D (Semi-)Leptonic and Rare Decays at BESIII

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Overview

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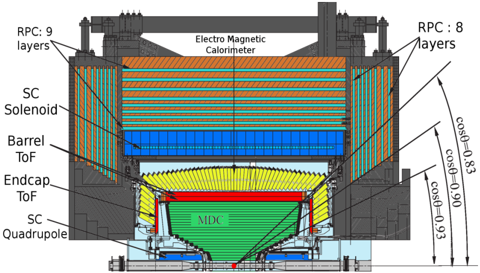
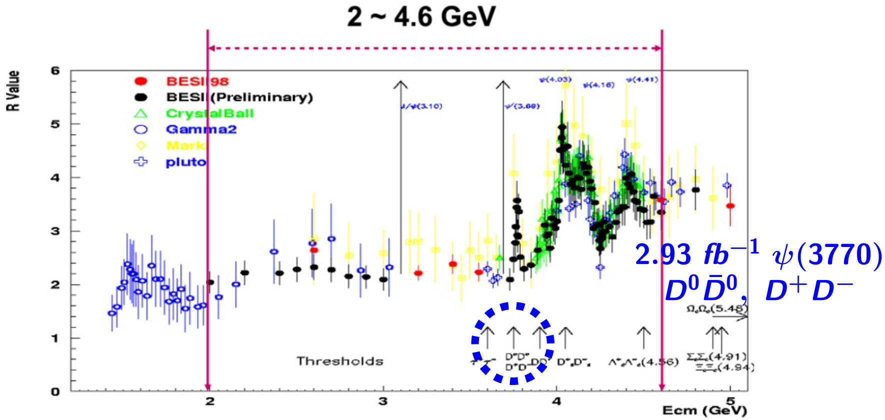
4. Summary



Charm Production

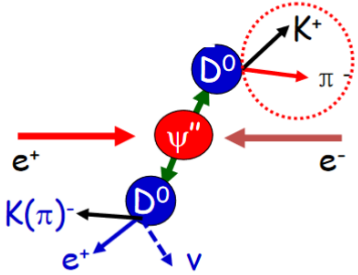


(Semi)leptonic decays: decay constants, form factors, $|V_{cd(s)}|$;

Rare and forbidden decays: search for new physics.

Quantum correlated $D^0\bar{D}^0$: strong phase measurements.

Analysis Method



1. Single Tag (ST)
   $\mathrm{M_{BC}} = \sqrt{\mathrm{E}^2_{\mathrm{beam}}/c^4 - |\mathbf{p}^2_{\bar{D}}|/c^2}$
2. Double Tag (DT)
   particles not used to form single tag $\bar{D}$
3. $\mathcal{B}_{\mathrm{sig}} = \frac{N_{\mathrm{sig}}}{\sum_\alpha N^\alpha_{\mathrm{tag}}\epsilon^\alpha_{\mathrm{tag,sig}}/\epsilon^\alpha_{\mathrm{tag}}}$
4. absolute branching fraction measurements

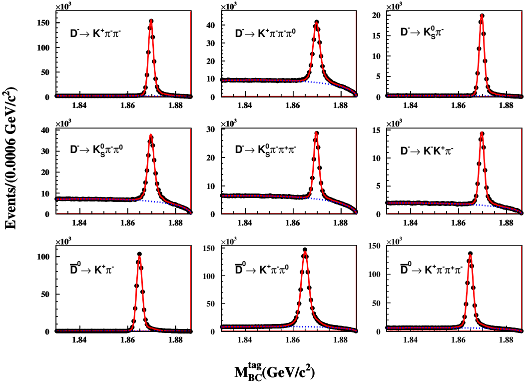
1. tag D^- via $K^+\pi^-\pi^-$, $K^+\pi^-\pi^-\pi^0$, $K^0_S\pi^-$, $K^0_S\pi^-\pi^0$, $K^0_S\pi^-\pi^+\pi^-$, $K^+K^-\pi^-$
2. tag $\bar{D}^0$ via $K^+\pi^-$, $K^+\pi^-\pi^0$, $K^+\pi^-\pi^+\pi^-$

1. reconstruct the 'missing' neutrino via $\mathrm{U_{miss}} = \mathrm{E_{miss}} - c|\mathbf{p}_{\mathrm{miss}}|$
2. fully reconstruct the final state particles via $\mathrm{M^{sig}_{BC}}$

all charge conjugates are implied

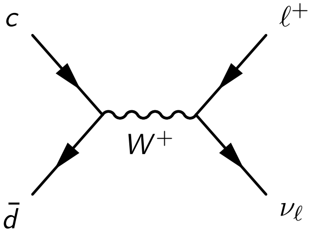
Single tag yields and efficiencies [PRD 97, 072015(2018)]

tags	$\varepsilon(\%)$	yields
1	50.47 $\pm$ 0.06	755661 $\pm$ 922
2	24.65 $\pm$ 0.05	231322 $\pm$ 729
3	54.44 $\pm$ 0.17	95346 $\pm$ 330
4	27.44 $\pm$ 0.06	210535 $\pm$ 638
5	36.12 $\pm$ 0.10	119249 $\pm$ 451
6	40.71 $\pm$ 0.16	64904 $\pm$ 259
7	64.64 $\pm$ 0.03	523265$\pm$763
8	33.60 $\pm$ 0.01	1022697$\pm$1448
9	38.26 $\pm$ 0.02	707936$\pm$1129

