Latest results on semileptonic charm decays

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on behalf of the BESIII Collaboration
with results from Belle

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The XV International Conference on Heavy Quarks and Leptons
University of Warwick

Outline

Introduction

Recent Measurements

Conclusions

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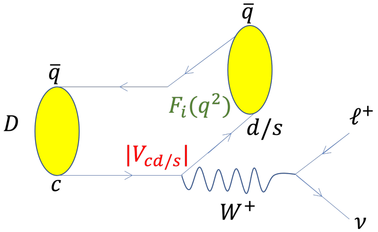
Why are semileptonic decays interesting?

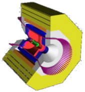


$$\frac{d\Gamma}{dq^2} \propto \sum_i \left(F_i(q^2)|V_{cd/s}|\right)^2, \;\; q^2 \equiv \ell^+\nu \text{ 4-mom.}$$

- Extract $F_i(q^2)|V_{cd/s}|$ from measured BFs and
  - Test CKM Unitarity with $|V_{cd}|$ and $|V_{cs}|$
  - OR Test QCD predictions of $F_i(q^2)$
- Test lepton universality in the charm sector
- Semileptonic decays provide laboratory for light meson physics

Experiments that contribute to SL Charm Measurements

CLEO-c



BABAR

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BESIII

Belle, Belle II

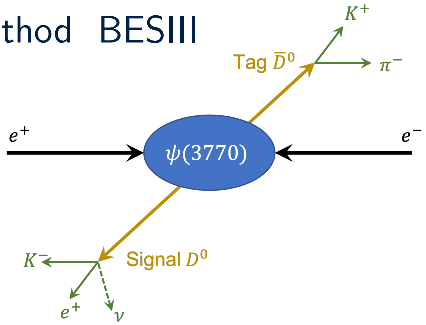
- Symmetric e^+e^-
- $\sqrt{s}$: $2.0 - 5.0$ GeV
- Charm collected through pair-production near threshold

- Asymmetric e^+e^-
- $\sqrt{s}$: 10.8 GeV
- Charm collected through $b\bar{b}$ decays and $c\bar{c}$

Datasets

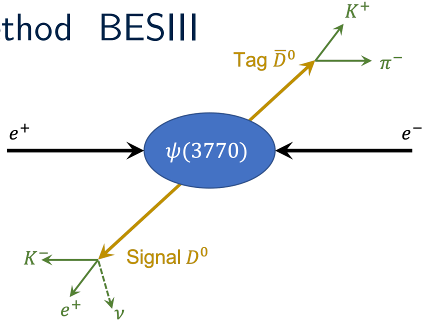
- CLEO-c: Data collected until 2008
  - $D^{+(0)}$ 0.82 fb^{-1} @ $E_{cm} = 3.77$ GeV.
  - D_s^+ 0.57 fb^{-1} @ $E_{cm} = 4.170$ GeV.
- BESIII
  - $D^{+(0)}$ 2.93 fb^{-1} @ $E_{cm} = 3.773$ GeV. Collected in 2011
  - D_s^+ 6.32 fb^{-1} @ $E_{cm} = 4.178 - 4.230$ GeV. Collected in 2013-2017
  - Λ_c^+ 0.587 fb^{-1} @ $E_{cm} = 4.600$ GeV. Collected in 2014
- BABAR: Data collected until 2008
  - 468 fb^{-1} near $\Upsilon(4S)$
- Belle: Data collected until 2010
  - 976 fb^{-1} near $\Upsilon(4S)$

Double Tag Method BESIII



- Reconstruct $\overline{D}^0$ through clean decay mode (the tag)

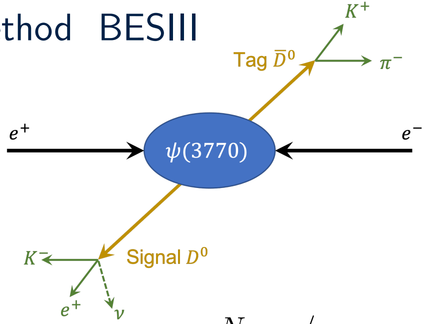
Double Tag Method BESIII



- Reconstruct $\overline{D}^0$ through clean decay mode (the tag)
- Search for signal process of the D^0 and determine N_{Signal} with

$$M^2_{\text{miss}} \text{ or } U_{\text{miss}} \equiv E_{\text{miss}} - p_{\text{miss}}$$

