$|V_{cs}|$ determination and LFU test in charm decays at BESIII

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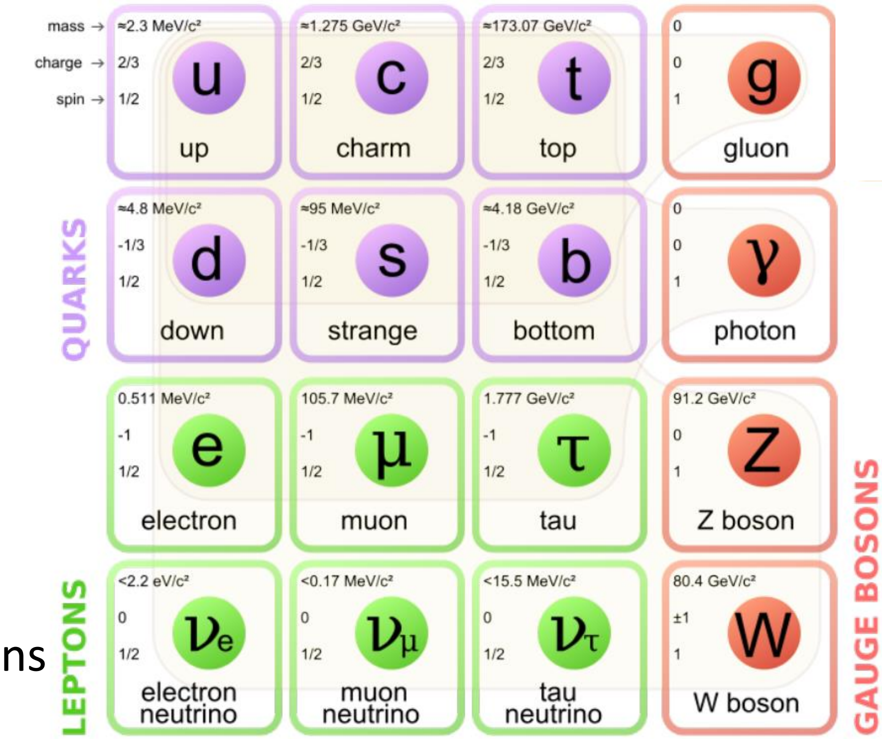
Physics motivation

- Precise measurement of CKM matrix element $|V_{cs}|$, to **test the unitarity of CKM matrix**

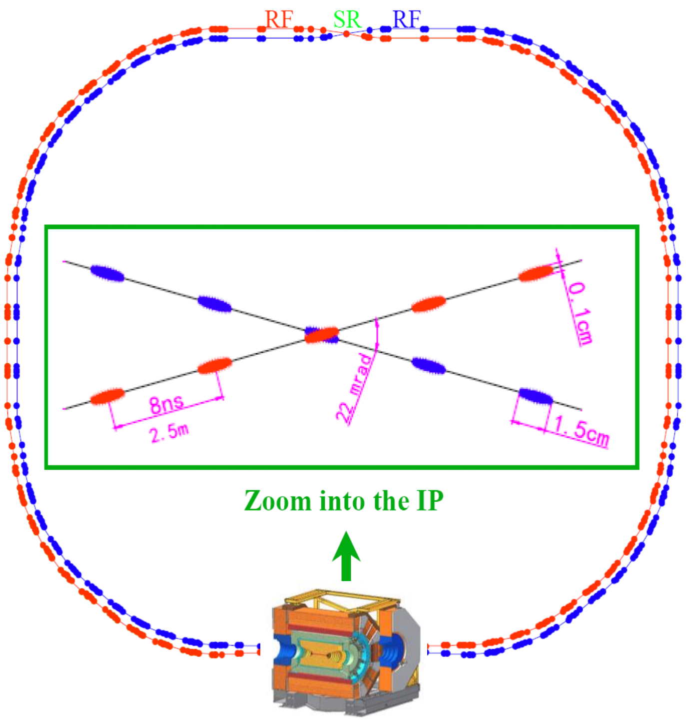
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

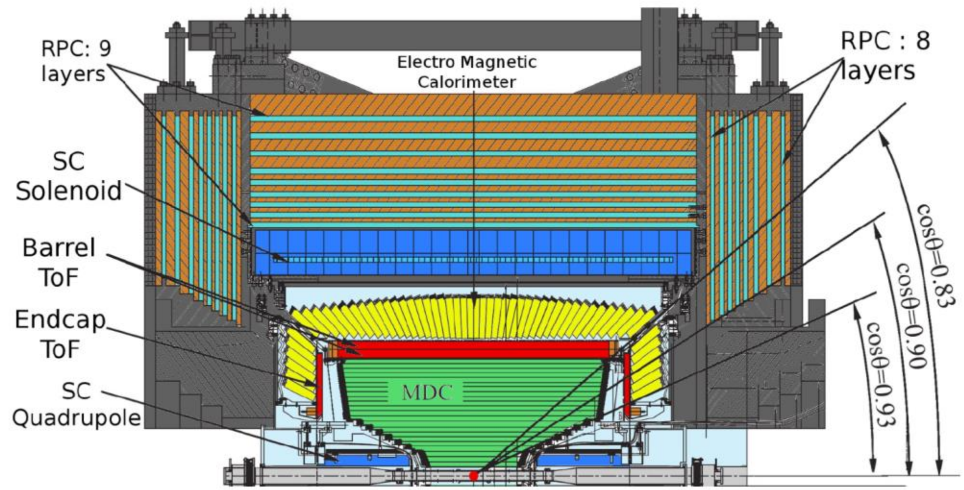
- In SM, Lepton Flavor Universality (LFU) requires equality of couplings between three families of leptons and gauge bosons



- Leptonic decays of charmed hadrons, well understood in the SM, offer an excellent opportunity to **test LFU and search for new physics effects**.

The BESIII detector at BEPCII collider





MDC
$\frac{\delta p}{p} < 0.5\%$ @1 GeV
$\frac{\delta(dE/dx)}{dE/dx} < 6\%$

TOF
δt 80 ps Barrel
δt 110 ps Endcap

EMC
$\frac{\delta E}{E} < 2.5\%$ @1 GeV
$\delta z = 0.6/\sqrt{E}$

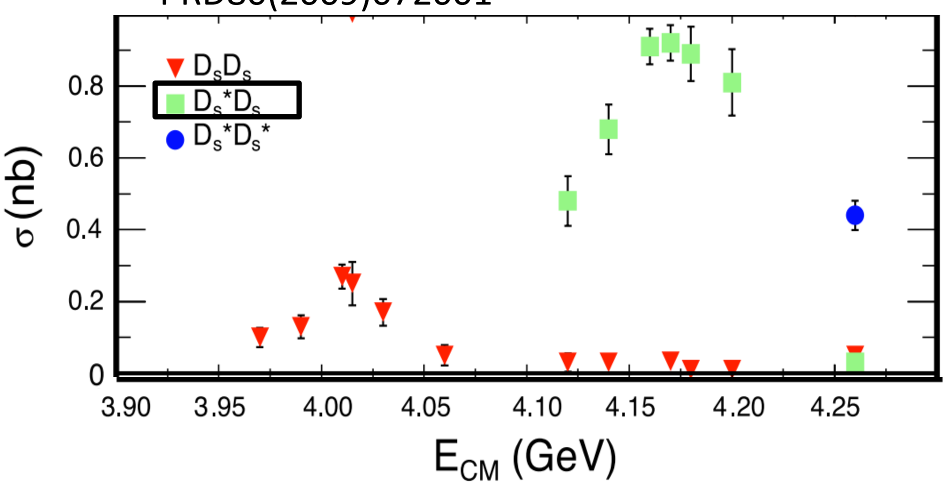
MUC
$\delta(xy)$ <2 cm

- Double-ring multi-bunch e^+e^- collider (2×93)
- Luminosity reached $1.1\text{x}10^{33}\text{cm}^{-2}\text{s}^{-1}$ (10% higher than the design value) in 2022
- Beam energy: $1.0 - 2.5$ GeV
- Circumference: 237m

Charmed hadron samples at BESIII

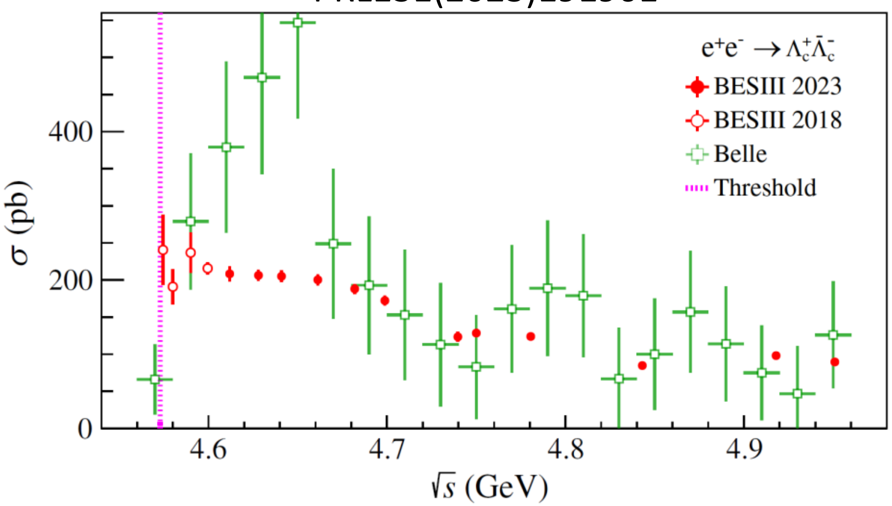
- Collected near the mass threshold of charmed hadron pairs
  - 7.9 fb^{-1} at $E_{cm} = 3.773$ GeV : $e^+e^- \to \psi(3770) \to D\bar{D}$
  - 7.3 fb^{-1} at $E_{cm} = 4.128 - 4.226$ GeV : $e^+e^- \to D_s D_s^* \to \gamma/\pi^0 D_s^+ D_s^-$
  - 4.5 fb^{-1} at $E_{cm} = 4.600 - 4.699$ GeV : $e^+e^- \to \Lambda_c^+ \bar{\Lambda}_c^-$

