Semileptonic and leptonic charm decays at BESIII

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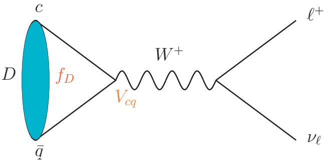
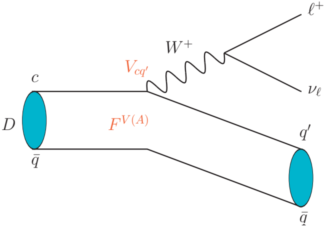
Motivation



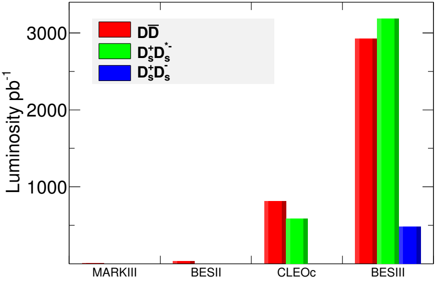


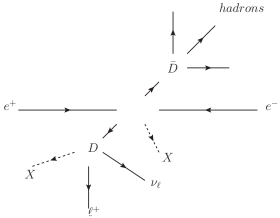
$$\mathcal{M} \propto |V_{cs(d)}| H^\mu L_\mu$$

- test the unitarity of quark mixing matrix and search for new physics.
- test the theoretical calculation on decay constants and form factors, especially LQCD.
- test the lepton flavor universality.
- help to understand the internal structure of light scalar mesons.
- measure the semileptonic Λ_c^+ decays.

$D^{0(+)}$(@3.773 GeV) and D_s^+(@4.18 and 4.01 GeV) data set at BESIII

Pair production at threshold, high efficiency and very low background.





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

$\epsilon^i_{\rm ST/DT}$: The efficiency of ST/DT
$\mathcal{B}^i_{\rm ST/DT}$: The BF of ST/DT

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

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

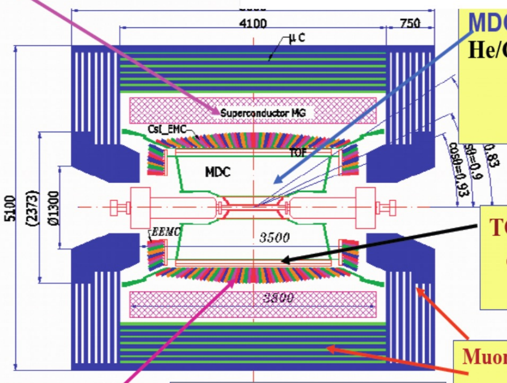
$$M^2_{\rm miss} = E^2_{\rm miss} - |\vec{p}|^2_{\rm miss}$$

BESIII

Nucl. Instr. Meth. A614, 345 (2010)

Magnet: 1 T Super conducting

MDC: small cell & Gas:
He/C_3H_8 (60/40), 43 layers
σ_{xy} = 130 μm
σ_p/p = 0.5% @1GeV
dE/dx = 6%



TOF:
σ_T = 100 ps Barrel
110 ps Endcap

Muon ID: 9 layers RPC
8 layers for endcap

EMC: CsI crystal, 28 cm
$\Delta E/E$ = 2.5% @1 GeV
$\sigma z = 0.6\ cm/\sqrt{E}$

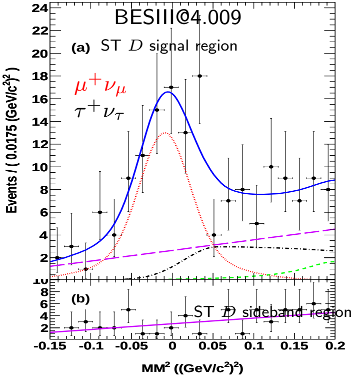
Data Acquisition:
Event rate = 4 kHz
Total data volume ~ 50 MB/s

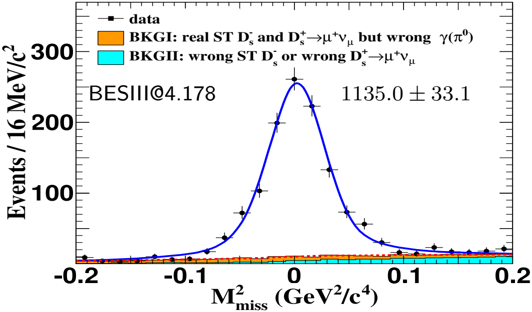
60 ps for ETOF after upgraded in 2015

$$\Gamma(D_s^+ \to \ell^+\nu_\ell) = \frac{G_F^2}{8\pi}|V_{cs}|^2 f^2_{D_s^+} m_\ell^2 m_{D_s^+}(1-\frac{m_\ell^2}{m^2_{D_s^+}})^2$$

BESIII PRL122(2019)071802

BESIII PRD94(2016)072004





$$\mathcal{B}(D_s^+ \to \mu^+\nu_\mu) = (5.49 \pm 0.16 \pm 0.15) \times 10^{-3}$$

$$f_{D_s^+}|V_{cs}| = 246.2 \pm 3.6 \pm 3.5 \text{ MeV}$$

$$R_{D_s^+} = \frac{\Gamma(D_s^+\to\tau^+\nu_\tau)}{\Gamma(D_s^+\to\mu^+\nu_\mu)} = 9.98 \pm 0.52$$

SM prediction 9.74 ± 0.01.

