Semi-leptonic decays of $D \to P\ell^+\nu_\ell$ at BESIII

潘祥

苏州大学

粲强子物理研讨会
中国科学技术大学
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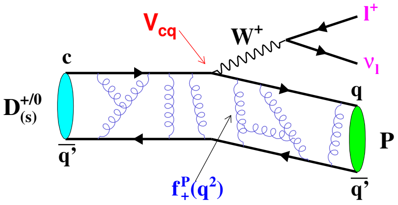
Main goal



Single pole model

- $f_+(q^2) = \frac{f_+(0)}{1 - \frac{q^2}{M^2_{\mathrm{pole}}}}$

Modified pole model

- $f_+(q^2) = \frac{f_+(0)}{(1 - \frac{q^2}{M^2_{\mathrm{pole}}})(1 - \alpha\frac{q^2}{M^2_{\mathrm{pole}}})}$

Series expansion model

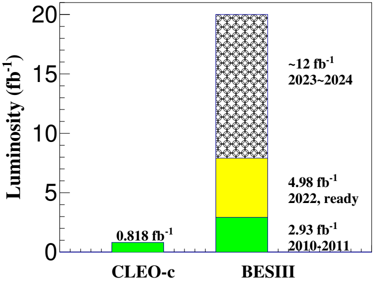
- $f_+(q^2) = \frac{1}{P(q^2)\Phi(q^2)} a_0 (1 + \sum_{k=1}^{\infty} r_k [z(q^2)]^k)$

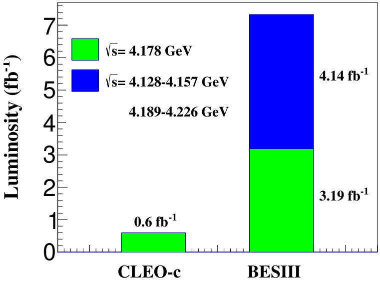
$$\frac{\Delta\Gamma}{dq^2} = X \frac{G_F^2 |V_{cq}|^2}{24\pi^3} \frac{(q^2 - m_\ell^2)^2 |\vec{p}_P|}{q^4 m_D^2} \quad \text{[PRD101(2020)013004]}$$

$$\left[(1 + \frac{m_\ell^2}{2q^2}) m_D^2 |\vec{p}_P|^2 |f_+(q^2)|^2 + \frac{3m_\ell^2}{8q^2} (m_D^2 - m_P^2)^2 |f_0(q^2)|^2 \right] dq^2 \Rightarrow \frac{\Delta\Gamma}{dq^2} \propto (|V_{cq}| f_+(0))^2$$

- FF measurement⇒Calibrate LQCD calculations
- $|V_{cq}|$ measurement ⇒Test CKM matrix unitarity
- BF ratios⇒Test lepton flavor universality (LFU)

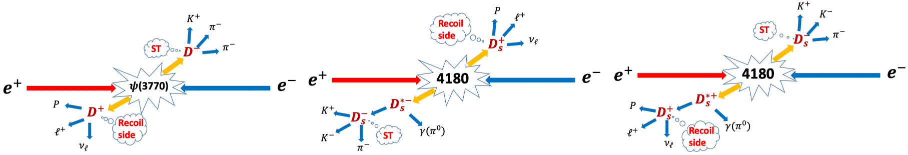
BESIII dataset





- $e^+e^- \to \psi(3770) \to D\bar{D}$, $\mathcal{L}_{\rm int}$ =2.93+4.98 (+12) fb^{-1}
- $e^+e^- \to D_sD_s^*$, $\sqrt{s} = 4.128 - 4.226$ GeV, $\mathcal{L}_{\rm int}$=7.33 fb^{-1}
- Advantages: Clean, double tag method

Double tag method



Tag modes

- $\bar{D}^0 \to K^+\pi^-$, ...
- $D^- \to K^+\pi^-\pi^-$, ...
- $D_s^- \to K^+K^-\pi^-$, ...

