Recent results of semi-leptonic *D* decays at BESIII

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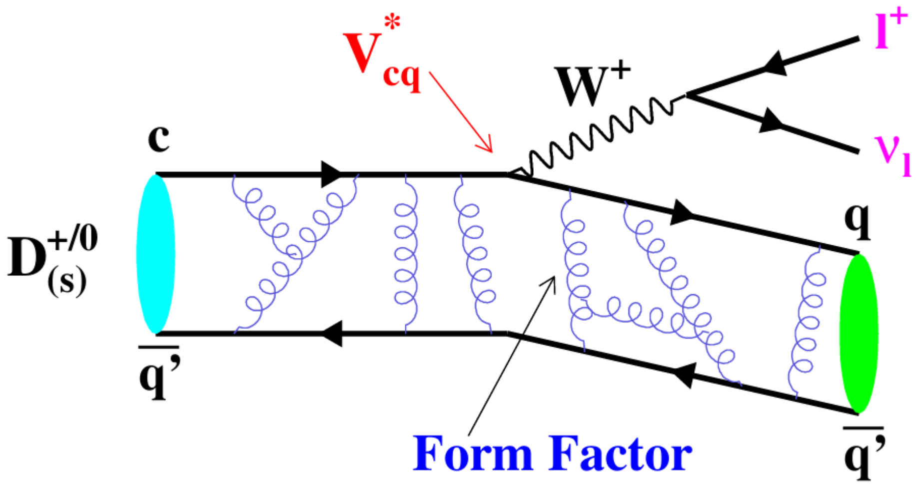
Outline

- Motivations
- BESIII Experiment
- Pseduoscalar: $D \to P\ell^+\nu_\ell$
- Scalar: $D \to S\ell^+\nu_\ell$
- Vector: $D \to V\ell^+\nu_\ell$
- Axial vector: $D \to A\ell^+\nu_\ell$
- Summary & Outlook

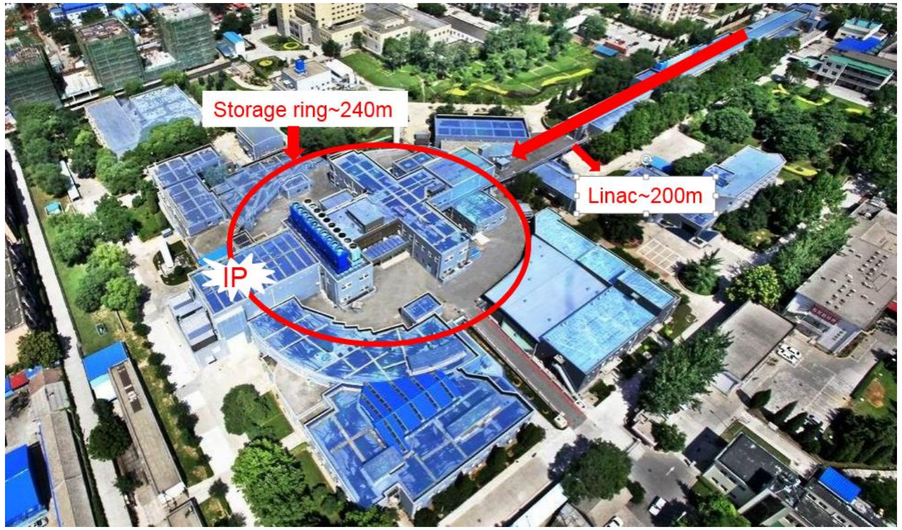
Motivations

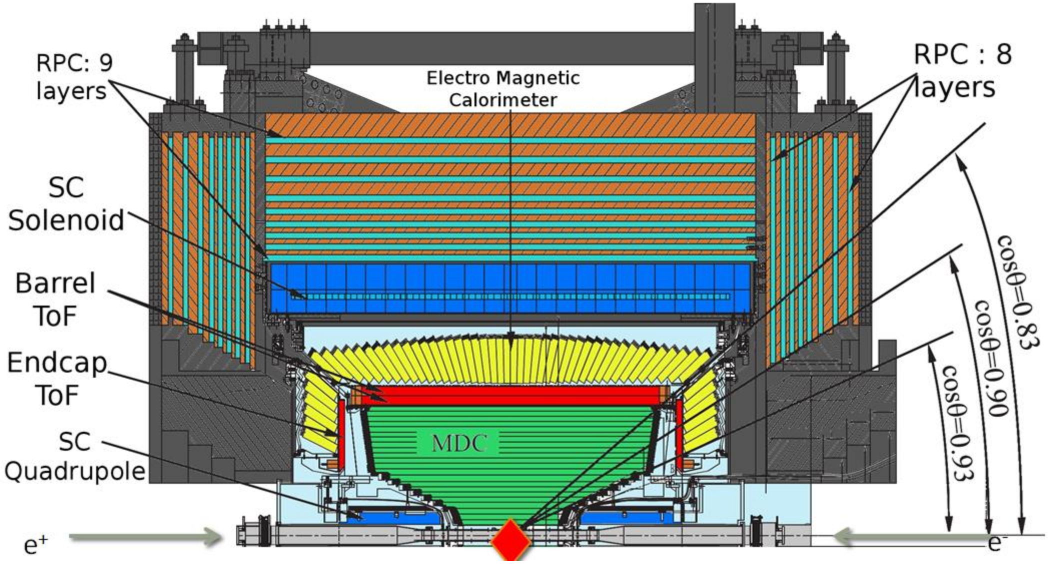
$$M_{fi} = \frac{G_F}{\sqrt{2}} V_{cq} \times \langle P,S,V,A | q\gamma_\mu(1-\gamma_5)c | D \rangle \times \bar{u}_\nu \gamma^\mu (1-\gamma_5) \nu_{\ell^+}$$



- Determination of $|V_{cq}|$: Validation of Unitary of CKM matrix & Basic parameters of SM
- Extraction of Form Factors: Test & Calibrate various theoretical calculations, e.g. LQCD
- Search for BSM: lepton flavor universality & BSM scalar/vector/tensor contributions

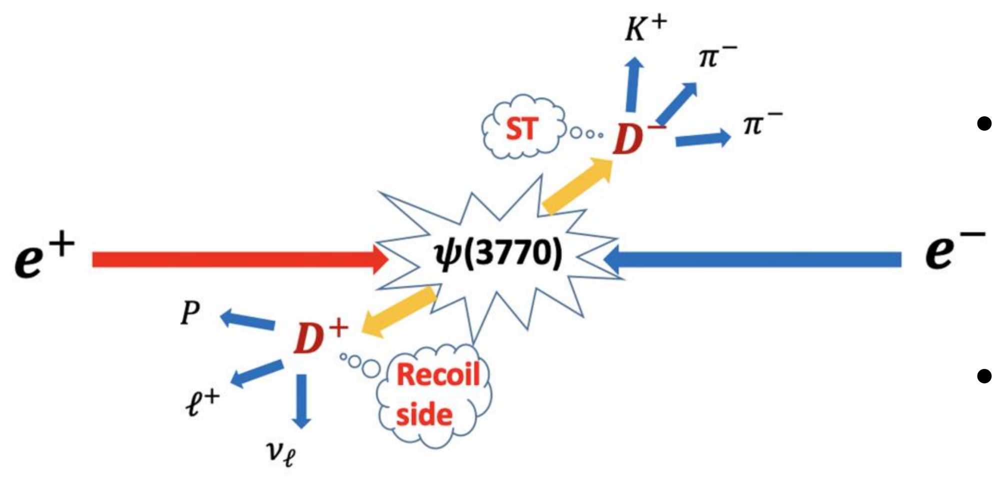
BESIII experiment





- $\sqrt{s} = (1.85 - 4.95)$ GeV
- Peak luminosity: $1.1 \times 10^{33}\ cm^{-2}s^{-1}$ @3.773 GeV
- MDC: $\sigma_p/P = 0.5\%$ @ 1 GeV; $\sigma_{dE/dx} = 6\%$
- TOF: $\sigma_T = 68(110)$ ps for barrel(endcap); endcap upgraded in 2015 $\sigma_T = 110 \rightarrow 68$ ps
- EMC: $\sigma_E/E = 2.5\%\ (5\%)$ for barrel(endcap)

Dataset & Double tag method



- e^+e^- annihilations data near threshold → Double-tag method & Clean environment
- Undetectable neutrinos → extract the (semi-)leptonic signals with

$$U_{miss} = E_{miss} - |\vec{p}_{miss}|, \mathrm{M}^2_{miss} = E^2_{miss} - \left|\vec{P}_{miss}\right|^2$$

- Branching fraction with double tag method: $B = \frac{N_{DT}}{N_{ST}\epsilon_{DT}/\epsilon_{ST}}$