PRD80(2009)072001



$e^+e^- \to D_s D_s^*$

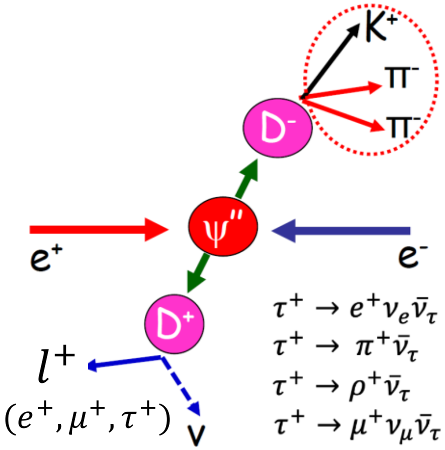
PRL131(2023)191901



$e^+e^- \to \Lambda_c^+ \bar{\Lambda}_c^-$

Determination of BF of charmed hadrons at BESIII

- **Hadronic tagging of charmed hadrons**



$$N_{\text{tag}} = 2N_{D\bar{D}}\mathcal{B}_{\text{tag}}\epsilon_{\text{tag}}$$

Charmed hadrons	$N_{\text{tag}} (\times 10^6)$
$D^0/\bar{D}^0$	7.3
$D^\pm$	4.6
$D_s^\pm$	0.8
$\Lambda_c^+/\bar{\Lambda}_c^-$	0.12

- **Features to extract the (semi-)leptonic signals**

$$N_{\text{DT}} = 2N_{D\bar{D}}\mathcal{B}_{\text{tag}}\mathcal{B}_{\text{sig}}\epsilon_{\text{DT}}$$

  - One, two or three neutrinos missing
  - $U_{miss} = E_{miss} - |\vec{p}_{miss}|$, $M_{miss}^2 = E_{miss}^2 - |\vec{p}_{miss}^{\,2}|$
  - $E_{extra\ \gamma}^{tot}$ the total energy of the good isolated EMC showers not used in tag selection

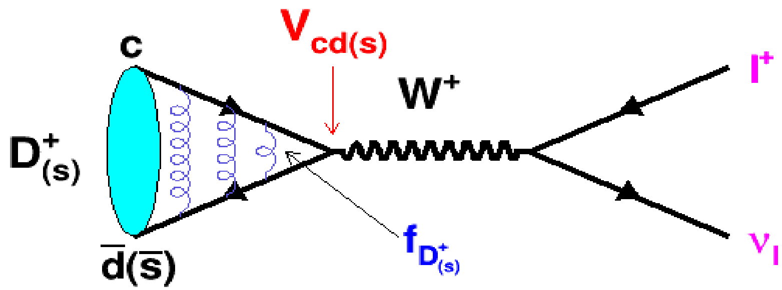
- **Branching fraction determined with the double tag method**

$$\mathcal{B}_{sig} = \frac{N_{\text{DT}}}{N_{\text{tag}}\epsilon_{\text{DT}}/\epsilon_{\text{tag}}}$$

Benefitting from the $D_{(s)}\bar{D}_{(s)}$/ $\Lambda_c^+\bar{\Lambda}_c^-$ pairs collected at the mass threshold

$|V_{cs}|$ determination

Extraction of $|V_{cs}|$ via $D_s^+ \to l^+\nu_l$



$$\Gamma(D_s^+ \to l^+\nu_l) = \frac{G_F^2}{8\pi}|V_{cs}|^2 f_{D_s^+}^2 m_l^2 m_{D_s^+}\left(1-\frac{m_l^2}{m_{D_s^+}^2}\right)^2$$

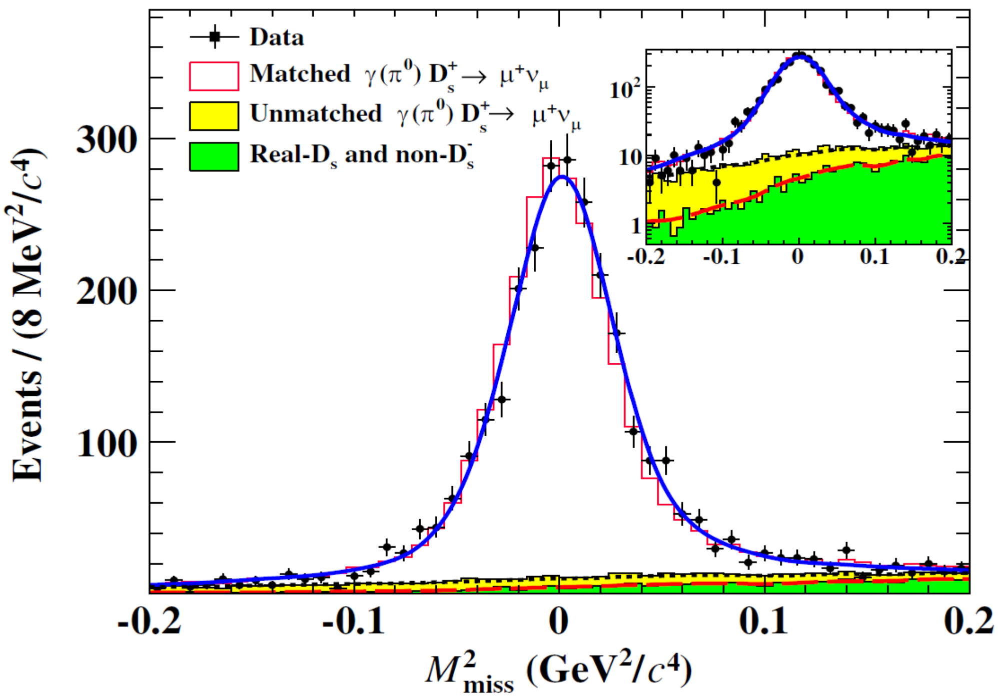
- G_F is the Fermi coupling constant
- D_s^+ decay constant $f_{D_s^+}$, describes strong interaction effects

$$\Gamma_{D_s^+\to l^+\nu_l} = \frac{\mathcal{B}(D_s^+ \to l^+\nu_l)}{\tau_{D_s}}$$

- $|V_{cs}|$ is determined by measuring $\mathcal{B}(D_s^+ \to l^+\nu_l)$ and taking $f_{D_s^+}$ from LQCD calculation as input

$D_s^+ \to \mu^+\nu_\mu$

Ref	$\mathcal{L}$ [fb^{-1}]	$\mathcal{B}$ [$\times 10^{-3}$]	$f_{D_s^+}\|V_{cs}\|$ [MeV]	Precision [%]
PRL122(2019)071802	3.2@4.18 GeV	$5.49 \pm 0.16 \pm 0.15$	$246.2 \pm 3.6 \pm 3.5$	2.1
PRD104(2021)05200	6.3@4.18-4.23GeV	$5.35 \pm 0.13 \pm 0.16$	$243.1 \pm 3.0 \pm 3.7$	2.0
PRD108(2023)112001	**7.3@4.13-4.23GeV**	$\mathbf{5.29 \pm 0.11 \pm 0.09}$	$\mathbf{241.8 \pm 2.5 \pm 2.2}$	**1.4**