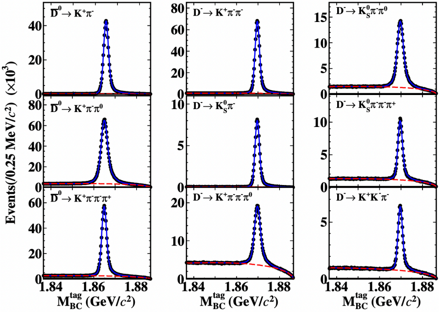
Branching fraction

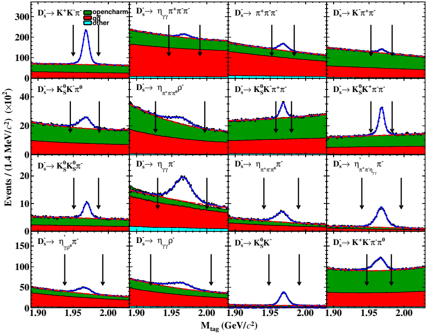
- $N_{\rm tag} = 2N_{D\bar{D}}\mathcal{B}_{\rm tag}\epsilon_{\rm tag}$
- $N_{\rm DT} = 2N_{D\bar{D}}\mathcal{B}_{\rm tag}\mathcal{B}_{\rm sig}\epsilon_{\rm DT}$
- $\mathcal{B}_{\rm sig} = \frac{N_{\rm DT}}{N_{\rm tag}\epsilon_{\rm DT}/\epsilon_{\rm tag}}$

Missing neutrino is determined by

- $U_{\rm miss} = E_{\rm miss} - |\vec{p}_{\rm miss}|$
- $E_{\rm miss} = E_{\rm cm} - E_{\rm tag} - E_P - E_{\ell+}$
- $M^2_{\rm miss} = E^2_{\rm miss} - |\vec{p}_{\rm miss}|^2$
- $\vec{p}_{\rm miss} = -\vec{p}_{\rm tag} - \vec{p}_P - \vec{p}_{\ell+}$

ST yields in data





- 2.93 fb^{-1} data

  $N_{\rm ST}^{\bar{D}^0} \sim 2.4$M with 3 golden tags

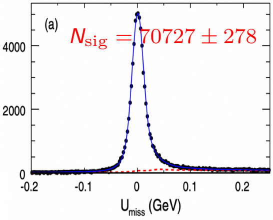
  $N_{\rm ST}^{D^-} \sim 1.6$M with 6 golden tags

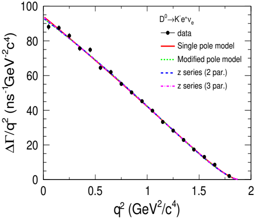
- 7.33 fb^{-1} data

  $N_{\rm ST}^{D_s^-} \sim 0.8$M with 16 possible tags

$D^0 \to K^-\ell^+\nu_\ell$ (2.93 fb^{-1})

$D^0 \to K^- e^+ \nu_e$ PRD92(2015)072012





$D^0 \to K^- e^+ \nu_e$

$\mathcal{B} = (3.505 \pm 0.014 \pm 0.033)\%$

$f_+^K(0)|V_{cs}| = 0.7172(25)(35)$

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

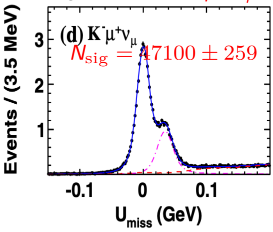
$\mathcal{B} = (3.413 \pm 0.019 \pm 0.035)\%$

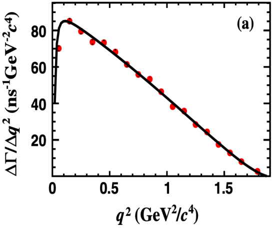
$f_+^K(0)|V_{cs}| = 0.7133(38)(30)$

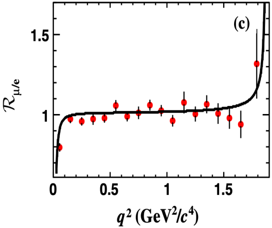
$\mathcal{R}_{\mu/e} = 0.974 \pm 0.007 \pm 0.012$

