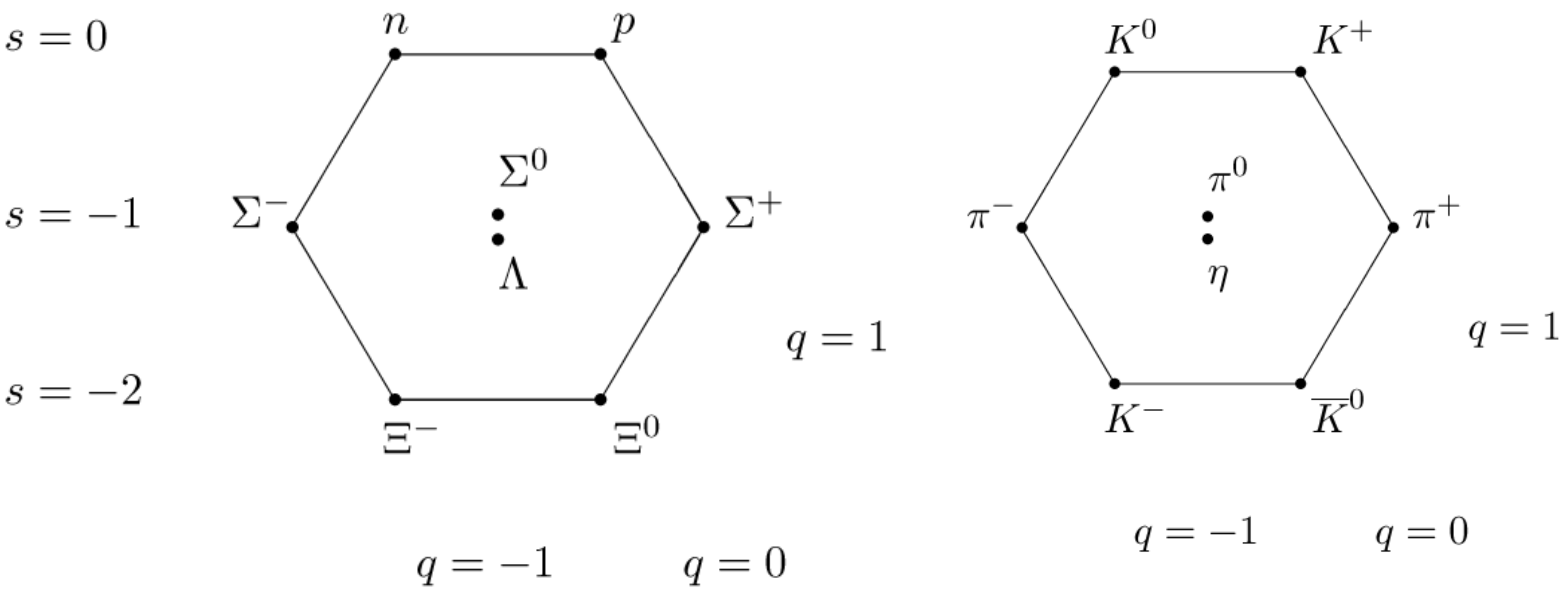
PRD **54**, 2132 (1996), PRD **93**, 056008 (2016), NPB **956**, 115048 (2020)

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

- Predicted **direct relations**: PLB **794**, 19(2019)

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

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

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

PRD **106**, 052003 (2022)

$\mathscr{B}(\Xi_c^0 \to \Xi^0 \pi^0)$ BELLE

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

JHEP **10**, 045 (2024)

- Tests on **predictions** of **global fits** since last year: PRD **109**, 093001; PRD **109**, L071302

