

Charmed baryon $\Xi_c \rightarrow \Xi$ decays From Lattice QCD

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第十三届全国粒子物理学术会议
2021-8-18

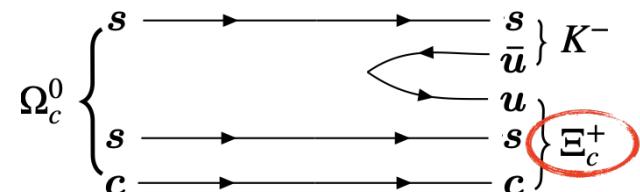
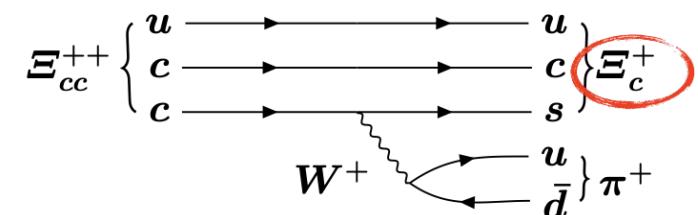
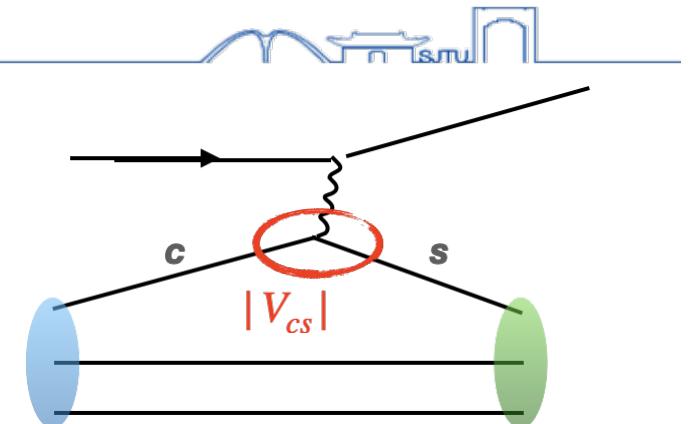
Outlines



- Motivation
- Lattice calculation of $\Xi_c \rightarrow \Xi$ form factors
- Semi-leptonic Ξ_c decays
- Differential decay width and branching fractions from lattice QCD
- Summary

Motivation

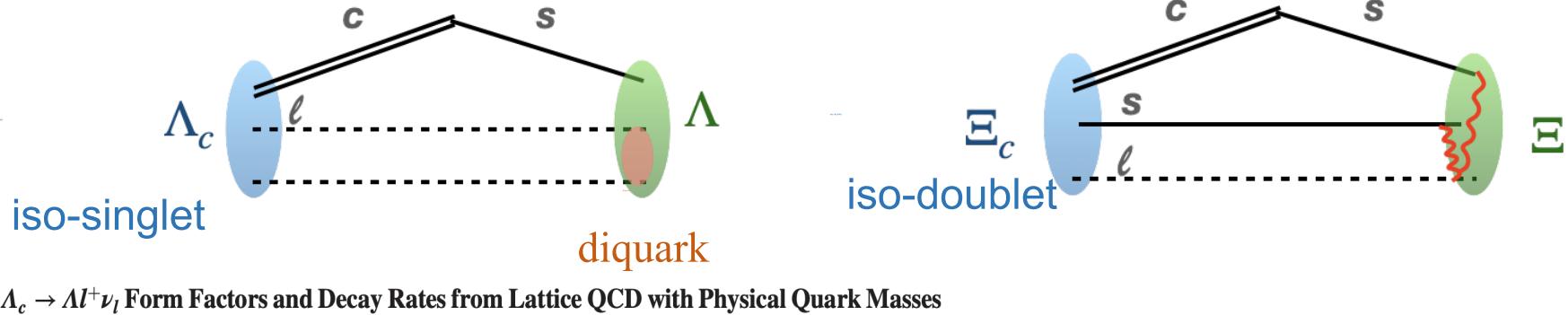
- Determine CKM matrix elements $|V_{cs}|$;
- Charmed baryons semileptonic decays are best way to study the strong and weak interactions;
- Important for the experimental researches of heavy baryons:
 - Studies of doubly-charmed baryon Ξ_{cc}^{++} decay
R. Aaij et al. [LHCb], PRL121, 162002 (2018)
 - Discovery of new exotic hadron candidates Ω_c^0
R. Aaij et al. [LHCb], PRL118, 182001(2017)
 -



