粲介子半轻衰变课题汇报:$D \to A\ell\nu_\ell$

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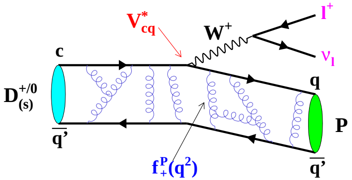
Outline

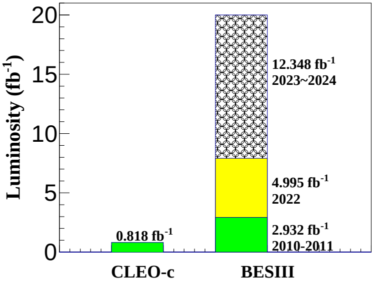
Main goal

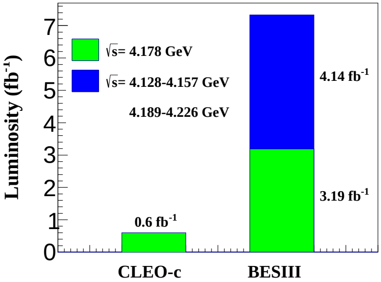


$$\frac{d\Gamma}{dq^2} = X\frac{G_F^2|\vec{p}_P|^3}{24\pi^3}|V_{cq}|^2|f_+(q^2)|^2$$

- Form Factors $f_+(0)$ measurements⇒Calibrate LQCD calculations
- $|V_{cq}|$ measurement ⇒Test CKM matrix unitarity
- Branching Fractions $\mathcal{B}_{\mu/e}$ ⇒Test lepton flavor universality (LFU)
- Rare decays ⇒ Search for new physics effects beyond the Standard Model
- The semi-leptonic decay of charmed mesons is an ideal probe for studying the nature of axial-vector mesons

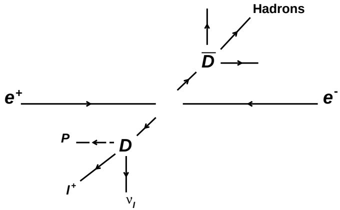
Data sample





- $e^+e^- \to \psi(3770) \to D\bar{D}$ $\sqrt{s}$=3.773 GeV, $\mathcal{L}_{\rm int}$=20.3 fb^{-1}
- $e^+e^- \to D_s^{\pm}D_s^{*\mp}$ $\sqrt{s}$=4.128-4.226 GeV, $\mathcal{L}_{\rm int}$=7.33 fb^{-1}
- $e^+e^- \to D_s^{*+}D_s^{*-}$ $\sqrt{s}$=4.237-4.669 GeV, $\mathcal{L}_{\rm int}$=10.64 fb^{-1}

BESIII dataset and double-tag method



- e^+e^- annihilations data near threshold
  ⇒Double-tag method& Clean environment
- Undetectable neutrinos⇒extract the semi-leptonic signals
  $U_{\rm miss} = E_{\rm miss} - |\vec{p}_{\rm miss}|$, $M^2_{\rm miss} = E^2_{\rm miss} - |\vec{p}_{\rm miss}|^2$
- Branching fraction with double-tag method: $\mathcal{B} = \frac{N_{\rm DT}}{N_{\rm ST}\epsilon_{\rm DT}/\epsilon_{\rm ST}}$
  ⇒Systematic uncertainties on the ST mostly canceled

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

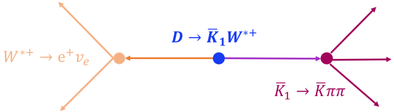
Publications

- A represents axial-vector mesons.

Topic	Channel	$\mathcal{L}_{\rm int}$ (fb^{-1}) / $E_{\rm cm}$ (GeV)	Reference
$D^+ \to A\ell^+\nu_\ell$	$D \to K_1(1270)e^+\nu_e$	20.3 / 3.773	arXiv:2503.02196
	$D \to K_1(1270)\mu^+\nu_\mu$	7.93 / 3.773	PRD(L)111,071101(2025)
	$D \to b_1(1235)e^+\nu_e$	7.93 / 3.773	arXiv:2407.20551

- $\mathcal{L}_{\rm int}$: Integrated luminosity, $E_{\rm cm}$: Center-of-mass energy.

