BESIII上粲介子半轻衰变研究

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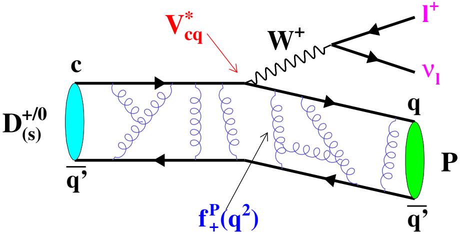
2024 粲物理研讨会

Outline

物理目标

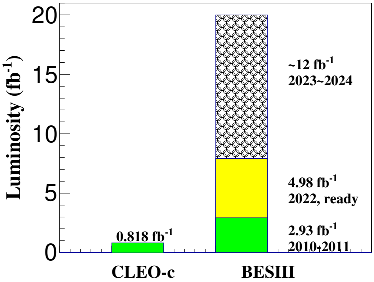


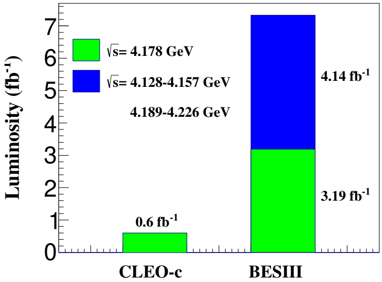
$$M_{D\to X\ell\nu} = \frac{G_F}{\sqrt{2}} V_{cq} \langle X(p_X)|\bar{q}\gamma_\mu(1-\gamma_5)c|D(p_D)\rangle \times \bar{u}(p_\nu)\gamma^\mu(1-\gamma_5)v(p_{\bar{\ell}})$$

$X = P, S, V, A$, 分别为赝标量(pseudoscalar),标量(scalar),矢量(vector),极矢量(axion)介子

- D 介子半轻衰变可以提取CKM矩阵元$|V_{cd}|$，提供更多数据检验其幺正性
- 抽取强子化形状因子，检验格点QCD计算
- 测量衰变宽度可检验轻子普适性是否破缺

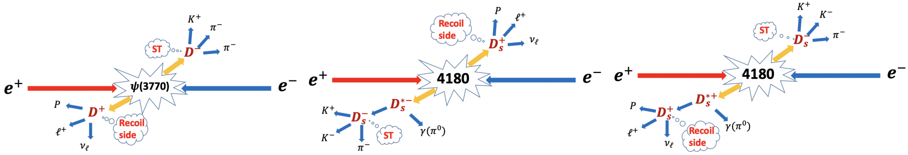
BESIII 实验数据





- $e^+e^- \to \psi(3770) \to D\bar{D}$, $\mathcal{L}_{\rm int}$ =2.93+4.98 (+12) fb^{-1}
- $e^+e^- \to D_s D_s^*$, $\sqrt{s} = 4.128 - 4.226$ GeV, $\mathcal{L}_{\rm int}$=7.33 fb^{-1}
- 优势: 正负电子对撞近阈产生，本底干净，介子对产生可用双标记进一步提高样本纯度

双标记实验方法

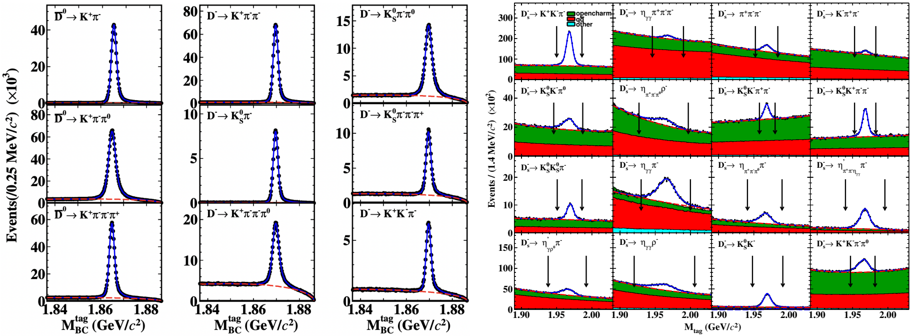


- 标记道
  - $\bar{D}^0 \to K^+\pi^-, \ldots$
  - $D^- \to K^+\pi^-\pi^-, \ldots$
  - $D_s^- \to K^+K^-\pi^-, \ldots$
- 分支比测量
  - $N_{\rm tag} = 2N_{D\bar{D}}\mathcal{B}_{\rm tag}\epsilon_{\rm tag}$
  - $N_{\rm DT} = 2N_{D\bar{D}}\mathcal{B}_{\rm tag}\mathcal{B}_{\rm sig}\epsilon_{\rm DT}$
  - $\mathcal{B}_{\rm sig} = \dfrac{N_{\rm DT}}{N_{\rm tag}\epsilon_{\rm DT}/\epsilon_{\rm tag}}$

丢失的中微子特征变量定义为：

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

单标记样本



- 2.93 fb^{-1} (7.9 fb^{-1}) data
  - 三个黄金标记道样本数$N_{\mathrm{ST}}^{\bar{D}^0} \sim 2.4$M (6.6M)
  - 六个黄金标记道样本数$N_{\mathrm{ST}}^{D^-} \sim 1.6$M (4.3M)
- 7.33 fb^{-1} data
  - 十六个标记道样本数$N_{\mathrm{ST}}^{D_s^-} \sim 0.8$M

