BESIII 上粲介子纯轻衰变的研究

潘祥
苏州大学

2025 年 8 月 6 日
BESIII 粲强子物理研讨会
兰州大学

Outline

1. Introduction
2. BESIII dataset and double-tag method
3. Leptonic decays
4. Comparison of $f_{D^+_{(s)}}$ and $|V_{cs(d)}|$
5. Summary

Introduction

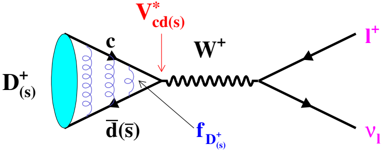
$$V_{\mathrm{CKM}}^{\mathrm{PDG2024}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 0.97367 \pm 0.00032 & 0.22431 \pm 0.00085 & 0.00382 \pm 0.00020 \\ 0.221 \pm 0.004 & 0.975 \pm 0.006 & 0.0411 \pm 0.0012 \\ 0.0086 \pm 0.0002 & 0.0415 \pm 0.0009 & 1.010 \pm 0.027 \end{pmatrix}$$

- CKM matrix is the basis of Standard Model and only determined at experiment
- $V^{+}V = 1$

  $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9984 \pm 0.0007 \quad |V_{cd}|^2 + |V_{cs}|^2 + |V_{cb}|^2 = 1.001 \pm 0.012$

  $|V_{ud}|^2 + |V_{cd}|^2 + |V_{td}|^2 = 0.9971 \pm 0.0020 \quad |V_{us}|^2 + |V_{cs}|^2 + |V_{ts}|^2 = 1.003 \pm 0.012$
- Uncertainties mainly contributed by $|V_{cs}|$ $(\sigma = 0.6\%)$ and $|V_{cd}|$ $(\sigma = 1.8\%)$
- Improving the precision of $|V_{cd(s)}|$ is extremely important;
- Leptonic and semileptonic $D_{(s)}$ decays are the most important way to determine $|V_{cd(s)}|$

Introduction

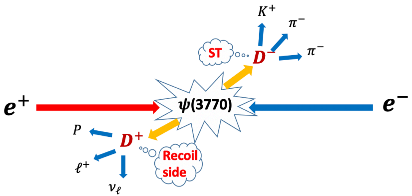


$$\Gamma(D^+_{(s)} \to \ell^+\nu_\ell) = \frac{G_F^2}{8\pi}|V_{cq}|^2|f_{D^+_{(s)}}|^2 m_\ell^2 m_{D^+_{(s)}}(1 - m_\ell^2/m^2_{D^+_{(s)}})^2$$

- Charm leptonic decays involve weak and strong interactions
- Latest LQCD: $f_{D_s^+} = 249.9(05)$ MeV ($\sigma = 0.2\%$); $f_{D^+} = 212.1(07)$ MeV ($\sigma = 0.3\%$);
- Decay constant $f_{D^+_{(s)}}$ measurements⇒Calibrate LQCD calculations
- $|V_{cq}|$ measurement ⇒Test CKM matrix unitarity
- BF ratios⇒Test lepton flavor universality (LFU)

$$D^+: \mathcal{R}^{\rm SM}_{\tau/\mu} = \frac{m_\tau^2(1-m_\tau^2/m^2_{D^+})^2}{m_\mu^2(1-m_\mu^2/m^2_{D^+})^2} = 2.66 \pm 0.01;\ D_s^+: \mathcal{R}^{\rm SM}_{\tau/\mu} = \frac{m_\tau^2(1-m_\tau^2/m^2_{D_s^+})^2}{m_\mu^2(1-m_\mu^2/m^2_{D_s^+})^2} = 9.75 \pm 0.01$$

