Experimental Studies of (Semi-)Leptonic Decays of D Mesons at BESIII

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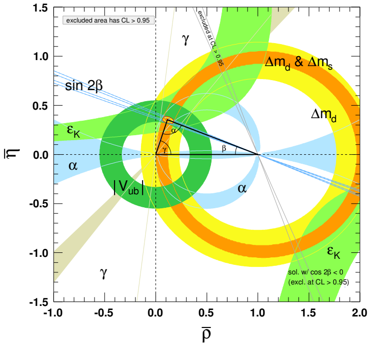
September 24, 2017
Joint Workshop on Charm Hadron Decays

Outline

Introduction

The (semi-)leptonic decays of D mesons open a window for study of both the weak and strong interactions

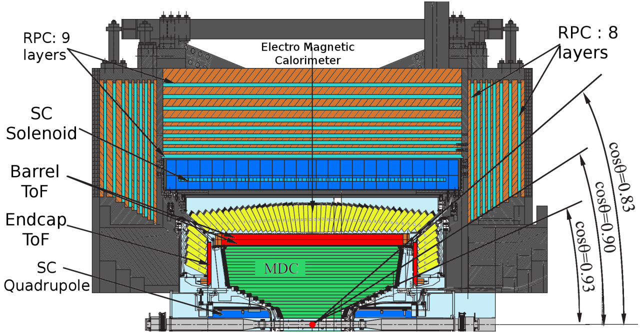
- Determine decay constants and form factors, validate LQCD
- Extract CKM matrix elements $|V_{cs}|$ and $|V_{cd}|$



- Use measurements in charm sector to reduce theoretical uncertainties in $|V_{ub}|$ and mixing
- Check unitarity of CKM matrix and search for New Physics

BESIII Experiment

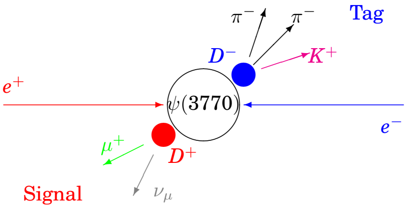
- **BEPCII collider**
  symmetric e^+e^- collider, double-rings, 2.0 GeV $< E_{\rm cm} <$ 4.6 GeV
- **BESIII detector**



- **Data sets**
  2.93 fb^{-1} at $E_{\rm cm} = 3.773$ GeV

Analysis Technique

$e^+e^- \to c\bar{c} \to \bar{D}_{\rm tag}\, D_{\rm sig}$: Double-tag technique, Absolute measurement



- Tag $\bar{D}_{\rm tag}$ in hadronic decay modes

$$\Delta E = E_{\bar{D}_{\rm tag}} - E_{\rm beam}$$

$$M_{\rm BC} = \sqrt{E^2_{\rm beam} - p^2_{\bar{D}_{\rm tag}}}$$

- Reconstruct $D_{\rm sig}$ using the remaining tracks not associated to $\bar{D}_{\rm tag}$
  - $E_{D_{\rm sig}} = E_{\rm beam}, \vec{p}_{D_{\rm sig}} = -\vec{p}_{\bar{D}_{\rm tag}}$
  - no additional tracks/showers
  - (semi-)leptonic decay: missing neutrino, $U_{\rm miss} \equiv E_{\rm miss} - |\vec{p}_{\rm miss}| \sim 0$

$$N_{\rm tag} = 2N_{D\bar{D}}\mathcal{B}_{\rm tag}\varepsilon_{\rm tag}$$

$$N_{\rm tag,sig} = 2N_{D\bar{D}}\mathcal{B}_{\rm tag}\mathcal{B}_{\rm sig}\varepsilon_{\rm tag,sig}$$

