QED Contributions to $\Xi_c - \Xi_c'$ mixing

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Cooperated with Zhi-Fu Deng, Jun Zeng, and Wei Wang

arXiv:2309.16386

Outline

- Ξ_c semi-leptonic decays from experiments and theory
- Interpretation by SU(3) breaking effect
- $\Xi_c - \Xi_c'$ mixing from SU(3) breaking
- $\Xi_c - \Xi_c'$ mixing angle in LFQM
- Conclusion

Ξ_c semi-leptonic decays

Deviation between exp & th

Ξ_c semi-leptonic decays

Belle: *Phys.Rev.Lett.* 127 (2021) 12, 121803

$$\mathcal{B}(\Xi_c^0 \to \Xi^- e^+ \nu_e) = 1.31 \pm 0.04 \pm 0.07 \pm 0.38\%,$$
$$\mathcal{B}(\Xi_c^0 \to \Xi^- \mu^+ \nu_\mu) = 1.27 \pm 0.06 \pm 0.1 \pm 0.37\%,$$
$$\mathcal{B}(\Xi_c^0 \to \Xi^- e^+ \nu_e)/\mathcal{B}(\Xi_c^0 \to \Xi^- \mu^+ \nu_\mu) = 1.03 \pm 0.05 \pm 0.01.$$

Alice: *Phys.Rev.Lett.* 127 (2021) 27, 272001

$$\mathcal{B}(\Xi_c^0 \to \Xi^- e^+ \nu_e) = 2.5 \pm 0.8\%$$

from
$$\begin{cases} \mathcal{B}(\Xi_c^0 \to \Xi^- e^+ \nu_e)/\mathcal{B}(\Xi_c^0 \to \Xi^- \pi^+) = 1.38 \pm 0.14 \pm 0.22 \\ \mathcal{B}(\Xi_c^0 \to \Xi^- \pi^+) = 1.8 \pm 0.7\% \end{cases}$$

Lattice:

$$\mathcal{B}(\Xi_c^0 \to \Xi^- e^+ \nu_e) = 2.38(0.30)_{\rm stat.}(0.32)_{\rm syst.}\%$$
$$\mathcal{B}(\Xi_c^0 \to \Xi^- \mu^+ \nu_\mu) = 2.29(0.29)_{\rm stat.}(0.31)_{\rm syst.}\%,$$
$$\mathcal{B}(\Xi_c^+ \to \Xi^0 e^+ \nu_e) = 7.18(0.90)_{\rm stat.}(0.98)_{\rm syst.}\%,$$
$$\mathcal{B}(\Xi_c^+ \to \Xi^0 \mu^+ \nu_\mu) = 6.91(0.87)_{\rm stat.}(0.93)_{\rm syst.}\%.$$

Chinese Physics C Vol. 46, No. 1 (2022) 011002

Editors' Suggestion

First lattice QCD calculation of semileptonic decays of charmed-strange baryons Ξ_c*

Qi-An Zhang(张其安)[1] Jun Hua(华俊)[2] Fei Huang(黄飞)[2] Renbo Li(李任博)[3] Yuanyuan Li(李园园)[3] Caidian Lü(吕才典)[4,5] Peng Sun(孙鹏)[3†] Wei Sun(孙玮)[4] Wei Wang(王伟)[2‡] Yibo Yang(杨一玻)[6,7,8§]

Ξ_c semi-leptonic decays

LCSR:

***Phys.Rev.D* 104 (2021) 5, 054030**

Semileptonic Ξ_c baryon decays in the light cone QCD sum rules

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Decay Channel	Present Work
$\Xi_c^0 \to \Xi^- e^+ \nu_e$	1.85 ± 0.56
$\Xi_c^0 \to \Xi^- \mu^+ \nu_\mu$	1.79 ± 0.54
$\Xi_c^+ \to \Xi^0 e^+ \nu_e$	5.51 ± 1.65
$\Xi_c^+ \to \Xi^0 \mu^+ \nu_\mu$	5.34 ± 1.61
$\Xi_c^+ \to \Lambda^0 e^+ \nu_e$	0.092 ± 0.028
$\Xi_c^+ \to \Lambda^0 \mu^+ \nu_\mu$	0.089 ± 0.027

Eur. Phys. J. A (2012) 48: 2

Light cone QCD sum rules study of the semileptonic heavy Ξ_Q and Ξ'_Q transitions to Ξ and Σ baryons

K. Azizi[1,a], Y. Sarac[2,b], and H. Sundu[3,c]

[1] Physics Department, Doğuş University, Acıbadem-Kadıköy, 34722 Istanbul, Turkey
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[3] Department of Physics, Kocaeli University, 41380 Izmit, Turkey

$\Xi_c \to \Xi e^+ \nu_e$	$(7.26 \pm 2.54) \times 10^{-2}$
$\Xi_c \to \Xi \mu^+ \nu_\mu$	$(7.15 \pm 2.50) \times 10^{-2}$

QCDSR:

arXiv: 2103.09436 $\mathcal{B}(\Xi_c^0 \to \Xi^- e^+ \nu_e) = 3.4 \pm 1.7\%.$ by Zhen-Xing Zhao

Ξ_c semi-leptonic decays

SU(3) analysis:

Branching ratio	$SU(3)_f$ (a)	$SU(3)_f$ (b)	$SU(3)_f$ (c)
$10^2\mathcal{B}(\Lambda_c^+ \to \Lambda e^+\nu_e)$	3.6 ± 0.4	3.6 ± 0.4	3.2 ± 0.3
$10^2\mathcal{B}(\Lambda_c^+ \to \Lambda \mu^+\nu_\mu)$	3.5 ± 0.5	3.6 ± 0.4	3.2 ± 0.3
$10^2\mathcal{B}(\Xi_c^+ \to \Xi^0 e^+\nu_e)$	11.9 ± 1.3	9.8 ± 1.1	10.7 ± 0.9
$10^2\mathcal{B}(\Xi_c^+ \to \Xi^0 \mu^+\nu_\mu)$	11.6 ± 1.7	9.8 ± 1.1	10.8 ± 0.9
$10^2\mathcal{B}(\Xi_c^0 \to \Xi^- e^+\nu_e)$	3.0 ± 0.3	2.4 ± 0.3	2.7 ± 0.2
$10^2\mathcal{B}(\Xi_c^0 \to \Xi^- \mu^+\nu_\mu)$	2.9 ± 0.4	2.4 ± 0.3	2.7 ± 0.2