Double Tag Method BESIII

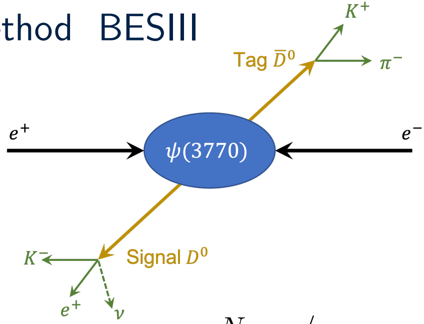


$$\mathcal{B}(D^0 \to \text{signal}) = \frac{N_{\text{Signal}}/\epsilon_{\text{Tag \& Signal}}}{N_{\text{Tag}}/\epsilon_{\text{Tag}}}$$

- Reconstruct $\overline{D}^0$ through clean decay mode (the tag)
- Search for signal process of the D^0 and determine N_{Signal} with

$$M^2_{\text{miss}} \text{ or } U_{\text{miss}} \equiv E_{\text{miss}} - p_{\text{miss}}$$

Double Tag Method BESIII



$$\mathcal{B}(D^0 \to \text{signal}) = \frac{N_{\text{Signal}}/\epsilon_{\text{Tag \& Signal}}}{N_{\text{Tag}}/\epsilon_{\text{Tag}}}$$

- Reconstruct $\overline{D}^0$ through clean decay mode (the tag)
- Search for signal process of the D^0 and determine N_{Signal} with

$$M^2_{\text{miss}} \text{ or } U_{\text{miss}} \equiv E_{\text{miss}} - p_{\text{miss}}$$

- Advantages: Don't need to know $N_{D\overline{D}}$, removes large component of backgrounds, allows access to recoil variables

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$D^0 \to K^-\mu^+\nu$

- Using BESIII data @ $E_{CM} = 3.773$ GeV
- Double tag with 3 D^0 tag modes
- Peaking background: $D^0 \to K^-\pi^+\pi^0$
- Phase space leads to differences in Γ, $\frac{d\Gamma}{dq^2}$

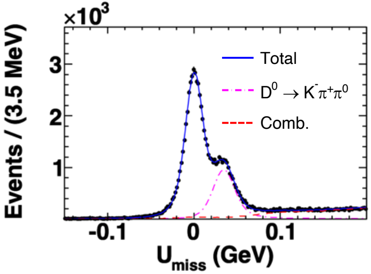
From PRD92(2015)072012:

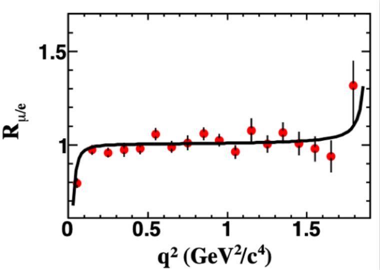
$$\mathcal{B}_{\text{BESIII}}\left(D^0 \to K^-e^+\nu\right) = 3.505(14)(33)\%$$

$$\frac{\mathcal{B}\left(D^0 \to K^-\mu^+\nu\right)}{\mathcal{B}\left(D^0 \to K^-e^+\nu\right)} = 0.974(07)(12)$$

SM Prediction[a]: 0.97

PRL122(2019)011804





$$\mathcal{B}\left(D^0 \to K^-\mu^+\nu\right) = 3.413(19)(35)\%$$

$q^2 \equiv \ell\nu$ mass squared

$\mathbf{R}_{\mu/e} \equiv \left(\Delta\Gamma_\mu/\Delta q^2\right) / \left(\Delta\Gamma_e/\Delta q^2\right)$

[a] Riggio, Salerno, Simula, Eur. Phys. J. C78, 501(2018).
Lubicz, Riggio, Salerno, S. Simula, Tarantino (ETM), Phys. Rev. D96, 054514(2017).