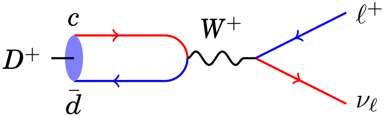
$$\mathcal{B}_{\rm sig} = \frac{N_{\rm tag,sig}}{N_{\rm tag}}\frac{\varepsilon_{\rm tag}}{\varepsilon_{\rm tag,sig}} = \frac{N_{\rm tag,sig}}{N_{\rm tag}\varepsilon}$$

- High tagging efficiency
- Extremely clean
- Systematic uncertainties associated to tag side are mostly canceled out

$$D^+ \to \ell^+ \nu_\ell$$

$D^+ \to \ell^+ \nu_\ell$

- D^+ meson decays to a lepton and its neutrino via a virtual W boson

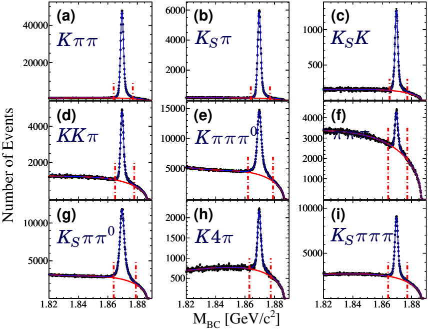


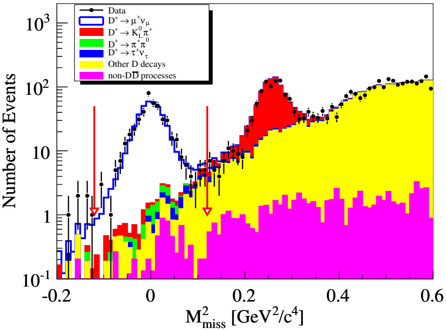
$$\Gamma[D \to \ell\nu] = \frac{G_F^2}{8\pi} m_\ell^2 M_D \left(1 - \frac{m_\ell^2}{M_D^2}\right)^2 f_D^2 |V_{cd}|^2$$

- Measure decay constants f_{D^+}
  - *To verify lattice QCD*
  - *Verified lattice QCD helps extract the CKM matrix elements $|V_{td}|$ and $|V_{ts}|$ from B-$\bar{B}$ oscillations*
- Extract the CKM matrix elements $|V_{cd}|$
  - *To test the unitarity of the CKM matrix*

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

Phys. Rev. D ***89****, 051104(R) (2014)*



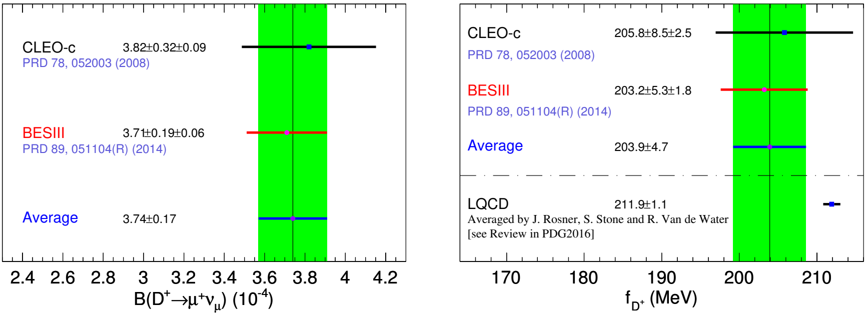


- $(170.31 \pm 0.34) \times 10^4$ D^- tags
- 409 ± 21 $D^+ \to \mu^+\nu_\mu$ events

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

- *Input* τ_D, M_D, m_μ *and* $|V_{cd}|$ *from CKMFitter*
  $\hookrightarrow$ $f_{D^+} = (203.2 \pm 5.3 \pm 1.8)$ MeV
- *Input* τ_D, M_D, m_μ *and* f_{D^+} *from LQCD calculation*
  $\hookrightarrow$ $|V_{cd}| = 0.2210 \pm 0.0058 \pm 0.0047$

