Charmed meson decays at BESIII

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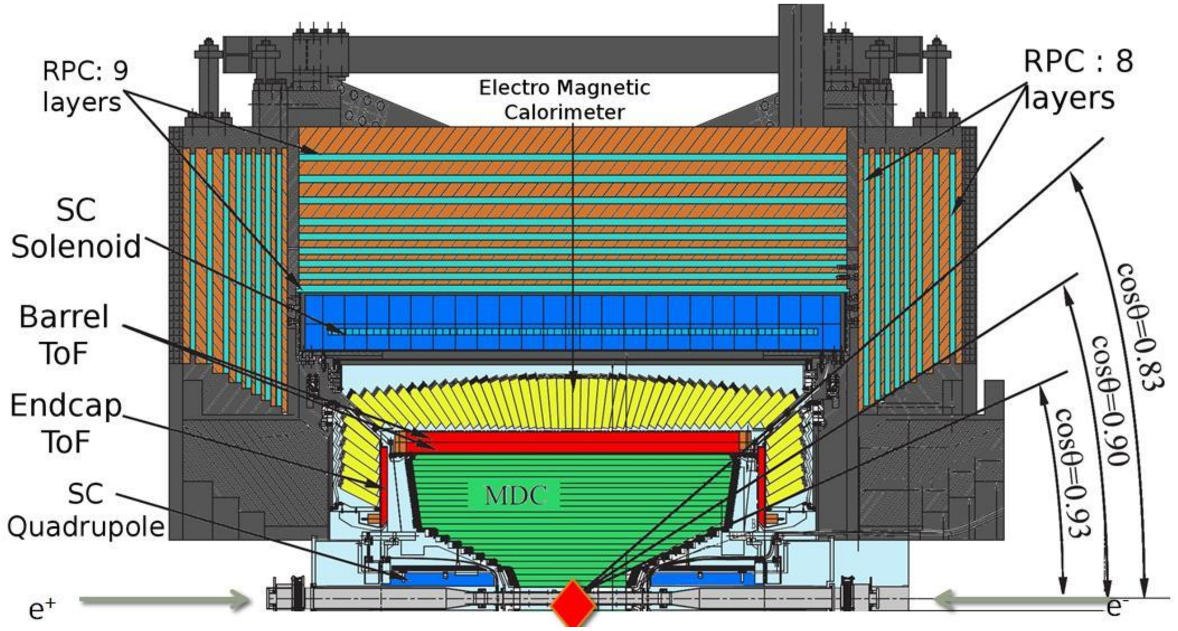
Outline

- BESIII Detector and datasets
- Leptonic and semileptonic decays
- Hadronic decays
  - Amplitude analysis
  - BF measurements
  - Quantum correlated $D\overline{D}$, strong phase measurements
- Summary and prospects

BESIII detector and datasets



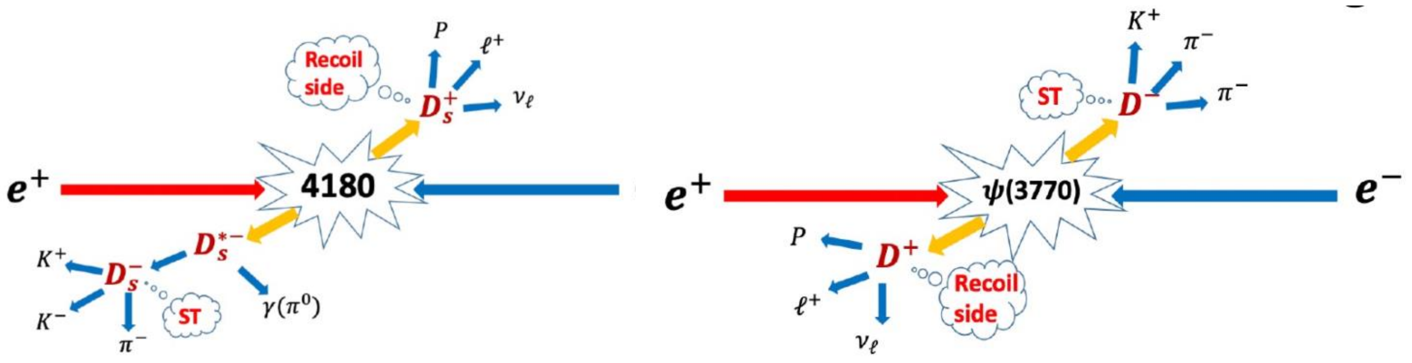
BESIII detector

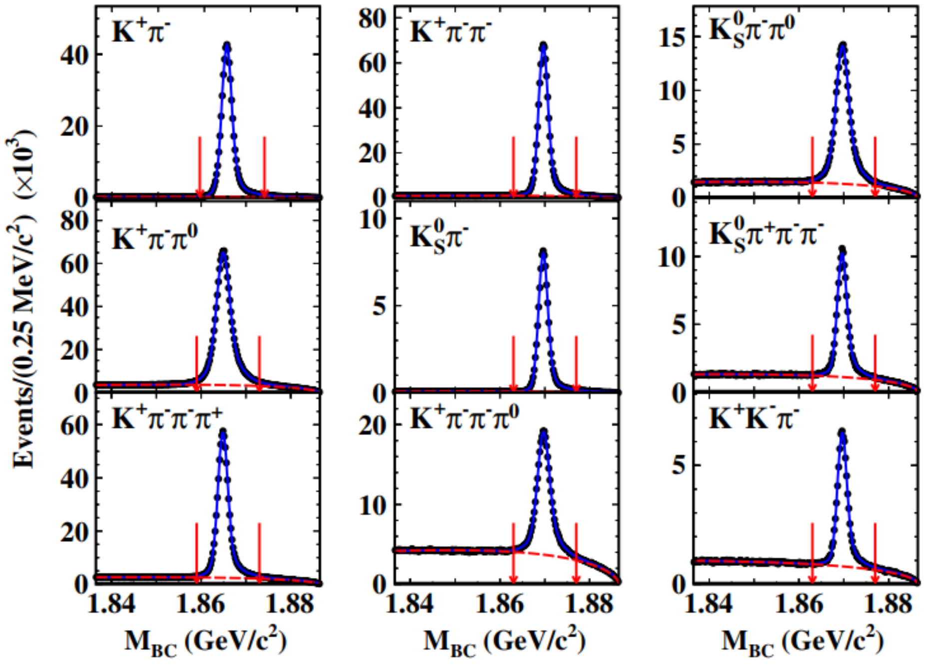
- Multilayer Drift Chamber (MDC)
- Time-of-Flight Detector (ToF)
- Electromagnetic Calorimeter (EMC)
- Muon Counter (MUC)

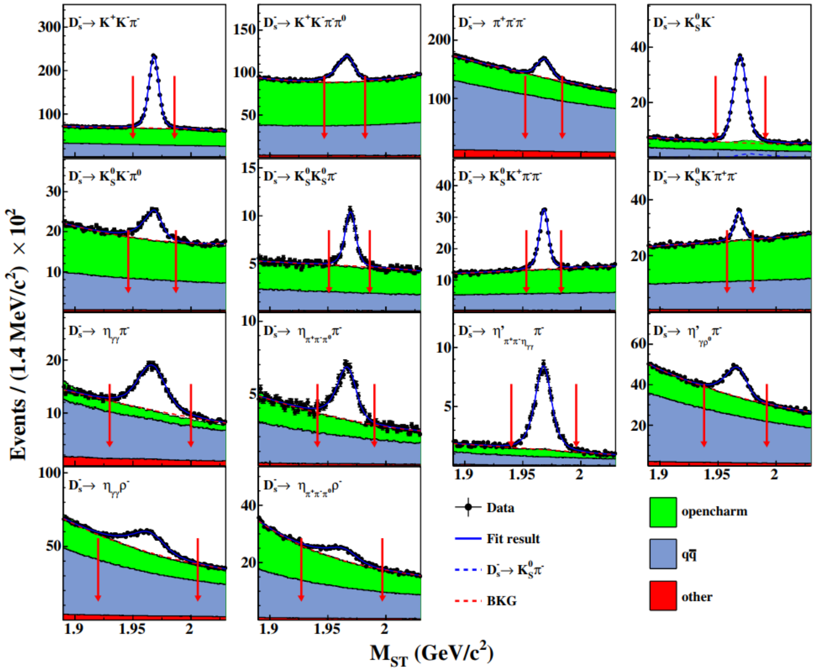
- Datasets
  - 2.93 fb^{-1} data $e^+e^- \to \psi(3770)$ at $\sqrt{s} = 3.773$ GeV
  - 7.33 fb^{-1} $e^+e^- \to D_s^+ D_s^{*-}$ data collected at $\sqrt{s} = 4.128\sim4.226$ GeV

Method

- Single tag (ST): reconstruct one $D_{(s)}$
  - Higher efficiency
  - Relatively high background
- Double tag (DT): reconstruct both $D_{(s)}$
  - Clean background
  - Kinematic constraint on missing particles
  - Systematic uncertainties on the tag side mostly canceled