$\mathcal{R}_{\mu/e}^{\rm SM} = 0.975 \pm 0.001$

$D^0 \to K^- \mu^+ \nu_\mu$ PRL122(2019)011804



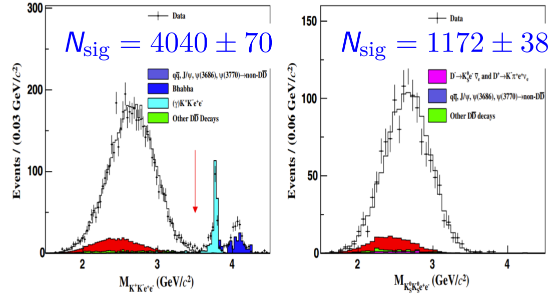




$D^0 \to K^- e^+ \nu_e$ and $D^+ \to \bar{K}^0 e^+ \nu_e$ (2.93 fb^{-1})

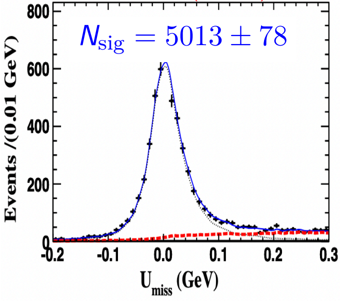
PRD104(2021)052008

$K^+ e^- \bar{\nu}_e$ vs. $K^- e^+ \nu_e$ $K^0 e^- \bar{\nu}_e$ vs. $\bar{K}^0 e^+ \nu_e$



CPC40(2016)113001

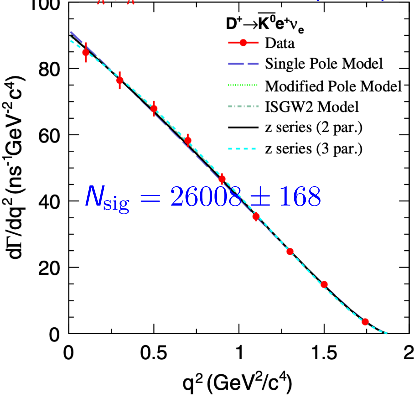
$D^+ \to \bar{K}^0(\pi^0\pi^0)e^+\nu_e$



- $\mathcal{B}_{D^0 \to K^- e^+ \nu_e} = (3.567 \pm 0.031 \pm 0.021)\%$
- $\mathcal{B}_{D^+ \to \bar{K}^0 e^+ \nu_e} = (8.68 \pm 0.14 \pm 0.16)\%$
- $\mathcal{B}_{D^+ \to \bar{K}^0 e^+ \nu_e} = (8.59 \pm 0.14 \pm 0.21)\%$

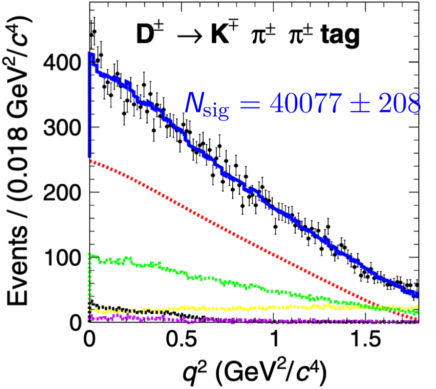
$D^+ \to \bar{K}^0\ell^+\nu_\ell$ (2.93 fb^{-1})

$D^+ \to \bar{K}^0_{\pi^+\pi^-} e^+\nu_e$ PRD96(2017)012002



- $\mathcal{B}_{D^+\to\bar{K}^0e^+\nu_e} = (8.60 \pm 0.06 \pm 0.15)\%$
- $f_+^K(0)|V_{cs}| =$ $0.7053 \pm 0.0040 \pm 0.0112$

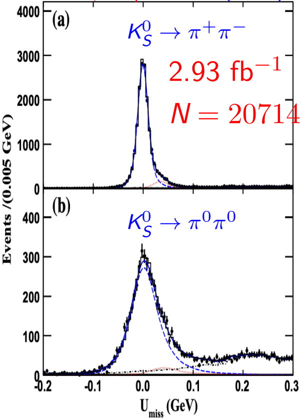
$D^+ \to K^0_L e^+\nu_e$ PRD92(2015)112008



- $\mathcal{B}_{D^+\to\bar{K}^0e^+\nu_e} = (8.96 \pm 0.05 \pm 0.20)\%$
- $f_+^K(0)|V_{cs}| = 0.728 \pm 0.006 \pm 0.011$