Comparions of $\mathcal{B}(D^+ \to \mu^+\nu_\mu)$ and f_{D^+}

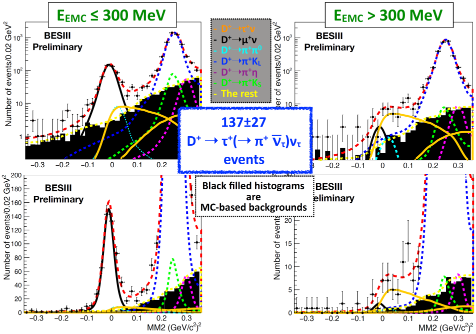


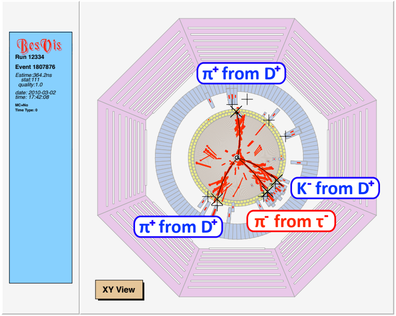
- BESIII made the most precise measurements
- Precision of the LQCD calculations of f_{D^+} reaches 0.5%, which is challenging the experiments

$D^+ \to \tau^+\nu_\tau$

BESIII Preliminary

Split samples into two: μ-like ($E_{\rm EMC} \leq 300$ MeV) and π-like ($E_{\rm EMC} > 300$ MeV), fit these two MM^2 distributions simultaneously





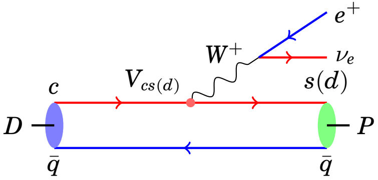
- $> 4\sigma$ statistical significance, first evidence
- $\mathcal{B}(D^+ \to \tau^+\nu_\tau) = (1.20 \pm 0.24_{\rm stat}) \times 10^{-3}$
- $R \equiv \frac{\Gamma(D^+ \to \tau^+\nu_\tau)}{\Gamma(D^+ \to \mu^+\nu_\mu)} = 3.21 \pm 0.64$

  Consistent with the SM prediction ($R_{\rm SM} = 2.66 \pm 0.01$)

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

$D \to P e^+ \nu_e$

- Consider the semileptonic decay where the D meson decays to a pseudoscalar meson, a lepton and its neutrino via a virtual W boson

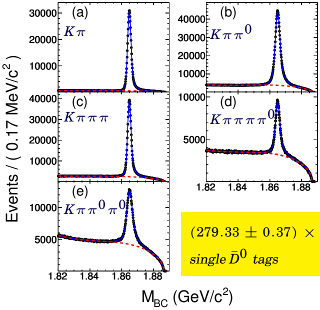


$$\frac{d\Gamma(D \to Pe\nu)}{dq^2} = \frac{G_F^2 |V_{cs(d)}|^2}{24\pi^3} p^3 |f_+(q^2)|^2$$

- Measure hadronic form factors $f_+^{D\to K}(0), f_+^{D\to\pi}(0), \cdots$
  - *To verify lattice QCD*
  - *Verified lattice QCD helps extract the CKM matrix elements $|V_{td}|$ and $|V_{ts}|$ from B-$\bar{B}$ oscillations*
- Extract the CKM matrix elements $|V_{cs}|$ and $|V_{cd}|$
  - *To test the unitarity of the CKM matrix*

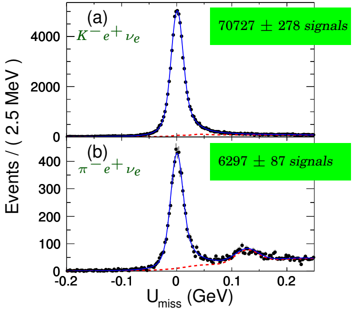
$D^0 \to K^- e^+ \nu_e,\ \pi^- e^+ \nu_e$

