Charm Physics at BESIII

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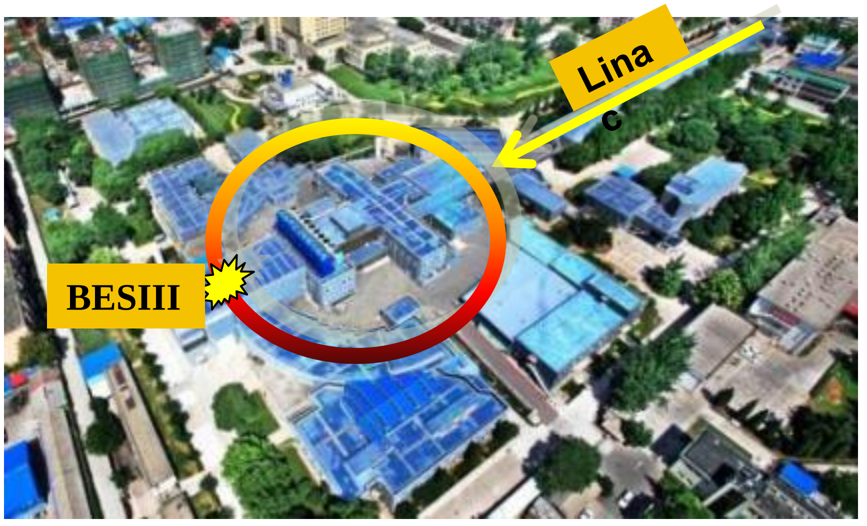
Outline

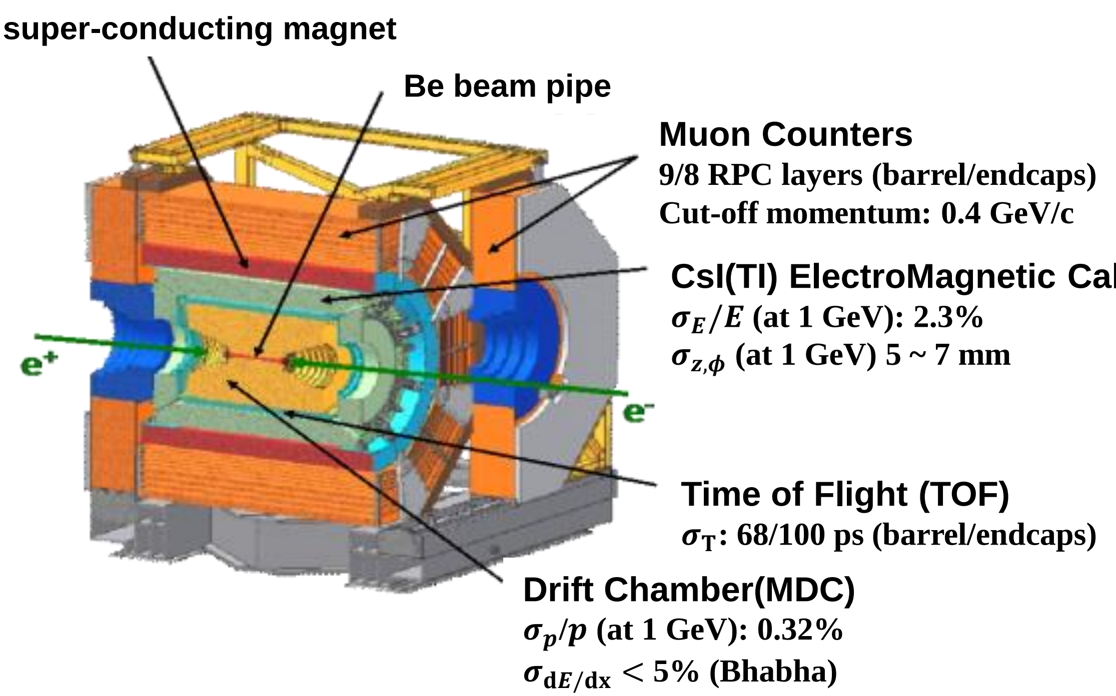
- **BEPCII Collider and BESIII Detector**
- **Data samples of charmed hadrons**
- $\boldsymbol{\Lambda_c^+}$ **decays**
  - $\boldsymbol{\Lambda_c^+}$ hadronic decays
  - $\boldsymbol{\Lambda_c^+}$ semi-leptonic decays
- $\boldsymbol{D}$ **decays**
  - D hadronic decays
  - D leptonic and semi-leptonic decays
- **Summary**

Beijing Electron Positron Collider (BEPCII)

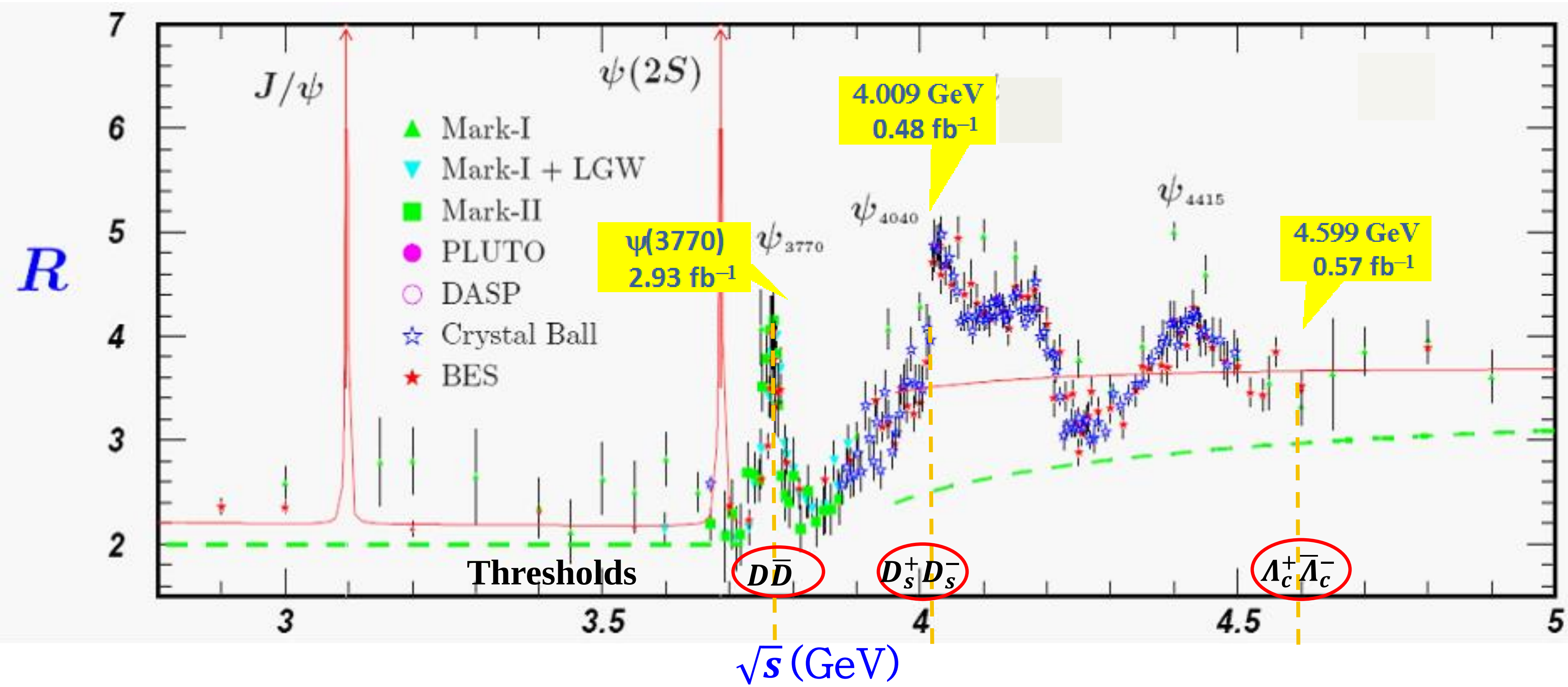


- ✓ Beam energy: 1.0 – 2.3 GeV
- ✓ Luminosity reached the design value (04/05/2016)
  $1.0\times10^{33}cm^{-2}s^{-1}$

