Charmed meson decays at BESIII

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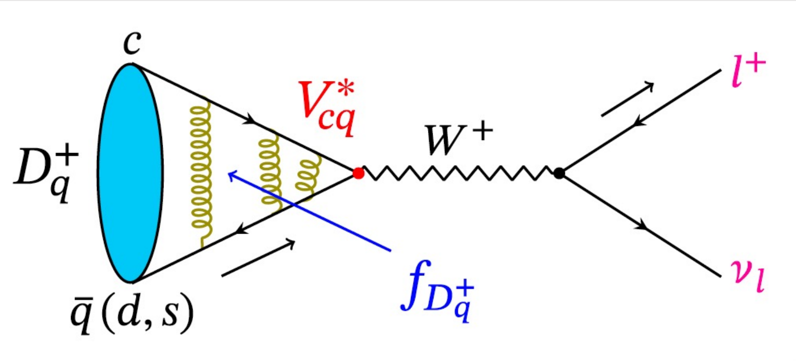
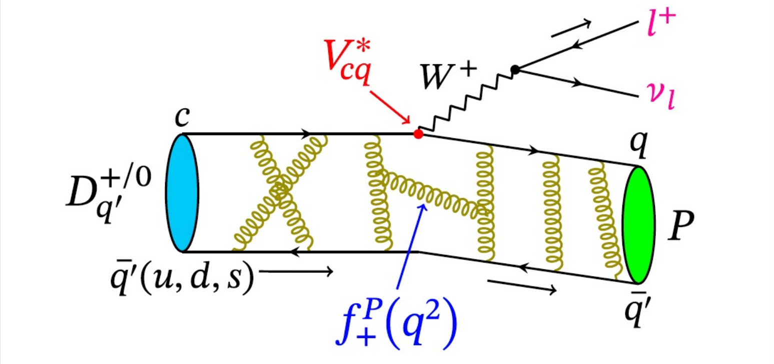
Topics of charm mesons @ BESIII

Pure leptonic decay



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

Semi-leptonic decay

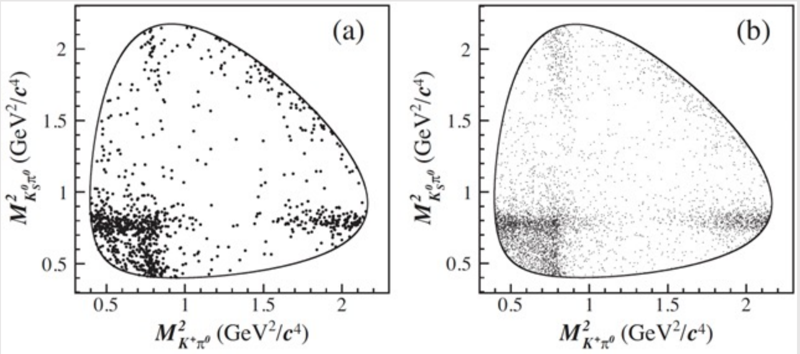


$$\Gamma(D_{(s)} \to P\, l^+\, \nu_l) \propto |f_+(q^2)|^2 \cdot |V_{cd(s)}|^2$$

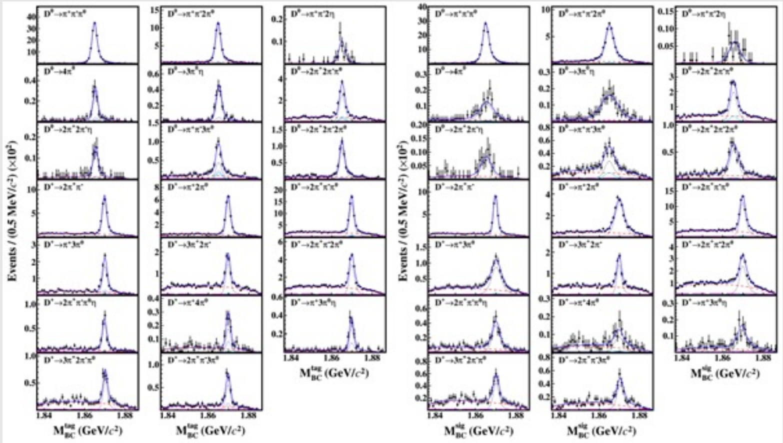
- **Decay constant $f_{D_{(s)}^+}$, form factor f_+^+**: calibrate Lattice QCD.
- **CKM matrix element $|V_{cd(s)}|$**: test the unitarity of the CKM matrix.
- Lepton flavor universality (LFU) test.

Topics of charm mesons @ BESIII

Amplitude Analysis



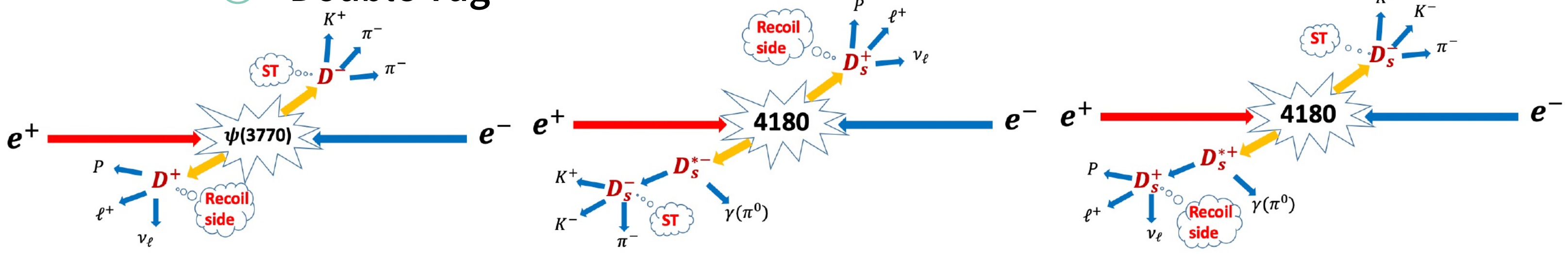
Branching Fraction Measurements



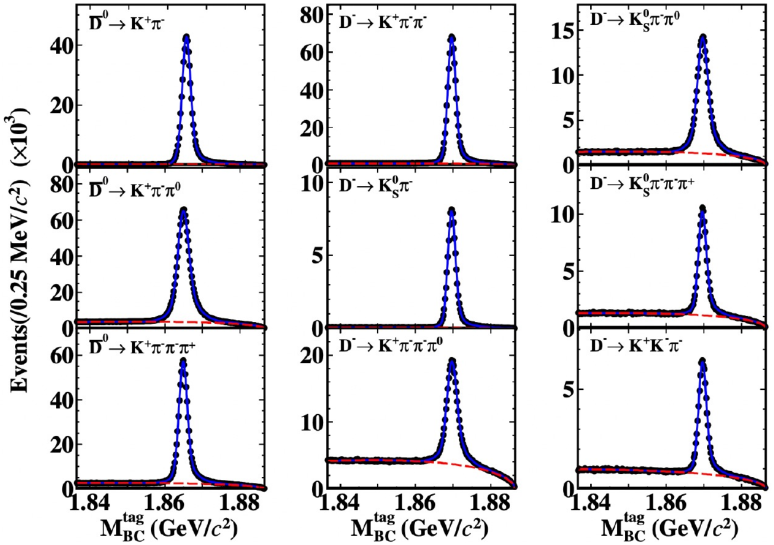
- **Amplitude Analysis of multi-body hadronic charm decays**
  - Mass and width of light hadrons which are beneficial to understand light hadron spectroscopy.
- **Branching Fraction Measurements**
  - Test theoretical calculations of these BFs or decay asymmetry parameters.
  - Benefit the understanding of the quark SU(3) flavor symmetry and its breaking effect.
  - Explore the effects of $D^0 - \overline{D}^0$ mixing and CP violation in charm sector.

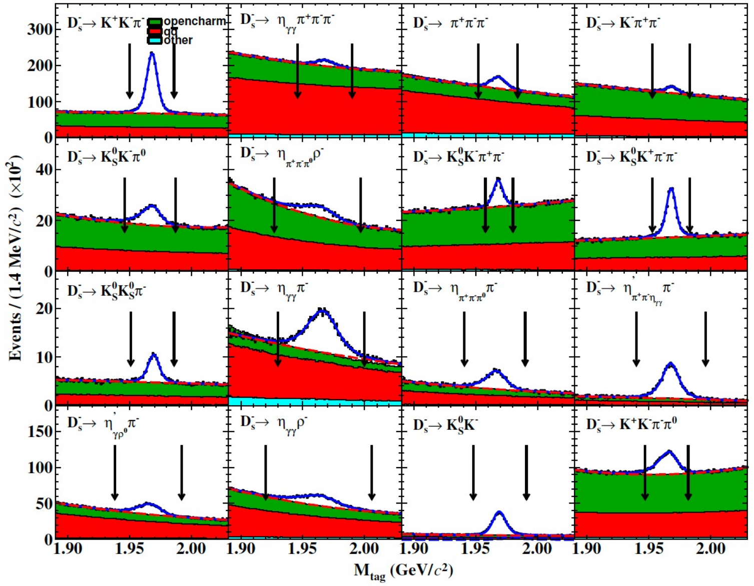
Production & Methodology

- **Datasets**
  - 2.93 fb^{-1} @3.773 GeV : $D\bar{D}$ threshold
  - 7.33 fb^{-1} @4.128-4.226 GeV : $D_s^*\bar{D}_s$



- **Double Tag**





$$M_{BC} = \sqrt{E_{\rm beam}^2 - |\vec{p}_{D^-}|^2}$$

$$\Delta E = E_{D^-} - E_{\rm beam}$$

Tag modes

- $\bar{D}^0 \to K^+\pi^-, \ldots$
- $D^- \to K^+\pi^-\pi^-, \ldots$
- $D_s^- \to K^+K^-\pi^-, \ldots$

Branching fraction

- $N_{\rm tag} = 2N_{D\bar{D}}\mathcal{B}_{\rm tag}\epsilon_{\rm tag}$
- $N_{\rm DT} = 2N_{D\bar{D}}\mathcal{B}_{\rm tag}\mathcal{B}_{\rm sig}\epsilon_{\rm DT}$
- $\mathcal{B}_{\rm sig} = \frac{N_{\rm DT}}{N_{\rm tag}\epsilon_{\rm DT}/\epsilon_{\rm tag}}$

Determination of spin and parity of $D^*_{(s)}$ mesons

arXiv: 2305.14631

highlight

- $3.19\ \text{fb}^{-1}$ @4.178 GeV
- There is no decisive experimental results of spin and parity have been reported for the ground 1S states $D^*_{(s)}$ since their discovery.
- The spin and parity of D_s^{*+}, D^{*0} and D^{*+} are firstly determined in the process of
  - $e^+e^- \to D_s^{*+}D_s^-$
  - $e^+e^- \to D^{*0}\bar{D}^0$
  - $e^+e^- \to D^{*+}D^-$
- Partial reconstruction of γ and D_s^+ and recoil side missing D_s^- (similar technique for D^{*0} and D^{*+})
- An application of a helicity amplitude analysis results in a preference of the quantum number $J^P = 1^-$ over the hypotheses 2^+ and 3^- with significance more than 10σ.

CHARMED, STRANGE MESONS
($C = S = \pm1$)
$D_s^+ = c\bar{s}$, $D_s^- = \bar{c}s$, similarly for D_s^*'s

$D_s^{*\pm}$ $\quad I(J^P) = 0(?^?)$

J^P is natural, width and decay modes consistent with 1^-.

