Charm Physics at BESIII

Yi FANG
On behalf of the BESIII Collaboration

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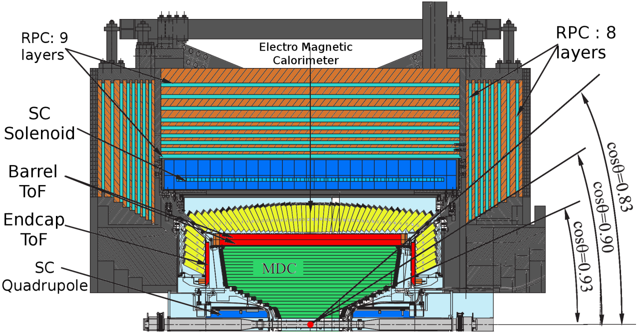
BESIII Experiment

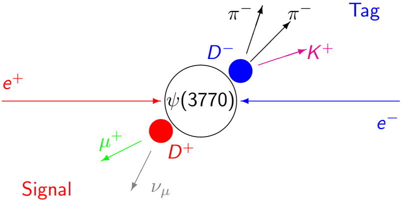
- BEPCII collider
  symmetric e^+e^- collider, double-rings, 2.0 GeV $< E_{\rm cm} <$ 4.6 GeV
- BESIII detector



- Data sets
  1. D^0 and D^+ Physics: 2.93 fb^{-1} at $E_{\rm cm} = 3.773$ GeV
  2. D_s Physics: 482 pb^{-1} at $E_{\rm cm} = 4.009$ 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, $U_{\rm miss} \equiv E_{\rm miss} - |\vec{p}_{\rm miss}| \sim 0$
- High tagging efficiency
- Extremely clean
- Systematic uncertainties associated to tag side are mostly canceled out

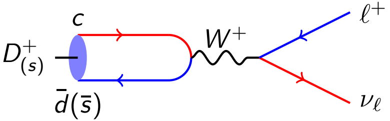
Topics for This Talk

1. Leptonic Decays
   - $D^+ \to \mu^+ \nu_\mu$
   - $D_s^+ \to \ell^+ \nu_\ell$

2. Semileptonic Decays
   - $D^0 \to K^- e^+ \nu_e$, $\pi^- e^+ \nu_e$
   - $D^+ \to \bar{K}^0 e^+ \nu_e$, $\pi^0 e^+ \nu_e$

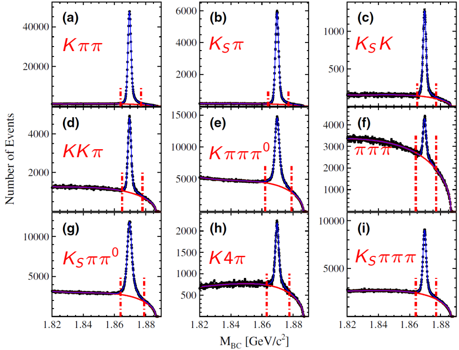
3. Hadronic Decays
   - $D^+ \to K_S^0 \pi^+ \pi^0$
   - $D^0 \to K_S^0 K^+ K^-$
   - $D^+ \to \omega \pi^+$, $D^0 \to \omega \pi^0$

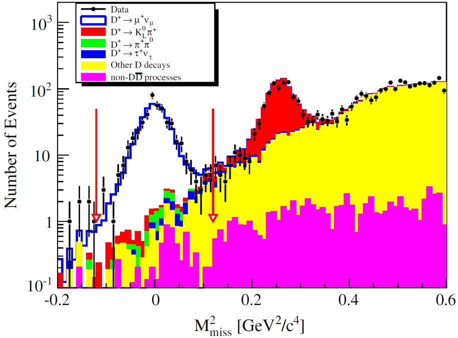
- D or D_s meson decays to a lepton and its neutrino via a virtual W boson



$$\Gamma[D_{(s)} \to \ell\nu] = \frac{G_F^2}{8\pi} m_\ell^2 M_{D_{(s)}} \left(1 - \frac{m_\ell^2}{M_{D_{(s)}}^2}\right)^2 f_{D_{(s)}}^2 |V_{cd(s)}|^2$$

