(Semi-)leptonic charmed meson decays at BESIII

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   - $D_s^+ \to \tau^+(\tau^+ \to \pi^+\bar{\nu}_\tau)\nu_\tau$
3. Semileptonic Decays of $D^{0(+)}$ and D_s^+
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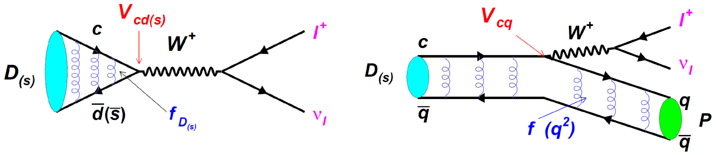
Introduction



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

$$\frac{d\Gamma(D_{(s)}\to Pl\nu_l)}{dq}=\frac{G_F^2 p^3}{24\pi^3}|f(q^2)|^2|V_{cq}|^2$$

- 测量衰变常数 $f_{D_s^+}$ 和形状因子 $f_+(0)$，检验理论格点 QCD 的计算
- 测量 CKM 矩阵元 $|V_{cs(d)}|$, 检验 CKM 矩阵的幺正性
- 精确检验 $\mu - e$, $\tau - \mu$ 轻子普适性

Double-tag method for $D^0\bar{D}^0$ and D^+D^-

The yields of tag modes can be written as

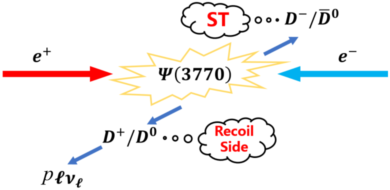
$$N_{\text{tag}} = 2 \cdot N_{D\bar{D}} \cdot \mathcal{B}_{\text{tag}} \cdot \varepsilon_{\text{ST}} \qquad (1)$$

The signal yields can be written as

$$N_{\text{sig}} = 2 \cdot N_{D\bar{D}} \cdot \mathcal{B}_{\text{tag}} \cdot \mathcal{B}_{\text{sig}} \cdot \varepsilon_{\text{DT}} \qquad (2)$$

The branching fractions of semi-leptonic D_s decays are determined by

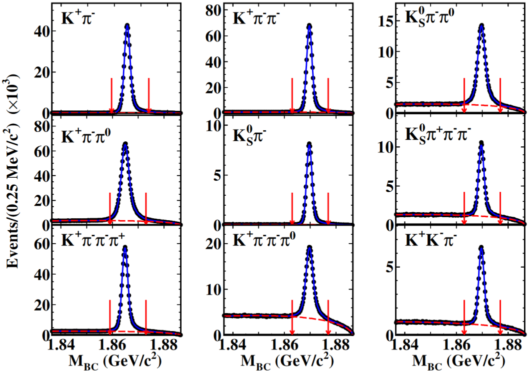
$$\boxed{\mathcal{B}_{\text{sig}} = \frac{N_{\text{sig}}/(\varepsilon_{DT}/\varepsilon_{ST})}{N_{\text{tag}}}} \qquad (3)$$



Double-tag method for $D^0\bar{D}^0$ and D^+D^-

9 possible single tags at BESIII

$N_{ST(D^0\bar{D}^0)}$~2.3M and $N_{ST(D^+D^-)}$~1.5M with 9 tags @3.773 GeV~2.93fb^{-1}

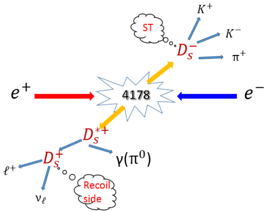


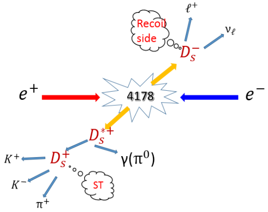
signal side: X (X =e,μ, hadron) is reconstructed, the missing neutrinos are determined by

$$M^2_{\rm miss} = E^2_{\rm miss} - |\vec{p}_{\rm miss}|^2$$
$$E_{\rm miss} = E_{\rm cm} - \sqrt{|\vec{p}_{\rm tag}|^2 + m_D} - E_X$$
$$\vec{p}_{\rm miss} = -\vec{p}_{\rm tag} - \vec{p}_X$$