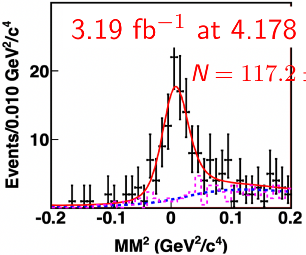
$D^+_{(s)} \to \bar{K}^0\ell^+\nu_\ell$

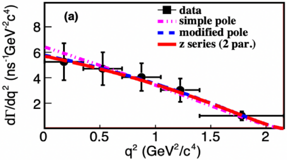
$D^+ \to \bar{K}^0\mu^+\nu_\mu$ EPJC76(2016)369



- $\mathcal{B}_{D^+\to\bar{K}^0\mu^+\nu_\mu} = (8.72 \pm 0.07 \pm 0.18)\%$
- $\mathcal{R}_{\mu/e} = 0.988 \pm 0.033$
- $\mathcal{R}^{\mathrm{SM}}_{\mu/e} = 0.975 \pm 0.001$

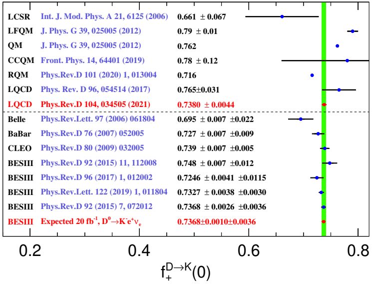
$D^+_s \to K^0 e^+\nu_e$ PRL122(2019)061801

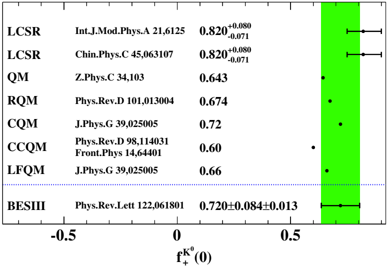




- $\mathcal{B}_{D^+_s\to K^0 e^+\nu_e} = (3.25 \pm 0.038 \pm 0.016)\%$
- $f^K_+(0)|V_{cd}| = 0.162 \pm 0.019 \pm 0.003$

Comparison of $f_+^{D\to K}(0)$



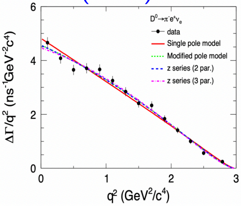


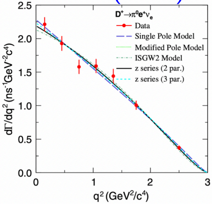
- $f_+^{D\to K}(0)$ 系统误差主导，实验精度与 LQCD 相当。基于最新 8 fb^{-1}（ongoing）和未来 20 fb^{-1}，实验精度预期 ($D^0 \to K^- e^+ \nu_e$)0.60%⇒0.53%⇒0.51%
- 使用 3.19 fb^{-1} @4.178 GeV 数据，$f_+^{D_s\to K}(0)$ 实验精度为11.8%，使用 7.33 fb^{-1} @4.128-4.226 GeV 数据，预期精度可提高到7-8%，该工作正在合作组内部审核 (BAM579)

$D^{0(+)} \to \pi^{-(0)}\ell^+\nu_\ell$ (2.93 fb^{-1})

$D^0 \to \pi^- e^+\nu_e$ PRD92(2015)072012

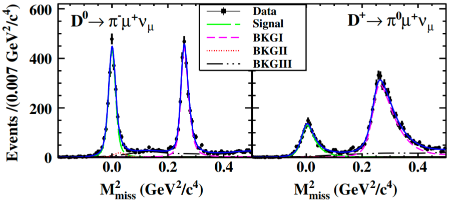
$D^+ \to \pi^0 e^+\nu_e$ PRD96(2017)012002