$D \to P\ell\nu$ 衰变

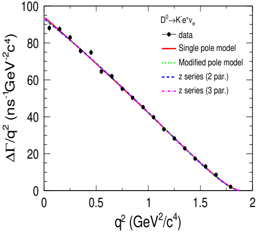
$$\frac{d\Gamma}{dq^2} = X \frac{G_F^2|V_{cq}|^2}{24\pi^3} \frac{(q^2-m_\ell^2)^2|\vec{p}_P|}{q^4 m_D^2} \left[(1+\frac{m_\ell^2}{2q^2})m_D^2|\vec{p}_P|^2|f_+(q^2)|^2 + \frac{3m_\ell^2}{8q^2}(m_D^2-m_P^2)^2|f_0(q^2)|^2\right] dq^2$$

$X = 1$ for K^-, π^-, $\bar{K}^0$, and $\eta^{(\prime)}$; $X = 1/2$ for π^0

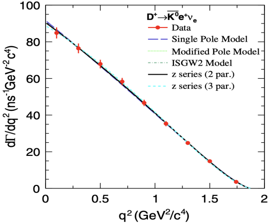
- Single pole model
  - $f_+(q^2) = \frac{f_+(0)}{1-\frac{q^2}{M_{\rm pole}^2}}$
- Modified pole model
  - $f_+(q^2) = \frac{f_+(0)}{(1-\frac{q^2}{M_{\rm pole}^2})(1-\alpha\frac{q^2}{M_{\rm pole}^2})}$
- Series expansion model
  - $f_+(q^2) = \frac{1}{P(q^2)\Phi(q^2)} a_0(1+\sum_{k=1}^{\infty} r_k[z(q^2)]^k)$

$D \to P\ell\nu$ 中 $c \to s\ell^+\nu_\ell$ 衰变

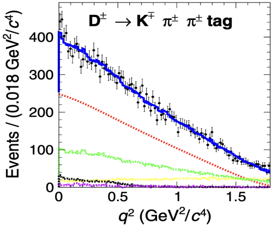
$D^0 \to K^- e^+ \nu_e$ PRD92,072012



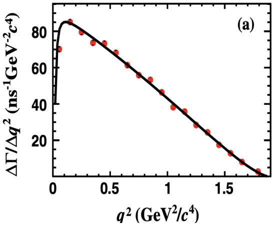
$D^+ \to \bar{K}^0 e^+ \nu_e$ PRD96,012002



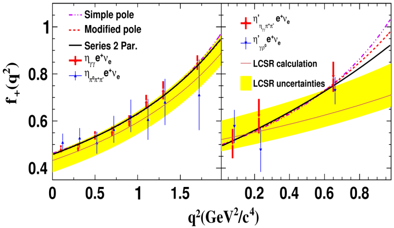
$D^+ \to K_L^0 e^+ \nu_e$ PRD92,112008



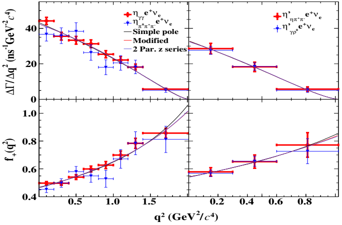
$D^0 \to K^- \mu^+ \nu_\mu$ PRL122,011804



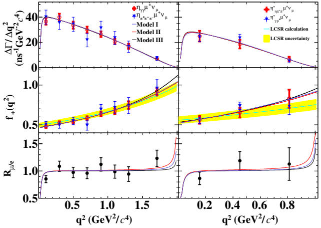
$D_s^+ \to \eta^{(\prime)} e^+ \nu_e$ PRL123,121801



$D_s^+ \to \eta^{(\prime)} e^+ \nu_e$ PRD108,092003



$D_s^+ \to \eta^{(\prime)} \mu^+ \nu_\mu$ PRL132,091802



总结 $D \to P\ell\nu$ 中 $c \to s\ell^+\nu_\ell$ 衰变的形状因子与 $|V_{cs}|$

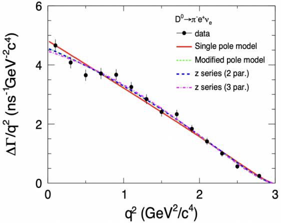
${f_+^{D\to K}}_{\rm LQCD} = 0.7452(31)$, ${f_+^{D_s\to\eta}}_{\rm LQCD} = 0.495(30)$, ${f_+^{D_s\to\eta'}}_{\rm LQCD} = 0.558(47)$,
$|V_{cs}|_{\rm GlobalFit} = 0.97349(16)$