Double-tag method for $D_s^{*\pm} D_s^{\mp}$

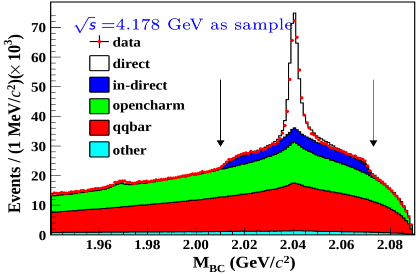
direct: Tag D_s from e^+e^- in-direct: Tag D_s from D_s^*





Tag mode: $K^+K^-\pi^-$, ...

$M_{\rm BC} = \sqrt{E_{\rm beam}^2 - |\overrightarrow{p}_{tag}|^2}$,
suppress non-$D_s D_s^*$ background



$$N_{\rm ST} = 2N_{D_s^- D_s^+} \mathcal{B}_{\rm tag} \epsilon_{\rm tag}$$

$$N_{\rm DT} = 2N_{D_s^- D_s^+} \mathcal{B}_{\rm tag} \mathcal{B}_{\rm sig} \epsilon_{\rm tag,sig}$$

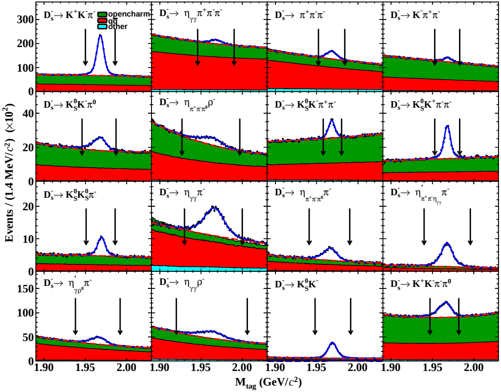
$$\mathcal{B}({\rm sig}) = \frac{N_{\rm DT}}{N_{\rm ST}\epsilon_{\rm DT}/\epsilon_{\rm ST}}$$

Double-tag method for $D_s^{*\pm} D_s^{\mp}$

16 possible single tags at BESIII

N_{ST}~0.78M with 16 tags @4.178-4.226 GeV~3.19fb^{-1}+3.13fb^{-1}

$\sqrt{s}$ =4.178 GeV as sample

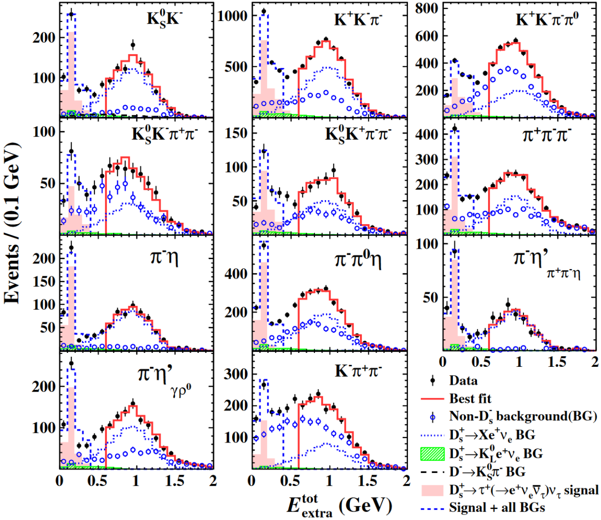


signal side: X ($X = \pi, e, \mu$) is reconstructed, the missing neutrinos are determined by

$$M^2_{\rm miss} = E^2_{\rm miss} - |\vec{p}_{\rm miss}|^2$$
$$E_{\rm miss} =$$
$$E_{\rm cm} - \sqrt{|\vec{p}_{\rm tag}|^2 + m^2_{D_s}} - E_{\gamma(\pi^0)} - E_X$$
$$\vec{p}_{\rm miss} = -\vec{p}_{\rm tag} - \vec{p}_{\gamma(\pi^0)} - \vec{p}_X$$