(a). Equal masses of initial and final baryons;

(b). Constant helicity amplitude

$$H^{V(A)}_{\lambda_2\lambda_W} = a^{V(A)}_{\lambda_2\lambda_W}(q^2)(\mathbf{B_n})^i_j T^j(\bar{3})(\mathbf{B_c})_i$$

(c). transition form factors in the heavy quark limit

Chao-Qiang Geng, Chia-Wei Liu, Tien-Hsueh Tsai, Shu-Wei Yeh
Phys.Lett.B 792 (2019) 214-218

Ξ_c semi-leptonic decays

SU(3) analysis with SU(3) breaking:

Xiao-Gang He, Fei Huang, Wei Wang, Zhi-Peng Xing

Phys.Lett.B 823 (2021) 136765

Mass matrix: $$M = \begin{pmatrix} m_u & 0 & 0 \\ 0 & m_d & 0 \\ 0 & 0 & m_s \end{pmatrix} \sim m_s \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix} = m_s \times \omega.$$

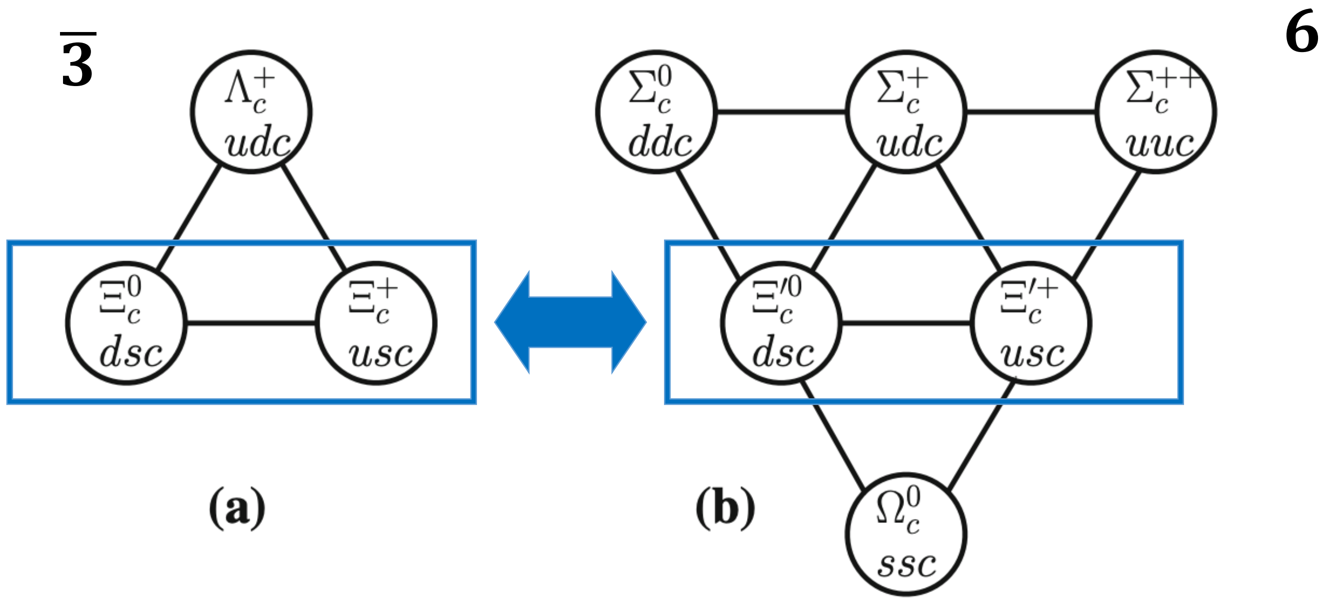
channel	branching ratio(%)	
	experimental data	SU(3) symmetry
$\Lambda_c^+ \to \Lambda^0 e^+ \nu_e$	3.6 ± 0.4 [33]	3.6 ± 0.4 (input)
$\Lambda_c^+ \to \Lambda^0 \mu^+ \nu_\mu$	3.5 ± 0.5 [33]	3.5 ± 0.5 (input)
$\Xi_c^+ \to \Xi^0 e^+ \nu_e$	2.3 ± 1.5 [33]	12.17 ± 1.35
$\Xi_c^0 \to \Xi^- e^+ \nu_e$	1.54 ± 0.35 [4, 5]	4.10 ± 0.46
$\Xi_c^0 \to \Xi^- \mu^+ \nu_\mu$	1.27 ± 0.44 [4]	3.98 ± 0.57

No SU(3) breaking

channel	branching ratio(%)		
	experimental data	fit data(pole model)	fit data(constant).
$\Lambda_c^+ \to \Lambda^0 e^+ \nu_e$	3.6 ± 0.4	3.61 ± 0.32	3.62 ± 0.32
$\Lambda_c^+ \to \Lambda^0 \mu^+ \nu_\mu$	3.5 ± 0.5	3.48 ± 0.30	3.45 ± 0.30
$\Xi_c^+ \to \Xi^0 e^+ \nu_e$	2.3 ± 1.5	3.89 ± 0.73	3.92 ± 0.73
$\Xi_c^0 \to \Xi^- e^+ \nu_e$	1.54 ± 0.35	1.29 ± 0.24	1.31 ± 0.24
$\Xi_c^0 \to \Xi^- \mu^+ \nu_\mu$	1.27 ± 0.44	1.24 ± 0.23	1.24 ± 0.23
fit parameter (pole model)	$f_1 = 1.01 \pm 0.87$, $\delta f_1 = -0.51 \pm 0.92$; $f_1' = 0.60 \pm 0.49$, $\delta f_1' = -0.23 \pm 0.41$		$\chi^2/d.o.f = 1.6$
fit parameter (constant)	$f_1 = 0.86 \pm 0.92$, $\delta f_1 = -0.25 \pm 0.88$; $f_1' = 0.85 \pm 0.36$, $\delta f_1' = -0.43 \pm 0.50$		$\chi^2/d.o.f = 1.9$