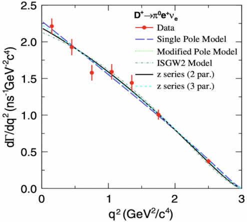
Channel	Reference	$L/E_{\rm cm}$ (fb^{-1}/GeV)	$f_+(0)$	$\lvert V_{cs}\rvert$	$\Delta_{\rm exp}$ (%)
$D^0 \to K^- e^+\nu_e$	PRD92,072012	2.93/3.773	0.7367(26)(36)(01)	0.9624(34)(47)(40)	0.6
$D^+ \to \bar{K}^0 e^+\nu_e$	PRD96,012002		0.724(04)(11)(01)	0.946(05)(15)(04)	1.7
$D^+ \to K_L^0 e^+\nu_e$	PRD92,112008		0.748(06)(11)(01)	0.977(08)(15)(04)	1.7
$D^0 \to K^-\mu^+\nu_\mu$	PRL122,011804		0.7327(39)(31)(01)	0.9572(50)(40)(40)	0.7
$D_s^+ \to \eta e^+\nu_e$	PRL123,121801	3.19/4.178	0.458(10)(07)	0.900(20)(14)(55)	2.7
$D_s^+ \to \eta' e^+\nu_e$			0.518(35)(09)	0.903(60)(15)(76)	7.0
$D_s^+ \to \eta e^+\nu_e$	PRD108,092003	7.33/4.128-4.226	0.4642(73)(66)	0.913(14)(13)(55)	2.1
$D_s^+ \to \eta' e^+\nu_e$			0.540(25)(09)	0.941(44)(16)(79)	4.9
$D_s^+ \to \eta\mu^+\nu_\mu$	PRL132,091802	7.33/4.128-4.226	0.463(10)(08)	0.911(20)(16)(55)	2.8
$D_s^+ \to \eta'\mu^+\nu_\mu$			0.520(38)(11)	0.907(67)(19)(76)	7.6
$D^0 \to K^-\ell^+\nu_\ell$ $D^+ \to \bar{K}^0\ell^+\nu_e$	simultanous fit ongoing	8/3.773 review(16/3.773 ongoing)			

实验测量的最高精度: 0.6% for $|V_{cs}|$ and $f_+^{D\to K}(0)$, 2.1% for $f_+^{D_s\to\eta}(0)$, 4.9% for $f_+^{D_s\to\eta'}(0)$

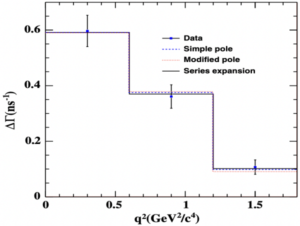
$D \to P\ell\nu$ 中 $c \to d\ell^+\nu_\ell$ 衰变

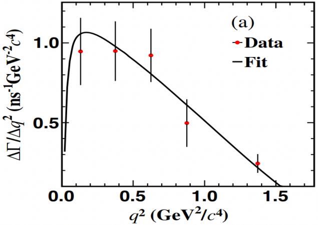
$D^0 \to \pi^- e^+ \nu_e$ PRD92,07201 $D^+ \to \pi^0 e^+ \nu_e$ PRD96,012002

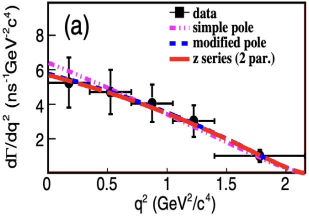




$D^+ \to \eta e^+ \nu_e$ PRD97,092009 $D^+ \to \eta \mu^+ \nu_\mu$ PRL124,231801 $D_s^+ \to K^0 e^+ \nu_e$ PRL122,061801







总结$D \to P\ell\nu$ 中$c \to d\ell^+\nu_\ell$ 衰变的形状因子与$|V_{cd}|$

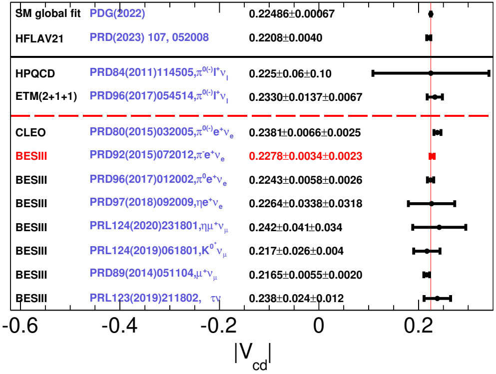
$f_+^{D\to\pi}{}_{\rm LQCD} = 0.6300(51)$, $f_+^{D\to\eta}{}_{\rm LQCD} = 0.36(5)$, $f_+^{D_s\to K}{}_{\rm LQCD} = 0.7452(31)$,
$|V_{cd}|_{\rm GlobalFit} = 0.22486(67)$

Channel	Reference	$L/E_{\rm cm}$ (fb^{-1}/GeV)	$f_+(0)$	$\lvert V_{cd}\rvert$	$\Delta_{\rm exp}$ (%)
$D^0 \to \pi^- e^+\nu_e$	PRD92,072012	2.93/3.773	0.6382(80)(40)(19)	0.2278(29)(14)(18)	1.8
$D^+ \to \pi^0 e^+\nu_e$	PRD96,012002		0.623(12)(03)(02)	0.222(04)(01)(02)	1.9
$D^+ \to \eta e^+\nu_e$	PRD97,092009	2.93/3.773	0.350(28)(09)(01)	0.218(18)(06)(30)	8.6
$D^+ \to \eta\mu^+\nu_\mu$	PRL124,23180		0.387(36)(09)(01)	0.242(22)(06)(34)	9.5
$D_s^+ \to K^0 e^+\nu_e$	PRL122,061801	3.19/4.178	0.720(84)(13)(02)	0.217(25)(04)(01)	11.9
$D_s^+ \to K^0 e^+\nu_e$	ongoing	7.33/4.128-4.226(review)			
$D^0 \to \pi^-\ell^+\nu_\ell$ $D^+ \to \pi^0\ell^+\nu_e$	simultanous fit ongoing	8/3.773 review(16/3.773 ongoing)			
$D^+ \to \eta\ell^+\nu_\ell$	simultanous fit ongoing	8/3.773 review			
$D^+ \to \eta'\ell^+\nu_\ell$	simultanous fit ongoing	8/3.773 review			

