Institute of High Energy Physics
Chinese Academy of Sciences

Charm meson decays at BESIII

Zehui Lu
On behalf of the BESIII Collaboration

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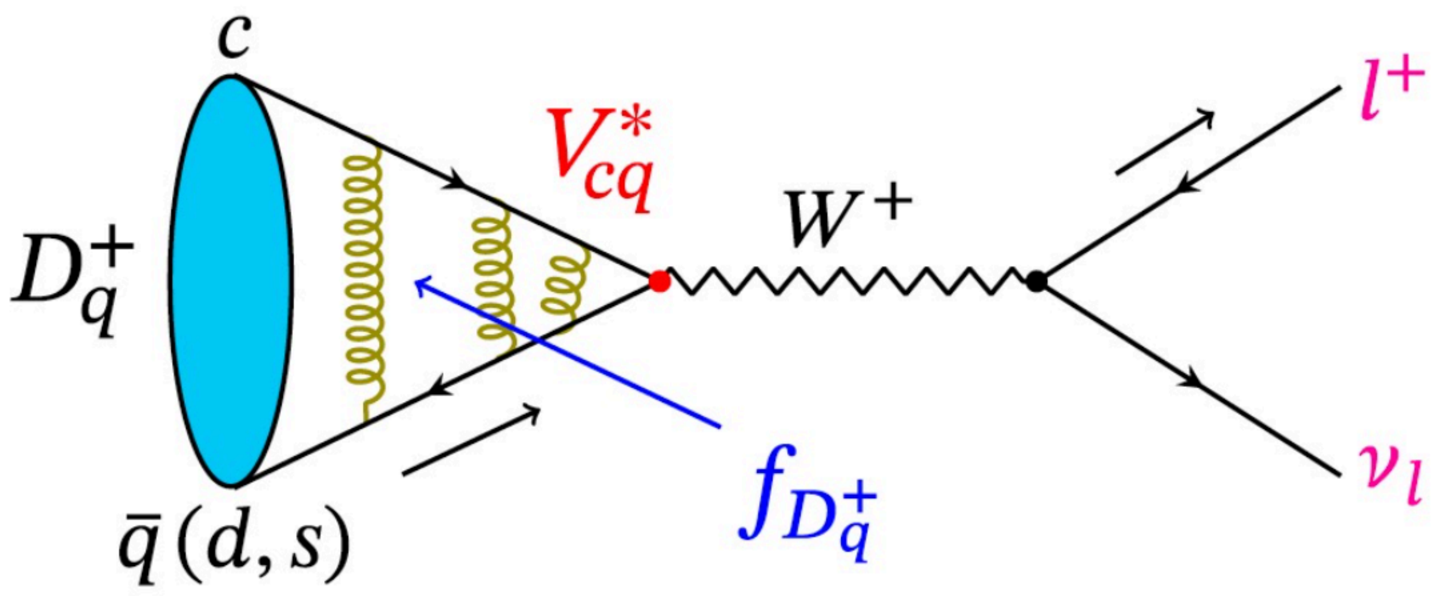
OutLine

- ✓ Charm meson physics
- ✓ BESIII experiment
- ✓ Highlight charm meson results @ BESIII
- ✓ Summary

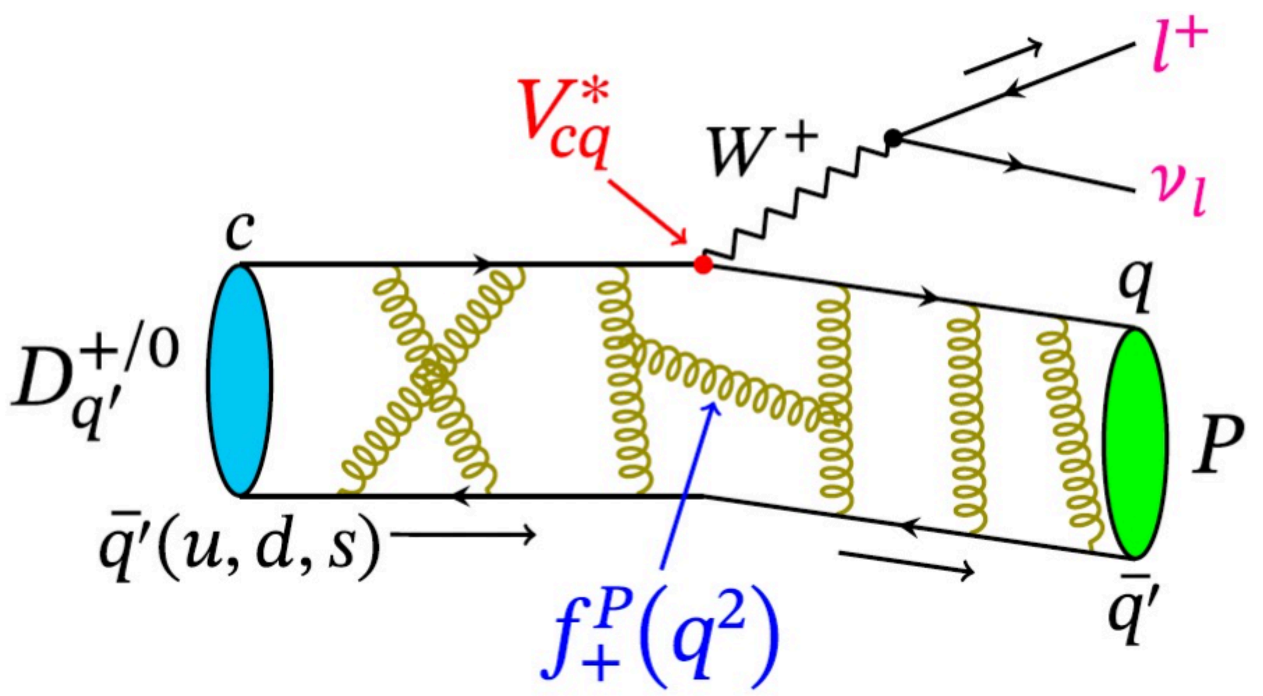
Why charm meson physics?

Pure leptonic decay



$\Gamma(D_{(s)}^+ \to l^+\nu_l) \propto |f_{D_s^+}|^2 \cdot |V_{cd(s)}|^2$

Semi-leptonic decay



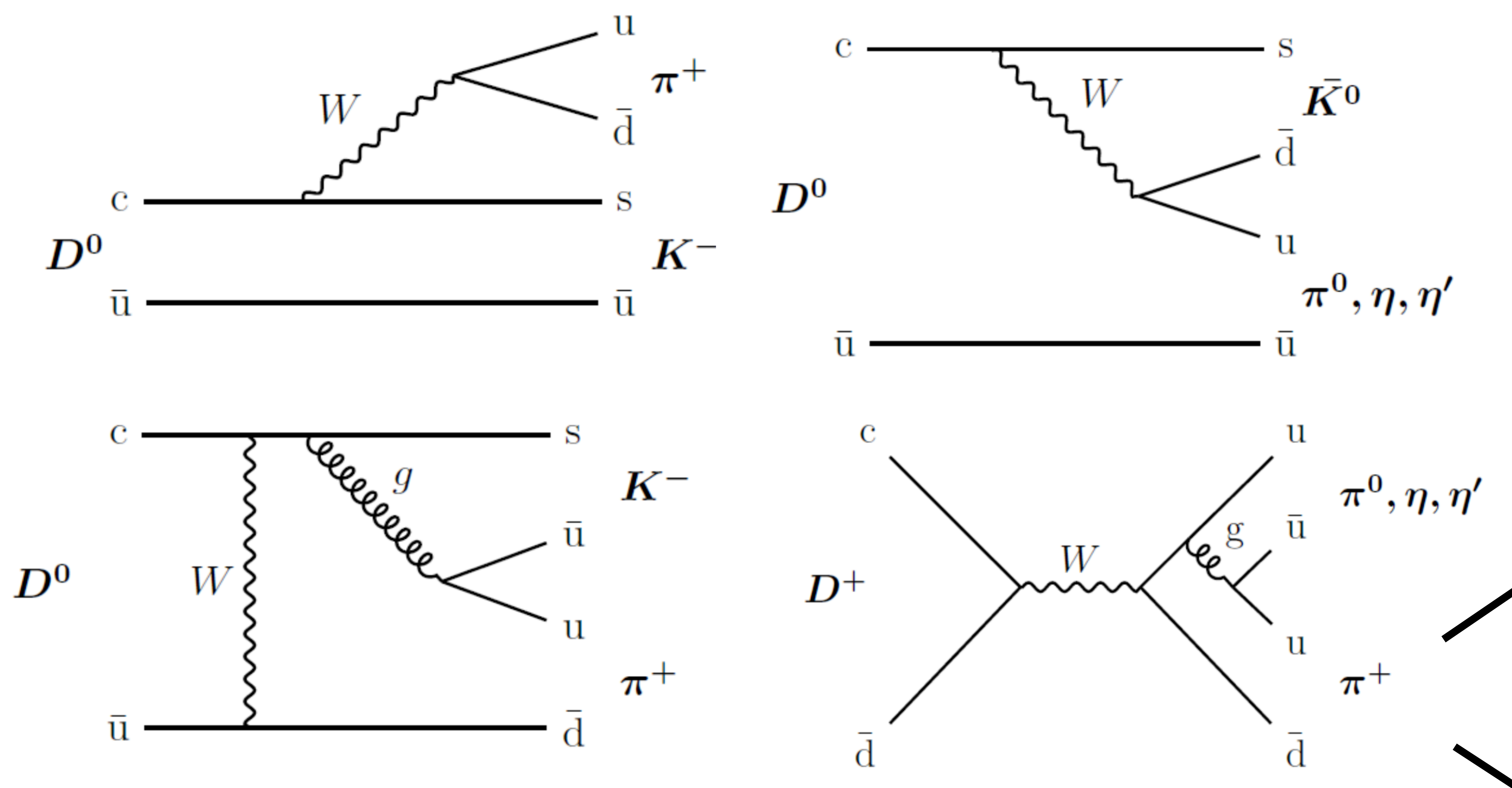
$\Gamma(D_{(s)} \to Pl^+\nu_l) \propto |f_+(q^2)|^2 \cdot |V_{cd(s)}|^2$

Ideal bridge to access the strong and weak effects between quarks

- ✓ $|V_{cs}|$ and $|V_{cd}|$ → Test CKM matrix unitarity
- ✓ Decay Constant $f_{D_{(s)}^+}$ and form factor f_+ → Calibrate LQCD
- ✓ Branching fraction (BF) ratio → Test lepton flavor universality

Why charm meson physics?

Hadronic decay



✓ Probe non-perturbative QCD

✓ Help to understand hadron spectroscopy

✓ Probe the weak decay mechanisms in DCS decays

Amplitude analysis

→ Get the information of $D \to VP, PP \ldots,$ where V and P denote vector and pseudoscalar, respectively.

Absolute BFs measurement

→ Test theoretical calculations of these BFs and benefit the understanding of the quark SU(3) flavor symmetry and CP violation.

Why charm meson physics?