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

Inputs:

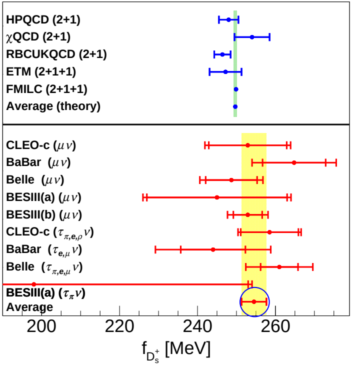
PDG2018 from CKM unitarity:

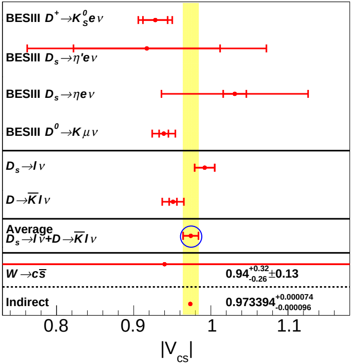
$$|V_{cs}| = 0.97359^{+0.00010}_{-0.00011}$$

LQCD average:

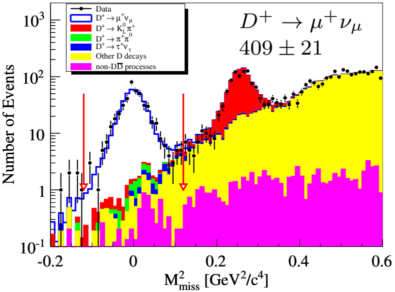
$$f_{D_s^+}^{\rm LQCD} = 249.7 \pm 0.4 \text{ MeV}$$

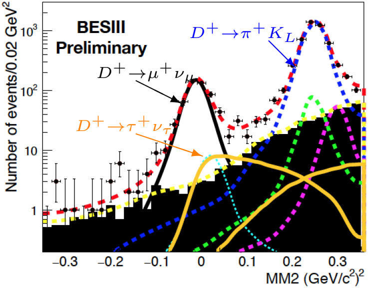
$$f_+^{D\to K}(0)^{\rm LQCD} = 0.760 \pm 0.011$$





D^+ leptonic decays





$$\mathcal{B}(D^+\to\mu^+\nu_\mu)=(3.71\pm0.19\pm0.06)\times10^{-4}$$

$$f_{D^+}|V_{cd}|=45.75\pm1.20\pm0.39\ \text{MeV}$$

$$\mathcal{B}(D^+\to\tau^+\nu_\tau)=(1.20\pm0.24_{\text{stat}})\times10^{-3}$$

$$f_{D^+}|V_{cd}|=50.4\pm5.0_{\text{stat}}\ \text{MeV}$$

First evidence with 4σ statistical significance.

$$R_{D^+}=\frac{\Gamma(D^+\to\tau^+\nu_\tau)}{\Gamma(D^+\to\mu^+\nu_\mu)}=3.21\pm0.64$$

SM prediction 2.66 ± 0.01.

Consistent

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

Inputs:

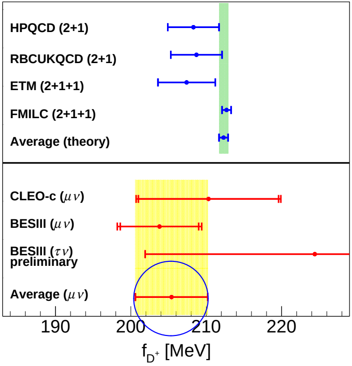
PDG2018 from CKM unitarity:

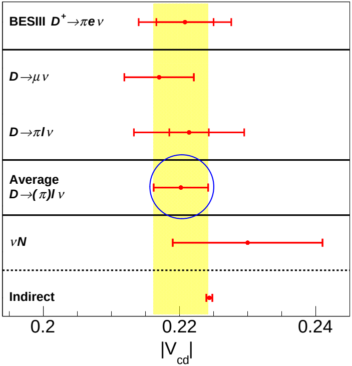
$$|V_{cd}| = 0.22438 \pm 0.00044$$

LQCD average:

$$f_{D^+}^{\rm LQCD} = 212.3 \pm 0.6 \text{ MeV}$$

$$f_+^{D\to\pi}(0)^{\rm LQCD} = 0.634 \pm 0.015$$





Dynamic study of $D^0 \to K^-(\pi^-)e^+\nu_e$

$$<P(p_2)|V^\mu|D(p_1)> = f_+(q^2)[P^\mu - \frac{M_1^2 - M_2^2}{q^2}q^\mu] + f_0(q^2)\frac{M_1^2 - M_2^2}{q^2}q^\mu$$

