Charm Physics at BESIII

Bai-Cian Ke
Shanxi Normal University

NCTS Dark Physics Workshop
01/09-01/11/2020, NTHU, Hsinchu

Outline

- Introduction
  - D^0, D^+,and D_s dataset
  - DTag and branching fraction
- Measurement of D (semi)leptonic decays
- Measurement of D hadronic decays
- Amplitude analysis
  - KK/ππ ev, $K^-\pi^+\pi^+\pi^-$, $K_S\pi^+\pi^+\pi^-$, $K^-\pi^+\pi^0\pi^0$, $\pi^+\pi^0\eta$ etc.
- Summary

BESIII Data Taken near DD^{bar} Threshold

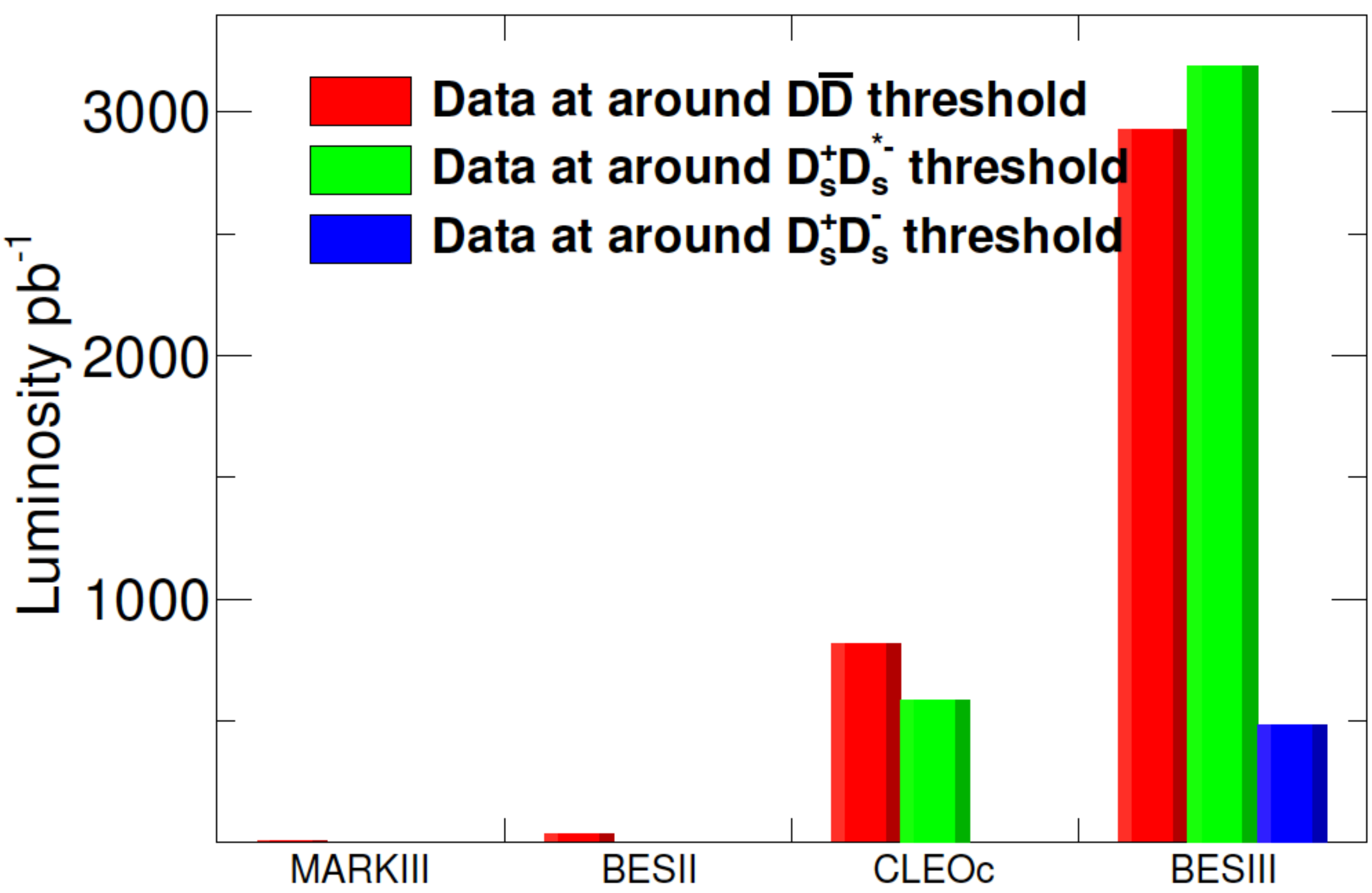
- BEPCII collider: $e^+e^- \to \psi(3770) \to DD^{bar}$
- 2.9 fb^{-1} dataset at $\psi(3770)$ resonance (~3.6x larger than CLEO's)

  M_{D0}= 1864.84 MeV M_{D+}= 1869.62 MeV

  $2M_{D0}$= 3729.68 MeV $2M_{D+}$= 3739.24 MeV

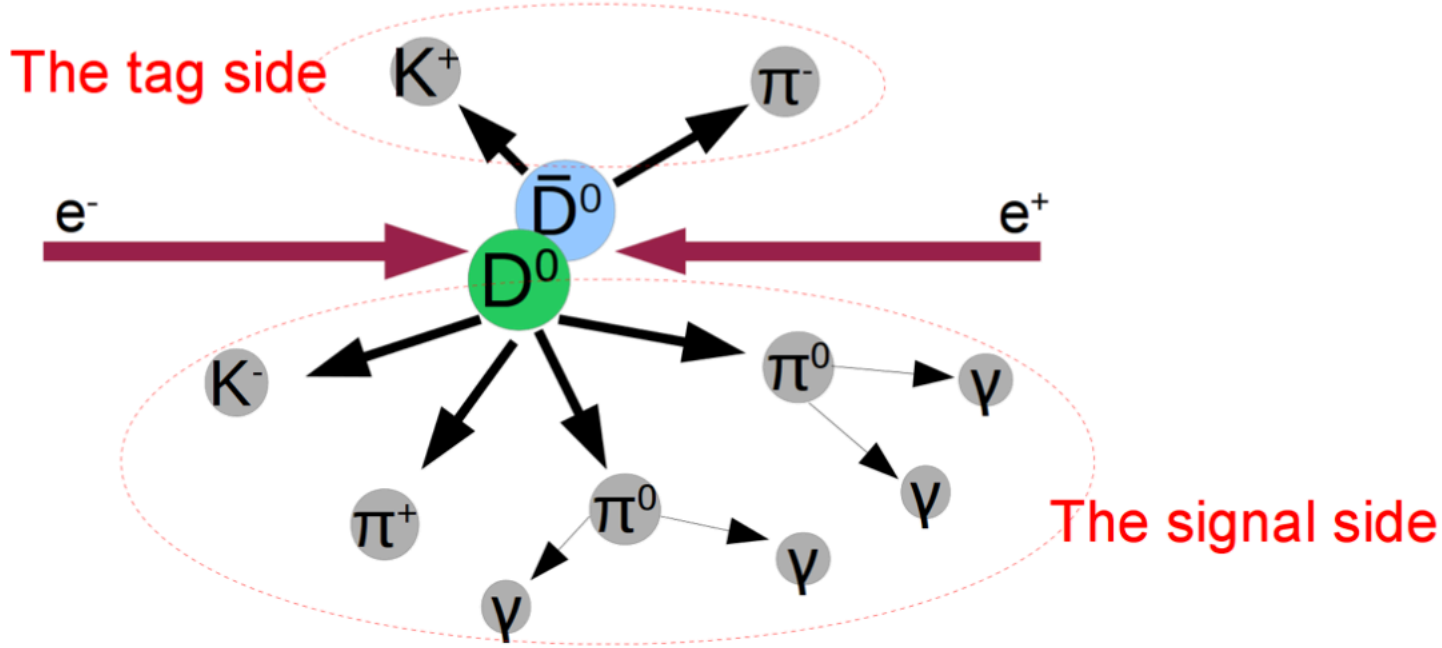
- 3.19 fb^{-1} dataset at E_{cm} 4.178GeV (~5.3x larger than CLEO's)
  - D_s are produced mostly via $e^+e^- \to D_sD_s^*$
  - more energy points are ready (4.190, 4.200, 4.210, 4.220.4.230 GeV. Total are about 0.8x of 4.178 data.)
- Advantages of DD^{bar} pair production near threshold
  - Clean; not enough energy for even one additional pion
  - Tagging reduces background
  - Double tag technique can provide access to absolute BFs
  - Many systematic uncertainties cancel with tagging technique
  - With fully reconstructed tracks, neutrino information can be accessed via missing energy and momentum

Experiments at Charm factories

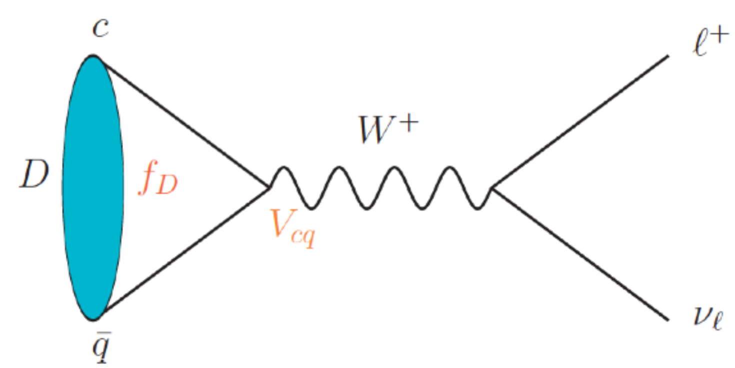


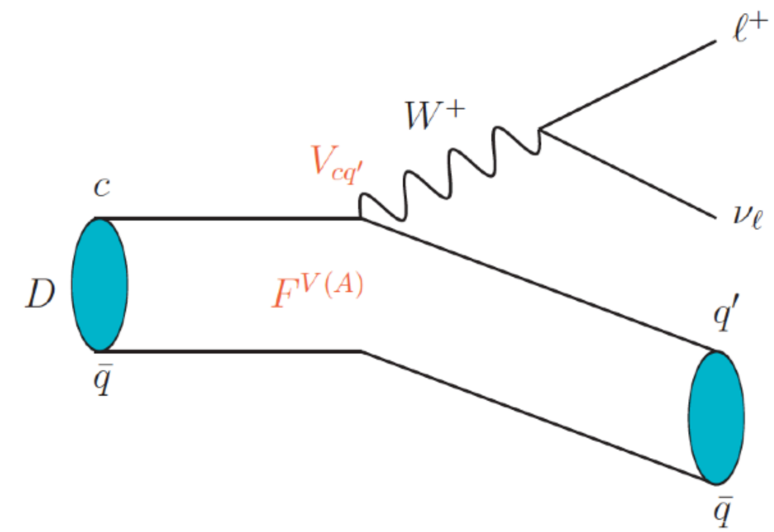
DTag Technique

- There are two types of samples used in the Dtag technique: single tag (ST) and double tag (DT).
- Single tag: only one D meson is reconstructed through a chosen hadronic decay.
- Double tag: both D and $\bar{D}$ are reconstructed,
- the D reconstructed through the studied hadronic decay is called “the signal side”.
- the $\bar{D}$ reconstructed through well-known and clean hadronic decay modes is called “the tag side”.
- (Charge-conjugate states are implied throughout this talk.)



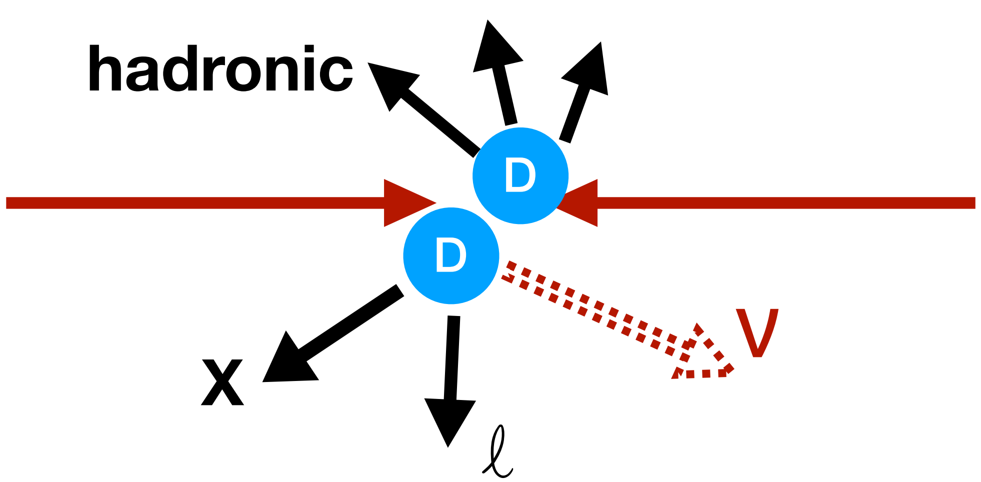
Measurements of D (semi)leptonic decays





(semi)leptonic decays provide a clearer view than hadronic decays

- Test the unitarity of quark mixing matrix and search for new physics.
- Test the theoretical calculation on decay constants and form factors, especially LQCD.
- Test the lepton avor universality.
- Help to understand the internal structure of light scalar mesons.

