Study of $D^{0(+)} \rightarrow P(S)l^{+}\nu_{l}$ at BESIII

$(P = Pseudoscalar, S = Scalar)$

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Outline

- Introduction
- First Observation of $D^0 \to a_0(980)^- e^+ \nu_e$ and Evidence for $D^+ \to a_0(980)^0 e^+ \nu_e$
- Analysis of $D^+ \to \bar{K}^0 e^+ \nu_e$ and $D^+ \to \pi^0 e^+ \nu_e$
- Measurement of $D^+ \to \bar{K}^0 (\pi^0 \pi^0) e^+ \nu_e$
- Improved measurement of $D^+ \to \bar{K}^0 \mu^+ \nu_\mu$
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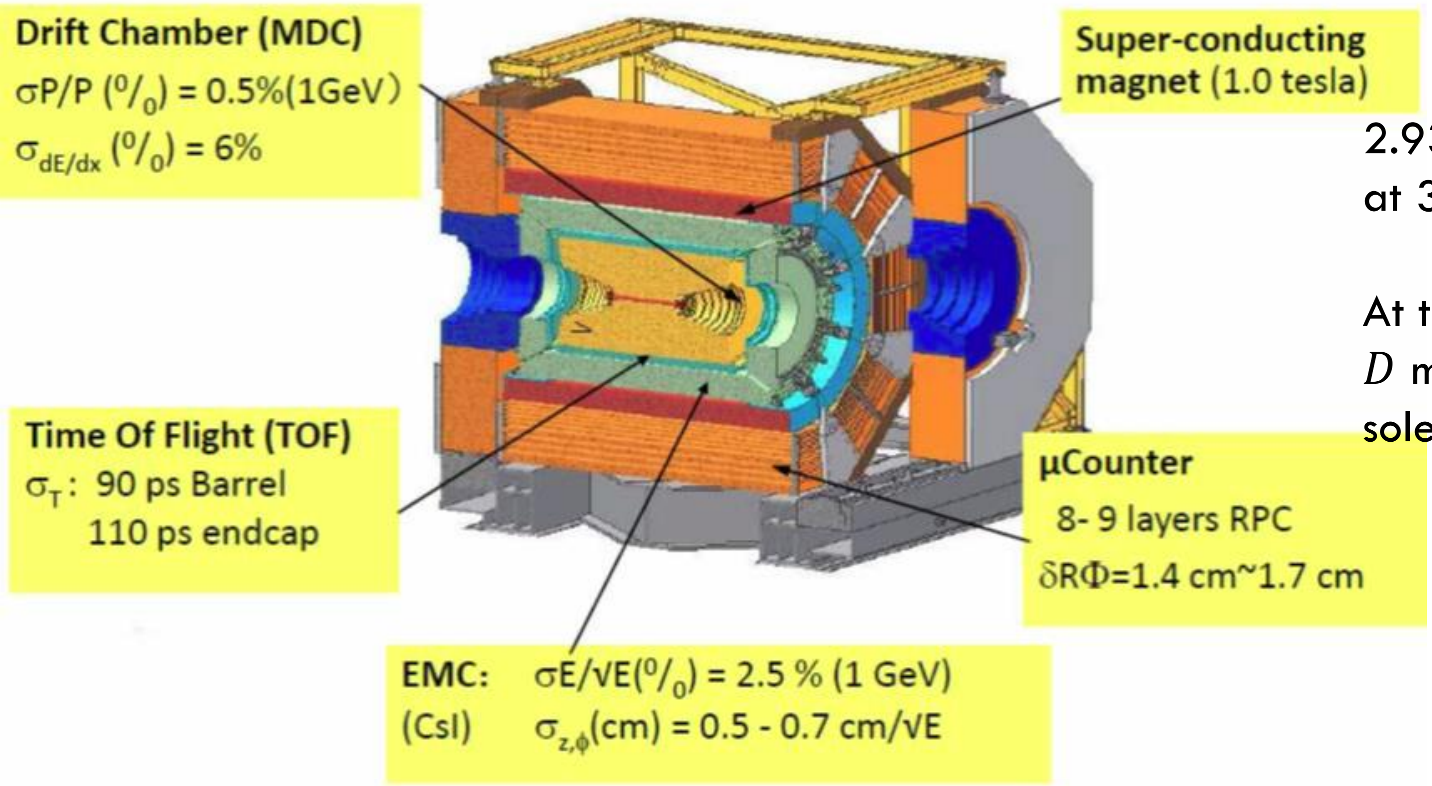
BESIII Detector and Data Sample



Drift Chamber (MDC)
$\sigma P/P$ ($^0/_0$) = 0.5%(1GeV)
$\sigma_{dE/dx}$ ($^0/_0$) = 6%

Super-conducting magnet (1.0 tesla)

Time Of Flight (TOF)
σ_T: 90 ps Barrel
110 ps endcap

µCounter
8- 9 layers RPC
$\delta R\Phi$=1.4 cm~1.7 cm

EMC: $\sigma E/\sqrt{E}$($^0/_0$) = 2.5 % (1 GeV)
(CsI) $\sigma_{z,\phi}$(cm) = 0.5 - 0.7 cm/$\sqrt{E}$