$q^\mu L_\mu \to 0$ when

$m_\ell \to 0$

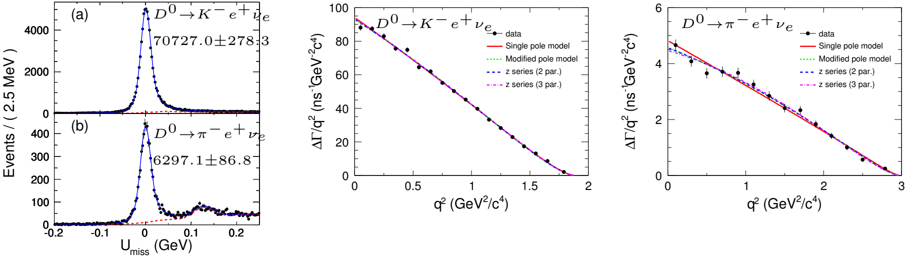
Single pole model: $f_+(q^2) = \frac{f_+(0)}{1 - \frac{q^2}{M_{\rm pole}^2}}$

Modified pole mode: $f_+(q^2) = \frac{f_+(0)}{(1 - \frac{q^2}{M_{\rm pole}^2})(1 - \alpha\frac{q^2}{M_{\rm pole}^2})}$

z series(2 par): $f_+(t) = \frac{1}{P(t)\Phi(t,t_0)}a_0(t_0) \times (1 + r_1(t_0)[z(t,t_0)])$

z series(3 par): $f_+(t) = \frac{1}{P(t)\Phi(t,t_0)}a_0(t_0) \times (1 + r_1(t_0)[z(t,t_0)] + r_2(t_0)[z(t,t_0)]^2)$

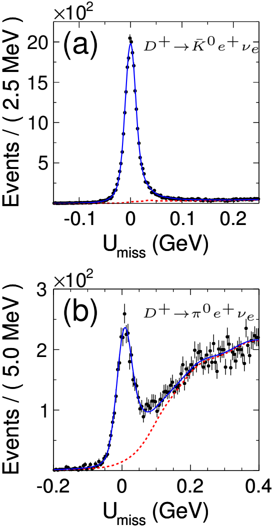
BESIII PRD92(2015)072012



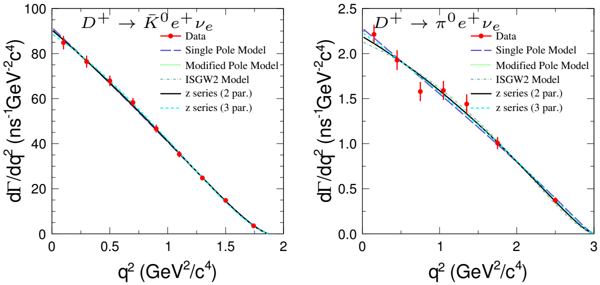
$\mathcal{B}(D^0 \to K^- e^+ \nu_e)$	$(3.505 \pm 0.014 \pm 0.033)\%$	$f_+^{D\to K}(0)\|V_{cs}\|$	$0.7172 \pm 0.0025 \pm 0.0035$
$\mathcal{B}(D^0 \to \pi^- e^+ \nu_e)$	$(0.295 \pm 0.004 \pm 0.003)\%$	$f_+^{D\to \pi}(0)\|V_{cd}\|$	$0.1435 \pm 0.0018 \pm 0.0009$

Dynamic study of $D^+ \to \bar{K}^0(\pi^0)e^+\nu_e$

BESIII PRD96(2017)012002

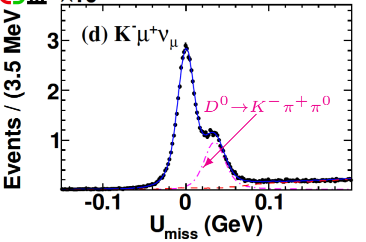


$\mathcal{B}(D^+ \to \bar{K}^0 e^+ \nu_e)$ (via K^0_S)	$(8.60 \pm 0.06 \pm 0.15)\%$
$f_+^{D\to K}(0)\lvert V_{cs}\rvert$	$0.7053 \pm 0.0040 \pm 0.0112$
$\mathcal{B}(D^+ \to \pi^0 e^+ \nu_e)$	$(0.363 \pm 0.008 \pm 0.005)\%$
$f_+^{D\to \pi}(0)\lvert V_{cd}\rvert$	$0.1400 \pm 0.0026 \pm 0.0007$

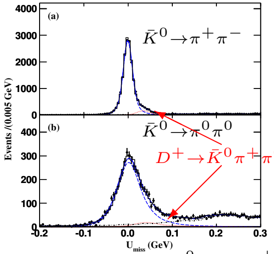


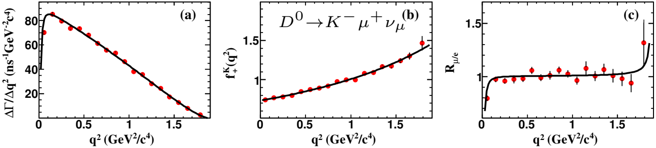
Dynamic study and LFU test with $D \to \bar{K}\mu^+\nu_\mu$

