Test lepton flavor universality with (semi)leptonic D decays at BESIII

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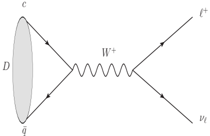
Outline

1. Introduction and status of D (semi)leptonic decays
   - Lepton flavor universality
   - Decay constants $f_{D^+_{(s)}}$, Form factors $f_+^{D\to K(\pi)}(0)$ and CKM matrix elements $|V_{cs(d)}|$
2. The BEPCII and BESIII
3. Recent results in BESIII
   - $D_s^+ \to \mu^+\nu_\mu$
   - $D^+ \to \ell^+\nu_\ell$
   - $D \to \bar{K}\mu^+\nu_\mu$
   - $D \to \pi\mu^+\nu_\mu$
4. Summary

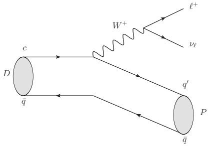
Leptonic decays in the SM



pure leptonic decays:

$$F_\mu = f_D(p_D^2)p_{D\mu}$$

$$L^\mu = \bar{u}\gamma^\mu(1-\gamma^5)v$$



semileptonic decays:

$$H_\mu = f_+(q^2)(p_D+p_P)_\mu + f_-(q^2)(p_D-p_P)_\mu,$$

$$(q = p_D - p_P)$$

$$L^\mu = \bar{u}\gamma^\mu(1-\gamma^5)v$$

Meanwhile, the quark weak interaction eigenstates are the mixing of flavor eigenstates described by the CKM matrix

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

We have $\Gamma(D\to\ell\nu_\ell) = \frac{G_F^2}{8\pi}(|V_{cs(d)}|f_D)^2 m_\ell^2 m_D \left(1-\frac{m_\ell^2}{m_{D_s^+}^2}\right)^2$ for pure leptonic decays,

$\frac{d\Gamma(D\to P\ell\nu_\ell)}{dq^2} = \frac{G_F^2}{24\pi^3}(|V_{cs(d)}|f_+(q^2))^2|\vec{p}_P|^3 + O(m_\ell^2)$ for semileptonic decays to pesudoscalar mesons.

The ratios of the decay rates can be precisely predicted: [1]

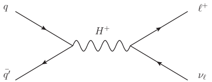
$$\frac{\Gamma(D_s^+\to\tau^+\nu_\tau)}{\Gamma(D_s^+\to\mu^+\nu_\mu)} = 9.74(1) \qquad \frac{\Gamma(D^+\to\tau^+\nu_\tau)}{\Gamma(D^+\to\mu^+\nu_\mu)} = 2.66(1) \qquad \frac{\Gamma(D\to\bar{K}\mu^+\nu_\mu)}{\Gamma(D\to\bar{K}e^+\nu_e)} = 0.975(1) \qquad \frac{\Gamma(D\to\pi\mu^+\nu_\mu)}{\Gamma(D\to\pi e^+\nu_e)} = 0.985(2)$$

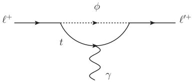
[1] EPJC78(2018)501, PRD96(2017)054514 using a modified z expansion parametrization.

Lepton flavor universality violation

Possible sources of LFUV:

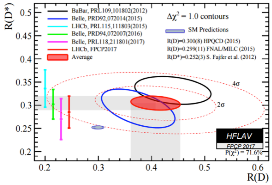
- Charged Higgs?
- Leptoquark?



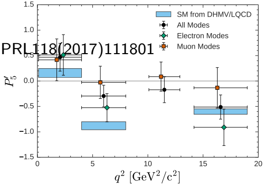


Evidence of LFUV at B factory:

- $R_{D^{(*)}} = \dfrac{\Gamma(B \to D^{(*)}\tau^+\nu_\tau)}{\Gamma(B \to D^{(*)}\mu^+\nu_\mu)}$
- $R_{K^{(*)}} = \dfrac{\Gamma(B^+ \to K^{(*)+}\mu^+\mu^-)}{\Gamma(B^+ \to K^{(*)+}e^+e^-)}$

