Charmed Meson Hadronic decays at BESIII

Bai-Cian Ke
IHEP

Outline

- **Introduction**
  - **Important variables**
  - **D^0, D^+,and D_s Dataset**
  - **DTag and Branching Fraction**
- **Branching Fraction Measurement of D Hadronic decays**
  - **η'X, omega π, p n^{bar}, etc.**
- **Amplitude Analysis**
  - **$K^-\pi^+\pi^+\pi^-$, $K_S\pi^+\pi^+\pi^-$, $K^-\pi^+\pi^0\pi^0$, $\pi^+\pi^0\eta$ etc.**
- **Summary**

Important Variables

- Beam-Constrained Mass (M_{BC})

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

M_{BC} peaks at D mass:
momentum conservation

- Energy Difference (ΔE)

$$\Delta E = E_D - E_{\mathrm{beam}}$$

ΔE peaks at zero:
energy conservation

Typically cut on ΔE, then fit to M_{BC} obtain yield

BESIII Data Taken near DD^{bar} Threshold

- BEPCII collider: $e^+e^- \rightarrow \psi(3770) \rightarrow DD^{bar}$
- 2.9 fb^{-1} dataset at $\psi(3770)$ resonance

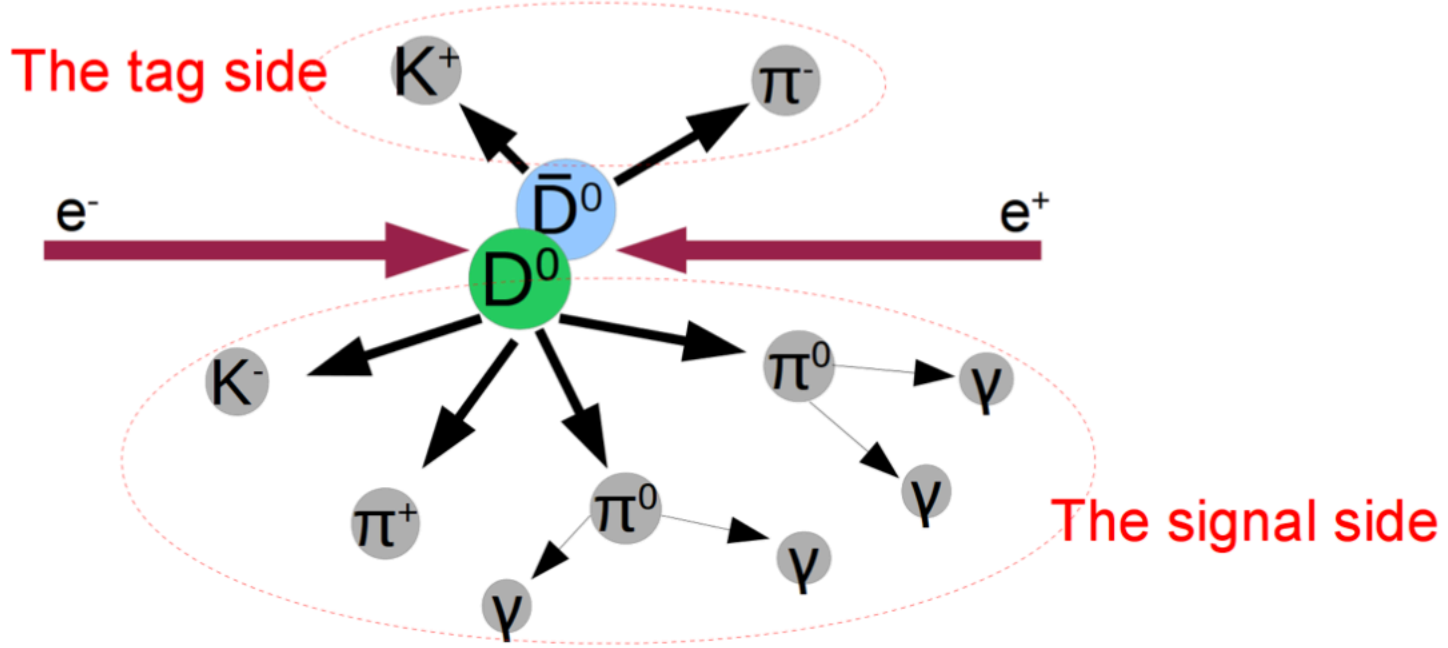
M_{D0}= 1864.84 MeV M_{D+}= 1869.62 MeV

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

- New 3.19 fb^{-1} dataset at E_{cm} 4.178GeV
  - D_s are produced mostly via $e^+e^- \rightarrow D_sD_s^*$
- Advantages of DD^{bar} pair production near threshold
  - The DD^{bar} events are clean; not enough energy for even one additional pion
  - Tagging reduces background from light-quark “continuum” and other charm final states
  - Double tag technique can provide access to absolute BFs
  - Many systematic uncertainties cancel with tagging technique

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.)



Branching Fraction and Tagging

- Single tag (ST)

$$N^{\mathrm{ST}}_{\mathrm{tag}} = 2N_{D^0\bar{D}^0}\mathcal{B}_{\mathrm{tag}}\varepsilon_{\mathrm{tag}}$$

- Double tag (DT)

$$N^{\mathrm{DT}}_{\mathrm{tag,sig}} = 2N_{D^0\bar{D}^0}\mathcal{B}_{\mathrm{tag}}\mathcal{B}_{\mathrm{sig}}\varepsilon_{\mathrm{tag,sig}}$$

$\varepsilon_{\mathrm{tag,sig}} \approx \varepsilon_{\mathrm{tag}}\varepsilon_{\mathrm{sig}}$ (factorization)

where $N_{D^0\bar{D}^0}$ is the total number of produced $D^0\bar{D}^0$ pairs, $\mathcal{B}_{\mathrm{tag(sig)}}$ is the branching fraction of the tag (signal) side, and the ε are the corresponding efficiencies.

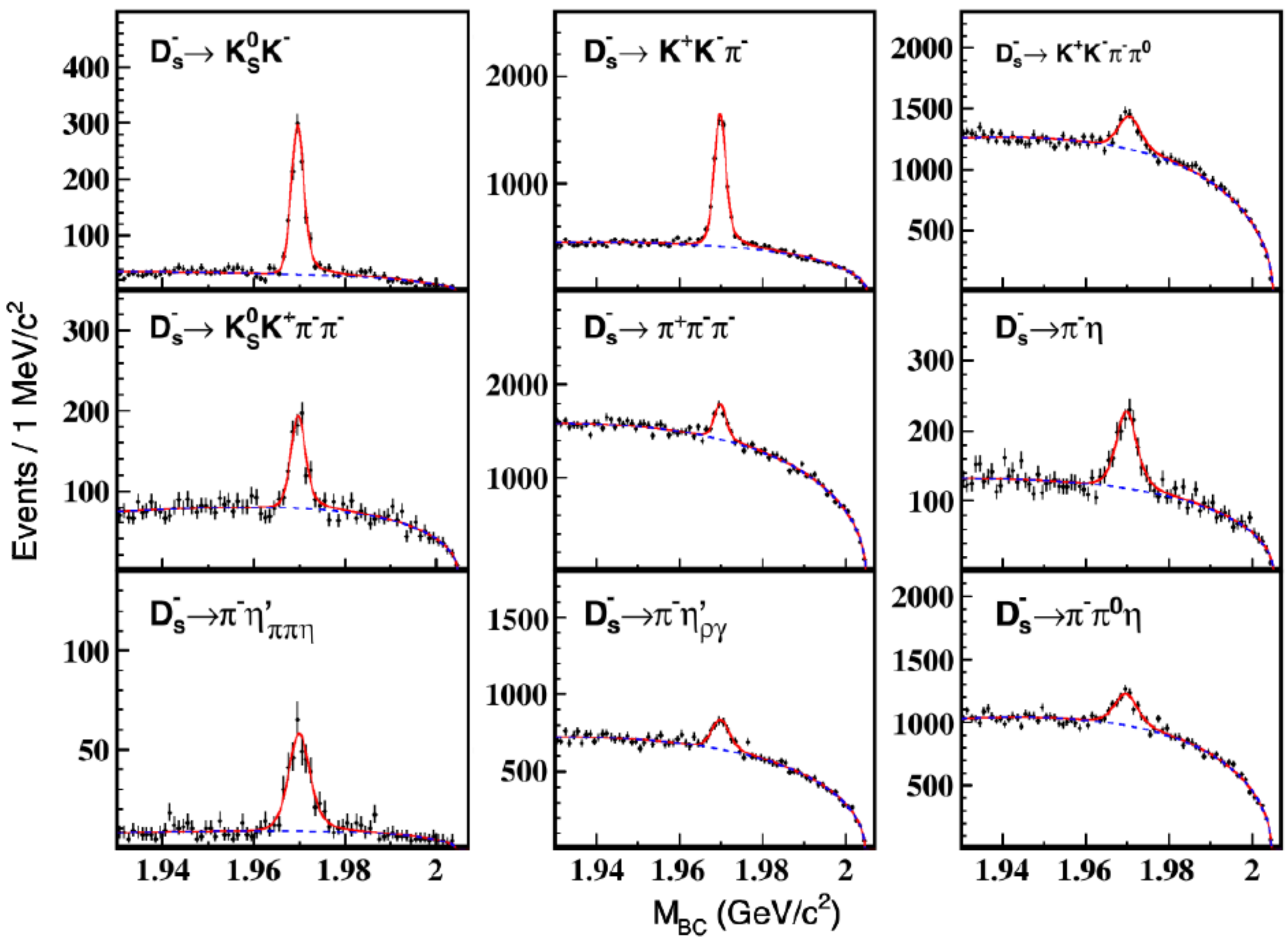
$$\mathcal{B}_{\mathrm{sig}} = \frac{N^{\mathrm{DT}}_{\mathrm{tag,sig}}}{N^{\mathrm{ST}}_{\mathrm{tag}}}\frac{\varepsilon_{\mathrm{tag}}}{\varepsilon_{\mathrm{tag,sig}}}$$

$N_{D^0\bar{D}^0}$, $\mathcal{B}_{\mathrm{tag}}$ are canceled.
$\varepsilon_{\mathrm{tag}}$ is approximately canceled due to factorization

This is the basic idea for branching fraction.
Equations used in analysis vary case by case.