Quantum correlation $D^0\bar{D}^0$: $|\psi(3770)\rangle \to \frac{1}{\sqrt{2}}(|D^0\rangle|\bar{D}^0\rangle - |\bar{D}^0\rangle|D^0\rangle)$

➡ Provide direct access to the $D^0 - \bar{D}^0$ strong-phase difference

✓ Important input in CKM γ measurement

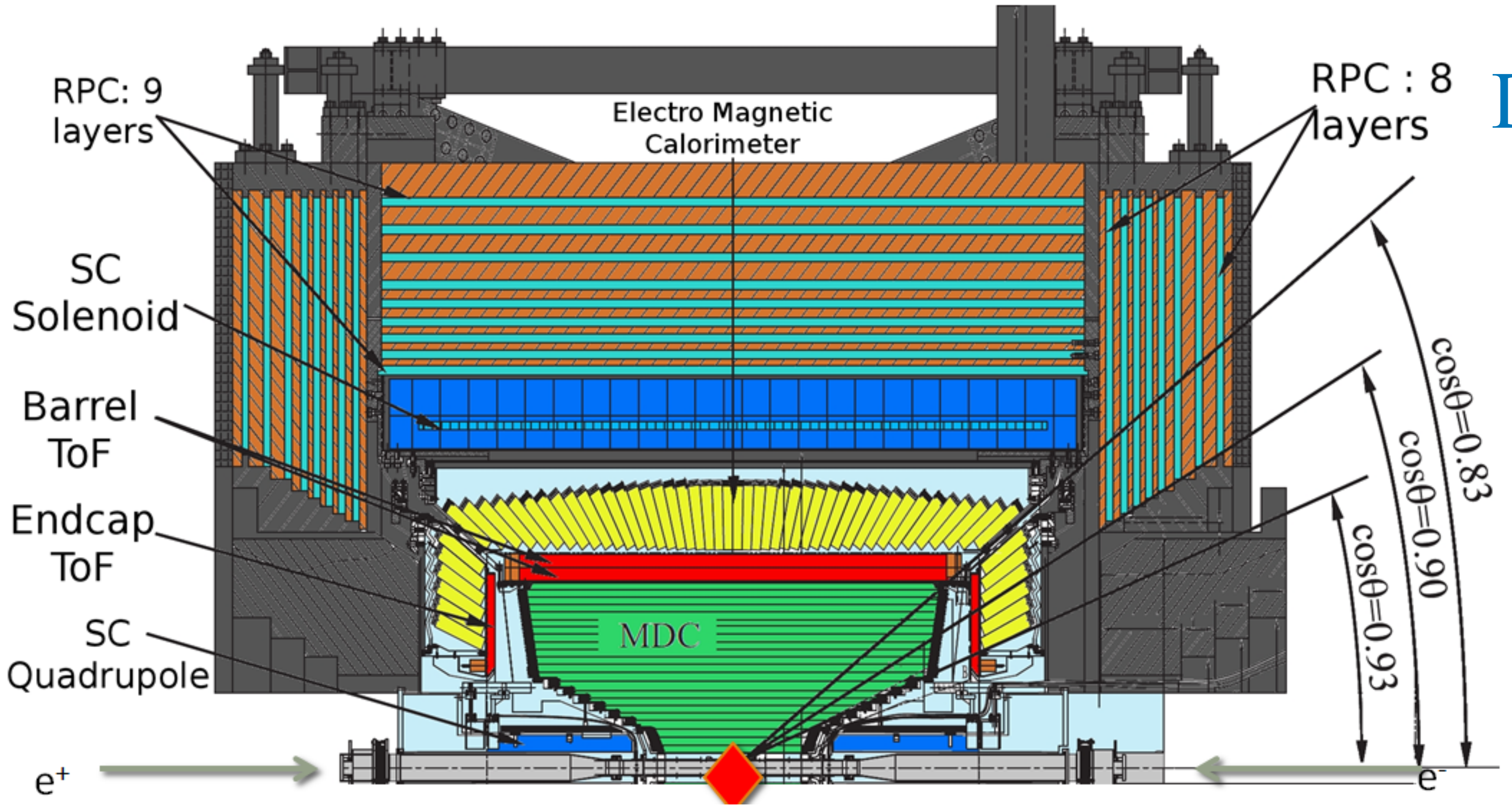
✓ Precise test of perturbative QCD calculations in charm decays, mixing and CPV

Different methods depending on the final states of D decays

- GLW : D decaying to CP eigenstates
- ADS : D decaying to CF/DCS eigenstates
- GGSZ : D decaying to self-conjugate eigenstates

Flavour	$K^\pm\pi^\mp\pi^\mp\pi^-$, $K^\pm\pi^\mp\pi^0$, $K^\pm\pi^\mp$, ...
CP-even	K^+K^-, $\pi^+\pi^-$, $\pi^0\pi^0$, $K^0_S\pi^0\pi^0$, $K^0_L\pi^0$, $K^0_L\omega$, $\pi^+\pi^-\pi^{0\dagger}$
CP-odd	$K^0_S\pi^0$, $K^0_S\eta$, $K^0_S\omega$, $K^0_S\eta'$, $K^0_S\phi$, $K^0_L\pi^0\pi^0$
Self-conjugate	$K^0_S\pi^+\pi^-$, $K^0_SK^+K^-$, ...

BESIII and Datasets



Datasets:

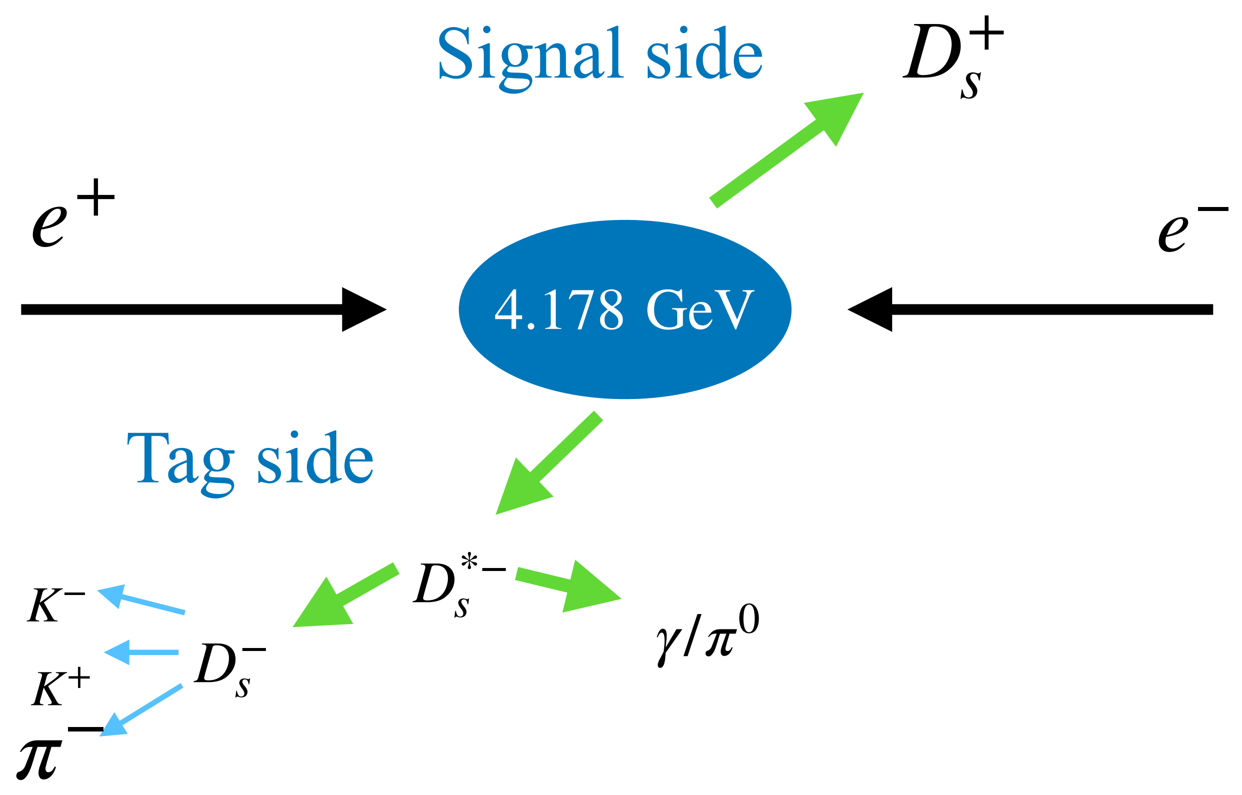
— $D^{+(0)}$: 2.93 fb^{-1} @ $E_{cm} = 3.773$ GeV. Collected in 2011

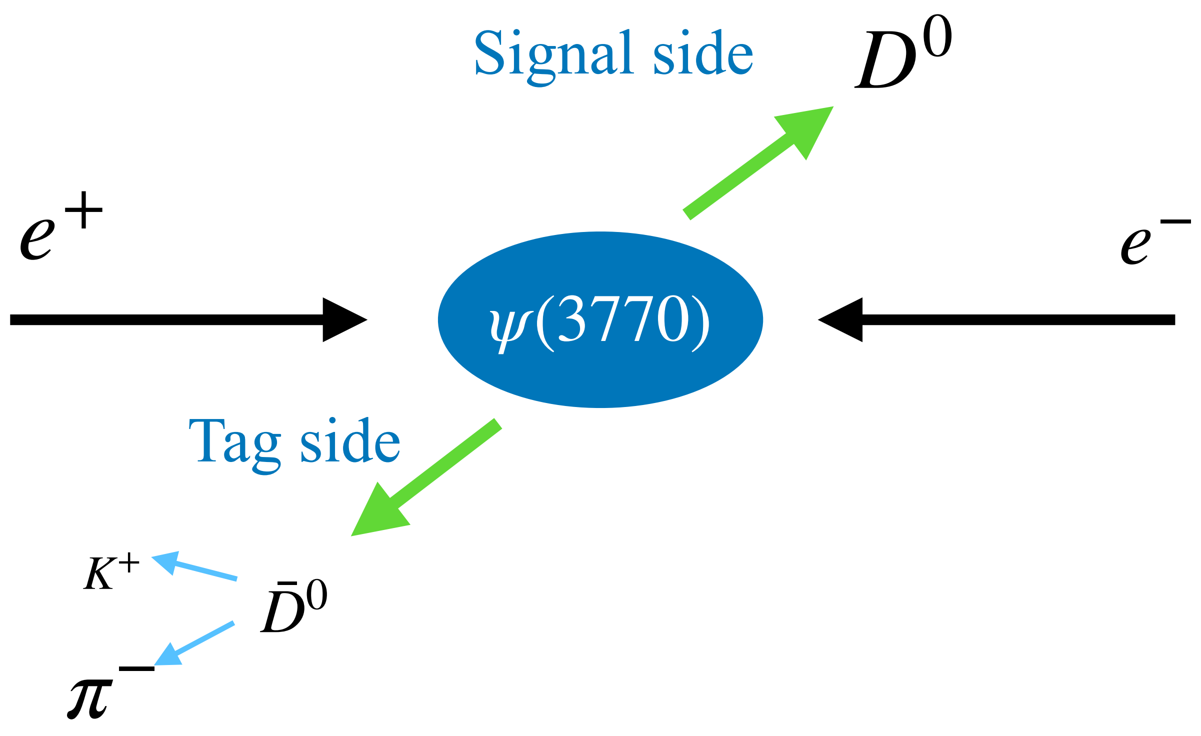
— D_s^+ : 7.33 fb^{-1} @ $E_{cm} = 4.128 - 4.226$ GeV. Collected in 2013-2017

Single Tag (ST) : reconstruct one $D_{(s)}$

— Relative high background

— Higher efficiency





Double Tag (DT) : reconstruct both $D_{(s)}$

— Clean background for study of various decays

— Systematics in the tag side almost cancel out

Absolute branching fraction via DT : $\mathscr{B}_{sig} = \dfrac{N_{sig}^{\mathrm{DT}}}{\Sigma_\alpha N_\alpha^{\mathrm{ST}} \epsilon_{\alpha,sig}^{\mathrm{DT}} / \epsilon_\alpha^{\mathrm{ST}}}$

(Semi-)Leptonic decays

Pure leptonic decays:

$D_s^+ \to \tau^+\nu_\tau, \tau^+ \to e^+\nu_e\bar{\nu}_\tau$, **Phys. Rev. Lett. 127, 171801 (2021)**