$D^0 \to \pi^- \mu^+\nu_\mu$ PRL121(2018)171803

$D^+ \to \pi^0 \mu^+\nu_\mu$



- $D^0 \to \pi^- e^+\nu_e$

  $\mathcal{B} = (0.295 \pm 0.004 \pm 0.003)\%$

  $f_+^\pi(0)|V_{cd}| = 0.1435(18)(09)$

- $D^+ \to \pi^0 e^+\nu_e$

  $\mathcal{B} = (0.363 \pm 0.008 \pm 0.005)\%$

  $f_+^\pi(0)|V_{cd}| = 0.1400(26)(07)$

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

  $\mathcal{B} = (0.272 \pm 0.008 \pm 0.006)\%$

  $\mathcal{R}_{\mu/e} = 0.922 \pm 0.030 \pm 0.022$

  $\mathcal{R}^{SM}_{\mu/e} = 0.985 \pm 0.002$ (1.7σ)

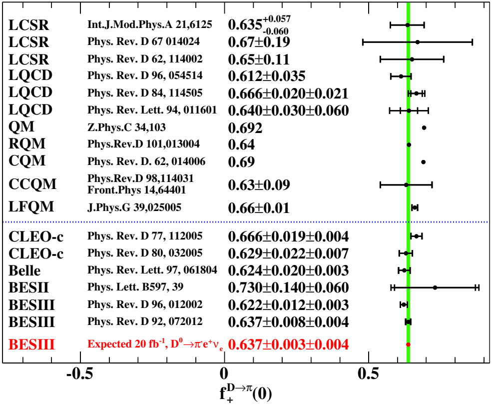
- $D^+ \to \pi^0 \mu^+\nu_\mu$

  $\mathcal{B} = (0.350 \pm 0.011 \pm 0.010)\%$

  $\mathcal{R}_{\mu/e} = 0.964 \pm 0.037 \pm 0.026$

  $\mathcal{R}^{SM}_{\mu/e} = 0.985 \pm 0.002$ (0.5σ)

Comparison of $f_+^{D\to\pi}(0)$

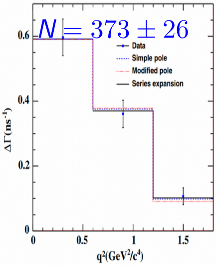


- $f_+^{D\to\pi}(0)$ 系统误差主导，实验精度好于 LQCD。基于最新 8 fb^{-1}（ongoing）和未来 20 fb^{-1} 数据，实验精度预期 $(D^0 \to \pi^- e^+\nu_e)$1.4%⇒1.0%⇒0.8%

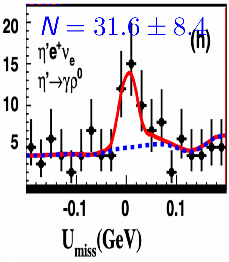
$D^+ \to \eta^{(\prime)}\ell^+\nu_\ell$ (2.93 fb^{-1})

PRD97(2018)092009

$D^+ \to \eta e^+\nu_e$

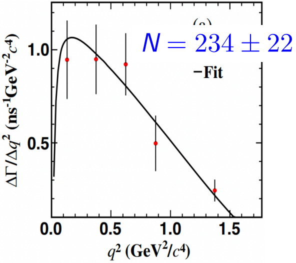


$D^+ \to \eta' e^+\nu_e$



PRL124(2020)231801

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



- $\mathcal{B}_{D^+\to\eta e^+\nu_e} = (10.74 \pm 0.81 \pm 0.51) \times 10^{-4}$
- $\mathcal{B}_{D^+\to\eta' e^+\nu_e} = (1.91 \pm 0.51 \pm 0.13) \times 10^{-4}$
- $f_+^{D\to\eta}(0)|V_{cd}| = (7.86 \pm 0.64 \pm 0.21)\%$

- $\mathcal{B}_{D^+\to\eta\mu^+\nu_\mu} = (10.4\pm1.0\pm0.5)\times10^{-4}$
- $f_+^{D\to\eta}(0)|V_{cd}| = (8.7 \pm 0.8 \pm 0.2)\%$
- $\mathcal{R}_{\mu/e} = 0.91 \pm 0.13$
- $\mathcal{R}_{\mu/e}^{\mathrm{SM}} = 0.93 \sim 0.96$

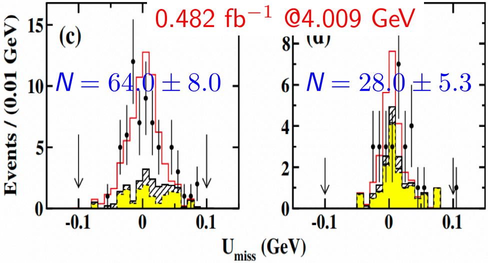
$D_s^+ \to \eta^{(\prime)}\ell^+\nu_\ell$

