

Прецизионные измерения распадов D-мезонов на Супер $c - \tau$ фабрике

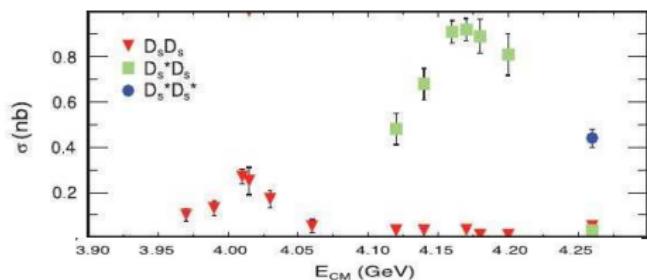
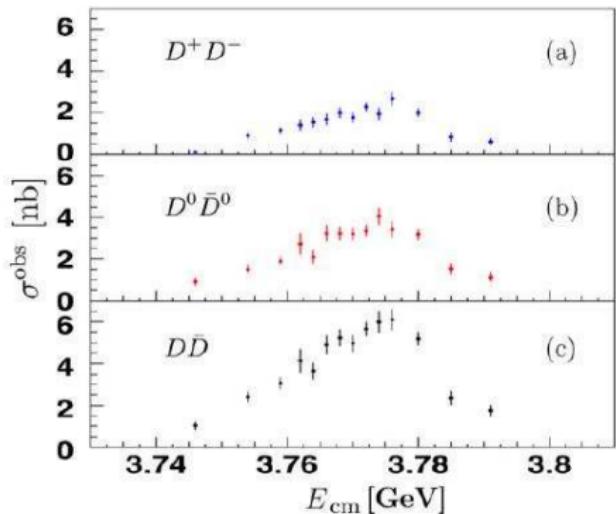
Дмитрий Матвиенко

Физическая программа Супер $c - \tau$ фабрики

19 декабря 2017

- $D_{(s)}^+ \rightarrow l^+ \nu_l, l = e, \mu, \tau$
- $D_{(s)} \rightarrow K(\pi)l^+ \nu_l, l = e, \mu$
- $D_{(s)} \rightarrow K\pi(\pi\pi, K\pi\pi, \dots)l^+ \nu_l, l = e, \mu$
- $D_{(s)} \rightarrow \omega(\phi, \eta, \eta')l^+ \nu_l, l = e, \mu$
- Адронные моды

Рождение D и D_s на SCTF



$$\begin{aligned}\sigma(e^+ e^- \rightarrow \psi(3770)) &= 6 \text{ nb} \\ \sigma(e^+ e^- \rightarrow D_s^* D_s) &= 0.92 \text{ nb} @ 4.17 \text{ GeV} \\ \sigma(e^+ e^- \rightarrow D_s D_s) &= 0.27 \text{ nb} @ 4.01 \text{ GeV}\end{aligned}$$

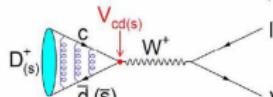
Светимость для D и D_s на SCTF

E , GeV	L , fb^{-1}		
3.097	300	J/ψ	Light meson spectroscopy, rare decays
3.554	50	$e^+e^- \rightarrow \tau^+\tau^-$ threshold	Precision measurements of τ decays
3.686	150	$\psi(2S)$	Light meson spectroscopy, Charmonium spectroscopy
3.770	300	$\psi(3770)$	D -meson study
4.170	100	$\psi(4160)$	D_s -meson study
4.650	100	maximum of $\sigma(e^+e^- \rightarrow \Lambda_c^+\Lambda_c^-)$	Λ_c study

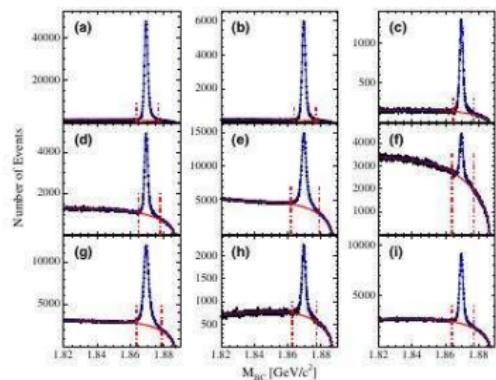
Распределение светимости в 1 ab^{-1}
(1/10 часть ожидаемого полного интеграла светимости)

$$D_{(s)}^+ \rightarrow l^+ \nu_l, l = e, \mu, \tau$$

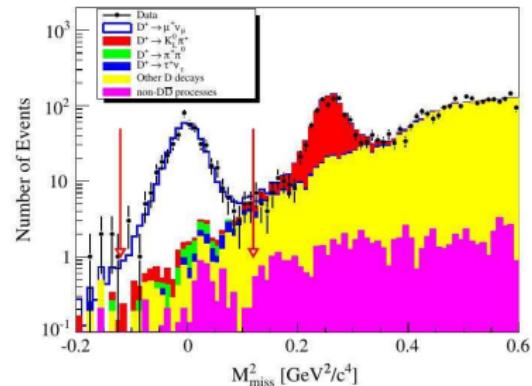
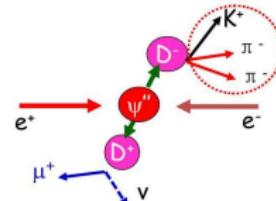
$$\Gamma(D_{(s)}^+ \rightarrow \ell^+ \nu_\ell) = \frac{G_F^2 r_{D_{(s)}}^2}{8\pi} |V_{cd(s)}|^2 m_\ell^2 m_{D_{(s)}} \left(1 - \frac{m_\ell^2}{m_{D_{(s)}}^2}\right)^2$$



