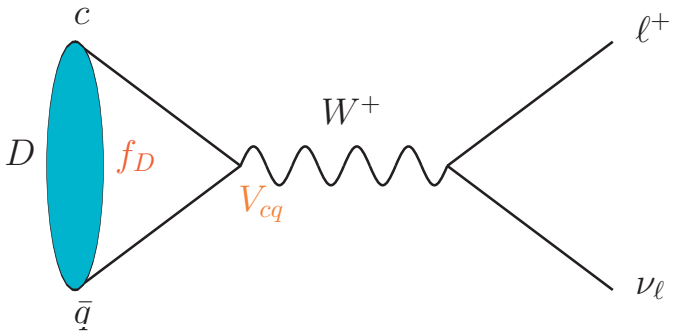
Leptonic and semileptonic charm decays at BESIII

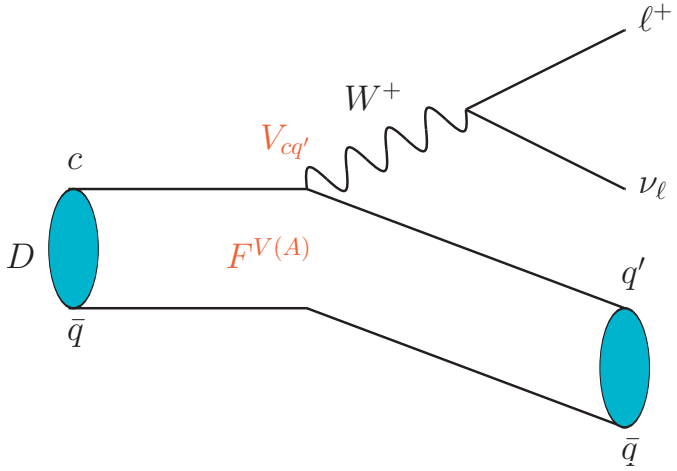
Ke Liu on behalf of the BESIII collaboration

CCNU, IHEP

Lepton Photon 2019, Toronto, Canada, August 5-10, 2019

Motivation





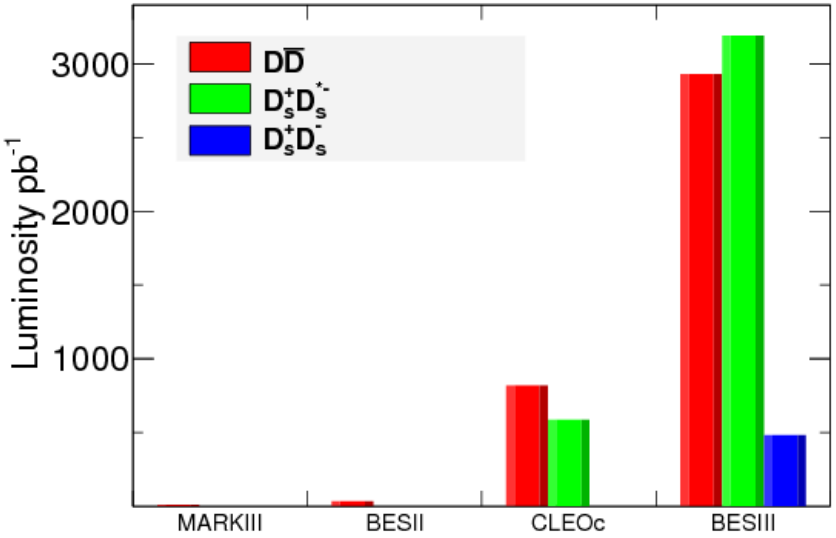
$\Gamma(D^+_{(s)} \to l^+\nu_l) \propto |f_{D^+_{(s)}}|^2 |V_{cs(d)}|^2$

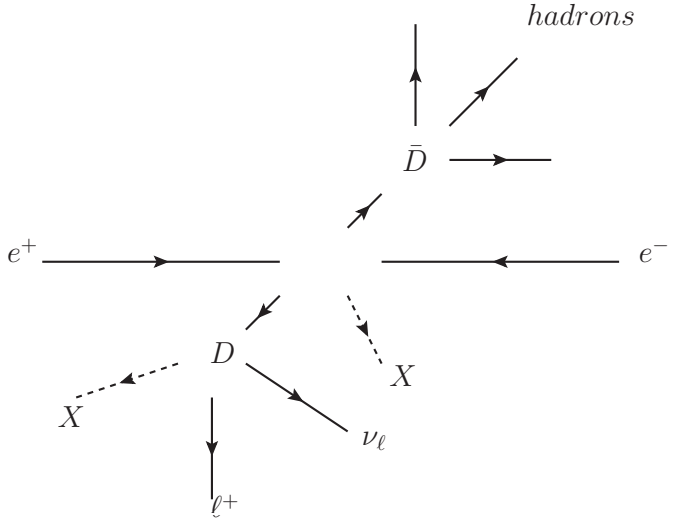
$\Gamma(D^+_{(s)} \to Pl^+\nu_l) \propto |f_+(q^2)|^2 |V_{cs(d)}|^2$

- test the unitarity of quark mixing matrix and search for new physics.
- test the theoretical calculation on decay constants and form factors (FF), especially LQCD.
- test the lepton flavor universality (LFU).
- help to understand the internal structure of light scalar mesons($a_0(980)$,$f_0(500)$).

$D^{0(+)}$ (@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.





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

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

$N_{D\bar{D}}$: The number of $D\bar{D}$ pair
$\epsilon^i_{\rm ST/DT}$: 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

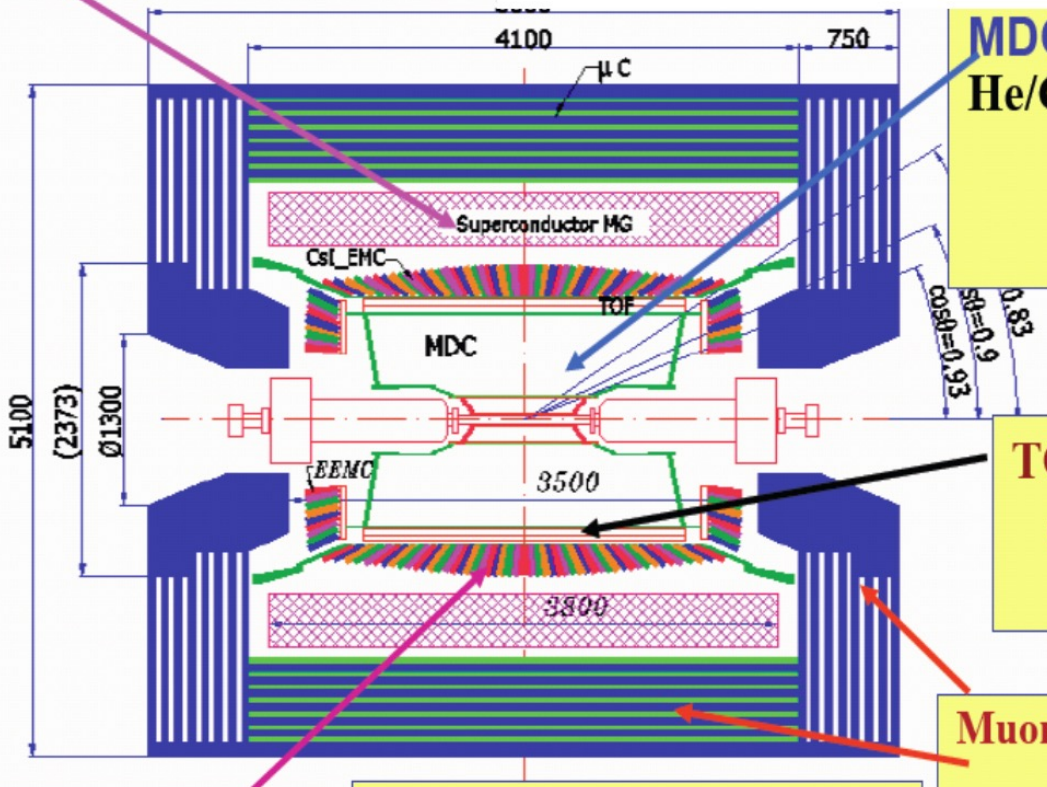
$$U_{\rm miss} = E_{\rm miss} - |\vec{p}|_{\rm miss}$$

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

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/$\sqrt{E}$

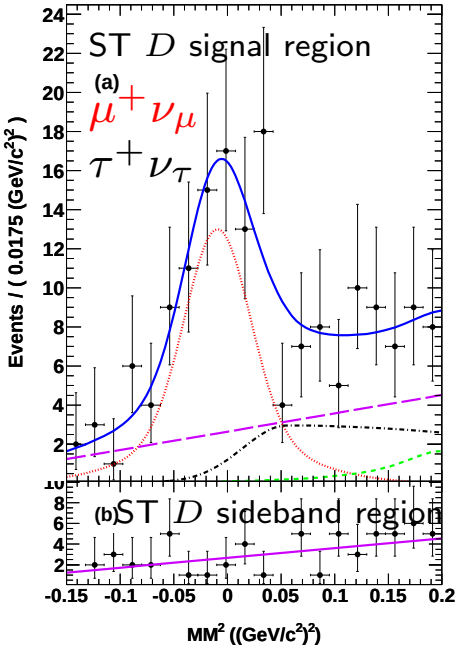
Data Acquisition:
Event rate = 4 kHz
Total data volume ~ 50 MB/s