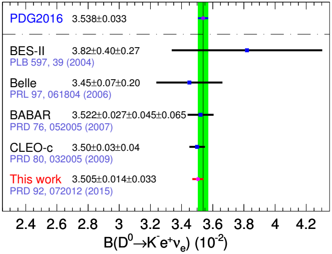
Phys. Rev. D ***92****, 072012 (2015)*

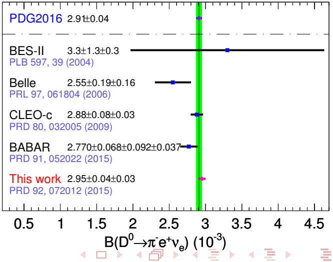


$(279.33 \pm 0.37) \times 10^4$

single $\bar{D}^0$ tags



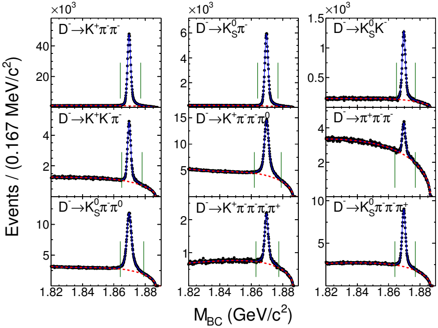


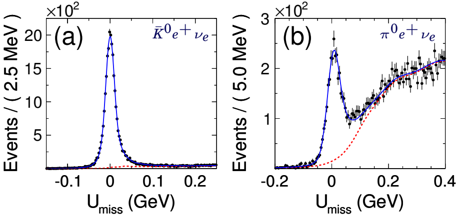


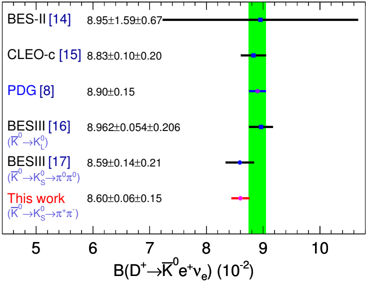
$D^+ \to \bar{K}^0 e^+ \nu_e,\ \pi^0 e^+ \nu_e$

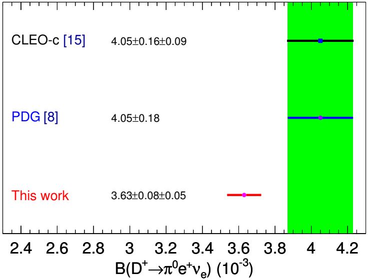
Phys. Rev. D ***96***, *012002 (2017)*

$(170.31 \pm 0.34) \times 10^4$ *single* D^- *tags*





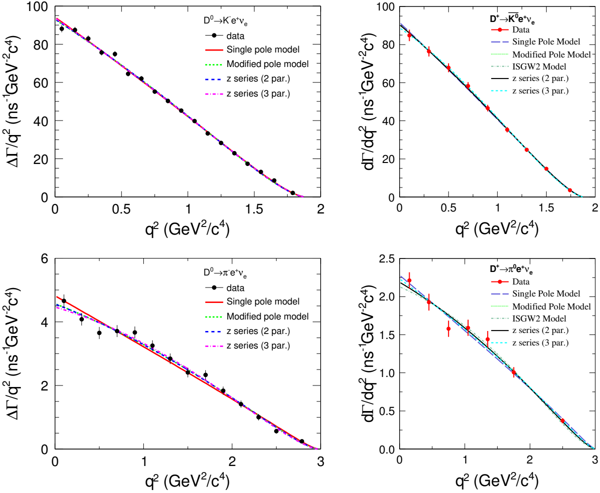




Fits to Partial Decay Rates

Measure partial decay rates in q^2 bins:

$$\Delta\Gamma_i = \frac{N^i_{\rm prd}}{\tau_D N_{\rm tag}} = \frac{1}{\tau_D N_{\rm tag}} \sum_j^{N_{\rm bins}} (\varepsilon^{-1})_{ij} N^j_{\rm obs}$$