 $\tau^+ \nu_\tau : \mu^+ \nu_\mu : e^+ \mu_e$
 $2.65 : 1 : 2.3 \times 10^{-5}$
 D_s^+
 $9.76 : 1 : 2 \times 10^{-5}$
 D_s^+



BESIII $D^+ \rightarrow \mu^+ \nu_\mu$
2.92 fb⁻¹ data@ 3.773 GeV
PRD89(2014)051104R

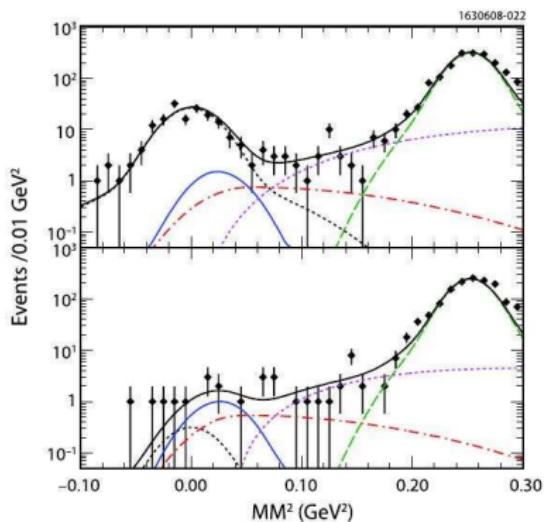


$$M_{\text{miss}}^2 = (E_{\text{beam}}^2 - E_{\mu^+})^2 - (-\vec{p}_{D^+} - \vec{p}_\mu)^2$$

$$\mathcal{B}(D^+ \rightarrow \mu^+ \nu_\mu) = (3.71 \pm 0.19 \pm 0.06) \times 10^{-4}$$

$$D_{(s)}^+ \rightarrow l^+ \nu_l, l = e, \mu, \tau$$

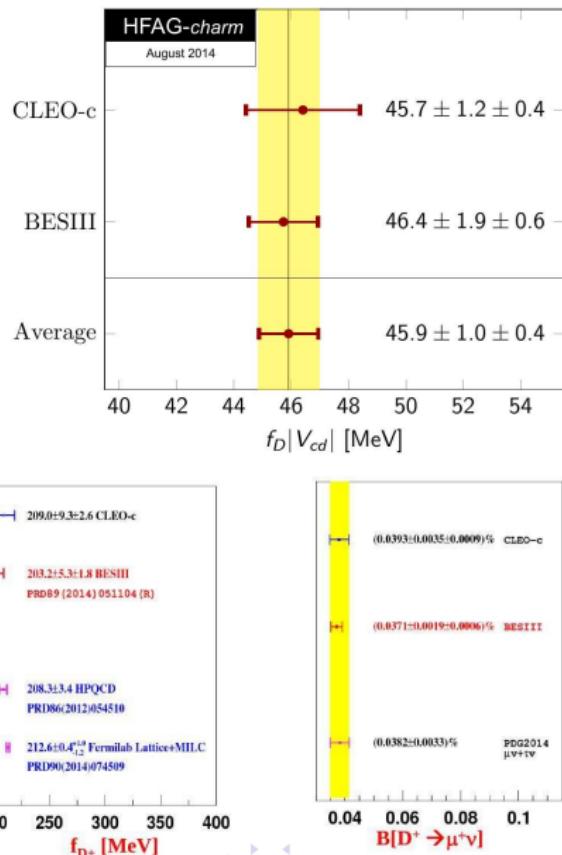
CLEO-c $D^+ \rightarrow \tau^+ \nu_\tau$
 0.82 fb⁻¹ @ 3.773 GeV
 PRD78,052003 (2008)



$$\mathcal{B}(D^+ \rightarrow \tau^+ \nu_\tau) < 1.2 \times 10^{-3}$$

$$\mathcal{B}(D^+ \rightarrow e^+ \nu_e) < 8.8 \times 10^{-6}$$

$$\frac{\mathcal{B}(D^+ \rightarrow \tau^+ \nu_\tau)}{2.65 \mathcal{B}(D^+ \rightarrow \mu^+ \nu_\mu)} < 1.2$$

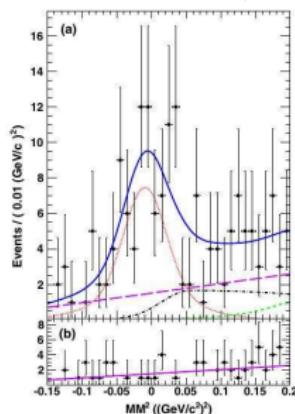


$$D_{(s)}^+ \rightarrow l^+ \nu_l, l = e, \mu, \tau$$

BESIII $D_s^+ \rightarrow l^+ \nu_l, \tau^+ \rightarrow \pi^+ \bar{\nu}_\tau$

0.48 fb⁻¹ @ 4009 GeV

PRD94,072004 (2016)