	PDG (2023)	Theory (2023)	Data (2025)	
👍 $\alpha(\Lambda_c^+ \to p K_S^0)$	0.18 ± 0.45	-0.40 ± 0.49	-0.744 ± 0.015	LHCb
👍 $10^4 \mathscr{B}(\Lambda_c^+ \to p \pi^0)$	< 0.8	1.6 ± 0.2	1.79 ± 0.41	BESIII
👍 $10^3 \mathscr{B}(\Lambda_c^+ \to \Lambda K_S^0 \pi^+)$	None	1.97 ± 0.38	1.73 ± 0.28	BESIII
👍 $10^3 \mathscr{B}(\Xi_c^0 \to \Xi^0 \eta)$	None	2.94 ± 0.97	1.6 ± 0.5	BELLE
😭 $10^3 \mathscr{B}(\Xi_c^0 \to \Xi^0 \eta')$	None	5.66 ± 0.93	1.2 ± 0.4	BELLE

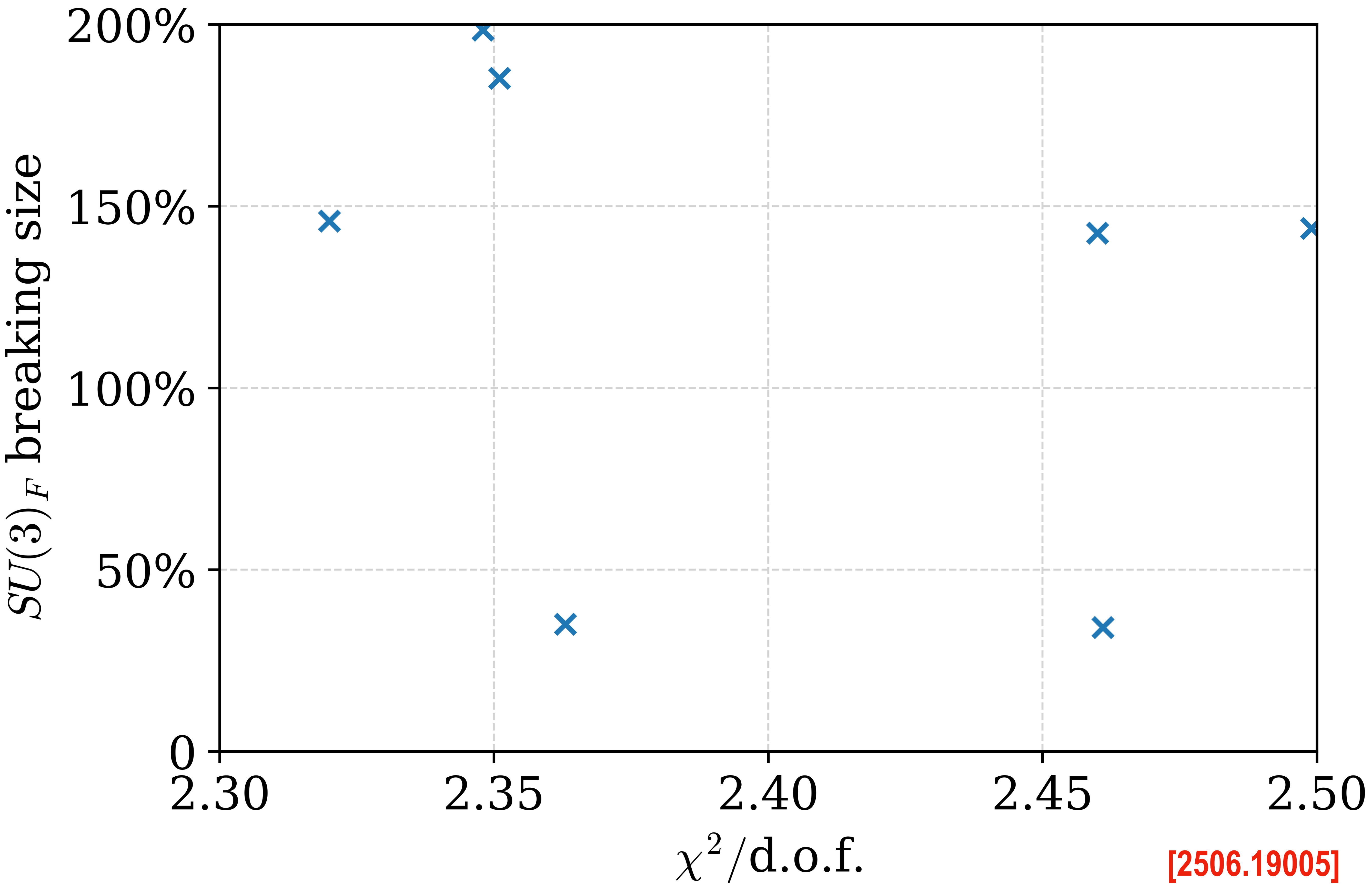
There are some ***shortcomings*** in $SU(3)_F$ symmetry approach.