Measurements of the branching fraction of $D_s^+ \to \eta' X$

Single tag nine tag modes

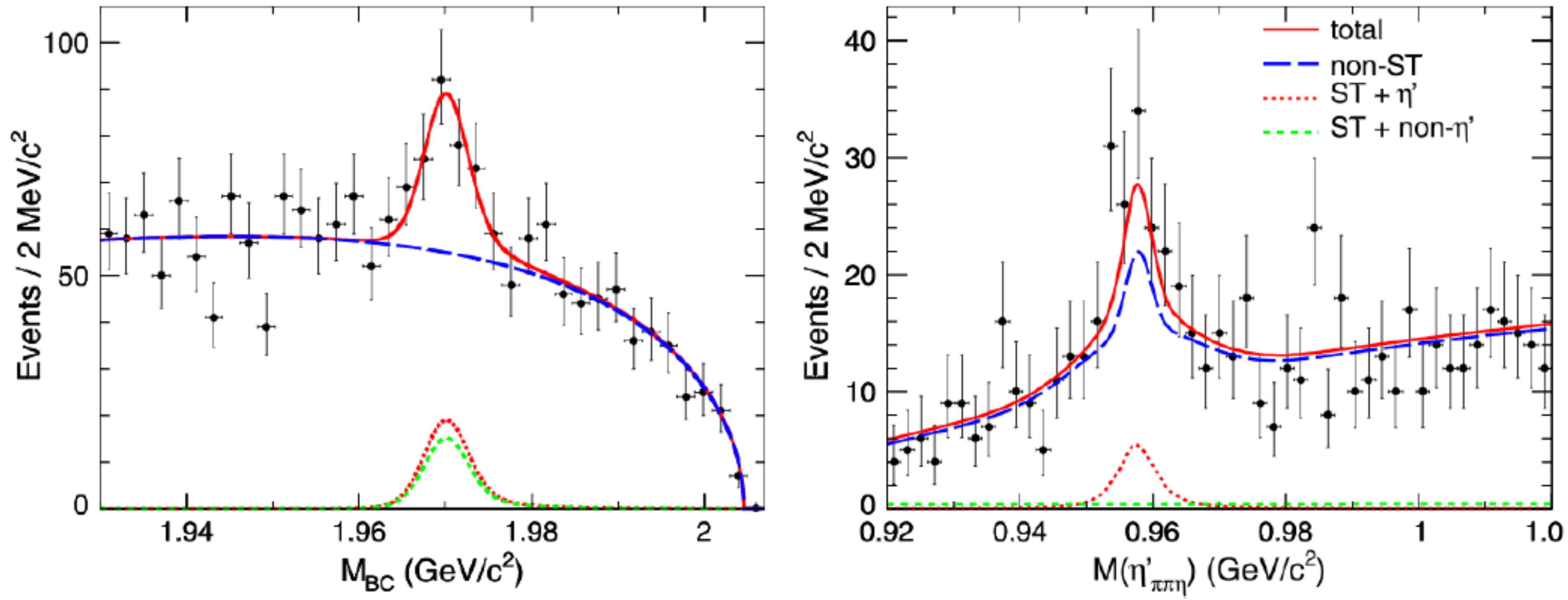


First, single tag nine tag modes. Then, reconstruct $\eta' \to \pi^+\pi^-\eta$ with $\eta \to \gamma\gamma$.

The decay mode $\eta' \to \rho^0\gamma$ is not used due to large combinatorial background.

$$\mathcal{B}(D_s^+ \to \eta' X)\mathcal{B}_{\eta'}^{\mathrm{PDG}} = \frac{\sum_\alpha y_{\mathrm{DT}}^\alpha}{\sum_\alpha y_{\mathrm{ST}}^\alpha \cdot \frac{\varepsilon_{\mathrm{DT}}^\alpha}{\varepsilon_{\mathrm{ST}}^\alpha}} = \frac{y_{\mathrm{DT}}}{\sum_\alpha y_{\mathrm{ST}}^\alpha \cdot \frac{\varepsilon_{\mathrm{DT}}^\alpha}{\varepsilon_{\mathrm{ST}}^\alpha}}$$

A two-dimensional fit to M_{BC} (tag) vs. $M(\eta'_{\pi+\pi-\eta})$ (signal) is performed to obtain the DT yields.



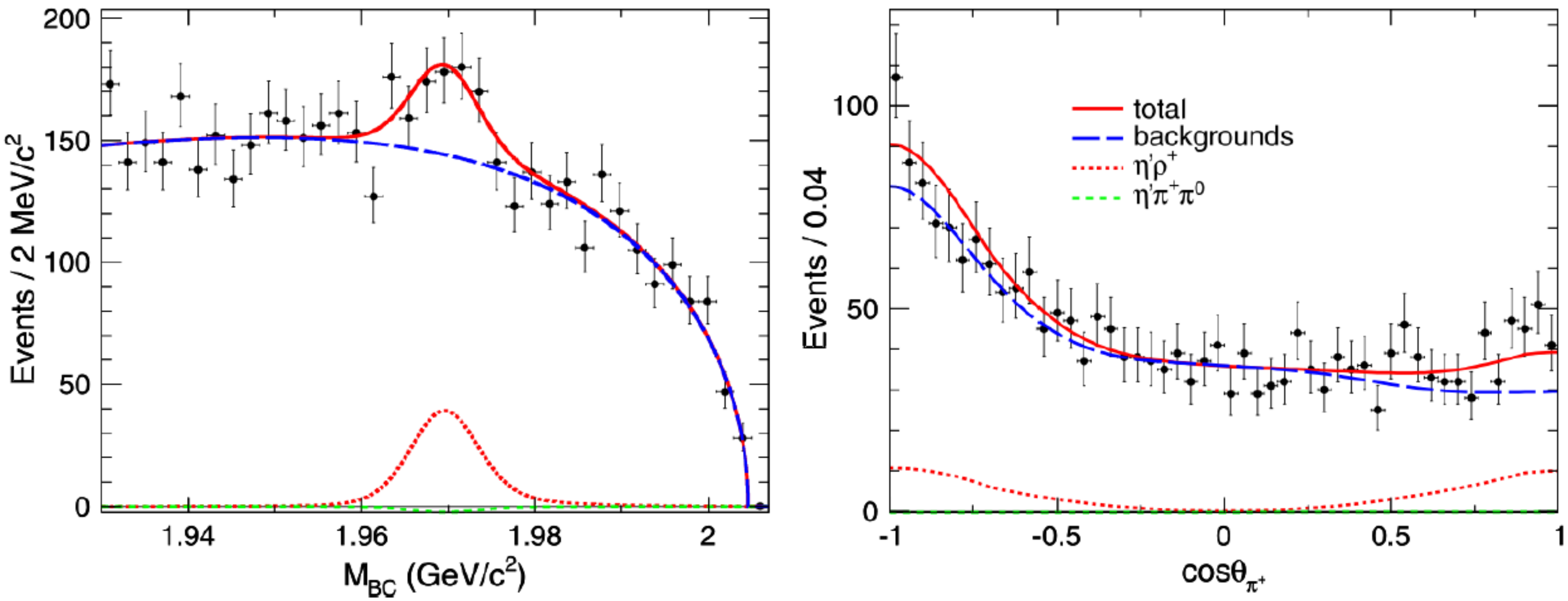
ST mode α	$\varepsilon^{\alpha}_{\rm ST}$ (%)	$y^{\alpha}_{\rm ST}$	$\varepsilon^{\alpha}_{\rm DT}$ (%)	$y_{\rm DT}$
$K^0_S K^-$	47.89 ± 0.35	1088 ± 40	13.75 ± 0.14	
$K^+K^-\pi^-$	44.16 ± 0.18	5355 ± 118	12.46 ± 0.14	
$K^+K^-\pi^-\pi^0$	13.25 ± 0.22	1972 ± 145	4.32 ± 0.08	
$K^0_S K^+\pi^-\pi^-$	24.27 ± 0.37	595 ± 50	6.05 ± 0.09	
$\pi^+\pi^-\pi^-$	60.26 ± 0.90	1657 ± 143	17.18 ± 0.16	68 ± 14
$\pi^-\eta$	48.39 ± 0.70	843 ± 54	14.82 ± 0.16	
$\pi^-\eta'_{\pi\pi\eta}$	29.48 ± 0.52	461 ± 41	7.91 ± 0.11	
$\pi^-\eta'_{\rho\gamma}$	43.11 ± 0.88	1424 ± 147	11.96 ± 0.13	
$\pi^-\pi^0\eta$	26.02 ± 0.32	2260 ± 156	7.90 ± 0.11	

$$\mathcal{B}(D_s^+ \to \eta' X) = (8.8 \pm 1.8 \pm 0.5)\%$$

Measurements of the branching fraction of $D_s^+ \to \eta'\rho^+$

Using the DT samples from $D_s^+ \to \eta' X$ analysis, invariant mass cuts on η' and ρ^+ are applied to enrich the $D_s^+ \to \eta'\rho^+$ signal events.