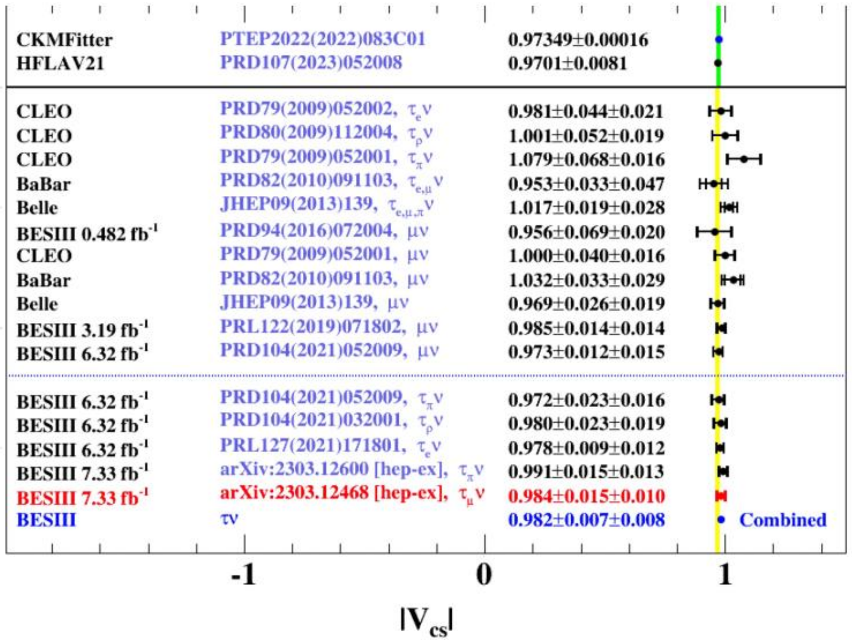
DT Branching Fraction (BF)

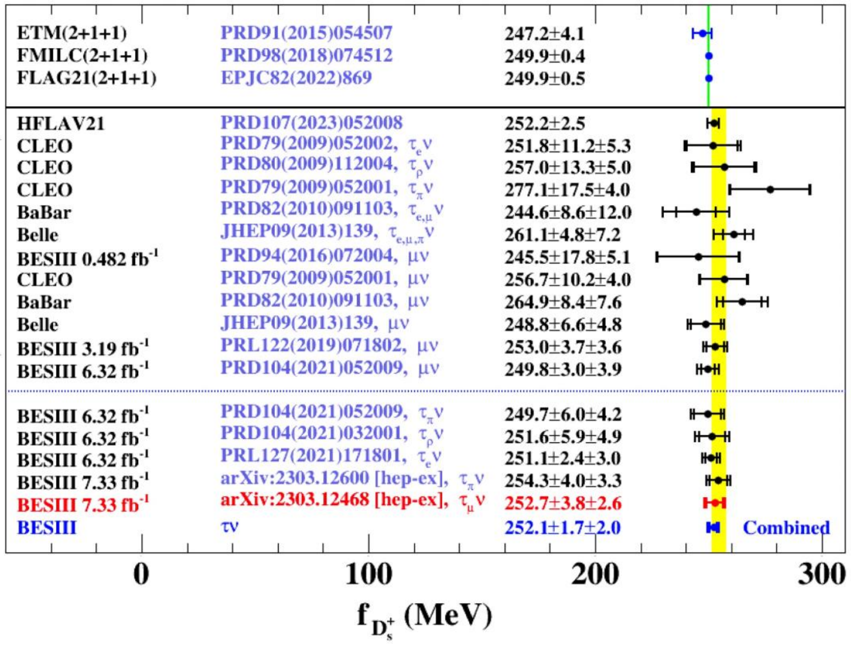
- $N_{\mathrm{DT}} = 2N_{D\bar{D}}\mathcal{B}_{\mathrm{sig}}\mathcal{B}_{\mathrm{tag}}\epsilon_{\mathrm{DT}}$
- $N_{\mathrm{tag}} = 2N_{D\bar{D}}\,\mathcal{B}_{\mathrm{tag}}\epsilon_{\mathrm{tag}}$
- $\mathcal{B}_{\mathrm{sig}} = \dfrac{N_{\mathrm{DT}}}{(N_{\mathrm{tag}}\,\epsilon_{\mathrm{DT}})/\epsilon_{\mathrm{tag}}}$

Leptonic decays

- Measurements of decay constant and CKM matrix element $|V_{cs}|$.
  - $D_s^+ \to \tau^+\nu_\tau, \tau^+ \to e^+\nu_e\bar{\nu}_\tau$ PRL 127, 171801 (2021)
  - $D_s^+ \to \tau^+\nu_\tau,\ \tau^+ \to \pi^+\pi^0\bar{\nu}_\tau$ PRD 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

New updates!



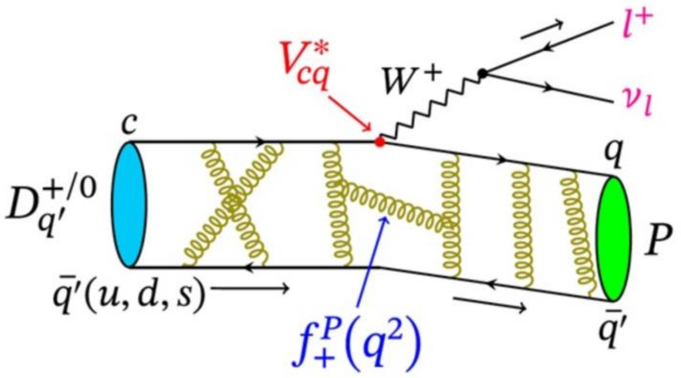


- $D_s^{*+} \to e^+\nu_e$ first experimental search 2.9σ arXiv:2304.12159

Semileptonic decays

- Measurements of form factors and CKM matrix element $|V_{cs}|$.
- Semileptonic decays as probes for the inner structures of light mesons.

- $D_s^+ \to \pi^+\pi^- e^+\nu_e$ arXiv: 2303.12927
  - $D_s^+ \to f^0(980)e^+\nu_e$
- $D_s^+ \to K^+K^-\mu^+\nu_\mu$ arXiv:2307.03024
  - $D_s^+ \to \phi\mu^+\nu_\mu$, upper limit on $D_s^+ \to f^0(980)\mu^+\nu_\mu$
- $D_s^+ \to \eta e^+\nu_e$ and $D_s^+ \to \eta' e^+\nu_e$ arXiv:2306.05194



See Shulei Zhang's talk on Thursday for more on leptonic and semileptonic decays

Hadronic decays

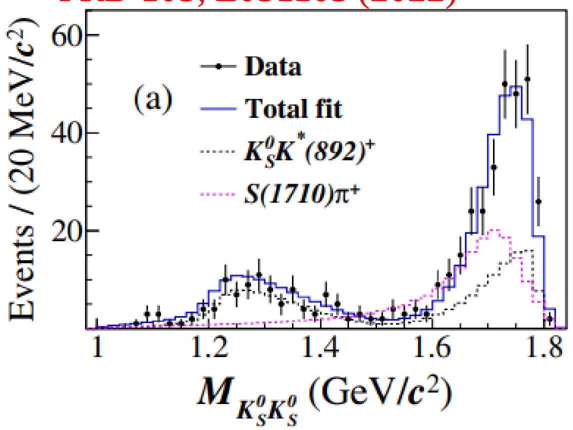
- Measurements of branching fractions
  - Test of theoretical calculations, non-perturbative QCD
  - SU(3) flavor symmetry and its breaking effect
  - CP violation

- Amplitude analysis
  - Light meson spectroscopy

- Quantum correlated $D\bar{D}$ pairs
  - Unique access to the strong phase measurements
  - Important input in the measurement of angle γ in the CKM unitarity triangle

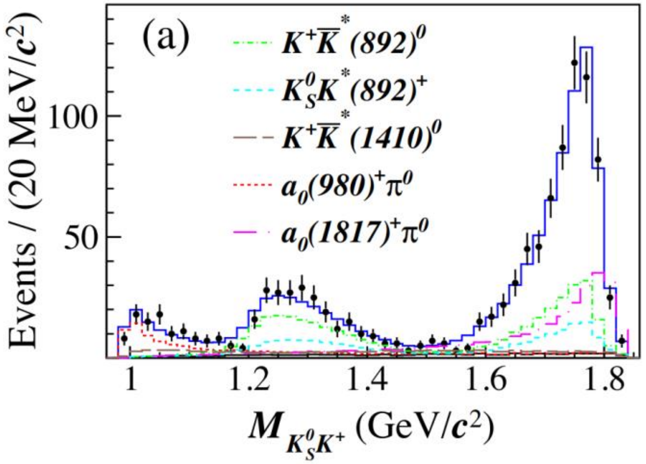
Amplitude analysis: observation of $a_0(1817)^+$

PRD 105, L051103 (2022)



- Amplitude analysis of $D_s^+ \to K_S^0 K_S^0 \pi^+$
- An enhancement on $K_S^0 K_S^0$ mass spectrum around 1.7 GeV/c^2
- BF one order of magnitude larger than the expectation for $f_0(1710) \to K_S^0 K_S^0$
- Implies the isospin-one partner of $f_0(1710)$?

PRL 129, 182001 (2022)



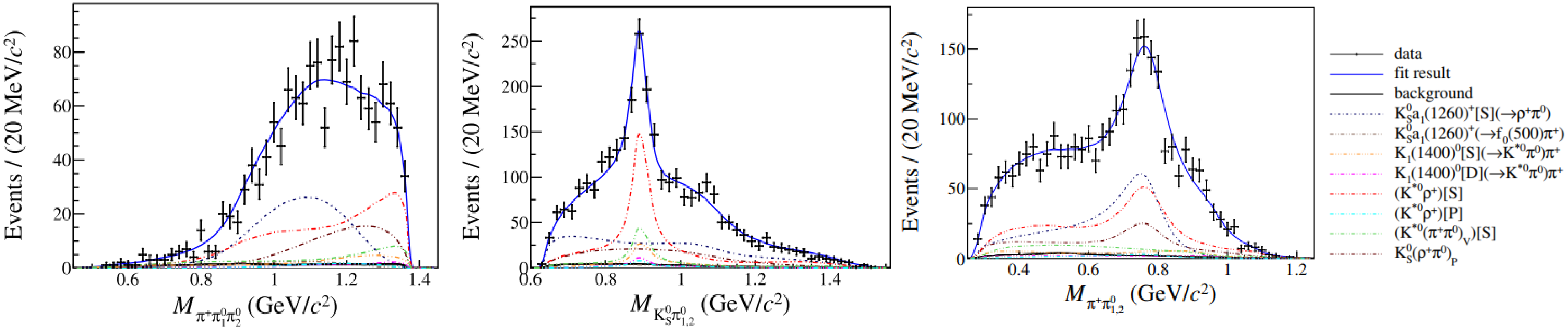
- Amplitude analysis of $D_s^+ \to K_S^0 K^+ \pi^0$
- Observation of an a_0-like state $a_0(1817)^+$ with $a_0(1817)^+ \to K_S^0 K^+$, over 10σ
  - $M = (1.817 \pm 0.008_{\text{stat.}} \pm 0.020_{\text{syst.}})$ GeV/c^2
  - $\Gamma = (0.097 \pm 0.022_{\text{stat.}} \pm 0.015_{\text{syst.}})$ GeV/c^2
  - The isospin-one partner of the $f_0(1710)$ (but mass ~100MeV higher) or $X(1812)$?

