Charm physics studies at BESIII, Belle (II) and STCF

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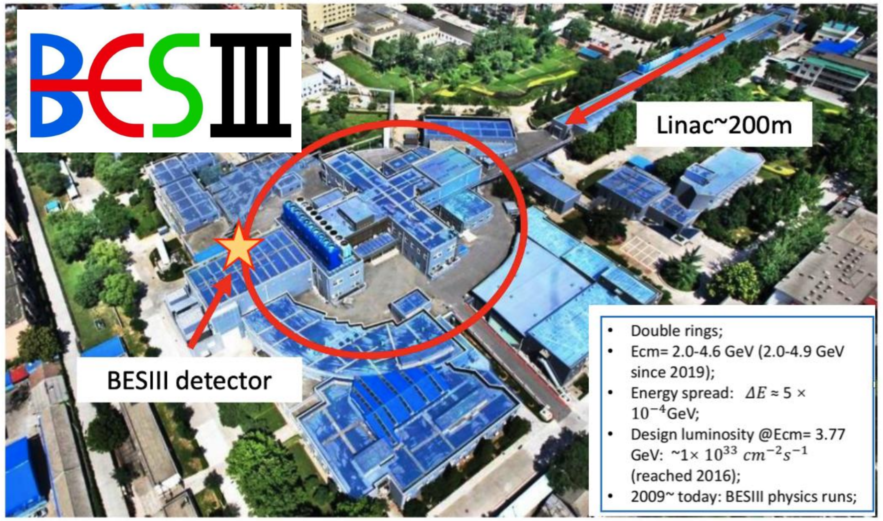
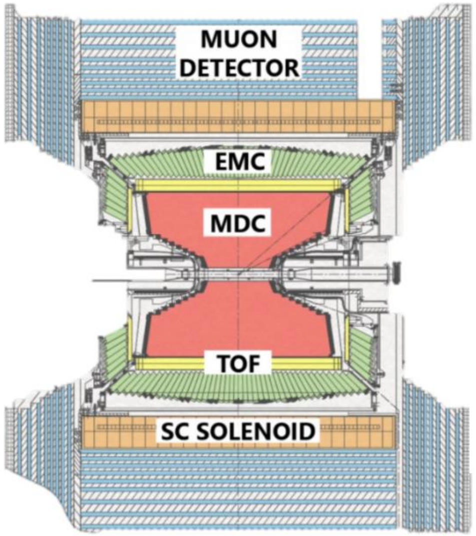
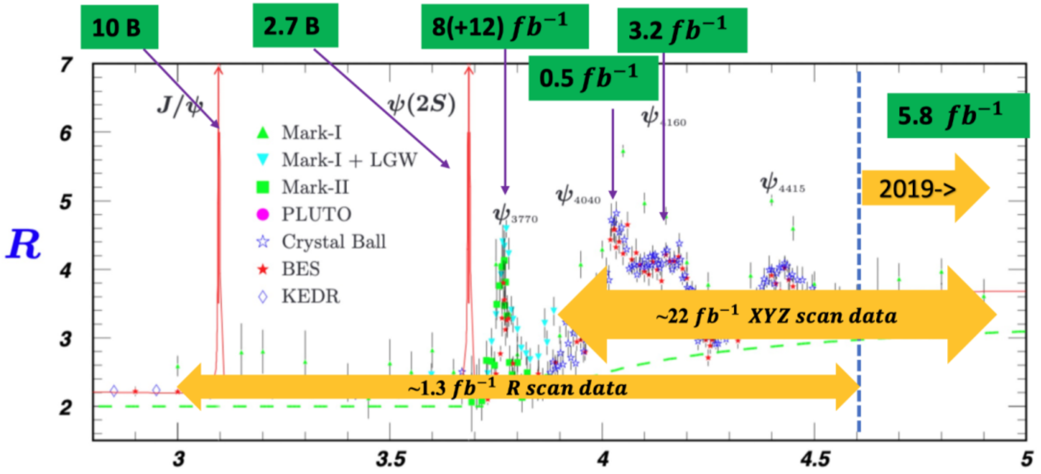
Outline

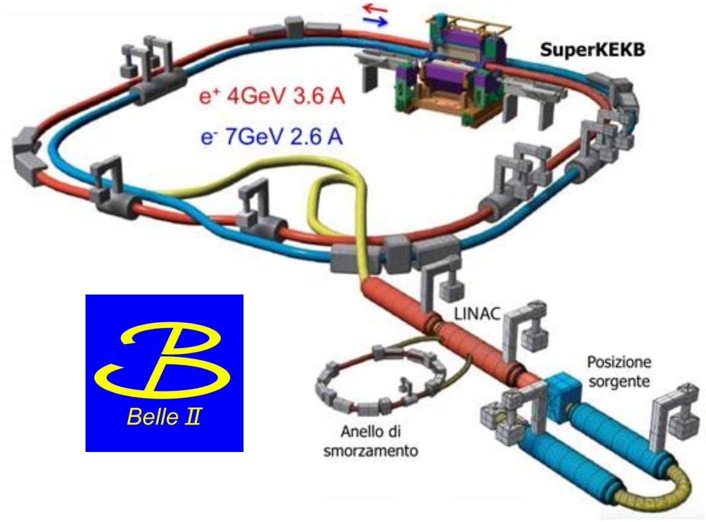
- Introduction
- Charm mixing and CPV studies
- Precision determination of $\left|V_{cs(d)}\right|$
- Summary

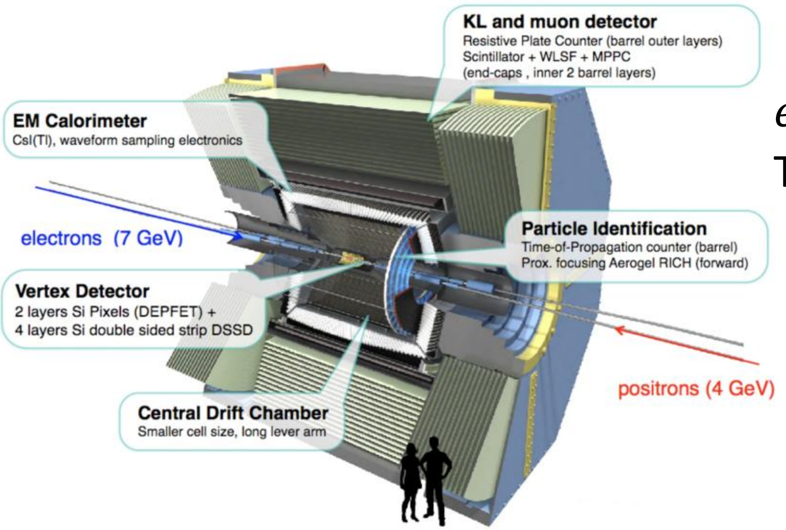
Electron-positron experiments for charm studies









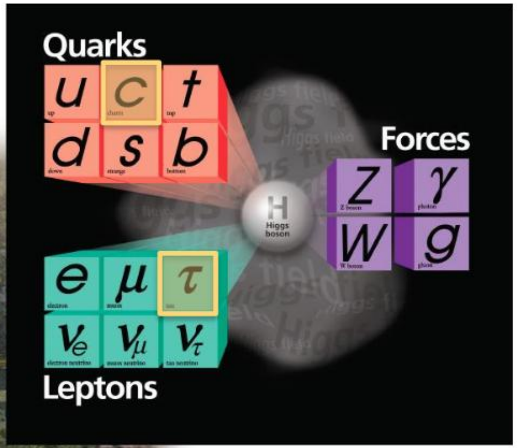


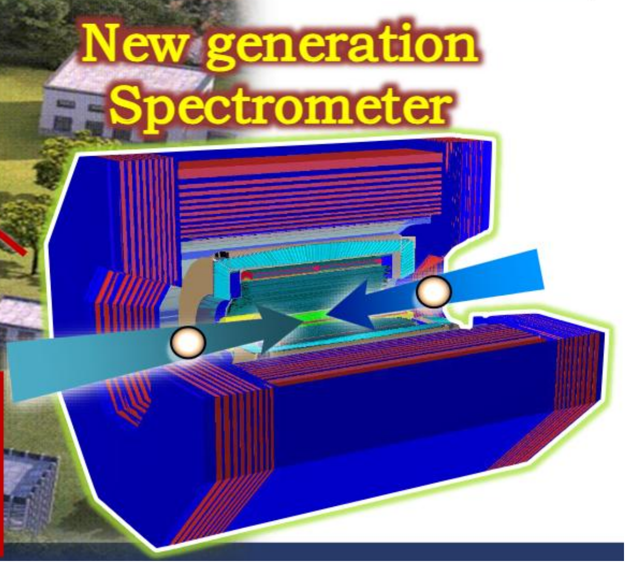
e^+e^- asymmetric collider at $\Upsilon(4S)$

To accumulate a dataset of $\int Ldt = 50ab^{-1}$

Future experiment—Super Tau Charm Facility

A factory producing massive **tau lepton** and **hadrons**, to unravel the mystery of **how quarks form matter** and the **symmetries** of fundamental interactions





- E_{cm}= 2-7 GeV, $\mathcal{L} > 0.5\times10^{35}$ cm^{-2} s^{-1}
- Potential for upgrade to **increase luminosity** and realize **polarized beam**
- Site: 1 km^2, Hefei's suburban "Future Big Science City"

From Jingyu Tang's talk

Expect to accumulate datasets for charm hadrons with an integrated luminosity 100 times that of BESIII

Charm mixing

Mass eigenstates: $|D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle$

Time evolution of an initially flavour eigenstate D meson:

$$|D^0_{phys}(t)\rangle = g_+(t)|D^0\rangle + \frac{q}{p} g_-(t)|\bar{D}^0\rangle, \; |\bar{D}^0_{phys}(t)\rangle = g_+(t)|\bar{D}^0\rangle + \frac{q}{p} g_-(t)|D^0\rangle$$

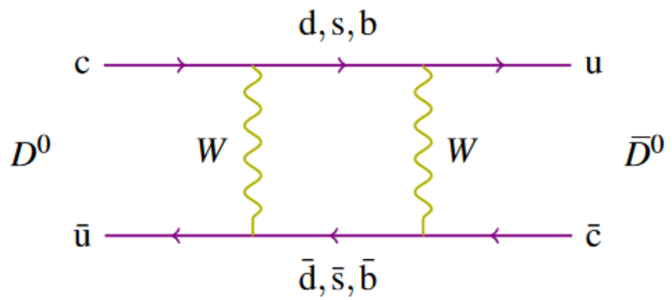
$$g_+(t) = \exp(-(im + \Gamma/2)t) \cosh((i\Delta m - \Gamma/2)t/2) \qquad m \equiv (m_1 + m_2)/2, \Delta m \equiv m_2 - m_1$$

$$g_-(t) = \exp(-(im + \Gamma/2)t) \sinh((i\Delta m - \Gamma/2)t/2) \qquad \Gamma \equiv (\Gamma_1 + \Gamma_2)/2, \Delta\Gamma \equiv \Gamma_1 - \Gamma_2$$

Charm mixing parameters: $x \equiv \frac{\Delta m}{\Gamma}, y \equiv \frac{\Delta\Gamma}{2\Gamma}$

Short distance contributions

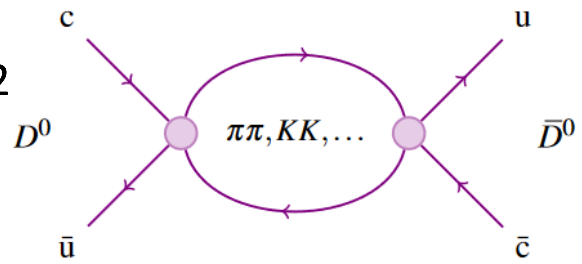
loop level $(\mathbf{x}, \mathbf{y}) \sim \mathbf{10^{-7}}$