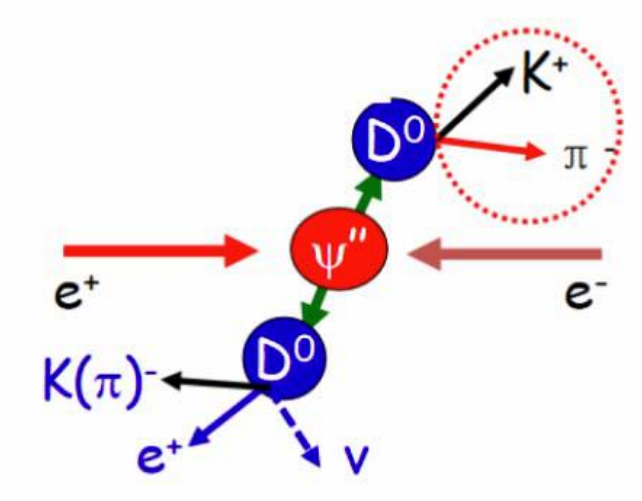
2.93fb^{-1} e^+e^- collision data at 3.773GeV 3.6xCLEO-c

At the $D\bar{D}$ threshold, and D meson is produced solely through $D\bar{D}$ pair

Double Tag Method

- Reconstruct one hadronic decaying D (single tag,ST), and search for the signal process in the remainder of the event (double tag, DT)
- Provide an absolute branching fraction measurement

$$B_{sig} = \frac{N_{sig}^{obs}}{\sum_{\alpha} N_{tag}^{obs,\alpha}\ \varepsilon_{tag,sig}^{\alpha} / \varepsilon_{tag}^{\alpha}}$$



The formula to calculate the branching fraction. α denotes different tag modes, $N_{tag}^{obs,\alpha}$ is the yield of ST events for tag mode α, N_{sig}^{obs} is the observed signal yield, $\varepsilon_{tag}^{\alpha}$ and $\varepsilon_{tag,sig}^{\alpha}$ refer to the ST and DT efficiencies of tag mode α.

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Motivation

- To uncover the nontrivial internal structure of the light scalar mesons, traditional $q\bar{q}$ state, tetra quark system, or etc.
- $R \equiv \frac{B(D^+ \to f_0 l^+ \nu) + B(D^+ \to \sigma l^+ \nu)}{B(D^+ \to a_0 l^+ \nu)}$ provides a model-independent way to understand the classification of the light scalar mesons. R=1(3) if those mesons are traditional qqbar (tetra quark) system. This analysis alone will not get us to the answer, but will provide an anchor for the further understanding of light scalar mesons.

  Phys. Rev. D **82**, 034016 (2010)
- Semileptonic D decays provide a suitable environment
- The first measurement of the two signal channels, $D^0 \to a_0(980)^- e^+ \nu_e$ and $D^+ \to a_0(980)^0 e^+ \nu_e$.

  Phys. Rev. D 92, 054038 (2015)
- With the chiral unitarity approach in coupled channels, the predicted BFs are order of $5(6)\text{x}10^{-5}$ for $D^0(D^+)$

Single tag $\bar{D}^0$ and D^-

- Tag modes

$\bar{D}^0 \to K^+\pi^-$

$\bar{D}^0 \to K^+\pi^-\pi^0$

$\bar{D}^0 \to K^+\pi^-\pi^+\pi^-$

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

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

$D^- \to K_S^0\pi^-$

$D^- \to K_S^0\pi^-\pi^0$

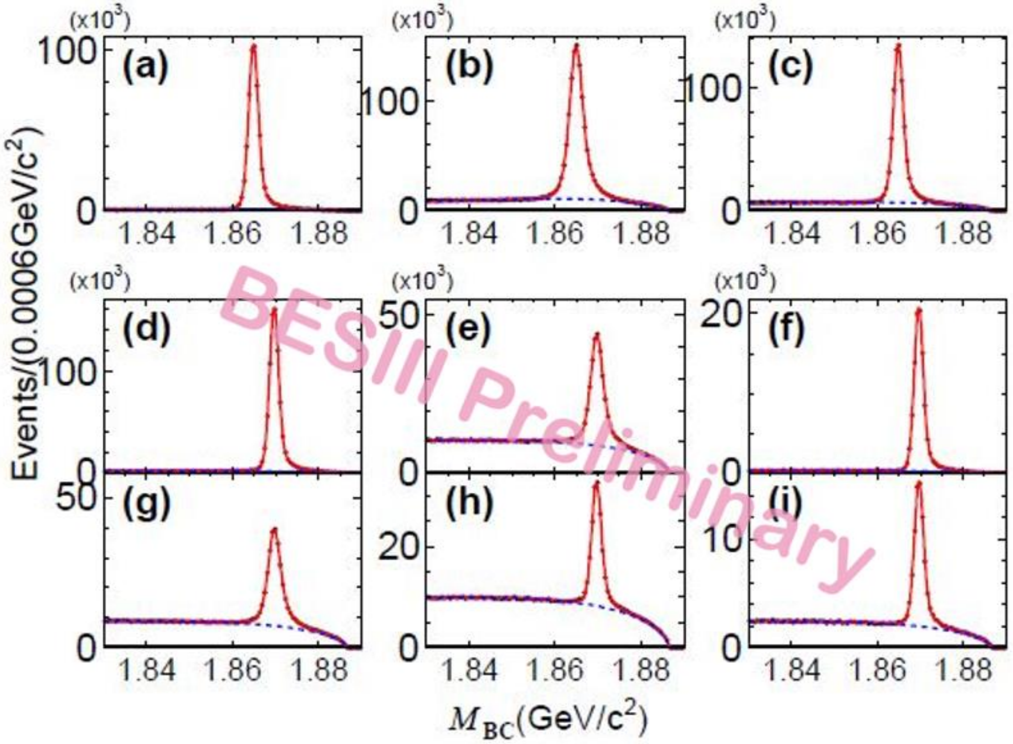
$D^- \to K_S^0\pi^-\pi^+\pi^-$

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

where $K_S^0 \to \pi^+\pi^-$ and $\pi^0 \to \gamma\gamma$. The invariant mass of the daughter $\gamma\gamma$ pair is constrained to the π^0 mass.