- Measure decay constants f_{D^+} and $f_{D_s^+}$
  - *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 $|V_{cd}|$ and $|V_{cs}|$
  - *To test the unitarity of the CKM matrix*

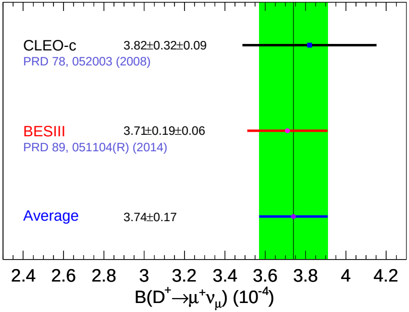


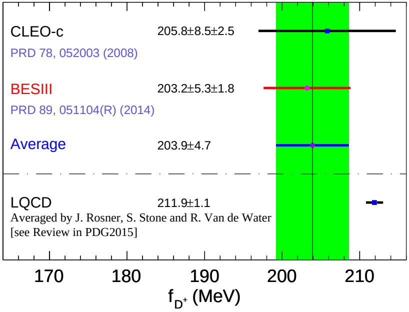


- $(170.31 \pm 0.34) \times 10^4$ D^- tags
- 409 ± 21 $D^+ \to \mu^+\nu_\mu$ events

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

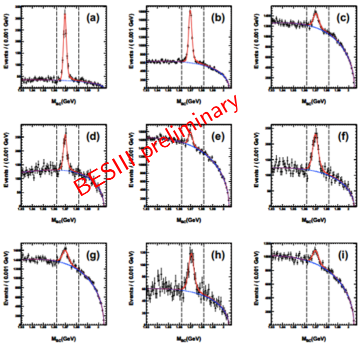
- *Input τ_D, M_D, m_μ and $|V_{cd}|$ from CKMFitter*
  $\hookrightarrow$ $f_{D^+} = (203.2 \pm 5.3 \pm 1.8)$ MeV
- *Input τ_D, M_D, m_μ and f_{D^+} from LQCD calculation*
  $\hookrightarrow$ $|V_{cd}| = 0.2210 \pm 0.0058 \pm 0.0047$



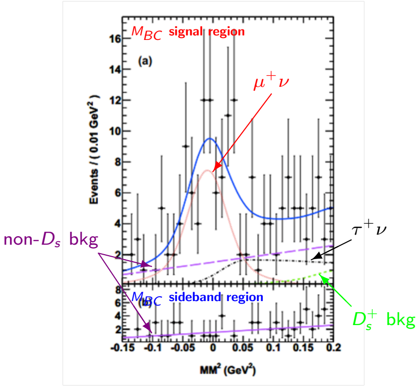


- BESIII made the most precise measurements
- Precision of the LQCD calculations of f_{D^+} reach 0.5%, which is challenging the experiments

$D_s^+ \to \ell^+ \nu_\ell$



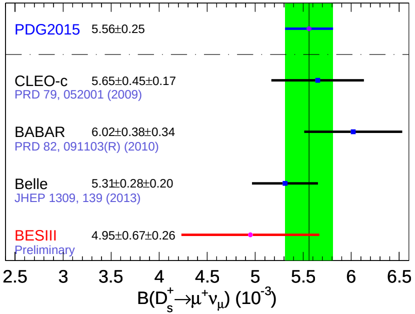
Mode		N_{tag}
(a)	$K_S^0 K^-$	1065 ± 39
(b)	$K^+ K^- \pi^-$	5172 ± 114
(c)	$K^+ K^- \pi^- \pi^0$	1900 ± 140
(d)	$K_S^0 K^+ \pi^- \pi^-$	576 ± 48
(e)	$\pi^+ \pi^- \pi^-$	1606 ± 139
(f)	$\pi^- \eta$	814 ± 52
(g)	$\pi^- \pi^0 \eta$	2172 ± 150
(h)	$\pi^- \eta'(\eta' \to \pi^+ \pi^- \eta)$	440 ± 39
(i)	$\pi^- \eta'(\eta' \to \gamma\gamma)$	1383 ± 143
Sum		15127 ± 312