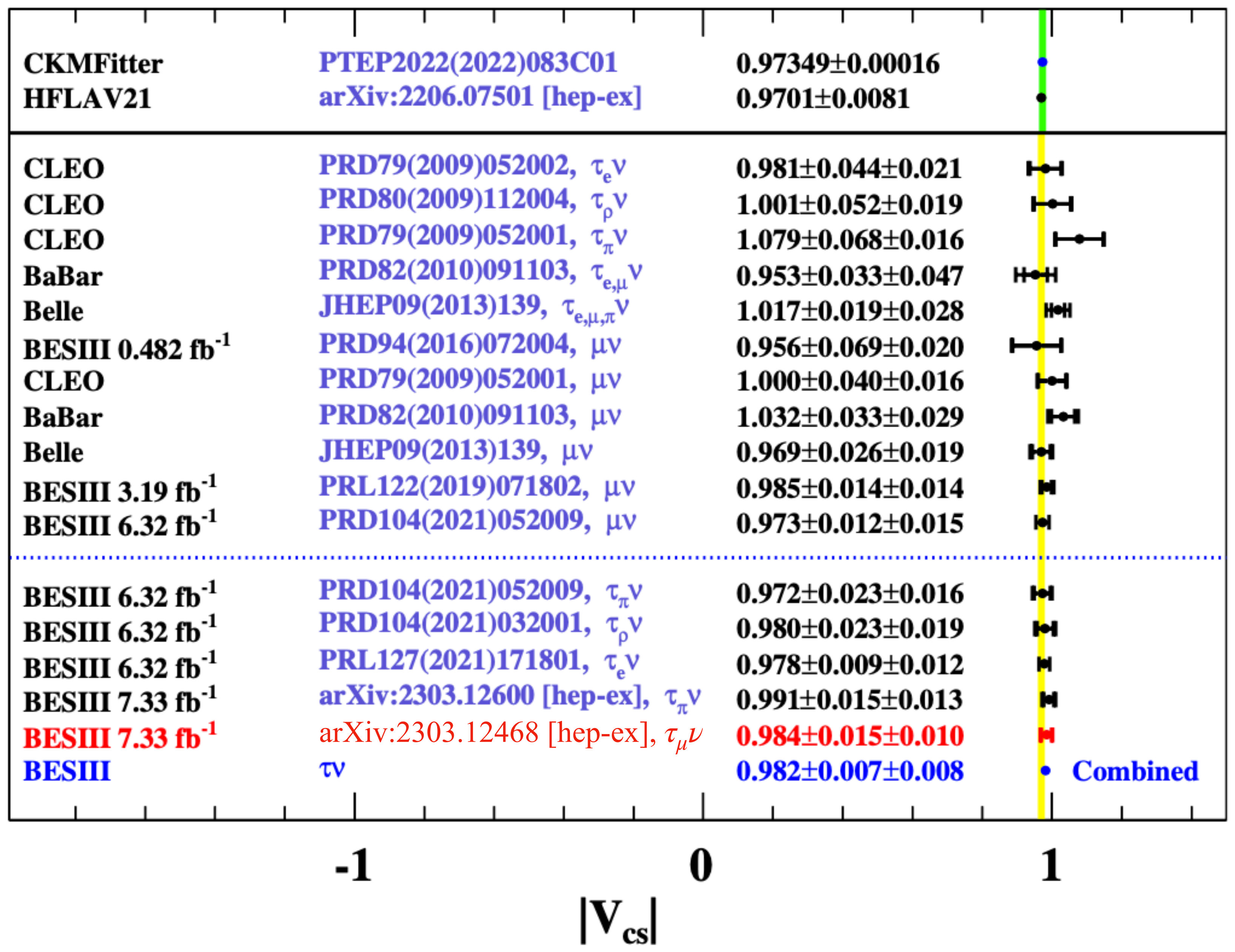
$D_s^+ \to \tau^+\nu_\tau, \tau^+ \to \pi^+\bar{\nu}_\tau$ & $D_s^+ \to \mu^+\nu_\mu$, **Phys. Rev. D 104, 052009 (2021)**

$D_s^+ \to \tau^+\nu_\tau, \tau^+ \to \pi^+\pi^0\bar{\nu}_\tau$, **Phys. Rev. D 104, 032001 (2021)**

$D_s^+ \to \tau^+\nu_\tau, \tau^+ \to \mu^+\nu_\mu\bar{\nu}_\tau$, **arXiv:2303.12468**

$D_s^+ \to \tau^+\nu_\tau, \tau^+ \to \pi^+\bar{\nu}_\tau$, **arXiv:2303.12600**

$D_s^{*+} \to e^+\nu_e$, **arXiv:2304.12159**, first experimental result on $f_{D_s^{*+}}$



Semi-leptonic decays:

$D^0 \to K_1(1270)^- e^+\nu_e$, **Phys. Rev. Lett. 127, 131801 (2021)**

$D_s^+ \to a_0(980)^0 e^+\nu_e$, **Phys. Rev. D 103, 092004(2021)**

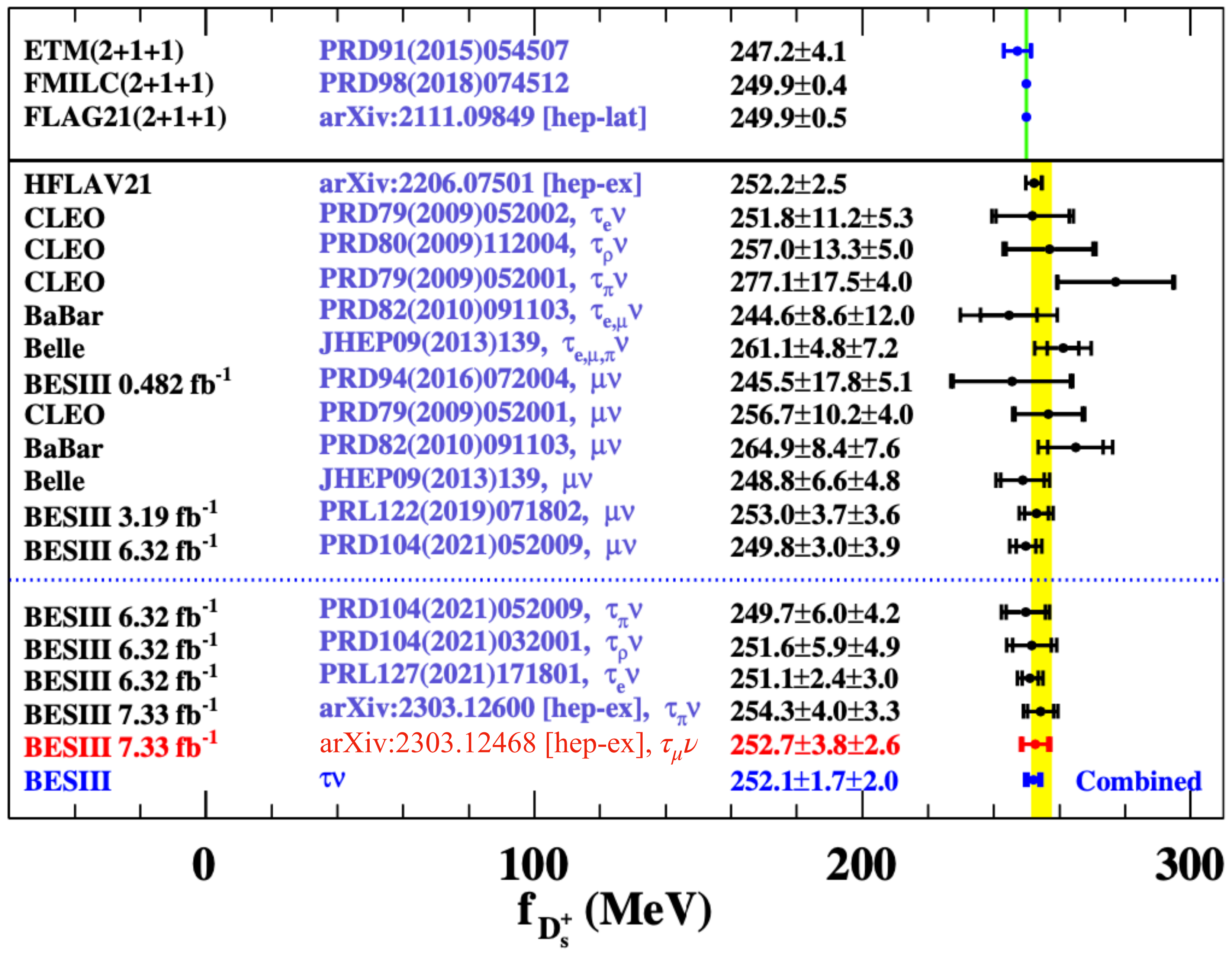
$D^0 \to K^- e^+\nu_e$ & $D^+ \to \bar{K}^0 e^+\nu_e$, **Phys. Rev. D 104, 052008 (2021)**

$D_s^+ \to \pi^0\pi^0 e^+\nu_e$ & $K_S^0 K_S^0 e^+\nu_e$, **Phys. Rev. D 105, L031101 (2022)**

$D_s^+ \to \pi^0 e^+\nu_e$, **Phys. Rev. D 106, 112004 (2022)**

$D_s^+ \to \pi^+\pi^- e^+\nu_e$, **arXiv:2303.12927**

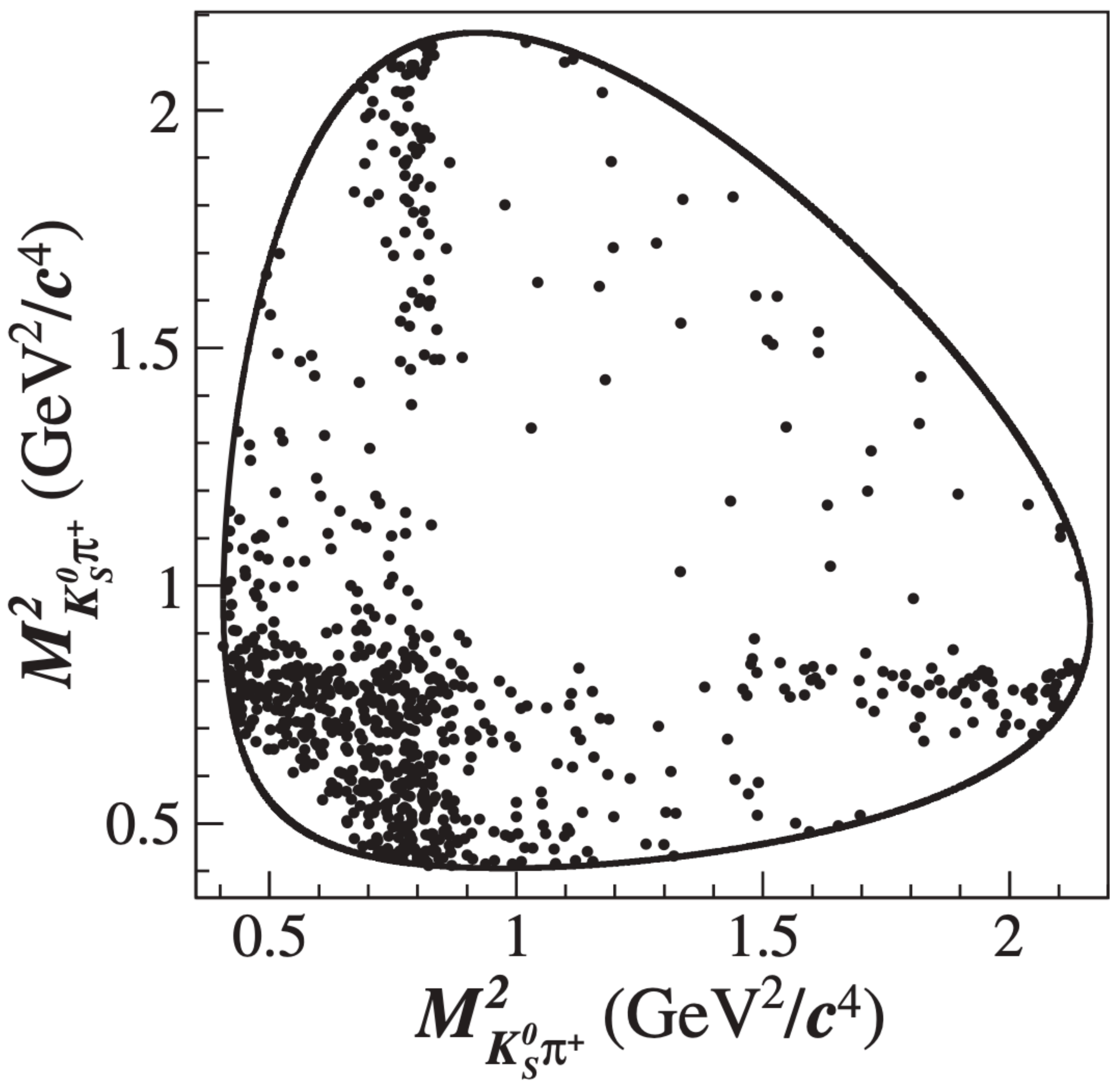
$D_s^+ \to \eta e^+\nu_e, \eta' e^+\nu_e$, **arXiv:2306.05194**