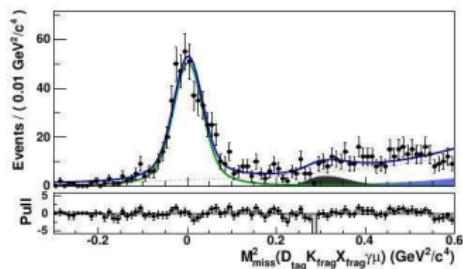


$$\mathcal{B}(D_s^+ \rightarrow \mu^+ \nu_\mu) = (5.17 \pm 0.75 \pm 0.21) \times 10^{-3}$$

$$\mathcal{B}(D_s^+ \rightarrow \tau^+ \nu_\tau) = (3.28 \pm 1.83 \pm 0.37) \times 10^{-2}$$

$$\frac{\mathcal{B}(D_s^+ \rightarrow \tau^+ \nu_\tau)}{9.76 \mathcal{B}(D_s^+ \rightarrow \mu^+ \nu_\mu)} = 0.65 \pm 0.38$$

Belle $D_s^+ \rightarrow l^+ \nu_l, \tau^+ \rightarrow e^+(\mu^+) \nu_{e(\mu)} \bar{\nu}_\tau, \tau^+ \rightarrow \pi^+ \bar{\nu}_\tau$
913 fb⁻¹ @ $\Upsilon(4S), \Upsilon(5S)$
JHEP 09, 139 (2013)

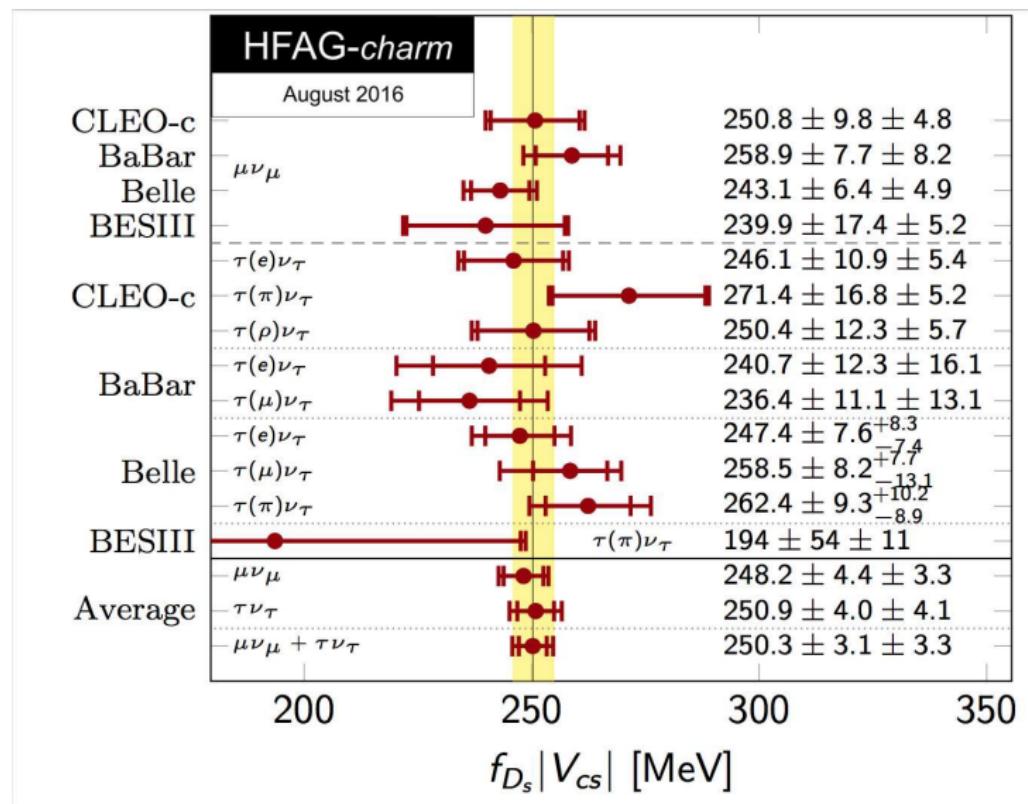


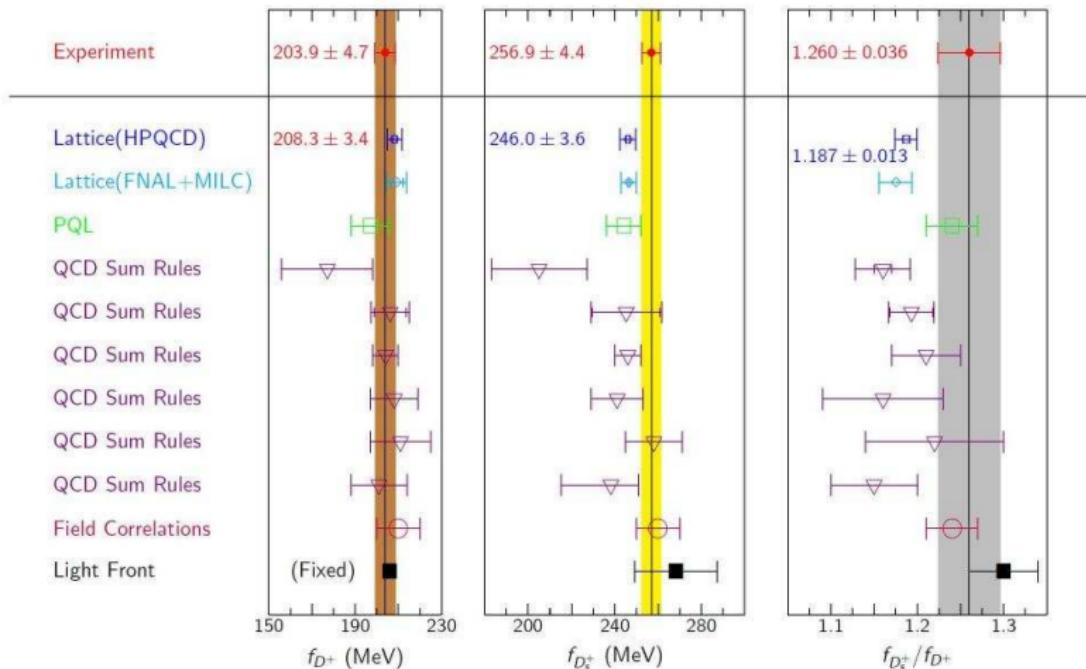
$$\mathcal{B}(D_s^+ \rightarrow \mu^+ \nu_\mu) = (5.31 \pm 0.28 \pm 0.20) \times 10^{-3}$$

