Charm meson leptonic and semileptonic decays at BESIII

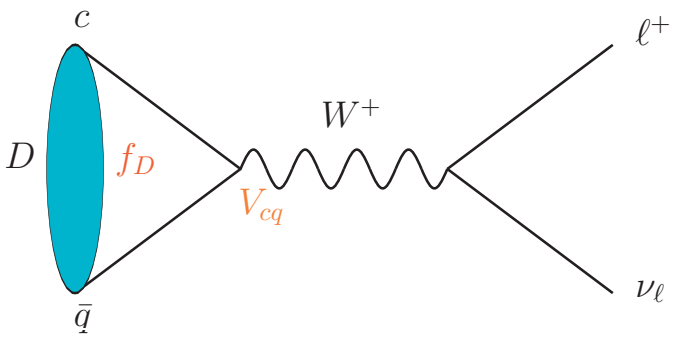
Sifan Zhang on behalf of the BESIII collaboration

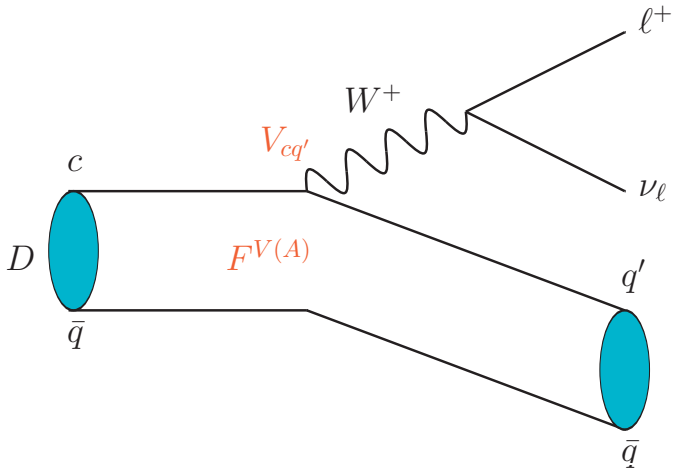
NJU, IHEP

November 2, 2019

Joint Workshoop on Charmed Hadron Decays @ BESIII, BELLE, LHCb 2019
Shanxi Normal University, Linfen

Motivation





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

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

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

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

$$<V(p_2, \epsilon_2)|V^\mu - A^\mu|D(p_1)> =$$

$$-(M_1 + M_2)\epsilon_2^{*\mu} A_1(q^2) + \frac{\epsilon_2^* q}{M_1 + M_2} P^\mu A_2(q^2) +$$

$$2M_2 \frac{\epsilon_2^* q}{q^2} q^\mu [A_3(q^2) - A_0(q^2)] + \frac{2i\epsilon_{\mu\nu\rho\sigma}\epsilon^{*\nu} p_1^\rho p_2^\sigma}{M_1 + M_2} V(q^2)$$

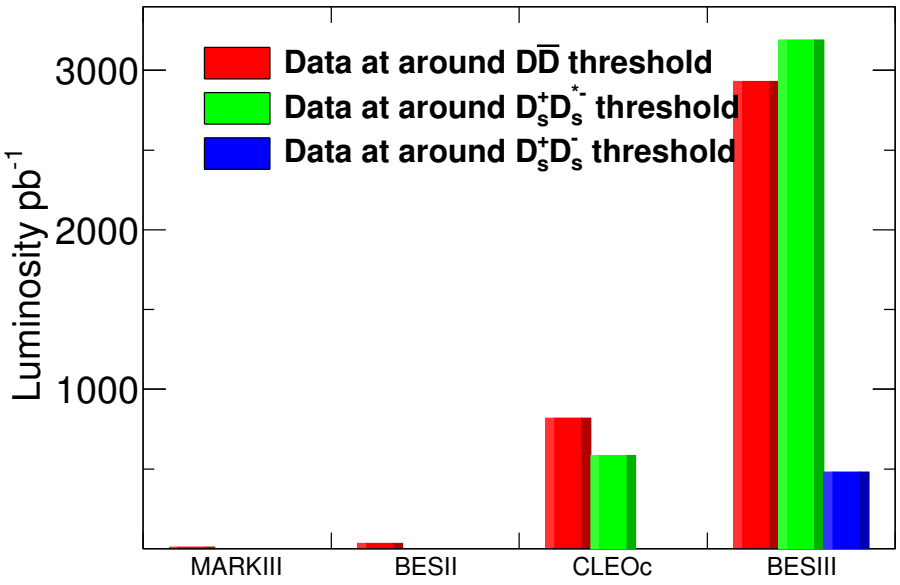
$$r_V = \frac{V(0)}{A_1(0)}$$

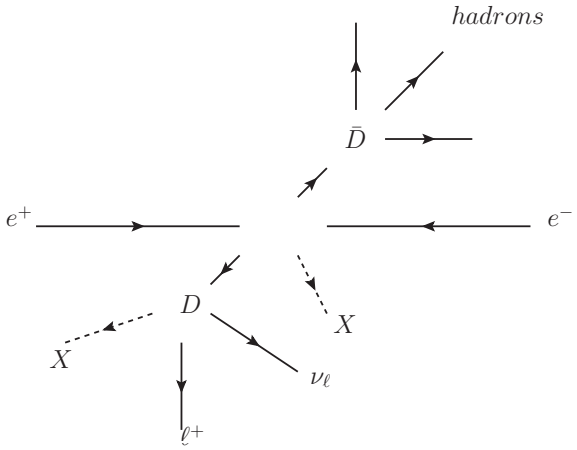
$$r_2 = \frac{A_2(0)}{A_1(0)}$$

- 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.

Experiments at the charm factory

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





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

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

With fully reconstructed tracks, neutrino information can be accessed via missing energy and momentum

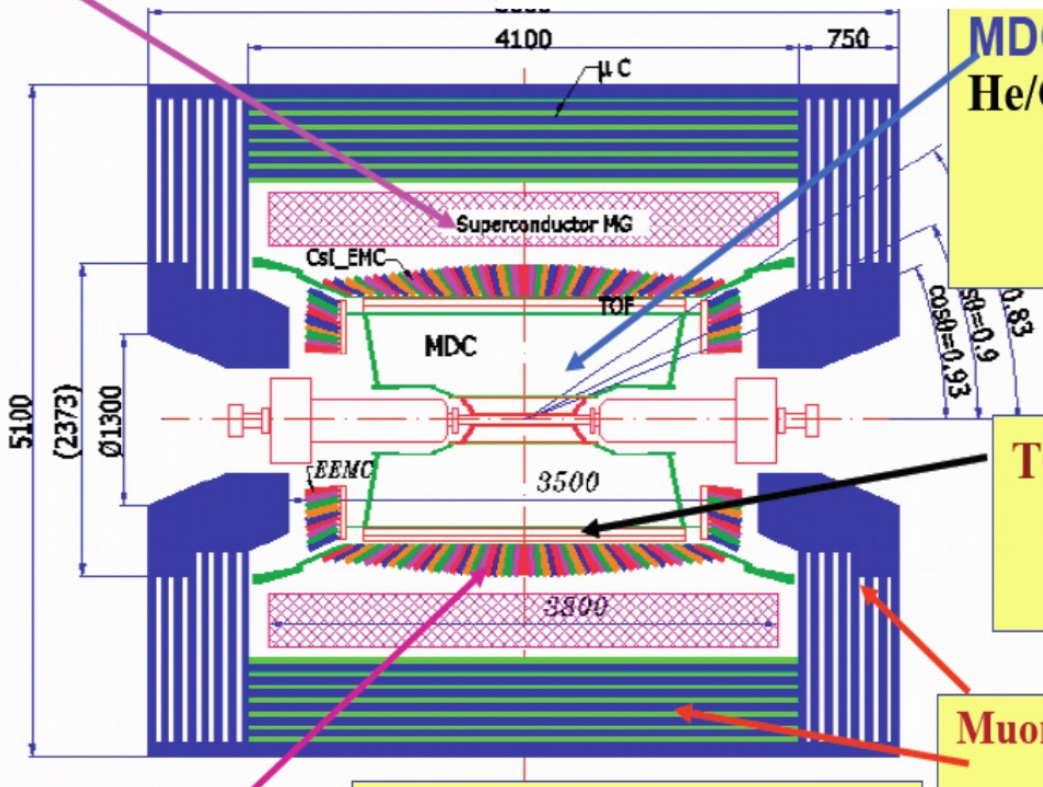
$$U_{\rm miss} = E_{\rm miss} - |\vec{p}|_{\rm miss}$$

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

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
$\sigma z = 0.6\ cm/\sqrt{E}$

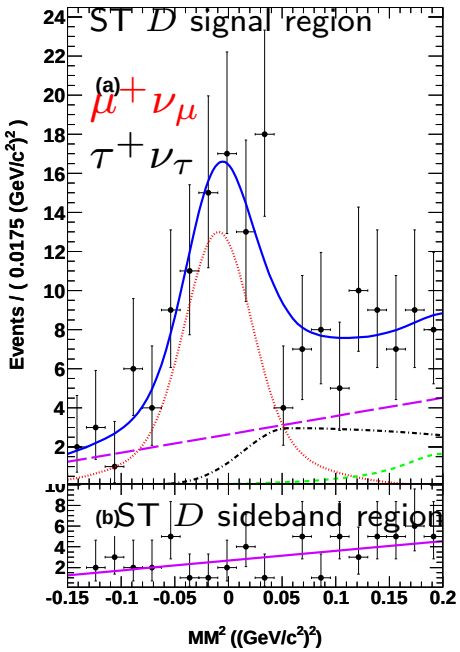
Data Acquisition:
Event rate = 4 kHz
Total data volume ~ 50 MB/s

