Precision measurements of $\mathcal{B}(D^+_{(s)} \to \ell^+\nu_\ell)$, $\mathcal{B}(D \to \bar{K}\mu^+\nu_\mu)$, $\mathcal{B}(D \to \pi\mu^+\nu_\mu)$ and LFU test at BESIII

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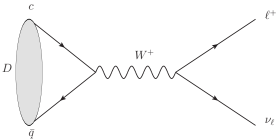
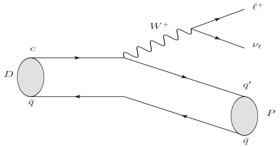
Outline

1. Motivation
2. Data samples and Analysis method
3. Physics Results
4. Summary

Leptonic decays as ideal places to study strong and weak interactions



pure leptonic decays
quark weak function with D unknown
$\rightarrow F_\mu = f_D(p_D^2)p_{D\mu}$



semileptonic decays
mesons can not be treated as point particles
$\rightarrow H_\mu = f_+(q^2)(p_D + p_P)_\mu + f_-(q^2)(p_D - p_P)_\mu$,
$(q = p_D - p_P)$

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

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

Leptonic decays as a testbed for SM

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)[1]	$212.6(0.4)^{(+1.0)}_{(-1.2)}$	$249.0(0.3)^{(+1.1)}_{(-1.5)}$	$0.73(3)(7)$	$0.64(3)(6)$
Lattice (HPQCD)[2]	$208.3(1.0)(3.3)$	$248.0(2.5)$	$0.747(11)(15)$	$0.666(20)(21)$
QCD Sum Rules[3]	$206.2(7.3)(5.1)$	$245.3(15.7)(4.5)$	$0.75^{(+11)}_{(-8)}$	$0.67^{(+10)}_{-(7)}$
PDG[4]	$203.9(4.7)$	$257.7(4.1)$	$0.739(4)$ 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.

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

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

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

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

Leptonic decays as a way to probe new physics

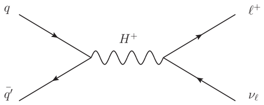
In SM, the weak leptonic current is simply $L^\mu = \bar{u}\gamma^\mu(1-\gamma^5)v$

For leptonic process involving different generation of leptons, the only difference in their decay rates is the lepton mass and their ratio can be precisely determined. for example:

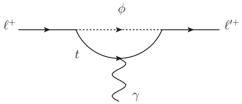
$$\frac{\Gamma(D_s^+ \to \tau^+\nu_\tau)}{\Gamma(D_s^+ \to \mu^+\nu_\mu)} = 9.74 \qquad \frac{\Gamma(D \to \bar{K}\mu^+\nu_\mu)}{\Gamma(D \to \bar{K}e^+\nu_e)} \sim 0.97$$

However, experiments in B meson semileptonic decays ($\bar{B} \to D^*(D)\tau^-\bar{\nu}_\tau$ [5], $\bar{B} \to K^*(K)\ell^+\ell^-$ [6]) in BaBar, LHCb and Belle show evidence of lepton universality violation.

These suggest new physics mechanisms with different coupling strengths to different generation of leptons.



Charged Higgs?



Leptoquark?

[5] PRL109(2012)101802, PRD88(2013)072012, PRL115(2015)111803

[6] PRL113(2014)151601, PRL118(2017)111801

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	

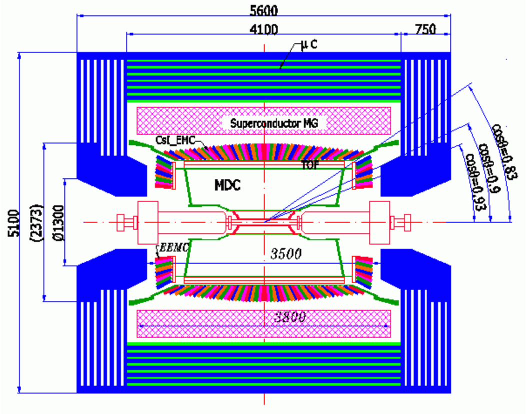
- Previous BESIII measurements have significantly improve the precison of the electron modes.
- Further study on the muon modes needed for precise LFU test.

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

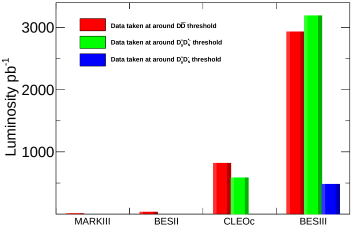
The precision can be improved by the BESIII data.