→ cancel most of systematic uncertainties due to ST

Data sample	$E_{\rm cm}$ (GeV)	$\mathcal{L}_{\rm int}$ ($\rm fb^{-1}$)	Single tag yields ($\times 10^6$)
$e^+e^- \to \psi(3770) \to D\bar{D}$	3.773	20.3	$\bar{D}^0$ ~16.9; D^- ~11.0
$e^+e^- \to D_s^{\pm}D_s^{*\mp}$	4.128-4.226	7.33	D_s^- ~0.8
$e^+e^- \to D_s^{*+}D_s^{*-}$	4.237-4.669	10.64	D_s^- ~0.12

Decay formalism of $D \to P/S\ell^+\nu_\ell$

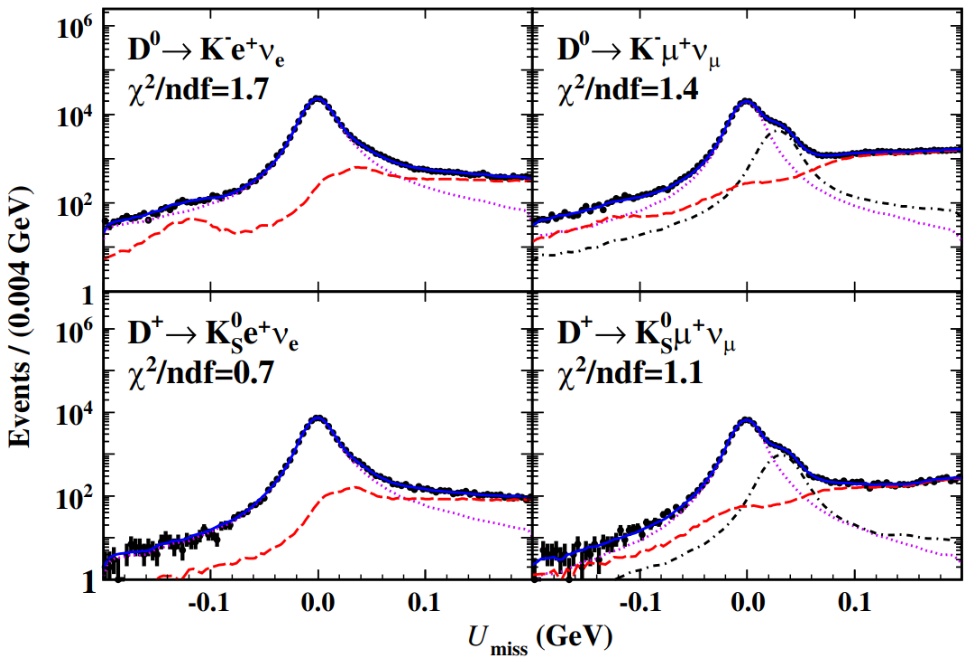
$$\frac{d\Gamma}{dq^2} = \frac{G_F^2|V_{cq}|^2}{24\pi^3}\frac{(q^2 - m_\ell^2)^2|p_X|}{q^4 m_D^2}\left[\left(1 + \frac{m_\ell^2}{2q^2}\right)m_D^2|p_X|^2|f_+^X(q^2)|^2 + \frac{3m_\ell^2}{8q^2}(m_D^2 - m_X^2)^2|f_0^X(q^2)|^2\right]$$

- X indicates (pseduo)-scalar particle
- Two FFs are included in $D \to P/S\ell^+\nu_\ell$: $f_+^X(q^2)$ & $f_0^X(q^2)$ with $f_+^X(0) = f_0^X(0)$
- Parametrization of q^2-dependence:

1. Single pole: $f(q^2) = f(0)/(1 - \frac{q^2}{M_{pole}^2})$
2. Modified pole: $f(q^2) = f(0)/\left(1 - \frac{q^2}{M_{pole}^2}\right)\left(1 - \alpha\frac{q^2}{M_{pole}^2}\right)$
3. Series expansion: $f(q^2) = \frac{1}{P(q^2)\Phi(q^2)}\sum a_k(t_0)[z(q^2, t_0)]^k$

Improved measurements of $D \to \bar{K}\ell^+\nu_\ell$

- Phys. Rev. D 110, 112006 (2024)
- 7.93 fb^{-1} data sample @3.773 GeV
- $\sum N_{DT}$~0.44 M



- Branching fractions:

$$B(D^0 \to K^- e^+ \nu_e) = (3.521 \pm 0.009 \pm 0.016)\%$$
$$B(D^0 \to K^- \mu^+ \nu_\mu) = (3.419 \pm 0.011 \pm 0.016)\%$$
$$B(D^+ \to \bar{K}^0 e^+ \nu_e) = (8.864 \pm 0.039 \pm 0.082)\%$$
$$B(D^+ \to \bar{K}^0 \mu^+ \nu_\mu) = (8.665 \pm 0.046 \pm 0.084)\%$$

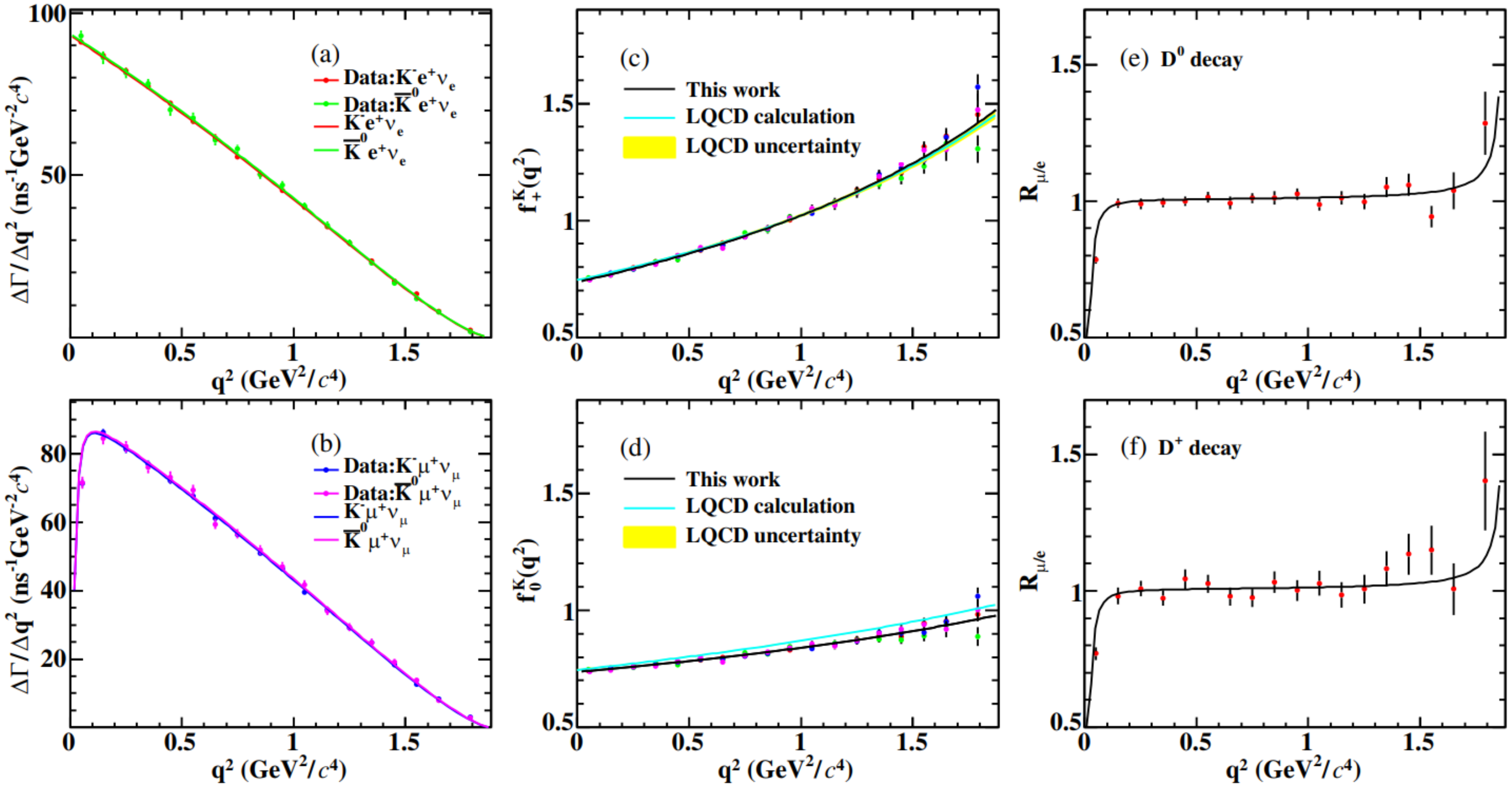
- LFU test: consistent with SM: 0.975 ± 0.001