60 ps for ETOF after upgraded in 2015

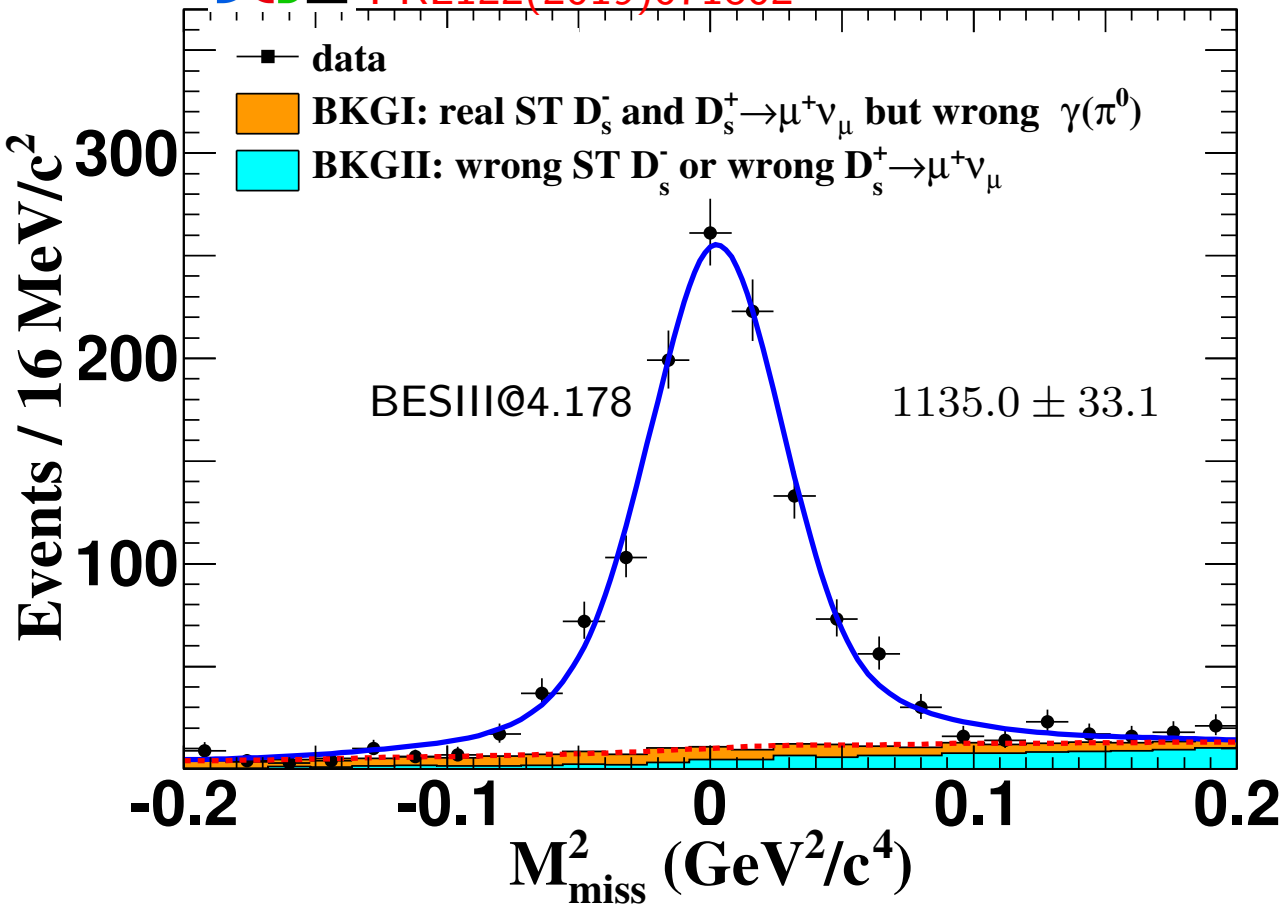
D_s^+ leptonic decays

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 $\tau^+\nu_\tau$

$$\mathcal{B}(D_s^+\to\mu^+\nu_\mu)=(5.49\pm0.16\pm0.15)\times10^{-3}$$

$$f_{D_s^+}|V_{cs}|=246.2\pm3.6\pm3.5$$

$$R_{D_s^+}=\frac{\Gamma(D_s^+\to\tau^+\nu_\tau)}{\Gamma(D_s^+\to\mu^+\nu_\mu)}=10.19\pm0.52$$

SM prediction 9.74 ± 0.01.

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

Inputs:

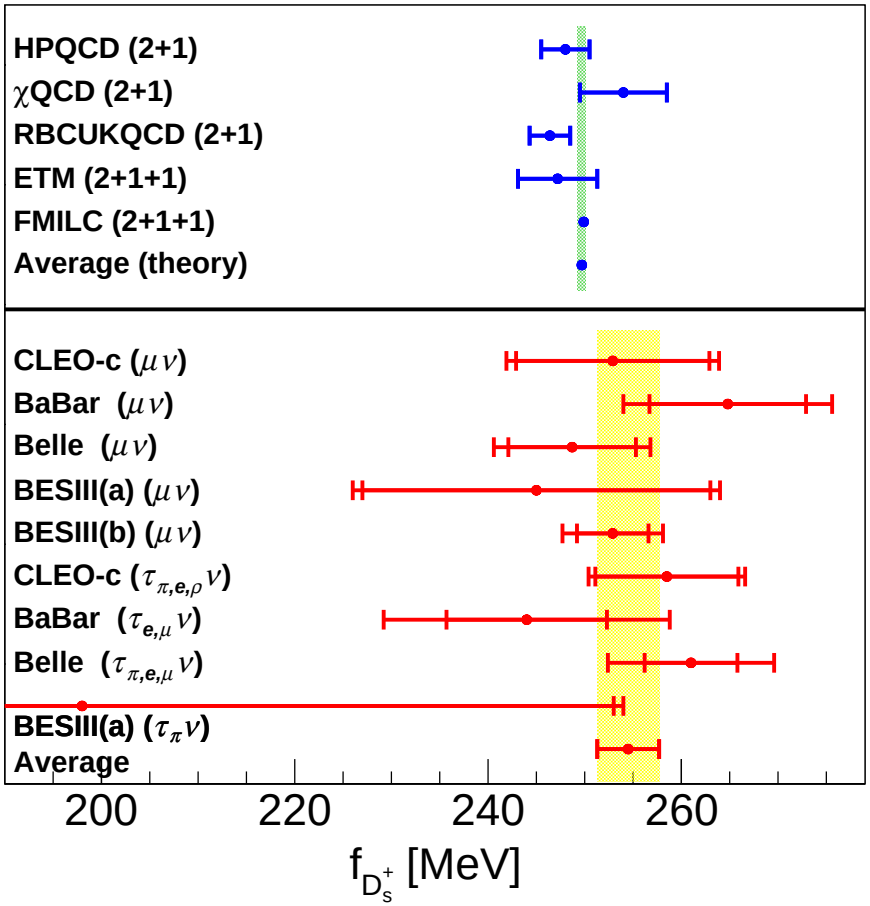
PDG2018 from CKM unitarity:

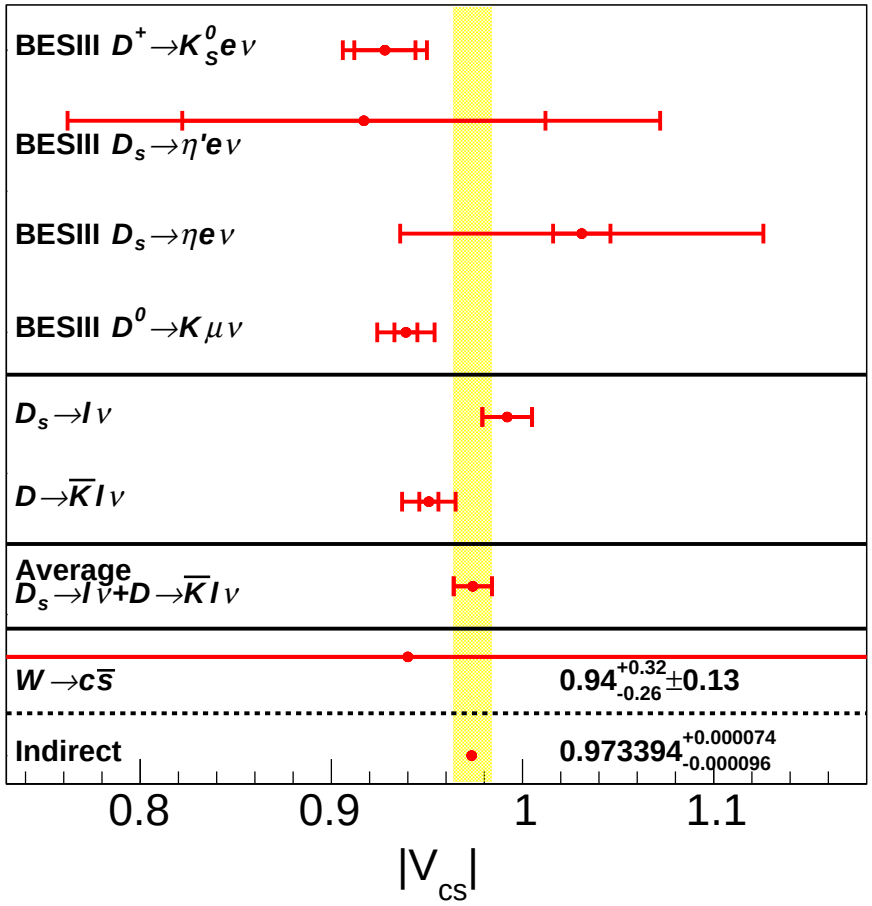
$$|V_{cs}| = 0.97359^{+0.00010}_{-0.00011}$$

LQCD average:

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

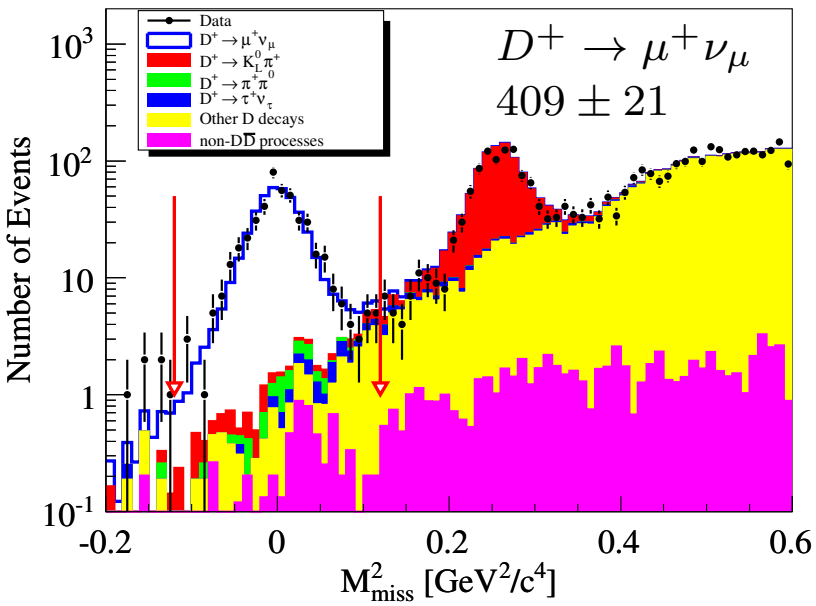
$$f_+^{D\to K}(0)^{\mathrm{LQCD}} = 0.760 \pm 0.011$$



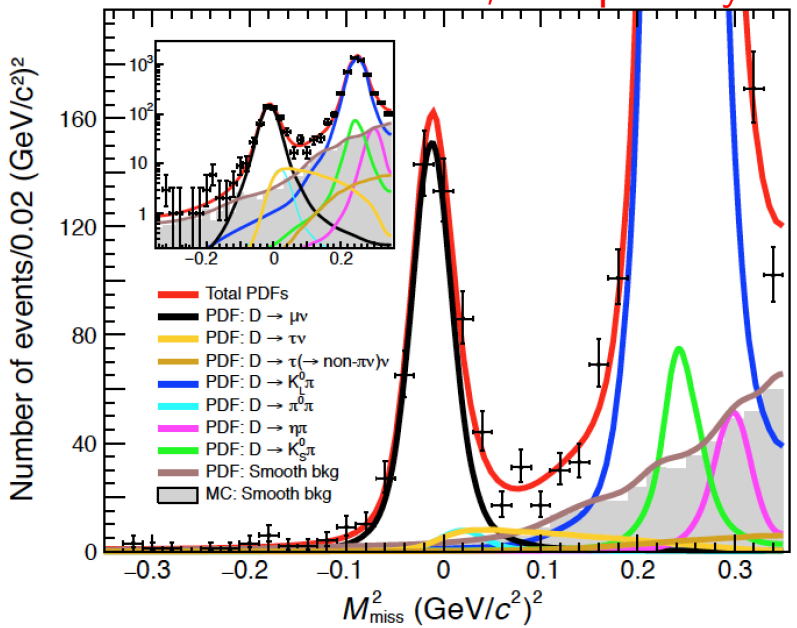


D^+ leptonic decays

BESIII PRD89(2014)051104



BESIII arXiv:1908.08877, accepted by PRL



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

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

$$\mathcal{B}(D^+ \to \tau^+\nu_\tau) = (1.20 \pm 0.24 \pm 0.12) \times 10^{-3}$$

$$f_{D^+}|V_{cd}| = 50.4 \pm 5.1 \pm 2.5 \text{ MeV}$$

First observation with 5.1σ signal significance.

$$R_{D^+} = \frac{\Gamma(D^+ \to \tau^+\nu_\tau)}{\Gamma(D^+ \to \mu^+\nu_\mu)} = 3.21 \pm 0.64 \pm 0.43$$

SM prediction 2.67 ± 0.01.