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

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

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

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

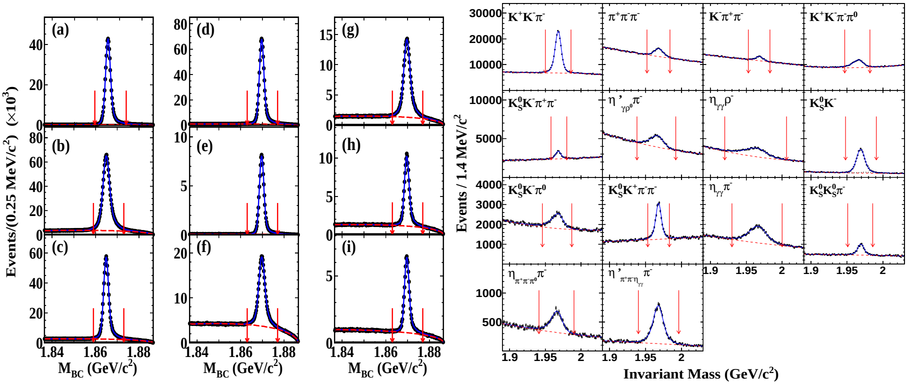
$$\bar{\epsilon}_{\rm sig} = \sum(N^i_{\rm ST}\epsilon^i_{\rm ST,sig}/\epsilon^i_{\rm ST})/N^{\rm tot}_{\rm ST}$$

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

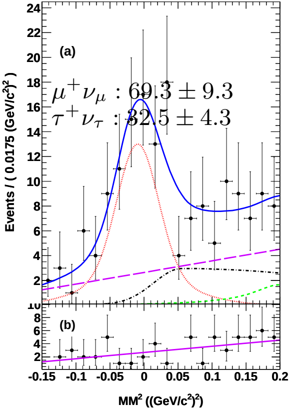
$$U_{\rm miss} = E_{\rm miss} - |\vec{p}|_{\rm miss}$$

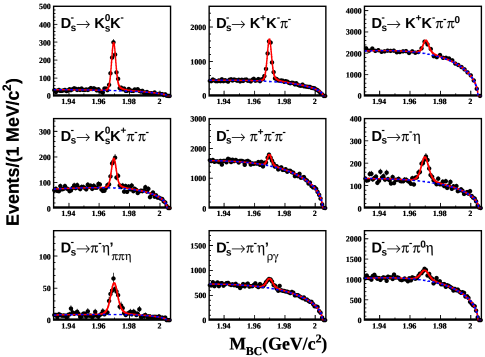
$$M^2_{\rm miss} = E^2_{\rm miss} - |\vec{p}|^2_{\rm miss}$$

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.





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

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

$\mathcal{B}(D_s^+\to\mu^+\nu_\mu)=(0.495\pm0.067\pm0.026)\%$

$\mathcal{B}(D_s^+\to\tau^+\nu_\tau)=(4.83\pm0.65\pm0.26)\%$

Published at PRD94(2016)072004.

An overall total of 15127 ± 321 ST D_s^- mesons are reconstructed.

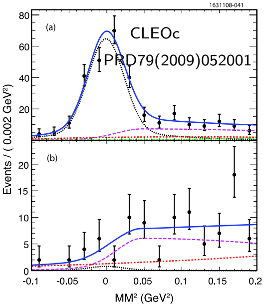
τ^+ reconstructed using $\tau^+ \to \pi^+\bar{\nu}_\tau$.

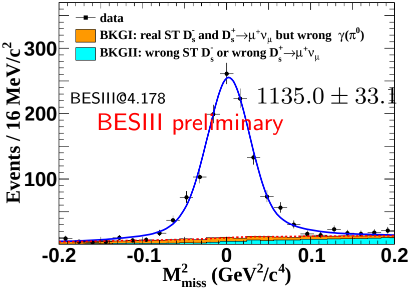
without the constraint:

$\mathcal{B}(D_s^+\to\mu^+\nu_\mu)=(0.517\pm0.075\pm0.021)\%$

$\mathcal{B}(D_s^+\to\tau^+\nu_\tau)=(3.28\pm1.83\pm0.37)\%$

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

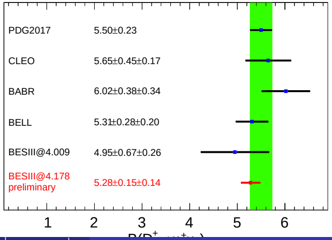




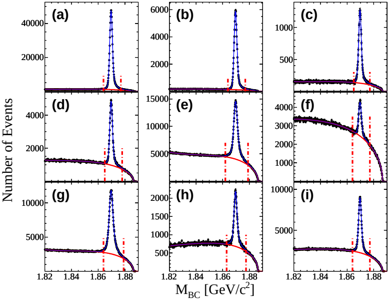
$$f_{D_s^+}|V_{cs}| = 242.5 \pm 3.5_{\text{stat.}} \pm 3.7_{\text{syst.}}$$

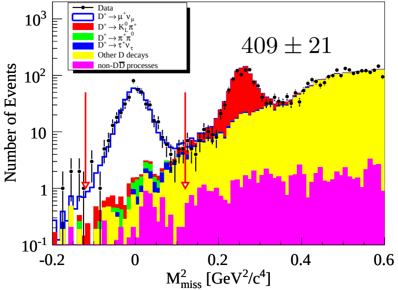
- Lower background level compared to CLEOc with MUC information
- The most precise measurement to date

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



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



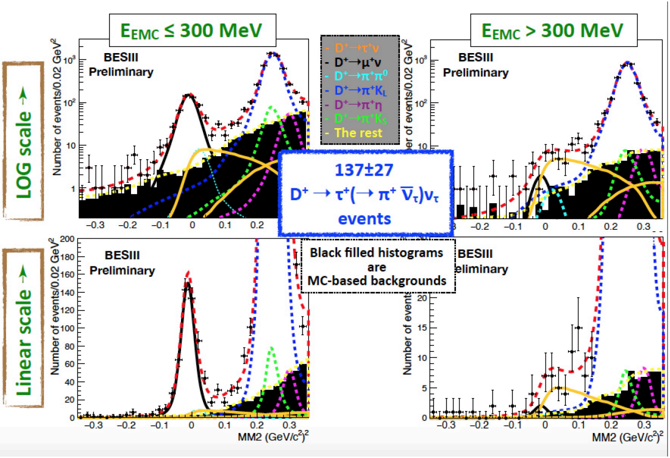


- Published at PRD89(2014)051104.
- 1703054 ± 3405 ST D^- mesons reconstructed using nine modes.
- MUC information used to suppress backgrounds.

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

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

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



First evidence with 4σ statistical significance.

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

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

SM prediction 2.66 ± 0.01.

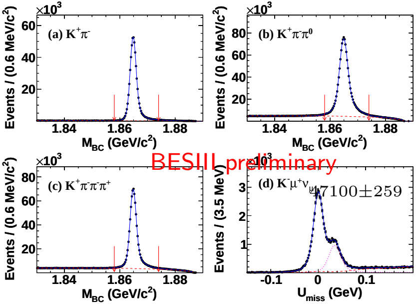
Analysis of $D^0 \to K^-\mu^+\nu_\mu$

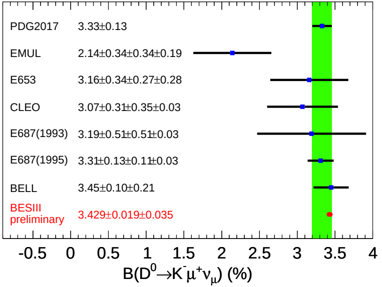
High order term in the decay rate concerning lepton mass is considered.

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

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

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



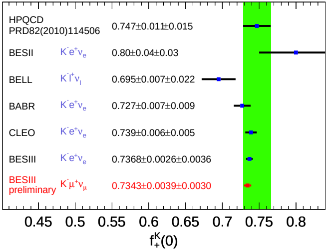


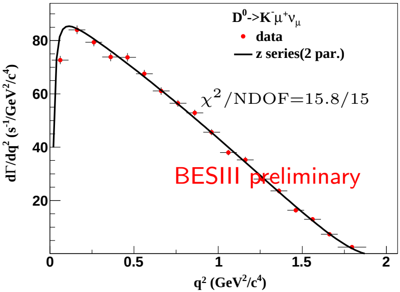
Analysis of $D^0 \to K^- \mu^+ \nu_\mu$

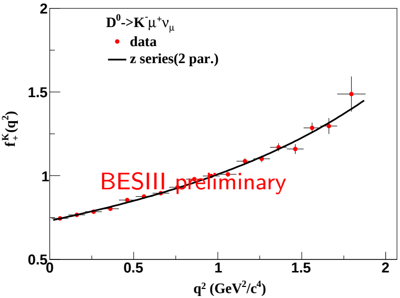
Using two parameter expansion parametrization for $f_+^{D\to K}(q^2)$ (PLB633(2006)61)