A two-dimensional fit to the distribution of M_{BC} vs. $\cos\theta_{\pi+}$ to determine the signal yield.



$$\frac{\mathcal{B}(D_s^+ \to \eta'\rho^+)\mathcal{B}^{\rm PDG}_{\rho^+}\mathcal{B}^{\rm PDG}_{\eta'}}{\mathcal{B}(D_s^+ \to K^+K^-\pi^+)} = \frac{y^{\eta'\rho^+}_{\rm ST}}{y^{K^+K^-\pi^+}_{\rm ST}} \cdot \frac{\varepsilon^{K^+K^-\pi^+}_{\rm ST}}{\varepsilon^{\eta'\rho^+}_{\rm ST}}$$

$$\mathcal{B}(D_s^+ \to \eta'\rho^+) = (5.8 \pm 1.4 \pm 0.4)\%$$

Physics Letters B 750 (2015) 466–474

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 $\omega \to \pi^+\pi^-\pi^0$.

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

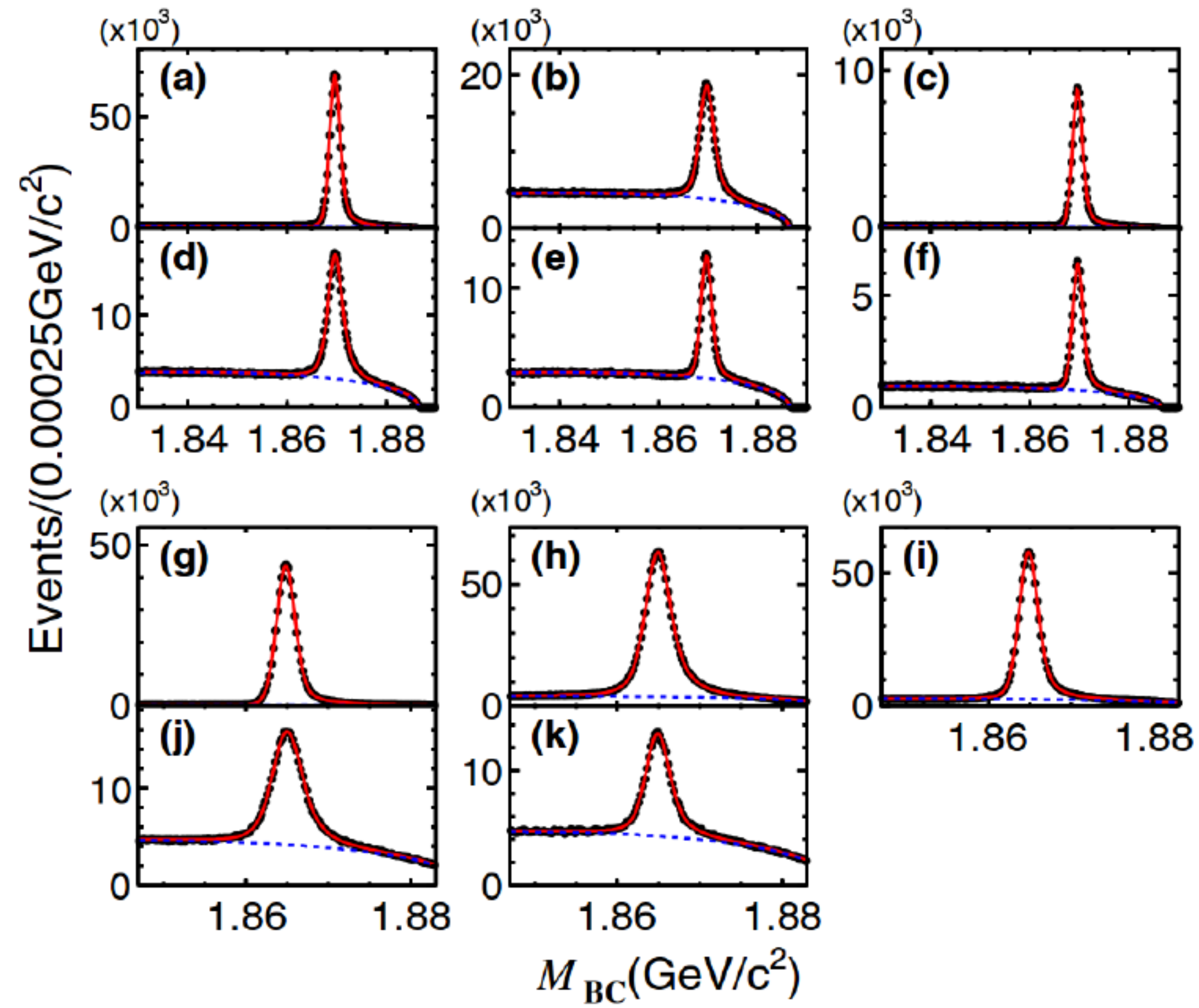


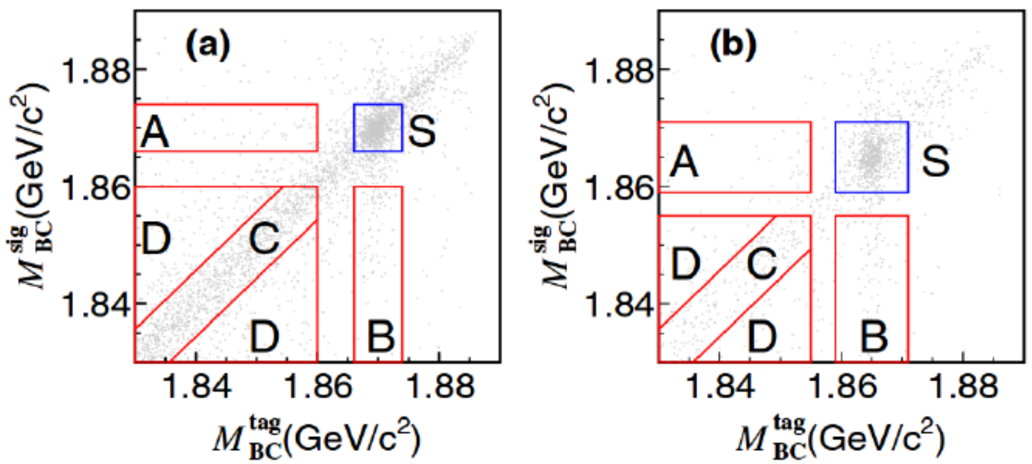
FIG. 1. $M_{\rm BC}$ distributions of ST samples for different tag modes. The first two rows show charged D decays: (a) $K^+\pi^-\pi^-$, (b) $K^+\pi^-\pi^-\pi^0$, (c) $K^0_S\pi^-$, (d) $K^0_S\pi^-\pi^0$, (e) $K^0_S\pi^+\pi^-\pi^-$, (f) $K^+K^-\pi^-$, the latter two rows show neutral D decays: (g) $K^+\pi^-$, (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.

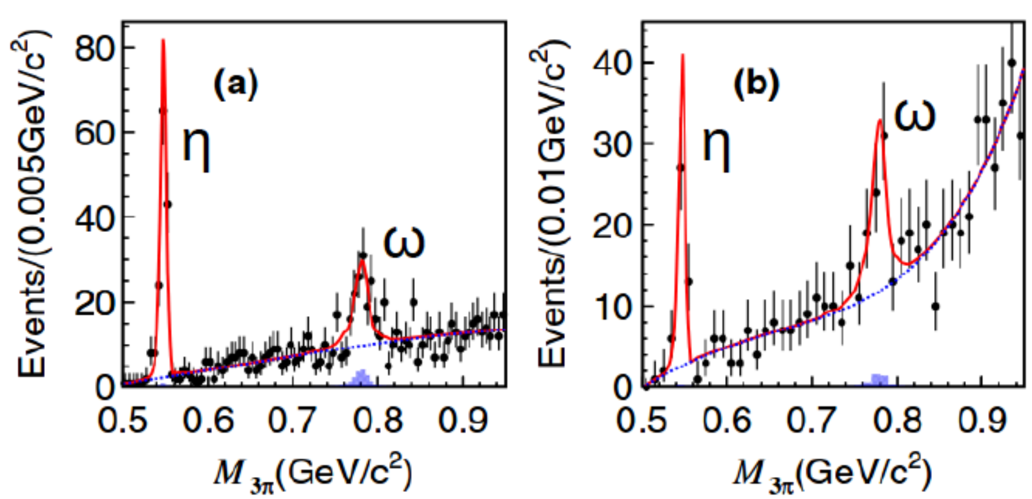
DT $D^{+(0)} \to \pi^+\pi^-\pi^0\pi^{+(0)}$ vs. tag modes

Fits to M3π 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.

