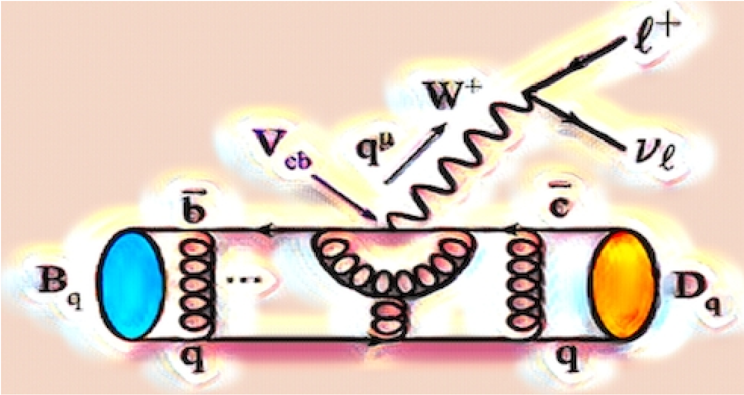


Charm decays @ BESIII

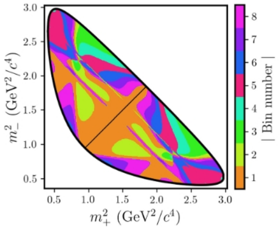
Giulio Mezzadri (INFN Ferrara) – gmezzadr@fe.infn.it

On behalf of the BESIII Collaboration

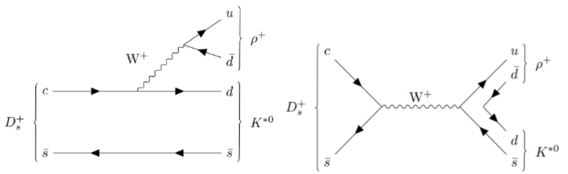
Open LHCb workshop on semileptonic $b \rightarrow c$ decays – 13/04/2023 – LNF

Charmed Mesons Decays

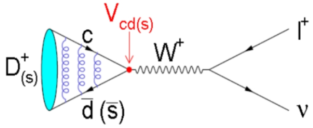
Hadronic



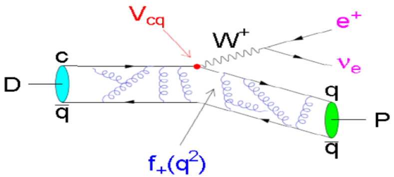
Exclusive vs inclusive
CP Violation
CP-even (odd) fractions



(Semi)Leptonic

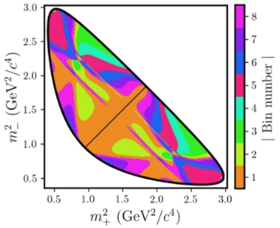


Lattice QCD tuning
Unitarity test of CKM
New Physics?

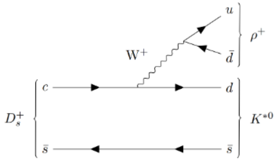


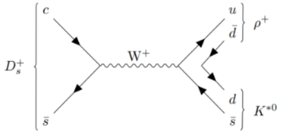
Charmed Mesons Decays

Hadronic

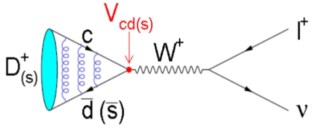


Exclusive vs inclusive
CP Violation
CP-even (odd) fractions

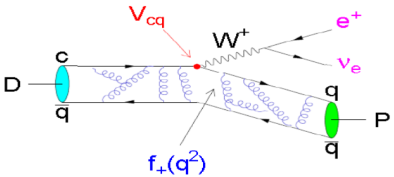




(Semi)Leptonic



Lattice QCD tuning
Unitarity test of CKM
New Physics?

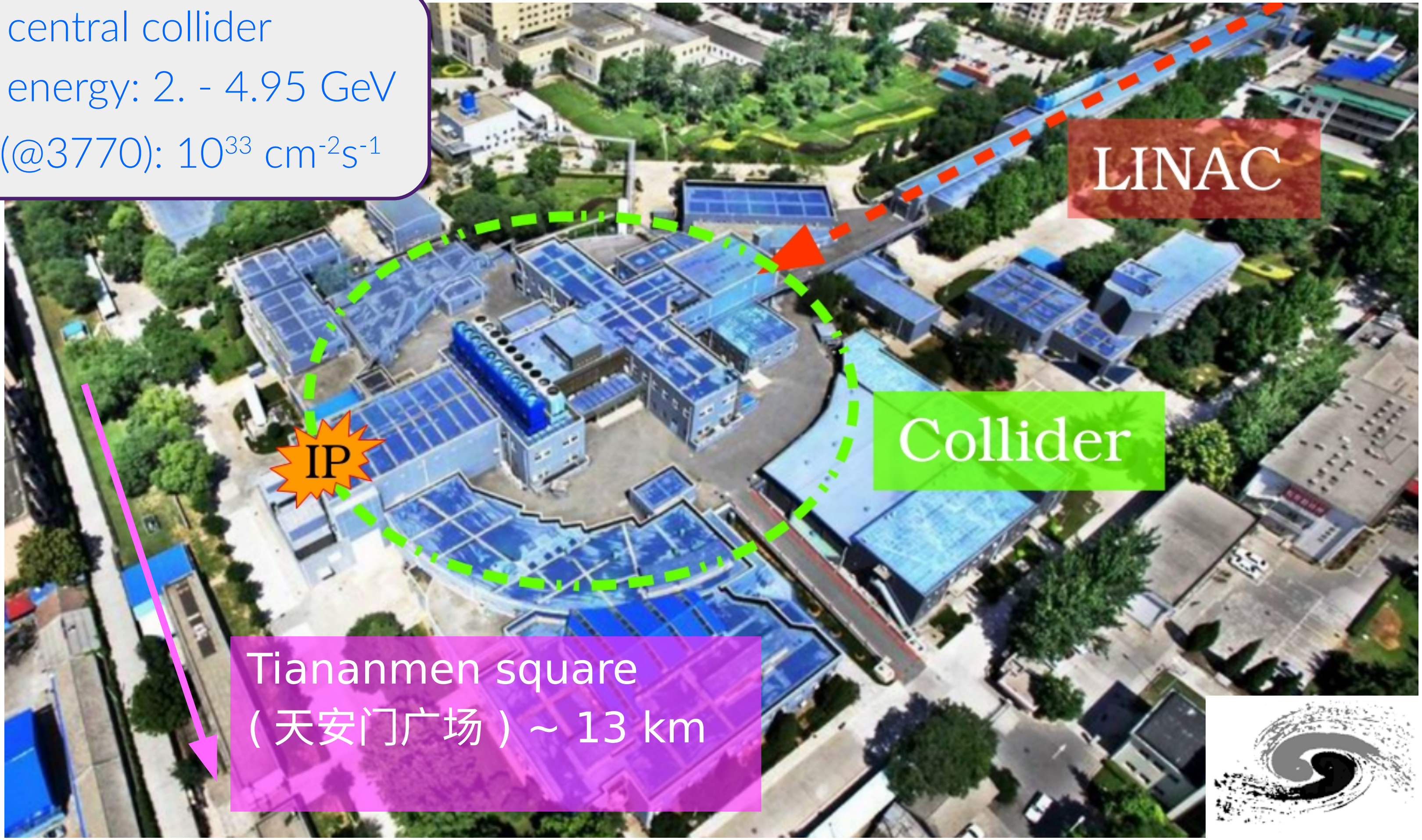


BEPCII @ IHEP (Beijing)