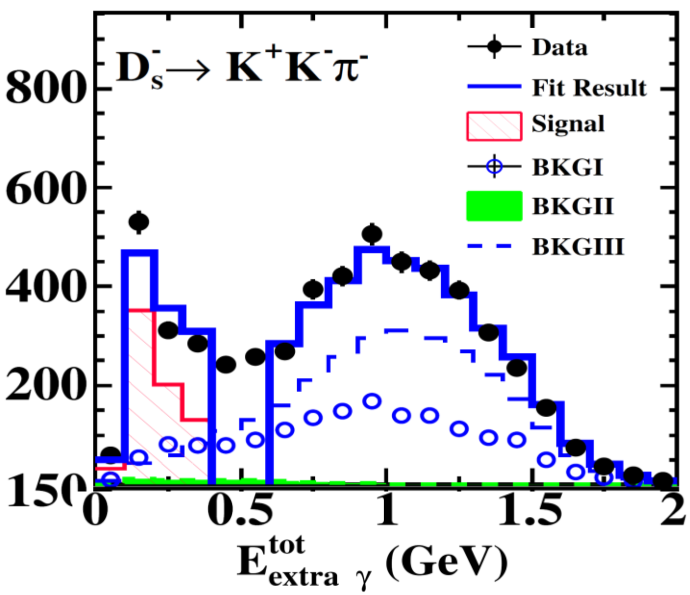


The most precise $\mathcal{B}(D_s^+ \to \mu^+\nu_\mu)$ to date

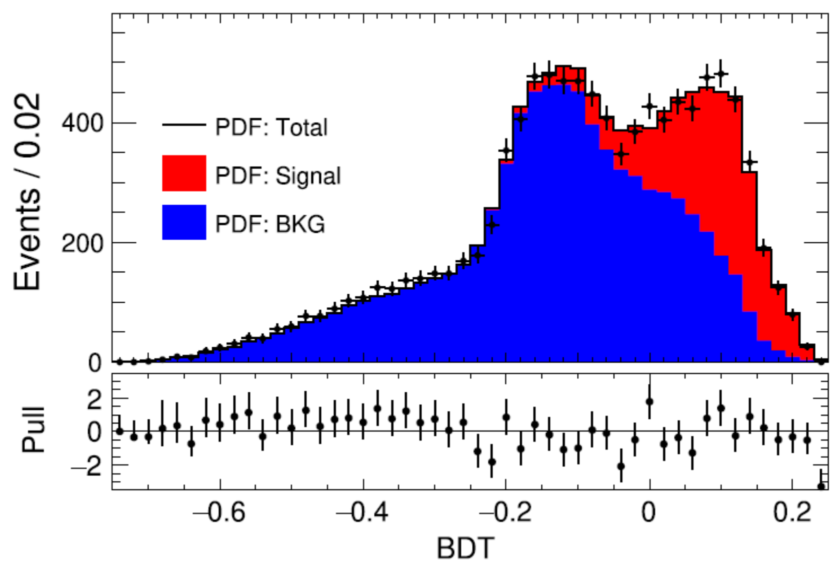
$D_s^+ \to \tau^+\nu_\tau$

Ref	τ^+ channel	$\mathcal{B}\ [\times 10^{-2}]$	$f_{D_s^+}\lvert V_{cs}\rvert$ [MeV]	Precision [%]
PRD104(2021)032001	$\rho^+\nu$	$5.29 \pm 0.25 \pm 0.20$	$244.8 \pm 5.8 \pm 4.8$	3.1
PRD104(2021)052009	$\pi^+\nu$	$5.21 \pm 0.25 \pm 0.17$	$243.0 \pm 5.8 \pm 4.0$	2.9
PRL127(2021)171801	$e^+\nu\nu$	$5.27 \pm 0.10 \pm 0.12$	$244.4 \pm 2.3 \pm 2.9$	1.5
JHEP09(2023)124	$\mu^+\nu\nu$	$\mathbf{5.37 \pm 0.17 \pm 0.15}$	$246.7 \pm 3.9 \pm 3.6$	**2.2**
PRD108(2023)092014	$\pi^+\nu$	$\mathbf{5.44 \pm 0.17 \pm 0.13}$	$248.3 \pm 3.9 \pm 3.2$	**2.0**

$D_s^+ \to \tau^+(\mu^+\nu\nu)\nu$

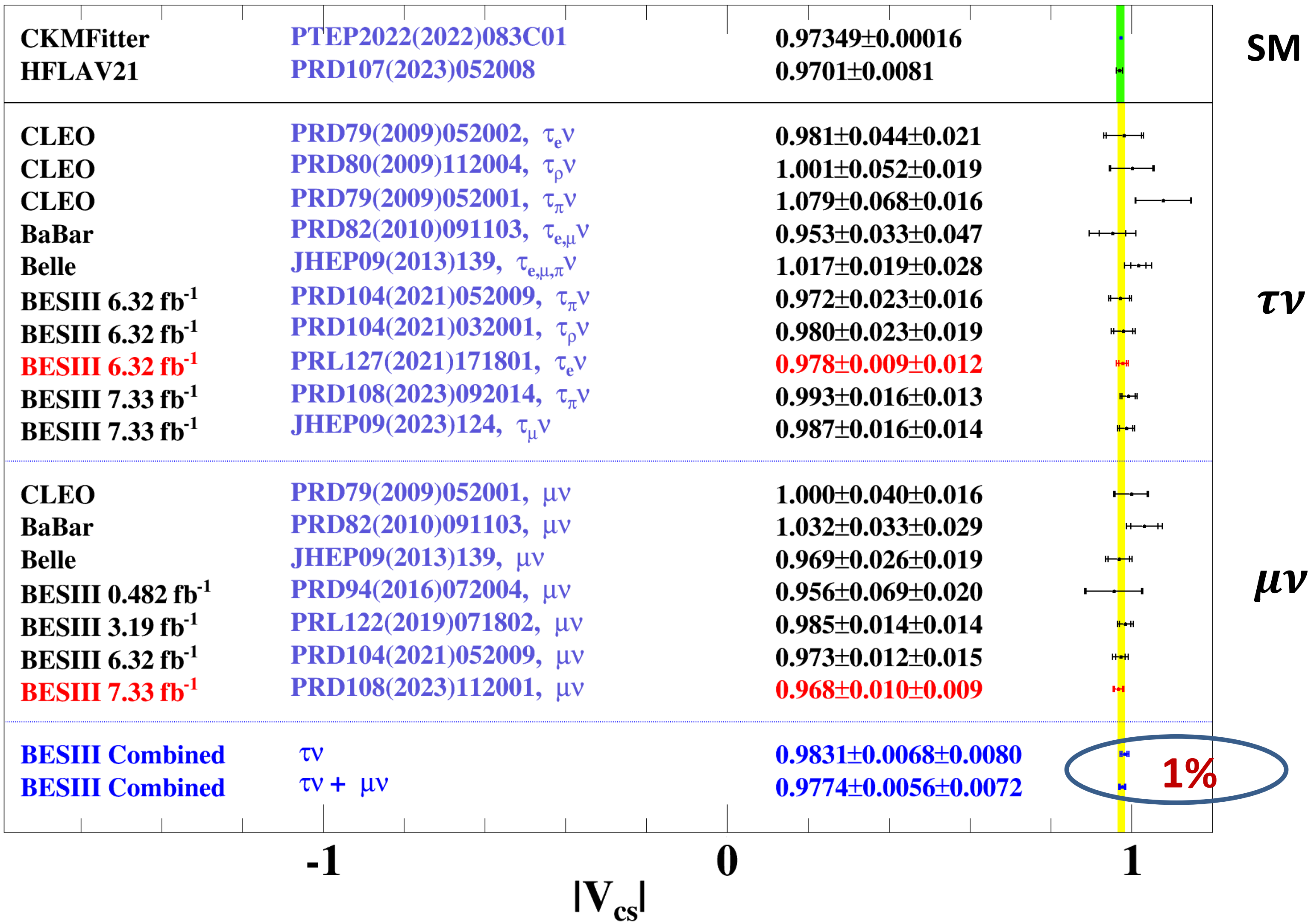


$D_s^+ \to \tau^+(\pi^+\nu)\nu$



$|V_{cs}|$ determined via $D_s^+ \to l^+\nu_l$

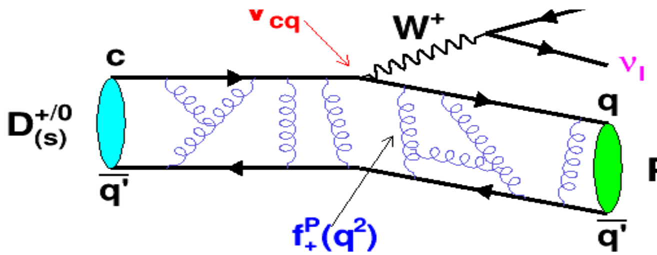
Combining measured $|V_{cs}| f_{D_s^+}$ with $f_{D_s^+}$ calculated by LQCD



Extraction of $|V_{cs}|$ via $D^{+/0}_{(s)} \to P l^+ \nu_l$

$$\frac{d\Gamma}{dq^2} = \frac{G_F^2|V_{cs}|^2}{24\pi^3}\frac{(q^2-m_l^2)^2|\overrightarrow{p}|}{q^4 m^2_{D^{+/0}_{(s)}}}[(1+\frac{m_l^2}{2q^2})m^2_{D^{+/0}_{(s)}}|\overrightarrow{p}|^2 f_+(q^2)|^2 + \frac{3m_l^2}{8q^2}(m^2_{D^{+/0}_{(s)}} - m_P^2)^2|f_0(q^2)|^2]$$

If $l^+ = e^+$ $\quad \frac{d\Gamma}{dq^2} = \frac{G_F^2}{24\pi^3}|V_{cs}|^2|f_+(q^2)|^2|\overrightarrow{p}|^3$



- Hadronic form factor(FF) $f_{+,0}$ depends on q^2, the square of the four-momentum transfer from $D^{+/0}_{(s)}$ to P , can be calculated in LQCD
- **The most general parametrization of FF:**

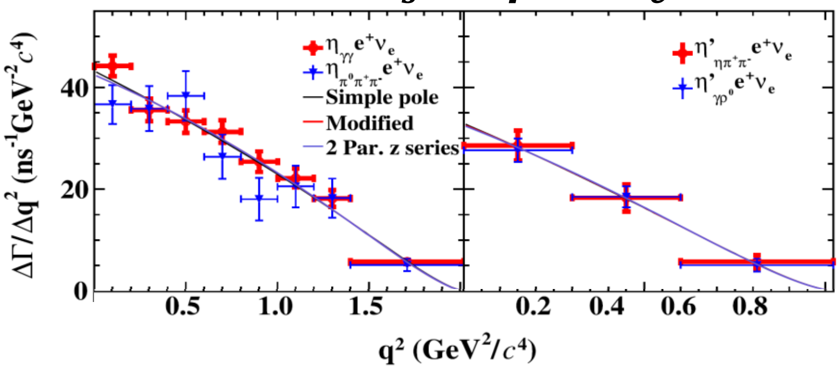
Series expansion $\quad f_+(q^2) = \frac{1}{P(q^2)\phi(q^2,t_0)}\sum_{k=0}^{\infty} a_k(t_0)[z(q^2,t_0)]^k$