A simultaneous amplitude analysis of $D_s^+ \to K_S^0 K^+ \pi^0$ and $D_s^+ \to K_S^0 K_S^0 \pi^+$ in the future to study the a_0-like state

Amplitude analysis: $D^+ \to K_S^0\pi^+\pi^0\pi^0$

arXiv:2305.15879

- $\mathcal{B}(D^+ \to K_S^0\pi^+\pi^0\pi^0) = (2.888 \pm 0.058_{\text{stat.}} \pm 0.069_{\text{syst.}})\%$
- Dominate intermediate processes
  - $\mathcal{B}(D^+ \to K_S^0 a_1(1260)^+(\to \rho^+\pi^0)) = (8.66 \pm 1.04_{\text{stat.}} \pm 1.39_{\text{syst.}}) \times 10^{-3}$
  - $\mathcal{B}\left(D^+ \to \bar{K}^{*0}\rho^+\right) = (9.70 \pm 0.81_{\text{stat.}} \pm 0.53_{\text{syst.}}) \times 10^{-3}$



1458 events. Purity $(96.86 \pm 0.46)\%$

Inclusive BF measurements

- $\mathcal{B}(D^+ \to K_S^0 X) = (33.11 \pm 0.13_{\text{stat.}} \pm 0.36_{\text{syst.}})\%$, improved 7.1 times

PRD 107, 112005 (2023)

- $\mathcal{B}(D^0 \to K_S^0 X) = (20.75 \pm 0.12_{\text{stat.}} \pm 0.20_{\text{syst.}})\%$, improved 7.6 times
- Difference with the BF of known exclusive decays containing K_S^0
  - $(1.10 \pm 0.41)\%$ for D^+, $(2.38 \pm 0.75)\%$ for D^0

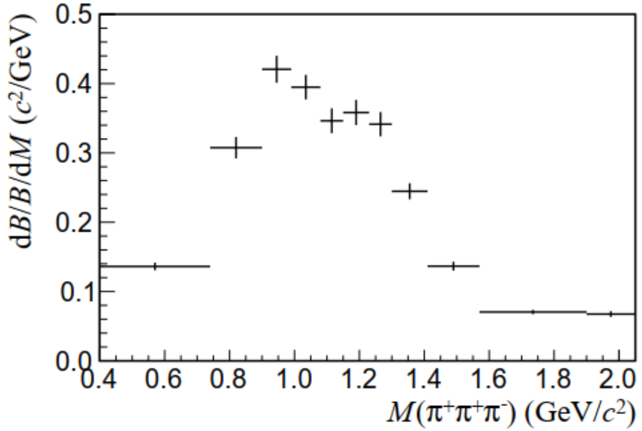
- $\mathcal{B}(D^0 \to \pi^+\pi^+\pi^- X) = (17.60 \pm 0.11_{\text{stat.}} \pm 0.22_{\text{syst.}})\%$
- $\mathcal{B}(D^+ \to \pi^+\pi^+\pi^- X) = (15.25 \pm 0.09_{\text{stat.}} \pm 0.18_{\text{syst.}})\%$
- consistent with the BF of known exclusive decays within about 3σ
- Little room for missing $D^0(D^+) \to \pi^+\pi^+\pi^- X$ decays

PRD 107, 032002 (2023)

Important inputs for LFU tests with the semileptonic B decays as background in $B^0 \to D^{*-}\tau^+\nu_\tau$ $(\tau^+ \to \pi^+\pi^+\pi^-\bar{\nu}_\tau)$

- $\mathcal{B}(D_s^+ \to \pi^+\pi^+\pi^- X) = (32.81 \pm 0.35_{\text{stat.}} \pm 0.82_{\text{syst.}})\%$
- Partial BFs as a function of $M(\pi^+\pi^+\pi^-)$ are measured
- Larger than the BF of known exclusive decays $(24.7 \pm 1.5)\%$

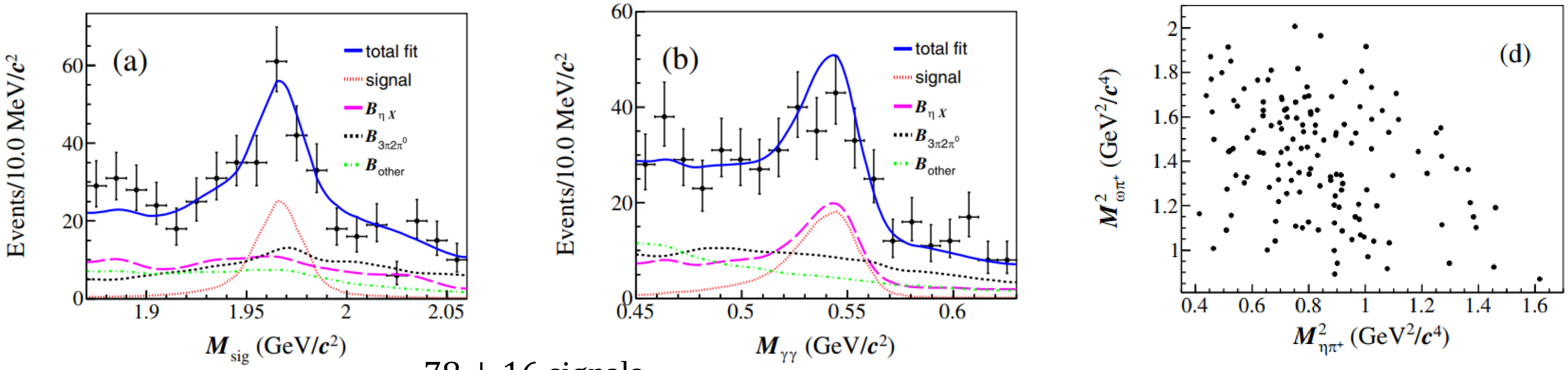
arXiv:2212.13072



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

PRD 107, 052010 (2023)

- $\mathcal{B}(D_s^+ \to \omega\pi^+\eta) = (0.54 \pm 0.12_{\text{stat.}} \pm 0.04_{\text{syst.}})\%$
- First observation with a statistical significance of 7.6σ
- $\omega \to \pi^+\pi^-\pi^0$, contribute in $D_s^+ \to \pi^+\pi^+\pi^- X$.
- Potential intermediate process $D_s^+ \to \omega a_0(980)^+$ and $D_s^+ \to \eta b_1(1235)^+$ can be searched for with larger statistics.



78 ± 16 signals

BF involving K_L^0

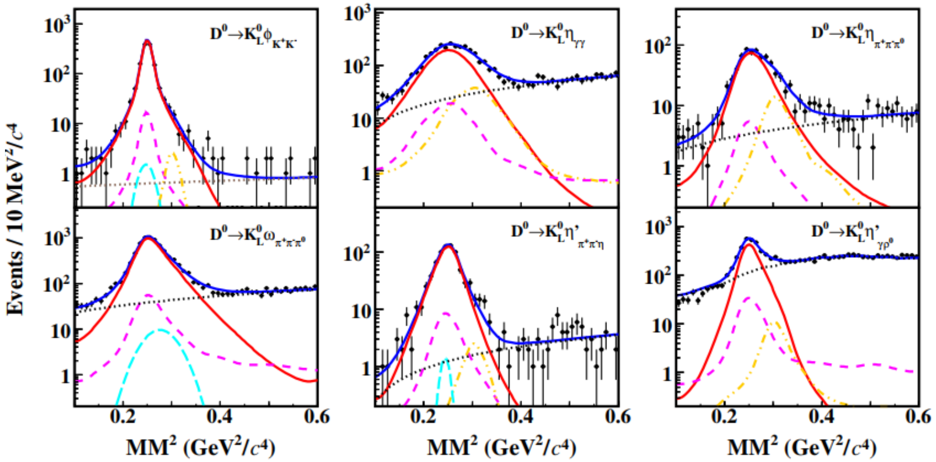
PRD 105, 092010 (2022)

- First measurements of their BFs.
- The interference between Cabibbo-favored (CF) and doubly Cabibbo-suppressed (DCS) amplitudes can lead to a significant asymmetry between the BFs of $D^0 \to K_S^0 X$ and $D^0 \to K_L^0 X$
- $\mathcal{R}(D^0, X) = \frac{\mathcal{B}(D^0 \to K_S^0 X) - \mathcal{B}(D^0 \to K_L^0 X)}{\mathcal{B}(D^0 \to K_S^0 X) + \mathcal{B}(D^0 \to K_L^0 X)} \sim 2\tan^2\theta_C$, θ_C is the Cabibbo mixing angle.