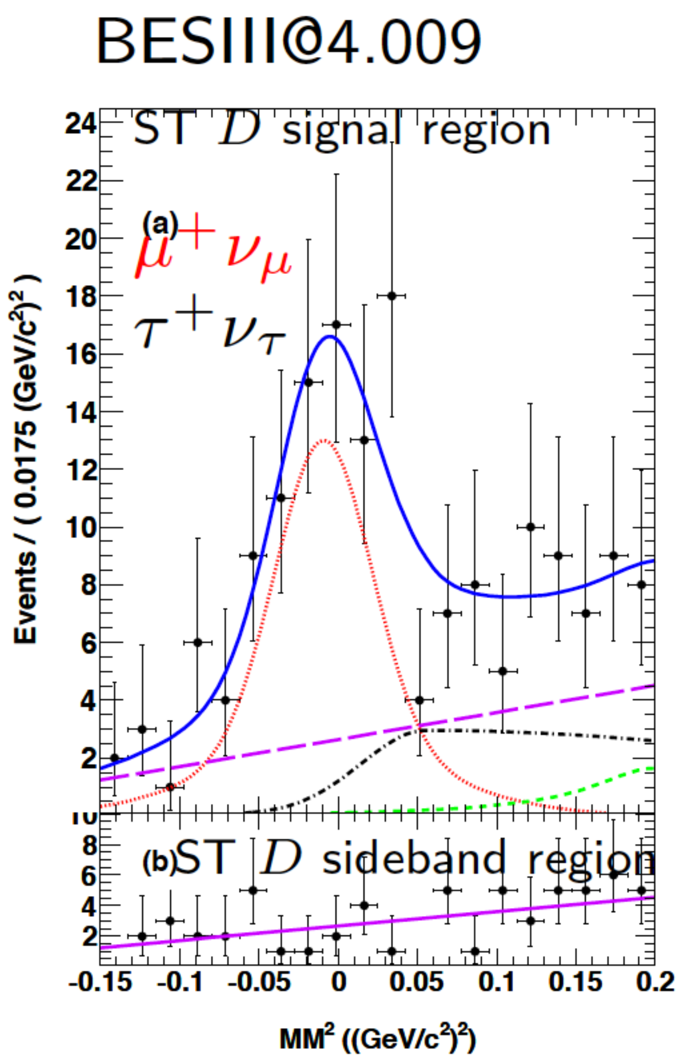


$$U_{\rm miss} = E_{\rm miss} - |\vec{p}|_{\rm miss}$$

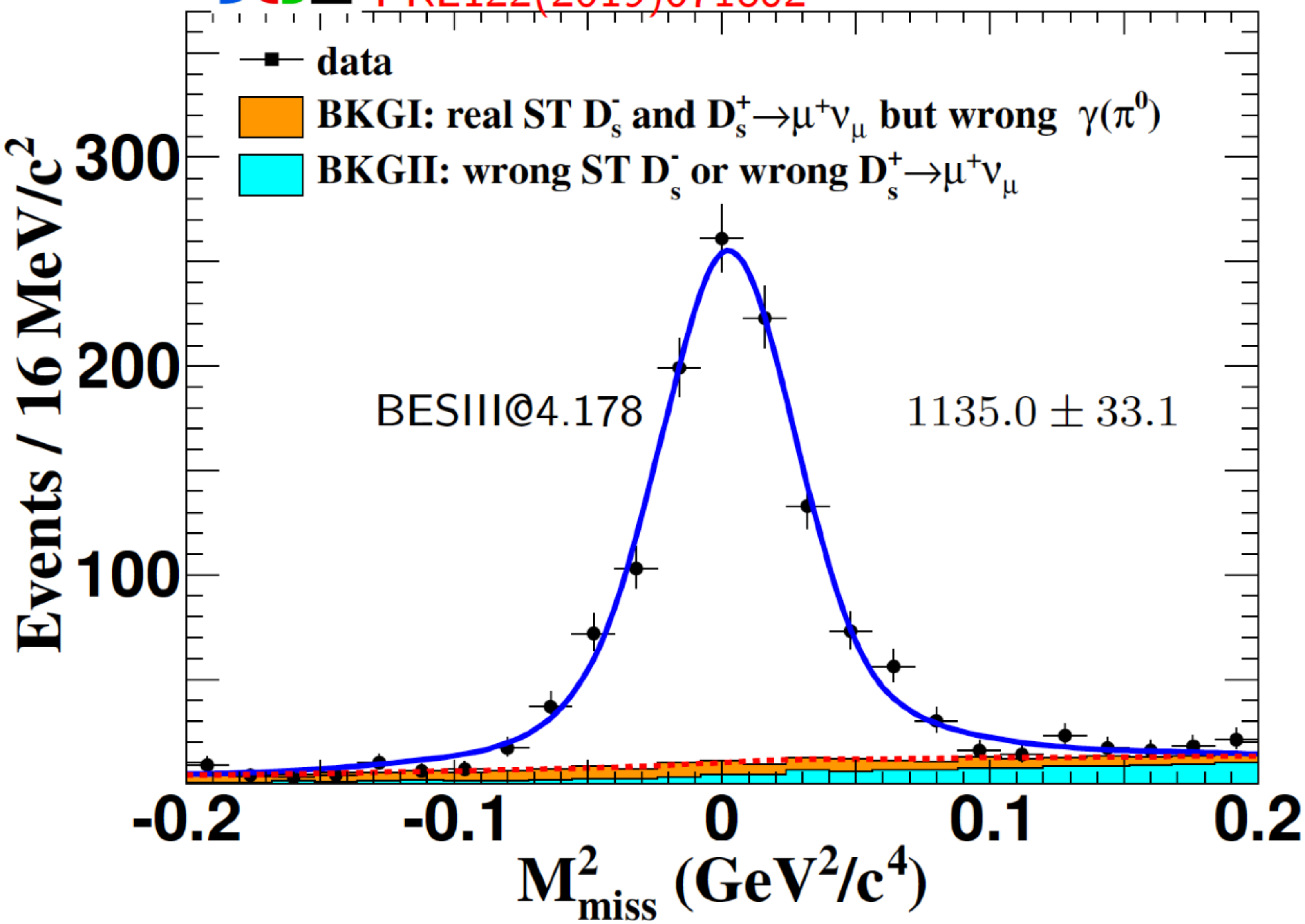
$$M^2_{\rm miss} = E^2_{\rm miss} - |\vec{p}|^2_{\rm miss}$$

D_s pure leptonic decays

BESIII PRD94(2016)072004



BESIII PRL122(2019)071802



$\mathcal{B}(D_s^+\to\mu^+\nu_\mu)=(5.17\pm0.75\pm0.21)\times10^{-3}$

$\mathcal{B}(D_s^+\to\tau^+\nu_\tau)=(3.28\pm1.83\pm0.37)\%$

$f_{D_s^+}|V_{cs}|=239\pm17\pm5$ MeV with $\mu^+\nu_\mu$

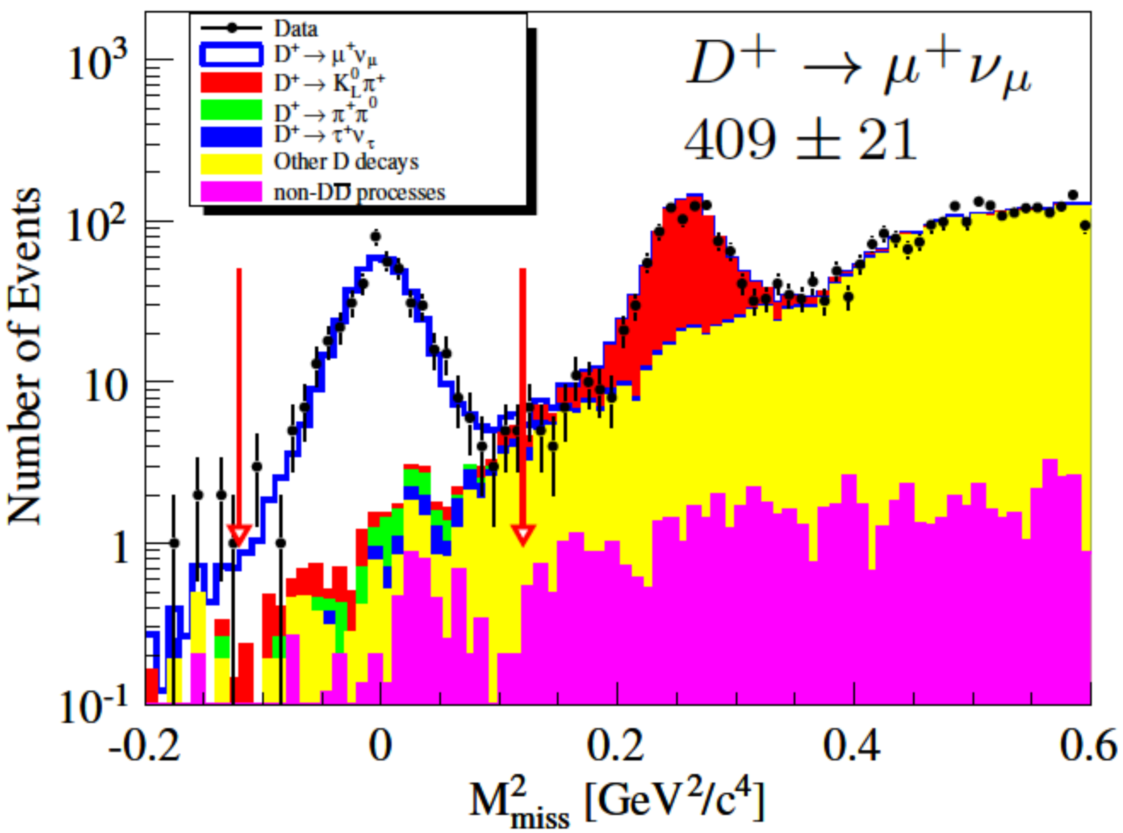
$f_{D_s^+}|V_{cs}|=193\pm54\pm11$ MeV with $\tau^+\nu_\tau$

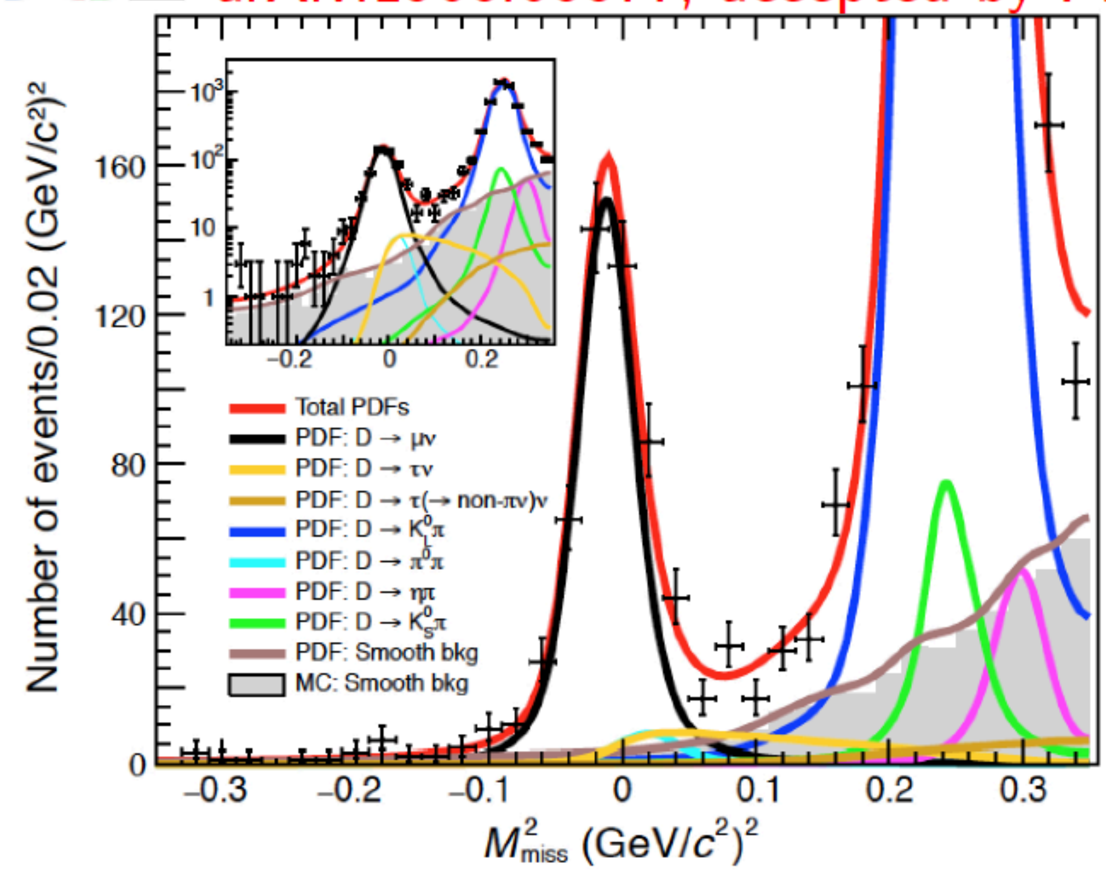
$$\mathcal{B}(D_s^+\to\mu^+\nu_\mu)=(5.49\pm0.16\pm0.15)\times10^{-3}$$

$$f_{D_s^+}|V_{cs}|=246.2\pm3.6\pm3.5$$

$$R_{D_s^+}=\frac{\Gamma(D_s^+\to\tau^+\nu_\tau)}{\Gamma(D_s^+\to\mu^+\nu_\mu)}=10.19\pm0.52$$

D^+ pure leptonic decays





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

$$f_{D^+}|V_{cd}| = 46.7 \pm 1.2 \pm 0.4 \text{ MeV}$$

$$\mathcal{B}(D^+ \to \tau^+\nu_\tau) = (1.20 \pm 0.24 \pm 0.12) \times 10^{-3}$$

$$f_{D^+}|V_{cd}| = 50.4 \pm 5.1 \pm 2.5 \text{ MeV}$$

First observation with 5.1σ signal significance.

$$R_{D^+} = \frac{\Gamma(D^+ \to \tau^+\nu_\tau)}{\Gamma(D^+ \to \mu^+\nu_\mu)} = 3.21 \pm 0.64 \pm 0.43$$

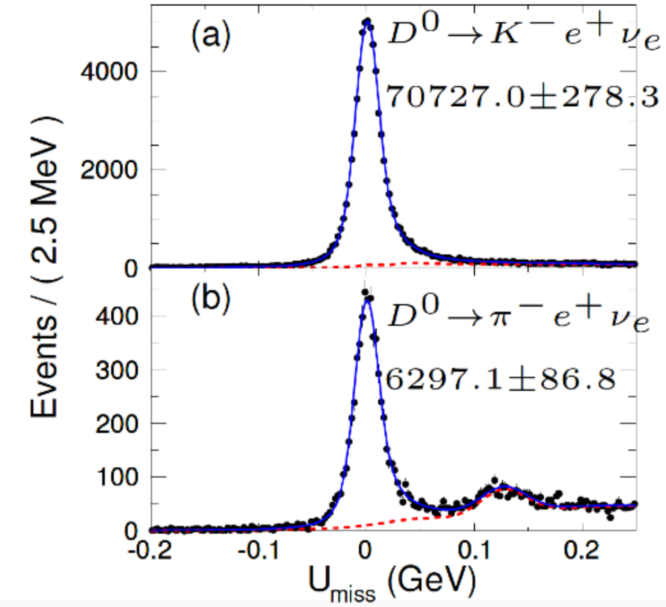
SM prediction 2.67 ± 0.01.