Extract $f_+(0)|V_{cs(d)}|$ and other form factor parameters from measured partial decay rates in q^2 bin

Form Factor Parameterizations:

1. Single Pole $f_+(q^2) = \frac{f_+(0)}{1-q^2/M^2_{\rm pole}}$
2. Modified Pole (BK)

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

3. ISGW2

$$f_+(q^2) = f_+(q^2_{\rm max})\left(1 + \frac{r^2_{\rm ISGW2}}{12}(q^2_{\rm max} - q^2)\right)^{-2}$$

4. Series Expansion

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

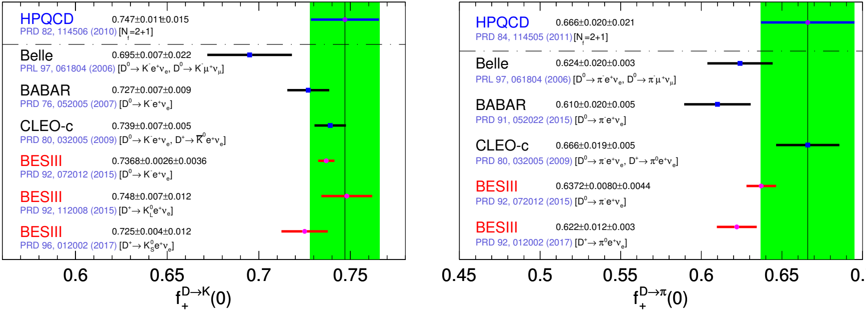
Fits to Partial Decay Rates

- Results of form factor fits for $D \to Pe^+\nu_e$ ($P = K^-, \pi^-, \bar{K}^0, \pi^0$)

Single pole model			
Decay mode	$f_+(0)\|V_{cs(d)}\|$	$M_{\rm pole}$ (GeV/c^2)	
$D^0 \to K^-e^+\nu_e$	$0.7209 \pm 0.0022 \pm 0.0035$	$1.921 \pm 0.010 \pm 0.007$	
$D^0 \to \pi^-e^+\nu_e$	$0.1475 \pm 0.0014 \pm 0.0005$	$1.911 \pm 0.012 \pm 0.004$	
$D^+ \to \bar{K}^0e^+\nu_e$	$0.7094 \pm 0.0035 \pm 0.0111$	$1.935 \pm 0.017 \pm 0.006$	
$D^+ \to \pi^0e^+\nu_e$	$0.1429 \pm 0.0020 \pm 0.0009$	$1.898 \pm 0.020 \pm 0.003$	
Modified pole model			
Decay mode	$f_+(0)\|V_{cs(d)}\|$	α	
$D^0 \to K^-e^+\nu_e$	$0.7163 \pm 0.0024 \pm 0.0034$	$0.309 \pm 0.020 \pm 0.013$	
$D^0 \to \pi^-e^+\nu_e$	$0.1437 \pm 0.0017 \pm 0.0008$	$0.279 \pm 0.035 \pm 0.011$	
$D^+ \to \bar{K}^0e^+\nu_e$	$0.7052 \pm 0.0038 \pm 0.0112$	$0.294 \pm 0.031 \pm 0.010$	
$D^+ \to \pi^0e^+\nu_e$	$0.1400 \pm 0.0024 \pm 0.0010$	$0.285 \pm 0.057 \pm 0.010$	
Two-parameter series expansion			
Decay mode	$f_+(0)\|V_{cs(d)}\|$	r_1	
$D^0 \to K^-e^+\nu_e$	$0.7172 \pm 0.0025 \pm 0.0035$	$-2.2286 \pm 0.0864 \pm 0.0573$	
$D^0 \to \pi^-e^+\nu_e$	$0.1435 \pm 0.0018 \pm 0.0009$	$-2.0365 \pm 0.0807 \pm 0.0257$	
$D^+ \to \bar{K}^0e^+\nu_e$	$0.7053 \pm 0.0040 \pm 0.0112$	$-2.18 \pm 0.14 \pm 0.05$	
$D^+ \to \pi^0e^+\nu_e$	$0.1400 \pm 0.0026 \pm 0.0007$	$-2.01 \pm 0.13 \pm 0.02$	
Three-parameter series expansion			
Decay mode	$f_+(0)\|V_{cs(d)}\|$	r_1	r_2
$D^0 \to K^-e^+\nu_e$	$0.7195 \pm 0.0035 \pm 0.0041$	$-2.3338 \pm 0.1587 \pm 0.0804$	$3.4188 \pm 3.9090 \pm 2.4098$
$D^0 \to \pi^-e^+\nu_e$	$0.1420 \pm 0.0024 \pm 0.0010$	$-1.8432 \pm 0.2212 \pm 0.0690$	$-1.3874 \pm 1.4615 \pm 0.4680$
$D^+ \to \bar{K}^0e^+\nu_e$	$0.6983 \pm 0.0056 \pm 0.0112$	$-1.76 \pm 0.25 \pm 0.06$	$-13.4 \pm 6.3 \pm 1.4$
$D^+ \to \pi^0e^+\nu_e$	$0.1413 \pm 0.0035 \pm 0.0012$	$-2.23 \pm 0.42 \pm 0.06$	$1.4 \pm 2.5 \pm 0.4$