$D_s^+ \to \tau^+\nu_\tau$ via $\tau^+ \to e^+\nu_e\bar{\nu}_\tau$

$E^{\rm tot}_{\rm extra}$: the total energy of the good EMC showers, excluding FSR and those associated in ST



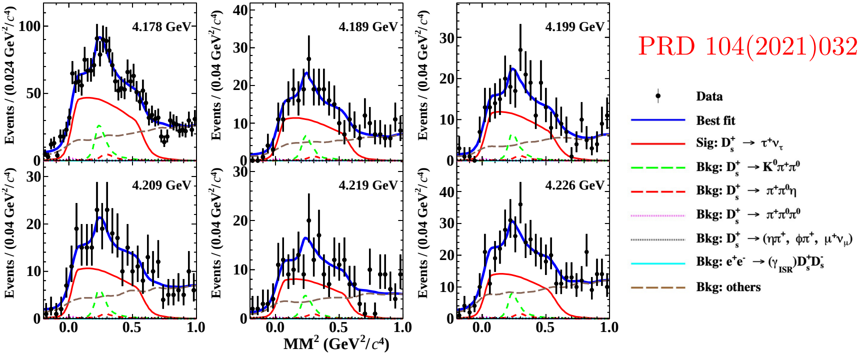
PRL127(2021)171801

- $N^{\rm tot}_{\rm DT} = 4940 \pm 94$
- $\mathcal{B}(D_s^+ \to \tau^+\nu_\tau) = (5.27 \pm 0.10 \pm 0.12)\%$
- $f_{D_s^+}|V_{cs}| = (244.4 \pm 2.3 \pm 2.9)$ MeV

The most precise result to date$\sim$1.5%

$D_s^+ \to \tau^+\nu_\tau$ via $\tau^+ \to \pi^+\pi^0\bar{\nu}_\tau$

Simultaneous fit to $M^2_{\rm miss}$ @$\sqrt{s}$ =4.178-4.226 GeV



PRD 104(2021)032001

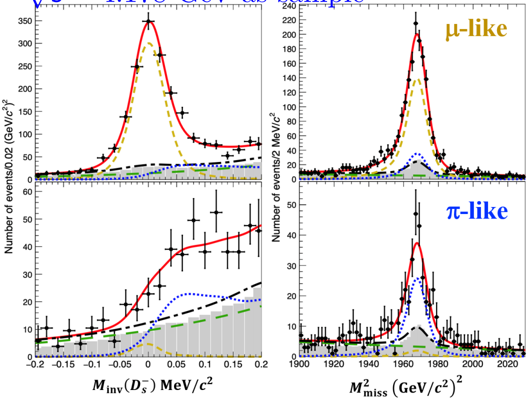
$N_{\rm DT} = 1745 \pm 84$ $\quad \mathcal{B}(D_s^+ \to \tau^+\nu_\tau) = (5.29 \pm 0.25 \pm 0.20)\%$

$f_{D_s^+}|V_{cs}| = (244.8 \pm 5.8 \pm 4.8)$ MeV $\quad$ Precision: 3.1%

$D_s^+ \to \tau^+\nu_\tau$ via $\tau^+ \to \pi^+\bar{\nu}_\tau$

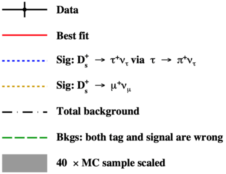
An unbinned simultaneous maximum likelihood fit to two dimensional distributions

$\sqrt{s} = 4.178$ GeV as sample



PRD 104(2021)052009

- μ-like (upper): $E_{\rm EMC} \leq 300$ MeV, mixture of $D_s^+ \to \tau^+(\to \pi^+\bar{\nu}_\tau)\nu_\tau$ and $D_s^+ \to \mu^+\nu_\nu$
- π-like (lower): $E_{\rm EMC} > 300$ MeV, dominated of $D_s^+ \to \tau^+(\to \pi^+\bar{\nu}_\tau)\nu_\tau$