e^+e^- central collider

CM energy: 2. - 4.95 GeV

L_{peak}(@3770): 10^{33} $cm^{-2}s^{-1}$

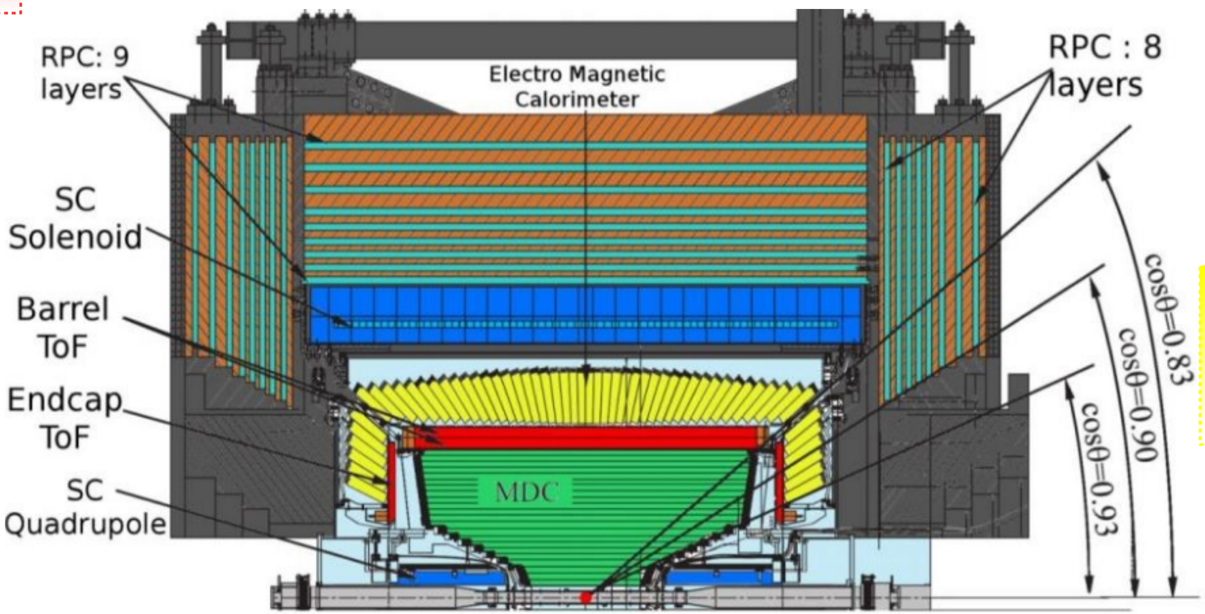


BESIII @ BEPCII

Time Of Flight:
σ_t (barrel) = 90 ps
σ_t (endcap) = 110 ps

1 Tesla Magnetic field

Muon counters:
$\delta_{r\varphi}$ = 1.4 cmv – 1.7 cm



Electromagnetic
Calorimeter:
dE/√E (1 GeV) = 2.5 %

Main Drift Chamber:
σ_x (1 GeV/c) ~ 130 μm
dp/p (1 GeV/c) = 0.5 %

Datasets

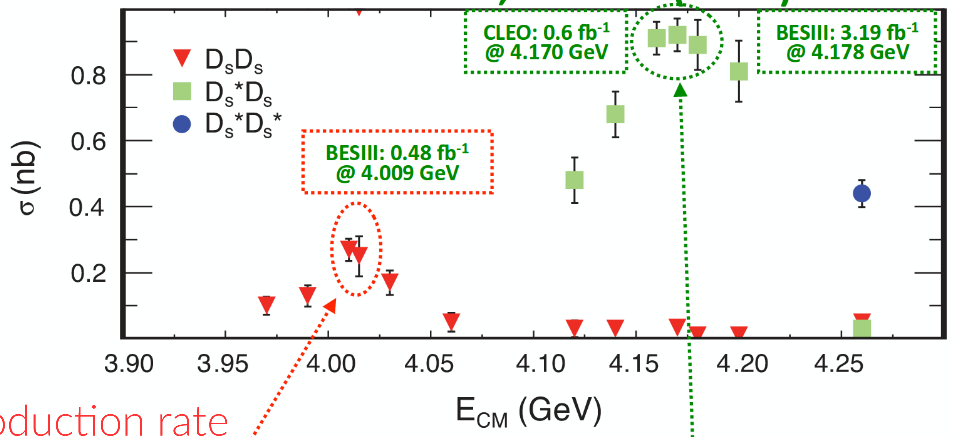
$\sqrt{s}$(GeV)	Integrated luminosity	Decay chain of interest
3.773	2.93 fb^{-1}	$e^+e^- \to \psi(3770) \to D^0\bar{D}^0$ $e^+e^- \to \psi(3770) \to D^+D^-$

$\sqrt{s}$(GeV)	Integrated luminosity(pb^{-1})	
4.178	$3189.0 \pm 0.9 \pm 31.9$	$e^+e^- \to D_s^* D_s$ Total: 6.32 fb^{-1}
4.189	$526.7 \pm 0.1 \pm 2.2$	
4.199	$526.0 \pm 0.1 \pm 2.1$	
4.209	$517.1 \pm 0.1 \pm 1.8$	
4.219	$514.6 \pm 0.1 \pm 1.8$	
4.226	$1047.3 \pm 0.1 \pm 10.2$	

BESIII can shift its center of mass energy to produce charmed mesons pairs at threshold

@psi(3770) ~ 21 M D^0 and 16 M D^+

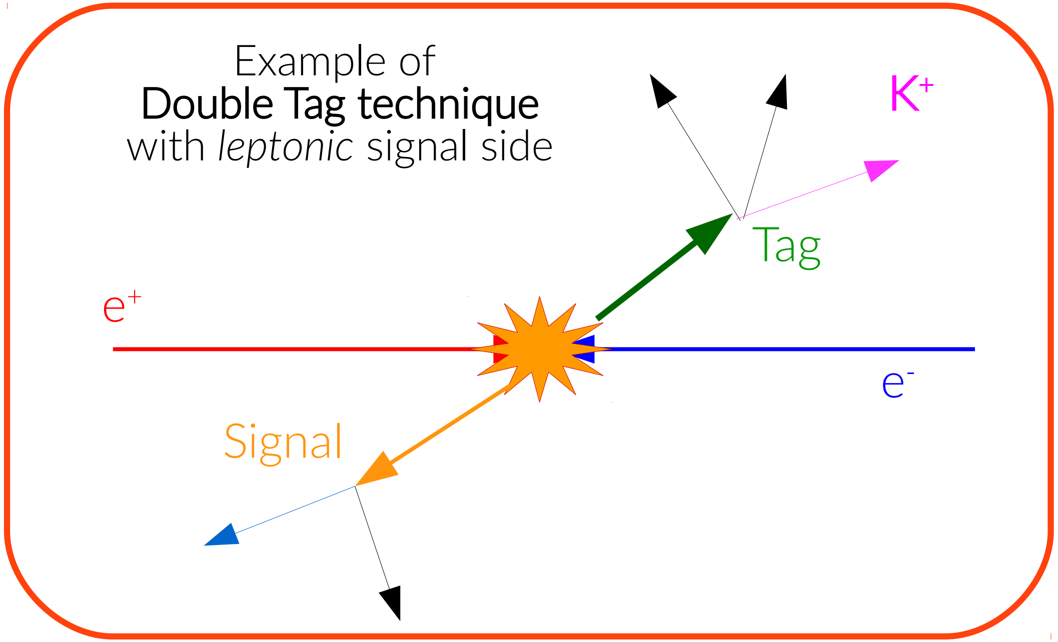
CLEO PRD80, 072001 (2009)



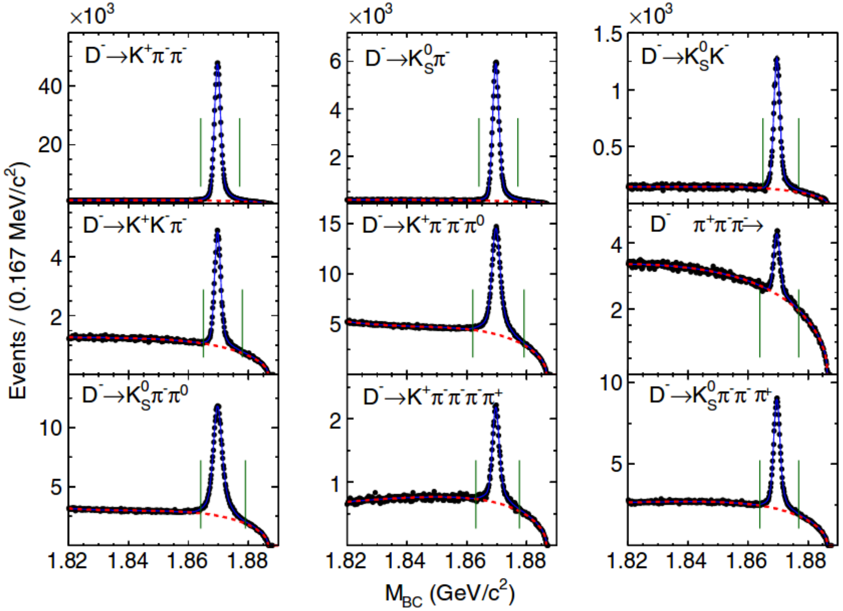
Clean sample, low production rate
~0.4 M D_s produced

