Study of $D^0 \to K^+\mu^-\nu_\mu$ in STCF

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Outline

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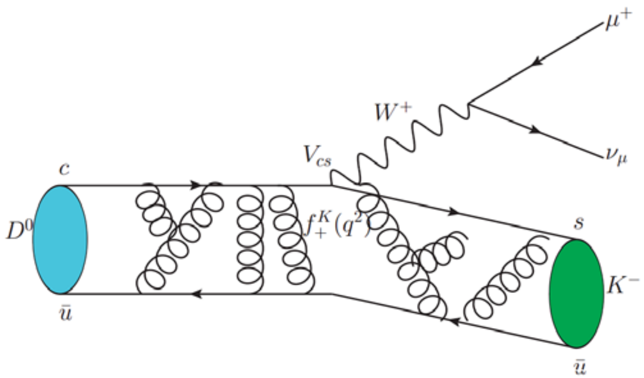
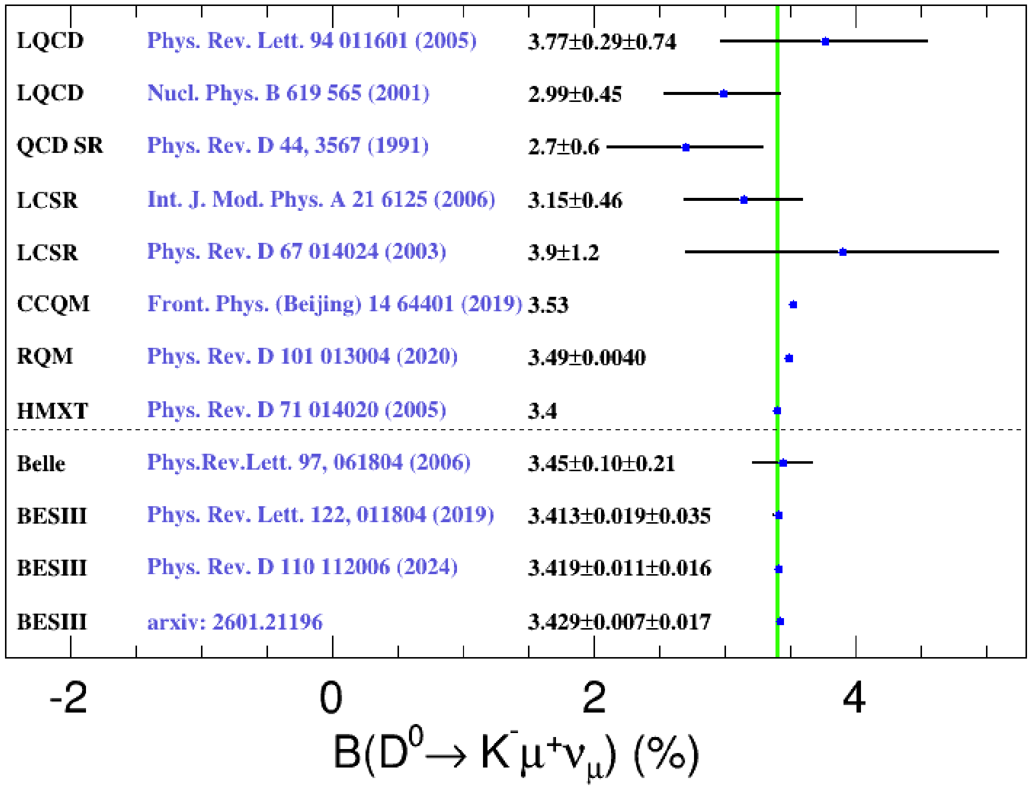
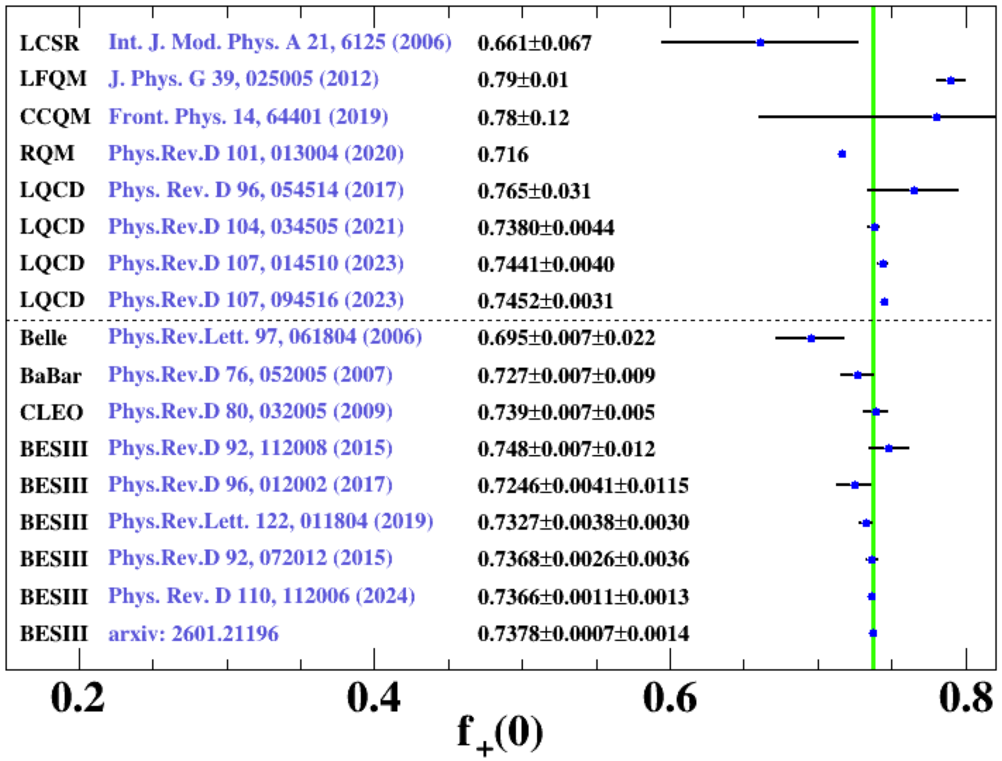