Decay	$\mathcal{B}_{\rm exp}$ (%)	$\mathcal{B}_{\rm FAT}$ (%)	Difference	$\mathcal{R}(D^0)_{\rm exp}$	$\mathcal{B}(D^0)_{\rm FAT}$	Difference
$D^0 \to K_L^0 \phi$	$0.414 \pm 0.021 \pm 0.010$	0.33 ± 0.03	2.2σ	-0.001 ± 0.047		2.4σ
$D^0 \to K_L^0 \eta$	$0.433 \pm 0.012 \pm 0.010$	0.40 ± 0.07	0.5σ	0.080 ± 0.022	0.113 ± 0.001	1.5σ
$D^0 \to K_L^0 \omega$	$1.164 \pm 0.022 \pm 0.028$	0.95 ± 0.15	1.4σ	-0.024 ± 0.031		4.4σ
$D^0 \to K_L^0 \eta'$	$0.809 \pm 0.020 \pm 0.016$	0.77 ± 0.07	0.5σ	0.080 ± 0.023		1.6σ

CP asymmetries
No significant CPV is found

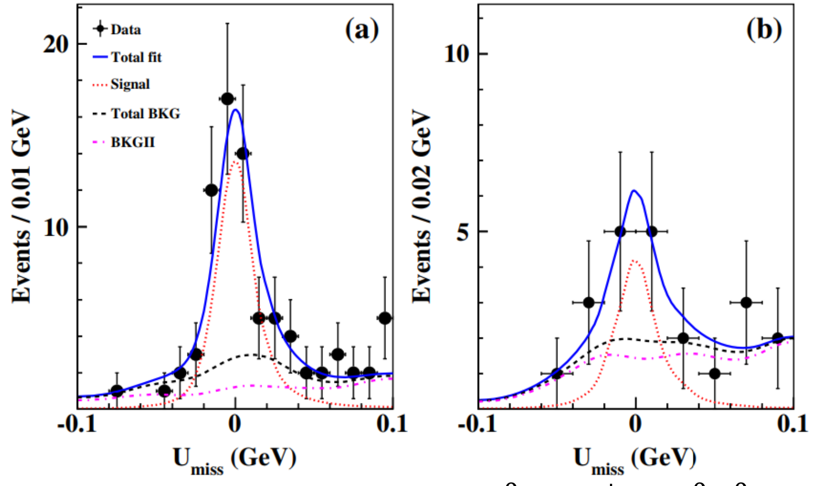
Decay	$\mathcal{B}^{+}_{\rm sig}$ (%)	$\mathcal{B}^{-}_{\rm sig}$ (%)	$\mathcal{A}_{CP}^{\rm sig}$ (%)
$D^0 \to K_L^0 \phi$	0.428 ± 0.029	0.405 ± 0.034	$2.7 \pm 5.4 \pm 0.7$
$D^0 \to K_L^0 \eta$	0.445 ± 0.018	0.421 ± 0.017	$2.8 \pm 2.9 \pm 0.4$
$D^0 \to K_L^0 \omega$	1.200 ± 0.030	1.121 ± 0.031	$3.4 \pm 1.9 \pm 0.6$
$D^0 \to K_L^0 \eta'$	0.789 ± 0.028	0.826 ± 0.028	$-2.2 \pm 2.5 \pm 0.4$



Doubly Cabibbo-Suppressed decays

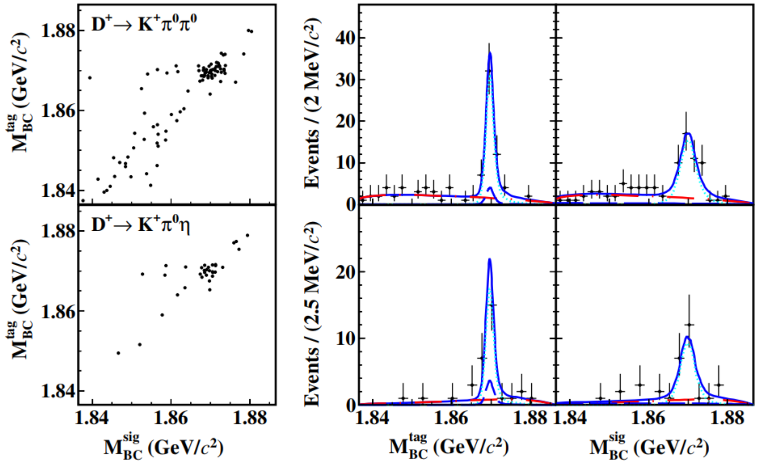
- $\mathcal{B}(D^0 \to K^+\pi^-\pi^0) = \left(3.13^{+0.60}_{-0.056\,\text{stat.}} \pm 0.015_{\text{syst.}}\right) \times 10^{-4}$
- $\mathcal{B}(D^0 \to K^+\pi^-\pi^0\pi^0) < 3.6 \times 10^{-4}$ at 90% C.L.

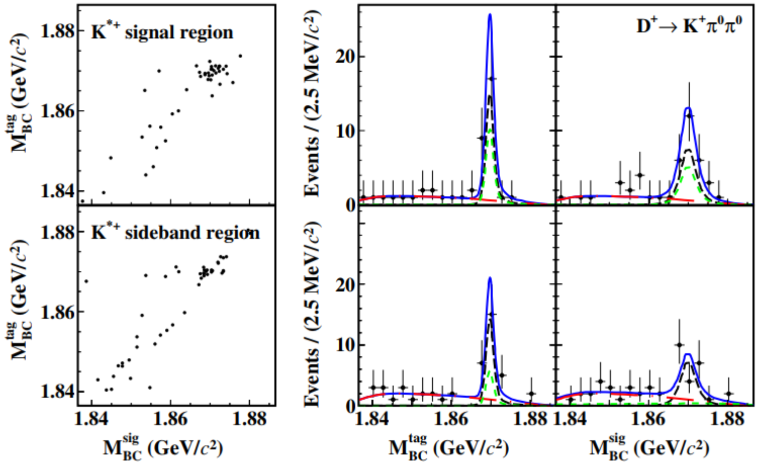
PRD 105 112001 (2022)

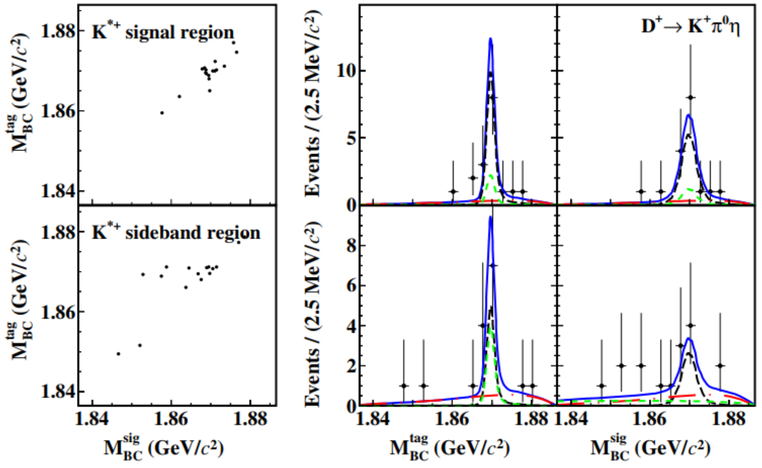


$D^0 \to K^+\pi^-\pi^0$ $D^0 \to K^+\pi^-\pi^0\pi^0$

- First observation JHEP09(2022)107
- $\mathcal{B}(D^0 \to K^+\pi^0\pi^0) = \left(2.1 \pm 0.4_{\text{stat.}} \pm 0.1_{\text{syst.}}\right) \times 10^{-4}$
  - $\mathcal{B}(D^0 \to K^*(892)^+\pi^0) < 4.5 \times 10^{-4}$
- $\mathcal{B}(D^0 \to K^+\pi^0\eta) = \left(2.1 \pm 0.5_{\text{stat.}} \pm 0.1_{\text{syst.}}\right) \times 10^{-4}$
  - $\mathcal{B}(D^0 \to K^*(892)^+\eta) = \left(4.7^{+1.9}_{-1.6\,\text{stat.}} \pm 0.2_{\text{syst.}}\right) \times 10^{-4}$







Strong phase difference $\delta_D^{K\pi}$

Eur. Phys. J. C (2022) 82:1009

- Quantum-correlated $D\bar{D}$ pairs.
- Most precise measurements $\delta_D^{K\pi} = (187.6^{+8.9+5.4}_{-9.7-6.4})°$
  - $r_D^{K\pi}\exp(-i\delta_D^{K\pi}) = \frac{\langle K^+\pi^-|D^0\rangle}{\langle K^+\pi^-|\bar{D}^0\rangle}$

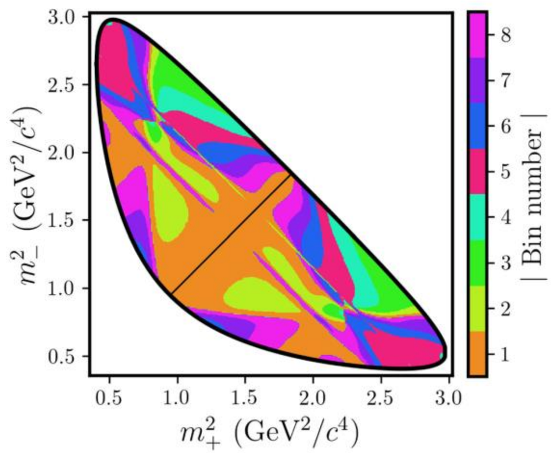
  $\delta_D^{K\pi}$: Strong phase difference between DCS and CF decays