60 ps for ETOF after upgraded in 2015

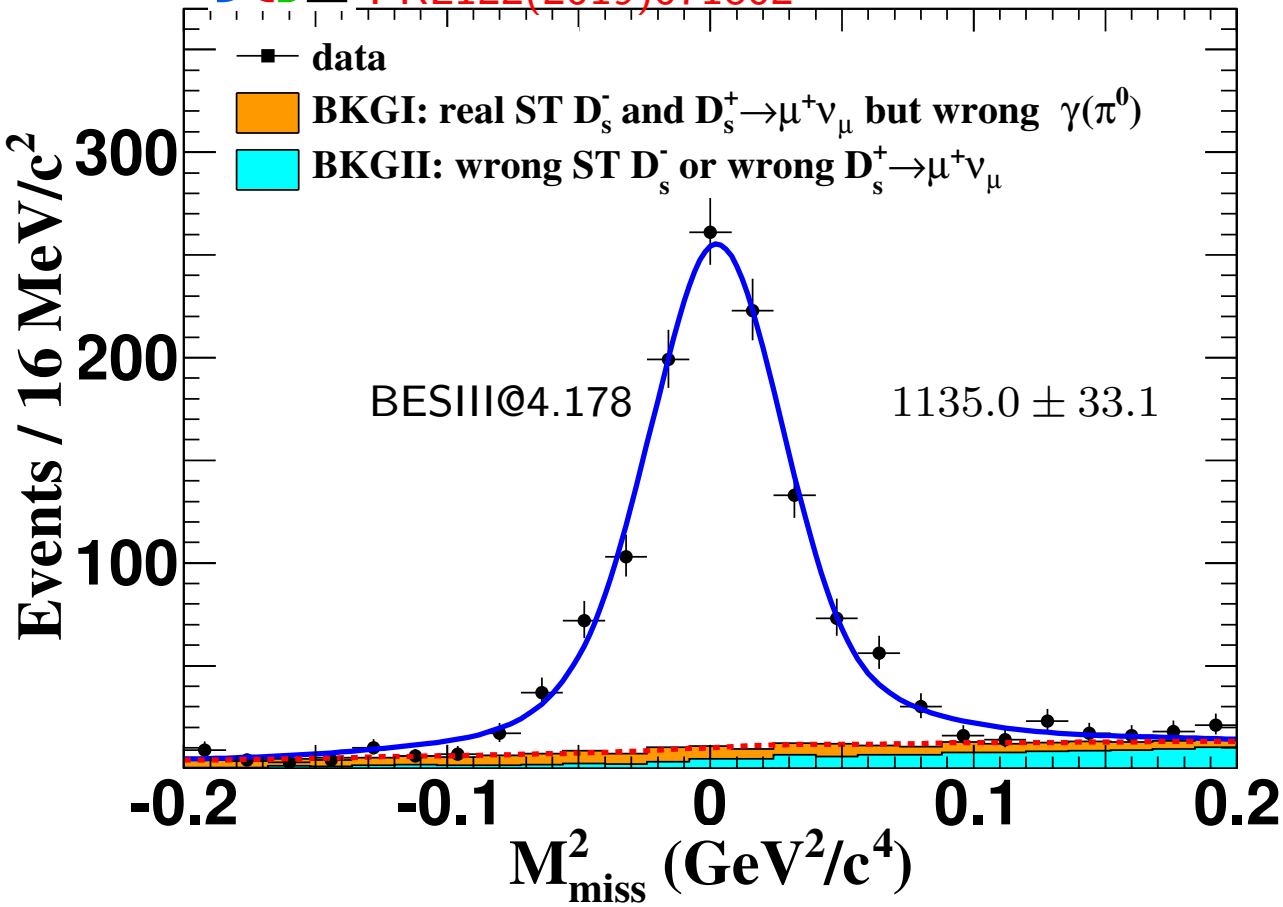
Measurement of $D_s^+ \to \ell^+\nu_\ell$, $f_{D_s^+}|V_{cs}|$, LFU test

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 $\tau^+\nu_\tau$

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

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

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

SM prediction 9.74 ± 0.01.

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

Inputs:

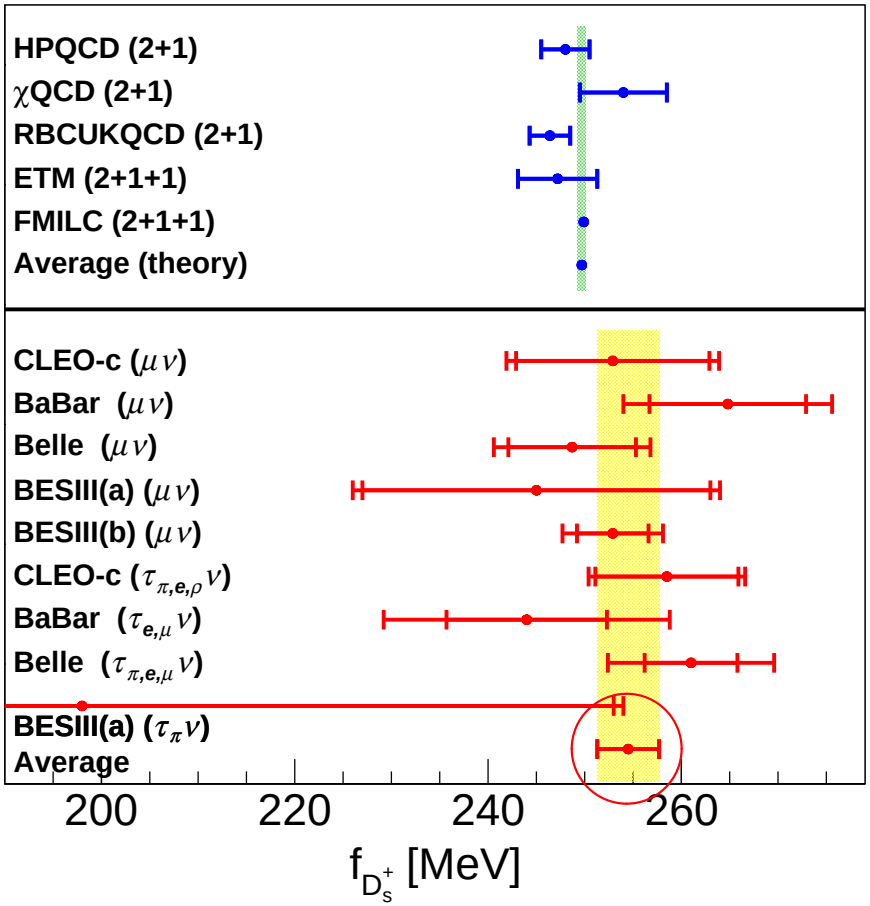
PDG2018 from CKM unitarity:

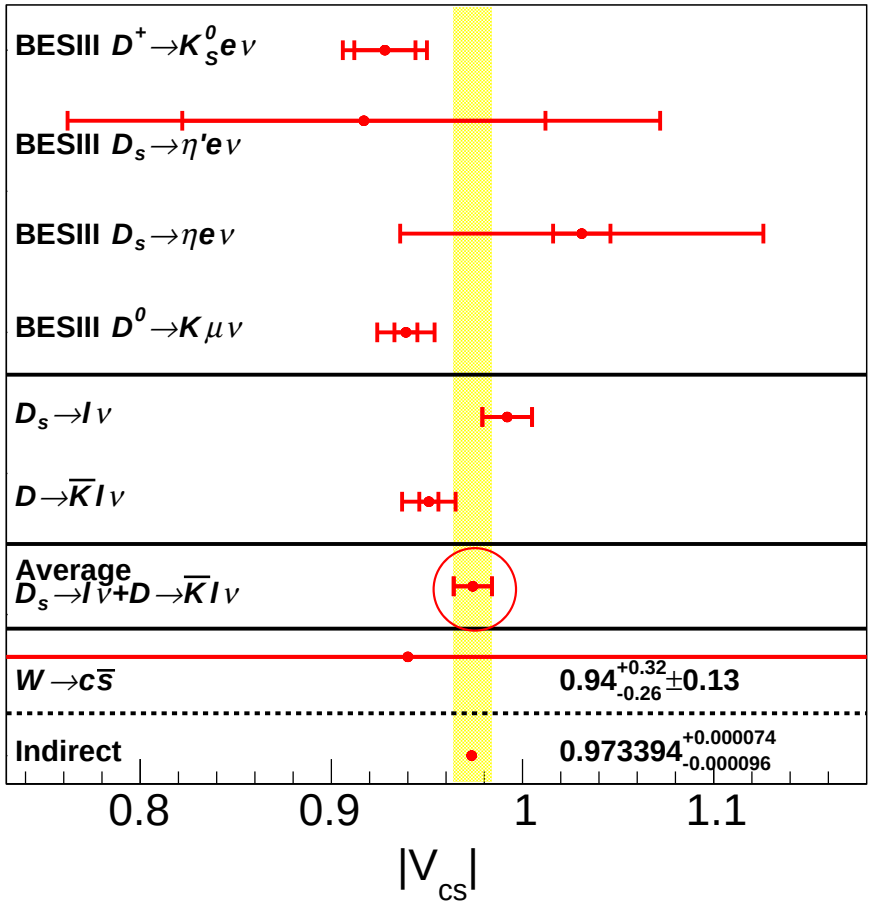
$$|V_{cs}| = 0.97359^{+0.00010}_{-0.00011}$$

LQCD average:

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

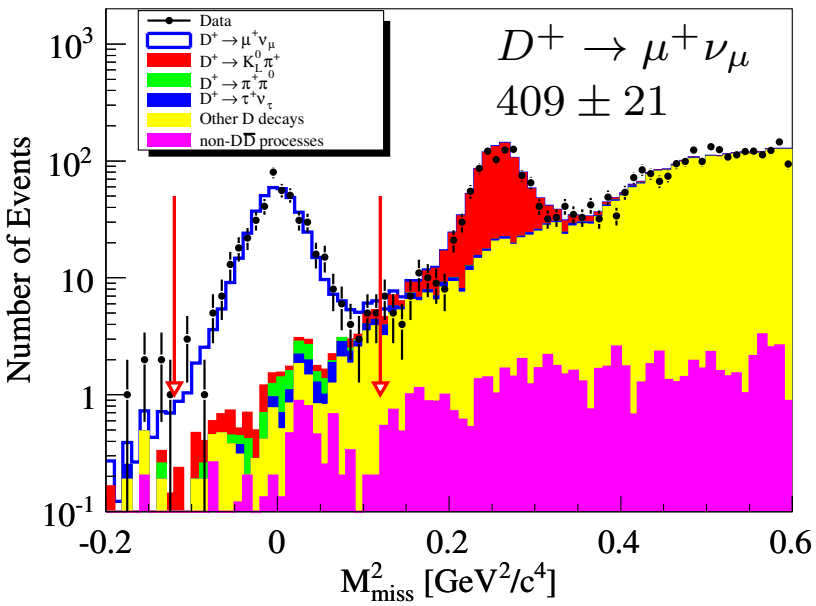
$$f_+^{D\to K}(0)^{\mathrm{LQCD}} = 0.760 \pm 0.011$$