$D_{(s)}$ semileptonic decays

PRD92(2015)072012

$$B(D^0 \to K^- e^+ \nu_e) = (3.505 \pm 0.014 \pm 0.033)\,\%$$
$$f_+^{D\to K}(0)\,|V_{cs}| = 0.7172 \pm 0.0025 \pm 0.0035$$

$$B(D^0 \to \pi^- e^+ \nu_e) = (0.295 \pm 0.004 \pm 0.003)\,\%$$
$$f_+^{D\to \pi}(0)\,|V_{cd}| = 0.1435 \pm 0.0018 \pm 0.0009$$

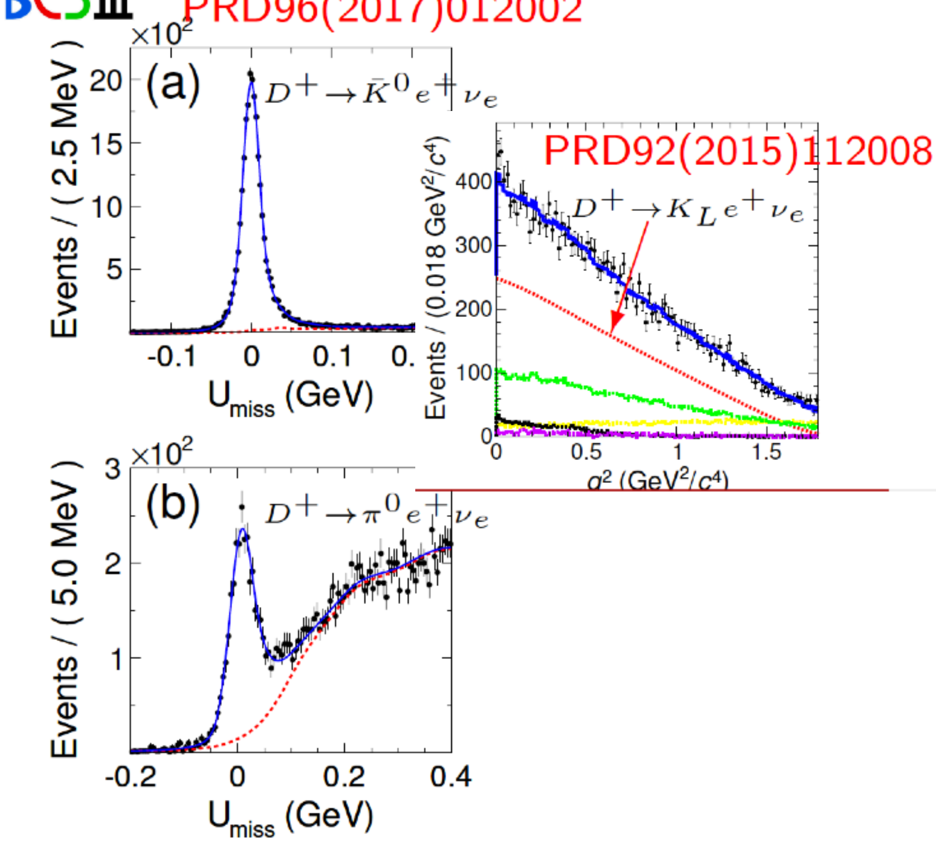


PRD96(2017)012002

$$B(D^+ \to \bar{K}^0 e^+ \nu_e)(\textbf{via } K_S^0) = (8.60 \pm 0.06 \pm 0.15)\,\%$$
$$f_+^{D\to K}(0)\,|V_{cs}| = 0.7053 \pm 0.0040 \pm 0.0112$$

$$B(D^+ \to \pi^0 e^+ \nu_e) = (0.363 \pm 0.008 \pm 0.005)\,\%$$
$$f_+^{D\to \pi}(0)\,|V_{cd}| = 0.1400 \pm 0.0026 \pm 0.0007$$

$$B(D^+ \to \bar{K}^0 e^+ \nu_e)(\textbf{via } K_L^0) = (8.962 \pm 0.054 \pm 0.206)\,\%$$
$$f_+^{D\to K}(0)\,|V_{cs}| = 0.728 \pm 0.006 \pm 0.011$$



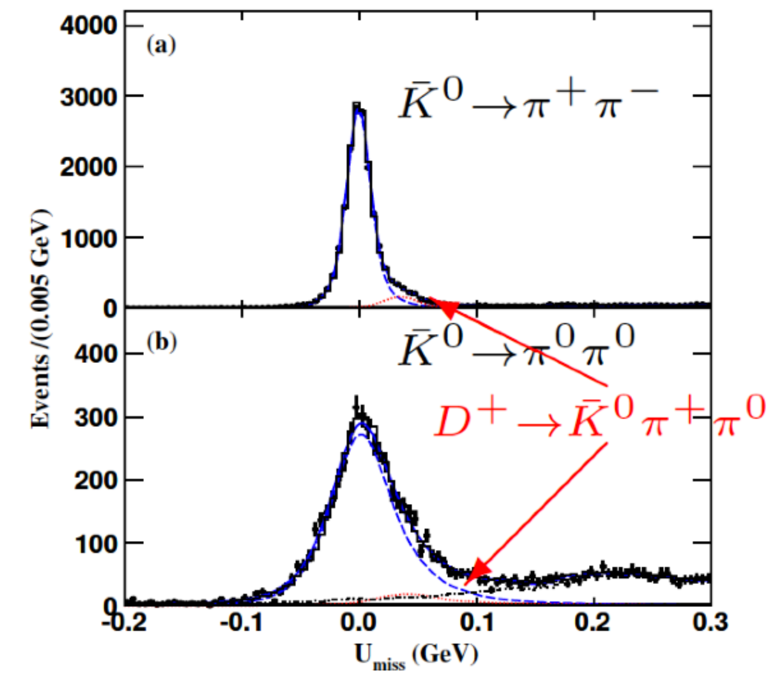
$D_{(s)}$ semileptonic decays

$$B(D^0 \to K^-\mu^+\nu_\mu) = (3.431 \pm 0.019 \pm 0.035)\,\%$$

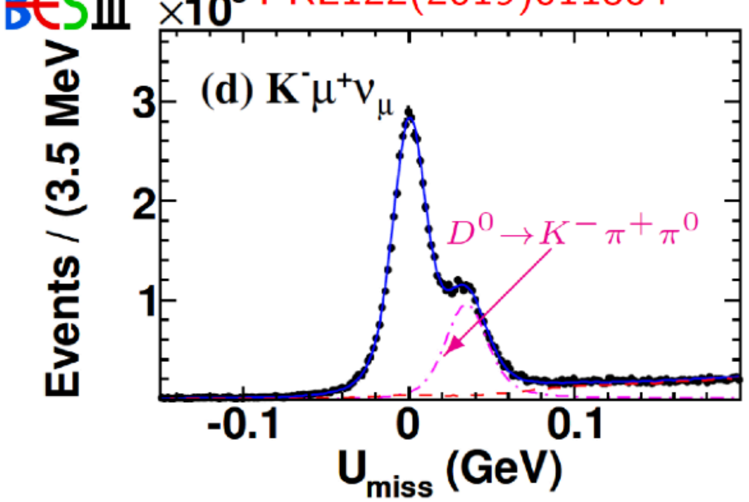
$$f_+^{D\to K}(0)\,|V_{cs}| = 0.7133 \pm 0.0038 \pm 0.0030$$

$$B(D^+ \to K^0\mu^+\nu_\mu) = (8.72 \pm 0.07 \pm 0.18)\,\%$$

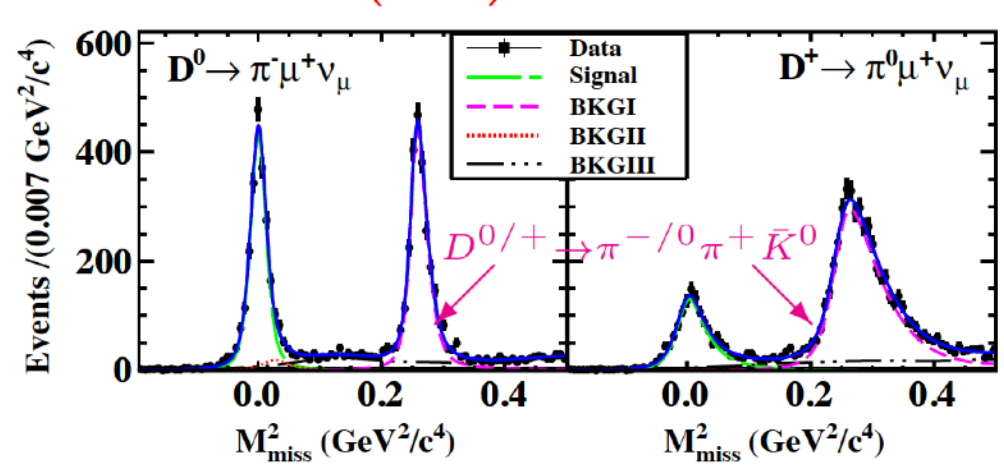
BESIII EPJC76(2016)369



BESIII PRL122(2019)011804



BESIII PRL121(2018)171803



$$B(D^0 \to \pi^-\mu^+\nu_\mu) = (0.272 \pm 0.008 \pm 0.006)\,\%$$

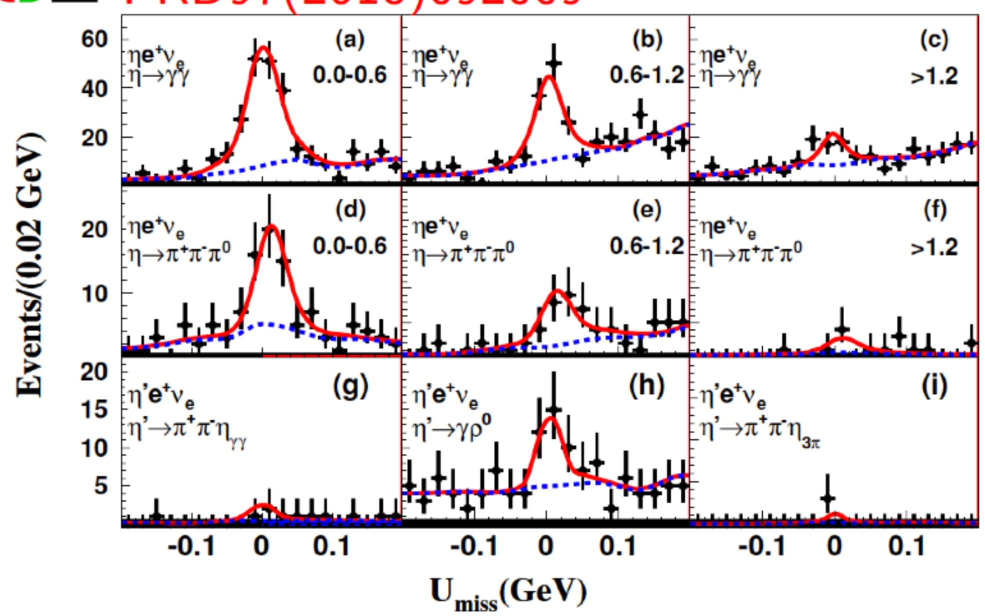
$$B(D^+ \to \pi^0\mu^+\nu_\mu) = (0.350 \pm 0.011 \pm 0.010)\,\%$$

$D_{(s)}$ semileptonic decays

$$B(D^+ \to \eta e^+ \nu_e) = (10.74 \pm 0.81 \pm 0.51) \times 10^{-4}$$

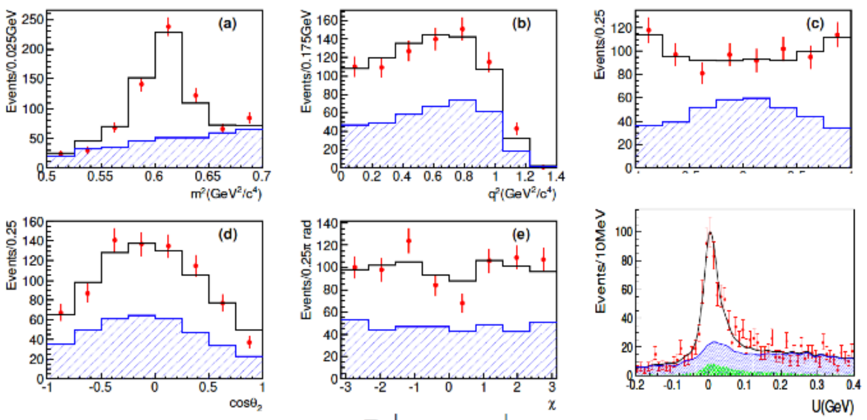
$$B(D^+ \to \eta' e^+ \nu_e) = (1.91 \pm 0.51 \pm 0.13) \times 10^{-4}$$

PRD97(2018)092009



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

PRD92(2015)071101



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

Measurements of D hadronic decays

Observation of the Singly Cabibbo-Suppressed Decay $D^+ \to \omega\pi^+$ and Evidence for $D^0 \to \omega\pi^0$

Chose six (five) decay modes for $D^{+(0)}$.