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

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

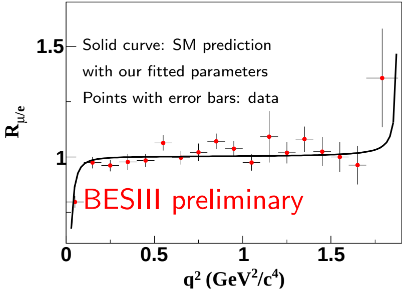


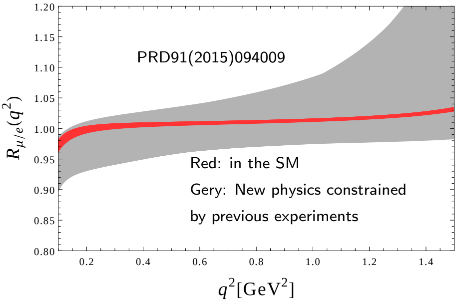




Analysis of $D^0 \to K^-\mu^+\nu_\mu$

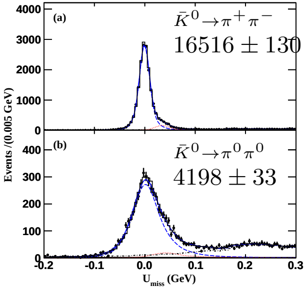
$$R_{\mu/e} = \frac{\Gamma(D^0 \to K^-\mu^+\nu_\mu)}{\Gamma(D^0 \to K^-e^+\nu_e)} = 0.978 \pm 0.007 \pm 0.012$$

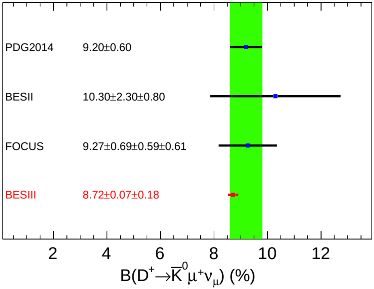




No deviation large than 2σ from 1 in q^2 interval $(0.2, 1.5)$ GeV$^2/c^4$.

Analysis of $D^+ \to \bar{K}^0\mu^+\nu_\mu$





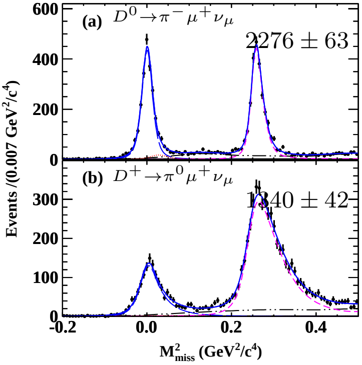
- Published at EPJC76(2016)369
- Simultaneous fit for $\bar{K}^0 \to \pi^+\pi^-$ and $\bar{K}^0 \to \pi^0\pi^0$

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

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

SM prediction:

$$\frac{\Gamma(D \to \pi\mu^+\nu_\mu)}{\Gamma(D \to \pi e^+\nu_e)} \sim 0.97$$



Submitted to PRL, arXiv:1802.05492

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

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

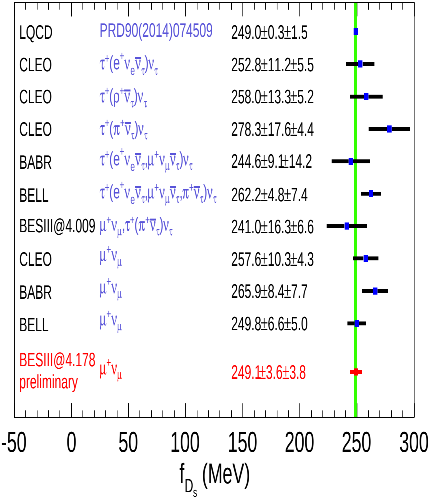
$R^0_{\rm LU} = \frac{\Gamma(D^0 \to \pi^- \mu^+ \nu_\mu)}{\Gamma(D^0 \to \pi^- e^+ \nu_e)} = 0.905 \pm 0.027 \pm 0.023$