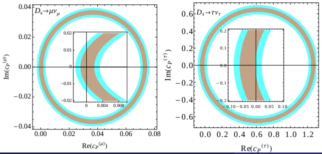


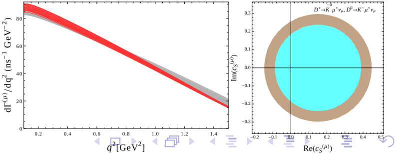
PRL118(2017)111801



Current status in the charm sector (PRD91(2015)094009):

$$\Gamma(D_s^+ \to \ell^+\nu_\ell) \to \Gamma_{\rm SM}|1 - c_P^\ell \frac{m_{D_s}^2}{(m_c+m_s)m_\ell}| \qquad H_t \to (1 - c_S^\ell \frac{q^2}{m_\ell(m_c+m_s)})H_t$$





Experimental status of $D \to \bar{K}(\pi)\ell^+\nu_\ell$ and $D^+_{(s)} \to \ell^+\nu_\ell$

Decay	Other experiments (%)	BESIII (%)
$\mathcal{B}(D^0 \to K^- e^+ \nu_e)$	3.55 ± 0.05	$3.505 \pm 0.014 \pm 0.033$
$\mathcal{B}(D^0 \to K^- \mu^+ \nu_\mu)$	3.31 ± 0.13	
$\mathcal{B}(D^+ \to \bar{K}^0 e^+ \nu_e)$	8.83 ± 0.22	8.70 ± 0.12
$\mathcal{B}(D^+ \to \bar{K}^0 \mu^+ \nu_\mu)$	9.4 ± 0.8	
$\mathcal{B}(D^0 \to \pi^- e^+ \nu_e)$	0.289 ± 0.008	$0.295 \pm 0.004 \pm 0.003$
$\mathcal{B}(D^0 \to \pi^- \mu^+ \nu_\mu)$	2.37 ± 0.24	
$\mathcal{B}(D^+ \to \pi^0 e^+ \nu_e)$	0.405 ± 0.018	$0.363 \pm 0.008 \pm 0.005$
$\mathcal{B}(D^+ \to \pi^0 \mu^+ \nu_\mu)$	Not measured	

- Previous BESIII measurements have significantly improve the precison of the electron modes.
- Further study on the muon modes needed for precise LFU test.

Decay	$\mathcal{B}(D_s^+ \to \mu^+ \nu_\mu)$ (%)	$\mathcal{B}(D_s^+ \to \tau^+ \nu_\tau)$ (%)
Other experiments	0.556 ± 0.025	5.55 ± 0.24
Decay	$\mathcal{B}(D^+ \to \mu^+ \nu_\mu)$ (%)	$\mathcal{B}(D^+ \to \tau^+ \nu_\tau)$ (%)
Other experiments	0.0382 ± 0.0033	< 0.12

The precision can be improved by the BESIII data.

Measurements of $f_{D^+_{(s)}}$, $f_+^{D\to K(\pi)}(0)$ and $|V_{cs(d)}|$

Some theoretical calculations for decay constants and form factors

Methods	f_{D^+} MeV	$f_{D_s^+}$ MeV	$f_+^{D\to K}(0)$	$f_+^{D\to\pi}(0)$
Lattice (MILC)[2]	$212.6(0.4)^{(+1.0)}_{(-1.2)}$	$249.0(0.3)^{(+1.1)}_{(-1.5)}$	$0.73(3)(7)$	$0.64(3)(6)$
Lattice (HPQCD)[3]	$208.3(1.0)(3.3)$	$248.0(2.5)$	$0.747(11)(15)$	$0.666(20)(21)$
QCD Sum Rules[4]	$206.2(7.3)(5.1)$	$245.3(15.7)(4.5)$	$0.75^{(+11)}_{(-8)}$	$0.67^{(+10)}_{-(7)}$
PDG[5]	$203.9(4.7)$	$257.7(4.1)$	$0.739(4)$ in D^0 decays $0.739(11)$ in D^+ decays	$0.638(12)$ in D^0 decays $0.625(11)$ in D^+ decays

Precision of D meson decay constants in experiment need to be improved to test theoretical calculations.
PDG average for $|V_{cs(d)}|$ in experiment: $|V_{cd}| = 0.218 \pm 0.004$ and $|V_{cs}| = 0.997 \pm 0.017$
CKM matrix unitarity test:

$$|V_{ud}|^2+|V_{us}|^2+|V_{ub}|^2=0.9994\pm0.0005 \qquad |V_{ud}|^2+|V_{cd}|^2+|V_{td}|^2=0.9967\pm0.0018$$

$$|V_{cd}|^2+|V_{cs}|^2+|V_{cb}|^2=1.043\pm0.034 \qquad |V_{us}|^2+|V_{cs}|^2+|V_{ts}|^2=1.046\pm0.034$$

Precison of $|V_{cs}|$ needs to be improved for more accurate unitarity test.