In order to have a better solution for $D^{+(0)} \to \pi^+\pi^-\pi^0\pi^{+(0)}$ background, DT samples $D^{+(0)} \to \pi^+\pi^-\pi^0\pi^{+(0)}$ vs. tag modes are reconstructed first. Then fits to $\pi^+\pi^-\pi^0$ mass are performed.

Note that we are searching for $\omega \to \pi^+\pi^-\pi^0$.

$$\mathcal{B}_{\rm sig} = \frac{\sum_\alpha N^{{\rm obs},\alpha}_{\rm sig}}{\sum_\alpha N^{{\rm obs},\alpha}_{\rm tag}\,\epsilon^{\alpha}_{\rm tag,sig}/\epsilon^{\alpha}_{\rm tag}}$$

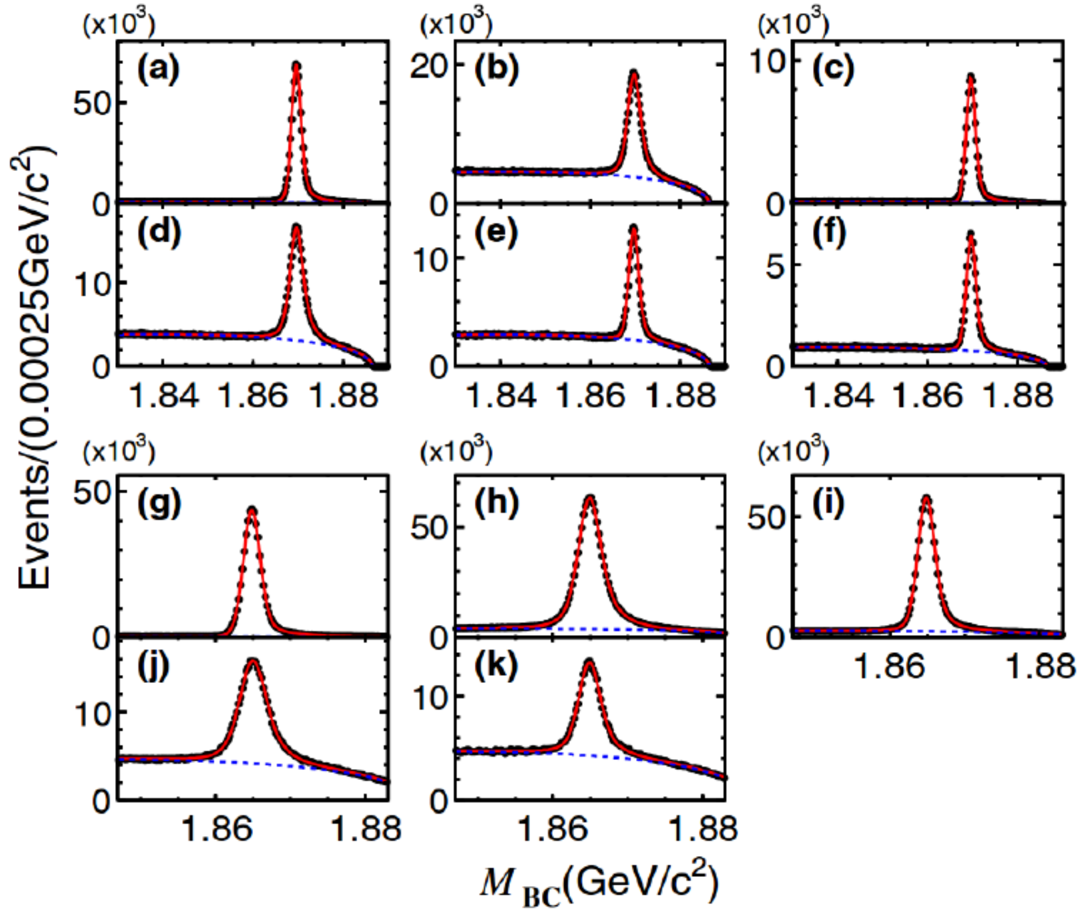


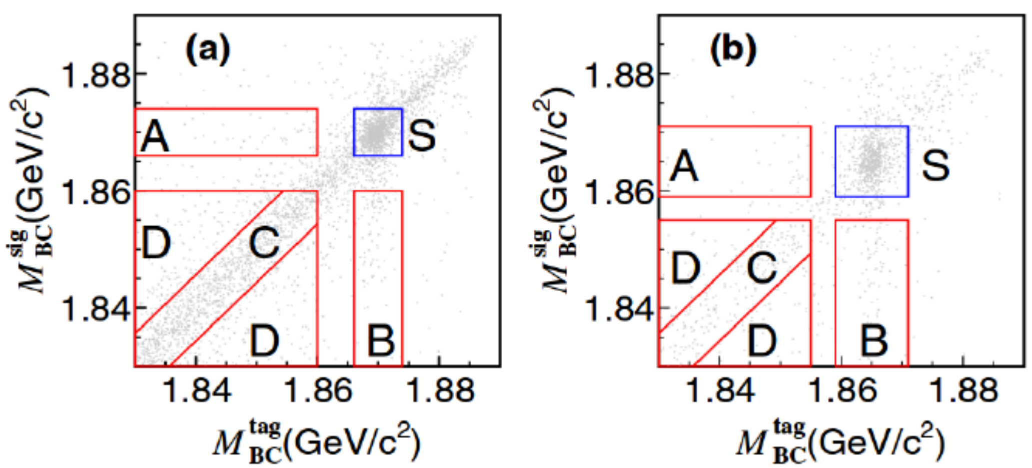
FIG. 1. $M_{\rm BC}$ distributions of ST samples for different tag modes. The first two rows show charged D decays: (a) $K^+\pi^-\pi^-$, (b) $K^+\pi^-\pi^-\pi^0$, (c) $K^0_S\pi^-$, (d) $K^0_S\pi^-\pi^0$, (e) $K^0_S\pi^+\pi^-\pi^-$, (f) $K^+K^-\pi^-$, the latter two rows show neutral D decays: (g) $K^+\pi^-$, (h) $K^+\pi^-\pi^0$, (i) $K^+\pi^-\pi^+\pi^-$, (j) $K^+\pi^-\pi^0\pi^0$, (k) $K^+\pi^-\pi^+\pi^-\pi^0$. Data are shown as points, the (red) solid lines are the total fits and the (blue) dashed lines are the background shapes. D and $\bar{D}$ candidates are combined.

DT $D^{+(0)} \to \pi^+\pi^-\pi^0\pi^{+(0)}$ vs. tag modes

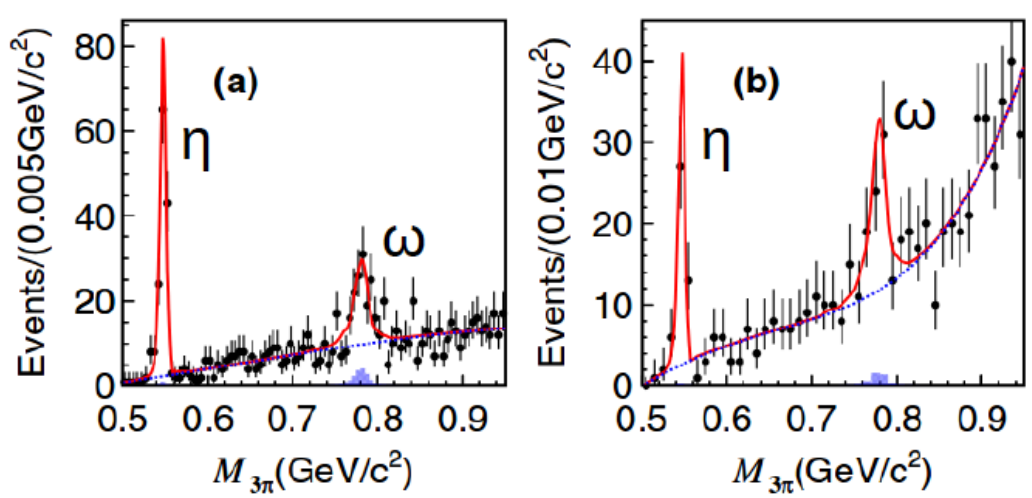
Fits to $M3\pi$ distributions of signal and sideband regions to obtain the signal and peaking background yields, respectively.

Events counts in sidebands are projected into the signal region with scale factors.

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



ModeH	$N_{\omega(\eta)}$	$N^{bkg}_{\omega(\eta)}$	N^{obs}_{sig}
$D^+ \to \omega\pi^+$	100 ± 16	21 ± 4	79 ± 16
$D^0 \to \omega\pi^0$	50 ± 12	5 ± 5	45 ± 13
$D^+ \to \eta\pi^+$	264 ± 17	6 ± 2	258 ± 18
$D^0 \to \eta\pi^0$	78 ± 10	3 ± 2	75 ± 10



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.
$D^+ \to \eta\pi^+$	$(3.07 \pm 0.22 \pm 0.13) \times 10^{-3}$	$(3.53 \pm 0.21) \times 10^{-3}$
$D^0 \to \eta\pi^0$	$(0.65 \pm 0.09 \pm 0.04) \times 10^{-3}$	$(0.68 \pm 0.07) \times 10^{-3}$

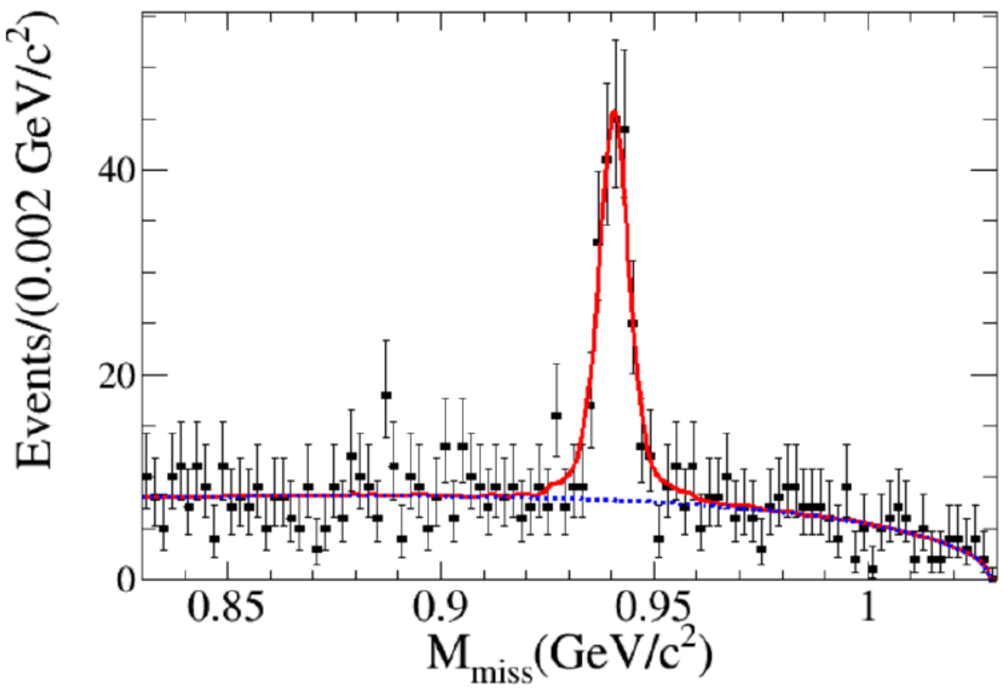
Red line: total fit

Blue line: background

Hatched histogram:
peaking background
From sidebands

PRL **116,** 082001 (2016)

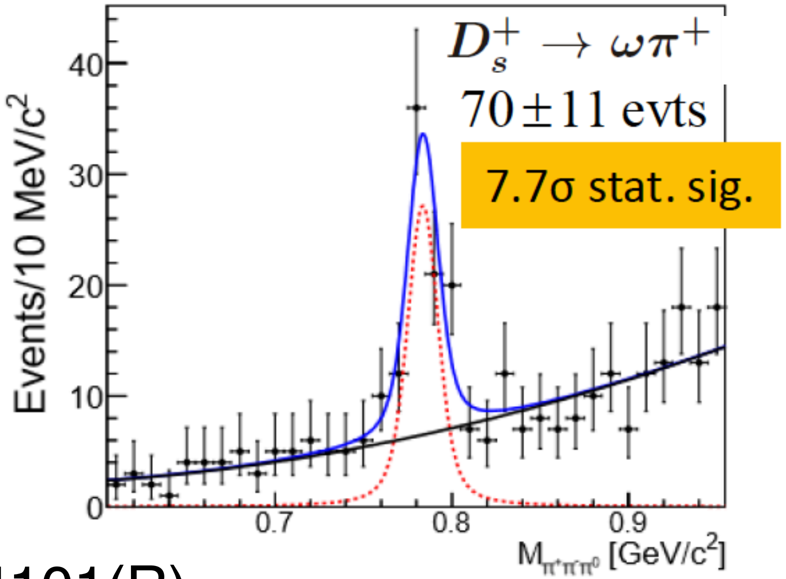
Measurements of pure W-annihilation decays in D_s^+

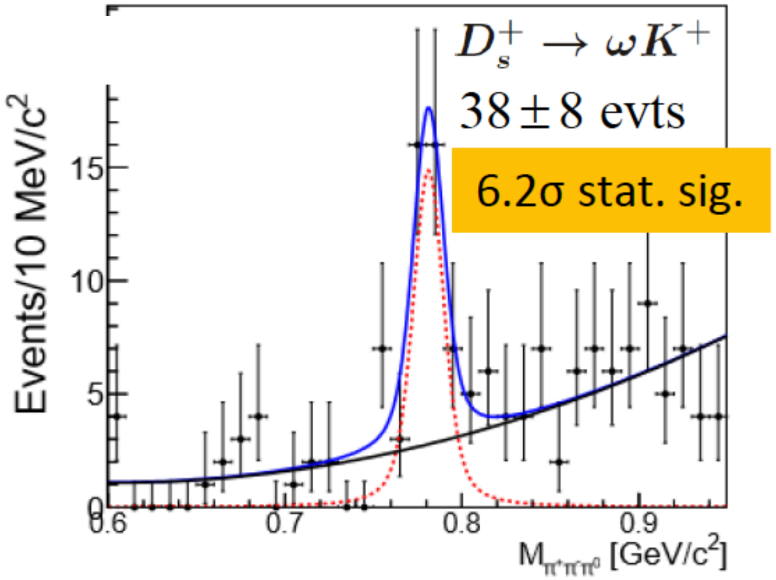


$$\mathcal{B}_{D_s^+ \to p\bar{n}} = (1.22 \pm 0.10) \times 10^{-3}$$

Consistent with long-distance expectation

Phys. Rev. D **99**, 031101(R)





Phys. Rev. D **99**, 091101(R)

Consistent with CLEO's measurement, but more precise.

$$\mathcal{B}(D_s^+ \to \omega\pi^+) = (1.85 \pm 0.30_{stat.} \pm 0.19_{sys.}) \times 10^{-3}$$

$$\mathcal{B}(D_s^+ \to \omega K^+) = (1.13 \pm 0.24_{stat.} \pm 0.14_{sys.}) \times 10^{-3}$$

First observation !