BESIII Detector



Data samples of charmed meson and baryon



- ✓ 2.93 fb^{-1} data@3.773 GeV for $D^0\overline{D}^0/D^+D^-$ production
- ✓ 0.48 fb^{-1} data@4.009 GeV for $D_s^+D_s^-$ production
- ✓ 0.57 fb^{-1} data@4.599 GeV for $\Lambda_c^+\overline{\Lambda}_c^-$ production

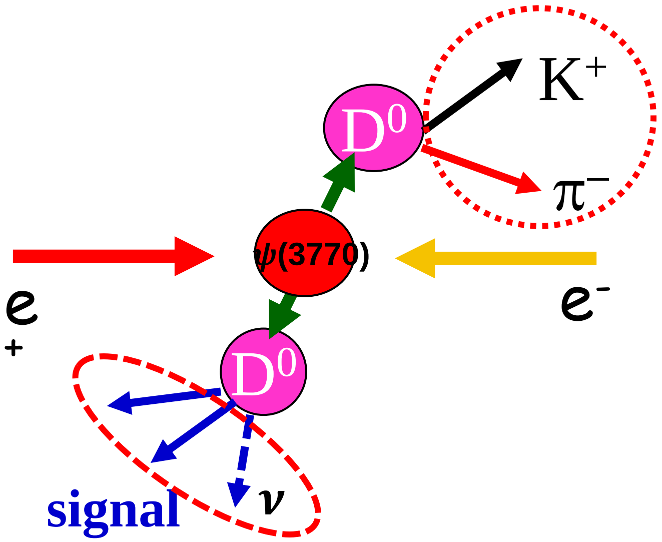
Charm physics at BESIII: Motivation

- **Unitarity test of CKM matrix: measuring $|V_{cs}|$ and $|V_{cd}|$**
- **Lattice QCD calibration: $f_{D\to K/\pi}(q^2)$ and other form factors, $f_{D(s)+}$ decay constant**

- **New Physics: finding evidence of CP violation, rare decays, significant deviations from CKM unitarity or from LQCD calculations, $D-\bar{D}$ mixing**
- **Providing inputs for b-physics**

Measurement of Absolute Branching Fractions

Illustration: $e^+e^- \to \psi(3770) \to D\bar{D}$



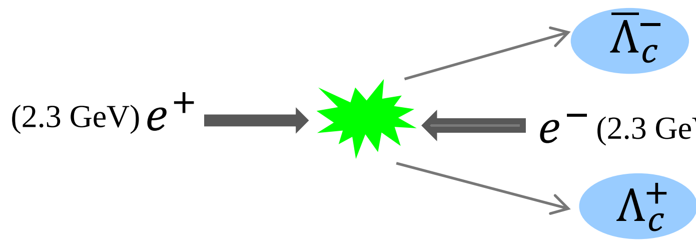
- **Single Tag (ST)**
  - ✓ Tag the charmed meson or baryon via hadronic decays with large Branching Fractions (BF)
  - ✓ $\Delta E \equiv E_{rec.} - E_{beam}$
  - ✓ $M_{BC}^2 c^4 \equiv E_{beam}^2 - p^2c^2$
- **Double Tag (DT)**
  - ✓ Reconstruct signals in the recoil side against
  - ✓ For (semi)leptonic decays: $U_{miss} \equiv E_{miss} - p_{miss}$
- **Absolute BF** $BF(D \to sig) = \frac{N_{sig}}{N_{tag} \times \epsilon_{sig}/\epsilon_{tag,sig}}$.

  only need the yields (N) and the efficiencies(ε) of ST and DT

The advantage of data at threshold

- ✓ **$D_{(s)}\bar{D}_{(s)}/\Lambda_c^+\bar{\Lambda}_c^-$ pairs produced at threshold, no additional hadrons**
- ✓ **Effectively suppress the background with the DT technique**
- ✓ **Enable the measurement of absolute BF, without knowing the number of $D\bar{D}$ pairs**
- ✓ **Most systematic uncertainty in tag side are cancelled out.**

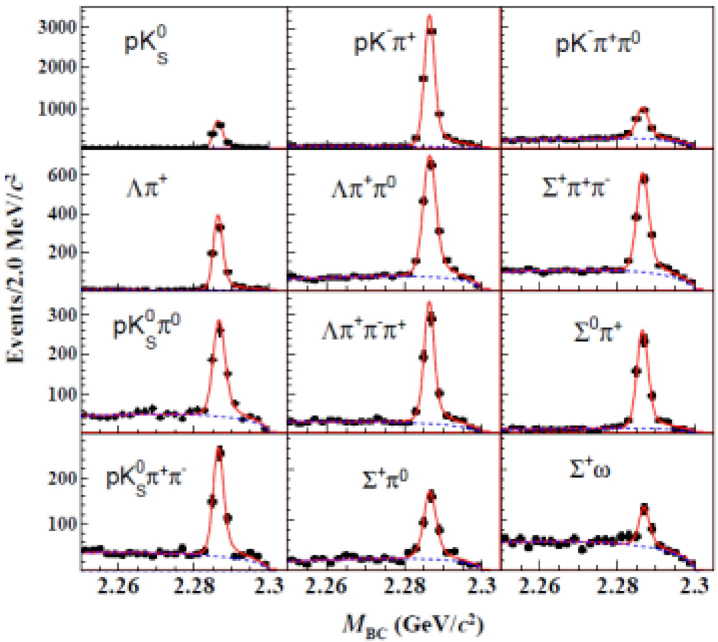
Absolute hadronic BFs of Λ_c^+ baryon



12 tag modes

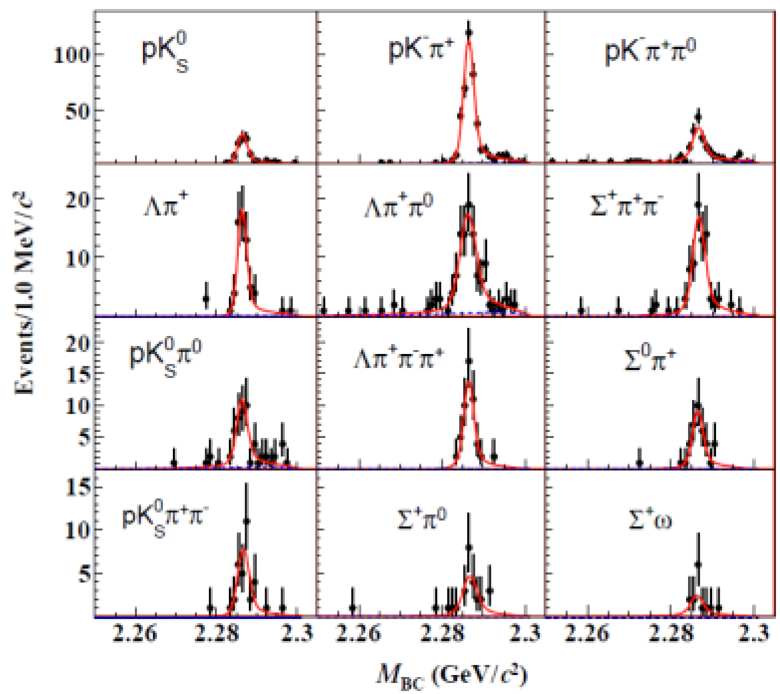
12 signal modes

- **ST events**



ST yield of $\bar{\Lambda}_c^- \to \alpha$ $N_{ST}^{\alpha} = N_{\Lambda_c^+\bar{\Lambda}_c^-} \cdot BF_{\alpha} \cdot \varepsilon_{ST}^{\alpha}$

