Charmed Baryon Ξ_c Decays From Lattice QCD

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- Based on arXiv:hep-lat/2103.07064, and work in progress
- In collaboration with Q.A. Zhang, J.Hua, F.Huang, R.Li, Y.Li, C.D.Lv, P.Sun, W.Sun and Y.B.Yang.

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Outline

- ✓ Charm Quark Physics
- ✓ Lattice QCD
- ✓ Ξ_c Decays
- ✓ Lattice Results for Ξ_c form factors and $|V_{cs}|$
- ✓ Summary

Charm Quark Physics: SM test

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

PDG2021

First row:

$$|V_{ud}| = 0.97370 \pm 0.00014$$
$$|V_{us}| = 0.2245 \pm 0.0008$$
$$|V_{ub}| = 0.00382 \pm 0.00024$$

10^{-4} *accuracy*

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9985 \pm 0.0006$$

Second row:

$$|V_{cd}| = 0.221 \pm 0.004$$
$$|V_{cs}| = 0.987 \pm 0.011$$
$$|V_{cb}| = 0.0410 \pm 0.0014$$

10^{-4} *accuracy*

$$|V_{cd}|^2 + |V_{cs}|^2 + |V_{cb}|^2 = 1.025 \pm 0.022$$

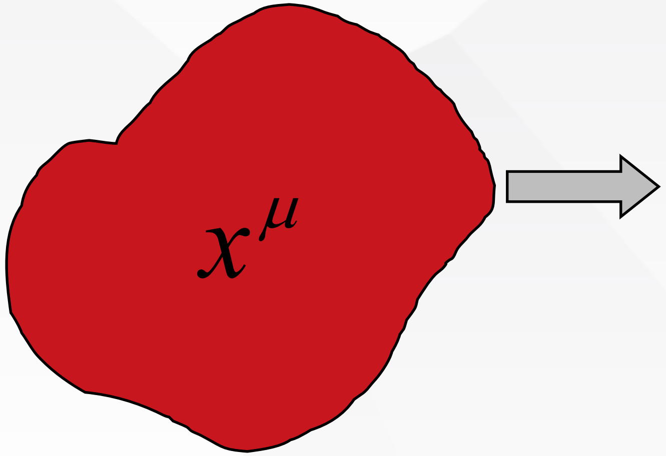
High precision determination of the second row provide strong tests of CKM unitarity.

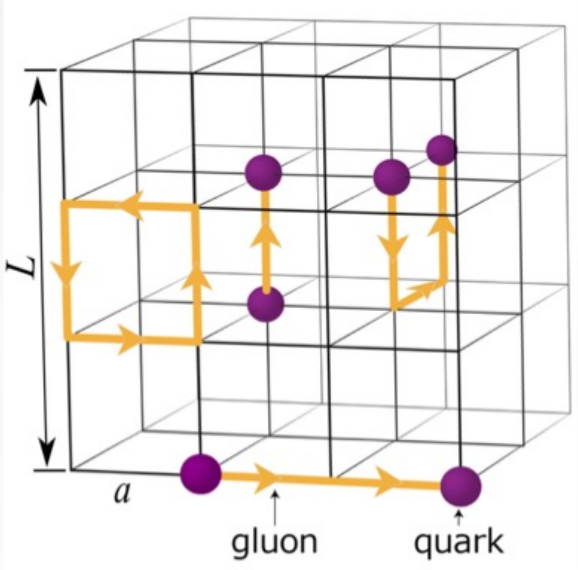
Lattice QCD

- Numerical simulation in discretized Euclidean space-time

- Finite volume (L should be large)

- Finite lattice spacing (a should be small)





Tremendous successes in hadron spectroscopy, decay constants, form factors, etc.

Path Integral: $$Z=\int DA_\mu D\psi D\overline{\psi}e^{-(S_g+S_f)}=\int DA_\mu \det M e^{-S_g}$$

Observable: $$\langle O(A_\mu,\bar{\Psi}\Psi)\rangle=\frac{1}{Z}\int \mathcal{D}A_\mu\mathcal{D}\bar{\Psi}\mathcal{D}\Psi\,\exp(-S(A_\mu,\bar{\Psi},\Psi)O(A_\mu,\bar{\Psi},\Psi)$$