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





Red line: total fit

Blue line: background

Hatched histogram: peaking background From sidebands

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

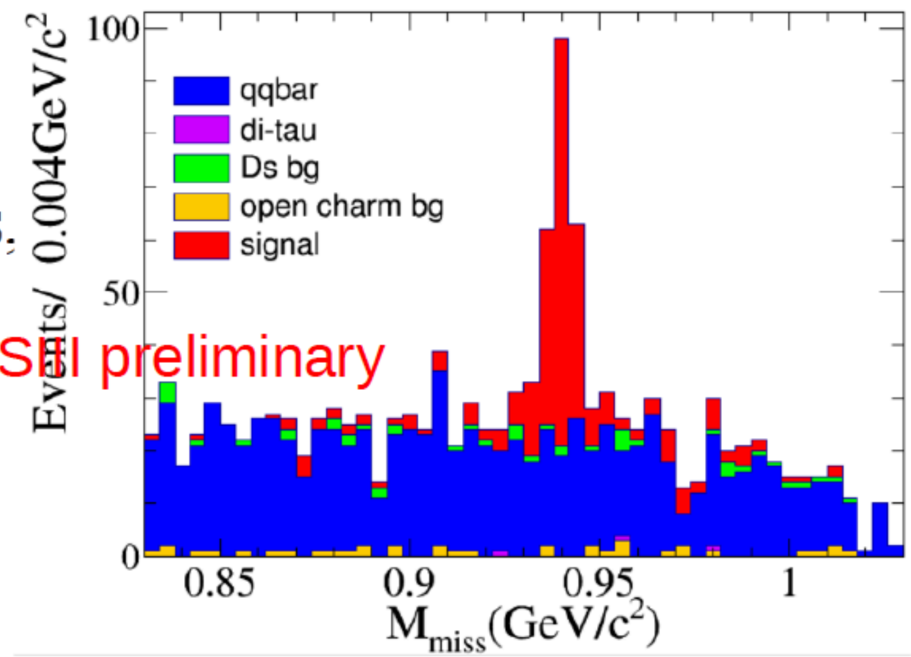
PRL **116,** 082001 (2016)

Preliminary result for $D_s \to pn^{bar}$

With 3.19 fb^{-1} data @ 4.178GeV collected by the BESIII

Double tag

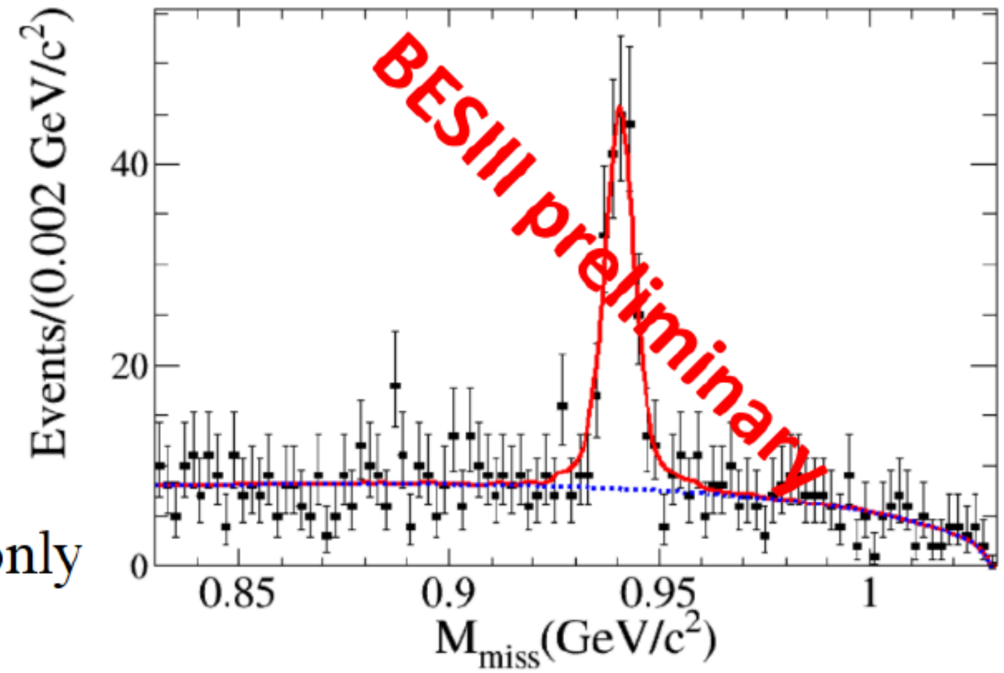
- Kinematic fit to improve missing neutron resolution
- Constraint the 4 momenta of the total events, the two Ds and Ds* mass, set anti-neutron 4 momenta free: (7-4)C
- Set two hypotheses to select the one with smaller χ^2
  - Ds*→γDs(→tag modes)
  - Ds*→ γDs(→$p\bar{n}$)
- No peaking background
- Signal efficiency ~ 48% from inclusive MC



Preliminary result

$$\mathcal{B}_{D_s\to p\bar{n}} = \frac{1}{\mathcal{B}_{D_s^*\to\gamma D_s}}\cdot\frac{N_{DT}}{N_{ST}}\cdot\frac{\epsilon_{ST}}{\epsilon_{DT}}$$

$$= \frac{1}{\mathcal{B}_{D_s^*\to\gamma D_s}}\cdot\frac{\sum N_{DT}}{\sum(N_{ST}\cdot\frac{\epsilon_{DT}}{\epsilon_{ST}})}$$



By combining the 11 tag modes together, we obtain (only statistic error here):

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

Signal: **MC shape ⊗Gaussian**
Background: **Argus function**

- Statistically limited.
- Uncertainty due to baryon ID dominates the systematic

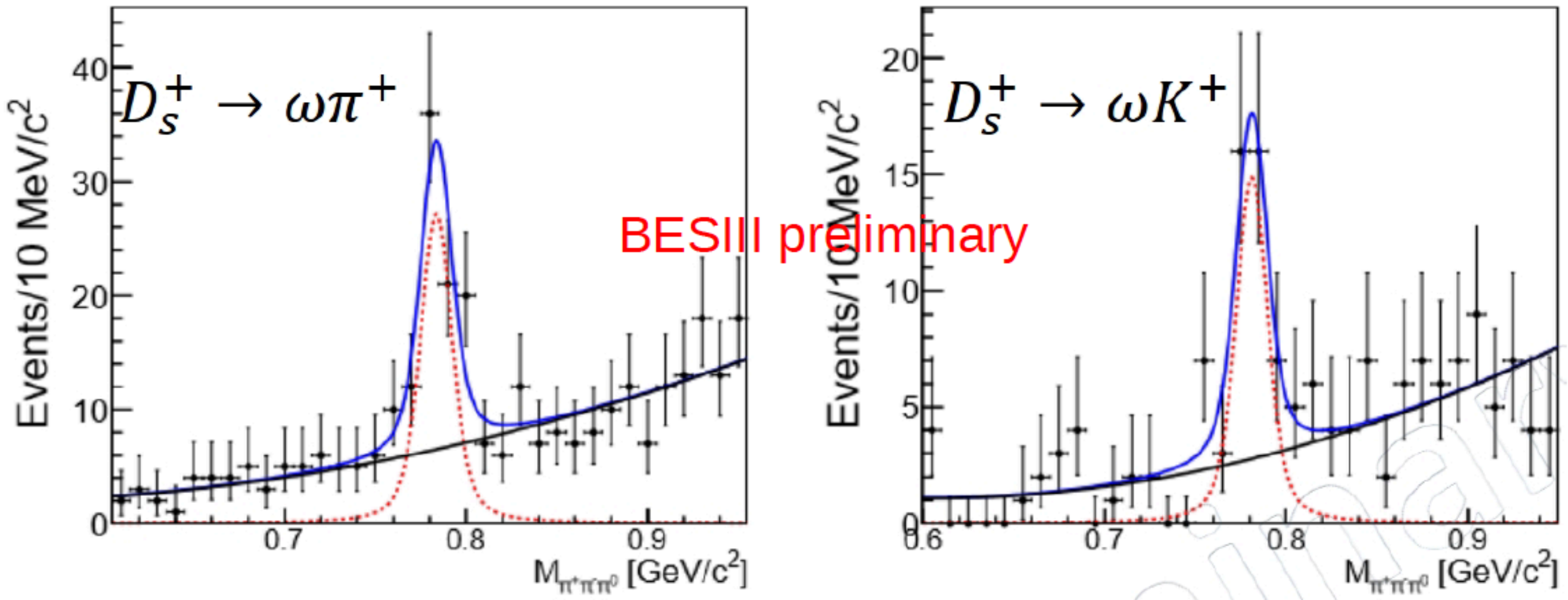
- Confirm CLEO-c's measurement with greatly improved accuracy
- Consistent with the prediction of the enhanced BR due to long-distance effect via hadronic loop

Preliminary results on observation of $D_s^+ \to \omega\pi^+$ and ωK^+

With 3.19 fb^{-1} data @ 4.178GeV collected by the BESIII

Double tag: One $M_{rec} > 2.1$ GeV

- Best candidate: average mass of two D_s mesons closet to PDG value.
- K_s^0 veto for $D_s^+ \to \omega K^+$ to suppress the background from $D_s^+ \to \overline{K}^{*0} K^+$:
  If $|m_{\pi\pi} - 0.4976| < 0.03\text{GeV},\ L_{decay}/\sigma_{L_{decay}} > 2.0$, veto this event.



