

# Leptonic and Semileptonic $D$ Decays Results from BESIII

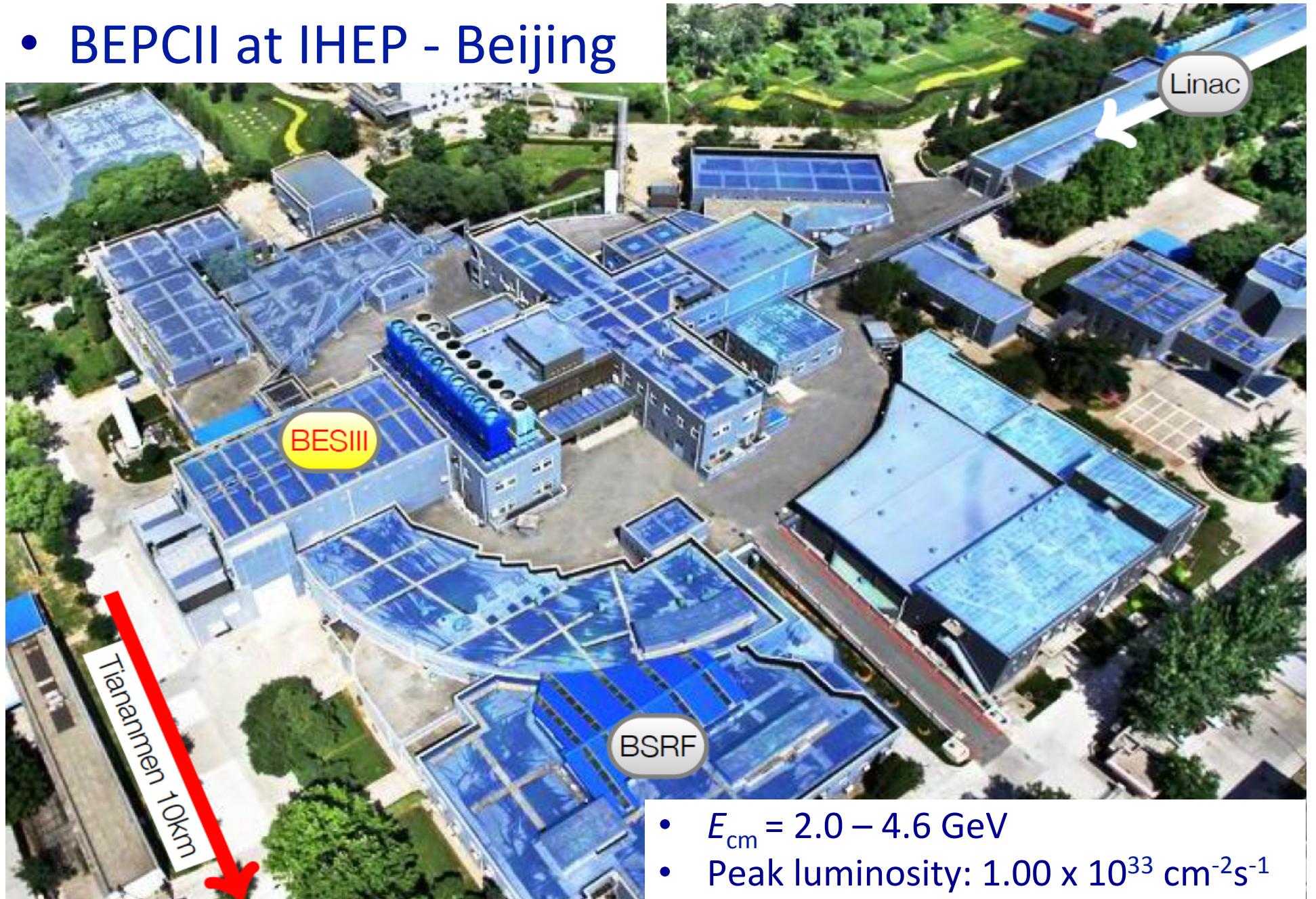


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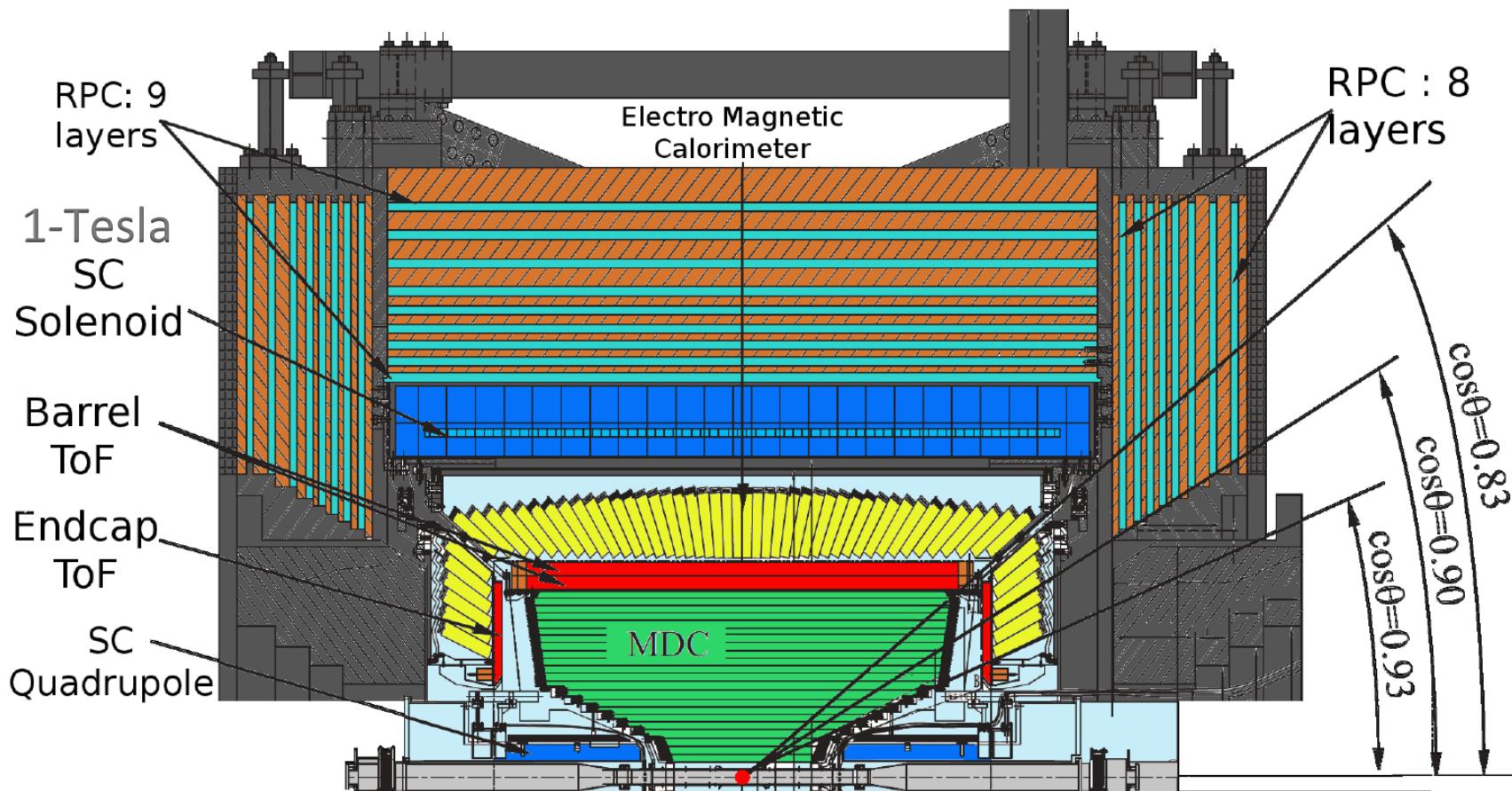


38th INTERNATIONAL CONFERENCE  
ON HIGH ENERGY PHYSICS  
AUGUST 3 - 10, 2016  
CHICAGO

- BEPCII at IHEP - Beijing

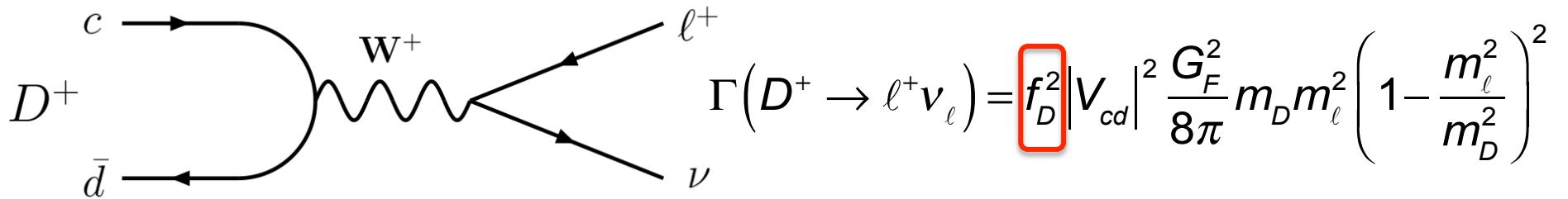


# BESIII Detector

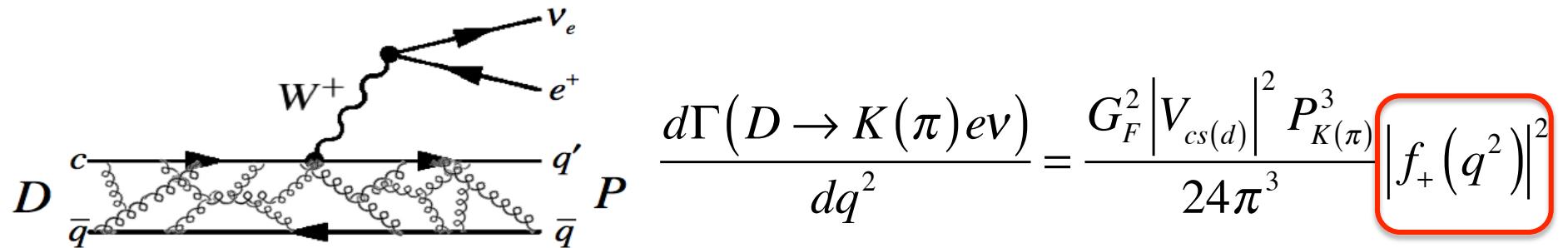


- Main Drift chamber:  $115 \mu\text{m}$  single-hit resolution,  $0.5\%$   $p$  resolution at  $1 \text{ GeV}/c$ ,  $<5\%$   $dE/dx$  resolution
- CsI EM calorimeter:  $2.5\%$  energy resolution at  $1 \text{ GeV}$

# Leptonic and Semileptonic $D_{(s)}$ Decays



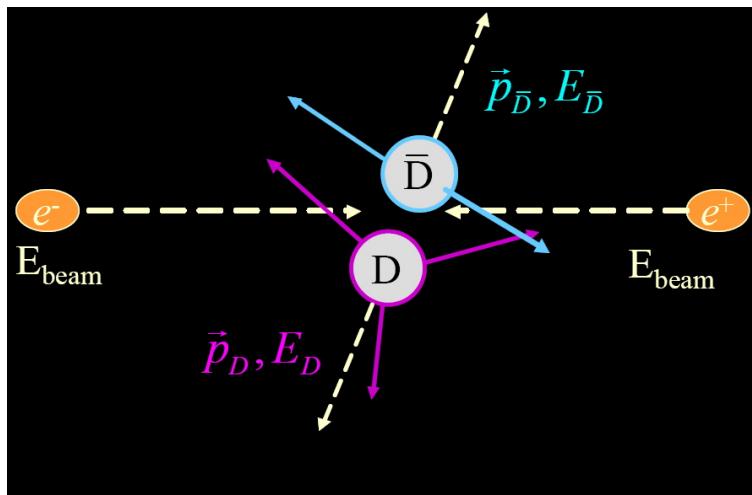
- Precision measurements test theory (LQCD), apply to  $B$
- Multiple tests with charm:  $f_D$ ,  $f_{D_s}$  (esp. ratios)
- Sensitivity to New Physics



