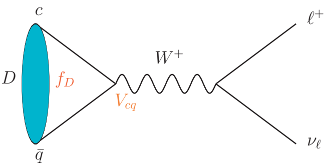
Experimental study for leptonic and semileptonic decays in charm sector

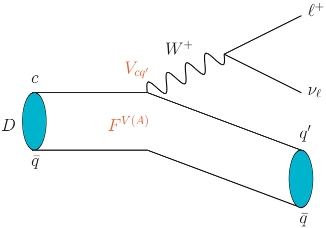
Sifan Zhang on behalf of the BESIII collaboration
including results from LHCb and BaBar

NJU, IHEP

May 9, 2019

Motivation





$\mathcal{M} \propto |V_{cs(d)}| H^\mu L_\mu$ $\quad$ $q^\mu L_\mu \to 0$ when $m_\ell \to 0$

$H^\mu = f_D p_D^\mu$

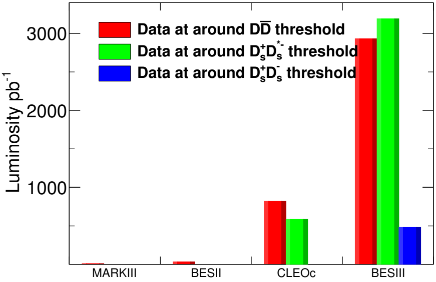
$$<P(p_2)|V^\mu|D(p_1)> = f_+(q^2)\left[P^\mu - \frac{M_1^2 - M_2^2}{q^2} q^\mu\right] + f_0(q^2)\frac{M_1^2 - M_2^2}{q^2} q^\mu$$

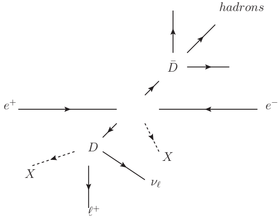
$$<V(p_2,\epsilon_2)|V^\mu - A^\mu|D(p_1)> =$$
$$-(M_1+M_2)\epsilon_2^{*\mu} A_1(q^2) + \frac{\epsilon_2^* q}{M_1+M_2} P^\mu A_2(q^2) +$$
$$2M_2 \frac{\epsilon_2^* q}{q^2} q^\mu [A_3(q^2) - A_0(q^2)] + \frac{2i\epsilon_{\mu\nu\rho\sigma}\epsilon^{*\nu} p_1^\rho p_2^\sigma}{M_1+M_2} V(q^2)$$

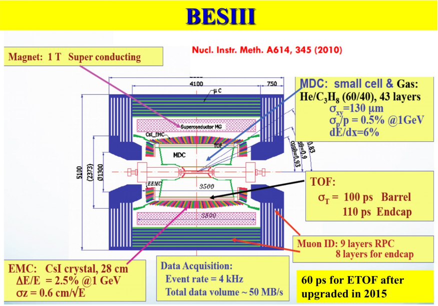
$$r_V = \frac{V(0)}{A_1(0)}$$
$$r_2 = \frac{A_2(0)}{A_1(0)}$$

- 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.

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







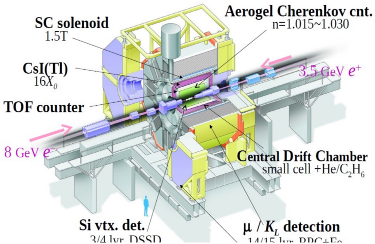
$$N^i_{\rm ST} = 2N_{D\bar{D}}\mathcal{B}^i_{\rm ST}\epsilon^i_{\rm ST}$$

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

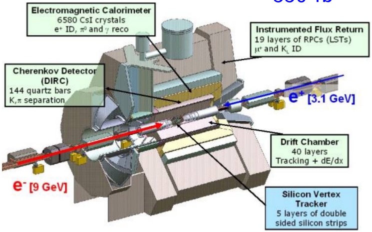
Experiments at the B factory and LHCb

$e^+ - e^-$ collider: high luminosity and relative clean environment

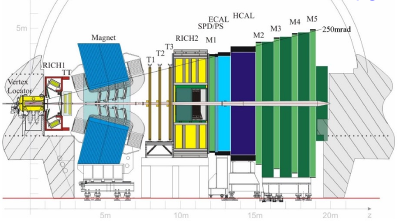
The Belle Detector 1 ab^{-1}, 50 ab^{-1} expected at BelleII