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

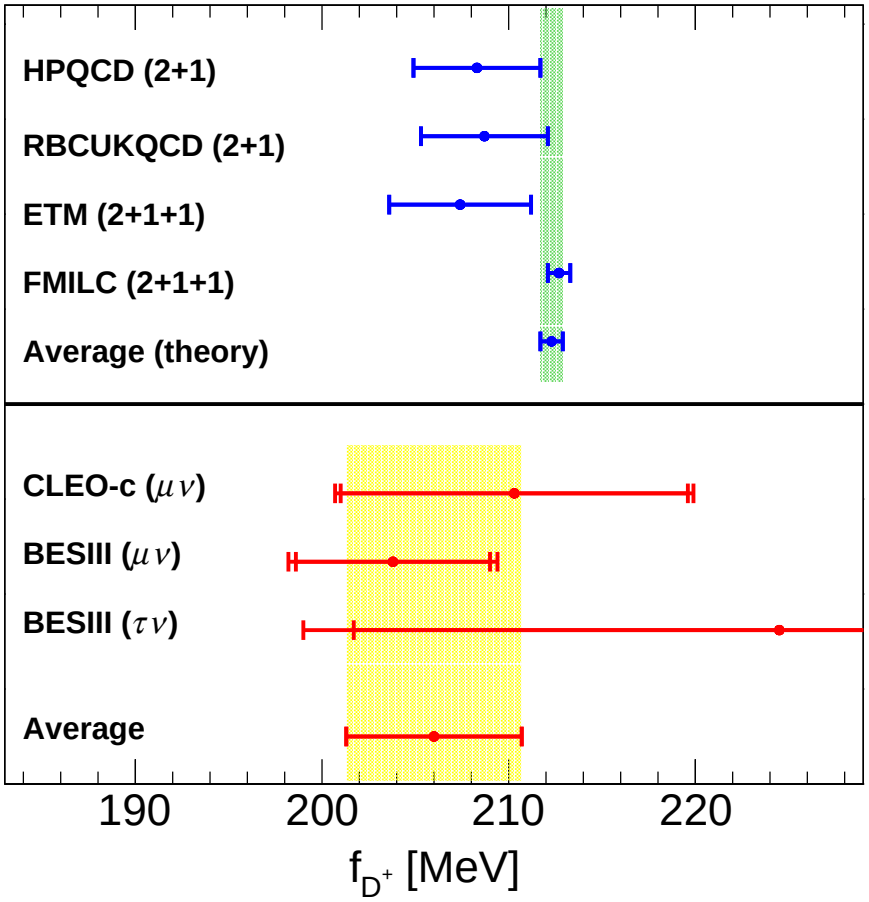
Inputs:

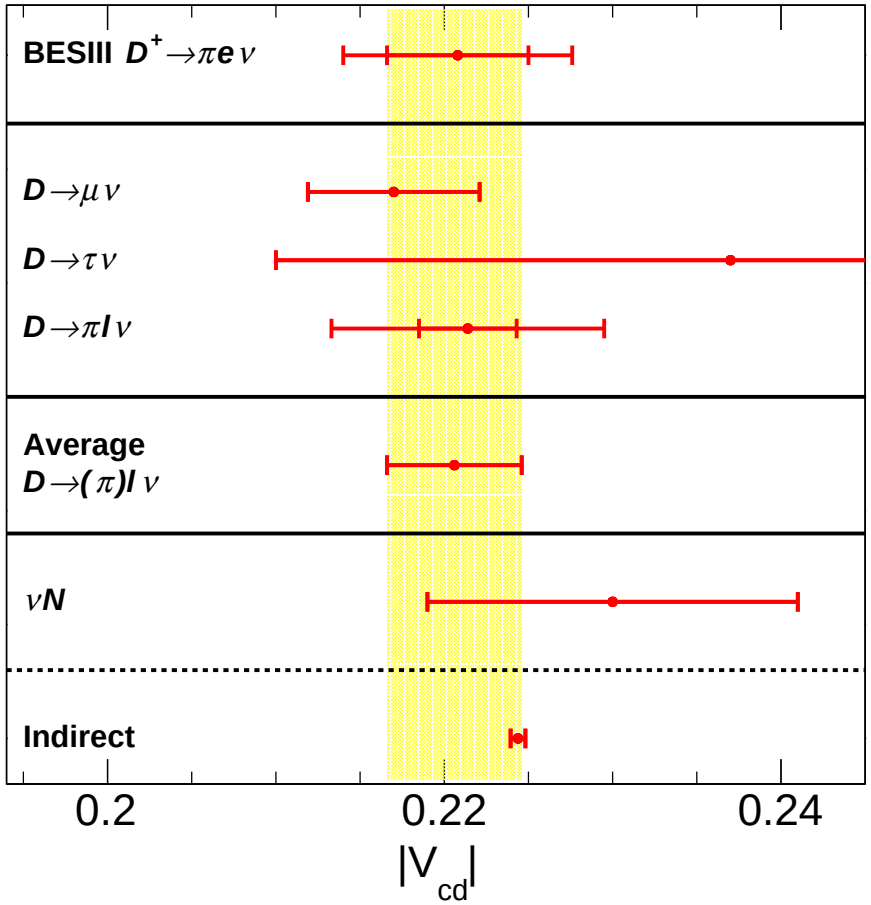
PDG2018 from CKM unitarity:

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

LQCD average:

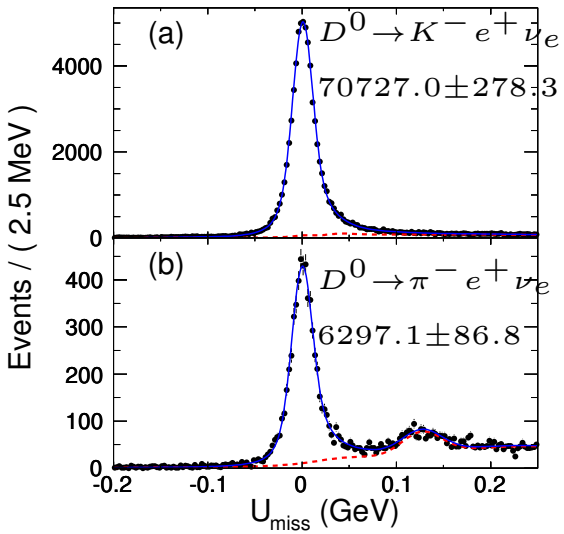
$$f_{D^+}^{\mathrm{LQCD}} = 212.3 \pm 0.6 \text{ MeV}$$
$$f_+^{D\to\pi}(0)^{\mathrm{LQCD}} = 0.634 \pm 0.015$$

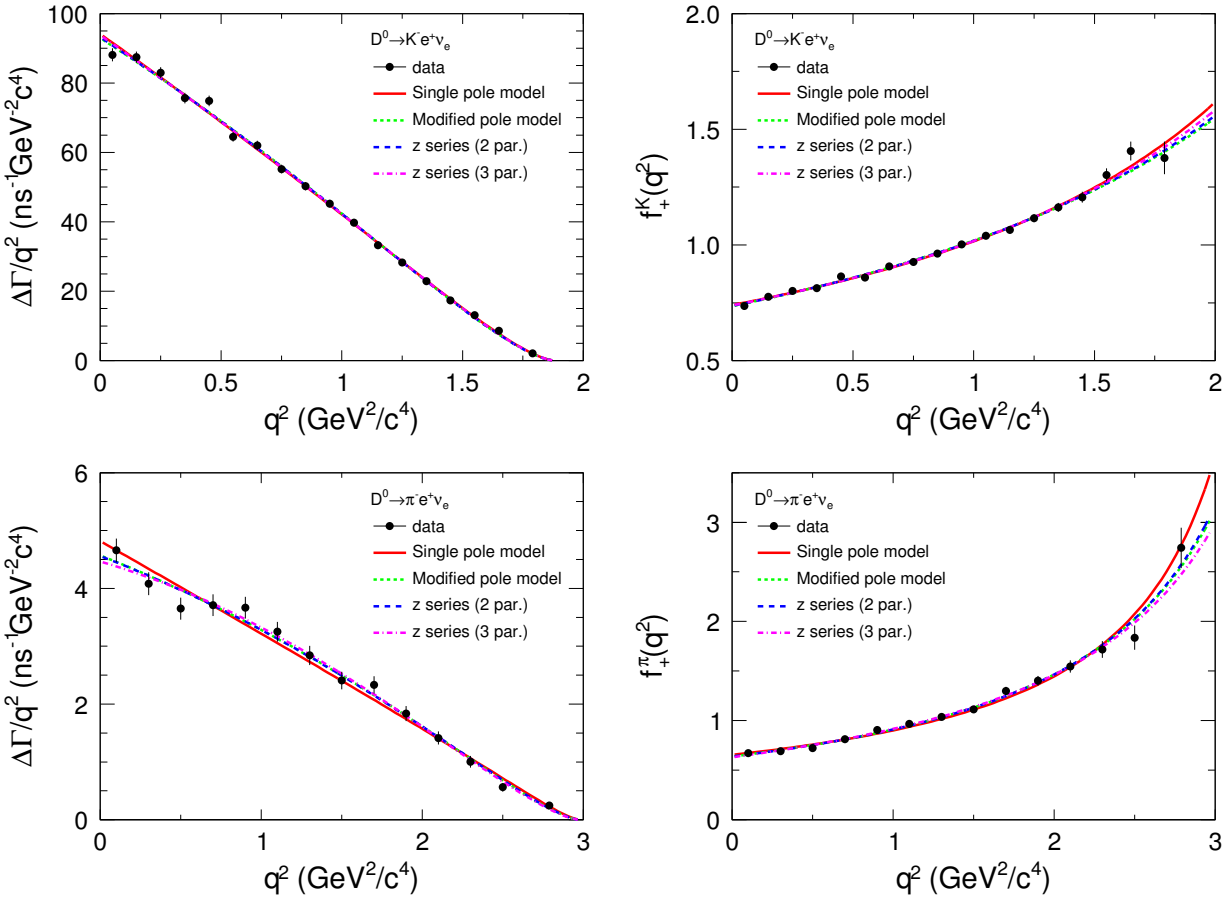




$D^0 \to K^-(\pi^-)e^+\nu_e$

BESIII PRD92(2015)072012

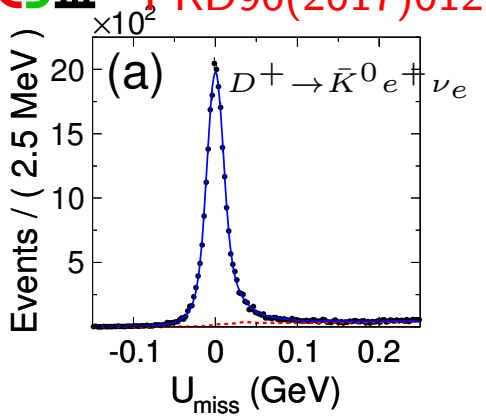


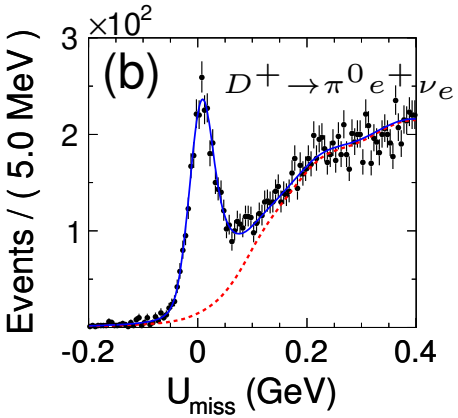


$\mathcal{B}(D^0 \to K^- e^+ \nu_e)$	$(3.505 \pm 0.014 \pm 0.033)\%$	$f_+^{D\to K}(0)\lvert V_{cs}\rvert$	$0.7172 \pm 0.0025 \pm 0.0035$
$\mathcal{B}(D^0 \to \pi^- e^+ \nu_e)$	$(0.295 \pm 0.004 \pm 0.003)\%$	$f_+^{D\to \pi}(0)\lvert V_{cd}\rvert$	$0.1435 \pm 0.0018 \pm 0.0009$