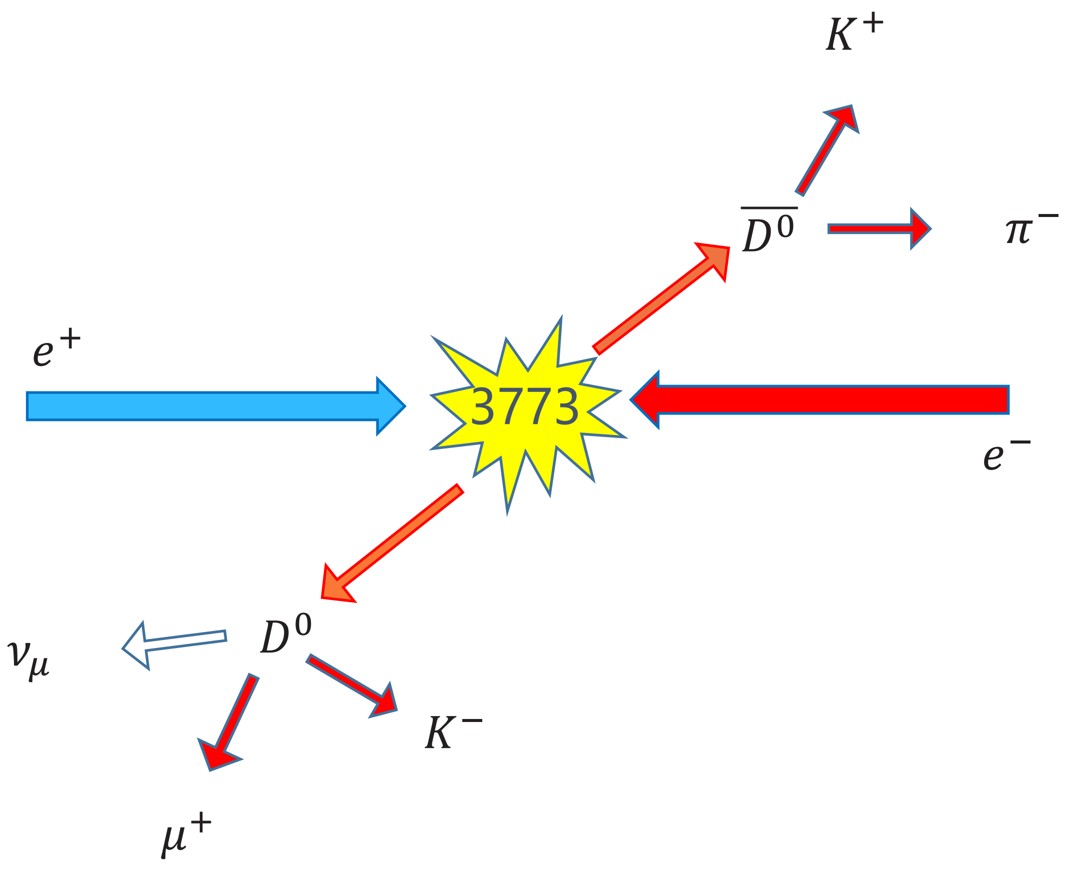
- Semi-leptonic D decays provide a wonderful platform to understand the strong and weak effect in charm physics.
- Experimentally, the study of semileptonic D decays can not only provide a way to measure the hadronic form factors of hadronic currents containing a heavy quark, but also evaluate the CKM matrix elements.
- In separate measurements of the form factors of semileptonic D decays, STCF has the highest accuracy in future.