Higher production rate, BF($D^*_s \to \gamma D_s$)
~6 M D_s produced

Charmed meson decay at threshold at BESIII



Example D^- Tag mode



Variables of interest (calculated in e^+e^- reference frame)

Mass beam constrained

$$M_{bc} = \sqrt{E^2_{beam} - p^2_{candidate}}$$

Energy difference

$$\mathrm{dE} = \mathrm{E}_{\mathrm{candidate}} - \mathrm{E}_{\mathrm{beam}}$$

Missing mass

$$\mathrm{U}_{\mathrm{miss}} = \mathrm{E}_{\mathrm{miss}} - |\vec{p}_{\mathrm{miss}}|$$

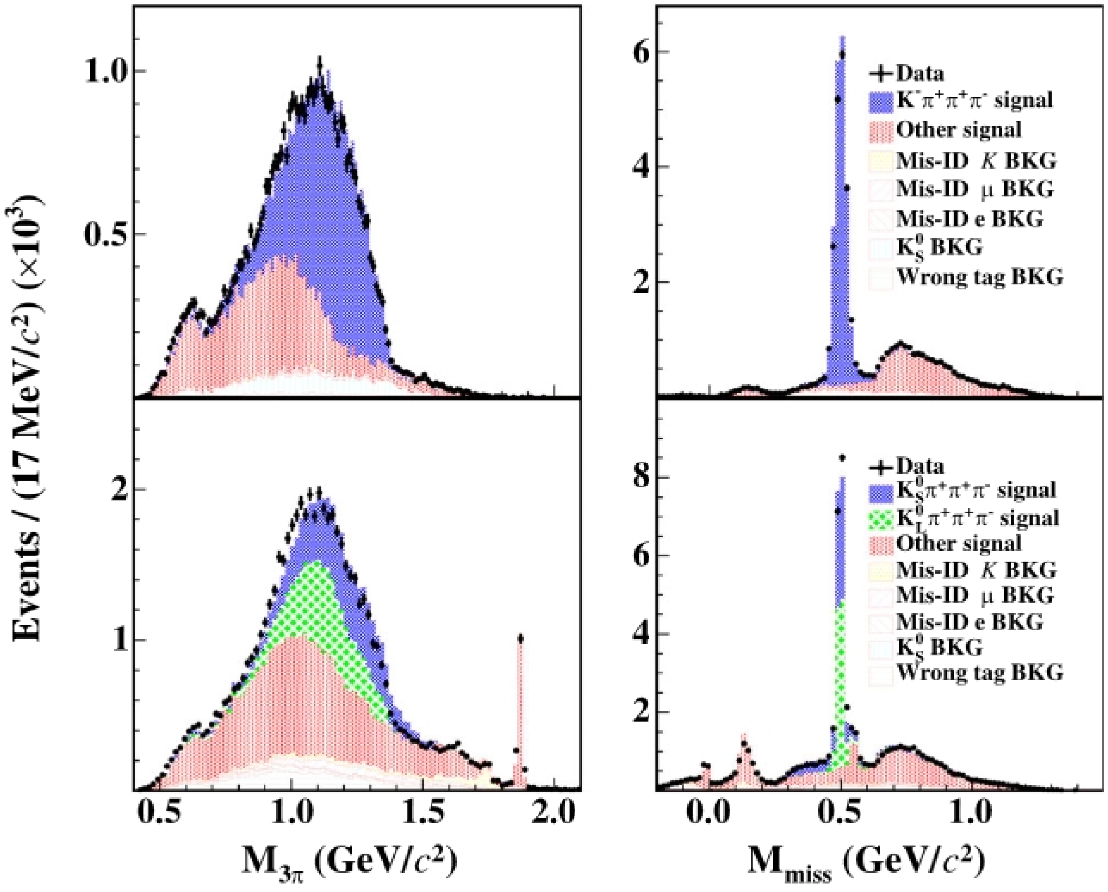
Selected results

- $D_{(s)} \to$ hadrons + X
  - $D \to \pi^+\pi^+\pi^- X$
  - $D_s \to \pi^+\pi^+\pi^- X$
  - $D_s \to K_s X$
- $D_{(s)} \to$ hadrons
  - $D \to$ multihadrons
  - $D \to K_s \pi^0 \omega$
  - $D_s \to \omega\pi^+\eta$
  - $D_s \to \pi^+\pi^+\pi^- \eta$
  - $D_s \to K \pi^+\pi^+\pi^0$
  - $D_s \to K^-K^+\pi^+\pi^+\pi^-$
  - $D_s \to K_sK_s\pi^+$
  - $D_s \to K_sK^+\pi^0$

Analyses that can provide input to R(X) measuments at LHCb

$D^{0(+)} \to \pi^+\pi^+\pi^- X$

PRD 107 (2023) 032002



Tag modes: $D^0 \to K^+\pi^-$ and $D^- \to K^-\pi^+\pi^-$

Number of produced final state is estimated in $M_{3\pi}$ mass bins through dedicated detector response matrix:

$$N^i_{\rm prod} = \sum_{j=1}^{N_{\rm intervals}} (\epsilon^{-1})_{ij} N^j_{\rm obs}$$

Quantum correlation effects:

$$d\mathcal{B}^{\rm corr}_{\rm sig} = f^{\rm corr}_{\rm QC} \times d\mathcal{B}_{\rm sig}$$

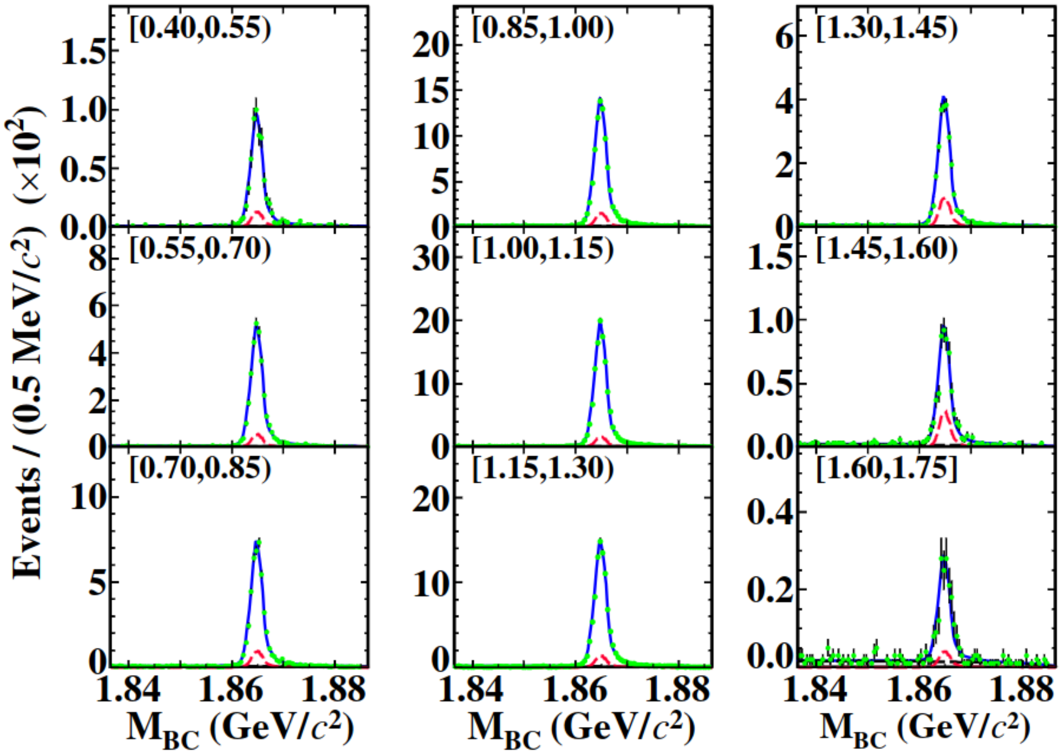
$$f^{\rm corr}_{\rm QC} = \frac{1}{1 - C_f(2f_{CP+} - 1)} \qquad C_f = \frac{2rR\cos\delta}{1 + r^2}$$