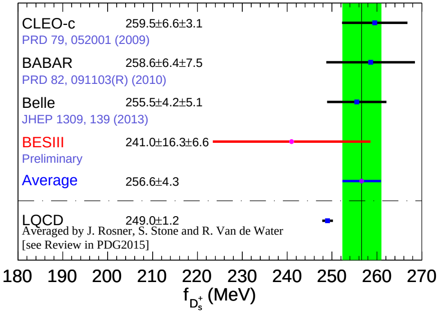


- SM constrained fits (fix $R \equiv \Gamma(D_s^+ \to \tau^+ \nu_\tau)/\Gamma(D_s^+ \to \mu^+ \nu_\mu) = 9.76$)

$D_s^+ \to$	N_{sig}	$\mathcal{B}$ (%)
$\mu^+ \nu_\mu$	69.3 ± 9.3	$0.495 \pm 0.067 \pm 0.026$
$\tau^+ \nu_\tau$	32.5 ± 4.3	$4.83 \pm 0.65 \pm 0.26$

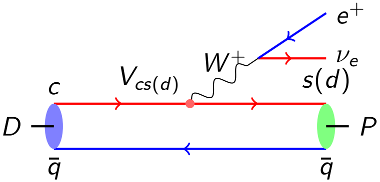
- *Input* τ_{D_s}, M_{D_s}, m_μ *and* $|V_{cs}| = |V_{ud}|$ from PDG
  $\hookrightarrow f_{D_s^+} = (241.0 \pm 16.3 \pm 6.6)$ MeV





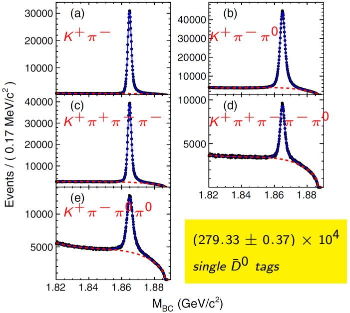
- Precision of the LQCD calculations of $f_{D_s^+}$ reach 0.5%, which is challenging the experiments
- Precise measurement of $f_{D_s^+}$ is hopefully to be done with 3 fb^{-1} data taken at 4.18 GeV in the near future

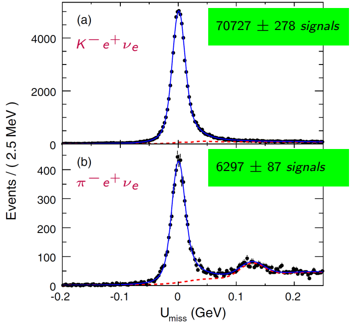
- Consider the semileptonic decay where the D meson decays to a pseudoscalar meson, a lepton and its neutrino via a virtual W boson

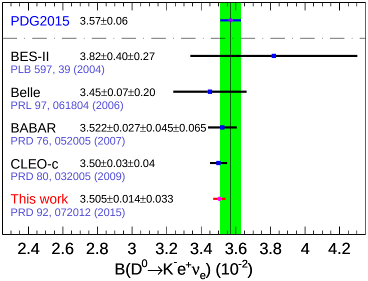


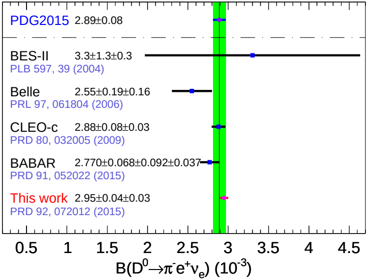
$$\frac{d\Gamma(D \to Pe\nu)}{dq^2} = \frac{G_F^2|V_{cs(d)}|^2}{24\pi^3} p^3 |f_+(q^2)|^2$$