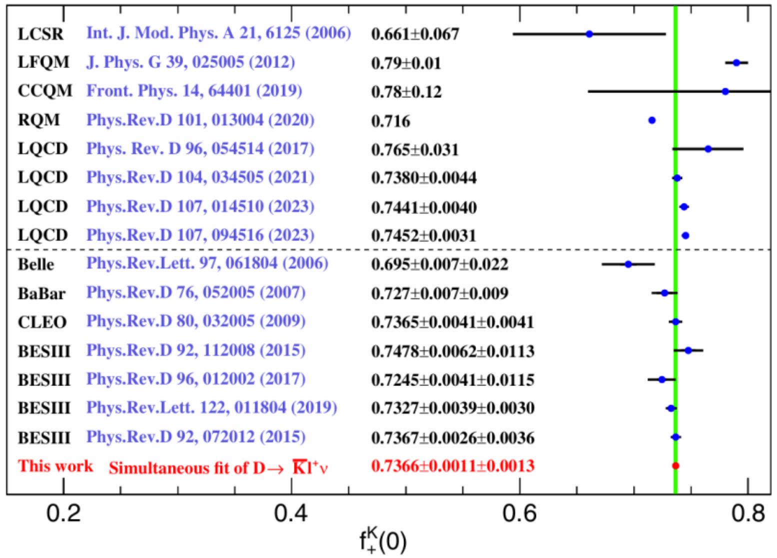
$$\frac{B(D^0 \to K^- \mu^+ \nu_\mu)}{B(D^0 \to K^- e^+ \nu_e)} = 0.971 \pm 0.004 \pm 0.006$$
$$\frac{B(D^+ \to \bar{K}^0 \mu^+ \nu_\mu)}{B(D^+ \to \bar{K}^0 e^+ \nu_e)} = 0.978 \pm 0.007 \pm 0.013$$

- Isospin test: consistent with 1

$$\frac{\Gamma(D^0 \to K^- e^+ \nu_e)}{\Gamma(D^+ \to \bar{K}^0 e^+ \nu_e)} = 1.000 \pm 0.007 \pm 0.012$$
$$\frac{\Gamma(D^0 \to K^- \mu^+ \nu_\mu)}{\Gamma(D^+ \to \bar{K}^0 \mu^+ \nu_\mu)} = 0.993 \pm 0.008 \pm 0.012$$

Improved measurements of $D \to \bar{K}\ell^+\nu_\ell$

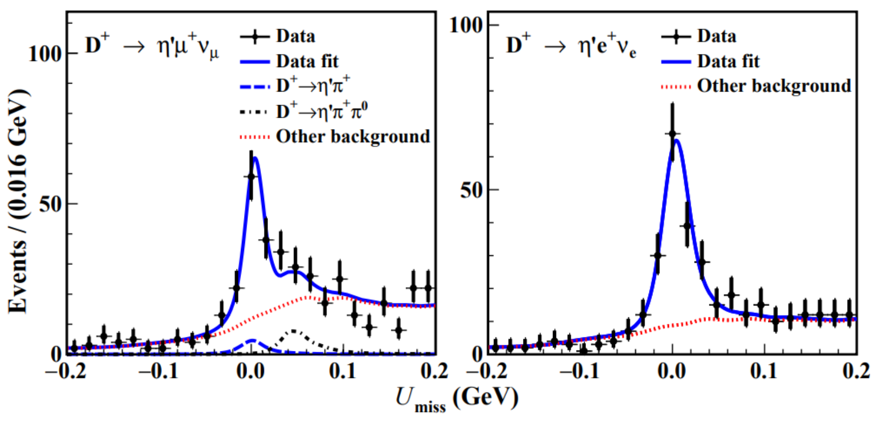


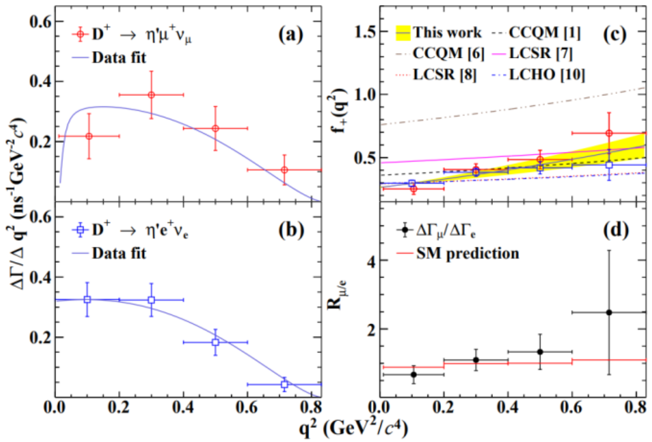


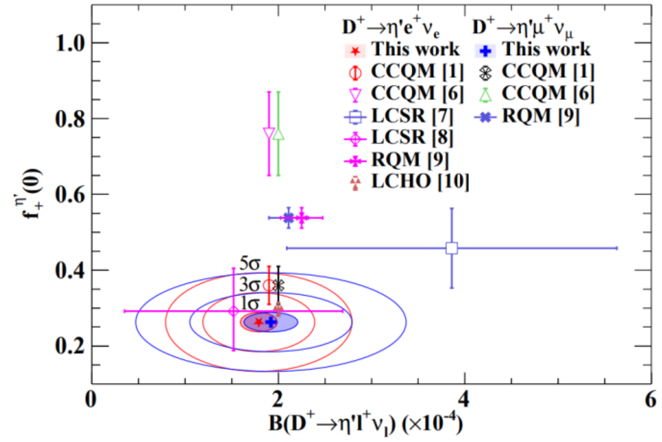
Simultaneous fit to $d\Gamma/dq^2$ to all four channels:

- $f_+^K(0) = 0.7366 \pm 0.0011_{stat.} \pm 0.0013_{syst.}$, precision $0.23\%_{exp.}$
- $|V_{cs}| = 0.9623 \pm 0.0015_{stat.} \pm 0.0017_{syst.} \pm 0.0040_{LQCD}$, precision $0.23\%_{exp.}$ & $0.42\%_{LQCD}$

First study of $D^+ \to \eta' \ell^+ \nu_\ell$ decay dynamics

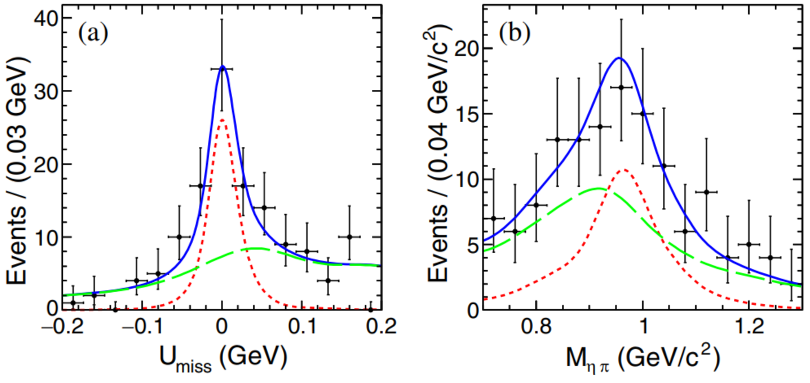


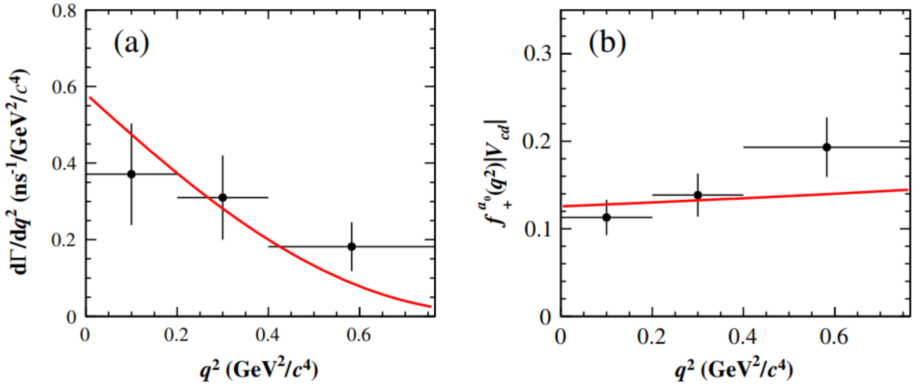


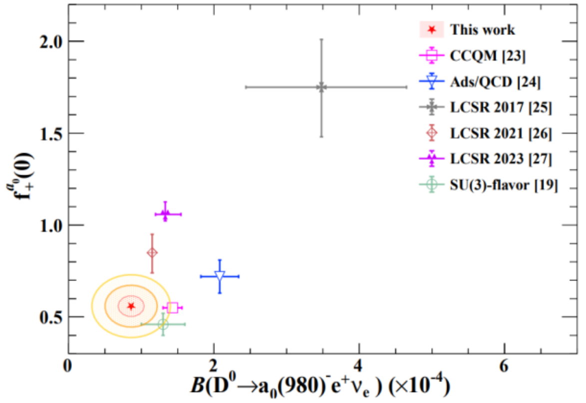


- Phys. Rev. Lett. 134, 111801 (2025) , based on 20.3 fb^{-1} data sample @3.773 GeV, $\sum N_{DT} \sim 240$
- First observation of $D^+ \to \eta' \mu^+ \nu_\mu$ decay with significance 8.6 σ
- First extraction of FF of $D^+ \to \eta' \ell^+ \nu_\ell$: $f_+^{\eta'}(0) = 0.263 \pm 0.025_{stat.} \pm 0.006_{syst.}$
- LFU test $R^{\eta}_{\mu/e} = 1.07 \pm 0.19_{stat.} \pm 0.03_{syst.}$, consistent with SM prediction.
- $\eta - \eta'$ mixing angle: $\cot^4 \phi_p = \frac{\Gamma(D_s^+\to\eta'\ell^+\nu_\ell)/\Gamma(D_s^+\to\eta\ell^+\nu_\ell)}{\Gamma(D^+\to\eta'\ell^+\nu_\ell)/\Gamma(D^+\to\eta\ell^+\nu_\ell)} \to \phi_p = (39.8 \pm 0.8 \pm 0.3)^\circ$