*Charge conjugation is implied

M_{BC} distributions and fits of ST samples



M_{BC} distributions of and fits ST samples for different tag modes. The first row shows the $\bar{D}^0$ modes : (a)$K^+\pi^-$, (b)$K^+\pi^-\pi^0$, (c)$K^+\pi^-\pi^+\pi^-$, and the last two rows show the D^- tag modes : (d)$K^+\pi^-\pi^-$, (e)$K^+\pi^-\pi^-\pi^0$, (f)$K_S^0\pi^-$, (g)$K_S^0\pi^-\pi^0$, (h)$K_S^0\pi^-\pi^+\pi^-$, (i)$K^+K^-\pi^-$. **[BESIII Preliminary]**

$$M_{BC} = \sqrt{E_{beam}^2/c^4 - |\vec{p}_D|^2/c^2}$$

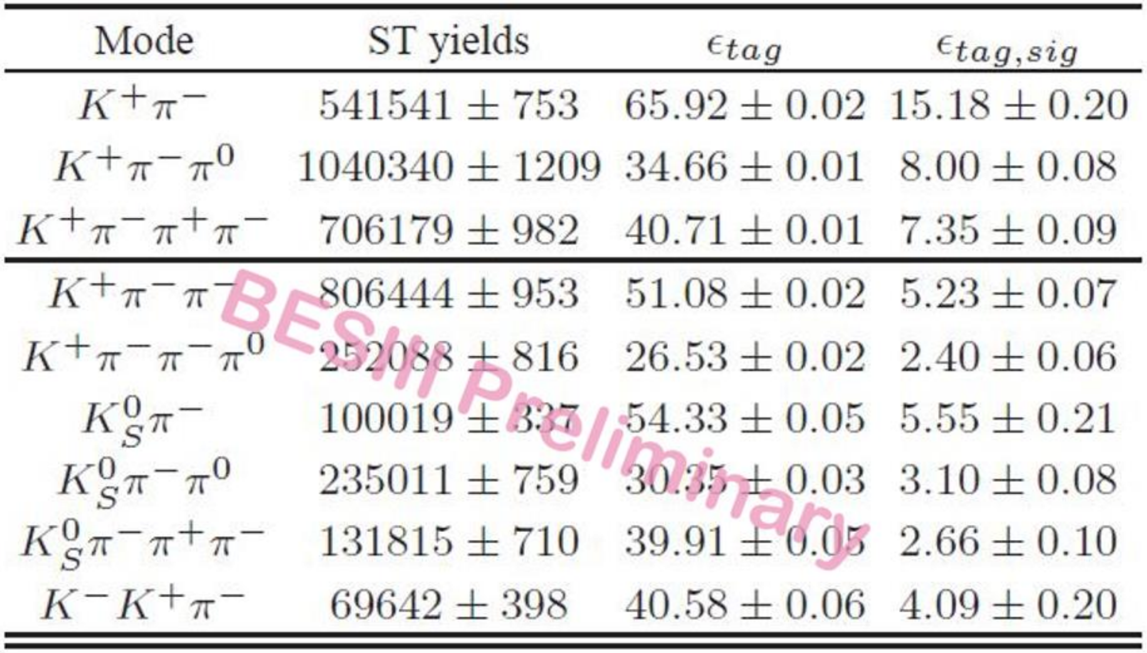
The ST yields are extracted by fitting the M_{BC} distributions. The signal is modeled with truth-matched MC shape convoluted with a Gaussian function, and the background is modeled by an ARGUS function.

$D \to a_0(980)e^+\nu_e$

- Signal candidates are searched in the remainders of the ST
- $a_0(980)$ is reconstructed with the $\eta\pi$ mode
  - $D^0 \to a_0(980)^- e^+\nu_e$, $a_0(980)^- \to \eta\pi^-$,$\eta \to \gamma\gamma$
  - $D^+ \to a_0(980)^0 e^+\nu_e$, $a_0(980)^0 \to \eta\pi^0$,$\eta \to \gamma\gamma$
- Two observables are used to extract the signal yields
  - $\eta\pi$ invariant mass: M($\eta\pi$)
  - U_{miss}: $U \equiv E_{miss} - c|\vec{p}_{miss}|$

    $*E_{miss} = E_{beam} - E_{\eta\pi} - E_e$, $\vec{p}_{miss} = -(\vec{p}_{tag} + \vec{p}_{\eta\pi} + \vec{p}_e)$

ST yields and ST/DT efficiencies



Mode	ST yields	ϵ_{tag}	$\epsilon_{tag,sig}$
$K^+\pi^-$	541541 ± 753	65.92 ± 0.02	15.18 ± 0.20
$K^+\pi^-\pi^0$	1040340 ± 1209	34.66 ± 0.01	8.00 ± 0.08
$K^+\pi^-\pi^+\pi^-$	706179 ± 982	40.71 ± 0.01	7.35 ± 0.09
$K^+\pi^-\pi^-$	806444 ± 953	51.08 ± 0.02	5.23 ± 0.07
$K^+\pi^-\pi^-\pi^0$	252088 ± 816	26.53 ± 0.02	2.40 ± 0.06
$K^0_S\pi^-$	100019 ± 337	54.33 ± 0.05	5.55 ± 0.21
$K^0_S\pi^-\pi^0$	235011 ± 759	30.35 ± 0.03	3.10 ± 0.08
$K^0_S\pi^-\pi^+\pi^-$	131815 ± 710	39.91 ± 0.05	2.66 ± 0.10
$K^-K^+\pi^-$	69642 ± 398	40.58 ± 0.06	4.09 ± 0.20