Long distance contributions

$(\mathbf{x}, \mathbf{y}) \sim \mathbf{10^{-3}}$

Phys. Lett. B 810 (2020) 135802
Chin. Phys. C 42 (2018) 063101
Phys. Rev. D 81 (2010) 114020
Phys. Rev. D 65 (2002) 054034



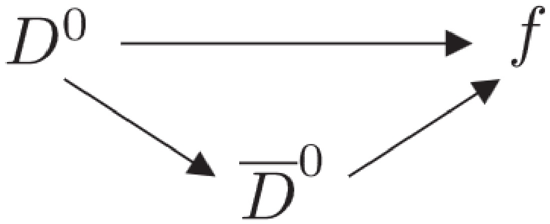
Plots from arXiv:1503.00032

Indirect CPV associated with charm mixing

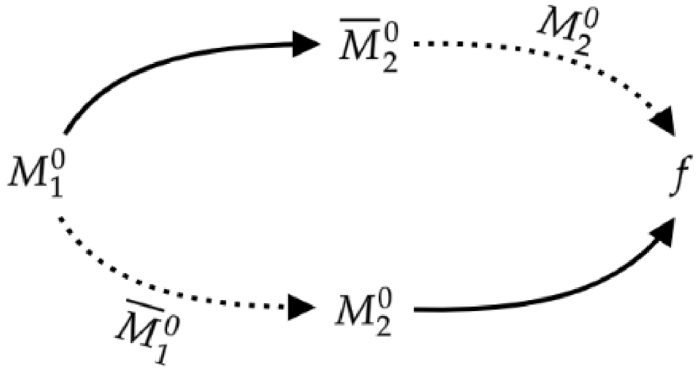
- Type 1. CP violation in mixing $|p| \neq |q|$
  - Mass eigenstates are not CP eigenstates
- Type 2. CPV due to interference between mixing and decay

$$Im\left(\frac{q}{p}\frac{A(\bar{D}^0 \to f)}{A(D^0 \to f)}\right) \neq Im\left(\frac{p}{q}\frac{A(D^0 \to \bar{f})}{A(\bar{D}^0 \to \bar{f})}\right)$$

  - Non-zero ϕ for $\frac{q}{p} = \left|\frac{q}{p}\right| e^{i\phi}$



- Type 3. Interference between charm mixing and kaon mixing



[PRD 110 (2024) L031301]

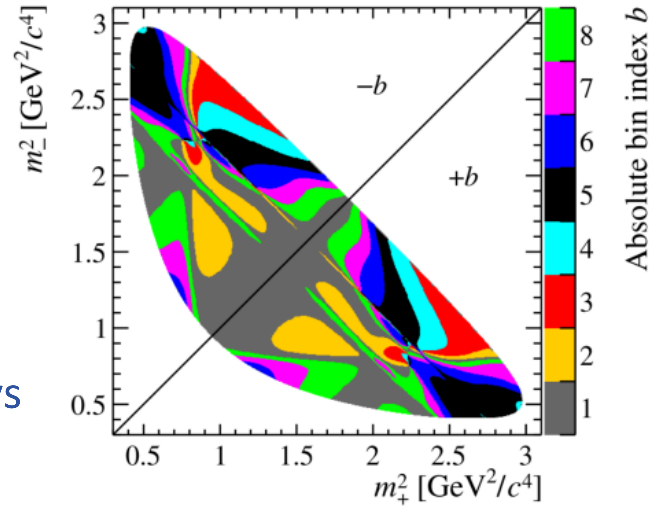
Determination of mixing parameters with Belle+Belle II data

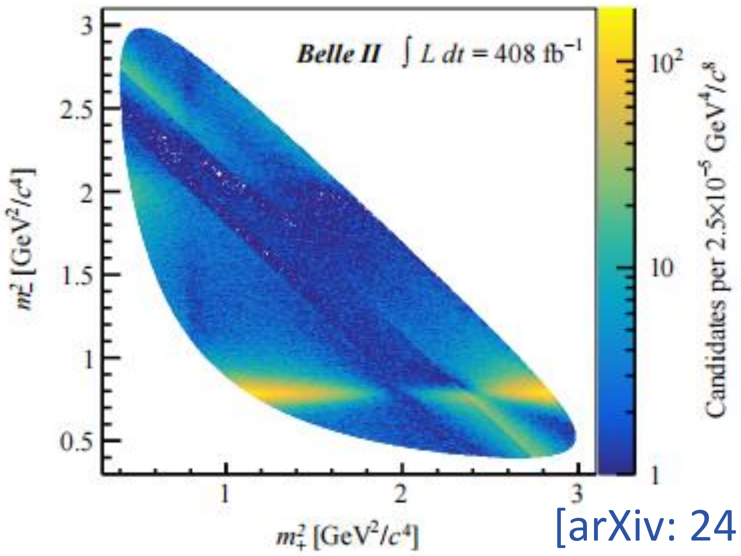
- Flavour-tagged D mesons from $D^* \rightarrow D\left(K_S^0\pi^+\pi^-\right)\pi$ decays
- Time-dependent distribution of decay rate

$$p_{\pm b}(t) \propto g_{\pm}^2(t) + r_b g_{\mp}^2(t) + 2\sqrt{r_b}Re[X_{\pm b}\, g_+^*(t)\, g_-(t)]$$

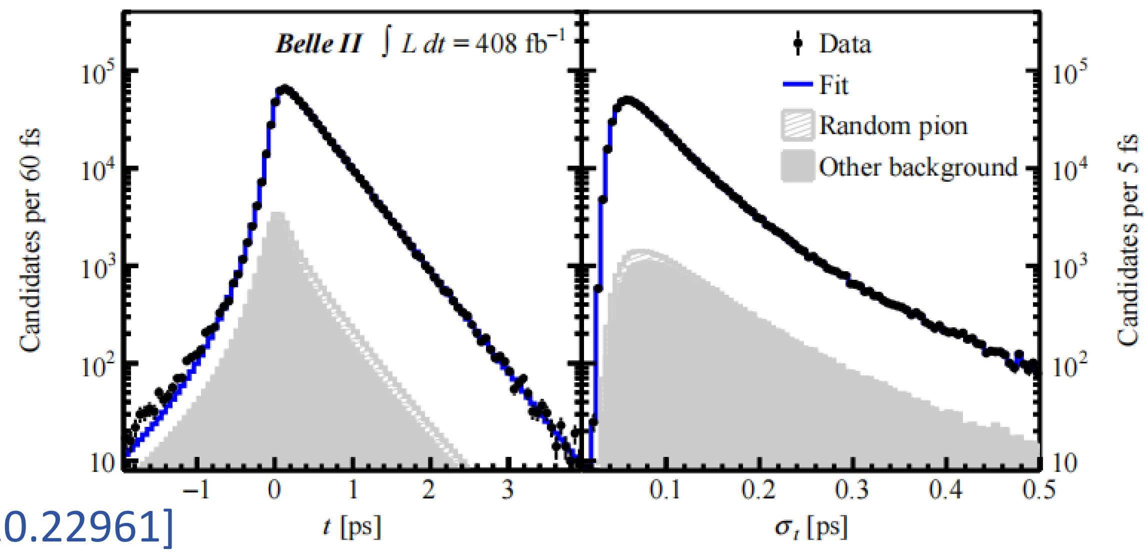
Charm mixing

$X_{\pm b}$: Strong-phase difference between D^0 and $\overline{D}^0$ decays
r_b: Ratio of D^0 and $\overline{D}^0$ decay amplitude square

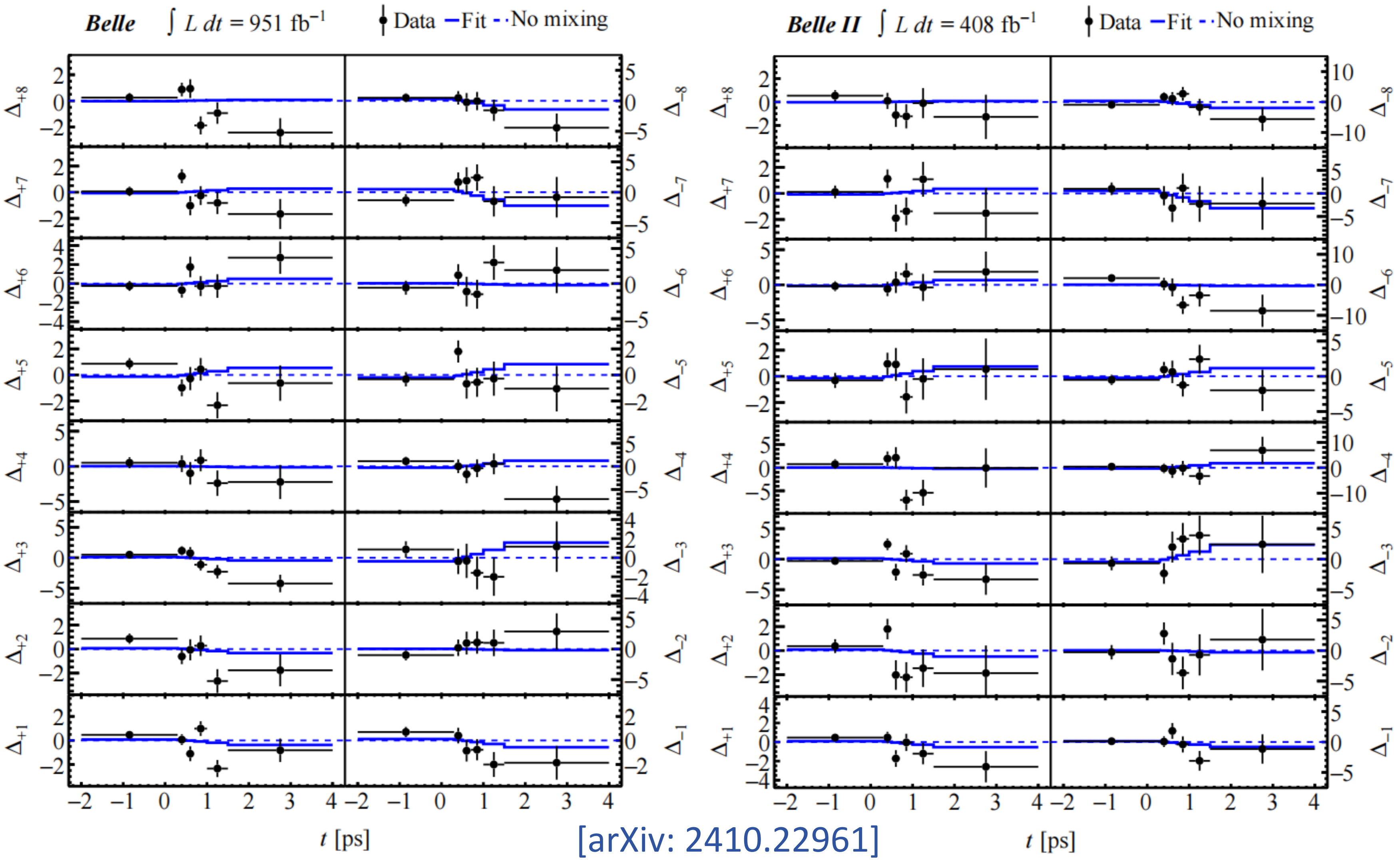




[arXiv: 2410.22961]



Binned time-dependent decay rate



[arXiv: 2410.22961]