see Li's talk in this morning

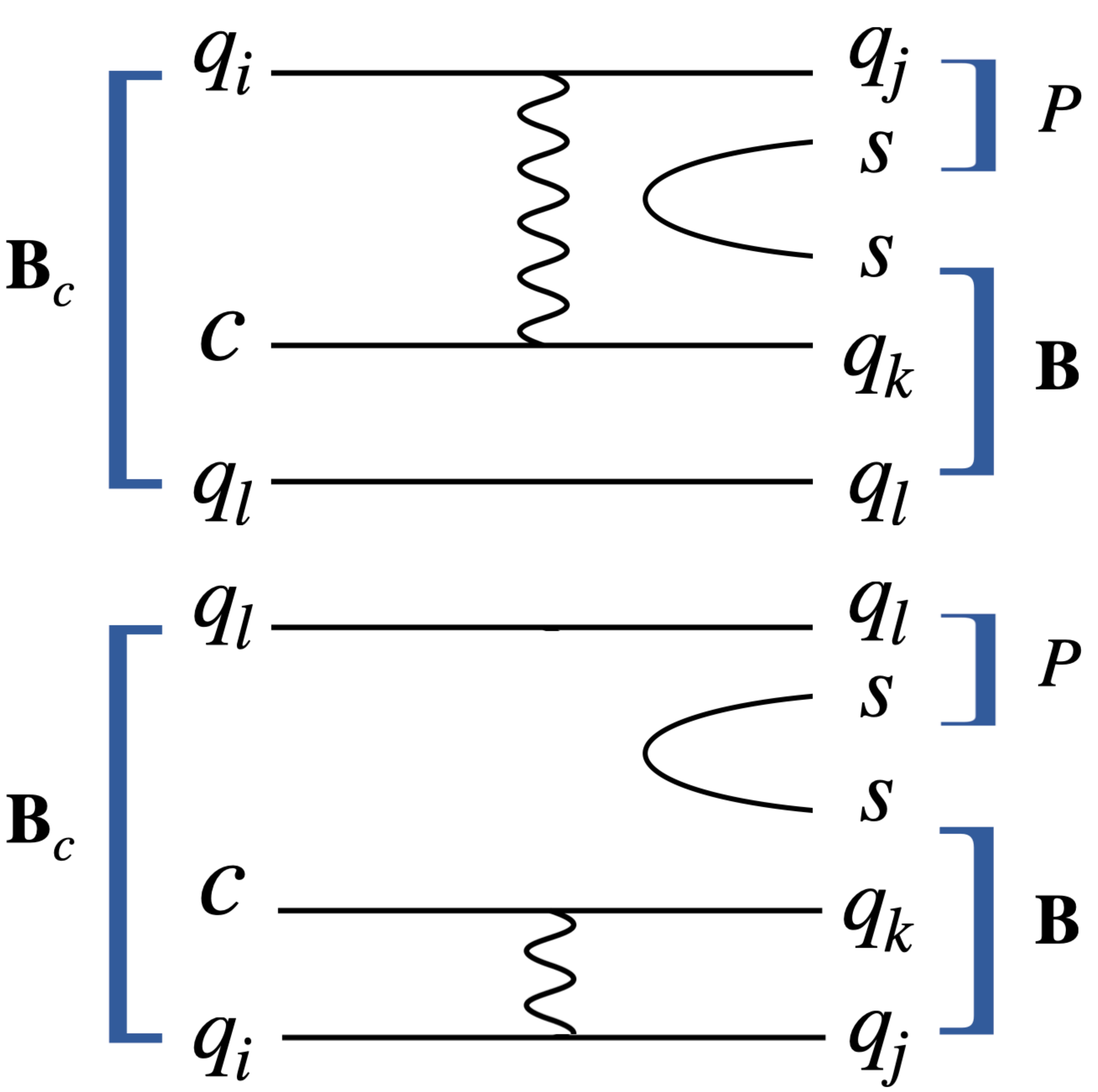
SU(3) flavor perspective of charmed baryon decays