- **DT events**



Total DT yield of $\Lambda_c^+ \to s$ over 12 $\bar{\Lambda}_c^- \to \alpha$

$$N_{DT}^{s} = N_{\Lambda_c^+\bar{\Lambda}_c^-} \cdot BF_s \sum_{\alpha} BF_{\alpha} \cdot \varepsilon_{DT}^{\alpha}$$

- **Extraction of the 12 BFs**
  - ✓ **BFs are constraint to common variable $N_{\Lambda_c^+\bar{\Lambda}_c^-}$**
  - ✓ **A global least-square fitter is used to improve the measurement precision** [Chinese Phys. C37(2013)106201]
    - $\chi^2 \equiv (\mathbf{c} - \tilde{\mathbf{c}})^T V_c^{-1} (\mathbf{c} - \tilde{\mathbf{c}})$
    - **$\mathbf{c} = \mathbf{n}/\mathbf{E}$, efficiency-corrected yields**
      - ✓ n is the ST and DT yields matrix (24×1)
      - ✓ E is the ST and DT efficiencies matrix (24×24)

Absolute hadronic BFs of Λ_c^+ baryon

- **The first model independent measurement of the Λ_c^+ BFs at the $\overline{\Lambda}_c^+\overline{\Lambda}_c^-$ production threshold, since the Λ_c^+ discovery 30 years ago**

PRL116, 052001 (2016)

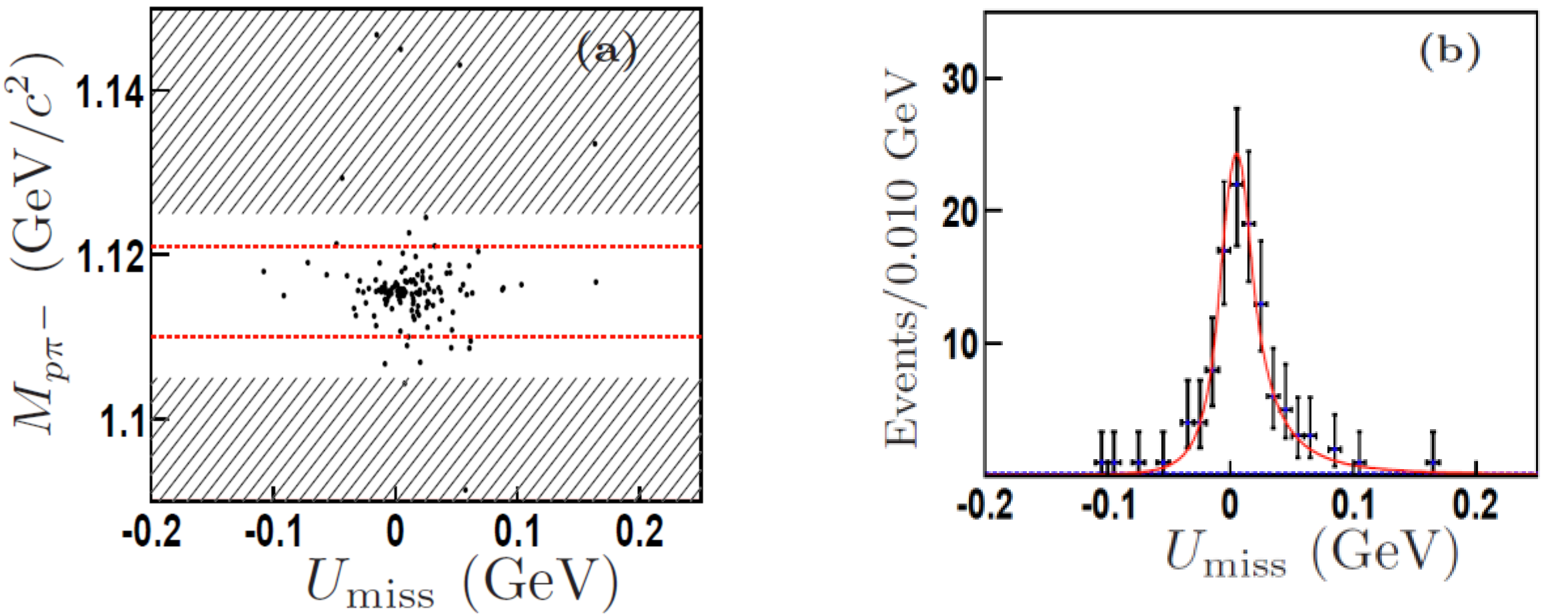
Mode	This work (%)	PDG (%)
pK_S^0	$1.52 \pm 0.08 \pm 0.03$	1.15 ± 0.30
$pK^-\pi^+$	$5.84 \pm 0.27 \pm 0.23$	5.0 ± 1.3
$pK_S^0\pi^0$	$1.87 \pm 0.13 \pm 0.05$	1.65 ± 0.50
$pK_S^0\pi^+\pi^-$	$1.53 \pm 0.11 \pm 0.09$	1.30 ± 0.35
$pK^-\pi^+\pi^0$	$4.53 \pm 0.23 \pm 0.30$	3.4 ± 1.0
$\Lambda\pi^+$	$1.24 \pm 0.07 \pm 0.03$	1.07 ± 0.28
$\Lambda\pi^+\pi^0$	$7.01 \pm 0.37 \pm 0.19$	3.6 ± 1.3
$\Lambda\pi^+\pi^-\pi^+$	$3.81 \pm 0.24 \pm 0.18$	2.6 ± 0.7
$\Sigma^0\pi^+$	$1.27 \pm 0.08 \pm 0.03$	1.05 ± 0.28
$\Sigma^+\pi^0$	$1.18 \pm 0.10 \pm 0.03$	1.00 ± 0.34
$\Sigma^+\pi^+\pi^-$	$4.25 \pm 0.24 \pm 0.20$	3.6 ± 1.0
$\Sigma^+\omega$	$1.56 \pm 0.20 \pm 0.07$	2.7 ± 1.0