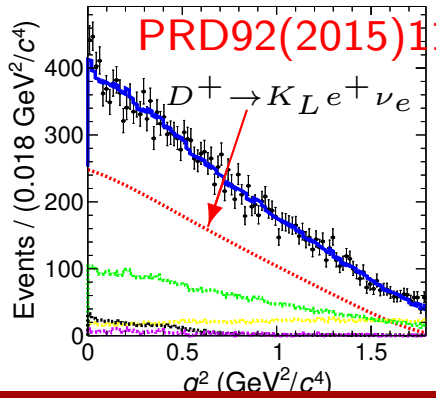
$D^+ \to \bar{K}^0(\pi^0)e^+\nu_e$

PRD96(2017)012002

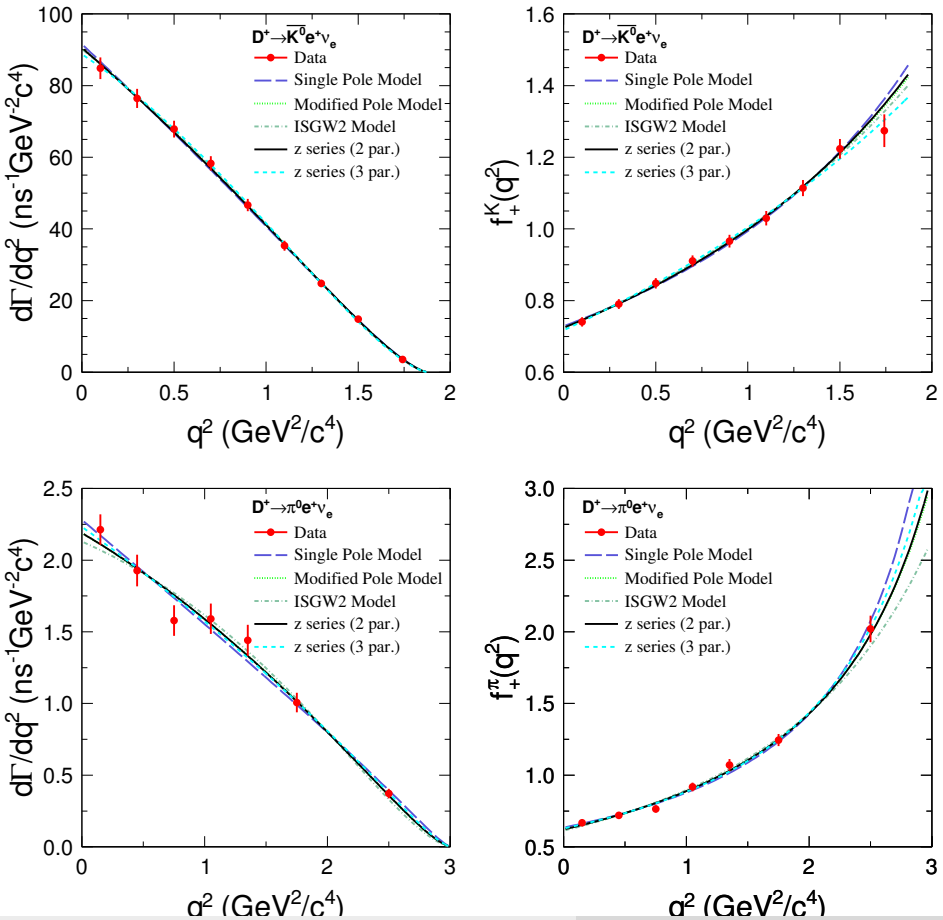




PRD92(2015)112008

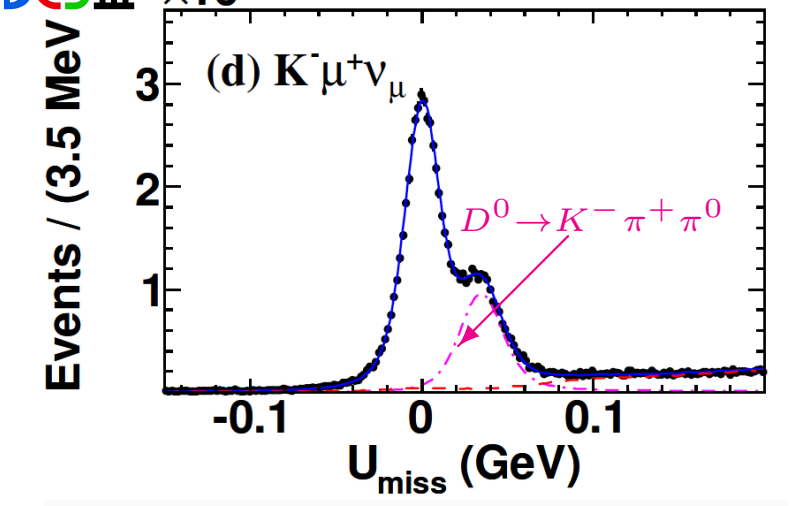


$\mathcal{B}(D^+ \to \bar{K}^0 e^+ \nu_e)$ (via K_S^0)	$(8.60 \pm 0.06 \pm 0.15)\%$
$f_+^{D\to K}(0)\lvert V_{cs}\rvert$	$0.7053 \pm 0.0040 \pm 0.0112$
$\mathcal{B}(D^+ \to \bar{\pi}^0 e^+ \nu_e)$	$(0.363 \pm 0.008 \pm 0.005)\%$
$f_+^{D\to \pi}(0)\lvert V_{cd}\rvert$	$0.1400 \pm 0.0026 \pm 0.0007$
$\mathcal{B}(D^+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

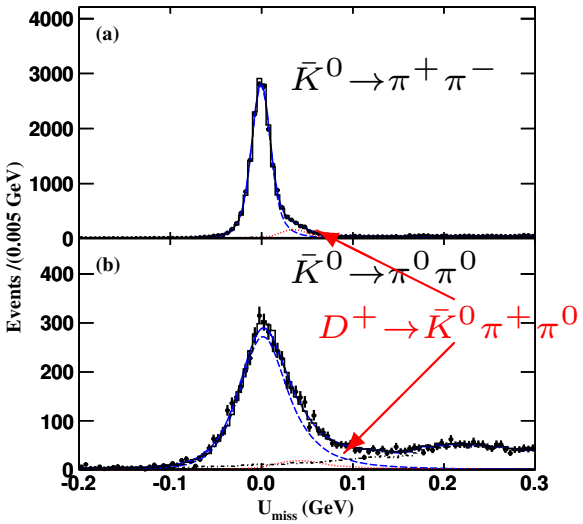


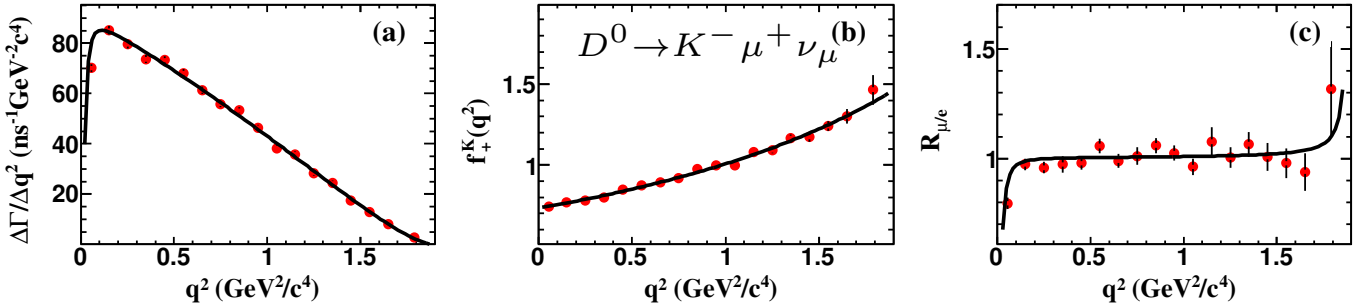
$D \to \bar{K}\mu^+\nu_\mu$

BESIII PRL122(2019)011804



BESIII EPJC76(2016)369





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

$$0.974 \pm 0.014$$

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

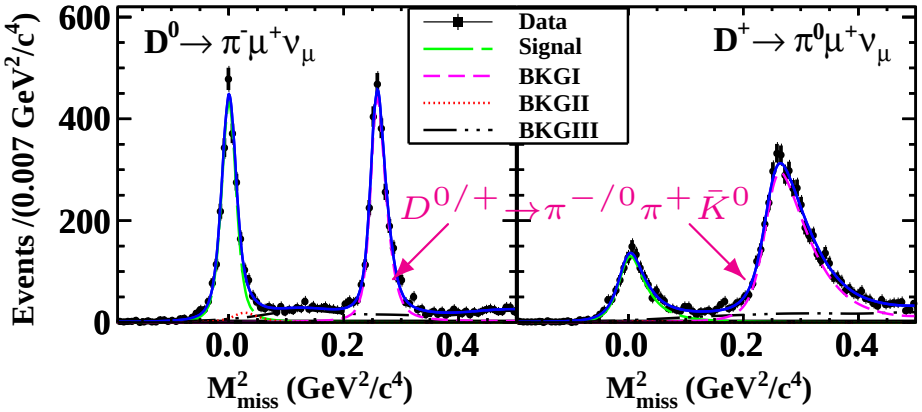
$$0.988 \pm 0.033$$

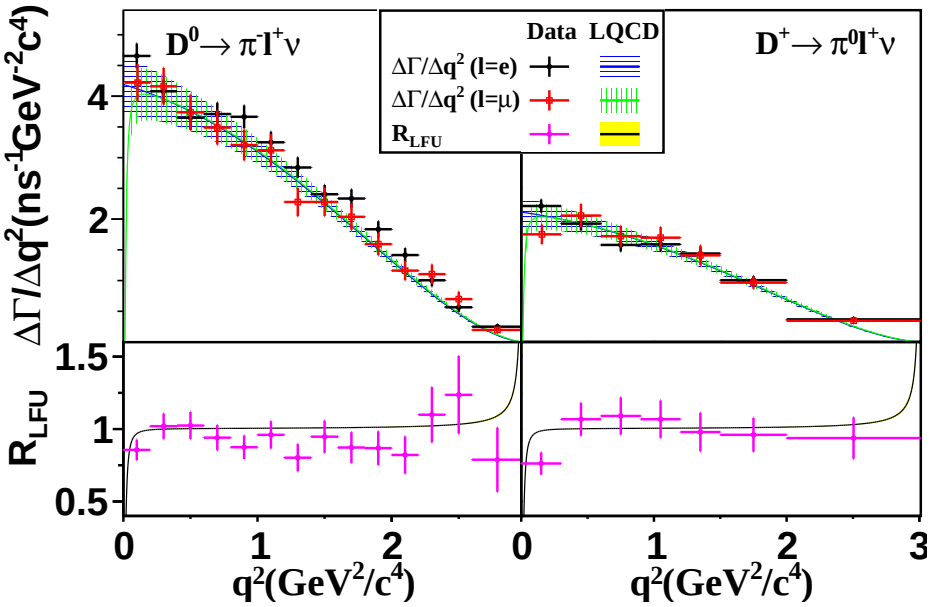
$\mathcal{B}(D^0 \to K^-\mu^+\nu_\mu)$	$(3.431 \pm 0.019 \pm 0.035)\%$
$f_+^{D\to K}(0)\lvert V_{cs}\rvert$	$0.7133 \pm 0.0038 \pm 0.0030$
$\mathcal{B}(D^+ \to \bar{K}^0\mu^+\nu_\mu)$	$(8.72 \pm 0.07 \pm 0.18)\%$