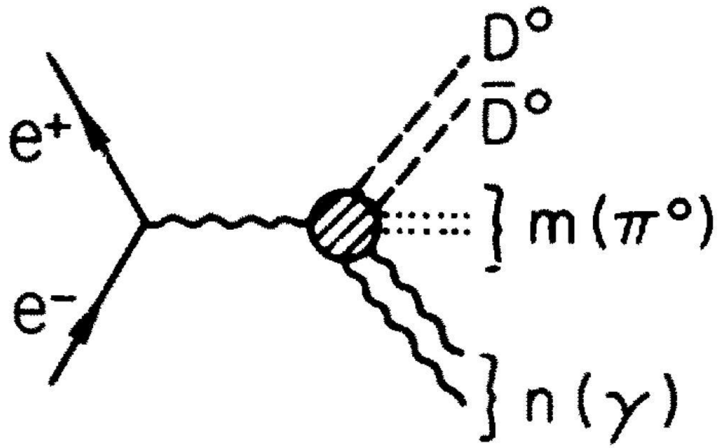
Assuming no CPV

$x = (4.0 \pm 1.7 \pm 0.4) \times 10^{-3}$

$y = (2.9 \pm 1.4 \pm 0.3) \times 10^{-3}$

Stat. Signifcance of 2.7σ

Charm mixing study with quantum correlated $D\bar{D}$



[Phys. Rev. D 15 (1997) 1254]

- $D^0\bar{D}^0$ pairs produced by e^+e^- annihilations near threshold at BESIII/STCF are in QC state with $C = (-1)^{n+1}$, n is the number of accompany photons
- @3770 MeV

  C odd for $e^+e^- \to D^0\bar{D}^0$
- @Higher energy points

  C even for $e^+e^- \to D^0\bar{D}^{*0} + c.c. \to \gamma D^0\bar{D}^0$

  C even for $e^+e^- \to D^{*0}\bar{D}^{*0} + c.c \to \gamma\pi^0 D^0\bar{D}^0$

  C odd for $e^+e^- \to D^0\bar{D}^{*0} + c.c. \to \pi^0 D^0\bar{D}^0$

  C odd for $e^+e^- \to D^{*0}\bar{D}^{*0} + c.c \to \gamma\gamma D^0\bar{D}^0$

  C odd for $e^+e^- \to D^{*0}\bar{D}^{*0} + c.c \to \pi^0\pi^0 D^0\bar{D}^0$

Quantum-correlated double decay rates

C-even

$$\Gamma(f_1,f_2) \propto 3(x^2+y^2)(|\lambda_{D^0}|^2+|\lambda_{\bar{D}^0}|^2+2R_{D^0}R_{\bar{D}^0}\lambda_{D^0}\lambda_{\bar{D}^0})$$
$$+(2-3(x^2-y^2))(1+2R_{D^0}R_{\bar{D}^0}\mathrm{Re}(\lambda_{D^0}\lambda_{\bar{D}^0})+|\lambda_{D^0}\lambda_{\bar{D}^0}|^2)$$
$$-4\boldsymbol{y}[R_{\bar{D}^0}(1+|\lambda_{D^0}|^2)\mathrm{Re}(\lambda_{\bar{D}^0})+R_{D^0}(1+|\lambda_{\bar{D}^0}|^2)\mathrm{Re}(\lambda_{D^0})]$$
$$-4\boldsymbol{x}[R_{\bar{D}^0}(1-|\lambda_{D^0}|^2)\mathrm{Im}(\lambda_{\bar{D}^0})+R_{D^0}(1-|\lambda_{\bar{D}^0}|^2)\mathrm{Im}(\lambda_{D^0})]$$

C-odd

$$\Gamma(f_1,f_2) \propto (x^2+y^2)(|\lambda_{D^0}|^2+|\lambda_{\bar{D}^0}|^2-2R_{D^0}R_{\bar{D}^0}\mathrm{Re}(\lambda_{D^0}\lambda_{\bar{D}^0}))$$
$$+(2-(x^2-y^2))(1-2R_{D^0}R_{\bar{D}^0}\mathrm{Re}(\lambda_{D^0}\lambda_{\bar{D}^0})+|\lambda_{D^0}\lambda_{\bar{D}^0}|^2)$$

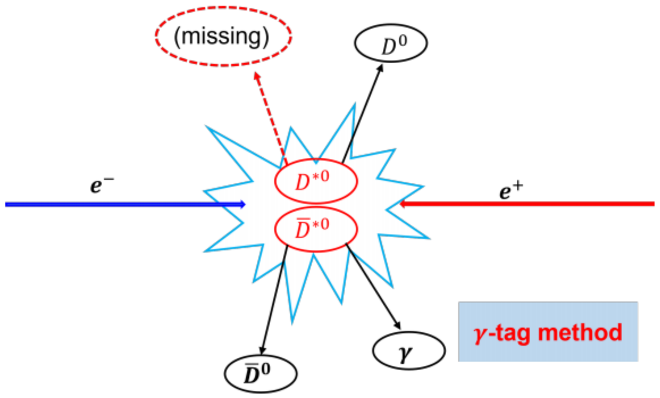
$$\lambda_{D^0} = r_{f_1}\left|\frac{q}{p}\right|e^{-i(\delta_D^{f_1}+\phi)} \qquad \lambda_{\bar{D}^0} = 1/r_{f_2}\left|\frac{p}{q}\right|e^{i(\delta_D^{f_2}+\phi)}$$

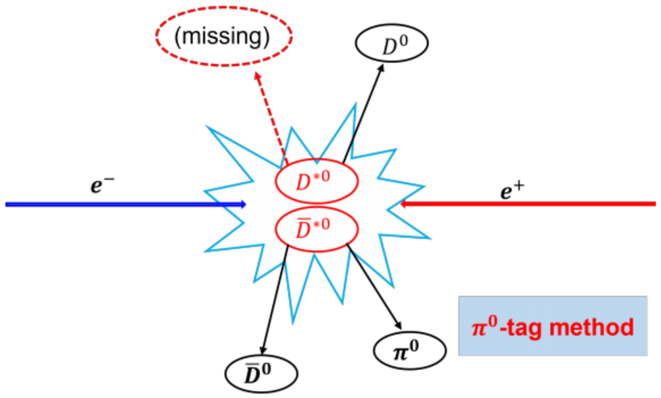
δ_D^f: CP-conserving phase, ϕ: indirect CPV phase, $\left|\frac{p}{q}\right|$: indirect CPV

Exploring the QC in $D^0\bar{D}^0$ decays allows to extract the mixing and CPV parameters along with CP-conserving strong-phase differences with time-integrated decay rates

Analysis strategy

$K^{\mp}\pi^{\pm}\pi^{0}$		tag modes
Flavour	OS	$K^{\pm}\pi^{\mp}\pi^{+}\pi^{-}$, $K^{\pm}\pi^{\mp}\pi^{0}$, $K^{\pm}\pi^{\mp}$
	LS	$K^{\mp}\pi^{\pm}\pi^{+}\pi^{-}$, $K^{\mp}\pi^{\pm}\pi^{0}$, $K^{\mp}\pi^{\pm}$
CP	even	$\pi^{+}\pi^{-}\pi^{0}$, $\pi^{+}\pi^{-}$, $K^{+}K^{-}$
	odd	$K^{0}_{S}\pi^{0}$, $K^{0}_{S}\eta'_{\gamma\pi^{+}\pi^{-}}$
Self-conjugate		$K^{0}_{S}\pi^{+}\pi^{-}$





$$e^+e^- \rightarrow D^0\bar{D}^{*0} + c.c.$$

$$N^{+}_{S,T} = 2N_{D^{*0}\bar{D}^0}\Gamma_{+}(S,T)\epsilon^{+}_{S,T}BF(D^{*0}\rightarrow\gamma D^0)$$

$$N^{-}_{S,T} = 2N_{D^{*0}\bar{D}^0}\Gamma_{-}(S,T)\epsilon^{-}_{S,T}BF(D^{*0}\rightarrow\pi^0 D^0)$$

$$\frac{\Gamma_{+}(S,T)}{\Gamma_{-}(S,T)} = \frac{N^{+}_{S,T}\epsilon^{+}_{S,T}BF(D^{*0}\rightarrow\gamma D^0)}{N^{-}_{S,T}\epsilon^{-}_{S,T}BF(D^{*0}\rightarrow\pi^0 D^0)}$$

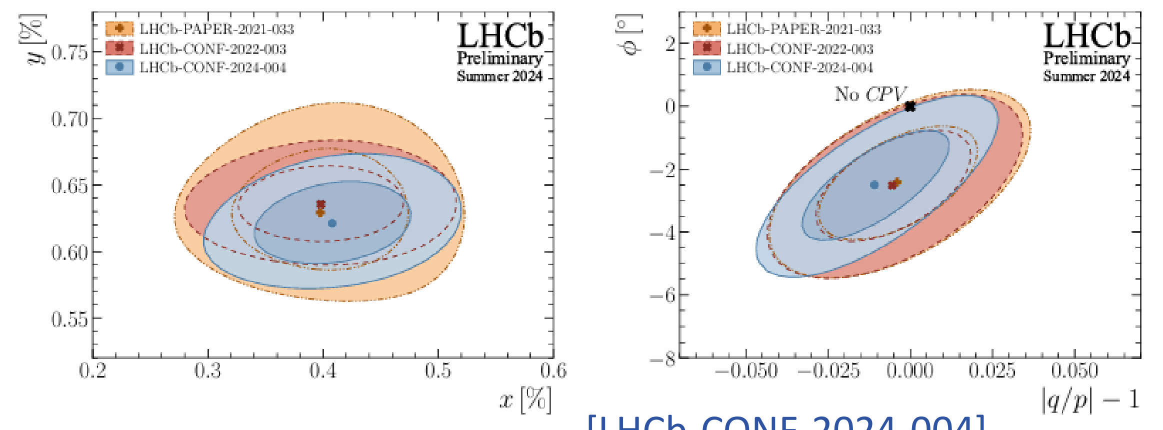
$$e^+e^- \rightarrow D^{*0}\bar{D}^{*0} + c.c$$

$$N^{+}_{S,T} = 2N_{D^{*0}\bar{D}^0}\Gamma_{+}(S,T)\epsilon^{+}_{S,T}BF(D^{*0}\rightarrow\gamma D^0)BF(D^{*0}\rightarrow\pi^0 D^0)$$

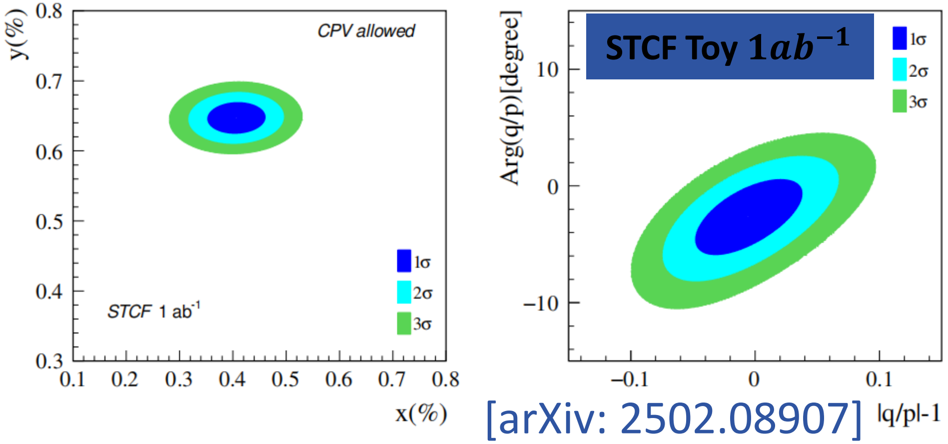
$$N^{-}_{S,T} = N_{D^{*0}\bar{D}^0}\Gamma_{-}(S,T)\epsilon^{-}_{S,T}BF(D^{*0}\rightarrow\pi^0 D^0)\ BF(D^{*0}\rightarrow\pi^0 D^0)$$

$$\frac{\Gamma_{+}(S,T)}{\Gamma_{-}(S,T)} = \frac{N^{+}_{S,T}\epsilon^{+}_{S,T}BF(D^{*0}\rightarrow\pi^0 D^0)}{2N^{-}_{S,T}\epsilon^{-}_{S,T}BF(D^{*0}\rightarrow\gamma D^0)}$$