- Measure form factors $f_+^{D\to K}(q^2 = 0)$ and $f_+^{D\to\pi}(q^2 = 0)$
  - *To verify lattice QCD*
- Extract the CKM matrix elements $|V_{cd}|$ and $|V_{cs}|$
  - *To test the unitarity of the CKM matrix*

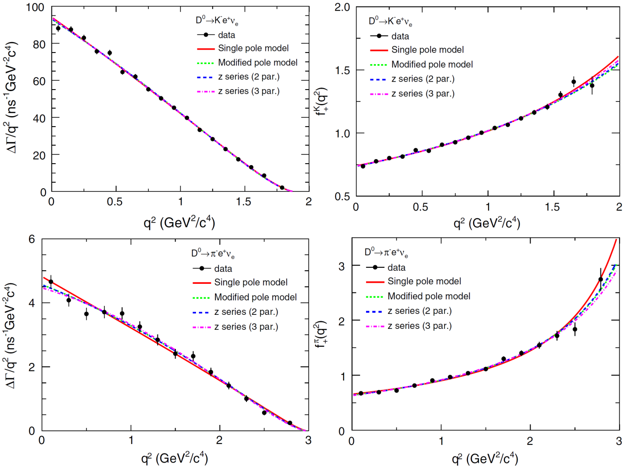

(a) $K^+\pi^-$
(b) $K^+\pi^-\pi^0$
(c) $K^+\pi^+\pi^-\pi^-$
(d) $K^+\pi^+\pi^-\pi^-\pi^0$
(e) $K^+\pi^-\pi^0\pi^0$
Events / (0.17 MeV/c^2)
M_{BC} (GeV/c^2)
$(279.33 \pm 0.37) \times 10^4$
single $\bar{D}^0$ tags


(a) $K^- e^+ \nu_e$
70727 ± 278 signals
(b) $\pi^- e^+ \nu_e$
6297 ± 87 signals
Events / (2.5 MeV)
U_{miss} (GeV)


PDG2015 3.57±0.06
BES-II 3.82±0.40±0.27
PLB 597, 39 (2004)
Belle 3.45±0.07±0.20
PRL 97, 061804 (2006)
BABAR 3.522±0.027±0.045±0.065
PRD 76, 052005 (2007)
CLEO-c 3.50±0.03±0.04
PRD 80, 032005 (2009)
This work 3.505±0.014±0.033
PRD 92, 072012 (2015)
$B(D^0 \to K^- e^+ \nu_e)$ (10^{-2})


PDG2015 2.89±0.08
BES-II 3.3±1.3±0.3
PLB 597, 39 (2004)
Belle 2.55±0.19±0.16
PRL 97, 061804 (2006)
CLEO-c 2.88±0.08±0.03
PRD 80, 032005 (2009)
BABAR 2.770±0.068±0.092±0.037
PRD 91, 052022 (2015)
This work 2.95±0.04±0.03
PRD 92, 072012 (2015)
$B(D^0 \to \pi^- e^+ \nu_e)$ (10^{-3})

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



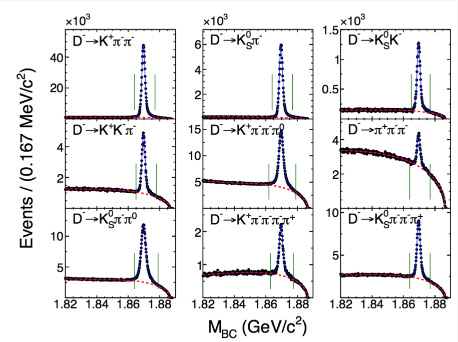
$f_+^{D\to K}(0)|V_{cs}| = 0.7172 \pm 0.0025 \pm 0.0035$