[2] PRD90(2014)074509, PRL94(2005)011601

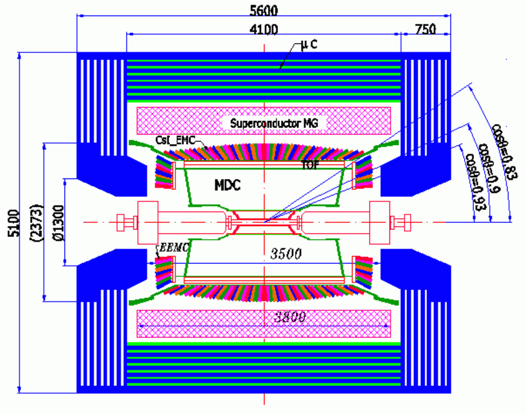
[3] PRD86(2012)054510, PRD82(2010)114504, PRD82(2010)114505, PRD82(2010)114506

[4] PLB701(2011)82, PRD80(2009)114005

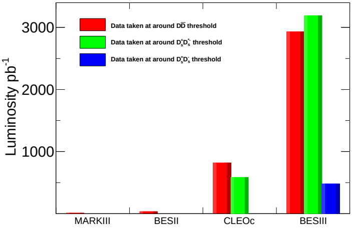
[5] using $|V_{cs(d)}|$ from CKMFitter

The view of BEPCII

The BESIII detector



Data samples and Analysis method



BESIII has the largest $D\bar{D}$ samples around threshold.
At center-mass energy near threshold, D mesons are produced in pair, which allows us to first tag a D meson (the Single Tagged D meson) and then looking for the leptonic decays in the remaining tracks (called Double Tag method)

Branching fraction of signal decay is calculated by

$$N^i_{\rm ST} = 2N_{D\bar{D}}\mathcal{B}^i_{\rm ST}\epsilon^i_{\rm ST}$$

$$N^i_{\rm DT} = 2N_{D\bar{D}}\mathcal{B}^i_{\rm ST}\mathcal{B}_{\rm sig}$$

$$\mathcal{B}_{\rm sig} = \frac{N^{\rm tot}_{\rm DT}}{N^{\rm tot}_{\rm ST}\bar{\epsilon}_{\rm sig}}$$

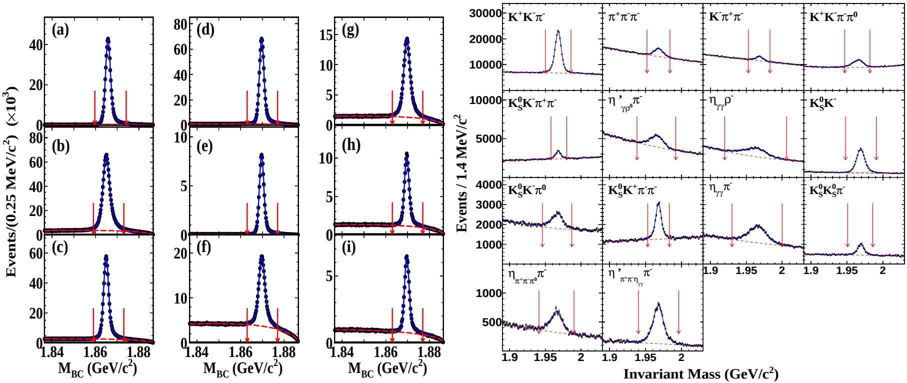
$$\bar{\epsilon}_{\rm sig} = \sum(N^i_{\rm ST}\epsilon^i_{\rm ST,sig}/\epsilon^i_{\rm ST})/N^{\rm tot}_{\rm ST}$$

The number of signal events is determined by examining the kinematic variables of the missing neutrino

$$U_{\rm miss} = E_{\rm miss} - |\vec{p}|_{\rm miss}$$

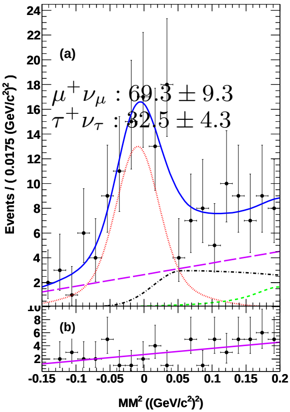
$$M^2_{\rm miss} = E^2_{\rm miss} - |\vec{p}|^2_{\rm miss}$$