Motivation


LQCD Phys. Rev. Lett. 94 011601 (2005) 3.77±0.29±0.74
LQCD Nucl. Phys. B 619 565 (2001) 2.99±0.45
QCD SR Phys. Rev. D 44, 3567 (1991) 2.7±0.6
LCSR Int. J. Mod. Phys. A 21 6125 (2006) 3.15±0.46
LCSR Phys. Rev. D 67 014024 (2003) 3.9±1.2
CCQM Front. Phys. (Beijing) 14 64401 (2019) 3.53
RQM Phys. Rev. D 101 013004 (2020) 3.49±0.0040
HMXT Phys. Rev. D 71 014020 (2005) 3.4
Belle Phys.Rev.Lett. 97, 061804 (2006) 3.45±0.10±0.21
BESIII Phys. Rev. Lett. 122, 011804 (2019) 3.413±0.019±0.035
BESIII Phys. Rev. D 110 112006 (2024) 3.419±0.011±0.016
BESIII arxiv: 2601.21196 3.429±0.007±0.017
-2
0
2
4
$B(D^0 \to K^- \mu^+ \nu_\mu)$ (%)


LCSR Int. J. Mod. Phys. A 21, 6125 (2006) 0.661±0.067
LFQM J. Phys. G 39, 025005 (2012) 0.79±0.01
CCQM Front. Phys. 14, 64401 (2019) 0.78±0.12
RQM Phys.Rev.D 101, 013004 (2020) 0.716
LQCD Phys. Rev. D 96, 054514 (2017) 0.765±0.031
LQCD Phys.Rev.D 104, 034505 (2021) 0.7380±0.0044
LQCD Phys.Rev.D 107, 014510 (2023) 0.7441±0.0040
LQCD Phys.Rev.D 107, 094516 (2023) 0.7452±0.0031
Belle Phys.Rev.Lett. 97, 061804 (2006) 0.695±0.007±0.022
BaBar Phys.Rev.D 76, 052005 (2007) 0.727±0.007±0.009
CLEO Phys.Rev.D 80, 032005 (2009) 0.739±0.007±0.005
BESIII Phys.Rev.D 92, 112008 (2015) 0.748±0.007±0.012
BESIII Phys.Rev.D 96, 012002 (2017) 0.7246±0.0041±0.0115
BESIII Phys.Rev.Lett. 122, 011804 (2019) 0.7327±0.0038±0.0030
BESIII Phys.Rev.D 92, 072012 (2015) 0.7368±0.0026±0.0036
BESIII Phys. Rev. D 110, 112006 (2024) 0.7366±0.0011±0.0013
BESIII arxiv: 2601.21196 0.7378±0.0007±0.0014
0.2
0.4
0.6
0.8
$f_+(0)$

Double tag method



- For the i-th tag mode:

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

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

- Measured branching fraction:

$$\mathcal{B}_{\mathrm{sig}} = \frac{\sum_i N^i_{\mathrm{DT}}}{\sum_i N^i_{\mathrm{ST}} \cdot \epsilon^i_{\mathrm{sig}}}$$

where , $\epsilon^i_{\mathrm{sig}} = \dfrac{\epsilon^i_{\mathrm{ST,sig}}}{\epsilon^i_{\mathrm{ST}}}$

MC samples

- OSCAR version： 2.6.2
- Ecm=3.773GeV
- $\overline{D^0} \to K^+\mu^+\nu_\mu$ Signal MC
  $D^0\overline{D^0}$inclusive MC

- Single tag mode

$$D^0 \to K^+\pi^-$$
$$D^0 \to K^-\pi^+\pi^0$$
$$D^0 \to K^-\pi^+\pi^-\ \pi^-$$

Good charged tracks

- $|V_z|$ < 0.5 cm
- $|V_{xy}|$ < 0.1 cm
- $|\cos\theta|$ < 0.94

Good photon

- Barrel E ≥ 25MeV，Endcap E ≥ 50 MeV
- $\theta_{\gamma-\mathrm{charged}} > 10°$
- -10 ≤ t ≤ 10 (ns)