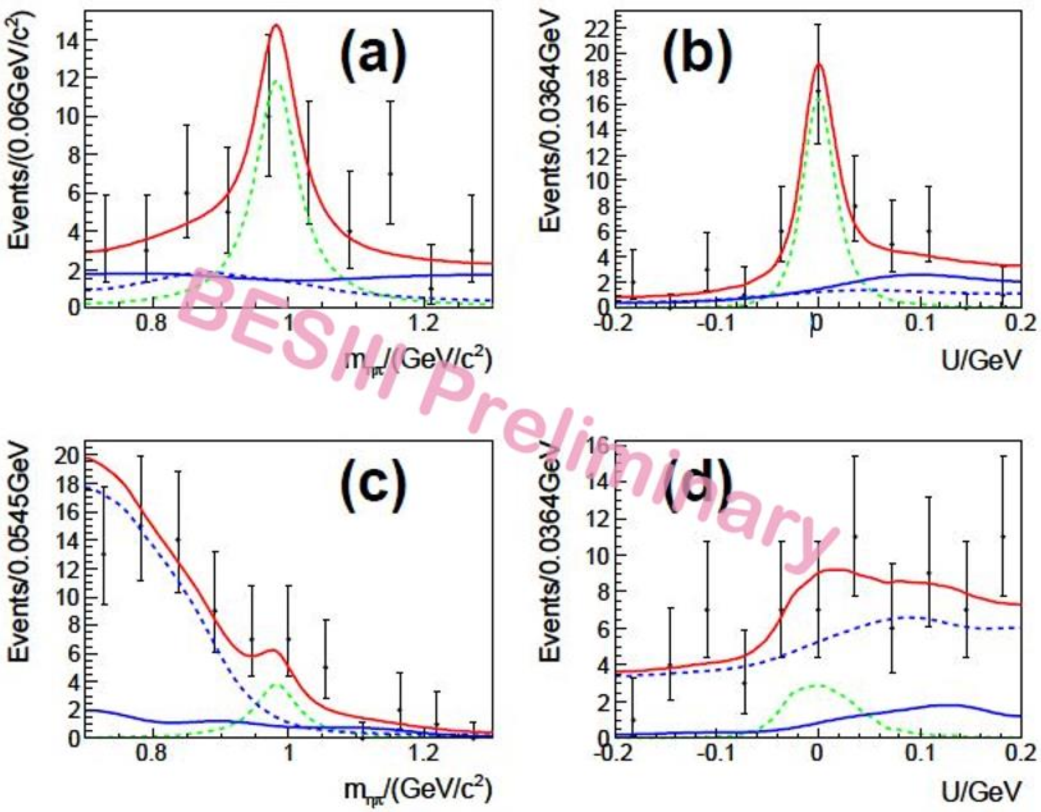
ST data yields, ST efficiencies and DT efficiencies with statistical uncertainties. Branching fractions of K^0_S and π^0 decays are not included in the efficiencies. The first three rows are for $\bar{D}^0$ and the last six rows are for D^-. **[BESIII Preliminary]**

Fitting Procedure

- All the background shapes are fixed based on MC simulation
- Background components:
  - Yields of $D\overline{D}$ background components are fixed by scaling the MC sample to the dataset based on the cross section and luminosity.
  - Yields of the non-$D\overline{D}$ backgrounds (qqbar dominant) are floated.
- Signal shape
  - U is modeled with MC shape
  - M($\eta\pi$) is modeled with a fixed BreitWigner Function.

Fit results

2-D unbinned extended maximum likelihood fits are performed



Projection of data set, the fit results and backgrounds on (left) $M_{\eta\pi}$ and (right) U for (top) $D^0 \to a_0(980)^- e^+ \nu_e$and (bottom) $D^+ \to a_0(980)^0 e^+ \nu_e$.

[BESIII Preliminary]

Fit results of D^0 Mode (a)(b) and D^+ Mode (c)(d).

Points with error are data. The red curves are the total fit. The dashed blue lines refer to the fixed $D\overline{D}$ backgrounds and the solid blue lines are the non-$D\overline{D}$ backgrounds. The dashed green lines are the fitted signal contributions.

Systematic Uncertainties

- The estimated total systematic uncertainty would be ~9%(relative) for both D^0 and D^+ cases, while their statistical uncertainties are ~26(45)% for $D^0(D^+)$.
- The systematic uncertainties are dominated by two sources:
    - Model of form factor: Form factor parameterizations by Becirevic and Kaidalov[6] is used as the nominal model, and we input ISGW2 model as a conservative treatment to estimate the corresponding uncertainty.
    - $a_0(980)$ line shape: The mass and width of $a_0(980)$ are poorly measured. We use the parameters measured by Belle Collaboration* as the nominal one and shift one times deviation of the mass and width in the nominal fit to estimate the corresponding uncertainty.

*Phys. Rev. D **80**, 032001 (2009)

Preliminary Results 1

- First observation of $D^0 \rightarrow a_0(980)^- e^+ \nu_e$ and evidence for $D^+ \rightarrow a_0(980)^0 e^+ \nu_e$.

Signal significance

- $B(D^0 \rightarrow a_0(980)^- e^+ \nu_e) \times B(a_0(980)^- \rightarrow \eta\pi^-)$

$$= (1.12^{+0.31}_{-0.28}(stat) \pm 0.10(syst)) \times 10^{-4}$$

5.9σ

- $B(D^+ \rightarrow a_0(980)^0 e^+ \nu_e) \times B(a_0(980)^0 \rightarrow \eta\pi^0)$

$$= (1.47^{+0.73}_{-0.59}(stat) \pm 0.14(syst)) \times 10^{-4}$$

3.0σ

*The branching fraction of $a_0(980)$ decay is not well measured, so the product branching fraction is presented here.