$$\mathcal{B}(D_s^+ \rightarrow \tau^+ \nu_\tau) = (5.70 \pm 0.21 \pm 0.30) \times 10^{-2}$$

$$\frac{\mathcal{B}(D_s^+ \rightarrow \tau^+ \nu_\tau)}{9.76 \mathcal{B}(D_s^+ \rightarrow \mu^+ \nu_\mu)} = 1.1 \pm 0.1$$

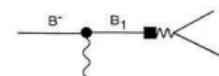
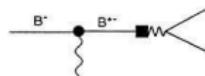
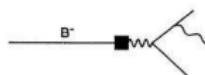
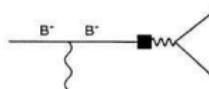
$$D_{(s)}^+ \rightarrow l^+ \nu_l, l = e, \mu, \tau$$





$$D_{(s)}^+ \rightarrow l^+ \nu_l, l = e, \mu, \tau$$

Радиационные лептонные распады



Bremsstrahlung

Structure-dependent

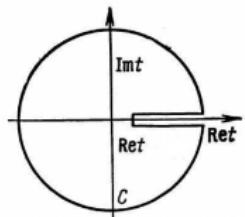
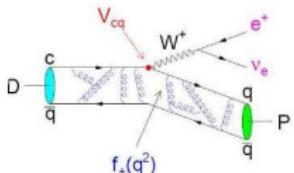
$$\Gamma(D \rightarrow e\nu\gamma) \sim \Gamma(D \rightarrow \mu\nu\gamma) \sim O(10^{-6}) \gg \Gamma(D \rightarrow e\nu) \sim O(10^{-8})$$

$$\Gamma(D_s \rightarrow e\nu\gamma) \sim \Gamma(D_s \rightarrow \mu\nu\gamma) \sim O(10^{-5}) \gg \Gamma(D_s \rightarrow e\nu) \sim O(10^{-7})$$

Измерение лептонных каналов на SCTF может иметь лучшую мировую точность

$$D_{(s)} \rightarrow K(\pi)l^+\nu_l, l = e, \mu$$

$$\frac{d\Gamma}{dq^2} = \frac{G_F^2}{24\pi^3} |V_{cd(s)}|^2 p^3 |f_+(q^2)|^2, m_e = 0$$



Simple Pole Model

$$f_+(q^2) = \frac{f_+(0)}{(1-q^2/M_{pole}^2)}$$

Modified Pole Model

$$f_+(q^2) = \frac{f_+(0)}{(1-q^2/M_{pole}^2)/(1-\alpha q^2/M_{pole}^2)}$$

ISGW2 Model

$$f_+(q^2) = f_+(q_{\max}^2)(1 + \frac{r^2}{12}(q_{\max}^2 - q^2))^{-2}$$

Series Expansion

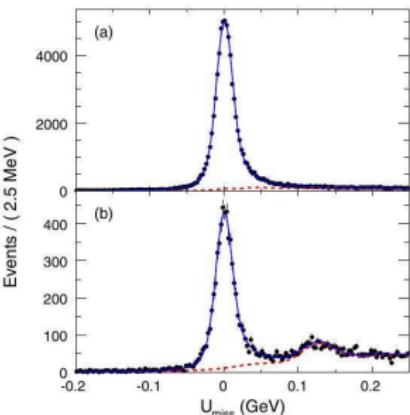
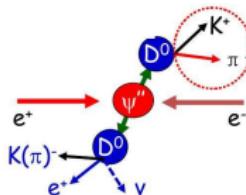
$$f_+(q^2) = \frac{1}{P(q^2)\Phi(q^2, t_0)} \sum_{k=0}^{\infty} a_k(t_0) [z(q^2, t_0)]^k$$

$$\begin{aligned} |V_{cd(s)}| &\xrightarrow{\text{CKMFitter}} f_+(0) \\ f_+(0) &\xrightarrow{\text{LQCD}} |V_{cd(s)}| \end{aligned}$$

BESIII $D^0 \rightarrow K^- e^+ \nu_e,$
 $D^0 \rightarrow \pi^- e^+ \nu_e$

2.92 fb⁻¹ data@ 3.773 GeV

PRD92,072012 (2015)