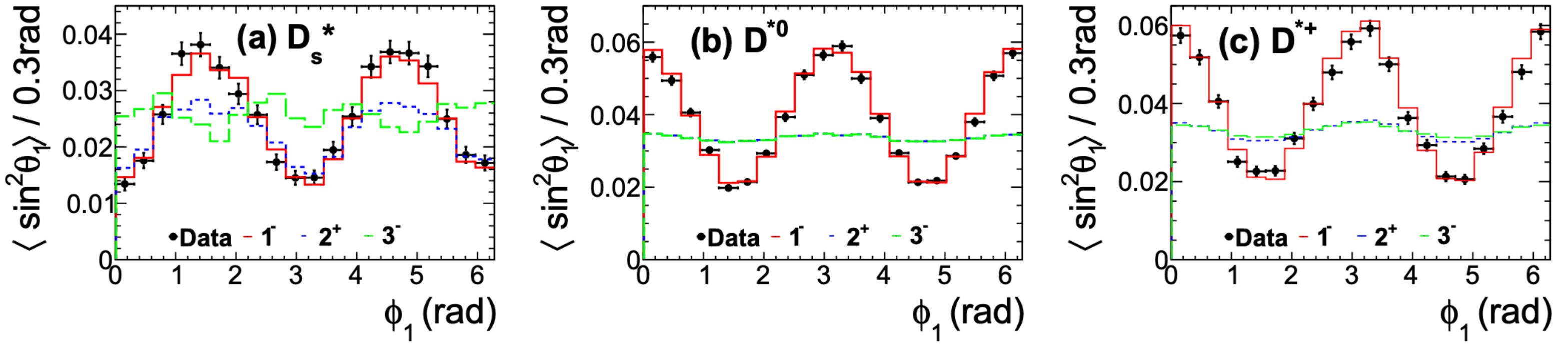
CHARMED MESONS
($C = \pm1$)
$D^+ = c\bar{d}$, $D^0 = c\bar{u}$, $\bar{D}^0 = \bar{c}u$, $D^- = \bar{c}d$, similarly for D^*'s

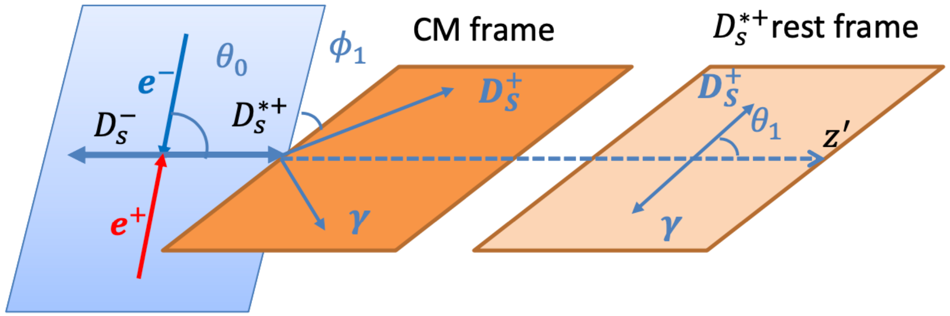
$D^*(2007)^0$ $\quad I(J^P) = 1/2(1^-)$ I, J, P need confirmation.

J consistent with 1, value 0 ruled out (NGUYEN 1977).

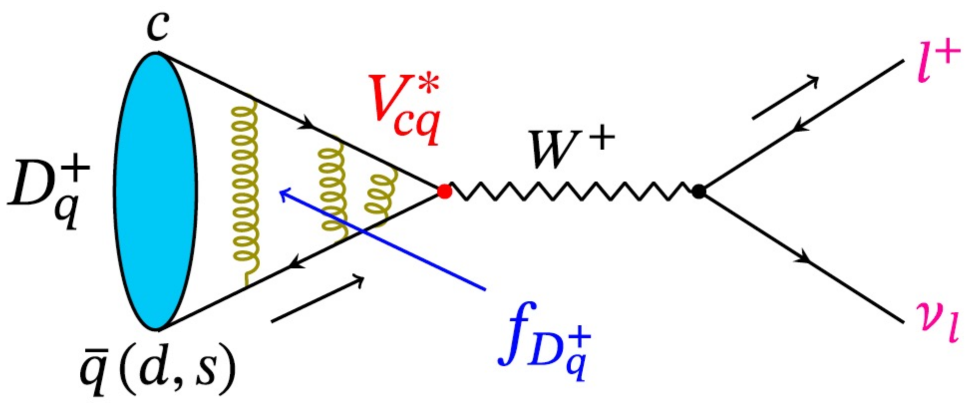
CHARMED MESONS
($C = \pm1$)
$D^+ = c\bar{d}$, $D^0 = c\bar{u}$, $\bar{D}^0 = \bar{c}u$, $D^- = \bar{c}d$, similarly for D^*'s

$D^*(2010)^\pm$ $\quad I(J^P) = 1/2(1^-)$ I, J, P need confirmation.





Pure leptonic decay



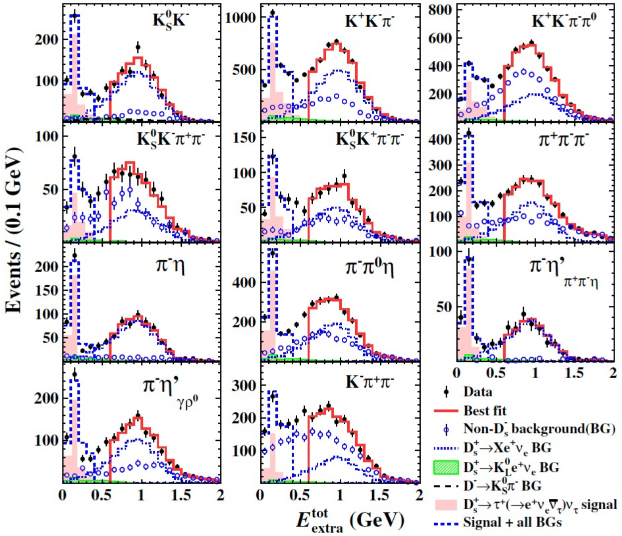
$D_s^+ \to \tau^+ \nu$

- Based on 6.32 fb^{-1} @4.178-4.226 GeV

Methodology:
1)Missing Mass
2)E_{extra}^{tot}: Sum of isolated the energy deposit in calorimeter

$\mathcal{B}(\tau^+ \to e^+ \nu_e \bar{\nu}_\tau) = 17.82\%$

PRL 127 171801 (2021)

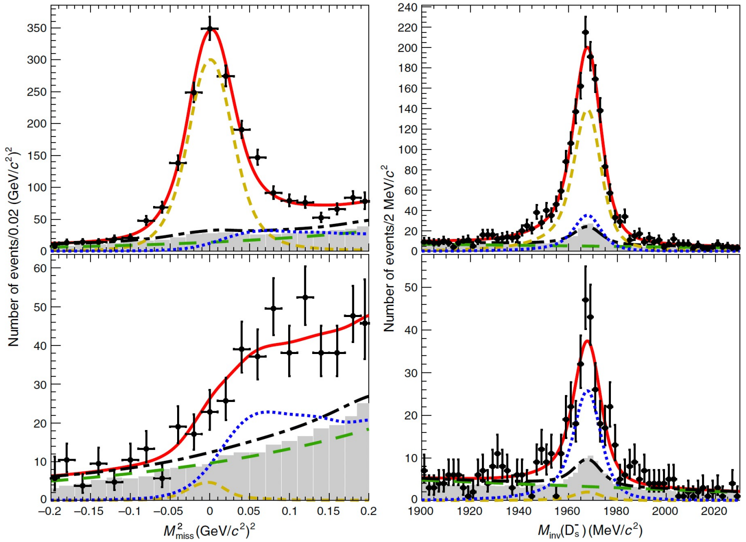


$\mathcal{B}(\boldsymbol{D_s^+} \to \boldsymbol{\tau^+ \nu}) = (5.27 \pm 0.10_{stat} \pm 0.12_{sys})\%$

$f_{D_s^+}|V_{cs}| = (244.4 \pm 2.3 \pm 2.9)$ MeV

$\mathcal{B}(\tau^+ \to \mu^+ \nu_\mu \bar{\nu}_\tau) = 17.39\%$

PRD 104 052009 (2021)

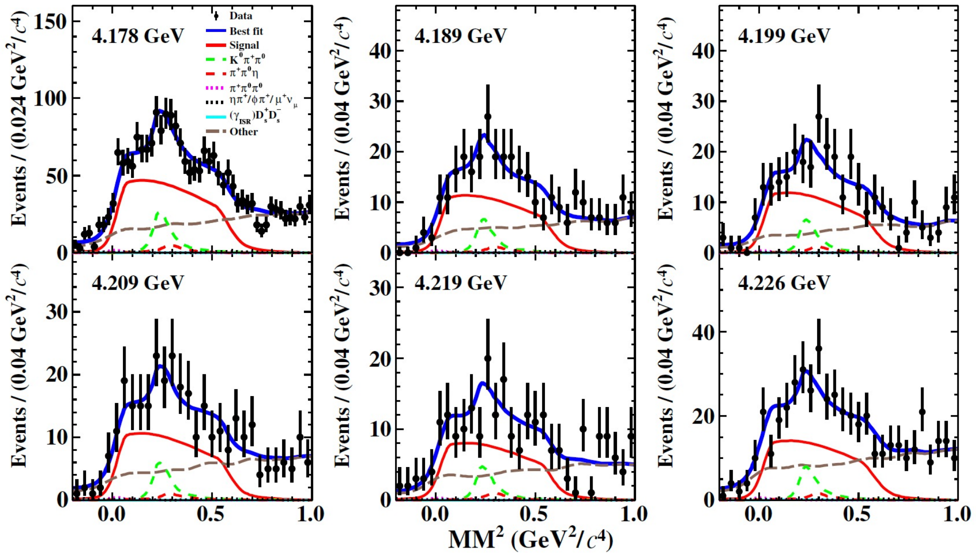


$\mathcal{B}(\boldsymbol{D_s^+} \to \boldsymbol{\tau^+ \nu}) = (5.21 \pm 0.25_{stat} \pm 0.17_{sys})\%$

$f_{D_s^+}|V_{cs}| = (243.2 \pm 2.3 \pm 3.3)$ MeV

$\mathcal{B}(\tau^+ \to \pi^+ \pi^0 \bar{\nu}_\tau) = 25.49\%$

PRD 104 032001 (2021)



$\mathcal{B}(\boldsymbol{D_s^+} \to \boldsymbol{\tau^+ \nu}) = (5.29 \pm 0.25_{stat} \pm 0.20_{sys})\%$

$f_{D_s^+}|V_{cs}| = (244.8 \pm 5.8 \pm 4.8)$ MeV

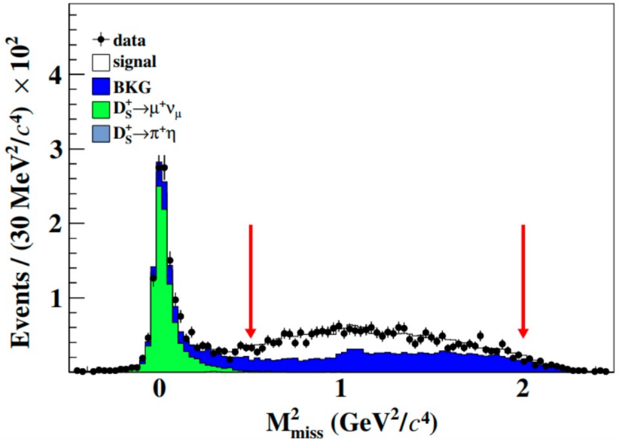
$D_s^+ \to \tau^+\nu: \tau^+ \to \mu^+\nu_\mu\bar{\nu}_\tau$