The $SU(3)_F$ is an approximate symmetry with errors in 10^{-1}.

We propose a new scenario that incorporates the $SU(3)_F$ breaking of strange quark pair production from the vacuum.



[2506.19005]



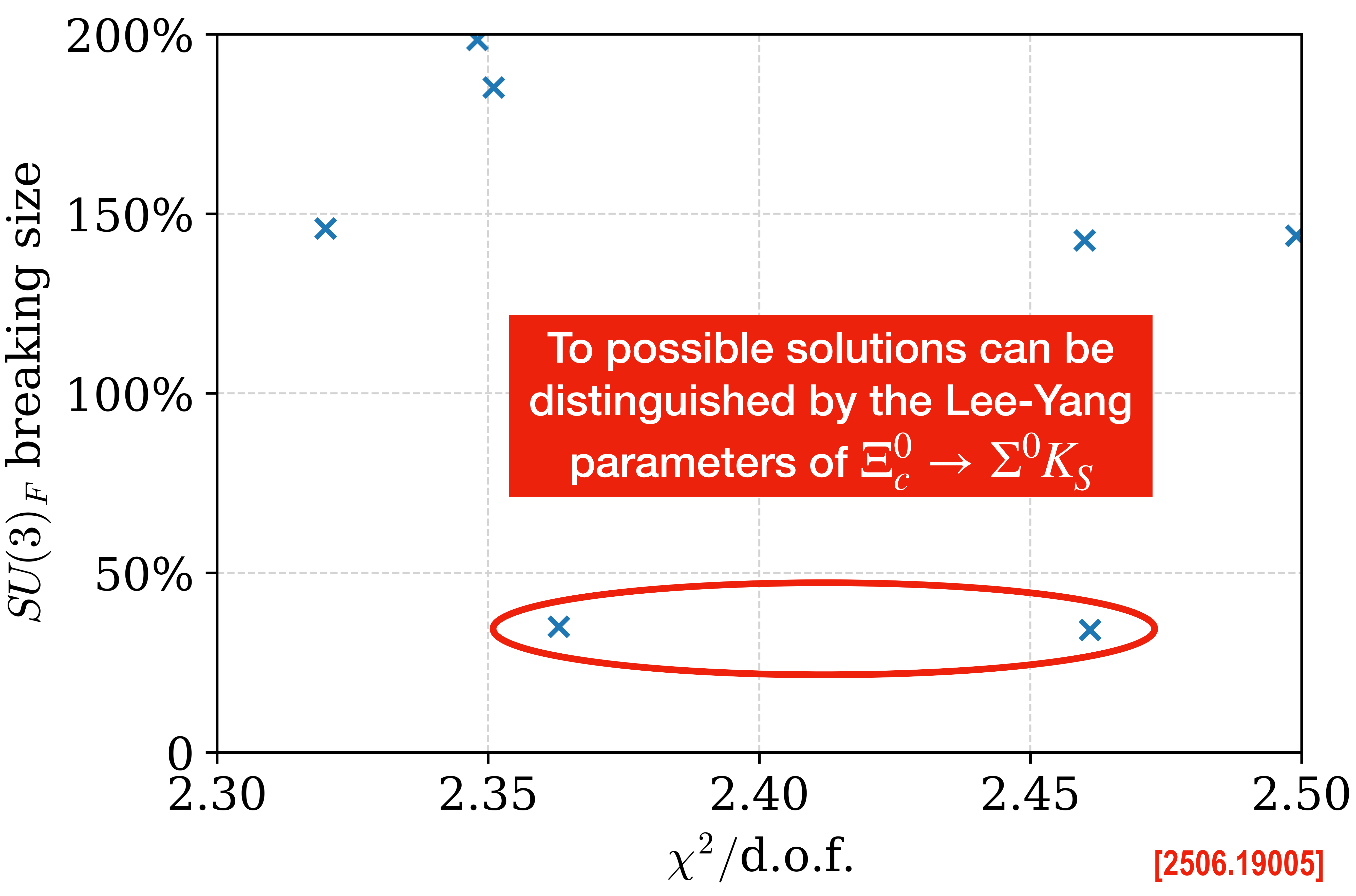
$m_s^{-2} : m_d^{-2} \approx 1 : 2$

(constituent quark masses)

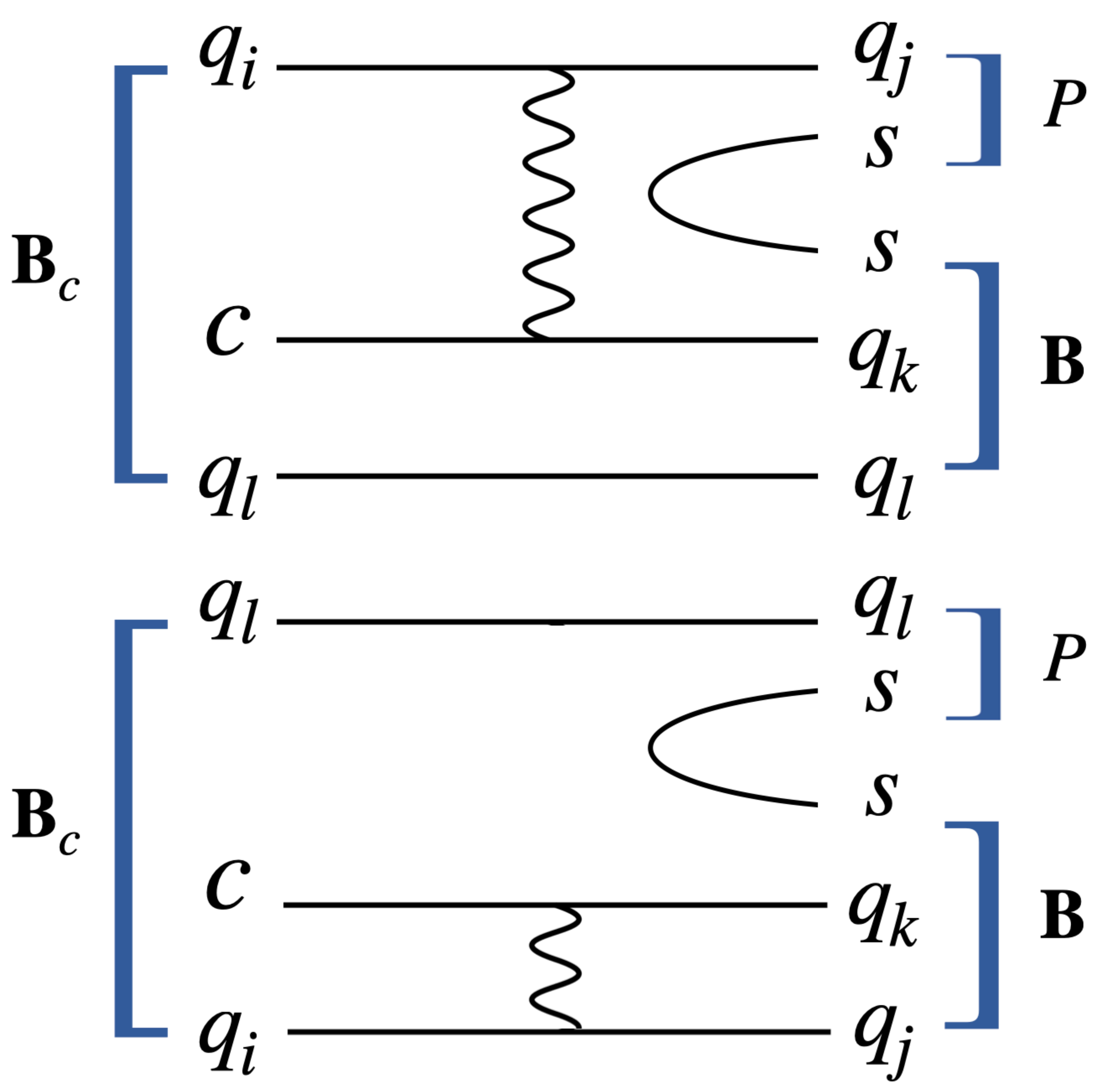
• SU(3) flavor perspective of charmed baryon decays