Status and prospects of charm mixing and indirect CPV



[LHCb-CONF-2024-004]



[arXiv: 2502.08907]

$$x = (4.1 \pm 0.5) \times 10^{-3}$$
$$y = (6.19 \pm 0.21) \times 10^{-3}$$
$$|q/p| = 0.984^{+0.014}_{-0.015}$$
$$\arg(q/p) = (-1.6^{+1.1}_{-1.2})^{o}$$

$$x = (? \pm 0.36) \times 10^{-3}$$
$$y = (? \pm 0.15) \times 10^{-3}$$
$$|q/p| = ? \pm 0.028$$
$$\arg(q/p) = (? \pm 2.14)^{o}$$

- Belle II could finally reach $\sigma(x) \sim 0.028\%$ and $\sigma(y) \sim 0.023\%$ with $K_S^0\pi^+\pi^-$ decay only by scaling the existing measurement results, see also in arXiv: 1808.10567
- As a comparison, $\sigma(x) < 0.005\%$, $\sigma(y) < 0.005\%$, $\sigma(|q/p|) < 0.004$ and $\sigma(\arg(q/p)) < 0.18^{o}$ with $K_S^0\pi^+\pi^-$ decay for LHCb Upgrade II, see also in arXiv: 1808.08865
- By then, STCF could still be critical to provide inputs of strong-phase differences between D^0 and $\overline{D}^0$ decays
- Currently, BESIII provide these inputs to charm mixing and indirect CPV studies in Belle (II) and LHCb

Status and prospects of strong-phase measurements

C-odd correlated $D^0\bar{D}^0$ pairs at BESIII (STCF) is an ideal place to determine the strong-phase parameters and provide best constraints

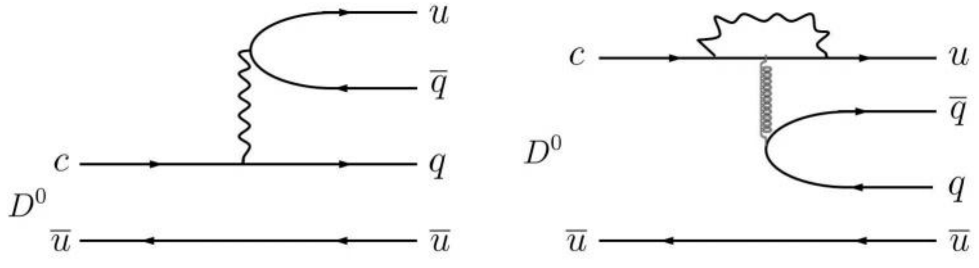
Decay	Strong-phase parameters	2.93 fb^{-1} data	Status
$K^0_{S,L}\pi^+\pi^-$	c_i, s_i	PRL 124 (2020) 241802 PRD 101 (2020) 112002	8 and 20 fb^{-1} ongoing Unbinned phase correction: ongoing
$K^0_{S,L}K^+K^-$	c_i, s_i	PRD 102 (2020) 052008	20 fb^{-1} ongoing Unbinned phase correction: ongoing
$K^\pm\pi^\mp\pi^+\pi^-$	δ_D, R_D	JHEP 05 (2021) 164	8 and 20 fb^{-1} ongoing
$\pi^+\pi^-\pi^+\pi^-$	F^+/c_i, s_i	PRD 106 (2022) 092004 PRD 110 (2024) 112008	20 fb^{-1} ongoing
$K^+K^-\pi^+\pi^-$	F^+/c_i, s_i	PRD 107 (2023) 032009	c_i, s_i: arXiv: 2502.12873
$K^0_S\pi^+\pi^-\pi^0$	F^+/c_i, s_i	PRD 108 (2023) 032003	c_i, s_i: ongoing
$K^\pm\pi^\mp\pi^0$	δ_D, R_D	JHEP 05 (2021) 164	8 and 20 fb^{-1} ongoing
$K^\pm\pi^\mp$	δ_D	EPJC 82 (2022) 1009	20 fb^{-1} ongoing
$K^0_S K^\pm\pi^\mp$	δ_D, R_D	–	20 fb^{-1} ongoing
$\pi^+\pi^-\pi^0$、 $K^+K^-\pi^0$	F^+	PRD 111 (2025) 012007	20 fb^{-1} ongoing

- Integrated luminosity of $\psi(3770)$ data at BESIII has reached 20 fb^{-1} by the year of 2024
- The uncertainty of strong-phase inputs will be further reduced
- STCF will provide more precise inputs for Belle II and LHCb Upgrade

CP Violation in direct charm-meson decays

- CPV in direct decays A and CP-transformed $\bar{A}$
- Non-zero CP-violating phase difference $\xi_j - \xi_k$ and CP-conserving phase difference $\delta_j - \delta_k$

$$A_{CP} = \frac{|A|^2 - |\bar{A}|^2}{|A|^2 + |\bar{A}|^2} = -\frac{2\Sigma|\mathrm{A_j}||A_k|\sin(\xi_j - \xi_k)\sin(\delta_j - \delta_k)}{\Sigma_j|\mathrm{A_j}|^2 + 2\Sigma|\mathrm{A_j}||A_k|\cos(\xi_j - \xi_k)\cos(\delta_j - \delta_k)}$$



LHCb made the first observation

$$\Delta a_{CP}^{\mathrm{dir}} = a_{K^+K^-}^{\mathrm{dir}} - a_{\pi^+\pi^-}^{\mathrm{dir}} = (-1.57 \pm 0.29) \times 10^{-3}$$

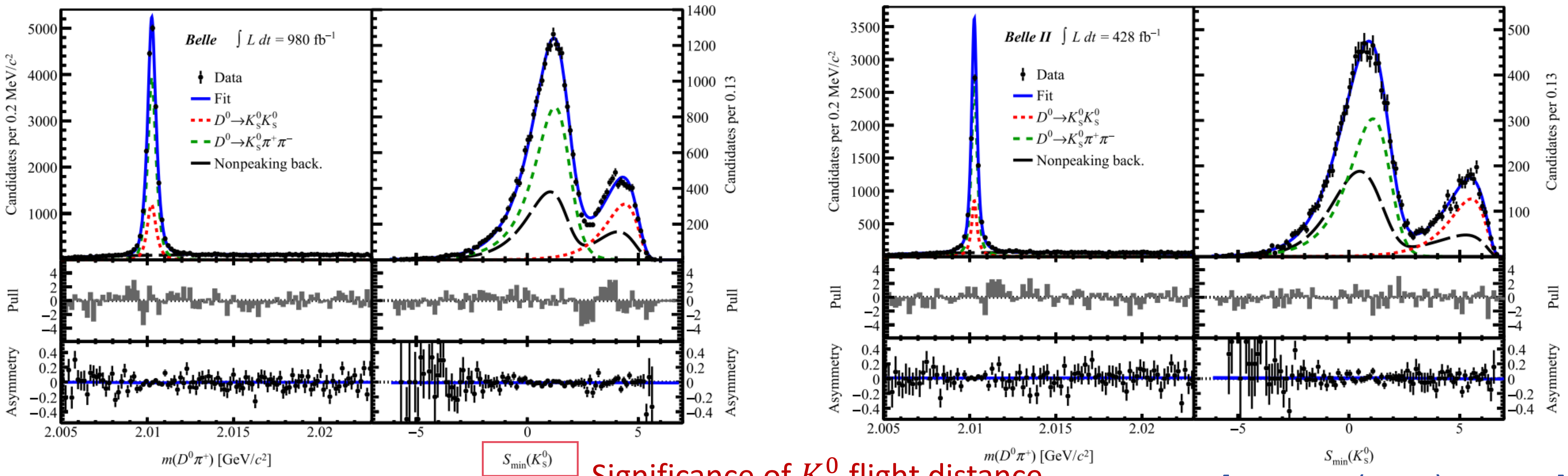
[PRL 122 (2019) 211803]

and first evidence for single decay

$$a_{K^+K^-}^{\mathrm{dir}} = (7.7 \pm 5.7) \times 10^{-4}, \qquad a_{\pi^+\pi^-}^{\mathrm{dir}} = (23.2 \pm 6.1) \times 10^{-4}$$

[PRL 131 (2023) 091802]

Measurement of direct CP asymmetry in $D^0 \to K_S^0 K_S^0$ with Belle and Belle II data



Significance of K_S^0 flight distance

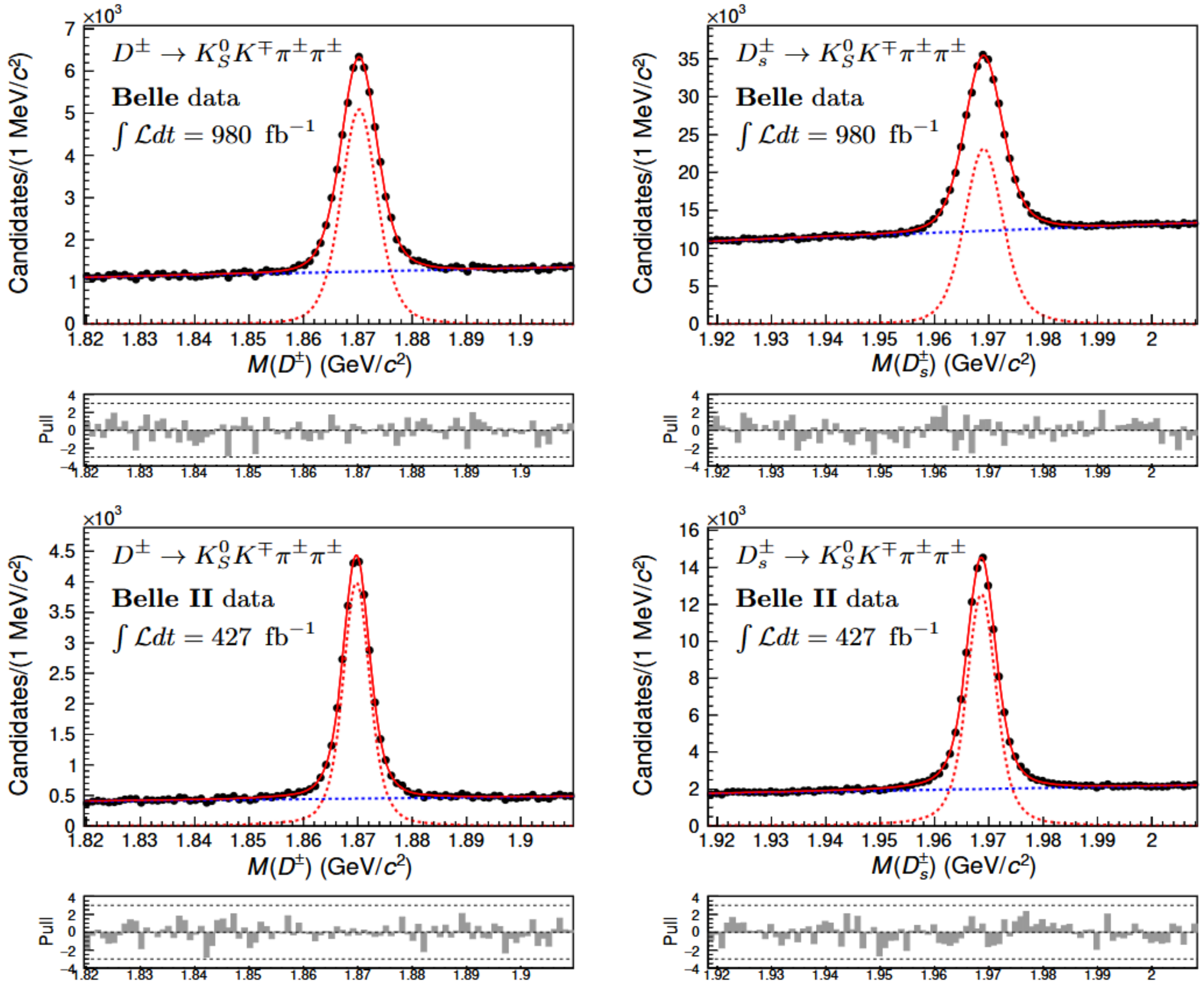
[PRD 111 (2025) 012015]

$$A_{CP}(D^0 \to K_S^0 K_S^0) = \frac{\Gamma(D^0 \to K_S^0 K_S^0) - \Gamma(\bar{D}^0 \to K_S^0 K_S^0)}{\Gamma(D^0 \to K_S^0 K_S^0) + \Gamma(\bar{D}^0 \to K_S^0 K_S^0)} = (-1.4 \pm 1.3 \pm 0.1)\%$$