PRD97(2018)012006

$D_s^+ \to \eta\mu^+\nu_\mu$ $D_s^+ \to \eta'\mu^+\nu_\mu$

0.482 fb^{-1} @4.009 GeV

$N = 64.0 \pm 8.0$ $N = 28.0 \pm 5.3$



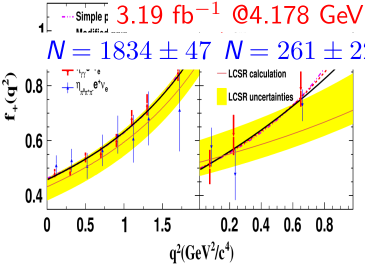
- $\mathcal{B}_{D^+ \to \eta\mu^+\nu_\mu} = (2.42 \pm 0.46 \pm 0.11)\%$
- $\mathcal{B}_{D^+ \to \eta'\mu^+\nu_\mu} = (1.06 \pm 0.54 \pm 0.07)\%$

PRL122(2019)121801

$D_s^+ \to \eta e^+\nu_e$ $D_s^+ \to \eta' e^+\nu_e$

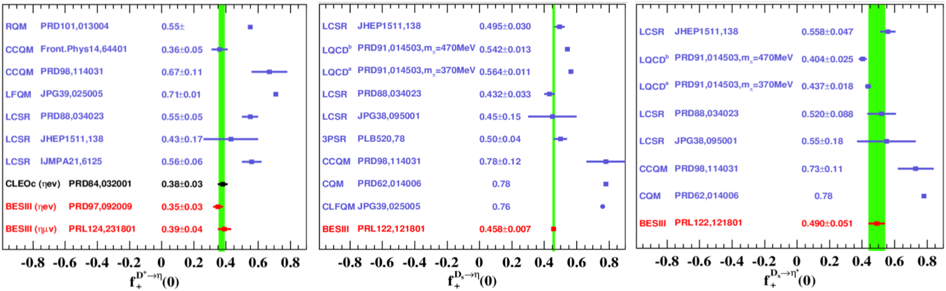
3.19 fb^{-1} @4.178 GeV

$N = 1834 \pm 47$ $N = 261 \pm 22$



- $\mathcal{B}_{D_s^+ \to \eta e^+\nu_e} = (2.323 \pm 0.063 \pm 0.063)\%$
- $\mathcal{B}_{D_s^+ \to \eta' e^+\nu_e} = (0.824 \pm 0.073 \pm 0.027)\%$
- $f_+^{D_s^+ \to \eta}(0)|V_{cs}| = 0.4455 \pm 0.0053 \pm 0.0044$
- $f_+^{D_s^+ \to \eta'}(0)|V_{cs}| = 0.477 \pm 0.049 \pm 0.011$

Comparison of $f_+^{D_{(s)}\to\eta^{(\prime)}}(0)$



- $f_+^{D\to\eta}(0)$ 统计误差主导。基于最新 8 fb^{-1}（ongoing）和未来 20 fb^{-1} 数据，实验精度预期 $(D^+ \to \eta e^+\nu_e)$8.6%⇒5.6%⇒4.1%
- $f_+^{D\to\eta'}(0)$ 将首次测量 (BAM659)
- $f_+^{D_s\to\eta}(0)$ 统计误差主导。基于 7.33 fb^{-1} 数据（BAM595，BAM503），实验精度预期2.5%⇒1.6%
- $f_+^{D_s\to\eta'}(0)$ 统计误差主导。基于 7.33 fb^{-1} 数据（BAM595，BAM503），实验精度预期10%⇒6%