Form Factors $f_+^{D\to K(\pi)}(0)$

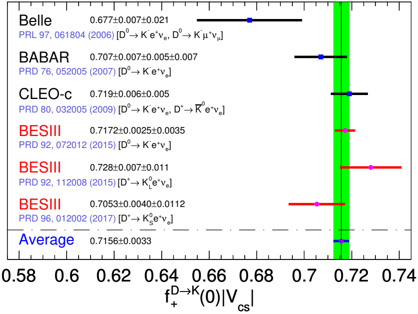
- To determine $f_+^{D\to K(\pi)}(0)$, use the measurements of $f_+^{D\to K(\pi)}(0)|V_{cs(d)}|$ and the PDG values for $|V_{cs(d)}|$ (assuming CKM unitarity)

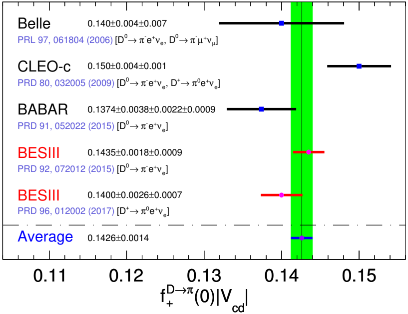


- BESIII made the best precise determinations of these two form factors
- The experimental accuracy is better than that of theoretical predictions

Determination of $|V_{cs(d)}|$

- Measurements of the normalization factors $f_{+}^{D\to K(\pi)}(0)|V_{cs(d)}|$

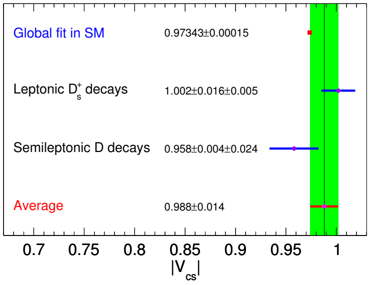


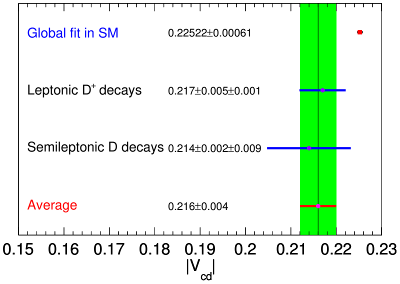


- Using the LQCD calculations [Phys. Rev. D **82**, 114506 (2010); **84**, 114505 (2011)]

