CHARM SEMILEPTONIC PHYSICS AT BESIII

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On behalf of the BESIII Collaboration

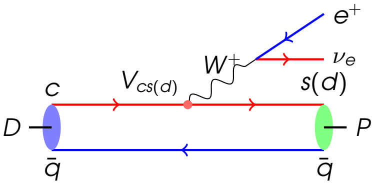
THE 15^{th} MEETING IN THE CONFERENCE SERIES OF FLAVOR PHYSICS & CP VIOLATION, June 5-9, 2017, PRAGUE, CZECH

Outline

Introduction

Charm semileptonic decays provide a window to study week and strong interactions.

- Consider the semileptonic decay where the D meson decays to a pseudoscalar meson, a lepton and its neutrino via a virtual W boson

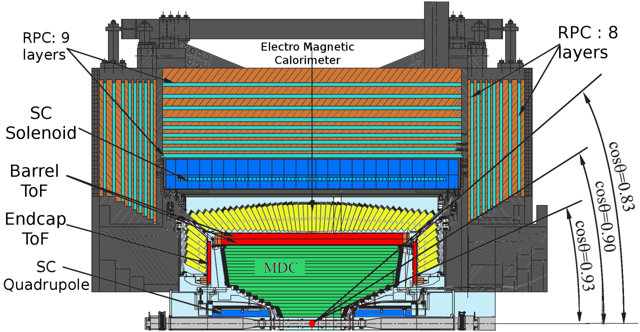


$$\frac{d\Gamma(D \to Pe\nu)}{dq^2} = \frac{G_F^2 |V_{cs(d)}|^2}{24\pi^3} p^3 |f_+(q^2)|^2$$

- Measure hadronic form factors $f_+^{D\to K}(0)$, $f_+^{D\to\pi}(0)$, $\cdots$
  - *To verify lattice QCD*
  - *Verified lattice QCD helps extract the CKM matrix elements $|V_{td}|$ and $|V_{ts}|$ from B-$\bar{B}$ oscillations*
- Extract the CKM matrix elements $|V_{cs}|$ and $|V_{cd}|$
  - *To test the unitarity of the CKM matrix*

BESIII Experiment

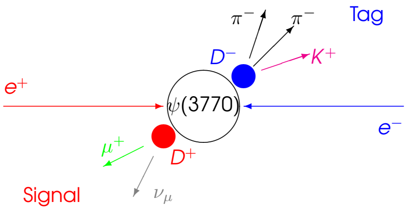
- BEPCII collider
  symmetric e^+e^- collider, double-rings, $2.0\ \text{GeV} < \sqrt{s} < 4.6\ \text{GeV}$
- BESIII detector



- Data sets
  1. D and D^+ Physics: $2.93\ \text{fb}^{-1}$ at $\sqrt{s} = 3.773$ GeV
  2. D_s Physics: $482\ \text{pb}^{-1}$ at $\sqrt{s} = 4.009$ GeV
  3. Λ_c Physics: $567\ \text{pb}^{-1}$ at $\sqrt{s} = 4.599$ GeV

Analysis Technique

$e^+e^- \to c\bar{c} \to \bar{D}_{\rm tag}\, D_{\rm sig}$: Double-tag technique, Absolute measurement



- Tag $\bar{D}_{\rm tag}$ in hadronic decay modes

$$\Delta E = E_{\bar{D}_{\rm tag}} - E_{\rm beam}$$

$$M_{\rm BC} = \sqrt{E^2_{\rm beam} - p^2_{\bar{D}_{\rm tag}}}$$

- Reconstruct $D_{\rm sig}$ using the remaining tracks not associated to $\bar{D}_{\rm tag}$
  - $E_{D_{\rm sig}} = E_{\rm beam}$, $\vec{p}_{D_{\rm sig}} = -\vec{p}_{\bar{D}_{\rm tag}}$
  - no additional tracks/showers
  - (semi-)leptonic decay: missing neutrino, $U_{\rm miss} \equiv E_{\rm miss} - |\vec{p}_{\rm miss}| \sim 0$

$$N_{\rm tag} = 2N_{D\bar{D}}\mathcal{B}_{\rm tag}\varepsilon_{\rm tag}$$

$$N_{\rm tag,SL} = 2N_{D\bar{D}}\mathcal{B}_{\rm tag}\mathcal{B}_{\rm SL}\varepsilon_{\rm tag,SL}$$