$N(D_s^+ \to \mu^+\nu_\mu) = 2198 \pm 55$ $N(D_s^+ \to \tau^+\nu_\tau) = 946^{+46}_{-45}$

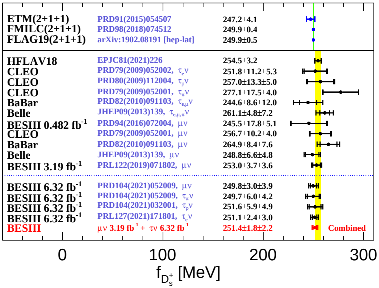
$\mathcal{B}(D_s^+ \to \mu^+\nu_\mu) = (0.535 \pm 0.013 \pm 0.016)\%$ $\mathcal{B}(D_s^+ \to \tau^+\nu_\tau) = (5.21 \pm 0.25 \pm 0.17)\%$

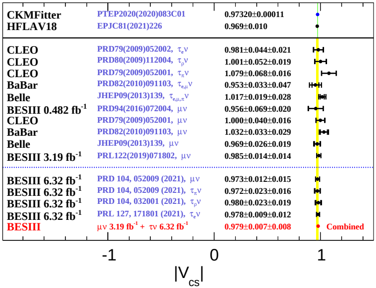
$f_{D_s^+}|V_{cs}|_\mu = (243.1 \pm 3.0 \pm 3.8)$ MeV $f_{D_s^+}|V_{cs}|_\tau = (243.0 \pm 5.8 \pm 4.1)$ MeV

Comparison of $f_{D_s^+}$ and $|V_{cs}|$

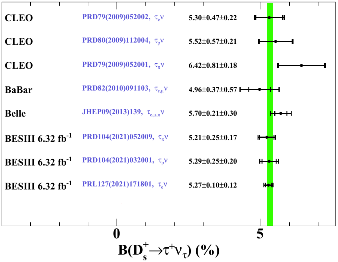
With the values of G_F, m_{D_s}, m_τ, and τ_{D_s} [PDG 2022].

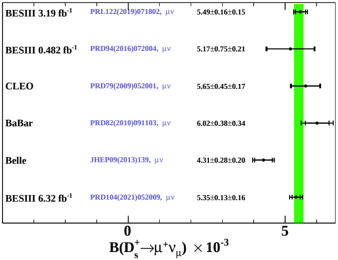
Input $|V_{cs}|_{\text{CKMFitter}} = 0.97349 \pm 0.00016$ Input $f_{D_s^+\,LQCD} = (249.9 \pm 0.5)$ MeV





Test of Lepton flavor universality





Combined results:

$\mathcal{B}(D_s^+ \to \mu^+\nu_\mu) = (5.43 \pm 0.15) \times 10^{-3}$

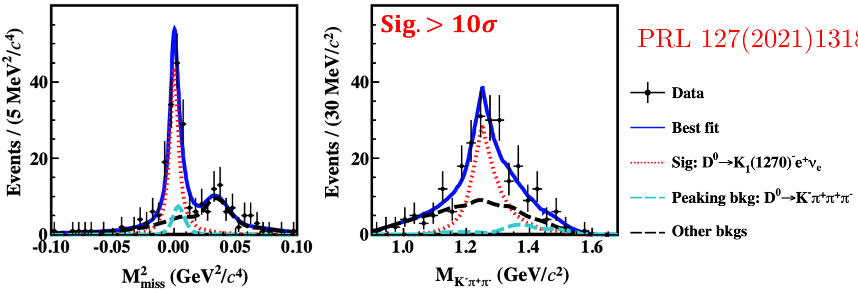
$\mathcal{B}(D_s^+ \to \tau^+\nu_\tau) = (5.32 \pm 0.11)\%$

$$R_{D_s} = \frac{\mathcal{B}(D_s^+ \to \mu^+\nu_\mu)}{\mathcal{B}(D_s^+ \to \tau^+\nu_\tau)} = 9.82 \pm 0.36 \quad \text{SM prediction: } 9.75$$

No LFU violation in $\tau - \mu$flavors with the current precision.