BESIII PRL122(2019)011804



BESIII EPJC76(2016)369





$\mathcal{B}(D^0 \to K^-\mu^+\nu_\mu)$	$(3.431 \pm 0.019 \pm 0.035)\%$
$f_+^{D\to K}(0)\lvert V_{cs}\rvert$	$0.7133 \pm 0.0038 \pm 0.0030$
$\mathcal{B}(D^+ \to \bar{K}^0\mu^+\nu_\mu)$	$(8.72 \pm 0.07 \pm 0.18)\%$

$$\frac{\Gamma(D^0 \to K^-\mu^+\nu_\mu)}{\Gamma(D^0 \to K^-e^+\nu_e)}$$

0.974 ± 0.014

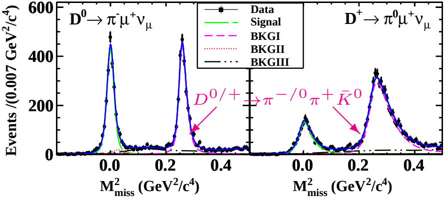
$$\frac{\Gamma(D^+ \to \bar{K}^0\mu^+\nu_\mu)}{\Gamma(D^+ \to \bar{K}^0e^+\nu_e)}$$

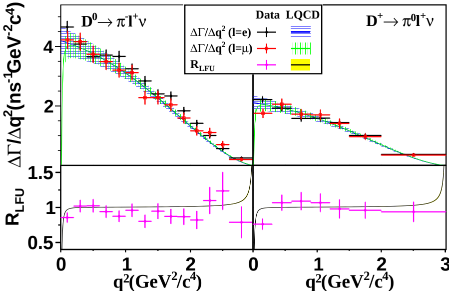
0.988 ± 0.033

Expected: 0.975 ± 0.001

Consistent

BESIII PRL121(2018)171803





$$\mathcal{B}(D^0 \to \pi^-\mu^+\nu_\mu) = (0.272 \pm 0.008 \pm 0.006)\%$$

$$\mathcal{B}(D^+ \to \pi^0\mu^+\nu_\mu) = (0.350 \pm 0.011 \pm 0.010)\%$$

$$\frac{\Gamma(D^0 \to \pi^-\mu^+\nu_\mu)}{\Gamma(D^0 \to \pi^- e^+\nu_e)} = 0.922 \pm 0.037$$

$$\frac{\Gamma(D^+ \to \pi^0\mu^+\nu_\mu)}{\Gamma(D^+ \to \pi^0 e^+\nu_e)} = 0.964 \pm 0.045$$

The LQCD calculations are taken from ETM's results published in PRD96(2017)054514, with

$$\frac{\Gamma(D \to \pi\mu^+\nu_\mu)}{\Gamma(D \to \pi e^+\nu_e)} = 0.985 \pm 0.002$$

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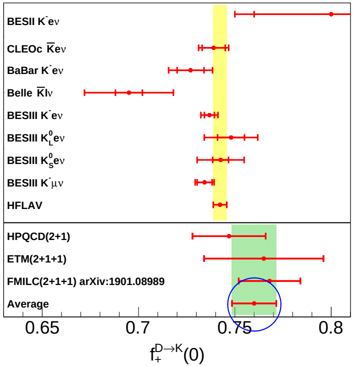
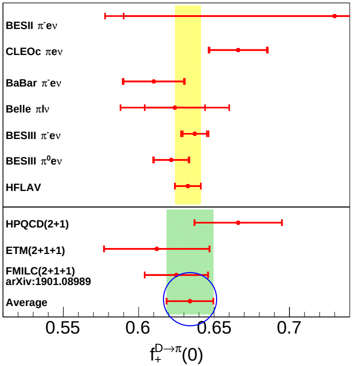
Inputs:
PDG2018 from CKM unitarity:

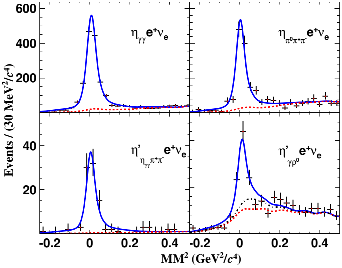
$$|V_{cs}| = 0.97359^{+0.00010}_{-0.00011}$$

$$|V_{cd}| = 0.22438 \pm 0.00044$$

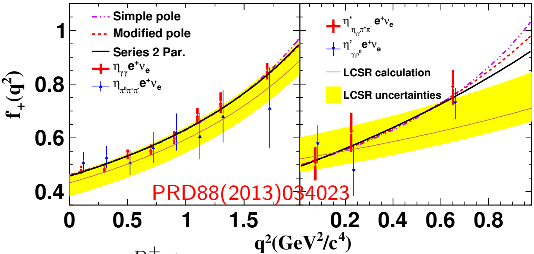




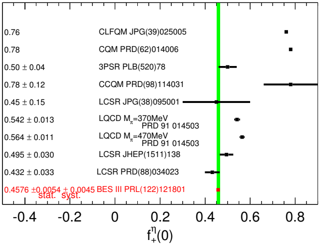
First measurement of FFs of $D_s^+ \to \eta^{(\prime)} e^+ \nu_e$