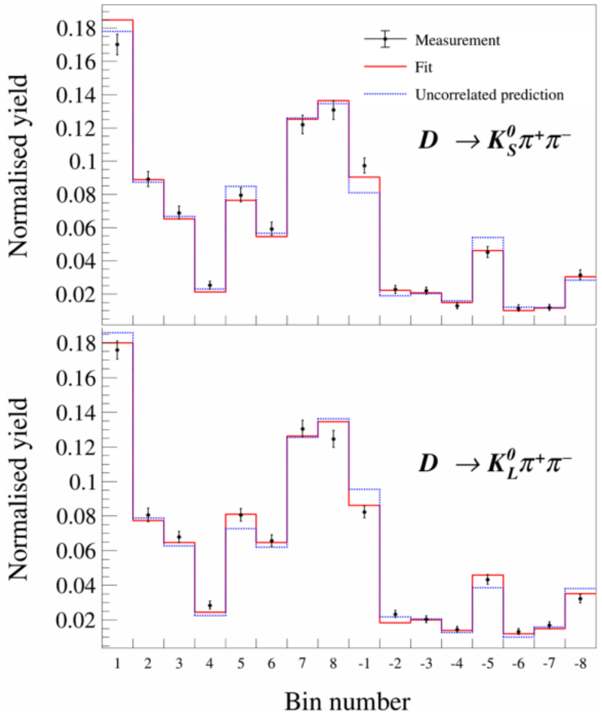
  $r_D^{K\pi}$: Ratio of amplitude between DCS and CF decays
- Asymmetry between CP-odd and CP-even eigenstate decays into $K^-\pi^+$
  - $\mathcal{A}_{K\pi} \equiv \frac{\mathcal{B}(D_-\to K^-\pi^+)-\mathcal{B}(D_+\to K^-\pi^+)}{\mathcal{B}(D_-\to K^-\pi^+)+\mathcal{B}(D_+\to K^-\pi^+)} = \frac{-2r_D^{K\pi}\cos\delta_D^{K\pi}+y}{1+(r_D^{K\pi})^2} = 0.132 \pm 0.011 \pm 0.007$

    30% more precise than previous BESIII measurement [PLB 734 (2014) 227–233].
  - Using the predominantly CP-even tag $D\to\pi^+\pi^-\pi^0$,

    $\mathcal{A}_{K\pi}^{\pi\pi\pi^0} \equiv \frac{\mathcal{B}(D_X\to K^-\pi^+)-\mathcal{B}(D_+\to K^-\pi^+)}{\mathcal{B}(D_X\to K^-\pi^+)+\mathcal{B}(D_+\to K^-\pi^+)} = \frac{(-2r_D^{K\pi}\cos\delta_D^{K\pi}+y)F_+^{\pi\pi\pi^0}}{1+(r_D^{K\pi})^2+(1-F_+^{\pi\pi\pi^0})(2r_D^{K\pi}\cos\delta_D^{K\pi}+y)}$

    $\mathcal{A}_{K\pi}^{\pi\pi\pi^0} = 0.130 \pm 0.012 \pm 0.008$
- $D\to K_{S,L}^+\pi^+\pi^-$ tags, sensitive to both $r_D^{K\pi}\cos\delta_D^{K\pi}$ and $r_D^{K\pi}\sin\delta_D^{K\pi}$
- Measured BF of $D^0\to K_L\pi^0$, $D^0\to K_L\omega$, $D^0\to K_L\pi^0\pi^0$

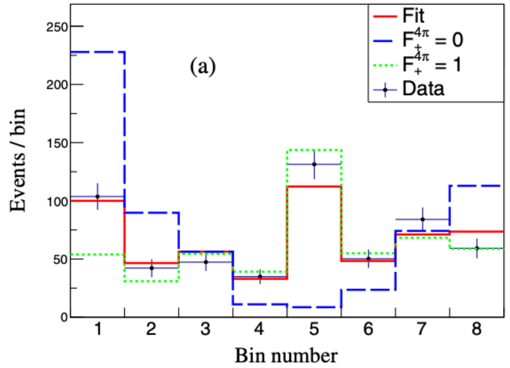


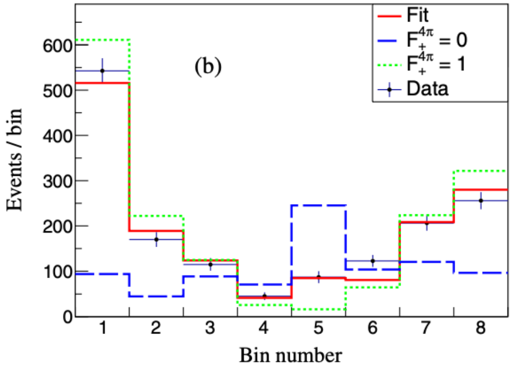


CP-even fraction measurements

- $D^0 \to \pi^+\pi^-\pi^+\pi^-$
- $F_+ = 0.735 \pm 0.015 \pm 0.005$

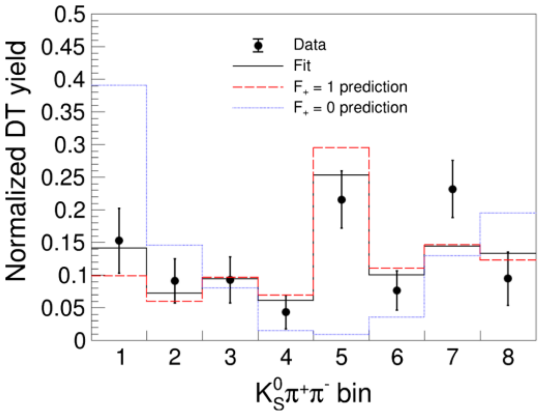
PRD 106 092004 (2022)

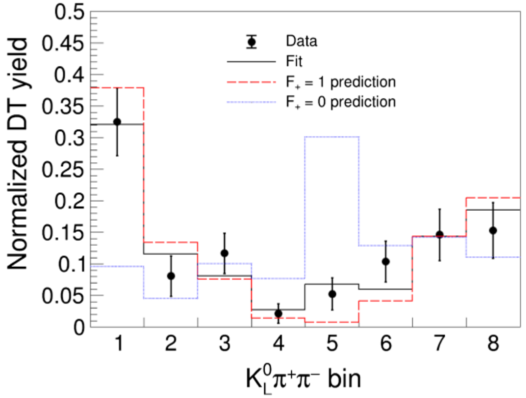




- $D^0 \to K^+K^-\pi^+\pi^-$
- $F_+ = 0.730 \pm 0.037 \pm 0.021$

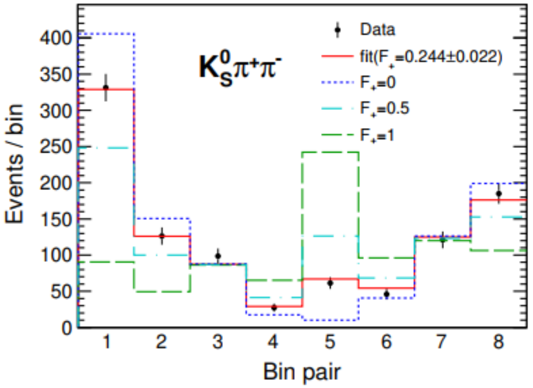
PRD 107 032009 (2023)

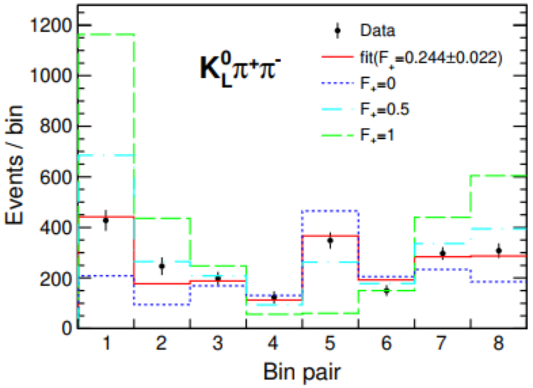




- $D^0 \to K_S^0\pi^+\pi^-\pi^0$
- $F_+ = 0.235 \pm 0.010 \pm 0.002$

arXiv: 2305.03975





Summary and prospects

- The BESIII experiment reports many important results on charmed meson decays.
  - Observation of a_0-like state $a_0(1817)^+$
  - Improved strong phase measurements
  - Provide important knowledge on charmed mesons

- 20 fb^{-1} $\psi(3770)$ data will be collected by 2024.
- Updates of the measurements with larger datasets are expected.
  - Strong phase measurements
  - D decays

Back up

D_s Datasets

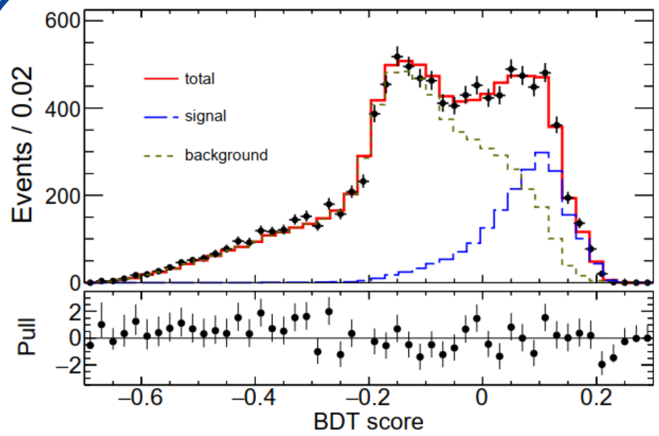
Sample	Year	Luminosity (pb^{-1})	E_{cm} (MeV)
4.128	2019	401.5 [19]	4128.48±0.44 [20]
4.157	2019	408.7 [19]	4157.44±0.44 [20]
4.178	2016	3189.0±0.2±31.9 [14]	4178.0 on average [15]
4.189	2017 2012	526.7±0.1±2.2 [16] 43.33±0.03±0.29 [18]	4188.99±0.06±0.41 [16] 4188.59±0.15±0.68 [17]
4.199	2017	526.0±0.1±2.1 [16]	4199.03±0.05±0.41 [16]
4.209	2017 2013	517.1±0.1±1.8 [16] 54.95±0.03±0.36 [18]	4209.25±0.06±0.42 [16] 4207.73±0.14±0.61 [17]
4.219	2017 2013	514.6±0.1±1.8 [16] 54.60±0.03±0.36 [18]	4218.84±0.05±0.40 [16] 4217.13±0.14±0.67 [17]
4.226	2012-2013	1047.34±0.14 ± 10.16 [18] 44.54±0.03±0.29 [18]	$4320.34-2.87\times10^{-3}\times N_{run}\pm0.05\pm0.60$ [17] 4225.54 ± 0.05 ± 0.65 [17] 4226.26±0.04±0.65 [17]