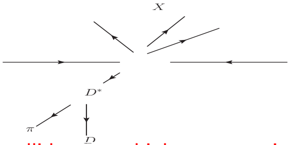


BaBar Detector 550 fb^{-1}



LHCb 9 fb^{-1} more with LHC upgrades

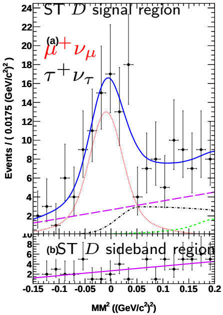




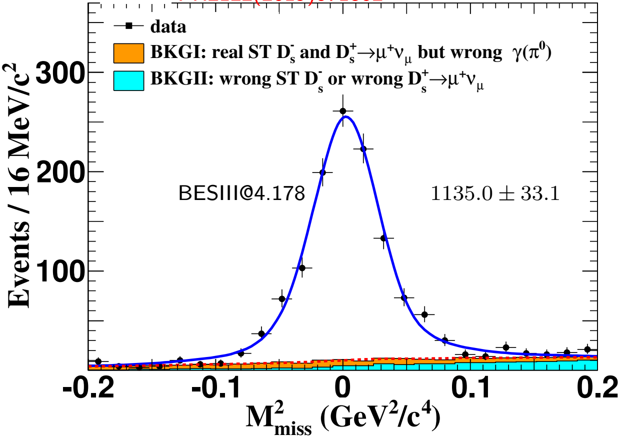
Hadron collider: very high cross section along with high background.
Complex environment $\rightarrow$ very difficult to analysis neutrinos.
High statistics $\rightarrow$ rare decay search.

BESIII PRD94(2016)072004

BESIII@4.009



BESIII PRL122(2019)071802



$\mathcal{B}(D_s^+\to\mu^+\nu_\mu)=(5.17\pm0.75\pm0.21)\times10^{-3}$

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

$f_{D_s^+}|V_{cs}|=239\pm17\pm5$ MeV with $\mu^+\nu_\mu$

$f_{D_s^+}|V_{cs}|=193\pm54\pm11$ MeV with $\tau^+\nu_\tau$

$$\mathcal{B}(D_s^+\to\mu^+\nu_\mu)=(5.49\pm0.16\pm0.15)\times10^{-3}$$
$$f_{D_s^+}|V_{cs}|=242.5\pm3.5\pm3.7$$
$$R_{D_s^+}=\frac{\Gamma(D_s^+\to\tau^+\nu_\tau)}{\Gamma(D_s^+\to\mu^+\nu_\mu)}=10.19\pm0.52$$

SM prediction 9.74 ± 0.01.

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

Inputs:

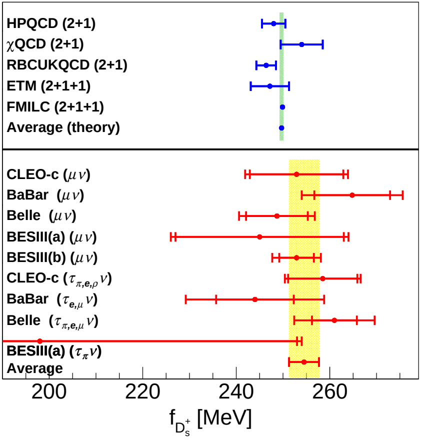
PDG2018 from CKM unitarity:

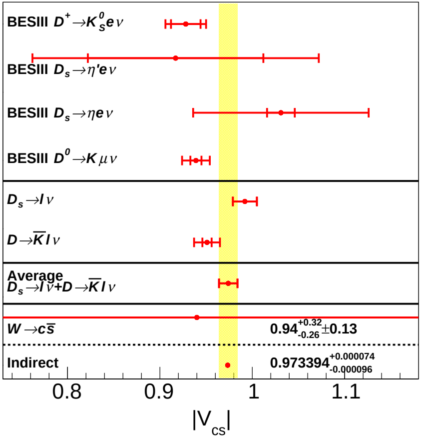
$$|V_{cs}| = 0.97359^{+0.00010}_{-0.00011}$$

LQCD average:

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

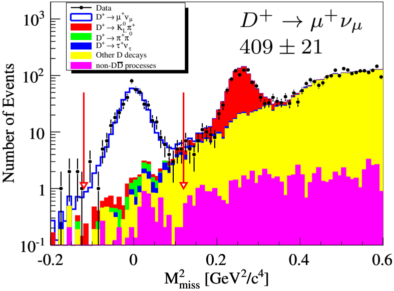
$$f_+^{D\to K}(0)^{\rm LQCD} = 0.760 \pm 0.011$$

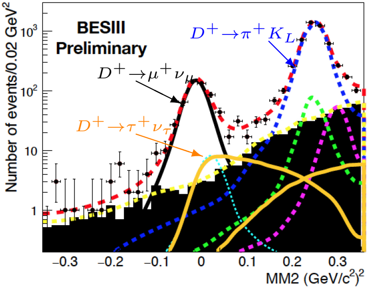




D^+ leptonic decays

PRD89(2014)051104





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

$$f_{D^+}|V_{cd}| = 46.7 \pm 1.2 \pm 0.4 \text{ MeV}$$

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

$$f_{D^+}|V_{cd}| = 50.4 \pm 5.0_{\text{stat}} \text{ MeV}$$

First evidence with 4σ statistical significance.

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

SM prediction 2.66 ± 0.01.