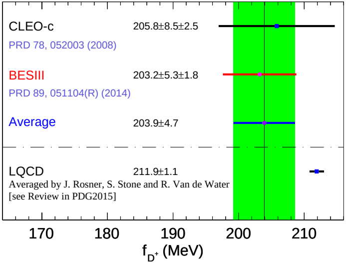


- about 28% of the total D^+ $\mathcal{B}'s$ and 26% of the total D^0 $\mathcal{B}'s$
- highly suppress the background from non-$D\bar{D}$ decays and high reconstruction efficiencies

Charmed leptonic decays



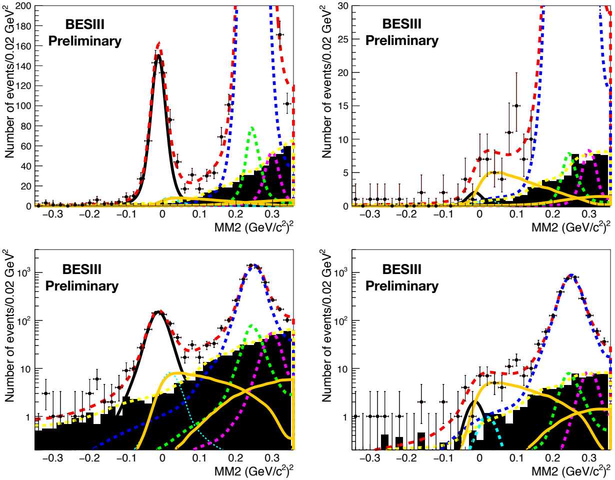
$D^+ \to \mu^+\nu_\mu$



- $\Gamma(D^+ \to \ell^+\nu_\ell) = \frac{G_F^2 f_{D^+}^2}{8\pi} |V_{cd}|^2 m_\ell^2 m_{D^+} \left(1 - \frac{m_\ell^2}{m_{D^+}^2}\right)^2$
- determine the decay constant f_{D^+} and $|V_{cd}|$
- $\mathcal{B}_{D^+\to\mu^+\nu_\mu} = (3.71 \pm 0.19 \pm 0.06) \times 10^{-4}$ by BESIII [PRD 89, 051104 (2014)]
- $\mathcal{B}_{D^+\to\tau^+\nu_\tau} < 1.2 \times 10^{-3}$@90% C.L. by CLEO [PRD 78, 052003 (2008)]
- $R = \frac{\Gamma(D^+\to\tau^+\nu_\tau)}{\Gamma(D^+\to\mu^+\nu_\mu)} = \frac{m_\tau^2\left(1-\frac{m_\tau^2}{m_{D^+}^2}\right)^2}{m_\mu^2\left(1-\frac{m_\mu^2}{m_{D^+}^2}\right)^2} = 2.66 \to \mathcal{B}_{D^+\to\tau^+\nu_\tau} = (9.99 \pm 0.45) \times 10^{-4}$

Search for $D^+ \to \tau^+\nu_\tau,\ \tau^+ \to \pi^+\bar{\nu}_\tau$

$\mathrm{E_{EMC}} \leq 300\,\mathrm{MeV}$ $\quad$ $\mathrm{E_{EMC}} > 300\,\mathrm{MeV}$



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

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

$D^+ \to \pi^+\pi^0$

$D^+ \to \pi^+K^0_L$

$D^+ \to \pi^+\eta$

$D^+ \to \pi^+K^0_S$

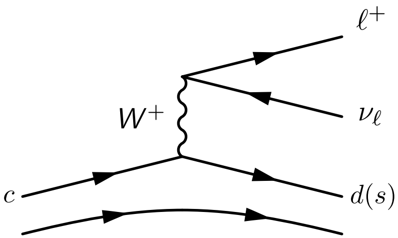
the rest

- $N_{sig} = 137 \pm 27$
- $\mathcal{B}_{D^+\to\tau^+\nu_\tau} = (1.20 \pm 0.24_{stat.}) \times 10^{-3}$
- significance $>4\sigma$

$$M^2_{\mathrm{miss}} = (E_{\mathrm{beam}} - E_{\pi^+})^2 - (-\vec{p}_{D^-} - \vec{p}_{\pi^+})^2$$