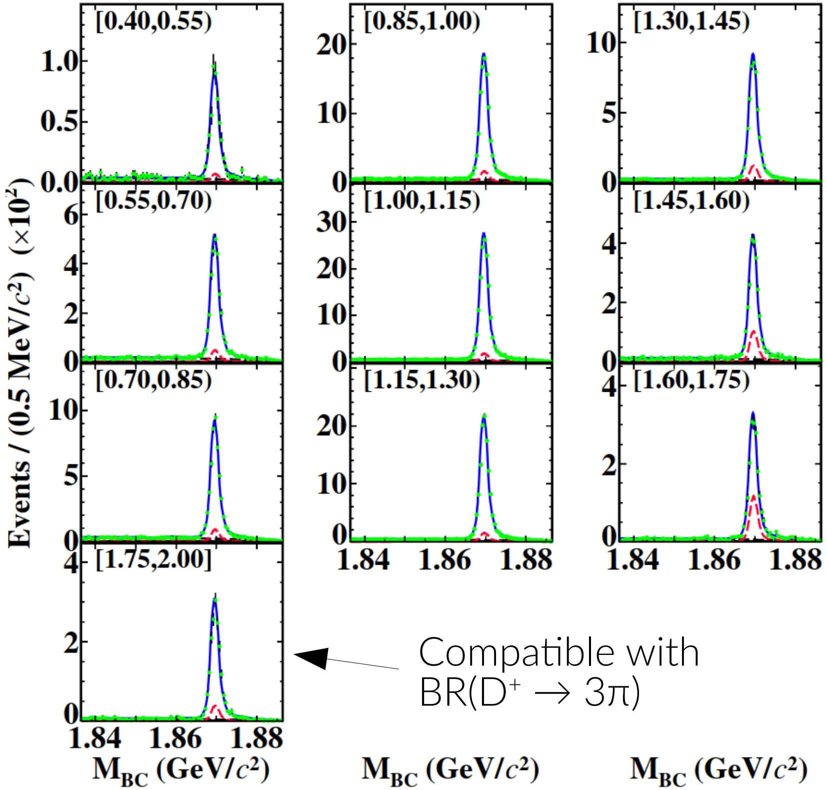
TABLE I. Input parameters for the QC correction.

Parameter	Value
$r_{K\pi}$	0.0586 ± 0.0002 [23]
$\delta_{K\pi}$	$(194.7^{+8.4}_{-17.0})^\circ$ [23]

$D^{0(+)} \to \pi^+\pi^+\pi^- X$

PRD 107 (2023) 032002



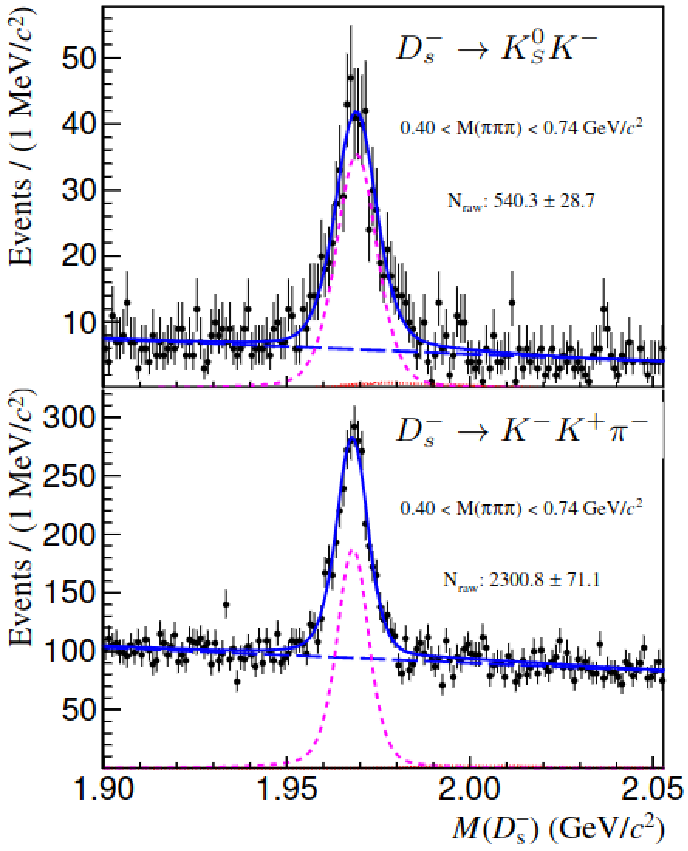


$$\mathcal{B}(D^0 \to \pi^+\pi^+\pi^- X) = (17.60 \pm 0.11 \pm 0.22)\% \qquad \mathcal{B}(D^+ \to \pi^+\pi^+\pi^- X) = (15.25 \pm 0.09 \pm 0.18)\%$$

Compatible with sum of exclusive final state. Little room for additional decays

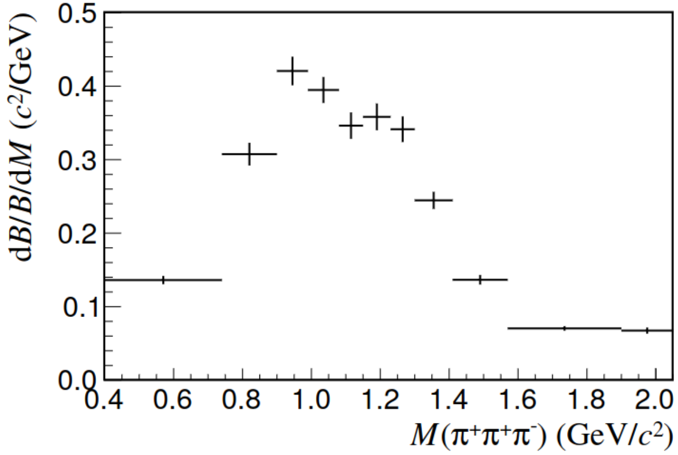
$D_s \to \pi^+\pi^+\pi^- X$

arXiv:2212.13072



Only dataset at 4.178 GeV, L = 3.19/fb
Two D_s^- tag modes.

Extracted partial branching ratio with respect to $M_{3\pi}$ mass

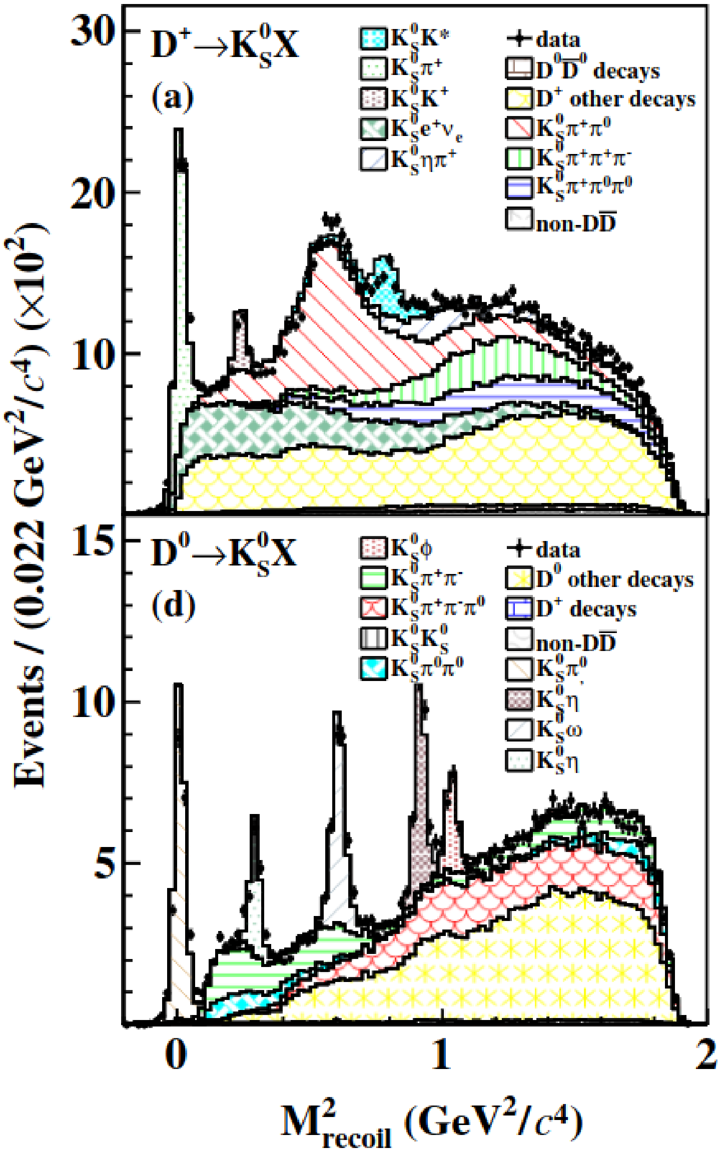


$$\mathcal{B}(D_s^+ \to \pi^+\pi^+\pi^- X) = (32.81 \pm 0.35_{\text{stat}} \pm 0.82_{\text{syst}})\,\%$$