- Consistent with no CP violation
- $A_{CP}(D^0 \to K_S^0 K_S^0) = (-3.1 \pm 1.2 \pm 0.4 \pm 0.2)$ by LHCb [PRD 104 (2021) L031102] with a significance of 2.4σ

Search for CPV in $D_{(s)}^{+} \to K_S^0 K^- \pi^+ \pi^+$ using triple and quadruple products with Belle and Belle II data

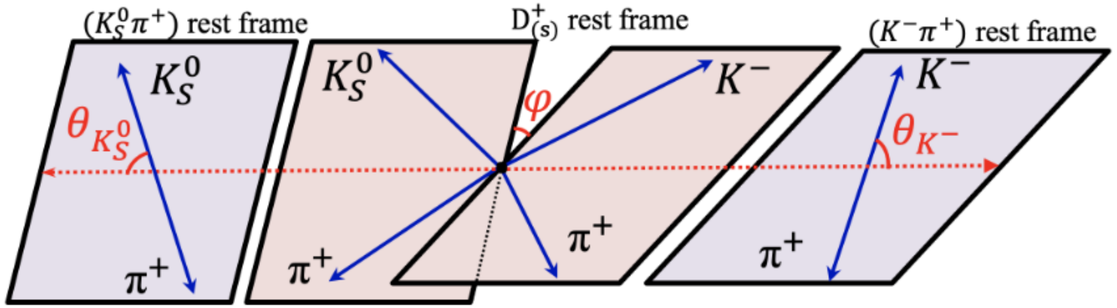
Singly Cabibbo suppressed



Cabibbo favored
No CPV in the SM

[arXiv: 2409.15777]

Search for CPV in $D^+_{(s)} \to K^0_S K^- \pi^+ \pi^+$ using triple and quadruple products with Belle and Belle II data



$$C_{\rm TP} = (\vec{p}_{K^-} \times \vec{p}_{\pi^+_h}) \cdot \vec{p}_{K^0_S}\,,$$
$$C_{\rm QP} = (\vec{p}_{K^-} \times \vec{p}_{\pi^+_h}) \cdot (\vec{p}_{K^0_S} \times \vec{p}_{\pi^+_l})$$

$$A_X(D^+_{(s)}) \equiv \frac{N(D^+_{(s)}, X>0) - N(D^+_{(s)}, X<0)}{N(D^+_{(s)}, X>0) + N(D^+_{(s)}, X<0)}$$

$$A_{\overline{X}}(D^-_{(s)}) \equiv \frac{N(D^-_{(s)}, \overline{X}>0) - N(D^-_{(s)}, \overline{X}<0)}{N(D^-_{(s)}, \overline{X}>0) + N(D^-_{(s)}, \overline{X}<0)}$$

$$\mathcal{A}^X_{CP} \equiv \frac{A_X(D^+_{(s)}) - A_{\overline{X}}(D^-_{(s)})}{2}$$

	X $\times 10^{-3}$	$\mathcal{A}^X_{CP}$ Belle	$\mathcal{A}^X_{CP}$ Belle II	Combined $\mathcal{A}^X_{CP}$	Significance
D^+	$C_{\rm TP}$	$-4.0 \pm 5.9 \pm 3.0$	$-0.2 \pm 7.0 \pm 1.8$	$-2.3 \pm 4.5 \pm 1.5$	0.5σ
	$C_{\rm QP}$	$-1.0 \pm 5.9 \pm 2.5$	$-0.4 \pm 7.0 \pm 2.4$	$-0.7 \pm 4.5 \pm 1.7$	0.2σ
	$C_{\rm TP}\, C_{\rm QP}$	$+6.4 \pm 5.9 \pm 2.2$	$+0.6 \pm 7.0 \pm 1.3$	$+3.9 \pm 4.5 \pm 1.1$	0.8σ
	$\cos\theta_{K^0_S} \cos\theta_{K^-}$	$-4.7 \pm 5.9 \pm 3.0$	$-0.6 \pm 6.9 \pm 3.0$	$-2.9 \pm 4.5 \pm 2.1$	0.6σ
	$C_{\rm TP} \cos\theta_{K^0_S} \cos\theta_{K^-}$	$+1.9 \pm 5.9 \pm 2.0$	$-0.2 \pm 7.0 \pm 1.9$	$+1.0 \pm 4.5 \pm 1.4$	0.2σ
	$C_{\rm QP} \cos\theta_{K^0_S} \cos\theta_{K^-}$	$+14.9 \pm 5.9 \pm 1.4$	$+7.0 \pm 7.0 \pm 1.6$	$+11.6 \pm 4.5 \pm 1.1$	2.5σ
D^+_s	$C_{\rm TP}$	$-0.3 \pm 3.1 \pm 1.3$	$+1.0 \pm 3.9 \pm 1.1$	$+0.2 \pm 2.4 \pm 0.8$	0.1σ
	$C_{\rm QP}$	$+0.6 \pm 3.1 \pm 1.2$	$+2.0 \pm 3.9 \pm 1.4$	$+1.1 \pm 2.4 \pm 0.9$	0.4σ
	$C_{\rm TP}\, C_{\rm QP}$	$+1.5 \pm 3.2 \pm 1.4$	$-2.7 \pm 3.9 \pm 1.7$	$-0.2 \pm 2.5 \pm 1.1$	0.1σ
	$\cos\theta_{K^0_S} \cos\theta_{K^-}$	$-3.7 \pm 3.1 \pm 1.1$	$-6.3 \pm 3.9 \pm 1.2$	$-4.7 \pm 2.4 \pm 0.8$	1.8σ
	$C_{\rm TP} \cos\theta_{K^0_S} \cos\theta_{K^-}$	$-4.4 \pm 3.2 \pm 1.4$	$+0.8 \pm 3.9 \pm 1.4$	$-2.2 \pm 2.5 \pm 1.0$	0.8σ
	$C_{\rm QP} \cos\theta_{K^0_S} \cos\theta_{K^-}$	$-1.6 \pm 3.1 \pm 1.3$	$-0.0 \pm 3.9 \pm 1.7$	$-1.0 \pm 2.4 \pm 1.0$	0.4σ

[arXiv: 2409.15777]

Precision measurement of $\left|V_{cd(s)}\right|$

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

BESIII+B factories+LQCD

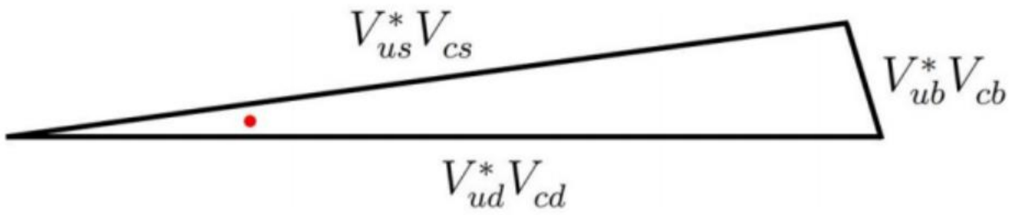
BESIII precision<2%?

$|V_{ud}| = 0.97367(32)$, $|V_{us}| = 0.22431(85)$, $|V_{ub}| = 0.00382(20)$

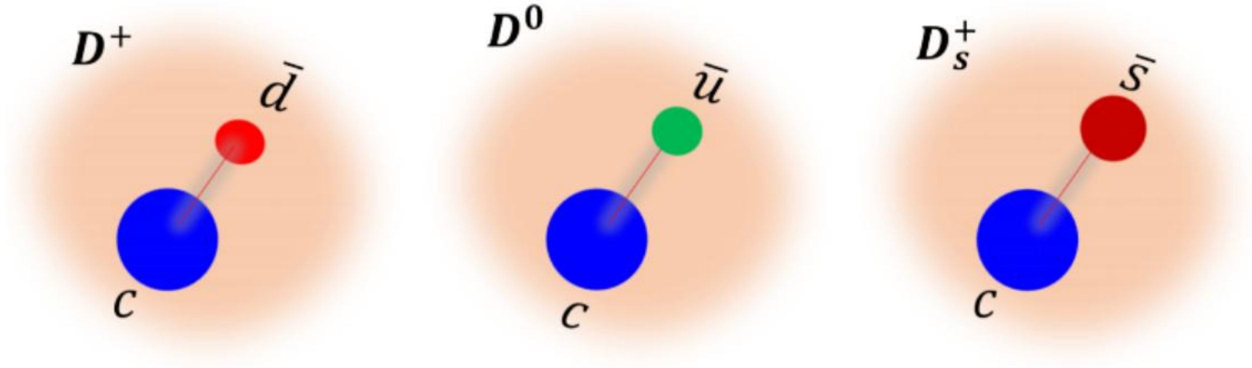
$|V_{cd}| = 0.221(4)$, $|V_{cs}| = 0.975(6)$, $|V_{cb}| = 0.0411(12)$

$|V_{td}| = 0.0086(2)$, $|V_{ts}| = 0.0415(9)$, $|V_{tb}| = 1.010(27)$

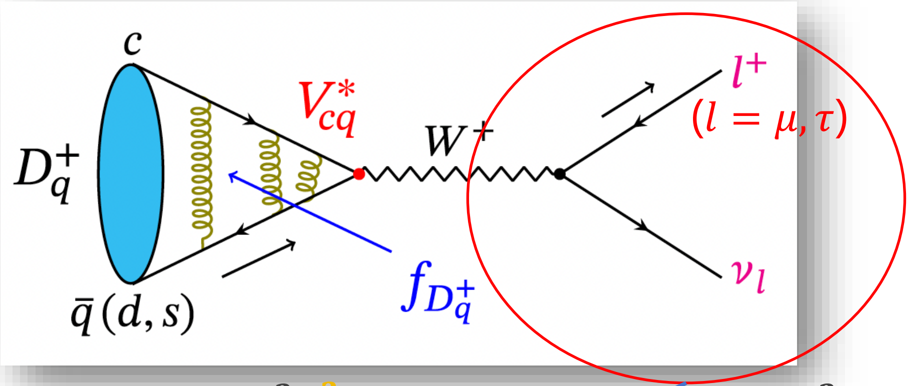
- Precision test of the CKM unitarity is an important approach to search for new physics
- Besides the CP-violating phases in the triangle $V_{ud}^*V_{cd} + V_{us}^*V_{cs} + V_{ub}^*V_{cb} = 0$, $\left|V_{cd(s)}\right|$ are also key parameters