Motivation



- Ξ_c contains more versatile decay modes



Stefan Meinel
Department of Physics, University of Arizona, Tucson, Arizona 85721, USA and RIKEN BNL Research Center,
Brookhaven National Laboratory, Upton, New York 11973, USA

- A different pattern between inclusive and exclusive decays of Λ_c and D:

$$\frac{\mathcal{B}(\Lambda_c^+ \rightarrow X e^+ \nu_e) = (3.95 \pm 0.34 \pm 0.09)\%}{\mathcal{B}(\Lambda_c^+ \rightarrow \Lambda e^+ \nu_e) = (3.63 \pm 0.38 \pm 0.20)\%}$$

~ 1

$$\frac{\mathcal{B}(D^0 \rightarrow X e^+ \nu_e) = (6.49 \pm 0.11)\%}{\mathcal{B}(D^0 \rightarrow K^- e^+ \nu_e) = (3.542 \pm 0.035)\%}$$

~ 2

Motivation



✓ Experimental

Belle $\mathcal{B}(\Xi_c^0 \rightarrow \Xi^- e^+ \nu_e) = (1.72 \pm 0.10 \pm 0.12 \pm 0.50) \%$

Y.B.Li et al.[Belle],
arXiv:2103.06496[hep-ex]

$$\mathcal{B}(\Xi_c^0 \rightarrow \Xi^- \mu^+ \nu_\mu) = (1.71 \pm 0.17 \pm 0.13 \pm 0.50) \%$$

ALICE $\mathcal{B}(\Xi_c^0 \rightarrow \Xi^- e^+ \nu_e) = (2.43 \pm 0.25 \pm 0.35 \pm 0.72) \%$

J.Zhu on behalf of the ALICE
collaboration, POSICHEP2020
(2021)524.

✓ Theoretical

QCD SR $\mathcal{B}(\Xi_c^0 \rightarrow \Xi^- e^+ \nu_e) = (3.4 \pm 1.7) \%$ Z. X. Zhao, arXiv:2103.09436.

LF QM $\mathcal{B}(\Xi_c^0 \rightarrow \Xi^- e^+ \nu_e) = (3.49 \pm 0.95) \%$ C.Q.Geng et al, arXiv:2012.04147.

LCSR $\mathcal{B}(\Xi_c^0 \rightarrow \Xi^- e^+ \nu_e) = (2.4^{+0.9}_{-1.0}) \%$ Y. L. Liu et al, J. Phys. G37, 115010(2010)

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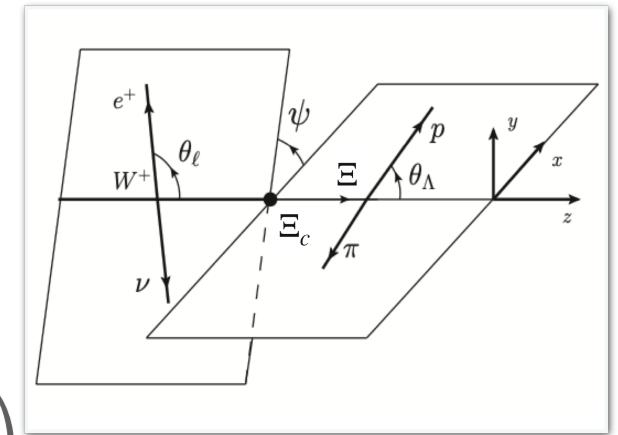
Lattice ?