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

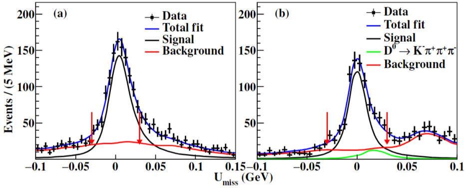


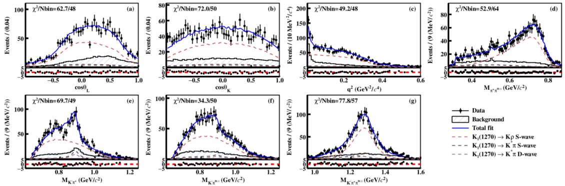
$$M = (V - A)^{\mu\eta} \cdot \left[\sum_{\lambda_{W^*}} \epsilon^*(\lambda_{W^*})_\mu \epsilon(\lambda_{W^*})_\rho \right] \cdot \left[\sum_{\lambda_{\bar{K}_1}} \epsilon^*(\lambda_{\bar{K}_1})_\eta \epsilon(\lambda_{\bar{K}_1})_\sigma \right] \cdot R_{\bar{K}_1} \cdot J^\sigma \cdot [\bar{u}_\nu \gamma^\rho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

- **Five-body** semi-leptonic decays involve more independent kinematic variables, requiring a general formalism.
- The transition $D \to \bar{K}_1 W^{*+}$ is described by the weak current matrix element $\langle \bar{K}_1 | s\gamma_\mu (1 - \gamma_5) | D \rangle$ [PRD 104, 052003 (2021)], with normalized form factor ratios $r_A = \frac{A(0)}{V_1(0)}$, $r_V = \frac{V_2(0)}{V_1(0)}$.
- The $\bar{K}_1 \to \bar{K}\pi\pi$ decay amplitude is constructed using the covariant tensor formalism [Eur. Phys. J. A 16, 537 (2023)].
- The electron mass is neglected ($m_e \to 0$), so $q^\mu [\bar{u}_\nu \gamma_\mu (1 - \gamma_5) \nu_\ell] = 0$ is used.

First amplitude and angular analyses of $D \to \bar{K}_1(1270)e^+\nu_e$

- Data: 20.3 fb^{-1}@3.773 GeV [arXiv:2503.02196]

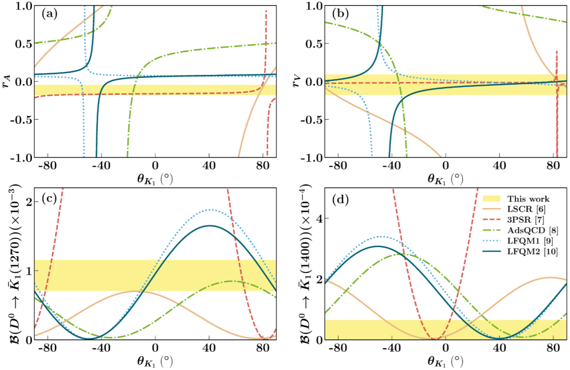




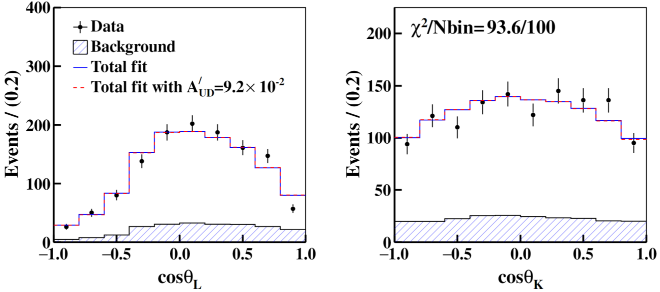
- Improve BFs measurement of $D \to \bar{K}_1(1270)e^+\nu_e$ and First upper limit on $D \to \bar{K}_1(1400)e^+\nu_e$
  - $\mathcal{B}(D^0 \to K_1(1270)^- e^+\nu_e) = (1.02 \pm 0.06_{\rm stat} \pm 0.06_{\rm syst} \pm 0.03_{\rm input}) \times 10^{-3}$
  - $\mathcal{B}(D^+ \to \bar{K}_1(1270)^0 e^+\nu_e) = (2.27 \pm 0.11_{\rm stat} \pm 0.07_{\rm syst} \pm 0.07_{\rm input}) \times 10^{-3}$
  - $\mathcal{B}(D^0 \to K_1(1400)^- e^+\nu_e) < 0.7 \times 10^{-4}$ and $\mathcal{B}(D^+ \to \bar{K}_1(1400)^0 e^+\nu_e) < 1.4 \times 10^{-4}$
- First study of the semileptonic decays of heavy mesons into axial-vector mesons
  - $r_A = (-11.2 \pm 1.0 \pm 0.9) \times 10^{-2}$ $r_V = (-4.3 \pm 1.0 \pm 2.4) \times 10^{-2}$
- Component: $K\rho(770)$ and $K^*(892)\pi$ $\to \frac{\mathcal{B}(K_1(1270) \to K^*\pi)}{\mathcal{B}(K_1(1270) \to K\rho)} = (20.3 \pm 2.1 \pm 8.7)\%$