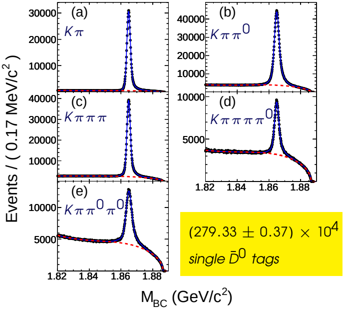
$$\mathcal{B}_{\rm SL} = \frac{N_{\rm tag,SL}}{N_{\rm tag}}\frac{\varepsilon_{\rm tag}}{\varepsilon_{\rm tag,SL}} = \frac{N_{\rm tag,SL}}{N_{\rm tag}\varepsilon}$$

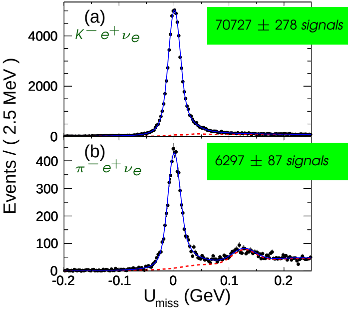
- High tagging efficiency
- Extremely clean
- Systematic uncertainties associated to tag side are mostly canceled out

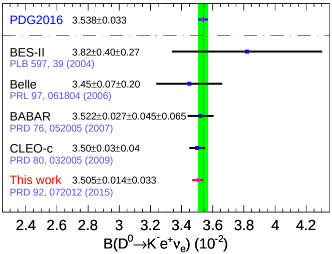
Semileptonic D Decays

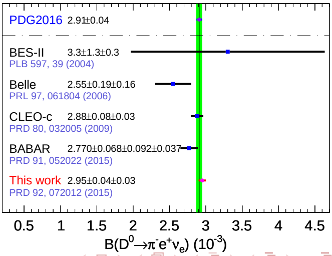
$D^0 \to K^- e^+ \nu_e, \pi^- e^+ \nu_e$

Phys. Rev. D **92**, 072012 (2015)





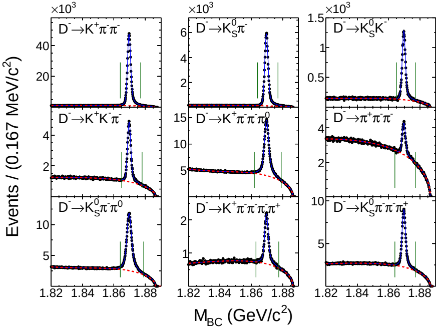


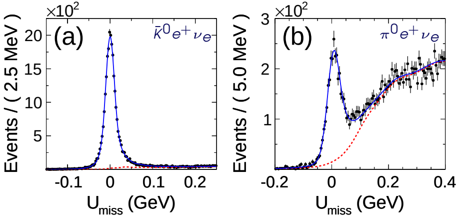


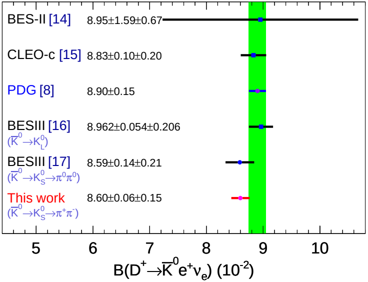
$D^+ \to \bar{K}^0 e^+ \nu_e, \pi^0 e^+ \nu_e$

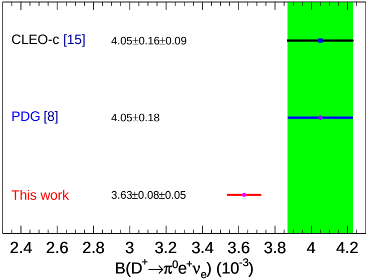
arXiv:1703.09084 (hep-ex)

$(170.31 \pm 0.34) \times 10^4$ *single D^- tags*





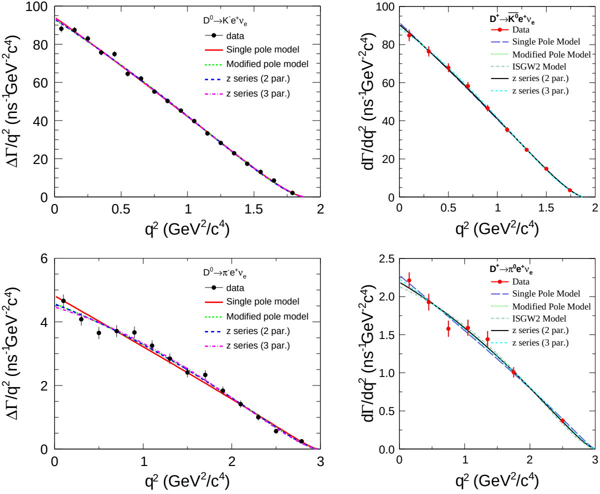




Fits to Partial Decay Rates

Measure partial decay rates in q^2 bins:

$$\Delta\Gamma_i = \frac{N^i_{\rm prd}}{\tau_D N_{\rm tag}} = \frac{1}{\tau_D N_{\rm tag}} \sum_j^{N_{\rm bins}} (\varepsilon^{-1})_{ij} N^j_{\rm obs}$$