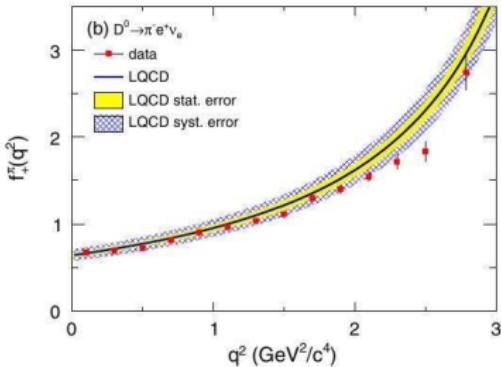
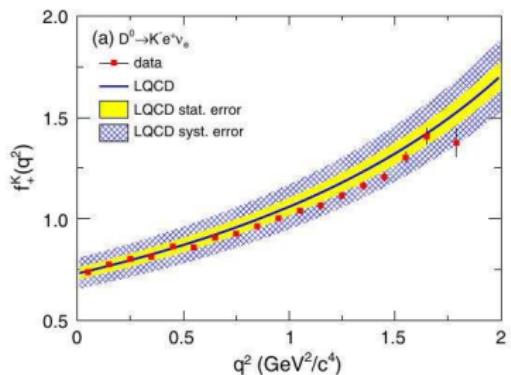
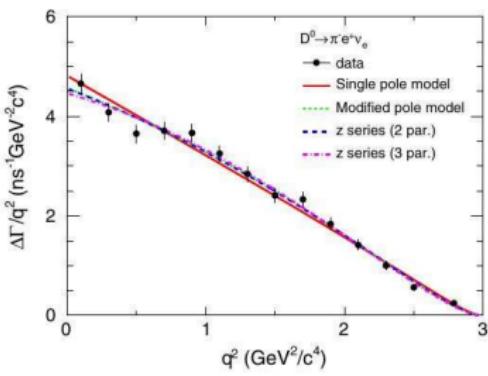
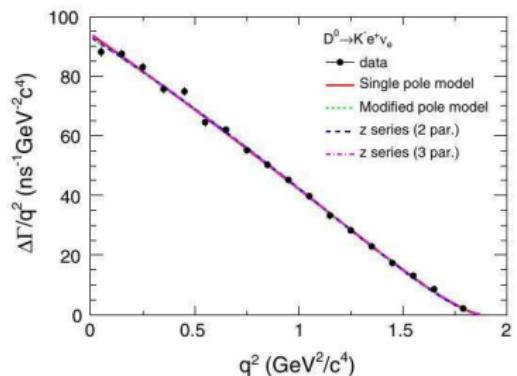


$U_{\text{miss}} = E_{\text{miss}} - p_{\text{miss}}$

$$D_{(s)} \rightarrow K(\pi) l^+ \nu_l, l = e, \mu$$

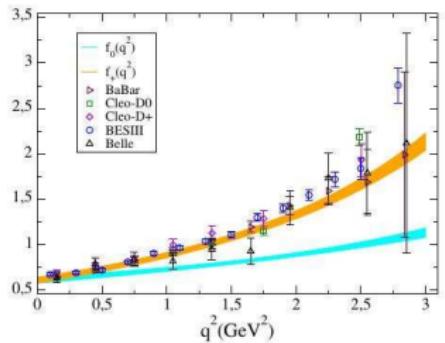
BCSIII

2.92 fb⁻¹ data@ 3.773 GeV

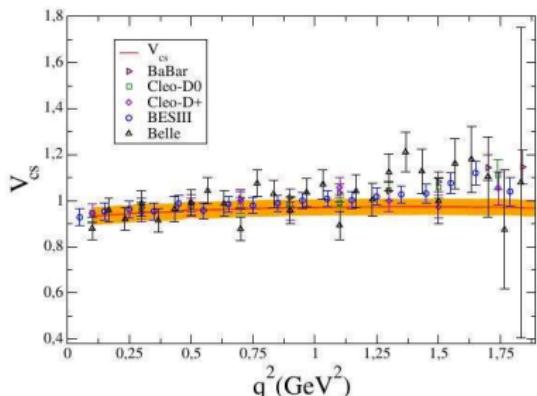
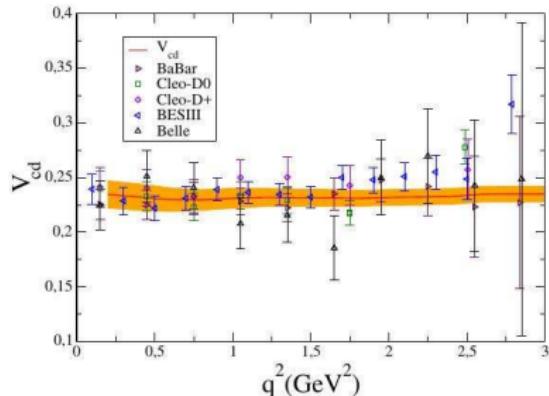
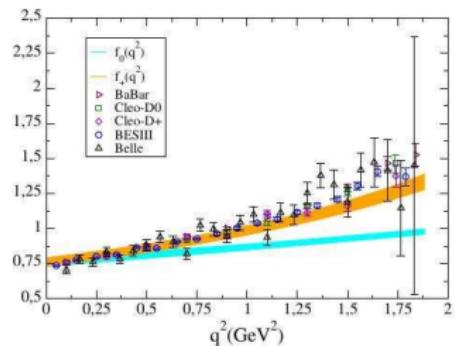