R=3.21 $\pm$ 0.64, consistent with SM prediction 2.66 within 0.9σ

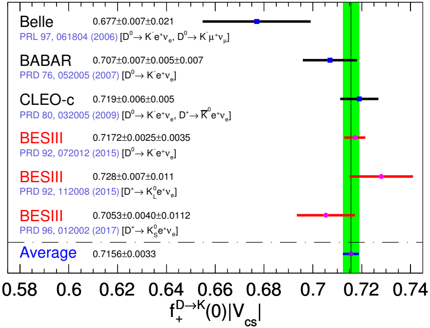
Semileptonic decays to pseudoscalar $D \to P\ell^+\nu_\ell$

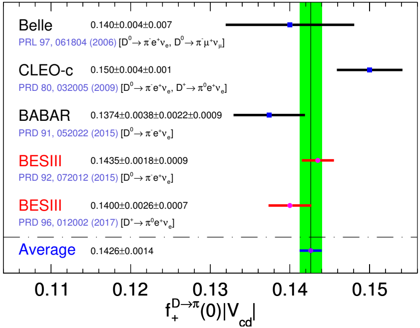


1. Simple pole: $f_+(q^2) = \frac{f_+(0)}{1-\frac{q^2}{m^2_{\mathrm{pole}}}}$
2. Modified pole:
   $f_+(q^2) = \frac{f_+(0)}{(1-\frac{q^2}{m^2_{\mathrm{pole}}})(1-\alpha\frac{q^2}{m^2_{\mathrm{pole}}})}$
3. Series expasion: $f_+(q^2) = \frac{1}{P(q^2)\phi(q^2,t_0)}\sum_{k=0}^{\infty} a_k(t_0)[z(q^2,t_0)]^k$

- partial decay width
  $$\frac{d\Gamma_{P\ell^+\nu_\ell}}{dq^2} = \frac{G_F^2|V_{cq}|^2}{8\pi^3 m_D}|\vec{p}_P||f_+^P(q^2)|^2(\frac{W_0-E_P}{F_0})^2 \times \left[\frac{1}{3}m_D|\vec{p}_P|^2 + \mathcal{O}(m_\ell^2)\right],$$
  $$W_0 = (m_D^2 + m_P^2 - m_\ell^2)/2m_D,\ F_0 = W_0 - E_P + m_\ell^2/2m_D$$
- measure $V_{cd(s)}$ to test the unitary of CKM matrix
- measure the form factors $f_+^P(0)$ to calibrate the Lattice QCD calculation
- test lepton universality via $\mathcal{R} = \Gamma_\mu/\Gamma_e$

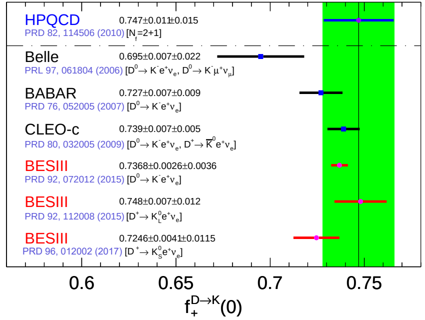
$|V_{cd(s)}|$ determination via $D \to K/\pi e^+\nu_e$

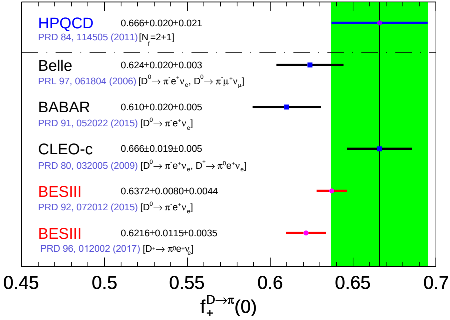




- BESIII contribute to the $|V_{cd(s)}|$ determination dominantly
- $|V_{cd}| = 0.214 \pm 0.002_{\mathrm{exp.}} \pm 0.009_{\mathrm{LQCD}}$,
  $|V_{cs}| = 0.214 \pm 0.004_{\mathrm{exp.}} \pm 0.024_{\mathrm{LQCD}}$ with LQCD calculations for $f_+^{D\to K/\pi}(0)$ [[PRD 82, 114506 (2010); 84, 114505 (2011)]
- CKM matrix elements determination suffers from large LQCD uncertainties

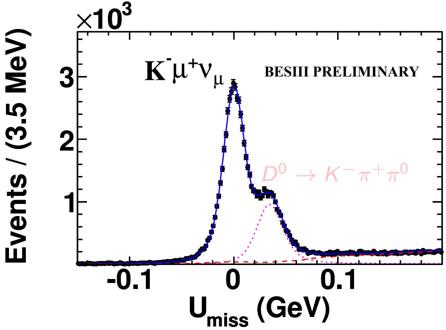
$f_+^{D\to K/\pi}(0)$ determination via $D \to K/\pi e^+\nu_e$