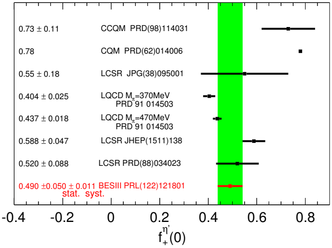


BESIII PRL122(2019)121801



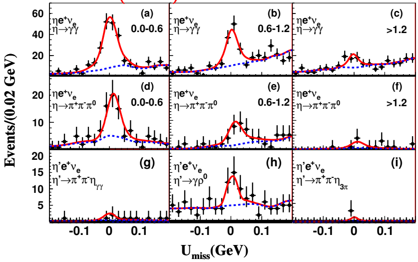
$$\mathcal{B}(D_s^+ \to \eta e^+ \nu_e) = (2.323 \pm 0.063 \pm 0.063)\%$$
$$\mathcal{B}(D_s^+ \to \eta' e^+ \nu_e) = (0.824 \pm 0.073 \pm 0.027)\%$$
$$f_+^{D_s^+ \to \eta}(0)|V_{cs}| = 0.4455 \pm 0.0053 \pm 0.0044$$
$$f_+^{D_s^+ \to \eta'}(0)|V_{cs}| = 0.477 \pm 0.049 \pm 0.011$$

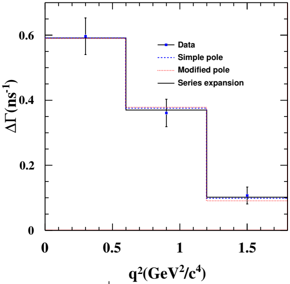




Measurement of $D^+ \to \eta^{(\prime)} e^+ \nu_e$, FF, $\eta - \eta'$ mixing angle

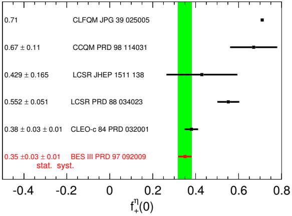
BESIII PRD97(2018)092009





$$\mathcal{B}(D^+ \to \eta e^+ \nu_e) = (10.74 \pm 0.81 \pm 0.51) \times 10^{-4}$$
$$\mathcal{B}(D^+ \to \eta' e^+ \nu_e) = (1.91 \pm 0.51 \pm 0.13)^{-4}$$

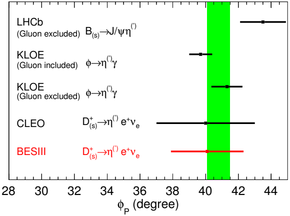
$$f_+^{D^+ \to \eta}(0)|V_{cd}| = (7.86 \pm 0.64 \pm 0.21) \times 10^{-2}$$



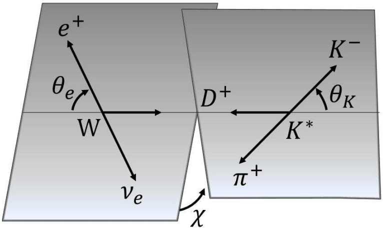
Model independent determination of $\eta - \eta'$ mixing angle.

$$\frac{\Gamma(D_s^+ \to \eta' e^+ \nu_e)/\Gamma(D_s^+ \to \eta e^+ \nu_e)}{\Gamma(D^+ \to \eta' e^+ \nu_e)/\Gamma(D^+ \to \eta e^+ \nu_e)} \simeq \cot^4 \Phi_P$$

$$\Phi_P = (40.1 \pm 2.1 \pm 0.7)^\circ$$



First measurement of FFs of $D^0 \to \bar{K}^0 \pi^- e^+ \nu_e$

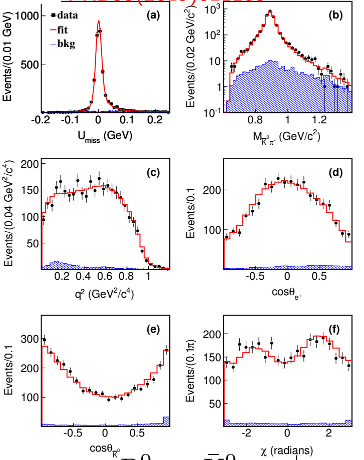


$$< V(p_2,\epsilon_2)|V^\mu - A^\mu|D(p_1) >=$$
$$-(M_1+M_2)\epsilon_2^{*\mu}A_1(q^2) + \frac{\epsilon_2^* q}{M_1+M_2}P^\mu A_2(q^2) +$$
$$2M_2\frac{\epsilon_2^* q}{q^2}q^\mu[A_3(q^2) - A_0(q^2)] + \frac{2i\epsilon_{\mu\nu\rho\sigma}\epsilon^{*\nu}p_1^\rho p_2^\sigma}{M_1+M_2}V(q^2)$$

$q^\mu L_\mu \to 0$ when $m_\ell \to 0$

$r_V = \frac{V(0)}{A_1(0)}$ $\quad$ $r_2 = \frac{A_2(0)}{A_1(0)}$

BESIII PRD99(2019)011103

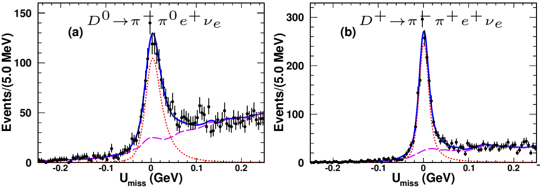


$D^0 \to \bar{K}^0 \pi^- e^+ \nu_e$

S($(\bar{K}^0\pi)_{\rm S-wave}$)	$(7.90 \pm 1.40 \pm 0.91) \times 10^{-4}$	P($K^*(892)^-$)	$(1.355 \pm 0.031 \pm 0.032)\%$
r_V	$1.46 \pm 0.07 \pm 0.02$	r_2	$0.67 \pm 0.06 \pm 0.01$