Measurement of $D^+ \to \ell^+\nu_\ell$, $f_{D^+}|V_{cd}|$, LFU test

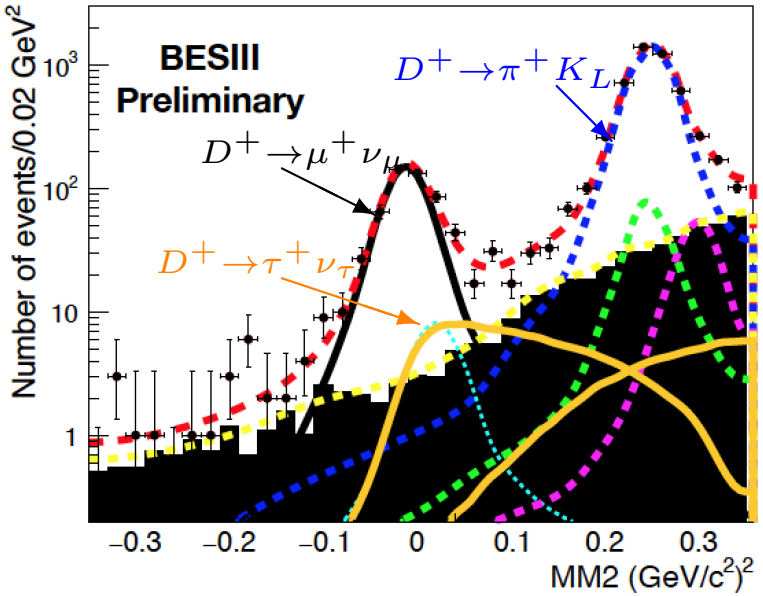
BESIII PRD89(2014)051104



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

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

BESIII



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

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

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^+}

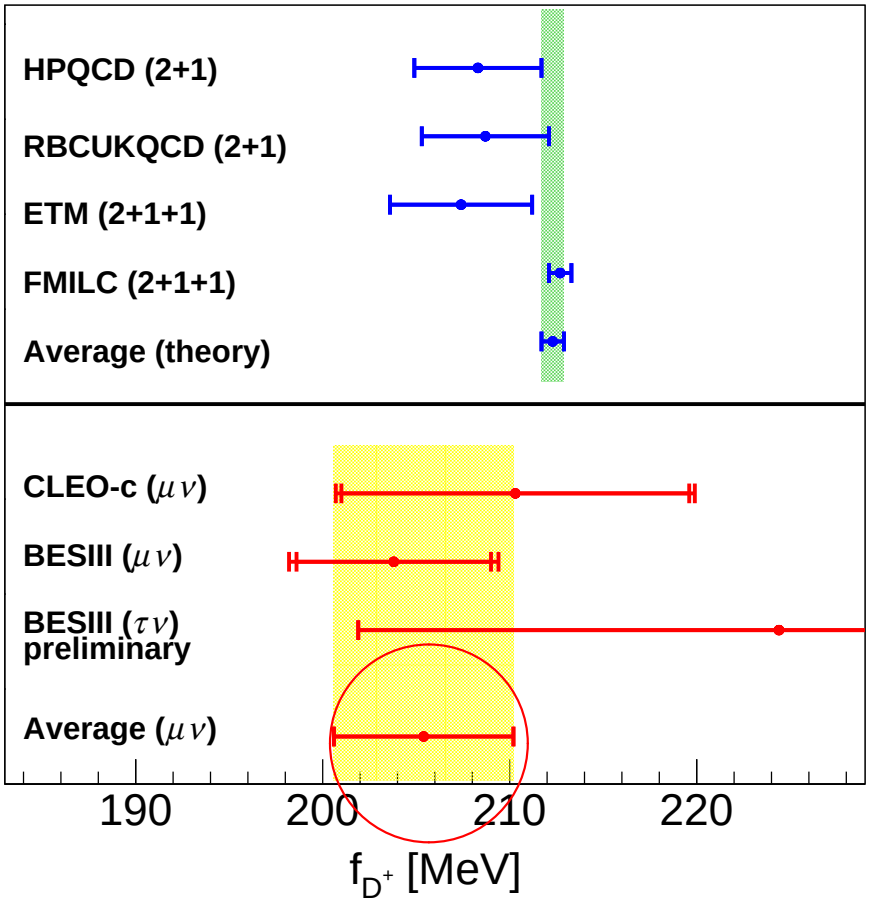
Inputs:

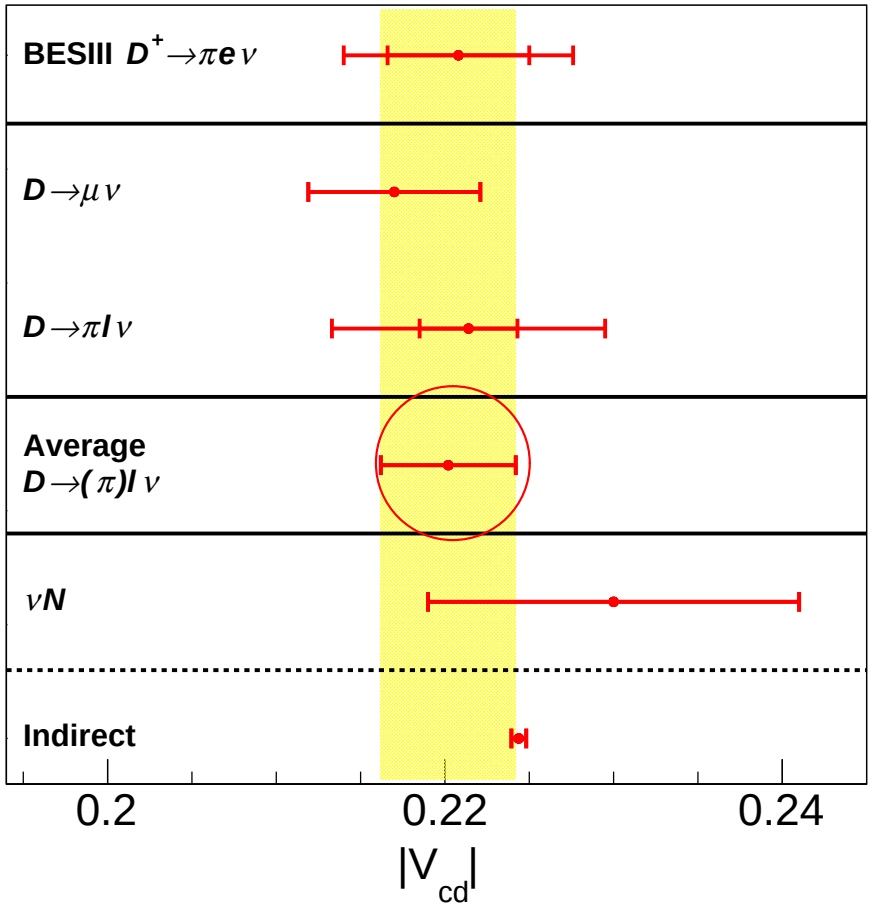
PDG2018 from CKM unitarity:

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

LQCD average:

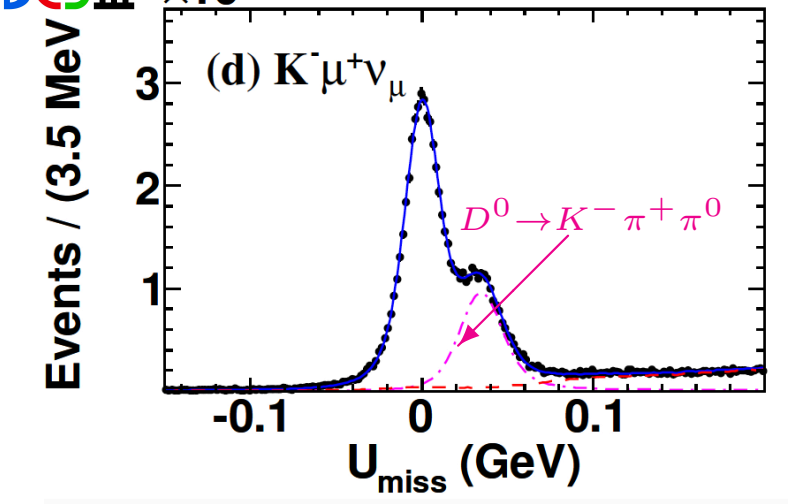
$$f_{D^+}^{\mathrm{LQCD}} = 212.3 \pm 0.6 \text{ MeV}$$
$$f_+^{D\to\pi}(0)^{\mathrm{LQCD}} = 0.634 \pm 0.015$$



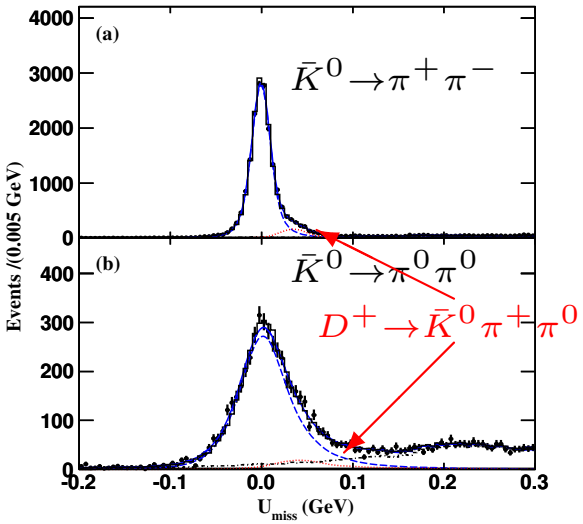


Measurement of $D \to \bar{K}\mu^+\nu_\mu$, $f_+^{D\to K}(0)|V_{cs}|$, LFU test

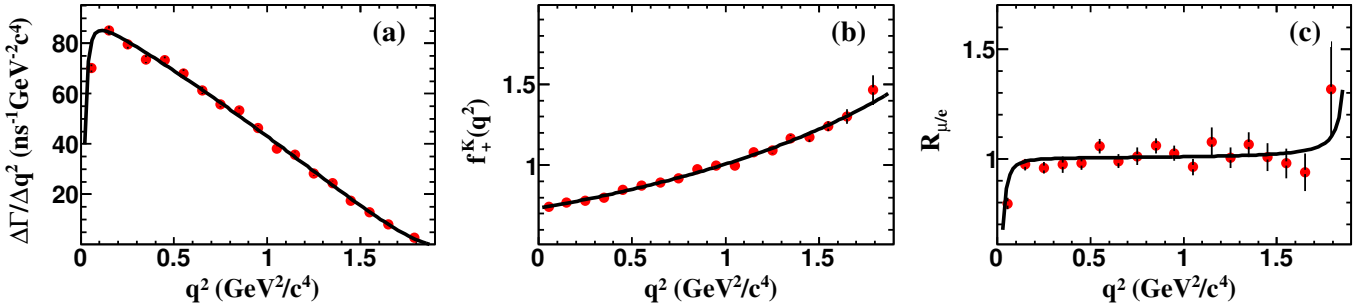
BESIII PRL122(2019)011804



BESIII EPJC76(2016)369



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



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

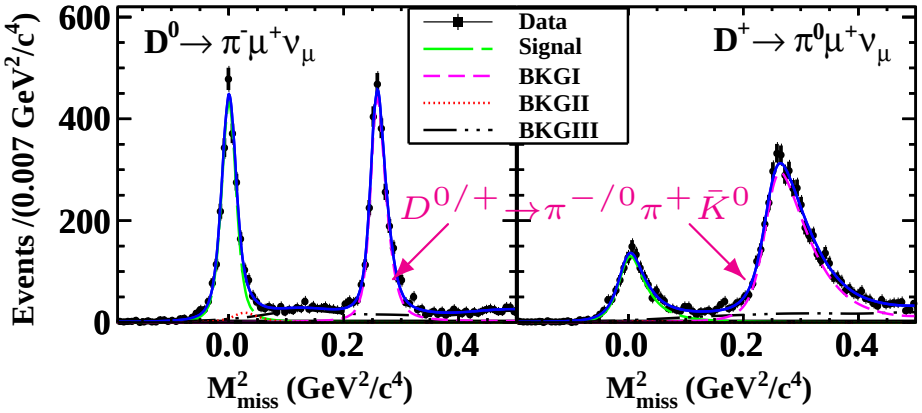
$$\frac{\Gamma(D^0 \to K^-\mu^+\nu_\mu)}{\Gamma(D^0 \to K^-e^+\nu_e)} = 0.974 \pm 0.014$$