Signal mode	Branching fraction (10^{-3})	Statistical significance (σ)
$D_s^+ \to \omega\pi^+$	$1.85 \pm 0.30(stat.) \pm 0.19(sys.)$	7.7
$D_s^+ \to \omega K^+$	$1.13 \pm 0.24(stat.) \pm 0.14(sys.)$	6.2

BESIII preliminary

Amplitude Analysis of Kπππ

- There are seven $D \to K3\pi$ modes:

  $D^0 \to K^-\pi^+\pi^+\pi^-$ (published on PRD) PhysRevD.95.072010

  $D^0 \to K^-\pi^+\pi^0\pi^0$ (expected to publish on PRD soon)

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

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

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

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

  $D^+ \to K_S\pi^+\pi^+\pi^-$ (expected to publish on PRD soon)
- 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

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

    $\to$ small statistical errors and clean background

Partial Wave Analysis

The Signal PDF

I am going to fit $A(a_i, p_j) = \sum_i a_i A_i(p_j)$

$$S(a_i, p_j) = \frac{\epsilon(p_j)|A(a_i, p_j)|^2 R_4(p_j)}{\int \epsilon(p_j)|A(a_i, p_j)|^2 R_4(p_j) dp_j}$$

where p_j is the daughter particles' four momenta and a_i is the complex coefficient for amplitude modes. $\epsilon(p_j)$ is the efficiency parameterized in terms of the daughter particles' four momenta. R_4 is the 4-body phase space

$$A_i(p_j) = P_i^1(p_j) P_i^2(p_j) S_i(p_j) F_i^1(p_j) F_i^2(p_j) F_i^D(p_j)$$

where $F_i^D(p_j)$ is the Blatt-Weisskopf Barrier factor for D meson. $P_i^{1,2}(p_j)$ and $F_i^{1,2}(p_j)$ is the propagator and the Blatt-Weisskopf Barrier factor, respectively, of the two resonance states for the quasi-two-body type or of the first and the second resonance states for the cascade type. $S_i(p_j)$ is the spin factor. Finally, the likelihood can be defined as

For n events $\prod_{j=1}^{n} S(a_i, p_j)$

Define the likelihood $L = \prod_{j=1}^{n} S(a_i, p_j)$

Partial Wave Analysis

Independent of a_i

$$\ln L = \sum_{j}^{N_{selected}} \ln\left(\frac{|A(a_i,p_j)|^2 R_4(p_j)}{\int \epsilon(p_j)|A(a_i,p_j)|^2 R_4(p_j)dp_j}\right) + \sum_{j}^{N_{selected}} \ln \epsilon(p_j)$$

$$\int \epsilon(p_j)|A(a_i,p_j)|^2 R_4(p_j)dp_j \approx \frac{1}{N_{generated}} \sum_{j}^{N_{selected}} |A(a_i,p_j)|^2$$

Phase space MC sample can be used to deal with the MC integration.
We replace phase space MC sample by signal MC sample
for better precision.

$$\int \epsilon(p_j)|A(a_i,p_j)|^2 R_4(p_j)dp_j \approx \frac{1}{N_{MC}} \sum_{j}^{N_{MC}} \frac{|A(a_i,p_j)|^2}{|A(a_i^{gen},p_j)|^2}$$

We further consider the effects of detector efficiency difference
between data and MC simulation for pi0 reconstruction, PID, and tracking

$$\int \epsilon(p_j)|A(a_i,p_j)|^2 R_4(p_j)dp_j \approx \frac{1}{N_{MC}} \sum_{j}^{N_{MC}} \frac{|A(a_i,p_j)|^2 \gamma_\epsilon(p_j)}{|A(a_i^{gen},p_j)|^2}$$

where $\gamma_\epsilon(p_j) = \prod_j \frac{\epsilon_{j,\mathrm{data}}(p_j)}{\epsilon_{j,\mathrm{MC}}(p_j)}$

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

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

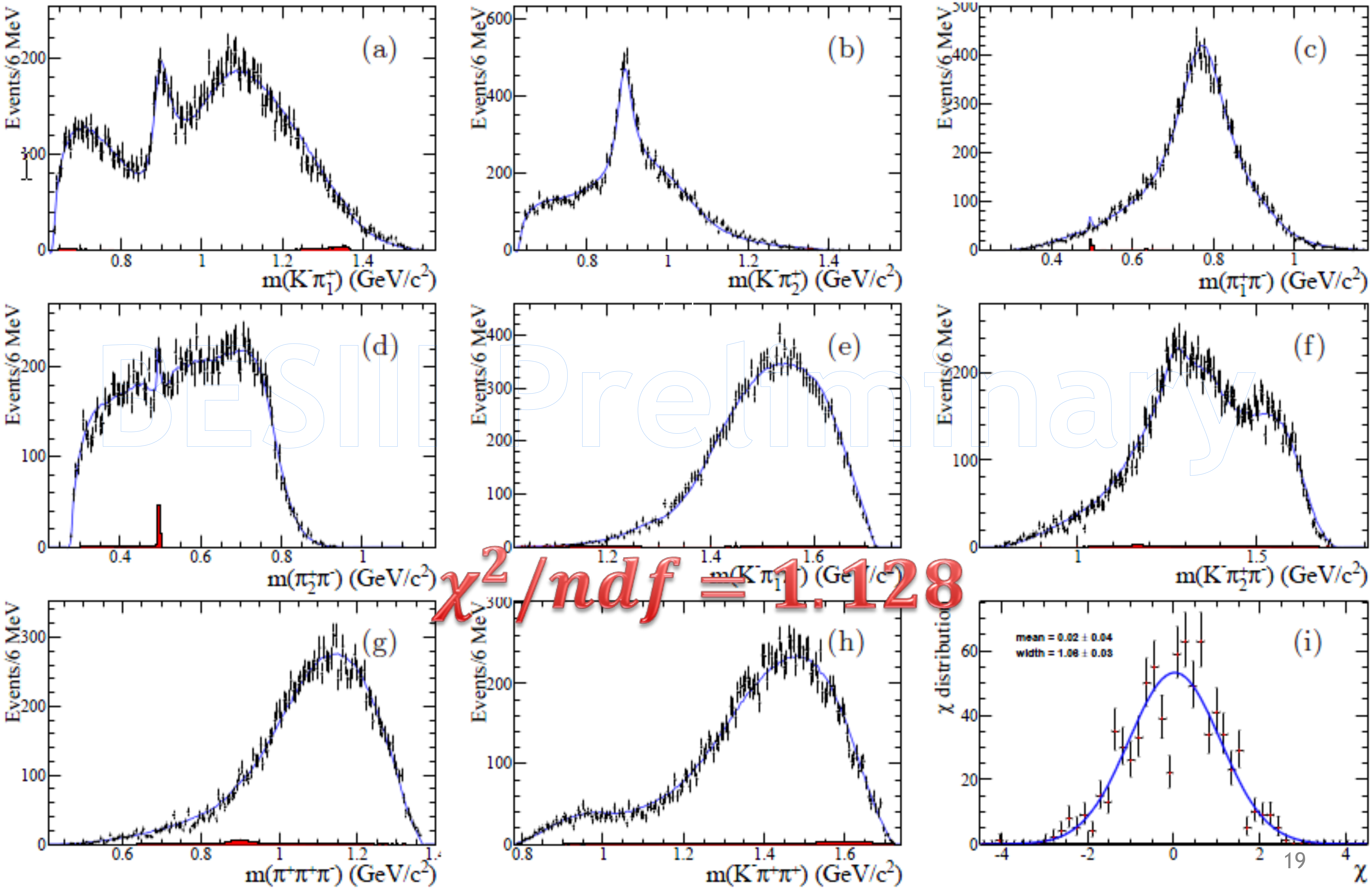
The number of event selected is 15912 with a purity of 99.4%

The data can be described with 23 amplitudes:

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

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

Projections of invariant mass (a-h) and χ distribution (i)



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

Results of branching fractions for different components:

Component	Branching fraction (%)	PDG value (%)
$D^0 \to \bar{K}^{*0}\rho^0$	$0.99 \pm 0.04 \pm 0.04 \pm 0.03$	1.05 ± 0.23
$D^0 \to K^- a_1^+(1260)(\rho^0\pi^+)$	$4.41 \pm 0.22 \pm 0.30 \pm 0.13$	3.6 ± 0.6
$D^0 \to K_1^-(1270)(\bar{K}^{*0}\pi^-)\pi^+$	$0.07 \pm 0.01 \pm 0.02 \pm 0.00$	0.29 ± 0.03
$D^0 \to K_1^-(1270)(K^-\rho^0)\pi^+$	$0.27 \pm 0.02 \pm 0.04 \pm 0.01$	
$D^0 \to K^-\pi^+\rho^0$	$0.68 \pm 0.09 \pm 0.20 \pm 0.02$	0.51 ± 0.23
$D^0 \to \bar{K}^{*0}\pi^+\pi^-$	$0.57 \pm 0.03 \pm 0.04 \pm 0.02$	0.99 ± 0.23
$D^0 \to K^-\pi^+\pi^+\pi^-$	$1.77 \pm 0.05 \pm 0.04 \pm 0.05$	1.88 ± 0.26

stat. uncertainty from FF

sys. uncertainty from FF

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

Published in PRD 95, 072010

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

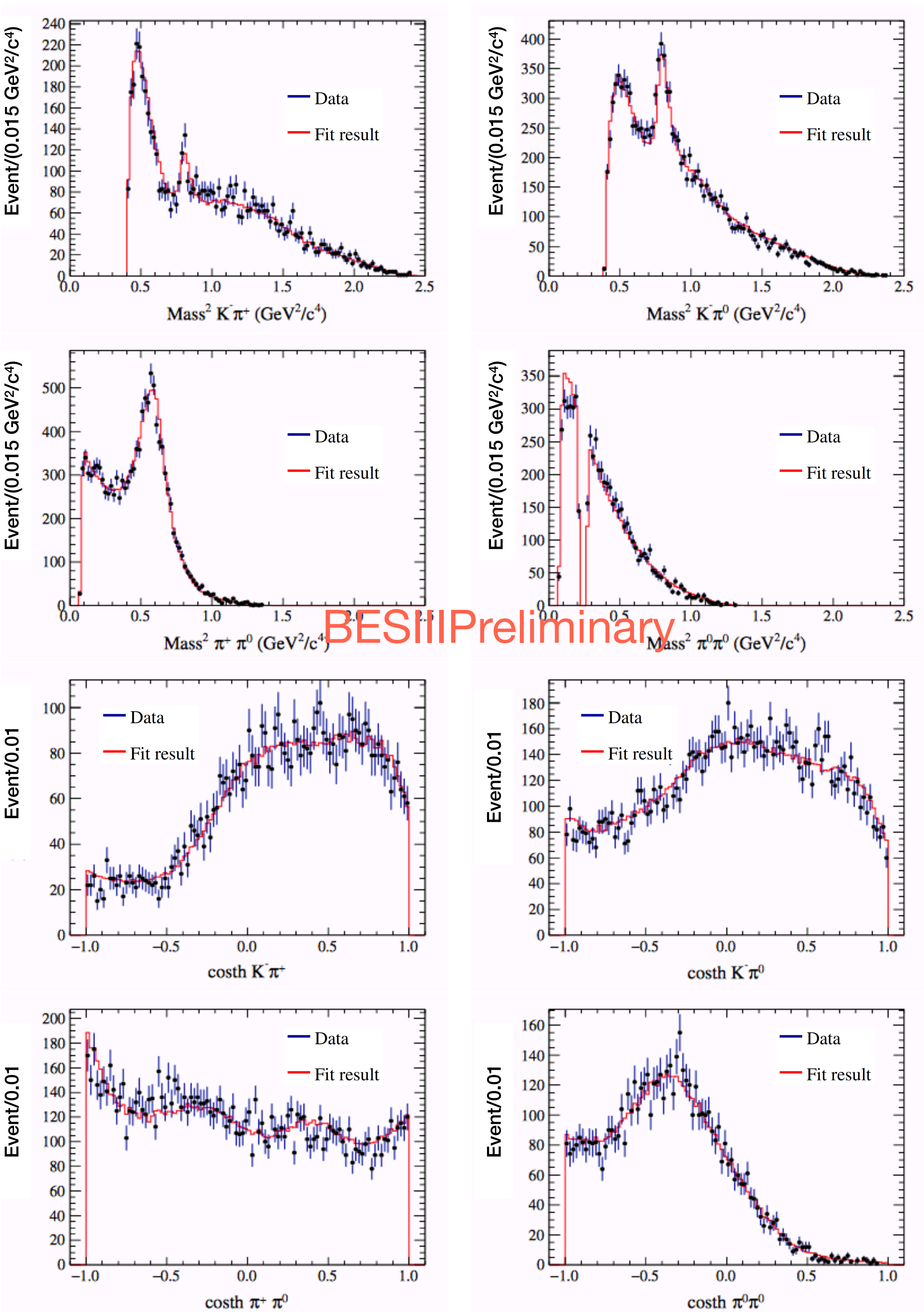
Double tag: $D^0 \to K^-\pi^+\pi^0\pi^0$ (signal) vs. $\bar{D}^0 \to K^+\pi^-$ (tag)

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

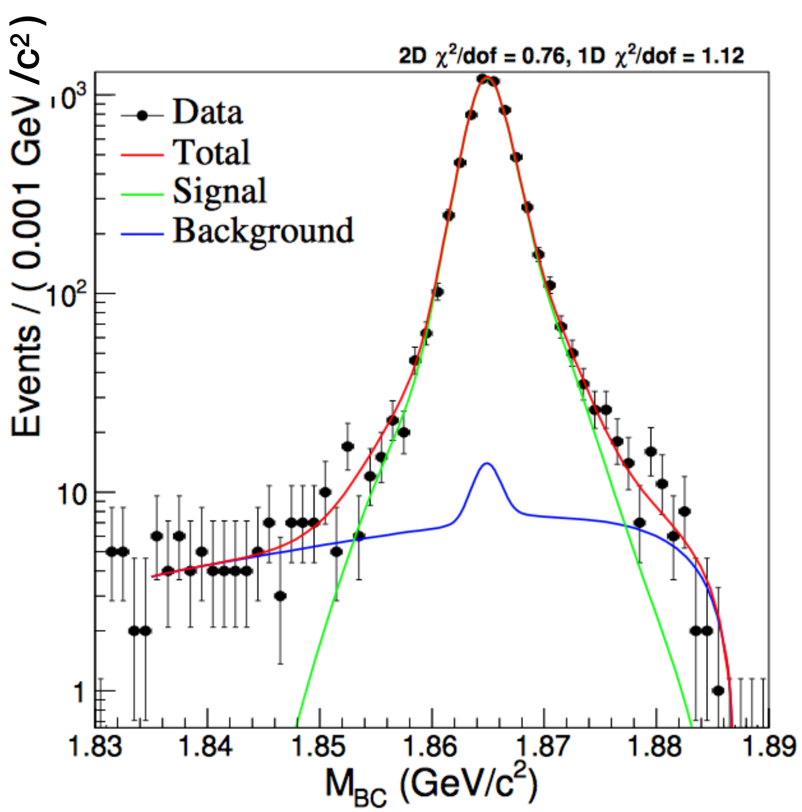
Amplitude Analysis Results of $D^0 \to K^-\pi^+\pi^0\pi^0$



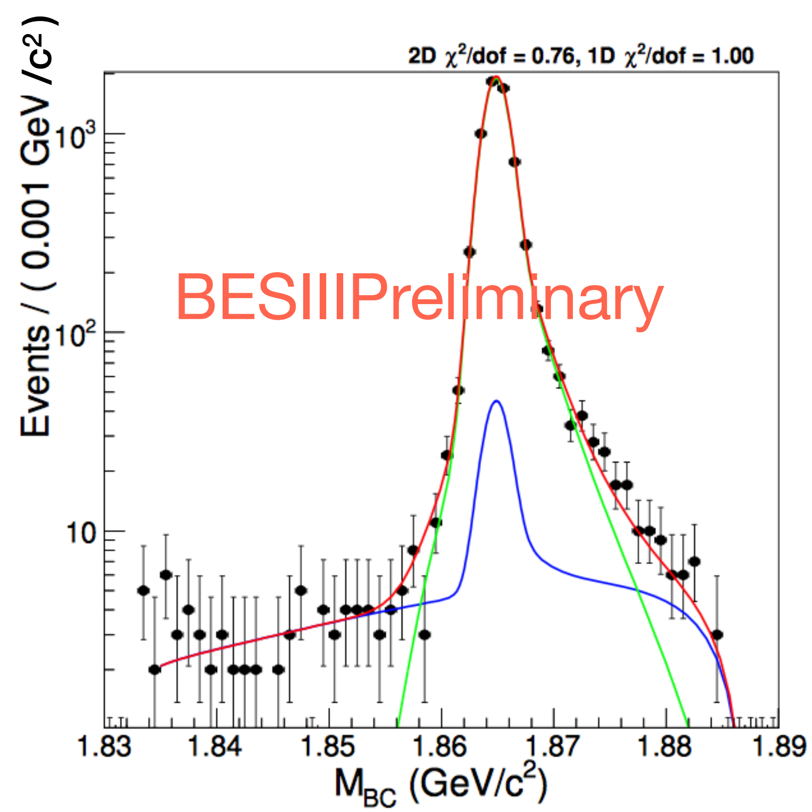
Branching Fraction Results of $D^0 \to K^-\pi^+\pi^0\pi^0$