Monte Carlo Integration and Configurations: $P=\frac{1}{Z}\times e^{-(S_g+S_f)}$

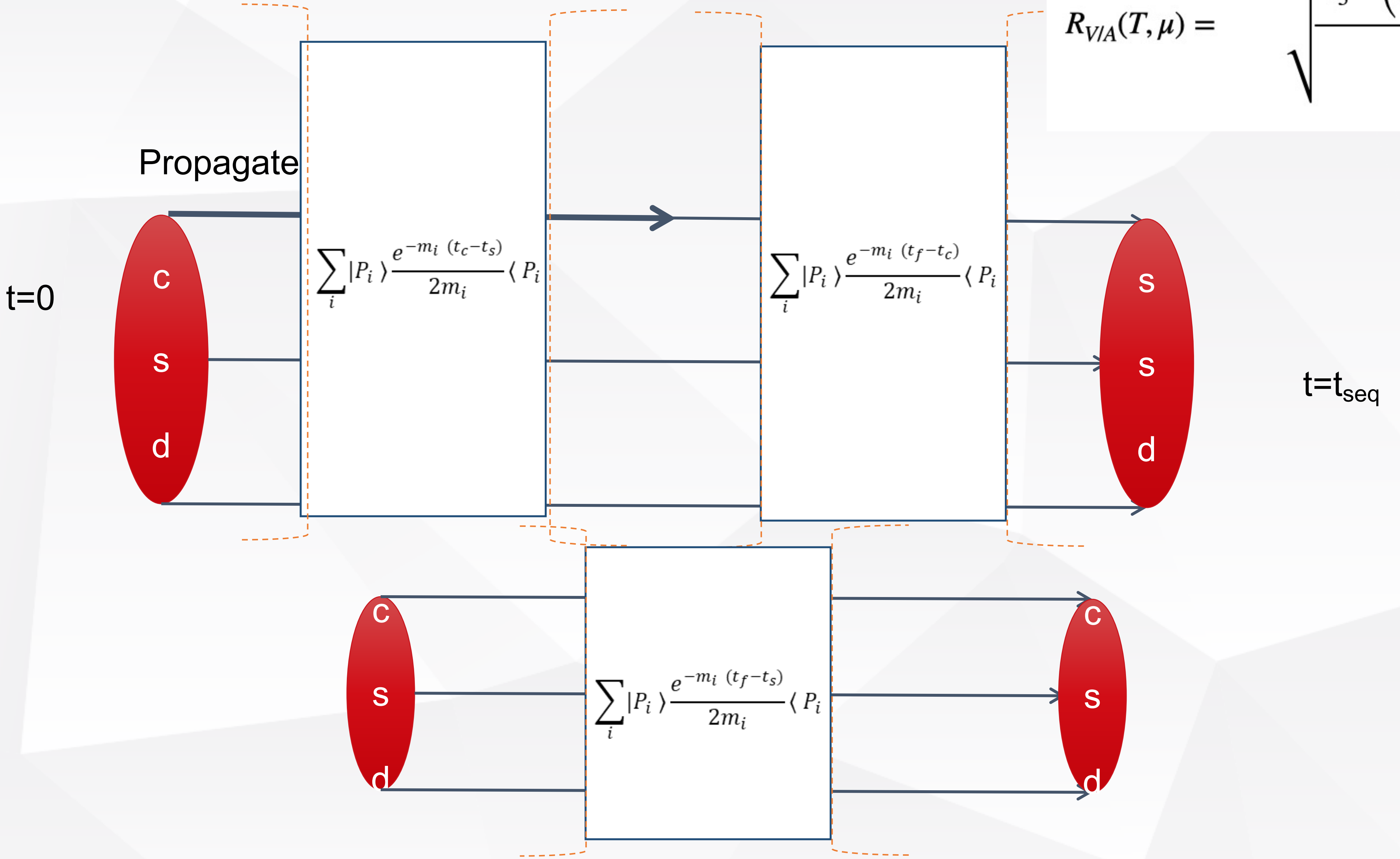
Lattice QCD

Lattice size	Lattice spacing	Pion mass	N cfg
24x72	0.108fm	280-290MeV	2000+
32x96	0.08fm	280-300MeV	1000+
48x144	0.055fm	280MeV	producing
48x96	0.108fm	200MeV	producing
48x96	0.108fm	140MeV	prepare