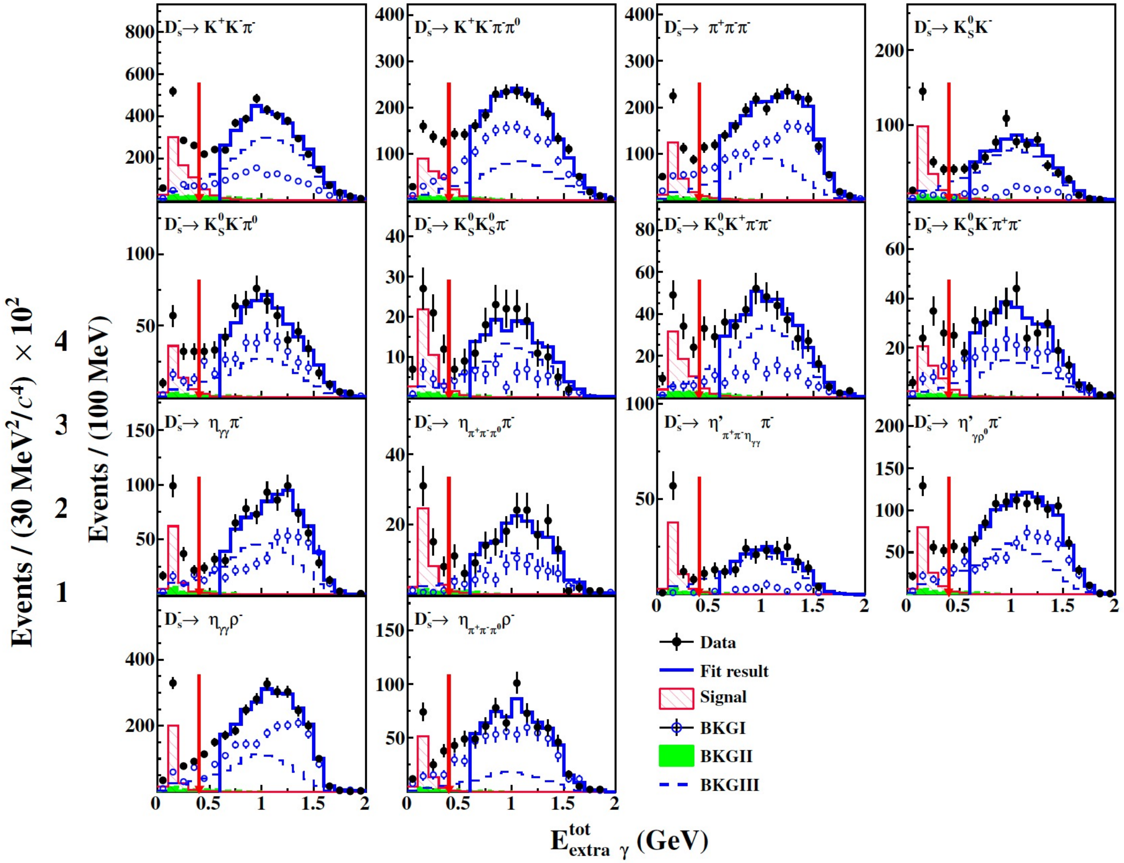
update

arXiv: 2303.12468

BESIII

- Based on 7.33 fb^{-1} @4.128-4.226 GeV
- Compare to the previous measurement:
  - From Missing Mass to E_{extra}^{tot} Methods
  - 15% more data.
- E_{extra}^{tot} Methods
  - Sum of isolated the energy deposit in calorimeter
  - Signal: E_{extra}^{tot} <0.4GeV
  - BKG: E_{extra}^{tot} >0.6GeV





update

$\mathcal{B}(D_s^+ \to \tau^+\nu) = (5.21 \pm 0.25_{stat} \pm 0.17_{sys})\%$

$f_{D_s^+}|V_{cs}| = (243.2 \pm 2.3 \pm 3.3)$ MeV

$\mathcal{B}(D_s^+ \to \tau^+\nu) = (5.34 \pm 0.16_{stat} \pm 0.10_{sys})\%$

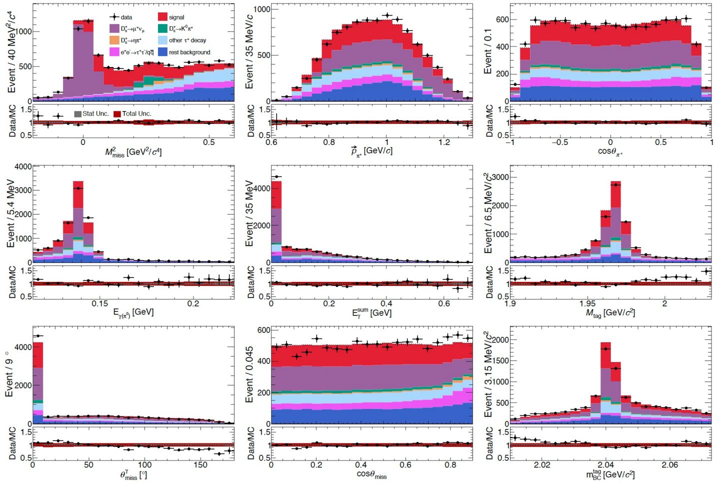
$f_{D_s^+}|V_{cs}| = (246.2 \pm 3.7 \pm 2.5)$ MeV

$D_s^+ \to \tau^+\nu: \tau^+ \to \pi^+\nu$

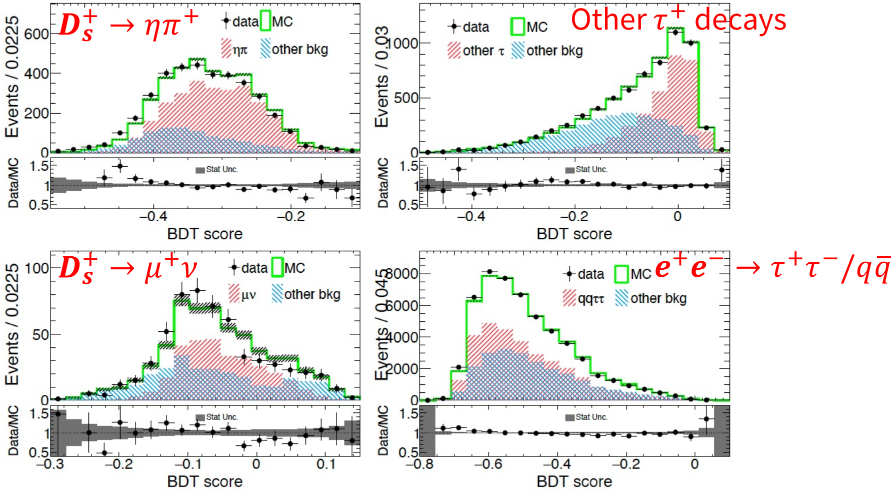
new arXiv: 2303.12600

- Based on 7.33 fb^{-1} @4.128-4.226 GeV

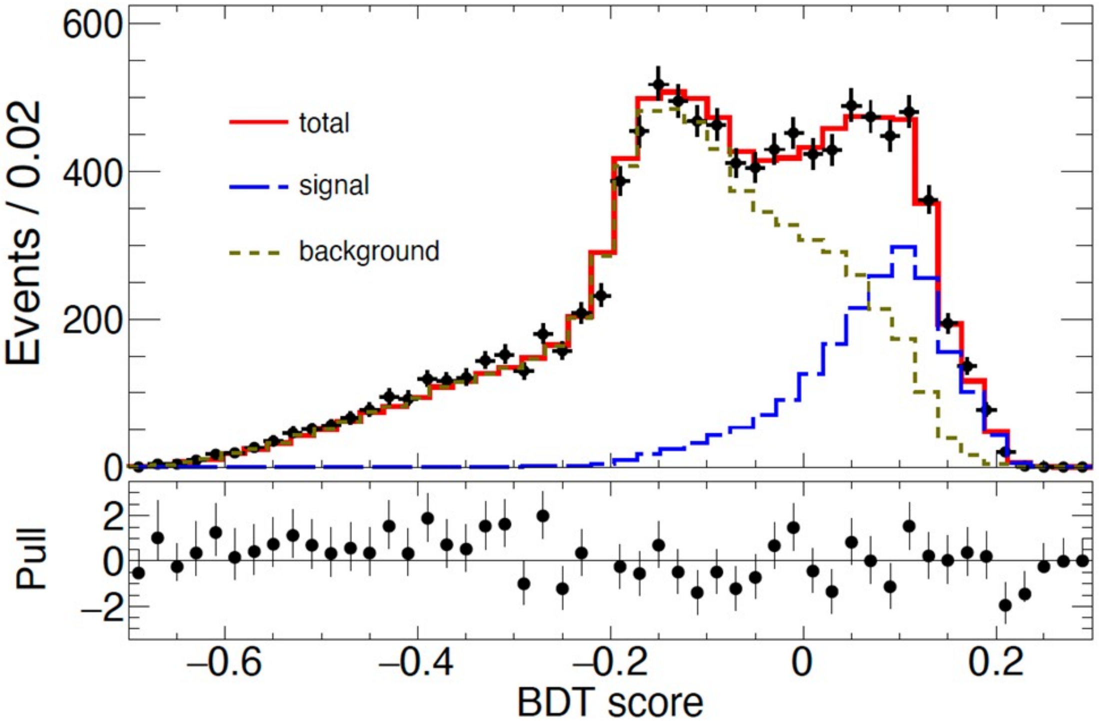
BDT input



BDT output on control channel for validation



BDT output on signal channel for measurement



$$f_{D_s^+}|V_{cs}| = (247.6 \pm 3.9 \pm 3.2)\ \text{MeV}$$

$$\mathcal{B}(D_s^+ \to \tau^+\nu) = (5.41 \pm 0.17_{stat.} \pm 0.13_{syst.})\%$$

arXiv: 2303.12600

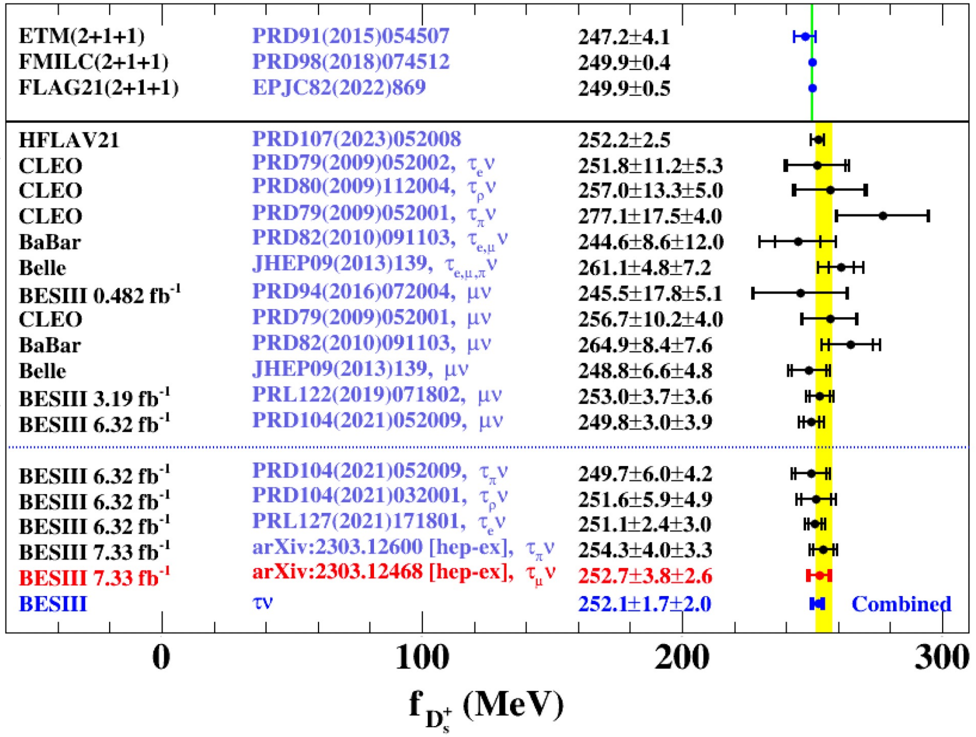
Experiment	$E_{\rm cm}$ (GeV)	Mode	τ^+ decay	$\mathcal{B}$ (%)	$f_{D_s^+}\lvert V_{cs}\rvert$ (MeV)
This work	**4.128-4.226**	$D_s^\pm D_s^{*\mp}$	$\pi^+\bar{\nu}_\tau$	**$5.41 \pm 0.17 \pm 0.13$**	**$247.6 \pm 3.9 \pm 3.2 \pm 1.0$**
BESIII [20]	4.128-4.226	$D_s^\pm D_s^{*\mp}$	$\mu^+\bar{\nu}_\tau\nu_\mu$	$5.34 \pm 0.16 \pm 0.09$	$246.2 \pm 3.7 \pm 2.3 \pm 1.0$
BESIII [19]	4.178-4.226	$D_s^\pm D_s^{*\mp}$	$e^+\bar{\nu}_\tau\nu_e$	$5.27 \pm 0.10 \pm 0.13$	$244.4 \pm 2.3 \pm 2.9 \pm 1.0$
BESIII [18]	4.178-4.226	$D_s^\pm D_s^{*\mp}$	$\pi^+\pi^0\bar{\nu}_\tau$	$5.30 \pm 0.25 \pm 0.20$	$245.1 \pm 5.8 \pm 4.7 \pm 1.0$
BESIII [17]	4.178-4.226	$D_s^\pm D_s^{*\mp}$	$\pi^+\bar{\nu}_\tau$	$5.21 \pm 0.25 \pm 0.17$	$243.0 \pm 5.8 \pm 4.0 \pm 1.0$
Weighted[a]	...	...	...	$5.32 \pm 0.07 \pm 0.07$	$245.4 \pm 1.7 \pm 1.7 \pm 1.0$
BESIII [21]	4.008	$D_s^+ D_s^-$	$\pi^+\bar{\nu}_\tau$	$3.28 \pm 1.83 \pm 0.37$	$192.8 \pm 44.2 \pm 10.9 \pm 0.8$
CLEO [12]	4.170	$D_s^\pm D_s^{*\mp}$	$e^+\bar{\nu}_\tau\nu_e$	$5.30 \pm 0.47 \pm 0.22$	$245.1 \pm 10.9 \pm 5.1 \pm 1.0$
CLEO [13]	4.170	$D_s^\pm D_s^{*\mp}$	$\pi^+\bar{\nu}_\tau$	$6.42 \pm 0.81 \pm 0.18$	$269.7 \pm 17.2 \pm 3.8 \pm 1.1$
CLEO [14]	4.170	$D_s^\pm D_s^{*\mp}$	$\rho^+\bar{\nu}_\tau$	$5.52 \pm 0.57 \pm 0.21$	$250.1 \pm 13.0 \pm 4.8 \pm 1.0$
BaBar [16]	10.56	$DKX\gamma D_s^-$	$e^+\bar{\nu}_\tau\nu_e, \mu^+\bar{\nu}_\tau\nu_\mu$	$4.96 \pm 0.37 \pm 0.57$	$237.1 \pm 8.9 \pm 13.7 \pm 1.0$
Belle [15]	10.56	$DKX\gamma D_s^-$	$\pi^+\bar{\nu}_\tau, e^+\bar{\nu}_\tau\nu_e, \mu^+\bar{\nu}_\tau\nu_\mu$	$5.70 \pm 0.21^{+0.31}_{-0.30}$	$254.1 \pm 4.7 \pm 7.0 \pm 1.0$
Average	...	...	...	5.35 ± 0.09	$246.3 \pm 2.0 \pm 1.0$