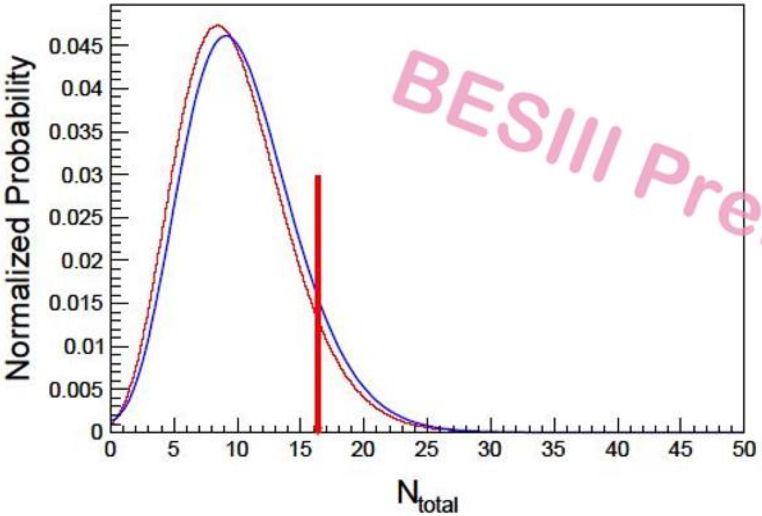
*The signal significance is taken to be $\sqrt{-2\ln(L_0/L_{best})}$,where L_{best} and L_0 are the maximum likelihood values with signal yields floated and fixed to 0.

Preliminary Results 2

- An upper limit on the branching fraction of the D+ mode is also set by scanning the likelihood distribution, considering the limited significance

- $B(D^+ \to a_0(980)^0 e^+ \nu_e) \times B(a_0(980)^0 \to \eta\pi^0)$

  $< 2.7 \times 10^{-4}$ @ 90% C.L.



The likelihood distributions before and after systematic uncertainties taken into consideration. We have the signal event number as 16.4 at 90% confidence level, as the red arrow shows. **[BESIII Preliminary]**

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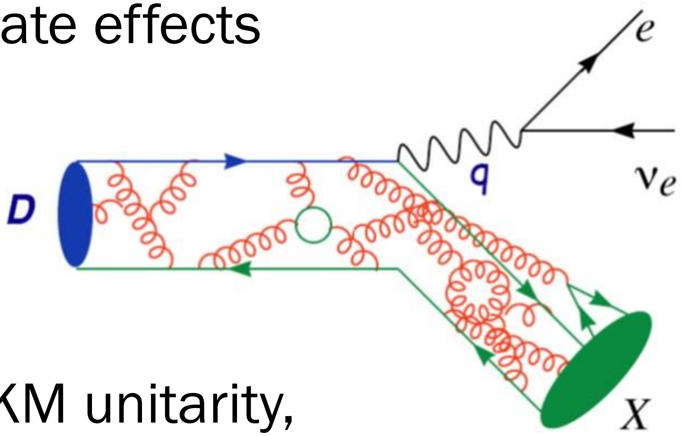
Motivation

- Decay rate depends on kinematics and V_{CKM}
- Form factor encapsulates QCD bound-state effects
- $\frac{d\Gamma}{dq^2} = \frac{G_F^2}{24\pi^3}|V_{cx}|^2 p_X^3 |f_+(q^2)|^2$
- Precise measurement of $|V_{cx}| \times f_+(q^2)$ can help to extract form factor as a test of Lattice QCD by getting the V_{cx} from CKM unitarity, or reverse the logic to test the CKM unitarity



- Form factor parameterizations:

>Single pole model

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

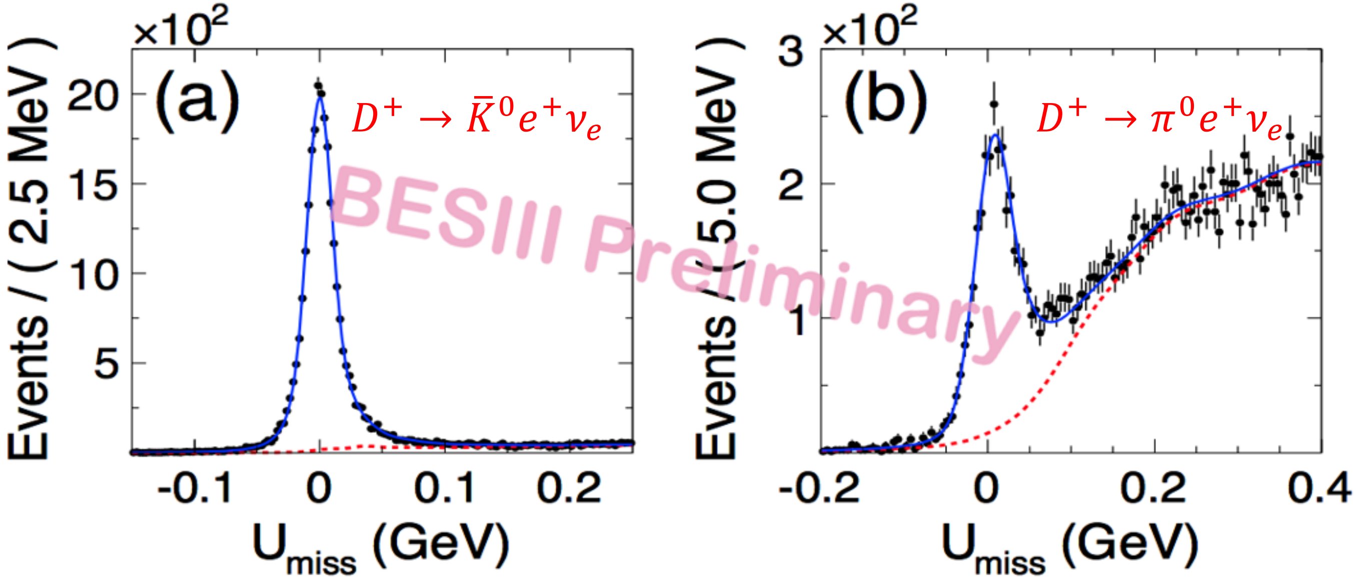
>Modified pole model

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

>Series expansion model

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

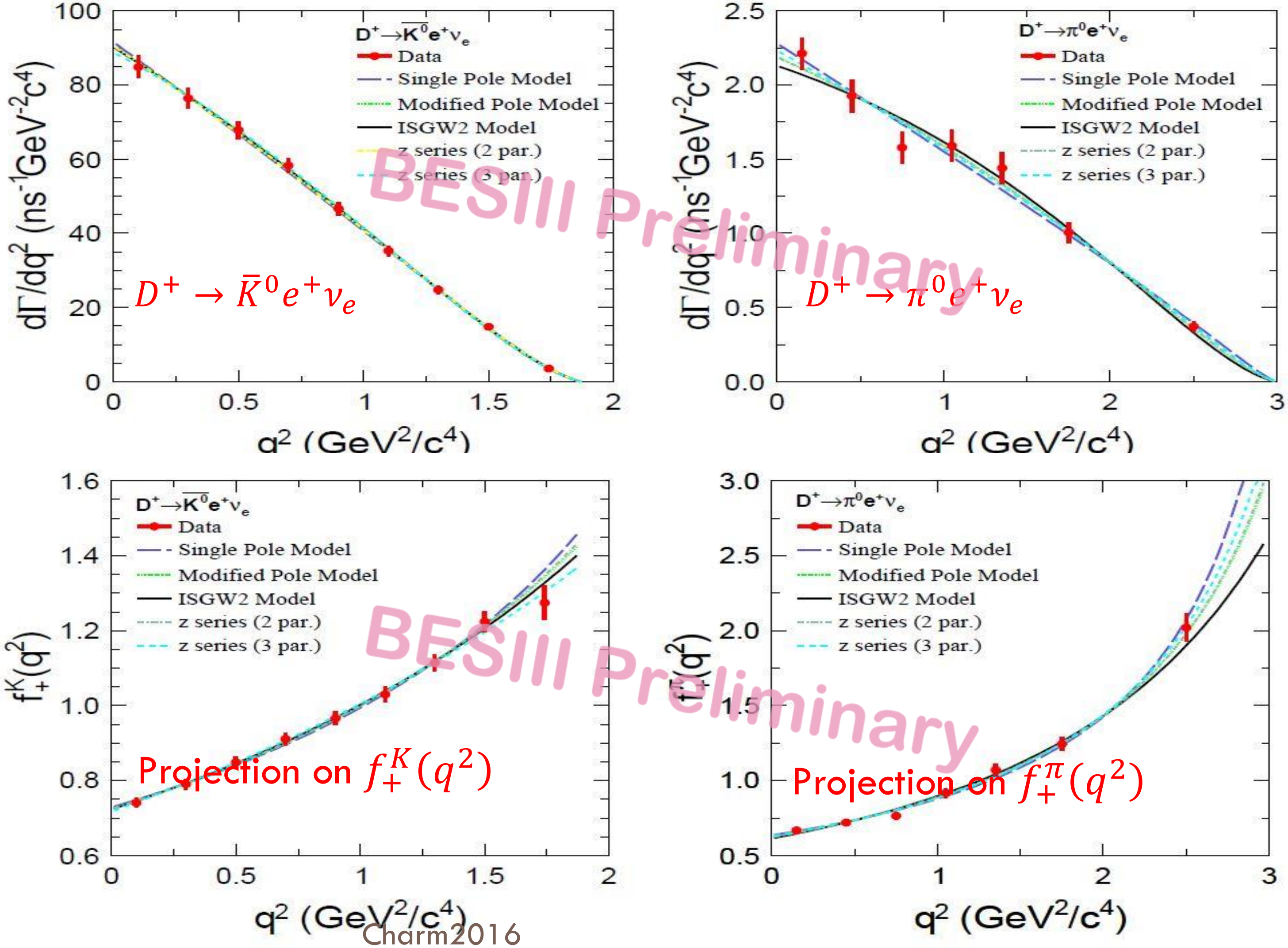
Absolute Branching Fraction



$$B(D^+ \to \bar{K}^0 e^+ \nu_e) = (8.604 \pm 0.056 \pm 0.151)\%$$

$$B(D^+ \to \pi^0 e^+ \nu_e) = (3.631 \pm 0.075 \pm 0.051) \times 10^{-3}$$

Differential Decay Rate $d\Gamma/dq^2$



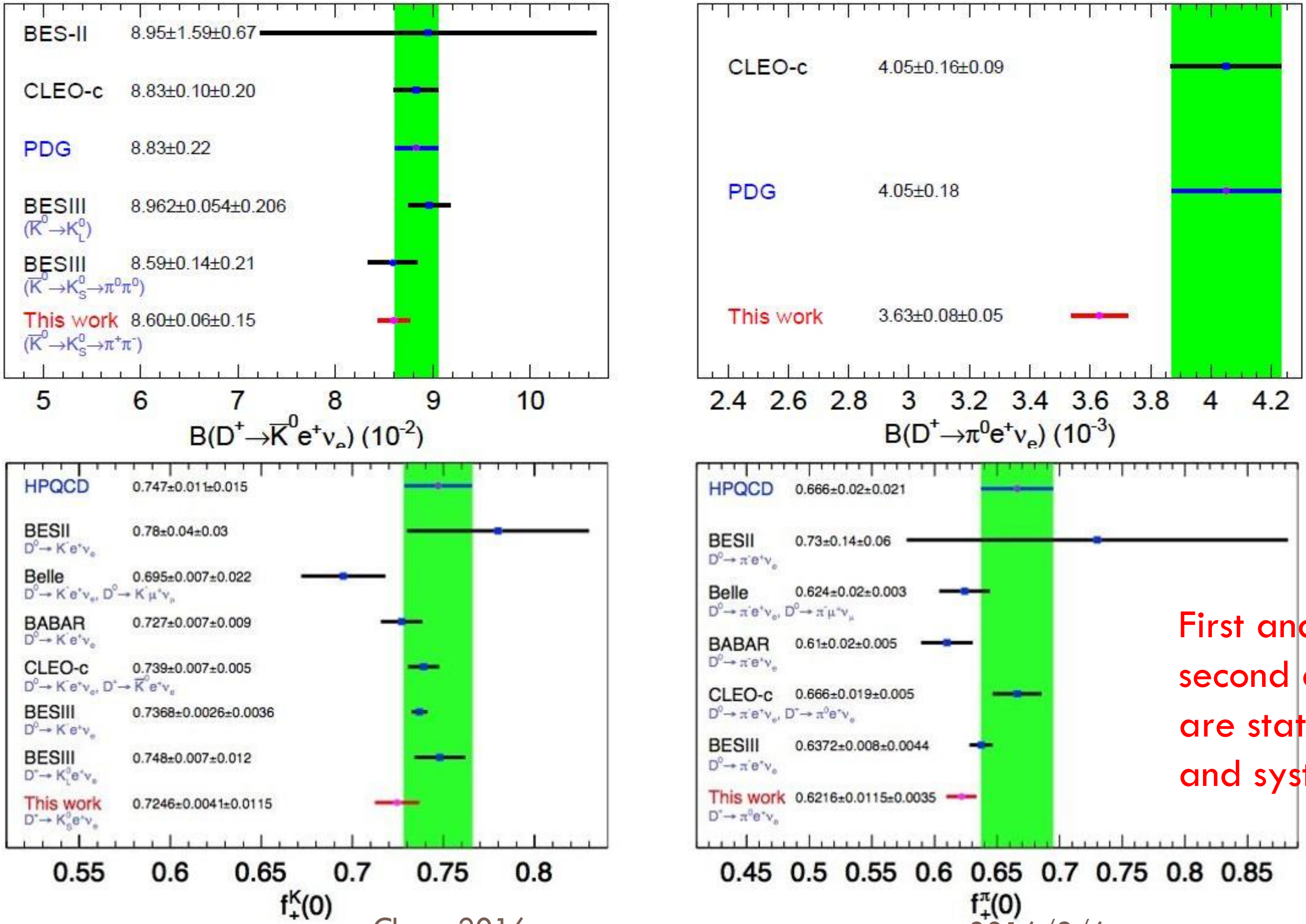
$D^+ \to \bar{K}^0 e^+ \nu_e$

$D^+ \to \pi^0 e^+ \nu_e$

Projection on $f_+^K(q^2)$

Projection on $f_+^\pi(q^2)$