BESIII dataset and double-tag method

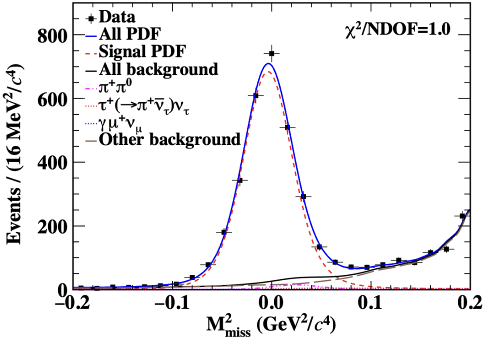


- e^+e^- annihilations data near threshold
  $\Rightarrow$Double-tag method& Clean environment
- Undetectable neutrinos$\Rightarrow$extract the leptonic signals
  $U_{\rm miss} = E_{\rm miss} - |\vec{p}_{\rm miss}|$, $M^2_{\rm miss} = E^2_{\rm miss} - |\vec{p}_{\rm miss}|^2$
- BF with double-tag method: $\mathcal{B} = \frac{N_{\rm DT}}{N_{\rm ST}\epsilon_{\rm DT}/\epsilon_{\rm ST}}$
  $\Rightarrow$Systematic uncertainties on the ST mostly canceled

Data sample	$E_{\rm cm}$ (GeV)	$\mathcal{L}_{\rm int}$ $({\rm fb}^{-1})$	Single tag yields $(\times 10^6)$
$e^+e^- \to \psi(3770) \to D\bar{D}$	3.773	20.3	$\bar{D}^0$ ~16.9; D^- ~11.0
$e^+e^- \to D_s^{\pm}D_s^{*\mp}$	4.128-4.226	7.33	D_s^- ~0.8
$e^+e^- \to D_s^{*+}D_s^{*-}$	4.237-4.669	10.64	D_s^- ~0.12

$D^+ \to \mu^+\nu_\mu$

$N_{\rm sig} = 2833 \pm 57$



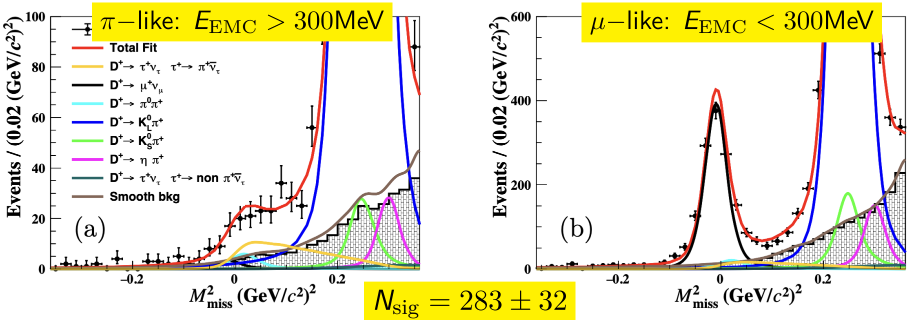
- $\Gamma_{D^+\to\ell^+\nu_\ell} = \Gamma^0_{D^+\to\ell^+\nu_\ell}[1+\frac{\alpha}{\pi}C_p] \Rightarrow$ Radiative correction term

1. Short-distance electroweak correction increases BF by 1.8% [PRD98,074512, NPB196,83]
2. Long-distance electroweak correction [inner bremsstrahlung and virtual photon] reduce BF by 2.5% with 0.6% uncertainty of unknown electromagnetic correction [PRD98,074512]

- 20.3 fb^{-1}@3.773 GeV [PRL135(2025)061801]
- $\mathcal{B}(D^+ \to \mu^+\nu_\mu) = (4.034 \pm 0.080 \pm 0.040) \times 10^{-4}$ Precision is improved by 2.4×

  $f_{D^+} = (213.5 \pm 2.1 \pm 1.1 \pm 0.8 \pm 0.7)$MeV(∼1.2%) $|V_{cd}| = 0.2265 \pm 0.0023 \pm 0.0011 \pm 0.0009 \pm 0.0007$