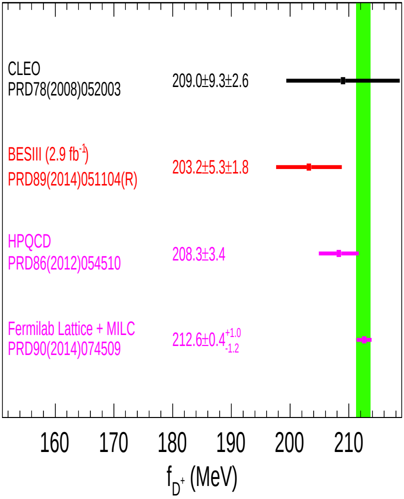
consistent with SM prediction within 1.9σ

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

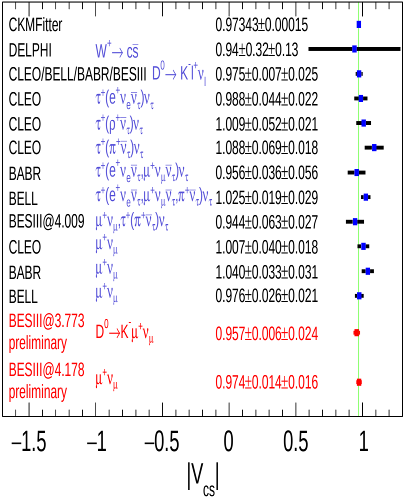
consistent with SM prediction within 0.6σ

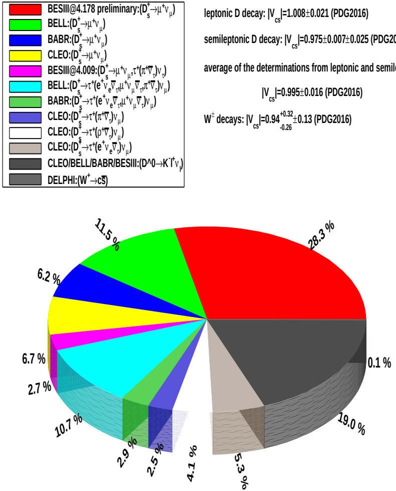
Comparison of $f_{D_s^+}$ and f_{D^+}





Comparison of $|V_{cs}|$





leptonic D decay: $|V_{cs}|$=1.008±0.021 (PDG2016)

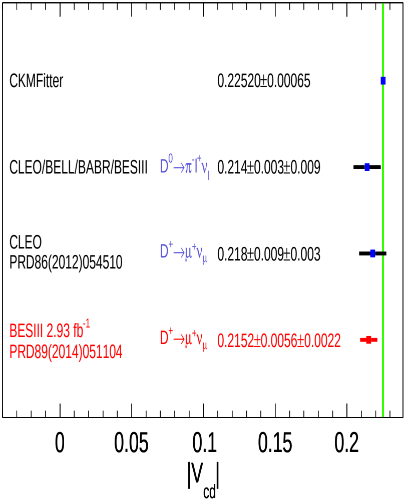
semileptonic D decay: $|V_{cs}|$=0.975±0.007±0.025 (PDG2016)

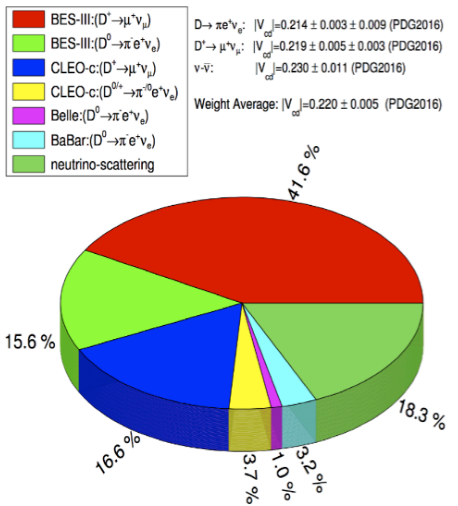
average of the determinations from leptonic and semileptonic:

$|V_{cs}|$=0.995±0.016 (PDG2016)

$W^\pm$ decays: $|V_{cs}|=0.94^{+0.32}_{-0.26}\pm0.13$ (PDG2016)

Comparison of $|V_{cd}|$





Summary

- Using data taken at BESIII, Precision measurements of $\mathcal{B}(D_{(s)}^+ \to \ell^+\nu_\ell)$, $\mathcal{B}(D \to \bar{K}\mu^+\nu_\mu)$ and $\mathcal{B}(D \to \pi\mu^+\nu_\mu)$ are performed
- 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