$$D_{(s)} \rightarrow K(\pi)l^+\nu_l, l = e, \mu$$

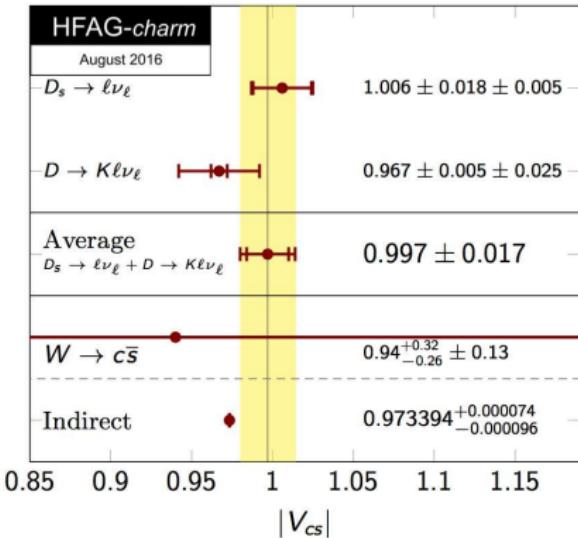
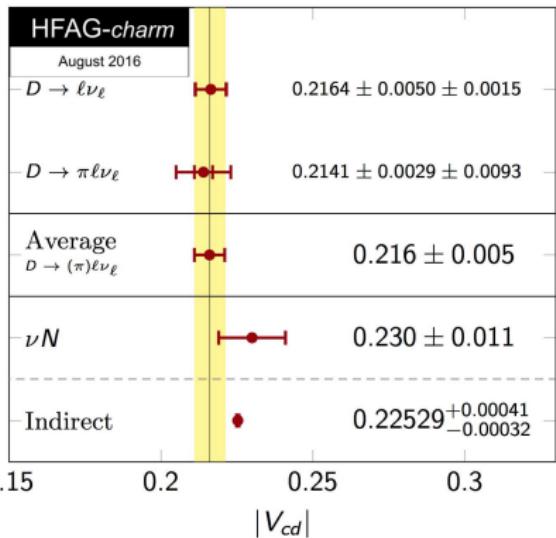
$$D \rightarrow \pi l \nu_l$$



$$D \rightarrow Kl\nu_l$$

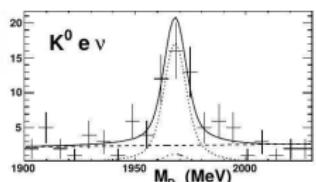
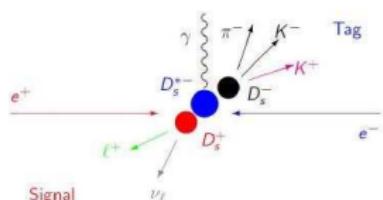


$$D_{(s)} \rightarrow K(\pi) l^+ \nu_l, l = e, \mu$$



$$D_{(s)} \rightarrow K(\pi)l^+\nu_l, l = e, \mu$$

CLEO-c
 0.59fb^{-1} data @ 4.17 GeV
 PRD92,012009 (2015)



$$\mathcal{B}(D_s^+ \rightarrow K^0 e^+ \nu_e) = (0.39 \pm 0.08 \pm 0.03)\%$$

$$\mathcal{B}(D^+ \rightarrow K^0 e^+ \nu_e) = (8.82 \pm 0.13)\% \quad (\text{BESIII'16})$$

$$\mathcal{B}(D^+ \rightarrow K^0 \mu^+ \nu_\mu) = (8.74 \pm 0.12)\% \quad (\text{BESIII'16})$$

$$\mathcal{B}(D^+ \rightarrow \pi^0 e^+ \nu_e) = (4.05 \pm 0.18) \times 10^{-3} \quad (\text{CLEO'07})$$

Belle
 282fb^{-1} data @ $\Upsilon(4S)$
 PRL,97,061804 (2006)

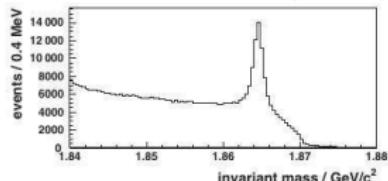


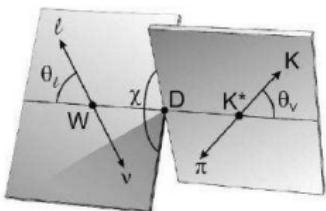
FIG. 1. Mass spectrum of \bar{D}_s^0 candidates.

$$\begin{aligned} \mathcal{B}(D^0 \rightarrow K^- \mu^+ \nu_\mu) &= (3.45 \pm 0.10 \pm 0.21)\% \\ \mathcal{B}(D^0 \rightarrow \pi^- \mu^+ \nu_\mu) &= (0.23 \pm 0.03 \pm 0.02)\% \end{aligned}$$

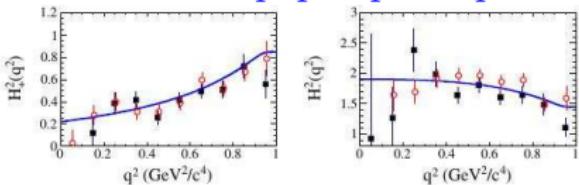
$$D_{(s)} \rightarrow K\pi(\pi\pi, K\pi\pi, \dots) l^+ \nu_l, l = e, \mu$$