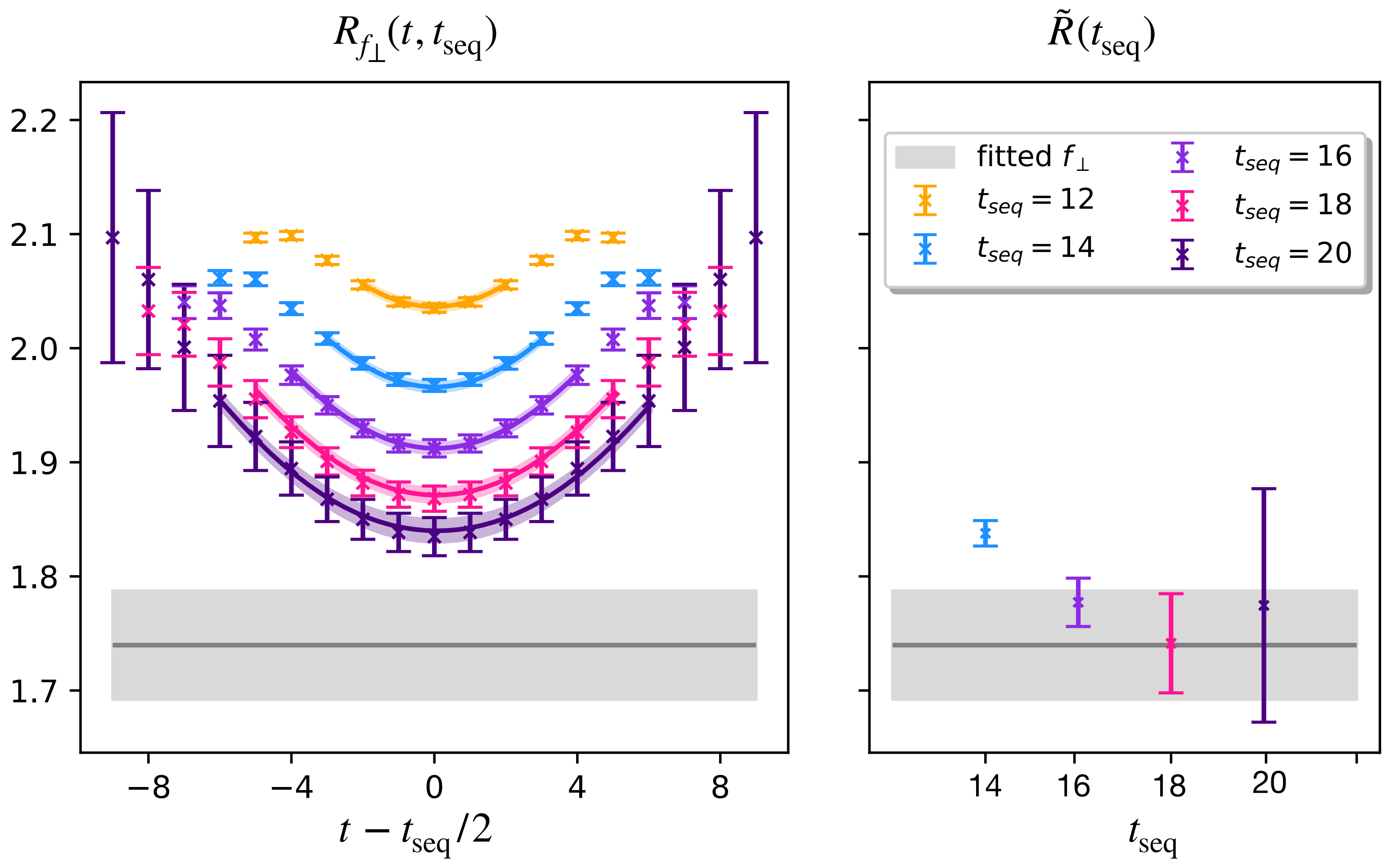
Peng Sun, Yibo Yang, Wei Sun, Liuming Liu

Form factor on the LQCD

$$R_{V/A}(T,\mu)=\sqrt{\frac{C_3^{V/A}\left(q^2,t,t_{\rm seq}\right)C_3^{V/A}\left(q^2,t_{\rm seq}-t,t_{\rm seq}\right)}{C_2^{B_1}\left(t_{\rm seq}\right)C_2^{B_2}\left(t_{\rm seq}\right)}}$$



Form factor on the LQCD



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

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- Ξ_c contains more **versatile decay modes**

  - $\Xi_c \to \Xi$ contain different QCD dynamics with $\Lambda_c \to \Lambda$;