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

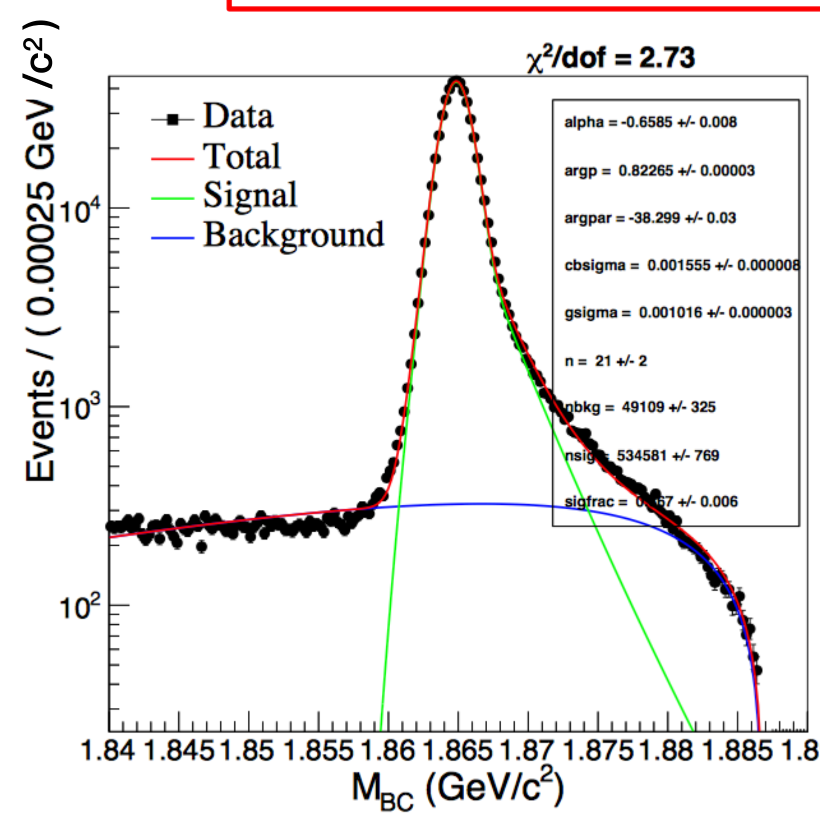
$$\mathcal{B}_{\rm sig} = \frac{N^{\rm DT}_{\rm tag,sig}}{N^{\rm ST}_{\rm tag}} \frac{\varepsilon_{\rm tag}}{\varepsilon_{\rm tag,sig}}$$



(a)DT $(K^-\pi^+\pi^0\pi^0)$



(b)DT $(K^+\pi^-)$



(c)ST

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

$$\mathcal{B}(D^0 \to K^-\pi^+\pi^0\pi^0) = (8.98 \pm 0.13({\rm stat}) \pm 0.40({\rm syst}))\%$$

BESIIIPreliminary

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

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

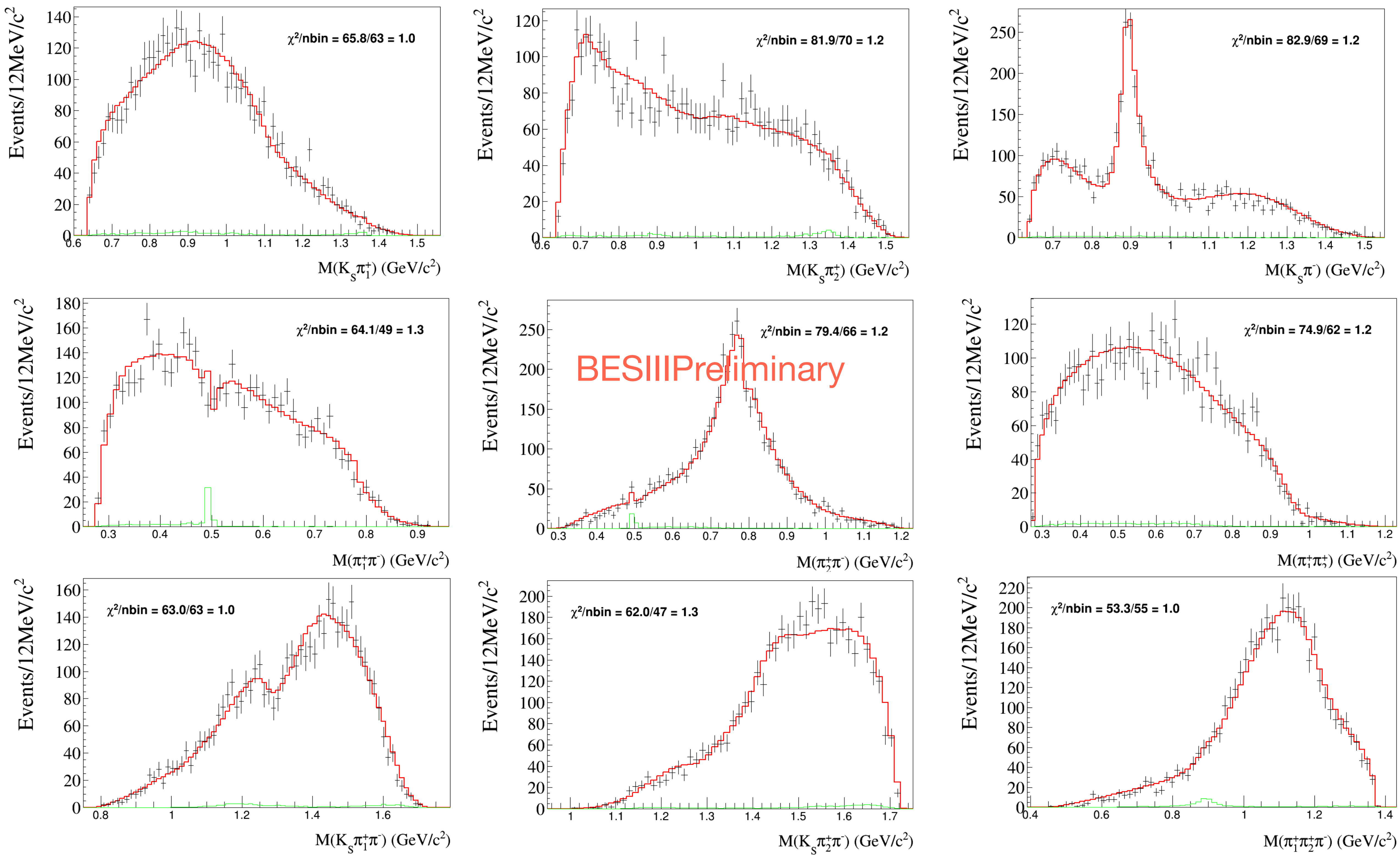
The number of event selected is 4559 with a purity of ~99%

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

BESIIIPreliminary

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



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

The preliminary results of branching fractions for different components：

BESIII *Preliminary*

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.

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

Event selected with double tag

Tag modes:

$$D_s^- \to K_S^0 K^-, D_s^- \to K^+ K^- \pi^-, D_s^- \to K_S^0 K^- \pi^0, D_s^- \to K^+ K^- \pi^- \pi^0,$$
$$D_s^- \to K_S^0 K^+ \pi^- \pi^-, D_s^- \to \pi^- \eta_{\gamma\gamma}, D_s^- \to \pi^- \eta'_{\pi^+\pi^-\eta}$$

Data sample for amplitude analysis:

- A multi-variate analysis is performed to suppress the background from fake η.
- The retained data sample has 1239 events with a purity of (97.7±0.5)%.

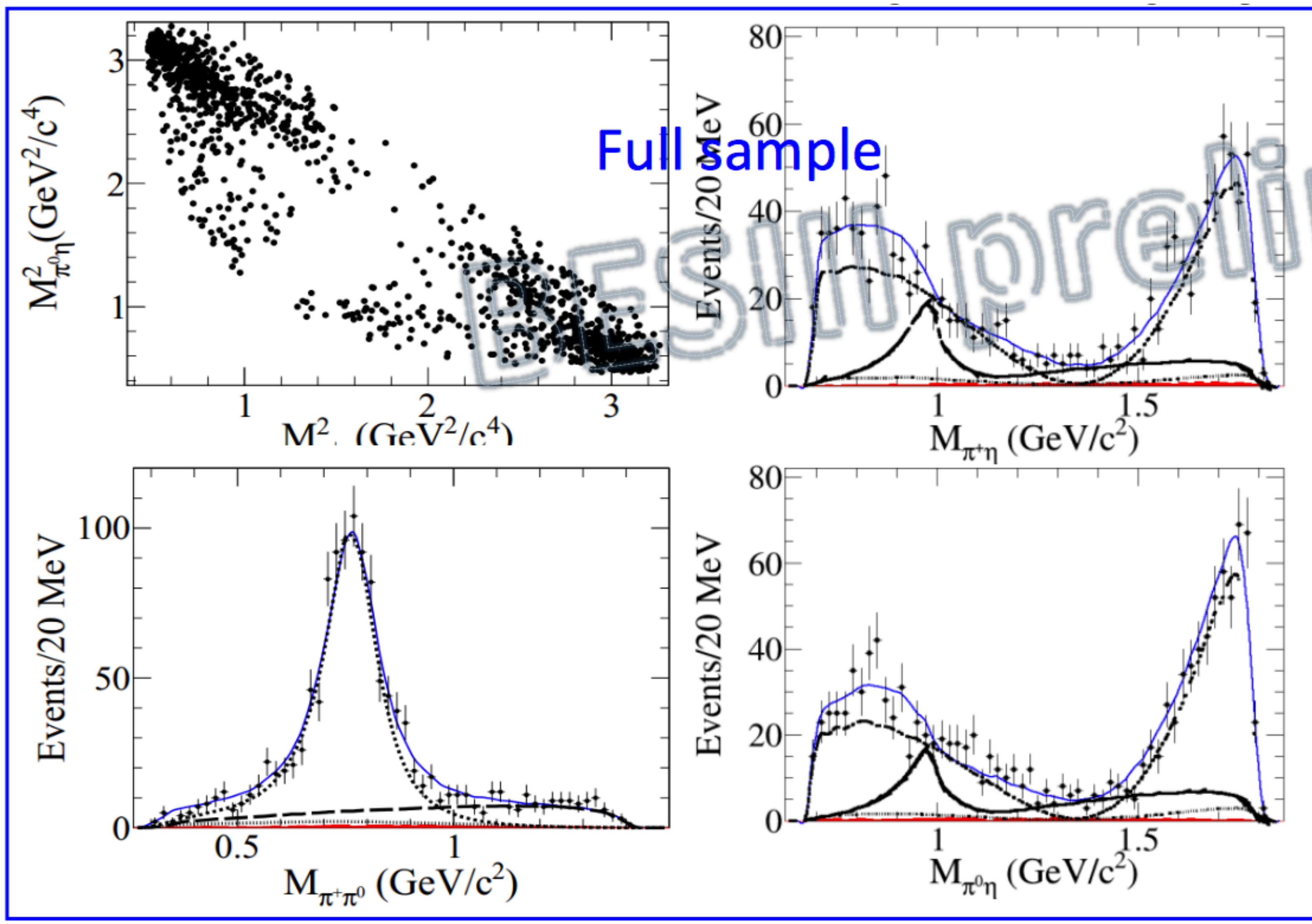
Amplitude Analysis of $D_S^+ \to \pi^+\pi^0\eta$