New Double Semileptonic Measurements of $D \to Ke\nu$

- Using BESIII data @ $E_{CM} = 3.773$ GeV
- Tag events with where both D and $\overline{D}$ decay to $\overline{K}(K)e^{\pm}\nu_e$

- $\mathcal{B} \propto \sqrt{N}_{\text{obs}}$
- Cut and Count, Backgrounds subtracted

$$\mathcal{B}\left(D^0 \to K^- e^+ \nu\right) = 3.574(31)(25)\%$$

From PRD92(2015)072012:

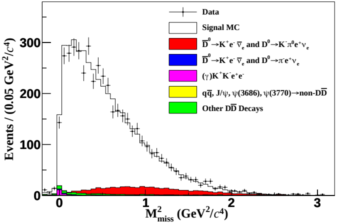
$$\mathcal{B}_{\text{BESIII}}\left(D^0 \to K^- e^+ \nu_e\right) = 3.505(14)(33)\%$$

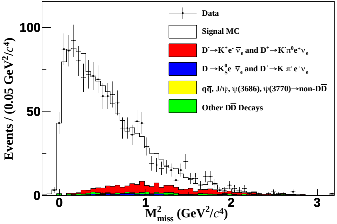
$$\mathcal{B}\left(D^+ \to \overline{K}^0 e^+ \nu_e\right) = 8.70(14)(16)\%$$

From PRD96(2017)012002:

$$\mathcal{B}_{\text{BESIII}}\left(D^+ \to \overline{K}^0 e^+ \nu_e\right) = 8.60(06)(15)\%$$

arXiv:2104.08081
Submitted to PRD

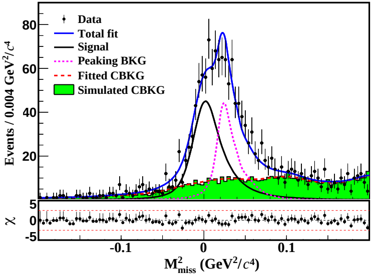




$D^0 \to \rho^- \mu^+ \nu$

- Using BESIII data @ $E_{CM} = 3.773$ GeV
- Double tag with 3 D^0 tag modes
- Peaking background: $D^0 \to \pi^+\pi^-\pi^0\pi^0$
- ρ^- reconstructed through $\pi^-\pi^0$

arXiv:2106.022924
Submitted to PRL



$$\mathcal{B}\left(D^0 \to \rho^- \mu^+ \nu\right) = 1.35(09)(09) \times 10^{-3}$$

$$\mathcal{B}_{\text{PDG}}\left(D^0 \to \rho^- e^+ \nu\right) = 1.50(12) \times 10^{-3}$$

$$\frac{\mathcal{B}\left(D^0 \to \rho^- \mu^+ \nu\right)}{\mathcal{B}\left(D^0 \to \rho^- e^+ \nu\right)} = 0.90(11)$$

SM Prediction[a]: $0.93 - 0.96$

With PDG values for $\mathcal{B}\left(D^+ \to \rho^0 e^+ \nu\right)$, τ_{D^0} and τ_{D^+}

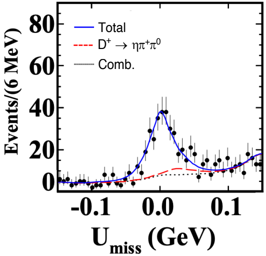
$$\frac{\Gamma\left(D^0 \to \rho^- \mu^+ \nu\right)}{2\Gamma\left(D^+ \to \rho^0 \mu^+ \nu\right)} = 0.71(14)$$

[a] See appendix for citations

▶ $D^+ \to \eta\mu^+\nu$

- Using BESIII data @ $E_{CM} = 3.773$ GeV
- Double tag with 6 D^+ tag modes
- Peaking Background: $D^0 \to \eta\pi^+\pi^0$

PRL124(2020)231801



$$\mathcal{B}\left(D^+ \to \eta\mu^+\nu\right) = (10.4 \pm 1.0 \pm 0.5) \times 10^{-4}$$

$$\frac{\mathcal{B}\left(D^+ \to \eta\mu^+\nu\right)}{\mathcal{B}\left(D^+ \to \eta e^+\nu\right)} = 0.91 \pm 0.13$$

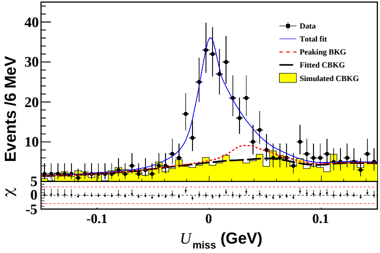
with PDG2020 Average of $\mathcal{B}(D^+ \to \eta e^+\nu)$