Amplitude analysis of $D_s^+ \to K_S^0 K_S^0 \pi^+$

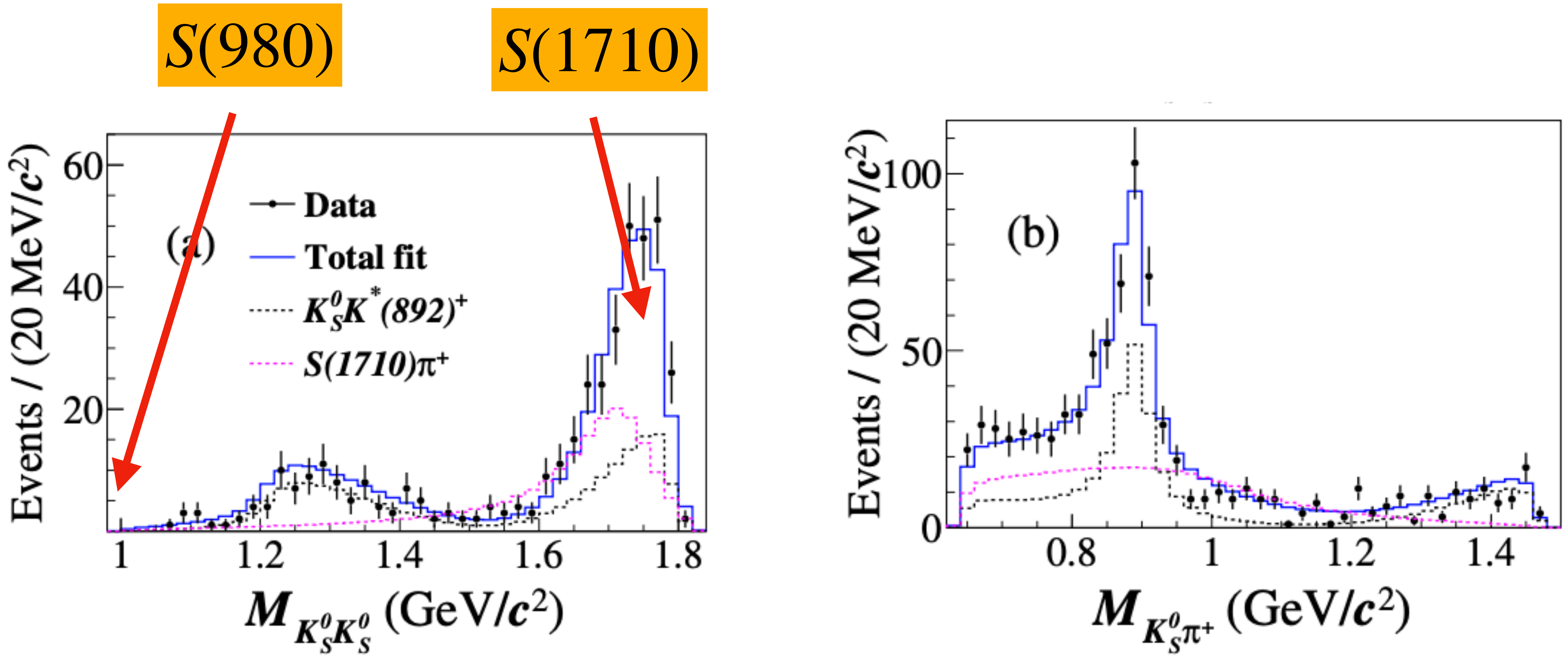
Phys. Rev. D 105, L051103 (2022)

412 events
about 97% purity



First amplitude analysis

Amplitude	FF (%)
$D_s^+ \to K_S^0 K^*(892)^+$	$43.5 \pm 3.9 \pm 0.5$
$D_s^+ \to S(1710)\pi^+$	$46.3 \pm 4.0 \pm 1.2$



$S(1710)$: mixture of $f_0(1710)$ and $a_0(1710)$:

- Destructive interference in $D_s^+ \to K^+K^-\pi^+$
  PRD 104, 012016 (2021)
- Constructive interference in $D_s^+ \to K_S^0 K_S^0 \pi^+$

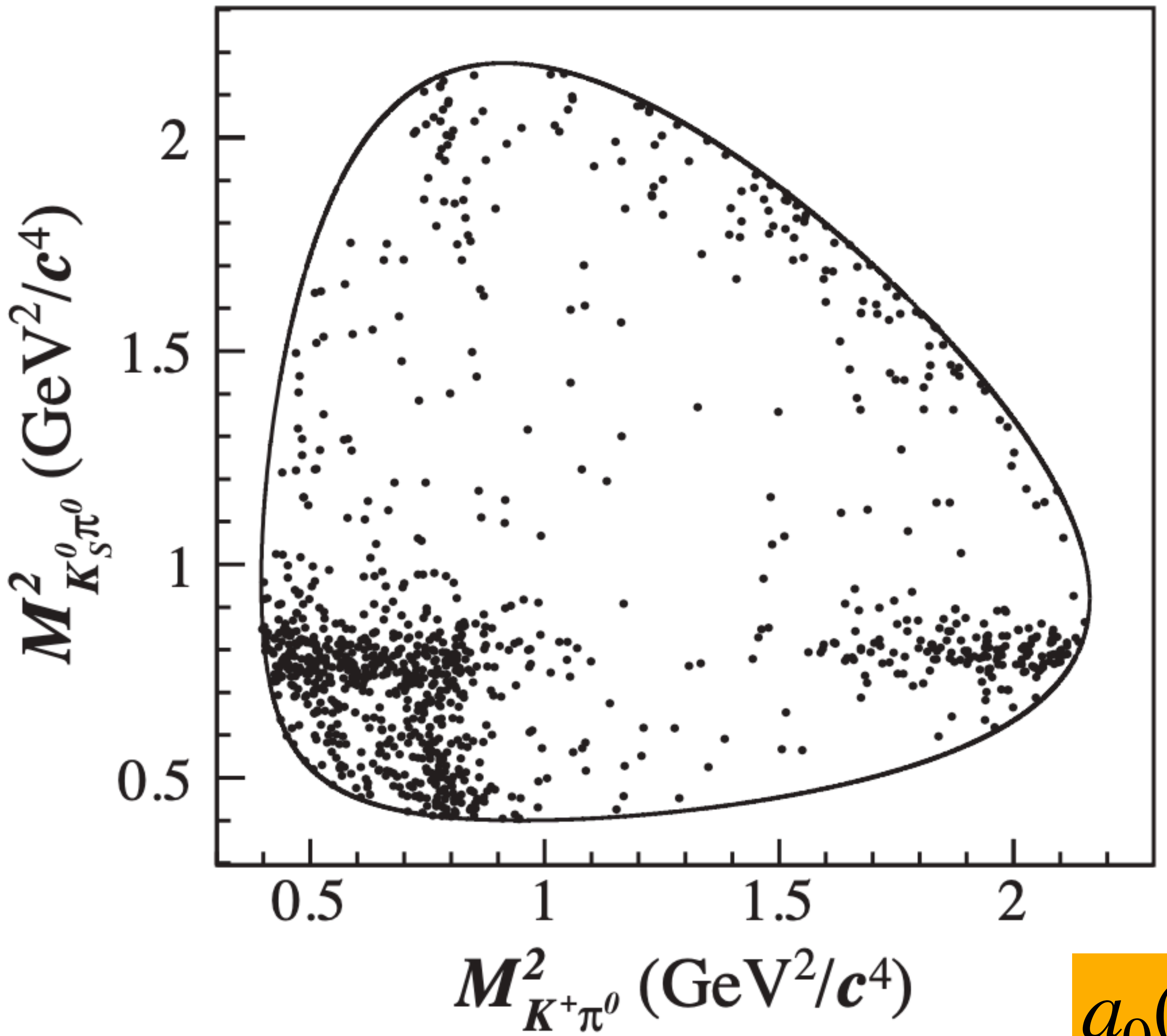
Observation of isospin-one $a_0(1710)$

➡Consistent with the $K^*\bar{K}^*$ molecule hypothesis of $f_0(1710)$

$$\mathcal{B}(D_s^+ \to K_S^0 K_S^0 \pi^+) = (0.68 \pm 0.04_{\text{stat.}} \pm 0.01_{\text{syst.}})\,\%$$

Amplitude analysis of $D_s^+ \to K_S^0 K^+ \pi^0$

Phys. Rev. Lett. 129, 182001 (2022)



First amplitude analysis

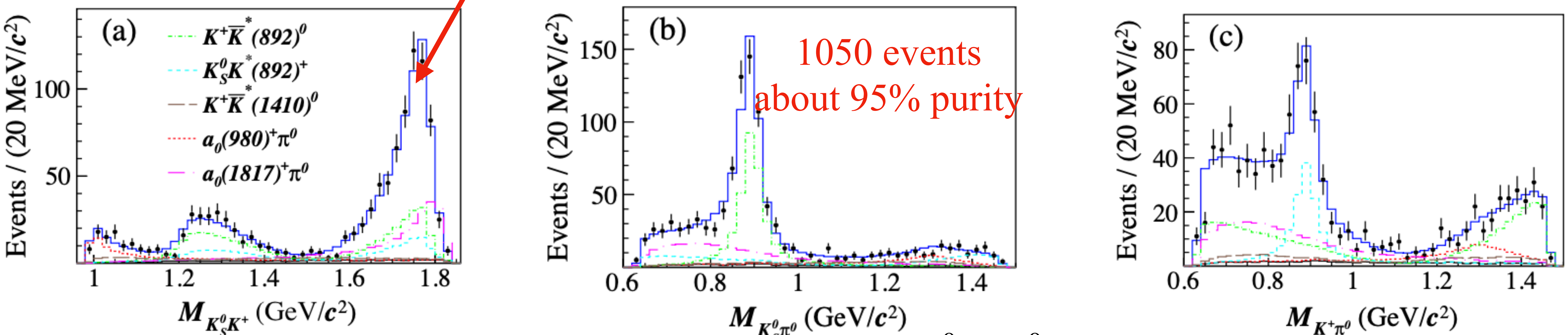
Amplitude	FF (%)	BF (10^{-3})	σ
$D_s^+ \to \bar{K}^*(892)^0 K^+$	$32.7 \pm 2.2 \pm 1.9$	$4.77 \pm 0.38 \pm 0.32$	> 10
$D_s^+ \to K^*(892)^+ K_S^0$	$13.9 \pm 1.7 \pm 1.3$	$2.03 \pm 0.26 \pm 0.20$	> 10
$D_s^+ \to a_0(980)^+ \pi^0$	$7.7 \pm 1.7 \pm 1.8$	$1.12 \pm 0.25 \pm 0.27$	6.7
$D_s^+ \to \bar{K}^*(1410)^0 K^+$	$6.0 \pm 1.4 \pm 1.3$	$0.88 \pm 0.21 \pm 0.19$	7.6
$D_s^+ \to a_0(1817)^+ \pi^0$	$23.6 \pm 3.4 \pm 2.0$	$3.44 \pm 0.52 \pm 0.32$	> 10

$$M(a_0(1817)^+) = (1.817 \pm 0.008_{\text{stat.}} \pm 0.020_{\text{syst.}})\ \text{GeV}/c^2$$

$$\Gamma(a_0(1817)^+) = (0.097 \pm 0.022_{\text{stat.}} \pm 0.015_{\text{syst.}})\ \text{GeV}/c^2$$