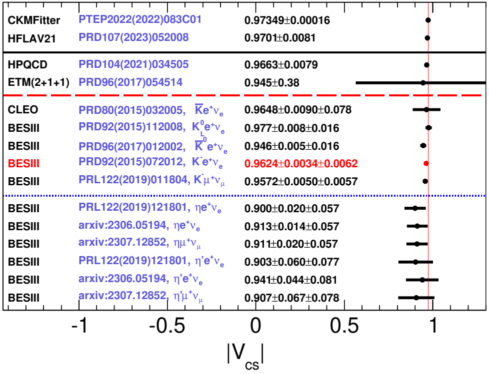
实验测量的最高精度: 1.8% for $|V_{cd}|$ and 1.4% for $f_+^{D\to\pi}(0)$

理论计算与实验测量的$|V_{cs}|$ 与$|V_{cd}|$ 比较

(Semi)leptonic $D^{0/+}$ decay

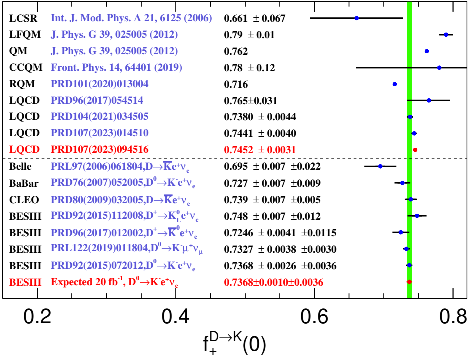


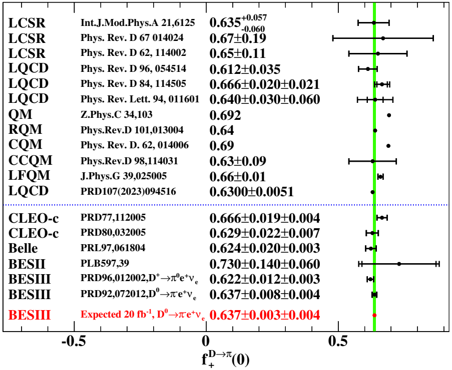
Semileptonic $D_{(s)}$ decay



- 单个衰变道中$|V_{cd}|$ 测量的最高精度:
  $D^0 \to \pi^- e^+ \nu_e$: 1.8% (2.93 fb^{-1})→1.3% (7.9 fb^{-1})→1.2% (20 fb^{-1})
- 单个衰变道中$|V_{cs}|$ 测量的最高精度:
  $D^0 \to K^- e^+ \nu_e$: 0.73% (2.93 fb^{-1})→0.68% (7.9 fb^{-1})→0.66% (20 fb^{-1})

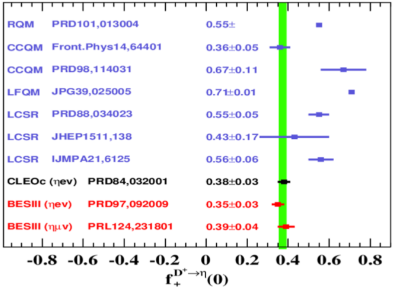
理论计算与实验测量的 $f_+^{D\to K}(0)$ 与 $f_+^{D\to\pi}(0)$ 比较

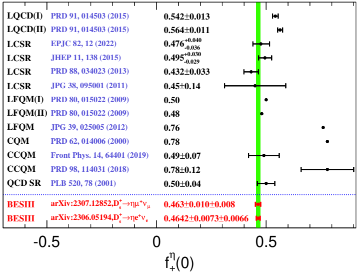


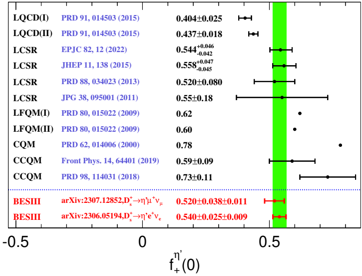


- 单个衰变道中 $f_+^{D\to K}(0)$ 测量的最高精度:
  $D^0\to K^-e^+\nu_e$: 0.60% (2.93 fb^{-1})→0.53% (7.9 fb^{-1})→0.51% (20 fb^{-1})
- 单个衰变道中 $f_+^{D\to\pi}(0)$ 测量的最高精度:
  $D^0\to \pi^-e^+\nu_e$: 1.4% (2.93 fb^{-1})→1.0% (7.9 fb^{-1})→0.8% (20 fb^{-1})

理论计算与实验测量的$f_+^{D_{(s)}\to\eta^{(\prime)}}(0)$ 比较







精度:

- $f_+^{D\to\eta}(0)$: 8.6% (2.93 fb^{-1})⇒5.6% (7.9 fb^{-1})⇒4.1% (20 fb^{-1})
- $f_+^{D_s\to\eta}(0)$: 2.1% for $D_s^+\to\eta e^+\nu_e$ and 2.8% for $D_s^+\to\eta\mu^+\nu_\mu$, 1.6% for $D_s^+\to\eta e^+\nu_e+\eta\mu^+\nu_\mu$
- $f_+^{D_s\to\eta'}(0)$: 4.9% for $D_s^+\to\eta' e^+\nu_e$ and 7.6% for $D_s^+\to\eta'\mu^+\nu_\mu$, 4.5% for $D_s^+\to\eta' e^+\nu_e+\eta'\mu^+\nu_\mu$

$D \to V\ell\nu$ 衰变

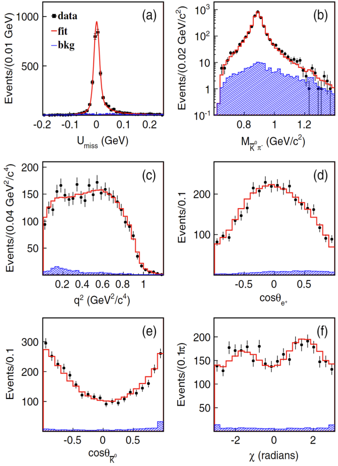
$$\frac{d^4\Gamma}{dq^2 d\cos\theta_V d\cos\theta_\ell d\chi} = \frac{G_F^2|V_{cq}|^2}{(4\pi)^6 m_D^3} X\beta\beta_\ell \Big(I_1^s \sin^2\theta_V + I_1^c \cos^2\theta_V + \left(I_2^s \sin^2\theta_V + I_2^c \cos^2\theta_V\right)\cos 2\theta_\ell$$
$$+ I_3 \sin^2\theta_V \sin^2\theta_\ell \cos 2\chi + I_4 \sin 2\theta_V \sin 2\theta_\ell \cos\chi$$
$$+ I_5 \sin 2\theta_V \sin\theta_\ell \cos\chi$$
$$+ \left(I_6^s \sin^2\theta_V + I_6^c \cos^2\theta_V\right)\cos\theta_\ell + I_7 \sin 2\theta_V \sin\theta_\ell \sin\chi$$
$$+ I_8 \sin 2\theta_V \sin 2\theta_\ell \sin\chi + I_9 \sin^2\theta_V \sin^2\theta_\ell \sin 2\chi\Big).$$

$$I_1^s = \frac{1}{2}(H_+^2 + H_-^2)(m_\ell^2 + 3q^2),$$
$$I_1^c = 4m_\ell^2 H_t^2 + 2H_0^2(m_\ell^2 + q^2),$$
$$I_2^s = -\frac{1}{2}(H_+^2 + H_-^2)(m_\ell^2 - q^2),$$
$$I_2^c = 2H_0^2(m_\ell^2 - q^2),$$
$$I_3 = 2H_+H_-(m_\ell^2 - q^2),$$
$$I_4 = H_0(H_+ + H_-)(m_\ell^2 - q^2),$$
$$I_5 = -2H_t(H_+ + H_-)m_\ell^2 - 2H_0(H_+ - H_-)q^2,$$
$$I_6^s = 2(H_+^2 - H_-^2)q^2,$$
$$I_6^c = -8H_tH_0m_\ell^2,$$
$$I_7 = 0, I_8 = 0, I_9 = 0.$$

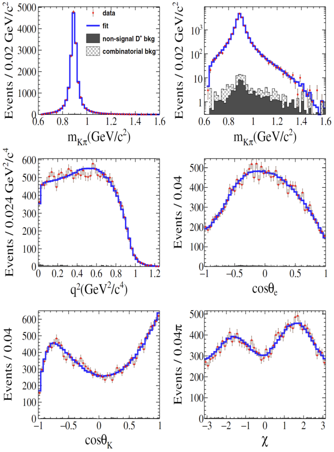
$$H_\pm(q^2) = \frac{\lambda^{1/2}}{M_D + M_V}\left[V(q^2) \mp \frac{(M_D + M_V)^2}{\lambda^{1/2}} A_1(q^2)\right],$$
$$H_0(q^2) = \frac{1}{2M_V\sqrt{q^2}}\left[(M_D + M_V)(M_D^2 - M_V^2 - q^2)A_1(q^2) - \frac{\lambda}{M_D + M_V} A_2(q^2)\right],$$
$$H_t(q^2) = \frac{\lambda^{1/2}}{\sqrt{q^2}} A_0(q^2).$$

$D \to V\ell\nu$ 中 $c \to s\ell^+\nu_\ell$ 衰变

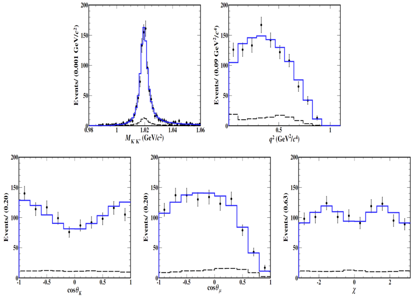
$D^0 \to \bar{K}^0\pi^- e^+\nu_e$ PRD99,011103