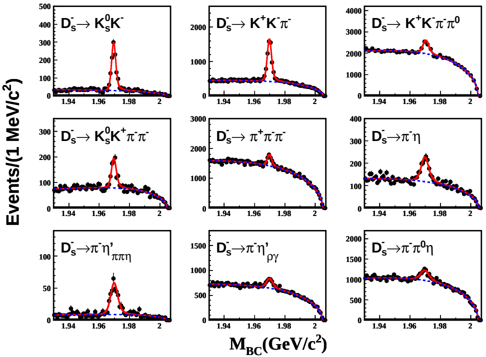
Number of ST D mesons



In total, about 2.5×10^6 ST D^0, 1.5×10^6 ST D^+ and 3.9×10^5 ST D_s^+ are reconstructed.

Analysis of $D_s^+ \to \ell^+\nu_\ell$ at 4.009 GeV





$f_{D_s}|V_{cs}| = 234.8 \pm 15.9 \pm 6.4$ MeV

with $\frac{\Gamma(D_s^+ \to \tau^+\nu_\tau)}{\Gamma(D_s^+ \to \mu^+\nu_\mu)}$ constrained:

$\mathcal{B}(D_s^+ \to \mu^+\nu_\mu) = (0.495 \pm 0.067 \pm 0.026)\%$

$\mathcal{B}(D_s^+ \to \tau^+\nu_\tau) = (4.83 \pm 0.65 \pm 0.26)\%$

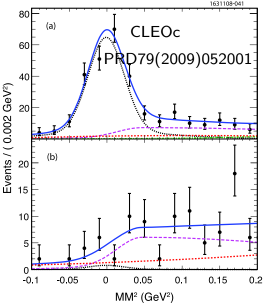
Published at PRD94(2016)072004.
An overall total of 15127 ± 321 ST D_s^- mesons are reconstructed.
τ^+ reconstructed using $\tau^+ \to \pi^+\bar{\nu}_\tau$.

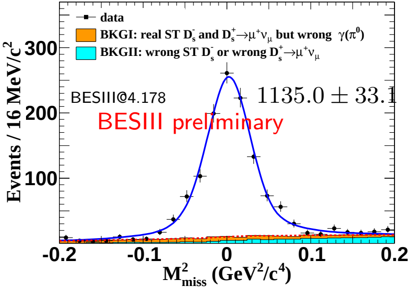
without the constraint:

$\mathcal{B}(D_s^+ \to \mu^+\nu_\mu) = (0.517 \pm 0.075 \pm 0.021)\%$

$\mathcal{B}(D_s^+ \to \tau^+\nu_\tau) = (3.28 \pm 1.83 \pm 0.37)\%$

Analysis of $D_s^+ \to \mu^+\nu_\mu$ at 4.178 GeV

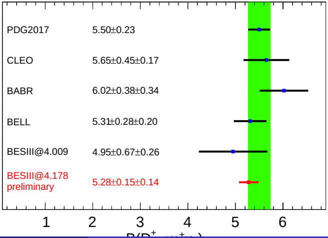




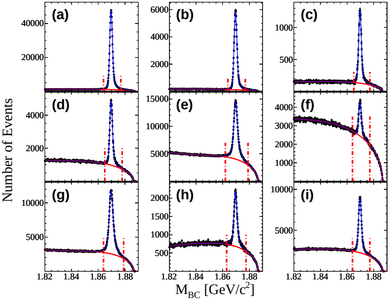
$$f_{D_s^+}|V_{cs}| = 242.5 \pm 3.5_{\text{stat.}} \pm 3.7_{\text{syst.}}$$

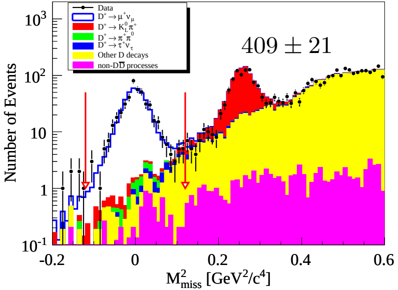
- Lower background level compared to CLEOc with MUC information
- The most precise measurement to date

$$R_{D_s^+} = \frac{\Gamma(D_s^+ \to \tau^+\nu_\tau)}{\Gamma(D_s^+ \to \mu^+\nu_\mu)} = 10.19 \pm 0.52$$