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

Inputs:

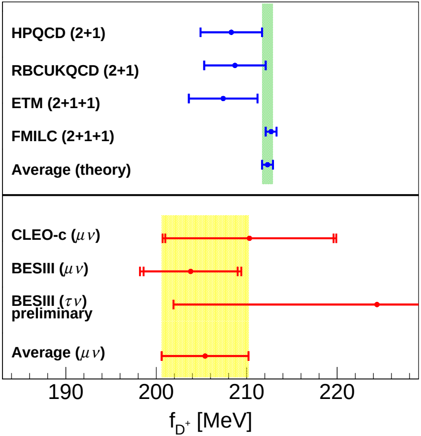
PDG2018 from CKM unitarity:

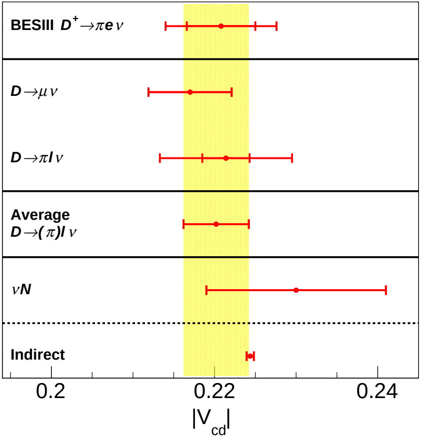
$$|V_{cd}| = 0.22438 \pm 0.00044$$

LQCD average:

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

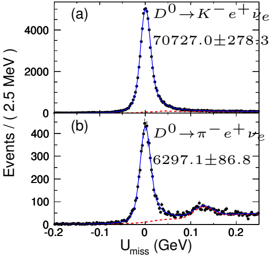
$$f_+^{D\to\pi}(0)^{\mathrm{LQCD}} = 0.634 \pm 0.015$$

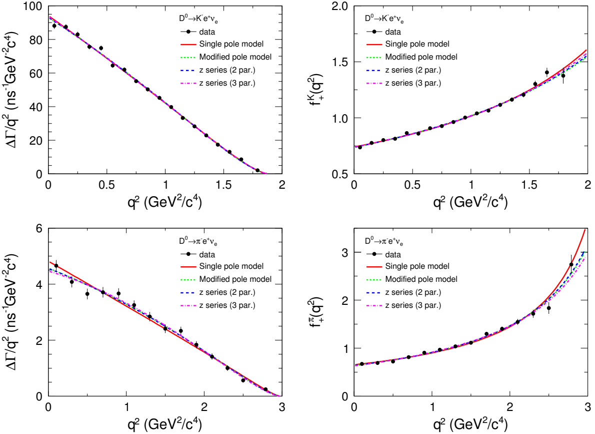




$D^0 \to K^-(\pi^-)e^+\nu_e$

PRD92(2015)072012



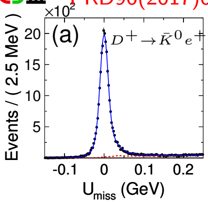


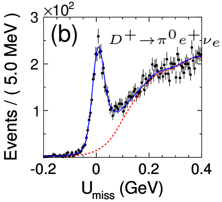
$\mathcal{B}(D^0 \to K^- e^+ \nu_e)$	$(3.505 \pm 0.014 \pm 0.033)\%$	$f_+^{D\to K}(0)\lvert V_{cs}\rvert$	$0.7172 \pm 0.0025 \pm 0.0035$
$\mathcal{B}(D^0 \to \pi^- e^+ \nu_e)$	$(0.295 \pm 0.004 \pm 0.003)\%$	$f_+^{D\to \pi}(0)\lvert V_{cd}\rvert$	$0.1435 \pm 0.0018 \pm 0.0009$

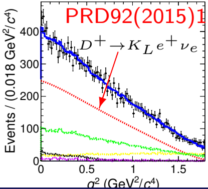
$D^+ \to \bar{K}^0(\pi^0)e^+\nu_e$

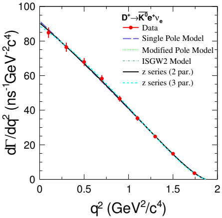
BESIII PRD96(2017)012002

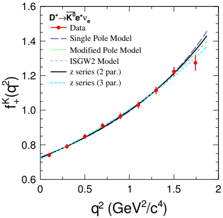
$\mathcal{B}(D^+\to\bar{K}^0e^+\nu_e)$ (via K^0_S)	$(8.60\pm0.06\pm0.15)\%$
$f_+^{D\to K}(0)\lvert V_{cs}\rvert$	$0.7053\pm0.0040\pm0.0112$
$\mathcal{B}(D^+\to\bar{\pi}^0e^+\nu_e)$	$(0.363\pm0.008\pm0.005)\%$
$f_+^{D\to\pi}(0)\lvert V_{cd}\rvert$	$0.1400\pm0.0026\pm0.0007$
$\mathcal{B}(D^+\to\bar{K}^0e^+\nu_e)$ (via K^0_L)	$(8.962\pm0.054\pm0.206)\%$
$f_+^{D\to K}(0)\lvert V_{cs}\rvert$	$0.728\pm0.006\pm0.011$