Extract $f_+(0)|V_{cs(d)}|$ and other form factor parameters from measured partial decay rates in q^2 bin

Form Factor Parameterizations:

1. Single Pole $f_+(q^2) = \frac{f_+(0)}{1 - q^2/M^2_{\rm pole}}$
2. Modified Pole (BK)

$$f_+(q^2) = \frac{f_+(0)}{\left(1 - q^2/M^2_{\rm pole}\right)\left(1 - \alpha q^2/M^2_{\rm pole}\right)}$$

3. ISGW2

$$f_+(q^2) = f_+(q^2_{\rm max}) \left(1 + \frac{r^2_{\rm ISGW2}}{12}(q^2_{\rm max} - q^2)\right)^{-2}$$

4. Series Expansion

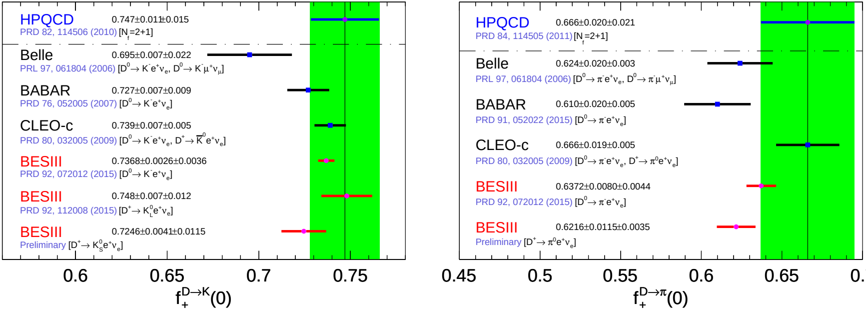
$$f_+(q^2) = \frac{1}{P(q^2)\phi(q^2, t_0)} \sum_{k=0}^{\infty} a_k(t_0) \left[z(q^2, t_0)\right]^k$$

Fits to Partial Decay Rates

- Results of form factor fits for $D \to Pe^+\nu_e$ ($P = K^-, \pi^-, \bar{K}^0, \pi^0$)