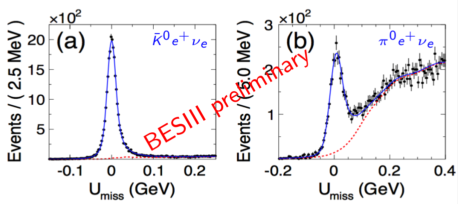
$f_+^{D\to \pi}(0)|V_{cd}| = 0.1435 \pm 0.0018 \pm 0.0009$

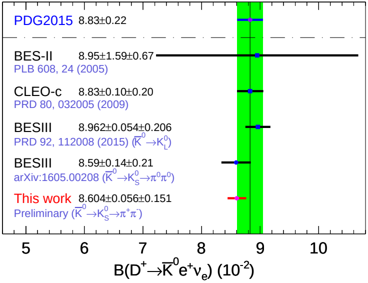
$D^+ \to \bar{K}^0 e^+ \nu_e,\ \pi^0 e^+ \nu_e$

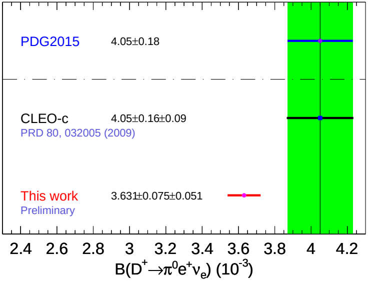
Preliminary

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



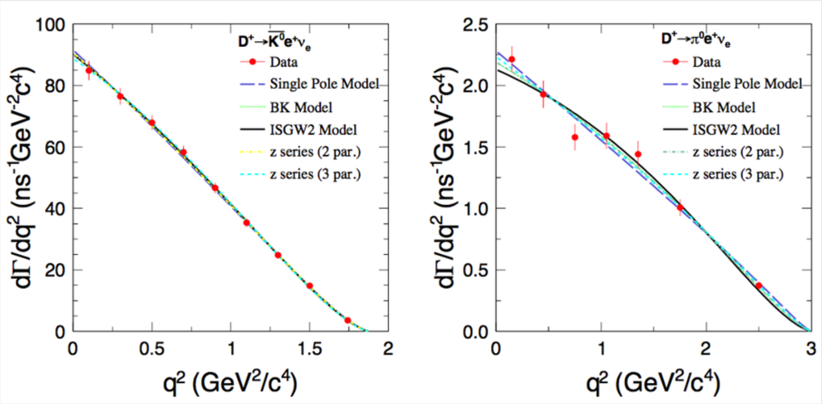






$D^+ \to \bar{K}^0 e^+ \nu_e,\ \pi^0 e^+ \nu_e$

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

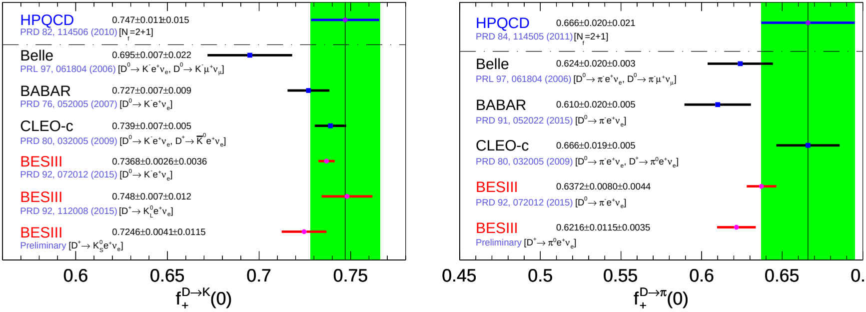


$f_+^{D\to K}(0)|V_{cs}| = 0.7053 \pm 0.0040 \pm 0.0112$

$f_+^{D\to \pi}(0)|V_{cd}| = 0.1400 \pm 0.0026 \pm 0.0007$

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

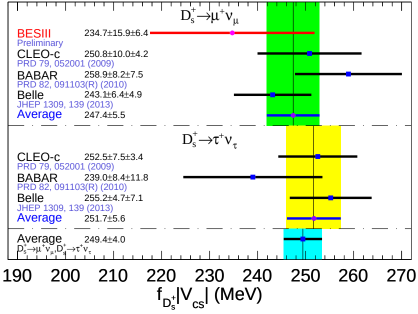
- To determine $f_+^{D\to K(\pi)}(0)$, use the measurements of $f_+^{D\to K(\pi)}(0)|V_{cs(d)}|$ and the PDG values for $|V_{cs(d)}|$ (assuming CKM unitarity)