Semileptonic Ξ_c decays:

- Helicity amplitude

$$\begin{aligned} \mathcal{M}(\Xi_c \rightarrow \Xi l^+ \nu_l) &= \frac{G_F}{\sqrt{2}} V_{cs} \langle \Xi | \bar{s} \gamma^\mu (1 - \gamma_5) c | \Xi_c \rangle \langle \bar{l} \nu_l | \bar{\nu} \gamma^\nu (1 - \gamma_5) l | 0 \rangle g_{\mu\nu} \\ &= \frac{G_F}{\sqrt{2}} V_{cs} \left(H^\mu \epsilon_\mu^*(t) \times L^\nu \epsilon_\nu(t) - \sum_\lambda H^\mu \epsilon_\mu^*(\lambda) \times L^\nu \epsilon_\nu(\lambda) \right) \end{aligned}$$

Hadronic part **Leptonic part**

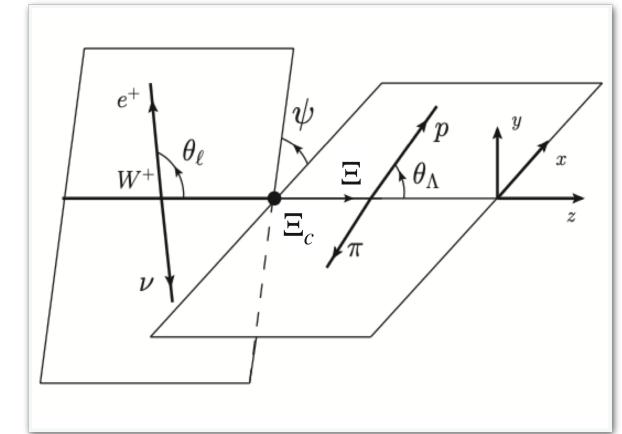


Semileptonic Ξ_c decays:



- Helicity amplitude

$$\begin{aligned} \mathcal{M}(\Xi_c \rightarrow \Xi l^+ \nu_l) &= \frac{G_F}{\sqrt{2}} V_{cs} \langle \Xi | \bar{s} \gamma^\mu (1 - \gamma_5) c | \Xi_c \rangle \langle \bar{l} \nu_l | \bar{\nu} \gamma^\nu (1 - \gamma_5) l | 0 \rangle g_{\mu\nu} \\ &= \frac{G_F}{\sqrt{2}} V_{cs} \left(H^\mu \epsilon_\mu^*(t) \times L^\nu \epsilon_\nu(t) - \sum_\lambda H^\mu \epsilon_\mu^*(\lambda) \times L^\nu \epsilon_\nu(\lambda) \right) \end{aligned}$$



$$\begin{aligned} \langle \Xi(P_\Xi) | V^\mu | \Xi_c(P_{\Xi_c}) \rangle &= \bar{u}(P_\Xi, S_2) \left[\left(m_{\Xi_c} - m_\Xi \right) \frac{q^\mu}{q^2} f_0(q^2) + \frac{m_{\Xi_c} + m_\Xi}{s_+} \left(P_{\Xi_c}^\mu + P_\Xi^\mu - \frac{q^\mu}{q^2} (m_{\Xi_c}^2 - m_\Xi^2) \right) f_+(q^2) \right. \\ &\quad \left. + \left(\gamma^\mu - \frac{2m_\Xi}{s_+} P_1^\mu - \frac{2m_{\Xi_c}}{s_+} P_\Xi^\mu \right) f_\perp(q^2) \right] u(P_{\Xi_c}), \end{aligned}$$