Updated measurement of $D^0 \to a_0(980)^- e^+ \nu_e$



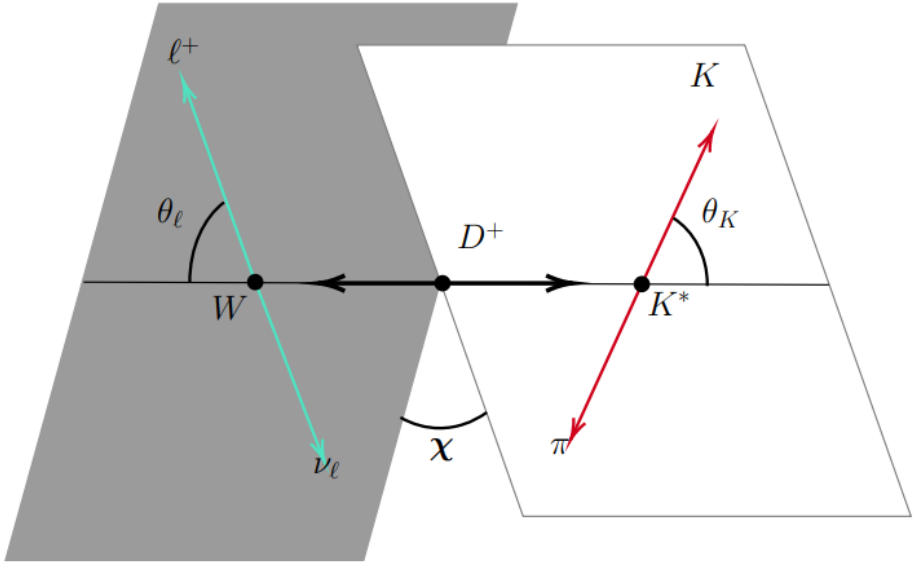




- Phys. Rev. D 111, L091501 (2025) , based on 7.93 fb^{-1} data sample @3.773 GeV , $N_{DT}\sim 50$
- $B(D^0 \to a_0(980)^- e^+ \nu_e) \times B(a_0(980)^- \to \eta\pi^-) = (0.86 \pm 0.17 \pm 0.05) \times 10^{-4}$
- First extraction of the FF: $f_+^{a_0(980)}(0) = 0.559 \pm 0.056 \pm 0.013$
- Pin down the nature of $a_0(980)$ by comparing with theoretical calculations

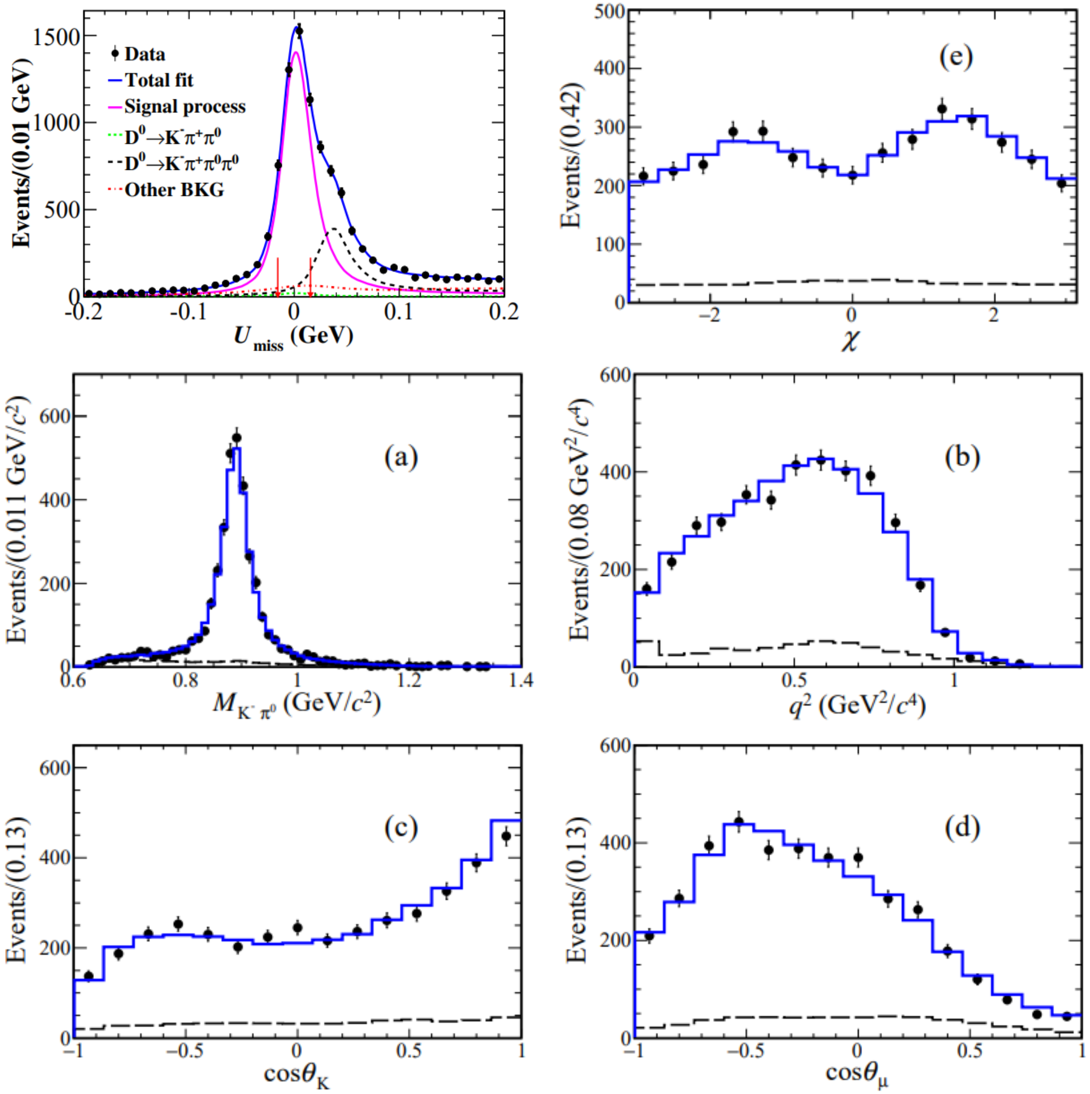
Decay formalism of $D \to V\ell^+\nu_\ell, V \to P_1P_2$

$$d^5\Gamma = \frac{G_F^2|V_{cq}|^2}{(4\pi)^6 m_D^3} X\beta\beta_l I(S_{p_1p_2}, q^2, \theta_K, \theta_l, \chi) ds_{p_1p_2} dq^2 d\cos\theta_{p_1}\, d\cos\theta_l\ d\chi$$



- Formalism based on Phys. Rev. D 46 5040 (1992)
- Five kinematic variables: $S_{p_1p_2}, q^2, \theta_K, \theta_l, \chi$
- Decay intensity: $I = \sum_1^9 I_i\left(\theta_K, q^2, S_{p_1p_2}\right) \times f_i(\theta_l, \chi)$
- The detailed expressions of I_i are given in reference.
- Three FFs: $A_{1,2}(q^2)$ & $V(q^2) \to r_2 = \frac{A_2(0)}{A_1(0)}$ & $r_V = \frac{V(0)}{A_1(0)}$

An example: $D^0 \to K^-\pi^0\mu^+\nu_\mu$



- PRL 134 011803 (2025), based on 7.93 fb^{-1} data sample @3.773 GeV, N_{DT}~6.4 K
- FFs described with single pole model
- Component $K^*(892) + (K\pi)_{S-wave}$
- Stringent test of various theoretical works.