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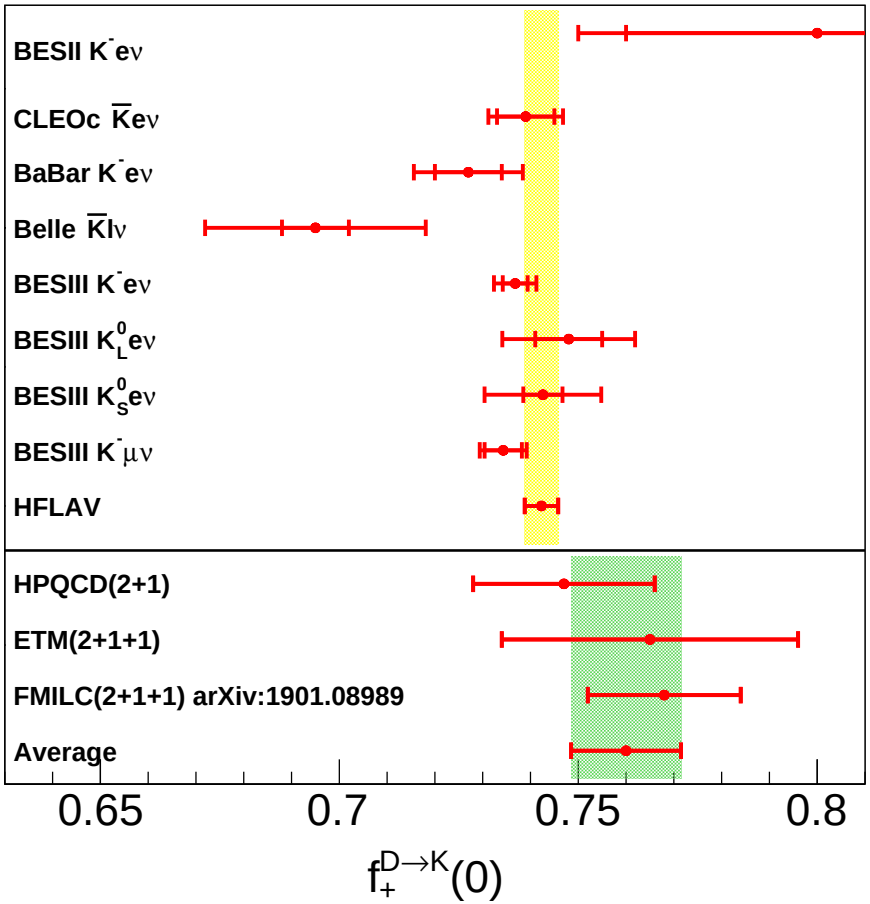
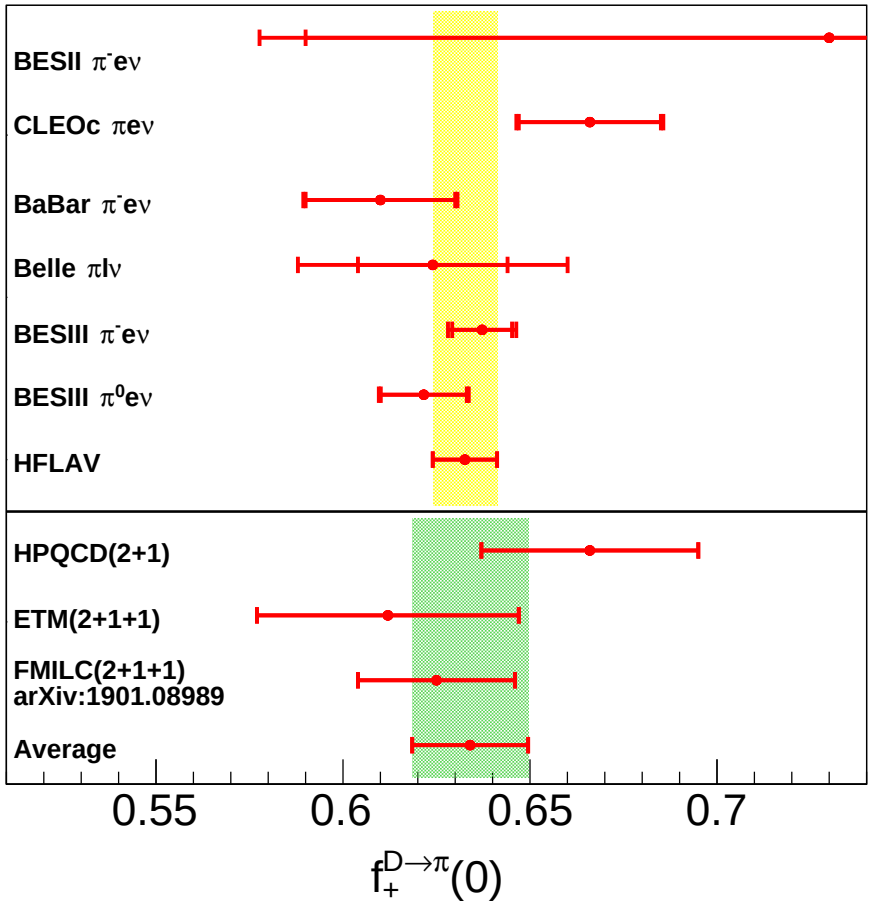
Comparison of $f_+^{D\to K}(0)$ and $f_+^{D\to\pi}(0)$

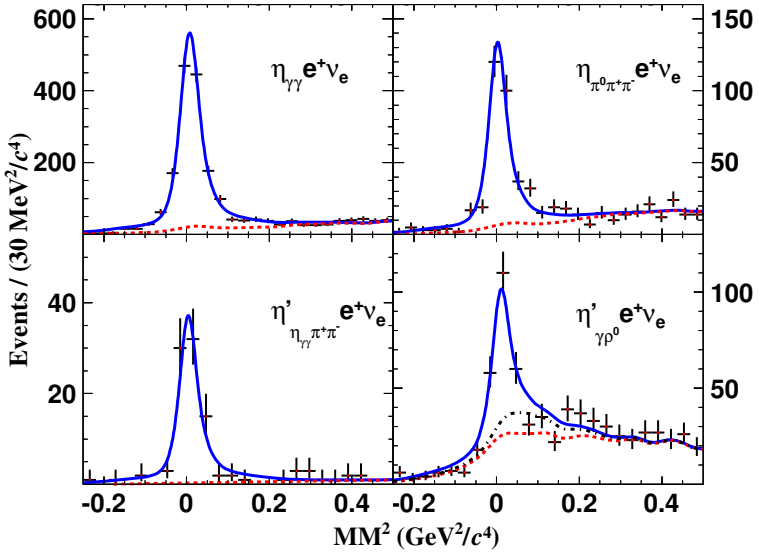
Inputs:
PDG2018 from CKM unitarity:

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

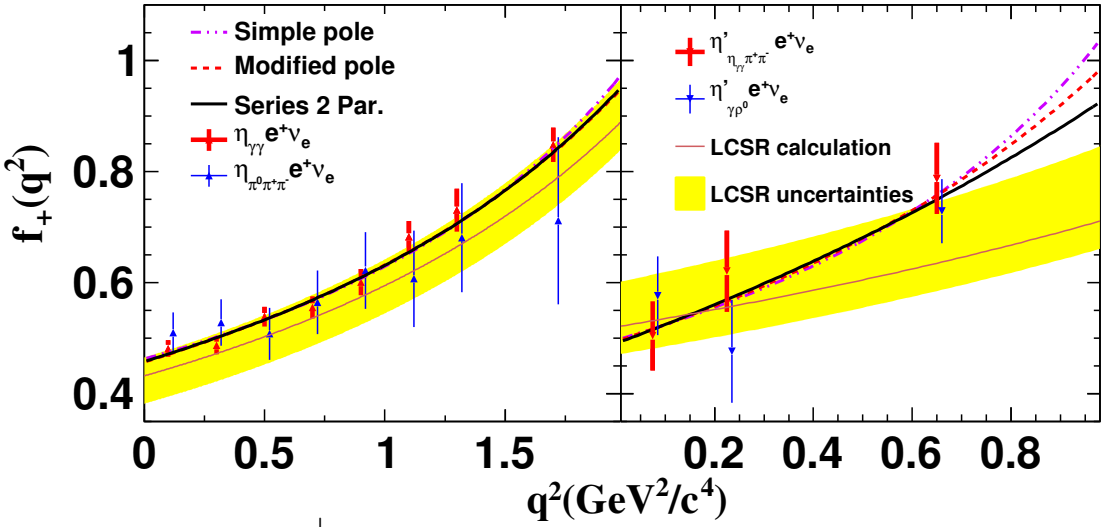




$D_s^+ \to \eta^{(\prime)} e^+ \nu_e$



BESIII PRL122(2019)121801

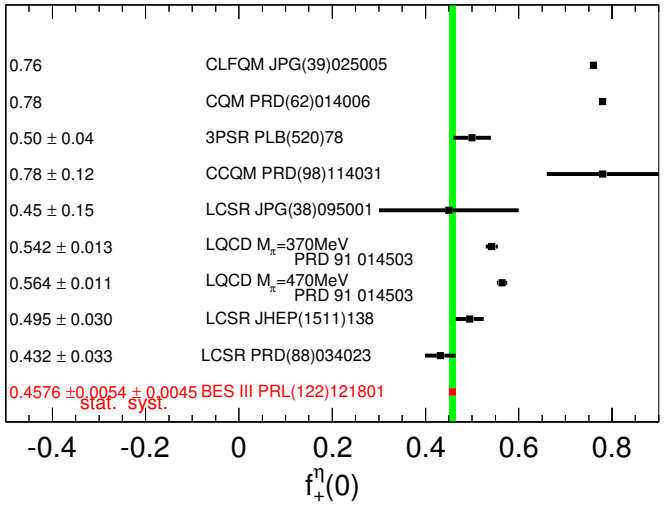


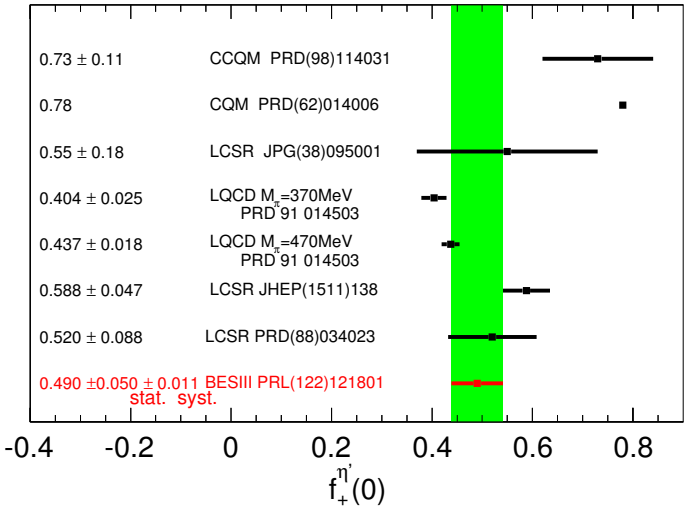
$$\mathcal{B}(D_s^+ \to \eta e^+ \nu_e) = (2.323 \pm 0.063 \pm 0.063)\%$$