SM Pred[a]: 0.97-1.00

▶ $D^+ \to \omega\mu^+\nu$

- Using BESIII data @ $E_{CM} = 3.773$ GeV
- Double tag with 6 D^+tag modes
- Peaking Background: $D^0 \to \omega\pi^+\pi^0$

PRD101(2020)072005



$$\mathcal{B}\left(D^+ \to \omega\mu^+\nu\right) = (17.7 \pm 1.8 \pm 1.1) \times 10^{-4}$$

$$\frac{\mathcal{B}\left(D^+ \to \omega\mu^+\nu\right)}{\mathcal{B}\left(D^+ \to \omega e^+\nu\right)} = 1.05 \pm 0.14$$

with PDG2020 Average of $\mathcal{B}(D^+ \to \omega e^+\nu)$

SM Pred[a]: 0.93-0.99

[a] See appendix for citations.

$\Xi_c^0 \to \Xi^- \ell^+ \nu$

- Using Belle data @ $E_{CM} = 10.52, 10.58$ GeV
- Ξ^- reconstructed through $\Lambda\pi^-, \Lambda \to p\pi^-$
- BF measured in reference to $\Xi_c^0 \to \Xi^-\pi^+$
- After selections, signal yields determined with fits to $M_{\Xi^- X^+}$ in bins of $p^*_{\Xi^- X}/p^*_{\text{max}}$

$$\mathcal{B}\left(\Xi_c^0 \to \Xi^- e^+ \nu_e\right) = 1.31(04)(07)(38)\%$$

$$\mathcal{B}\left(\Xi_c^0 \to \Xi^- \mu^+ \nu_\mu\right) = 1.27(06)(10)(37)\%$$

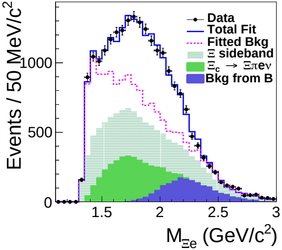
$$\frac{\mathcal{B}\left(\Xi_c^0 \to \Xi^- \mu^+ \nu_\mu\right)}{\mathcal{B}\left(\Xi_c^0 \to \Xi^- e^+ \nu_e\right)} = 0.97(05)(07)$$

arXiv:2103.06496

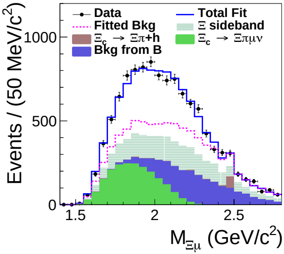
To Appear in PRL

$p^*_{\Xi^- X}/p^*_{\text{max}} \in (0.55, 0.65)$

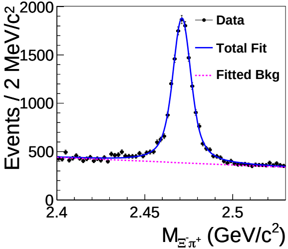
Ξe



$\Xi\mu$



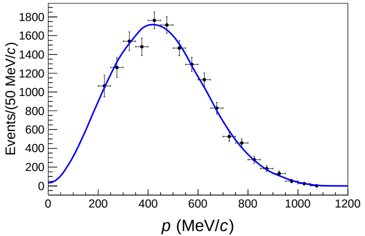
$\Xi\pi$



$D_s^+ \to X e^+ \nu_e$

- Using BESIII data @ $E_{CM} = 4.178 - 4.230$ GeV
- $D_s^* D_s$ Double tag with $D_s^+ \to K^+ K^- \pi^+$ tag mode
- Detector effects corrected through unfolding
- $D_s^+ \to \tau^+ \nu_\tau \to e^+ \nu_e \overline{\nu}_\tau \nu_\tau$ events subtracted
- Events with $p_e < 200$ MeV$/c$ estimated with fit

PRD104(2021)012003



Solid Blue: Predicted momentum spectrum based on observed exclusive D_s^+ SL decays

$$\mathcal{B}\left(D_s^+ \to X e^+ \nu_e\right) = 6.30(13)(10)\%$$

Comparing with PDG branching fractions for exclusive BF's

Unobserved SL D_s^+ BF: $-0.04(13)(09)(17)\%$

- D_s^+ ideal to study non-spectator effects

With PDG values for $\mathcal{B}\left(D^0 \to X e^+ \nu_e\right)$, τ_{D^0} and τ_{D^s}

$$\frac{\Gamma\left(D_s^+ \to X e^+ \nu_e\right)}{\Gamma\left(D^0 \to X e^+ \nu_e\right)} = 0.790(16)(11)(16)$$