PID (GlobalPID)

μ, π, K
maximum probility

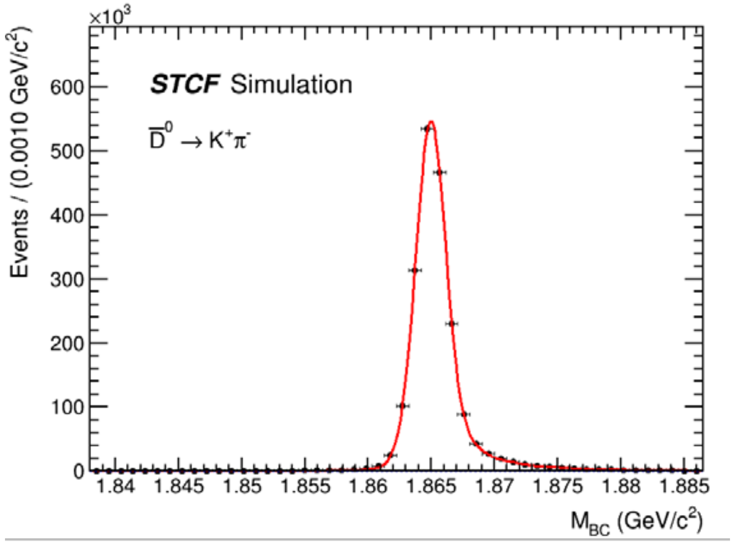
π^0

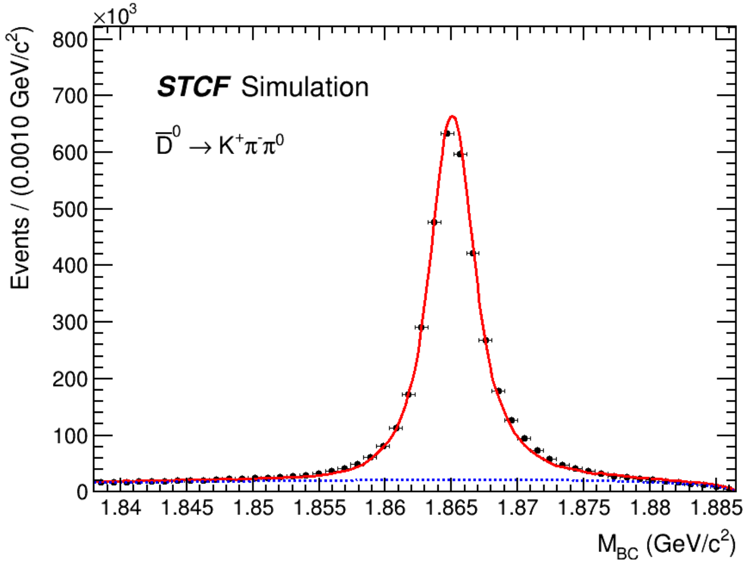
- π^0 : $M(\gamma\gamma) \in (0.115, 0.150)$ GeV/c^2
- $\chi^2_{1C} < 50$

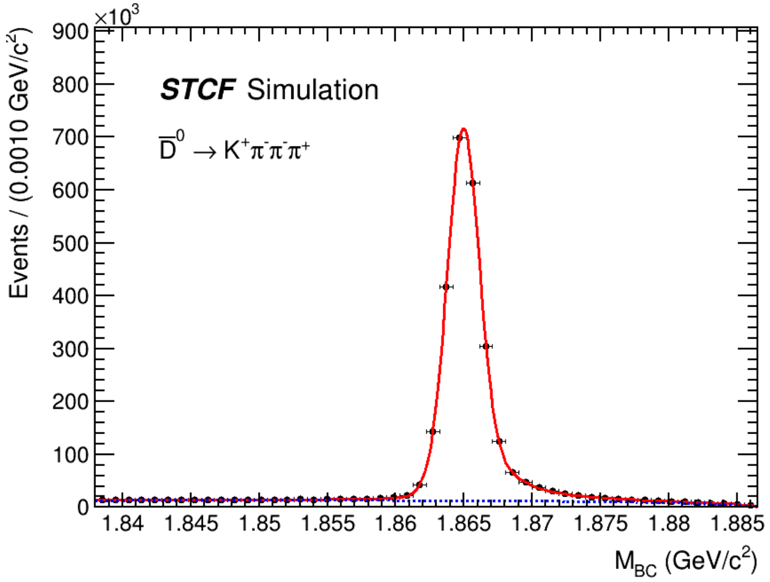
D^0

$$\Delta E = E_{\bar{D}} - E_{\rm beam} \qquad M_{\rm BC} = \sqrt{E_{\rm beam}^2 - |\vec{p}_{\bar{D}}|^2}$$