- Theory for form factor, extract CKM
- Unitarity + other measurements to test theory (many modes)
- Use charm to reduce theory uncertainty in  $|V_{ub}|$

# Charm Physics at Threshold with BESIII

- Just above threshold charm production is just  $D_{(s)}\bar{D}_{(s)}$
- Fully reconstruct  $\gtrsim 20\%$  of  $D$  decays

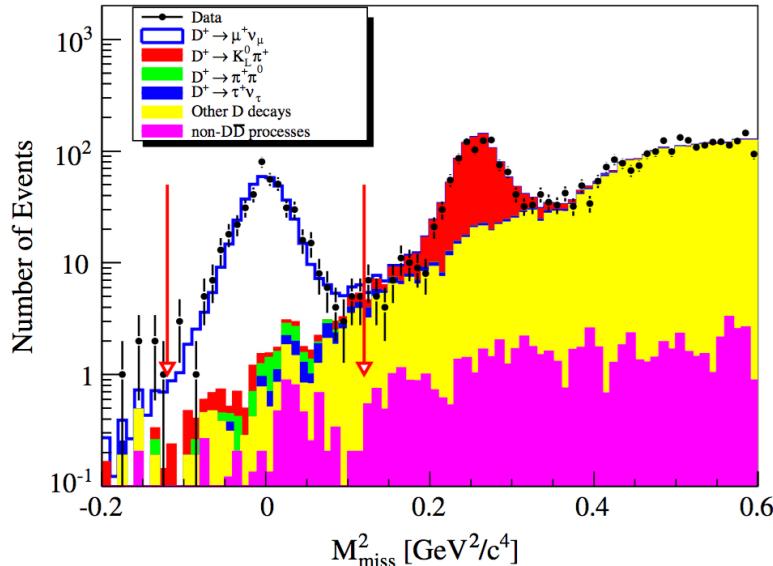
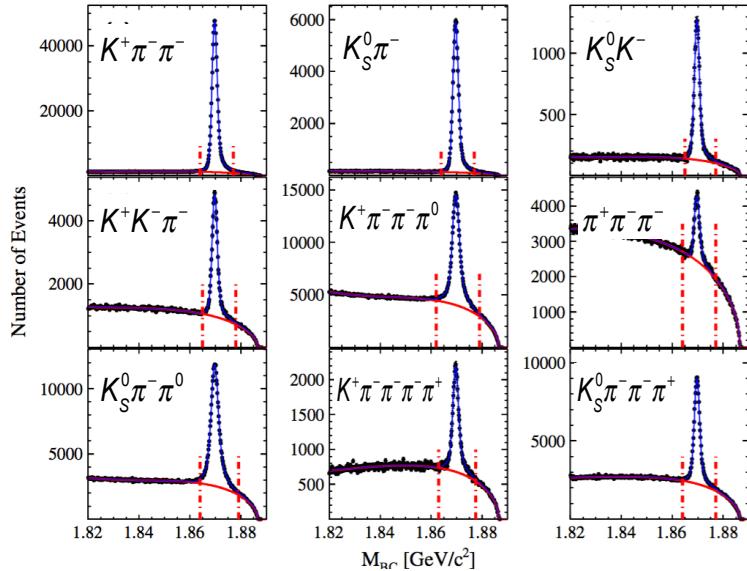


$$\Delta E = E_D - E_{\text{Beam}}$$
$$M_{\text{BC}} = \sqrt{E_{\text{Beam}}^2 - p_D^2}$$

- Hadronic tag on one side uniquely defines the charmed meson on the other side for leptonic/semileptonic studies. Neutrino via missing energy/momentum
- Data samples:
  - 2.93  $\text{fb}^{-1}$  near  $\psi(3770)$  peak at  $E_{CM} = 3.773 \text{ GeV}$  for  $D$
  - 0.482  $\text{fb}^{-1}$  at  $E_{CM} = 4.009 \text{ GeV}$  for  $D_s$

# $D^+ \rightarrow \mu^+ \nu$

Phys. Rev. D **89**, 051104(R) (2014)  
 $\psi(3770)$  -  $2.93 \text{ fb}^{-1}$



5 August 2016

$$N_{D_{tag}^-} = (1.703 \pm 0.003) \times 10^6$$

$$N(D^+ \rightarrow \mu^+ \nu) = 409 \pm 21^*$$

$$\mathcal{B}(D^+ \rightarrow \mu^+ \nu) = (0.0371 \pm 0.0019 \pm 0.0006)\%$$

\* 1% correction for  $D^+ \rightarrow \gamma \mu^+ \nu_\mu$

Most precise to date, statistics limited

Using  $|V_{cd}|$  from PDG (CKMFitter):

$$f_{D^+} = (203.2 \pm 5.3 \pm 1.8) \text{ MeV}$$

Using  $f_{D^+} = (207 \pm 4)$  MeV from LQCD:

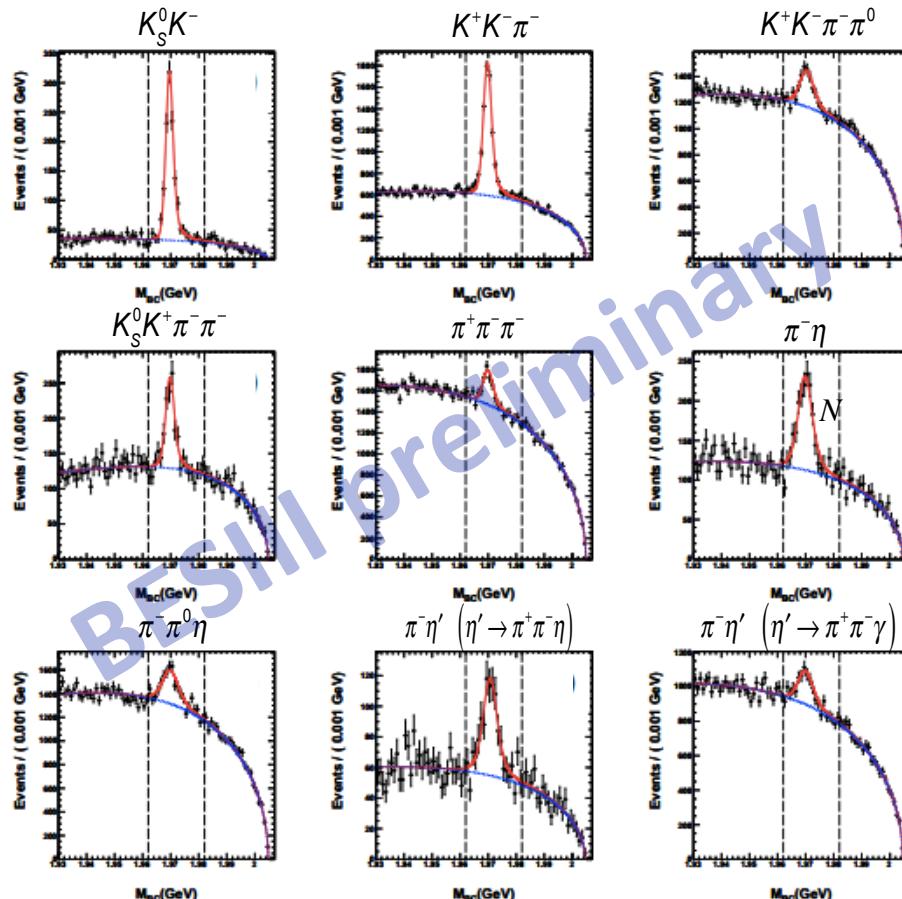
$$|V_{cd}| = 0.2210 \pm 0.0058 \pm 0.0047$$

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$$D_s^+ \rightarrow \mu^+ \nu_\mu$$

BESIII Preliminary  
0.482 fb<sup>-1</sup> at  $E_{CM} = 4.009$  GeV

$$e^+ e^- \rightarrow D_s^+ D_s^-$$

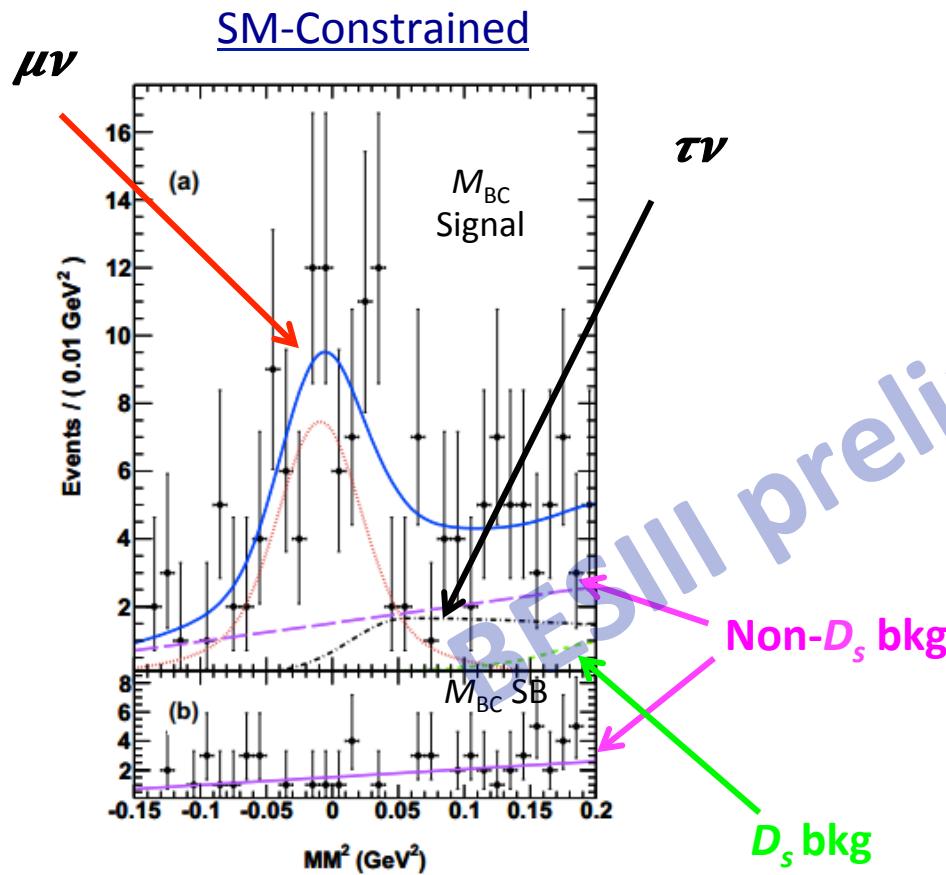


$$N_{D_s^- \text{ tag}} = 15127 \pm 312$$

- Signal side requirements
  - 1 good right-charged track
  - Energy of highest energy shower < 300 MeV
- Compute MM<sup>2</sup> and fit
  - $\tau/\mu$  ratio fixed to SM (9.76)
  - $\tau/\mu$  ratio unconstrained, sample partitioned with PID into  $\mu$ -enriched,  $\mu$ -depleted and PID-inconclusive subsamples, fitted simultaneously