These 12 modes served the measurement of Λ_c^+ leptonic decays, as the tag modes

✓ **The precisions are improved by factors of 3~6**

Absolute BF of $\Lambda_c^+ \to \Lambda e^+ \nu_e$

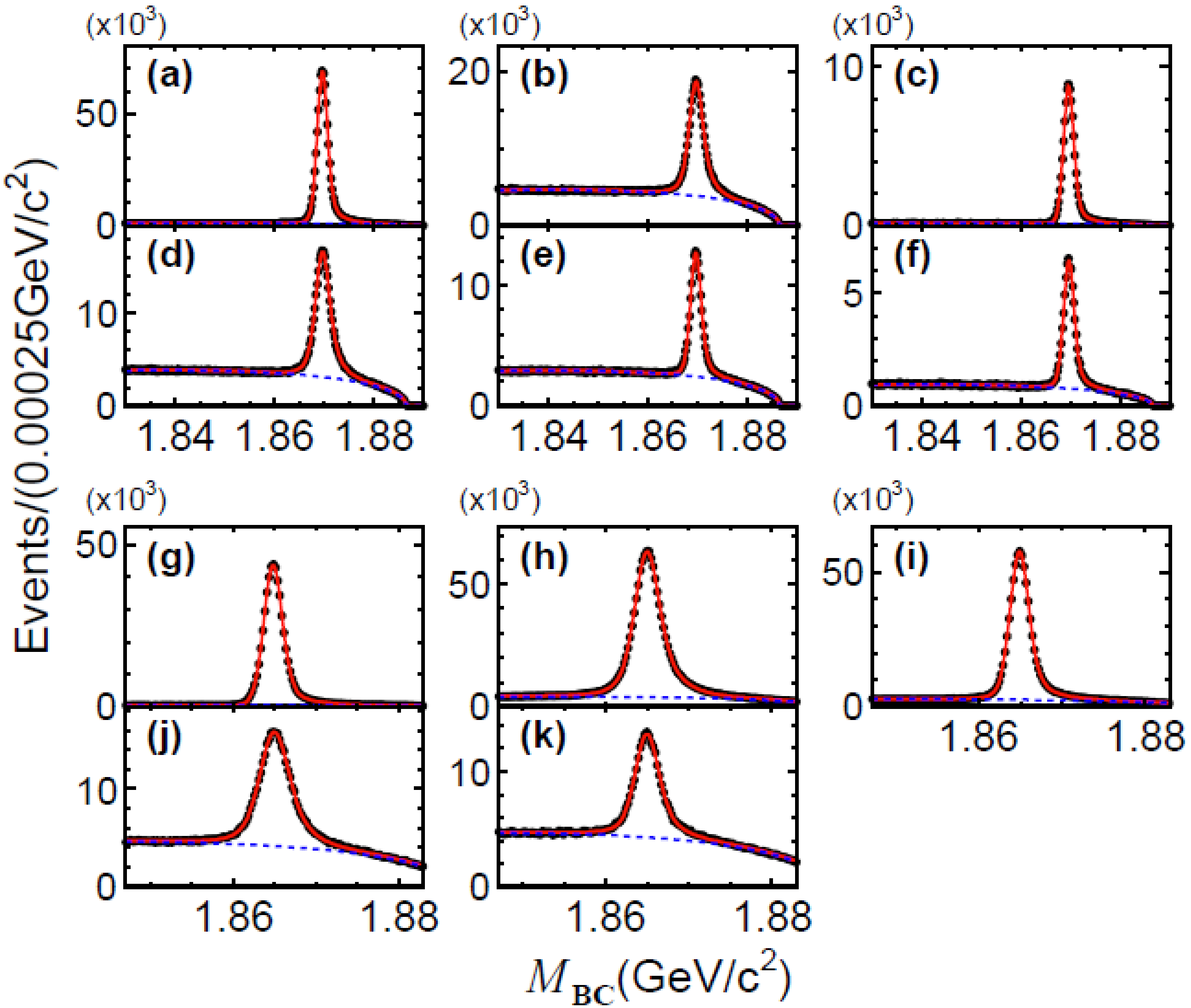
PRL115, 221805 (2015)



$\mathrm{BF}(\Lambda_c^+ \to \Lambda e^+ \nu_e) = (3.63 \pm 0.38 \pm 0.20)\%$

- **The first absolute measurement**
- **Improvement of the precision of the PDG value (2.9±0.5)%**
- **Important for the testing and calibration of the LQCD calculations**

Observation of $D^+ \to \omega\pi^+$ and Evidence for $D^0 \to \omega\pi^0$



Charged D tag modes:

(a) $K^+\pi^-\pi^-$
(b) $K^+\pi^-\pi^-\pi^0$
(c) $K_S^0\pi^-$
(d) $K_S^0\pi^-\pi^0$
(e) $K_S^0\pi^+\pi^-\pi^-$
(f) $K^+K^-\pi^-$

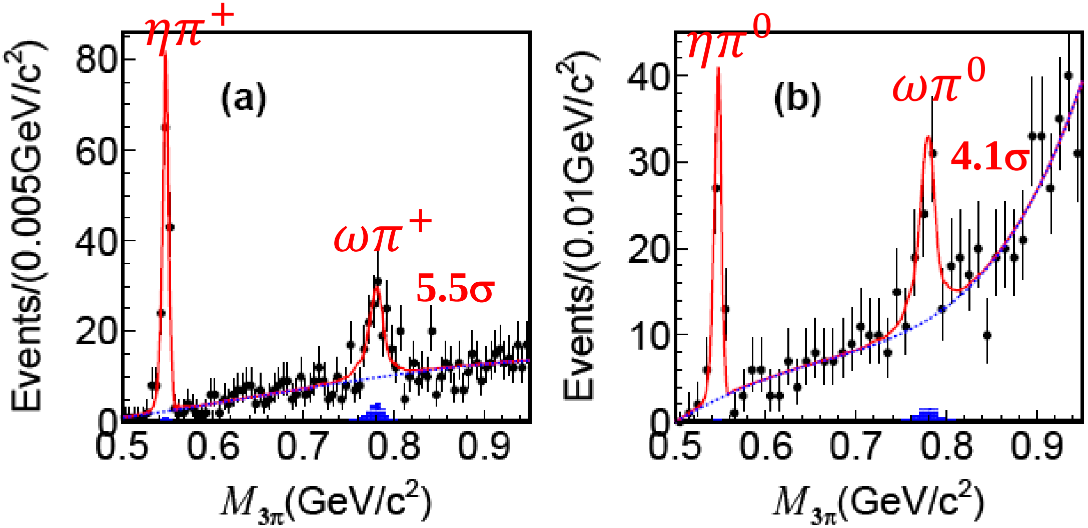
Neutral D tag modes:

(g) $K^+\pi^-$
(h) $K^+\pi^-\pi^0$
(i) $K^+\pi^-\pi^+\pi^-$
(j) $K^+\pi^-\pi^0\pi^0$
(k) $K^+\pi^-\pi^+\pi^-\pi^0$

Observation of $D^+ \to \omega\pi^+$ and Evidence for $D^0 \to \omega\pi^0$

Suppress background via DT method

PRL116, 082001 (2016)



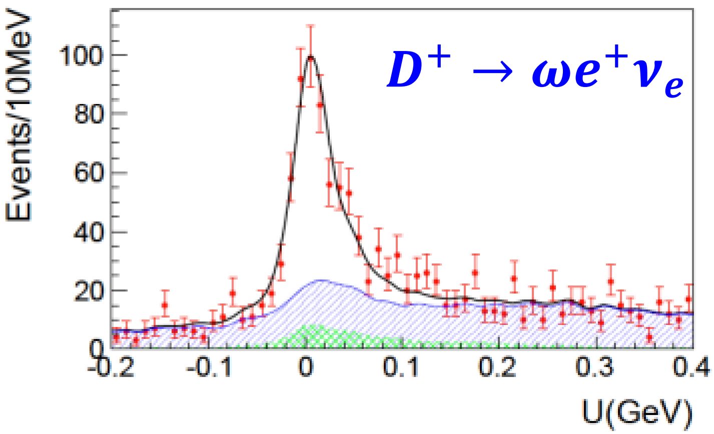
- **Predications of BF$(D \to \omega\pi) \sim 1.0 \times 10^{-4}$**
- **Studied by CLEO-c with ST method →upper limit**