First amplitude and angular analyses of $D \to \bar{K}_1(1270)e^+\nu_e$

- 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_{K1A},f_{K1B}, θ_{K_1}) and Two equations $\to$ Determine θ_{K_1} requires one parameter input!
  - r_A, r_V , and $\mathcal{B}(D \to K_1(1270)e^+\nu_e)$ are consistent with the 3PSR predictions, and disfavor all other theoretical calculations by more than 5σ
  - Upper limits on $\mathcal{B}(D \to K_1(1400)e^+\nu_e)$ contradict 3PSR predictions.



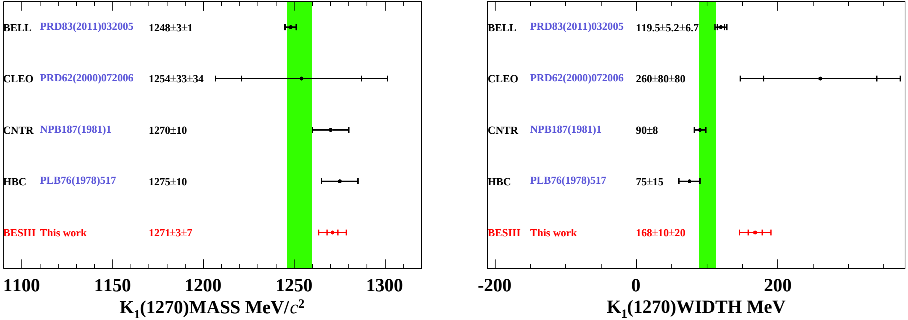
First amplitude and angular analyses of $D \to \bar{K}_1(1270) e^+ \nu_e$



- $\bar{b} \to \bar{s}\gamma$: polarization of photon ($\lambda_\gamma \sim +1$) in the SM. Any deviation can signal new physics (NP).
- LHCb measured photon polarization in $B^+ \to K_1^+(1270)(\to K\pi\pi)\gamma$ via the up-down asymmetry: $A_{ud} = f_h \lambda_\gamma = (6.9 \pm 1.7) \times 10^{-2}$.
- Theoretical evaluation of f_h is limited by the incomplete knowledge of current J^μ in $K_1 \to K\pi\pi$ decays.
- PRL 125, 051802 (2020): Up-down asymmetry in $D \to K_1(1270) e^+ \nu_e$ relates as $A'_{ud} = \frac{4}{3} f_h$.
- 2D angular fit yields $A'_{ud} = 0.01 \pm 0.11$, consistent with the SM prediction $\frac{4}{3} A_{ud} = 0.092 \pm 0.022$.

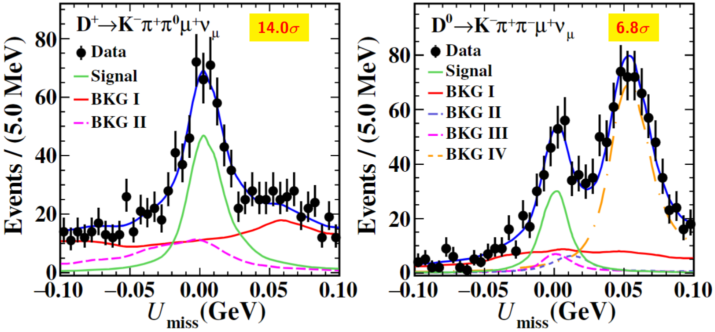
First amplitude and angular analyses of $D \to \bar{K}_1(1270)e^+\nu_e$

- $K_1(1270)$ mass $= (1.271 \pm 0.003 \pm 0.007)$ GeV/c^2
- $K_1(1270)$ width $= (0.168 \pm 0.010 \pm 0.020)$ GeV/c^2