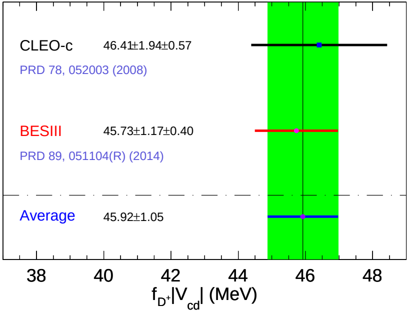


- BESIII made the best precise determinations of these two form factors
- The experimental accuracy is better than that of theoretical predictions

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

- Comparisons of $f_{D_s^+}|V_{cs}|$ and $f_{D^+}|V_{cd}|$



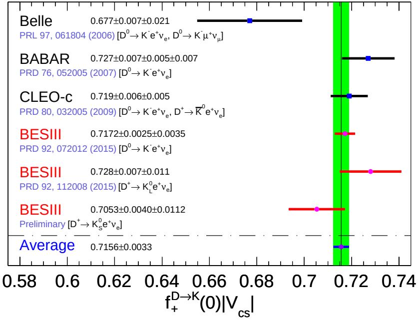


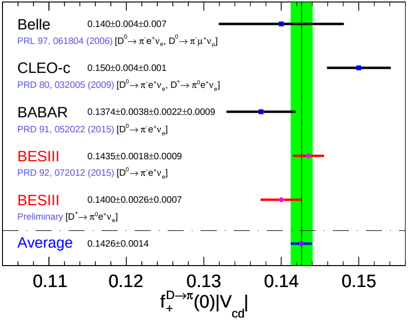
- Using the average of LQCD results [Averaged by J. Rosner, S. Stone and R. Van de Water, see review in PDG2015]

$$f_{D_s^+} = 249.0 \pm 1.2 \text{ MeV} \quad \Rightarrow \quad |V_{cs}| = 1.002 \pm 0.016_{\rm expt} \pm 0.005_{\rm LQCD}$$

$$f_{D^+} = 211.9 \pm 1.1 \text{ MeV} \quad \Rightarrow \quad |V_{cd}| = 0.217 \pm 0.005_{\rm expt} \pm 0.001_{\rm LQCD}$$

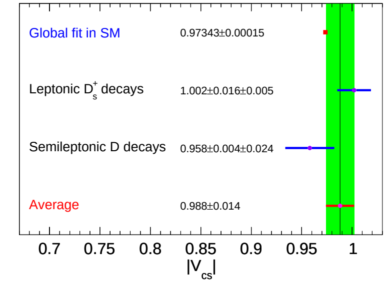
- Measurements of the normalization factors $f_+^{D\to K}(0)|V_{cs}|$ and $f_+^{D\to\pi}(0)|V_{cd}|$

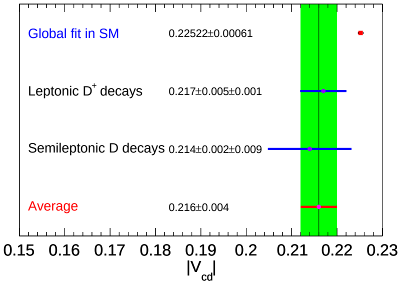




- Using the LQCD calculations [PRD **82**, 114506 (2010); **84**, 114505 (2011)]