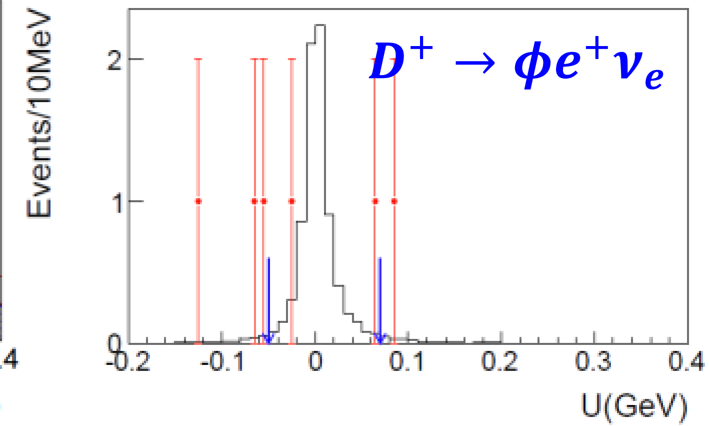
Mode	This work	Previous measurements
$D^+ \to \omega\pi^+$	$(2.79 \pm 0.57 \pm 0.16) \times 10^{-4}$	$< 3.4 \times 10^{-4}$ at 90% C.L.
$D^0 \to \omega\pi^0$	$(1.17 \pm 0.34 \pm 0.07) \times 10^{-4}$	$< 2.6 \times 10^{-4}$ at 90% C.L.
$D^+ \to \eta\pi^+$	$(3.07 \pm 0.22 \pm 0.13) \times 10^{-3}$	$(3.53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

✓ **Improved understanding of U-spin and SU(3)-flavor symmetry breaking effects in *D* decays**

Study of $D^+ \to \omega e^+ \nu_e$ and Search for $D^+ \to \phi e^+ \nu_e$

PRD92, 071101R(2015)





Dots: data

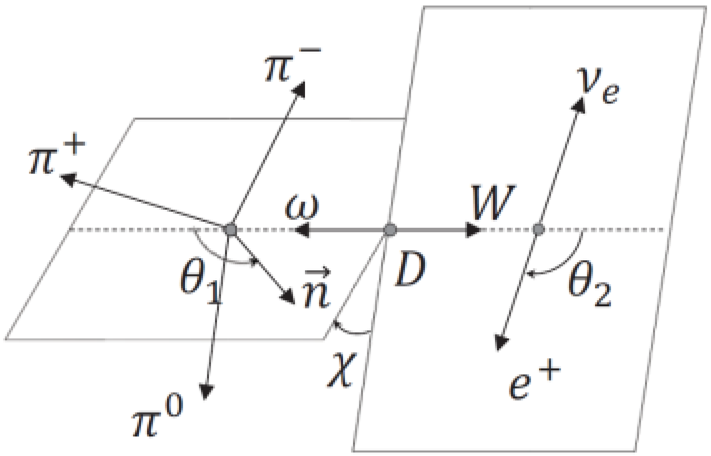
Arrows: signal region

Mode	This work	Previous
$\omega e^+ \nu_e$	$(1.63 \pm 0.11 \pm 0.08) \times 10^{-3}$	$(1.82 \pm 0.18 \pm 0.07) \times 10^{-3}$
$\phi e^+ \nu_e$	$< 1.3 \times 10^{-5}$ (90%C.L.)	$< 9.0 \times 10^{-5}$ (90%C.L.)

- **No significant excess of $D^+ \to \phi e^+ \nu_e$ is observed**
- **More precise BFs**

Form factors measurement of $D^+ \to \omega e^+ \nu_e$

PRD92, 071101R(2015)



$$\frac{d\Gamma}{dq^2 d\cos\theta_1 d\cos\theta_2 d\chi dm_{\pi\pi\pi}} = \mathcal{F}(V(q^2),\ A_{1,2}(q^2)\ \cdots)$$

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

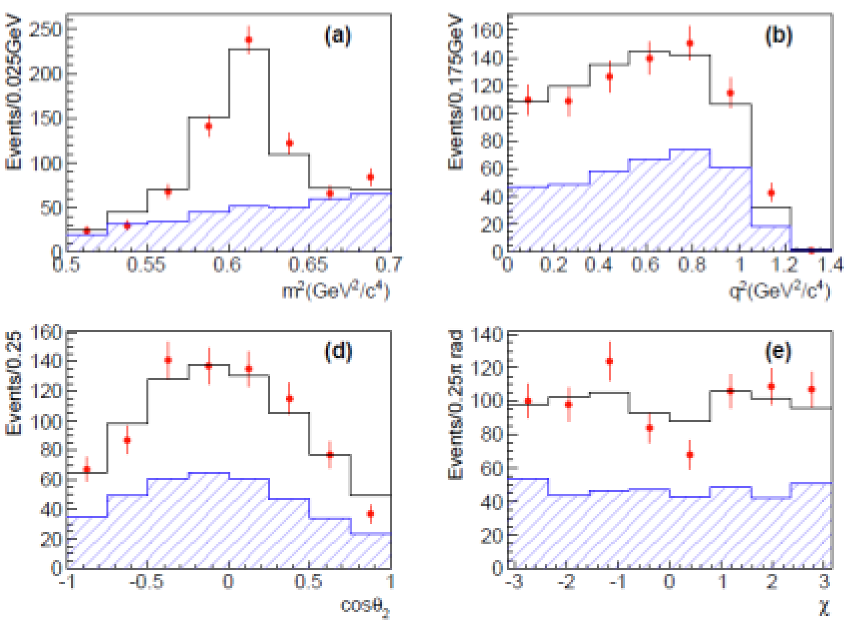
$$A_{1,2}(q^2) = \frac{A_{1,2}(0)}{1 - q^2/m_A^2}$$

A five-dimensional maximum likelihood fit is performed in the space of $m^2_{\pi\pi\pi}$, $q^2_{e\nu_e}$, $\cos\theta_1$, $\cos\theta_2$ and χ

$\theta_1(\omega)$: the angle between the ω decay plane normal in the $\pi\pi\pi$ rest frame and the flight direction of the ω in the D rest frame

$\theta_2(e^+)$: the angle between the e^+direction in the $e\nu_e$ rest frame and the flight direction of the $(e\nu_e)$ in the D rest frame

- **Amplitude analysis of $D^+ \to \omega e^+ \nu_e$ is performed for the first time**



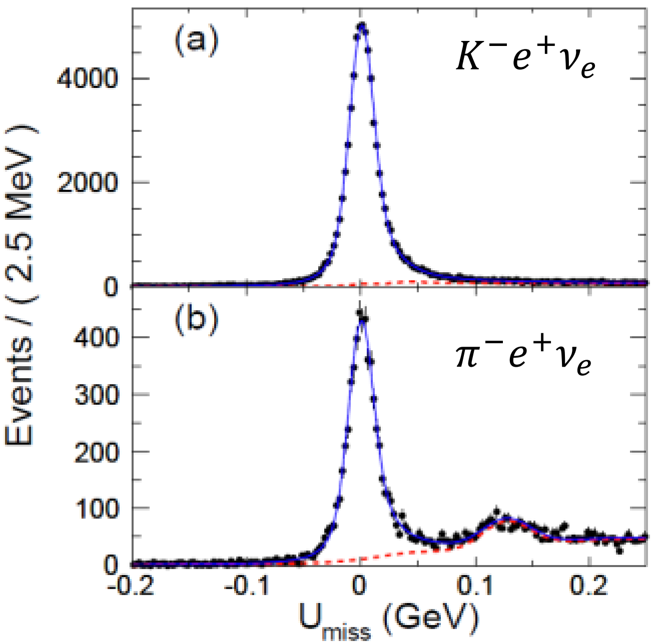
The ratios of the vector and axial form factors