vector

$$\begin{aligned} \langle \Xi(P_\Xi) | A^\mu | \Xi_c(P_{\Xi_c}) \rangle &= -\bar{u}(P_\Xi, S_2) \gamma^5 \left[\left(m_{\Xi_c} + m_\Xi \right) \frac{q^\mu}{q^2} g_0(q^2) + \frac{m_{\Xi_c} - m_\Xi}{s_-} \left(P_{\Xi_c}^\mu + P_\Xi^\mu - \frac{q^\mu}{q^2} (m_{\Xi_c}^2 - m_\Xi^2) \right) g_+(q^2) \right. \\ &\quad \left. + \left(\gamma^\mu + \frac{2m_\Xi}{s_-} P_{\Xi_c}^\mu - \frac{2m_{\Xi_c}}{s_-} P_\Xi^\mu \right) g_\perp(q^2) \right] u(P_{\Xi_c}) \end{aligned}$$

axial-vector

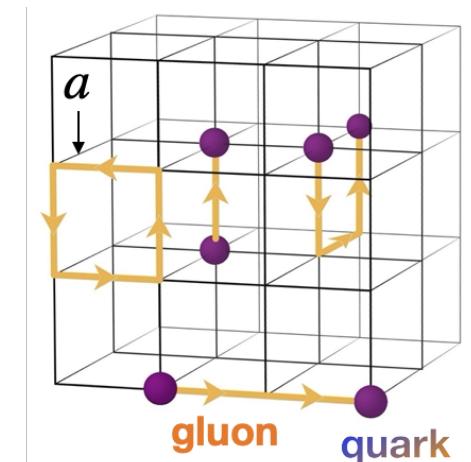
Lattice QCD calculation of form factors



- **Helicity based form factors:** $f_\perp, f_0, f_+, g_\perp, g_0, g_+$
 - **Non-perturbative**
 - **QCD sum rules, light-cone sum rules, light-front quark model, ...**
=> **model dependent**

Lattice QCD: non-perturbative theory

- Discretization, and wick rotation to Euclidean spacetime;
- Quark fields on lattice sites, gauge links connecting the sites;
- Pion mass to benchmark the light quark mass;



Credit: M. Savage@NNPSS2015

Lattice setup



- This work is based on **2+1 flavor** ensembles generated with tree level tadpole improved clover fermion action and tadpole improved Symanzik gauge action;
- Basic informations of **two ensembles** used in this calculation;

	$\beta = \frac{10}{g^2}$	$L^3 \times T$	a	c_{sw}	κ_l	m_π	κ_s	m_{η_s}
s108	6.20	$24^3 \times 72$	0.108	1.161	-0.2770	290	0.1330	640
s080	6.41	$32^3 \times 96$	0.080	1.141	-0.2295	300	0.1318	650

- Determining the **charm quark mass** by requiring the J/Phi mass to its physical value $m_{J/\psi} = 3.96900$ (6) within 0.3% accuracy.

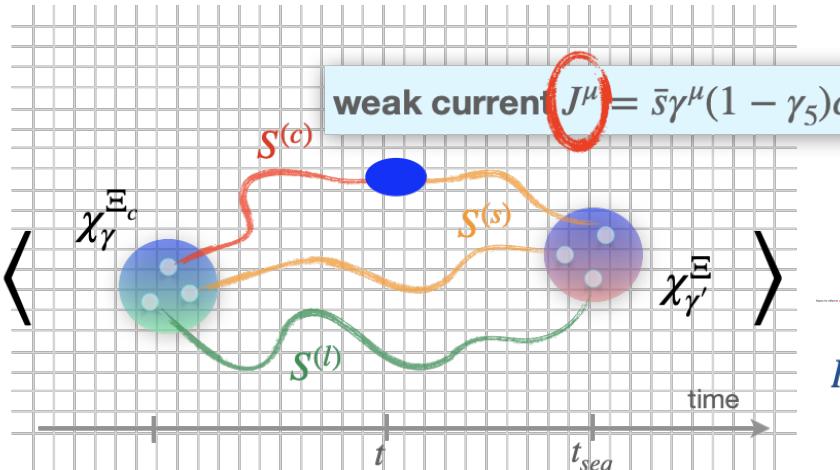
$$m_c^{\text{s108}} a = 0.485 \quad m_c^{\text{s080}} a = 0.235$$