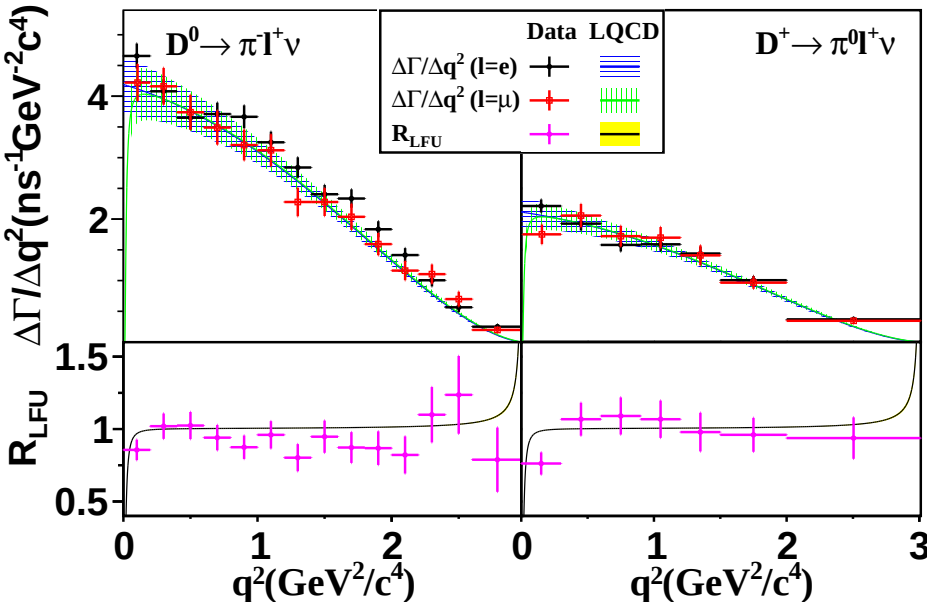
$$\frac{\Gamma(D^+ \to \bar{K}^0\mu^+\nu_\mu)}{\Gamma(D^+ \to \bar{K}^0e^+\nu_e)} = 0.988 \pm 0.033$$

Expected:
0.975 ± 0.001

Measurement of $D \to \pi\mu^+\nu_\mu$, LFU test

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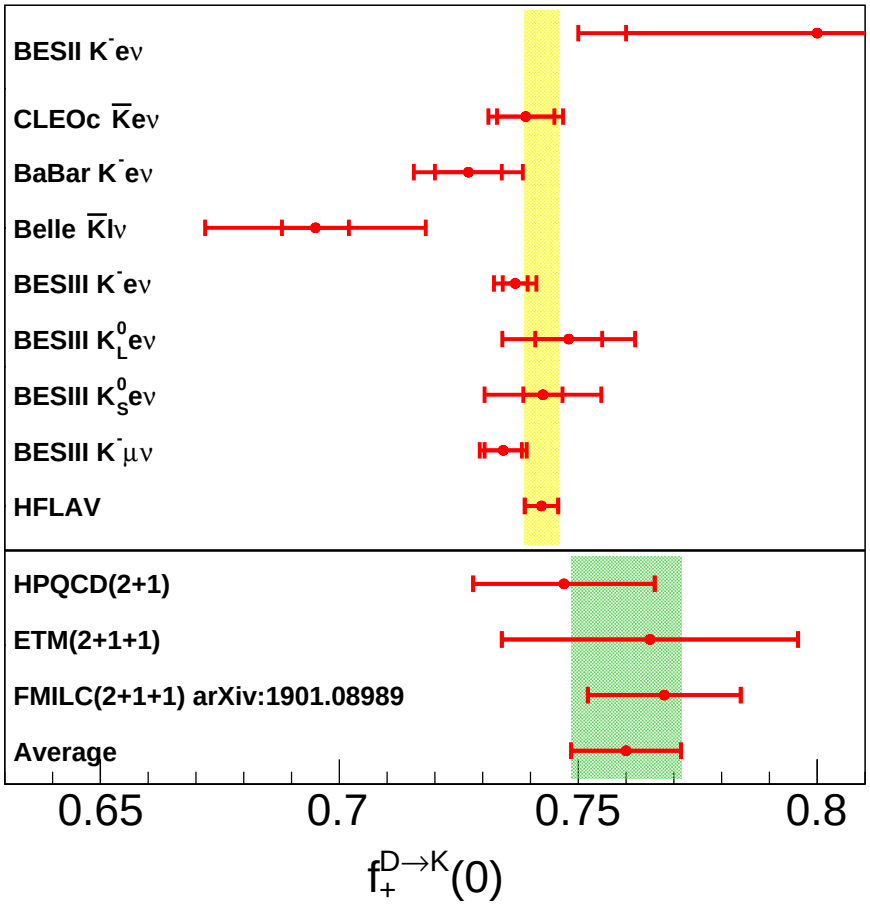
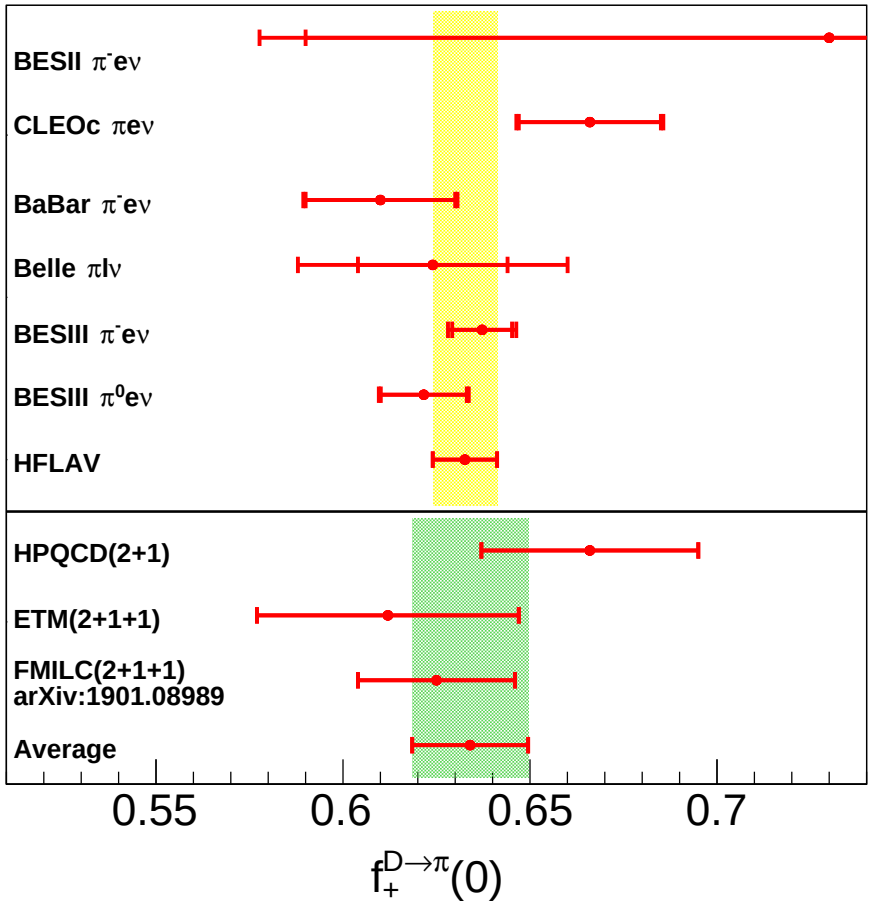
Comparison of $f_+^{D\to K}(0)$ and $f_+^{D\to\pi}(0)$

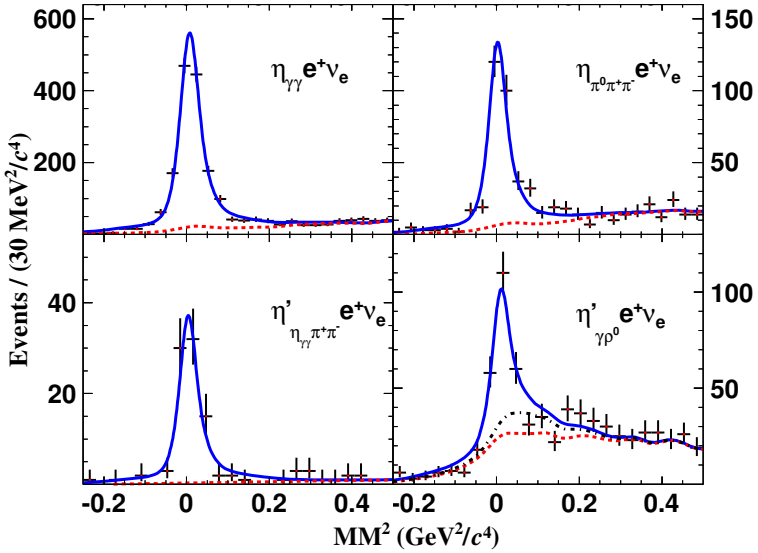
Inputs:
PDG2018 from CKM unitarity:

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

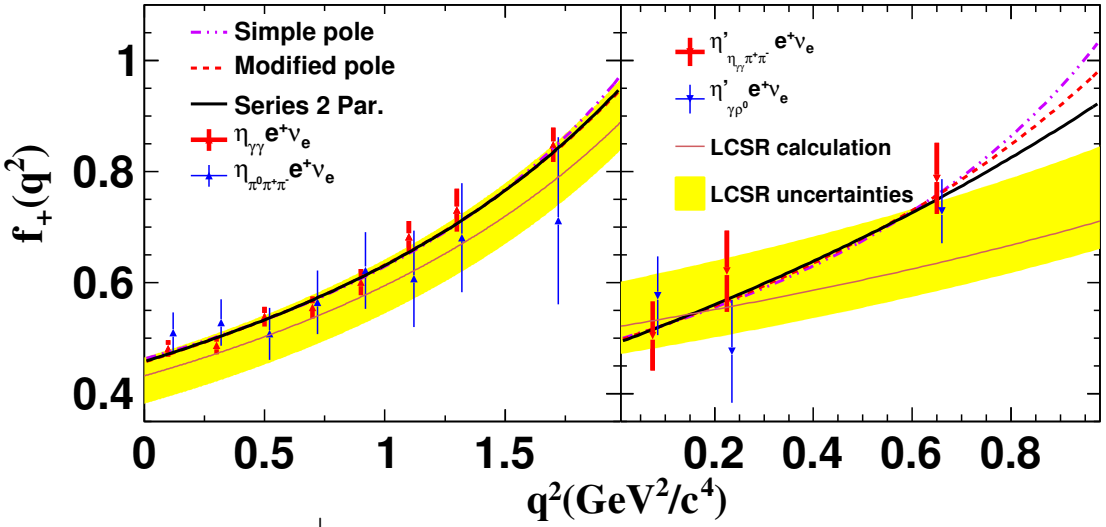




First measurement FF of $D_s^+ \to \eta^{(\prime)} e^+ \nu_e$



BESIII PRL122(2019)121801

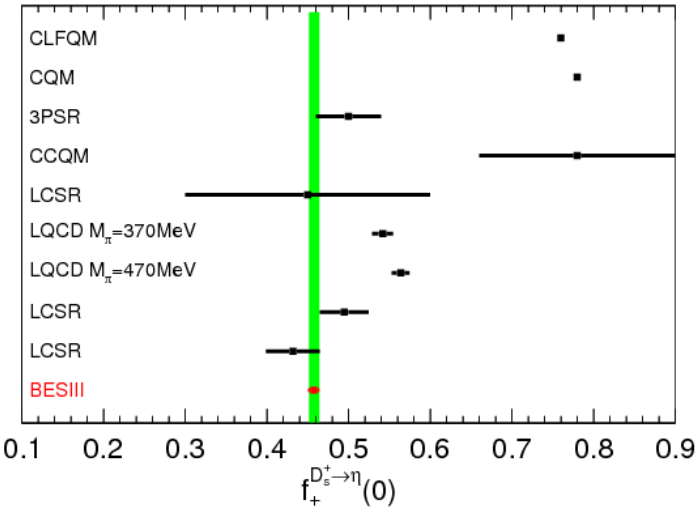


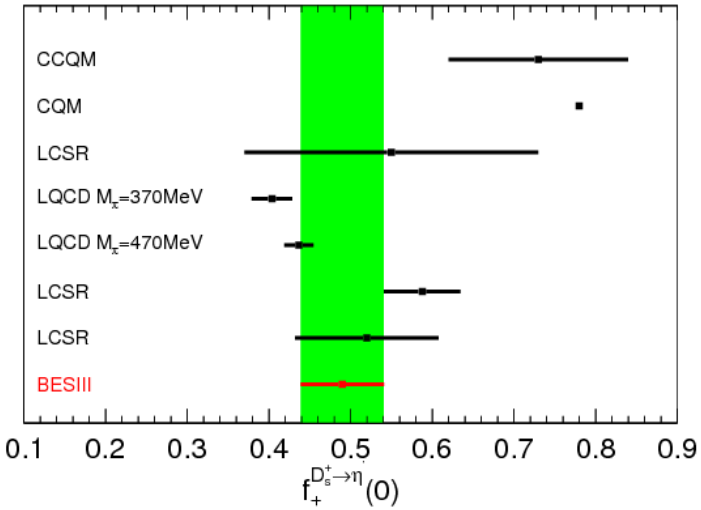
$$\mathcal{B}(D_s^+ \to \eta e^+ \nu_e) = (2.323 \pm 0.063 \pm 0.063)\%$$

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

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

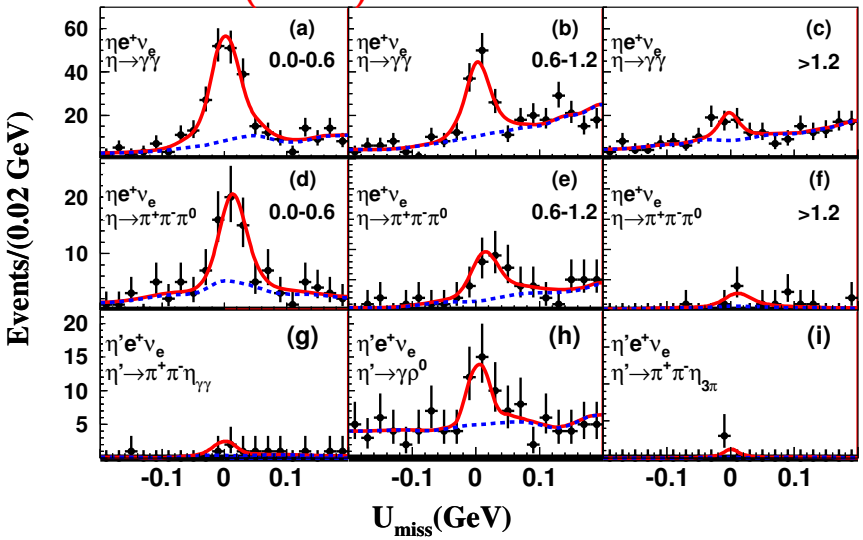
$$f_+^{D_s^+ \to \eta'}(0)|V_{cs}| = 0.477 \pm 0.049 \pm 0.011$$

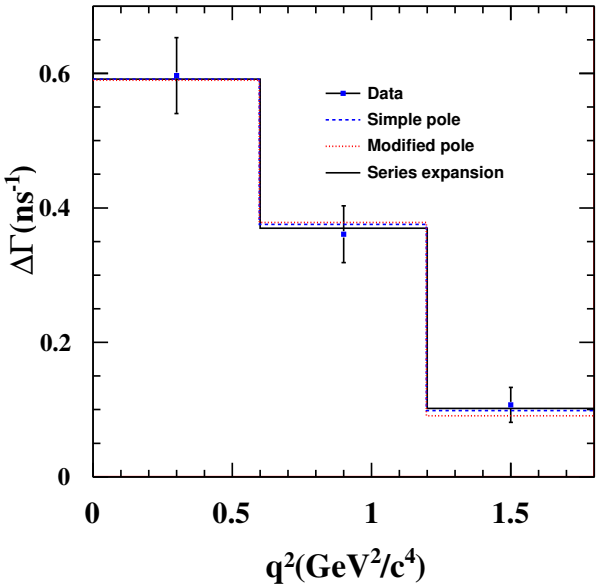




Measurement of $D^+ \to \eta^{(\prime)} e^+ \nu_e$, FF, $\eta - \eta'$ mixing angle

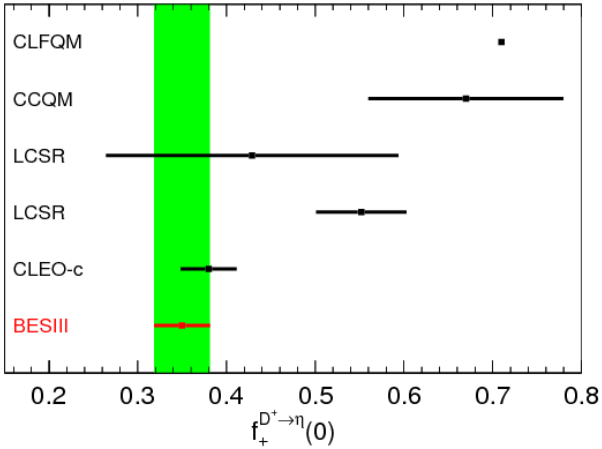
BESIII PRD97(2018)092009





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

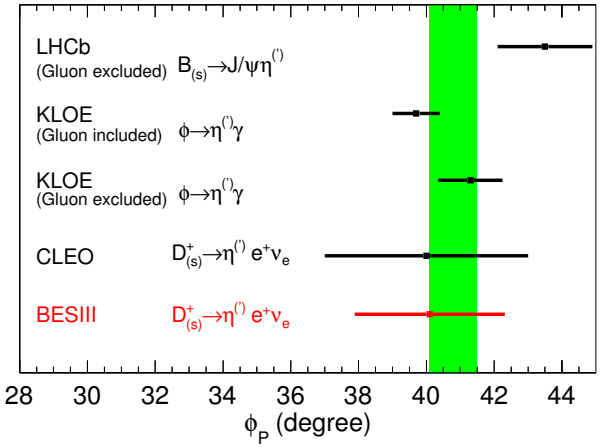
$$f_+^{D^+ \to \eta}(0)|V_{cd}| = (7.86 \pm 0.64 \pm 0.21) \times 10^{-2}$$



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

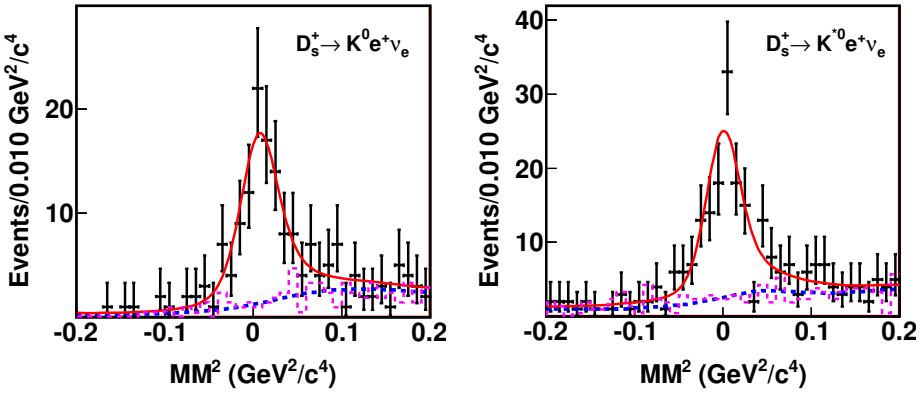
$$\frac{\Gamma(D_s^+ \to \eta' e^+ \nu_e)/\Gamma(D_s^+ \to \eta e^+ \nu_e)}{\Gamma(D^+ \to \eta' e^+ \nu_e)/\Gamma(D^+ \to \eta e^+ \nu_e)} \simeq \cot^4 \Phi_P$$

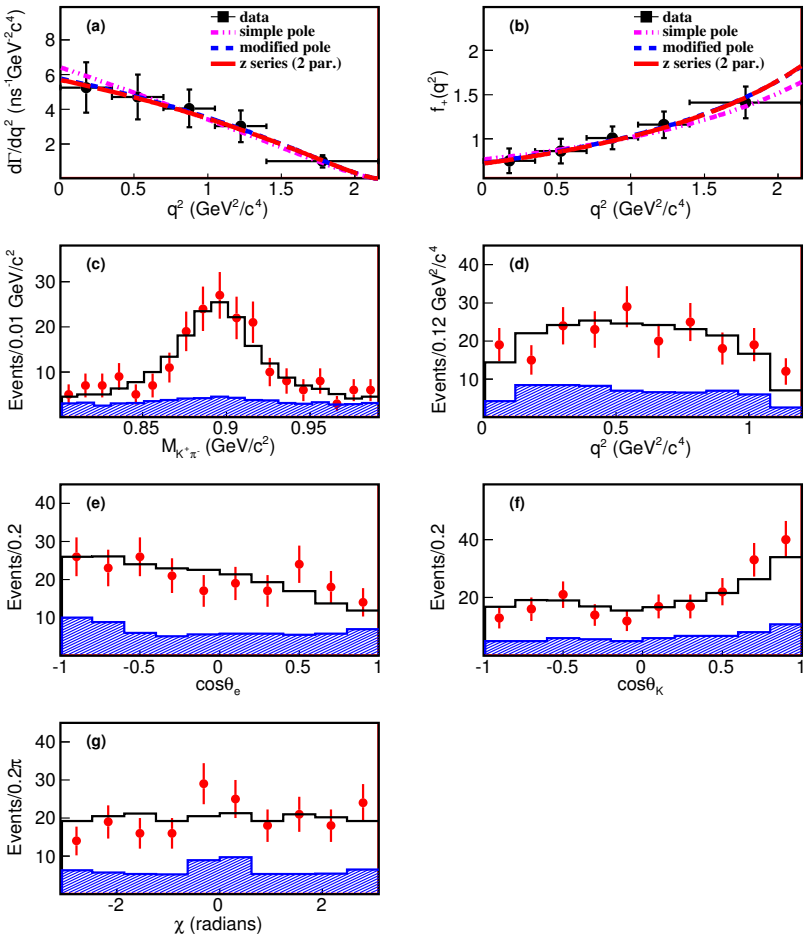
$$\Phi_P = (40.1 \pm 2.1 \pm 0.7)^\circ$$