25% larger than sum of exclusive BR

$D^{0(+)} \to K_s X$

ArXiv:2302.14488



Use full psi(3770) dataset, improve precision and compare with exclusive datasets

Extracted QC correction factor in two tag modes

CP tag mode	$\bar{D}^0 \to K^+K^-$	$\bar{D}^0 \to K^0_S\pi^0$
$S^{\pm}_{\rm measured}$	57779 ± 287	70512 ± 311
$M^{\pm}_{\rm measured}$	4760 ± 81	4068 ± 78
f_{CP+}	0.413 ± 0.010	
Correction factor	1.0204 ± 0.0024	

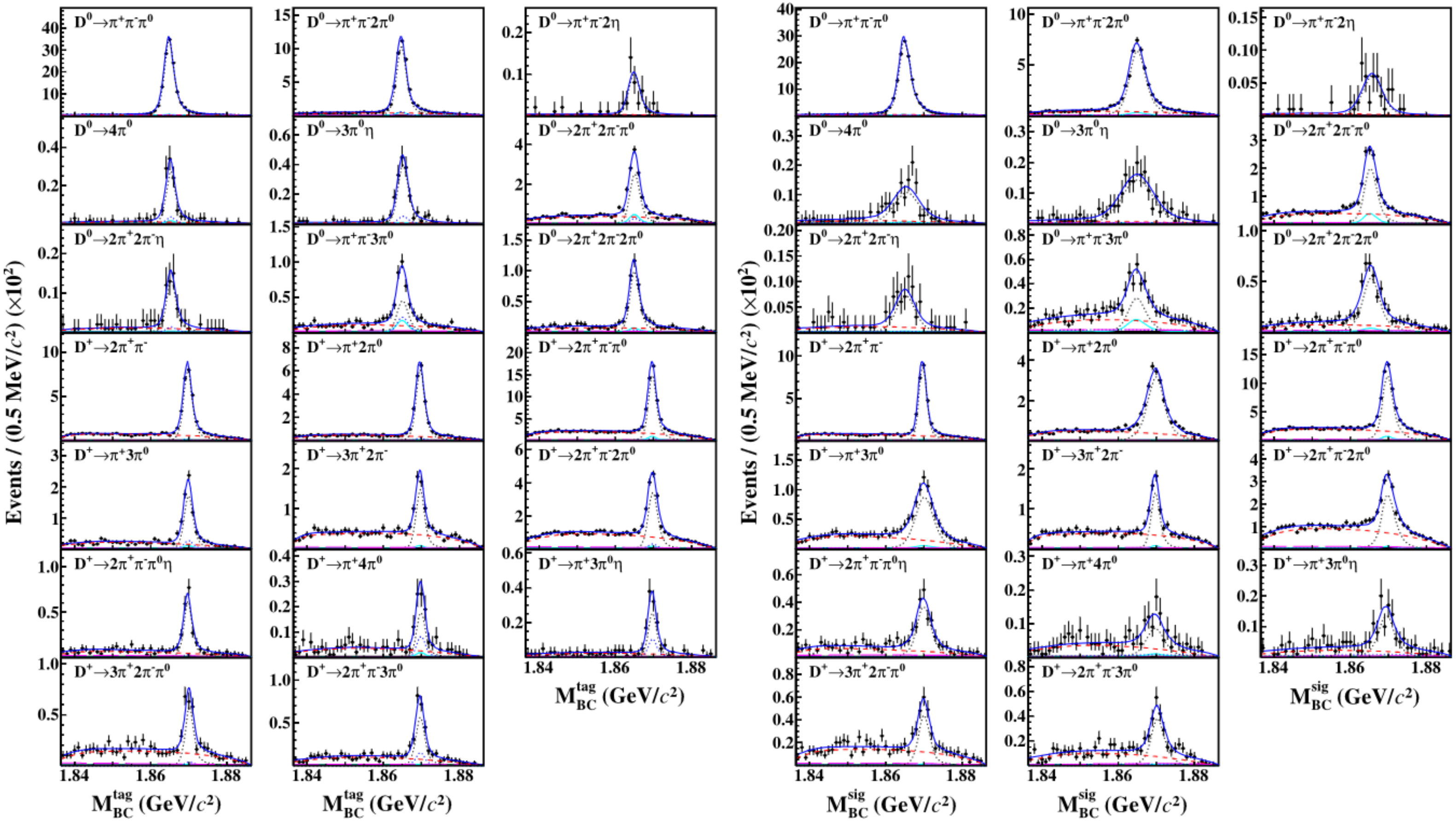
Decay mode	PDG (%) [3]	This study (%)	$\mathcal{B}^{\rm sum}_{\rm exclusive}$ (%)
$D^+ \to K^0_S X$	30.5 ± 2.5	$32.78 \pm 0.13 \pm 0.27$	31.68 ± 0.32
$D^0 \to K^0_S X$	23.5 ± 2.0	$20.54 \pm 0.12 \pm 0.18$	18.16 ± 0.72

Some space for additional new $D^{0(+)}$ decays with K_s

D to multihadrons

PRD 106 (2022) 092005

Extraction of absolute BR of 20 CS final states with multihadrons using ψ(3770) dataset



D to multihadrons

PRD 106 (2022) 092005

TABLE II. The DT yields tagged by $CP \mp$ tags ($M^{\pm}_{\text{measured}}$), the $CP+$ fractions (f_{CP+}), and the QC factors (f_{QC}). The f_{CP+} for $D^0 \to \pi^+\pi^-\pi^0$ is quoted from Ref. [34]; the f_{CP+} values for $D^0 \to \pi^+\pi^-2\pi^0$, $D^0 \to 2\pi^+2\pi^-\pi^0$, $D^0 \to \pi^+\pi^-3\pi^0$, and $D^0 \to 2\pi^+2\pi^-2\pi^0$ are determined in this work; and the f_{CP+} values for $D^0 \to 4\pi^0$ and $D^0 \to 3\pi^0\eta$ are taken to be 1 based on theoretical expectations. The uncertainties are statistical only.

Decay	M^-_{measured}	M^+_{measured}	f_{CP+}	f_{QC} (%)
$D^0 \to \pi^+\pi^-\pi^0$	...	...	0.973 ± 0.017 [34]	93.5 ± 0.5
$D^0 \to \pi^+\pi^-2\pi^0$	65.7 ± 11.1	169.8 ± 13.9	0.682 ± 0.077	97.4 ± 0.7
$D^0 \to 4\pi^0$	...	...	1	93.1 ± 0.5
$D^0 \to 3\pi^0\eta$	...	...	1	93.1 ± 0.5
$D^0 \to 2\pi^+2\pi^-\pi^0$	37.8 ± 8.3	35.5 ± 6.6	0.438 ± 0.104	100.9 ± 0.9
$D^0 \to \pi^+\pi^-3\pi^0$	$5.2^{+3.5}_{-2.8}$	$6.8^{+3.4}_{-2.7}$	$0.520^{+0.338}_{-0.269}$	$99.7^{+3.0}_{-2.4}$
$D^0 \to 2\pi^+2\pi^-2\pi^0$	$3.5^{+2.8}_{-2.1}$	15.9 ± 3.7	$0.790^{+0.269}_{-0.255}$	$95.9^{+2.2}_{-2.1}$