Tag mode	ΔE (GeV)	$M_{\rm BC}$(GeV/c^2)
$\bar{D}^0 \to K^+\pi^-$	$(-0.027,\ 0.027)$	$(1.859,\ 1.873)$
$\bar{D}^0 \to K^+\pi^-\pi^0$	$(-0.062,\ 0.049)$	$(1.859,\ 1.873)$
$\bar{D}^0 \to K^+\pi^-\pi^-\pi^+$	$(-0.026,\ 0.024)$	$(1.859,\ 1.873)$







Fit mBC distribution using signal MC shape for signal and the ARGUS function for background.

tagmode	ST yield	ST / %
$D^0 \to K^+\pi^-$	1766593±1327	68.44±0.13
$D^0 \to K^-\pi^+\pi^0$	3518035±1970	37.34±0.09
$D^0 \to K^-\pi^+\pi^-\pi^-$	2497258±1703	36.58±0.09

DT analysis

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

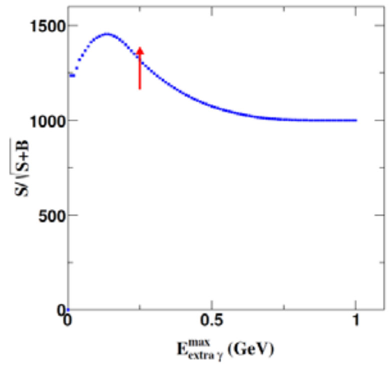
- Good charged track ==2

- PID μ and K (GlobalPID)

K : P_K > P_π & P_K > P_μ >0

μ : P_μ > P_π & P_μ > P_K >0

- $E^{\max}_{\mathrm{extra}\gamma}$ < 0.25 GeV



- We use beam constrained Umiss to obtain the number of signal events.

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

$$E_{\mathrm{miss}} = E_{\mathrm{beam}} - E_K - E_\mu$$

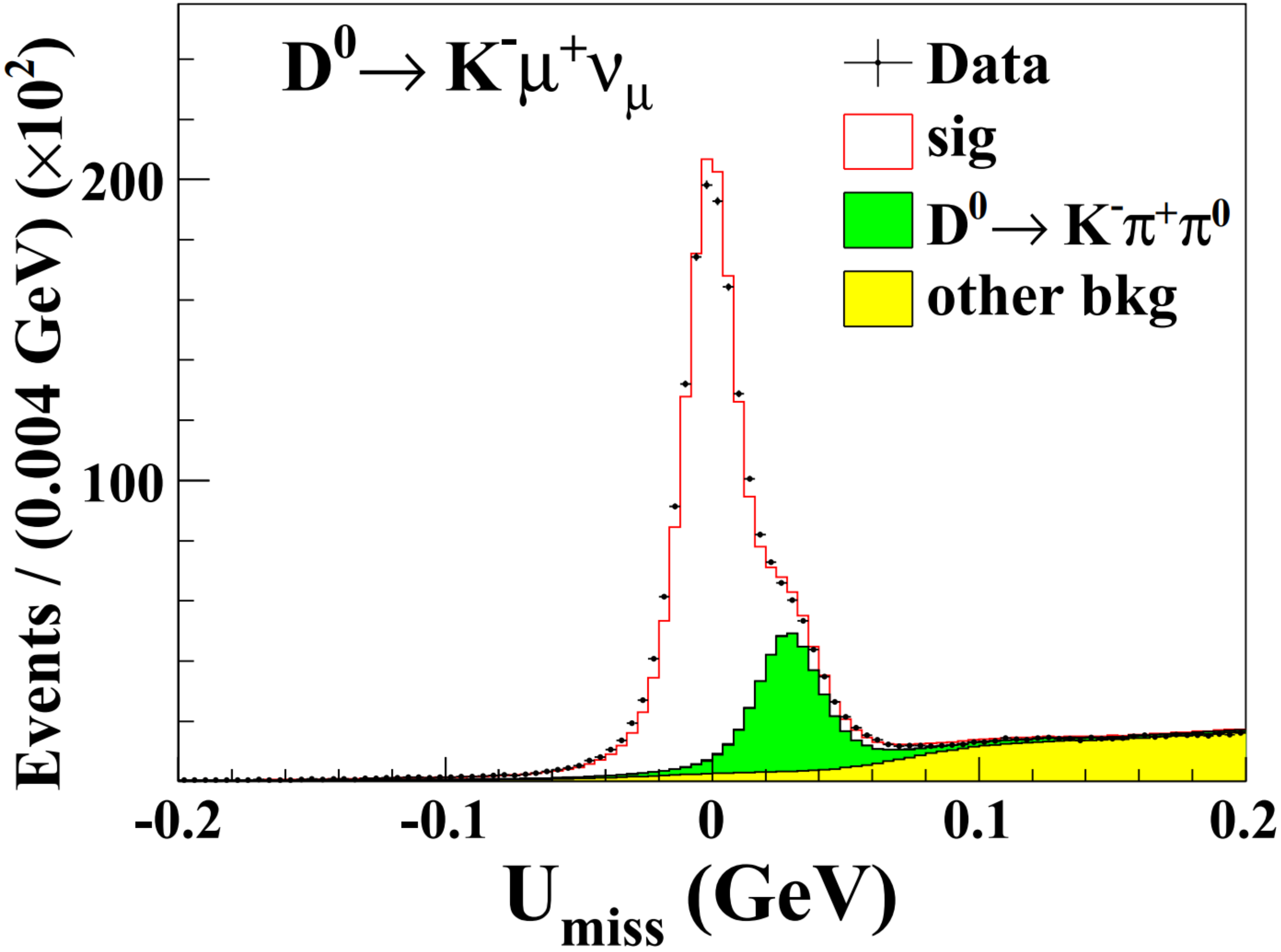
$$\vec{p}_{\mathrm{miss}} = \vec{p}_{D^0} - \vec{p}_K - \vec{p}_\mu$$