Precision test of lepton flavor universality in charm sector



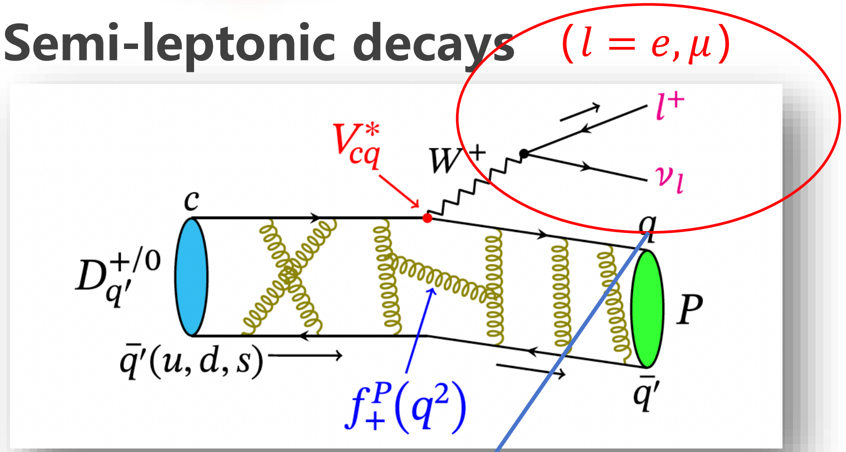
Purely leptonic decays



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

$$\mathcal{R}_{\tau/\mu}=\frac{\mathcal{B}(D^+\to\tau^+\nu_\tau)}{\mathcal{B}(D^+\to\mu^+\nu_\mu)}$$

Semi-leptonic decays

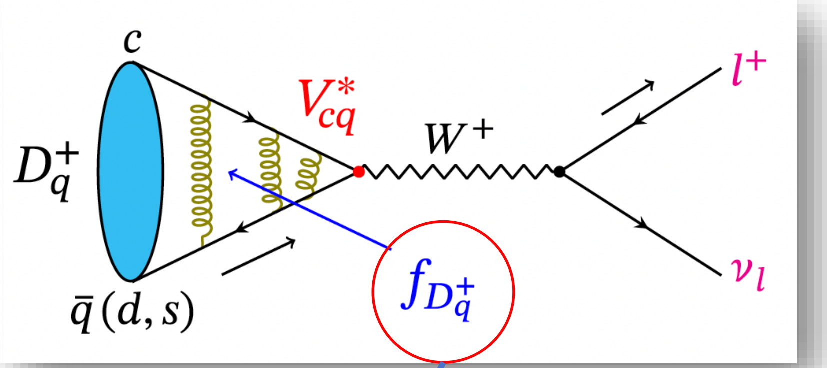


$$\frac{d\Gamma}{dq^2}=x\frac{G_F^2 p^3}{24\pi^3}\left|f_+^P(q^2)\right|^2\left|V_{cd(s)}\right|^2$$

$$\mathcal{R}_{\mu/e}=\frac{\mathcal{B}(D\to X\,\mu^+\nu_\mu)}{\mathcal{B}(D\to X\,e^+\nu_e)}$$

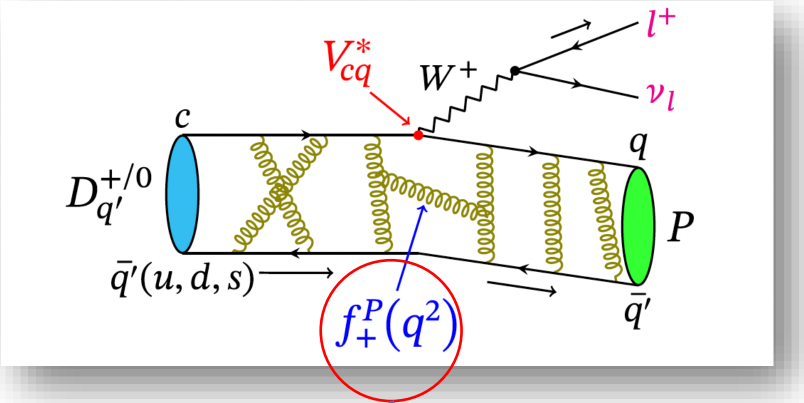
Precision test of LQCD calculations

Purely leptonic decays



$$\Gamma(D^+ \to l^+\nu_l) = \frac{G_F^2 f_{D^+}^2}{8\pi}|V_{cd(s)}|^2 m_l^2 m_{D^+}(1-\frac{m_l^2}{m_{D^+}^2})^2$$

Semi-leptonic decays



$$\frac{d\Gamma}{dq^2} = x\frac{G_F^2 p^3}{24\pi^3}|f_+^P(q^2)|^2|V_{cd(s)}|^2$$

Decay constant

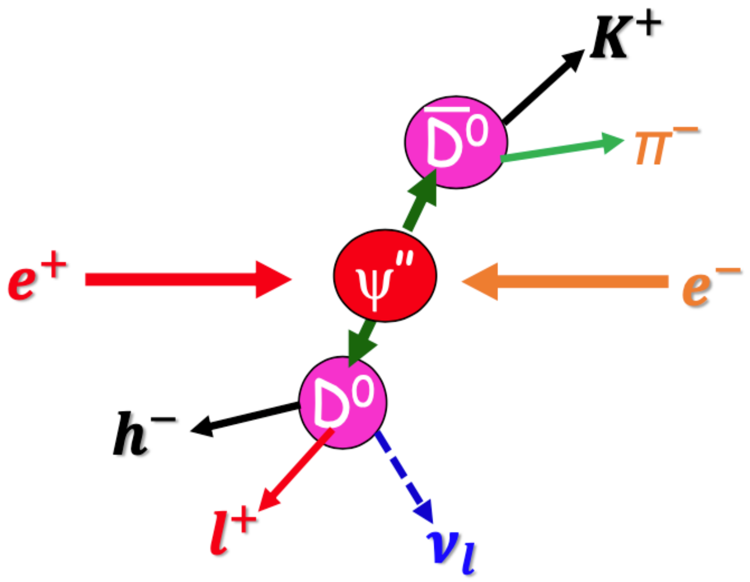
Form factors

LQCD calculations

Probe the nature of light mesons like $f_0(500)$ / $a_0(980)$ / $K_1(1270)$...

- $D \to \ell^+\nu_\ell$
- $D \to$ Pesudoscalar$\ell^+\nu_\ell$
- $D \to$ Vector$\ell^+\nu_\ell$
- $D \to$ Scalar$\ell^+\nu_\ell$
- $D \to$ Axialvector$\ell^+\nu_\ell$

Double tagged D mesons

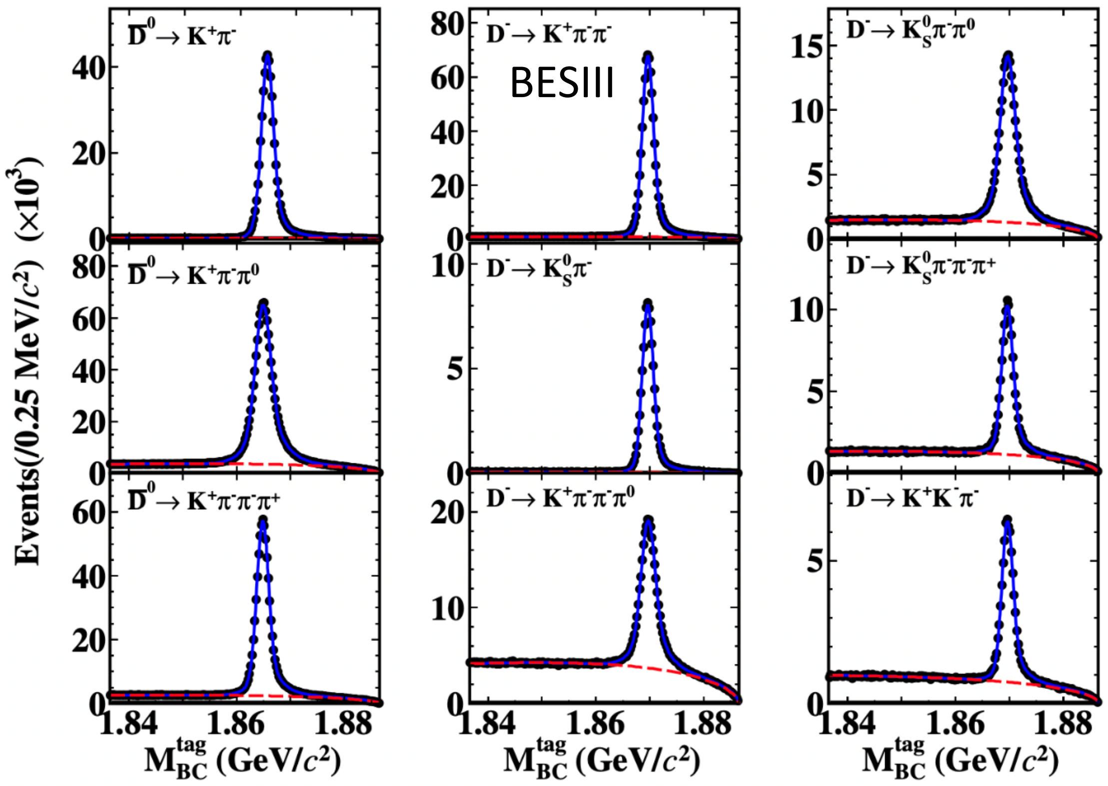


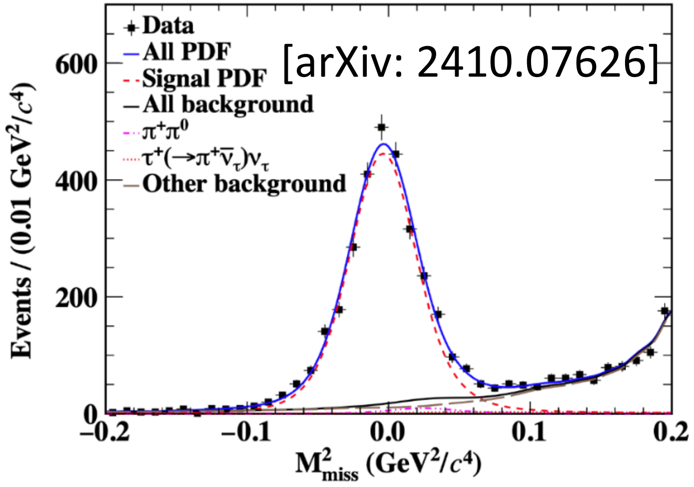
- 20.3 fb^{-1} @3.773GeV
- 7.33 fb^{-1} @4.128-4.226GeV