From PRD83(2011)034025

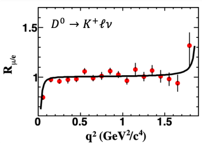
$$\frac{\Gamma\left(D_s^+ \to X e^+ \nu_e\right)}{\Gamma\left(D^0 \to X e^+ \nu_e\right)} = 0.813$$

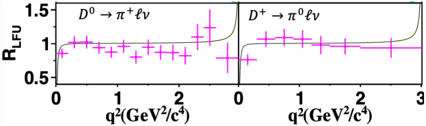
Outline

Charm LFU Overview

Mode	Measured[a] $\mathcal{B}(\ell)/\mathcal{B}(\ell')$	SM Prediction
$D^+ \to \frac{\tau}{\mu}\nu$	3.21 ± 0.77	2.66
$D_s^+ \to \frac{\tau}{\mu}\nu$	9.72 ± 0.37	9.75
$D^0 \to \rho^- \frac{\mu}{e}\nu$	0.90 ± 0.11	$0.93 - 0.96$
$D^+ \to \eta \frac{\mu}{e}\nu$	0.91 ± 0.13	$0.97 - 1.00$
$D^+ \to \omega \frac{\mu}{e}\nu$	1.05 ± 0.14	$0.93 - 0.99$
$D^+ \to \pi^0 \frac{\mu}{e}\nu$	0.964 ± 0.045	~ 0.985
$D^0 \to \pi^+ \frac{\mu}{e}\nu$	0.922 ± 0.037	~ 0.985
$D^0 \to K^+ \frac{\mu}{e}\nu$	0.974 ± 0.014	~ 0.970
$\Lambda_c^+ \to \Lambda \frac{\mu}{e}\nu$	0.96 ± 0.16	~ 1
$\Xi_c^0 \to \Xi^- \frac{\mu}{e}\nu$	0.97 ± 0.08	~ 1

μ/e Ratios of $\frac{d\Gamma}{dq^2}$

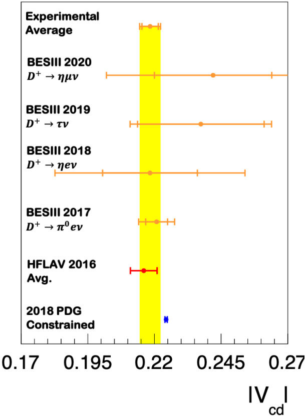


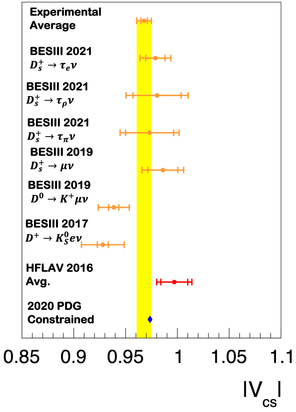


[a] See appendix for citations.

$|V_{cd}|$ and $|V_{cs}|$: Selected Recent Results

$f_{D_{(s)}}$ and $f_+^{D\to K(\pi)}$ averaged from FLAG 2019 Avgs. + FMILC 2019 $D \to K(\pi)e^+\nu_e$
$f_+^{D\to\eta}$ from . from Front. Phys. 14(2019)64401.





Inner Error Bars are statistics only
Orange points not included in HFLAV Averages

Summary & Prospects

- Several recent precision measurements of $|V_{cs}|$
- No evidence for LFUV in leptonic/semileptonic charm decays
- Semimuonic D_s^+ decays currently being analyzed @ BESIII
- Large BESIII data sets (~ 3.7 fb^{-1}) recently collected between $4.6 - 4.7$ GeV, first data at Ξ_c pair production thresholds
- Significantly more data collection planned @ $\psi(3770)$ in the near future @ BESIII
- More detail on future prospects in BESIII white paper: Chin. Phys. C 44, 040001 (2020)
- Belle II data will provide competitive measurements of charm SL decays, Belle II Physics Book: PTEP 12, 123C01 (2019)

Thanks for your attention!