	Single pole model		
Decay mode	$f_+(0)\|V_{cs(d)}\|$	$M_{\rm pole}$ (GeV/c^2)	
$D^0 \to K^- e^+\nu_e$	$0.7209 \pm 0.0022 \pm 0.0035$	$1.921 \pm 0.010 \pm 0.007$	
$D^0 \to \pi^- e^+\nu_e$	$0.1475 \pm 0.0014 \pm 0.0005$	$1.911 \pm 0.012 \pm 0.004$	
$D^+ \to \bar{K}^0 e^+\nu_e$	$0.7094 \pm 0.0035 \pm 0.0111$	$1.935 \pm 0.017 \pm 0.006$	
$D^+ \to \pi^0 e^+\nu_e$	$0.1429 \pm 0.0020 \pm 0.0009$	$1.898 \pm 0.020 \pm 0.003$	
	Modified pole model		
Decay mode	$f_+(0)\|V_{cs(d)}\|$	α	
$D^0 \to K^- e^+\nu_e$	$0.7163 \pm 0.0024 \pm 0.0034$	$0.309 \pm 0.020 \pm 0.013$	
$D^0 \to \pi^- e^+\nu_e$	$0.1437 \pm 0.0017 \pm 0.0008$	$0.279 \pm 0.035 \pm 0.011$	
$D^+ \to \bar{K}^0 e^+\nu_e$	$0.7052 \pm 0.0038 \pm 0.0112$	$0.294 \pm 0.031 \pm 0.010$	
$D^+ \to \pi^0 e^+\nu_e$	$0.1400 \pm 0.0024 \pm 0.0010$	$0.285 \pm 0.057 \pm 0.010$	
	Two-parameter series expansion		
Decay mode	$f_+(0)\|V_{cs(d)}\|$	r_1	
$D^0 \to K^- e^+\nu_e$	$0.7172 \pm 0.0025 \pm 0.0035$	$-2.2286 \pm 0.0864 \pm 0.0573$	
$D^0 \to \pi^- e^+\nu_e$	$0.1435 \pm 0.0018 \pm 0.0009$	$-2.0365 \pm 0.0807 \pm 0.0257$	
$D^+ \to \bar{K}^0 e^+\nu_e$	$0.7053 \pm 0.0040 \pm 0.0112$	$-2.18 \pm 0.14 \pm 0.05$	
$D^+ \to \pi^0 e^+\nu_e$	$0.1400 \pm 0.0026 \pm 0.0007$	$-2.01 \pm 0.13 \pm 0.02$	
	Three-parameter series expansion		
Decay mode	$f_+(0)\|V_{cs(d)}\|$	r_1	r_2
$D^0 \to K^- e^+\nu_e$	$0.7195 \pm 0.0035 \pm 0.0041$	$-2.3338 \pm 0.1587 \pm 0.0804$	$3.4188 \pm 3.9090 \pm 2.4098$
$D^0 \to \pi^- e^+\nu_e$	$0.1420 \pm 0.0024 \pm 0.0010$	$-1.8432 \pm 0.2212 \pm 0.0690$	$-1.3874 \pm 1.4615 \pm 0.4680$
$D^+ \to \bar{K}^0 e^+\nu_e$	$0.6983 \pm 0.0056 \pm 0.0112$	$-1.76 \pm 0.25 \pm 0.06$	$-13.4 \pm 6.3 \pm 1.4$
$D^+ \to \pi^0 e^+\nu_e$	$0.1413 \pm 0.0035 \pm 0.0012$	$-2.23 \pm 0.42 \pm 0.06$	$1.4 \pm 2.5 \pm 0.4$

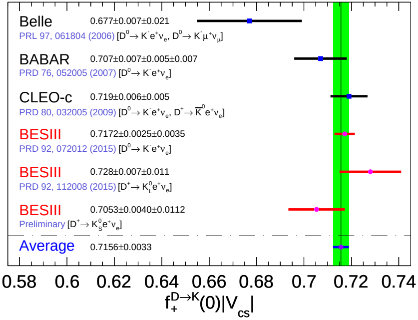
- To determine $f_+^{D\to K(\pi)}(0)$, use the measurements of $f_+^{D\to K(\pi)}(0)|V_{cs(d)}|$ and the PDG values for $|V_{cs(d)}|$ (assuming CKM unitarity)

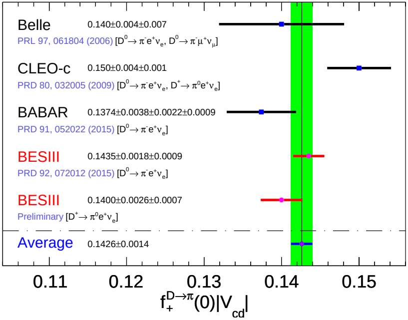


- BESIII made the best precise determinations of these two form factors
- The experimental accuracy is better than that of theoretical predictions

Determination of $|V_{cs(d)}|$

- Measurements of the normalization factors $f_+^{D\to K(\pi)}(0)|V_{cs(d)}|$

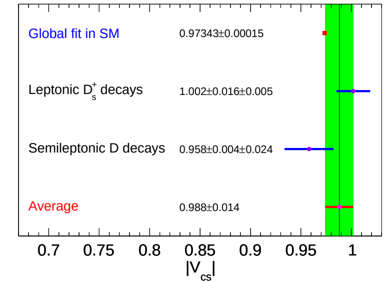


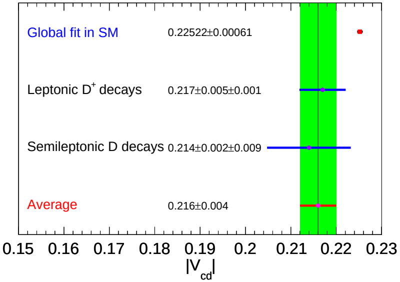


- Using the LQCD calculations [Phys. Rev. D **82**, 114506 (2010); **84**, 114505 (2011)]