Амплитудный анализ

$$\begin{aligned} d^5\Gamma &= \frac{G_F^2 |V_{cs}|^2}{(4\pi)^6 m_D^3} X \beta \mathcal{I}(m^2, q^2, \theta_K, \theta_e, \chi) \\ &\quad \times dm^2 dq^2 d\cos(\theta_K) d\cos(\theta_e) d\chi, \\ X &= p_{K\pi} m_D, \quad \beta = 2p^*/m, \end{aligned}$$

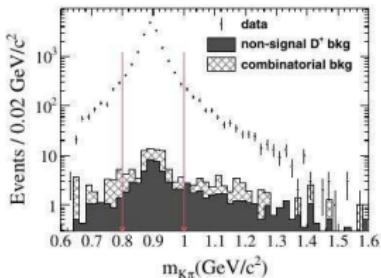


Модельно-независимое
извлечение форм-факторов



BESIII $D^+ \rightarrow K^- \pi^+ e^+ \nu_e$
2.92 fb⁻¹ data@ 3.773 GeV

PRD94,032001 (2016)



$\mathcal{B}(D^0 \rightarrow K^- \pi^+ e^+ \nu_e) =$
 $(3.77 \pm 0.03 \pm 0.08)\%$
Насыщение $K^*(892)^0$ и вклад
от $(K\pi)_{S\text{-wave}}$

$$D_{(s)} \rightarrow K\pi(\pi\pi, K\pi\pi, \dots) l^+ \nu_l, l = e, \mu$$

$$D^+ \rightarrow K\pi(\pi\pi, K\pi\pi, \dots) l^+ \nu_l, l = e, \mu$$

- $\mathcal{B}(D^+ \rightarrow \rho^0 e^+ \nu_e) = (2.18^{+0.17}_{-0.25}) \times 10^{-3}$ (CLEO'13)
- $\mathcal{B}(D^+ \rightarrow \rho^0 \mu^+ \nu_\mu) = (2.4 \pm 0.4) \times 10^{-3}$ (FOCUS'06)
- $\mathcal{B}(D^+ \rightarrow K^*(892)^0 \mu^+ \nu_\mu) = (3.52 \pm 0.10)\%$ (CLEO'10)

$$D^0 \rightarrow K\pi(\pi\pi, K\pi\pi, \dots) l^+ \nu_l, l = e, \mu$$

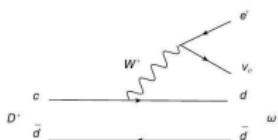
- $\mathcal{B}(D^0 \rightarrow \bar{K}^0 \pi^- e^+ \nu_e) = (2.7^{+0.9}_{-0.7})\%$ (BESII'06)
- $\mathcal{B}(D^0 \rightarrow K^- \pi^+ \pi^- e^+ \nu_e) = (2.8^{+1.4}_{-1.1}) \times 10^{-4}$ (CLEO'07)
- $\mathcal{B}(D^0 \rightarrow \rho^- e^+ \nu_e) = (1.77 \pm 0.16) \times 10^{-3}$ (CLEO'13)

$$D_s^+ \rightarrow K\pi(\pi\pi, K\pi\pi, \dots) l^+ \nu_l, l = e, \mu$$

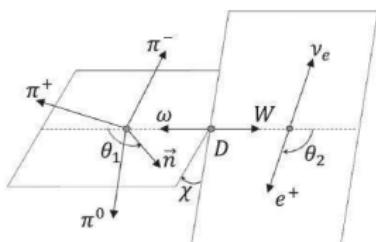
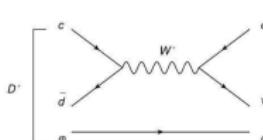
- $\mathcal{B}(D_s^+ \rightarrow K^*(892)^0 e^+ \nu_e) = (1.8 \pm 0.4) \times 10^{-3}$ (CLEO'15)

$$D_{(s)} \rightarrow \omega(\phi, \eta, \eta') l^+ \nu_l, l = e, \mu$$

$$D^+ \rightarrow \omega e^+ \nu_e$$



$$D^+ \rightarrow \phi e^+ \nu_e$$



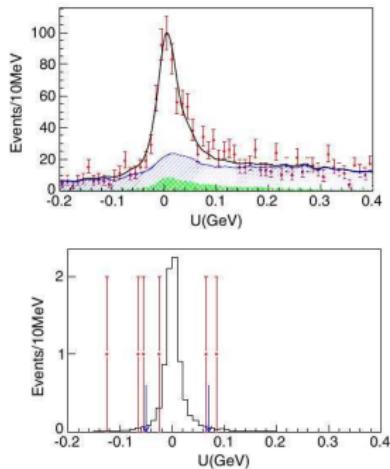
$$V(q^2) = \frac{V(0)}{1-q^2/m_V^2}$$

$$A_{1,2}(q^2) = \frac{A_{1,2}(0)}{1-q^2/m_A^2}$$

$$\mathcal{B}(D^+ \rightarrow \omega e^+ \nu_e) = (1.63 \pm 0.11 \pm 0.08) \times 10^{-3}$$

BESIII
2.92 fb⁻¹ data@ 3.773 GeV

PRD92,071101 (2015)



$$\mathcal{B}(D^+ \rightarrow \phi e^+ \nu_e) < 1.3 \times 10^{-5} \text{ 90% C.L.}$$