This measurement of implies the ρ–ω mixing is negligible.

Amplitude Analysis of $D_{(s)}$ three- and four-body decays

The amplitude of the n^{th} intermediate state

$$A_n = P_n S_n F_n^r F_n^D$$

- P_n: propagator
- S_n: spin factor
- F_n^r, F_n^D: Blatt-Weisskopf barrier factor

The total amplitude M

$$\sum c_n A_n$$

- c_n: complex coefficient (we are going to fit)

The signal probability density function (PDF)

$$f_S(p_j) = \frac{\epsilon(p_j)\left|M(p_j)\right|^2 R_3(p_j)}{\int \epsilon(p_j)\left|M(p_j)\right|^2 R_3(p_j)\,dp_j}$$

Likelihood

$$\ln L = \sum_k^{N_{data}} \ln f_S(p_j^k),$$

The normalization is determined by MC integration

$$\int \epsilon(p_j)\left|M(p_j)\right|^2 R_3(p_j)\,dp_j \approx \frac{1}{N_{MC}} \sum_{k_{MC}}^{N_{MC}} \frac{\left|M(p_j^{k_{MC}})\right|^2}{\left|M^{gen}(p_j^{k_{MC}})\right|^2}$$

Propagator

K*(892), K*(1680): RBW

$$P = \frac{1}{(m_0^2 - s_a) - i m_0 \Gamma(m)}$$

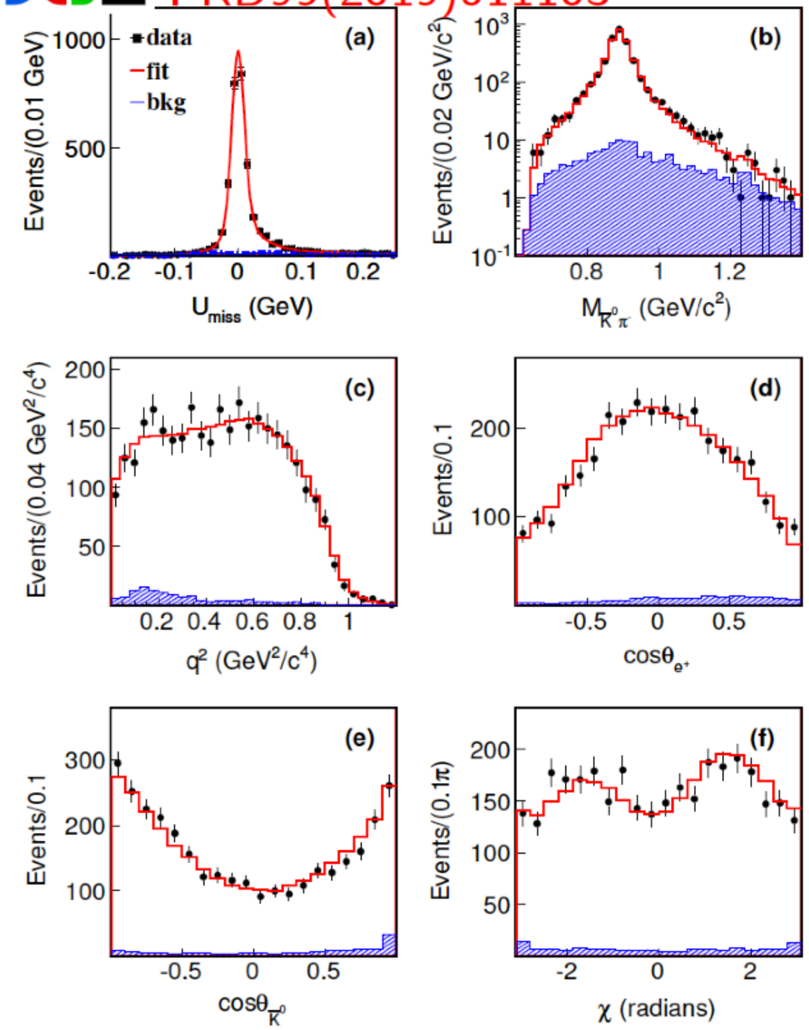
Phys. Rev. D 95, no. 3, 032002 (2017)

a_0: two-channel-coupled Flatte formula

$$1/[(m_0^2 - s_a) - i(g_{\eta\pi}^2 \rho_{\eta\pi} + g_{K\bar{K}}^2 \rho_{K\bar{K}})]$$

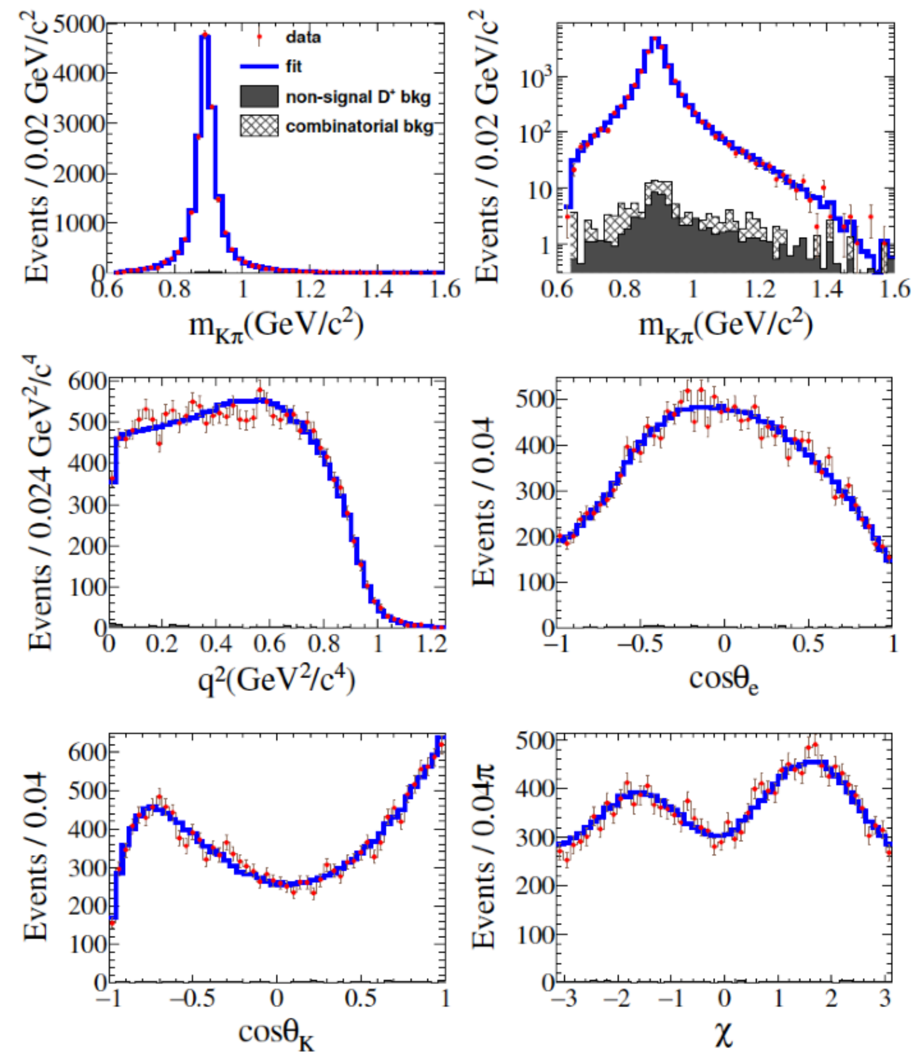
Amplitude Analysis of $D_{(s)}$ smileptonic decays

BESIII PRD99(2019)011103



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

BESIII PRD94(2016)032001

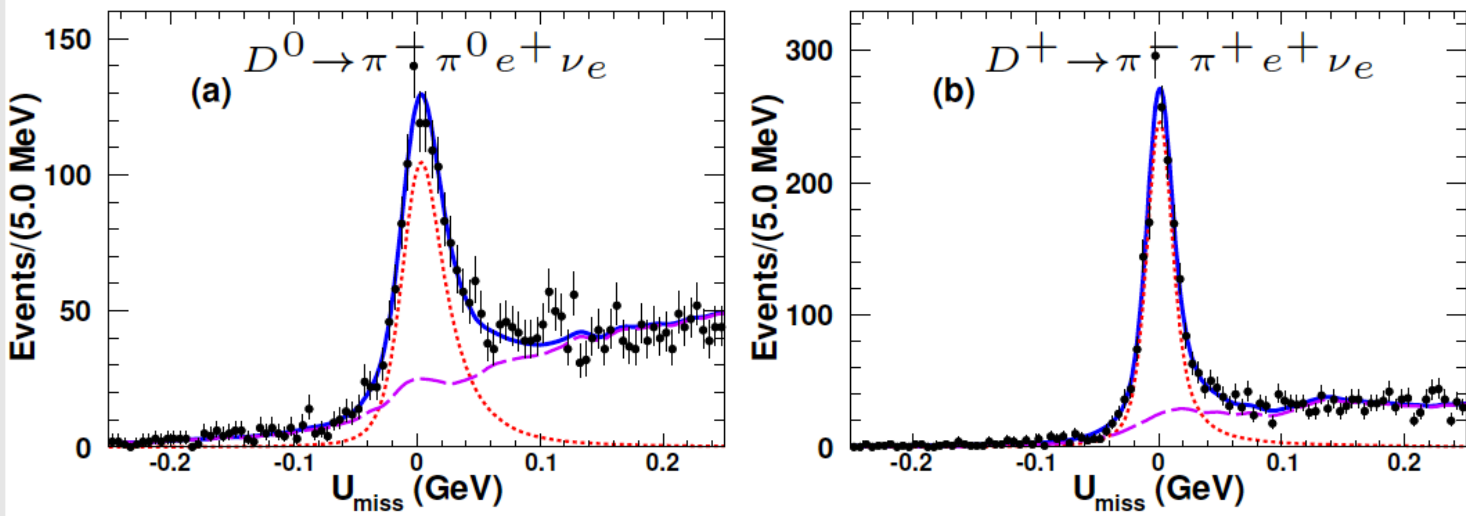


P($\bar{K}^*(892)^0$)	Simple Pole plus BW with mass-dependent width	$(3.54 \pm 0.03 \pm 0.08)\%$
S($\bar{K}_0^*(1430)^0$ and non-resonant part)	LASS plus BW with mass-dependent width	$(0.228 \pm 0.008 \pm 0.008)\%$

S($(\bar{K}^0\pi)_{\mathrm{S-wave}}$)	$(7.90 \pm 1.40 \pm 0.91) \times 10^{-4}$	P($K^*(892)^-$)	$(1.355 \pm 0.031 \pm 0.032)\%$
r_V	$1.46 \pm 0.07 \pm 0.02$	r_2	$0.67 \pm 0.06 \pm 0.01$

Amplitude Analysis of $D_{(s)}$ smileptonic decays

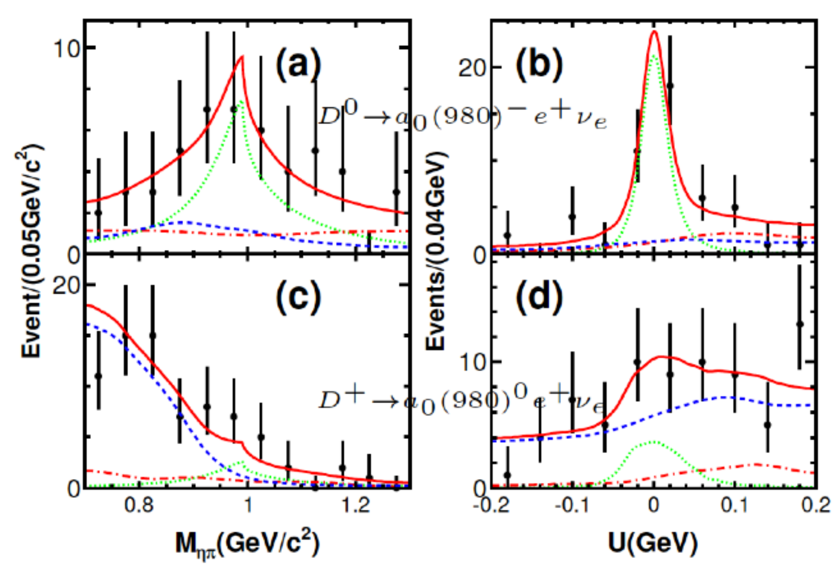
BESIII PRL122(2019)062001



Signal mode	BF ($\times 10^{-3}$)
$D^0 \to \pi^- \pi^0 e^+ \nu_e$	$1.445 \pm 0.058 \pm 0.039$
$D^0 \to \rho^- e^+ \nu_e$	$1.445 \pm 0.048 \pm 0.039$
$D^+ \to \pi^- \pi^+ e^+ \nu_e$	$2.449 \pm 0.074 \pm 0.073$
$D^+ \to \rho^0 e^+ \nu_e$	$1.860 \pm 0.070 \pm 0.061$
$D^+ \to \omega e^+ \nu_e$	$2.05 \pm 0.66 \pm 0.30$
$D^+ \to f_0(500) e^+ \nu_e$, $f_0(500) \to \pi^+ \pi^-$	$0.630 \pm 0.043 \pm 0.032$
$D^+ \to f_0(980) e^+ \nu_e$, $f_0(980) \to \pi^+ \pi^-$	< 0.028