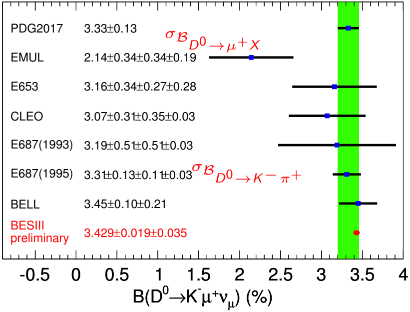




- assuming the CKM matrix is unitary, BESIII contribute to the $f_+^{D\to K/\pi}(0)$ determination dominantly
- LQCD uncertainties overwhelm the experimental uncertainties

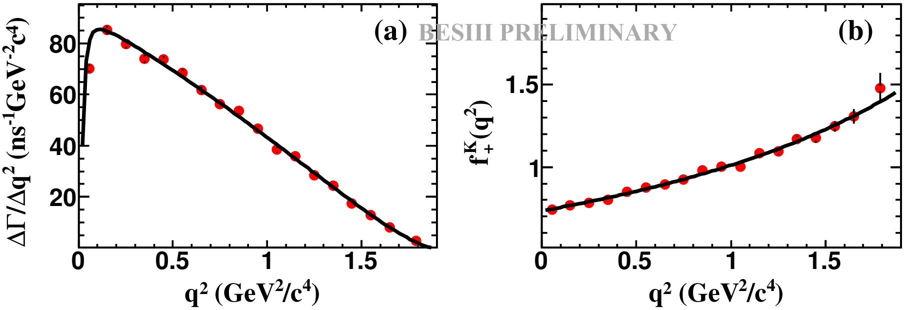
$\mathcal{B}$ of $D^0 \to K^- \mu^+ \nu_\mu$





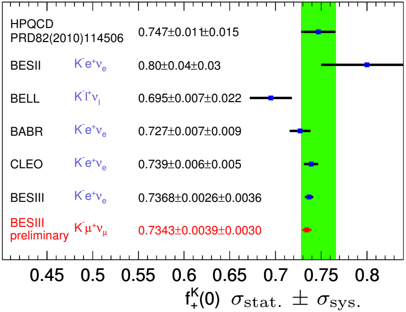
- $N_{sig} = 47100 \pm 259$, $\mathcal{B}_{D^+ \to K^- \mu^+ \nu_\mu} = (3.429 \pm 0.019 \pm 0.035)\%$
- statistics similar to the BESIII measurement
  $\mathcal{B}_{D^+ \to K^- e^+ \nu_e} = (3.505 \pm 0.014 \pm 0.033)\%$ [PRD 92, 072012 (2015)]
- BESIII made the most precise measurement

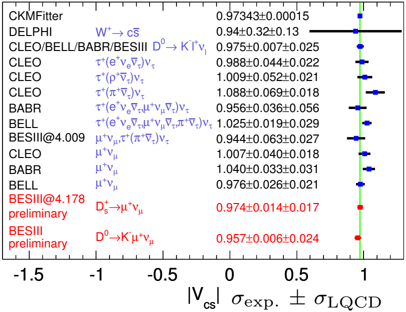
Form factor of $D^+ \to K^-\mu^+\nu_\mu$



- taking the form of second order series expansion,
  $f_+^K(t) = \frac{1}{P(t)\phi(t,t_0)} \frac{f_+^K(0)P(0)\phi(0,t_0)}{1+r_1(t_0)z(0,t_0)}(1 + r_1(t_0)[z(t,t_0)])$
- $\chi^2 = \Delta\Gamma^T C^{-1} \Delta\Gamma$ is constructed, where $\Delta\Gamma = \Delta\Gamma_{\mathrm{mea.}} - \Delta\Gamma_{\mathrm{exp.}}$
- $f_+^K(0)|V_{cs}| = 0.7148 \pm 0.0038 \pm 0.0029$
- statistics similar to the BESIII measurement
  $f_+^K(0)|V_{cs}|(D^+ \to K^-e^+\nu_e) = 0.7172 \pm 0.0025 \pm 0.0035$ [PRD 92, 072012 (2015)]

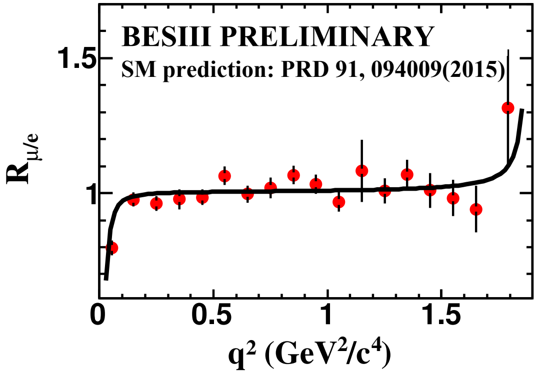
$f_+^K(0)$ and $|V_{cs}|$ determination via $D^+ \to K^- \mu^+ \nu_\mu$