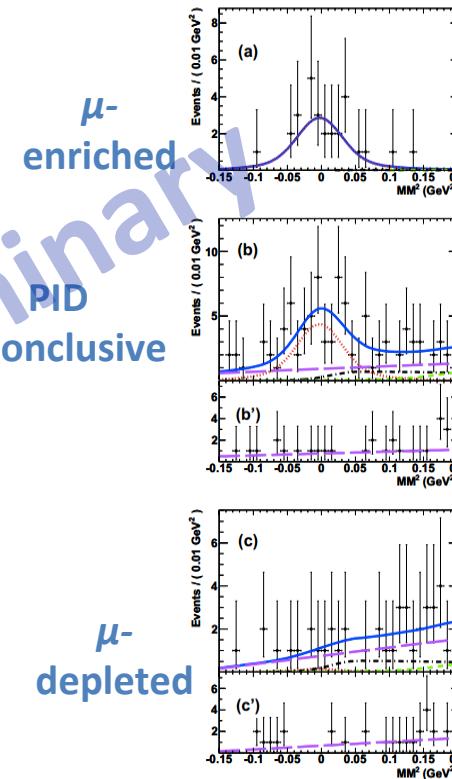
$$D_s^+ \rightarrow \mu^+ \nu_\mu$$

BESIII Preliminary  
0.482 fb<sup>-1</sup> at  $E_{CM} = 4.009$  GeV



$D_s^+ \rightarrow \mu^+ \nu_\mu$  Signal:  $69.3 \pm 9.3$  events  
 $\mathcal{B}(D_s^+ \rightarrow \mu^+ \nu_\mu) = (0.495 \pm 0.067 \pm 0.026)\%$   
 $f_{D_s} = (241.0 \pm 16.3 \pm 6.6)$  MeV

Unconstrained – Cross-Check



Color-code:

- $\mu\nu$
- $\tau\nu$
- Non- $D_s$  bkg
- $D_s$  bkg

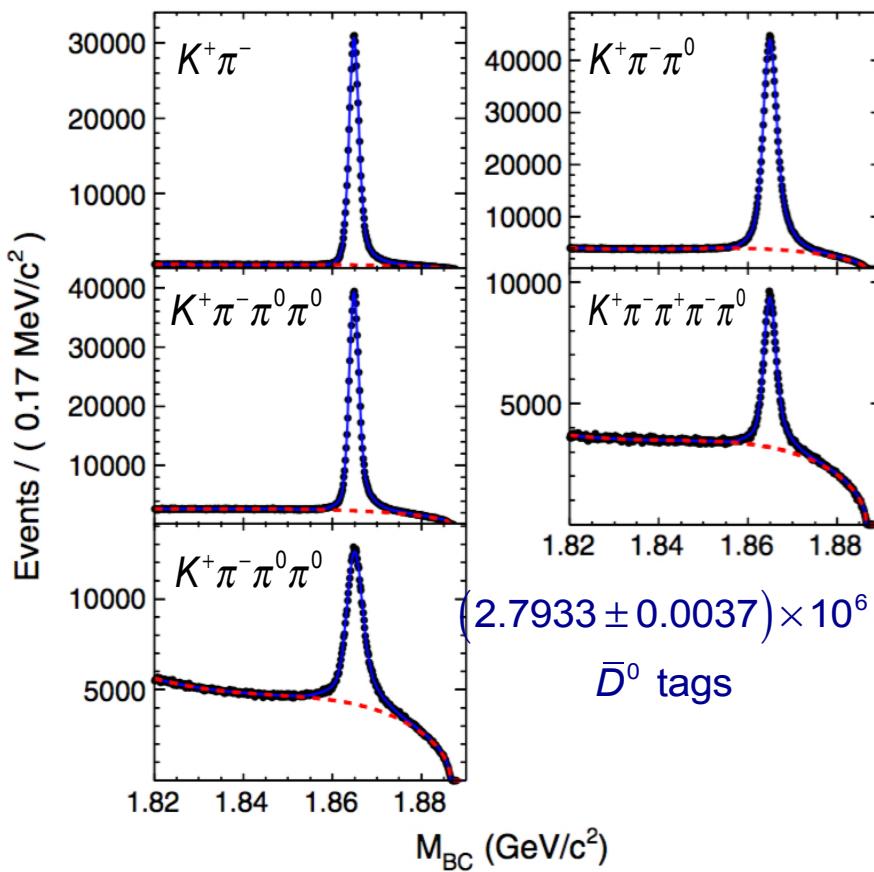
$$\mathcal{B}(D_s^+ \rightarrow \mu^+ \nu_\mu) = (0.517 \pm 0.075 \pm 0.021)\%$$

$$\mathcal{B}(D_s^+ \rightarrow \tau^+ \nu_\tau) = (3.28 \pm 1.83 \pm 0.37)\%$$

Need more  $D_s$  data!

$$D^0 \rightarrow K^-(\pi^-) e^+ \nu_e$$

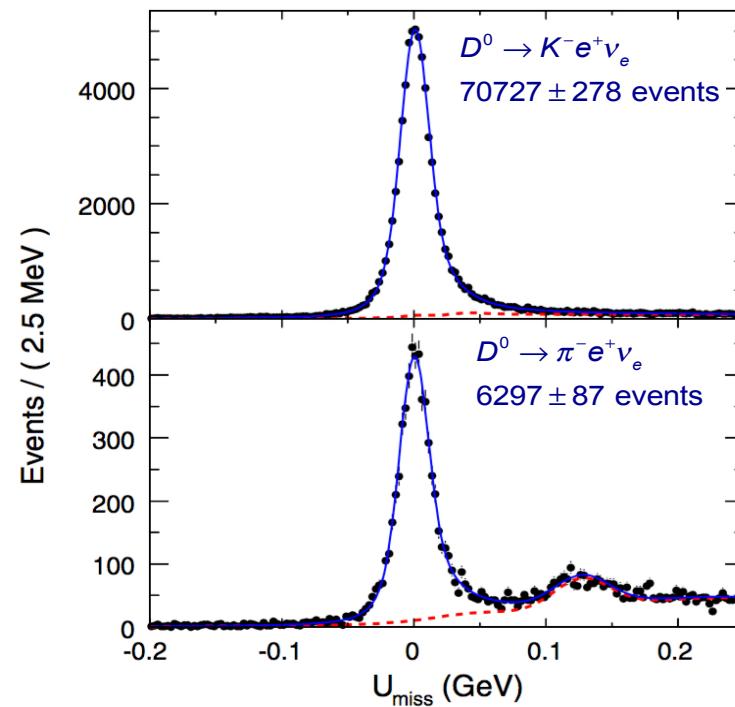
Phys. Rev. D 92, 072012 (2015)  
 $\psi(3770)$  -  $2.93 \text{ fb}^{-1}$



Branching fraction results are in excellent agreement with previous measurements and more precise

- Select SL signal: just positron and  $K^-/\pi^-$ , minimal extra energy, and  $\nu$  consistency:

$$U = E_{\text{miss}} - c |\vec{P}_{\text{miss}}| \approx 0$$



$$\mathcal{B}(D^0 \rightarrow K^- e^+ \nu_e) = (3.505 \pm 0.014 \pm 0.033)\% \\ \mathcal{B}(D^0 \rightarrow \pi^- e^+ \nu_e) = (0.2950 \pm 0.0041 \pm 0.0026)\%$$

$$D^0 \rightarrow K^-(\pi^-) e^+ \nu_e$$

Phys. Rev. D 92, 072012 (2015)  
 $\psi(3770)$  - 2.93 fb<sup>-1</sup>

$$\frac{d\Gamma(D \rightarrow K(\pi)ev)}{dq^2} = \frac{G_F^2 |V_{cs(d)}|^2 P_{K(\pi)}^3}{24\pi^3} |f_+(q^2)|^2$$

– Single pole form

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

– ISGW2 model

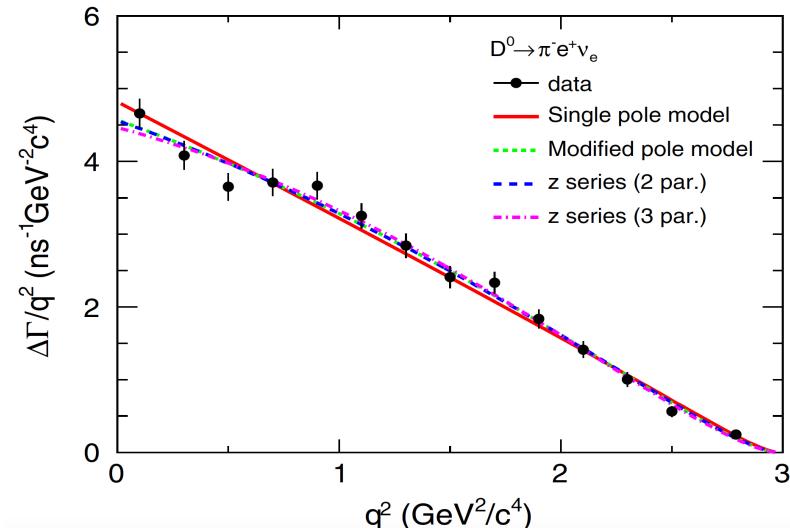
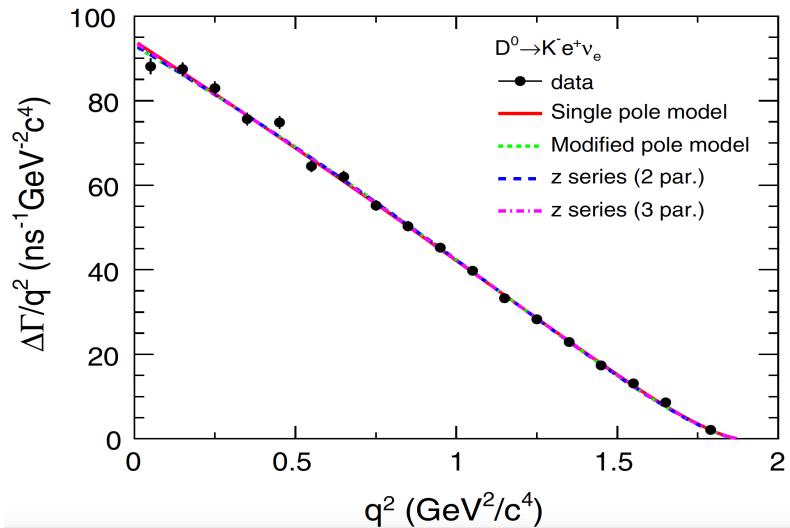
$$f_+(q^2) = f_+(q_{\max}^2) \left(1 + \frac{r_{ISGW2}^2}{12} (q_{\max}^2 - q^2)\right)^{-2}$$

– Modified pole model

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

– Series expansion model

$$f_+(t) = \frac{1}{P(t)\Phi(t, t_0)} a_0(t_0) \left(1 + \sum_{k=1}^{\infty} r_k(t_0) [z(t, t_0)]^k\right)$$