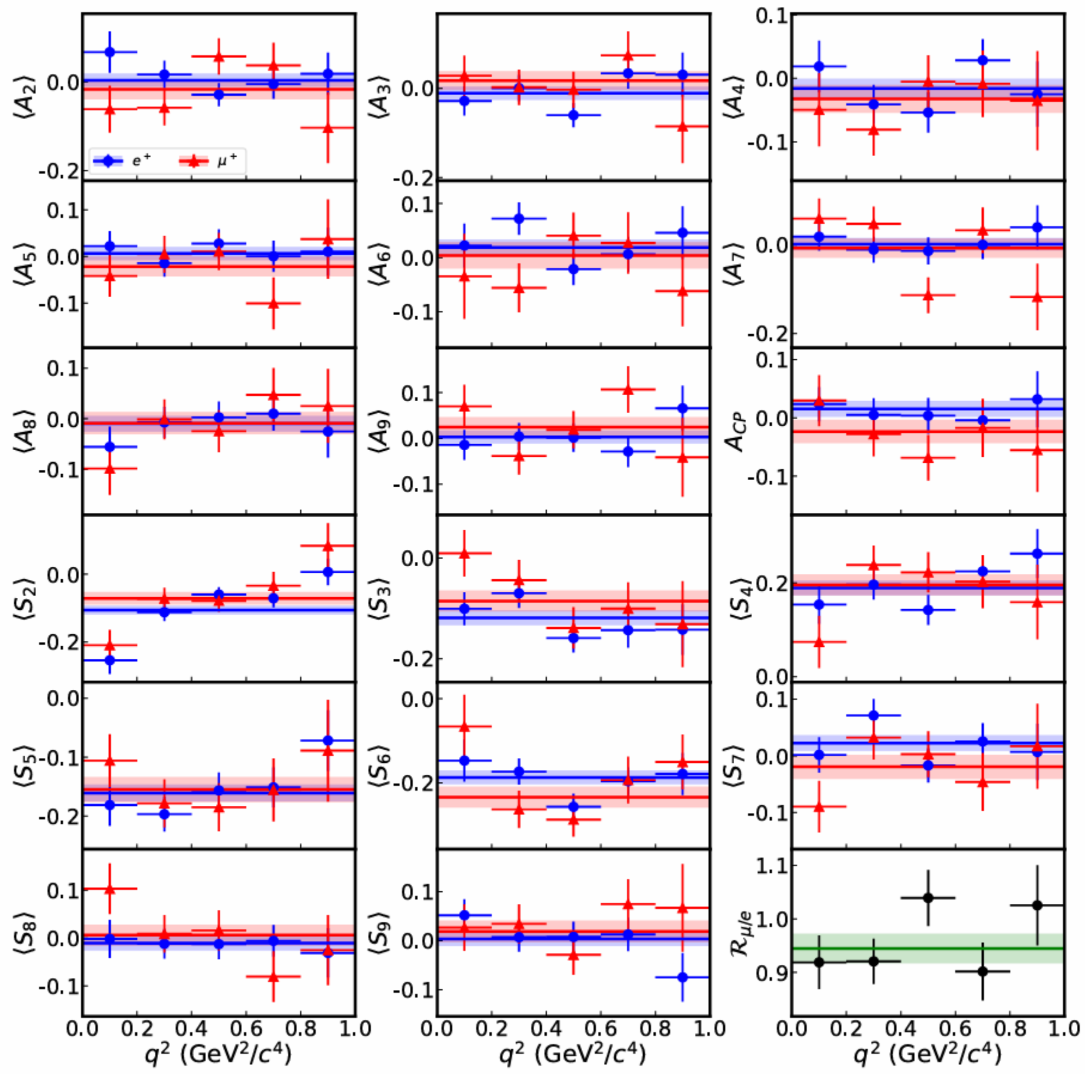
Theory	$\mathcal{B}(\%)$	r_V	r_2
LCSR [7, 16]	$2.01^{+0.09}_{-0.08}$	1.39	0.60
χUA [17]	1.98	...	...
CCQM [6]	2.80	1.22 ± 0.24	0.92± 0.18
CQM [8, 18]	3.09	1.56	0.74
LFQM [9]	...	1.36	0.83
HM$_\chi$T [10]	...	1.60	0.50
Experiments	$\mathcal{B}(\%)$	r_V	r_2
BESIII [39]	...	1.46 ± 0.07 ± 0.02	0.67 ± 0.06 ± 0.01
FOCUS [11]	1.89 ± 0.24	1.71 ± 0.68 ± 0.34	0.91 ± 0.37 ± 0.10
This work	2.073 ± 0.039 ± 0.032	1.37 ± 0.09 ± 0.03	0.76 ± 0.06 ± 0.02

The Collection of $D \to \bar{K}\pi\ell^+\nu_\ell$ works

Similar works of isospin channels are listed here.

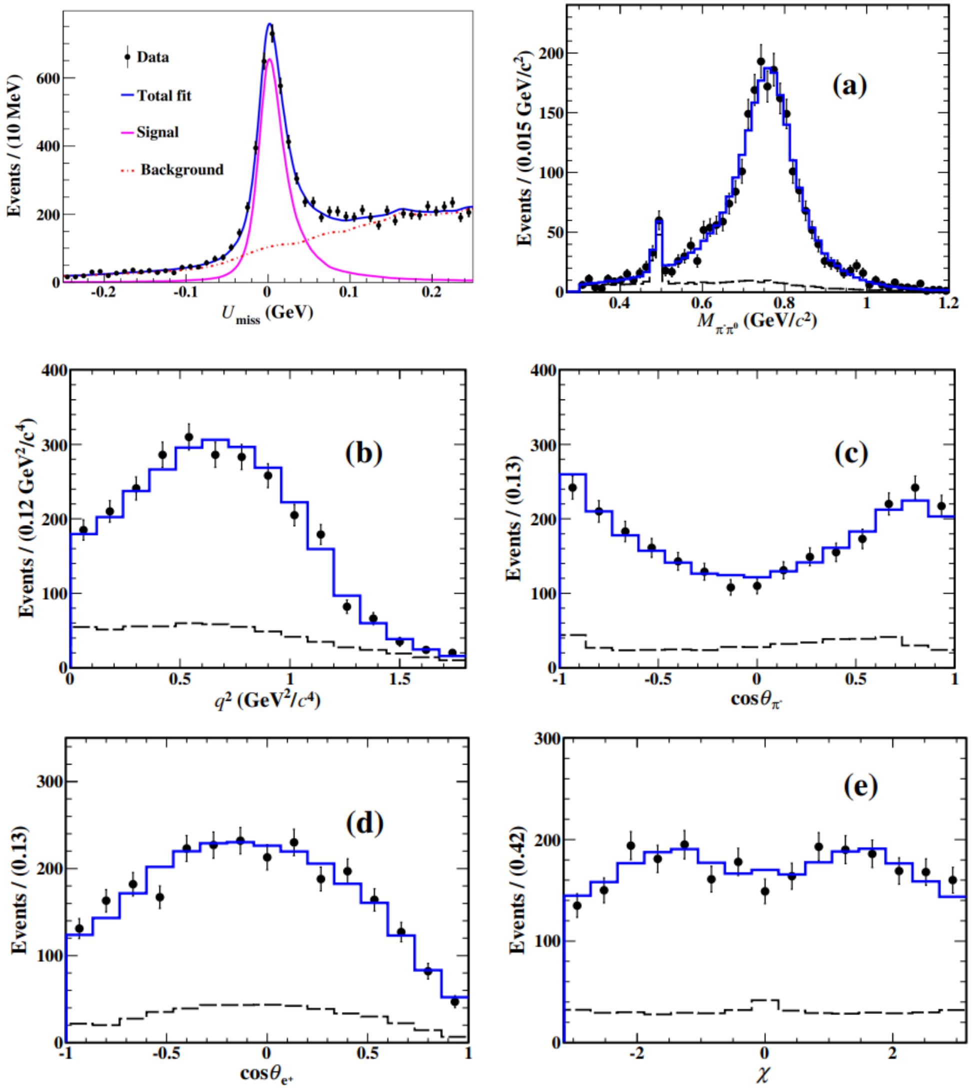
	$D^0 \to \bar{K}^0\pi^- e^+\nu_e$	$D^0 \to \bar{K}^0\pi^-\mu^+\nu_\mu$	$D^0 \to K^-\pi^0\mu^+\nu_\mu$	$D^+ \to \bar{K}^0\pi^0\ell^+\nu_\ell$
Ref	JHEP 03 197 (2025)	arXiv:2504.10867	PRL 134 011803 (2025)	arXiv:2506.05761
Data Set (fb^{-1})	7.93	7.93	7.93	20.3
$B(D \to \bar{K}\pi\ell^+\nu_\ell)$ (%)	$1.444 \pm 0.022 \pm 0.024$	$1.373 \pm 0.020 \pm 0.023$	$0.773 \pm 0.014 \pm 0.012$	μ: $0.896 \pm 0.017 \pm 0.008$ e: $0.943 \pm 0.012 \pm 0.010$
$B(D \to \bar{K}^*\ell^+\nu_\ell)$ (%)	$2.039 \pm 0.032 \pm 0.034$	$1.948 \pm 0.033 \pm 0.036$	$2.073 \pm 0.039 \pm 0.032$	μ: $4.99 \pm 0.10 \pm 0.05$ e: $5.29 \pm 0.07 \pm 0.06$
r_V	$1.48 \pm 0.05 \pm 0.02$	$1.46 \pm 0.11 \pm 0.04$	$1.37 \pm 0.09 \pm 0.03$	$1.42 \pm 0.03 \pm 0.02$
r_2	$0.70 \pm 0.04 \pm 0.02$	$0.71 \pm 0.08 \pm 0.03$	$0.76 \pm 0.06 \pm 0.02$	$0.75 \pm 0.03 \pm 0.01$
N_{obs} (K)	8.7	6.8	6.4	17.9
$R_{\mu/e}$ of $K^*/K\pi$	$0.96 \pm 0.02 \pm 0.02$		$1.02 \pm 0.03 \pm 0.03$	$0.94 \pm 0.02 \pm 0.01$