$D^+ \to \tau^+\nu_\tau$ via $\tau^+ \to \pi^+\bar{\nu}_\tau$

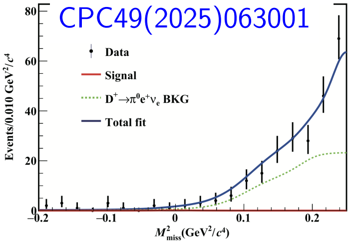


$N_{\rm sig} = 283 \pm 32$

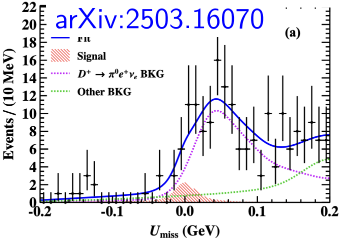
- 7.93 fb^{-1}@3.773 GeV [JHEP01(2025)89]
- Precision of BF is improved by 1.8×: $\mathcal{B}(D^+ \to \tau^+\nu_\tau) = (9.9 \pm 1.1 \pm 0.5) \times 10^{-4}$
- $f_{D^+} = (204 \pm 11 \pm 5 \pm 1)$MeV $(\sim 5.9\%)$ $|V_{cd}| = 0.216 \pm 0.012 \pm 0.006 \pm 0.001$ $(\sim 6.2\%)$
- LFU test: $\mathcal{R}_{\tau/\mu} = \frac{\Gamma_{D^+\to\tau^+\nu_\tau}}{\Gamma_{D^+\to\mu^+\nu_\mu}} = 2.45 \pm 0.31$, consistent with $\mathcal{R}^{\rm SM}_{\tau/\mu} = 2.66 \pm 0.01$

$D^+ \to e^+\nu_e$, $D^+ \to \gamma e^+\nu_e$, and $D_s^+ \to \gamma e^+\nu_e$

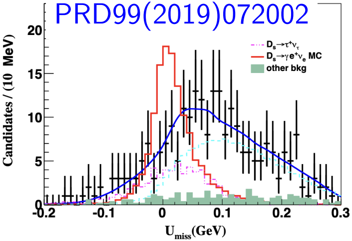
$D^+ \to e^+\nu_e$ 20.3 fb^{-1}
CPC49(2025)063001



$D^+ \to \gamma e^+\nu_e$ 20.3 fb^{-1}
arXiv:2503.16070

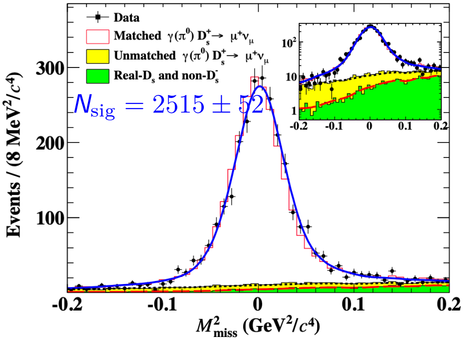


$D_s^+ \to \gamma e^+\nu_e$ 3.19 fb^{-1}
PRD99(2019)072002



- $D^+ \to e^+\nu_e$ is helicity suppression; $D^+_{(s)} \to \gamma e^+\nu_e$ mitigates helicity suppression
- Theoretical predictions: $\mathcal{B}(D^+ \to e^+\nu_e) < 10^{-8}$; $\mathcal{B}(D^+_{(s)} \to \gamma e^+\nu_e) \sim (10^{-5} - 10^{-3})$
- $\mathcal{B}(D^+ \to e^+\nu_e) < 9.7 \times 10^{-7}$@90% C.L.
- $\mathcal{B}(D^+ \to \gamma e^+\nu_e) < 1.2 \times 10^{-5}$@90% C.L.. Deep learning method is used
- $\mathcal{B}(D_s^+ \to \gamma e^+\nu_e) < 1.3 \times 10^{-4}$@90% C.L.