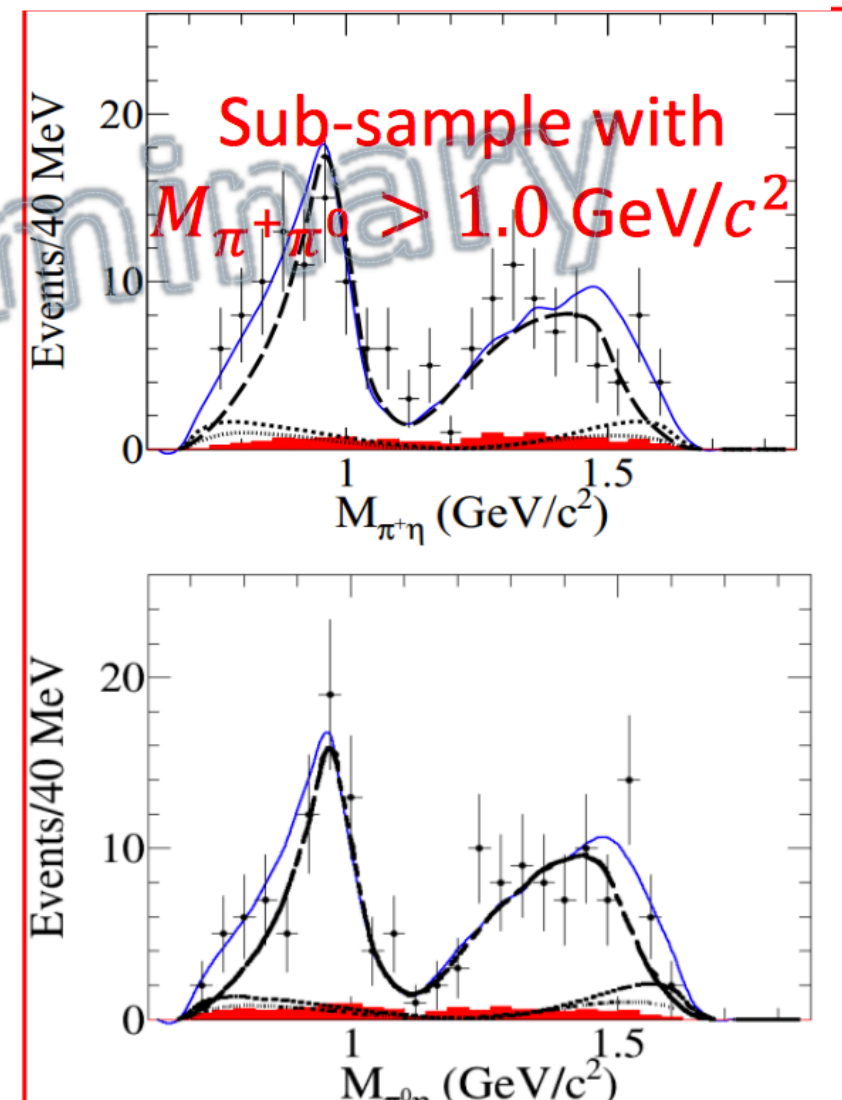
Observation of $D_S^+ \to a^0(980)^+\pi^0$

Amplitude	Significance (σ)	Phase	FF
$D_s^+ \to \rho^+\eta$	> 20	0.0 (fixed)	$0.783 \pm 0.050 \pm 0.021$
$D_s^+ \to (\pi^+\pi^0)_V\eta$	5.7	$0.612 \pm 0.172 \pm 0.342$	$0.054 \pm 0.021 \pm 0.026$
$D_s^+ \to a_0(980)\pi$	16.2	$2.794 \pm 0.087 \pm 0.041$	$0.232 \pm 0.023 \pm 0.034$

BESIII preliminary

The amplitudes agree with: $A(D_s^+ \to a_0(980)^+\pi^0) = -A(D_s^+ \to a_0(980)^0\pi^+)$ within stat. uncertainty, thus we set the magnitudes to be the same with the phase difference fixed to π.

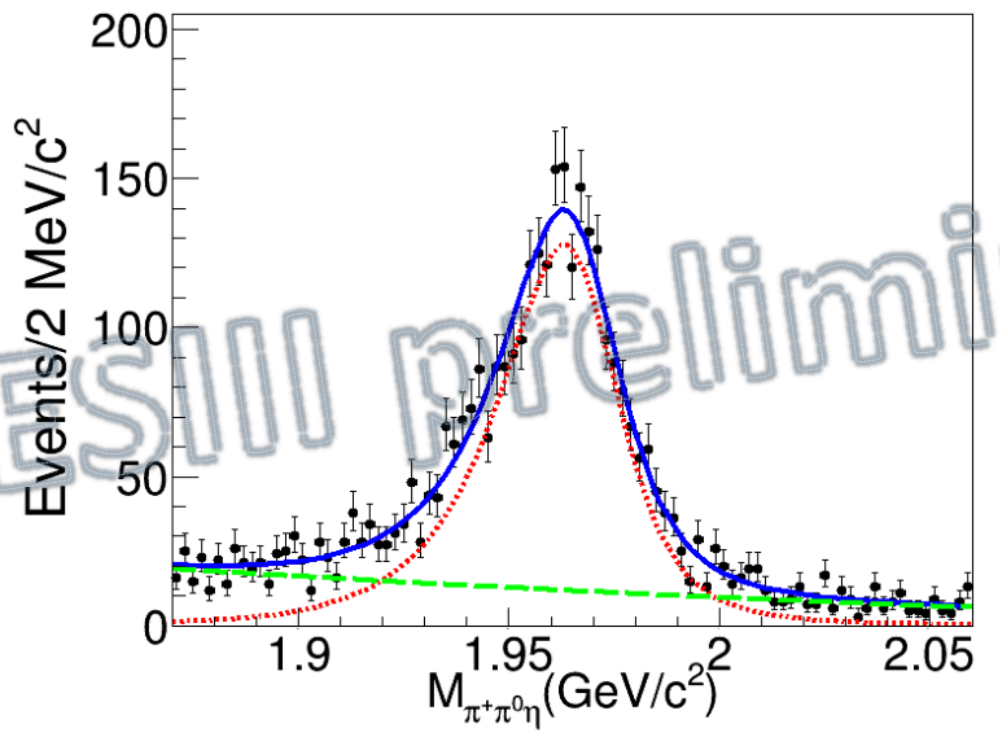




Dots with error bar: data; solid: total fit; dashed: $D_s^+ \to \rho^+\eta$; dotted: $D_s^+ \to (\pi^+\pi^0)_V\eta$; long dashed: $D_s^+ \to a_0(980)\pi$ (**with a Stat. significance of 16. 2σ**).

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

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

First observation (last three branching fractions)

- 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. This provides theoretical challenge in understanding such a large *W*-annihilation contribution in D→SP.

Summary

- DTag and DD^{bar} threshold data allows us to perform inclusive and exclusive branching fraction measurement
- Double tag provides clean samples for amplitude analysis
- Many D^0 and D^+ studies have been published, including strong phase and y_{cp} measurements, and more related measurements are on-going
- More D_s studies are on going based on our new 3.19 fb^{-1} data at E_{cm} = 4.178 GeV
  - K_SK-K_LK asymmetry, amplitude analyses of KKπ, ππeta, πππ, and four-body decays, such as KKππ and πππeta