$$\vec{p}_{D^0} = -\hat{p}_{\mathrm{tag}}\sqrt{E^2_{\mathrm{beam}} - m^2_{D^0}}$$

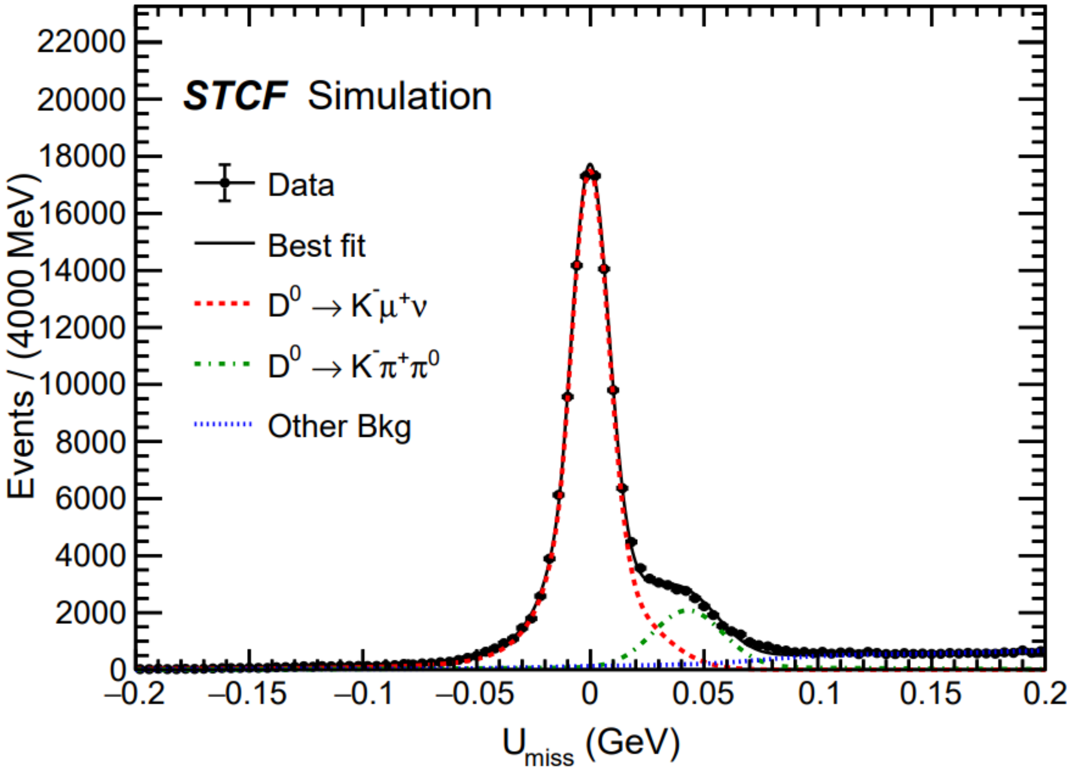
DT efficiencies

Tagmode	DT_eff (%)
$D^0 \to K^-\pi^+$	33.71±0.09
$D^0 \to K^-\pi^+\pi^0$	15.89±0.06
$D^0 \to K^+\pi^-\pi^-\pi^+$	20.85±0.07