- **$f_+(0)|V_{cs}|$ is obtained by the fit to the differential decay rates**
- **$|V_{cs}|$ is extracted by taking the $f_+(0)$ predicted by LQCD as input**

$D_{(s)}^{+/0} \to P l^+ \nu_l$

	$f_+^{D\to K}(0)\lvert V_{cs}\rvert$	Ref
$D^0 \to K^- e^+ \nu_e$	$0.717 \pm 0.003 \pm 0.004$	PRD92(2015)072012
$D^+ \to \bar{K}^0 e^+ \nu_e$	$0.705 \pm 0.004 \pm 0.011$	PRD96(2017)012002
$D^+ \to K_L^0 e^+ \nu_e$	$0.728 \pm 0.006 \pm 0.011$	PRD92(2015)112008
$D^0 \to K^- \mu^+ \nu_\mu$	$0.715 \pm 0.004 \pm 0.003$	PRL122(2019)011804

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

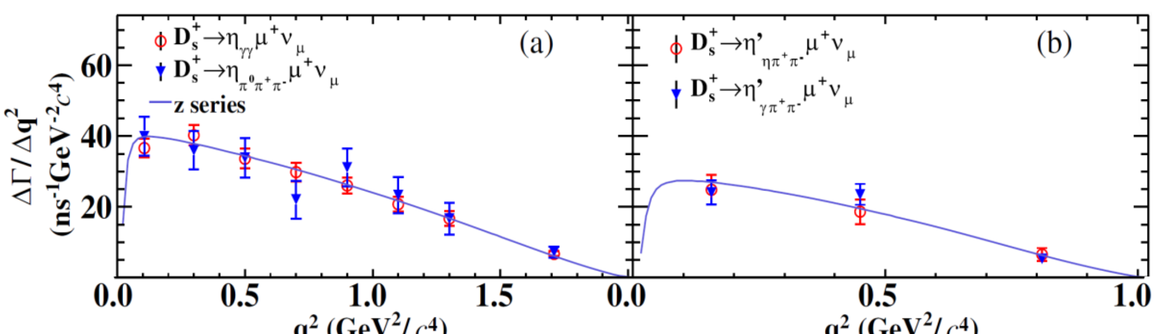


PRD108(2023)092003

$$f_+^{D_s\to\eta}(0)\lvert V_{cs}\rvert = 0.452 \pm 0.007 \pm 0.007$$

$$f_+^{D_s\to\eta'}(0)\lvert V_{cs}\rvert = 0.525 \pm 0.024 \pm 0.009$$

$D_s^+ \to \eta^{(\prime)} \mu^+ \nu_\mu$ 1st measurement



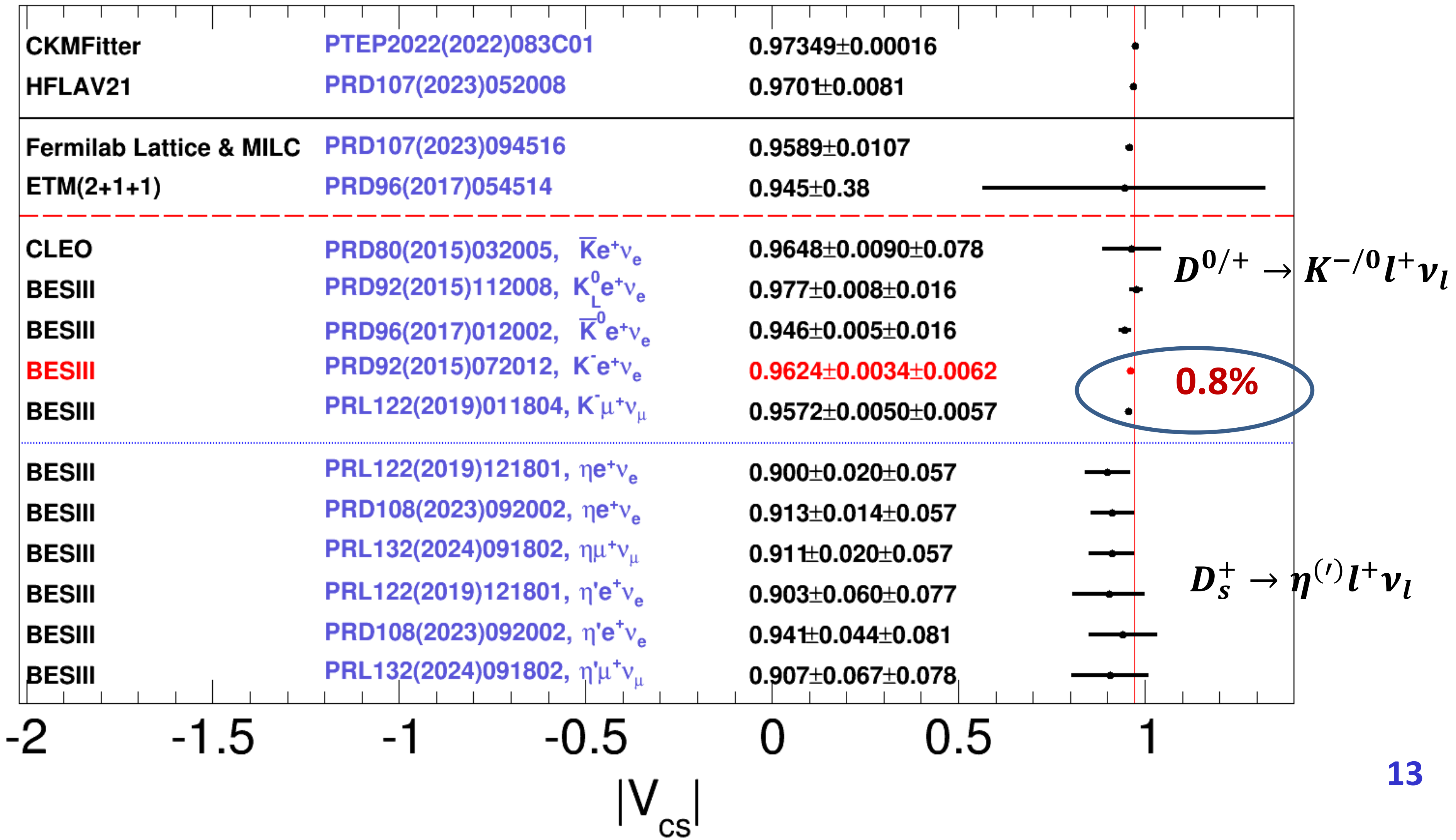
PRL132(2024)091802

$$f_+^{D_s\to\eta}(0)\lvert V_{cs}\rvert = 0.451 \pm 0.010 \pm 0.008$$

$$f_+^{D_s\to\eta'}(0)\lvert V_{cs}\rvert = 0.506 \pm 0.037 \pm 0.011$$

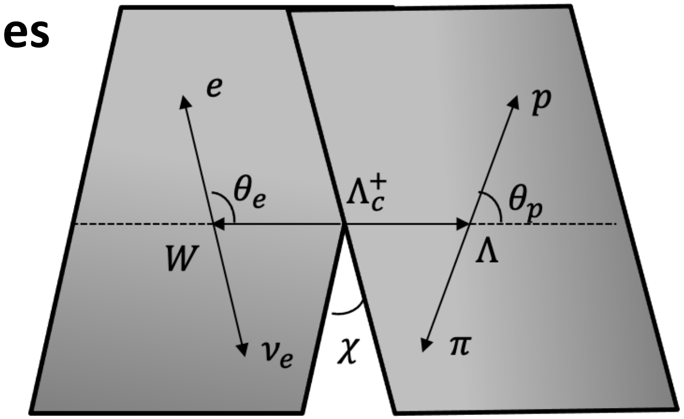
$|V_{cs}|$ determined via $D^{+/0}_{(s)} \to P l^+ \nu_l$

Combining measured $|V_{cs}|f_+(0)$ with $f_+(0)$ calculated by LQCD

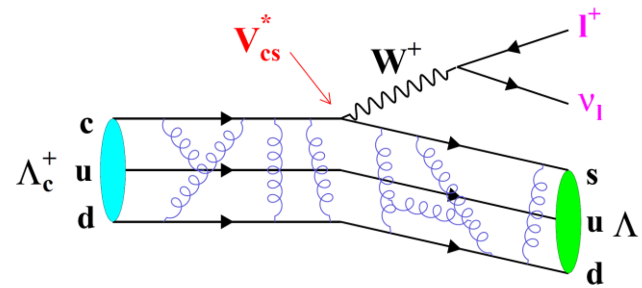


$\Lambda_c^+ \to \Lambda e^+ \nu_e$

- **The differential decay rate in terms of four variables**



$$\frac{d^4\Gamma}{dq^2 d\cos\theta_e d\cos\theta_p d\chi} = \frac{G_F^2|V_{cs}|^2}{2(2\pi)^4} \cdot \frac{Pq^2}{24M_{\Lambda_c}^2} \times$$
$$\left\{\frac{3}{8}(1-\cos\theta_e)^2|H_{\frac{1}{2}1}|^2(1+\alpha_\Lambda\cos\theta_p)\right.$$
$$+\frac{3}{8}(1+\cos\theta_e)^2|H_{-\frac{1}{2}-1}|^2(1-\alpha_\Lambda\cos\theta_p)$$
$$+\frac{3}{4}\sin^2\theta_e[|H_{\frac{1}{2}0}|^2(1+\alpha_\Lambda\cos\theta_p)+|H_{-\frac{1}{2}0}|^2(1-\alpha_\Lambda\cos\theta_p)]$$
$$+\frac{3}{2\sqrt{2}}\alpha_\Lambda\cos\chi\sin\theta_e\sin\theta_p \times$$
$$\left.[(1-\cos\theta_e)H_{-\frac{1}{2}0}H_{\frac{1}{2}1}+(1+\cos\theta_e)H_{\frac{1}{2}0}H_{-\frac{1}{2}-1}]\right\} \quad (2)$$