SU(3) breaking

SU(3) breaking → $\Xi_c - \Xi_c{}'$ mixing



$$\begin{pmatrix} |\Xi_Q\rangle \\ |\Xi_Q'\rangle \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} |\Xi_Q^{\bar{3}}\rangle \\ |\Xi_Q^{6}\rangle \end{pmatrix}$$

Mixing angle

$\Xi_c - \Xi_c'$ mixing to match experiments

From semi-leptonic decays

$|\theta_c| = 0.137(5)\pi$ ($\approx 24°$) from $\Xi_c^0 \to \Xi^- e^+ \nu_e$ (LFQM)

Chao-Qiang Geng, Xiang-Nan Jin, Chia-Wei Liu
Phys.Lett.B 838 (2023) 137736

From non-leptonic decays

LHCb: $$\frac{\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^{+\prime}\pi^+)}{\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^{+}\pi^+)} \equiv \frac{\mathcal{B}'}{\mathcal{B}} = 1.41 \pm 0.17 \pm 0.1$$

Phys. Rev. Lett. 121, 162002 (2018) JHEP 05 (2022) 038

To fit this ratio:

$$\theta = 16.27° \pm 2.30° \text{ or } 85.54° \pm 2.30°$$ (LFQM)

Hong-Wei Ke, Xue-Qian Li, *Phys.Rev.D* 105 (2022) 9, 096011

$\Xi_c - \Xi_c{}'$ mixing in QCDSR

$$\Pi^{(\prime)}(p) = i\int d^4x e^{ip\cdot x}\langle 0|T\{J^{(\prime)}(x)\bar{J}^{(\prime)}(0)\}|0\rangle,$$

$$\begin{pmatrix} J \\ J' \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} J_0 \\ J_1 \end{pmatrix}$$

$$i\int d^4x e^{ip\cdot x}\langle 0|T\{J(x)\bar{J}'(0)\}|0\rangle = 0,$$
$$i\int d^4x e^{ip\cdot x}\langle 0|T\{J'(x)\bar{J}(0)\}|0\rangle = 0.$$

$$\begin{cases} \theta_c = (1.2 \sim 2.8)^\circ \text{ for the } Q = c \\ \theta_b = (0.28 \sim 0.34)^\circ \text{ for the } Q = b \end{cases}$$

Heavy quark limit: $\theta \to 0$

Eur.Phys.J.C 83 (2023) 10, 961

Revisiting $\Xi_Q - \Xi'_Q$ mixing in QCD sum rules

Xiao-Yu Sun[1], Fu-Wei Zhang[1], Yu-Ji Shi[2,a], Zhen-Xing Zhao[1,b]

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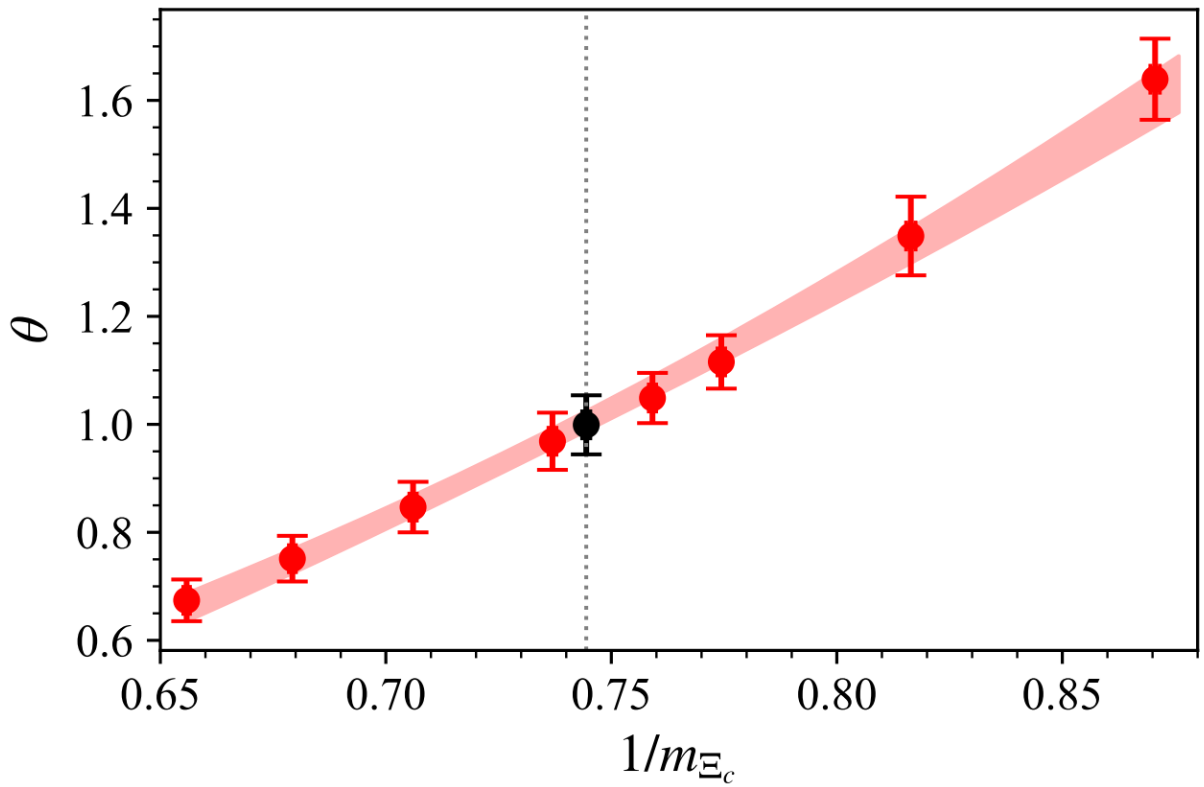
$\Xi_c - \Xi_c{}'$ mixing in LQCD