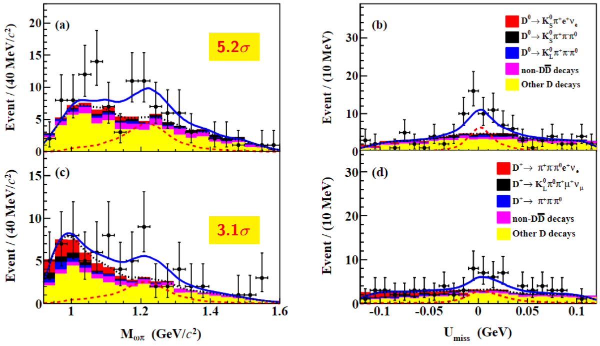


$D \to K_1(1270)\mu^+\nu_\mu$

- Data: 7.93 fb^{-1}@3.773 GeV[PRD(L)111,071101(2025)]
- First observation of $D \to K_1(1270)\mu^+\nu_\mu$
  - $\mathcal{B}(D^0 \to K_1(1270)^-\mu^+\nu_\mu) = (2.36 \pm 0.20^{+0.18}_{-0.27} \pm 0.48) \times 10^{-3}$
  - $\mathcal{B}(D^+ \to \bar{K}_1(1270)\mu^+\nu_\mu) = (0.78 \pm 0.11^{+0.05}_{-0.09} \pm 0.15) \times 10^{-3}$
- 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 conservation check: $\frac{\Gamma(D^+\to\bar{K}_1^0(1270)\mu^+\nu_\mu)}{\Gamma(D^0\to K_1^-(1270)\mu^+\nu_\mu)} = 1.22 \pm 0.10^{+0.06}_{-0.09}$



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



- Data: 7.93 fb^{-1}@3.773 GeV[arXiv:2407.20551]
- First observation of $D^0 \to b_1(1235)^- e^+\nu_e$ and evidence for $D^+ \to b_1(1235)^0 e^+\nu_e$
  - $\mathcal{B}(D^0 \to b_1(1235)^- e^+\nu_e) \times \mathcal{B}(b_1(1235)^- \to \omega\pi^-) = (0.72 \pm 0.18^{+0.06}_{-0.08}) \times 10^{-4}$
  - $\mathcal{B}(D^+ \to b_1(1235)^0 e^+\nu_e) \times \mathcal{B}(b_1(1235)^0 \to \omega\pi^0) = (1.16 \pm 0.44 \pm 0.16) \times 10^{-4}$

- Isospin conservation check: $\frac{\Gamma(D^0 \to b_1^- e^+\nu_e)}{2\Gamma(D^+ \to b_1^0 e^+\nu_e)} = 0.78 \pm 0.19^{+0.04}_{-0.05}$

Summary and prospect

- Summary
  - BESIII has the largest data samples at $D\bar{D}/D_sD_s^*$ threshold
  - Axial-vector mesons are studied systematically via semi-leptonic charm decays
  - BFs/FF measurements help to test different QCD modes and understand their nature!
- Prospect
  - More axial-vector mesons could be studied via semi-leptonic charm decays
  - Machine learning is promising for future searches of rare decays

Decay Mode	BESIII Publication	BESIII Prospect
$D \to K_1(1270)e^+\nu_e$	20.3:arXiv:2503.02196	
$D \to K_1(1270)\mu^+\nu_\mu$	7.93: PRD(L)111,071101(2025)	Charm group report(20.3fb^{-1})
$D \to b_1(1235)\ell^+\nu_\ell$	7.93:arXiv:2407.20551	Charm group report(20.3fb^{-1})
$D \to K_1(1270)(\to K\omega)e^+\nu_e$	NONE	CWR(20.3fb^{-1})
$D \to K_1(1270)(\to K\pi\pi)e^+\nu_e$	NONE	Charm group review(20.3fb^{-1})
$D \to f_1(1420)\ell^+\nu_\ell$	NONE	Charm group review(20.3fb^{-1})
$D_s \to f_1(1285)e^+\nu_e$ and $D_s \to f_1(1420)e^+\nu_e$	NONE	Draft review(7.33fb^{-1})
$D \to \pi\pi\eta e^+\nu_e$	NONE	Memo review(20.3fb^{-1})