Comparisons of BFs and FFs



First and second errors are statistical and systematic

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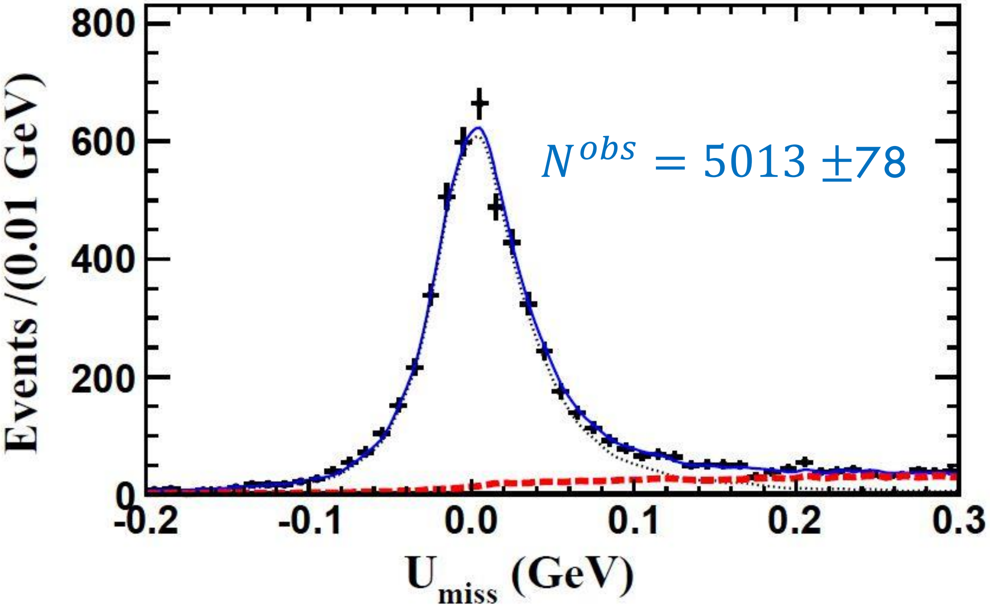
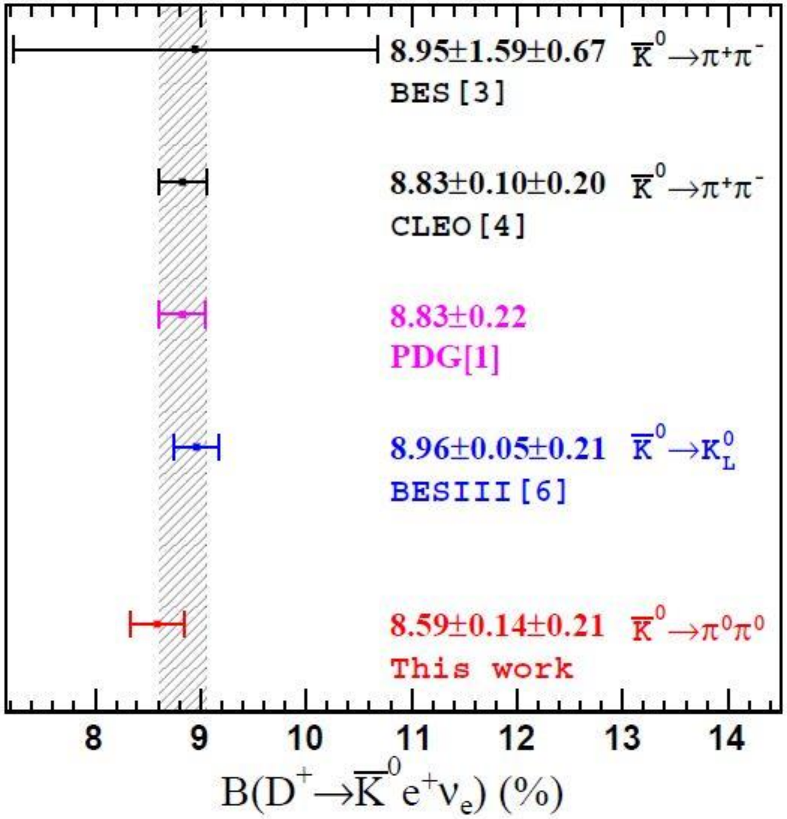


$N^{obs} = 5013 \pm 78$



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

Comparison of the result in this work with those from the other experiments.

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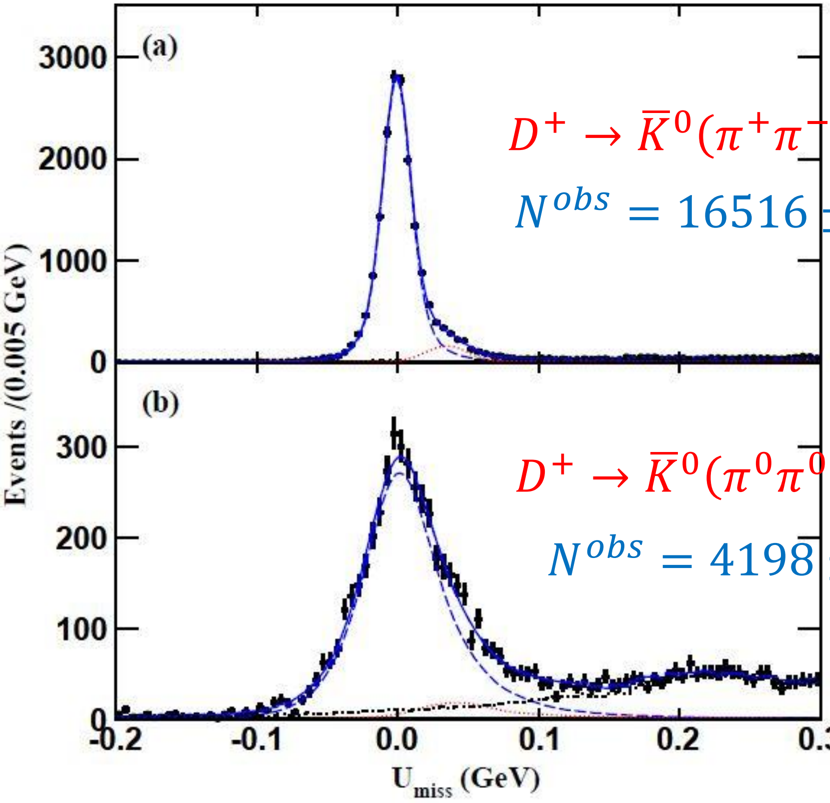

$D^+ \to \bar{K}^0(\pi^+\pi^-)\mu^+\nu_\mu$

$N^{obs} = 16516 \pm 130$

$D^+ \to \bar{K}^0(\pi^0\pi^0)\mu^+\nu_\mu$

$N^{obs} = 4198 \pm 33$

Simultaneous fits on the two Umiss distributions (different Ks decay modes) are performed to extract the signal yields. All shapes are extracted from MC simulations.

Dots with error are data, the blue solid curves are the best fits, blue dashed lines are signals, red dotted lines are $D^+ \to \bar{K}^0\pi^+\pi^0$ peaking backgrounds, and the black dot-dashed curves are from other backgrounds

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

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Summary

- With 2.93fb^{-1} data collected at 3.773GeV, we can approach the rare semileptonic D decays, as well as perform some precise measurements
- More results will come out in the future
- With about 3fb^{-1} data collected at 4.180GeV this year, D_S^+ analysis is on the way

Thanks