$\theta = (1.22 \pm 0.13 \pm 0.01)^\circ$

$\Xi_c - \Xi_c'$ mixing From Lattice QCD

Phys.Lett.B 841 (2023) 137941

Hang Liu,[1] Liuming Liu,[2,3] Peng Sun,[2,3] Wei Sun,[4] Jin-Xin Tan,[1] Wei Wang,[1,5,*] Yi-Bo Yang,[6,7,8,3] and Qi-An Zhang[9,†]

$\Xi_c - \Xi_c'$ mixing from SU(3) breaking

Extracting $\Xi_c - \Xi_c{}'$ mixing angle

The Lagrangian can be decomposed into SU(3) conserving and breaking terms:

$$\mathcal{L}_{\mathrm{QCD+QED}} = \mathcal{L}_0 + \Delta\mathcal{L}$$

$$\begin{aligned}\mathcal{L}_0 &= \sum_q \bar{\psi}_q(i\not{D} - m_u)\psi_q + e\sum_q e_s\bar{\psi}_q \not{A}\psi_q \\ &+ \; ee_c\bar{\psi}_c\not{A}\psi_c,\end{aligned}$$

The same mass and charge for u, d, s, SU(3) conserving

$$\Delta\mathcal{L} = \bar{\psi}_s(m_u - m_s)\psi_s + e(e_u - e_s)\bar{\psi}_u\not{A}\psi_u$$

The mass and charge differences are attributed to the SU(3) breaking terms

Extracting $\Xi_c - \Xi_c{}'$ mixing angle

Hamiltonian: $H = H_0 + \Delta H$

The SU(3) conserving Hamiltonian is diagonalized by $\Xi_c^{\bar{3}}$ and Ξ_c^{6} :

$$H_0|\Xi_c^{\bar{3}}\rangle = m_{\Xi_c^{\bar{3}}}|\Xi_c^{\bar{3}}\rangle, \quad H_0|\Xi_c^{6}\rangle = m_{\Xi_c^{6}}|\Xi_c^{6}\rangle$$

The full Hamiltonian is diagonalized by Ξ_c and $\Xi_c{}'$:

$$H|\Xi_c\rangle = m_{\Xi_c}|\Xi_c\rangle, \quad H|\Xi_c'\rangle = m_{\Xi_c'}|\Xi_c'\rangle$$

Transformation between doublets: $|S\rangle = \left(|\Xi_c^{\bar{3}}\rangle, |\Xi_c^{6}\rangle\right)^T$, $|P\rangle = \left(|\Xi_c\rangle, |\Xi_c'\rangle\right)^T$

$$|P\rangle = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} |S\rangle = U|S\rangle.$$

Extracting $\Xi_c - \Xi_c{}'$ mixing angle

In the basis of $|S\rangle = \left(|\Xi_c^{\bar{3}}\rangle, |\Xi_c^{6}\rangle\right)^T$:

$$\mathbf{H} = \begin{pmatrix} \langle\Xi_c^{\bar{3}}(S'_z)|H|\Xi_c^{\bar{3}}(S_z)\rangle & \langle\Xi_c^{6}(S'_z)|H|\Xi_c^{\bar{3}}(S_z)\rangle \\ \langle\Xi_c^{\bar{3}}(S'_z)|H|\Xi_c^{6}(S_z)\rangle & \langle\Xi_c^{6}(S'_z)|H|\Xi_c^{6}(S_z)\rangle \end{pmatrix}$$

$$|S\rangle = U^T|P\rangle$$

$$=2(2\pi)^3\delta^{(3)}(\vec{0})\delta_{S_z S'_z} \times \begin{pmatrix} m^2_{\Xi_c}\cos^2\theta + m^2_{\Xi'_c}\sin^2\theta & (m^2_{\Xi_c} - m^2_{\Xi'_c})\cos\theta\sin\theta \\ (m^2_{\Xi_c} - m^2_{\Xi'_c})\cos\theta\sin\theta & m^2_{\Xi_c}\sin^2\theta + m^2_{\Xi'_c}\cos^2\theta \end{pmatrix}$$

$$\langle\Xi_c^{6}(S'_z)|H|\Xi_c^{\bar{3}}(S_z)\rangle = (2\pi)^3\delta^{(3)}(\vec{0})\delta_{S_z S'_z}(m^2_{\Xi_c} - m^2_{\Xi'_c})\sin 2\theta.$$

Extracting $\Xi_c - \Xi_c{}'$ mixing angle

On the another hand: $H = H_0 + \Delta H$

$\langle \Xi_c^6 | H_0 | \Xi_c^{\bar{3}} \rangle = 0$

H_0 conserves SU(3) symmetry

$$\langle \Xi_c^6(S_z') | H | \Xi_c^{\bar{3}}(S_z) \rangle = (2\pi)^3 \delta^{(3)}(\vec{0}) \langle \Xi_c^6(S_z') | \Delta\mathcal{H}(0) | \Xi_c^{\bar{3}}(S_z) \rangle$$

An unkown matrix element

$$\langle \Xi_c^6(S_z') | H | \Xi_c^{\bar{3}}(S_z) \rangle = (2\pi)^3 \delta^{(3)}(\vec{0}) \delta_{S_z S_z'} (m_{\Xi_c}^2 - m_{\Xi_c'}^2) \sin 2\theta.$$