For the neutral final state extracted the Quantum correlation factors

For six of the largest yield, calculated CP asymmetry from their BR

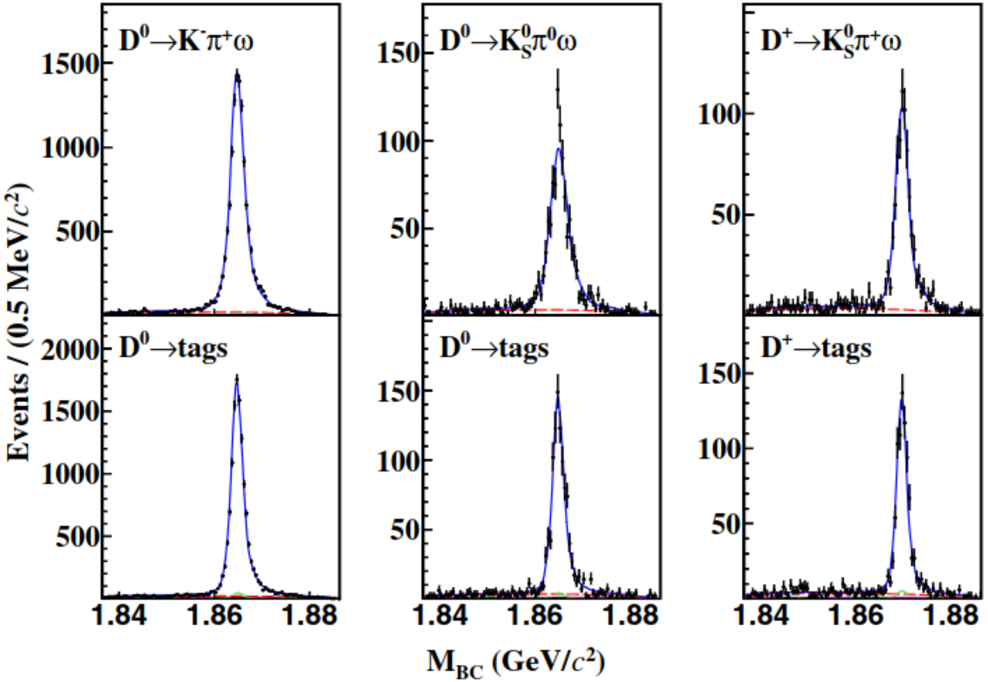
No CP violation is observed

Decay	$\mathcal{B}^+_{\text{sig}} (\times 10^{-4})$	$\mathcal{B}^-_{\text{sig}} (\times 10^{-4})$	$\mathcal{A}^{\text{sig}}_{CP}$ (%)
$\pi^+\pi^-\pi^0$	134.8 ± 1.8	133.3 ± 1.8	$+0.6 \pm 0.9 \pm 0.4$
$\pi^+\pi^-2\pi^0$	97.6 ± 2.6	102.7 ± 2.7	$-2.5 \pm 1.9 \pm 0.7$
$2\pi^+\pi^-$	33.1 ± 1.0	32.3 ± 1.0	$+1.2 \pm 2.2 \pm 0.6$
$\pi^+2\pi^0$	48.3 ± 1.8	43.2 ± 1.7	$+5.6 \pm 2.7 \pm 0.5$
$2\pi^+\pi^-\pi^0$	116.7 ± 3.0	116.0 ± 3.0	$+0.3 \pm 1.8 \pm 0.8$
$2\pi^+\pi^-2\pi^0$	102.7 ± 5.6	111.6 ± 5.8	$-4.2 \pm 3.8 \pm 1.3$

$D \to K_s \pi^0 \omega$

PRD 105 (2022) 032009

Restrict available phase space for new physics in $D \to \overline{K} \pi l^+ l^-$ and test statistical isospin model predictions



Decay mode	$\mathcal{B}_{\text{sig}}$ (%)	$\mathcal{B}_{\text{PDG}}$ (%)
$D^0 \to K^-\pi^+\omega$	$3.392 \pm 0.044 \pm 0.085$	3.0 ± 0.6
$D^0 \to K^0_S\pi^0\omega$	$0.848 \pm 0.046 \pm 0.031$	...
$D^+ \to K^0_S\pi^+\omega$	$0.707 \pm 0.041 \pm 0.029$	...

$$\mathcal{R}^0 \equiv \frac{\mathcal{B}(D^0 \to K^0_S\pi^0\omega)}{\mathcal{B}(D^0 \to K^-\pi^+\omega)} = 0.23 \pm 0.01_{\text{stat}} \pm 0.01_{\text{syst}}$$

$$\mathcal{R}^+ \equiv \frac{\mathcal{B}(D^+ \to K^0_S\pi^+\omega)}{\mathcal{B}(D^0 \to K^-\pi^+\omega)} = 0.21 \pm 0.01_{\text{stat}} \pm 0.01_{\text{syst}}$$

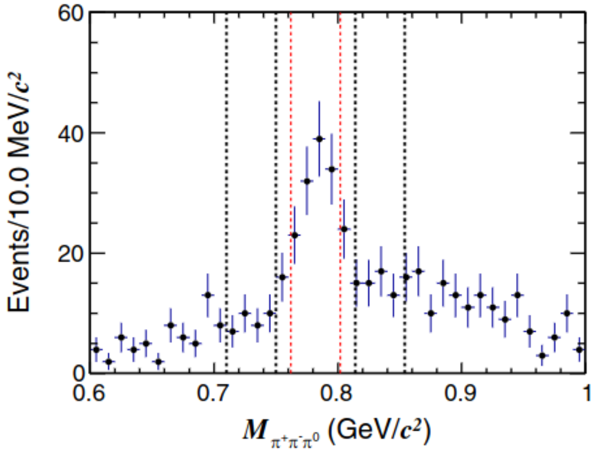
Both results deviates from predictions (0.4 and 0.9)

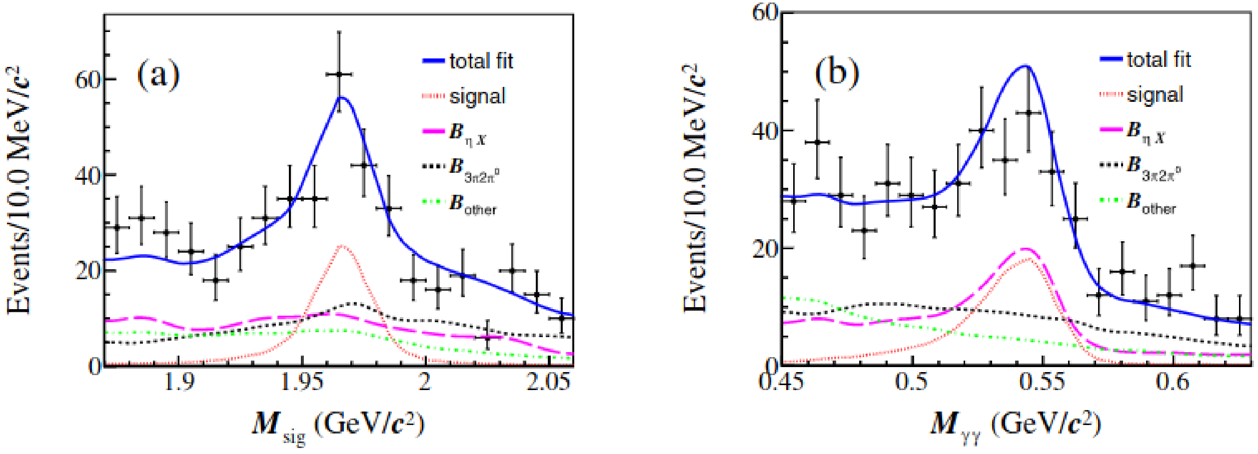
Difference may arise from strong phase between final state decay amplitudes

$D_s^+ \to \omega\pi^+\eta$

PRD 107 (2023) 052010

Use larger D_s dataset from 4.128 to 4.226 GeV. Reconstruct $\omega \to \pi^+\pi^-\pi^0$





First observation of this process at 7.6σ level. No structures in intermediate processes.