$D_s^+ \to \mu^+\nu_\mu$

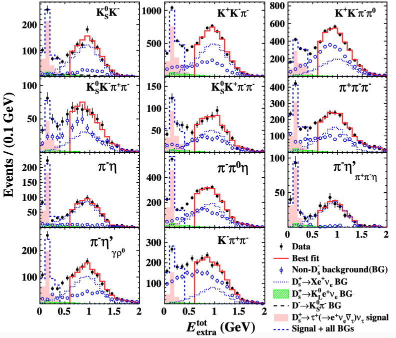


- 7.33 fb^{-1} @4.128-4.226 GeV [PRD108(2023)112001]
- $\mathcal{B}(D_s^+ \to \mu^+\nu_\mu) = (5.294 \pm 0.108 \pm 0.085) \times 10^{-3}$ $\Longrightarrow$Precision is improved by 1.5$\times$
- Most precision measurements in $D_{(s)}$ leptonic decays

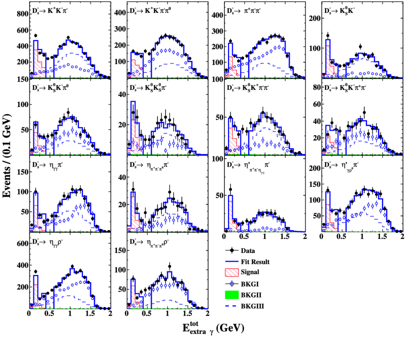
  $f_{D_s^+} = (248.4 \pm 2.5 \pm 2.2)$ MeV $(\sim 1.4\%)$ $|V_{cs}| = 0.968 \pm 0.010 \pm 0.009$ $(\sim 1.4\%)$

$D_s^+ \to \tau^+\nu_\tau$ via $\tau^+ \to \ell^+\nu_\ell\bar{\nu}_\tau$ $(\ell = e, \mu)$

$6.32\ \mathrm{fb}^{-1}$@4.178-4.226 GeV



$7.33\ \mathrm{fb}^{-1}$@4.128-4.226 GeV



- $\tau^+ \to e^+\nu_e\bar{\nu}_\tau$ [PRL127(2021)171801]

  $\mathcal{B}(D_s^+ \to \tau^+\nu_\tau) = (5.27 \pm 0.10 \pm 0.12)\%$

  $f_{D_s^+} = (251.1 \pm 2.4 \pm 3.0)\mathrm{MeV}$ $(\sim 1.5\%)$

  $|V_{cs}| = 0.978 \pm 0.009 \pm 0.012)$ $(\sim 1.5\%)$

- $\tau^+ \to \mu^+\nu_\mu\bar{\nu}_\tau$ [JHEP09 (2023)124]

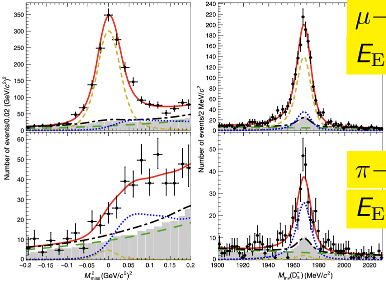
  $\mathcal{B}(D_s^+ \to \tau^+\nu_\tau) = (5.37 \pm 0.17 \pm 0.15)\%$

  $f_{D_s^+} = (253.4 \pm 4.0 \pm 3.7)\mathrm{MeV}$ $(\sim 2.2\%)$

  $|V_{cs}| = 0.987 \pm 0.016 \pm 0.014$ $(\sim 2.2\%)$

$D_s^+ \to \tau^+\nu_\tau$ via $\tau^+ \to \pi^+\bar{\nu}_\tau$

6.32 fb^{-1}@4.178-4.226 GeV



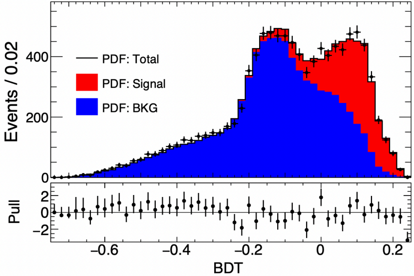
$\mu-$like

$E_{\rm EMC} < 300$MeV

$\pi-$like

$E_{\rm EMC} > 300$MeV

7.33 fb^{-1}@4.128-4.226 GeV



- $\tau^+ \to \pi^+\bar{\nu}_\tau$ [PRD104(2021)052009]