$D^+ \to K^+\pi^- e^+\nu_e$ PRD94,032001



$D_s^+ \to \phi\mu^+\nu_\mu$ JHEP12(2023)072

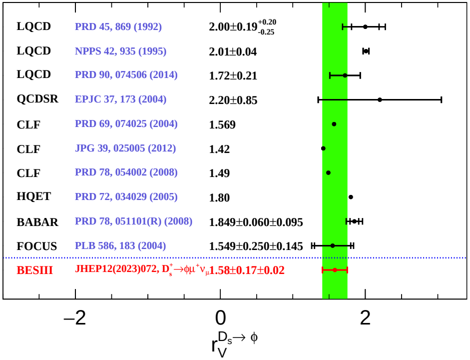


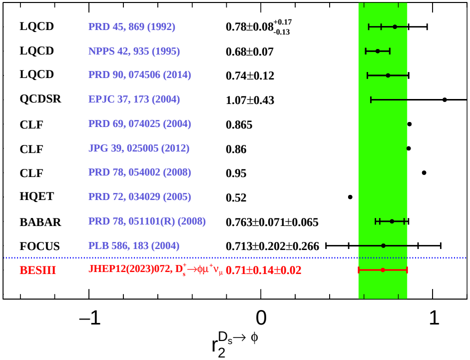
总结$D \to V \ell \nu$ 中$c \to s\ell^+\nu_\ell$ 衰变的分支比与形状因子

$$r_V{}^{D_s\to\phi}{}_{\rm LQCD} = 1.72(21),\ r_2{}^{D_s\to\phi}{}_{\rm LQCD} = 0.74(12),\ r_V{}^{D\to K^*}{}_{\rm LQCD} = 1.83(9),\ r_2{}^{D\to K^*}{}_{\rm LQCD} = 0.74(19)$$

Channel	Reference	$L/E_{\rm cm}$ (fb^{-1}/GeV)	BF(%)	FF	$\Delta_{\rm exp}$ (%)
$D^0 \to K^{*-}e^+\nu_e$	PRD99,011103	2.93/3.773	1.434(29)(32)	$r_V = 1.46(7)(2)$ $r_2 = 0.67(6)(1)$	5.0
$D^+ \to K^{*0}e^+\nu_e$	PRD94,032001	2.93/3.773	3.77(3)(8)	$r_V = 1.411(58)(07)$ $r_2 = 0.788(42)(08)$	4.1
$D_s^+ \to \phi e^+\nu_e$ $D_s^+ \to \phi\mu^+\nu_\mu$	PRD97,012006	0.482/4.009	2.26(0.45)(0.09) 1.94(53)(09)	- -	- -
$D_s^+ \to \phi\mu^+\nu_\mu$	JHEP12(2023)072	7.33/4.128-4.226	2.25(9)(7)	$r_V = 1.58(17)(02)$ $r_2 = 0.71(14)(02)$	10.8
$D_s^+ \to \phi e^+\nu_e$	ongoing	7.33/4.128-4.226 review			
$D^+ \to K^{*0}\ell^+\nu_\ell$ $D^+ \to K^{*+}\ell^+\nu_e$	simultanous fit ongoing	16/3.773 review			

理论计算与实验测量的$r_V^{D_s\to\phi}$与$r_2^{D_s\to\phi}$比较

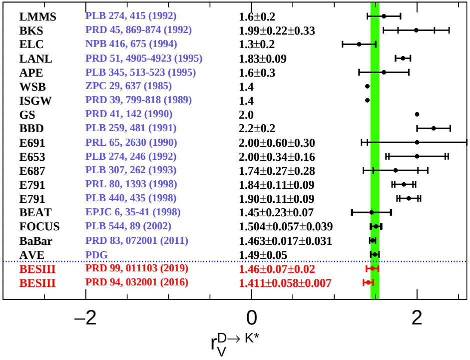


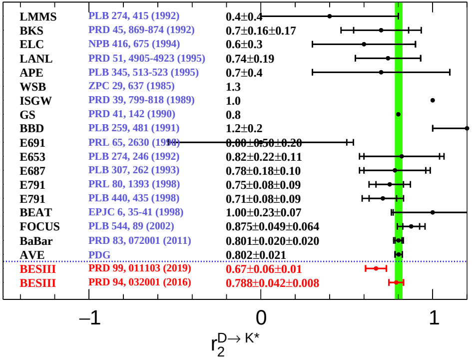


精度:

- $r_V^{D_s\to\phi}$ and $r_2^{D_s\to\phi}$: 10.8% (7.33 fb^{-1}(muon))⇒6.2% (7.33 fb^{-1}(electron))

理论计算与实验测量的$r_V^{D\to K^*}$ 与$r_2^{D\to K^*}$ 比较



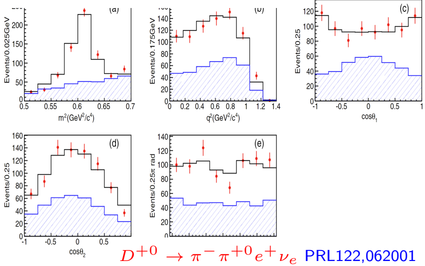


精度:

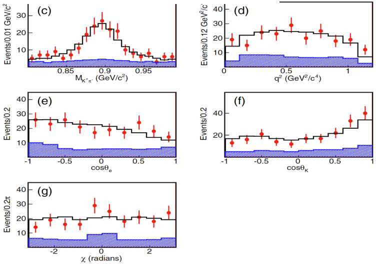
- $r_V^{D\to K^*}$ and $r_2^{D\to K^*}$: 4.1% (2.93 fb^{-1})⇒2.0% (20 fb^{-1}(all channel))

$D \to V\ell\nu$ 中 $c \to d\ell^+\nu_\ell$ 衰变

$D^+ \to \omega e^+\nu_e$ PRD92, 071101(R)



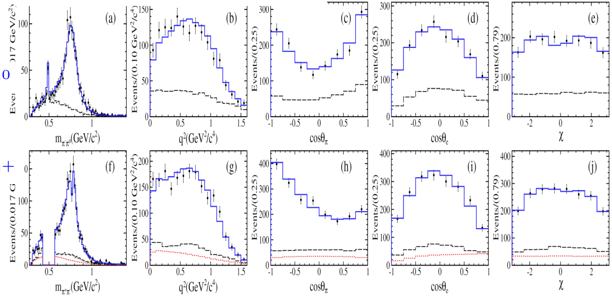
$D_s^+ \to K^* e^+\nu_e$ PRL122, 061801



$D^{+0} \to \pi^-\pi^{+0} e^+\nu_e$ PRL122,062001

D^0

D^+



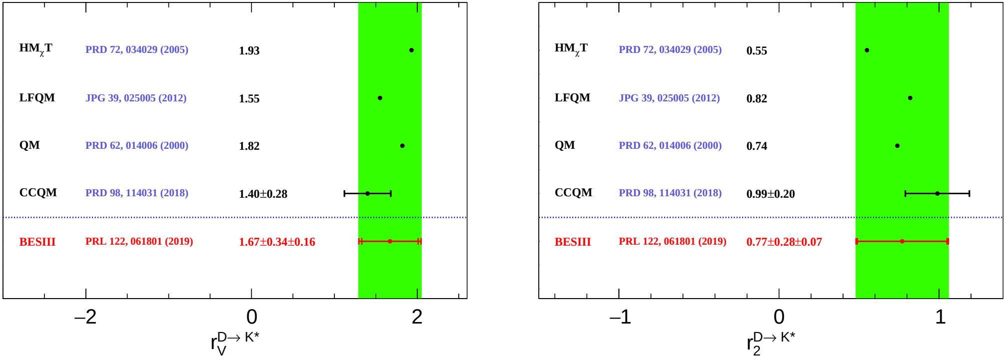
总结$D \to V\ell\nu$ 中$c \to d\ell^+\nu_\ell$ 衰变的分支比与形状因子

${r_V^{D_s\to K^*}}_{\rm CCQM} = 1.40(28)$, ${r_2^{D_s\to K^*}}_{\rm CCQM} = 0.99(20)$, ${r_V^{D\to\rho}}_{\rm LCSR} = 1.41(17)$, ${r_2^{D\to\rho}}_{\rm LCSR} = 0.81(12)$
${r_V^{D\to\omega}}_{\rm CCQM} = 1.24(25)$, ${r_2^{D\to\omega}}_{\rm CCQM} = 0.95(19)$

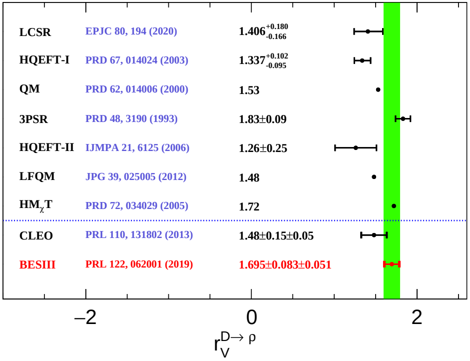
Channel	Reference	$L/E_{\rm cm}$ (fb^{-1}/GeV)	BF(%)	FF	$\Delta_{\rm exp}$ (%)
$D \to \rho e^+\nu_e$	PRL122,062001	2.93/3.773	D^0: 0.1445(58)(39) D^+: 0.1860(70)(61)	$r_V = 1.695(83)(51)$ $r_2 = 0.845(56)(39)$	5.7
$D^0 \to \rho^-\mu^+\nu_\mu$	PRD104,L091103	2.93/3.773	0.135(9)(9)		
$D^+ \to \omega e^+\nu_e$	PRD92,071101(R)	2.93/3.773	0.163(11)(08)	$r_V = 1.24(9)(6)$ $r_2 = 1.06(15)(05)$	8.7
$D^+ \to \omega\mu^+\nu_\mu$	PRD101,072005	2.93/3.773	0.177(18)(11)		
$D_s^+ \to K^{*0}e^+\nu_e$	PRL122,061801	3.19/4.178	0.237(26)(20)	$r_V = 1.67(34)(16)$ $r_2 = 0.77(28)(07)$	22.5

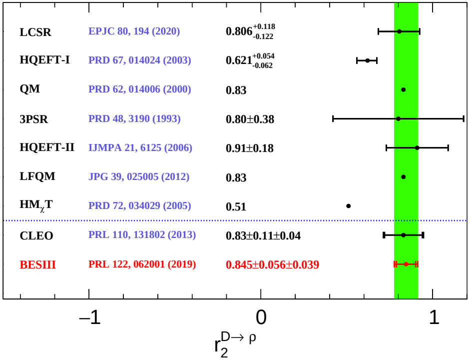
首次实验测量$D^+ \to \omega$ 和$D_s^+ \to K^{*0}$ 形状因子