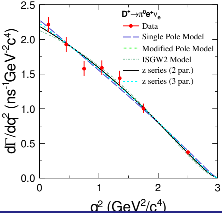


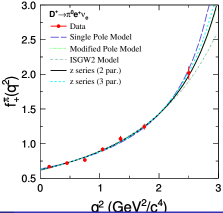






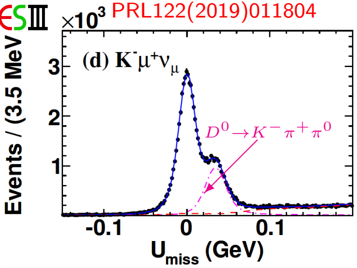




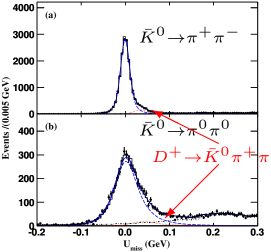


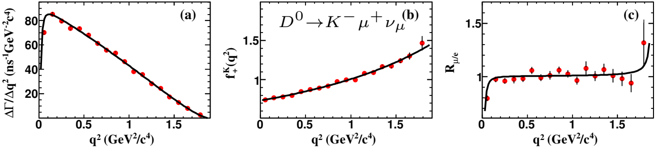
$D \to \bar{K}\mu^+\nu_\mu$

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

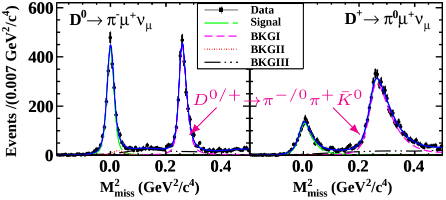
$$\frac{\Gamma(D^+ \to \bar{K}^0\mu^+\nu_\mu)}{\Gamma(D^+ \to \bar{K}^0e^+\nu_e)}$$

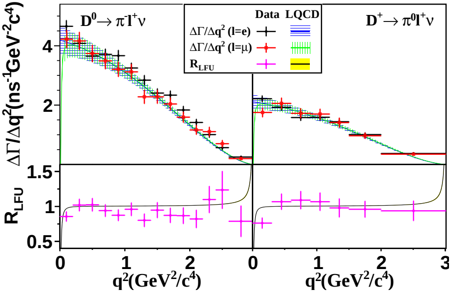
0.988 ± 0.033

Expected:
0.975 ± 0.001

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

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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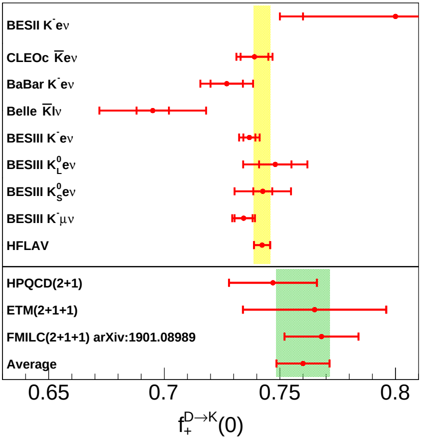
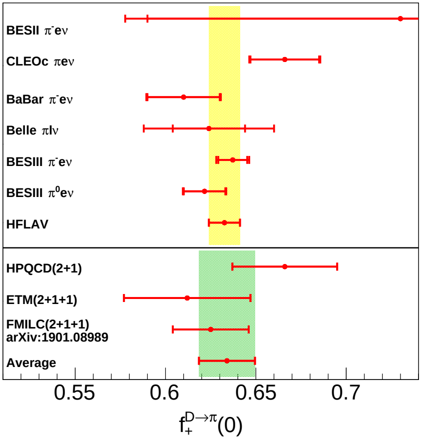
Comparison of $f_+^{D\to K}(0)$ and $f_+^{D\to\pi}(0)$

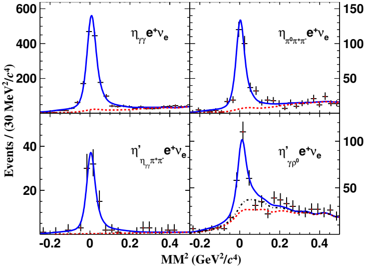
Inputs:
PDG2018 from CKM unitarity:

$$|V_{cs}| = 0.97359^{+0.00010}_{-0.00011} \qquad |V_{cd}| = 0.22438 \pm 0.00044$$

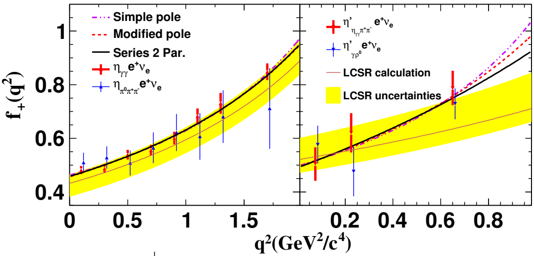




$D_s^+ \to \eta^{(\prime)} e^+ \nu_e$



BESIII PRL122(2019)121801

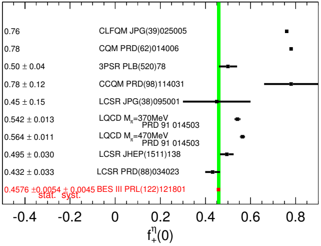


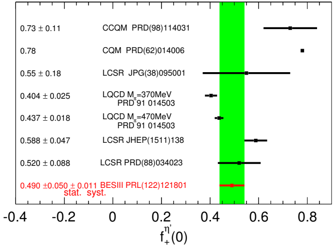
$$\mathcal{B}(D_s^+ \to \eta e^+ \nu_e) = (2.323 \pm 0.063 \pm 0.063)\%$$

$$f_+^{D_s^+ \to \eta}(0)|V_{cs}| = 0.4455 \pm 0.0053 \pm 0.0044$$

$$\mathcal{B}(D_s^+ \to \eta' e^+ \nu_e) = (0.824 \pm 0.073 \pm 0.027)\%$$

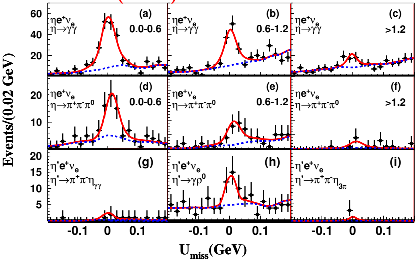
$$f_+^{D_s^+ \to \eta'}(0)|V_{cs}| = 0.477 \pm 0.049 \pm 0.011$$