  $\mathcal{B}(D_s^+ \to \tau^+\nu_\tau) = (5.21 \pm 0.25 \pm 0.17)\%$

  $f_{D_s^+} = (249.7 \pm 6.0 \pm 4.2)\text{MeV}$ $(\sim 2.9\%)$

  $|V_{cs}| = 0.972 \pm 0.023 \pm 0.016$ $(\sim 2.9\%)$

- $\tau^+ \to \pi^+\bar{\nu}_\tau$ with BDT [PRD108(2023)092014]

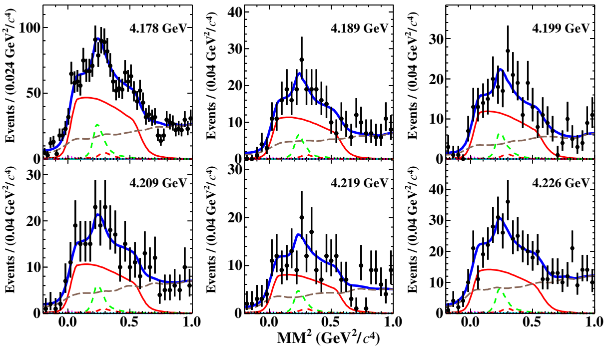
  $\mathcal{B}(D_s^+ \to \tau^+\nu_\tau) = (5.44 \pm 0.17 \pm 0.13)\%$

  $f_{D_s^+} = (255.0 \pm 4.0 \pm 3.4)\text{MeV}$ $(\sim 2.1\%)$

  $|V_{cs}| = 0.993 \pm 0.015 \pm 0.013$ $(\sim 2.0\%)$

$D_s^+ \to \tau^+\nu_\tau$ via $\tau^+ \to \pi^+\pi^0\bar{\nu}_\tau$

Simultaneous fit to $M^2_{\rm miss}$ @$\sqrt{s}$ =4.178-4.226 GeV

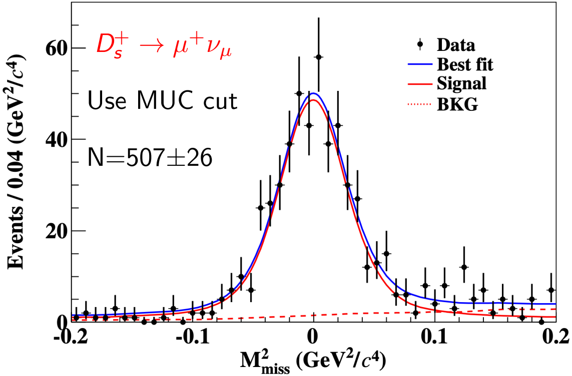


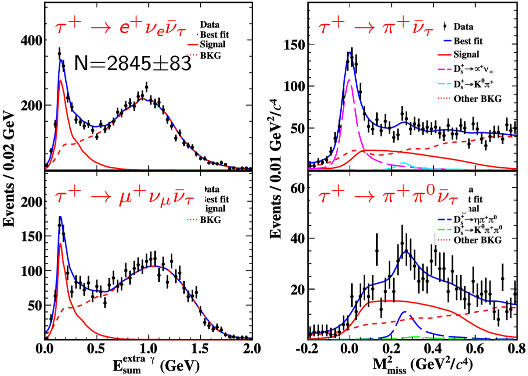
- 7.33 fb^{-1} @4.128-4.226 GeV [PRD104(2021)032001]
- $\mathcal{B}(D_s^+ \to \tau^+\nu_\tau) = (5.29 \pm 0.25 \pm 0.20)\%$