Isospin partner of $X(1812)$? Phys.Rev.D 105 (2022) 11, 114014

$a_0(1817)^+$



1050 events
about 95% purity

$$\mathscr{B}(D_s^+ \to K_S^0 K^+ \pi^0) = (1.46 \pm 0.06_{\text{stat.}} \pm 0.05_{\text{syst.}})\ \%$$

Amplitude analysis of $D_s^+ \to \pi^+\pi^0\eta'$

JHEP04(2022)058

Decay		$\mathcal{B}(\%)$	
Theory	$D_s^+ \to \rho^+\eta'$	3.0 ± 0.5 [1]	1.7 [2] 1.6 [2]
Experiment	$D_s^+ \to \pi^+\pi^0\eta'$	$5.6 \pm 0.5 \pm 0.6$	CLEO
	$D_s^+ \to \rho^+\eta'$	$5.8 \pm 1.4 \pm 0.4$	BESIII
	$D_s^+ \to \pi^+\pi^0\eta'$ (nonresonant)	< 5.1 (90% confidence level)	

Large deviation between theoretical predictions and experimental measurements

[1] Phys. Rev. D 84 (2011) 074019

[2] Phys. Rev. D 89 (2014) 054006

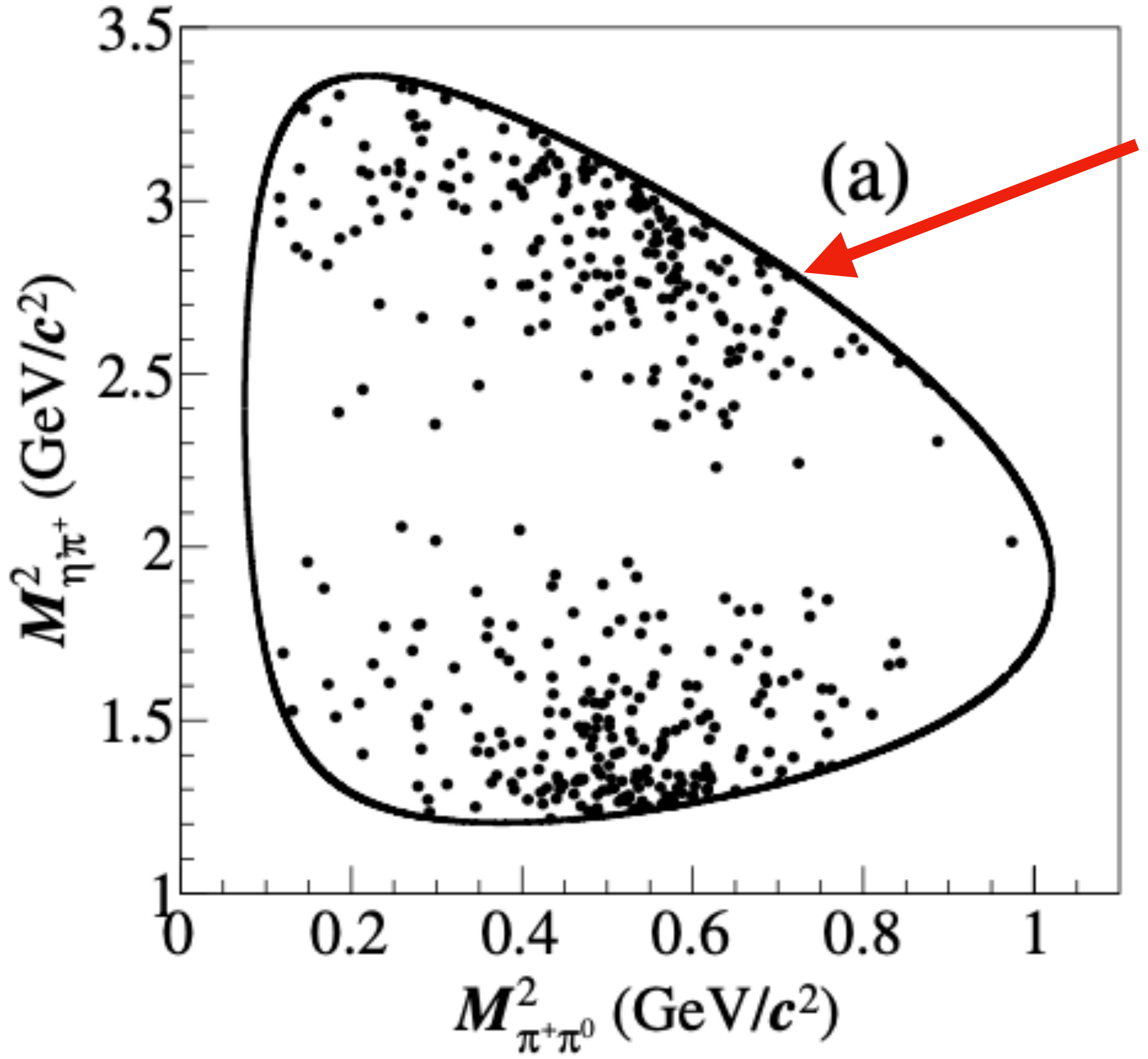
Branching fraction measurement with best precision :

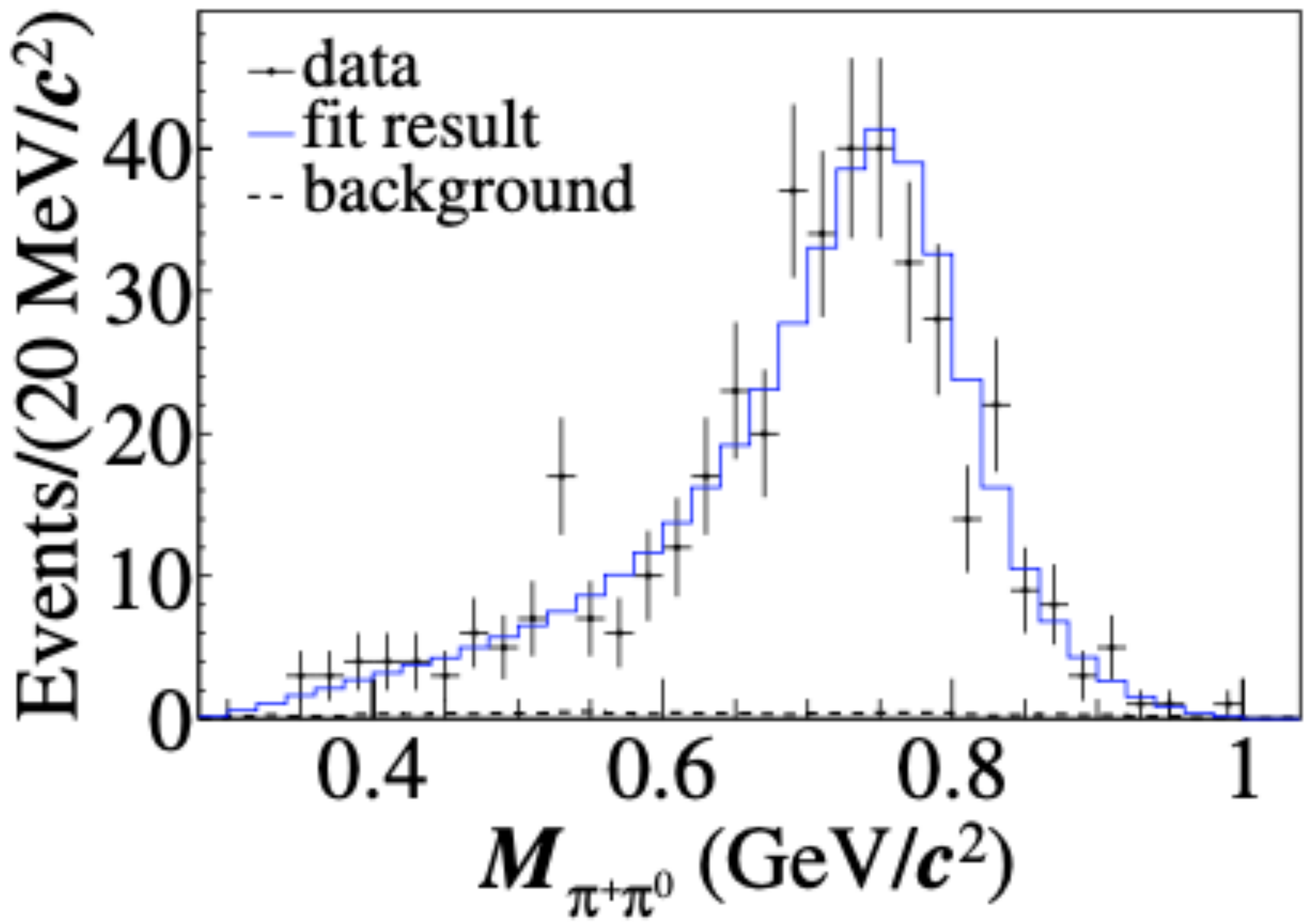
$\mathcal{B}(D_s^+ \to \pi^+\pi^0\eta') = (6.15 \pm 0.25_{\text{stat.}} \pm 0.18_{\text{syst.}})\,\%$

$\mathcal{B}(D_s^+ \to (\pi^+\pi^0)_S\eta') < 0.1\,\%$ @ 90% CL

$\mathcal{B}(D_s^+ \to (\pi^+\pi^0)_P\eta') < 0.74\,\%$ @ 90% CL

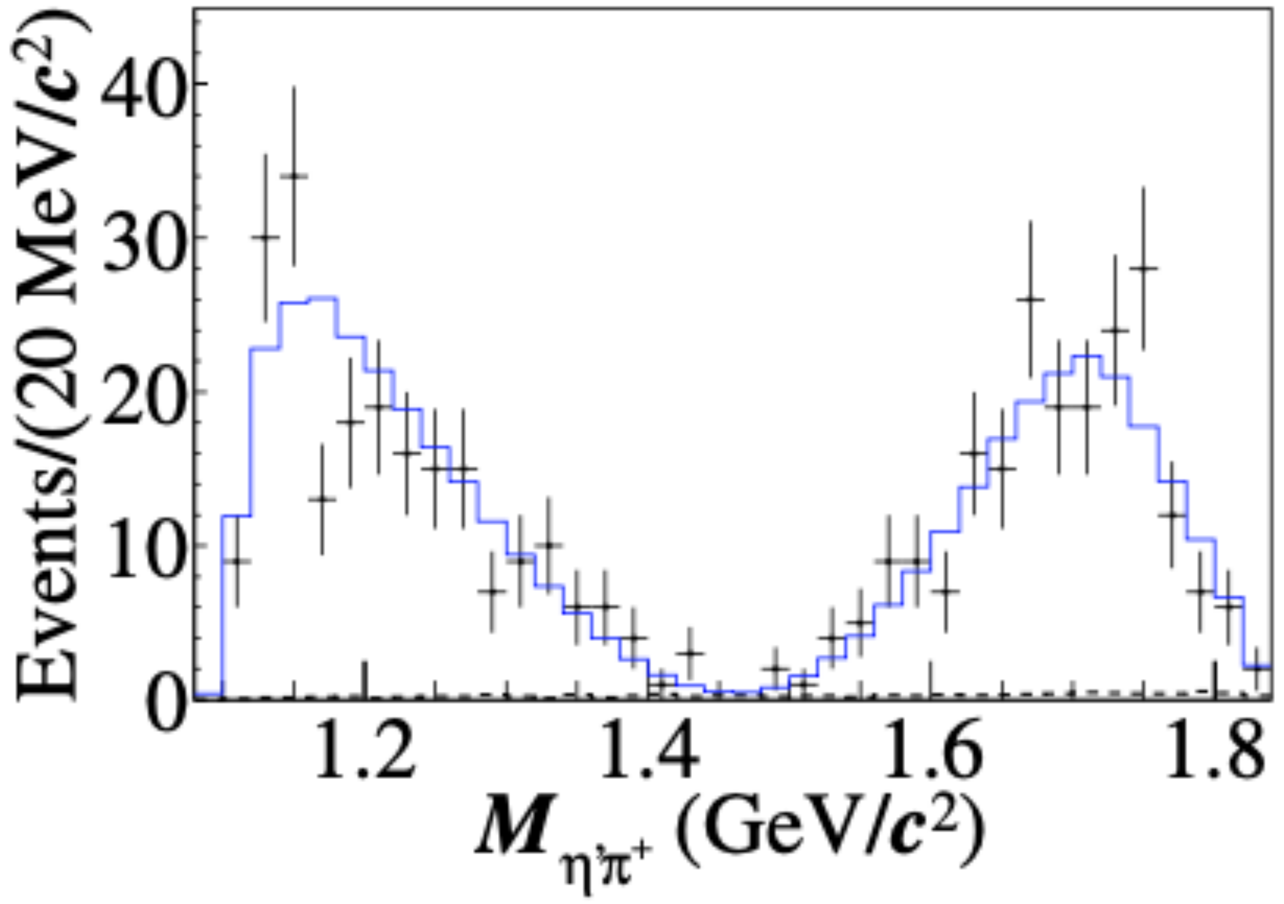
Only $D_s^+ \to \rho^+\eta'$ contributes