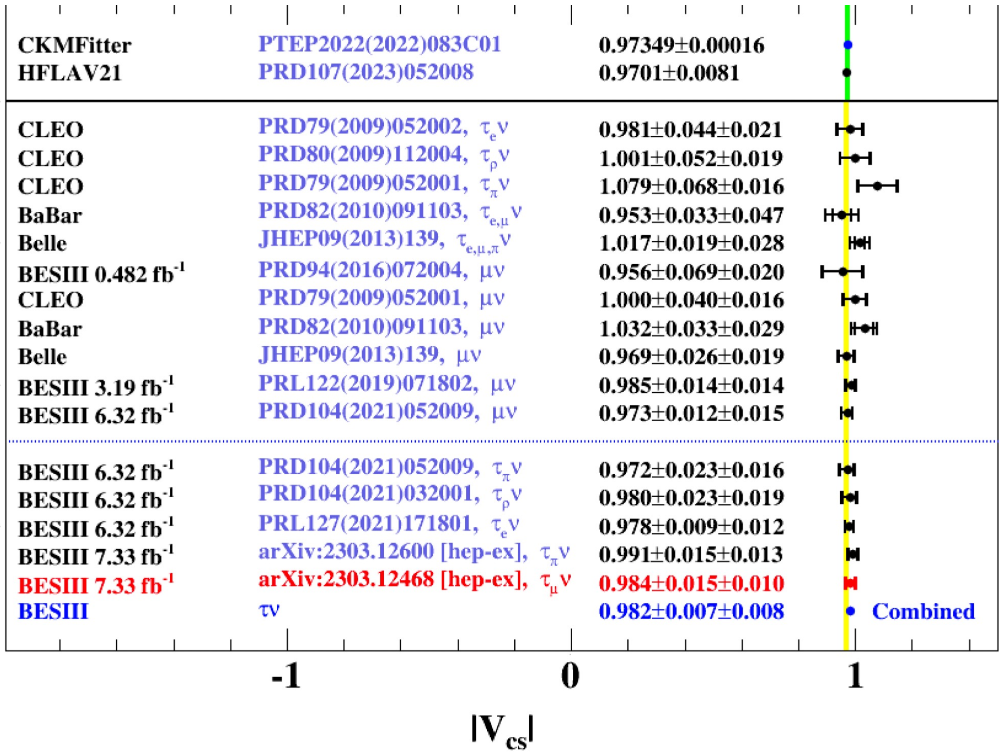
[a] It excludes "BESIII [17]".

$f_{D_s^+}$ & $|V_{cs}|$

Input:

$f_{D_s^+}$	249.9±0.5 MeV	LQCD
$\|V_{cs}\|$	0.97346±0.00016	CKM fitter
m_τ	1776.86±0.12 MeV	PDG2022
m_μ	105.6483755±0.0000023 MeV	PDG2022
m_{D_s}	1978.35 ±0.07 MeV	PDG2022

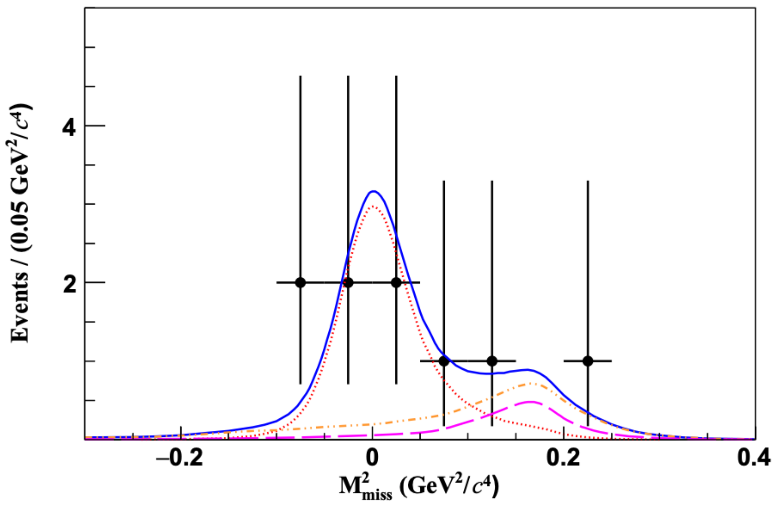




$D_s^{*+} \to e^+\nu$

Double Tag

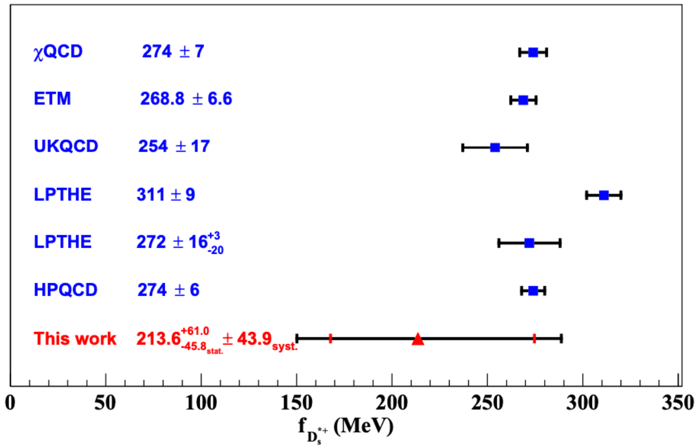
- Motivated by theoretical prediction[1,2]
- First study based on 7.33 fb^{-1} @4.128-4.226 GeV with $D_s^*\bar{D}_s$ process.
- $B(D_s^{*+} \to e^+\nu) = (2.1^{+1.2}_{-0.9}{}_{stat} \pm 0.2_{syst})\times10^{-5}$. (2.9σ)
- Combine $\frac{f_{D_s^{*+}}^{+}}{f_{D_s^{+}}^{+}} = 1.12 \pm 0.01$ from LQCD calculation
  - $\Gamma_{D_s^{*+}}^{total} = (121.9^{+69.6}_{-52.2} \pm 11.8)$ eV
  - Agree with (70 ± 28) eV predicted by LQCD in $\pm1\sigma$
  - **Indirectly constrains the upper limit on the total width $\Gamma_{D_s^{*+}}^{total}$ from MeV to keV level.**



$D_s^{*\pm}$ WIDTH < 1.9 MeV CL=90.0%

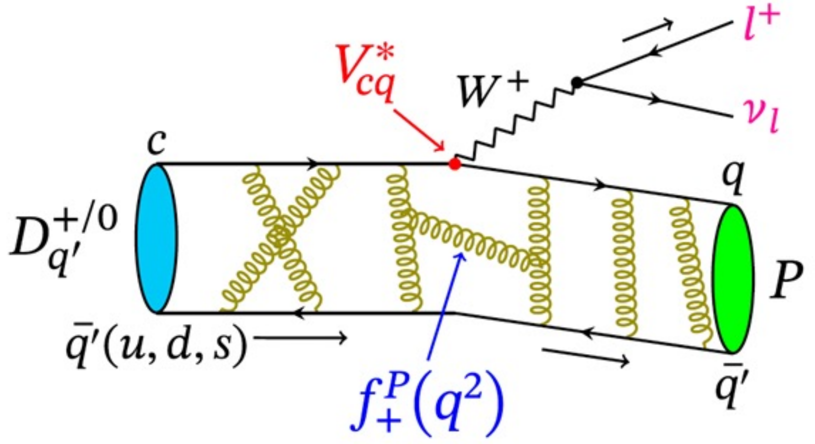
VALUE (MeV)	CL%	DOCUMENT ID		TECN	COMMENT
< 1.9	90	GRONBERG	1995	CLE2	e^+e^-
< 4.5	90	ALBRECHT	1988	ARG	$E_{cm}^{ee} = 10.2$ GeV
• • We do not use the following data for averages, fits, limits, etc. • •					
< 4.9	90	BROWN	1994	CLE2	e^+e^-
< 22	90	BLAYLOCK	1987	MRK3	$e^+e^- \to D_s^{\pm}\gamma X$

First experimental result on $f_{D_s^{*+}}$



1)EPJC 82, 1037 (2022)
2)PRL 112, 212002 (2022)

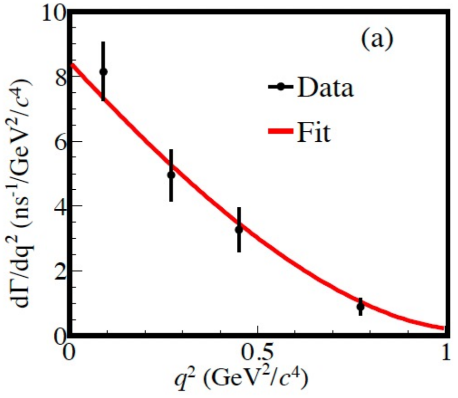
Semi-leptonic decay

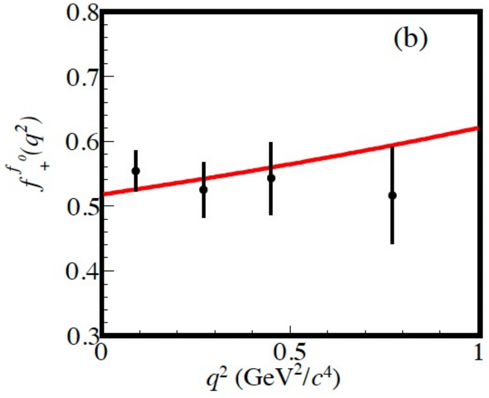


- Based on $7.33 fb^{-1}$ @4.128-4.226 GeV
- The BF of $D_s^+ \to f_0(980)e^+\nu, f_0(980) \to \pi^+\pi^-$ is measured to be $(1.72 \pm 0.13_{stat} \pm 0.10_{sys})\times 10^{-3}$, 2.6 times more accurate than previous measurement.
- Determine $f_+^{f_0}|V_{cs}| = (0.504 \pm 0.017_{stat} \pm 0.035_{syst})$ for the first time in $D_s^+ \to f_0(980)e^+\nu, f_0(980) \to \pi^+\pi^-$
- The measured FF and BF are both important to probe the quark component in $f_0(980)$.
  - Using the relation between the BF and the mixing angle ϕ involved in the $q\bar{q}$ mixture picture for $f_0(980)$[*], we find that the $S\bar{S}$ component is dominant.