Observation of $D^0 \to K_1(1270)^- e^+ \nu_e$

Two dimensional unbinned extended maximum likelihood simultaneous fits($K_1(1270)^- \to K^- \pi^+ \pi^-$).



PRL 127(2021)131801

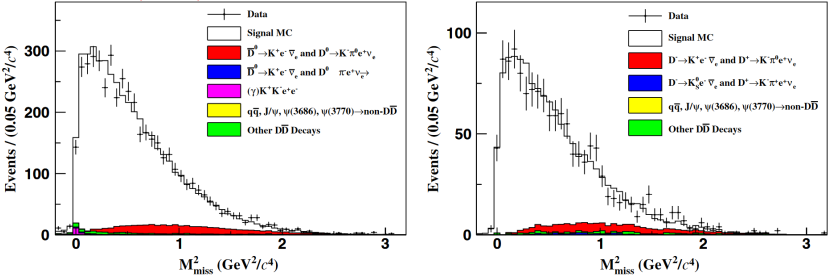
- $N_{\mathrm{DT}} = 109.0 \pm 12.5$
- $\mathcal{B}(D^0 \to K_1(1270)^- e^+ \nu_e) = (1.09 \pm 0.13^{+0.09}_{-0.13} \pm 0.12_{ex.})\%$
- $\frac{\Gamma_{D^0 \to K_1(1270)^- e^+ \nu_e}}{\Gamma_{D^+ \to \bar{K}_1(1270)^0 e^+ \nu_e}} = 1.20 \pm 0.02_{stat.} \pm 0.14_{syst.} \pm 0.04_{ex.}$ (Isospin conservation test)

Measurement of branching fractions of $D^{0(+)} \to \bar{K}e^+\nu_e$

Independent measurement with new method at BESIII.

$$N_{\rm sig} = N_{D\bar{D}}\mathcal{B}^2(D \to \bar{K}e\nu_e)\epsilon_{\rm sig} \Rightarrow \mathcal{B}(D \to \bar{K}e\nu_e) = \sqrt{\frac{N_{\rm sig}}{N_{D\bar{D}}\epsilon_{\rm sig}}}$$

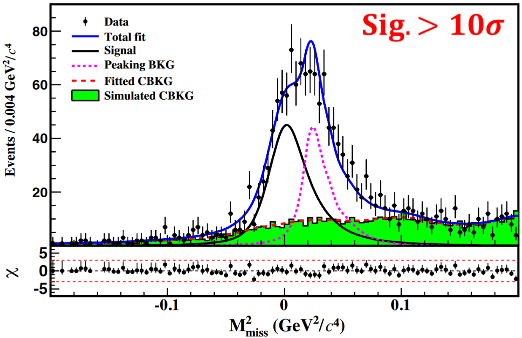
PRD104(2021)052008



$$\mathcal{B}(D^0 \to K^-e^+\nu_e) = (3.567 \pm 0.031 \pm 0.021)\%$$
$$\mathcal{B}(D^+ \to \bar{K}e^+\nu_e) = (8.68 \pm 0.14 \pm 0.16)\%$$
$$\frac{\Gamma_{(D^0\to K^-e^+\nu_e)}}{\Gamma_{(D^+\to\bar{K}e^+\nu_e)}} = 1.039 \pm 0.021 (\text{Support isospin symmetry within } 1.9\sigma)$$

Observation of $D^0 \to \rho^- \mu^+ \nu_\mu$

First measurement of $D^0 \to \rho^- \mu^+ \nu_\mu (\rho^- \to \pi^- \pi^0)$ PRD104(2021)L091103



- $N_{\rm DT} = 570 \pm 40$
- $\mathcal{B}(D^0 \to \rho^- \mu^+ \nu_\mu) = (1.35 \pm 0.09 \pm 0.09) \times 10^{-3}$

$$R_{\mu/e} = \frac{\mathcal{B}(D^0 \to \rho^- \mu^+ \nu_\mu)}{\mathcal{B}(D^0 \to \rho^- e^+ \nu_e)} = 0.90 \pm 0.11 \quad \text{SM(0.93-0.96)}$$