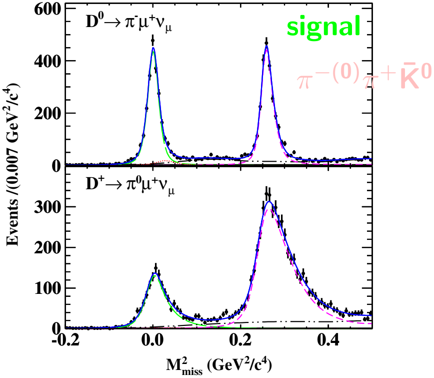
- taking $f_+^K(0) = 0.747 \pm 0.011 \pm 0.015$ from LQCD [PRD 82, 114506(2010)], $|V_{cs}| = 0.957 \pm 0.006 \pm 0.024$, LQCD uncertainties are dominant
- taking $|V_{cs}|$ from CKMfitter, $f_+^K(0) = 0.7343 \pm 0.0039 \pm 0.0030$

Test the lepton universality



- deviation from SM prediction in B semileptonic decays $\bar{B} \to D^{(\star)}\tau^-\bar{\nu}_\tau$ [PRL 109, 101802(2012); PRD 88, 072012(2013); PRL 115, 111803(2015)] and $B \to K^{(\star)}\ell^+\ell^-$ [PRL 113, 151601(2014); PRL 118, 111801(2017)]
- $R_{\mu/e} = \frac{\Gamma(D^+ \to K^-\mu^+\nu_\mu)}{\Gamma(D^+ \to K^- e^+\nu_e)[PRD92,072012(2015)]} = 0.978 \pm 0.007 \pm 0.012$, no deviation larger than 2σ over the q^2 interval

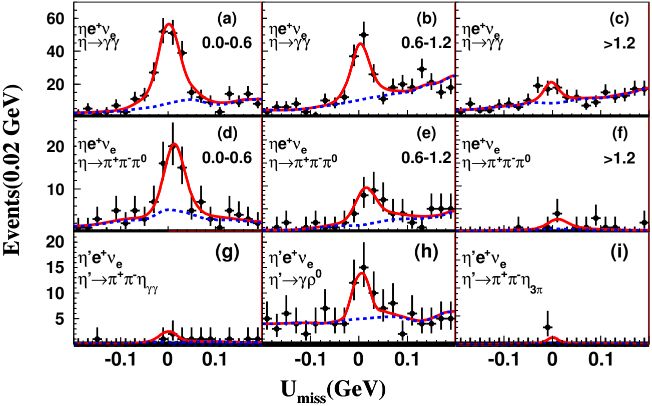
Study of the decays $D \to \pi\mu^+\nu_\mu$ arxiv: [hep-ex] 1802.05492



- $\mathcal{B}_{D^+\to\pi^0\mu^+\nu_\mu} = (0.342 \pm 0.011 \pm 0.010)\%$
- $\mathcal{B}_{D^0\to\pi^-\mu^+\nu_\mu} = (0.267 \pm 0.007 \pm 0.007)\%$
- $\mathcal{R}^{D^0}_{\mu/e} = \mathcal{B}_\mu/\mathcal{B}_e = 0.905 \pm 0.027 \pm 0.023$
- $\mathcal{R}^{D^+}_{\mu/e} = \mathcal{B}_\mu/\mathcal{B}_e = 0.942 \pm 0.037 \pm 0.027$
- $\mathcal{R}^{\mu}_{IS} = \Gamma^{D^0\to\pi^-}/2\Gamma^{D^+\to\pi^0} = 0.990 \pm 0.041 \pm 0.035$

- taking $\mathcal{B}_{D^{+(0)}\to\pi^{0(-)}e^+\nu_e}$ from [PRD 92, 072012 (2010); 96, 012002 (2017)], $\mathcal{R}^{D^{0(+)}}_{\mu/e}$ coincides with SM prediction 0.97 [PLB 633, 61 (2006)] within $1.9(0.6)\sigma$
- $\mathcal{R}^{\mu}_{IS}$ is consistent with no isospin violation and the value of electronic decay $\mathcal{R}^{e}_{IS}$ [PRD 96, 012002 (2017)]

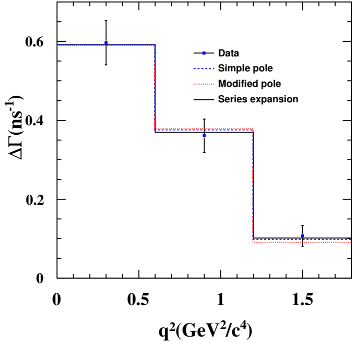
Branching fractions of $D^+ \to \eta^{(\prime)} e^+ \nu_e$ arxiv: [hep-ex] 1803.05570