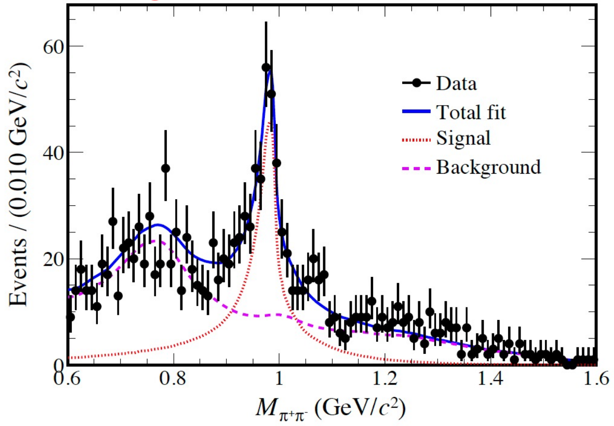
$$|f_0(980)\rangle = \sin\phi \left| \frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d}) \right\rangle + \cos\phi |s\bar{s}\rangle$$

	This work	CLFD [6]	DR [6]	QCDSR [7]	QCDSR [8]	LCSR [9]	LFQM [11]	CCQM [12]
$f_+^{f_0}(0)$	$0.518 \pm 0.018_{\rm stat} \pm 0.036_{\rm syst}$	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°





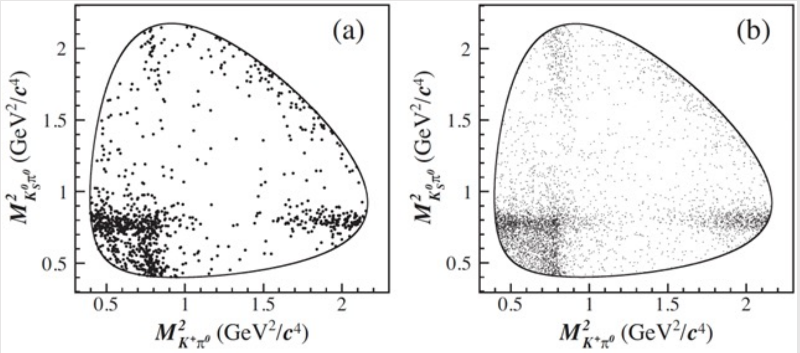
Signal yields: 439 ± 33



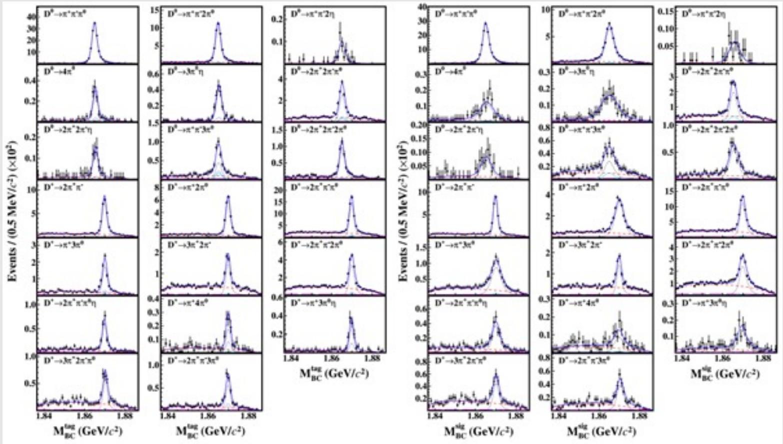
[*]PRD 80, 074030 (2009)

Hadronic Decays

Amplitude Analysis



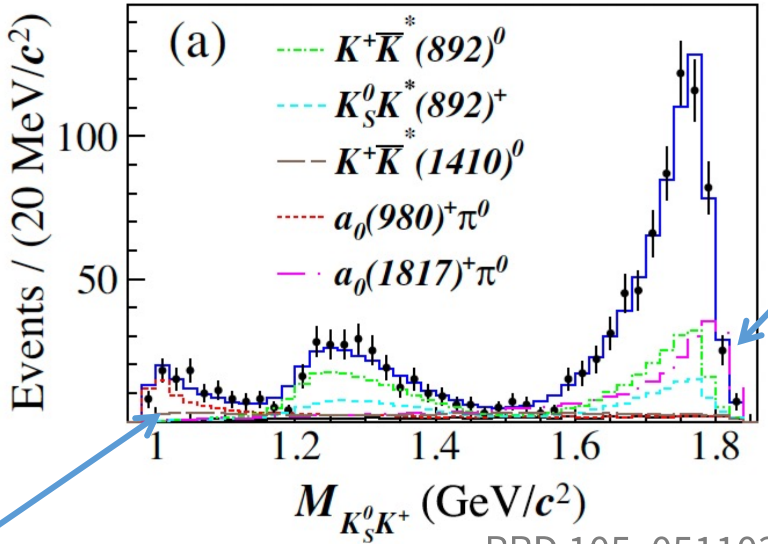
Branching Fraction Measurements



Observation of $a_0(1817)^+$ at D_s^+ decays

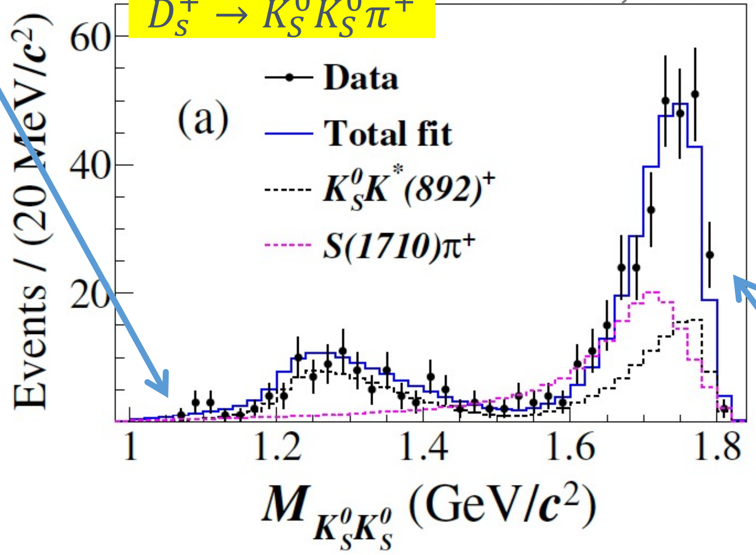
highlight

$D_s^+ \to K_S^0 K^+ \pi^0$ PRL 129, 182001 (2022)



PRD 105, 051103 (2022)

$D_s^+ \to K_S^0 K_S^0 \pi^+$



destructive interference: $a_0(980)$ and $f_0(980)$

$a_0(1817)^+$ in $K_S^0K^+$ mass spectrum

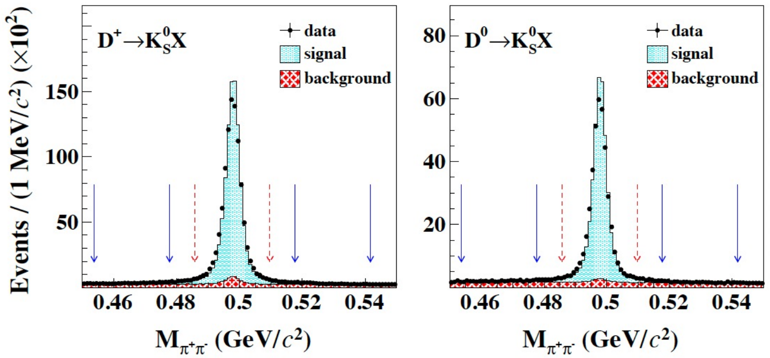
- $M = 1.817 \pm 0.008 \pm 0.020$ GeV/c^2
- $\Gamma = 0.097 \pm 0.022 \pm 0.015$ GeV/c^2
- $\mathcal{B}(D_s^+ \to a_0(1817)^+\pi^0) = (3.44 \pm 0.52 \pm 0.32)\times 10^{-3}$
- Significance > 10 σ
- The isovector partner of $f_0(1710)$ or $X(1812)$?
- A simultaneous amplitude analysis of $D_s^+ \to K_S^0K^+\pi^0$ and $D_s^+ \to K_S^0K_S^0\pi^+$ can be expected.

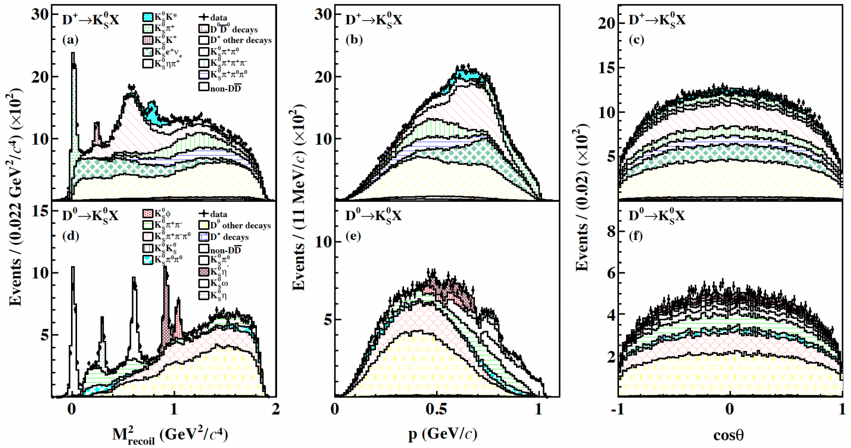
constructive interference: $a_0(1817)$ and $f_0(1710)$?

$D \to K_S^0 X$

arXiv: 2302.14488

- The precision of BFs $D^+ \to K_S^0 X$ and $D^0 \to K_S^0 X$ are improved by factors of 9.0 and 8.1.
- The differences between the inclusive and exclusive decay BF are
  - For D^+: $(1.10 \pm 0.41)\%$
  - For D^0: $(2.38 \pm 0.75)\%$





Decay mode	Mark-III (%) [1]	BES (%) [2]	PDG (%) [3]	This study (%)	$\mathcal{B}^{\rm sum}_{\rm exclusive}$ (%)
$D^+ \to K_S^0 X$	$30.60 \pm 3.25 \pm 2.15$	$30.25 \pm 2.75 \pm 1.65$	30.5 ± 2.5	$32.78 \pm 0.13 \pm 0.27$	31.68 ± 0.32
$D^0 \to K_S^0 X$	$22.75 \pm 2.50 \pm 1.60$	$23.80 \pm 2.40 \pm 1.50$	23.5 ± 2.0	$20.54 \pm 0.12 \pm 0.18$	18.16 ± 0.72