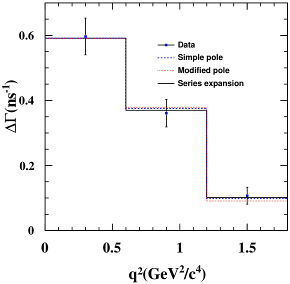




$D^+ \to \eta^{(\prime)} e^+ \nu_e$

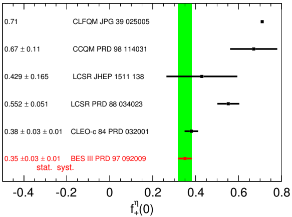
BESIII PRD97(2018)092009





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

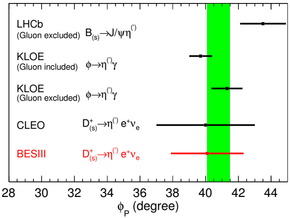
$$f_+^{D^+ \to \eta}(0)|V_{cd}| = (7.86 \pm 0.64 \pm 0.21) \times 10^{-2}$$



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

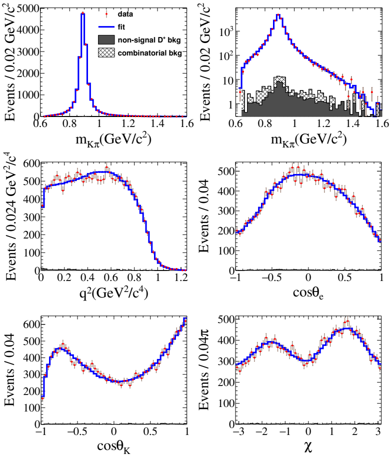
$$\frac{\Gamma(D_s^+ \to \eta' e^+ \nu_e)/\Gamma(D_s^+ \to \eta e^+ \nu_e)}{\Gamma(D^+ \to \eta' e^+ \nu_e)/\Gamma(D^+ \to \eta e^+ \nu_e)} \simeq \cot^4 \Phi_P$$

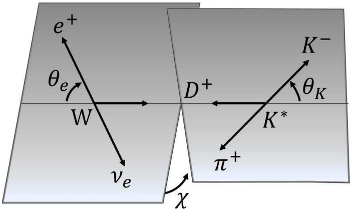
$$\Phi_P = (40.1 \pm 2.1 \pm 0.7)^\circ$$



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

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:

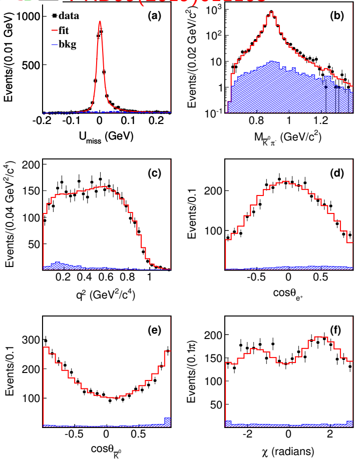
$\mathcal{B}(D^+ \to \bar{K}^*(1410)^0 e^+\nu_e)$ $(0 \pm 0.009 \pm 0.008)\%$
$< 0.028\%$ (90% C.L.)

$\mathcal{B}(D^+ \to \bar{K}_2^*(1430)^0 e^+\nu_e)$ $(0.011 \pm 0.003 \pm 0.007)\%$
$< 0.023\%$ (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	$(0.228 \pm 0.008 \pm 0.008)\%$

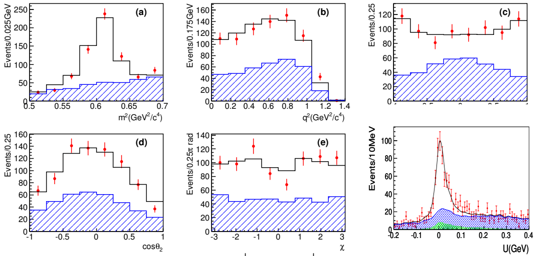
$D^0 \to \bar{K}^0\pi^- e^+\nu_e$ and $D^+ \to \omega e^+\nu_e$

BESIII PRD99(2019)011103



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

BESIII PRD92(2015)071101



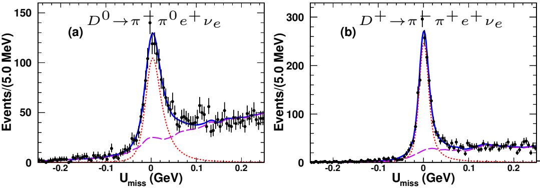
$D^+ \to \omega e^+\nu_e$

$\mathcal{B}(D^+ \to \omega e^+\nu_e)$	$(1.63 \pm 0.11 \pm 0.08) \times 10^{-3}$
r_V	$1.24 \pm 0.09 \pm 0.06$
r_2	$1.06 \pm 0.15 \pm 0.05$