- $\langle \eta | = \cos\phi_P \, \langle \eta_q | - \sin\phi_P \, \langle \eta_s |$,
- $\langle \eta' | = \cos\phi_G (\sin\phi_P \, \langle \eta_q | + \cos\phi_P \, \langle \eta_s |) + \sin\phi_G \, \langle gg |$;
- $\frac{\Gamma(D^+ \to \eta' \ell^+ \nu_\ell)}{\Gamma(D^+ \to \eta \ell^+ \nu_\ell)} = \tilde{R}_D \tan^2 \phi_P$,
- $\frac{\Gamma(D_s^+ \to \eta' \ell^+ \nu_\ell)/\Gamma(D_s^+ \to \eta \ell^+ \nu_\ell)}{\Gamma(D^+ \to \eta' \ell^+ \nu_\ell)/\Gamma(D^+ \to \eta \ell^+ \nu_\ell)} = \cot^4 \phi_P$(next talk)

$\mathcal{B}_{\eta e^+ \nu_e} = (10.74 \pm 0.81 \pm 0.51) \times 10^{-4}$
$\mathcal{B}_{\eta' e^+ \nu_e} = (1.91 \pm 0.51 \pm 0.13) \times 10^{-4}$
$\phi_P = (40 \pm 3 \pm 3)^\circ (\phi_G{=}0)$

Form factor fit of $D^+ \to \eta e^+ \nu_e$



In the fit, $\chi^2 = \Delta\Gamma^T V^{-1} \Delta\Gamma$ is constructed, where $\Delta\Gamma = \Delta\Gamma_m - \Delta\Gamma_p$

1. Simple pole: $f_+(q^2) = \frac{f_+(0)}{1 - \frac{q^2}{m^2_{\mathrm{pole}}}}$

   $f_+(0)|V_{cd}| = 8.15 \pm 0.45 \pm 0.18$
2. Modified pole:

   $f_+(q^2) = \frac{f_+(0)}{(1 - \frac{q^2}{m^2_{\mathrm{pole}}})(1 - \alpha \frac{q^2}{m^2_{\mathrm{pole}}})}$

   $f_+(0)|V_{cd}| = 8.24 \pm 0.51 \pm 0.22$
3. Series expasion: $f_+(q^2) =$

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

   $f_+(0)|V_{cd}| = (7.86 \pm 0.64 \pm 0.21) \times 10^{-2}$

- $\mathcal{B}_{\eta^{(\prime)} e^+ \nu_e}$ and are $f_+^{\eta}(0)|V_{cd}|$ consistent with CLEO's measurement [PRD 84, 032001(2011), tag+'GR' method]

decays ($\times 10^{-4}$)	BESIII (tag)	CLEO (tag)	CLEO ('GR')	CLEO (tag+'GR')
$\mathcal{B}_{\eta e^+ \nu_e}$	10.74(81)(51)	11.1(1.3)(0.4)	11.7(1.0)(0.4)	11.4(9)(4)
$\mathcal{B}_{\eta' e^+ \nu_e}$	1.91(51)(13)	$2.5^{+1.6}_{-1.0}(0.1)$	2.16(53)(7)	2.16(53)(7)

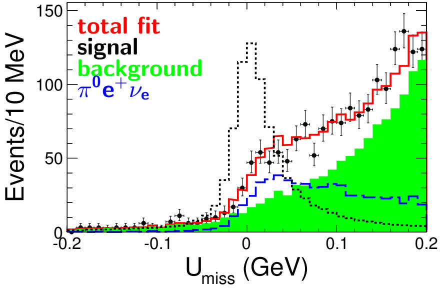
Search for the radiative leptonic decay $D^+ \to \gamma e^+ \nu_e$

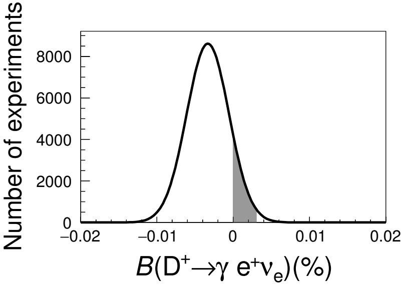
[PRD 95, 071102(2017)]

- no helicity suppression in contrast to pure leptonic decay, and simpler non-perturbative QCD calculation without final-state hadron

models	pQCD[1]	light front quark[2] & NR constituent quark model[3]	VMD[4]	factorization[5]
$\mathcal{B}_{theo.}$	10^{-4}	10^{-6}	10^{-5}(enhanced by LD)	10^{-5}

[1][PRD 51, 111 (1995)] [2]MPLA 15, 2087 (2000); [3]PLB 562, 75 (2003);
[4]MPLA 27, 1250120 (2012);[5]Nucl. Phys. B 889, 778 (2014); 914, 301 (2017)