Investigation of Angular info in $D \to \bar{K}\pi\ell^+\nu_\ell$



- NP contributions may result CPV or LFV in $D \to \bar{K}\pi\ell^+\nu_\ell$
- LFV can be test via: integrated and q^2-binned $R_{\mu/e}$
- CPV can be test via: A_{cp} and a full set of angular observables $\langle A_i \rangle$& $\langle S_i \rangle$
- In SM model, all $\langle A_i \rangle$ & A_{cp}&$\langle S_{6,7,8} \rangle$ are zero.
- In arXiv:2506.05761, all these variables are measured, and no deviation from SM is seen.

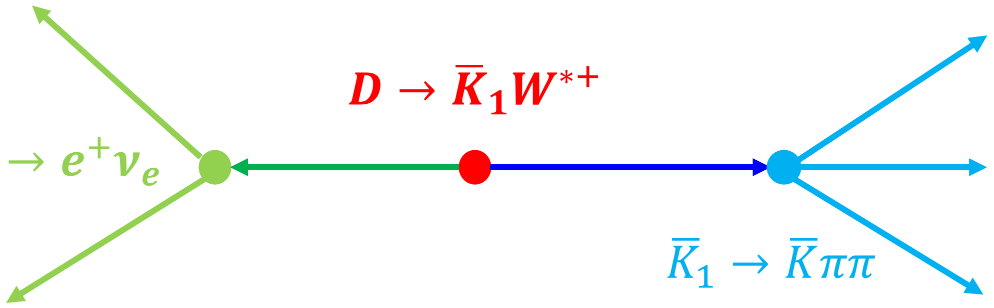
Updated measurement of $D^0 \to \rho^- e^+ \nu_e$



- PRD 110, 112018(2024) , based on 7.93 fb^{-1} data sample @3.773 GeV, N_{DT}~3.3 K
- $B(D^0 \to \rho^- e^+ \nu_e) = (1.439 \pm 0.033 \pm 0.027) \times 10^{-3}$
- The only component is $\rho(770)$
- $r_V = 1.548 \pm 0.079 \pm 0.041$, $r_2 = 0.823 \pm 0.056 \pm 0.026$, improved by a factor 1.6.

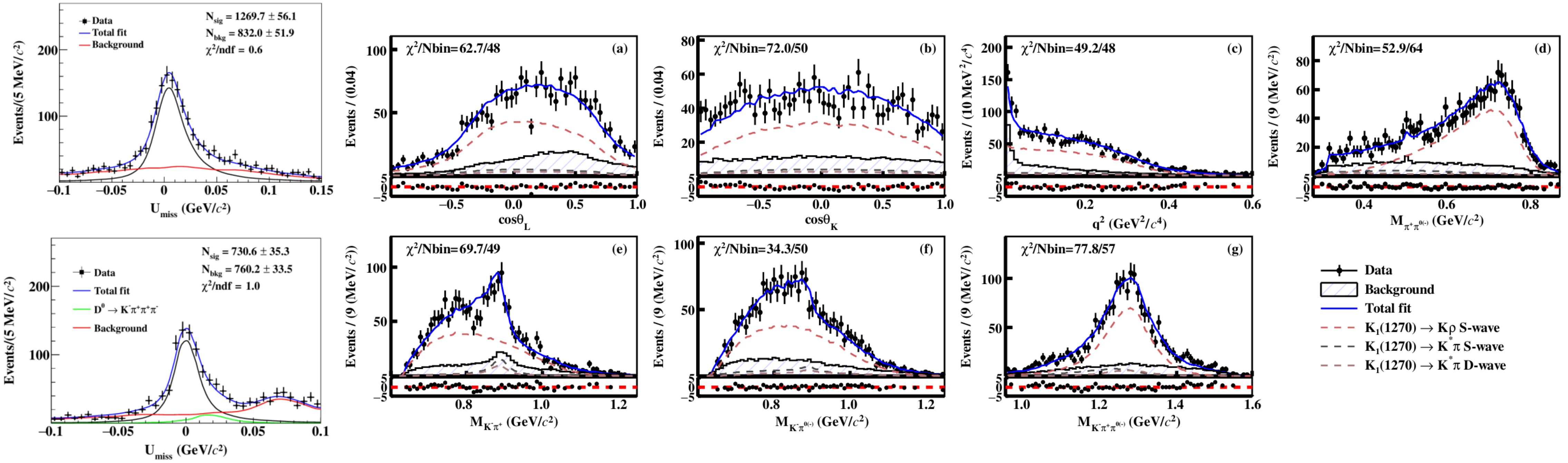
Decay formalism of $D \to A e^+ \nu_e, A \to P_1 P_2 P_3$

$$M = (V-A)^{\mu\eta} \cdot \left[\sum_{\lambda_{W^*}} \epsilon^*(\lambda_{W^*})_\mu \epsilon(\lambda_{W^*})_\rho\right] \cdot \left[\sum_{\lambda_{\bar{K}_1}} \epsilon^*(\lambda_{\bar{K}_1})_\eta \epsilon(\lambda_{\bar{K}_1})_\sigma\right] \cdot R_{\bar{K}_1} \cdot J^\sigma \cdot [\bar{u}_\nu \gamma^\rho (1-\gamma_5) \nu_l]$$



- More independent kinematic variables of **five body** semi-leptonic decay → general formalism is required!
- $D \to \bar{K}_1 W^{*+}$: $\langle \bar{K}_1 | s\gamma_\mu (1-\gamma_5) | D \rangle$, cited from PRD 104, 053003 (2021) → $V_{1,2}$ & $A \to r_A = \frac{A(0)}{V_1(0)}$ & $r_V = \frac{V_2(0)}{V_1(0)}$
- $\bar{K}_1 \to \bar{K}\pi\pi$: Constructed in covariant tensor formalism, following Eur. Phys. J. A 16, 537(2003)
- $m_e \to 0$: $q^\mu [\bar{u}_\nu \gamma_\mu (1-\gamma_5) \nu_l] = 0$ is used.