Appendix - Citations

Standard Model predictions for $\frac{\mathcal{B}(D^+ \to \eta\mu^+\nu)}{\mathcal{B}(D^+ \to \eta e^+\nu)}$:

- Y. L. Wu, M. Zhong, and Y. B. Zuo, Int. J. Mod. Phys. A21,6125 (2006)
- H. Y. Cheng and X. W. Kang, Eur. Phys. J. C77, 587(2017);77, 863(E) (2017)
- M. A. Ivanov, J. G. Körner, J. N. Pandya, P. Santorelli, N. R. Soni, and C. T. Tran, Front. Phys.14, 64401 (2019)

Standard Model predictions for $\frac{\mathcal{B}(D^+ \to \omega\mu^+\nu)}{\mathcal{B}(D^+ \to \omega e^+\nu)}$:

- H. Y. Cheng and X. W. Kang, Eur. Phys. J. C77, 587(2017);77, 863(E) (2017)
- T. Sekihara and E. Oset, Phys. Rev. D92, 054038 (2015)
- N. R. Soni, M. A. Ivanov, J. G. Körner, J. N. Pandya, P. Santorelli, and C. T. Tran, Phys. Rev. D98, 114031 (2018)
- M. A. Ivanov, J. G. Körner, J. N. Pandya, P. Santorelli, N. R. Soni, and C. T. Tran, Front. Phys.14, 64401 (2019)
- H.B. Fu, W. Cheng, L. Zheng, D.D. Hu, T. Zhong, Phys. Rev. Research 2, 043129 (2020)
- R. N. Faustov, V. O. Galkin, and X. W. Kang, Phys. Rev. D101, 013004 (2020)

Appendix - Citations

Standard Model predictions for $\frac{\mathcal{B}(D^0 \to \rho^- \mu^+ \nu)}{\mathcal{B}(D^0 \to \rho^- e^+ \nu)}$:

- Y. L. Wu, M. Zhong, and Y. B. Zuo, Int. J. Mod. Phys. A 21, 6125 (2006)
- T. Sekihara and E. Oset, Phys. Rev. D92, 054038 (2015)
- N. R. Soni, M. A. Ivanov, J. G. Körner, J. N. Pandya, P. Santorelli, and C. T. Tran, Phys. Rev. D98, 114031 (2018)
- M. A. Ivanov, J. G. Körner, J. N. Pandya, P. Santorelli, N. R. Soni, and C. T. Tran, Front. Phys.14, 64401 (2019)
- H. Y. Cheng and X. W. Kang, Eur. Phys. J. C77, 587(2017);77, 863(E) (2017)
- R. N. Faustov, V. O. Galkin, and X. W. Kang, Phys. Rev. D101, 013004 (2020)

Appendix - Citations

- $D^+ \to \tau^+\nu_\tau$: M. Ablikim et al. (BESIII Collaboration), Phys. Rev. Lett. 123, 211802 (2019)
- $D_s^+ \to \tau^+\nu_\tau$: M. Ablikim et al. (BESIII Collaboration), arXiv:2106.02218
- $D^0 \to \rho^-\mu^+\nu_\mu$: M. Ablikim et al. (BESIII Collaboration), arXiv:2106.022924
- $D^+ \to \eta^-\mu^+\nu_\mu$: M. Ablikim et al. (BESIII Collaboration), Phys. Rev. Lett. 124, 231801 (2020)
- $D^+ \to \omega^-\mu^+\nu_\mu$: M. Ablikim et al. (BESIII Collaboration), Phys. Rev. D101, 072005 (2020)
- $D \to \pi\mu^+\nu_\mu$: M. Ablikim et al. (BESIII Collaboration), Phys. Rev. Lett. 121, 171803 (2018)
- $D^0 \to K^-\mu^+\nu_\mu$: M. Ablikim et al. (BESIII Collaboration), Phys. Rev. Lett. 122, 011804 (2019)
- $\Lambda_c^+ \to \Lambda\mu^+\nu_\mu$: M. Ablikim et al. (BESIII Collaboration), Phys. Lett. B, 767 (2017), p. 42
- $\Xi_c^0 \to \Xi^-\ell^+\nu_\mu$: Y. B. Li et al. (Belle Collaboration), arXiv:2103.06496