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

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

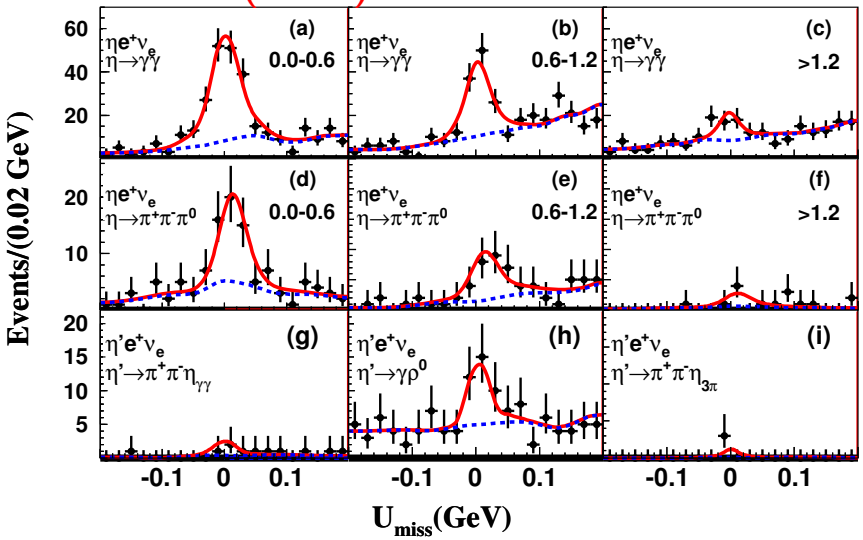
$$f_+^{D_s^+ \to \eta'}(0)|V_{cs}| = 0.477 \pm 0.049 \pm 0.011$$

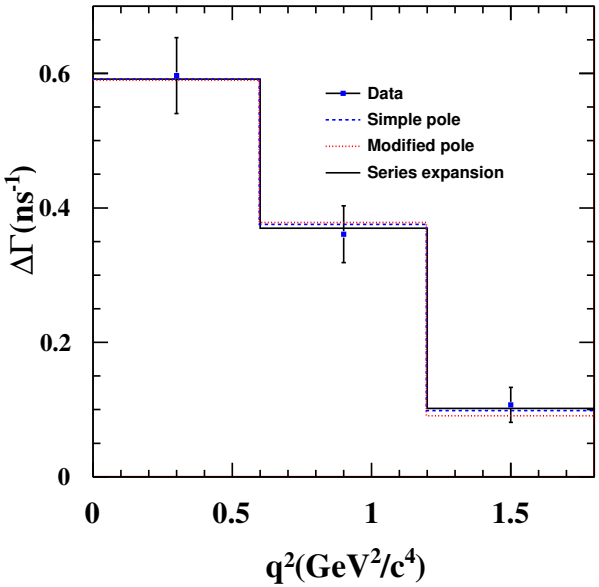




$D^+ \to \eta^{(\prime)} e^+ \nu_e$

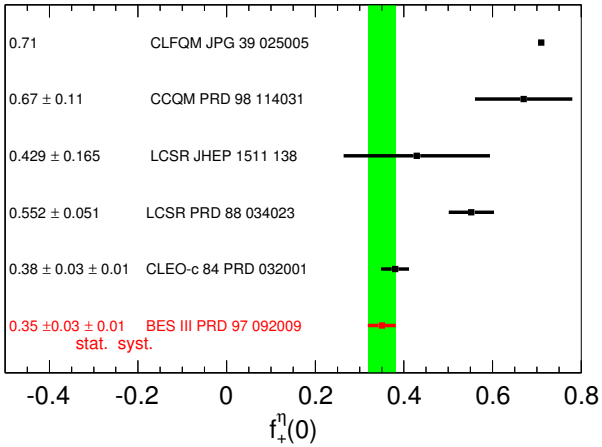
BESIII PRD97(2018)092009





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

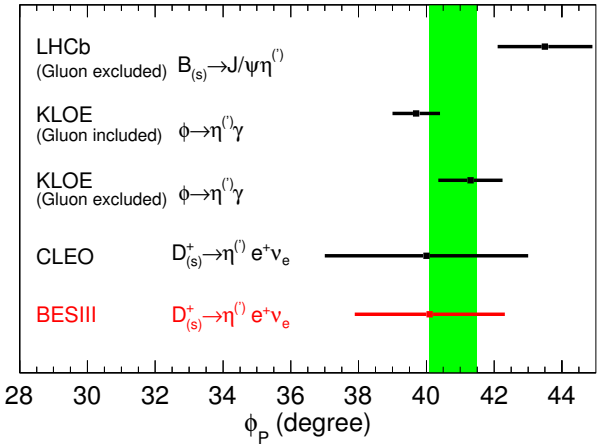
$$f_+^{D^+ \to \eta}(0)|V_{cd}| = (7.86 \pm 0.64 \pm 0.21) \times 10^{-2}$$



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

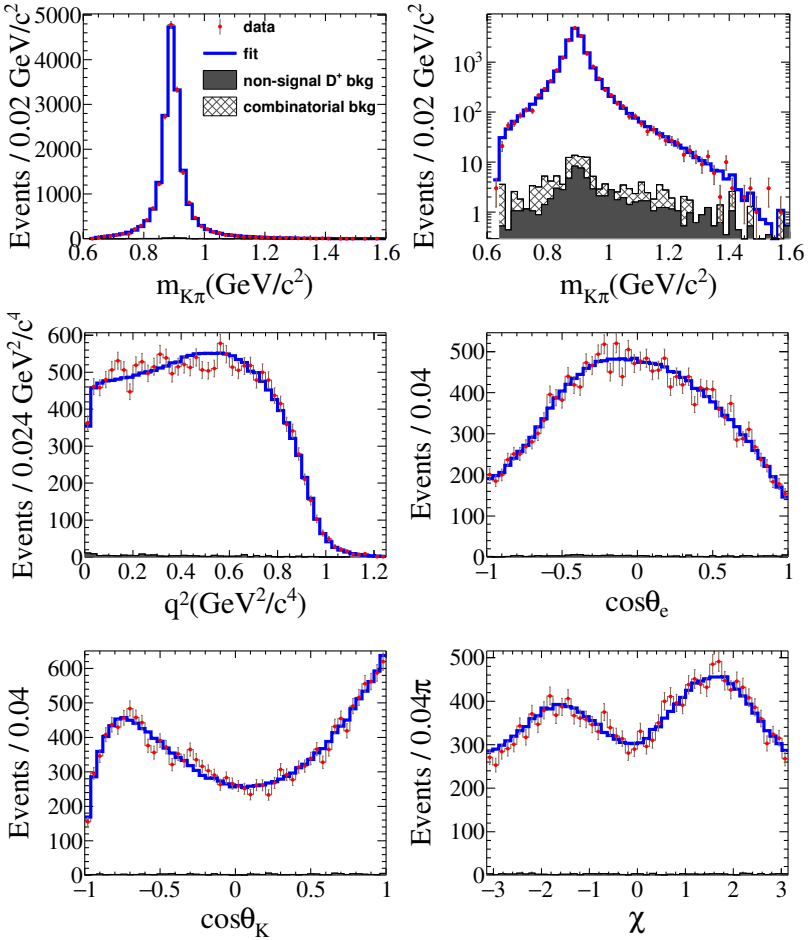
$$\frac{\Gamma(D_s^+ \to \eta' e^+ \nu_e)/\Gamma(D_s^+ \to \eta e^+ \nu_e)}{\Gamma(D^+ \to \eta' e^+ \nu_e)/\Gamma(D^+ \to \eta e^+ \nu_e)} \simeq \cot^4 \Phi_P$$

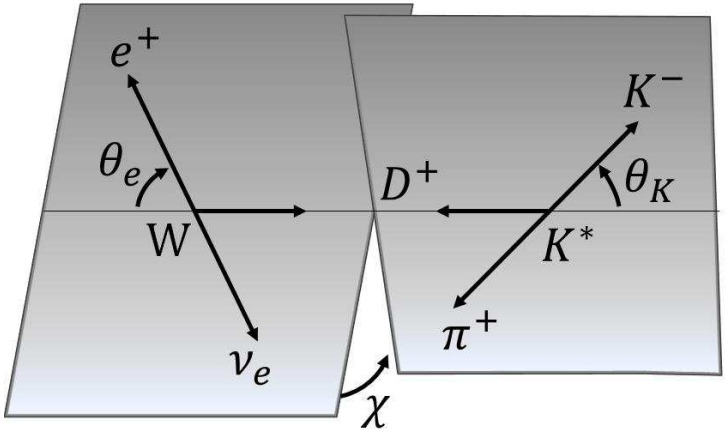
$$\Phi_P = (40.1 \pm 2.1 \pm 0.7)^\circ$$



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

BESIII PRD94(2016)032001





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

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

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

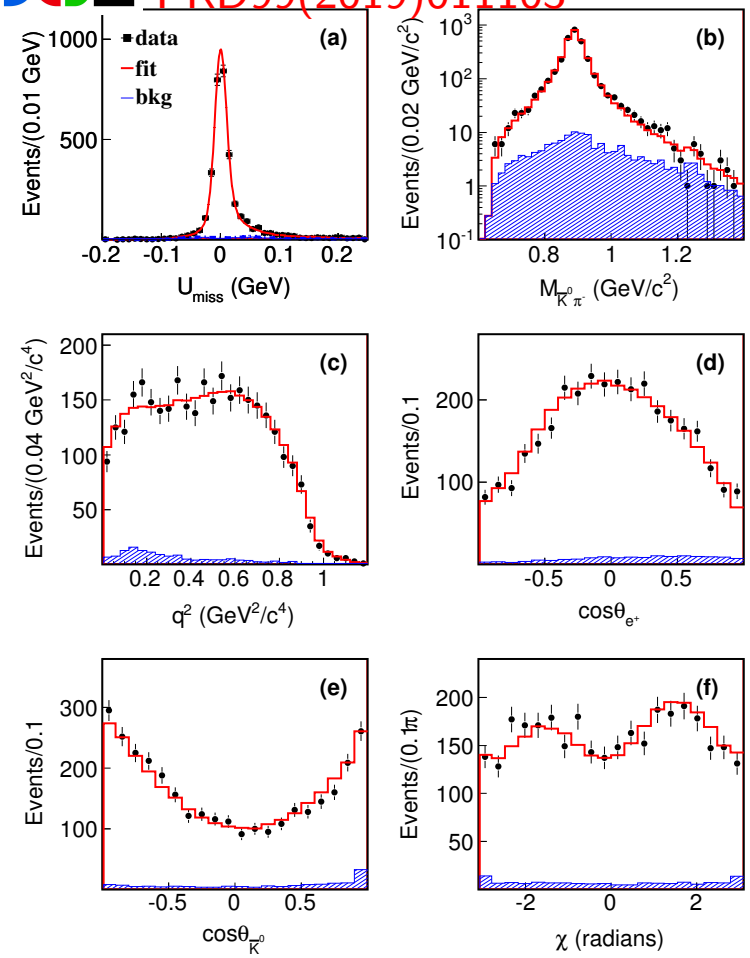
Not included in the nominal fit:

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

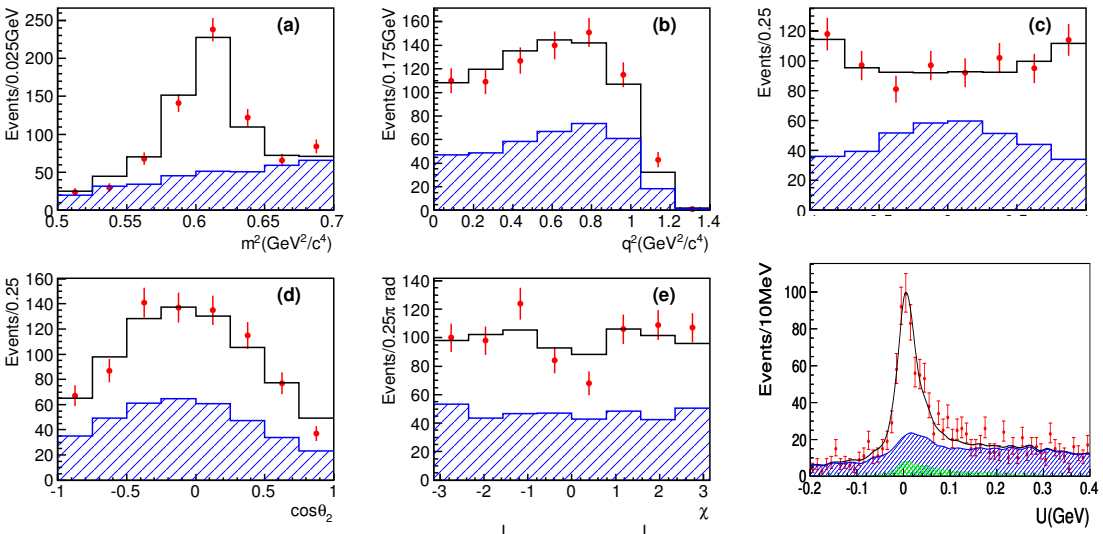
$D^0 \to \bar{K}^0\pi^-e^+\nu_e$ and $D^+ \to \omega e^+\nu_e$