Reconstruct the missing neutrino

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

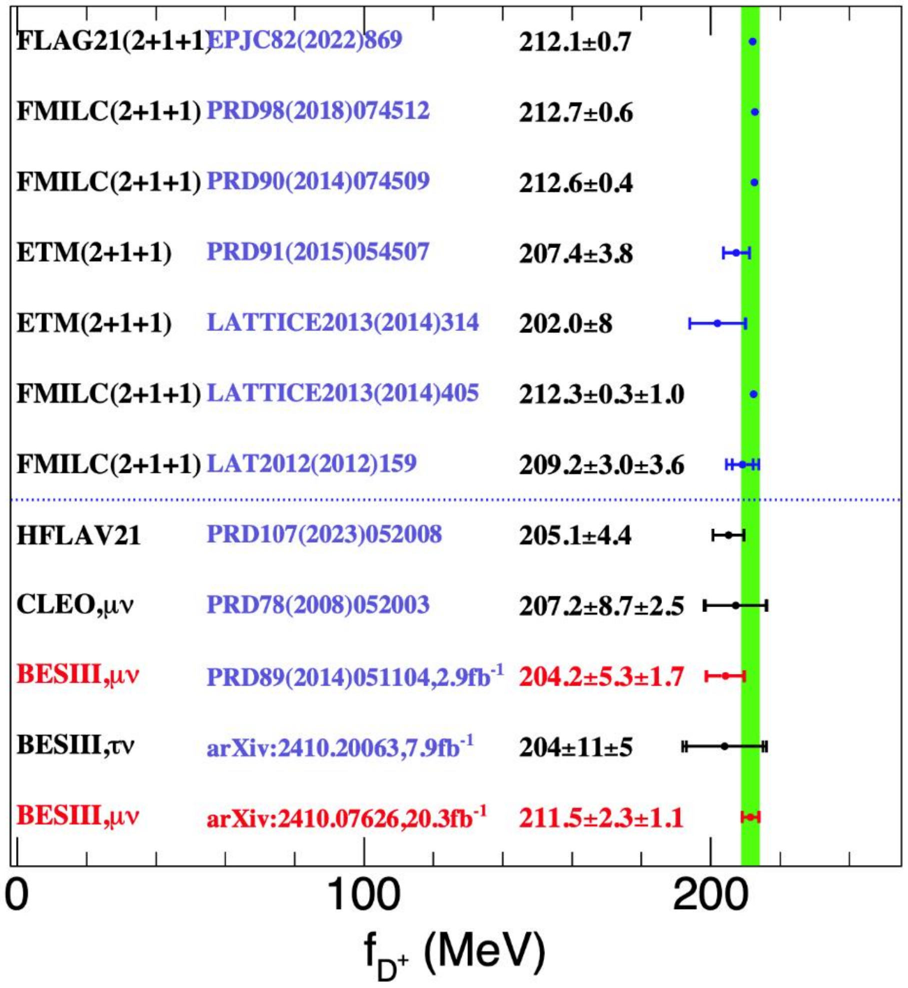
$$M^2_{miss} = E^2_{miss} - |\vec{p}_{miss}|^2$$

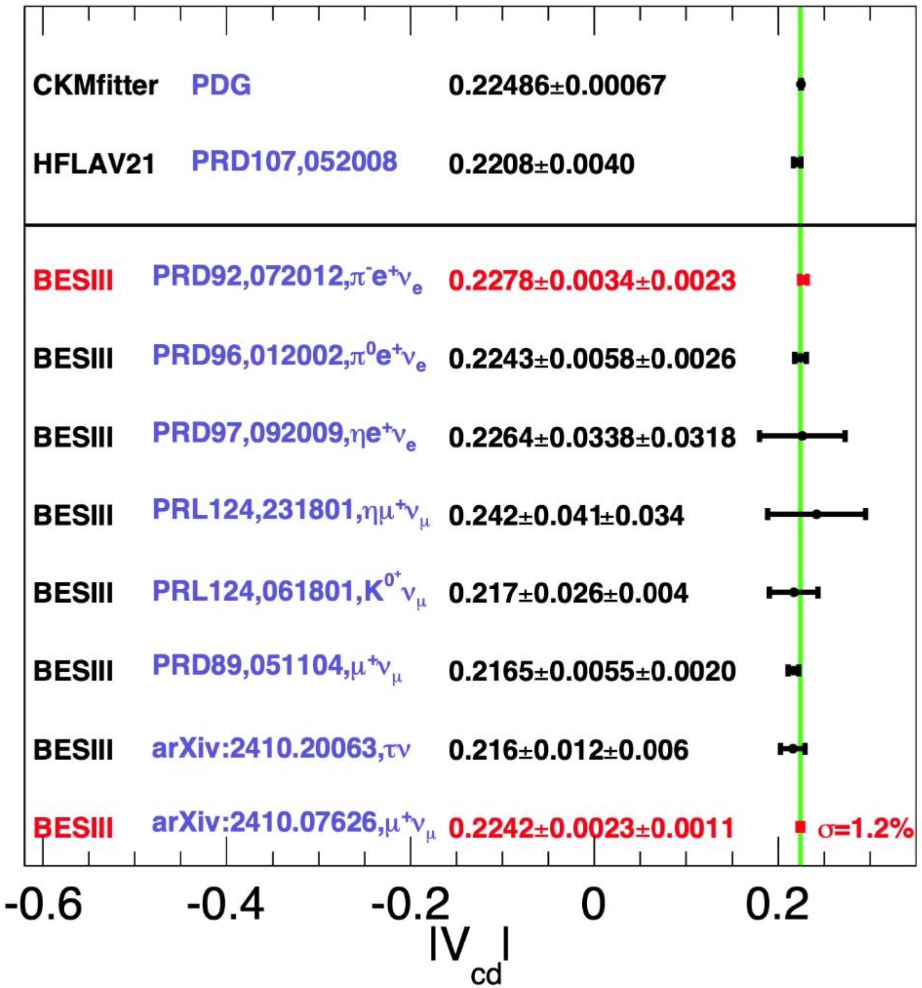




[arXiv: 2410.07626]

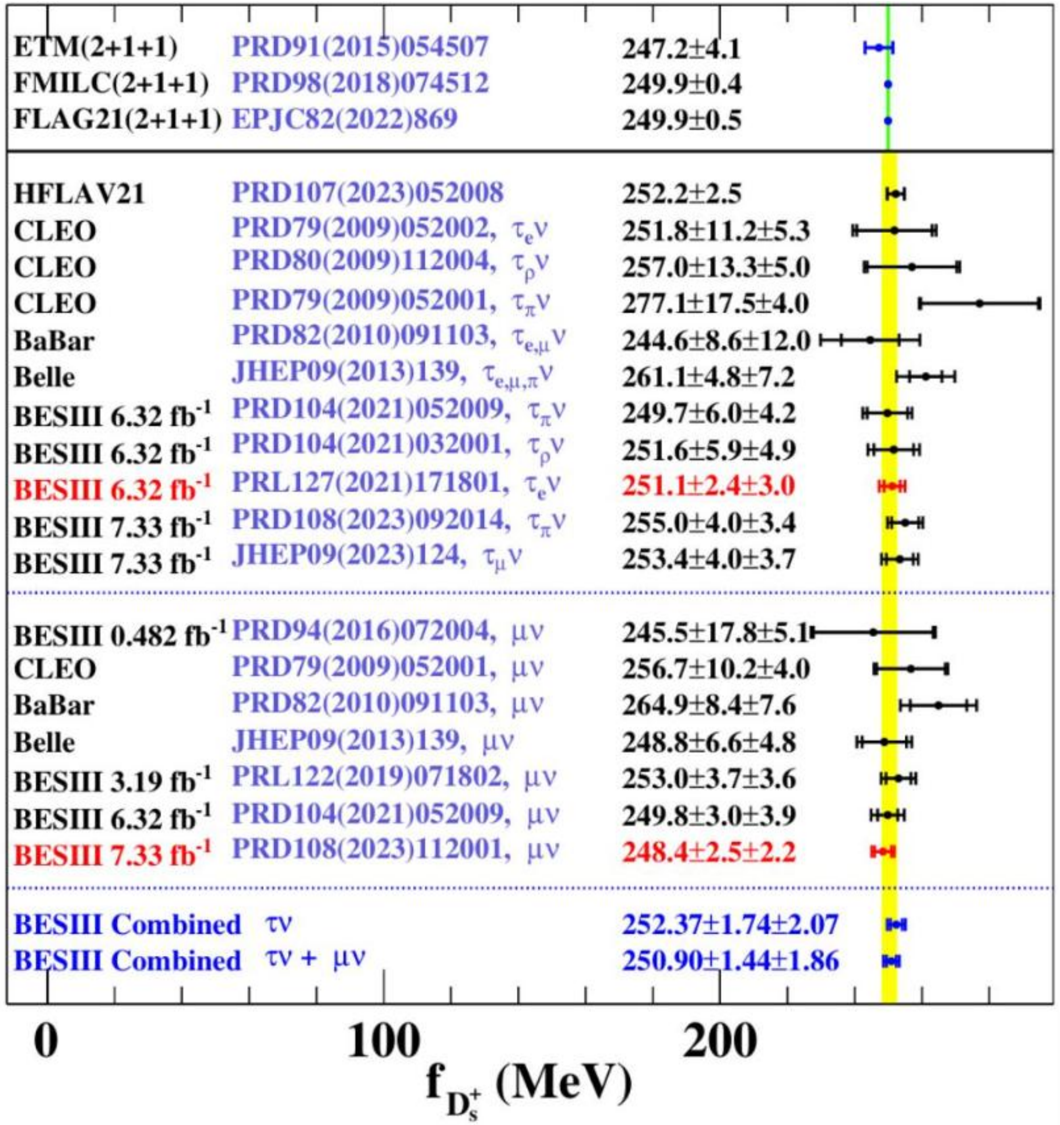
Decay constant f_{D^+} and $|V_{cd}|$ with $D^+ \to l^+\nu_l$