DT efficiency get from signal MC


$D^0 \to K^- \mu^+ \nu_\mu$
Data
sig
$D^0 \to K^- \pi^+ \pi^0$
other bkg
Events / (0.004 GeV) ($\times 10^2$)
200
100
-0.2
-0.1
0
0.1
0.2
U_{miss} (GeV)

Sample: $D\overline{D}$ inclusive MC



N_sig = 125686 ± 449

B = (3.38 ± 0.014)%

Input B = 3.41 %

$$\frac{\delta B}{B} = 0.41\%$$

Expend to 1 ab^-1

N_sig = 11311740

err = √ N_sig = 3363

$$\frac{\delta B}{B} = 0.03\%$$

Systematic uncertainty

Source	Uncertainty/%
N tag	0.20
K+ tracking	0.01
K+ PID	0.01
μ+ tracking	0.01
μ+ PID	0.01
E_ex^max gam	0.01
Umiss fit	0.48
MC statistics	0.16

The number of ST D^- candidates

The systematic uncertainty in the fit to the M_{BC} distributions is estimated by varying signal shape and background shape. For the signal shape, we convolve the signal shape with a Gaussian function as a replacement, For the background shape, we vary the endpoint of Argus function from 1.8865 to 1.8864 or 1.8866, and take the difference of 0.2 % as the systematic uncertainty.

μ^+ tracking

This uncertainty is determined using control samples of $e^+e^- \to \gamma\mu^+\mu^-$ by BESIII, and control samples will also be adopted for the same purpose in the future STCF experiment. At present, we estimate it using the normalized luminosity method. With a sample of 20 fb^{-1}, BESIII obtains an uncertainty of 0.06%. When normalized to the expected 1 ab^{-1} sample of the STCF experiment, this uncertainty becomes 0.007%. For conservativeness, we take 0.01%.

μ^+ PID

For the PID uncertainty, we also adopt normalized luminosity method and take 0.01%.

$U^2_{\rm miss}$ fit

To study the systematic uncertainty caused by the signal shape and background shape in the fit, for singnal shape of $D^0 \to K^+\mu^-\nu_\mu$, we use the Gaussian functions to replace the MC shape, The relative change between the remeasured BF and the normal one,is taken as this systematic uncertainty. The systematic uncertainty caused by the signal shape assigned to be 0.35%. For background shape of $D^0 \to K^+\pi^-\pi^0$, we also use the Gaussian functions to replace the MC shape, The relative change between the remeasured BF and the normal one,is taken as this systematic uncertainty. The systematic uncertainty caused by the signal shape assigned to be 0.15%.

For background shape of other backgrounds, we alter the MC samples adopted for shape extraction. The systematic uncertainty caused by the signal shape assigned to be 0.30%.

The tot uncertainty from $U^2_{\rm miss}$ fit is obtained to be 0.48% by adding 0.35%, 0.15% and 0.30% in quadrature.

MC statistics

The uncertainty due to the limited MC statistics is assigned by

$$\sqrt{\frac{\varepsilon \times (1-\varepsilon)}{N}},$$

where the ε is detection efficiency and N is total number of MC events produced. The uncertainties of the MC statistics for both ST and DT MC samples have been considered. We assign 0.16% as the systematic uncertainty due to the MC statistics.

- Based on the MC samples, the ST efficiencies , DT efficiencies , BF are obtained.

- The predicted result shows a large enhancement(from 0.2% to 0.03%) in statistical precision compared to the world's current most accurate result (BESIII).