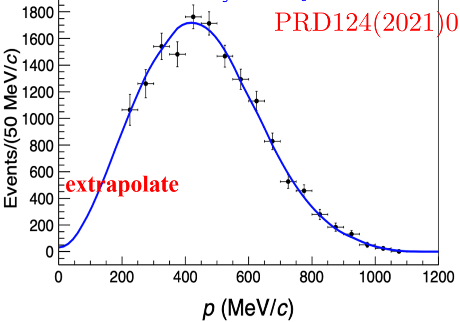
$$\frac{\Gamma_{(D^0 \to \rho^- \mu^+ \nu_\mu)}}{2\Gamma_{(D^+ \to \rho^0 \mu^+ \nu_\mu)}} = 0.71 \pm 0.14 (\text{Support isospin symmetry within } 2.1\sigma)$$

Precision measurement of $D_s^+ \to Xe^+\nu_e$

Sort recoil side selected tracks into eighteen momentum (p_e) bins for $p_e > 200$ MeV/c

The signal yields $N^{\text{signal}}_{D_s^+ \to Xe^+\nu_e} = N_{p_e > 200 MeV/c} + N_{p_e \le 200 MeV/c}$(extrapolate)

PRD124(2021)012003



- X means Inclusive MC
- $N^{\text{signal}}_{D_s^+ \to Xe^+\nu_e} = 16648 \pm 326$
- $\mathcal{B}(D_s^+ \to Xe^+\nu_e) = (6.30 \pm 0.13 \pm 0.10) \times 10^{-2}$
- Consistent, improved by a factor of 2.5 compared to that from CLEO

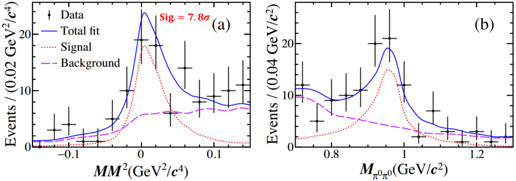
$\mathcal{B}(D_s^+ \to Xe^+\nu_e) - \sum_i B(D_s^+ \to X_i e^+\nu_e)_{known} = (-0.04 \pm 0.13 \pm 0.20) \times 10^{-2}$

No evidence for the existence of unobserved D_s^+ semileptonic decay modes

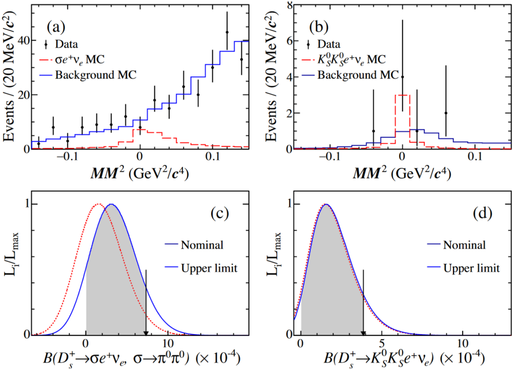
$\frac{\Gamma_{D_s^+ \to Xe^+\nu_e}}{\Gamma_{D^0 \to Xe^+\nu_e}} = 0.790 \pm 0.016 \pm 0.020$ (consistent with prediction~0.813)

Measurement of branching fraction of $D_s^+ \to f_0 e^+ \nu_e$

Two dimensional unbinned extended maximum likelihood fit($f_0 \to \pi^0\pi^0$).