  $f_{D_s^+} = (251.6 \pm 5.9 \pm 4.9)\mathrm{MeV}$ ($\sim 3.0\%$) $|V_{cs}| = 0.980 \pm 0.023 \pm 0.019$ ($\sim 3.0\%$)

$D_s^+ \to \mu^+\nu_\mu$ and $D_s^+ \to \tau^+\nu_\tau$ via $e^+e^- \to D_s^{*+}D_s^{*-}$

10.64 fb^{-1}@ 4.237-4.669 GeV PRD110(2024)052002 $D_s^+ \to \tau^+\nu_\tau$, constrain the same BF



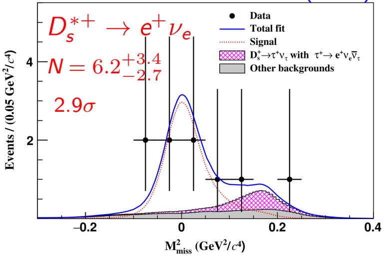


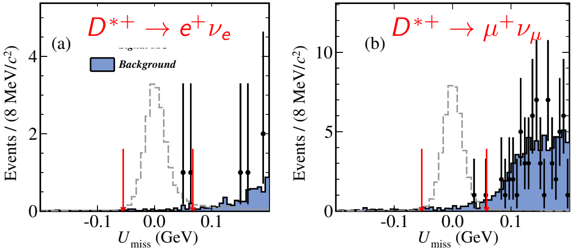
- $\mathcal{B}(D_s^+ \to \mu^+\nu_\mu) = (0.547 \pm 0.026 \pm 0.016)\%$
- $\mathcal{B}(D_s^+ \to \tau^+\nu_\tau) = (5.60 \pm 0.16 \pm 0.20)\%$
- $\mathcal{R}(\tau/\mu) = 10.24 \pm 0.57$ (SM:9.75±0.01)

- $f_{D_s}|V_{cs}|_{\mu\nu_\mu} = (246.5 \pm 5.9 \pm 3.6)$ MeV ($\sim 2.8\%$)
- $f_{D_s}|V_{cs}|_{\tau\nu_\tau} = (252.7 \pm 3.6 \pm 4.5)$ MeV ($\sim 2.3\%$)

$D_s^{*+} \to e^+\nu_e$ and $D^{*+} \to \ell^+\nu_\ell$

7.33 fb^{-1}@4.128-4.226 GeV PRL131(2023)141802 6.32 fb^{-1}@4.178-4.226 GeV PRD110(2024)012003