Extract form factors



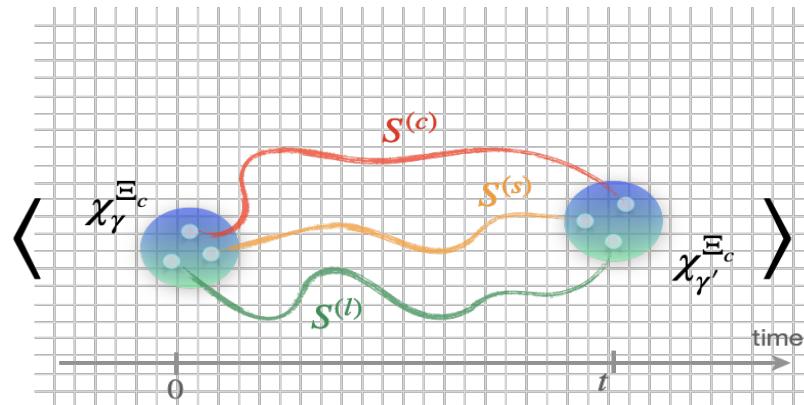
C_3

$$C_3(q^2, t, t_{seq}) \sim T^{\gamma\gamma'} \left\langle \chi_\gamma^{\Xi_c} \right.$$



$$T = \{I, \gamma_5, \gamma^t, \gamma^x, \dots\}$$

$$\mu = \{t, x, y, z\}$$



$$R_{V/A}(T, \mu) =$$

$$\sqrt{\frac{C_3^{V/A}(q^2, t, t_{seq}) C_3^{V/A}(q^2, t_{seq} - t, t_{seq})}{C_2^{B_1}(t_{seq}) C_2^{B_2}(t_{seq})}}$$

-Ratios for the six form factors can be constructed by different combinations of $R_{V/A}(T, \mu)$

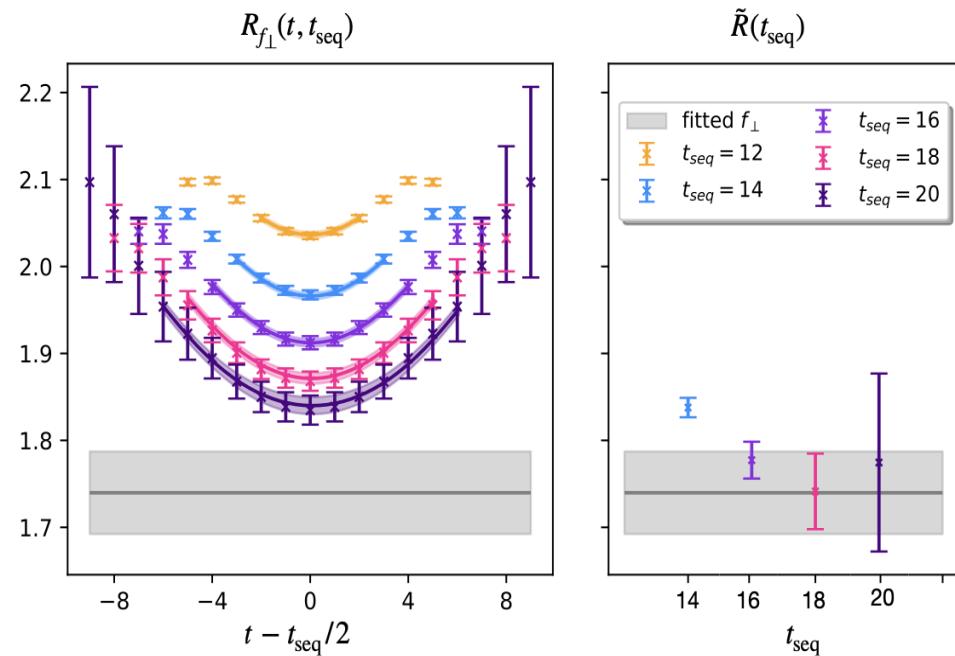
Extract $\Xi_c \rightarrow \Xi$ form factors