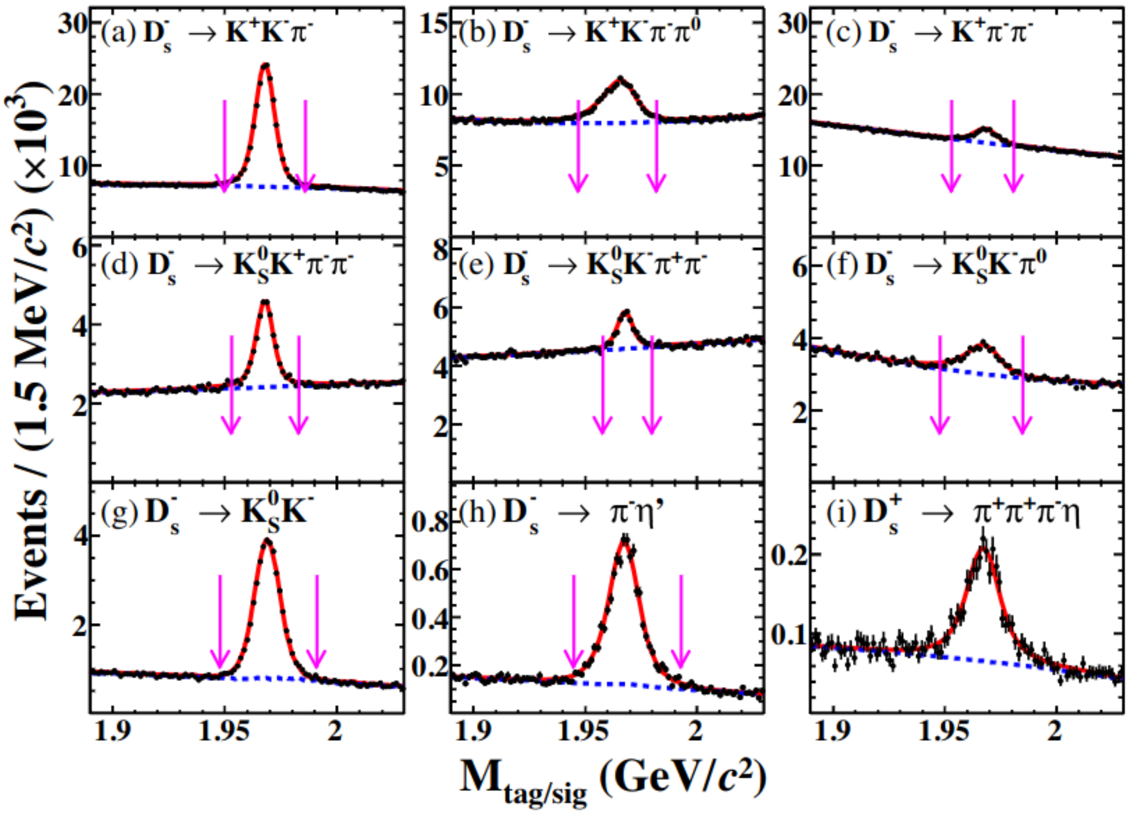
$$\mathcal{B}(D_s^+ \to \omega\pi^+\eta) = (0.54 \pm 0.12 \pm 0.04)\%$$

Branching ratio to provide further detail for $D_s \to \pi\pi\pi X$ contribution

$D_s \to \pi^+\pi^+\pi^- \eta$

PRD 104 (2021) L071101

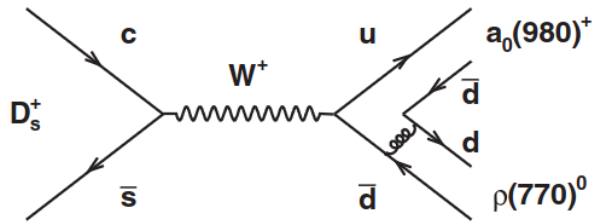
Missing $D_s \to \eta X$ final state with a very large contribution. Use 6.32/fb in 4.178-4.226 GeV range



First measurement of the exclusive BR

$$\mathcal{B}(D_s^+ \to \pi^+\pi^+\pi^-\eta) = (3.12 \pm 0.13_{\rm stat} \pm 0.09_{\rm syst})\%$$

leaving little room for additional $D_s \to \eta X$

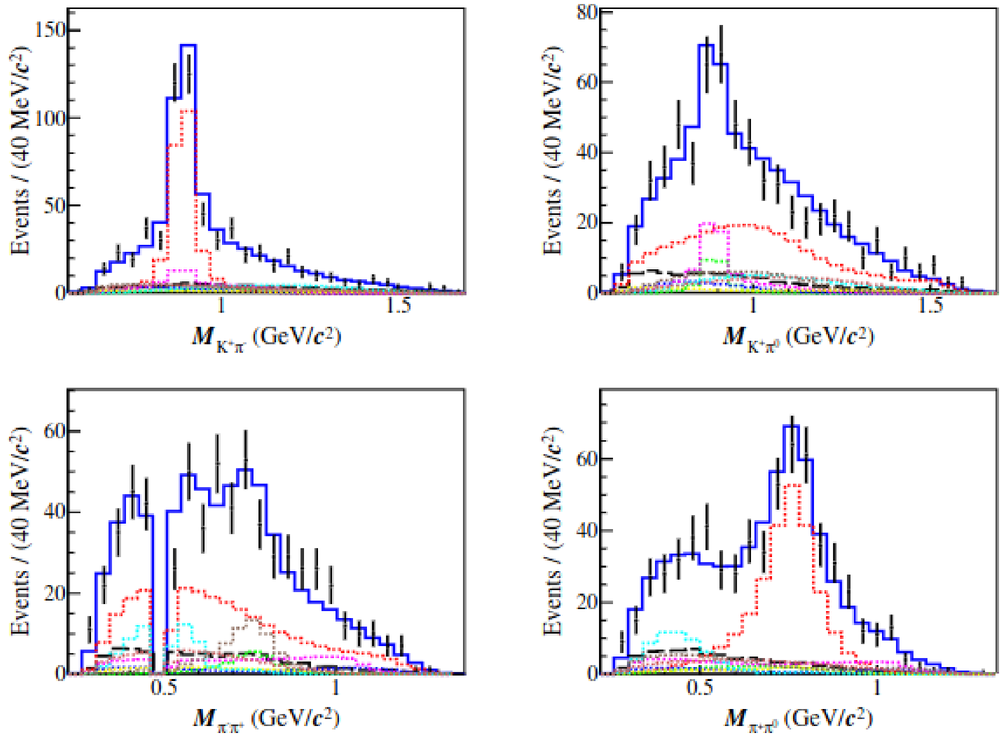


First observation of the W-Annihilation process $D_s \to a_0(980)^+\rho(770)$

Branching ratio is 1 order of magnitude larger than pure WA $D_s \to \rho^0\pi^+$ or $D_s \to \pi^0\pi^+$ processes