First study of $D^{0(+)} \to K^-\pi^+\pi^{0(-)}e^+\nu_e$

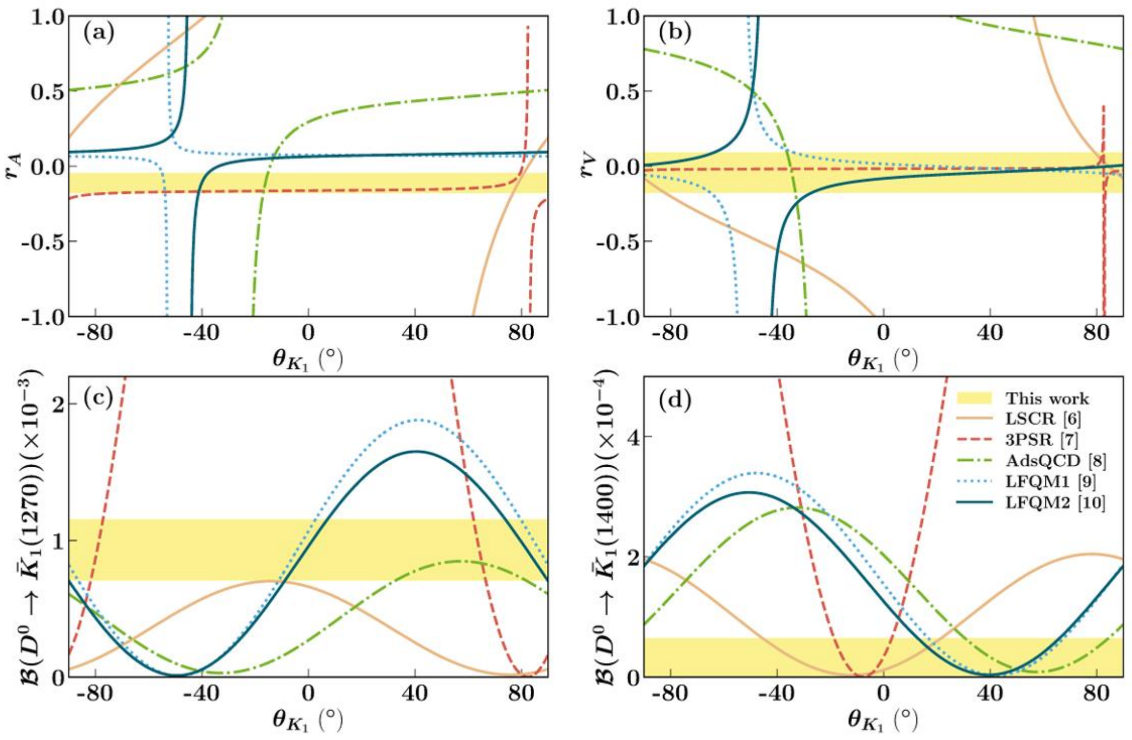


- arXiv:2503.02196, based on 20.3 fb^{-1} data sample @3.773 GeV, $\sum N_{DT}$~2.0 K
- Improve BFs measurement of $D \to \bar{K}_1(1270)e^+\nu_e$ & First upper limit on $D \to \bar{K}_1(1400)e^+\nu_e$

  $B(D^+ \to \bar{K}_1^0(1270)e^+\nu_e) = (2.27 \pm 0.11 \pm 0.07 \pm 0.07) \times 10^{-3}$; $B(D^+ \to \bar{K}_1^0(1400)e^+\nu_e) < 1.4 \times 10^{-4}$

  $B(D^0 \to K_1^-(1270)e^+\nu_e) = (1.02 \pm 0.06 \pm 0.06 \pm 0.03) \times 10^{-3}$; $B(D^0 \to K_1^-(1400)e^+\nu_e) < 0.7 \times 10^{-4}$
- First FFs measurement: $r_A = (-11.2 \pm 1.0 \pm 0.9) \times 10^{-2}$ & $r_V = (-4.3 \pm 1.0 \pm 2.5) \times 10^{-2}$
- Component: $K\rho(770)$ & $K^*(892)\pi$ → $B(K_1(1270) \to K^*\pi)/B(K_1(1270) \to K\rho) = (20.3 \pm 2.1 \pm 8.7)\%$

First study of $D^{0(+)} \to K^- \pi^+ \pi^{0(-)} e^+ \nu_e$

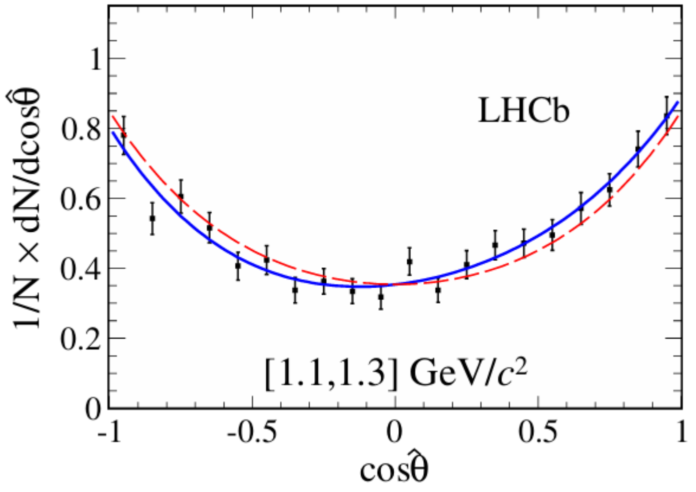


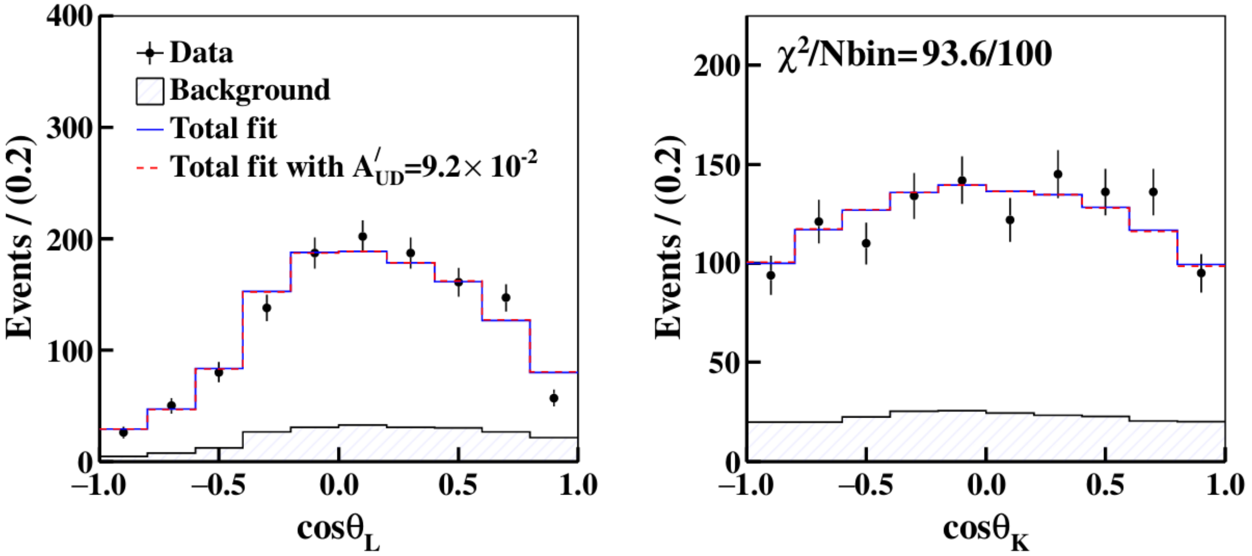
- K_{1A} $({}^1P_1)$ & K_{1B} $({}^3P_1)$ mix into $K_1(1270)$ & $K_1(1400)$
- FFs are sensitive to the mixing angle θ_{K_1}:

$$f_{K_1(1270)} = f_{K_{1A}} \sin\theta_{K_1} + f_{K_{1B}} \cos\theta_{K_1}$$
$$f_{K_1(1400)} = f_{K_{1A}} \cos\theta_{K_1} - f_{K_{1B}} \sin\theta_{K_1}$$

- Three unknow pars. $(f_{K_{1A}}, f_{K_{1B}}, \theta_{K_1})$ & Two equations
  → Determine θ_{K_1} requires one parameter input!
- However, for all theoretical predictions, we have four observables to give stringent test on them without assuming the value of θ_{K_1}.