总结与展望

Chain	2.93 fb^{-1}	8 fb^{-1}
$D^0 \to K^- e^+ \nu_e$	$\surd$	Ongoing
$D^0 \to K^- \mu^+ \nu_\mu$	$\surd$	
$D^+ \to \bar{K}^0 e^+ \nu_e$	$\surd$	
$D^+ \to \bar{K}^0 \mu^+ \nu_\mu$	$\surd$	
$D^0 \to \pi^- e^+ \nu_e$	$\surd$	Ongoing
$D^0 \to \pi^- \mu^+ \nu_\mu$	$\surd$	
$D^+ \to \pi^0 e^+ \nu_e$	$\surd$	
$D^+ \to \pi^0 \mu^+ \nu_\mu$	$\surd$	
$D^+ \to \eta e^+ \nu_e$	$\surd$	Ongoing
$D^+ \to \eta \mu^+ \nu_\mu$	$\surd$	
$D^+ \to \eta' e^+ \nu_e$	$\surd$	BAM659
$D^+ \to \eta' \mu^+ \nu_\mu$	NA	

Chain	3.19 fb^{-1}	7.33 fb^{-1}
$D_s^+ \to \eta^{(\prime)} e^+ \nu_e$	$\surd$	BAM595
$D_s^+ \to \eta^{(\prime)} \mu^+ \nu_\mu$	4.009 GeV	BAM503
$D_s^+ \to K^0 e^+ \nu_e$	$\surd$	BAM579
$D_s^+ \to K^0 \mu^+ \nu_\mu$	NA	Ongoing

总结与展望

- 形状因子预期精度改进（2.93 $\mathrm{fb}^{-1} \Rightarrow 8\ \mathrm{fb}^{-1} \Rightarrow 20\ \mathrm{fb}^{-1}$）
  - $f_+^{D\to K}$: σ =0.60%⇒0.53%⇒0.51%
  - $f_+^{D\to \pi}$: σ =1.4%⇒1.0%⇒0.8%
  - $f_+^{D\to \eta}$: σ =9%⇒6%⇒4%
  - $f_+^{D\to \eta'}$: 首次测量
  - $f_+^{D_s\to K}$: σ =12%⇒8%
  - $f_+^{D_s\to \eta}$: σ =2.5%⇒1.6%
  - $f_+^{D_s\to \eta'}$: σ =10%⇒6%
- $|V_{cd(s)}|$: 理论计算形状因子误差较大且不同理论预期值存在差异，限制使用半轻衰变测量 $|V_{cd(s)}|$

总结与展望

- 轻子普适性预期精度改进（2.93 fb^{-1} $\Rightarrow$ 8 fb^{-1} $\Rightarrow$ 20 fb^{-1}）
  - $D \to \bar{K}\ell^+\nu_\ell$ SM: 0.975$\pm$0.001 [EPJC78(2018)501]
    - $\mathcal{R}_{\mu/e}^{D^0\to K^-\ell^+\nu_\ell}$=0.974(07)(12) $\sigma = 1.4\% \Rightarrow 1.3\% \Rightarrow 1.3\%$
    - $\mathcal{R}_{\mu/e}^{D^+\to \bar{K}^0\ell^+\nu_\ell}$=0.988(33) σ=3.3%
  - $D \to \pi\ell^+\nu_\ell$ SM: 0.985$\pm$0.002 [EPJC78(2018)501]
    - $\mathcal{R}_{\mu/e}^{D^0\to \pi^-\ell^+\nu_\ell}$=0.922(30)(22) $\sigma = 4.0\% \Rightarrow 3.1\% \Rightarrow 2.7\%$
    - $\mathcal{R}_{\mu/e}^{D^+\to \pi^0\ell^+\nu_\ell}$=0.964(37)(26) $\sigma = 4.7\% \Rightarrow 3.6\% \Rightarrow 3.1\%$
  - $D \to \eta\ell^+\nu_\ell$ SM: 0.93$\sim$0.96
    - $\mathcal{R}_{\mu/e}^{D^+\to \eta\ell^+\nu_\ell}$=0.91(13) $\sigma = 14\%$
  - $D_s \to \eta^{(\prime)}\ell^+\nu_\ell$ SM: 0.95$\sim$0.99
    - $\mathcal{R}_{\mu/e}^{D_s^+\to \eta\ell^+\nu_\ell}$=1.08(21)(05) $\sigma = 20\% \Rightarrow 3.3\%$
    - $\mathcal{R}_{\mu/e}^{D_s^+\to \eta'\ell^+\nu_\ell}$=1.31(67)(09) $\sigma = 52\% \Rightarrow 9.0\%$