- **The helicity amplitudes $H_{\lambda_\Lambda\lambda_W}$ are related to four form factors**

$$H^V_{\frac{1}{2}1} = \sqrt{2Q_-}\, f_\perp(q^2), \quad H^A_{\frac{1}{2}1} = \sqrt{2Q_+}\, g_\perp(q^2),$$
$$H^V_{\frac{1}{2}0} = \sqrt{Q_-/q^2}\, f_+(q^2)\,(M_{\Lambda_c}+M_\Lambda),$$
$$H^A_{\frac{1}{2}0} = \sqrt{Q_+/q^2}\, g_+(q^2)\,(M_{\Lambda_c}-M_\Lambda),$$

$$Q_\pm = (M_{\Lambda_c} \pm M_\Lambda)^2 - q^2$$
$$H_{\lambda_\Lambda\lambda_W} = H^V_{\lambda_\Lambda\lambda_W} - H^A_{\lambda_\Lambda\lambda_W}$$
$$H^{V(A)}_{-\lambda_\Lambda-\lambda_W} = +(-)H^{V(A)}_{\lambda_\Lambda\lambda_W}$$

$\Lambda_c^+ \to \Lambda e^+ \nu_e$

- **Four FFs are parameterized following a z-expansion**

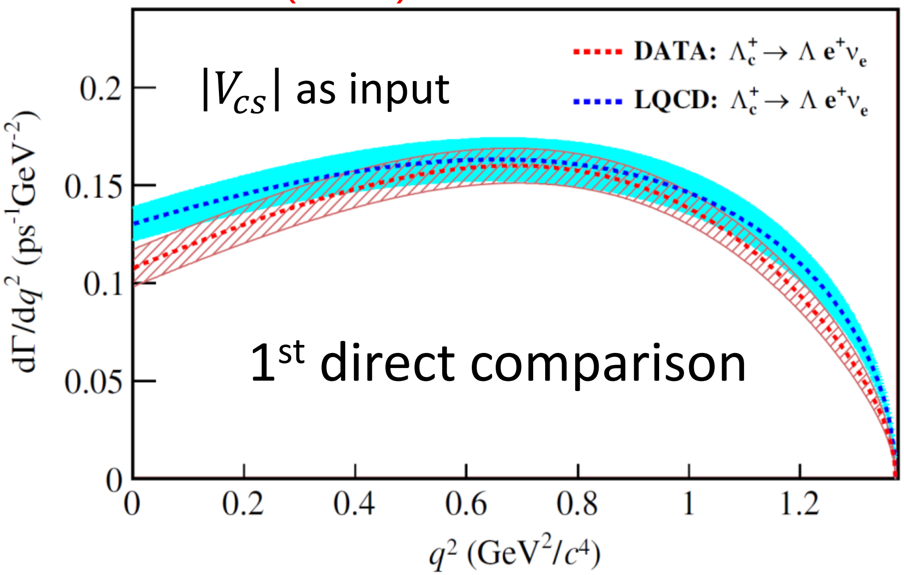
$$f(q^2) = \frac{a_0^f}{1 - q^2/\left(m_{\rm pole}^f\right)^2}\left[1 + \alpha_1^f \times z(q^2)\right]$$

- **A four-dimensional ML fit is performed with five independent free parameters**

$$\alpha_1^{g_\perp},\ \alpha_1^{f_\perp},\ r_{f_+} = a_0^{f_+}/a_0^{g_\perp},\ r_{f_\perp} = a_0^{f_\perp}/a_0^{g_\perp},\ r_{g_+} = a_0^{g_+}/a_0^{g_\perp}$$

- $$\frac{d\Gamma}{dq^2} = \frac{G_F^2|V_{cs}|^2}{192\pi^3 M_{\Lambda_c}^2} \times \left[|H_{\frac{1}{2}1}|^2 + |H_{-\frac{1}{2}-1}|^2 + |H_{\frac{1}{2}0}|^2 + |H_{-\frac{1}{2}0}|^2\right]$$

PRL129(2022)231803

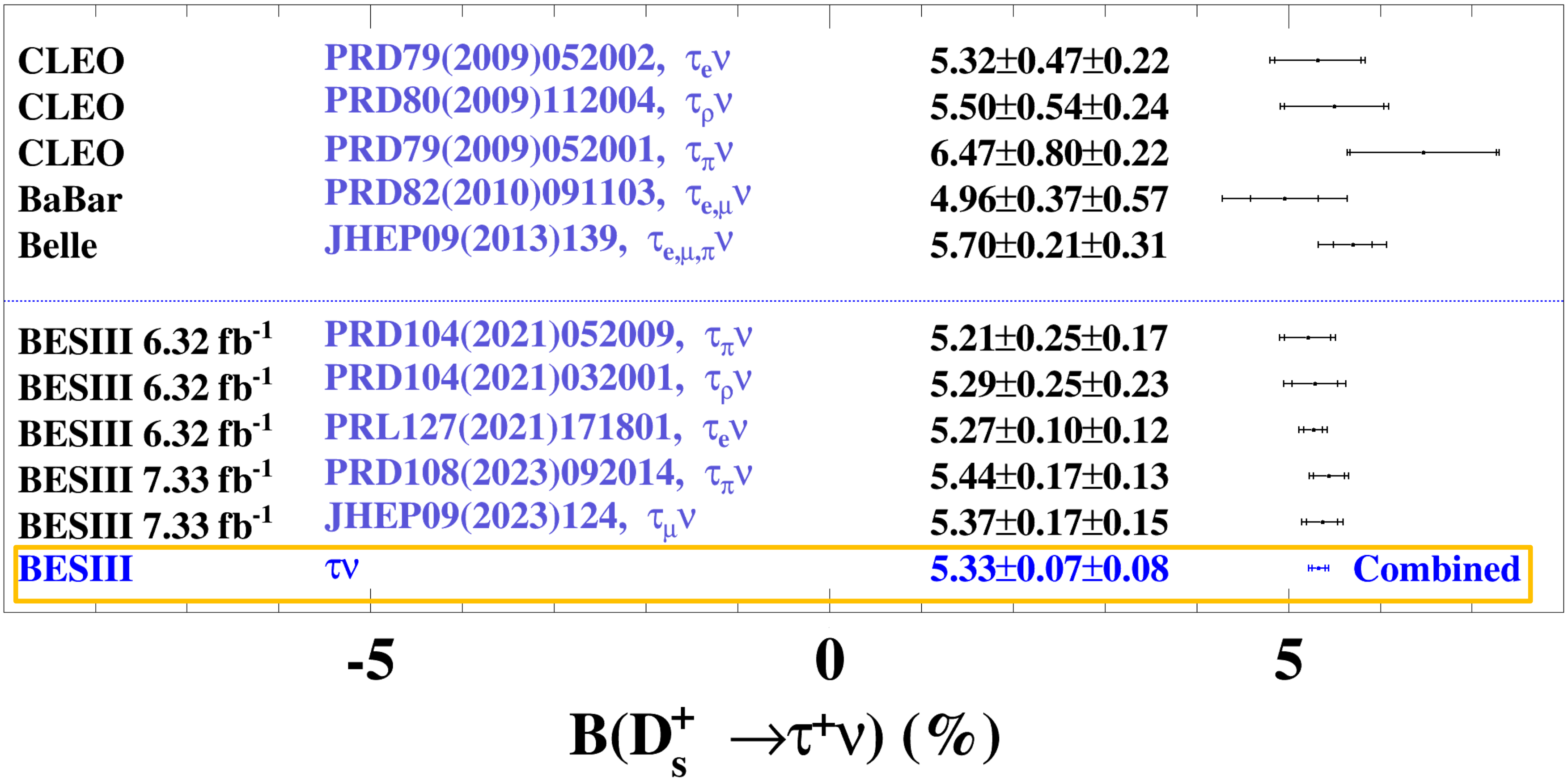


- $\mathcal{B}(\Lambda_c^+ \to \Lambda e^+ \nu_e) = (3.56 \pm 0.11 \pm 0.07)\%$
- $|V_{cs}| = 0.936 \pm 0.030$, by combining $\mathcal{B}(\Lambda_c^+ \to \Lambda e^+ \nu_e)$ and the q^2-integrated rate predicted by LQCD
- $\boldsymbol{\Lambda_c^+ \to \Lambda \mu^+ \nu_\mu}$ PRD108(2023)L031105

LFU test

LFU test in $D_s^+ \to l^+ \nu_l$

BESIII PRD108(2023)11200, $\mu\nu$ $(5.29 \pm 0.11 \pm 0.09) \times 10^{-3}$



$R_{\tau/\mu} = \frac{\mathcal{B}[D_s^+ \to \tau^+ \nu]}{\mathcal{B}[D_s^+ \to \mu^+ \nu]} = \mathbf{10.05 \pm 0.35}$, consistent with the SM prediction 9.75