Leptonic decays $D_s^+ \to \tau^+\nu_\tau$

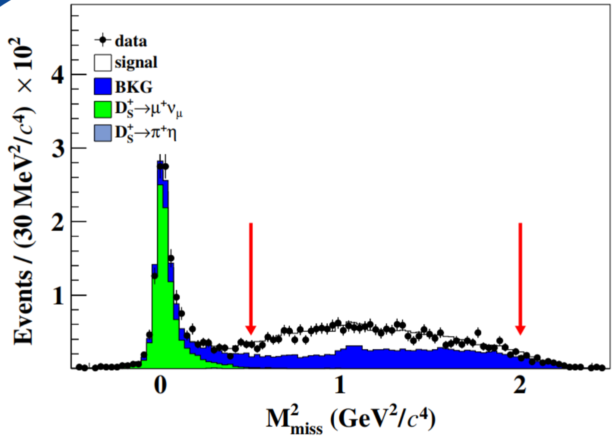
BESIII results

Work	Dataset	τ^+ decay	$\mathcal{B}(D_s^+ \to \tau^+\nu_\tau)$ (%)	$f_{D_s^+}\lvert V_{cs}\rvert$ (MeV)
PRL 127, 171801 (2021)	6.32 fb^{-1} 4.178~4.226 GeV	$\tau^+ \to e^+\nu_e\bar{\nu}_\tau$	$5.27 \pm 0.10 \pm 0.13$	$244.4 \pm 2.3 \pm 2.9 \pm 1.0$
PRD 104, 032001 (2021)	6.32 fb^{-1} 4.178~4.226 GeV	$\tau^+ \to \pi^+\pi^0\bar{\nu}_\tau$	$5.30 \pm 0.25 \pm 0.20$	$245.1 \pm 5.8 \pm 4.7 \pm 1.0$
arXiv:2303.12468	7.33 fb^{-1} 4.128~4.226 GeV	$\tau^+ \to \mu^+\nu_\mu\bar{\nu}_\tau$	$5.34 \pm 0.16 \pm 0.10$	$246.2 \pm 3.7 \pm 2.3 \pm 1.0$
arXiv:2303.12600	7.33 fb^{-1} 4.128~4.226 GeV	$\tau^+ \to \pi^+\bar{\nu}_\tau$	$5.41 \pm 0.17 \pm 0.13$	$247.6 \pm 3.9 \pm 3.2 \pm 1.0$

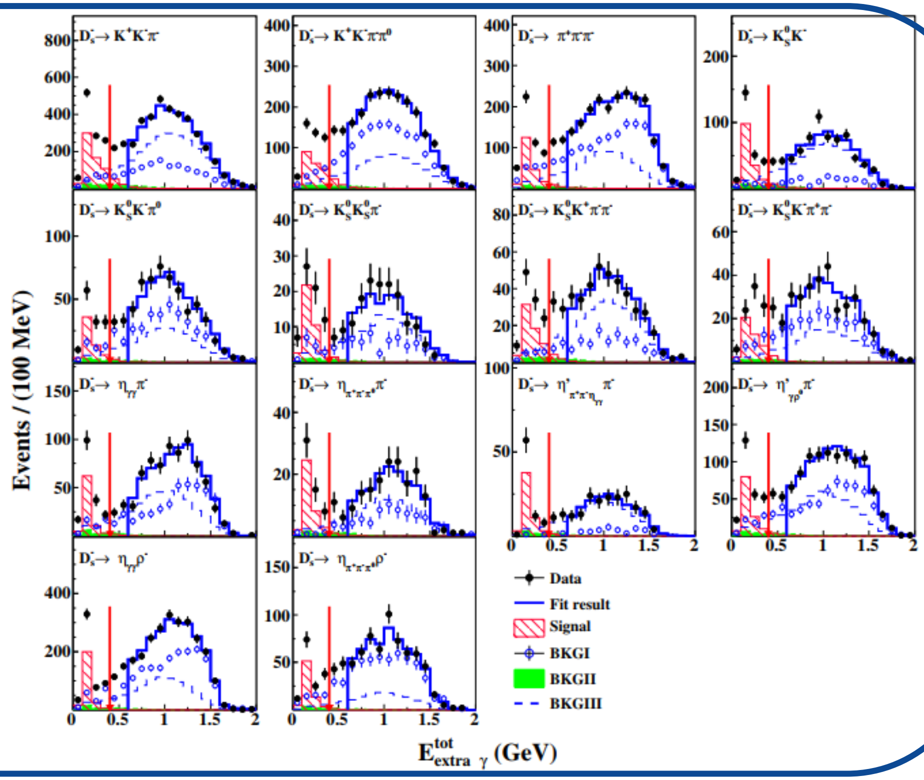
New updates!



arXiv:2303.12600 $\tau^+ \to \pi^+\bar{\nu}_\tau$
using BDT training method



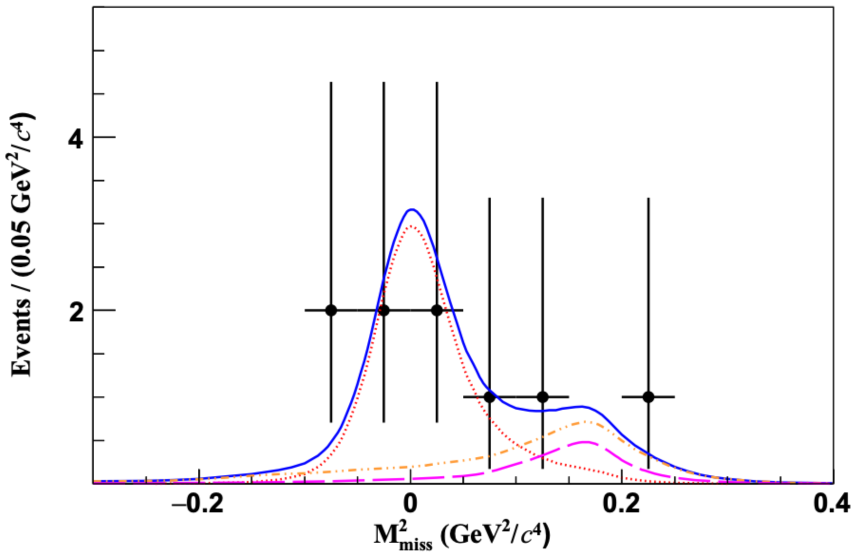
arXiv:2303.12468 $\tau^+ \to \mu^+\nu_\mu\bar{\nu}_\tau$
Extract the singal using $E_{\text{extra}\,\gamma}^{\text{tot}}$, total energy of extra showers in the calorimeter.

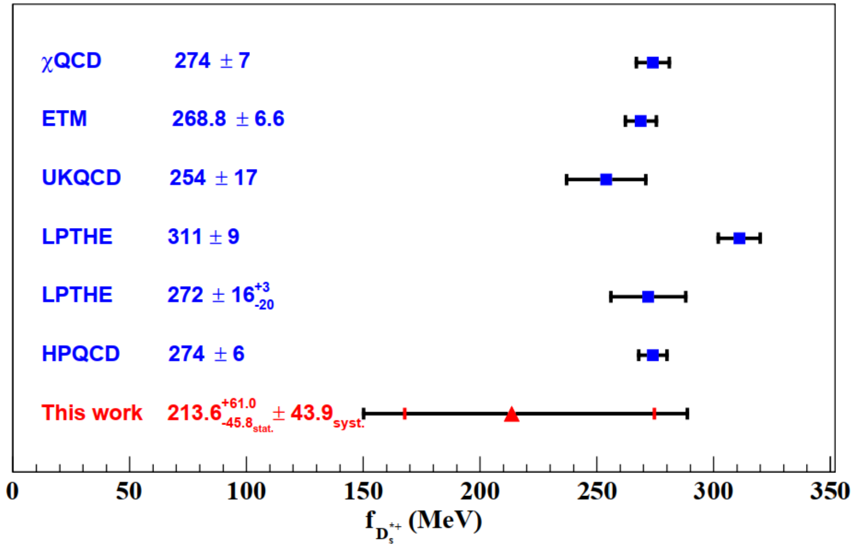


$D_s^{*+} \to e^+\nu_e$

arXiv:2304.12159

- First experimental search
- $\mathcal{B}(D_s^{*+} \to e^+\nu_e) = (2.1^{+1.2}_{-0.9\,\mathrm{stat.}} \pm 0.2_{\mathrm{syst.}}) \times 10^{-5}$ statistical significance 2.9σ
  - Upper limit at 90% C.L. 4.0×10^{-5}
- D_s^{*+} decay constant $f_{D_s^{*+}} = (213.6^{+61.0}_{-45.8\,\mathrm{stat.}} \pm 43.9_{\mathrm{syst.}})$ MeV
  - Upper limit at 90% C.L. 353.8 MeV
- Indirectly constrains the upper limit on the total width $\Gamma^{\mathrm{total}}_{D_s^{*+}}$ from MeV to keV level.