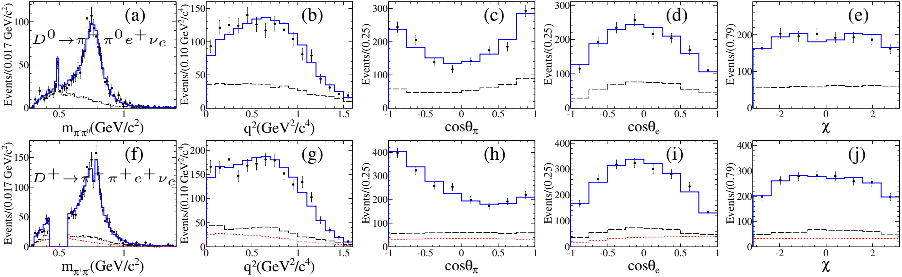
Observation of $D \to \pi\pi e^+\nu_e(S \text{ wave})$

BESIII PRL122(2019)062001



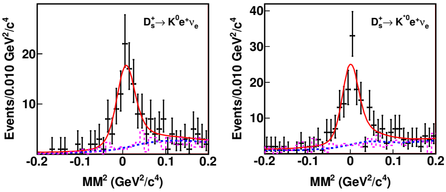
Signal mode	BF ($\times 10^{-3}$)
$D^0 \to \pi^-\pi^0 e^+\nu_e$	$1.445 \pm 0.058 \pm 0.039$
$D^0 \to \rho^- e^+\nu_e$	$1.445 \pm 0.048 \pm 0.039$
$D^+ \to \pi^-\pi^+ e^+\nu_e$	$2.449 \pm 0.074 \pm 0.073$
$D^+ \to \rho^0 e^+\nu_e$	$1.860 \pm 0.070 \pm 0.061$
$D^+ \to \omega e^+\nu_e$	$2.05 \pm 0.66 \pm 0.30$
$D^+ \to f_0(500) e^+\nu_e$, $f_0(500) \to \pi^+\pi^-$	$0.630 \pm 0.043 \pm 0.032$
$D^+ \to f_0(980) e^+\nu_e$, $f_0(980) \to \pi^+\pi^-$	< 0.028

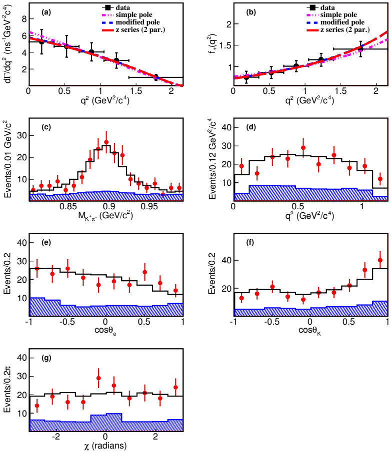
$r_V = 1.695 \pm 0.083 \pm 0.051 \quad r_2 = 0.845 \pm 0.056 \pm 0.039$



First measurement of FFs of $D_s^+ \to K^{(*)0} e^+ \nu_e$

BESIII PRL122(2019)061801





$$\mathcal{B}(D_s^+ \to K^0 e^+ \nu_e) = (3.25 \pm 0.38 \pm 0.16) \times 10^{-3}$$
$$f_+^{D_s^+ \to K^0}(0)|V_{cd}| = 0.162 \pm 0.019 \pm 0.003$$

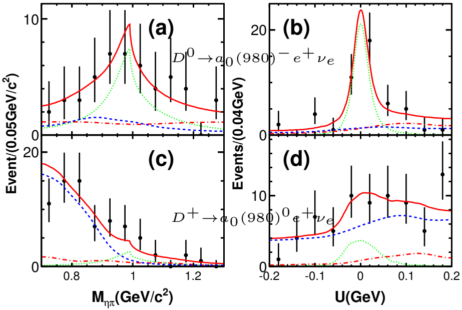
$$\mathcal{B}(D_s^+ \to K^{*0} e^+ \nu_e) = (2.37 \pm 0.26 \pm 0.20) \times 10^{-3}$$
$$r_V = 1.67 \pm 0.34 \pm 0.16$$
$$r_2 = 0.77 \pm 0.28 \pm 0.07$$

$$f_+^{D_s^+ \to K^0}(0) / f_+^{D^+ \to \pi^0}(0) = 1.16 \pm 0.14 \pm 0.02$$
$$r_V^{D_s^+ \to K^{*0}} / r_V^{D^+ \to \rho^0} = 1.13 \pm 0.26 \pm 0.11$$
$$r_2^{D_s^+ \to K^{*0}} / r_2^{D^+ \to \rho^0} = 0.93 \pm 0.36 \pm 0.10$$

Agrees with U-spin ($d \leftrightarrow s$) symmetry.