$r_V = V(0)/A_1(0) = 1.24 \pm 0.09 \pm 0.06$

$r_2 = A_2(0)/A_1(0) = 1.06 \pm 0.15 \pm 0.05$

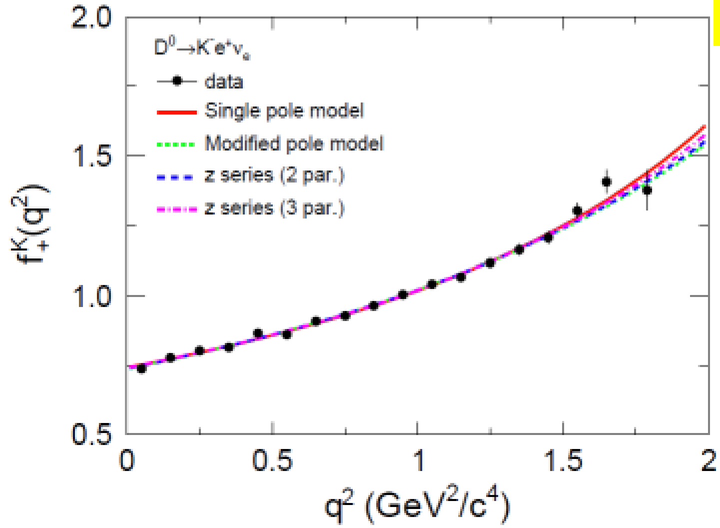
Study of dynamics of $D^0 \to (K^-/\pi^-)e^+\nu_e$

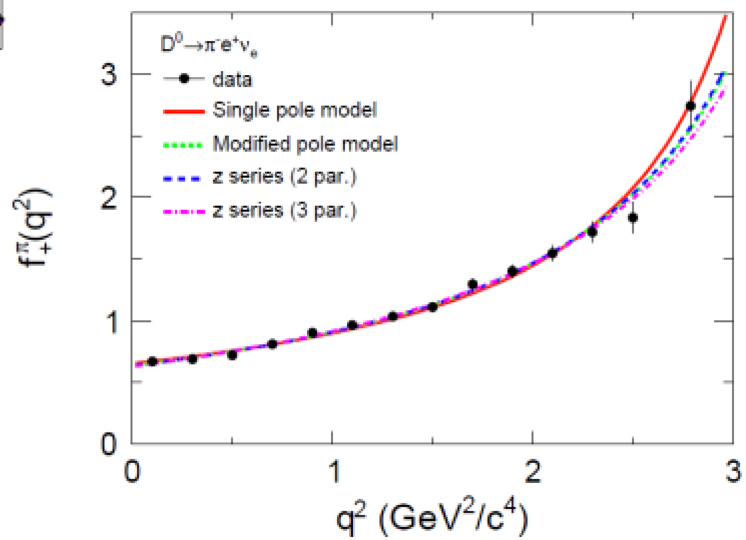
PRD92,072012(2015)



$\mathrm{BF}(D^0 \to K^-e^+\nu_e) =$
$(3.505 \pm 0.014 \pm 0.033)\%$

$\mathrm{BF}(D^0 \to \pi^-e^+\nu_e) =$
$(0.295 \pm 0.004 \pm 0.003)\%$





$$\frac{d\Gamma}{dq^2} = \frac{G_F^2}{24\pi^3}|V_{cs(d)}|^2|\vec{p}_{K^-(\pi^-)}|^3 |f_+^{K(\pi)}(q^2)|^2$$

$f_+(q^2)$

Simple pole model:

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

Modified pole model:

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

Series expansion:

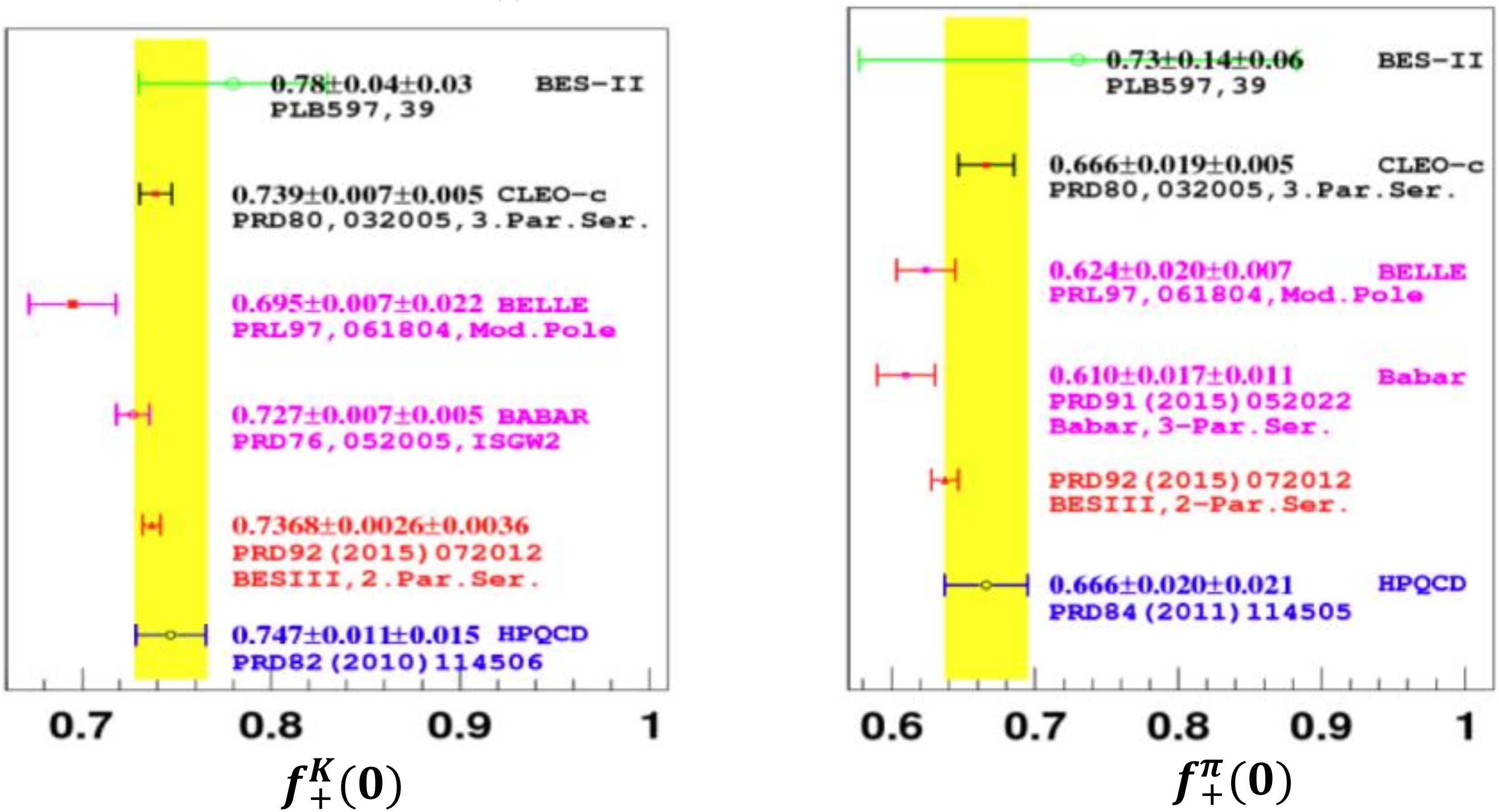
$$= \frac{1}{P(t)\Phi(t, t_0)} a_0(t_0) \times (1 + r_1(t_0)[z(t, t_0)])$$