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

BESIII PRL122(2019)061801





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

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

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

$$r_V = \frac{V(0)}{A_1(0)} \quad r_V = 1.67 \pm 0.34 \pm 0.16$$

$$r_2 = \frac{A_2(0)}{A_1(0)} \quad r_2 = 0.77 \pm 0.28 \pm 0.07$$

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

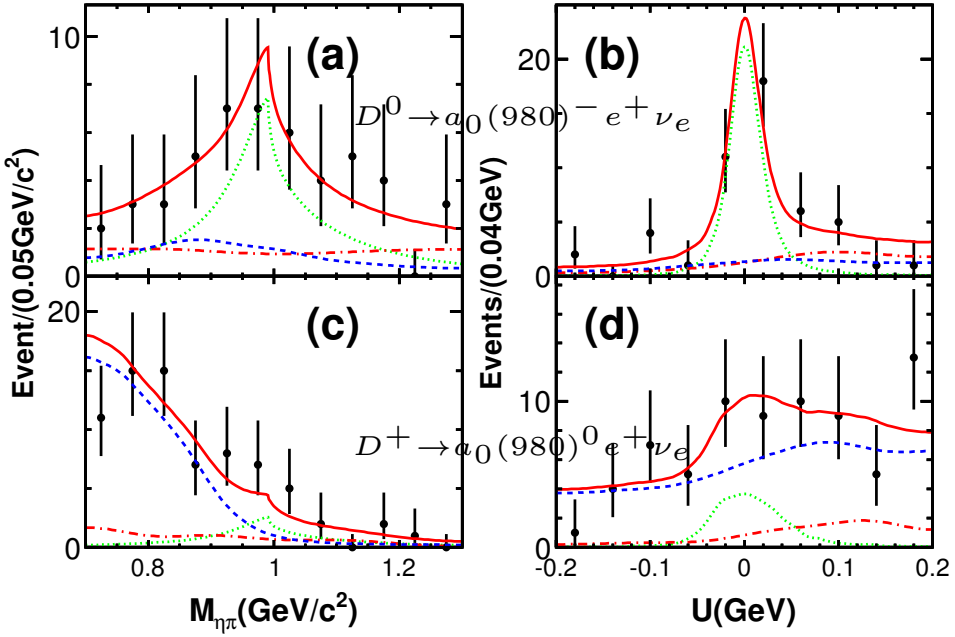
$$r_V^{D_s^+ \to K^{*0}}/r_V^{D^+ \to \rho^0} = 1.13 \pm 0.26 \pm 0.11$$

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

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

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

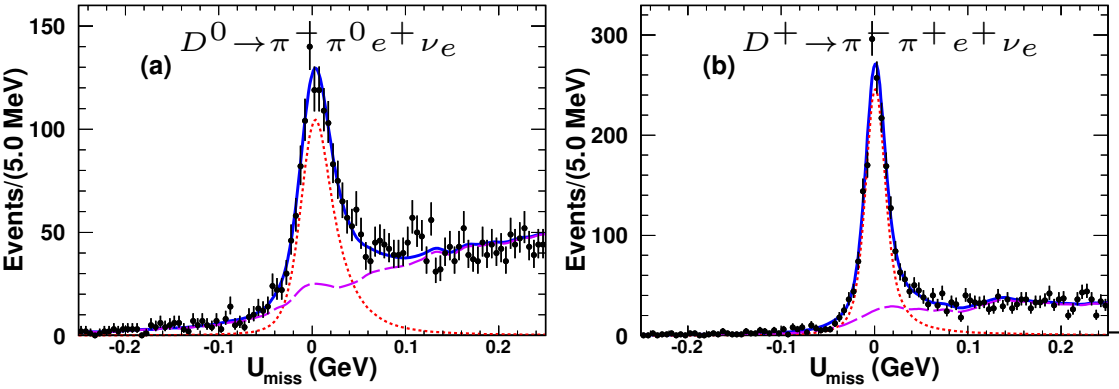
R=1.0±0.3 for two-quark description;
R=3.0±0.9 for tetraquark description.

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 $D \to \pi\pi e^+\nu_e$(S wave)

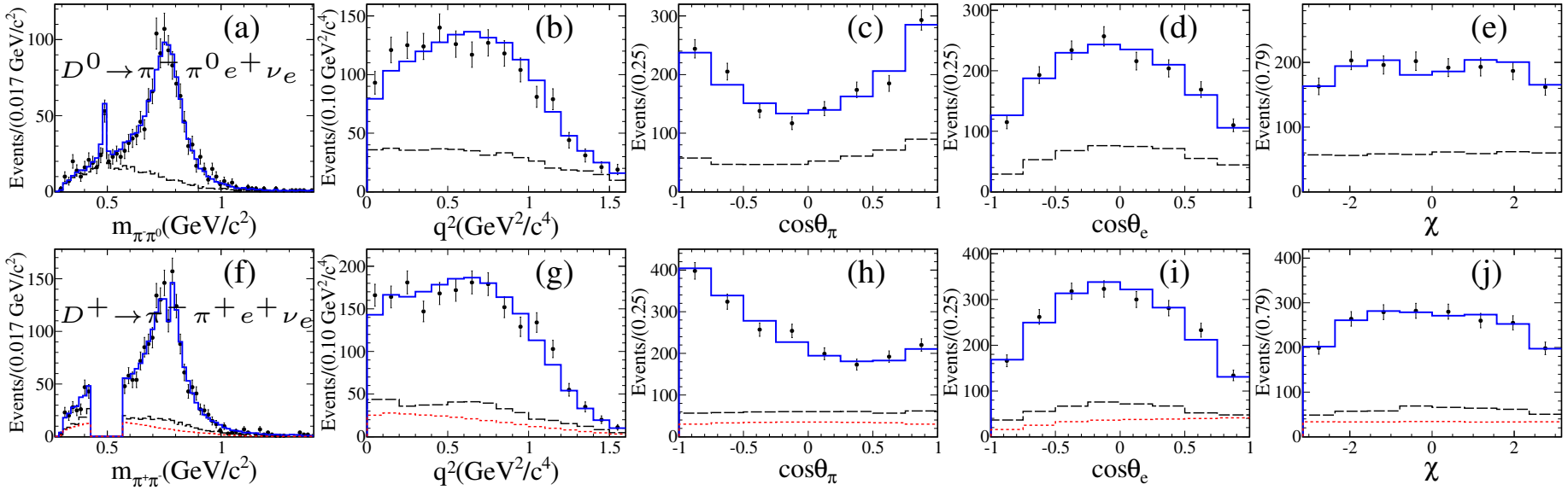
BESIII PRL122(2019)062001



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

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

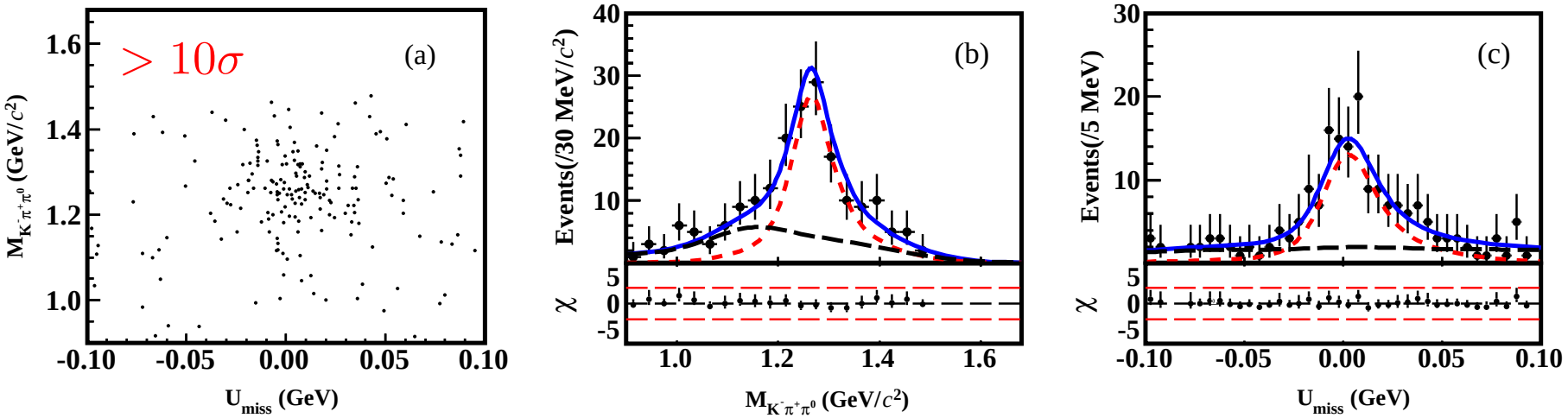
$$R = [\mathcal{B}(D^+ \to f_0(980) e^+\nu_e) + \mathcal{B}(D^+ \to f_0(500) e^+\nu_e)]/\mathcal{B}(D^+ \to a_0(980) e^+\nu_e) > 2.7$$



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

Semileptonic D transitions into P-wave states were predicted 30 years ago, but not experimentally confirmed yet. Predictions of ISGW2 model[PRD52,2783(1995)]: $\mathcal{B}[D^{0(+)} \to \bar{K}_1(1270)^{-(0)} e^+ \nu_e] \to$ 0.1%(0.3%). Evidence of $D^0 \to \bar{K}_1(1270)^- e^+ \nu_e$ has been found by CLEO Collaboration[PRL99,191801 (2007)]. In theory, the predicted BFs are sensitive to K_1 mixing angle(θ_{K_1}) and its sign[PRD79,036004(2009),EPJC77,369(2017)].

BESIII 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 $\bar{K}_1(1270)$.