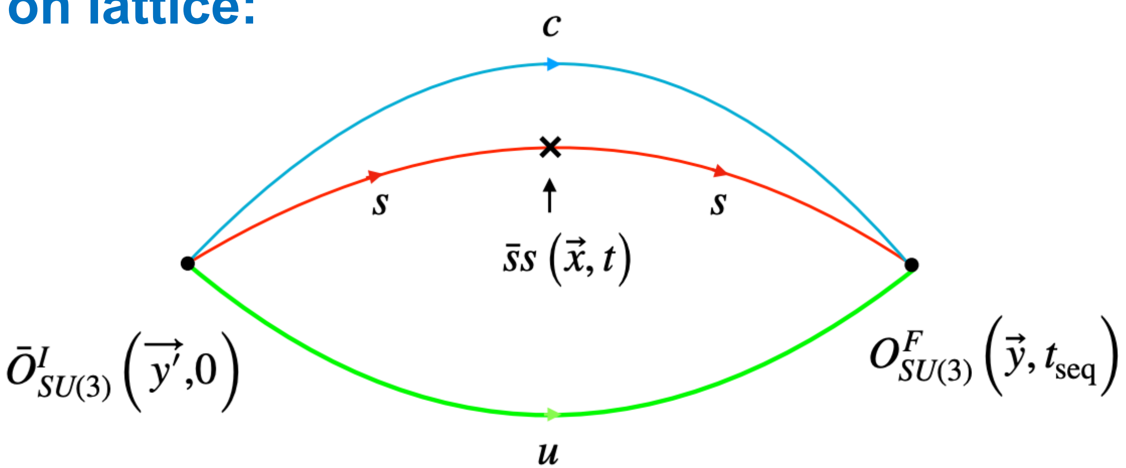
Mixing angle

Extracting θ $\Rightarrow$ $$\sin 2\theta = \frac{1}{2} \sum_{S_z} \frac{\langle \Xi_c^6(S_z) | \Delta\mathcal{H}(0) | \Xi_c^{\bar{3}}(S_z) \rangle|}{m_{\Xi_c}^2 - m_{\Xi_c'}^2}$$

QCD contribution to $\Xi_c - \Xi_c'$

$$\Delta\mathcal{H}_m = (m_s - m_u)\bar{s}s$$

Calculate a three-point correlation function on lattice:

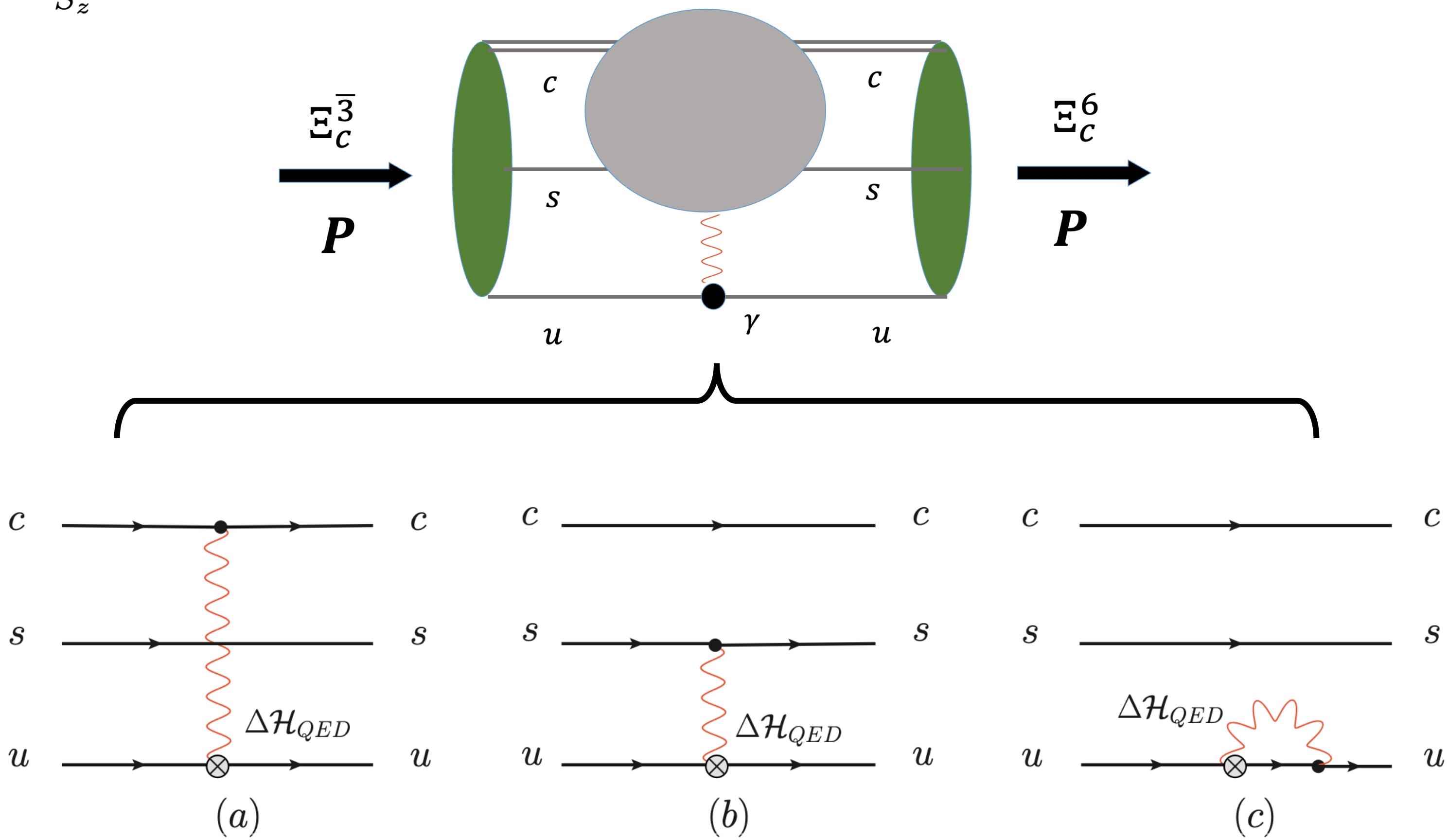


	$\lvert M^{6-\bar{3}}_{\bar{s}s}\rvert$	$\lvert\theta\rvert$
C11P29S	0.155(14)GeV	$(0.97 \pm 0.08 \pm 0.25)^\circ$