Using  $f_+^{K(\pi)}(0)|V_{cs(d)}|$  from the 2-par.  
series fit and FFs from HPQCD:

$$|V_{cs}| = 0.9601 \pm 0.0033 \pm 0.0047 \pm 0.0239$$

$$|V_{cd}| = 0.2155 \pm 0.0027 \pm 0.0014 \pm 0.0094$$

$$\begin{array}{ll} \text{Decay mode} & f_+^{K(\pi)}(0)|V_{cs(d)}| \\ D^0 \rightarrow K^- e^+ \nu_e & 0.7209 \pm 0.0022 \pm 0.0035 \\ D^0 \rightarrow \pi^- e^+ \nu_e & 0.1475 \pm 0.0014 \pm 0.0005 \end{array}$$

$$\begin{array}{ll} \text{Single pole model} & M_{pole}(\text{GeV}/c^2) \\ & 1.921 \pm 0.010 \pm 0.007 \\ & 1.911 \pm 0.012 \pm 0.004 \end{array}$$

$$\chi^2/\text{d.o.f.} \quad 18.8/16 \quad 20.0/12$$

$$\begin{array}{ll} \text{Decay mode} & f_+^{K(\pi)}(0)|V_{cs(d)}| \\ D^0 \rightarrow K^- e^+ \nu_e & 0.7163 \pm 0.0024 \pm 0.0034 \\ D^0 \rightarrow \pi^- e^+ \nu_e & 0.1437 \pm 0.0017 \pm 0.0008 \end{array}$$

$$\begin{array}{ll} \text{Modified pole model} & \alpha \\ & 0.309 \pm 0.020 \pm 0.013 \\ & 0.279 \pm 0.035 \pm 0.011 \end{array}$$

$$\chi^2/\text{d.o.f.} \quad 20.2/16 \quad 12.6/12$$

$$\begin{array}{ll} \text{Decay mode} & f_+^{K(\pi)}(0)|V_{cs(d)}| \\ D^0 \rightarrow K^- e^+ \nu_e & 0.7172 \pm 0.0025 \pm 0.0035 \\ D^0 \rightarrow \pi^- e^+ \nu_e & 0.1435 \pm 0.0018 \pm 0.0009 \end{array}$$

$$\begin{array}{ll} \text{Two-parameter series expansion} & r_1 \\ & -2.2286 \pm 0.0864 \pm 0.0573 \\ & -2.0365 \pm 0.0807 \pm 0.0257 \end{array}$$

$$\chi^2/\text{d.o.f.} \quad 19.6/16 \quad 12.8/12$$

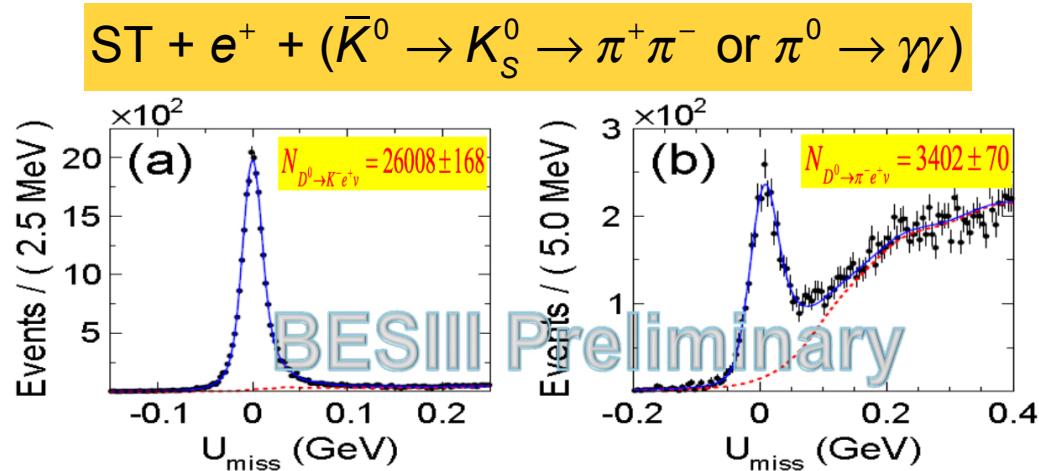
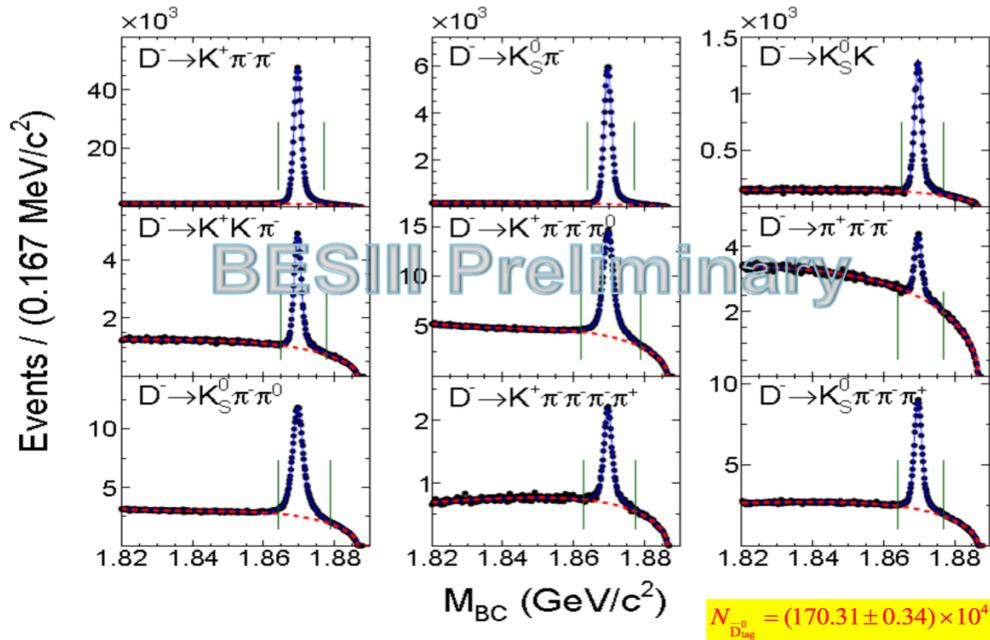
$$\begin{array}{ll} \text{Decay mode} & f_+^{K(\pi)}(0)|V_{cs(d)}| \\ D^0 \rightarrow K^- e^+ \nu_e & 0.7195 \pm 0.0035 \pm 0.0041 \\ D^0 \rightarrow \pi^- e^+ \nu_e & 0.1420 \pm 0.0024 \pm 0.0010 \end{array}$$

$$\begin{array}{ll} \text{Three-parameter series expansion} & r_1 \\ & -2.3338 \pm 0.1587 \pm 0.0804 \\ & -1.8432 \pm 0.2212 \pm 0.0690 \end{array}$$

$$\begin{array}{ll} & r_2 \\ & 3.4188 \pm 3.9090 \pm 2.4098 \\ & -1.3874 \pm 1.4615 \pm 0.4680 \end{array} \quad \chi^2/\text{d.o.f.} \quad 19.1/15 \quad 11.9/11$$

$$D^+ \rightarrow \bar{K}^0 (\pi^0) e^+ \nu_e$$

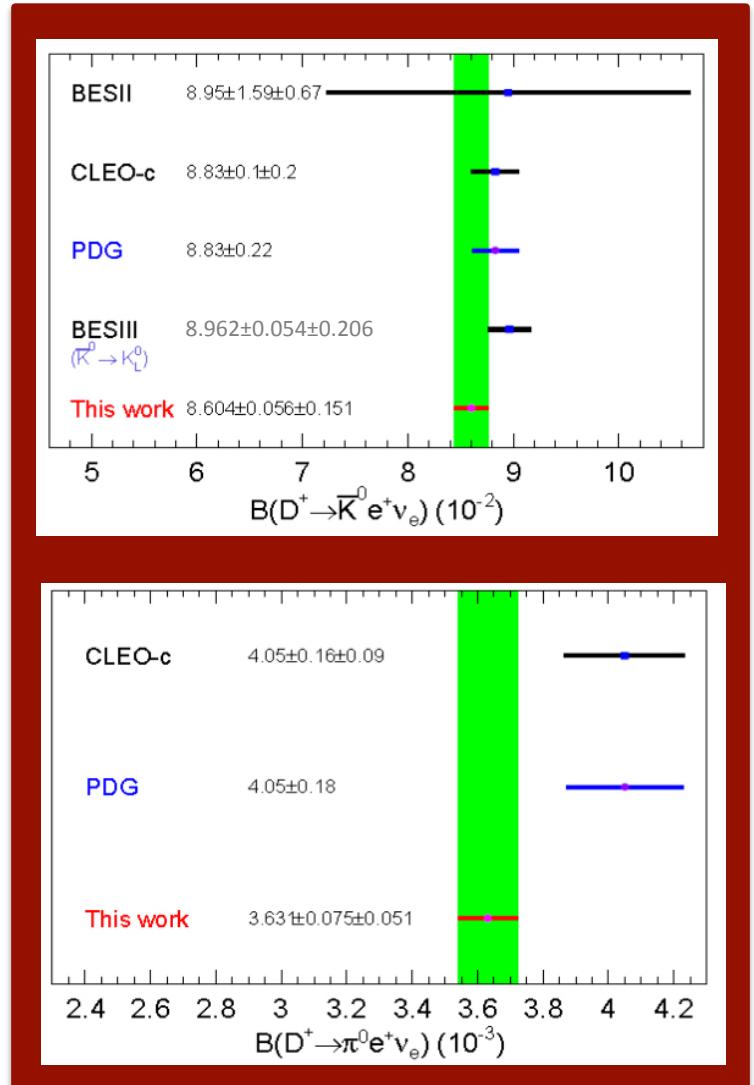
BESIII Preliminary  
 $\psi(3770)$  - 2.93 fb $^{-1}$



$$B[D^+ \rightarrow \bar{K}^0 e^+ v] = (8.604 \pm 0.056 \pm 0.151)\%$$

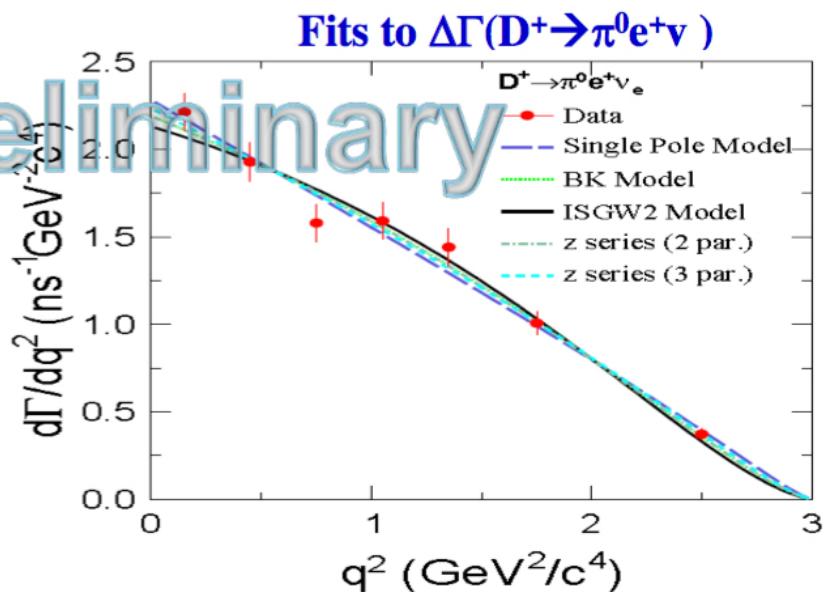
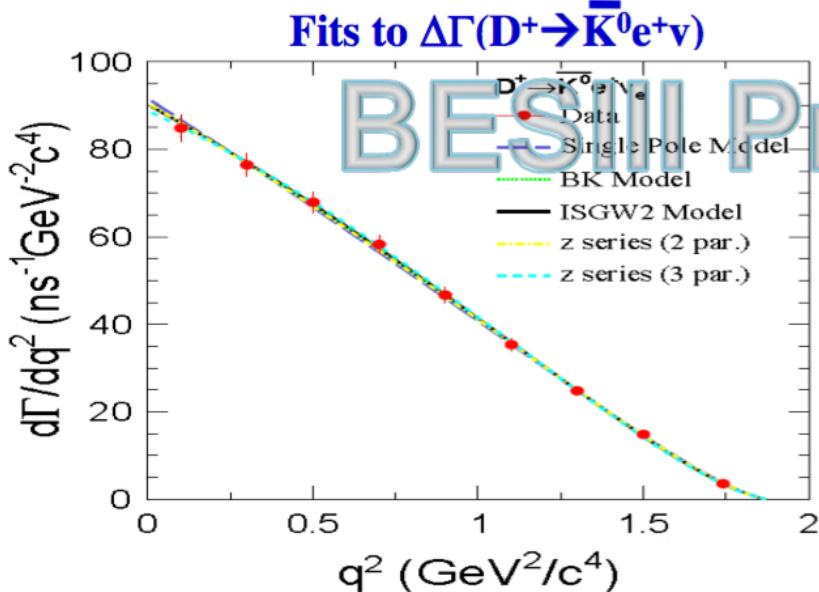
5 August 2016