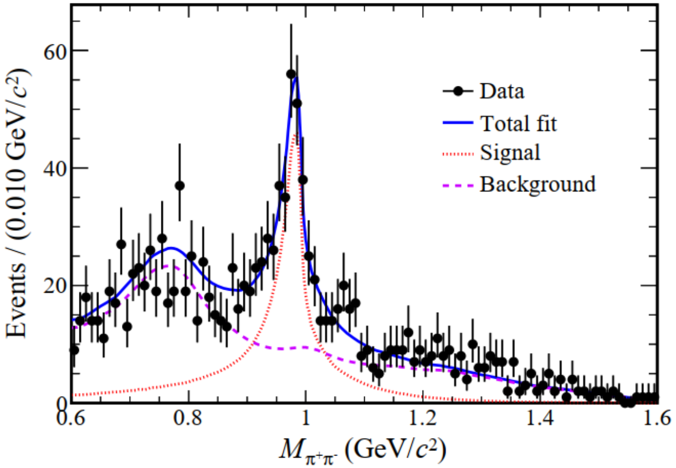


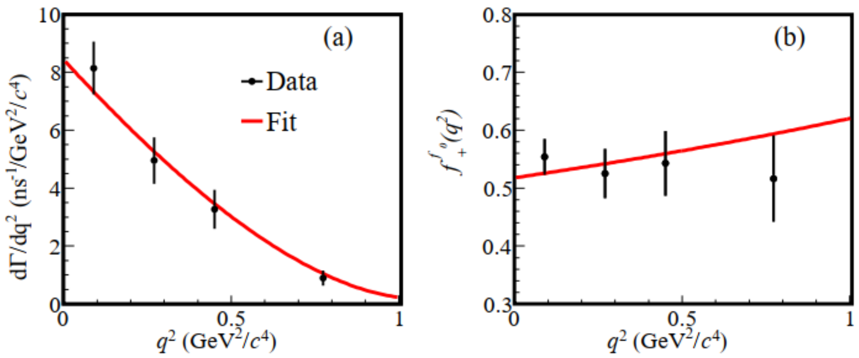


$D_s^+ \to \pi^+\pi^- e^+\nu_e$

arXiv: 2303.12927

- Study the light scalar meson $f^0(980)$
- Measured BF of $D_s^+ \to f^0(980)\, e^+\nu_e$, $f^0(980) \to \pi^+\pi^-$ is $1.72 \pm 0.31_{\text{stat.}} \pm 0.10_{\text{syst.}}$, 2.6 time more accurate than previous analysis.
- First time measurement of form factor, $f_+^{f^0}(0)|V_{cs}| = 0.504 \pm 0.017_{\text{stat.}} \pm 0.035_{\text{syst.}}$
- Using the relation between the BF and the mixing angle ϕ involved in the $q\bar{q}$ mixture picture for $f^0(980)$ as $\sin\phi \frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d}) + \cos\phi s\bar{s}$, we find that the $s\bar{s}$ compoment is dominant.





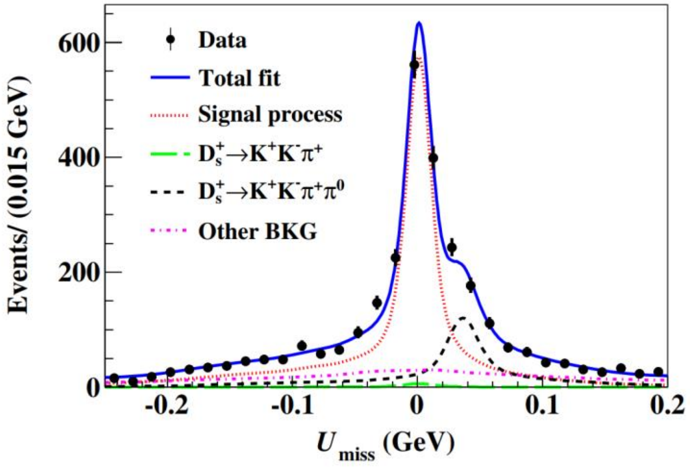
Comparison of form factor with theoretical calculations

	This work	CLFD [6]	DR [6]	QCDSR [7]	QCDSR [8]	LCSR [9]	LFQM [11]	CCQM [12]
$f_+^{f_0}(0)$	$0.518 \pm 0.018_{\text{stat}} \pm 0.036_{\text{syst}}$	0.45	0.46	0.50 ± 0.13	0.48 ± 0.23	0.30 ± 0.03	0.24 ± 0.05	0.39 ± 0.02
Difference (σ)	—	—	—	0.1	0.2	4.3	4.3	2.8
ϕ in theory	—	$(32 \pm 4.8)°$	$(41.3 \pm 5.5)°$	35°	$(8^{+21}_{-8})°$	—	$(56 \pm 7)°$	31°

$D_s^+ \to K^+K^-\mu^+\nu_\mu$

arXiv:2307.03024

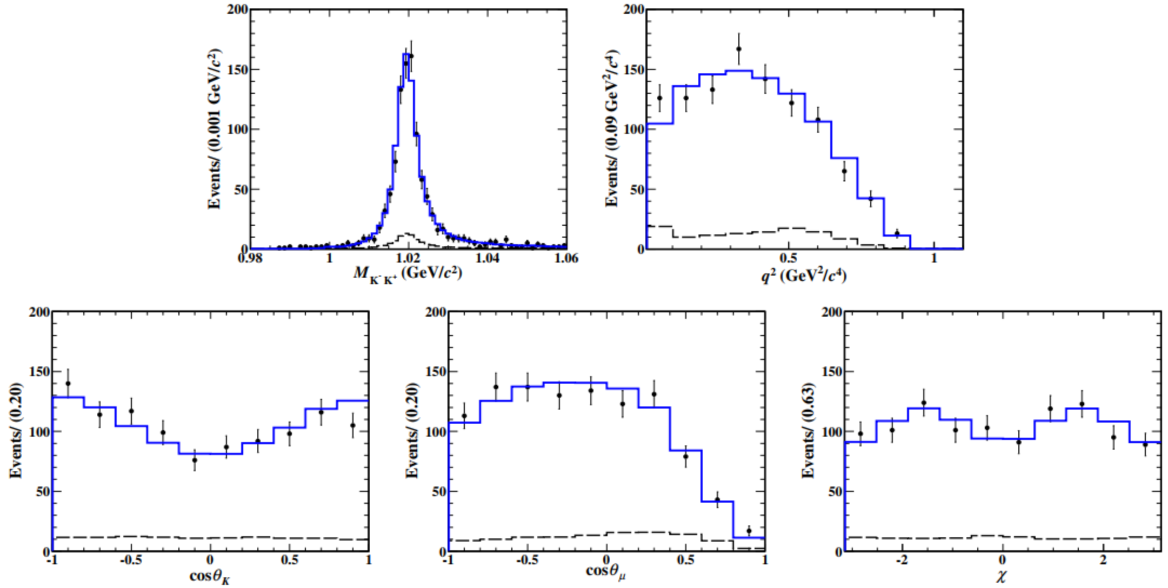
- A partial wave analysis is performed. The structure of the K^+K^- system is dominated by the vector meson ϕ.
- $\mathcal{B}(D_s^+ \to \phi\mu^+\nu_\mu) = (2.25 \pm 0.09_{\text{stat.}} \pm 0.07_{\text{syst.}}) \times 10^{-2}$, 4.3 times better than world average value.
- $\mathcal{B}(D_s^+ \to f^0(980)\mu^+\nu_\mu) \cdot \mathcal{B}(f^0(980) \to K^+K^-) < 5.45 \times 10^{-4}$ at 90% confidence level, assuming that the only S-wave contribution is from $f^0(980)$.



- Form factor ratio

Measured FF ratios and comparison with previous measurements.

Experiments	r_V	r_2
PDG [42]	1.80±0.08	0.84±0.11
This analysis	1.58±0.17±0.02	0.71±0.14±0.02
BABAR [25]	1.807±0.046±0.065	0.816±0.036±0.030
FOCUS [58]	1.549±0.250±0.148	0.713±0.202±0.284
Theory	r_V	r_2
CCQM [5]	1.34±0.27	0.99±0.20
CQM [6]	1.72	0.73
LFQM [7]	1.42	0.86
LQCD [3]	1.72±0.21	0.74±0.12
HMχT [8]	1.80	0.52