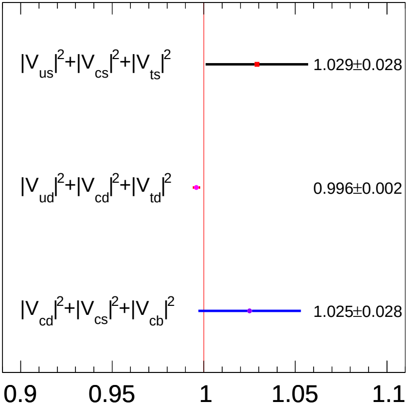
$f_+^{D\to K}(0) = 0.747 \pm 0.019$	$\Rightarrow$	$|V_{cs}| = 0.958 \pm 0.004_{\rm expt} \pm 0.024_{\rm LQCD}$
$f_+^{D\to\pi}(0) = 0.666 \pm 0.029$	$\Rightarrow$	$|V_{cd}| = 0.214 \pm 0.002_{\rm expt} \pm 0.009_{\rm LQCD}$



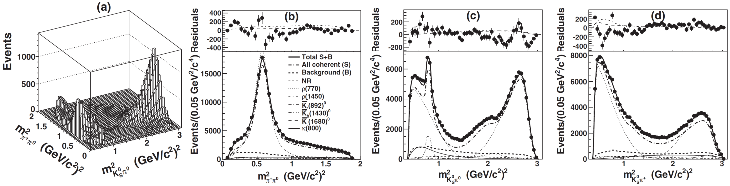


- Unitarity checks

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



- Distribution of (a) fitted p.d.f. and projections on (b) $m^2_{\pi^+\pi^0}$, (c) $m^2_{K_S^0\pi^0}$, (d) $m^2_{K_S^0\pi^+}$



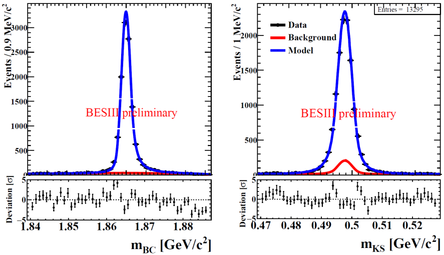
- Partial BFs calculated by combining fitted fractions with PDG's $\mathcal{B}(D^+ \to K_S^0\pi^+\pi^0)$

Mode	Partial branching fraction (%)
$D^+ \to K_S^0\pi^+\pi^0$ nonresonant	$0.32 \pm 0.05 \pm 0.25^{+0.28}_{-0.25}$
$D^+ \to \rho^+ K_S^0$, $\rho^+ \to \pi^+\pi^0$	$5.83 \pm 0.16 \pm 0.30^{+0.45}_{-0.15}$
$D^+ \to \rho(1450)^+ K_S^0$, $\rho(1450)^+ \to \pi^+\pi^0$	$0.15 \pm 0.02 \pm 0.09^{+0.07}_{-0.11}$
$D^+ \to \bar{K}^*(892)^0\pi^+$, $\bar{K}^*(892)^0 \to K_S^0\pi^0$	$0.250 \pm 0.012 \pm 0.015^{+0.025}_{-0.024}$
$D^+ \to \bar{K}_0^*(1430)^0\pi^+$, $\bar{K}_0^*(1430)^0 \to K_S^0\pi^0$	$0.26 \pm 0.04 \pm 0.05 \pm 0.06$
$D^+ \to \bar{K}^*(1680)^0\pi^+$, $\bar{K}^*(1680)^0 \to K_S^0\pi^0$	$0.09 \pm 0.01 \pm 0.05^{+0.04}_{-0.08}$
$D^+ \to \bar{\kappa}^0\pi^+$, $\bar{\kappa}^0 \to K_S^0\pi^0$	$0.54 \pm 0.09 \pm 0.28^{+0.36}_{-0.19}$
$NR + \bar{\kappa}^0\pi^+$	$1.30 \pm 0.12 \pm 0.12^{+0.12}_{-0.30}$
$K_S^0\pi^0$ S-wave	$1.21 \pm 0.10 \pm 0.16^{+0.19}_{-0.27}$