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$$D^+ \rightarrow \bar{K}^0 (\pi^0) e^+ \nu_e$$

BESIII Preliminary  
 $\psi(3770)$  - 2.93 fb<sup>-1</sup>



<i>Single pole model</i>			
Decay mode	$f_+(0) V_{cq} $	$m_{pole}$ (GeV/c <sup>2</sup> )	
$D^+ \rightarrow \bar{K}^0 e^+ \nu_e$	$0.7094 \pm 0.0035 \pm 0.0111$	$1.935 \pm 0.017 \pm 0.006$	
<hr/>			
$D^+ \rightarrow \pi^0 e^+ \nu_e$	$0.1429 \pm 0.0020 \pm 0.0009$	$1.898 \pm 0.020 \pm 0.003$	
<i>Modified pole model</i>			
Decay mode	$f_+(0) V_{cq} $	$\alpha$	
$D^+ \rightarrow \bar{K}^0 e^+ \nu_e$	$0.7052 \pm 0.0038 \pm 0.0112$	$0.294 \pm 0.031 \pm 0.010$	
$D^+ \rightarrow \pi^0 e^+ \nu_e$	$0.1400 \pm 0.0024 \pm 0.0010$	$0.285 \pm 0.057 \pm 0.010$	
<i>ISGW2 model</i>			
Decay mode	$f_+(0) V_{cq} $	$r$ (GeV <sup>-1</sup> )	
$D^+ \rightarrow \bar{K}^0 e^+ \nu_e$	$0.7039 \pm 0.0037 \pm 0.0111$	$1.587 \pm 0.023 \pm 0.007$	
$D^+ \rightarrow \pi^0 e^+ \nu_e$	$0.1381 \pm 0.0023 \pm 0.0007$	$2.078 \pm 0.067 \pm 0.011$	
<i>Two-parameter series expansion</i>			
Decay mode	$f_+(0) V_{cq} $	$r_1$	
$D^+ \rightarrow \bar{K}^0 e^+ \nu_e$	$0.7053 \pm 0.0040 \pm 0.0112$	$-2.18 \pm 0.14 \pm 0.05$	
$D^+ \rightarrow \pi^0 e^+ \nu_e$	$0.1400 \pm 0.0026 \pm 0.0007$	$-2.01 \pm 0.13 \pm 0.02$	
<i>Three-parameter series expansion</i>			
Decay mode	$f_+(0) V_{cq} $	$r_1$	$r_2$
$D^+ \rightarrow \bar{K}^0 e^+ \nu_e$	$0.6983 \pm 0.0036 \pm 0.0112$	$-1.76 \pm 0.25 \pm 0.06$	$-13.4 \pm 6.3 \pm 1.4$
$D^+ \rightarrow \pi^0 e^+ \nu_e$	$0.1413 \pm 0.0035 \pm 0.0012$	$-2.23 \pm 0.42 \pm 0.06$	$1.4 \pm 2.5 \pm 0.4$

$$|V_{cs}| = 0.9442 \pm 0.0054 \pm 0.0015 \pm 0.0235$$

$$|V_{cd}| = 0.2102 \pm 0.0039 \pm 0.0011 \pm 0.0092$$

$$D^+ \rightarrow K_L^0 e^+ \nu_e$$

Phys. Rev. D **92**, 072012 (2015)  
 $\psi(3770)$  -  $2.93 \text{ fb}^{-1}$

$D^-$  tag modes:

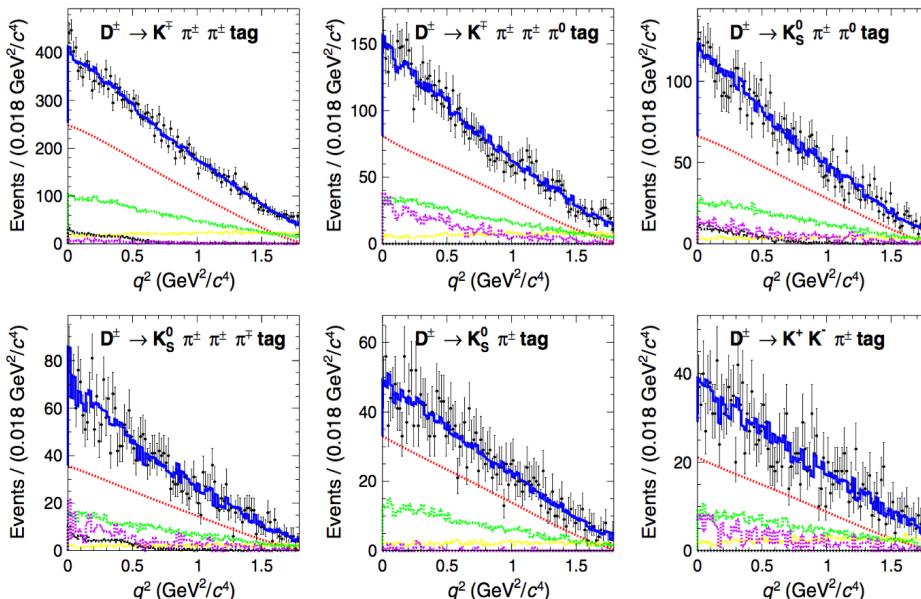
$$\begin{array}{ccc} K^+ \pi^- \pi^- & K_S^0 \pi^- & K^+ \pi^- \pi^- \pi^0 \\ K_S^0 \pi^- \pi^0 & K_S^0 \pi^+ \pi^- \pi^- & K^+ K^- \pi^- \end{array}$$

Double-tag selection

ST + positron +  $K_L^0$  EM shower (direction)

Use 4-mom. cons and  $U_{miss} = E_{miss} - c|\vec{p}_{miss}| = 0$

Gives  $|\vec{p}_{K_L^0}| \rightarrow E_{K_L^0} \rightarrow q^2$



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BG-corrected ST yields + DT yields  
 give BF and CP asymmetry

First Measurements

$$\begin{aligned} \mathcal{B}(D^+ \rightarrow K_L^0 e^+ \nu_e) &= (4.481 \pm 0.027 \pm 0.103)\% \\ A_{CP} &= (-0.59 \pm 0.60 \pm 1.48)\% \end{aligned}$$

Extract yields as function of  $q^2$   
 Fit  $q^2$  distributions to FF  
 parameterizations

$$f_+^K(0)|V_{cs}| = 0.748 \pm 0.007 \pm 0.012$$

Using FF from HPQCD:

$$|V_{cs}| = 0.975 \pm 0.008 \pm 0.025$$

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$D^+ \rightarrow \bar{K}^0 e^+ \nu_e$  via  $\bar{K}^0 \rightarrow \pi^0 \pi^0$

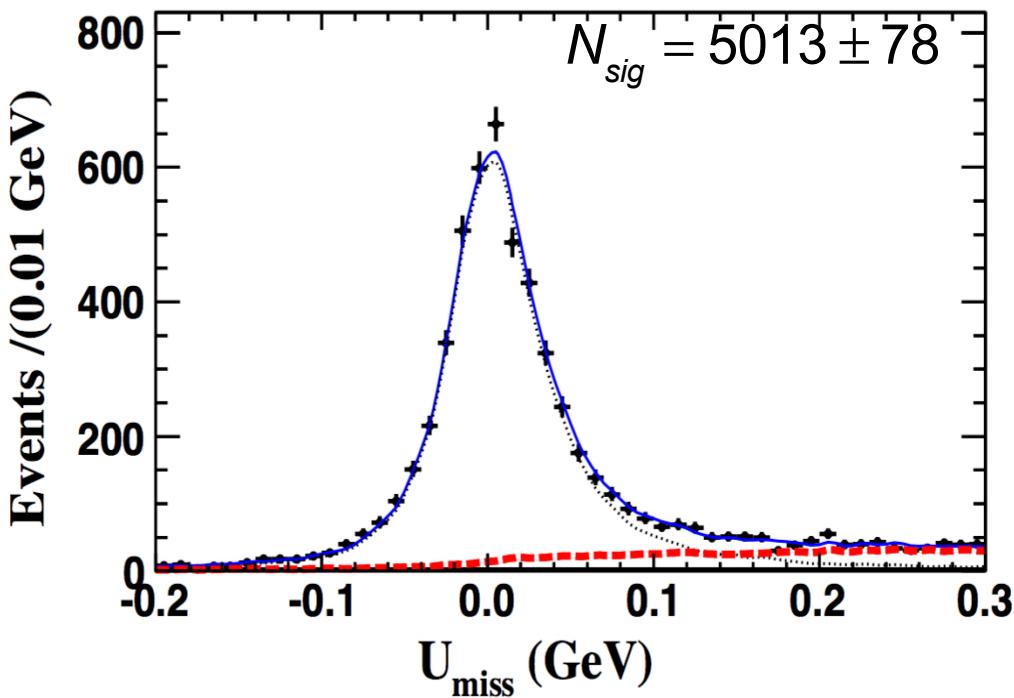
BESIII submitted – arXiv:1605.00208  
 $\psi(3770)$  -  $2.93 \text{ fb}^{-1}$