BF of exclusive $D^{0/+}$ decays involving K_S^0

Initial state	$\mathcal{B}$ (%)	Final state	$\mathcal{B}$ (%)
$K_S^0\pi^+$	1.49 ± 0.03 [30]	$K_S^0\pi^+$	1.49 ± 0.03
$\bar{K}^0 e^+\nu_e$	8.73 ± 0.10 [3]	$K_S^0 e^+\nu_e$	4.37 ± 0.05
$\bar{K}^{*0} e^+\nu_e$	5.40 ± 0.10 [3]	$K_S^0\pi^0 e^+\nu_e$	0.89 ± 0.02
$\bar{K}^0\mu^+\nu_\mu$	8.76 ± 0.19 [3]	$K_S^0\mu^+\nu_\mu$	4.380 ± 0.095
$\bar{K}^{*0}\mu^+\nu_\mu$	5.27 ± 0.15 [3]	$K_S^0\pi^0\mu^+\nu_\mu$	0.88 ± 0.02
$K_S^0K_S^0K^+$	0.254 ± 0.013 [3]	$K_S^0K_S^0K^+$	0.254 ± 0.013
$K_S^0K_L^0K^+$	0.508 ± 0.026 [3]	$K_S^0K_L^0K^+$	0.508 ± 0.026
$K_S^0K_S^0\pi^+$	0.270 ± 0.013 [3]	$K_S^0K_S^0\pi^+$	0.270 ± 0.013
$\bar{K}^0\pi^+\pi^+\pi^-$	6.20 ± 0.18 [3]	$K_S^0\pi^+\pi^+\pi^-$	3.10 ± 0.09
$\bar{K}^0K^+K^-\pi^+$	0.048 ± 0.010 [3]	$K_S^0K^+K^-\pi^+$	0.024 ± 0.005
$K_S^0\pi^+\pi^0$	7.36 ± 0.21 [3]	$K_S^0\pi^+\pi^0$	7.36 ± 0.21
$\bar{K}^0K^{*+}$	1.738 ± 0.182 [31]	$K_S^0K^{*+}$	0.869 ± 0.091
$\bar{K}_1^0(1270)e^+\nu_e$	0.231 ± 0.030 [32]	$K_S^0\pi^0\pi^0 e^+\nu_e$	0.0055 ± 0.0007
$\bar{K}_1^0(1270)e^+\nu_e$	0.231 ± 0.030 [32]	$K_S^0\pi^+\pi^- e^+\nu_e$	0.039 ± 0.005
$\bar{K}_1^0(1270)\mu^+\nu_\mu$	0.231 ± 0.030 [32]	$K_S^0\pi^+\pi^-\mu^+\nu_\mu$	0.039 ± 0.005
$\bar{K}_1^0(1270)\mu^+\nu_\mu$	0.231 ± 0.030 [32]	$K_S^0\pi^0\pi^0\mu^+\nu_\mu$	0.0055 ± 0.0007
$K_S^0\pi^+\eta$	1.309 ± 0.048 [26]	$K_S^0\pi^+\eta$	1.309 ± 0.048
$K_S^0K^+\eta$	0.0185 ± 0.0050 [26]	$K_S^0K^+\eta$	0.0185 ± 0.0050
$K_S^0\pi^+\pi^0\eta$	0.12 ± 0.03 [26]	$K_S^0\pi^+\pi^0\eta$	0.12 ± 0.03
$K_S^0K^+\pi^+\pi^-$	0.189 ± 0.013 [15]	$K_S^0K^+\pi^+\pi^-$	0.189 ± 0.013
$K_S^0K^-\pi^+\pi^+$	0.227 ± 0.013 [15]	$K_S^0K^-\pi^+\pi^+$	0.227 ± 0.013
$K_S^0K^+\pi^0\pi^0$	0.058 ± 0.013 [15]	$K_S^0K^+\pi^0\pi^0$	0.058 ± 0.013
$K_S^0K_S^0\pi^+\pi^0$	0.134 ± 0.021 [15]	$K_S^0K_S^0\pi^+\pi^0$	0.134 ± 0.021
$K_S^0K_L^0\pi^+\pi^0$	0.268 ± 0.042 [15]	$K_S^0K_L^0\pi^+\pi^0$	0.268 ± 0.042
$\bar{K}^0K^+$	0.604 ± 0.024 [33]	$K_S^0K^+$	0.302 ± 0.012
$K_S^0K^+\pi^0$	0.507 ± 0.003 [33]	$K_S^0K^+\pi^0$	0.507 ± 0.003
$\phi\pi^+$	0.570 ± 0.015 [34]	$K_S^0K_L^0\pi^+$	0.193 ± 0.006
$\bar{K}^0\pi^+\eta'$	0.380 ± 0.042 [35]	$K_S^0\pi^+\eta'$	0.190 ± 0.021
$K_S^0\omega\pi^+$	0.707 ± 0.050 [16]	$K_S^0\omega\pi^+$	0.707 ± 0.050
$K_S^0\pi^+\pi^0\pi^0$	2.2516 ± 0.1068 [36]	$K_S^0\pi^+\pi^0\pi^0$	2.2516 ± 0.1068
$K_S^0\pi^+\pi^+\pi^-\pi^0$	0.4001 ± 0.0550 [36]	$K_S^0\pi^+\pi^+\pi^-\pi^0$	0.4001 ± 0.0550
$K_S^0\pi^+\pi^0\pi^0\pi^0$	0.126 ± 0.050 [36]	$K_S^0\pi^+\pi^0\pi^0\pi^0$	0.126 ± 0.050
$\phi\pi^+\pi^0$	0.579 ± 0.055 [37]	$K_S^0K_L^0\pi^+\pi^0$	0.196 ± 0.019
Sum	...	...	31.68 ± 0.32

$D \to K_L^0 X$

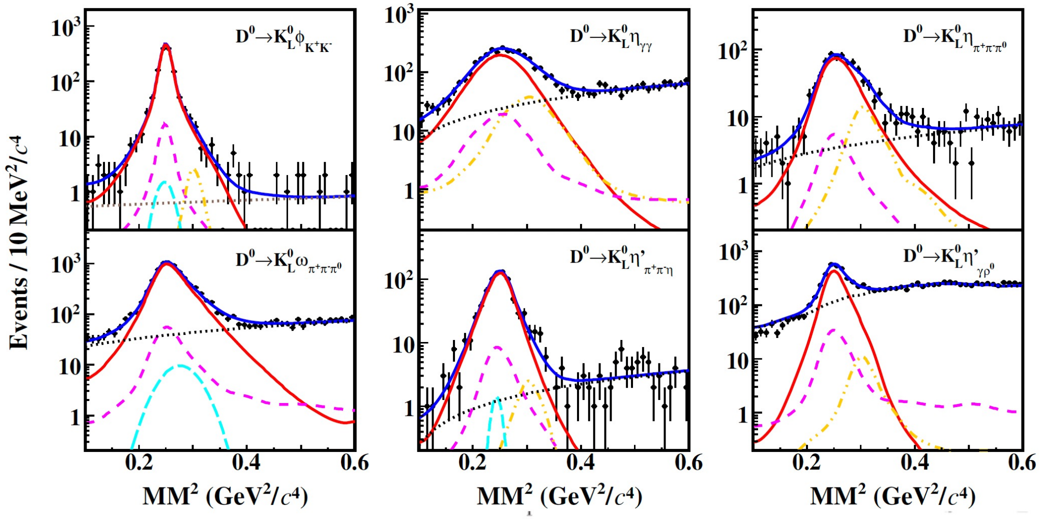
PRD 105 092010 (2022)

- First measurement of their decay branching fractions
- 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 $D^0 \to K_L^0 X$

$$\mathcal{R}(D^0, X) = \frac{\mathcal{B}(D^0 \to K_S^0 X) - \mathcal{B}(D^0 \to K_L^0 X)}{\mathcal{B}(D^0 \to K_S^0 X) + \mathcal{B}(D^0 \to K_L^0 X)} = 2\tan^2\theta_C$$

θ_C: Cabibbo mixing angle

- Asymmetries of branching fractions of $D^0/\bar{D}^0 \to K_L^0\eta, K_L^0\eta', K_L^0\omega, K_L^0\phi$



Decay	$\mathcal{B}^+_{\rm sig}$ (%)	$\mathcal{B}^-_{\rm sig}$ (%)	$\mathcal{A}^{\rm sig}_{CP}$ (%)
$D^0 \to K_L^0\phi$	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	$-2.2 \pm 2.5 \pm 0.4$

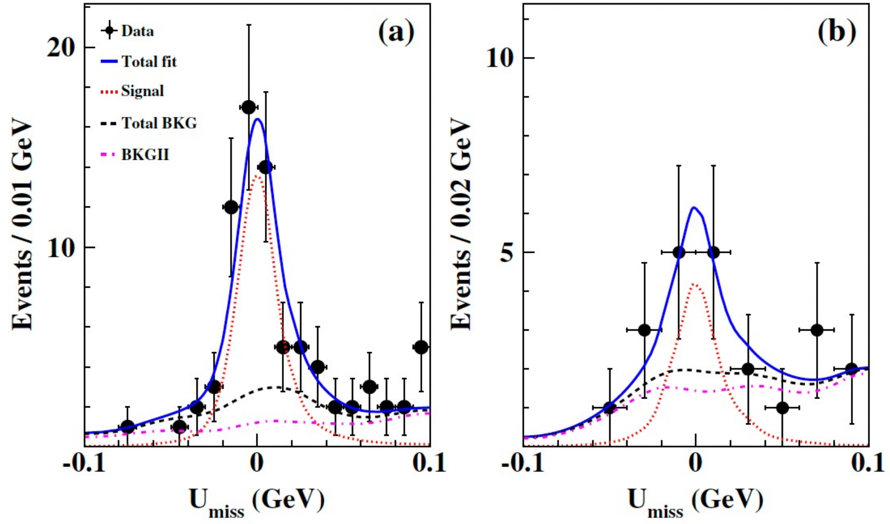
Decay	$\mathcal{B}_{\rm exp}$ (%)	$\mathcal{B}_{\rm FAT}$ (%)	Difference	$\mathcal{R}(D^0)_{\rm exp}$	$\mathcal{B}(D^0)_{\rm FAT}$	Difference
$D^0 \to K_L^0\phi$	$0.414 \pm 0.021 \pm 0.010$	0.33 ± 0.03	2.2σ	-0.001 ± 0.047	0.113 ± 0.001	2.4σ
$D^0 \to K_L^0\eta$	$0.433 \pm 0.012 \pm 0.010$	0.40 ± 0.07	0.5σ	0.080 ± 0.022		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

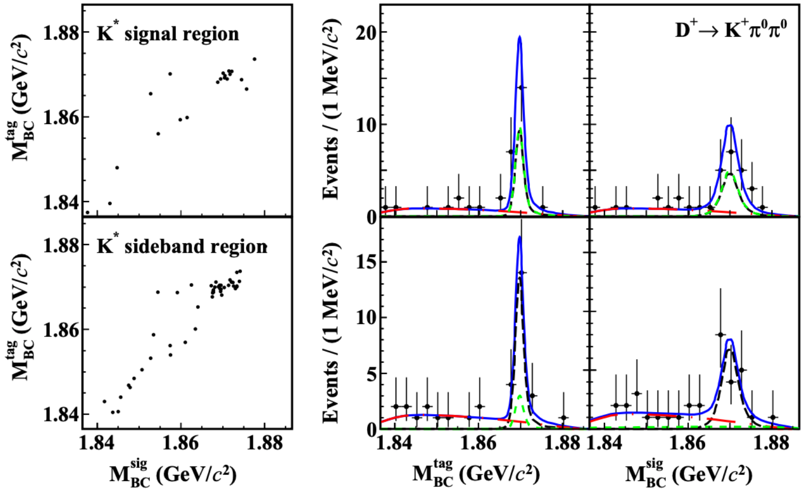
Doubly Cabibbo Suppressed decays

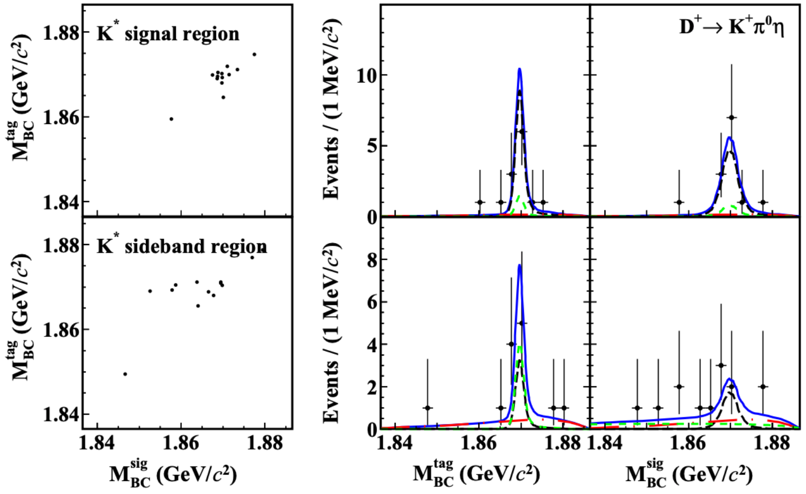
PRD 105 112001 (2022)
JHEP 09 107 (2022)