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



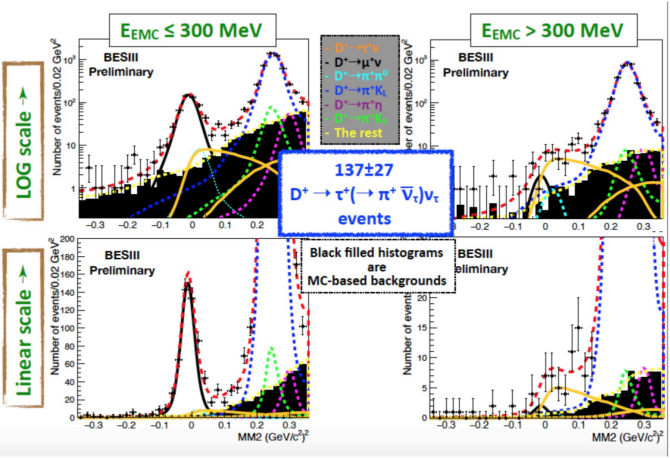


- Published at PRD89(2014)051104.
- 1703054 ± 3405 ST D^- mesons reconstructed using nine modes.
- MUC information used to suppress backgrounds.

$$\mathcal{B}(D^+ \to \mu^+\nu_\mu) = (3.71 \pm 0.19 \pm 0.06) \times 10^{-4}$$

$$f_{D^+}|V_{cd}| = (45.75 \pm 1.20 \pm 0.39) \text{ MeV}$$

Analysis of $D^+ \to \tau^+\nu_\tau$



First evidence with 4σ statistical significance.

$$\mathcal{B}(D^+ \to \tau^+\nu_\tau) = (1.20 \pm 0.24) \times 10^{-3}$$

$$R_{D^+} = \frac{\Gamma(D^+ \to \tau^+\nu_\tau)}{\Gamma(D^+ \to \mu^+\nu_\mu)} = 3.21 \pm 0.64$$

SM prediction 2.66 ± 0.01.

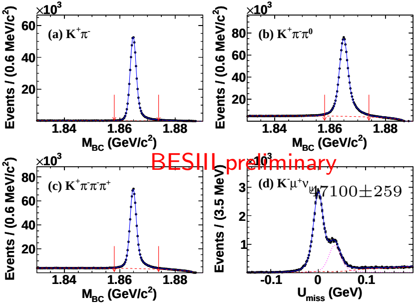
Analysis of $D^0 \to K^-\mu^+\nu_\mu$

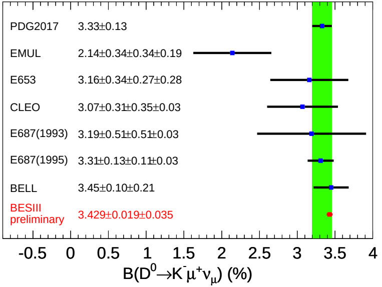
High order term in the decay rate concerning lepton mass is considered.

$$
\begin{aligned}
\frac{d\Gamma}{dq^2} = & \frac{G_F^2|V_{cs}|^2}{8\pi^3 m_D}|\vec{p}_K||f_+^K(q^2)|^2\left(\frac{W_0-E_K}{F_0}\right)^2 \\
& \times \Big[\frac{1}{3}m_D|\vec{p}_K|^2 + \frac{m_\ell^2}{8m_D}(m_D^2+m_K^2+2m_DE_K) \\
& + \frac{1}{3}m_\ell^2\frac{|\vec{p}_K|^2}{F_0} + \frac{1}{4}m_\ell^2\frac{m_D^2-m_K^2}{m_D}\mathrm{Re}\left(\frac{f_-^K(q^2)}{f_+^K(q^2)}\right) \\
& + \frac{1}{4}m_\ell^2 F_0\left|\frac{f_-^K(q^2)}{f_+^K(q^2)}\right|^2\Big]
\end{aligned}
$$