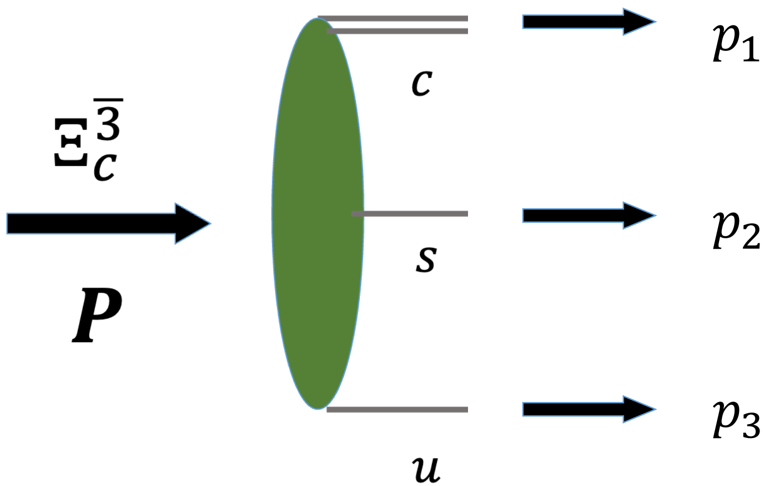
Hang Liu, Wei Wang, Qi-An Zhang, arXiv:2309.05432

QCD contribution to $\Xi_c - \Xi_c{}'$

$$\frac{1}{2}\sum_{S_z}\langle\Xi_c^6(P,S_z)|\Delta\mathcal{H}_{\rm QED}(0)|\Xi_c^{\bar{3}}(P,S_z)\rangle \qquad \Delta\mathcal{H}_{\rm QED} = e(e_u - e_s)\bar{\psi}_u \not{A}\psi_u$$



The three-quark picture of LFQM



Light-cone 3-momentum $\tilde{p} = (p^+, \vec{p}_\perp)$

$$p_i^+ = x_i P^+, \quad \vec{p}_{i\perp} = x_i \vec{P}_\perp + \vec{k}_{i\perp},$$

$$\sum_{i=1}^3 x_i = 1 \qquad \sum_{i=1}^{3} \vec{k}_{i\perp} = 0,$$

On shell: $p_i^+ p_i^- - \vec{p}_{i\perp}^{\,2} = m_i^2$

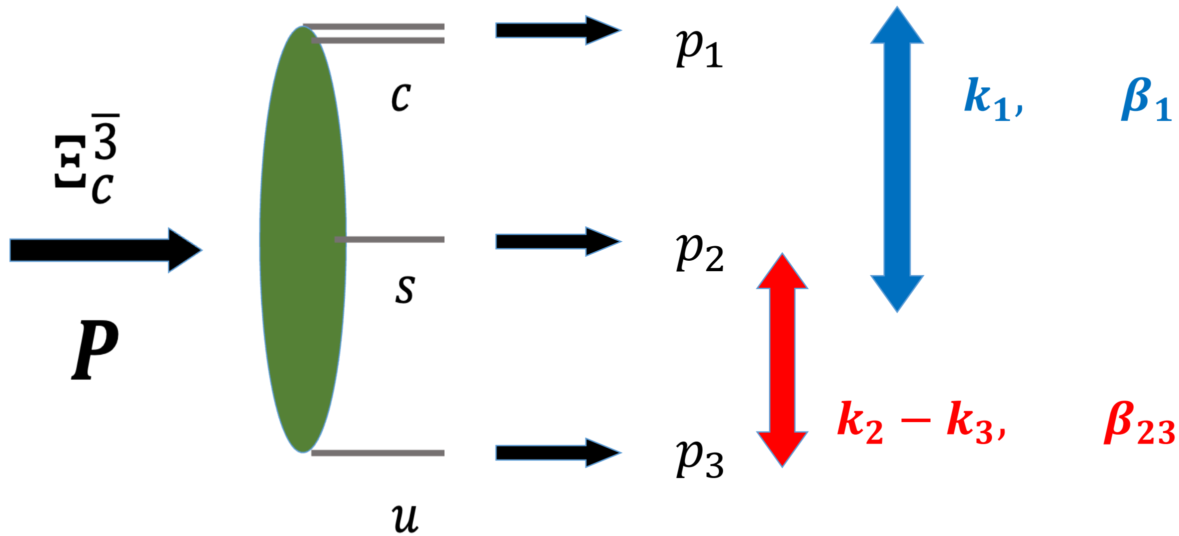
Light-cone 3-momentum conservation

$$\left|\Xi_c^{\bar{3}/6}\right\rangle = \int \left(\Pi_{i=1}^3 \left\{d^3\tilde{p}_i\right\}\right) 2(2\pi)^3 \frac{\delta^{(3)}\left(\tilde{P} - \tilde{p}_1 - \tilde{p}_2 - \tilde{p}_3\right)}{\sqrt{P^+}} \sum_{\lambda_i} \Psi_{\bar{3}/6}^{S,S_z} \frac{\epsilon^{ijk}}{\sqrt{6}} \left|c^i\left(p_1, \lambda_1\right) s^j\left(p_2, \lambda_2\right) u^k\left(p_3, \lambda_3\right)\right\rangle$$

$$\left\{d^3\tilde{p}\right\} \equiv \frac{dp^+ d^2 p_\perp}{2(2\pi)^3 \sqrt{p^+}}$$