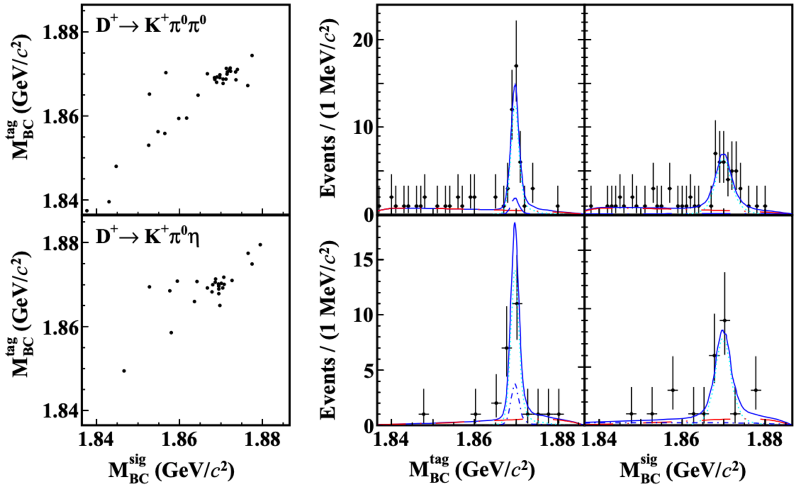
- $B(D^0 \to K^+\pi^-\pi^0) = [3.13^{+0.60}_{-0.56}(stat) \pm 0.15(syst)]\times 10^{-4}$
- $B(D^0 \to K^+\pi^-\pi^0\pi^0) < 3.6\times 10^{-4}$@$90\%CL.$
- $B(D^+ \to K^+\pi^0\pi^0) = [2.1 \pm 0.4(stat) \pm 0.1(syst)]\times 10^{-4}$
  - $B(D^+ \to K^*(892)^+\pi^0) < 4.5\times 10^{-4}$
- $B(D^+ \to K^+\pi^0\eta) = [2.1 \pm 0.5(stat) \pm 0.1(syst)]\times 10^{-4}$
  - $B(D^+ \to K^*(892)^+\eta) = [4.7^{+1.9}_{-1.6}(stat) \pm 0.2(syst)]\times 10^{-4}$

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



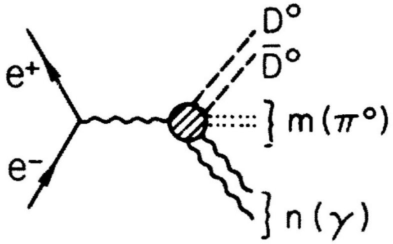






Quantum correlated $D^0\bar{D}^0$ at BESIII

- $e^+e^- \to D^0\bar{D}^0 + m(\pi^0) + n(\gamma)$



- $C(D^0\bar{D}^0) = (-1)^{n+1}$
- QC samples:

3773 MeV $\to$ C-odd: $e^+e^- \to D^0\bar{D}^0$

4180 MeV $\to$ C-odd: $e^+e^- \to D^{*0}\bar{D}^0 + D^0\bar{D}^{*0},\ D^{*0} \to \gamma D^0$

4180 MeV $\to$ C-even: $e^+e^- \to D^{*0}\bar{D}^0 + D^0\bar{D}^{*0},\ D^{*0} \to \pi^0 D^0$

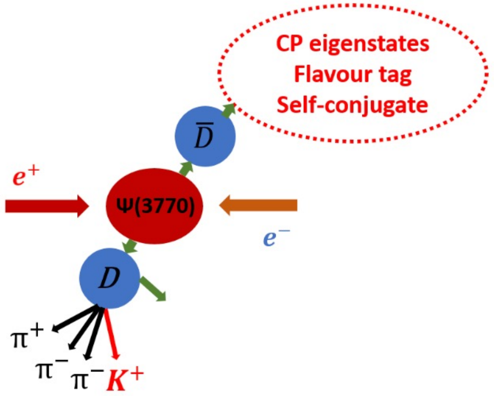
- Best laboratory to measure strong-phase parameters
- Inputs for CPV studies at B experiments.
- Precision test of perturbative QCD calculation in charm decays, mixing and CPV

- Compare the double tag yields w/w.o. quantum correlation

$$\Gamma_{\rm QC}(S|T) = \Gamma_0 A_S^2 A_T^2 [(r_D^S)^2 + (r_D^T)^2 - 2R_S R_T r_D^S r_D^T \cos(\delta_D^T - \delta_D^S)]$$

$$\Gamma(ST) = \Gamma_0 A_S^2 A_T^2 [(r_D^S)^2 + (r_D^T)^2]$$

- Strong-phase measurements using various tags



Flavour	$K^\pm\pi^\mp\pi^\mp\pi^-,\ K^\pm\pi^\mp\pi^0,\ K^\pm\pi^\mp,\ \ldots$
CP-even	$K^+K^-,\ \pi^+\pi^-,\ \pi^0\pi^0,\ K_S^0\pi^0\pi^0,\ K_L^0\pi^0,\ K_L^0\omega,\ \pi^+\pi^-\pi^{0\dagger}$
CP-odd	$K_S^0\pi^0,\ K_S^0\eta,\ K_S^0\omega,\ K_S^0\eta',\ K_S^0\phi,\ K_L^0\pi^0\pi^0$
Self-conjugate	$K_S^0\pi^+\pi^-,\ K_S^0K^+K^-,\ \ldots$

- Provide comprehensive constraints on strong-phase parameters.

Determination of $\delta_D^{K\pi}$

EPJC 82 1009 (2022)

- An update measurement of the asymmetry between CP -odd and CP -even eigenstate decays into $K^-\pi^+$

30% more precise ！

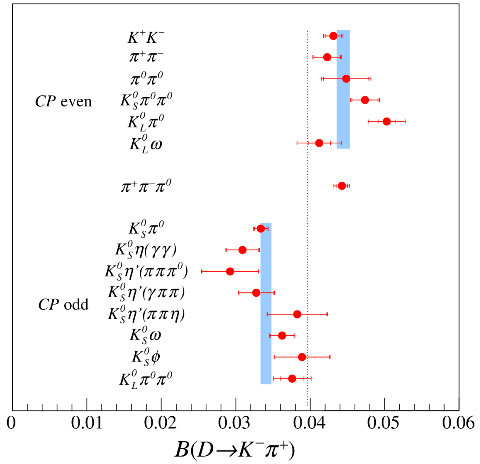
$$\mathcal{A}_{K\pi} \equiv \frac{\mathcal{B}(D_- \to K^-\pi^+) - \mathcal{B}(D_+ \to K^-\pi^+)}{\mathcal{B}(D_- \to K^-\pi^+) + \mathcal{B}(D_+ \to K^-\pi^+)} = \frac{-2r_D^{K\pi}\cos\delta_D^{K\pi} + y}{1 + \left(r_D^{K\pi}\right)^2} = 0.132 \pm 0.011 \pm 0.007$$

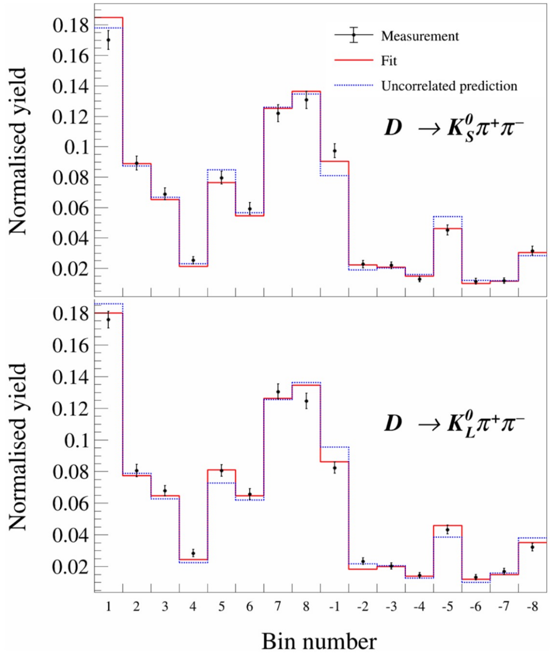
- Using the predominantly CP -even tag $D \to \pi^+\pi^-\pi^0$ and CP-odd eigenstate tags, we measured:

$$\mathcal{A}_{K\pi}^{\pi\pi\pi^0} \equiv \frac{\mathcal{B}(D_X \to K^-\pi^+) - \mathcal{B}(D_+ \to K^-\pi^+)}{\mathcal{B}(D_X \to K^-\pi^+) + \mathcal{B}(D_+ \to K^-\pi^+)} = \frac{\left(-2r_D^{K\pi}\cos\delta_D^{K\pi} + y\right)F_+^{\pi\pi\pi^0}}{1 + \left(r_D^{K\pi}\right)^2 + \left(1 - F_+^{\pi\pi\pi^0}\right)\left(2r_D^{K\pi}\cos\delta_D^{K\pi} + y\right)} = 0.130 \pm 0.012 \pm 0.008$$

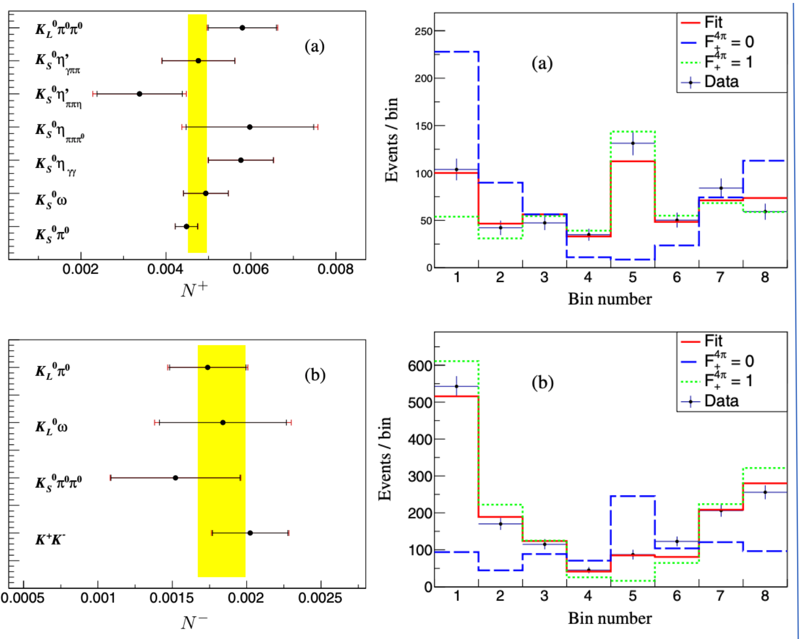
- $\delta_D^{K\pi} = (187.6^{+8.9+5.4}_{-9.7-6.4})°$
  - With events containing both $D \to K^-\pi^+$ and $D \to K_{S,L}^0\pi^+\pi^-$ decays, which sensitive to $r_D^{K\pi}\cos\delta_D^{K\pi}$
  - Studied in bins of phase space of the three-body decays
  - Precision test of the theoretical prediction $\delta_D^{K\pi} = (183 \pm 5.7)°$[*]
  - Most precise single measurements.
  - $r_D^{K\pi}$, y and $F_+^{\pi\pi\pi^0}$ are constrained to measured values .