The $SU(3)_F$ is an approximate symmetry with errors in 10^{-1}.

We propose a new scenario that incorporates the $SU(3)_F$ breaking of strange quark pair production from the vacuum.



[2506.19005]



$m_s^{-2} : m_d^{-2} \approx 1 : 2$

(constituent quark masses)

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]
$10^2\mathscr{B}(\Xi_c^0 \to \Xi^-\pi^+)$	1.43 ± 0.32	2.72 ± 0.09	2.9 ± 0.1
$10^2\mathscr{B}(\Xi_c^+ \to \Xi^-\pi^+\pi^+)$	2.9 ± 1.3	6.82 ± 0.36	6.0 ± 0.4

Both of them are the normalized channels in $\Xi_c^{0,+}$, indicating an possible underestimation of factor two in the experimental side.

Same underestimations occurs in $\Xi_c^0 \to \Xi^-\ell^+\nu_\ell$.

	PDG	$SU(3)_F$	Lattice	Lattice
$10^2\mathscr{B}(\Xi_c^0 \to \Xi^-e^+\nu_e)$	1.05 ± 0.20*	4.10 ± 0.46	2.38 ± 0.44	3.58 ± 0.12
$10^2\mathscr{B}(\Xi_c^0 \to \Xi^-\mu^+\nu_\mu)$	1.02 ± 0.21*	3.98 ± 0.57	2.29 ± 0.42	3.47 ± 0.12
		[2110.04179]	[2103.07064]	[2504.07302]