$D_s^+ \to \pi\pi e^+ \nu_e$ **is under study**

BESIII PRL121(2018)081802



$D_s^+ \to a_0(980)^0 e^+ \nu_e$

is under study

Decay	BF ($\times 10^{-4}$)	Significance
$D^0 \to a_0(980)^- e^+ \nu_e$, $a_0(980)^- \to \eta\pi^-$	$1.33^{+0.33}_{-0.29} \pm 0.09$	6.4σ
$D^+ \to a_0(980)^0 e^+ \nu_e$, $a_0(980)^0 \to \eta\pi^0$	$1.66^{+0.81}_{-0.66} \pm 0.11$ < 3.0 (90% C.L.)	2.9σ

Amplitude Analysis of $K\pi\pi\pi$

- There are seven $D \to K\pi\pi\pi$ modes:

  $D^0 \to K^-\pi^+\pi^+\pi^-$ (published on PRD)

  $D^0 \to K^-\pi^+\pi^0\pi^0$ (published on PRD)

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

  $D^0 \to K_S\pi^+\pi^-\pi^0$ (on-going)

  $D^+ \to K^-\pi^+\pi^+\pi^0$ (on-going)

  $D^+ \to K_S\pi^+\pi^0\pi^0$ (on-going)

  $D^+ \to K_S\pi^+\pi^+\pi^-$ (published on PRD)

- Four-body decays are in five-dimensions
- We have
  - Partial Wave Analysis Tools based on CPU and GPU kernel
  - Great Electro-Magnetic Calorimeter (EMC) with CsI

    → superior resolution and efficiency of π^0
  - Largest dataset at $\psi(3770)$ resonance

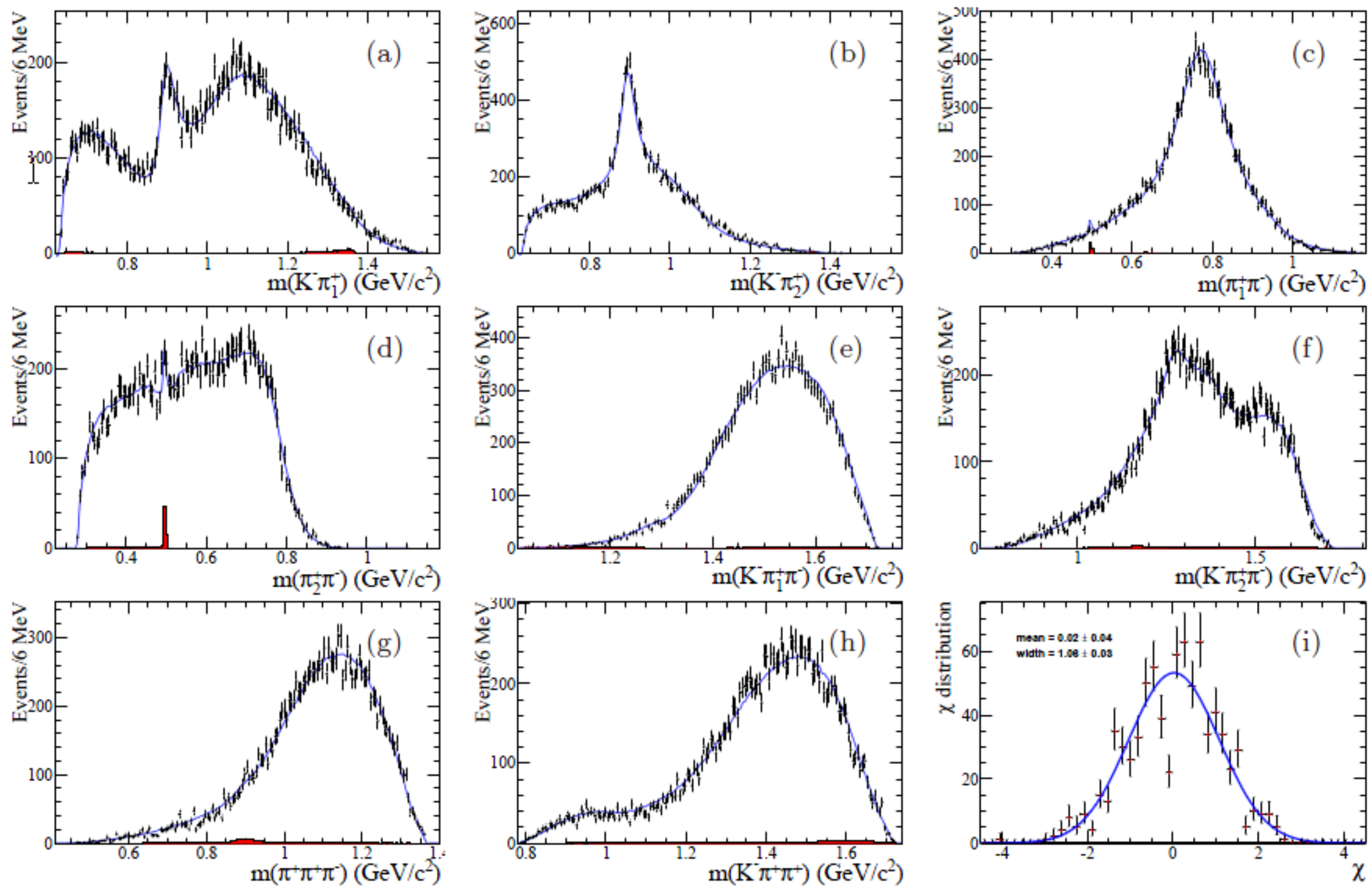
    → small statistical errors and clean background

Amplitude Analysis Results of $D^0 \to K^-\pi^+\pi^+\pi^-$

Double tag $D^0 \to K^-\pi^+\pi^+\pi^-$ vs. $D^0 \to K^+\pi^-$

Amplitude	ϕ_i	Fit fraction (%)
$D^0[S] \to \bar{K}^*\rho^0$	$2.35 \pm 0.06 \pm 0.18$	$6.5 \pm 0.5 \pm 0.8$
$D^0[P] \to \bar{K}^*\rho^0$	$-2.25 \pm 0.08 \pm 0.15$	$2.3 \pm 0.2 \pm 0.1$
$D^0[D] \to \bar{K}^*\rho^0$	$2.49 \pm 0.06 \pm 0.11$	$7.9 \pm 0.4 \pm 0.7$
$D^0 \to K^- a_1^+(1260),\ a_1^+(1260)[S] \to \rho^0\pi^+$	0(fixed)	$53.2 \pm 2.8 \pm 4.0$
$D^0 \to K^- a_1^+(1260),\ a_1^+(1260)[D] \to \rho^0\pi^+$	$-2.11 \pm 0.15 \pm 0.21$	$0.3 \pm 0.1 \pm 0.1$
$D^0 \to K_1^-(1270)\pi^+,\ K_1^-(1270)[S] \to \bar{K}^{*0}\pi^-$	$1.48 \pm 0.21 \pm 0.24$	$0.1 \pm 0.1 \pm 0.1$
$D^0 \to K_1^-(1270)\pi^+,\ K_1^-(1270)[D] \to \bar{K}^{*0}\pi^-$	$3.00 \pm 0.09 \pm 0.15$	$0.7 \pm 0.2 \pm 0.2$
$D^0 \to K_1^-(1270)\pi^+,\ K_1^-(1270) \to K^-\rho^0$	$-2.46 \pm 0.06 \pm 0.21$	$3.4 \pm 0.3 \pm 0.5$
$D^0 \to (\rho^0 K^-)_{\rm A}\pi^+,\ (\rho^0 K^-)_{\rm A}[D] \to K^-\rho^0$	$-0.43 \pm 0.09 \pm 0.12$	$1.1 \pm 0.2 \pm 0.3$
$D^0 \to (K^-\rho^0)_{\rm P}\pi^+$	$-0.14 \pm 0.11 \pm 0.10$	$7.4 \pm 1.6 \pm 5.7$
$D^0 \to (K^-\pi^+)_{\rm S}\rho^0$	$-2.45 \pm 0.19 \pm 0.47$	$2.0 \pm 0.7 \pm 1.9$
$D^0 \to (K^-\rho^0)_{\rm V}\pi^+$	$-1.34 \pm 0.12 \pm 0.09$	$0.4 \pm 0.1 \pm 0.1$
$D^0 \to (\bar{K}^{*0}\pi^-)_{\rm P}\pi^+$	$-2.09 \pm 0.12 \pm 0.22$	$2.4 \pm 0.5 \pm 0.5$
$D^0 \to \bar{K}^{*0}(\pi^+\pi^-)_{\rm S}$	$-0.17 \pm 0.11 \pm 0.12$	$2.6 \pm 0.6 \pm 0.6$
$D^0 \to (\bar{K}^{*0}\pi^-)_{\rm V}\pi^+$	$-2.13 \pm 0.10 \pm 0.11$	$0.8 \pm 0.1 \pm 0.1$
$D^0 \to ((K^-\pi^+)_{\rm S}\pi^-)_{\rm A}\pi^+$	$-1.36 \pm 0.08 \pm 0.37$	$5.6 \pm 0.9 \pm 2.7$
$D^0 \to K^-((\pi^+\pi^-)_{\rm S}\pi^+)_{\rm A}$	$-2.23 \pm 0.08 \pm 0.22$	$13.1 \pm 1.9 \pm 2.2$
$D^0 \to (K^-\pi^+)_{\rm S}(\pi^+\pi^-)_{\rm S}$	$-1.40 \pm 0.04 \pm 0.22$	$16.3 \pm 0.5 \pm 0.6$
$D^0[S] \to (K^-\pi^+)_{\rm V}(\pi^+\pi^-)_{\rm V}$	$1.59 \pm 0.13 \pm 0.41$	$5.4 \pm 1.2 \pm 1.9$
$D^0 \to (K^-\pi^+)_{\rm S}(\pi^+\pi^-)_{\rm V}$	$-0.16 \pm 0.17 \pm 0.43$	$1.9 \pm 0.6 \pm 1.2$
$D^0 \to (K^-\pi^+)_{\rm V}(\pi^+\pi^-)_{\rm S}$	$2.58 \pm 0.08 \pm 0.25$	$2.9 \pm 0.5 \pm 1.7$
$D^0 \to (K^-\pi^+)_{\rm T}(\pi^+\pi^-)_{\rm S}$	$-2.92 \pm 0.14 \pm 0.12$	$0.3 \pm 0.1 \pm 0.1$
$D^0 \to (K^-\pi^+)_{\rm S}(\pi^+\pi^-)_{\rm T}$	$2.45 \pm 0.12 \pm 0.37$	$0.5 \pm 0.1 \pm 0.1$

Amplitude Analysis Results of $D^0 \rightarrow K^-\pi^+\pi^+\pi^-$



Component	Fit fraction (%)
$D^0 \to \bar{K}^{*0}\rho^0$	$12.3 \pm 0.4 \pm 0.5$
$D^0 \to K^- a_1^+(1260)(\rho^0\pi^+)$	$54.6 \pm 2.8 \pm 3.7$
$D^0 \to K_1^-(1270)(\bar{K}^{*0}\pi^-)\pi^+$	$0.8 \pm 0.2 \pm 0.2$
$D^0 \to K_1^-(1270)(K^-\rho^0)\pi^+$	$3.4 \pm 0.3 \pm 0.2$
$D^0 \to K^-\pi^+\rho^0$	$8.4 \pm 1.1 \pm 2.2$
$D^0 \to \bar{K}^{*0}\pi^+\pi^-$	$7.0 \pm 0.4 \pm 0.3$
$D^0 \to K^-\pi^+\pi^+\pi^-$	$21.9 \pm 0.6 \pm 0.6$

Published in PRD 95, 072010

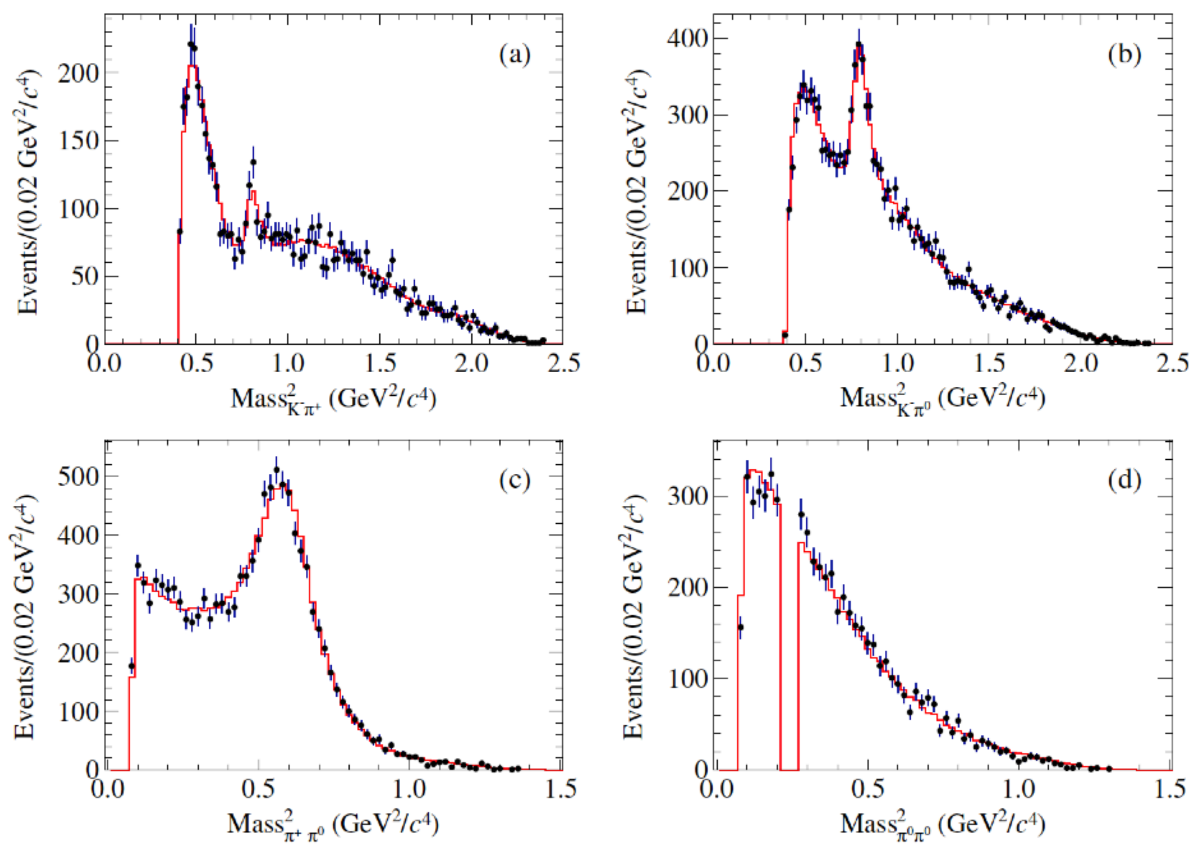
Amplitude Analysis Results of $D^0 \to K^-\pi^+\pi^0\pi^0$