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

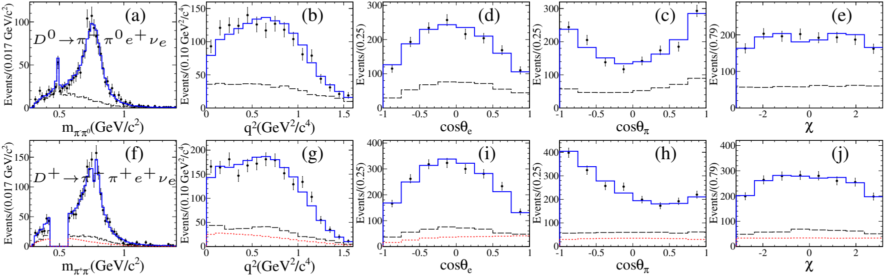
$D \to \pi\pi e^{+}\nu_e$

BESIII PRL122(2019)062001

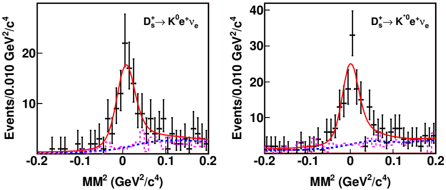


Signal mode	BF $(\times 10^{-3})$
$D^0 \to \pi^- \pi^0 e^+ \nu_e$	$1.445 \pm 0.058 \pm 0.039$
$D^0 \to \rho^- e^+ \nu_e$	$1.445 \pm 0.048 \pm 0.039$
$D^+ \to \pi^- \pi^+ e^+ \nu_e$	$2.449 \pm 0.074 \pm 0.073$
$D^+ \to \rho^0 e^+ \nu_e$	$1.860 \pm 0.070 \pm 0.061$
$D^+ \to \omega e^+ \nu_e$	$2.05 \pm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

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



BESIII PRL122(2019)061801



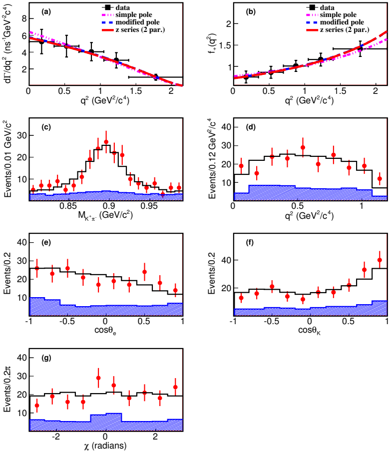
$$\mathcal{B}(D_s^+ \to K^0 e^+ \nu_e) = (3.25 \pm 0.38 \pm 0.16) \times 10^{-3}$$

$$f_+^{D_s^+ \to K^0}(0)|V_{cd}| = 0.162 \pm 0.019 \pm 0.003$$

$$\mathcal{B}(D_s^+ \to K^0 e^+ \nu_e) = (2.37 \pm 0.26 \pm 0.20) \times 10^{-3}$$

$$r_V = 1.67 \pm 0.34 \pm 0.16$$

$$r_2 = 0.77 \pm 0.28 \pm 0.07$$



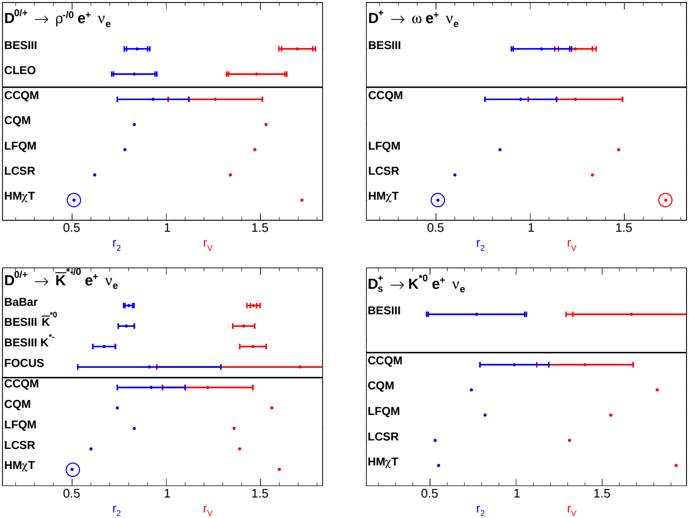
$$f_+^{D_s^+ \to K^0}(0) / f_+^{D^+ \to \pi^0}(0) = 1.16 \pm 0.14 \pm 0.02$$

$$r_V^{D_s^+ \to K^{*0}} / r_V^{D^+ \to \rho^0} = 1.13 \pm 0.26 \pm 0.11$$

$$r_2^{D_s^+ \to K^{*0}} / r_2^{D^+ \to \rho^0} = 0.93 \pm 0.36 \pm 0.10$$

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

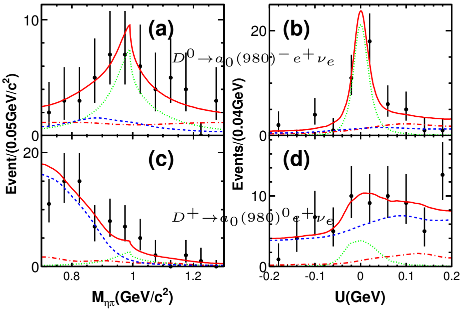
Comparison of r_V and r_2 with theoretical calculations



CCQM	arXiv:1904.07740	CQM	PRD62(2000)014006
LFQM	JPG39(2012)025005	LCSR	Int. J. Mod. Phys. A 21(2006)6125
HMχT	PRD72(2005)034029	(not applicable?)	