Current results

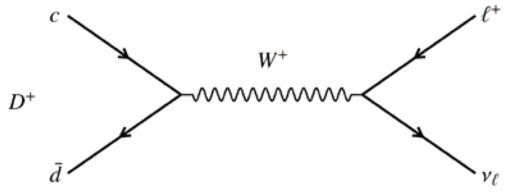
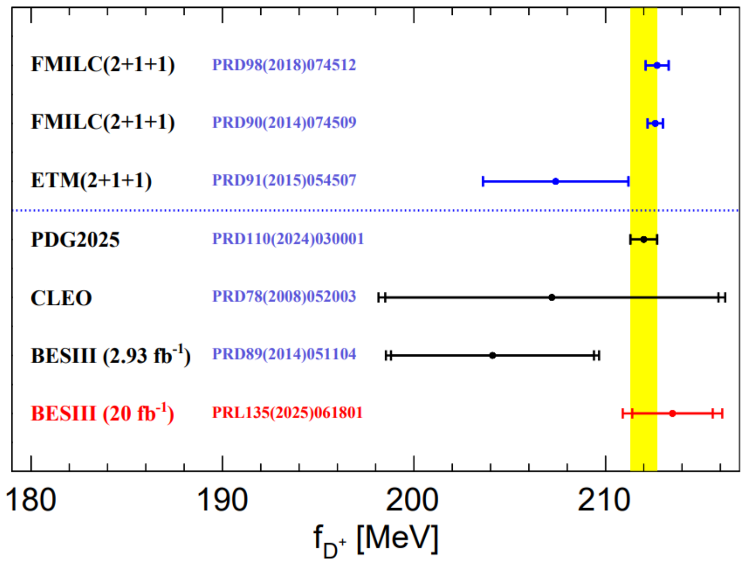
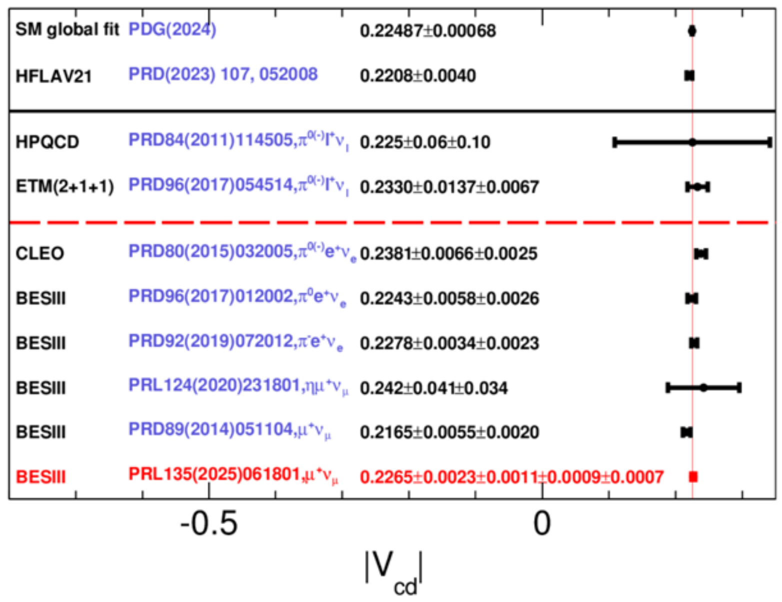


Fig. 1: The Feynman diagram of the leptonic decay $D^+ \to \ell^+ \nu_\ell$.

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

Experiment	$\mathcal{B}(D^+ \to \mu^+ \nu_\mu)$ ($\times 10^{-4}$)	f_{D^+} (MeV/c^2)	$\lvert V_{cd} \rvert$
MARK-III [26]	< 7.2	< 290	–
BESI [27]	8^{+16+5}_{-5-2}	$300^{+180+80}_{-150-40}$	–
BESII [29]	$12.2^{+11.1}_{-5.3} \pm 1.0$	$371^{+129}_{-119} \pm 25$	–
CLEO [30]	$3.5 \pm 1.4 \pm 0.6$	$202 \pm 41 \pm 17$	–
CLEO [31]	$4.40 \pm 0.66^{+0.09}_{-0.12}$	$222.6 \pm 16.7^{+2.8}_{-3.4}$	–
CLEO [32]	$3.82 \pm 0.32 \pm 0.09$	$205.8 \pm 8.5 \pm 2.5$	–
BESIII [33]	$3.71 \pm 0.19 \pm 0.06$	$203.2 \pm 5.3 \pm 1.8$	$0.2210 \pm 0.0058 \pm 0.0047$
BESIII [34]	$3.74 \pm 0.17 \pm 0.06$	$224.5 \pm 22.8 \pm 11.3 \pm 0.9$	–
BESIII [35]	$4.03 \pm 0.08 \pm 0.04$	$213.5 \pm 2.1 \pm 1.1 \pm 0.9$	$0.2265 \pm 0.0024 \pm 0.0011$





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

STCF expectation