- Ratios for the six form factors can be constructed by different combinations**

of $R_{V/A}(T, \mu)$:

$$R_{f_\perp} \equiv \frac{R_V(\gamma_5 \gamma^x, \gamma^y)}{4m_{\Xi_c} N_z \hat{p}} = f_\perp \left(\frac{\left(1 + c_1 e^{-\Delta E_1 t} + c_2 e^{-\Delta E_2 (t_{\text{seq}} - t)} \right) \left(1 + c_1 e^{-\Delta E_1 (t_{\text{seq}} - t)} + c_2 e^{-\Delta E_2 t} \right)}{(1 + d_1 e^{-\Delta E_1 t_{\text{seq}}}) (1 + d_2 e^{-\Delta E_2 t_{\text{seq}}})} \right)^{1/2}$$



- The differential summed ratio
for validity check:

$$\tilde{R}(t_{\text{seq}}) \equiv \frac{SR(t_{\text{seq}}) - SR(t_{\text{seq}} - \Delta t)}{\Delta t}$$

$$SR(t_{\text{seq}}) \equiv \sum_{t_c < t < t_{\text{seq}} - t_c} R_F(t, t_{\text{seq}})$$

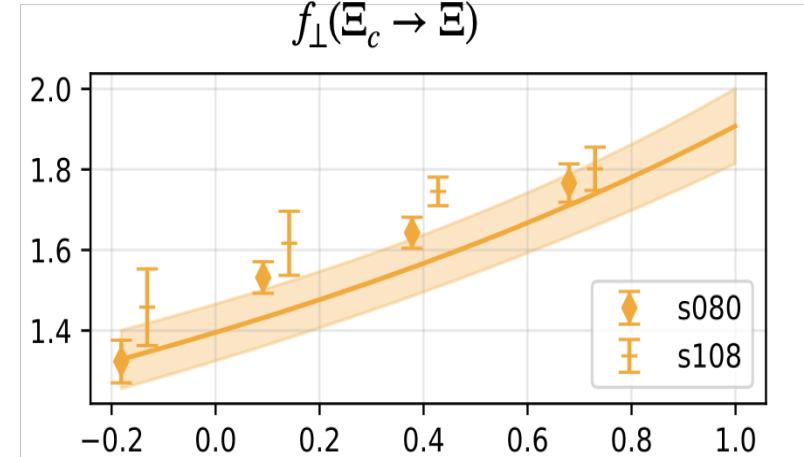
q^2 distribution for form factors



- Extrapolate to the **continuum limit** (shaded regions);
- **z -expansion parametrization of form factors to obtain the q^2 -distribution:**

$$f(q^2) = \frac{1}{1 - q^2 / (m_{\text{pole}}^f)^2} \sum_{n=0}^{n_{\text{max}}} (c_n^f + d_n^f a^2) [z(q^2)]^n$$

- Use D_s meson pole mass for m_{pole}^f , ...
- Consider the **discretization effects** by estimating the d_n^f terms.