*Using $\mathscr{B}(\Xi_c^0 \to \Xi^-\pi^+) = (1.42 \pm 0.32)\,\%$

SU(3) flavor perspective of charmed baryon decays

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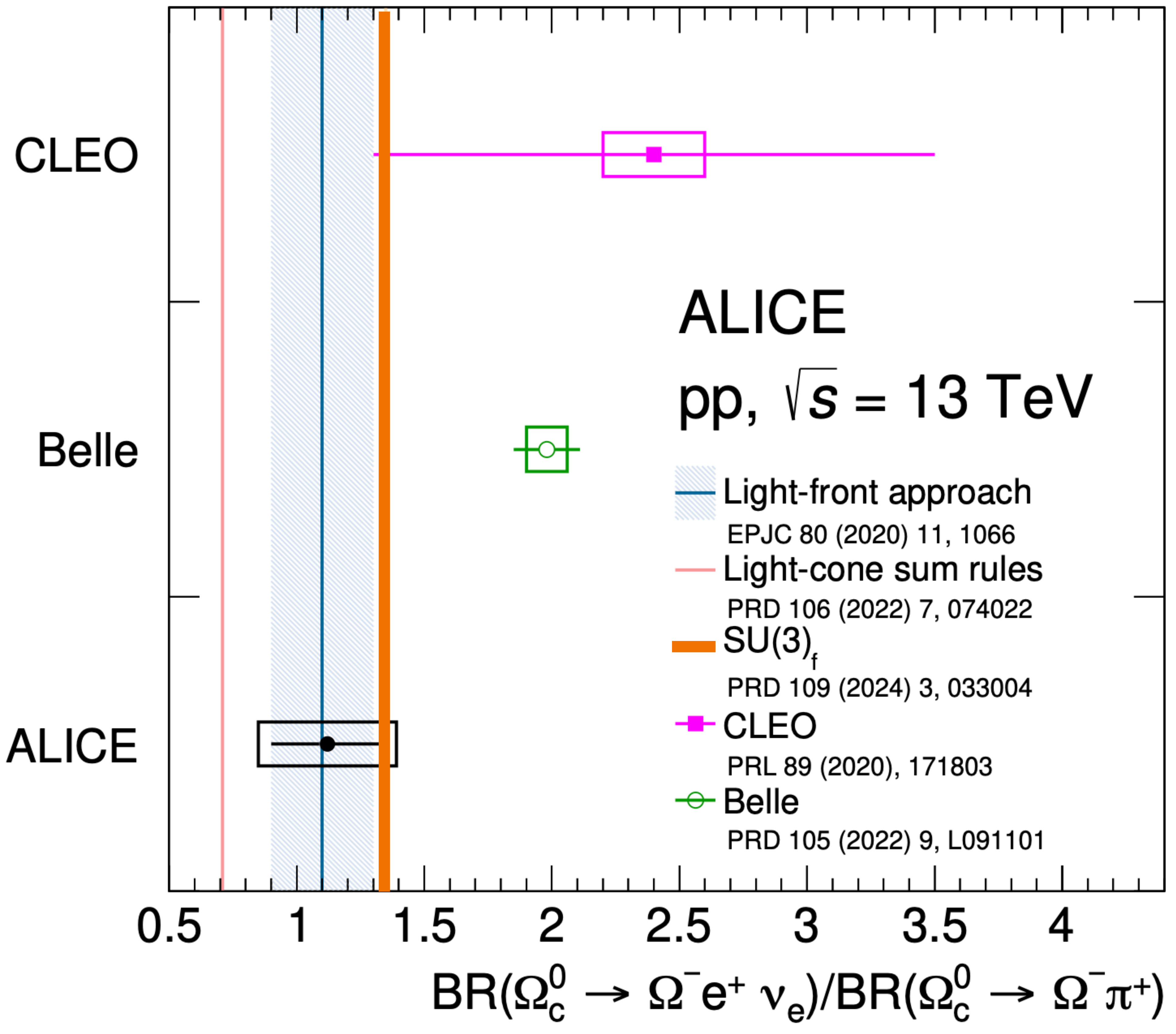
Same underestimations occurs in $\Xi_c^0 \to \Xi^-\ell^+\nu_\ell$.

	PDG	$SU(3)_F$	Lattice	Lattice
$10^2\mathcal{B}(\Xi_c^0 \to \Xi^-e^+\nu_e)$	2.12 ± 0.13*	4.10 ± 0.46	2.38 ± 0.44	3.58 ± 0.12
$10^2\mathcal{B}(\Xi_c^0 \to \Xi^-\mu^+\nu_\mu)$	2.05 ± 0.19*	3.98 ± 0.57	2.29 ± 0.42	3.47 ± 0.12
		[2110.04179]	[2103.07064]	[2504.07302]