Summary

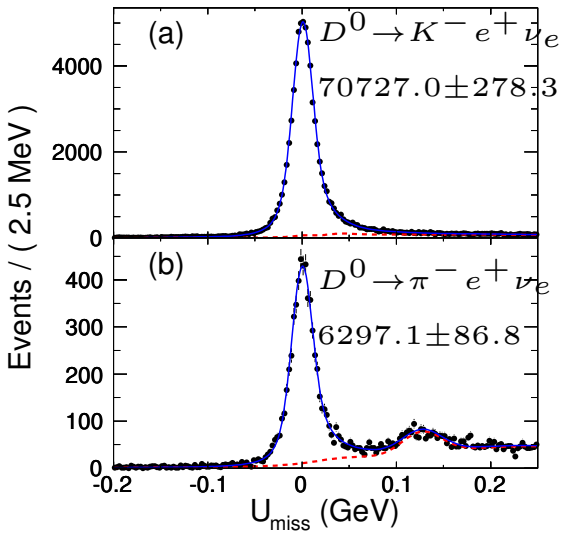
- Precise measurement of decay constants, form factors and quark mixing matrix elements $\rightarrow$ precision improved with BESIII measurement.
- Lepton flavor universality test $\rightarrow$ no evidence of violation found in the charm sector at the precision of 1.5% for cabbibo favored decays and 4% for single cabbibo suppressed decays.
- Study the nature of light scalar mesons $\rightarrow$ tetraquark description favored with BESIII's results($a_0(980)$,$f_0(500)$).

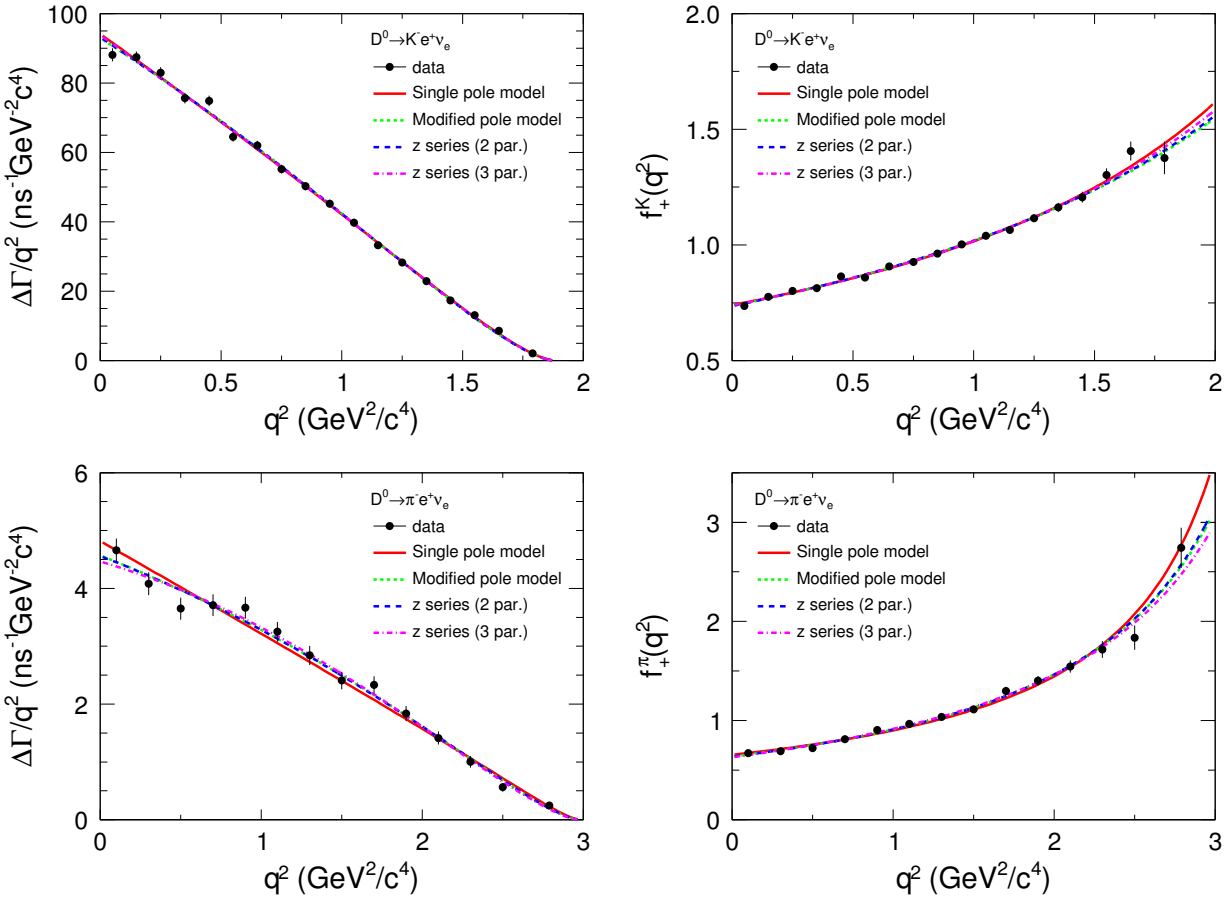
Thanks for your attention!

Back up

Measurement of $D^0 \to K^-(\pi^-)e^+\nu_e$, $f_+^{D\to K(\pi)}(0)|V_{cs(d)}|$

BESIII PRD92(2015)072012

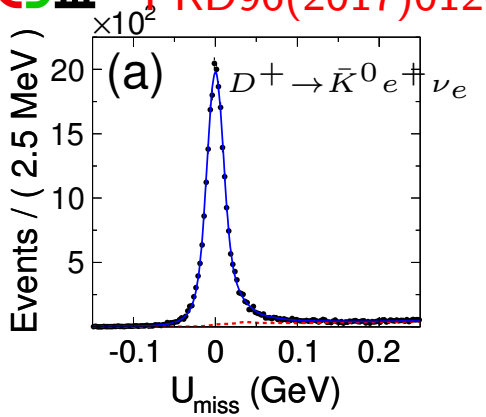


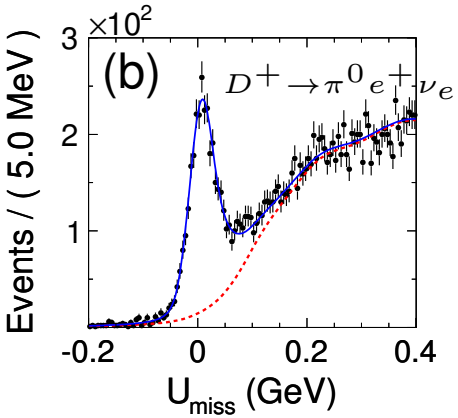


$\mathcal{B}(D^0 \to K^- e^+ \nu_e)$	$(3.505 \pm 0.014 \pm 0.033)\%$	$f_+^{D\to K}(0)\lvert V_{cs}\rvert$	$0.7172 \pm 0.0025 \pm 0.0035$
$\mathcal{B}(D^0 \to \pi^- e^+ \nu_e)$	$(0.295 \pm 0.004 \pm 0.003)\%$	$f_+^{D\to \pi}(0)\lvert V_{cd}\rvert$	$0.1435 \pm 0.0018 \pm 0.0009$

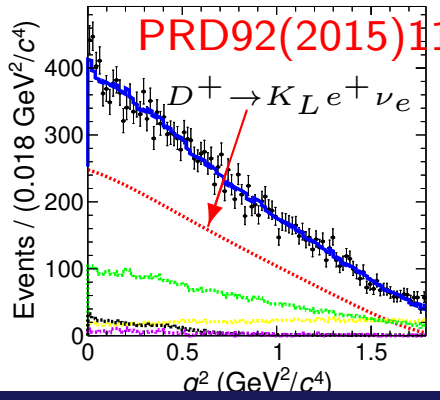
Measurement of $D^+ \to \bar{K}^0(\pi^0)e^+\nu_e$, $f_+^{D\to K(\pi)}(0)|V_{cs(d)}|$