First study of $D^{0(+)} \to K^-\pi^+\pi^{0(-)}e^+\nu_e$



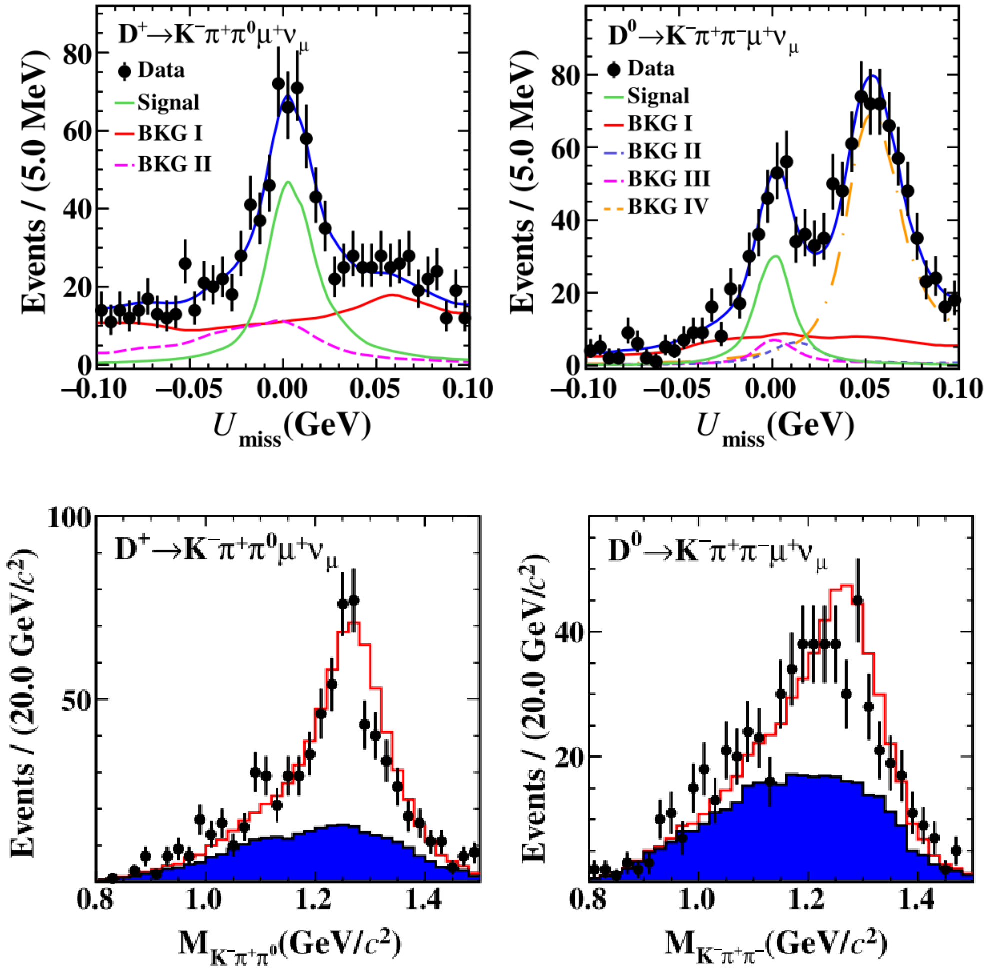


- $\bar{b} \to \bar{s}\gamma$: polarization of photon $\lambda_\gamma \sim +1$, any deviation indicates NP effects
- LHCb observed photon polarization in $B^+ \to K_1^+(1270)(\to K\pi\pi)\gamma$ with up-down asymmetry

$$A_{ud} = f_h\lambda_\gamma = (6.9 \pm 1.7) \times 10^{-2}$$

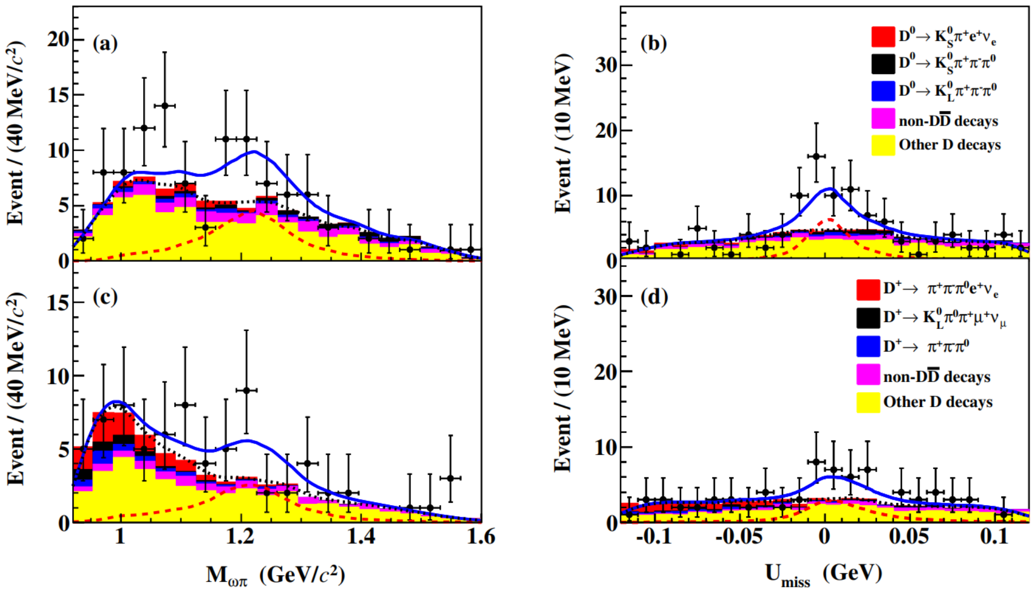
- Theoretical calculation of f_h suffers from limited knowledge of current J^μ in $K_1 \to K\pi\pi$.
- PRL 125 051802 (2020) suggests up-down asymmetry in $D \to K_1(1270)e^+\nu_e$: $A'_{ud} = \frac{4}{3} f_h$
- 2D Angular fit → $A'_{ud} = 0.01 \pm 0.11$, consistent with SM prediction $\frac{4}{3} A_{ud} = (0.092 \pm 0.022)$

Observation of $D \to \bar{K}_1(1270)\mu^+\nu_\mu$



- PRD 111, L071101 (2025), based on 7.93 fb^{-1} data sample @3.773 GeV, N_{DT}~0.6 K
- $B\left(D^+ \to \bar{K}_1^0(1270)\mu^+\nu_\mu\right) = (2.36 \pm 0.20^{+0.18}_{-0.27} \pm 0.48) \times 10^{-3}$, $B\left(D^0 \to K_1^-(1270)\mu^+\nu_\mu\right) = \left(0.78 \pm 0.11^{+0.05}_{-0.09} \pm 0.15\right) \times 10^{-3}$
- LFU test: $R_{D^0} = 0.74 \pm 0.13^{+0.08}_{-0.13}$, $R_{D^+} = 1.03 \pm 0.14^{+0.11}_{-0.15}$
- Isospin test: $1.22 \pm 0.10^{+0.06}_{-0.09}$

Observation of $D \to b_1(1235)e^+\nu_e$



- [arXiv:2407.20551](), based on 7.93 fb^{-1} data sample @3.773 GeV, N_{DT}~60
- First observation of $D \to b_1(1235)e^+\nu_e$
- $B(D^0 \to b_1(1235)^- e^+\nu_e) \times B(b_1(1235)^- \to \omega\pi^-) = (0.72 \pm 0.18^{+0.06}_{-0.08}) \times 10^{-4}$
- $B(D^+ \to b_1(1235)^0 e^+\nu_e) \times B(b_1(1235)^0 \to \omega\pi^0) = (1.16 \pm 0.44 \pm 0.16) \times 10^{-4}$

Outlook of $D \to \bar{K}\ell^+\nu_\ell$: Angular info. & BSM search

- With 20.3 fb^{-1} @ 3.773 GeV: $\sum N_{DT}$: 0.44 M → 1.12 M
- Forward-backward asymmetry measurement:

$$A_{FB}(q^2) = \frac{d\Gamma(\cos\theta_W > 0) - d\Gamma(\cos\theta_W < 0)}{d\Gamma(\cos\theta_W > 0) + d\Gamma(\cos\theta_W < 0)}$$

- BSM search: including BSM operators,

$$(\bar{s}\gamma_\mu P_L c)(\bar{\nu}_\ell \gamma^\mu P_L \ell) + (\bar{s}[\boldsymbol{C_R} P_R + \boldsymbol{C_L} P_L]c)(\bar{\nu}_\ell P_R \ell)$$

$D \to \bar{K}\ell^+\nu_\ell$: Combined fit to $d\Gamma/\mathrm{d}q^2$ & $A_{FB}(q^2) \to C_S = C_R + C_L$

$D_s \to \ell^+\nu_\ell$: Compare measured and LQCD calculated BF → $C_P = C_R - C_L$

→ Most stringent constrain on scalar current in charm sector!

Outlook of $D \to \bar{K}\pi\ell^+\nu_\ell$: Precision & New

- The expected signal yields of all channels: > 0.3 M
- Search for more excited kaon in $D \to K_l^*(1410,1430,1680)\ell^+\nu_\ell$
- Combined fit for more precise r_A & r_V, currently is still statistical uncertainty dominated
- Measure $r_{A,V}(q^2)$ in different q^2 region → Model independent extraction
- Search for NP contributions via massive angular observables
- Extraction of $|V_{cs}|$: Limited by theoretical uncertainty…

Summary & Outlook

$$M_{fi} = \frac{G_F}{\sqrt{2}} V_{cq} \times \langle P, S, V, A | q\gamma_\mu(1-\gamma_5)c | D \rangle \times \bar{u}_\nu \gamma^\mu (1-\gamma_5) \nu_{\ell^+}$$

- $|V_{cq}|$ related: Unprecedented precision ~0.23% of $f_+^K \cdot |V_{cs}|$ has been achieved in $D \to K\ell^+\nu_\ell$ measurement
- FFs related: precise measurements of FFs in $D \to (K, K^*, \rho)\ell^+\nu_\ell$, first measurements of FFs in $D \to (\eta', a_0(980), K_1(1270))\ell^+\nu_\ell$
- BFs related: Observation of $D \to K_1(1270)\mu^+\nu_\mu, b_1(1235)e^+\nu_e$, upper limit of $D \to K_1(1400)e^+\nu_e$
- NP related: LFU test, Angular/CPV observable in $D \to K\pi\ell^+\nu_\ell$, up-down asymmetry in $D \to K_1(1270)e^+\nu_e$
- **Outlook:** More Precise & More decay modes & Search for NP with 20.3 fb^{-1} data!