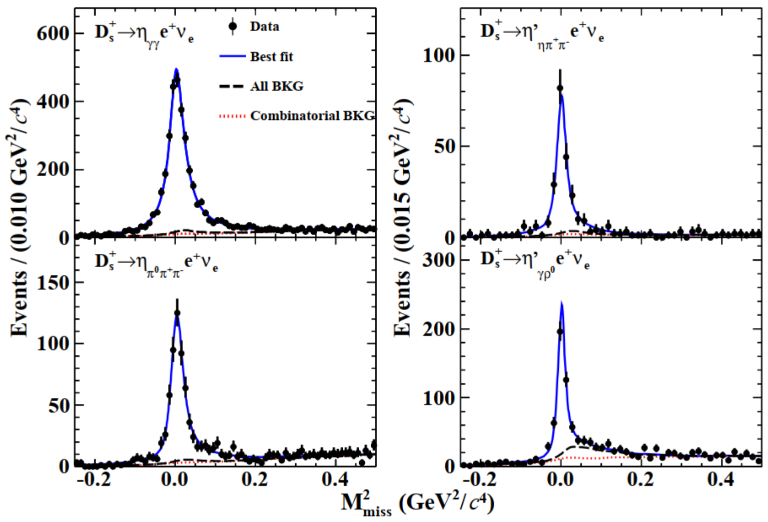


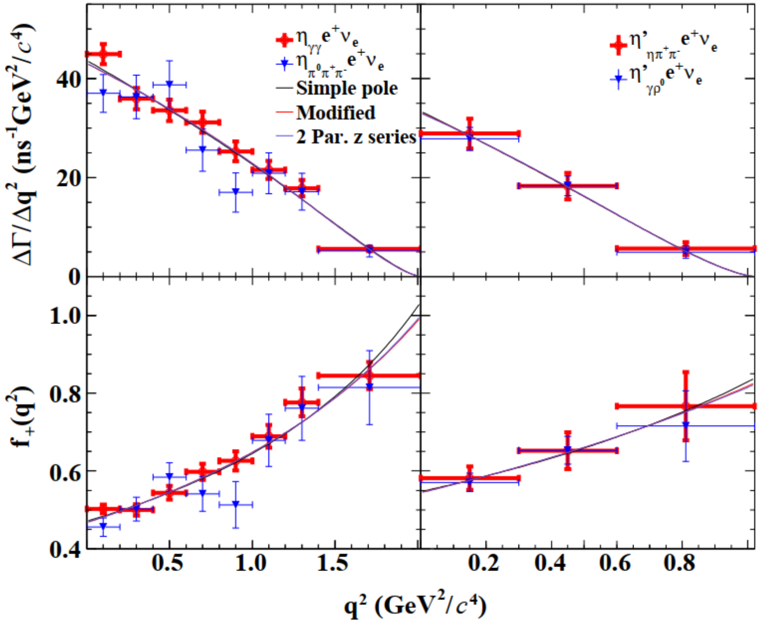
Projection of data and PWA fit results on kinematic variables.

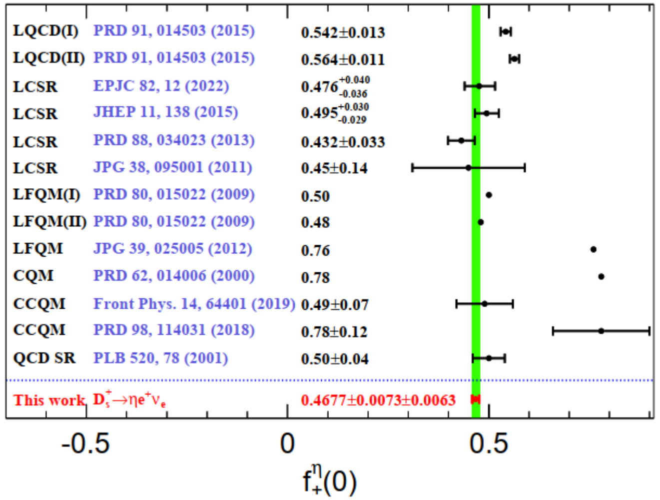
$D_s^+ \to \eta e^+ \nu_e$ and $D_s^+ \to \eta' e^+ \nu_e$

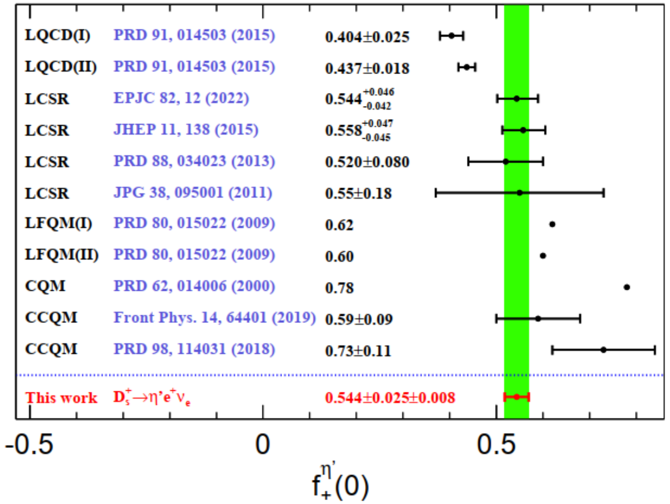
arXiv:2306.05194

- Measured BF
  - $\mathcal{B}(D_s^+ \to \eta e^+ \nu_e) = (2.251 \pm 0.039_{\text{stat.}} \pm 0.051_{\text{syst.}})\%$
  - $\mathcal{B}(D_s^+ \to \eta' e^+ \nu_e) = (0.810 \pm 0.038_{\text{stat.}} \pm 0.024_{\text{syst.}})\%$
  - Improved by a factor of 1.3 and 1.7
- Form factor measurements
  - $f_+^{\eta}(0)|V_{cs}| = 0.4553 \pm 0.0071_{\text{stat.}} \pm 0.0061_{\text{syst.}}$
  - $f_+^{\eta'}(0)|V_{cs}| = 0.529 \pm 0.024_{\text{stat.}} \pm 0.008_{\text{syst.}}$
- Combined with the BESIII measurements of $D^+ \to \eta^{(\prime)} e^+ \nu_e$, the $\eta - \eta'$ mixing angle $\phi_P = (40.0 \pm 2.0_{\text{stat.}} \pm 0.6_{\text{syst.}})^\circ$

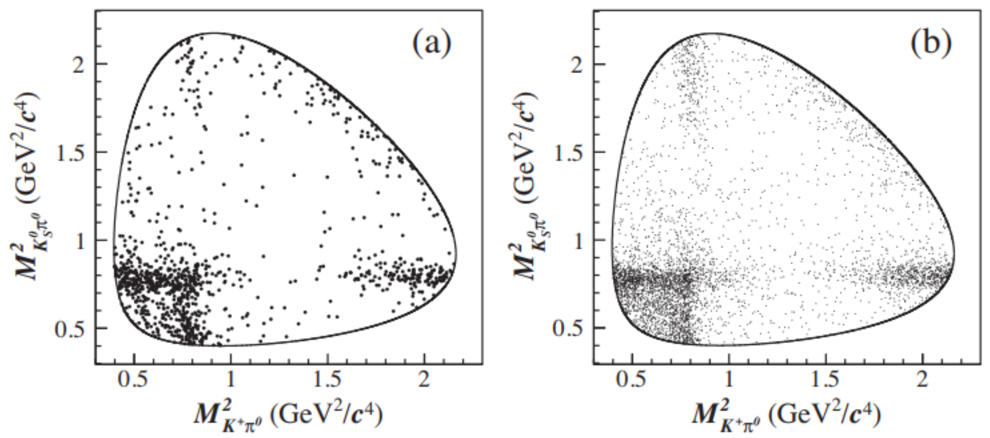




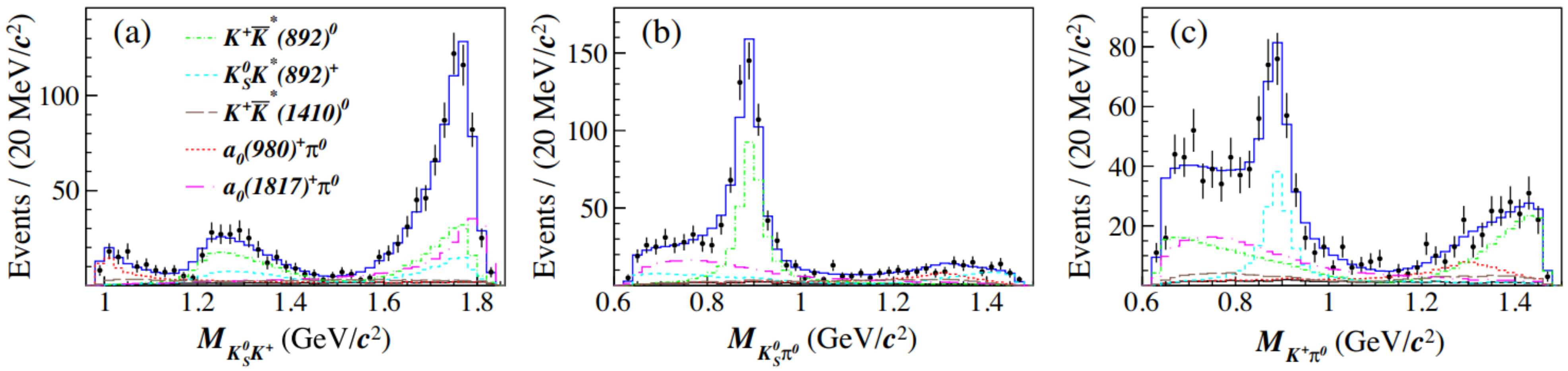




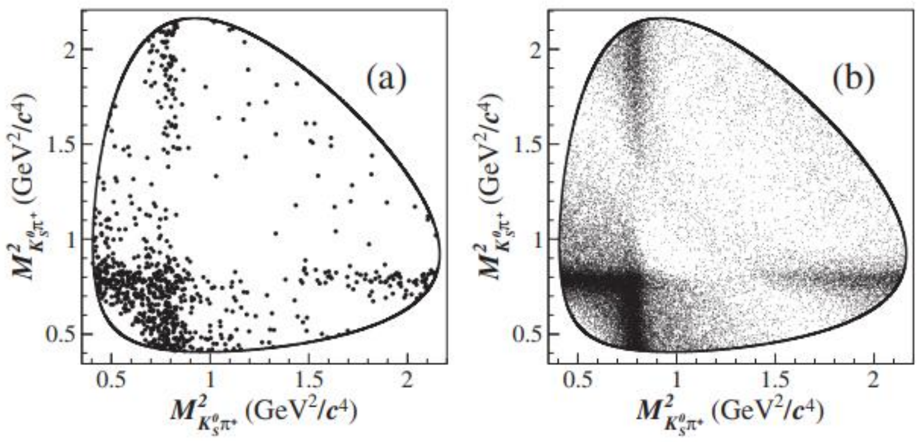
Amplitude analysis: $D_s^+ \to K_S^0 K^+ \pi^0$



1050 events
94.7% purity



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



412 events
97.3% purity