Observation of $D \to a_0(980)e^+\nu_e$

BESIII PRL121(2018)081802



A model-independent way to study the nature of light scalar mesons proposed by PRD82(2016)034016

$$R = \frac{\mathcal{B}(D^+ \to f_0(980)e^+\nu_e) + \mathcal{B}(D^+ \to f_0(500)e^+\nu_e)}{\mathcal{B}(D^+ \to a_0(980)^0 e^+\nu_e)}$$

$R = 1.0 \pm 0.3$ for two-quark description;
$R = 3.0 \pm 0.9$ for tetraquark description.

We have $R > 2.7$ @90% C.L. at BESIII
Which favors the tetraquark description.

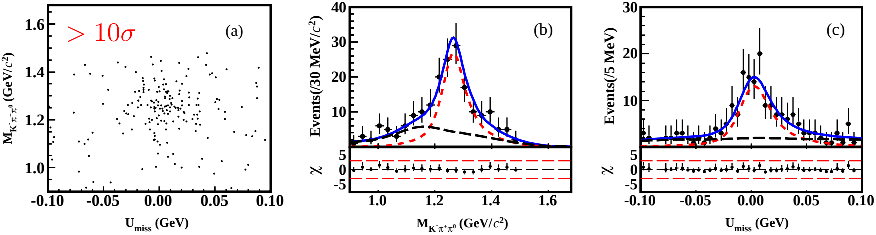
Decay	BF ($\times 10^{-4}$)	Significance
$D^0 \to a_0(980)^- e^+\nu_e,\ a_0(980)^- \to \eta\pi^-$	$1.33^{+0.33}_{-0.29} \pm 0.09$	6.4σ
$D^+ \to a_0(980)^0 e^+\nu_e,\ a_0(980)^0 \to \eta\pi^0$	$1.66^{+0.81}_{-0.66} \pm 0.11$ < 3.0 (90% C.L.)	2.9σ

Observation of $D^+ \to \bar{K}_1(1270)^0 e^+ \nu_e$

Semileptonic D transitions into axial vector meson were predicted 30 years ago, but not experimentally confirmed yet.

In theory, the predicted BFs are sensitive to K_1 mixing angle(θ_{K_1}) and its sign [PRD79(2009)036004, EPJC77(2017)369].

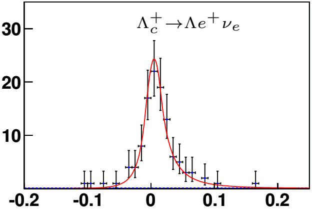
arXiv:1907.11370 $\mathcal{B}[D^+ \to \bar{K}_1(1270)^0 e^+ \nu_e] = (2.30 \pm 0.26 \pm 0.18 \pm 0.25) \times 10^{-3}$



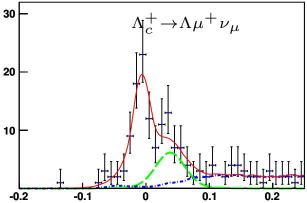
Our result indicates $\theta_{K_1} \sim 33^\circ$ or 57° and opens up opportunity to precisely study nature of $\bar{K}_1(1270)$.

0.567 fb^{-1} data @4.6 GeV

BESIII PRL115(2015)221805



BESIII PLB767(2017)42



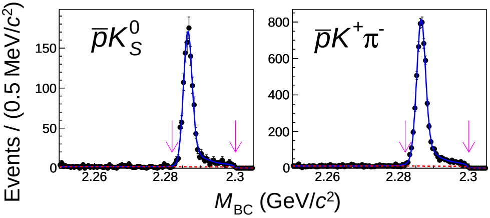
Previously expected: $1.4\% \to 9.2\%$.

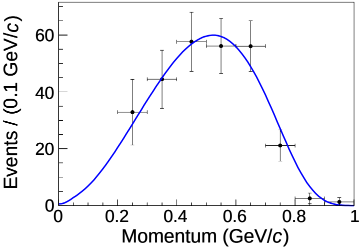
$$\mathcal{B}(\Lambda_c^+ \to \Lambda e^+ \nu_e) = (3.63 \pm 0.38 \pm 0.20)\%$$

$$\mathcal{B}(\Lambda_c^+ \to \Lambda \mu^+ \nu_\mu) = (3.49 \pm 0.46 \pm 0.26)\%$$

$$\frac{\Gamma(\Lambda_c^+ \to \Lambda e^+ \nu_e)}{\Gamma(\Lambda_c^+ \to \Lambda \mu^+ \nu_\mu)} = 0.96 \pm 0.16 \pm 0.04$$

BESIII PRL121(2018)251801





Decay channel	$\mathcal{B}$ (%)	Model
$\Lambda_c^+ \to \Lambda e^+ \nu_e$	3.63 ± 0.43	$F_1^V(q^2) = \frac{2.52}{5.09 - q^2}$
$\Lambda_c^+ \to \Lambda(1405) e^+ \nu_e$	0.38 ± 0.38	PYTHIA
$\Lambda_c^+ \to n e^+ \nu_e$	0.27 ± 0.27	PYTHIA

$$\mathcal{B}(\Lambda_c^+ \to X e^+ \nu_e) = (3.95 \pm 0.34 \pm 0.09)\%$$

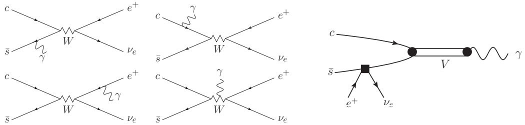
$$\frac{\mathcal{B}(\Lambda_c^+ \to \Lambda e^+ \nu_e)}{\mathcal{B}(\Lambda_c^+ \to X e^+ \nu_e)} = (91.9 \pm 12.5 \pm 5.4)\%$$