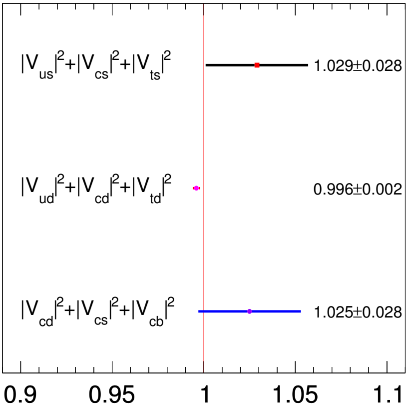
$$f_{+}^{D\to K}(0) = 0.747 \pm 0.019 \quad \Rightarrow \quad |V_{cs}| = 0.958 \pm 0.004_{\rm expt} \pm 0.024_{\rm LQCD}$$
$$f_{+}^{D\to \pi}(0) = 0.666 \pm 0.029 \quad \Rightarrow \quad |V_{cd}| = 0.214 \pm 0.002_{\rm expt} \pm 0.009_{\rm LQCD}$$

Determination of $|V_{cs(d)}|$



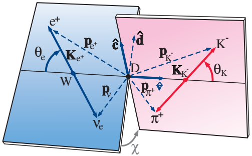


- **Unitarity checks**
  Use $|V_{cs(d)}|$ values extracted from leptonic and semileptonic decays



$$D \to V e^{+} \nu_e$$

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



- $m^2 = (p_{\pi^+} + p_{K^-})^2$
- $\cos(\theta_K) = \frac{\hat{\boldsymbol{\nu}} \cdot \boldsymbol{K}_{K^-}}{|\boldsymbol{K}_{K^-}|}$
- $\cos(\chi) = \hat{\boldsymbol{c}} \cdot \hat{\boldsymbol{d}}$
- $q^2 = (p_{e^+} + p_{\nu_e})^2$
- $\cos(\theta_e) = -\frac{\hat{\boldsymbol{\nu}} \cdot \boldsymbol{K}_{e^+}}{|\boldsymbol{K}_{e^+}|}$
- $\sin(\chi) = (\hat{\boldsymbol{c}} \times \hat{\boldsymbol{\nu}}) \cdot \hat{\boldsymbol{d}}$

$$d^5\Gamma = \frac{G_F^2|V_{cs}|^2}{(4\pi)^6 m_D^2} X\beta\mathcal{I}(m^2, q^2, \theta_K, \theta_e, \chi)dm^2dq^2d\cos(\theta_K)d\cos(\theta_e)d\chi$$

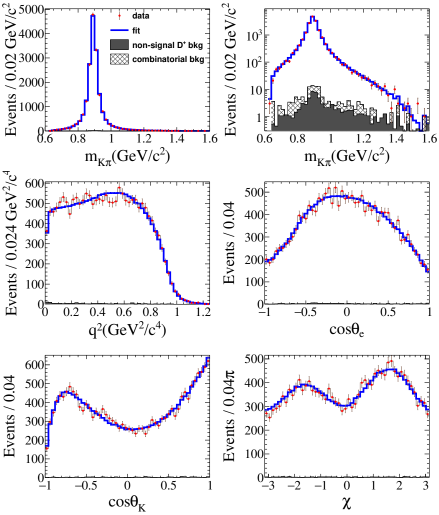
- $X = p_{K\pi}m_D$, $p_{K\pi}$ — momentum of $K\pi$ system in the D rest frame
- $\beta = 2p^*/m$, p^* — breakup momentum of $K\pi$ system in its rest frame
- $\mathcal{I}$ can be expressed in terms of helicity form factors $H_{0,\pm}$:

  $H_0(q^2) = \frac{1}{2m_q}\left[(m_D^2 - m^2 - q^2)(m_D + m)A_1(q^2) - 4\frac{m_D^2 p_{K\pi}^2}{m_D+m}A_2(q^2)\right]$