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

$$\frac{\mathcal{B}(\Lambda_c^+ \to X e^+ \nu_e) = (3.95 \pm 0.34 \pm 0.09)\,\%}{\mathcal{B}(\Lambda_c^+ \to \Lambda e^+ \nu_e) = (3.63 \pm 0.38 \pm 0.20)\,\%} \sim 1$$

$$\frac{\mathcal{B}(D^0 \to X e^+ \nu_e) = (6.49 \pm 0.11)\,\%}{\mathcal{B}(D^0 \to K^- e^+ \nu_e) = (3.542 \pm 0.035)\,\%} \sim 2$$

M. Ablikim et al. [BESIII], PRL121, 251801 (2018)

Ξ_c Decays

- **Importance for the experimental researches of heavy baryons:**

  - Studies of doubly-charmed baryon Ξ_{cc}^{++} decay

    R. Aaij et al. [LHCb], PRL121, 162002 (2018)

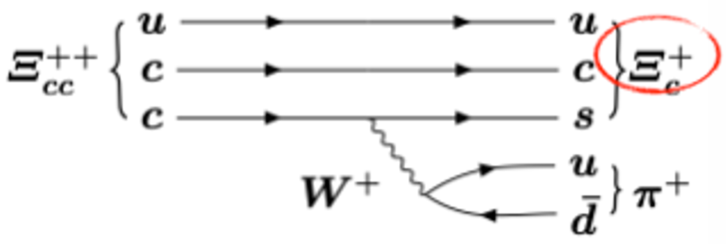
  - Precision measurement of the lifetime of Ξ_b^0

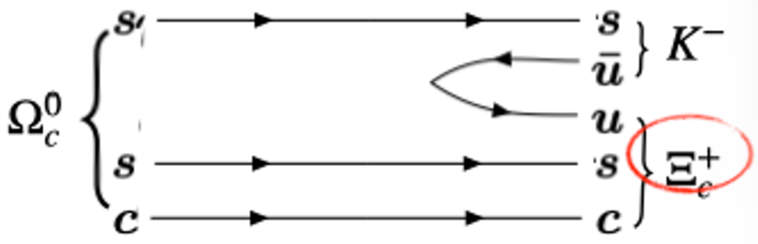
    R. Aaij et al. [LHCb], PRL113, 032001 (2014)

  - Discovery of new exotic hadron candidates Ω_c

    R. Aaij et al. [LHCb], PRL118, 182001 (2017)

  - ......





Ξ_c Decays

✓ Experimental

Belle

$$\mathscr{B}\left(\Xi_c^0 \to \Xi^- e^+ \nu_e\right) = (1.72 \pm 0.10 \pm 0.12 \pm 0.50)\,\%$$

$$\mathscr{B}\left(\Xi_c^0 \to \Xi^- \mu^+ \nu_\mu\right) = (1.71 \pm 0.17 \pm 0.13 \pm 0.50)\,\%$$

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

ALICE

$$\mathscr{B}\left(\Xi_c^0 \to \Xi^- e^+ \nu_e\right) = (2.43 \pm 0.25 \pm 0.35 \pm 0.72)\,\%$$

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

✓ Theoretical

QCD SR

$$\mathscr{B}\left(\Xi_c^0 \to \Xi^- e^+ \nu_e\right) = (3.4 \pm 1.7)\,\%$$

Z. X. Zhao, arXiv:2103.09436 [hep-ph].

LF QM

$$\mathscr{B}\left(\Xi_c^0 \to \Xi^- e^+ \nu_e\right) = (3.49 \pm 0.95)\,\%$$

C. Q. Geng et al, arXiv:2012.04147 [hep-ph].

LCSR

$$\mathscr{B}\left(\Xi_c^0 \to \Xi^- e^+ \nu_e\right) = (2.4^{+0.9}_{-1.0})\,\%$$

Y. L. Liu et al, J. Phys. G 37, 115010 (2010).

Lattice ?

Ξ_c Decays on the Lattice

	$\beta = \frac{10}{g^2}$	$L^3 \times T$	a	$c_{\rm SW}$	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