0.82 fb⁻¹ data @ 3.773 GeV

$$\mathcal{B}(D^+ \rightarrow \eta e^+ \nu_e) = (11.4 \pm 0.9 \pm 0.4) \times 10^{-4} \text{ (CLEO'11)}$$

$$\mathcal{B}(D^+ \rightarrow \eta' e^+ \nu_e) = (2.16 \pm 0.53 \pm 0.07) \times 10^{-4} \text{ (CLEO'11)}$$

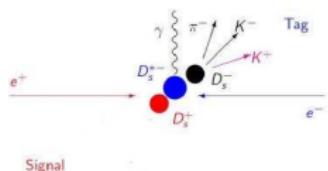
$$D_{(s)} \rightarrow \omega(\phi, \eta, \eta') l^+ \nu_l, l = e, \mu$$

CLEO-c $D_s \rightarrow \eta(\eta', \phi) e^+ \nu_e$
 0.59fb^{-1} data @ 4.17 GeV

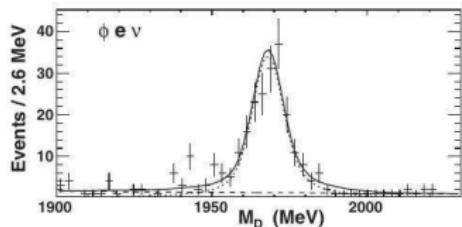
PRD92,012009 (2015)

Адронное тагирование

без реконструкции γ от $D_s^* \rightarrow D_s \gamma$



Signal



$$\mathcal{B}(D_s^+ \rightarrow \eta e^+ \nu_e) = (2.28 \pm 0.14 \pm 0.19)\%$$

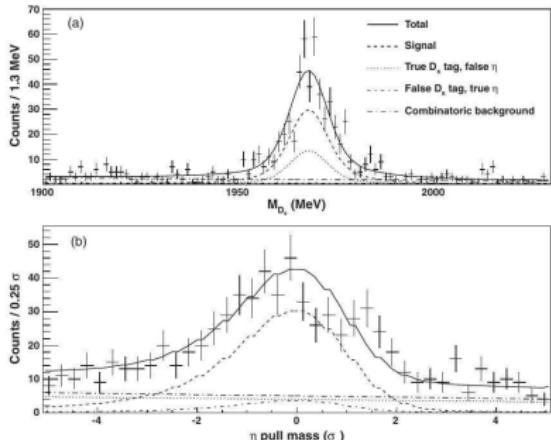
$$\mathcal{B}(D_s^+ \rightarrow \eta' e^+ \nu_e) = (0.68 \pm 0.15 \pm 0.06)\%$$

$$\mathcal{B}(D_s^+ \rightarrow \phi e^+ \nu_e) = (2.14 \pm 0.17 \pm 0.08)\%$$

Каналы в $\eta, \eta' K^0, K^*, f_0$ почти

насыщают инклузивную

Дмитрий Матвиенко



$$|\eta'\rangle = \sin \phi |n\bar{n}\rangle + \cos \phi |s\bar{s}\rangle,$$

$$|\eta\rangle = \cos \phi |n\bar{n}\rangle - \sin \phi |s\bar{s}\rangle$$

$$|n\bar{n}\rangle = \frac{1}{\sqrt{2}} |u\bar{u} + d\bar{d}\rangle$$

$$\frac{\Gamma(D_s \rightarrow \eta' e\nu)}{\Gamma(D_s \rightarrow \eta e\nu)} = R_D \cot^2 \phi$$

$$\phi = 41^\circ \pm 4^\circ$$

$$\theta = -13^\circ \pm 4^\circ, \quad (\theta = 0, \text{ SU(3) symmetry})$$

- $D \rightarrow PP$
 - $D \rightarrow PV$
 - $D \rightarrow VV$
- Факторизация, FSI - эффекты
- $D \rightarrow SP$, ($D \rightarrow f_0\pi(K)$, $D \rightarrow a_0\pi(K)$, ...)
Легкая скалярная спектроскопия
 - $D \rightarrow AP$, $A = {}^3P_1(1^{++})$, $A = {}^1P_1(1^{+-})$
($D \rightarrow K a_1(1260)$, $D \rightarrow K_1(1270)\pi$, ...) FSI-эффекты
 - $D \rightarrow TP$, ($D \rightarrow f_2(1270)\pi$, $D \rightarrow K_2^*(1430)K$)
Факторизация, Динамические эффекты
 - $D \rightarrow AV, \dots$, ($D \rightarrow K^*a_1(1260)$, $D_s \rightarrow \phi a_1(1260)$)
Динамические эффекты
 - **Многочастичные распады**
Динамические эффекты, Интерференция резонансов

Несмотря на работу экспериментов BESIII, BelleII, LHCb, данные с SCTF будут крайне полезны для изучения распадов очарованных мезонов:

- Высокая светимость, $10^{-35} \text{ cm}^{-2}\text{sec}^{-1}$
- $\sim 10^9 D\bar{D}$ -пар, $\sim 10^8 D_sD_s^*$ -пар
- Низкая множественность, $\frac{M(\psi(3770))}{M(\Upsilon(4S))} \sim \frac{1}{2}$
- Эффективность реконструкции, $O(10\%)$