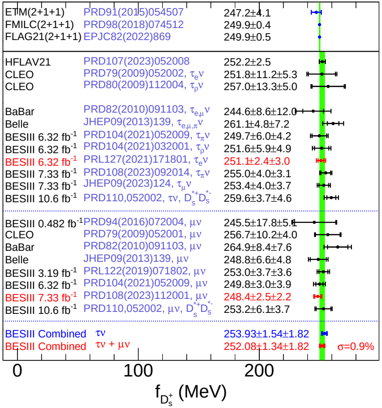


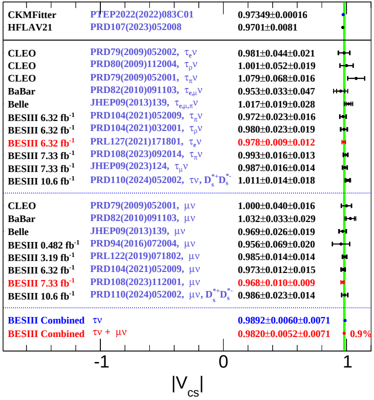


- First experimental study of the $D^{*+}_{(s)}$ purely leptonic decay
- $\mathcal{B}(D_s^{*+} \to e^+\nu_e) = (2.1^{+1.2}_{-0.9} \pm 0.2) \times 10^{-5}$
- $\Gamma^{\rm tot}_{D_s^{*+}} = 2.04 \times 10^{-3} \times (\frac{f_{D_s^*}}{f_{D_s}})^2 / \mathcal{B}(D_s^{*+} \to e^+\nu_e)$
- $\Gamma^{\rm total}_{D_s^{*+}} = 70 \pm 28$ eV (LQCD) $\Rightarrow f_{D_s^{*+}} = (214^{+61}_{-46} \pm 44)$ MeV
- $f_{D_s^{*+}}/f_{D_s^+} = 1.12 \pm 0.01$ (LQCD) $\Rightarrow \Gamma^{\rm total}_{D_s^{*+}} = (122^{+70}_{-52} \pm 12)$ eV
- Indirectly constrains the upper limit on the $\Gamma^{\rm total}_{D_s^{*+}}$ from the MeV (<1.9 MeV@90% C.L. PDG2024) to sub-keV level

- Upper limits are set at 90% C. L.
- $\mathcal{B}(D^{*+} \to e^+\nu_e) < 1.1 \times 10^{-5}$
- $\mathcal{B}(D^{*+} \to \mu^+\nu_\mu) < 4.3 \times 10^{-6}$

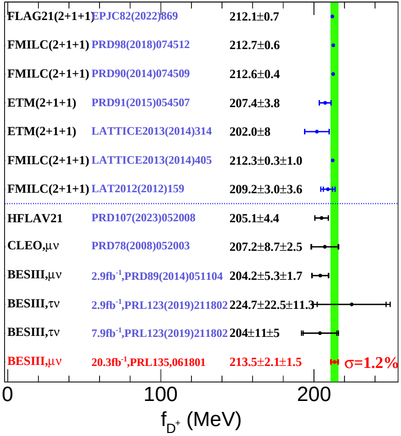
Comparison of $f_{D_s^+}$ and $|V_{cs}|$

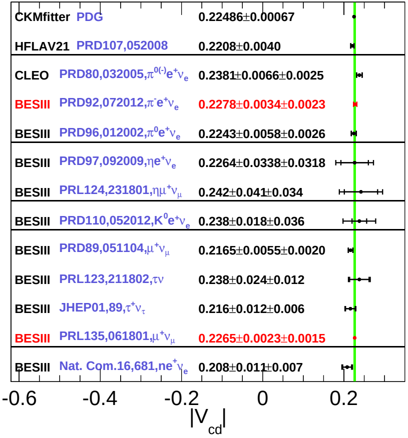




- Averaged BESIII results, precisions of f_{D_s} and $|V_{cs}|$: 0.9%
- $\mathcal{B}(D_s^+ \to \mu^+\nu_\mu) = (0.5310 \pm 0.0099 \pm 0.0053)\%$ and $\mathcal{B}(D_s^+ \to \tau^+\nu_\tau) = (5.359 \pm 0.067 \pm 0.074)\%$
  $\mathcal{R}(\tau/\mu) = 10.09 \pm 0.28$ $(\sigma \sim 2.8\%)$, consistent within SM (9.75$\pm$0.01) 1.2σ

Comparison of f_{D^+} and $|V_{cd}|$





- Precisions of f_D and $|V_{\rm cd}|$: 1.2%

Summary

- Purely leptonic decays of charm mesons are important for determining CKM matrix elements, calibrating LQCD, testing LFU, *et al.*;
- Precisions of $|V_{cs}|$ and $f_{D_s^+}$ have been reduced to 0.9%
- Precisions of $|V_{cd}|$ and f_{D^+} have been reduced to 1.2%
- No evidence of $\tau-\mu$ LFU violation is found via $D^+_{(s)} \to \ell^+\nu_\ell$ ($\sigma \sim 2.8\%$ for D_s)
- 2.9σ significance for $D_s^{*+} \to e^+\nu_e$ and no signal for $D^{*+} \to \ell^+\nu_\ell$ and $D^+_{(s)} \to \gamma e^+\nu_e$
- Additional 3 fb^{-1}data @4.178 GeV in future [CPC44(2020)040001] will further improve the precisions in D_s sector.

Thank you