BESIII PRD99(2019)011103



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

BESIII PRD92(2015)071101



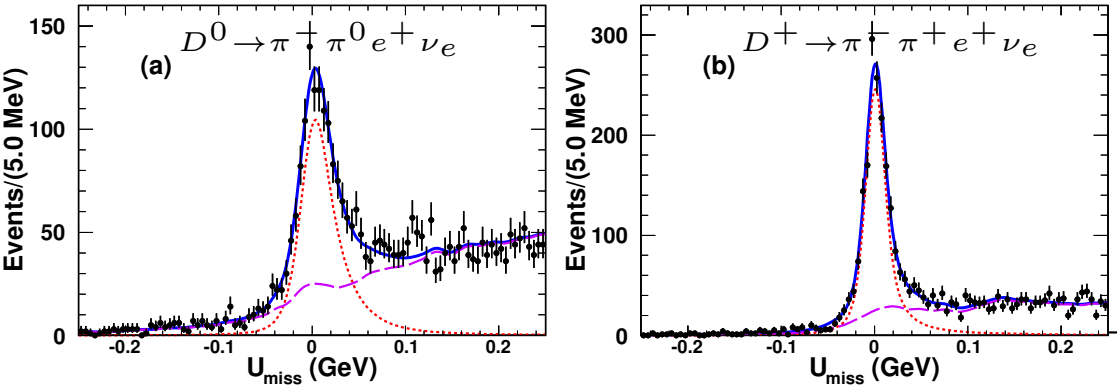
$D^+ \to \omega e^+\nu_e$

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

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

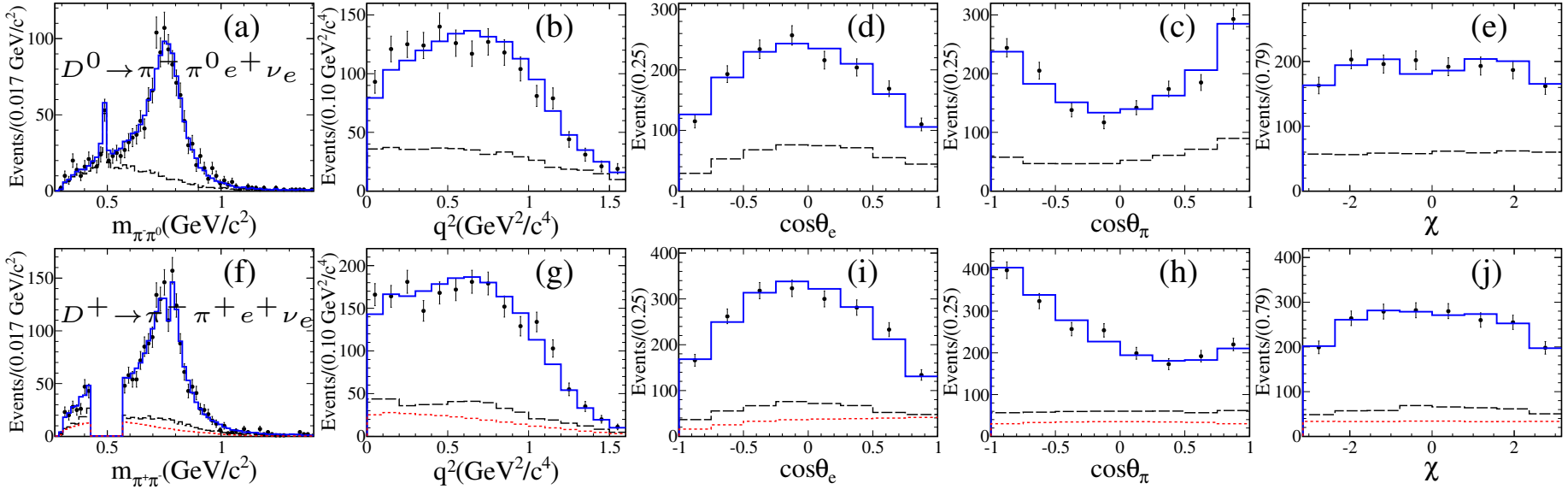
$D \to \pi\pi e^+\nu_e$

BESIII PRL122(2019)062001



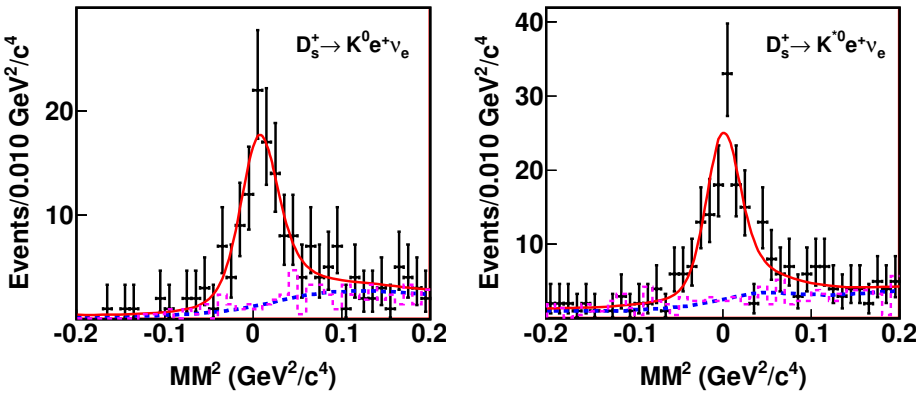
Signal mode	BF ($\times 10^{-3}$)
$D^0 \to \pi^-\pi^0 e^+\nu_e$	$1.445 \pm 0.058 \pm 0.039$
$D^0 \to \rho^- e^+\nu_e$	$1.445 \pm 0.048 \pm 0.039$
$D^+ \to \pi^-\pi^+ e^+\nu_e$	$2.449 \pm 0.074 \pm 0.073$
$D^+ \to \rho^0 e^+\nu_e$	$1.860 \pm 0.070 \pm 0.061$
$D^+ \to \omega e^+\nu_e$	$2.05 \pm 0.66 \pm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

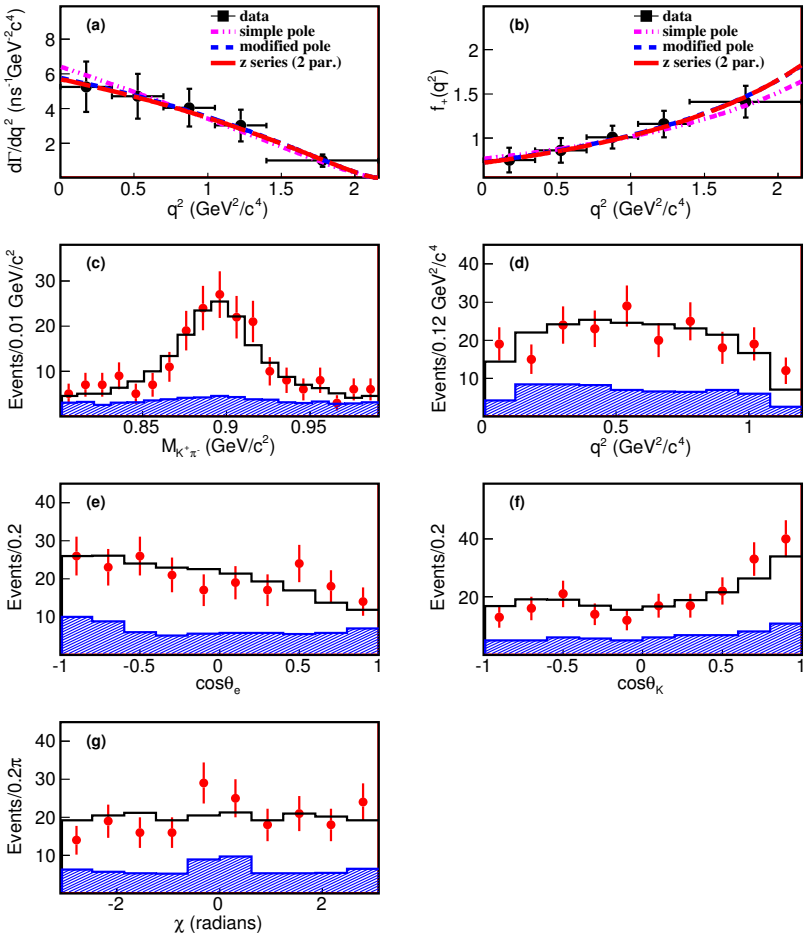
$$r_V = 1.695 \pm 0.083 \pm 0.051 \qquad r_2 = 0.845 \pm 0.056 \pm 0.039$$



$D_s^+ \to K^{(*)0} e^+ \nu_e$

BESIII PRL122(2019)061801





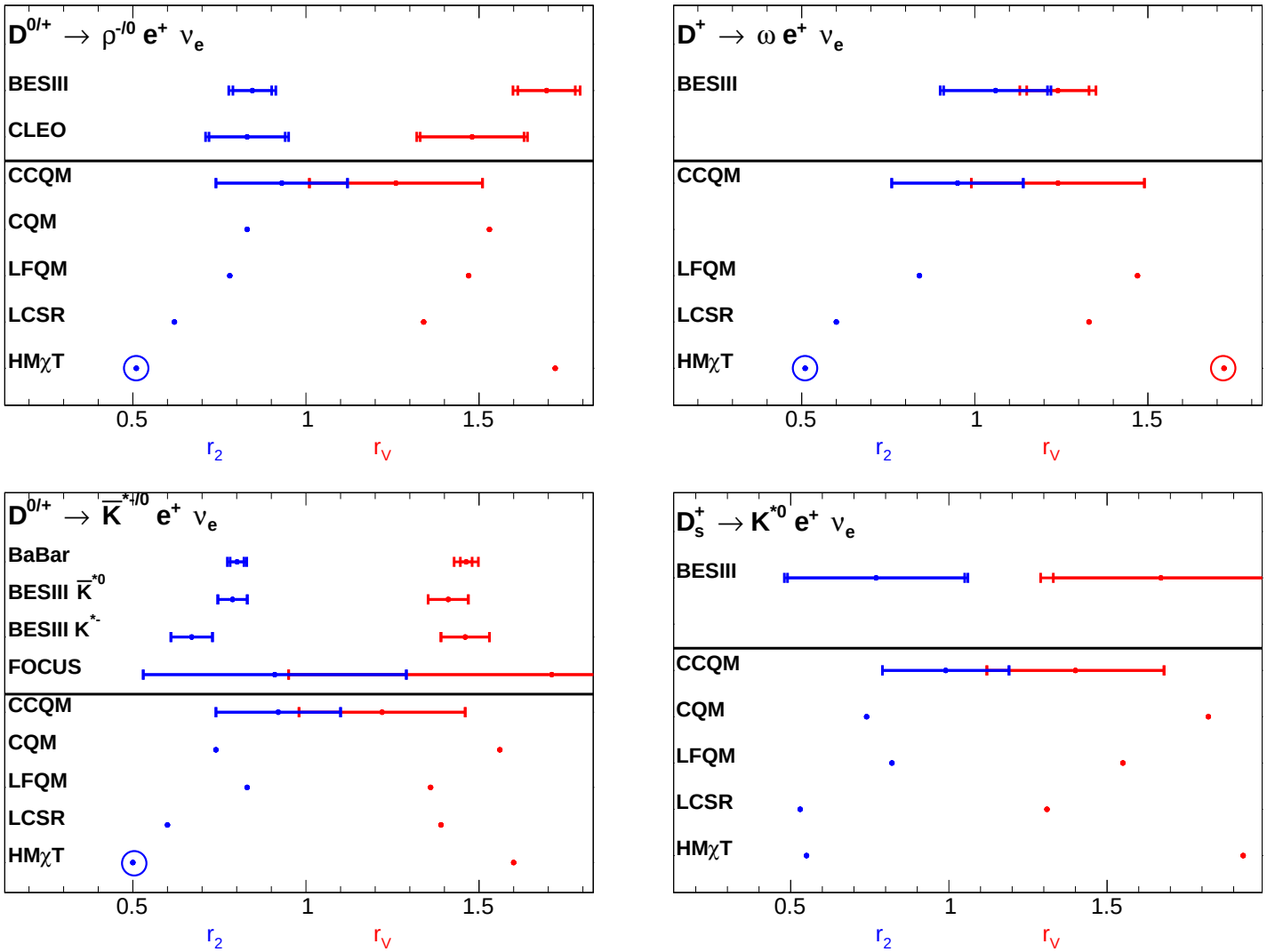
$$\mathcal{B}(D_s^+ \to K^0 e^+ \nu_e) = (3.25 \pm 0.38 \pm 0.16) \times 10^{-3}$$
$$f_+^{D_s^+ \to K^0}(0)|V_{cd}| = 0.162 \pm 0.019 \pm 0.003$$