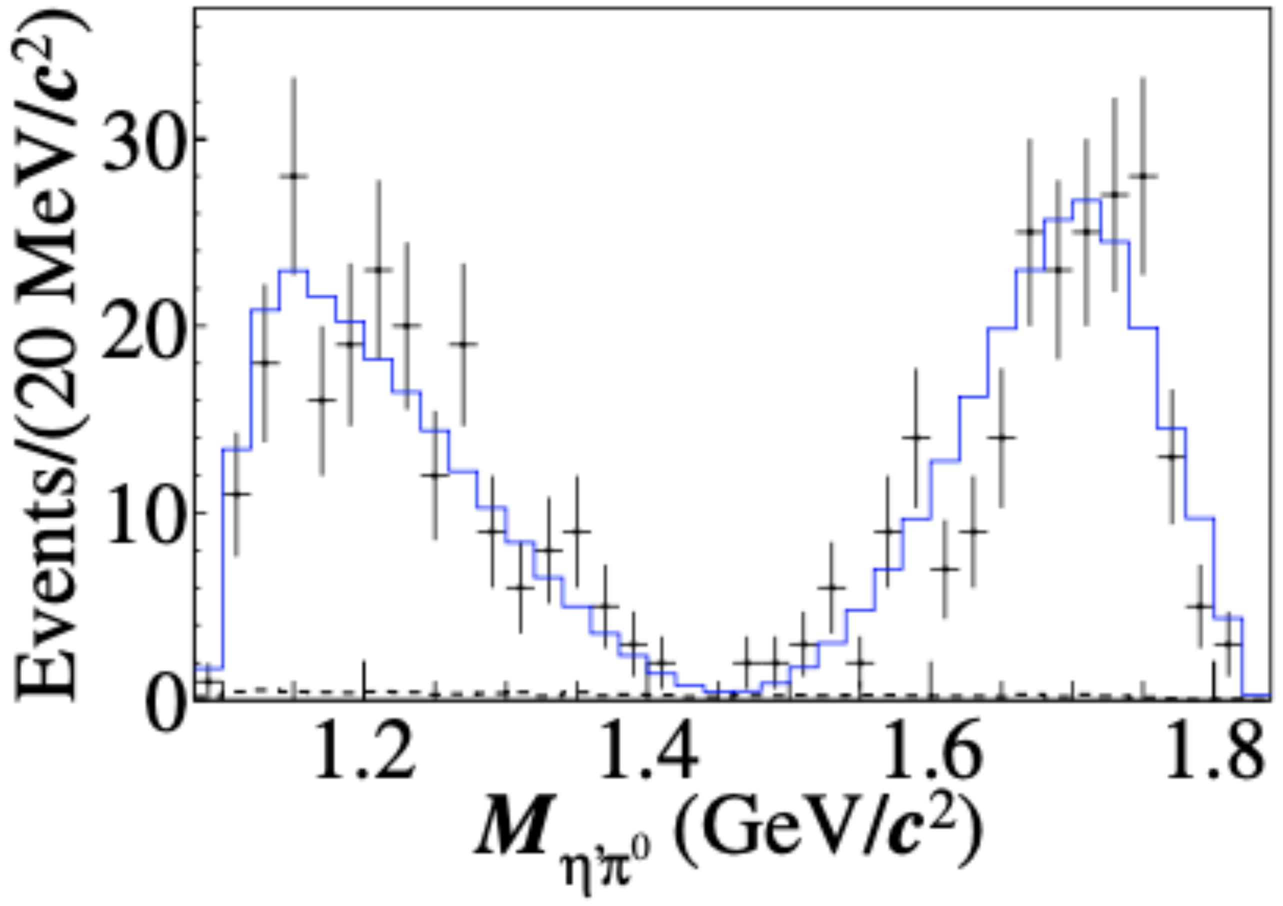




411 events
about 96% purity

First amplitude analysis

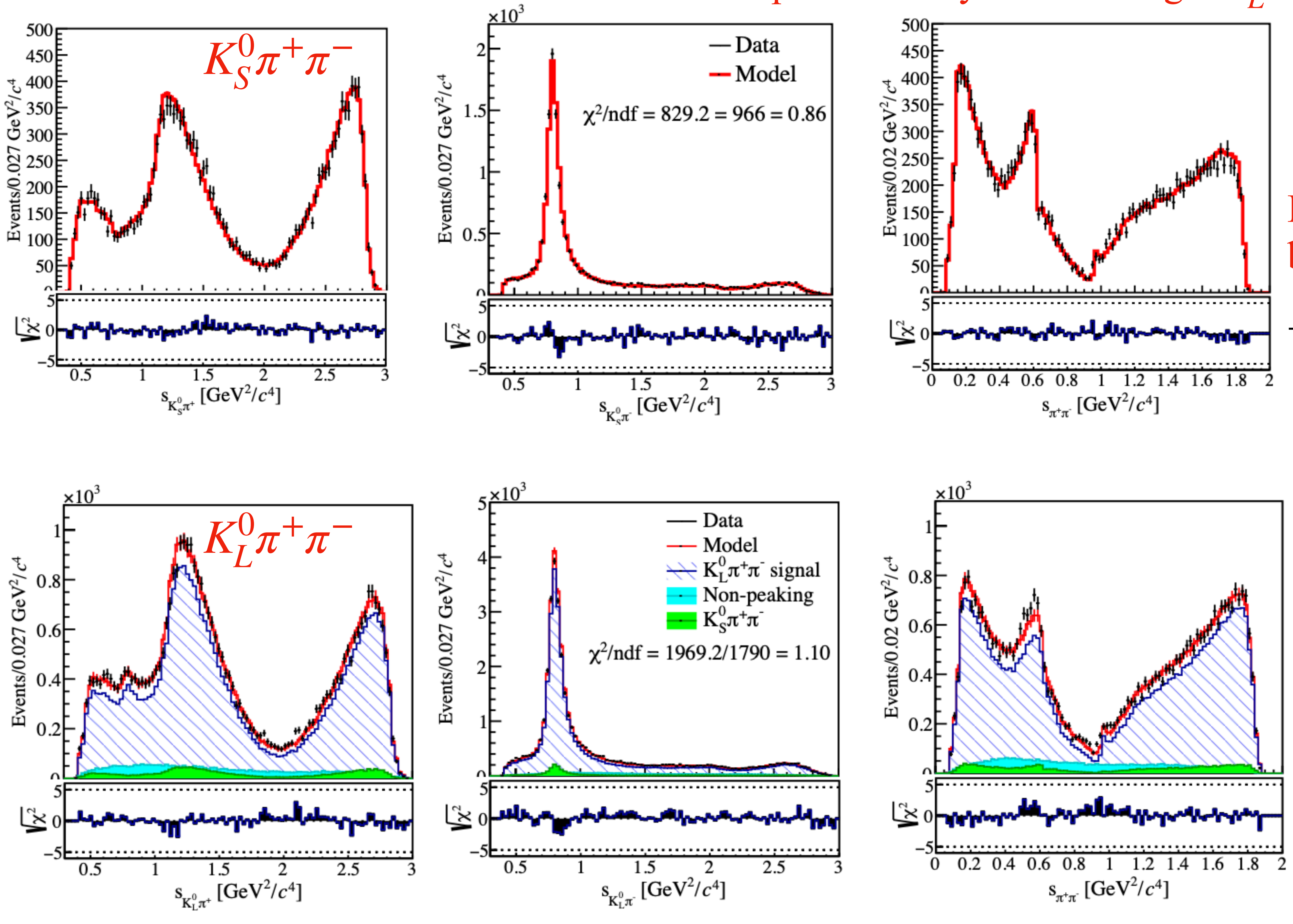




Amplitude analysis of $D^0 \to K^0_{S,L}\pi^+\pi^-$

arXiv:2212.09048

First amplitude analysis involving a K^0_L



16490 events for $K^0_S\pi^+\pi^-$, 39085 for $K^0_L\pi^+\pi^-$

The U-spin parameters are assumed to be unity in the model-independent strong phase measurement of $D^0 \to K^0_{S,L}\pi^+\pi^-$.

Determine the complex U-spin breaking parameters by simultaneous fit of $D^0 \to K^0_{S,L}\pi^+\pi^-$

$\to$ Reduce the main uncertainty from predicted $\Delta c_i(s_i)$

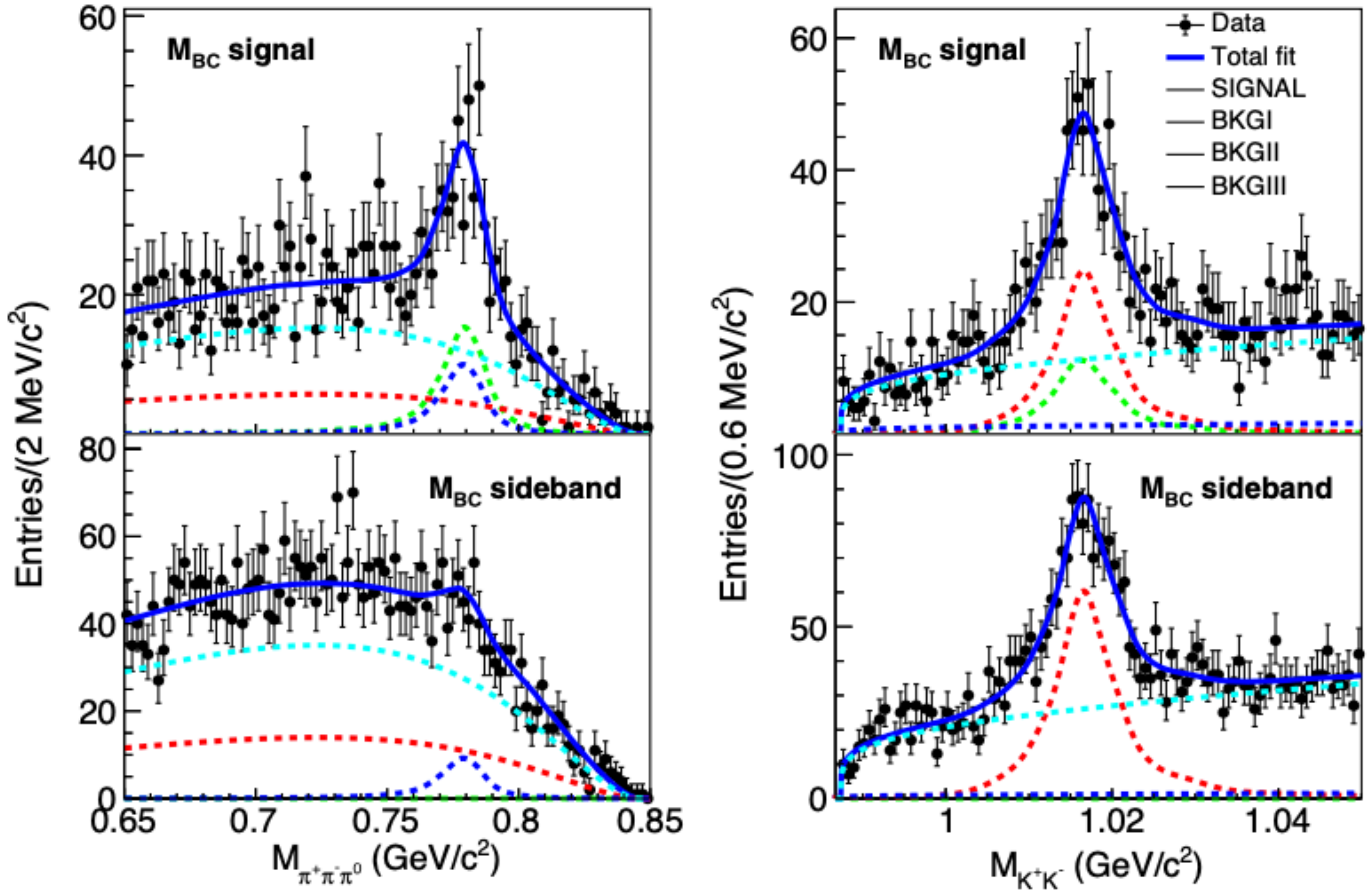
Resonance	$K^0_L\pi^+\pi^-$ FF_R [%]	$K^0_S\pi^+\pi^-$ FF_R [%]
$\rho(770)$	$18.16^{+0.53}_{-0.45} \pm 2.50$	$18.90 \pm 0.42 \pm 2.12$
$\omega(782)$	$0.06^{+0.03}_{-0.02} \pm 0.04$	$0.54 \pm 0.09 \pm 0.14$
$f_2(1270)$	$0.40 \pm 0.08 \pm 0.37$	$0.61^{+0.13}_{-0.11} \pm 0.29$
$\rho(1450)$	$0.42 \pm 0.08 \pm 0.53$	$0.21 \pm 0.10 \pm 0.40$
$\pi\pi$ S-wave	$10.12^{+0.32}_{-0.33} \pm 0.96$	$10.24 \pm 0.23 \pm 1.62$