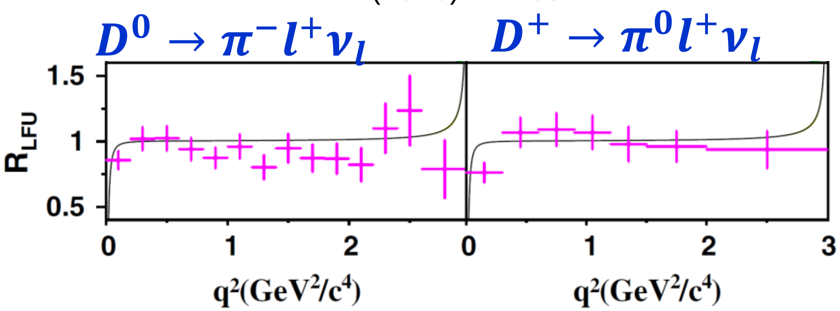
LFU test in semileptonic decays

- $\mathcal{R}_{\mu/e}$ **obtained by measuring BFs**

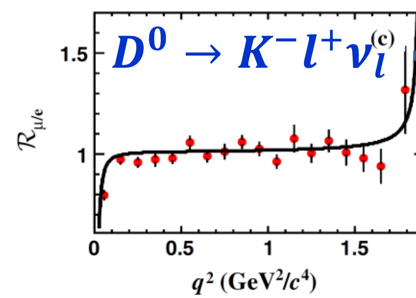
	Ref	$\mathcal{R}_{\mu/e}$	SM prediction
$D^+ \to \eta l^+ \nu_l$	PRL124(2020)231801	0.91 ± 0.13	$0.97 - 1.00$
$D^+ \to \omega l^+ \nu_l$	PRD101(2020)072005	1.05 ± 0.14	$0.93 - 0.99$
$D^+ \to \rho l^+ \nu_l$	PRD104(2021)L091103	0.90 ± 0.11	$0.93 - 0.96$

- $\mathcal{R}_{\mu/e}$ **in the full kinematic region**

PRL121(2018)171803

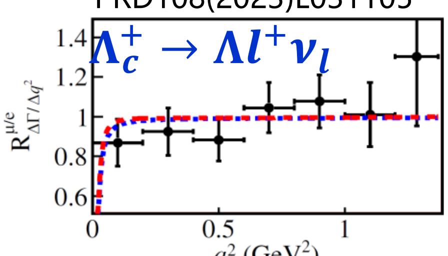


PRL122(2019)011804

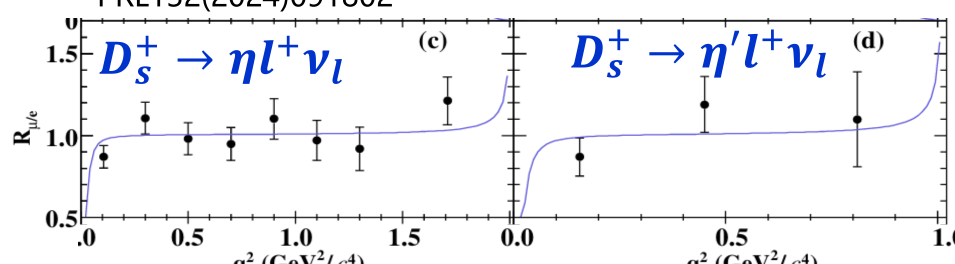


SM prediction

PRD108(2023)L031105



PRL132(2024)091802



Summary

- Thanks to the largest data samples collected at $D\bar{D}/D_sD_s^*/\ \Lambda_c^+\bar{\Lambda}_c^-$ mass threshold, purely and semi leptonic decays of charmed hadrons have been studied in a clean environment.
- Precise measurement of the CKM matrix element at 1% precision level
- No evidence of LFU violation found at 1.5% precision level
- BESIII just finished taking the data @$3.773\mathrm{GeV}$, and collected $20\mathrm{fb}^{-1}$ of $D\bar{D}$ sample
  - Combined study of $D^{0/+} \to K^{-/0}e^+\nu_e$ and $D^{0/+} \to K^{-/0}\mu^+\nu_\mu$ for a high precise measurement of $|V_{cs}|$
  - Higher precise LFU test

backup

$\Lambda_c^+ \to \Lambda e^+ \nu_e$

- Form factors $f_{\perp,+}(q^2)$ and $g_{\perp,+}(q^2)$ are defined following a z-expansion of the parameters

$$f(q^2) = \frac{a_0^f}{1 - q^2/\left(m_{\rm pole}^f\right)^2}\left[1 + \alpha_1^f \times z(q^2)\right]$$

where $m_{\rm pole}^f$ is the pole mass; a_0^f, α_1^f are free parameters; $z(q^2) = \frac{(\sqrt{t_+ - q^2} - \sqrt{t_+ - t_0})}{(\sqrt{t_+ - q^2} + \sqrt{t_+ - t_0})}$ with $t_0 = q^2_{\rm max} = (m_{\Lambda_c} - m_\Lambda)^2$, $t_+ = (m_D + m_K)^2$, $m_D = 1.870$ GeV$/c^2$ and $m_K = 0.494$ GeV$/c^2$. The pole masses are $m_{\rm pole}^{f_+, f_\perp} = 2.112$ GeV$/c^2$ and $m_{\rm pole}^{g_+, g_\perp} = 2.460$ GeV$/c^2$ [14].

Five independent free parameters in the ML fit for the differential decay amplitude :

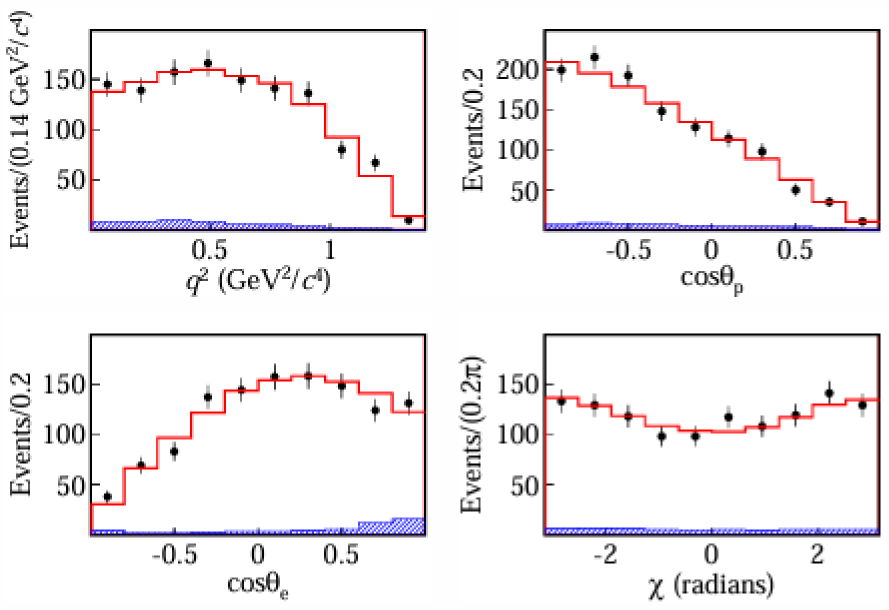
- The differential decay rate has to be normalized. Only the ratios of a_0^f are determined in the maximum likelihood fit:

$$r_{f_+} = a_0^{f_+}/a_0^{g_\perp},\quad r_{f_\perp} = a_0^{f_\perp}/a_0^{g_\perp},\quad r_{g_+} = a_0^{g_+}/a_0^{g_\perp}.$$

- $a_1^{g_\perp} \equiv a_1^{g_+}$ and $a_1^{f_\perp} \equiv a_1^{f_+}$, the kinematic dependences of $g_\perp(q^2)$ and $g_+(q^2)$, $f_\perp(q^2)$ and $f_+(q^2)$ as a function of q^2 are similar according to LQCD.

$\Lambda_c^+ \rightarrow \Lambda e^+ \nu_e$

- A four-dimensional ML fit is performed as a function of q^2, $\cos\theta_e$, $\cos\theta_p$, and χ



Parameters	$\alpha_1^{g_\perp}$	$\alpha_1^{f_\perp}$	r_{f_+}	$r_{f_\perp}$	r_{g_+}
Values	$1.43 \pm 2.09 \pm 0.16$	$-8.15 \pm 1.58 \pm 0.05$	$1.75 \pm 0.32 \pm 0.01$	$3.62 \pm 0.65 \pm 0.02$	$1.13 \pm 0.13 \pm 0.01$

Coefficients	$\alpha_1^{g_\perp}$	$\alpha_1^{f_\perp}$	r_{f_+}	$r_{f_\perp}$	r_{g_+}
$a_0^{g_\perp}$	-0.64	0.60	-0.66	-0.83	-0.40
$\alpha_1^{g_\perp}$		-0.63	0.62	0.53	-0.33
$\alpha_1^{f_\perp}$			-0.79	-0.67	-0.07
r_{f_+}				0.57	-0.09
$r_{f_\perp}$					0.39