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

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

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

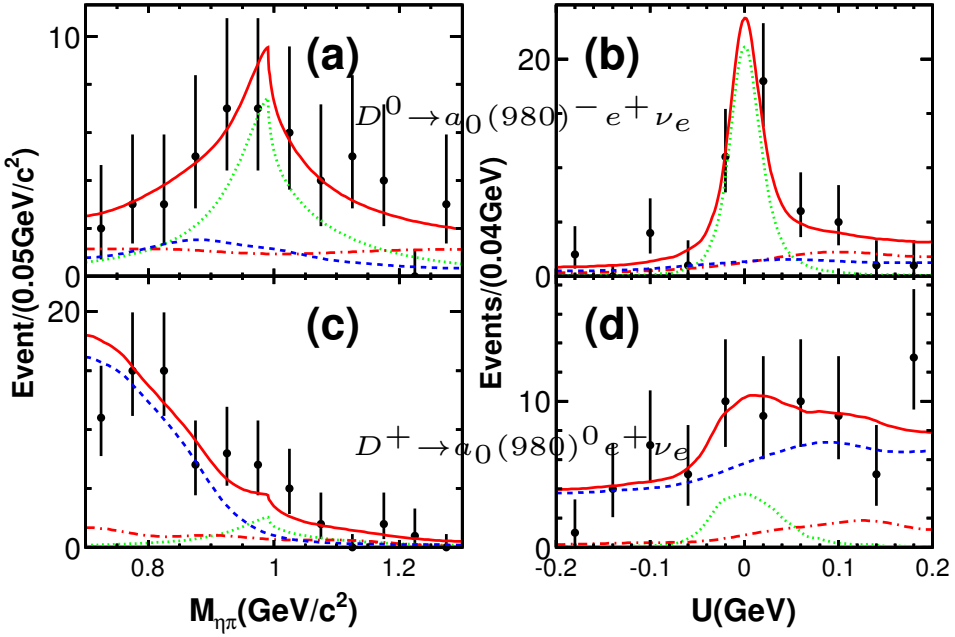
Comparison of r_V and r_2 with theoretical calculations



CCQM	arXiv:1904.07740	CQM	PRD62(2000)014006
LFQM	JPG39(2012)025005	LCSR	Int. J. Mod. Phys. A 21(2006)6125
HM$_\chi$T	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±0.3 for two-quark description;
R=3.0±0.9 for tetraquark description.

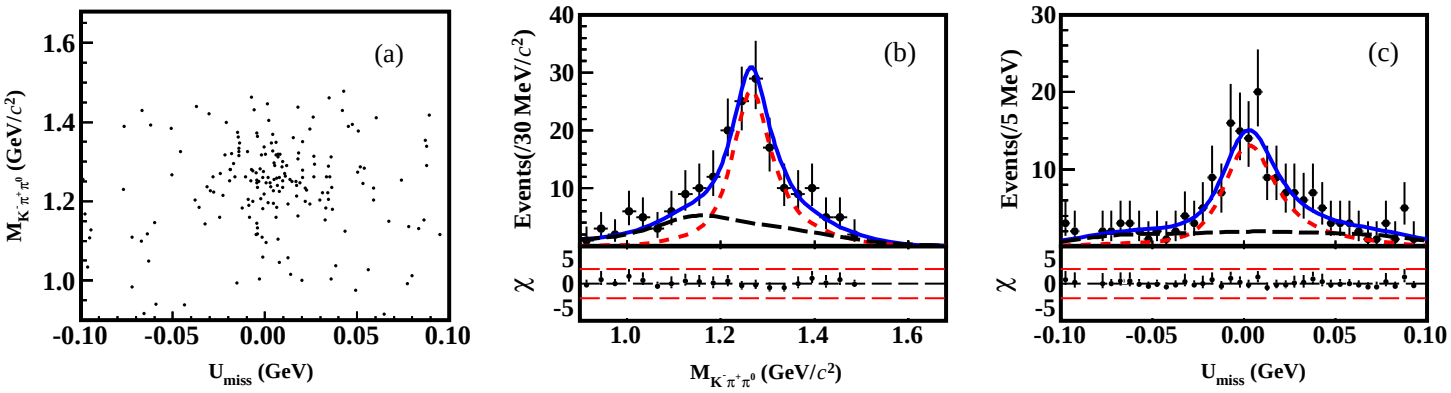
We have $R>2.7$ @90% C.L. at BESIII
Which favors the tetraquark description.

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

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

- First observation of D meson semileptonic decay into axial-vector mesons.
- Provide insight into the mixing angle of $^1P_1$ and $^3P_1$ states θ_{K_1}.
- Test various theoretical calculations.
- Provide important input to study the photon polarisation in $B \to K_1\gamma$ by measuring the ration of up-down asymmetries of θ_K and θ_l (more statistics needed). (See Dr. Zhen-Xing Zhao's talk)

BESIII arXiv:1907.11370, accepted by PRL

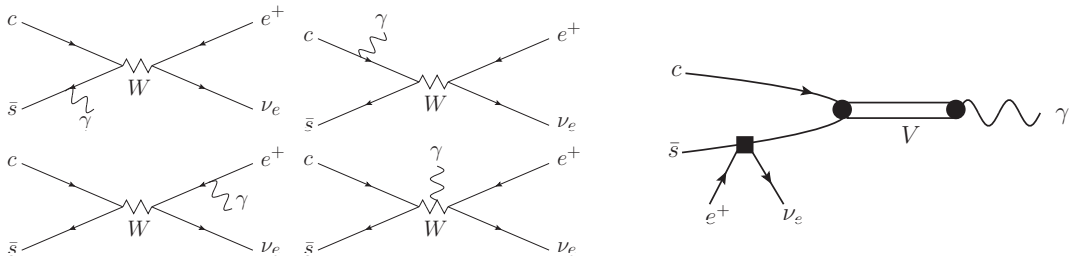


$$\mathcal{B}(D^+ \to \bar{K}_1(1270)^0 e^+ \nu_e) = (2.30 \pm 0.26 \pm 0.18 \pm 0.25) \times 10^{-3}$$

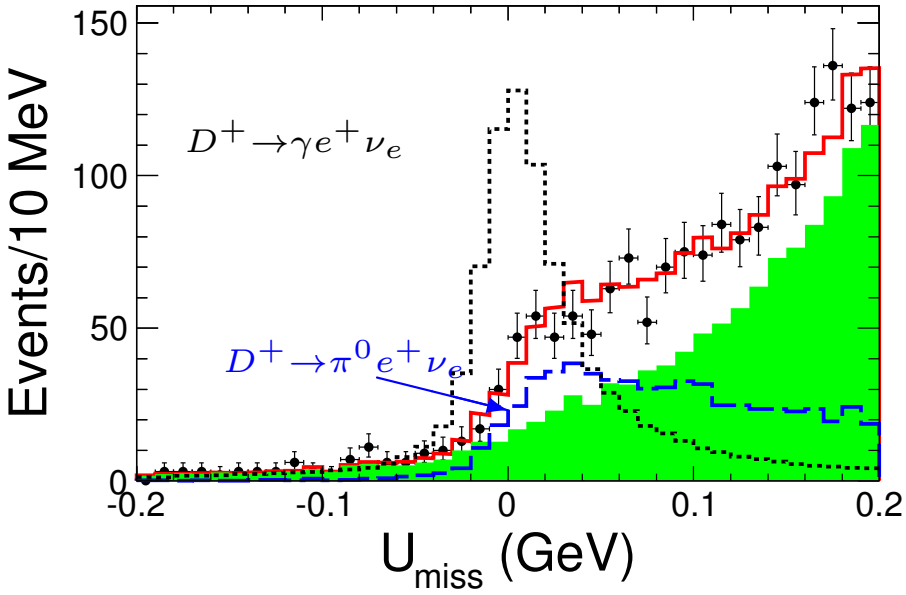
The measured BF agrees with CLFQM and LCSR predictions when $\theta_{K_1} \sim 33^\circ$ or 57° and clearly rules out the case when setting θ_{K_1} negative.

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

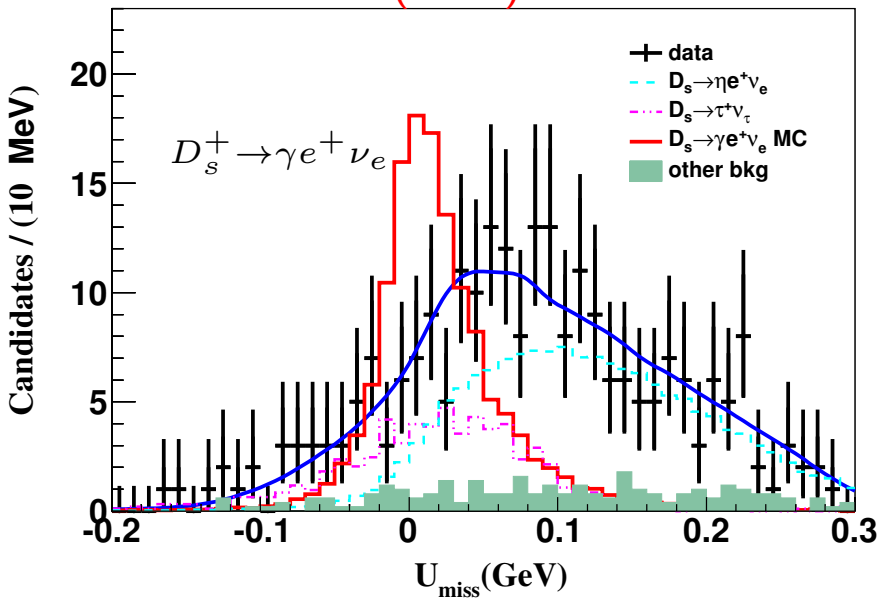
Not subject to helicity suppression.
Only photon energy larger than 10 MeV are considered.
The BFs are predicated to be $10^{-5} \to 10^{-3}$ in various models.



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.

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 CF decays and 4% for SCS decays..
- Study the nature of light scalar mesons $\rightarrow$ tetraquark description favored with BESIII's results.
- First observation of D meson semileptonic decay to axias vector meson at BESIII.

Thanks for your attention!