[*]PRD 99, 113001 (2019)



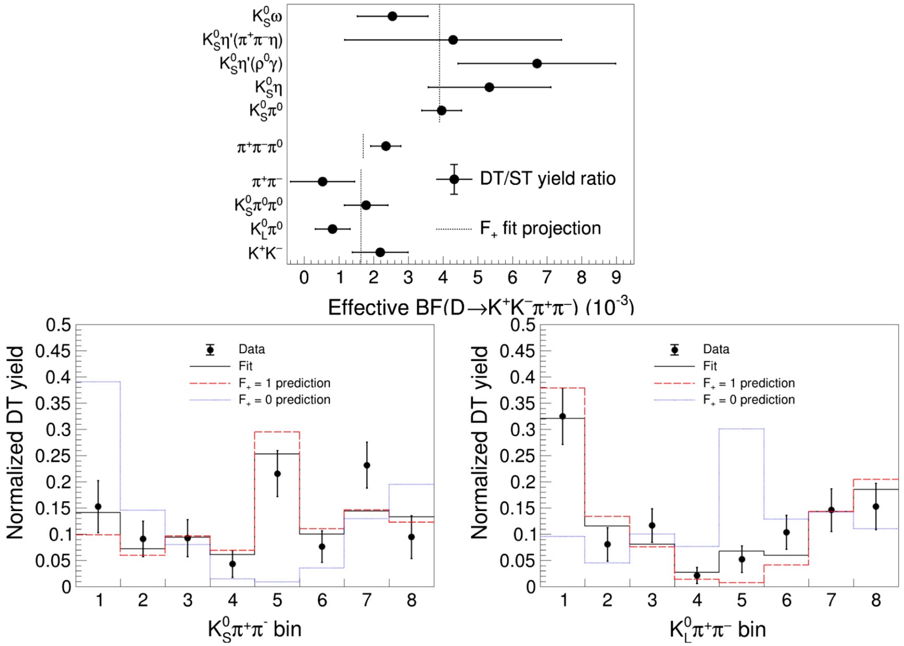


CP-even fraction measurements



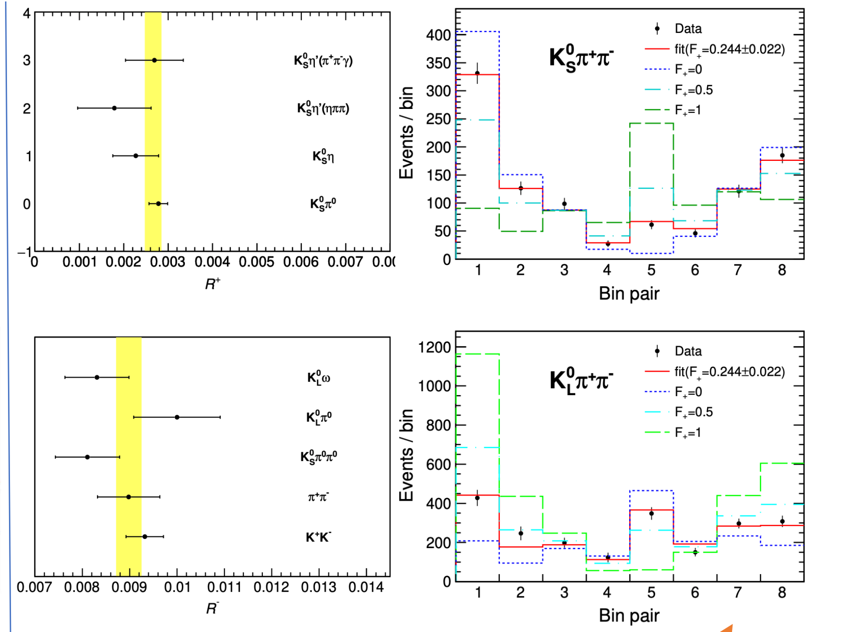
$$D^0 \to \pi^+\pi^-\pi^+\pi^-$$
$$F_+ = 0.735 \pm 0.015_{stat} \pm 0.005_{syst}$$

PRD 106 092004 (2022)



$$D^0 \to K^+K^-\pi^+\pi^-$$
$$F_+ = 0.730 \pm 0.037_{stat} \pm 0.021_{syst}$$

PRD 107 032009 (2023)



new

$$D^0 \to K_S^0\pi^+\pi^-\pi^0$$
$$F_+ = 0.235 \pm 0.010_{stat} \pm 0.002_{syst}$$

arXiv: 2305.03975

More

Decay mode	Quantities	Status (2.93 fb^{-1})
$K_S^0\pi^+\pi^-$	c_i, s_i	Finished(2020)
$K_S^0K^+K^-$	c_i, s_i	Finished(2021)
$K^-\pi^+\pi^+\pi^-$	R, δ	Finished(2020)
$K^+K^-\pi^+\pi^-$	F_+ or c_i, s_i	F_+Finished(2022),c_i, s_i on going
$\pi^+\pi^-\pi^+\pi^-$	F_+ or c_i, s_i	F_+Finished(2022),c_i, s_i on going
$K^-\pi^+\pi^0$	R, δ	Finished(2021)
$K_S^0K^\pm\pi^\mp$	R, δ	On going
$\pi^+\pi^-\pi^0$	F_+	On going
$K_S^0\pi^+\pi^-\pi^0$	F_+ or c_i, s_i	F_+Finished(2023),c_i, s_i on going
$K^+K^-\pi^0$	F_+	On going
$K^-\pi^+$	δ	Updated Finished (2022)

- Making progress in past few years.
- Many ongoing projects, eventually $20fb^{-1}\psi(3770)$ data samples.

Summary and Prospects

- **In recent years, many important results of charm mesons decays were reported by BESIII.**

- **In the near future, BESIII will collect 20 fb^{-1}@3.773 GeV data sample, further results are expected:**
  - Precision of f_{D^+}, f_{D^+}, $|V_{cs}|, |V_{cd}|, f_+^{D\to K}(0)$ and $f_+^{D\to\pi}(0)$ reached (0.5-1.0)% level;
  - Intensive LFU tests with (semi-)leptonic decays → the expected best precision is better than 1% for $\mu - e$ and 3% for $\tau - \mu$;
  - Improved measurement of strong phase differences of neutral D decay → constrain the γ measurement to about $0.5°$ level;
  - Precision of the absolute BFs of the golden decays $D^0 \to K^-\pi^+$, $D^0 \to K^-\pi^+\pi^+\pi^-$, $D^+ \to K^-\pi^+\pi^+$, $D^+ \to K^+K^-\pi^+$ reaches 1% level.

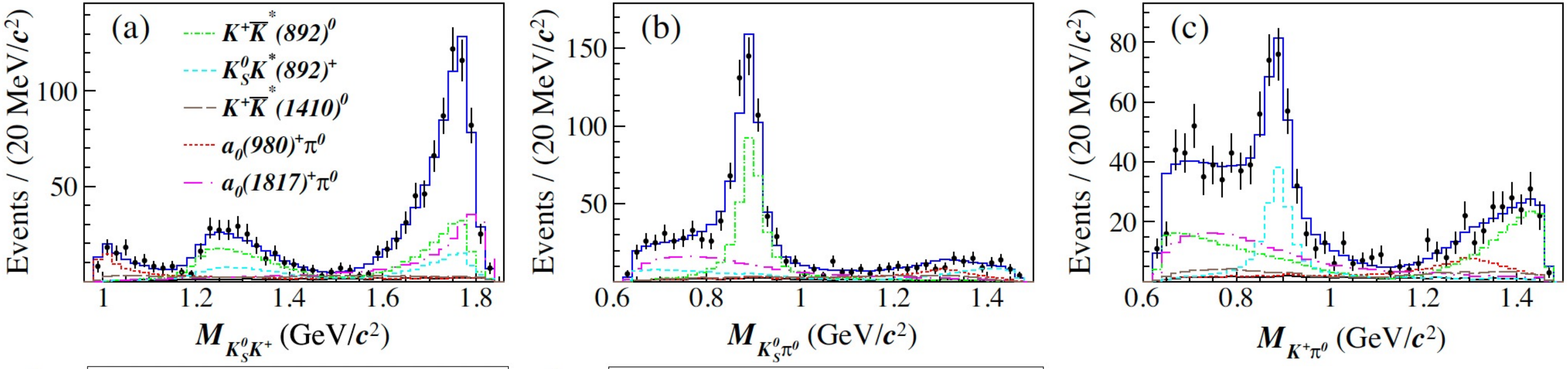
- **BESIII has the great knowledge in charm mesons, especially in**
  - Branching fraction measurement.
  - Amplitude analysis for multibody hadron final states.
  - Form factors in semi-leptonic decays.
  - Provide the great decay model in EvtGen !

BACKUP

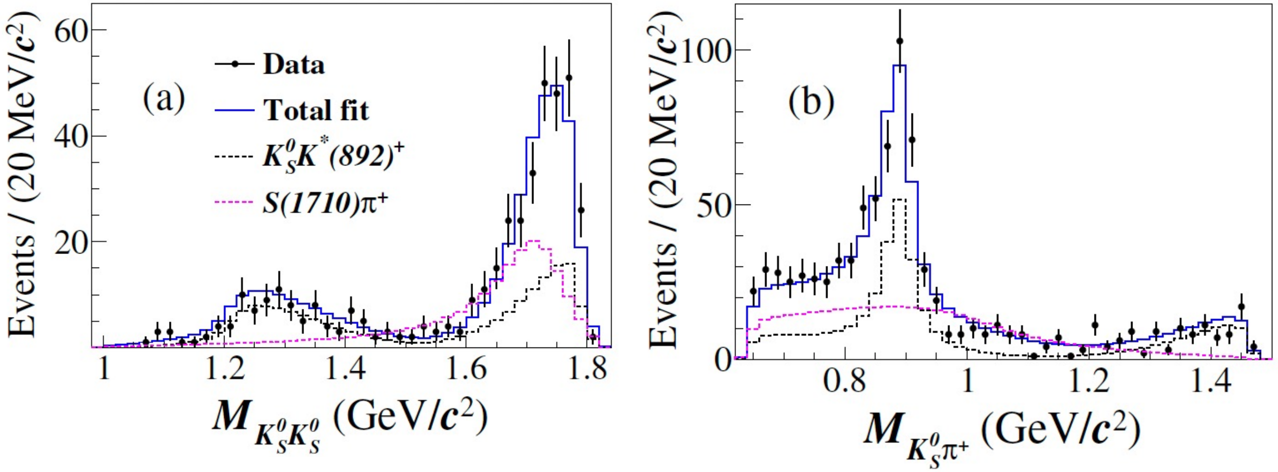
Observation of $a_0(1817)^+$ at D_s^+ decays

highlight

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



$D_s^+ \to K_S^0 K_S^0 \pi^+$



Joint angular distribution

- Decay chains: $e^+e^- \to D_s^{*+}D_s^-$, $D_s^{*+} \to \gamma D_s^+$, $D_s^+ \to K_S K^+$
  $e^+e^- \to D^{*0}\,\overline{D}^0, D^{*0} \to \pi^0 D^0, D^0 \to K^-\pi^+$ and $\pi^0 \to \gamma\gamma$
  $e^+e^- \to D^{*+}D^-$, $D^{*+} \to \pi^0 D^+, D^+ \to K^-\pi^+\pi^+$ and $\pi^0 \to \gamma\gamma$

Partial reconstruction of γ and D_s^+ and recoil side missing D_s^- (similar technique for D^{*0} and D^{*+})

- The joint amplitude of process $e^+e^- \to \gamma^* \to D_s^{*+}(\lambda_R)D_s^-, D_s^{*+} \to \gamma(\lambda_1)D_s^+$ shown as

$$A(m,\lambda_1,\vec{\omega}) = \sum_{\lambda_R} F_{\lambda_R,0} D^{1*}_{m,\lambda_R}(\phi_0,\theta_0,0) BW(m_{12}) F^J_{0,\lambda_1} D^{J*}_{\lambda_R,-\lambda_1}(\phi_1,\theta_1,0)$$

- $\vec{\omega} = (\theta_0,\phi_0,\theta_1,\phi_1,m_{12})$, $D^{1*}_{m,\lambda_R}(\phi_0,\theta_0,0)$ is the Wigner-D function, BW is the Breit-Wigner function,
- m_{12} is the γD_s^+ invariant mass, and $F_{\lambda_R,0}$ and F^J_{0,λ_1} are the helicity amplitudes of the two sequential decays
- $\mathcal{W}^{(J^P)}$ is the differential cross section of the sequential decay: $\sum_{m,\lambda_1}|A(m,\lambda_1,\vec{\omega})|^2$

$$\mathcal{W}^{(1^-)} \propto (3+\cos2\theta_0)(3+\cos2\theta_1) - 4\cos2\phi_1 \sin^2\theta_0 \sin^2\theta_1$$

$$\mathcal{W}^{(2^+)} \propto (3+\cos2\theta_0)(2+\cos2\theta_1+\cos4\theta_1) - 4(1+2\cos2\theta_1)\cos2\phi_1 \sin^2\theta_0 \sin^2\theta_1$$

$$\mathcal{W}^{(3^-)} \propto (3+\cos2\theta_0)(398+271\cos2\theta_1+130\cos4\theta_1 + 255\cos6\theta_1) - 8(163+380\cos2\theta_1 + 225\cos4\theta_1)\cos2\phi_1 \sin^2\theta_0 \sin^2\theta_1$$