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

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.

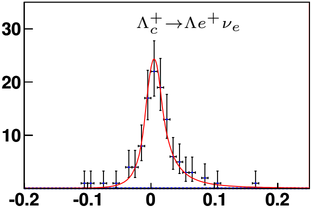
We have $R > 2.7$ @90% C.L. at BESIII
Which favors the tetraquark description.

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

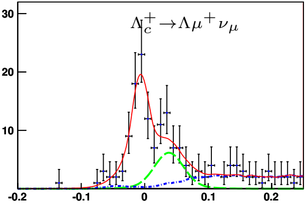
$\Lambda_c^+ \to \Lambda \ell^+ \nu_\ell$

0.567 fb^{-1} data @4.6 GeV

BESIII PRL115(2015)221805



BESIII PLB767(2017)42



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

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

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

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

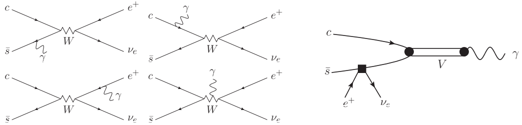
PRL118(2017)082001

$$\mathcal{B}(\Lambda_c^+ \to \Lambda e^+ \nu_e) = (3.80 \pm 0.19_{\text{LQCD}} \pm 0.11_{\tau_{\Lambda_c}})\%$$

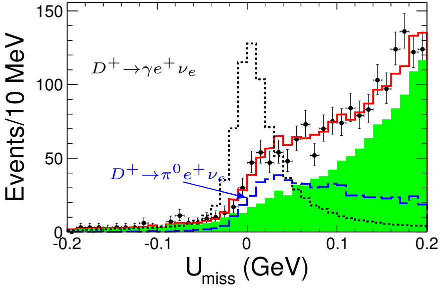
$$\mathcal{B}(\Lambda_c^+ \to \Lambda \mu^+ \nu_\mu) = (3.69 \pm 0.19_{\text{LQCD}} \pm 0.11_{\tau_{\Lambda_c}})\%$$

$D \to \gamma e^+ \nu_e$

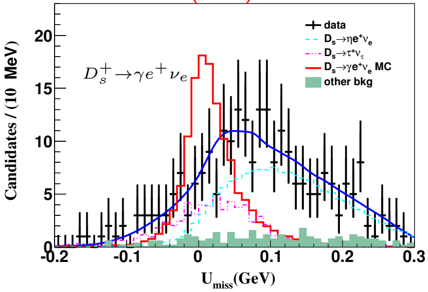
Not subject to helicity suppression.
Only photon energy larger than 10 MeV are considered.
The BFs are predicated to be $10^{-5} \to 10^{-3}$ in various models.



BESIII PRD95(2017)071102



BESIII PRD99(2019)072002

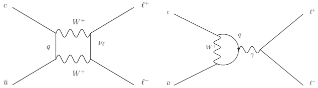


$\mathcal{B}(D^+ \to \gamma e^+ \nu_e) < 3.0 \times 10^{-5}$ @90% C.L.

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

Flavor-changing neutral currents

$D^0 \to \ell^+\ell^-$: GIM suppressed, $\sim 10^{-13}$ including long distance contribution



Enhanced by SUSY or leptoquark to 10^{-8} [a] and 10^{-7} [b].

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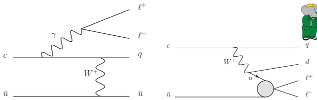
[a] PRD79(2009)114030
[b] PLB682(2009)67

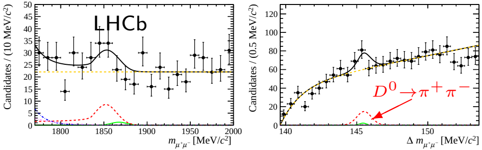
$D^0 \to h(h')\ell^+\ell^-$: Long distance contribution ($\sim 10^{-6}$).



Refer to Abi Soffer's report for details (Parallel 1, Tuesday).

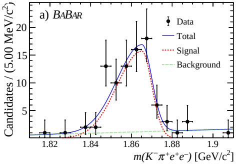
$\mathcal{B}(D^0 \to \mu^+\mu^-) < 6.2 \times 10^{-9}$ @90% C.L.