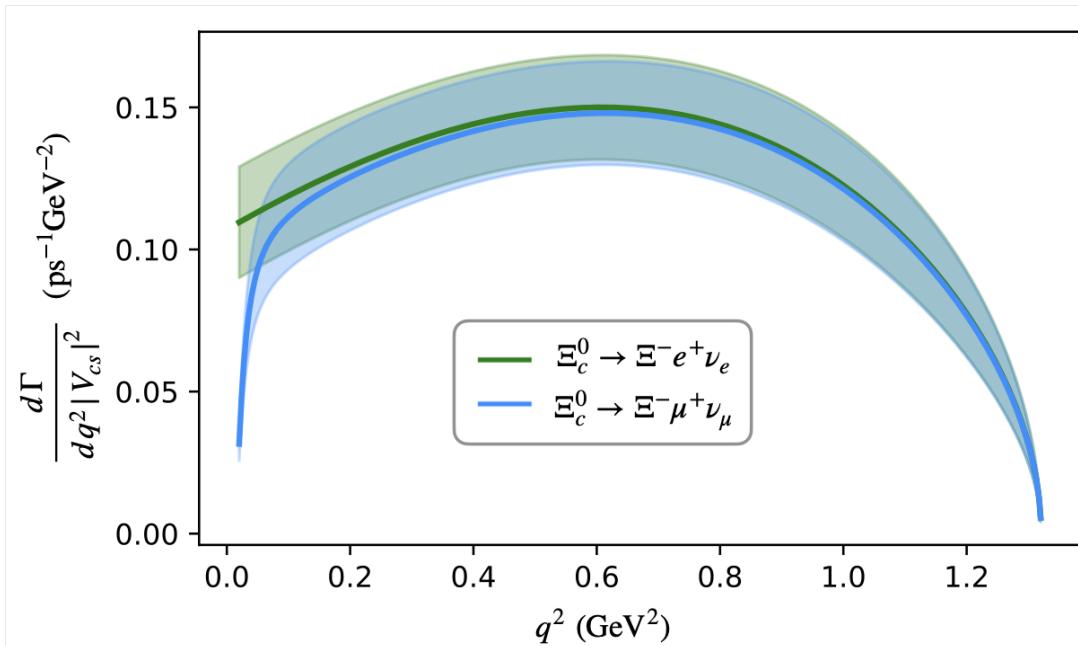
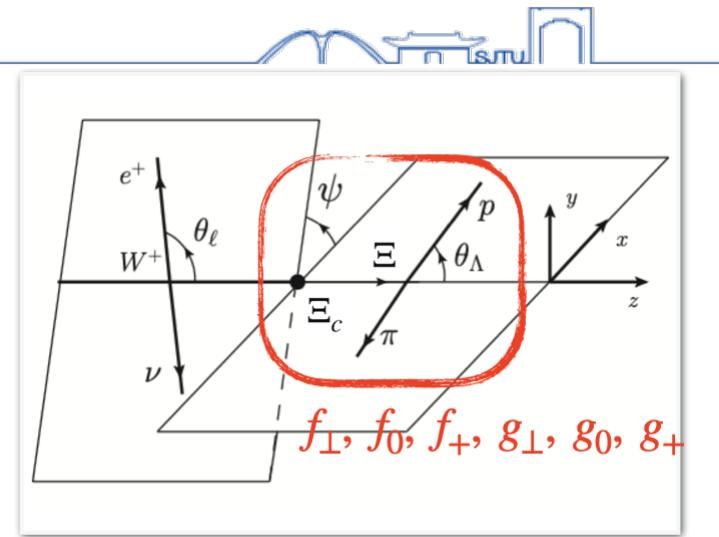
Fit results for the z -expansion parameters

	c_0	c_1	c_2
f_{\perp}	1.51 ± 0.09	-1.88 ± 1.21	1.71 ± 0.49
f_0	0.64 ± 0.09	-1.83 ± 1.22	0.56 ± 0.51
f_+	0.77 ± 0.07	-4.09 ± 1.18	0.35 ± 0.49
g_{\perp}	0.56 ± 0.07	-0.35 ± 1.26	0.15 ± 0.29
g_0	0.63 ± 0.07	-1.37 ± 1.36	0.15 ± 0.29
g_+	0.56 ± 0.08	0.00 ± 1.38	0.14 ± 0.29

Differential decay widths

- The differential decay widths of $\Xi_c^0 \rightarrow \Xi^- l^+ \nu_l$:

$$\frac{d\Gamma}{dq^2 |V_{cs}|^2} \quad (\text{ps}^{-1}\text{GeV}^{-2})$$



- Results for $\Xi_c^+ \rightarrow \Xi^0 l^+ \nu_l$ are similar.