Wave function

Three-quark picture in LFQM



Spin: $\Psi_{\bar{3}} = A\bar{u}_{\lambda_3}(p_3)\left(\not{\bar{P}} + M_0\right)(-\gamma_5)\,C\bar{u}^T_{\lambda_2}(p_2)\,\bar{u}_{\lambda_1}(p_1)\,u\left(\bar{P}\right)\Phi(x_i, k_{i\perp})$

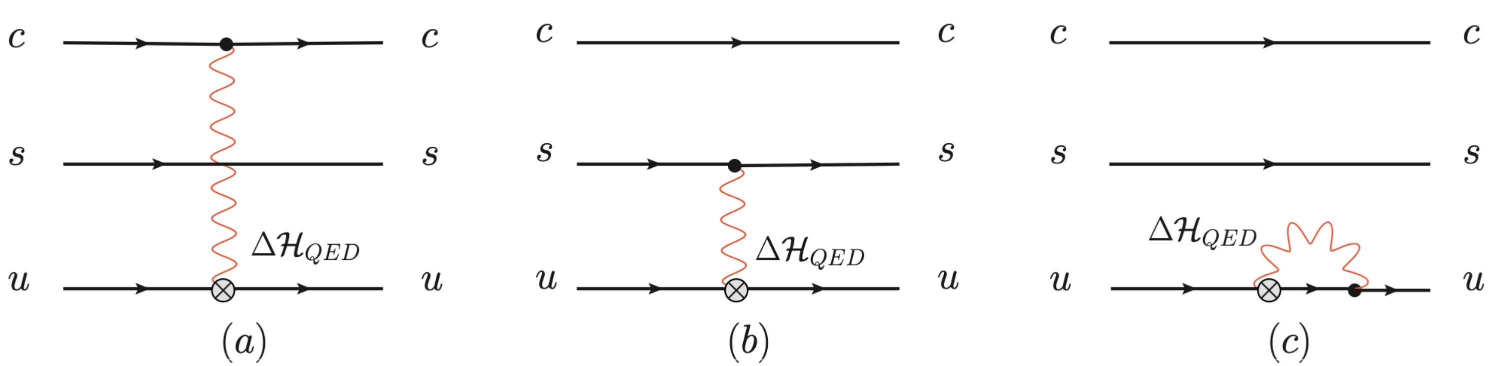
Momentum:

$$\Phi(x_i, k_{i\perp}) = \sqrt{\frac{e_1 e_2 e_3}{x_1 x_2 x_3 M_0}}\phi(\vec{k}_1, \beta_1)\phi(\frac{\vec{k}_2 - \vec{k}_3}{2}, \beta_{23}),$$

$$\phi(\vec{k}, \beta) = 4\left(\frac{\pi}{\beta^2}\right)^{\frac{3}{4}} e^{\frac{-k_\perp^2 - k_z^2}{2\beta^2}},$$

Zhen-Xing Zhao, Fu-Wei Zhang, Xiao-Hui Hu, Yu-Ji Shi
Phys.Rev.D 107 (2023) 11, 116025

LFQM Calculation



Contributes **Vanishes** **Vanishes**

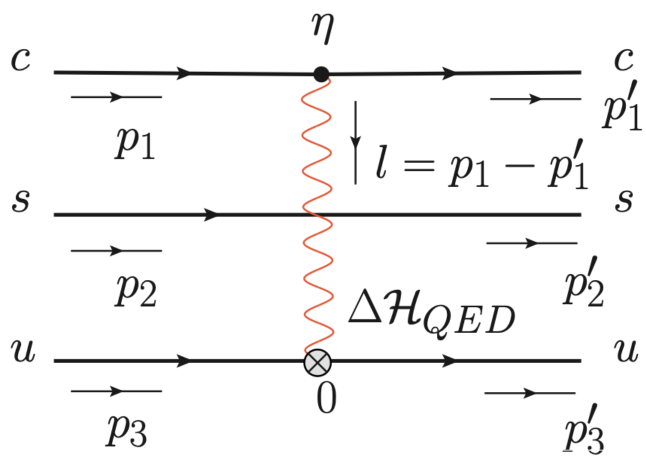
The charm quark spin is changed by photon, a $1/m_c$ effect.

$$\bar{h}_v i(v\cdot D)h_v - \frac{1}{2m_Q}\bar{h}_v \not{D}^{\perp} \sum_{n=0}^{N}\left(\frac{-i(v\cdot D)}{2m_Q}\right)^n \not{D}^{\perp} h_v$$

Spin conserved **Spin changed**

$$\boldsymbol{m_Q} \uparrow \longrightarrow \boldsymbol{\theta_{QED}} \downarrow$$