$$W_0 = (m_D^2 + m_K^2 - m_\ell^2)/(2m_D)$$

$$F_0 = W_0 - E_K + m_\ell^2/(2m_D)$$



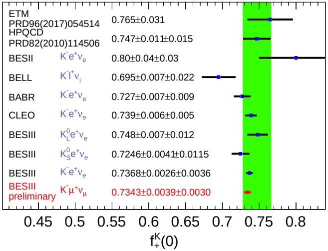


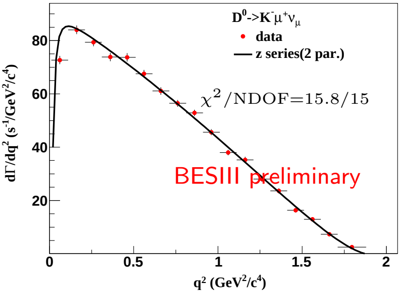
Analysis of $D^0 \to K^- \mu^+ \nu_\mu$

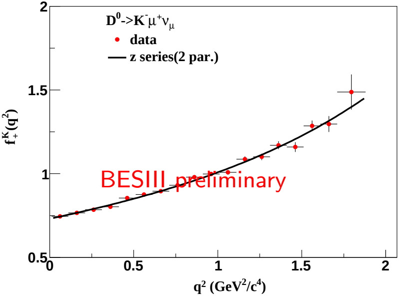
Using two parameter expansion parametrization for $f_+^{D\to K}(q^2)$ (PLB633(2006)61)

In the fit, $f_-(q^2)/f_+(q^2)$ is assumed to be independent of q^2

$$f_+^{D\to K}(0)|V_{cs}| = 0.7148 \pm 0.0038_{\text{stat.}} \pm 0.0029_{\text{syst.}}$$

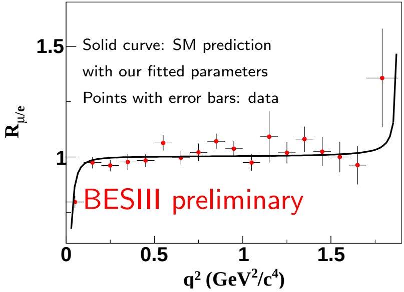


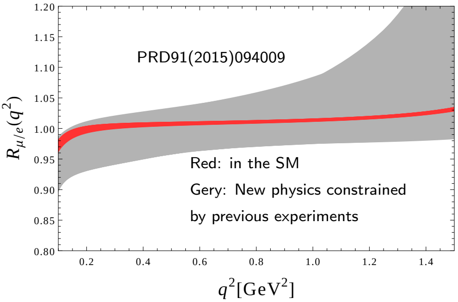




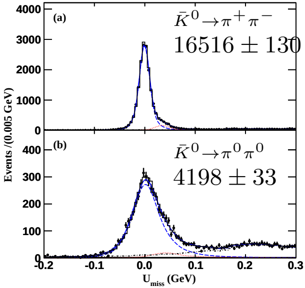
Analysis of $D^0 \to K^-\mu^+\nu_\mu$

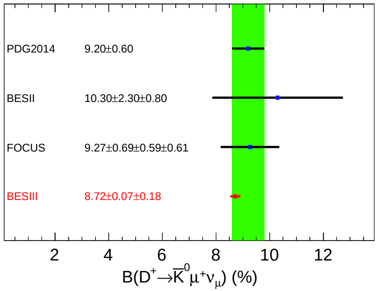
$$R_{K^-} = \frac{\Gamma(D^0 \to K^-\mu^+\nu_\mu)}{\Gamma(D^0 \to K^-e^+\nu_e)} = 0.978 \pm 0.007 \pm 0.012$$





No deviation large than 2σ from 1 in q^2 interval $(0.2,\ 1.5)$ GeV$^2/c^4$.





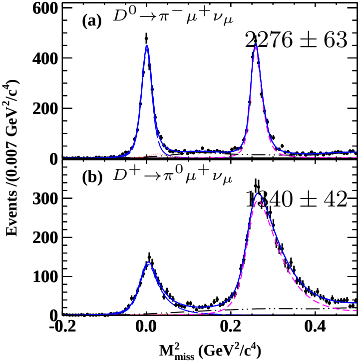
- Published at EPJC76(2016)369
- Simultaneous fit for $\bar{K}^0 \to \pi^+\pi^-$ and $\bar{K}^0 \to \pi^0\pi^0$

$$R_{\bar{K}^0} = \frac{\Gamma(D^+ \to \bar{K}^0 \mu^+ \nu_\mu)}{\Gamma(D^+ \to \bar{K}^0 e^+ \nu_e)} = 0.988 \pm 0.033$$