PRD96(2017)012002

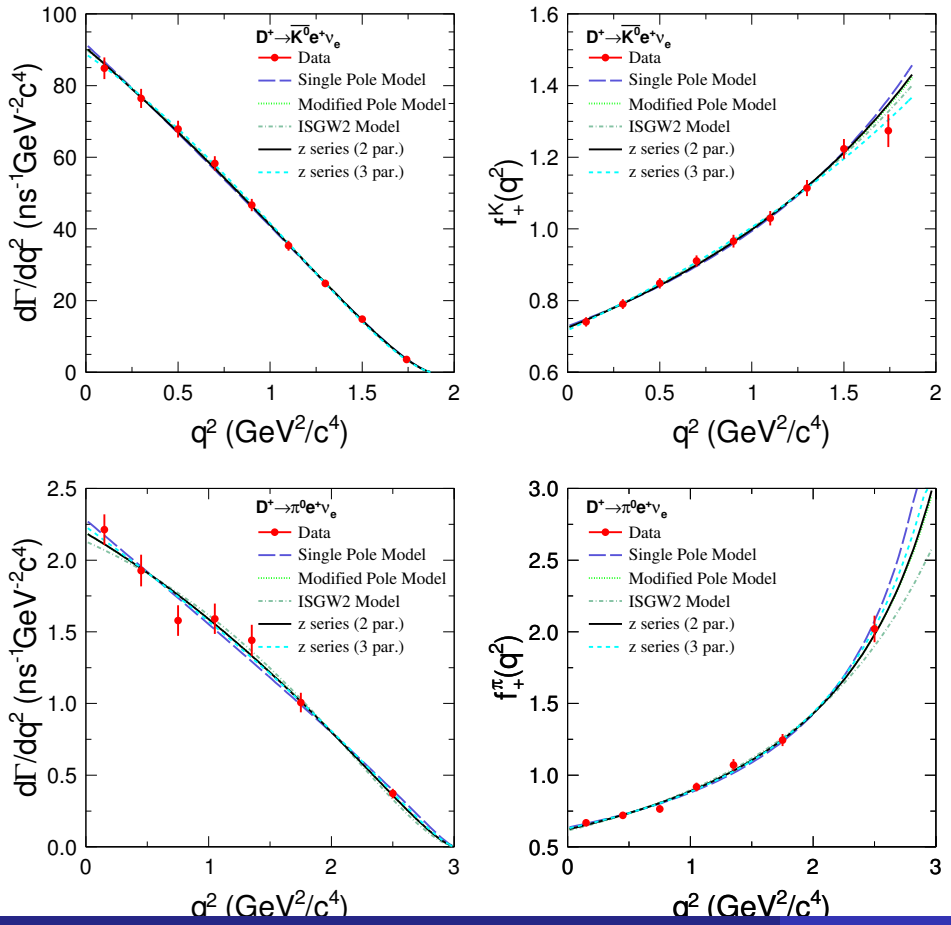




PRD92(2015)112008

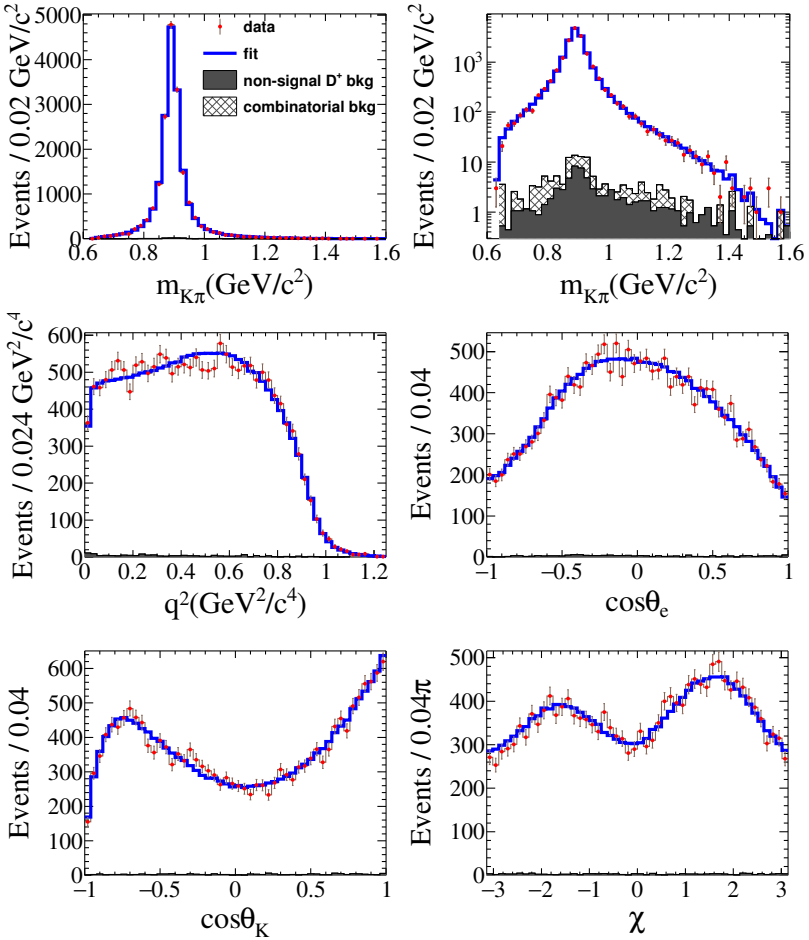


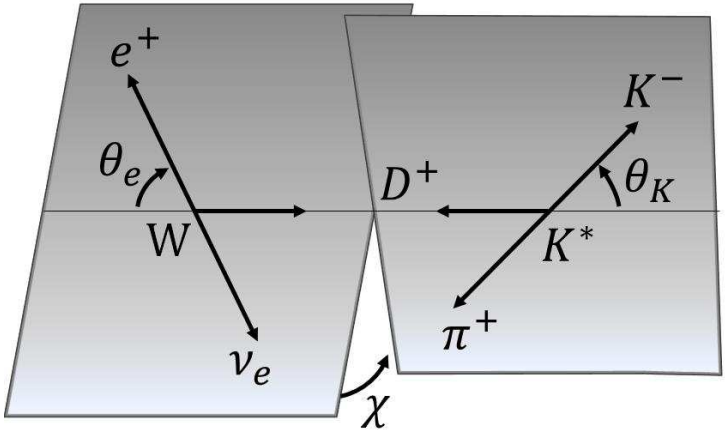
$\mathcal{B}(D^+ \to \bar{K}^0 e^+ \nu_e)$ (via K_S^0)	$(8.60 \pm 0.06 \pm 0.15)\%$
$f_+^{D\to K}(0)\lvert V_{cs}\rvert$	$0.7053 \pm 0.0040 \pm 0.0112$
$\mathcal{B}(D^+ \to \bar{\pi}^0 e^+ \nu_e)$	$(0.363 \pm 0.008 \pm 0.005)\%$
$f_+^{D\to \pi}(0)\lvert V_{cd}\rvert$	$0.1400 \pm 0.0026 \pm 0.0007$
$\mathcal{B}(D^+ \to \bar{K}^0 e^+ \nu_e)$ (via K_L^0)	$(8.962 \pm 0.054 \pm 0.206)\%$
$f_+^{D\to K}(0)\lvert V_{cs}\rvert$	$0.728 \pm 0.006 \pm 0.011$



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

BESIII PRD94(2016)032001





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

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

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

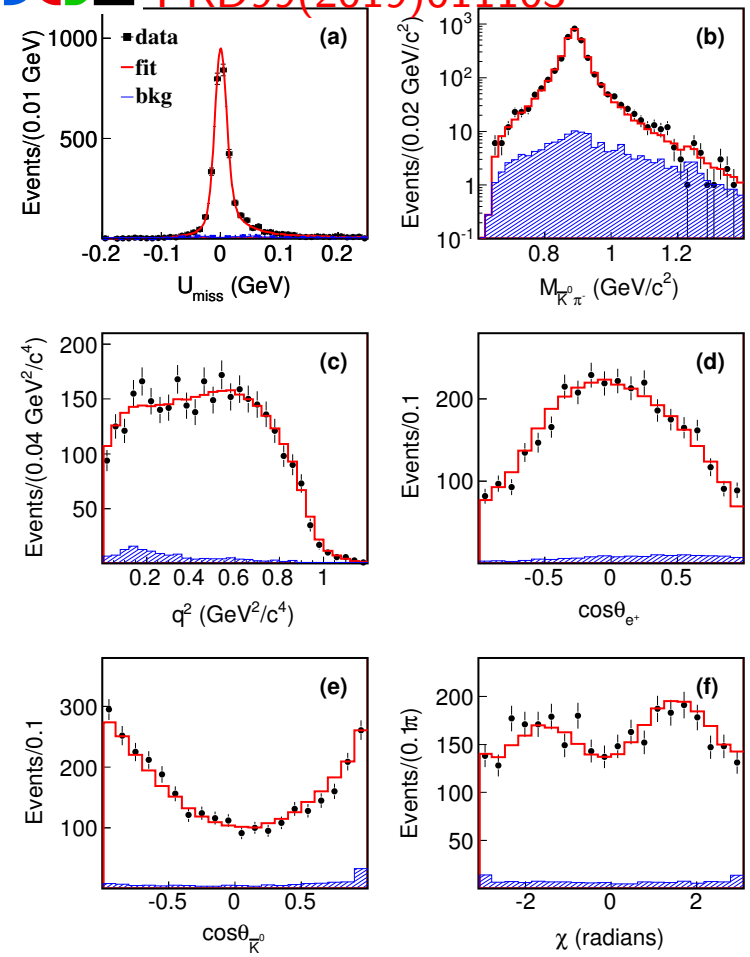
Not included in the nominal fit:

$\mathcal{B}(D^+ \to \bar{K}^*(1410)^0 e^+\nu_e)$	$(0 \pm 0.009 \pm 0.008)\%$ $< 0.028\%$ (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	$(0.228 \pm 0.008 \pm 0.008)\%$

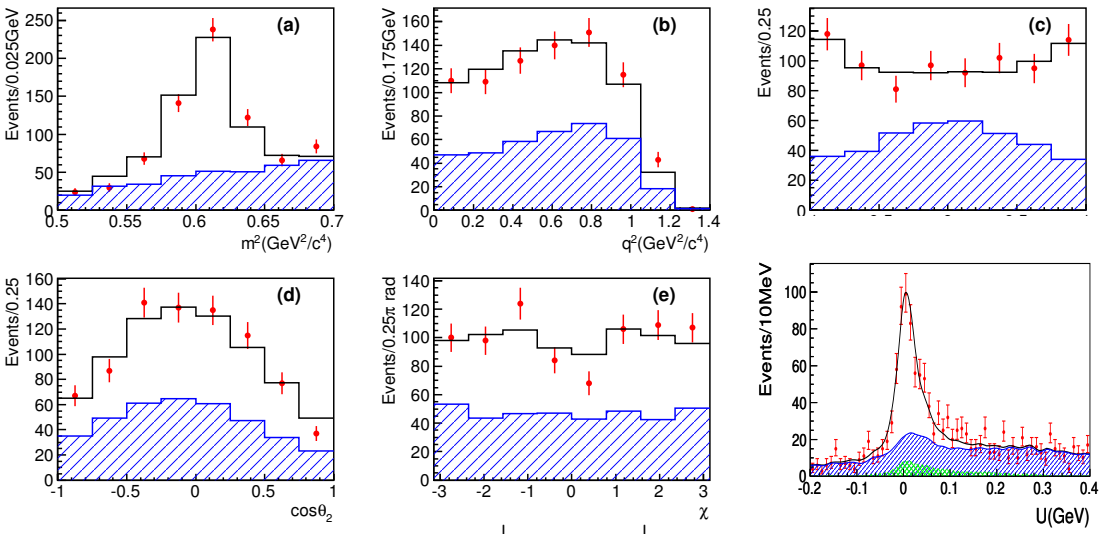
$D^0 \to \bar{K}^0\pi^- e^+\nu_e$ and $D^+ \to \omega e^+\nu_e$

BESIII PRD99(2019)011103



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

BESIII PRD92(2015)071101



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

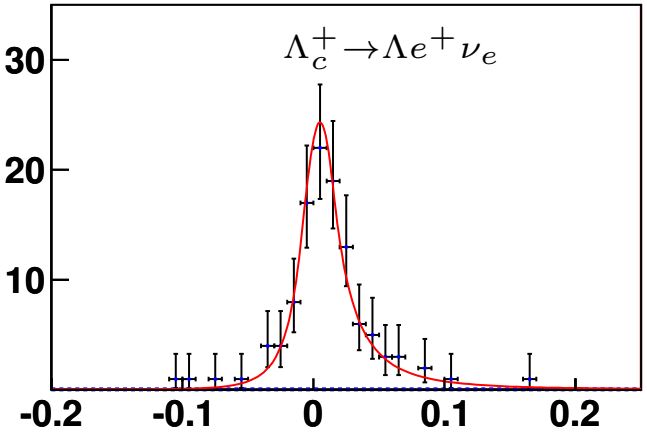
$\mathcal{B}(D^+ \to \omega e^+\nu_e)$	$(1.63 \pm 0.11 \pm 0.08) \times 10^{-3}$
r_V	$1.24 \pm 0.09 \pm 0.06$
r_2	$1.06 \pm 0.15 \pm 0.05$

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

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

0.567 fb^{-1} data @4.6 GeV

BESIII PRL115(2015)221805



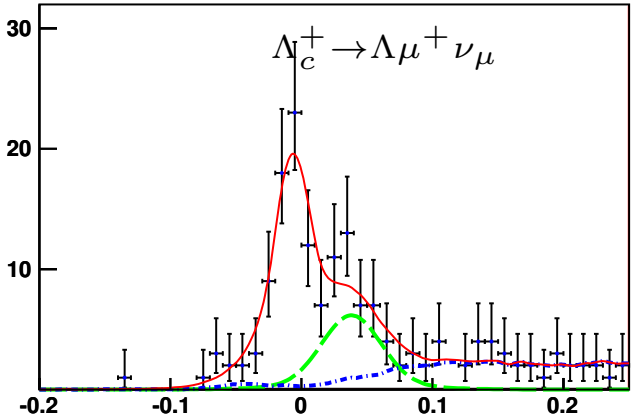
Previously expected: $1.4\% \to 9.2\%$.

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

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

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

BESIII PLB767(2017)42



PRL118(2017)082001

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

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