First measurement using

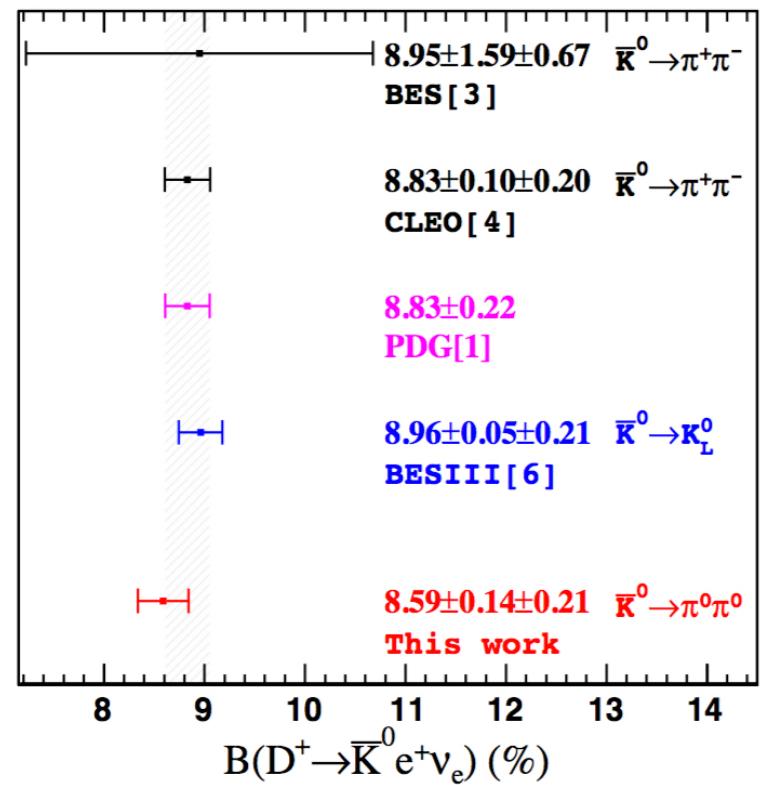
$$\bar{K}^0 \rightarrow K_S^0 \rightarrow \pi^0 \pi^0$$

Six  $D^-$  tag modes:

$$\begin{array}{ccc} K^+ \pi^- \pi^- & K_S^0 \pi^- & K^+ \pi^- \pi^- \pi^0 \\ K_S^0 \pi^- \pi^0 & K_S^0 \pi^+ \pi^- \pi^- & K^+ K^- \pi^- \end{array}$$



$$\mathcal{B}(D^+ \rightarrow \bar{K}^0 e^+ \nu_e) = (8.59 \pm 0.14 \pm 0.21)\%$$



$$\begin{aligned} \frac{\Gamma(D^0 \rightarrow K^- e^+ \nu_e)}{\Gamma(D^+ \rightarrow \bar{K}^0 e^+ \nu_e)} &= \frac{\mathcal{B}(D^0 \rightarrow K^- e^+ \nu_e) \times \tau_{D^+}}{\mathcal{B}(D^+ \rightarrow \bar{K}^0 e^+ \nu_e) \times \tau_{D^0}} \\ &= 0.969 \pm 0.025 \end{aligned}$$

$$D^+ \rightarrow \bar{K}^0 \mu^+ \nu_\mu$$

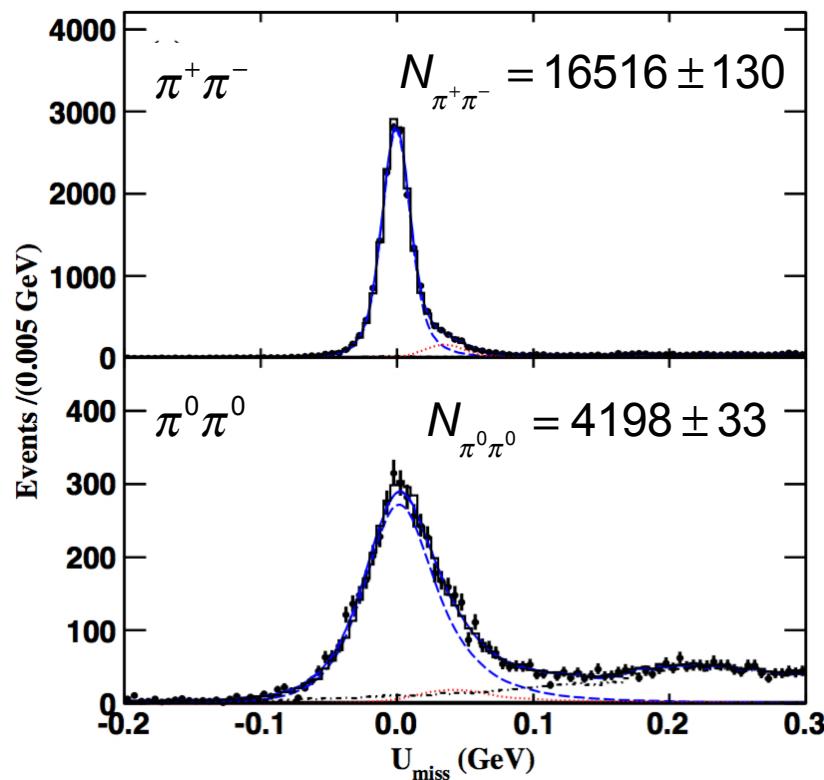
BESIII submitted – arXiv:1605.00068  
 $\psi(3770)$  -  $2.93 \text{ fb}^{-1}$

$D^-$  tag modes:

$$\begin{array}{ccc} K^+ \pi^- \pi^- & K_S^0 \pi^- & K^+ \pi^- \pi^- \pi^0 \\ K_S^0 \pi^- \pi^0 & K_S^0 \pi^+ \pi^- \pi^- & K^+ K^- \pi^- \end{array}$$

$$\bar{K}^0 \rightarrow K_S^0 \rightarrow \pi^+ \pi^- \text{ or } \pi^0 \pi^0$$

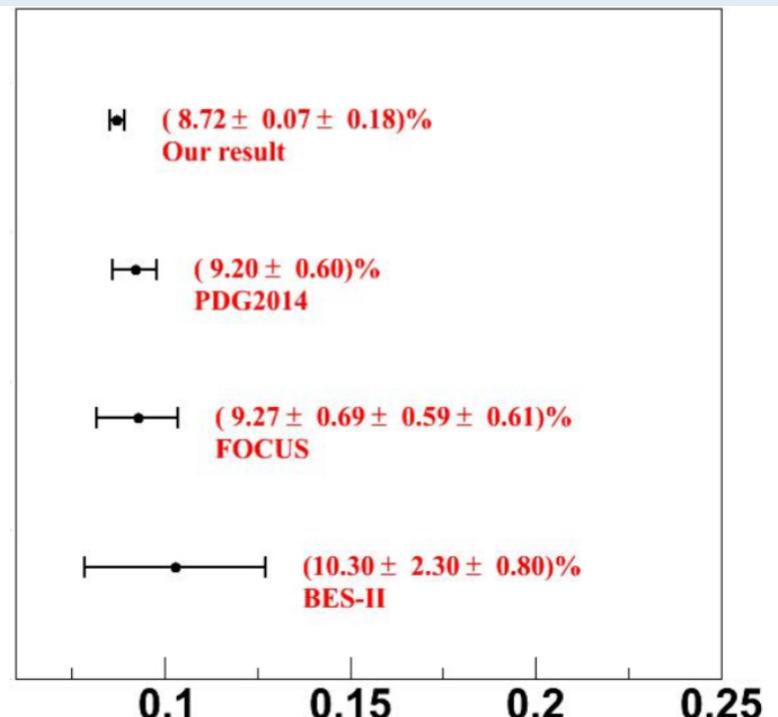
Right-charge track consistent with  $\mu$



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$$\mathcal{B}(D^+ \rightarrow \bar{K}^0 \mu^+ \nu_\mu) = (8.72 \pm 0.07 \pm 0.18)\%$$

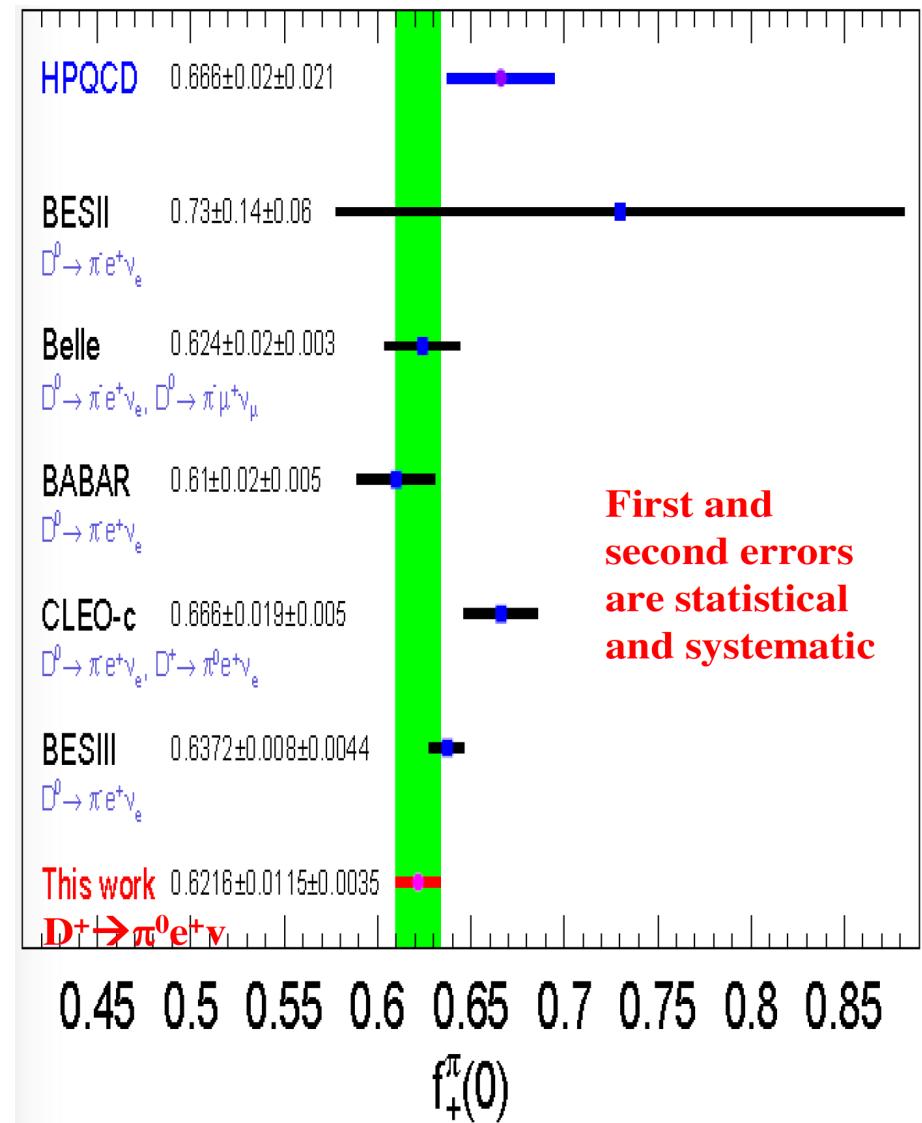
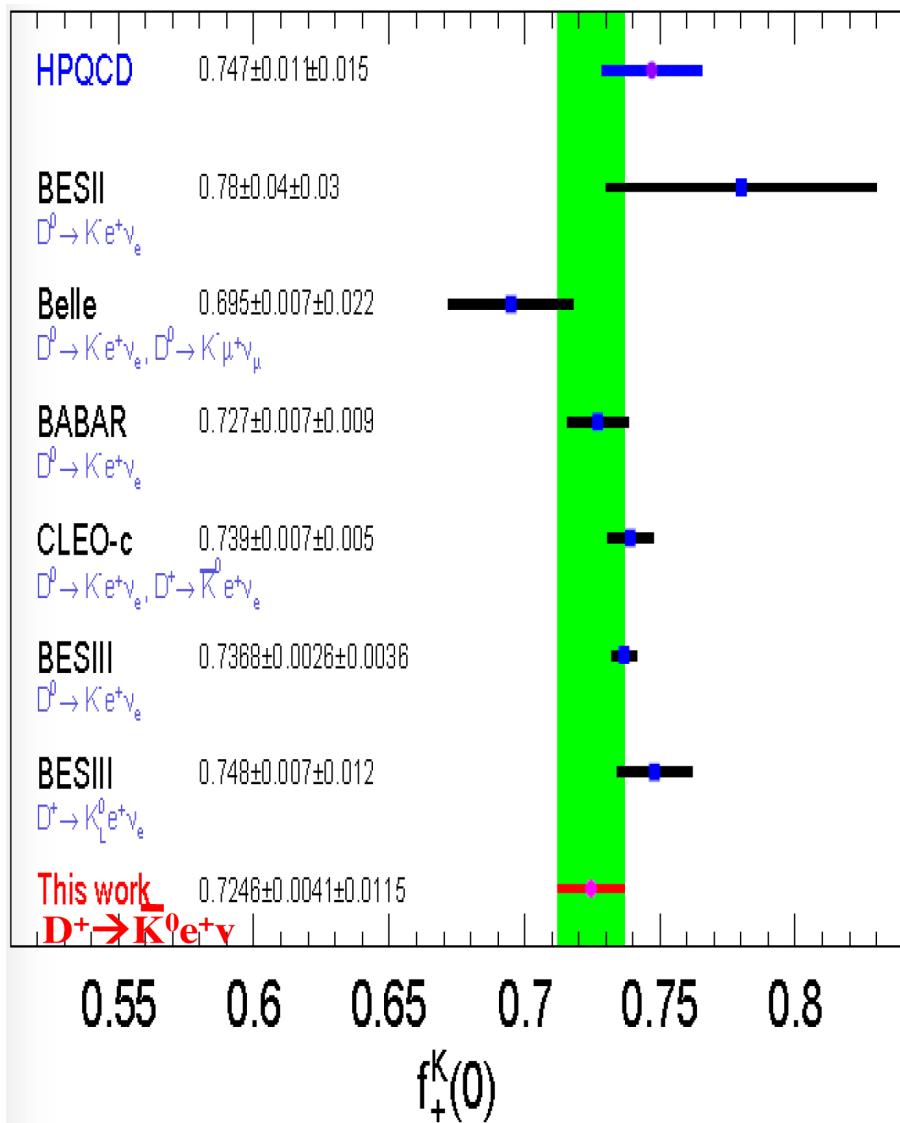