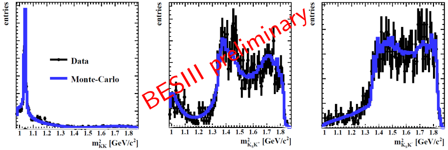
- Partial BFs are measured with higher precision than previous measurements

$D^0 \to K_S^0 K^+ K^-$

- Preliminary result on the branching fraction measurement via single tag



- Fit to "$m_{\rm BC}$ vs. $m_{K_S^0}$"
- Dalitz analysis is ongoing



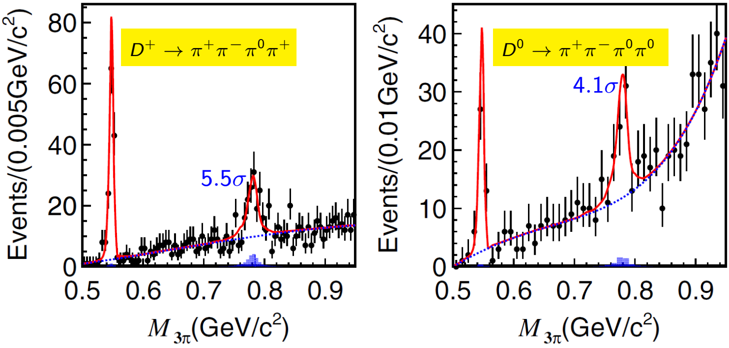
$$\mathcal{B}(D^0 \to K_S^0 K^+ K^-) = (4.622 \pm 0.045 \pm 0.181) \times 10^{-3}$$

- Relative uncertainty: 4.0%
- Good agreement with PDG2015 value:

$$\mathcal{B}(D^0 \to K_S^0 K^+ K^-) = (4.51 \pm 0.34)\%$$

↪ 7.5% relative uncertainty

- The first observation of the singly Cabibbo-Suppressed decay $D^+ \to \omega\pi^+$



Branching fraction	This work	Previous measurements
$\mathcal{B}(D^+ \to \omega\pi^+)$ (10^{-4})	$2.79 \pm 0.57 \pm 0.16$	< 3.4 at 90% C.L.
$\mathcal{B}(D^0 \to \omega\pi^0)$ (10^{-4})	$1.17 \pm 0.34 \pm 0.07$	< 2.6 at 90% C.L.
$\mathcal{B}(D^+ \to \eta\pi^+)$ (10^{-3})	$3.07 \pm 0.22 \pm 0.13$	3.53 ± 0.21
$\mathcal{B}(D^0 \to \eta\pi^0)$ (10^{-3})	$0.65 \pm 0.09 \pm 0.04$	0.68 ± 0.07

Summary

- With 2.93 fb^{-1} data taken at 3.773 GeV and 482 pb^{-1} data taken at 4.009 GeV, BESIII provided many important results on charm physics:
  - Decay constants and form factors in (semi-)leptonic $D_{(s)}$ decays
  - CKM matrix elements $|V_{cs}|$ and $|V_{cd}|$
  - Improved measurements of D hadronic decays
- Topics not shown today:
  - $D^+ \to K^-\pi^+e^+\nu_e$
  - $D^+ \to \omega e^+\nu_e$
  - $D^0 \to K^-\pi^+\pi^+\pi^-$
  - Measurement of the $D \to K^-\pi^+$ strong phase difference
  - y_{CP} in D^0-$\bar{D}^0$ oscillation
  - $D_s^+ \to \eta' X$ and $\eta'\rho^+$
  - ······
- Prospect:
  - 3 fb^{-1} data at 4.18 GeV is almost in hand, more results on D_s^+ physics are expected in the near future

Thank you!

Form Factor Parameterizations

1. *Single Pole*

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

2. *Modified Pole (BK)*

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

3. *ISGW2*

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

4. *Series Expansion*

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