Ξ_c Decays on the Lattice

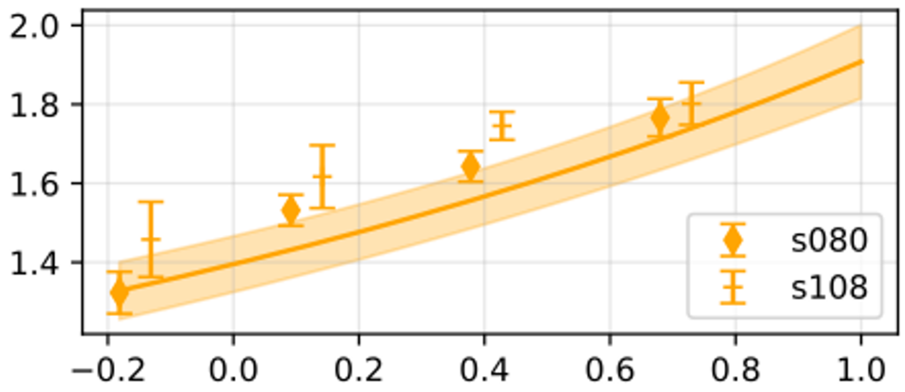
- Extrapolate to the **continuum limit** (shaded regions);

- z-expansion parametrization to obtain the q^2-distribution:

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

- Use **D_s meson pole mass** for $m_{\rm pole}^{f_\perp}$, …

- Consider the **discretization effects** by estimating the d_n^f terms.

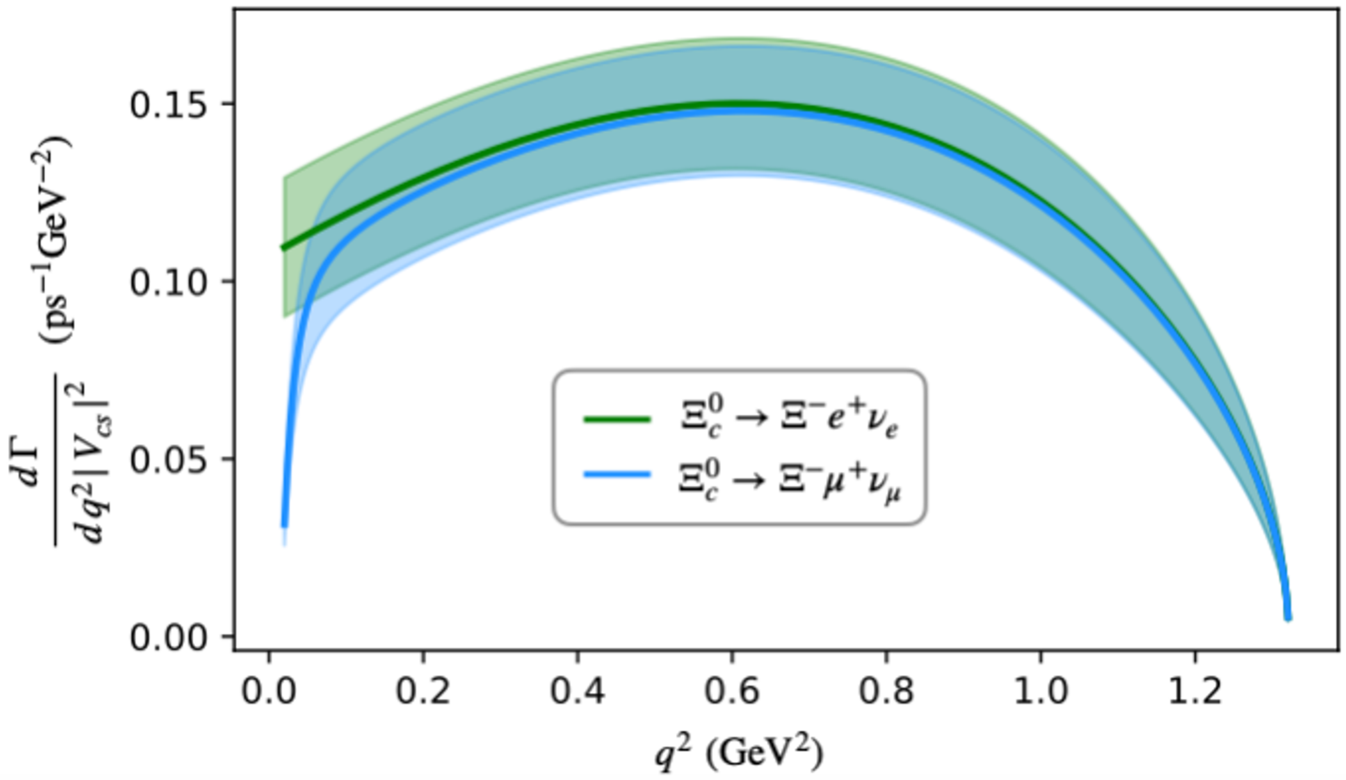


Fit results for the z-expansion parameters

	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

Ξ_c Decays on the Lattice

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



Ξ_c Decays on the Lattice

-Predicted decay branching fractions:

$$\mathcal{B}\left(\Xi_c^0 \to \Xi^- e^+ \nu_e\right) = 2.38(0.30)(0.32)(0.07)\ \%$$
$$\mathcal{B}\left(\Xi_c^0 \to \Xi^- \mu^+ \nu_\mu\right) = 2.29(0.29)(0.30)(0.06)\ \%$$
$$\mathcal{B}\left(\Xi_c^+ \to \Xi^0 e^+ \nu_e\right) = 7.18(0.90)(0.96)(0.20)\ \%$$
$$\mathcal{B}\left(\Xi_c^+ \to \Xi^0 \mu^+ \nu_\mu\right) = 6.91(0.87)(0.91)(0.19)\ \%$$

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

$(2.38 \pm 0.44)\ \%$

-Compare with PDG, experiment and theory:

PDG	$\mathcal{B}\left(\Xi_c^0 \to \Xi^- e^+ \nu_e\right) = (1.8 \pm 1.2)\ \%$	✓
Belle	$\mathcal{B}\left(\Xi_c^0 \to \Xi^- e^+ \nu_e\right) = (1.72 \pm 0.10 \pm 0.12 \pm 0.50)\ \%$	✓
ALICE	$\mathcal{B}\left(\Xi_c^0 \to \Xi^- e^+ \nu_e\right) = (2.43 \pm 0.25 \pm 0.35 \pm 0.72)\ \%$	✓
QCD SR	$\mathcal{B}\left(\Xi_c^0 \to \Xi^- e^+ \nu_e\right) = (3.4 \pm 1.7)\ \%$	✓
LF QM	$\mathcal{B}\left(\Xi_c^0 \to \Xi^- e^+ \nu_e\right) = (3.49 \pm 0.95)\ \%$	✓
LCSR	$\mathcal{B}\left(\Xi_c^0 \to \Xi^- e^+ \nu_e\right) = (2.4^{+0.9}_{-1.0})\ \%$	✓

Fitted well with all data (within 1-σ) !

Ξ_c Decays on the Lattice

-From Belle measurements:

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

$$\mathscr{B}\left(\Xi_c^0 \to \Xi^- e^+ \nu_e\right) = (1.72 \pm 0.10 \pm 0.12 \pm 0.50)\ \%$$

$$\mathscr{B}\left(\Xi_c^0 \to \Xi^- \mu^+ \nu_\mu\right) = (1.71 \pm 0.17 \pm 0.13 \pm 0.50)\ \%$$

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

$$|V_{cs}| = 0.834 \pm (0.051)_{\text{stat.}} \pm (0.056)_{\text{syst.}} \pm (0.127)_{\text{exp.}}$$

Theo. error ~ 8.9% Exp. error ~ 15.2%

-From ALICE measurements:

J. Zhu, PoS ICHEP2020 (2021) 524.

$$\mathscr{B}\left(\Xi_c^0 \to \Xi^- e^+ \nu_e\right) = (2.43 \pm 0.25 \pm 0.35 \pm 0.72)\ \%$$

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

Exp. error ~ 17.0%

-Compare with PDG result:

$$|V_{cs}| = 0.987 \pm 0.011$$

$$|V_{cs}| = 0.939 \pm 0.038 \quad D \to K\ell\nu$$

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%

Charmed Baryon Decays on the Lattice: Prospect

- **More precise:**
  - Continuum limit: one more lattice spacing;
  - Physical pion mass: 290MeV/300MeV $\to$ 140MeV;
  - A finer grid to obtain a better resolution of q^2-dependence;
- **More general:**
  - Generalized analysis of semileptonic weak decays of singly charmed baryons $(\Lambda_c^+, \Xi_c^{0,+}, \Omega_c^0)$;
  - Doubly charmed baryon decays;
  - ......

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Summary

✓ Weak decays of charmed hadrons can play a very important role in testing SM and probing NP.

✓ A set of new configurations have been generated and can be used for multi-purpose phenomenological analysis.

✓ The first lattice QCD calculation of $\Xi_c \to \Xi$ form factors and the CKM matrix element

$|V_{cs}| = 0.834 \pm 0.051 \pm 0.056 \pm 0.127.$ Belle data

$|V_{cs}| = 0.983 \pm 0.060 \pm 0.065 \pm 0.167.$ ALICE data

✓ More exciting analyses of charmed hadrons are undergoing.

Thank you very much!

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