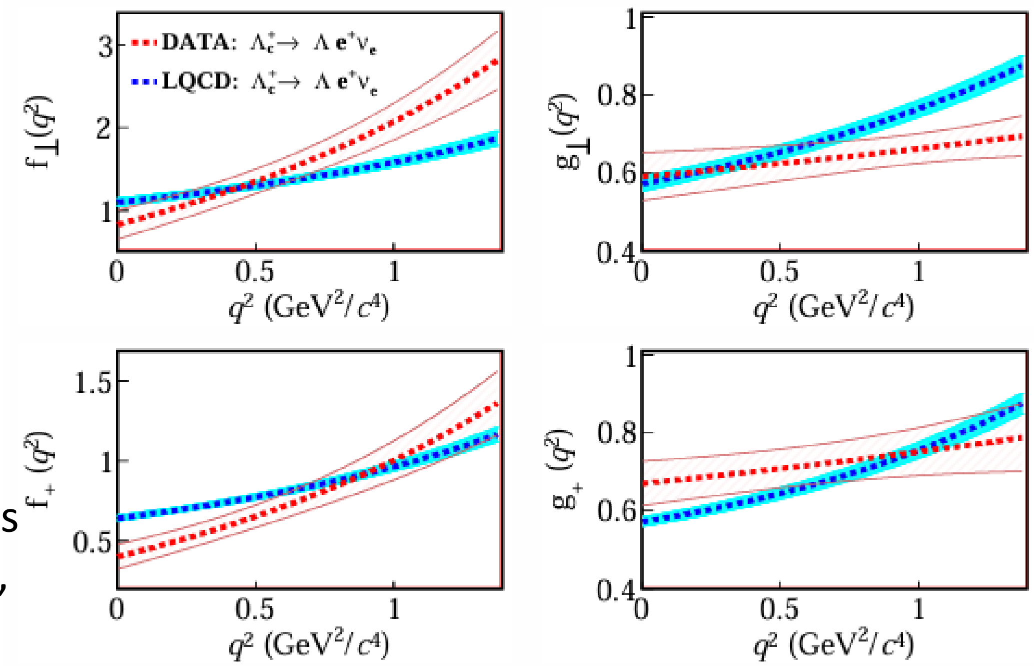
$\Lambda_c^+ \to \Lambda e^+ \nu_e$

$$r_{f_+} = a_0^{f_+}/a_0^{g_\perp},\ r_{f_\perp} = a_0^{f_\perp}/a_0^{g_\perp},\quad r_{g_+} = a_0^{g_+}/a_0^{g_\perp}.$$

- In order to determine the parameter of $a_0^{g_\perp}$ (the FF at q2 being 0), the differential decay rate is related to $\mathcal{B}(\Lambda_c^+ \to \Lambda e^+ \nu_e)$ and the lifetime of lambda_c by

$$\int_0^{q^2_{\max}} \frac{d\Gamma}{dq^2} dq^2 = \frac{\mathcal{B}(\Lambda_c^+ \to \Lambda e^+ \nu_e)}{\tau_{\Lambda_c}}$$

$$\frac{d\Gamma}{dq^2} = \frac{G_F^2 |V_{cs}|^2}{192\pi^3 M_{\Lambda_c}^2} \times P q^2 \times \left[|H_{\frac{1}{2}1}|^2 + |H_{-\frac{1}{2}-1}|^2 + |H_{\frac{1}{2}0}|^2 + |H_{-\frac{1}{2}0}\right.$$



τ_{Λ_c} $|V_{cs}|$ and the helicity amplitudes parameterized with form factors, We determine

$$a_0^{g_\perp} = 0.54 \pm 0.04_{\text{stat.}} \pm 0.01_{\text{syst.}}$$

FIG. 3. Comparison of form factors with LQCD calculations. The bands show the total uncertainties.

$\Lambda_c \to \Lambda \ell^+ \nu_\ell$ form factors and decay rates from lattice QCD with physical quark masses

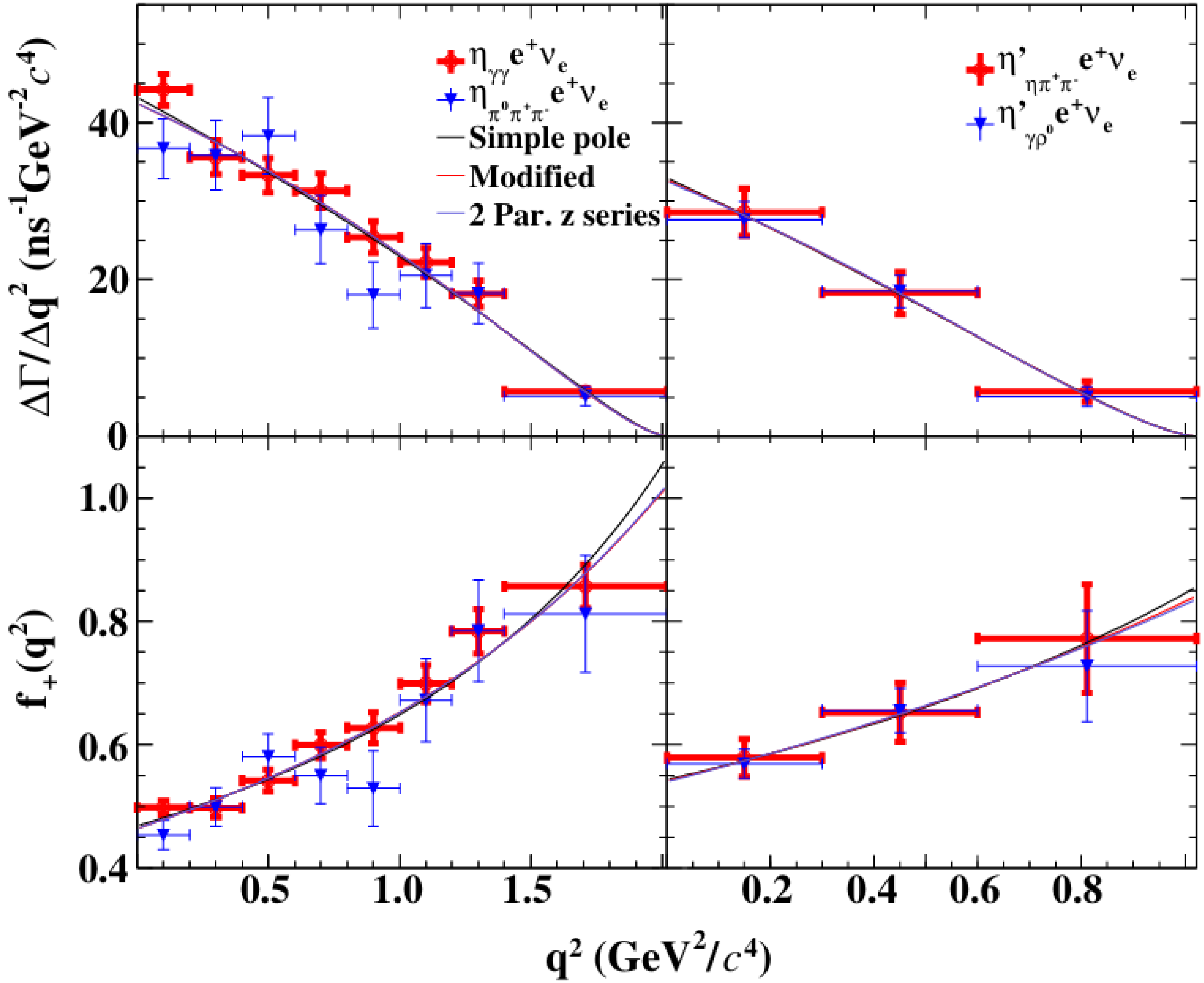
Extraction of $|V_{cs}|$ via $D_{(s)}^{+/0} \to P l^+ \nu_l$

$$\frac{d\Gamma}{dq^2} = \frac{G_F^2 |V_{cs}|^2}{24\pi^3} \frac{(q^2 - m_l^2)^2 |\overrightarrow{p}|}{q^4 m^2_{D_{(s)}^{+/0}}} [(1 + \frac{m_l^2}{2q^2}) m^2_{D_{(s)}^{+/0}} |\overrightarrow{p}|^2 f_+(q^2)|^2 + \frac{3m_l^2}{8q^2} (m^2_{D_{(s)}^{+/0}} - m_P^2)^2 |f_0(q^2)|^2]$$

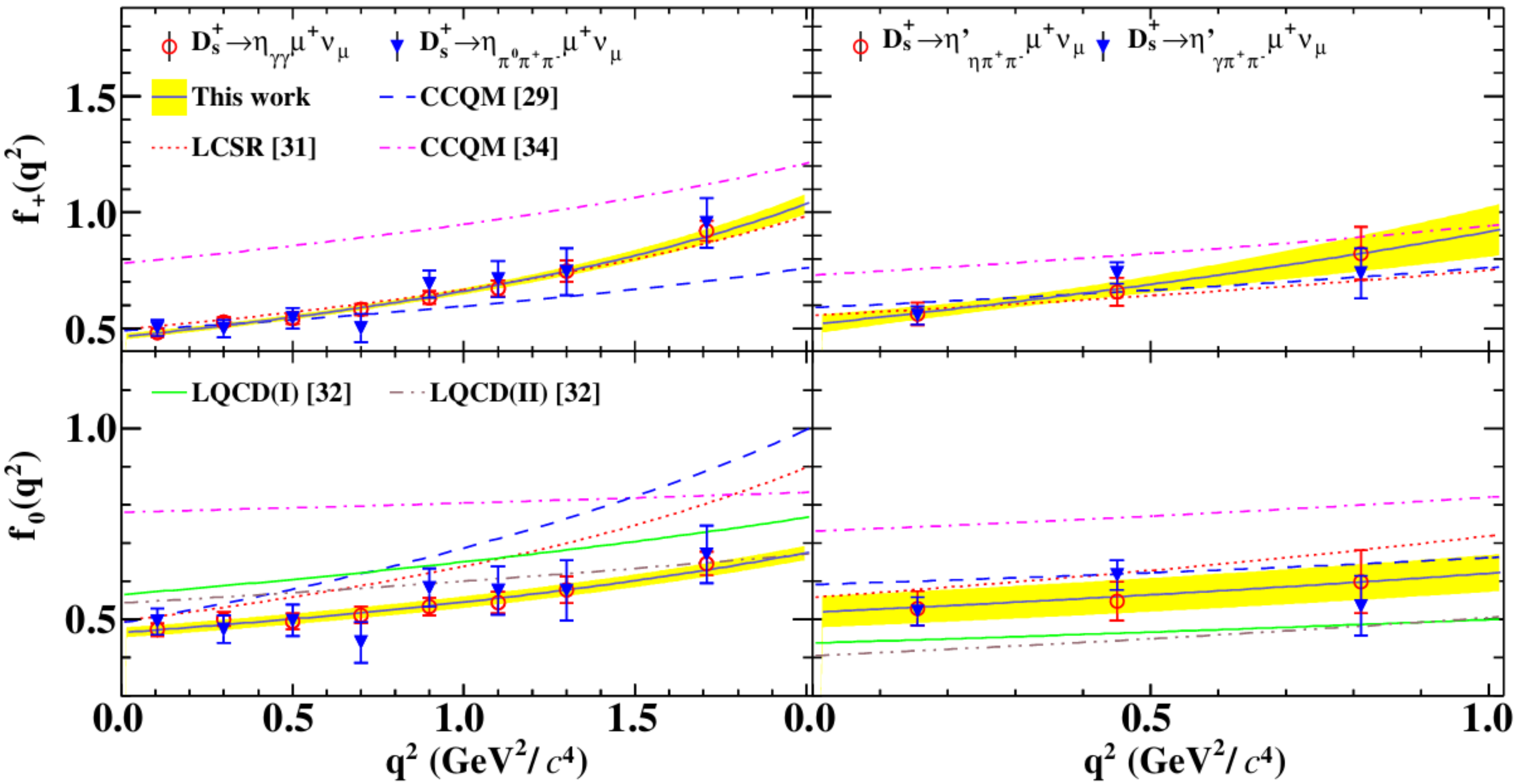
$f_{+(0)}$ is the vector (scalar) FF.
Theoretically , $f_+(0)$ and $f_0(0)$ have to be equal