Study of dynamics of $D^0 \to (K^-/\pi^-)e^+\nu_e$

PRD92,072012(2015)

$$|V_{cs(d)}|f_+^{D^0\to(K^-/\pi^-)e^+\nu_e}(0) \to f_+^{D^0\to(K^-/\pi^-)e^+\nu_e}(0)$$

Input $V_{cs(d)}$ of CKM Fitter



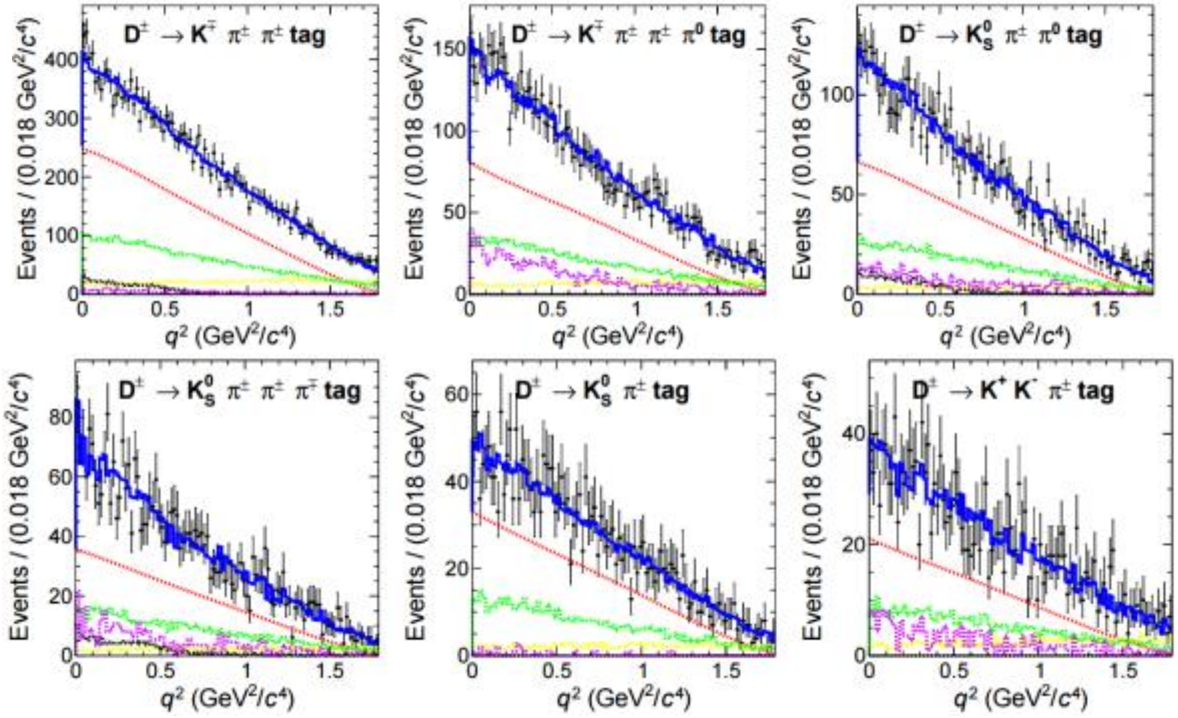
The most precise form factor measurement to calibrate the LQCD

Decay dynamics and CP asymmetry in $D^+ \to K_L^0 e^+ \nu_e$

- **Regardless of long flight distance, K_L^0 interact with EMC and deposit part of energy, thus giving position information**
- **After reconstructing all other particles, K_L^0 can be inferred with position information and constraint $U_{miss} \to 0$**

PRD92, 112008(2015)

- **Simultaneous fit to the yields of DT candidates**



$\text{BF}(D^+ \to K_L e^+ \nu_e) = (4.454 \pm 0.038 \pm 0.102)\%$

$\text{BF}(D^- \to K_L e^- \bar{\nu}_e) = (4.507 \pm 0.038 \pm 0.104)\%$

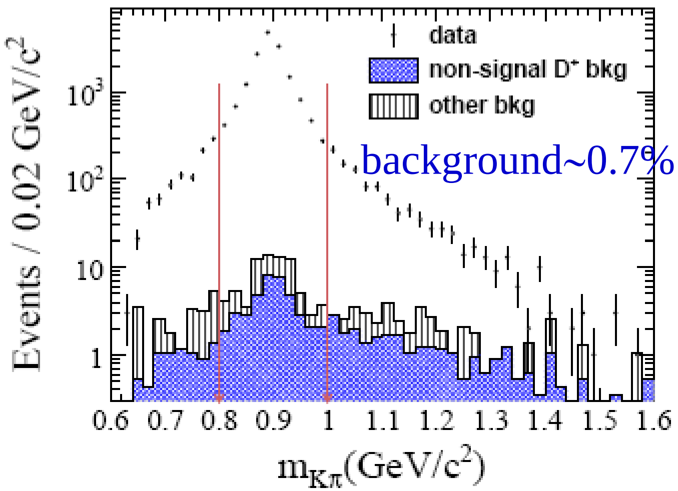
$|V_{cs}| = 0.975 \pm 0.008 \pm 0.015 \pm 0.025$(with LQCD input $f_+^K(0)$), consistent with 0.986 ± 0.016 in PDG

- ✓ **The first measurement of $\text{BF}(D^+ \to K_L e^+ \nu_e)$**
- ✓ $A_{CP} \equiv \frac{BF(D^+ \to K_L e^+ \nu_e) - BF(D^- \to K_L e^- \bar{\nu}_e)}{BF(D^+ \to K_L e^+ \nu_e) + BF(D^- \to K_L e^- \bar{\nu}_e)} = (-0.59 \pm 0.60 \pm 1.48)\%$