Double tag: $D^0 \to K^-\pi^+\pi^0\pi^0$ (signal) vs. $\bar{D}^0 \to K^+\pi^-$ (tag)

The number of event selected is 5950 with a purity of ~99%

The data can be described with 26 amplitudes:

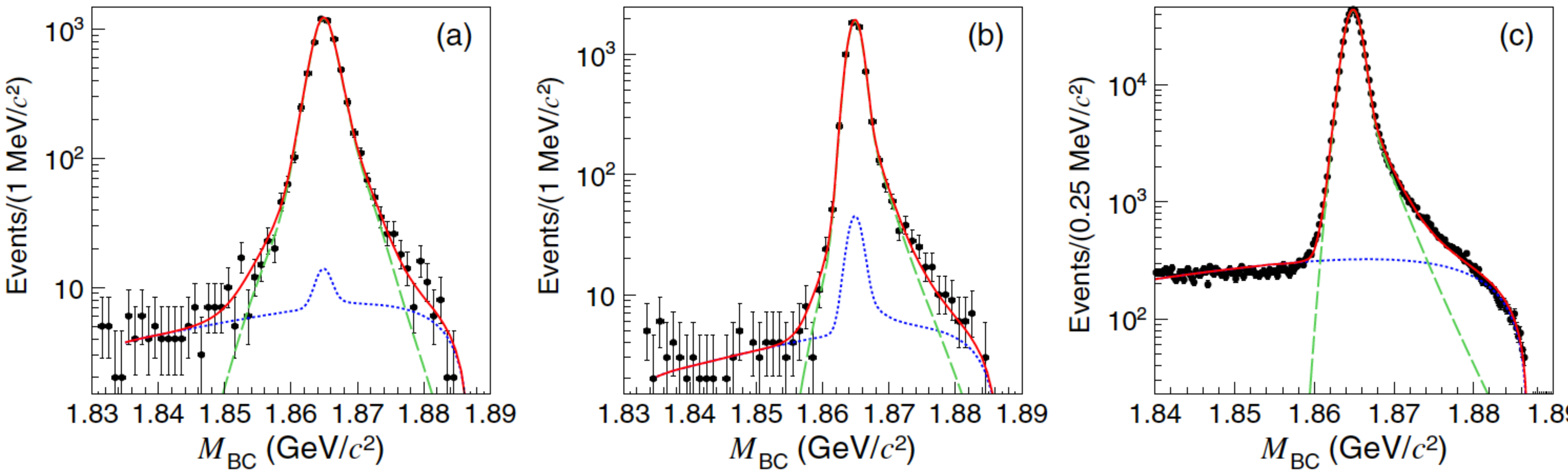
Amplitude mode	FF(%)	Phase (ϕ)
$D \to SS$		
$D \to (K^-\pi^+)_{S\text{-wave}}(\pi^0\pi^0)_S$	$6.92 \pm 1.44 \pm 2.86$	$-0.75 \pm 0.15 \pm 0.47$
$D \to (K^-\pi^0)_{S\text{-wave}}(\pi^+\pi^0)_S$	$4.18 \pm 1.02 \pm 1.77$	$-2.90 \pm 0.19 \pm 0.47$
$D \to AP, A \to VP$		
$D \to K^-a_1(1260)^+, \rho^+\pi^0[S]$	$28.36 \pm 2.50 \pm 3.53$	0 (fixed)
$D \to K^-a_1(1260)^+, \rho^+\pi^0[D]$	$0.68 \pm 0.29 \pm 0.30$	$-2.05 \pm 0.17 \pm 0.25$
$D \to K_1(1270)^-\pi^+, K^{*-}\pi^0[S]$	$0.15 \pm 0.09 \pm 0.18$	$1.84 \pm 0.34 \pm 0.43$
$D \to K_1(1270)^0\pi^0, K^{*0}\pi^0[S]$	$0.39 \pm 0.18 \pm 0.30$	$-1.55 \pm 0.20 \pm 0.26$
$D \to K_1(1270)^0\pi^0, K^{*0}\pi^0[D]$	$0.11 \pm 0.11 \pm 0.13$	$-1.35 \pm 0.43 \pm 0.48$
$D \to K_1(1270)^0\pi^0, K^-\rho^+[S]$	$2.71 \pm 0.38 \pm 0.29$	$-2.07 \pm 0.09 \pm 0.20$
$D \to (K^{*-}\pi^0)_A\pi^+, K^{*-}\pi^0[S]$	$1.85 \pm 0.62 \pm 1.11$	$1.93 \pm 0.10 \pm 0.15$
$D \to (K^{*0}\pi^0)_A\pi^0, K^{*0}\pi^0[S]$	$3.13 \pm 0.45 \pm 0.58$	$0.44 \pm 0.12 \pm 0.21$
$D \to (K^{*0}\pi^0)_A\pi^0, K^{*0}\pi^0[D]$	$0.46 \pm 0.17 \pm 0.29$	$-1.84 \pm 0.26 \pm 0.42$
$D \to (\rho^+K^-)_A\pi^0, K^-\rho^+[D]$	$0.75 \pm 0.40 \pm 0.60$	$0.64 \pm 0.36 \pm 0.53$
$D \to AP, A \to SP$		
$D \to ((K^-\pi^+)_{S\text{-wave}}\pi^0)_A\pi^0$	$1.99 \pm 1.08 \pm 1.55$	$-0.02 \pm 0.25 \pm 0.53$
$D \to VS$		
$D \to (K^-\pi^0)_{S\text{-wave}}\rho^+$	$14.63 \pm 1.70 \pm 2.41$	$-2.39 \pm 0.11 \pm 0.35$
$D \to K^{*-}(\pi^+\pi^0)_S$	$0.80 \pm 0.38 \pm 0.26$	$1.59 \pm 0.19 \pm 0.24$
$D \to K^{*0}(\pi^0\pi^0)_S$	$0.12 \pm 0.27 \pm 0.27$	$1.45 \pm 0.48 \pm 0.51$
$D \to VP, V \to VP$		
$D \to (K^{*-}\pi^+)_V\pi^0$	$2.25 \pm 0.43 \pm 0.45$	$0.52 \pm 0.12 \pm 0.17$
$D \to VV$		
$D[S] \to K^{*-}\rho^+$	$5.15 \pm 0.75 \pm 1.28$	$1.24 \pm 0.11 \pm 0.23$
$D[P] \to K^{*-}\rho^+$	$3.25 \pm 0.55 \pm 0.41$	$-2.89 \pm 0.10 \pm 0.18$
$D[D] \to K^{*-}\rho^+$	$10.90 \pm 1.53 \pm 2.36$	$2.41 \pm 0.08 \pm 0.16$
$D[P] \to (K^-\pi^0)_V\rho^+$	$0.36 \pm 0.19 \pm 0.27$	$-0.94 \pm 0.19 \pm 0.28$
$D[D] \to (K^-\pi^0)_V\rho^+$	$2.13 \pm 0.56 \pm 0.92$	$-1.93 \pm 0.22 \pm 0.25$
$D[D] \to K^{*-}(\pi^+\pi^0)_V$	$1.66 \pm 0.52 \pm 0.61$	$-1.17 \pm 0.20 \pm 0.39$
$D[S] \to (K^-\pi^0)_V(\pi^+\pi^0)_V$	$5.17 \pm 1.91 \pm 1.82$	$-1.74 \pm 0.20 \pm 0.31$
$D \to TS$		
$D \to (K^-\pi^+)_{S\text{-wave}}(\pi^0\pi^0)_T$	$0.30 \pm 0.21 \pm 0.32$	$-2.93 \pm 0.31 \pm 0.82$
$D \to (K^-\pi^0)_{S\text{-wave}}(\pi^+\pi^0)_T$	$0.14 \pm 0.12 \pm 0.10$	$2.23 \pm 0.38 \pm 0.65$



Branching Fraction Results of $D^0 \to K^-\pi^+\pi^0\pi^0$

Double tag(DT) $D^0 \to K^-\pi^+\pi^0\pi^0$ vs. $\bar{D}^0 \to K^+\pi^-$
Single tag(ST) $\bar{D}^0 \to K^+\pi^-$

$$\mathcal{B}_{\rm sig} = \frac{N^{\rm DT}_{\rm tag,sig}}{N^{\rm ST}_{\rm tag}} \frac{\varepsilon_{\rm tag}}{\varepsilon_{\rm tag,sig}}$$



The amplitude analysis result is used to determine the detection efficiency, where the DT efficiency is 8.39%

The branching fraction is determined to be

$$(8.86 \pm 0.13(\text{stat}) \pm 0.19(\text{syst}))\%$$

Phys. Rev. D 99, 092008 (2019)

Amplitude Analysis of $D^+ \to K_S \pi^+ \pi^+ \pi^-$

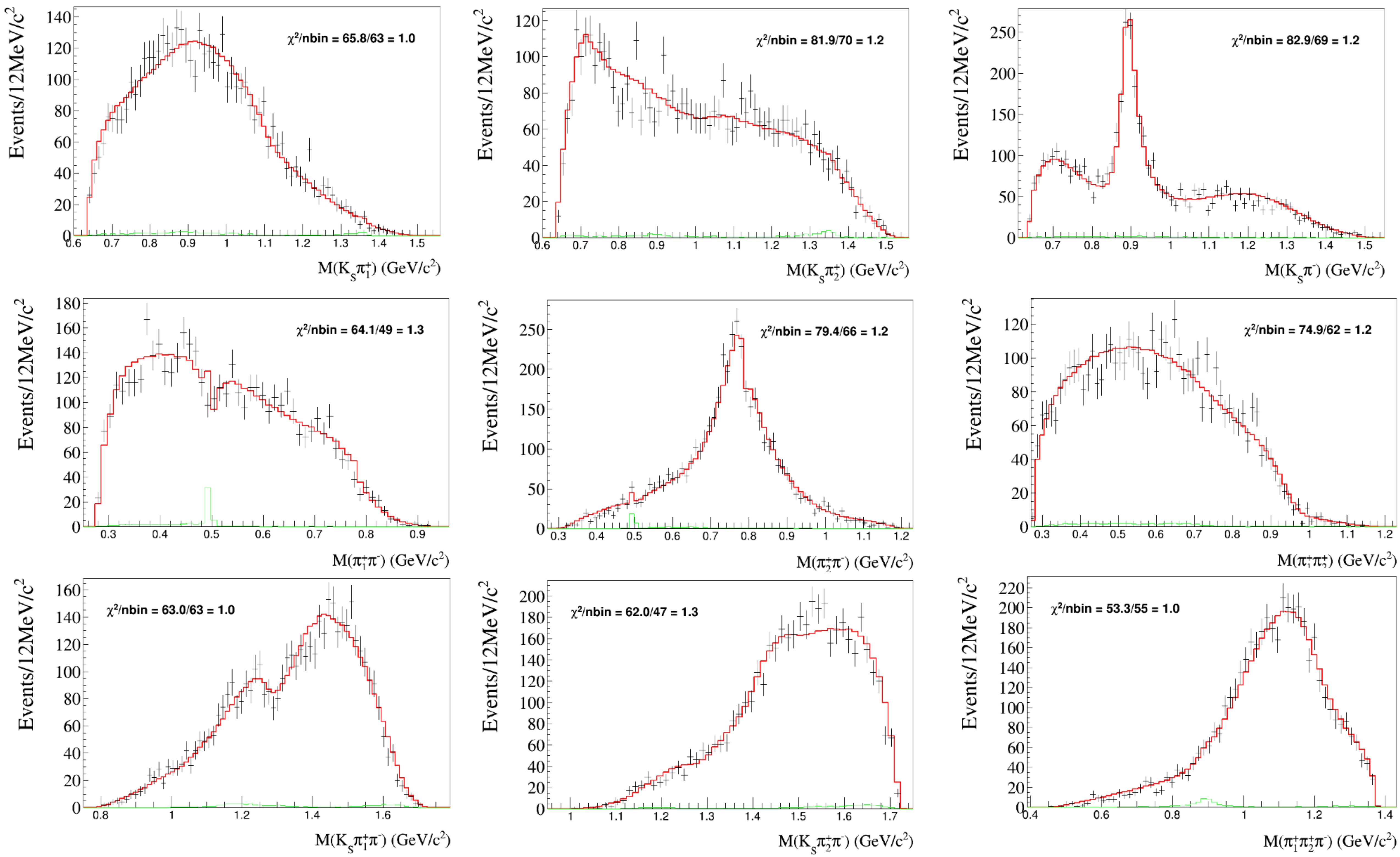
Double tag $D^+ \to K_S \pi^+ \pi^+ \pi^-$ vs. $D^- \to K^+ \pi^- \pi^-$