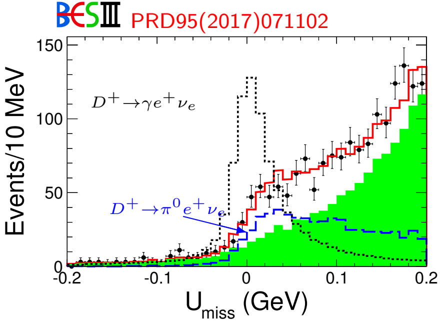
Result	$\Lambda_c^+ \to X e^+ \nu_e$	$\frac{\Gamma(\Lambda_c^+ \to X e^+ \nu_e)}{\bar{\Gamma}(D \to X e^+ \nu_e)}$
BESIII	3.95 ± 0.35	1.26 ± 0.12
MARK II	4.5 ± 1.7	1.44 ± 0.54

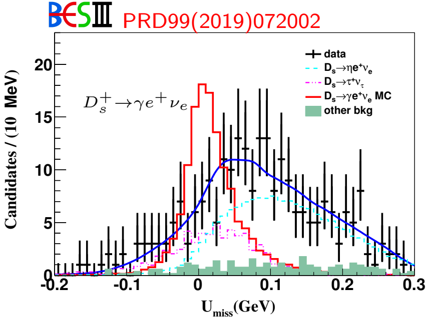
This ratio is predicted to be
1.67 using an effective-quark theory calculation
1.2 based on a calculation using the heavy-quark expansion.

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

Not subject to helicity suppression.
Only photon energy larger than 10 MeV are considered.
The BFs are predicated to be $10^{-5} \to 10^{-3}$ in various models.







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

$\mathcal{B}(D_s^+ \to \gamma e^+ \nu_e) < 1.3 \times 10^{-4}$ @90% C.L.

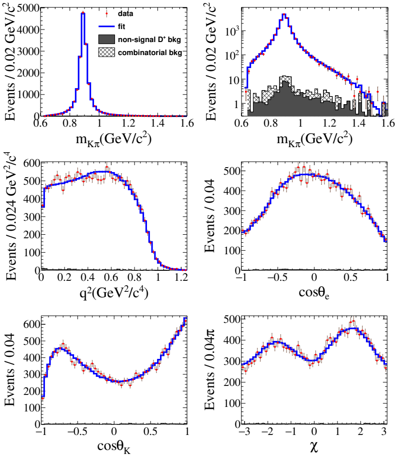
Summary

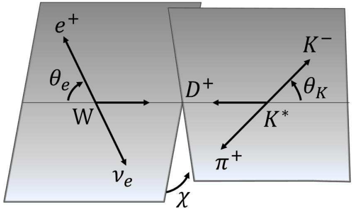
1. Precise measurement of decay constants, form factors and quark mixing matrix elements $\rightarrow$ precision improved with BESIII measurement.
   - $f_{D^+}|V_{cd}| \sim 2.8\%$
   - $f_{D_s^+}|V_{cs}| \sim 2.0\%$
   - $f_+^{D\rightarrow K}(0)|V_{cs}| \sim 0.6\%$
   - $f_+^{D\rightarrow\pi}(0)|V_{cd}| \sim 1.4\%$
2. Lepton flavor universality test $\rightarrow$ no evidence of violation found in the charm sector at the precision of 1.5% for CF decays and 4% for SCS decays.
3. The results of $(a_0(980)e^+\nu, f_0(500)e^+\nu)$ favor the tetraquark description.
4. First measurement of absolute branching fractions of semileptonic Λ_c^+ decays.
5. Upcoming data at BESIII $\rightarrow$ more results to be expected.

Back up

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

BESIII PRD94(2016)032001





$$r_V = V(0)/A_1(0) = 1.411 \pm 0.058 \pm 0.007$$

$$r_2 = A_2(0)/A_1(0) = 0.788 \pm 0.042 \pm 0.008$$

$$A_1(0) = 0.589 \pm 0.010 \pm 0.012$$

Not included in the nominal fit:

$\mathcal{B}(D^+ \to \bar{K}^*(1410)^0 e^+ \nu_e)$	$(0 \pm 0.009 \pm 0.008)\%$ $< 0.028\%$ (90% C.L.)
$\mathcal{B}(D^+ \to \bar{K}_2^*(1430)^0 e^+ \nu_e)$	$(0.011 \pm 0.003 \pm 0.007)\%$ $< 0.023\%$ (90% C.L.)

P($\bar{K}^*(892)^0$)	Simple Pole plus BW with mass-dependent width	$(3.54 \pm 0.03 \pm 0.08)\%$
S($\bar{K}_0^*(1430)^0$ and non-resonant part)	LASS plus BW with mass-dependent width	$(0.228 \pm 0.008 \pm 0.008)\%$