PLB725(2013)15

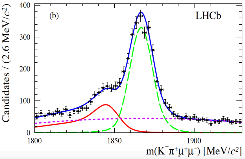


$\mathcal{B}(D^0 \to K^-\pi^+e^+e^-) = (4.0 \pm 0.5 \pm 0.2 \pm 0.1) \times 10^{-6}$
$\mathcal{B}(D^0 \to K^-\pi^+\mu^+\mu^-) = (4.17 \pm 0.12 \pm 0.40) \times 10^{-6}$
at ρ/ω region.
$\mathcal{B}(D^0 \to K^-\pi^+e^+e^-) < 3.1 \times 10^{-6}$ @90% C.L. at continuum region.

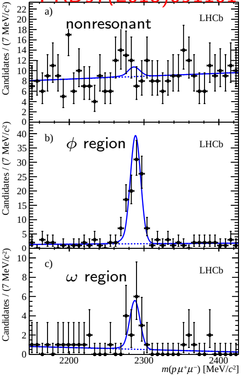
PRL122(2019)081802



PLB757(2016)558



PRD97(2018)091101



$\mathcal{B}(\Lambda_c^+ \to p\mu^+\mu^-) < 7.7\times10^{-8}$ @90% C.L. at nonresonant region.

PRL121(2018)091801

$A_{\rm FB}(D^0\to\pi^+\pi^-\mu^+\mu^-)=(3.3\pm3.7\pm0.6)\%$

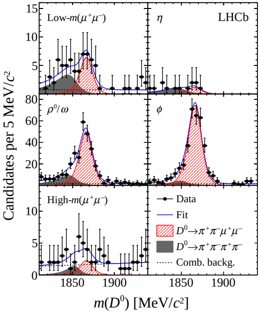
$A_{2\phi}(D^0\to\pi^+\pi^-\mu^+\mu^-)=(-0.6\pm3.7\pm0.6)\%$

$A_{\rm CP}(D^0\to\pi^+\pi^-\mu^+\mu^-)=(4.9\pm3.8\pm0.7)\%$

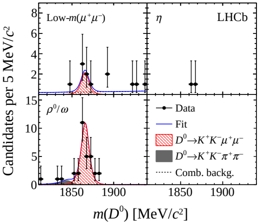
$A_{\rm FB}(D^0\to K^+K^-\mu^+\mu^-)=(0\pm11\pm2)\%$

$A_{2\phi}(D^0\to K^+K^-\mu^+\mu^-)=(9\pm11\pm1)\%$

$A_{\rm CP}(D^0\to K^+K^-\mu^+\mu^-)=(0\pm11\pm2)\%$



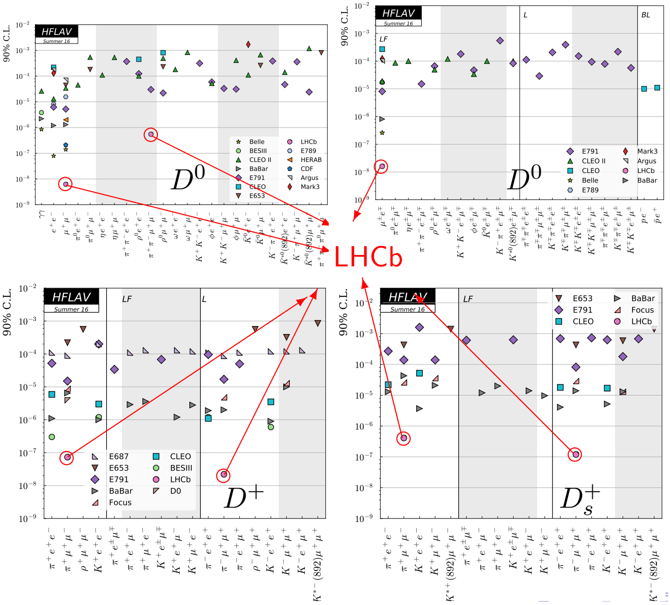
PRL119(2017)181805



$D^0\to\pi^+\pi^-\mu^+\mu^-$		
$M_{\mu^+\mu^-}$ region	[MeV/c^2]	$\mathcal{B}$ [10^{-8}]
Low mass	<525	$7.8\pm1.9\pm0.5\pm0.8$
η	525–565	<2.4 (2.8)
ρ^0/ω	565–950	$40.6\pm3.3\pm2.1\pm4.1$
ϕ	950–1100	$45.4\pm2.9\pm2.5\pm4.5$
High mass	>1100	<2.8 (3.3)

$D^0\to K^+K^-\mu^+\mu^-$		
$M_{\mu^+\mu^-}$ region	[MeV/c^2]	$\mathcal{B}$ [10^{-8}]
Low mass	<525	$2.6\pm1.2\pm0.2\pm0.3$
η	525–565	<0.7 (0.8)
ρ^0/ω	>565	$12.0\pm2.3\pm0.7\pm1.2$

Experimental status of D rare decays



Summary

- Precise measurement of decay constants, form factors and quark mixing matrix elements → precision improved with BESIII measurement.
- Lepton flavor universality test → no evidence of violation found in the charm sector at the precision of 1.5% for CF decays and 4% for SCS decays..
- Study the nature of light scalar mesons → tetraquark description favored with BESIII's results.
- Rare decays especially FCNC process → limits improved by several magnitude with measurements at LHCb.
- Upcoming data at BESIII, LHCb and BelleII → more results to be expected.

Thanks for your attention!