Analysis of $D \to \pi\mu^+\nu_\mu$

SM prediction:

$$\frac{\Gamma(D \to \pi\mu^+\nu_\mu)}{\Gamma(D \to \pi e^+\nu_e)} = 0.985(2)$$



Submitted to PRL, arXiv:1802.05492

$$\mathcal{B}(D^0 \to \pi^-\mu^+\nu_\mu) = (0.267 \pm 0.007 \pm 0.007)\%$$

$$\mathcal{B}(D^+ \to \pi^0\mu^+\nu_\mu) = (0.342 \pm 0.011 \pm 0.010)\%$$

$$R_{\pi^-} = \frac{\Gamma(D^0 \to \pi^-\mu^+\nu_\mu)}{\Gamma(D^0 \to \pi^- e^+\nu_e)} = 0.905 \pm 0.027 \pm 0.023$$

consistent with SM prediction within 2.3σ

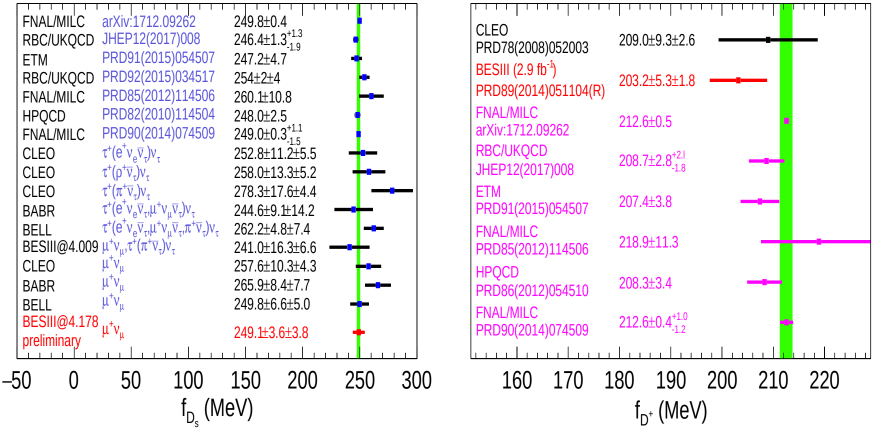
$$R_{\pi^0} = \frac{\Gamma(D^+ \to \pi^0\mu^+\nu_\mu)}{\Gamma(D^+ \to \pi^0 e^+\nu_e)} = 0.942 \pm 0.037 \pm 0.027$$

consistent with SM prediction within 0.9σ

Comparison of $f_{D_s^+}$ and f_{D^+}

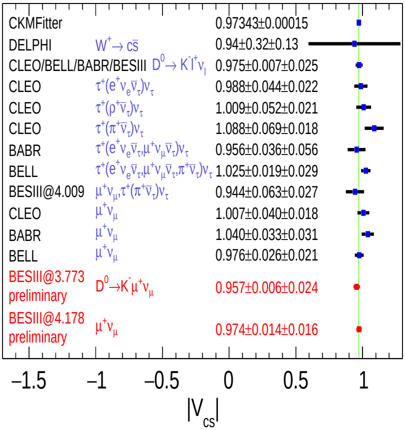
Using

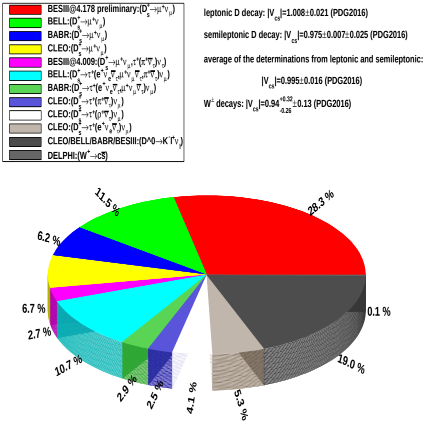
- $V_{cs} = 0.97343 \pm 0.00015$, $V_{cd} = 0.22520 \pm 0.00065$;
- $\tau_{D_s^+} = 0.5 \pm 0.007$ ps, $\tau_{D^+} = 1.040 \pm 0.007$ ps.