Branching fractions and differential decay widths



$$\mathcal{B}(\Xi_c^0 \rightarrow \Xi^- e^+ \nu_e) = 2.38(0.30)(0.32)(0.07)\%$$

$$\mathcal{B}(\Xi_c^0 \rightarrow \Xi^- \mu^+ \nu_\mu) = 2.29(0.29)(0.30)(0.06)\%$$

$$\mathcal{B}(\Xi_c^+ \rightarrow \Xi^0 e^+ \nu_e) = 7.18(0.90)(0.96)(0.20)\%$$

$$\mathcal{B}(\Xi_c^+ \rightarrow \Xi^0 \mu^+ \nu_\mu) = 6.91(0.87)(0.91)(0.19)\%$$

- Statistical errors
- Systematic errors from continuum extrapolation
- Systematic errors from renormalization

$$(2.38 \pm 0.44)\%$$

PDG $\mathcal{B}(\Xi_c^0 \rightarrow \Xi^- e^+ \nu_e) = (1.8 \pm 1.2)\%$

Belle $\mathcal{B}(\Xi_c^0 \rightarrow \Xi^- e^+ \nu_e) = (1.72 \pm 0.10 \pm 0.12 \pm 0.50)\%$

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QCD SR $\mathcal{B}(\Xi_c^0 \rightarrow \Xi^- e^+ \nu_e) = (3.4 \pm 1.7)\%$

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LCSR $\mathcal{B}(\Xi_c^0 \rightarrow \Xi^- e^+ \nu_e) = (2.4^{+0.9}_{-1.0})\%$

Our results fit the experimental measurements and theoretical predictions well!

Determination of $|V_{cs}|$



- From Belle measurements: Y. B. Li et al. [Belle], arXiv:2103.06496 [hep-ex].

$$\mathcal{B}(\Xi_c^0 \rightarrow \Xi^- e^+ \nu_e) = (1.72 \pm 0.10 \pm 0.12 \pm 0.50)\%$$

From the uncertainty of $\Xi_c^0 \rightarrow \Xi^- \pi^+$

$$\mathcal{B}(\Xi_c^0 \rightarrow \Xi^- \mu^+ \nu_\mu) = (1.71 \pm 0.17 \pm 0.13 \pm 0.50)\%$$

$$|V_{cs}| = 0.834 \pm (0.051)_{\text{stat.}} \pm (0.56)_{\text{syst.}} \pm (0.127)_{\text{exp.}}$$

Theo. error ~ 8.9%

Exp. error ~ 15.2%

- From ALICE measurements: J. Zhu on behalf of the ALICE collaboration, PoS ICHEP2020 (2021) 524.

$$\mathcal{B}(\Xi_c^0 \rightarrow \Xi^- e^+ \nu_e) = (2.43 \pm 0.25 \pm 0.35 \pm 0.72)\%$$

$$|V_{cs}| = 0.983 \pm (0.060)_{\text{stat.}} \pm (0.065)_{\text{syst.}} \pm (0.167)_{\text{exp.}}$$

Exp. error ~ 17.0%

- Compare with PDG result:

$$|V_{cs}| = 0.97320 \pm 0.00011$$

Theoretical uncertainties:

- total ~ 8.9%
- statistical ~ 6.1%
- systematic from extrapolation ~ 6.5%
- systematic from renormalization ~ 1.5%

Experimental uncertainties:

- Belle ~ 15.2%
- ALICE ~ 17.0%

SUMMARY



- ◆ The **first lattice QCD calculation** of $\Xi_c \rightarrow \Xi$ form factors: predicted the **differential decay widths, branching fractions**, and extracted the CKM matrix element $|V_{cs}|$;
- ◆ The lattice calculation was done on **two lattice spacings** and **extrapolated to the continuum**;
- ◆ A more precise experimental measurement will greatly **improve the precision** in $|V_{cs}|$ and can be achieved in future especially by Belle-II, LHCb and other experiments.



Thank you for your attentions!