Resonance	$\lvert\hat{\rho}\rvert$	$\arg(\hat{\rho})$ [°]	$\lvert 1 - 2\tan^2\theta_C\hat{\rho}\rvert^2$
$\rho(770)$	$1.93 \pm 0.27 \pm 0.42$	$-90.6 \pm 5.8 \pm 7.6$	$1.05 \pm 0.04 \pm 0.06$
$\omega(782)$	$6.13 \pm 0.75 \pm 0.53$	$2.2 \pm 7.0 \pm 4.8$	$0.12 \pm 0.05 \pm 0.04$
$f_2(1270)$	$3.75 \pm 0.90 \pm 0.81$	$-56.5 \pm 16.8 \pm 12.9$	$0.72 \pm 0.20 \pm 0.15$
$\rho(1450)$	$12.12 \pm 2.92 \pm 1.88$	$78.4 \pm 14.4 \pm 15.6$	$2.19 \pm 0.95 \pm 0.83$
$\pi\pi$ S-wave	$0.37 \pm 0.21 \pm 0.37$	$-164.4 \pm 15.7 \pm 13.4$	$1.08 \pm 0.04 \pm 0.08$

Polarizations in $D^0 \to \omega\phi$

Phys. Rev. Lett. 128, 011803 (2022)

Single tag method — only one D^0 meson is reconstructed



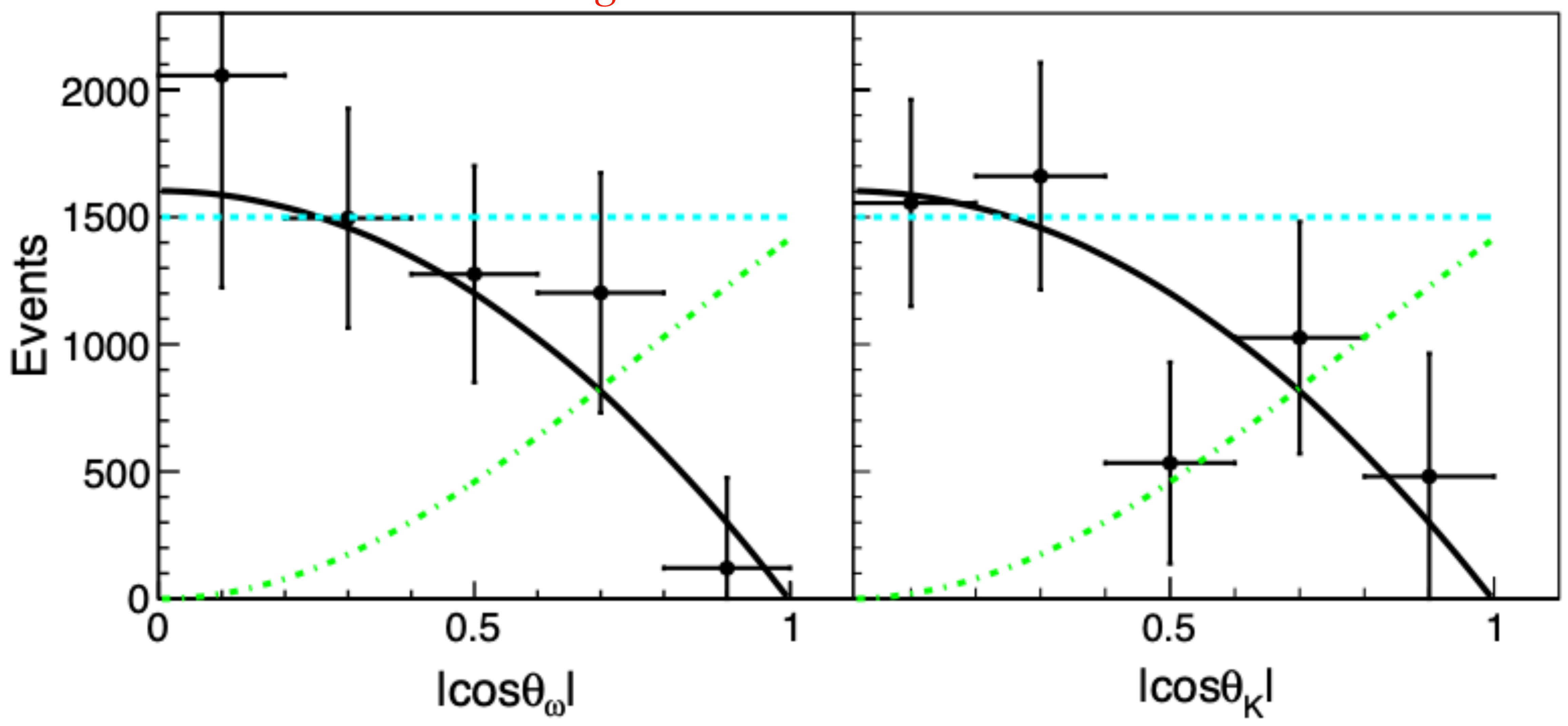
- $D^0 \to \omega\phi$ is observed for the first time:

  $\mathscr{B}(D^0 \to \omega\phi)$

  $= (6.48 \pm 0.96_{\text{stat.}} \pm 0.40_{\text{syst.}}) \times 10^{-4}$

  with a significance of 6.3σ

$N_{sig} = 195.9 \pm 29.1$



Black dots: data

Black curves: fit results

Green: longitudinal

Cyan: PHSP

- ω and ϕ are transversely polarized

➡ Contradict existing model predictions

Phys. Rev. D 81, 114020 (2010); J. High Energy Phys. 03 (2014) 042

BF measurements of DCS decays

- $D^+ \to K^+\pi^+\pi^-\pi^0$ **Phys. Rev. Lett. 125, 141802 (2020)**

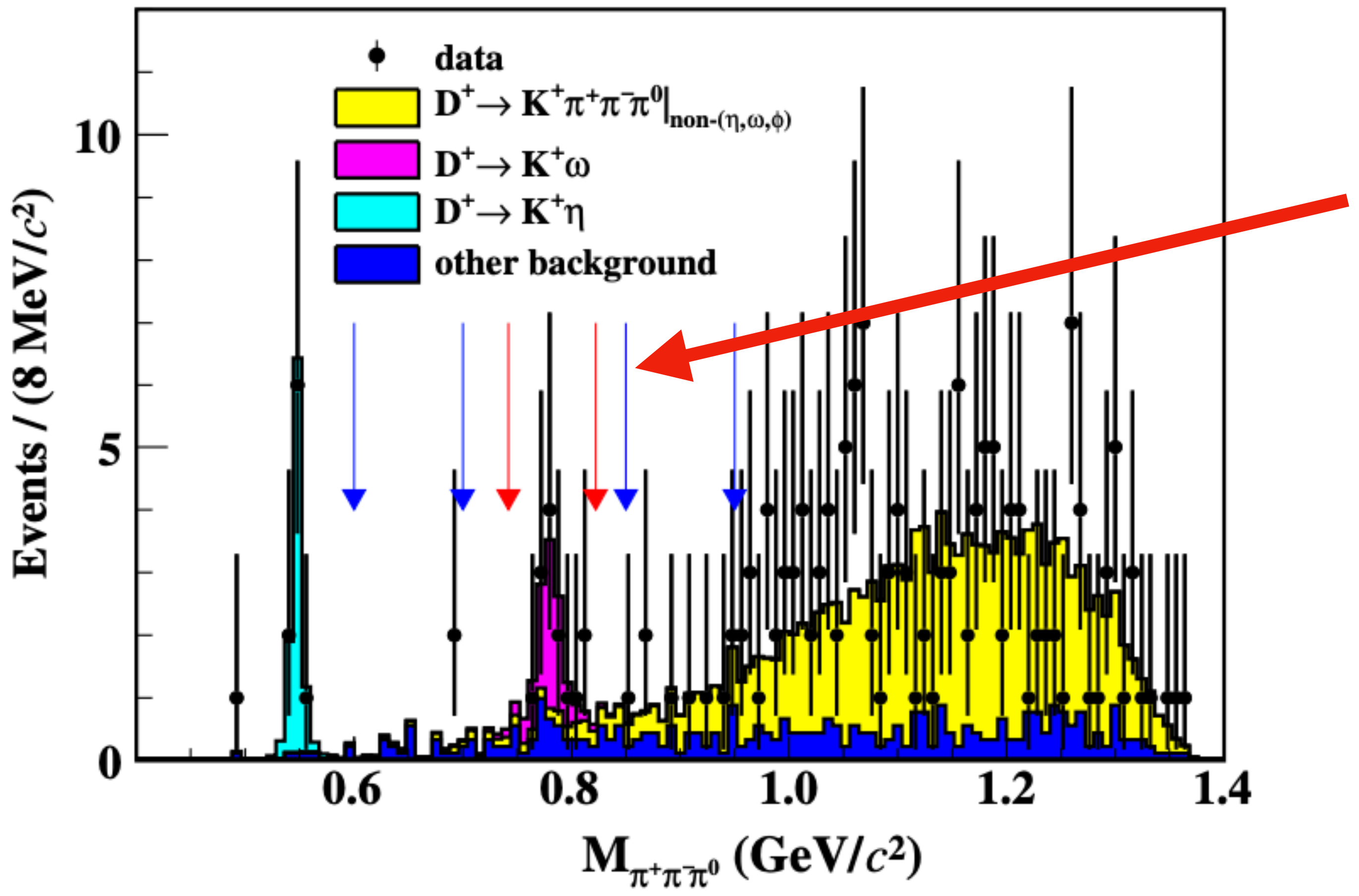
$\mathscr{B}(D^+ \to K^+\pi^+\pi^-\pi^0) = (1.13 \pm 0.08(\text{stat}) \pm 0.03(\text{syst})) \times 10^{-3}$

with removing the contribution of the known decays

$D^+ \to K^+\eta, K^+\omega, K^+\phi$

$\mathscr{B}(D^+ \to K^+\pi^+\pi^-\pi^0)/\mathscr{B}(D^+ \to K^-\pi^+\pi^+\pi^0) = (1.81 \pm 0.15)\,\%$

$\to$ Significantly larger than the values (0.21–0.58)% measured for the other DCS decays



Observation of $D^0 \to K^+\omega$:

$(5.7^{+2.5}_{-2.1}(\text{stat}) \pm 0.2(\text{syst})) \times 10^{-5}$

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

$\mathscr{B}(D^0 \to K^+\pi^-\pi^0) = [3.13^{+0.60}_{-0.56}(\text{stat}) \pm 0.15(\text{syst})] \times 10^{-4}$

$\mathscr{B}(D^0 \to K^+\pi^-\pi^0\pi^0) < 3.6 \times 10^{-4}$ @ 90 % CL .