理论计算与实验测量的$r_V^{D_s\to K^*}$ 与$r_2^{D_s\to K^*}$ 比较

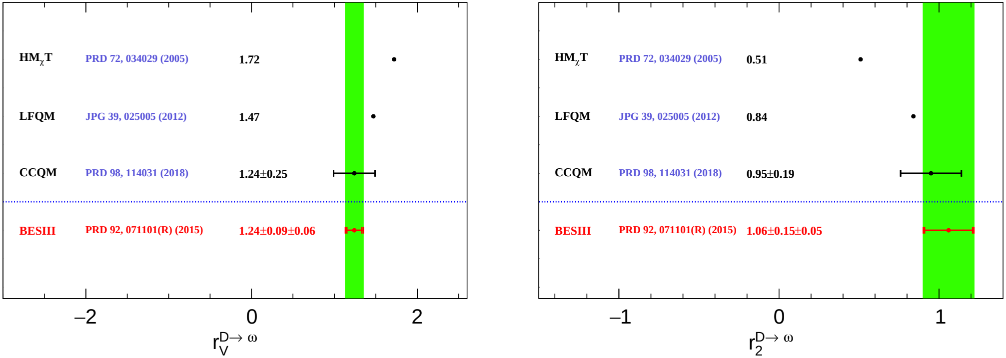


理论计算与实验测量的$r_V^{D\to\rho}$ 与$r_2^{D\to\rho}$ 比较





理论计算与实验测量的$r_V^{D\to\omega}$ 与$r_2^{D\to\omega}$ 比较



$D \to (S, A)\ell\nu$ 衰变

Chain	Ref.	$L/E_{\rm cm}$ (fb^{-1}/GeV)	BF($\times 10^{-4}$)
$D^{0/+} \to a(980)^{-(0)} e^+ \nu_e$	PRL121,081802	2.93/3.773	D^0: $1.33^{+0.33}_{-0.29} \pm 0.09$ D^+: $1.66^{+0.81}_{-0.66} \pm 0.11$
$D_s^+ \to f_0(980)_{\pi^0\pi^0} e^+ \nu_e$	PRD105,L031101	6.32/4.178-4.226	$7.9 \pm 1.4 \pm 0.3$
$D_s^+ \to f_0(500)_{\pi^0\pi^0} e^+ \nu_e$	PRD105,L031101	6.32/4.178-4.226	< 6.4
$D^0 \to \bar{K}_1(1270)^- e^+ \nu_e$	PRL127,131801	2.93/3.773	$3.59 \pm 0.41^{+0.31}_{-0.44}$
$D^+ \to \bar{K}_1(1270)^0 e^+ \nu_e$	PRL123,231801	2.93/3.773	$10.6 \pm 1.2 \pm 0.8$
$D^{0(+)} \to b_1(1235)^{-(0)} e^+ \nu_e$	PRD102,112005	2.93/3.773	$D^+ :< 1.75$ $D^0 :< 1.12$
$D_s^+ \to K_1(1270)^0 e^+ \nu_e$	arXiv:2309.04090	7.33/4.128-4.226	< 4.1
$D_s^+ \to b_1(1235)^0 e^+ \nu_e$	arXiv:2309.04090	7.33/4.128-4.226	< 6.4

许多半轻衰变正在研究，$K_1(1270)$和$a(980)$形状因子研究正在进行中...

总结与展望

$\lvert V_{cd}\rvert$ 精度预期		
	2.93 fb^{-1}	20 fb^{-1}
$D^0 \to \pi^- e^+ \nu_e$	1.8%	
$D^{0(+)} \to \pi^{-(0)} \ell^+ \nu_\ell$		(1.2%)
$D^+ \to \mu^+ \nu_\mu$ 与 $D^{0(+)} \to \pi^{-(0)} \ell^+ \nu_\ell$ 衰变道合并		$\lvert V_{cd}\rvert$ 的误差预期将在1%以下
$\lvert V_{cs}\rvert$ 精度预期		
$D^0 \to K^- e^+ \nu_e$	0.73%	
$D^{0(+)} \to K^-(\bar{K}^0) \ell^+ \nu_\ell$		∼0.45%
形状因子的精度预期		
$D^0 \to K^- e^+ \nu_e (D \to \bar{K} \ell^+ \nu_\ell)$	0.60%	0.51%(∼0.20%)
$D^0 \to \pi^- e^+ \nu_e (D \to \pi \ell^+ \nu_\ell)$	1.4%	0.8%(∼0.6%)
$D \to \eta e^+ \nu_e (D \to \eta \ell^+ \nu_\ell)$	∼10%	(∼2.0%)
$D \to \eta' \ell^+ \nu_\ell$		∼10%
$D \to K^* e^+ \nu_e (D \to K^* \ell^+ \nu_\ell)$	∼4%	(∼2%)
$D \to \rho e^+ \nu_e$	∼6%	∼3%
$D \to \omega e^+ \nu_e$	∼9%	∼5%