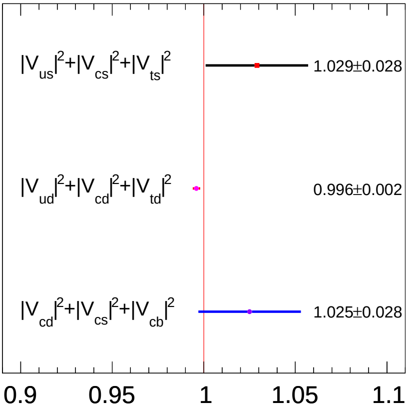
$$f_+^{D\to K}(0) = 0.747 \pm 0.019 \quad \Rightarrow \quad |V_{cs}| = 0.958 \pm 0.004_{\rm expt} \pm 0.024_{\rm LQCD}$$
$$f_+^{D\to \pi}(0) = 0.666 \pm 0.029 \quad \Rightarrow \quad |V_{cd}| = 0.214 \pm 0.002_{\rm expt} \pm 0.009_{\rm LQCD}$$

Determination of $|V_{cs(d)}|$





- **Unitarity checks**
  Use $|V_{cs(d)}|$ values extracted from leptonic and semileptonic decays

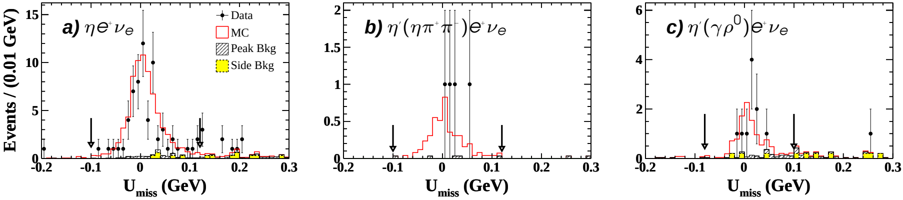


Semileptonic D_s Decays

$D_s^+ \to \eta e^+ \nu_e, \eta' e^+ \nu_e$

Phys. Rev. D **94**, 112003 (2016)

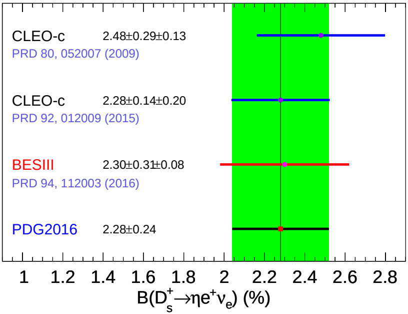
- 10 D_s^- tag modes, $N_{\rm tag} = 13157 \pm 240$

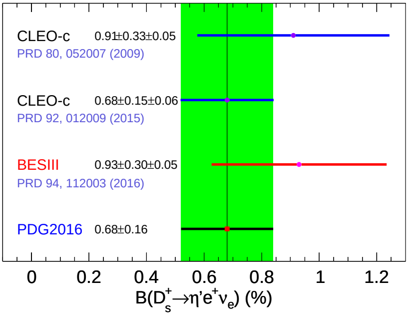


Decay mode		$N_{\rm DT}^{\rm net}$	$\mathcal{B}$ (%)
$D_s^+ \to \eta e^+ \nu_e$		58.5 ± 8.0	$2.30 \pm 0.31 \pm 0.08$
$D_s^+ \to \eta' e^+ \nu_e$	$\eta' \to \eta\pi^+\pi^-$	3.8 ± 2.0	$0.93 \pm 0.30 \pm 0.05$
	$\eta' \to \gamma\rho^0$	8.2 ± 3.8	

- $\mathcal{B}(D_s^+ \to \eta' e^+ \nu_e)/\mathcal{B}(D_s^+ \to \eta e^+ \nu_e) = 0.40 \pm 0.14 \pm 0.02$

$D_s^+ \to \eta e^+ \nu_e, \eta' e^+ \nu_e$

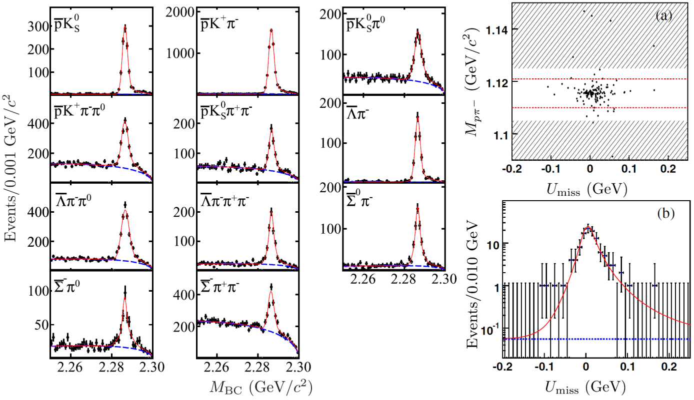




- Agree to previous measurements within uncertainties
- Help improve upon the D_s^+ semileptonic branching ratio precision
- Provide complementary information to understand η-η' mixing