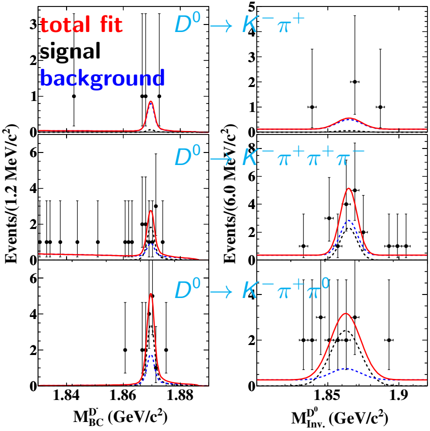




$\mathcal{B}_{\gamma e^+ \nu_e} < 3.0 \times 10^{-5}$ @90% C.L.

Search for the rare decay $D^+ \to D^0 e^+ \nu_e$ [PRD 96, 092002(2017)]

- the heavy c quark remains unchanged while the lighter d quark decays weakly
- $\mathcal{B}_{theo.} = 2.78 \times 10^{-13}$ by it's form factors in the SM [EPJC 59, 841 (2009)]



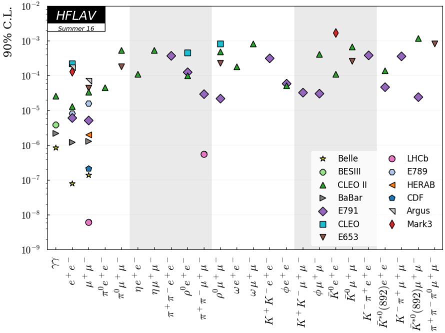
- 2D fit to each D^0 decay mode
- $N_{\rm obs} = 0.2 \pm 2.8,\ 5.9 \pm 2.9,\ 10.0 \pm 4.3$
- $N_{\rm bkg} = 2.8 \pm 0.6,\ 6.0 \pm 0.9,\ 12.4 \pm 1.3$ obtained by fitting to "inclusive" MC

upper limit

$N_{\rm sig} = N_{\rm obs} - N_{\rm bkg} = N_{\rm tot}^{\rm ST} \times \varepsilon \times \mathcal{B}_{D^0} \times \mathcal{B}$
likelihood values of different $\mathcal{B}$s
$\mathcal{B}_{D^+ \to D^0 e^+ \nu_e} < 1.0 \times 10^{-4}$@90% C.L.

Experimental status of $D \to X_u \ell^+\ell^-$ measurements

[EPJC 77, 895, HFLAV2016]



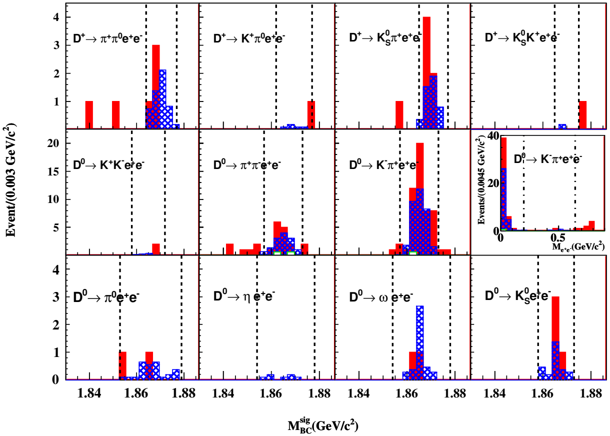
D^0 (observation)	LHCb
$\pi^+\pi^-e^+e^-$	-
$\pi^+\pi^-\mu^+\mu^-$	$9.64(48)(51)(97) \times 10^{-7}$ [1]
$K^-\pi^+e^+e^-$	-
$K^-\pi^+\mu^+\mu^-$	$4.17(12)(40) \times 10^{-6}$ [2]
$K^+K^-e^+e^-$	-
$K^+K^-\mu^+\mu^-$	$1.54(27)(9)(16) \times 10^{-6}$ [1]

[1][PRL 119, 181805(2017)]
[2]PLB 757, 558(2016): $M_{e^+e^-}$ in $\rho - \omega$ region

- $D \to X_u \ell^+\ell^-$ are good channels to study the $c \to u$ FCNC transitions
- electronic modes haven't been observed, compared to muonic modes
- both are essential to test the lepton universality and new physics search

Search for the rare decay $D \to h(h^{(\prime)})e^+e^-$@ BESIII

[PRD 97, 072015(2018)]