$$\frac{\Gamma(D^0 \rightarrow K^- \mu^+ \nu_\mu)}{\Gamma(D^+ \rightarrow \bar{K}^0 \mu^+ \nu_\mu)} = 0.963 \pm 0.044$$

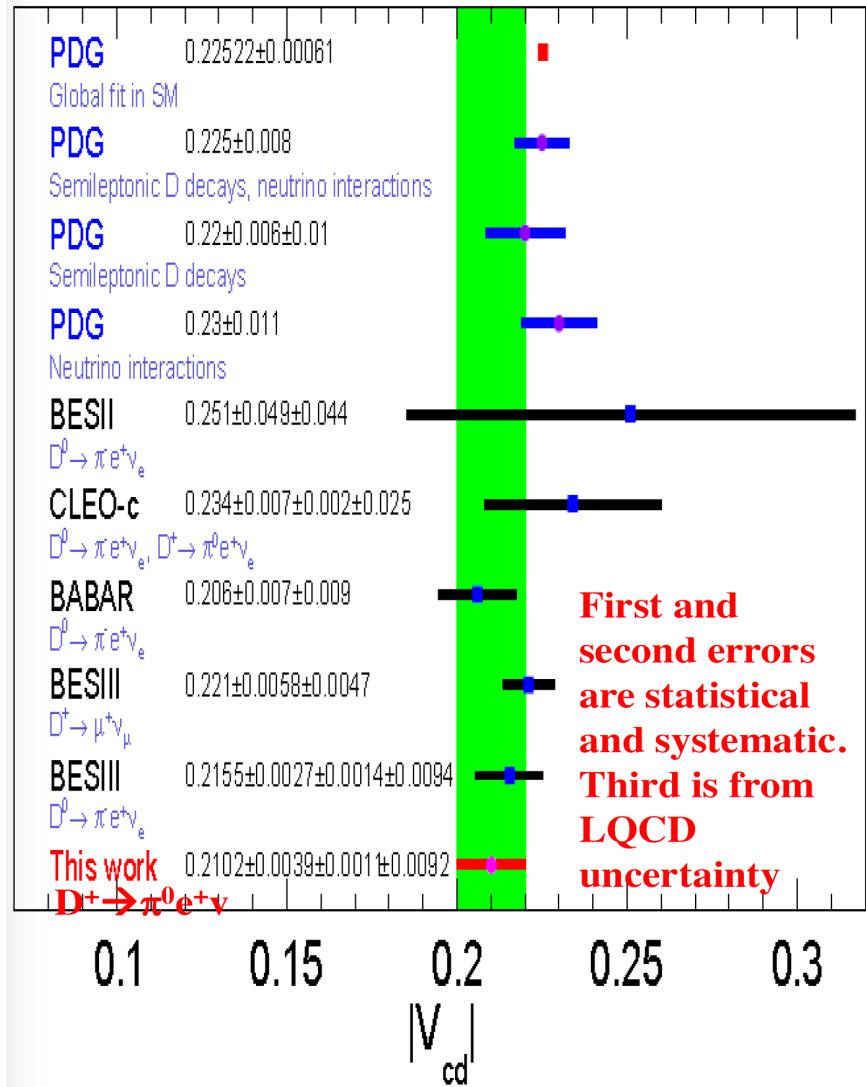
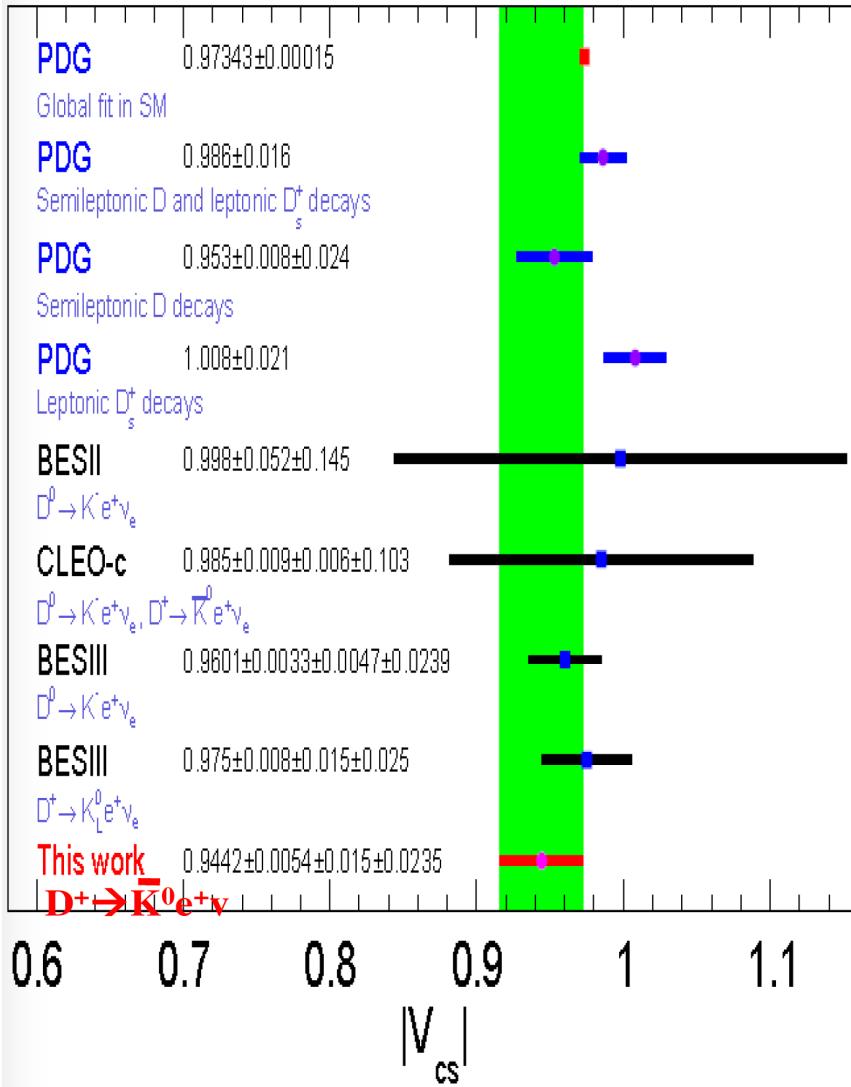
$$\frac{\Gamma(D^0 \rightarrow \bar{K}^0 \mu^+ \nu_\mu)}{\Gamma(D^+ \rightarrow \bar{K}^0 e^+ \nu_e)} = 0.988 \pm 0.033$$

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# Form Factor Status



# $|V_{cs}|$ and $|V_{cd}|$ Status

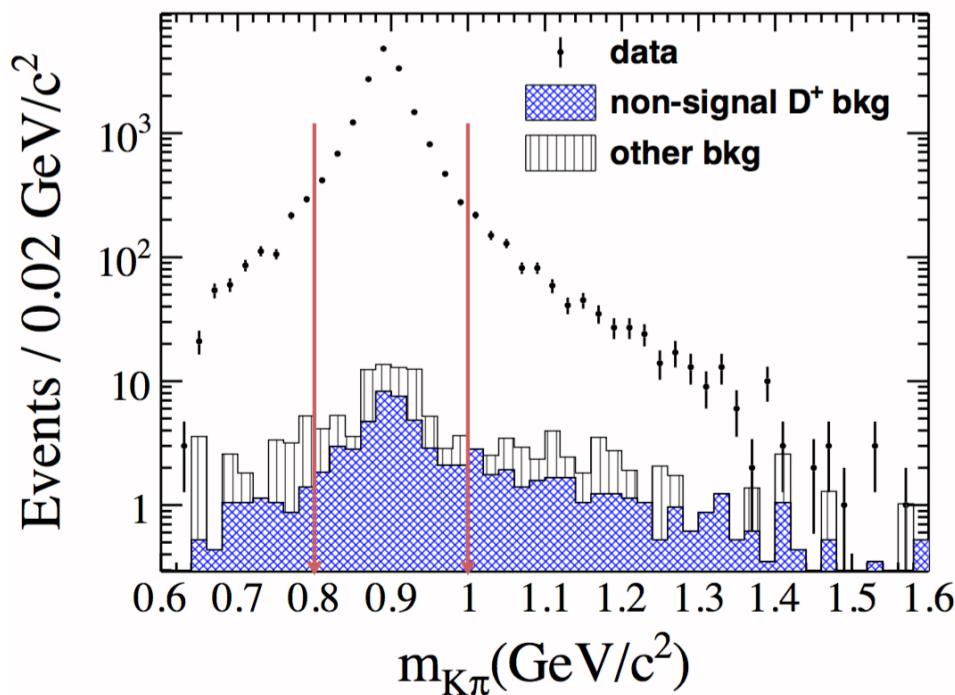


$$D^+ \rightarrow K^- \pi^+ e^+ \nu_e$$

BESIII accepted by PRD – arXiv:1512.08627  
 $\psi(3770)$  - 2.93 fb<sup>-1</sup>