The number of event selected is 4559 with a purity of ~99%

The data can be described with 12 amplitudes:

Amplitude	ϕ	fit fraction
$D^+ \to K_S^0 a_1(1260)^+, a_1(1260)^+ \to \rho^0\pi^+[S]$	0.000(fixed)	$0.567 \pm 0.020 \pm 0.044$
$D^+ \to K_S^0 a_1(1260)^+, a_1(1260)^+ \to f_0(500)\pi^+$	$-2.023 \pm 0.068 \pm 0.113$	$0.050 \pm 0.006 \pm 0.007$
$D^+ \to \bar{K}_1(1400)^0\pi^+, \bar{K}_1(1400)^0 \to K^{*-}\pi^+[S]$	$-2.714 \pm 0.038 \pm 0.051$	$0.380 \pm 0.013 \pm 0.014$
$D^+ \to \bar{K}_1(1400)^0\pi^+, \bar{K}_1(1400)^0 \to K^{*-}\pi^+[D]$	$3.431 \pm 0.137 \pm 0.117$	$0.015 \pm 0.004 \pm 0.005$
$D^+ \to \bar{K}_1(1270)^0\pi^+, \bar{K}_1(1270)^0 \to K_S^0\rho^0[S]$	$-0.418 \pm 0.070 \pm 0.087$	$0.036 \pm 0.004 \pm 0.002$
$D^+ \to \bar{K}(1460)^0\pi^+, \bar{K}(1460)^0 \to K_S^0\rho^0$	$-1.850 \pm 0.120 \pm 0.223$	$0.014 \pm 0.004 \pm 0.003$
$D^+ \to (K_S^0\rho^0)_A[D]\pi^+$	$2.328 \pm 0.097 \pm 0.068$	$0.011 \pm 0.003 \pm 0.002$
$D^+ \to K_S^0(\rho^0\pi^+)_P$	$1.656 \pm 0.083 \pm 0.056$	$0.031 \pm 0.004 \pm 0.010$
$D^+ \to (K^{*-}\pi^+)_A[S]\pi^+$	$-4.321 \pm 0.047 \pm 0.073$	$0.132 \pm 0.011 \pm 0.011$
$D^+ \to (K^{*-}\pi^+)_A[D]\pi^+$	$0.989 \pm 0.158 \pm 0.229$	$0.013 \pm 0.004 \pm 0.004$
$D^+ \to (K_S^0(\pi^+\pi^-)_S)_A\pi^+$	$-2.935 \pm 0.060 \pm 0.125$	$0.051 \pm 0.004 \pm 0.003$
$D^+ \to ((K_S^0\pi^-)_S\pi^+)_P\pi^+$	$1.864 \pm 0.069 \pm 0.288$	$0.022 \pm 0.003 \pm 0.003$

Amplitude Analysis of $D^+ \rightarrow K_S\pi^+\pi^+\pi^-$



Amplitude Analysis of $D^+ \to K_S\pi^+\pi^+\pi^-$

The preliminary results of branching fractions for different components：

Component	Branching fraction (%)
$D^+ \to K_S^0 a_1(1260)^+(\rho^0\pi^+)$	$1.684 \pm 0.059 \pm 0.131 \pm 0.062$
$D^+ \to K_S^0 a_1(1260)^+(f_0(500)\pi^+)$	$0.149 \pm 0.018 \pm 0.021 \pm 0.006$
$D^+ \to \bar{K}_1(1400)^0(K^{*-}\pi^+)\pi^+$	$1.105 \pm 0.045 \pm 0.048 \pm 0.041$
$D^+ \to \bar{K}_1(1270)^0(K_S^0\rho^0)\pi^+$	$0.107 \pm 0.012 \pm 0.006 \pm 0.004$
$D^+ \to \bar{K}(1460)^0(K_S^0\rho^0)\pi^+$	$0.042 \pm 0.012 \pm 0.009 \pm 0.002$
$D^+ \to K_S^0\pi^+\rho^0$	$0.131 \pm 0.015 \pm 0.015 \pm 0.005$
$D^+ \to K^{*-}\pi^+\pi^+$	$0.413 \pm 0.036 \pm 0.059 \pm 0.015$
$D^+ \to K_S^0\pi^+\pi^+\pi^-$	$0.220 \pm 0.015 \pm 0.024 \pm 0.008$

stat. uncertainty from FF

sys. uncertainty from FF

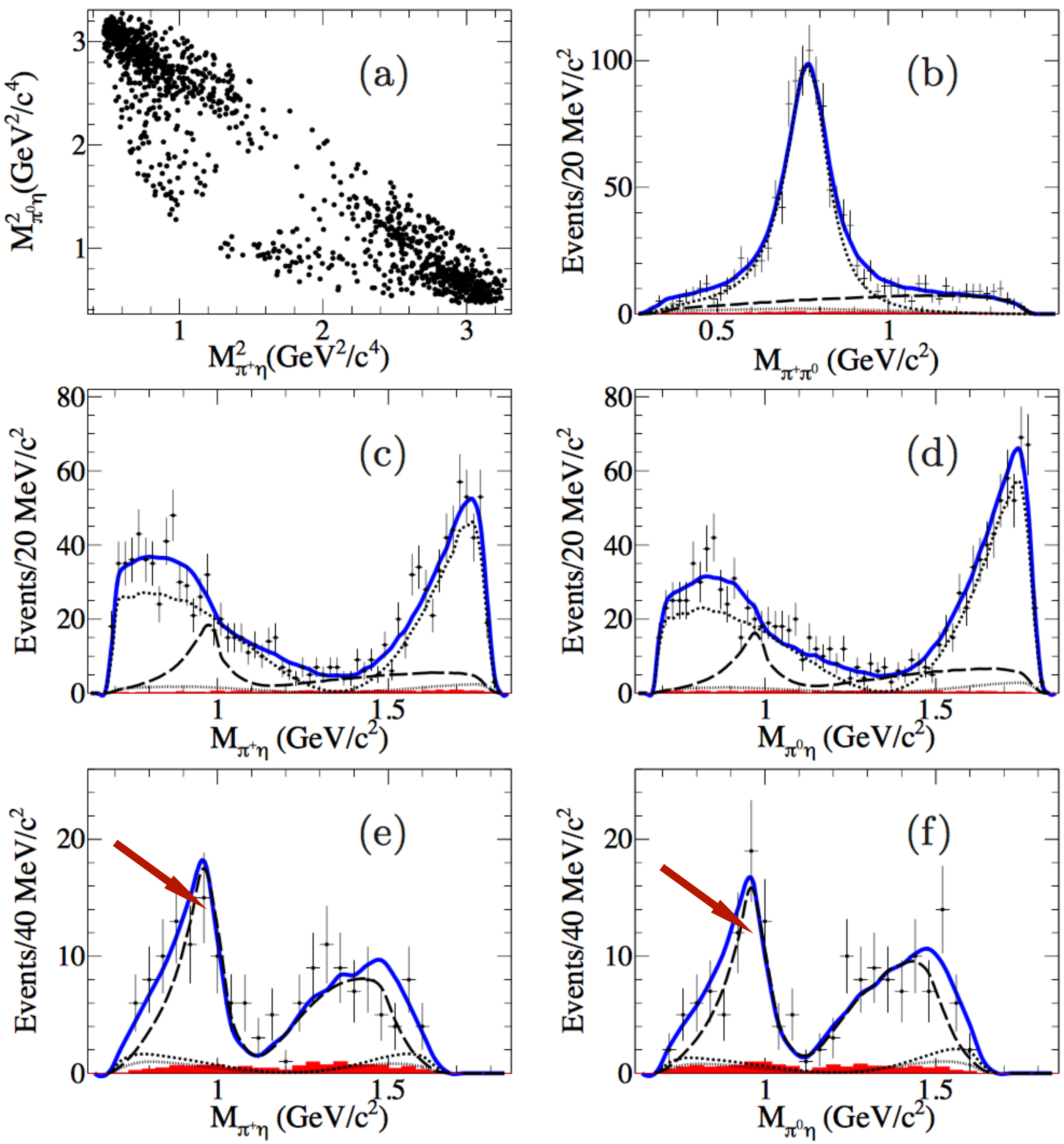
uncertainties related to BF($D^+ \to K_S^0\pi^+\pi^+\pi^-$) in PDG

The measurements of the decays with $K1(1270)$and $K1(1400)$involved provide some experimental information in understanding the mixture of the two excited Kaons.

Phys. Rev. D **100**, 072008 (2019)

Amplitude Analysis of $D_S^+ \to \pi^+\pi^0\eta$

Observation of $D_S^+ \to a^0(980)^+\pi^0$

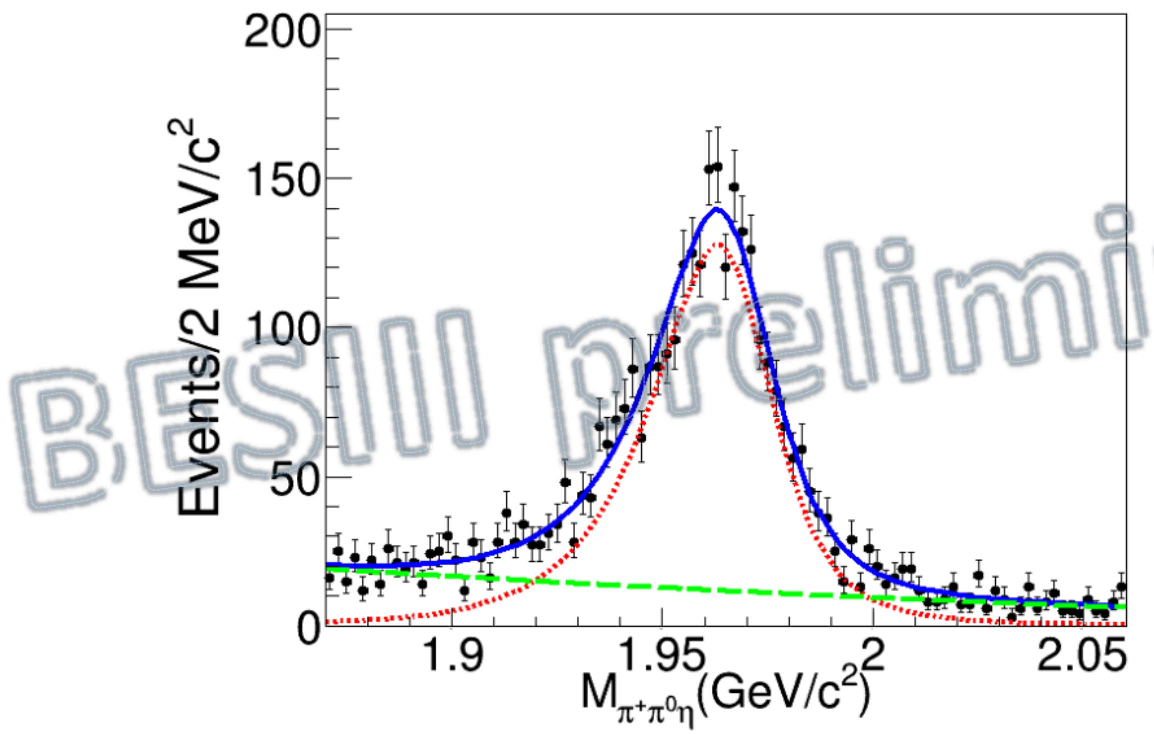


Dots with error bar: data
Solid line: total fit
Dashed line: rho+ eta
Lond-dashed line: a0(980)π

The phase difference between $a_0(980)^0\pi^+$ and $a_0(980)^+\pi^0$ is found to agree with 180^o

Amplitude Analysis of $D_s^+ \to \pi^+\pi^0\eta$

Fit to signal mode



Total Tag yield: 255895 ± 1358 .

DT yield: 2626 ± 77.

Efficiency is determined with the amplitude analysis result.

- Dots with error bars: data.
- Total fit.
- Signal: MC shape convoluted with a Gaussian.
- Background: second-order Chebychev.

$BF(D_s^+ \to \pi^+\pi^0\eta) = (9.50 \pm 0.28_{stat.} \pm 0.41_{sys.})\%$

Branching fraction (%)
$\mathcal{B}(D_s^+ \to \rho^+\eta) = 7.44 \pm 0.48_{stat.} \pm 0.44_{sys.}$
$\mathcal{B}(D_s^+ \to a_0(980)\pi)^* = 2.20 \pm 0.22_{stat.} \pm 0.34_{sys.}$
$\mathcal{B}(D_s^+ \to a_0(980)^+\pi^0)^* = 1.46 \pm 0.15_{stat.} \pm 0.22_{sys.}$
$\mathcal{B}(D_s^+ \to a_0(980)^0\pi^+)^* = 1.46 \pm 0.15_{stat.} \pm 0.22_{sys.}$

BF(sub-mode n) = $\mathcal{B}(D_s^+ \to \pi^+\pi^0\eta)FF(n)$

First observation

The measured $\mathcal{B}(D_s^+ \to a^0(980)^+\pi^0)$ is larger than other measured pure *W*-annihilation decays ($D_s^+ \to pn$, $D_s^+ \to w\pi^+$) by one order.

Phys. Rev. Lett. **123**, 112001 (2019)

Summary

- DTag and $D\bar{D}$ threshold data allows us to perform inclusive and exclusive branching fraction measurement
- Double tag provides clean samples for amplitude analysis
- Many D^0, D^+, and D_s studies have been published, including $D^+ \to \tau\nu_\tau$
- A series measurements of scalar meson could provide complete information for theoretical approaches to judgment of quark models of light scalar mesons
- Excellent D_s studies are published based on our 3.19 fb^{-1} data at E_{cm} = 4.178 GeV (and at 4.190-4.230 GeV)
  - "Many" D_s amplitude analyses of three- and four-body (semi)leptonic/hadronic decays are expected to be published in the next year.