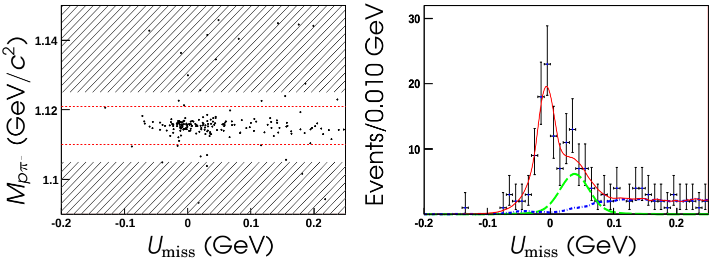
Semileptonic Λ_c Decays

- Theoretical predictions on $\mathcal{B}(\Lambda_c^+ \to \Lambda \ell^+ \nu_\ell)$ vary from 1.4% to 9.2%
- BESIII performed the first absolute measurement of $\mathcal{B}(\Lambda_c^+ \to \Lambda e^+ \nu_e)$



N_{tag}	N_{semi}	ε_{semi} (%)	$\mathcal{B}(\Lambda_c^+ \to \Lambda e^+ \nu_e)$ (%)
14415 ± 159	103.5 ± 10.9	30.92 ± 0.26	$3.63 \pm 0.38 \pm 0.20$

- BESIII performed the first absolute measurement of $\mathcal{B}(\Lambda_c^+ \to \Lambda\mu^+\nu_\mu)$

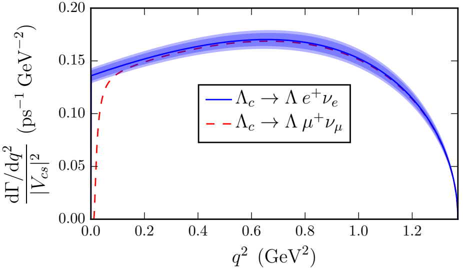


$N_{\rm tag}$	$N_{\rm semi}$	$\varepsilon_{\rm semi}$ (%)	$\mathcal{B}(\Lambda_c^+ \to \Lambda\mu^+\nu_\mu)$ (%)
14415 ± 159	78.7 ± 10.5	24.5 ± 0.2	$3.49 \pm 0.46 \pm 0.27$

- Test of lepton universality
  - $\Gamma(\Lambda_c^+ \to \Lambda\mu^+\nu_\mu)/\Gamma(\Lambda_c^+ \to \Lambda e^+\nu_e) = 0.96 \pm 0.16 \pm 0.04$, compatible with unity
- Our results provide stringent tests on the non-perturbative models

$\Lambda_c^+ \to \Lambda \ell^+ \nu_\ell$

- The BESIII results provide important input for calibrating the LQCD calculations
- The first LQCD calculation of form factors governing $\Lambda_c^+ \to \Lambda \ell^+ \nu_\ell$ decays [Phys. Rev. Lett. **118**, 082001 (2017)]



- The first determination of $|V_{cs}|$ based on $\mathcal{B}(\Lambda_c^+ \to \Lambda \ell^+ \nu_\ell)$ measured by BESIII

$$|V_{cs}| = \begin{cases} 0.951(24)_{\rm LQCD}(14)_{\tau_{\Lambda_c}}(56)_{\mathcal{B}}, & \ell = e \\ 0.947(24)_{\rm LQCD}(14)_{\tau_{\Lambda_c}}(72)_{\mathcal{B}}, & \ell = \mu \\ 0.949(24)_{\rm LQCD}(14)_{\tau_{\Lambda_c}}(49)_{\mathcal{B}}, & \ell = e, \mu \end{cases}$$

Summary

- With 2.93 fb^{-1}, 482 pb^{-1} and 567 pb^{-1} data taken at 3.773 GeV, 4.009 GeV and 4.599 GeV, respectively, BESIII provided many key measurements on heavy flavor physics:
  - **Branching fractions and semileptonic form factors;**
  - **CKM matrix elements $|V_{cs}|$ and $|V_{cd}|$.**
- Prospect:
  - **In 2016, ~ 3 fb^{-1} data were collected at 4.18 GeV, many interesting studies of semileptonic D_s^+ decays will be done at the BESIII experiment in the near future.**

Thank you!