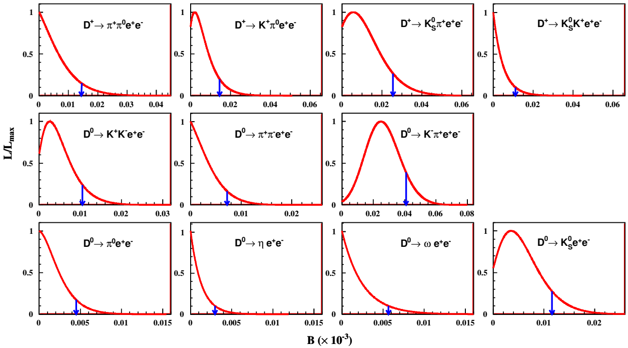
data
background from
$D\bar{D}$ 'inclusive'
MC
$M_{\mathrm{BC}}^{\mathrm{tag}}$ sideband

- inset: $M_{e^+e^-}$ distributions in $D^0 \to K^-\pi^+e^+e^-$ shows some contributions from the photon pole [0, 0.2) $\mathrm{GeV/c^2}$ and $\rho - \omega$ region [0.65, 0.90] $\mathrm{GeV/c^2}$

Upper limits of $D \to h(h^{(\prime)})e^+e^-$

Joint likelihood of $n_{\rm obs}$, $n_{\rm bkg}$ and signal efficiencies[Nucl. Instrum. Meth. A 551 493]

$$\begin{aligned}\mathcal{L} =& \mathcal{P}(n_{\rm obs}, n_{\rm tag}\cdot\mathcal{B}\cdot\varepsilon_{\rm sig} + n_{\rm bkg1} + n_{\rm bkg2})\cdot\mathcal{G}(\varepsilon_{\rm sig}, \varepsilon_{\rm sig}^{\rm MC}, \varepsilon_{\rm sig}^{\rm MC}\cdot\sigma_{\varepsilon}^{\rm MC}) \\ &\cdot\mathcal{P}(n_{\rm bkg1}^{\rm SB}, n_{\rm bkg1}\cdot f)\cdot\mathcal{G}(n_{\rm bkg2}, n_{\rm bkg2}^{\rm MC}, \sigma_{\rm bkg2}^{\rm MC})\end{aligned} \tag{1}$$



Upper limits of $D \to h(h^{(\prime)})e^+e^-$

decay modes	$\mathcal{B}$ ($\times 10^{-5}$)	PDG2015 ($\times 10^{-5}$)
$D^+ \to \pi^+\pi^0 e^+e^-$	< 1.4	-
$D^+ \to K^+\pi^0 e^+e^-$	< 1.5	-
$D^+ \to \pi^+ K_S^0 e^+e^-$	< 2.6	-
$D^+ \to K^+ K_S^0 e^+e^-$	< 1.1	-
$D^0 \to K^- K^+ e^+e^-$	< 1.1	< 31.5
$D^0 \to \pi^+\pi^- e^+e^-$	< 0.7	< 37.3
$D^0 \to K^-\pi^+ e^+e^{-\dagger}$	$< 4.1(2.5\pm1.1,\ 2.6\sigma)$	< 38.5
$D^0 \to \pi^0 e^+e^-$	< 0.4	< 4.5
$D^0 \to \eta e^+e^-$	< 0.3	< 11
$D^0 \to \omega e^+e^-$	< 0.6	< 18
$D^0 \to K_S^0 e^+e^-$	< 1.2	< 11
† in $M_{e^+e^-}$ regions:		
$[0.00,\ 0.20)\ \mathrm{GeV}/c^2$	$< 3.0\ (1.5^{+1.0}_{-0.9})$	-
$[0.20,\ 0.65)\ \mathrm{GeV}/c^2$	< 0.7	-
$[0.65,\ 0.90]\ \mathrm{GeV}/c^2$	$< 1.9\ (1.0^{+0.5}_{-0.4})$	-

- study the 4 body D^+ decays for the first time, improve the sensitivity of D^0 3 and 4 body decays by a magnitude of 10
- the current results are all within SM predictions

Summary

1. measure D^+ decay constant via leptonic decays
2. determine form factors $f_+^P(0)$ and CKM matrix elements $|V_{cd(s)}|$ via semileptonic decays and leptonic decays, test the CKM matrix unitary and calibrate the LQCD calculations; precision measurements of muonic semileptonic decays provide more data to determine $f_+^{K/\pi}(0)$ and $|V_{cd(s)}|$ and test the lepton universality in charged current process
3. $f_+^{\eta}(0)|V_{cd}|$ measurement will perhaps never be used to determine the $f_+^{\eta}(0)$ and $|V_{cd}|$ due to rather limited statistics and absence of LQCD calculations, but $\mathcal{B}_{\eta^{(\prime)}e^+\nu_e}$ are useful to extract the $\eta-\eta'$ mixing angle
4. study the charm FCNC decays, constrain the new physics models
5. low background to search for charm rare decays
6. based on the world's largest $\psi(3770)$ data taken near threshold, more results are on *BESIII* PUBLICATIONS

The End