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

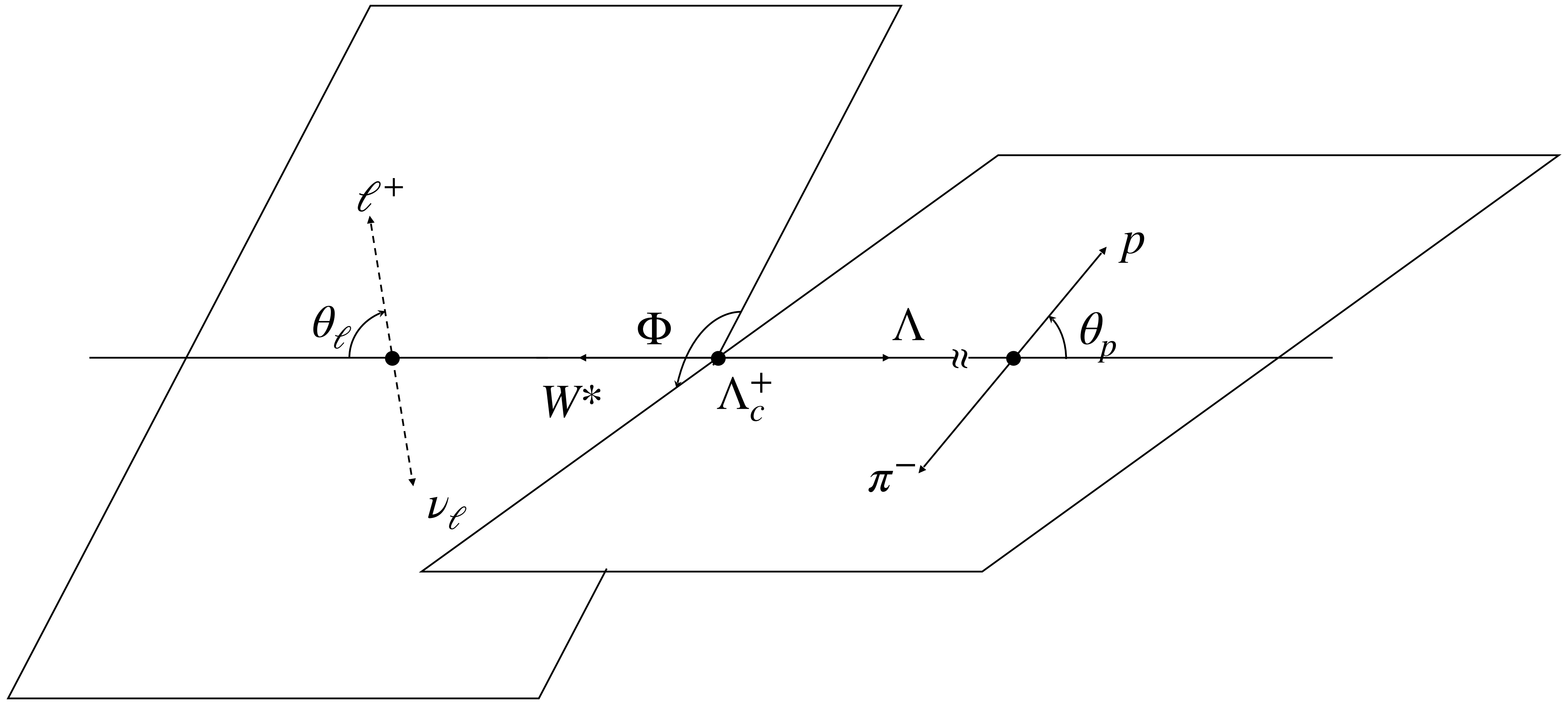
Semileptonic decays (exclusive): Future aspect

Probing other charmed baryons



[2404.17272]

Triple product asymmetries



Vanish in the SM.

NP unlikely shares the same complex phase with the SM.

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

PRD **108**, L031105 (2023)

$\Xi_c^0 \to \Xi^- e^+ \nu_e$ remains one of the most urgent problems to solve in charm decays.

The study of charmed baryon decays — as fascinating as it is flavorful!

$\mathscr{B}\left(\Xi_c^0 \to \Xi^- e^+ \nu_e\right)(\%)$