Using

- $f_{D_s^+} = 249.0 \pm 0.3^{+1.1}_{-1.5}$ MeV, $f_+^{D\to K}(0) = 0.747 \pm 0.011 \pm 0.015$;
- $\tau_{D_s^+} = 0.5 \pm 0.007$ ps.

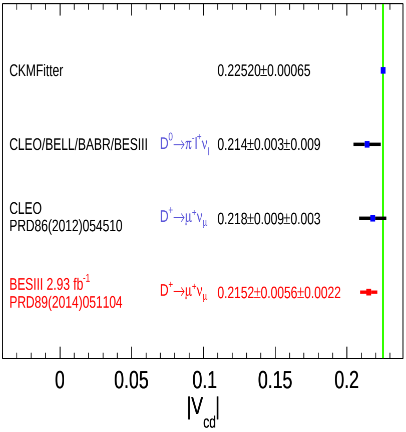


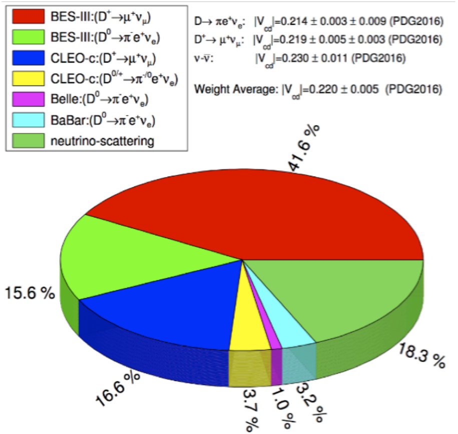


Comparison of $|V_{cd}|$

Using

- $f_{D^+} = 212.6 \pm 0.4^{+1.0}_{-1.2}$ MeV, $f_+^{D\to\pi}(0) = 0.666 \pm 0.020 \pm 0.021$;
- $\tau_{D^+} = 1.040 \pm 0.007$ ps.





Summary

- Precision measurements of $\mathcal{B}(D^+_{(s)} \to \ell^+\nu_\ell)$, $\mathcal{B}(D \to \bar{K}\mu^+\nu_\mu)$ and $\mathcal{B}(D \to \pi\mu^+\nu_\mu)$ were performed at BESIII.
- CKM matrix elements $|V_{cs(d)}|$, D meson decay constants $f_{D^+_{(s)}}$ and hadronic form factor $f_+^{D\to K}(0)$ are extracted. These results can help to test the unitarity of CKM matrix and calibrate various theoretical calculations
- LFU test are perfromed and no significant deviation from the SM prediction is found at current statistics

	$R(D_s^+)$	$R(D^+)$	$R(K^-)$	$R(\bar{K}^0)$	$R(\pi^-)$	$R(\pi^0)$
SM	$9.74(1)$	$2.66(1)$	$0.975(1)$	$0.975(1)$	$0.985(2)$	$0.985(2)$
BESIII	$10.19(52)$	$3.21(64)$	$0.978(14)$	$0.988(33)$	$0.905(35)$	$0.942(46)$

Thanks for your attention!
Dank ye!

Backup: two parameter z expansion parametrization for form factors

$$f_+(t)=\frac{1}{P(t)\Phi(t,t_0)}\frac{f_+(0)P(0)\Phi(0,t_0)}{1+r_1(t_0)z(0,t_0)}(1+r_1(t_0)[z(t,t_0)])$$

where

$$z(t,t_0)=\frac{\sqrt{t_+-t}-\sqrt{t_+-t_0}}{\sqrt{t_+-t}+\sqrt{t_+-t_0}},$$

$$t_\pm=(m_D\pm m_K)^2,$$

$$t_0=t_+(1-\sqrt{1-t_-/t_+}).$$

$$P(t)=z(t,m^2_{D_s^*})$$

$$\Phi(t,t_0)=\sqrt{\frac{1}{24\pi\chi_V}}(\frac{t_+-t}{t_+-t_0})^{1/4}(\sqrt{t_+-t}+\sqrt{t_+})^{-5}$$

$$\times(\sqrt{t_+-t}+\sqrt{t_+-t_0})(\sqrt{t_+-t}+\sqrt{t_+-t_-})^{3/2}$$

$$\times(t_+-t)^{3/4}$$

$$\chi_V=\frac{3}{32\pi^2m_c^2}$$