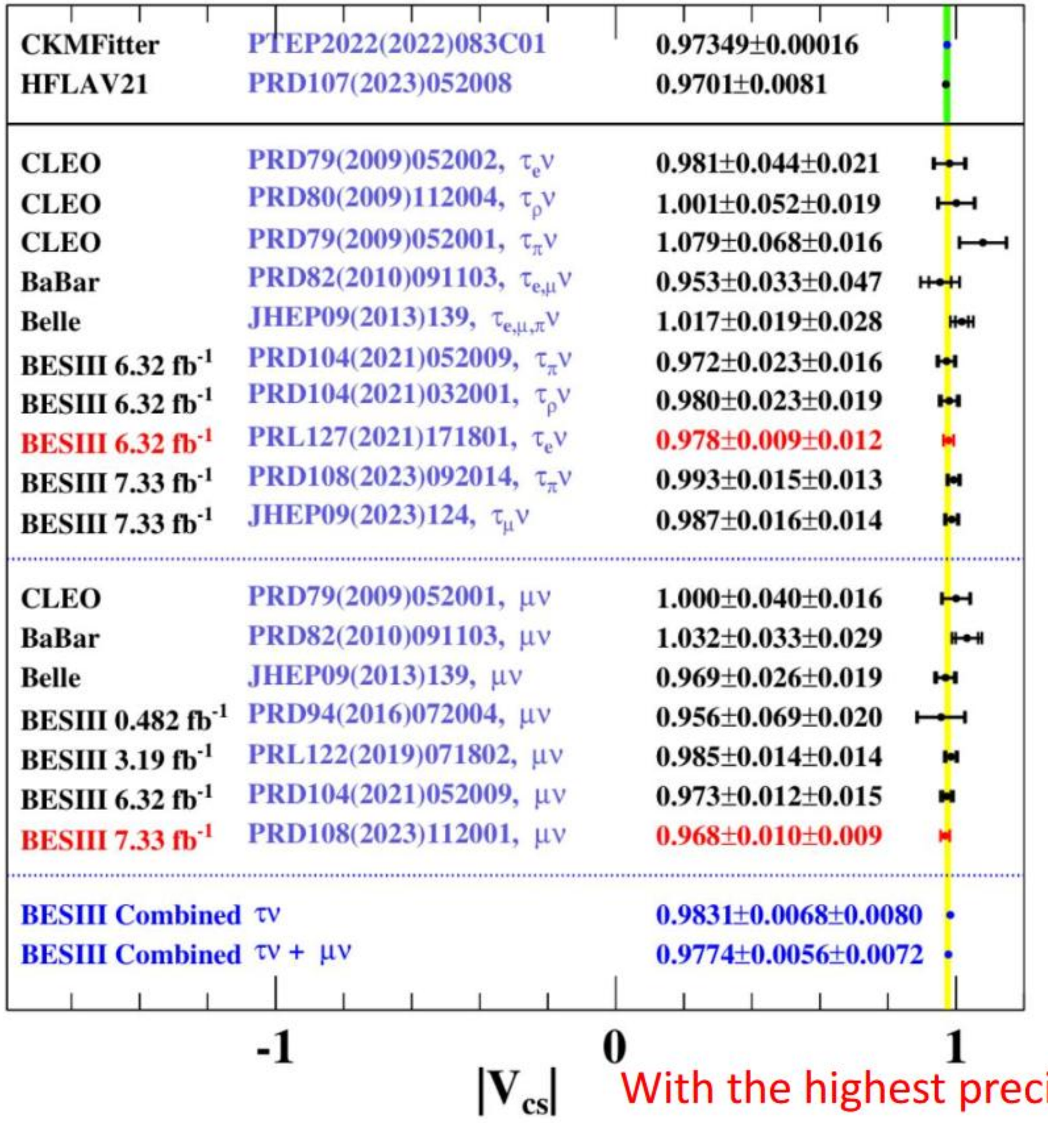




Precision of decay constant and $|V_{cd}|$ reach 1.2%

Decay constant $f_{D_s^+}$ and $|V_{cs}|$ with $D_s^+ \to l^+ \nu_l$





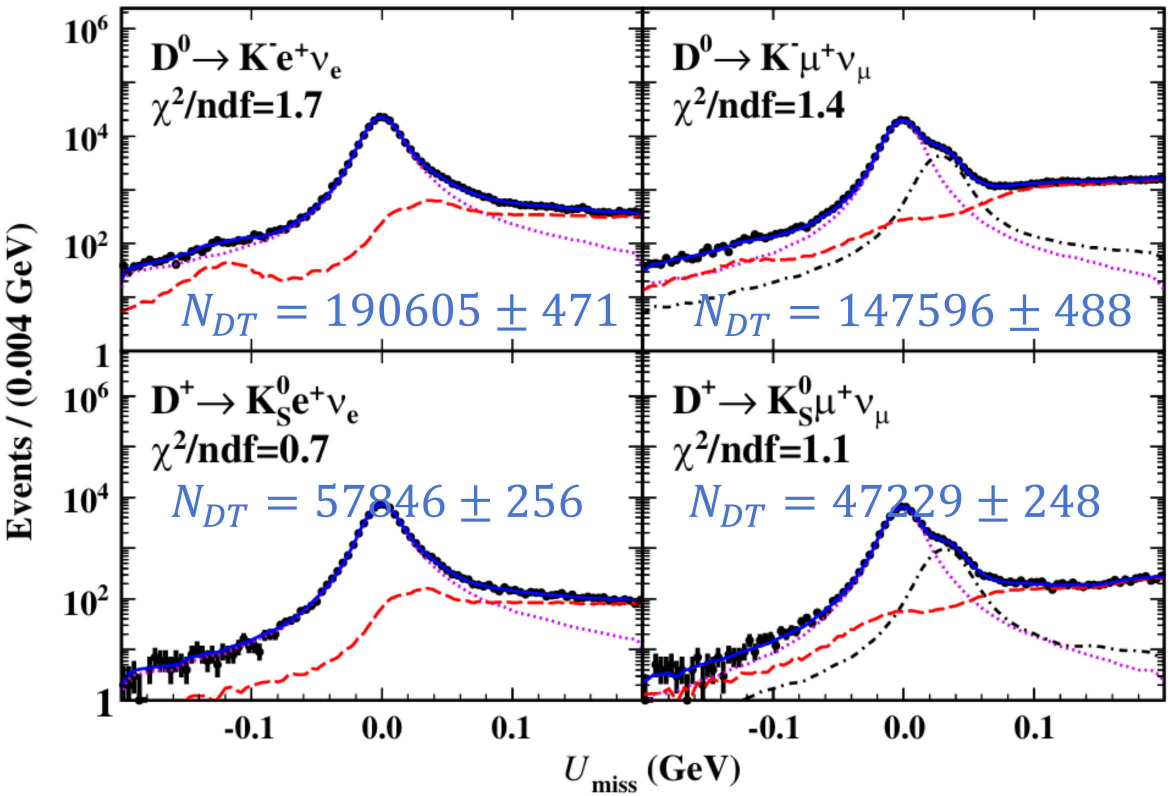
With the highest precision: 0.9%

Study of the $D \to K\ell^+\nu_\ell$ decay

- 7.93 fb^{-1} data @ 3.773 GeV
- $\mathcal{B}(D^0 \to K^- e^+ \nu_e) = (3.521 \pm 0.009 \pm 0.016)\%$
  $\mathcal{B}(D^0 \to K^- \mu^+ \nu_\mu) = (3.419 \pm 0.011 \pm 0.016)\%$
  $\mathcal{B}(D^+ \to \bar{K}^0 e^+ \nu_e) = (8.864 \pm 0.039 \pm 0.082)\%$
  $\mathcal{B}(D^+ \to \bar{K}^0 \mu^+ \nu_\mu) = (8.665 \pm 0.046 \pm 0.084)\%$
- LFU test (SM: 0.975±0.001)

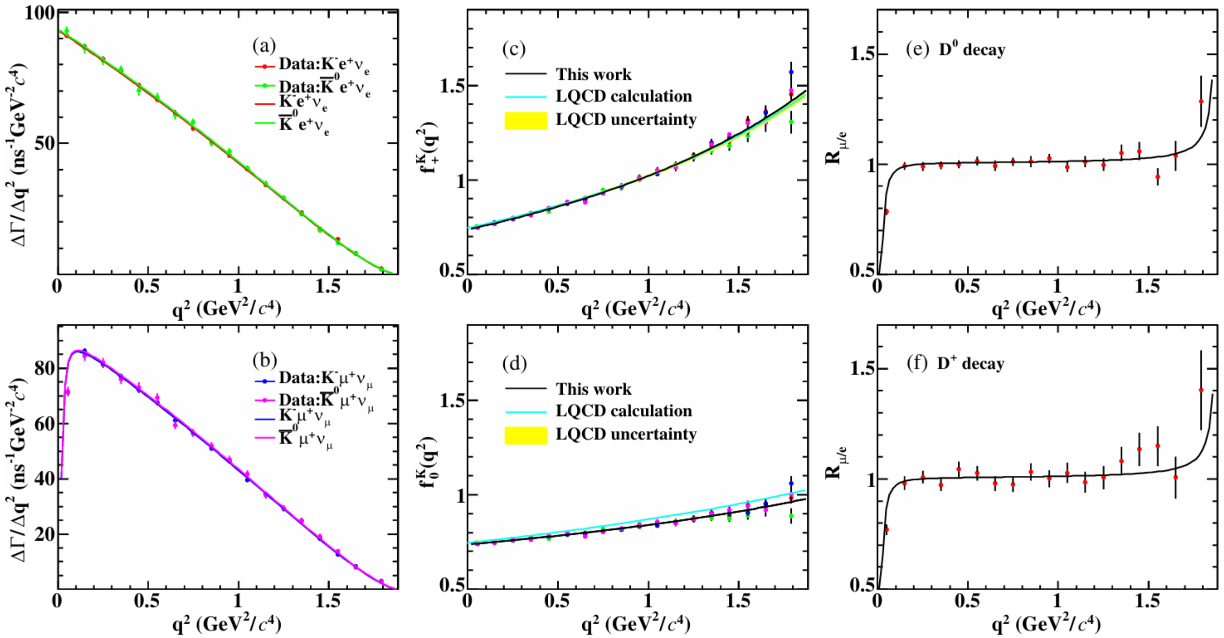
$$\frac{\mathcal{B}(D^0 \to K^- \mu^+ \nu_\mu)}{\mathcal{B}(D^0 \to K^- e^+ \nu_e)} = 0.971 \pm 0.004 \pm 0.006 \ (\sim 0.7\%)$$

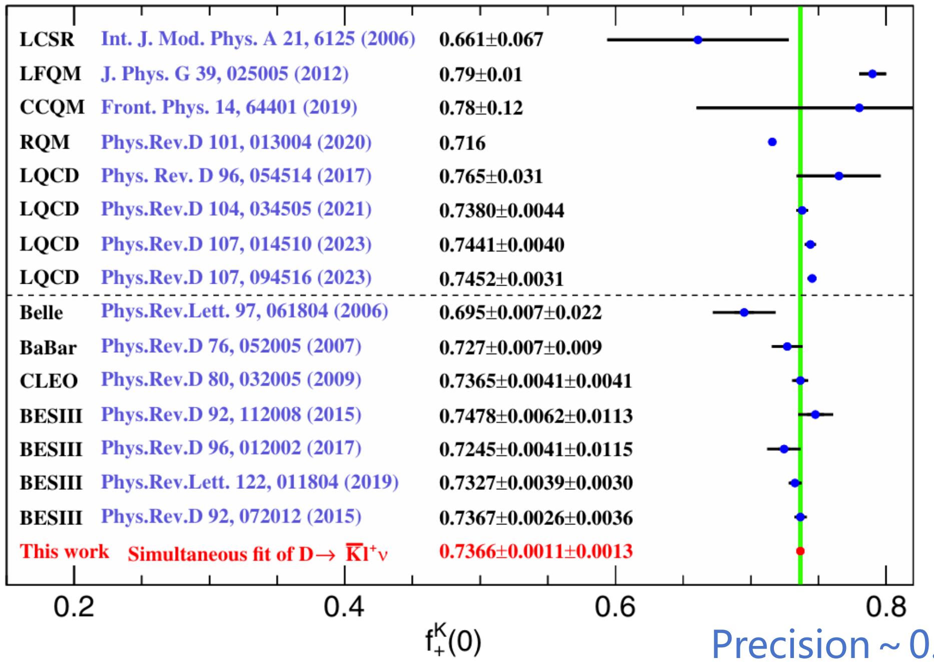
$$\frac{\mathcal{B}(D^+ \to \bar{K}^0 \mu^+ \nu_\mu)}{\mathcal{B}(D^+ \to \bar{K}^0 e^+ \nu_e)} = 0.978 \pm 0.007 \pm 0.013 \ (\sim 1.5\%)$$



[PRD 110 (2024) 112006]

Study of the $D \to K\ell^+\nu_\ell$ decay





Precision ~ 0.4%

[PRD 110 (2024) 112006]

- $f_+^K(0) = 0.7366 \pm 0.0011 \pm 0.0013$, consistent with the LQCD calculation
- $|V_{cs}| = (0.9623 \pm 0.0015 \pm 0.0017 \pm 0.0040\ )\ \mathrm{MeV}$

Summary

- Precision study of charm mixing and CP violation would be one of the most important goals of heavy flavor physics in coming years
- More precise determination of the CKM matrix elements in the charm sector is also essential to test SM
- Charm physics studies at Belle (II) and BESIII (or STCF in the future) are complementary to each other
- There are a lot of other progresses, eg. charmed baryons, rare charm decays etc…
  - See Belle , Belle II, BESIII

Thanks!