More theoretical details in PRD 101, 013004 (2020)

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

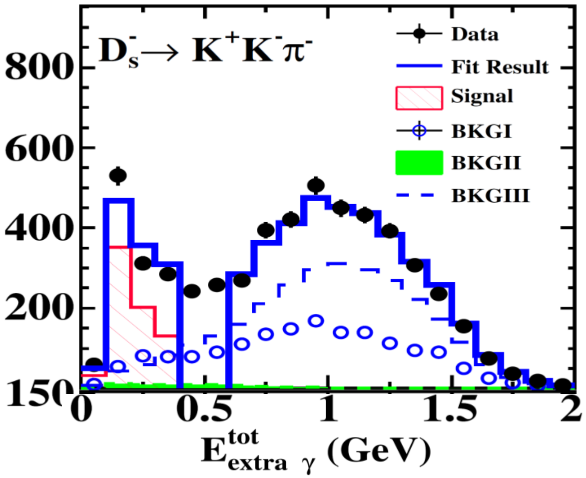


$D_s^+ \to \eta^{(\prime)} \mu^+ \nu_\mu$



- The yellow bands are the $\pm 1\sigma$ limits of fitted parameters
- Curves in different colors are from various theoretical calculations

$D_s^+ \to \tau^+(\mu^+ \nu\nu)\nu$



BKG I: incorrectly tagged D_s^-

BKG II : correctly tagged D_s^- and $D_s^+ \to K_L^0 \mu^+ \nu_\mu$

BKG III : correctly tagged D_s^- and $D_s^+ \to$ non-$\tau^+\nu$

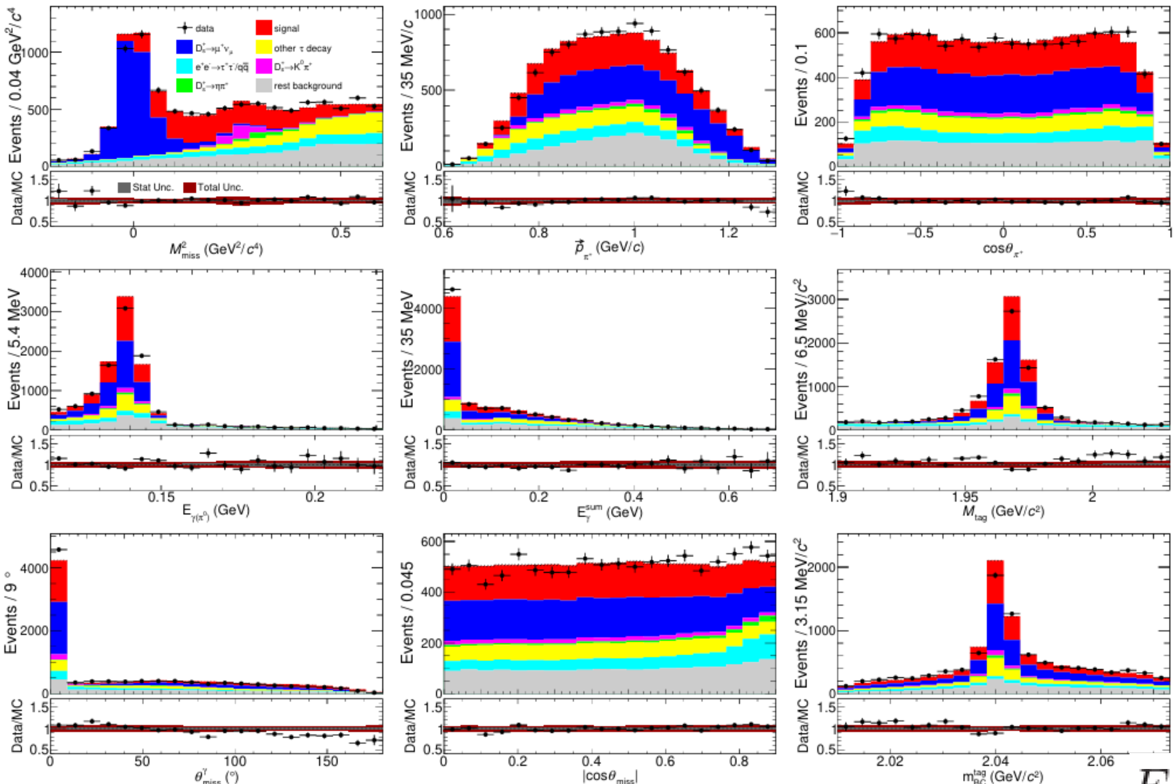
expect for $D_s^+ \to K_L^0 \mu^+ \nu_\mu$

To minimize the effect of the imperfect signal shape, we adopt an extrapolation technique. The extrapolation factor, defined as the ratio of the number of events between the signal region and the background region, is determined by MC sample.

A bin maximum likelihood fit is performed on the events with $E^{tot}_{extra\ \gamma}$ > 0.6GeV, where the signal is negligible, and the sizes and shapes of BKGI and BKGII, and the shape of BKGIII are fixed.

The signal DT yield is obtained by subtracting bkgs in the signal region $E^{tot}_{extra\ \gamma}$ < 0.4GeV

$D_s^+ \to \tau^+(\pi^+ v)v$



$E_{\gamma(\pi^0)}$ from the transition $\gamma(\pi^0)$.

$\theta^{\gamma}_{\rm miss}$, $\cos\theta_{\rm miss}$, and $M^2_{\rm miss}$

$E^{\rm sum}_{\gamma}$ representing the summed energy of extra photons

$\cos\theta_{\pi^+}$ and $\vec{p}_{\pi^+}$ of the π^+ from the signal

Aside from the M2 , the search sensitivity is further improved by incorporating additional kinematic and topological information from the selected events using a multivariate analysis technique known as BDT

Branching fractions of semileptonic D and D_s decays from the covariant light-front quark model

$D \to X\mu\nu$

Channel	$D \to \rho$	$D \to \omega$	$D \to \eta$
Theory (10^{-2})	0.22 ± 0.02	0.20 ± 0.02	0.12 ± 0.01

$D \to Xe\nu$

Channel	$D \to \rho$	$D \to \omega$	$D \to \eta$
Theory (10^{-2})	0.23 ± 0.02	0.21 ± 0.02	0.12 ± 0.01

Investigating the nature of light scalar mesons with semileptonic decays of D mesons

Mode	$l = e$	$l = \mu$
$\rho(770)^0$	2.54×10^{-3}	2.37×10^{-3}
$\omega(782)$	2.46×10^{-3}	2.29×10^{-3}

Semileptonic $D_{(s)}$-meson decays in the light of recent data

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Channel	Unit	Present	Other	Reference
$D^+ \to \rho^0 e^+ \nu_e$	10^{-3}	2.09	2.54	χUA [38]
			$2.217^{+0.534}_{-0.376} \pm 0.015$	LCSR [25]
			2.5	HMχT [35]
$D^+ \to \rho^0 \mu^+ \nu_\mu$	10^{-3}	2.01	2.37	χUA [38]
$D^+ \to \omega e^+ \nu_e$	10^{-3}	1.85	2.46	χUA [38]
			2.5	HMχT [35]
			2.1 ± 0.2	LFQM [33]
$D^+ \to \omega \mu^+ \nu_\mu$	10^{-3}	1.78	2.29	χUA [38]
			2.0 ± 0.2	LFQM [33]
$D^+ \to \eta e^+ \nu_e$	10^{-4}	9.37	12 ± 1	LFQM [33]
			24.5 ± 5.26	LCSR [22]
			14.24 ± 10.98	LCSR [24]
$D^+ \to \eta \mu^+ \nu_\mu$	10^{-4}	9.12	12 ± 1	LFQM [33]