$D_s \to K\pi\pi\pi$

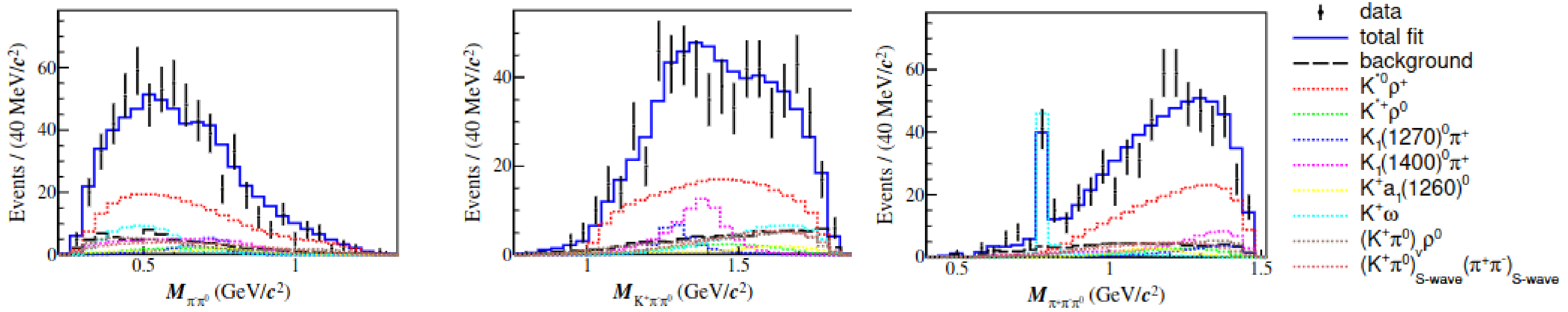
JHEP 09 (2022) 242



First measurement of the singly Cabibbo suppressed decay. Analysis with 6.32/fb

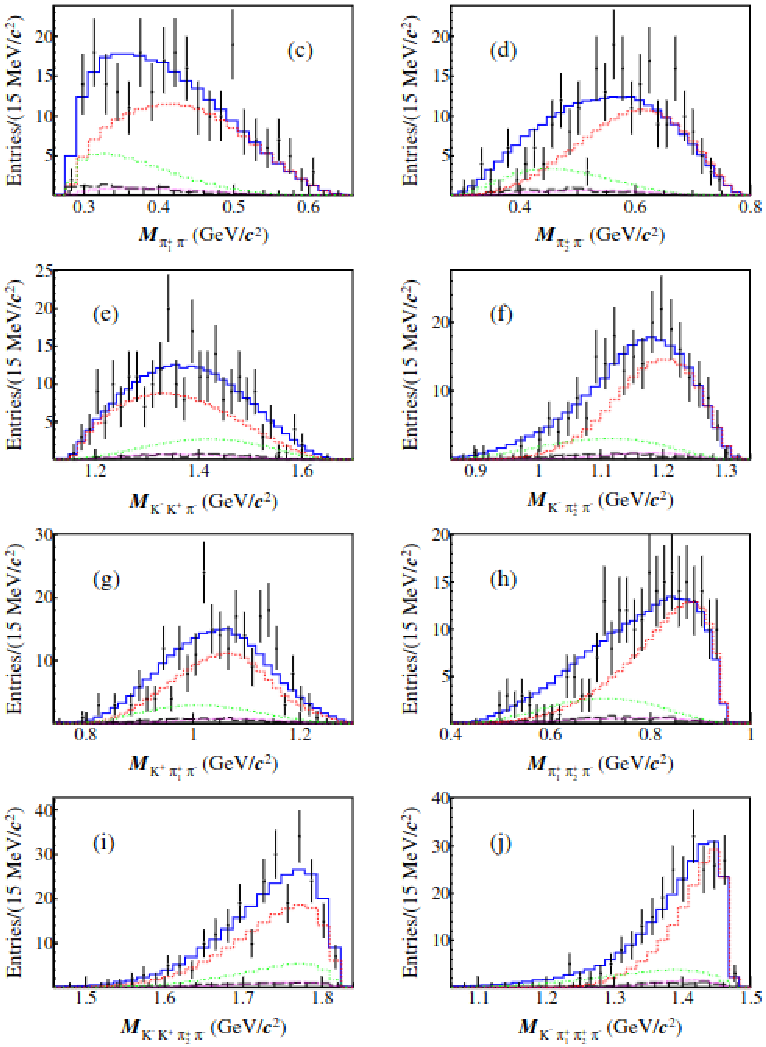
Amplitude analysis is performed to take into account in efficiency estimation all possible intermediate states
Dominant intermediate process $D_s \to K^*\rho$

No CP violation observed by looking at
$D_s^+ \to K^+ \pi^+\pi^-\pi^0$ and $D_s^- \to K^- \pi^+\pi^-\pi^0$



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

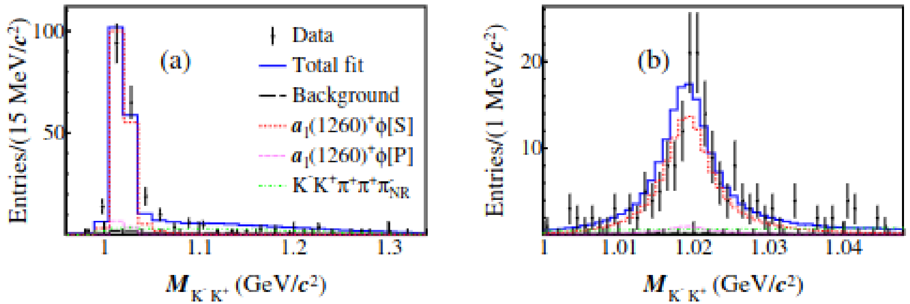
JHEP 07 (2022) 051



Analysis with 6.32/fb

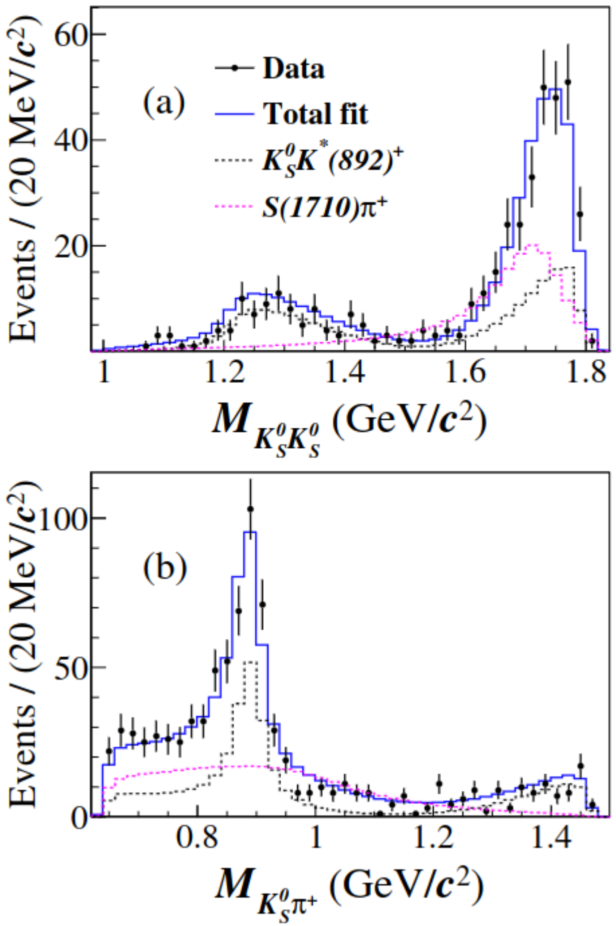
First ever amplitude analysis is performed to take into account in efficiency estimation all possible intermediate states, but only with >5σ significance are kept in the final result.

Good agreement with PDG but improved precision



$D_s \to K_s K_s \pi^+$

PRD 105 (2022) L051103



D_s decay can be also used to shed new light on nature of light hadrons, like $f_0(1710)$

Due to high interference between f_0 and a_0, in the paper denoted generically as S-state.

Branching ratio of the full process is measured and it is compatible with PDG

Based on $f_0(1710)$ results, it is necessary that an $a_0(1710)^0$ state exists, as observed by BaBar (Phys. Rev. D 104, 072002 (2021))

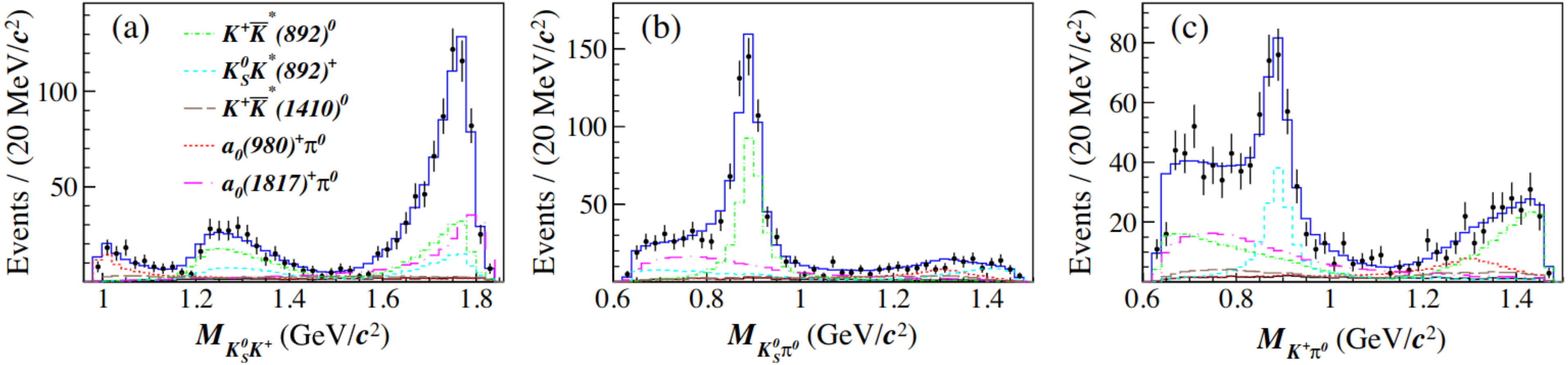
An $a_0(1710)^0$ charged partner is also expected in KsK mass to be searched in $D_s \to K_s K^+ \pi^0$

$D_s \to K_s K^+ \pi^0$

PRL 129 (2022) 182001

Using 6.28/fb D_s data, study the decay to search for possible $a_0(1710)$ charged partner

Total BR is found to be compatible with previous measurements



Observed a charged a_0-like structure in K_sK^+ mass with significance greater than 10σ. This results supports the existence of a new a_0 triplet, as predicted by Phys. Rev. D 79, 074009 (2009) and other works

Its mass is 100 MeV larger than expectation for $f_0(1710)$ isospin-1 partner. To extract further details on its nature, combined amplitude analysis of $D_s \to K_sK_s\pi^+$ and $D_s \to K_sK\pi^0$ is needed

Summary and outlook

- BESIII powerful machine for charmed hadron decays
  - Not only as input for B physics, but for CKM matrix measurement, LQCD calculation, Light Hadrons

- In the next future, additional steps:
  - A total of 20/fb at psi(3770) on tape by early 2024
    - Crucial contribution to QC measurement, CKM gamma extraction

  - Upgraded accelerator will provide more efficient data taking for D_s analyses
    - Further reduce systematics for R measurements

  - New data always allows for improved techniques to reduce errors
    - Tag based analyses
    - Machine learning


谢谢
P. ALLORA
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