  $H_\pm(q^2) = (m_D + m)A_1(q^2) \mp \frac{2m_D p_{K\pi}}{m_D+m}V(q^2)$
- Vector form factor: $V(q^2) = \frac{V(0)}{1-q^2/m_V^2}$
- Axial-vector form factor: $A_1(q^2) = \frac{A_1(0)}{1-q^2/m_A^2}$, $A_2(q^2) = \frac{A_2(0)}{1-q^2/m_A^2}$

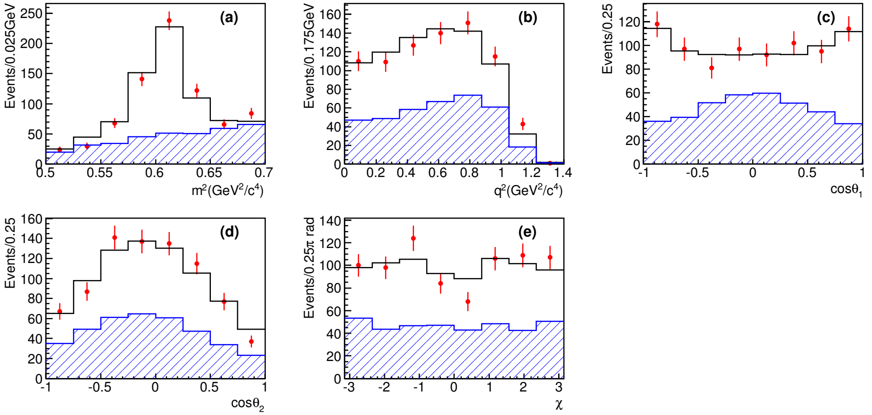
$D^+ \to K^-\pi^+e^+\nu_e$ Phys. Rev. D **94**, 032001 (2016)

- 1.5 M D^- tags, 18262 $D^+ \to K^-\pi^+e^+\nu_e$ candidates
- Partial Wave Analysis



Variable	S+P
$r_S(\mathrm{GeV})^{-1}$	-11.57±0.58±0.46
$r_S^{(1)}$	0.08±0.05±0.05
$a^{1/2}_{\mathrm{S,BG}}(\mathrm{GeV}/c)^{-1}$	1.94±0.21±0.29
$b^{1/2}_{\mathrm{S,BG}}(\mathrm{GeV}/c)^{-1}$	-0.81±0.82±1.24
$m_{\bar{K}^*(892)^0}(\mathrm{MeV}/c^2)$	894.60±0.25±0.08
$\Gamma^0_{\bar{K}^*(892)^0}$ (MeV/c^2)	46.42±0.56±0.15
r_{BW} $(\mathrm{GeV}/c)^{-1}$	3.07±0.26±0.11
m_V (GeV/c^2)	$1.81^{+0.25}_{-0.17}$±0.02
m_A (GeV/c^2)	$2.61^{+0.22}_{-0.17}$±0.03
r_V	1.411±0.058±0.007
r_2	0.788±0.042±0.008
$f_S(\%)$	6.05±0.22±0.18
$f_{\bar{K}^*(892)^0}(\%)$	93.93±0.22±0.18
$\chi^2/n.d.f.$	292.7/291

- $\mathcal{B}(D^+ \to \omega e^+ \nu_e) = (0.163 \pm 0.011 \pm 0.008)\%$
- Amplitude analysis



- Hadronic form factor ratios at zero momentum transfer
$r_V \equiv \frac{V(0)}{A_1(0)} = 1.24 \pm 0.09 \pm 0.06$, $r_2 \equiv \frac{A_2(0)}{A_1(0)} = 1.06 \pm 0.15 \pm 0.05$

Summary

- With 2.93 fb^{-1} data taken at 3.773 GeV, BESIII provided many key measurements on (semi-)leptonic D decays:
  1. Branching fractions
  2. Decay constant
  3. Form factors
  4. CKM matrix elements $|V_{cs}|$ and $|V_{cd}|$

Thank you!