LFQM Calculation

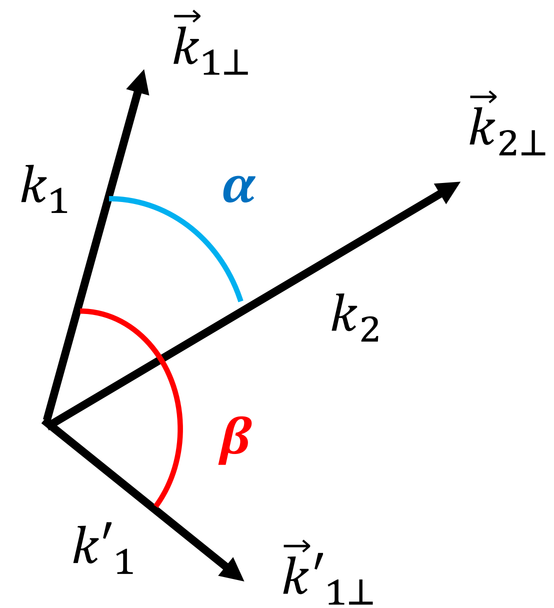


The only possible IR region is $l^2 = 0$

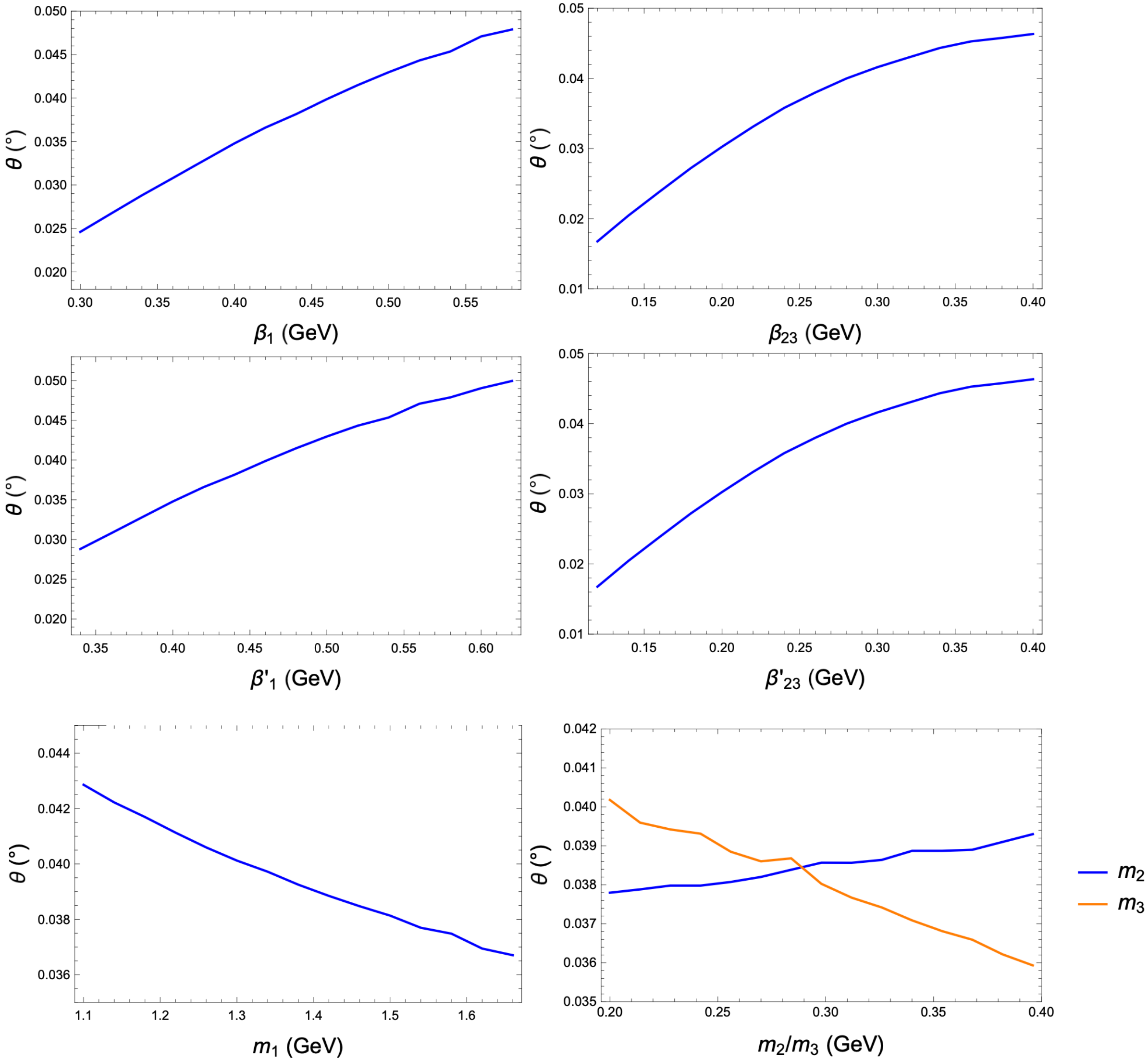
$$\propto \frac{l^\mu l^\nu}{l^2}$$

No IR divergence

$$\begin{aligned} & e(e_u - e_s)\langle \Xi_c(1)|\, \bar{\psi}_u(0) \not{A}(0) \psi_u(0)\, |\Xi_c(0)\rangle \\ = & -\frac{2e^2}{3}\int_0^1 dx_1 \int_0^{1-x_1} dx_2 \int_0^{1-x_2} dx_1' \int_0^\infty \frac{dk_1 dk_2 dk_1'}{\left[2(2\pi)^3\right]^3} \\ & \times 2\pi \int_0^{2\pi} d\alpha d\beta \frac{k_1 k_2 k_1' A^2}{\sqrt{x_1 x_1'(1-x_1-x_2)(1-x_1'-x_2)}} \\ & \times \Phi(x_i, k_{i\perp})\Phi(x_i', k_{i\perp}') \frac{\mathrm{Tr}_A \mathrm{Tr}_B}{l^2 + i\epsilon} \end{aligned}$$



Mixing Angle



$$\theta_{\mathrm{QED}} \approx 0.04^\circ$$

Very small !

Conclusion

- To match the measured semi-leptonic decay BF, the required $\Xi_c - \Xi_c'$ mixing angle is around $10° - 30°$
- QCD contributes only $\sim 1°$
- QED contribution is much smaller: $0.04°$
- It seems that the $\Xi_c - \Xi_c'$ mixing effect is too small to affect the Ξ_c decays

Any other mechanisms to explain the gap between exp. & th. ?

$K_1(1270) - K_1(1400)$ mixing

$$\begin{pmatrix} |K_1(1270)\rangle \\ |K_1(1400)\rangle \end{pmatrix} = \begin{pmatrix} \cos\theta_{K_1} & \sin\theta_{K_1} \\ -\sin\theta_{K_1} & \cos\theta_{K_1} \end{pmatrix} \begin{pmatrix} |K_{1B}\rangle \\ |K_{1A}\rangle \end{pmatrix}$$

$$\theta_{K_1} = 22^\circ \pm 7^\circ \text{ or } \theta_{K_1} = 68^\circ \pm 7^\circ$$

Yu-Ji Shi, Jun Zeng, Zhi-Fu Deng, arXiv:2310.20429

Thank you for your attention !