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

arXiv:1512.08627

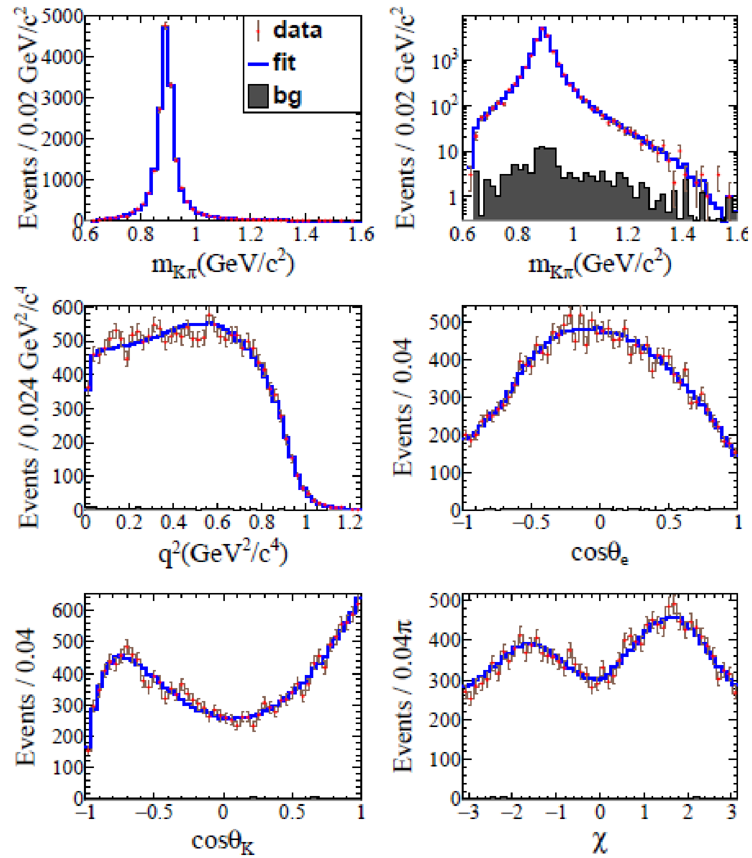
$M_{K\pi}$



$$BF(D^+ \to K^-\pi^+e^+\nu_e) = (3.71 \pm 0.03 \pm 0.08)\%$$

$$BF(D^+ \to K^-\pi^+e^+\nu_e)_{[0.8,1]} = (3.33 \pm 0.03 \pm 0.07)\%$$

Uniquely described by 5 kinematic variables



Fractions of the component

$$f(D^+ \to (K^-\pi^+)_{K^{*0}(892)}\, e^+\nu_e) = (93.93 \pm 0.22 \pm 0.18)\%$$

$$f(D^+ \to (K^-\pi^+)_{S\text{-}wave}\, e^+\nu_e) = (6.05 \pm 0.22 \pm 0.18)\%$$

Parameters of $K^{*0}(892)$

$$m_{K^{*0}(892)} = (894.60 \pm 0.25 \pm 0.08)\ \mathrm{MeV}/c^2$$

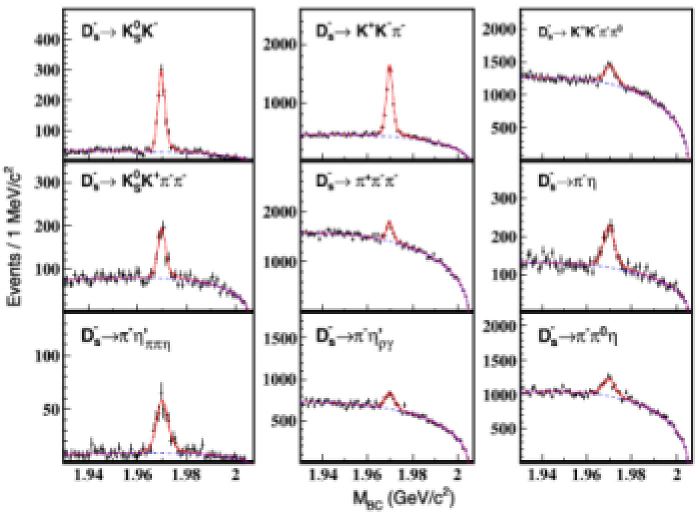
$$\Gamma_{K^{*0}(892)} = (46.42 \pm 0.56 \pm 0.15)\ \mathrm{MeV}/c^2$$

Study of $D_s^+ \to \eta' X$ and $\eta'\rho^+$

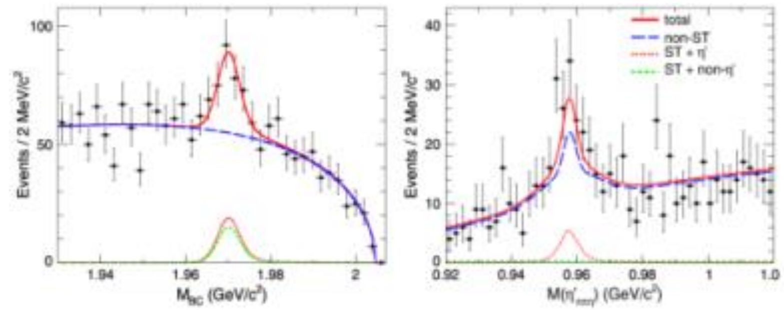
PLB750 466(2015)

- **BFs "puzzle" in PDG 2012**
  - All exclusive rates involving η' : BF($D_s^+ \to \eta' K^+, \eta'\pi^+, \eta'\rho^+, \eta' l^+\nu_l$) = (18.6±2.3)% (PDG2012)
    while the inclusive measurement: BF($D_s^+ \to \eta' X$) = (11.7±1.8)%
  - In the exclusive measurements, BF($D_s^+ \to \eta'\rho^+$) = (12.5±2.2)% (CLEO @Υ(4S), 1998)
    Theoretical prediction is (3.0±0.5)%

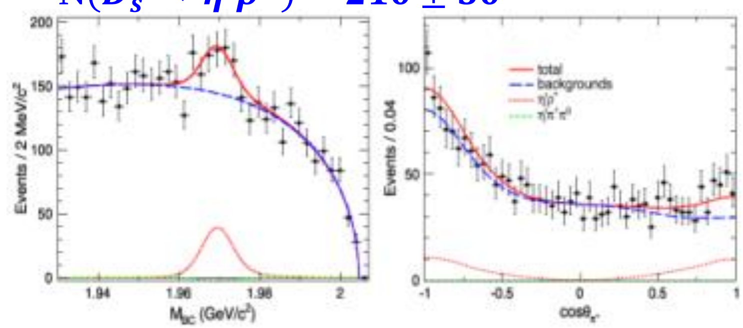
About 15.6k ST D_s^- events by using 9 ST modes



$N(D_s^+ \to \eta' X) = 68 \pm 14$



$N(D_s^+ \to \eta'\rho^+) = 210 \pm 50$



- **BF($D_s^+ \to \eta' X$) = (8.8±1.8±0.5)%**, consistent with PDG =(11.7±1.8)% within $\sim 1\sigma$
- **BF($D_s^+ \to \eta'\ \rho^+$) = (5.8±1.4±0.4)%**, consistent with CLEO-c updated result (5.6±0.8)%

- **BF($D_s^+ \to \eta' K^+, \eta'\pi^+, \eta'\rho^+, \eta' l^+\nu_l$) = (11.9±1.6)%**
  compatible with BF($D_s^+ \to \eta' X$) = (10.3±1.3)% (combined result of this measurement and PDG value)

Other results

$D^+ \to \mu^+ \upsilon_\mu$ (Phys. Rev. D **89**, 051104(R) (2014))

$D^+ \to K_S^0 \pi^+ \pi^0$ (Phys. Rev. D **89**, 052001 (2014))

$D^0 \to \gamma\gamma$ and $D^0 \to \pi^0 \pi^0$ (Phys. Rev. D **91**, 112015 (2015))

Strong phase difference in $D^0 \to K^- \pi^+$ (Phys. Lett. B **734**, 227(2014))

y_{cp} in $D^0 - \overline{D}^0$ oscillation (Phys. Lett. B **744**, 339 (2015))

BF of D^{*0} decay (Phys. Rev. D **91**, 031101(R) (2015))

Observation of $\Lambda_c^+ \to nK_S^0\pi^+$ BESIII preliminary

$D^+ \to \overline{K}^0 e^+ \nu_e$ and $\pi^0 e^+ \nu_e$ BESIII preliminary

Summary

- **With $D\bar{D}/D_s^+D_s^-/\Lambda_c^+\bar{\Lambda}_c^-$ produced at mass threshold, BESIII released many new results**
  - Form factors measurement in (semi)leptonic decays of charmed hadrons provide important test to LQCD calculations and CKM matrix unitarity
  - Hadronic charmed hadrons decays improve the understanding of non-perturbative QCD
  - The first absolute BFs measurement of the Λ_c^+ hadronic decays

- **BESIII is taking data at 4.18GeV to study physics related to D_s**

- **Many charm analyses are ongoing!**

Thanks!