- Objectives:
- 1) Measure branching fractions and  $K\pi$  amplitudes via Partial Wave Analysis
  - 2) Measure  $q^2$ -dependent transition form factors for

$$D^+ \rightarrow \bar{K}^{*0}(892) e^+ \nu_e$$



18262 signal events  
 $\sim 0.7\%$  BG

$$\mathcal{B}(D^+ \rightarrow K^- \pi^+ e^+ \nu_e) = (3.71 \pm 0.03 \pm 0.08)\%$$

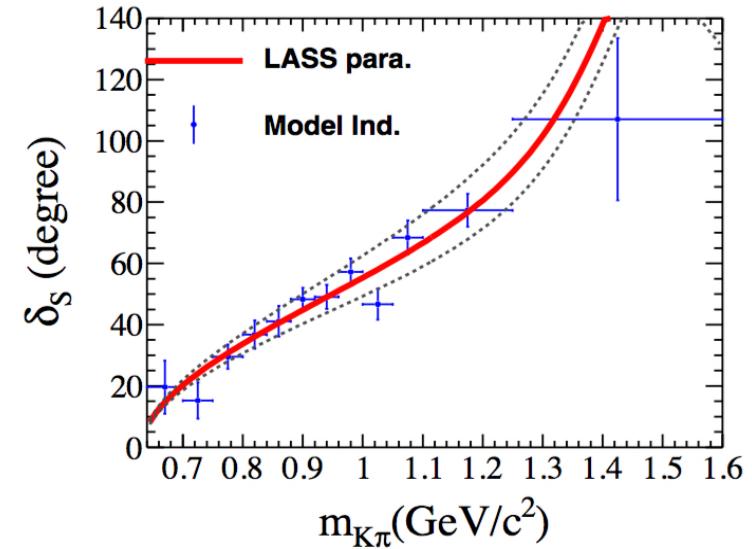
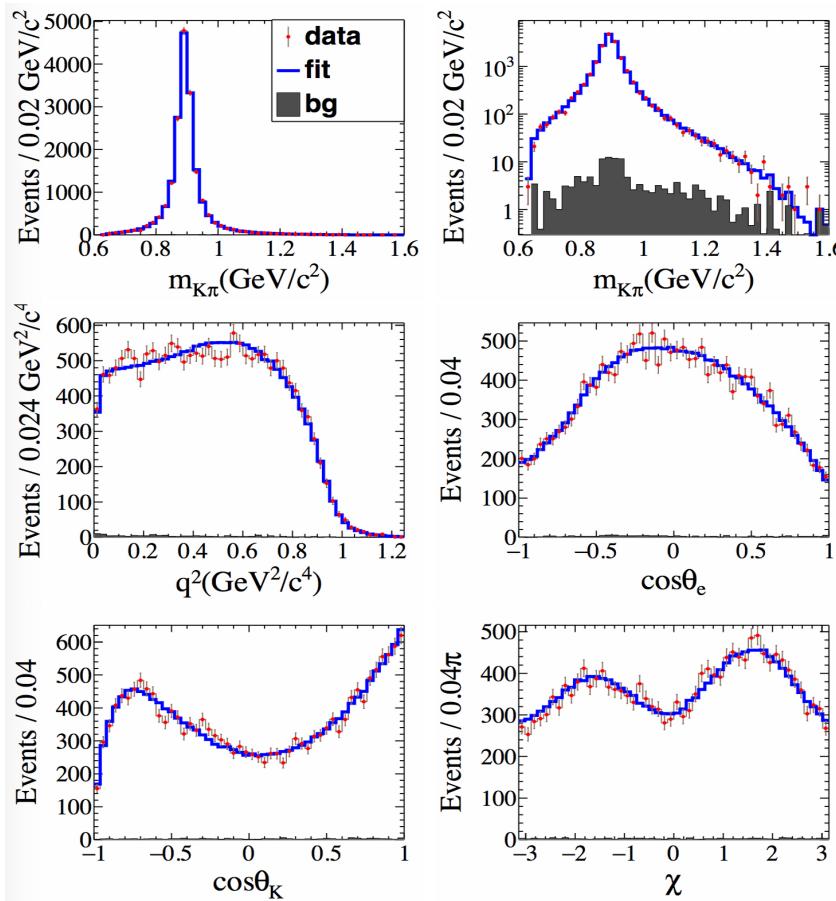
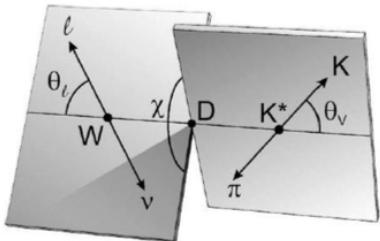
For  $0.8 < m_{K\pi} < 1.0 \text{ GeV}/c^2$  ( $K^*$  dominated):

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

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

BESIII accepted by PRD – arXiv:1512.08627  
 $\psi(3770)$  -  $2.93 \text{ fb}^{-1}$

## 4-body Decay Kinematics



Fractions  $> 5\sigma$  significance

$$D^+ \rightarrow (K^-\pi^+)_{K^{*0}(892)} e^+ \nu_e \quad (93.93 \pm 0.22 \pm 0.18)\%$$

$$D^+ \rightarrow (K^-\pi^+)_{S\text{-wave}} e^+ \nu_e \quad (6.05 \pm 0.22 \pm 0.18)\%$$

## FF Parameters

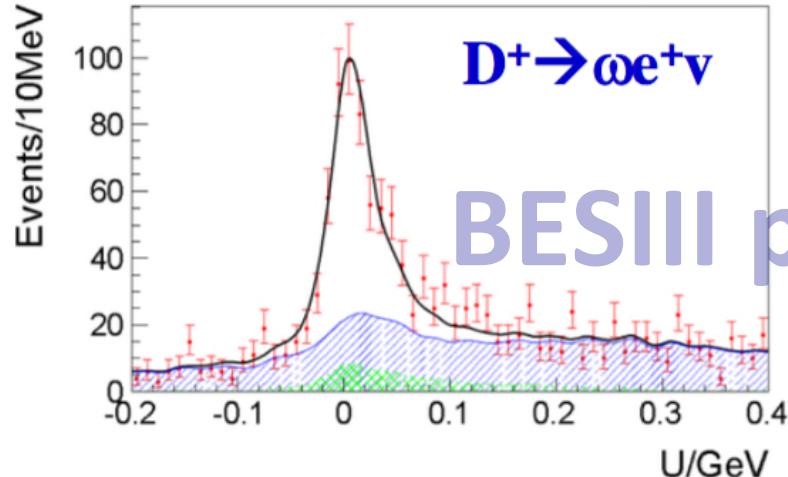
$$m_V = (1.81^{+0.25}_{-0.17} \pm 0.02) \text{ GeV}/c^2 \quad m_A = (2.61^{+0.22}_{-0.17} \pm 0.03) \text{ GeV}/c^2$$

$$A_1(0) = 0.573 \pm 0.011 \pm 0.020$$

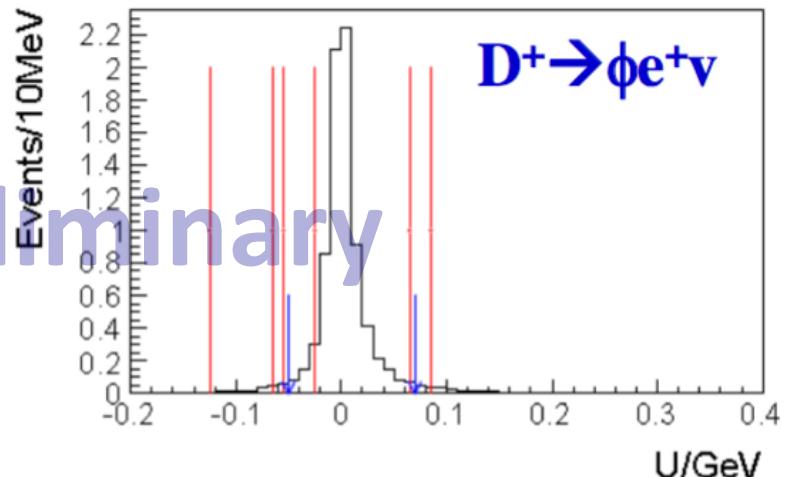
$$r_V = \frac{V(0)}{A_1(0)} = 1.411 \pm 0.058 \pm 0.007 \quad r_2 = \frac{A_2(0)}{A_1(0)} = 0.788 \pm 0.042 \pm 0.008$$

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

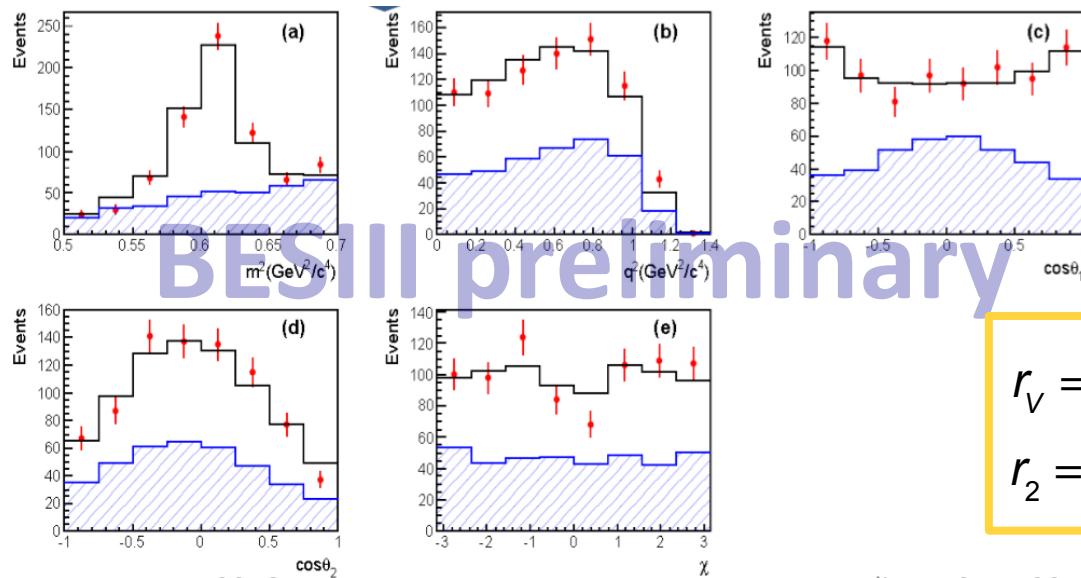
Phys. Rev. D 92, 071101R (2015)  
 $\psi(3770) - 2.93 \text{ fb}^{-1}$



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



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



5 August 2016

First measurement  
 $D^+ \rightarrow \omega e^+ \nu_e$   
 FF parameters

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

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

Ron Poling - ICHEP 2016

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# Summary and Prospects

- BESIII has large and clean  $e^+e^-$  data samples near threshold, well suited to precision measurements of semileptonic and leptonic charm decays
- Many recent results on  $D$  decays at  $\psi(3770)$ : leptonic and semileptonic branching fractions, form factors and decay constants. More in preparation
- First results on  $D_s$  decays at threshold, statistics limited. Many more, with greater precision coming soon with newly acquired  $3 \text{ fb}^{-1}$  data sample at 4.18 GeV
- Longer term prospects: additional  $\psi(3770)$ , more samples at higher energy, including  $\gtrsim 4.6 \text{ GeV}$  for  $\Lambda_c$
- Also at ICHEP 2016
  - Absolute branching fractions for  $\Lambda_c$  decays at BESIII
    - *Poster presentation, 6 August*
    - *Peilian Li, USTC*