σ means $f_0(500)$



PRD105(2022)L031101

$N_{\mathrm{DT}} = 54.8 \pm 10.1$

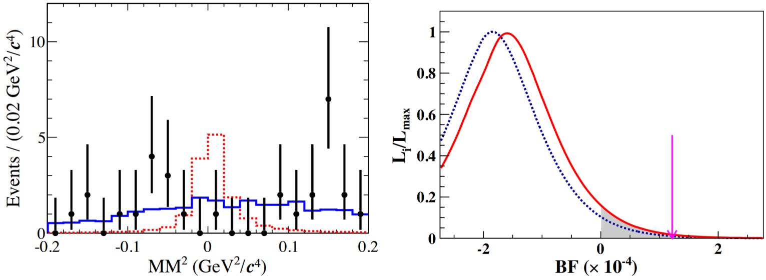
$\mathcal{B}(D_s^+ \to f_0(980) e^+ \nu_e) = (7.9 \pm 1.4 \pm 0.4) \times 10^{-4}$

$\mathcal{B}(D_s^+ \to f_0(500) e^+ \nu_e) < 7.3 \times 10^{-4}$

$\mathcal{B}(D_s^+ \to K_S^0 K_S^0 e^+ \nu_e) < 3.8 \times 10^{-4}$

Search for $D_s^+ \to a_0(980)e^+\nu_e$

PRD103(2021)092004

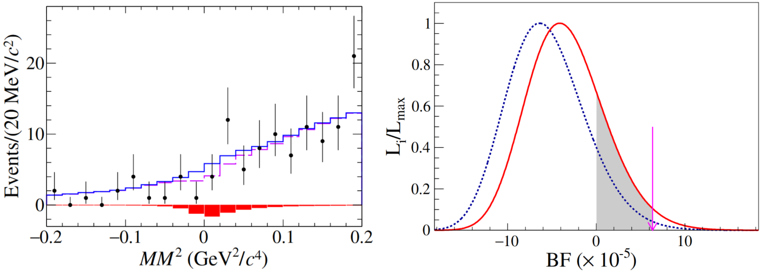


No significant signal is observed

$$\mathcal{B}(D_s^+ \to a_0(980)e^+\nu_e) \times \mathcal{B}(a_0(980) \to \pi^0\eta) < 1.2 \times 10^{-4}$$

Search for $D_s^+ \to \pi^0 e^+ \nu_e$

arXiv:2206.13870



No significant signal is observed

$\mathcal{B}(D_s^+ \to \pi^0 e^+ \nu_e) < 6.4 \times 10^{-5}$
consistent with the predicted BF of $D_s^+ \to \pi^0 e^+ \nu_e$, $(2.65 \pm 0.38) \times 10^{-5}$

Prospects

- More analyses of $D_s \to \mu\nu_\mu$ and $D_s \to \tau\nu_\tau$
- Improved analyses of $D_s \to \eta^{(\prime)}\ell\nu$
- Improved analyses of $D_s \to K^0\ell\nu$
- Improved analyses of $D_s \to KK\ell\nu$
- Improved analyses of $D_s \to \pi\pi\ell\nu$
- Improved measurements of $D \to \mu\nu_\mu$ and $D \to \tau\nu_\tau$
- Improved measurements of $D^{0(+)} \to$(P,V,S, and A)$\ell\nu$

Conclusions

In recent two years, with 2.93fb^{-1} at 3.773 GeV and 6.32 fb^{-1} from 4.178-4.226 GeV data samples, BESIII have studied leptonic and semi-leptonic decays.

- Precisely measured
  - $D_s^+ \to \tau^+ \nu_\tau$
    - $\tau^+ \to e \nu_e \bar{\nu}_\tau$
    - $\tau \to \pi^+ \pi^0 \bar{\nu}_\tau$
    - $\tau \to \pi \bar{\nu}_\tau$
  - $D_s^+ \to \mu^+ \nu_\mu$
  - $D_s^+ \to X e^+ \nu_e$
- First observation for
  - $D^0 \to K_1(1270)^- e^+ \nu_e$
  - $D^0 \to \rho^- \mu^+ \nu_\mu$
- Searches for
  - $D_s^+ \to a_0(980) e^+ \nu_e$
  - $D_s^+ \to \pi^0 e^+ \nu_e$
- New method
  - $D^{0(+)} \to \bar{K} e^+ \nu_e$

In the near future, BESIII will collect 20 fb^{-1}@ 3.773 GeV data sample, and another 3fb^{-1}@ 4.178 GeV, the precisions will be further improved.

Thank you!