Phys. Rev. D 105, 112001 (2022)

- $D^+ \to K^+\pi^0\pi^0,\ K^+\pi^0\eta$ **JHEP09(2022)107**

Decay mode	N_{DT}	ϵ_{sig} (%)	$\mathcal{B}_{sig}$ ($\times 10^{-4}$)
$D^+ \to K^+\pi^0\pi^0$	42.8 ± 7.2	18.08 ± 0.03	$2.1 \pm 0.4 \pm 0.1$
$D^+ \to K^+\pi^0\eta$	19.2 ± 5.0	20.50 ± 0.03	$2.1 \pm 0.5 \pm 0.1$
$D^+ \to K^{*+}\pi^0$	$16.6^{+6.6}_{-6.2}$	13.02 ± 0.03	$3.4^{+1.4}_{-1.3} \pm 0.1$
$D^+ \to K^{*+}\eta$	$10.9^{+4.4}_{-3.8}$	16.60 ± 0.04	$4.4^{+1.8}_{-1.5} \pm 0.2$

Strong phase measurements

- $D^0 \to K^-\pi^+$ Eur. Phys. J. C 82, 1009 (2022)

$\delta_D^{K\pi} = (187.6^{+8.9+5.4}_{-9.7-6.4})^\circ$, most precise measurement

$$r_D^{K\pi} exp(-i\delta_D^{K\pi}) = \frac{\langle K^+\pi^- | D^0 \rangle}{\langle K^+\pi^- | \bar{D}^0 \rangle},$$

where $r_D^{K\pi}$ are $\delta_D^{K\pi}$ the ratio of amplitudes and phase difference, respectively, between the DCS and CF decays.

$A_{K\pi} = 0.132 \pm 0.001 \pm 0.007$, 30% more precision

$A_{K\pi}^{\pi\pi\pi^0} = 0.130 \pm 0.012 \pm 0.008$

$\mathscr{B}(D^0 \to K_L^0\pi^0) = (0.97 \pm 0.03 \pm 0.02) \times 10^{-2}$

$\mathscr{B}(D^0 \to K_L^0\omega) = (1.09 \pm 0.06 \pm 0.03) \times 10^{-2}$

$\mathscr{B}(D^0 \to K_L^0\pi^0\pi^0) = (1.26 \pm 0.05 \pm 0.03) \times 10^{-2}$.

- $D^0 \to \pi^+\pi^-\pi^+\pi^-$ Phys. Rev. D 106, 092004 (2022)

$F_+ = 0.735 \pm 0.015 \pm 0.005$,

$\to$ predominantly CP – even

most precise determination

- $D^0 \to K^+K^-\pi^+\pi^-$ Phys. Rev. D 107, 032009 (2023)

$F_+ = 0.730 \pm 0.037 \pm 0.021$,

$\to$ predominantly CP – even

first model-independent measurement of F_+ of this decay

- $D^0 \to K_S^0\pi^+\pi^-\pi^0$ arXiv:2305.03975

$F_+ = 0.235 \pm 0.010 \pm 0.002$,

$\to$ predominantly CP – odd

Summary

- ✓ **Charm is charming**
  - (Semi-)leptonic decays access to CKM matrix elements and calibrate LQCD
  - Hadronic decays are key labs to understand non-perturbative QCD; provide crucial inputs to model-independent determination of γ and charm mixing/CPV
- ✓ **BESIII makes great achievements**
  - Precise measurements of $D_s^+ \to \tau^+\nu_\tau$
  - Observation of new isospin-one particle $a_0(1817)$
  - Puzzle of $P \to VV$ polarization
- ✓ **Bright future of charm meson decays at BESIII**
  - Lots of results are ready to be published
  - 20 fb^{-1} $\psi(3770)$ data at BESIII by next year **CPC 44, 040001 (2020)**

Thanks for your attention!

Back up

Amplitude formalization in $D^0 \to K^0_{S,L}\pi^+\pi^-$

In simultaneous fit of $D^0 \to K^0_S\pi^+\pi^-$ and $D^0 \to K^0_L\pi^+\pi^-$, they share the same model, magnitudes and phases, while the total amplitude are:

$$A(D^0 \to K^0_S\pi^+\pi^-) = \sum_r A^{CF} + \sum_{r'} A^{DCS} + \sum_k A^{CP}_{K^0_S\pi^+\pi^-},$$

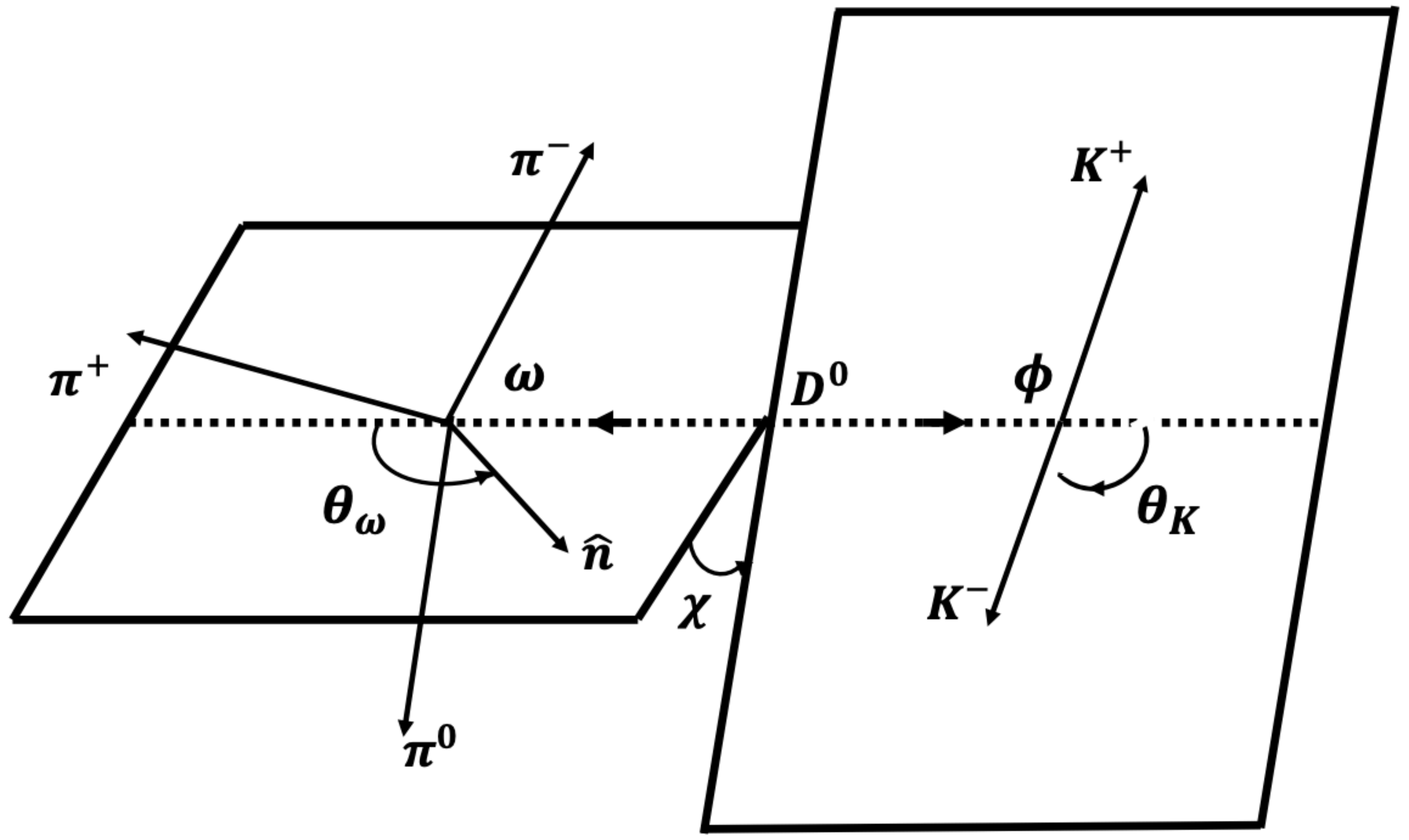
$$A(D^0 \to K^0_L\pi^+\pi^-) = \sum_r A^{CF} - \sum_{r'} A^{DCS} + \sum_k (1 - 2\tan^2\theta_{\mathrm{C}}\hat{\rho}_{\mathrm{kCP}}) \times A^{CP}_{K^0_S\pi^+\pi^-},$$

where θ_C is Cabibbo missing angle ($\sin\theta_{\mathrm{C}} = 0.22650 \pm 0.00048$), $\hat{\rho}_{kCP}$ is U-spin breaking parameter.

Standalone results of $D^0 \to K^0_{S,L}\pi^+\pi^-$

Resonance	$K^0_L\pi^+\pi^-$ FF(%) (Simultaneous fit)	$K^0_L\pi^+\pi^-$ FF(%) (Standalone $K^0_L\pi^+\pi^-$)
$\rho(770)$	$18.16^{+0.53}_{-0.45}$	18.94 ± 1.20
$\omega(782)$	$0.06^{+0.03}_{-0.02}$	0.06 ± 0.03
$f_2(1270)$	0.40 ± 0.08	0.36 ± 0.08
$\rho(1450)$	0.42 ± 0.08	0.43 ± 0.10
$K^*(892)^-$	$56.98^{+0.58}_{-0.56}$	57.1 ± 1.65
$K_2^*(1430)^-$	$1.64^{+0.10}_{-0.09}$	1.58 ± 0.15
$K^*(1680)^-$	$0.25^{+0.06}_{-0.05}$	0.22 ± 0.11
$K^*(1410)^-$	0.19 ± 0.06	0.11 ± 0.06
$K^*(892)^+$	0.45 ± 0.05	0.37 ± 0.06
$K_2^*(1430)^+$	0.05 ± 0.02	0.02 ± 0.02
$K^*(1410)^+$	0.04 ± 0.02	0.02 ± 0.02
$K_0^*(1430)^-$	$6.84^{+0.24}_{-0.25}$	5.80 ± 0.38
$\pi\pi$ S-wave	$10.12^{+0.32}_{-0.33}$	10.39 ± 1.72
Total FF	$95.59^{+2.16}_{-2.07}$	95.40 ± 5.58

Definitions in $D^0 \to \omega\phi$



θ_ω is the angle between $\mathbf{p}^\omega_{\pi^+} \times \mathbf{p}^\omega_{\pi^-}$ and $-\mathbf{p}^\omega_{D^0}$ in the ω rest frame, and θ_K is the angle between $\mathbf{p}^\phi_{K^-}$ and $-\mathbf{p}^\phi_{D^0}$ in the ϕ rest frame. Here, $\mathbf{p}^\omega_{\pi^+}$, $\mathbf{p}^\omega_{\pi^-}$, $\mathbf{p}^\phi_{K^-}$, and $\mathbf{p}^{\omega/\phi}_{D^0}$ are the momenta of the π^+, π^-, K^-, and D^0 in the rest frame of either the ω or ϕ meson, respectively.