BESIII上粲物理的研究

李惠静
河南师范大学
(On behalf of BESIII Collaboration)

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lihuijing@htu.edu.cn

Outline

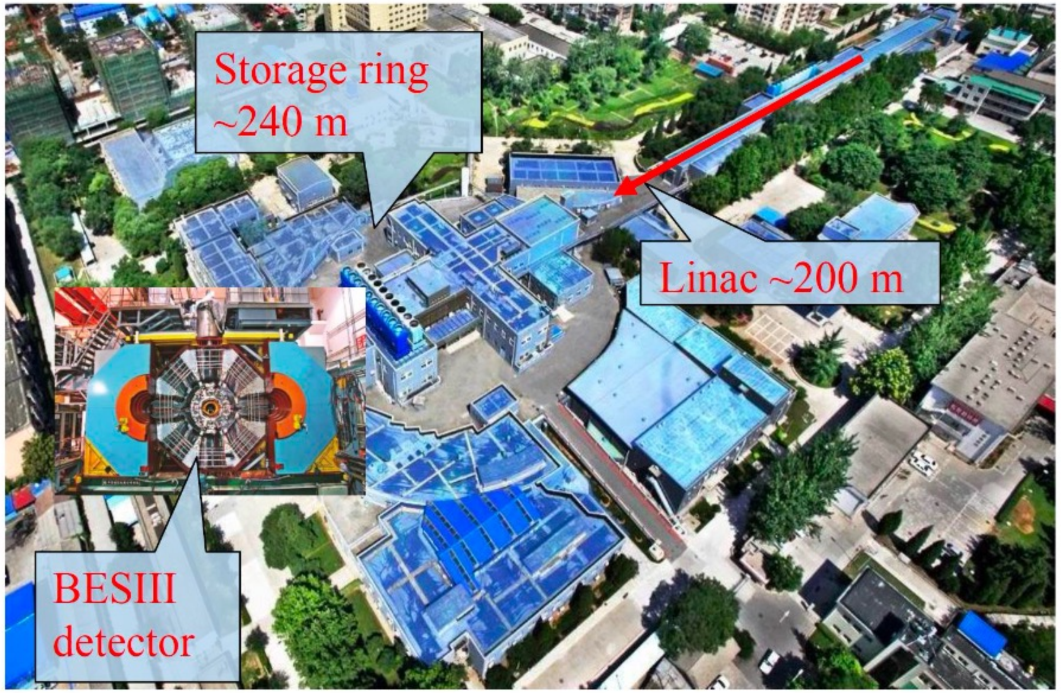
✍ **Hadronic decays**

✍ **(Semi-) leptonic decays**

✍ **Rare decays**

BESIII@BEPCII

Beijing Electron Positron Collider(BEPCII)



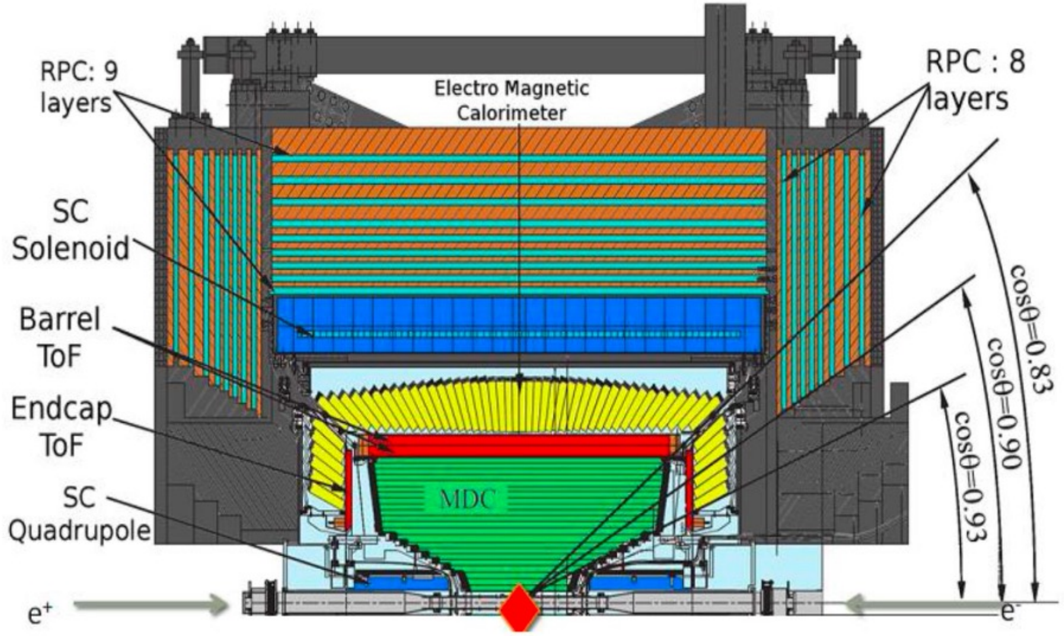
Double-ring, symmetry, multi-bunch $e^+ e^-$ collider

E_{cm}= 1.84 to 4.95 GeV

Energy spread: $\Delta E \approx 5 \times 10^{-4}$

Peak luminosity in continuously operation @E_{cm}= 3.77 GeV: 1.1×10^{33} $cm^{-2}s^{-1}$

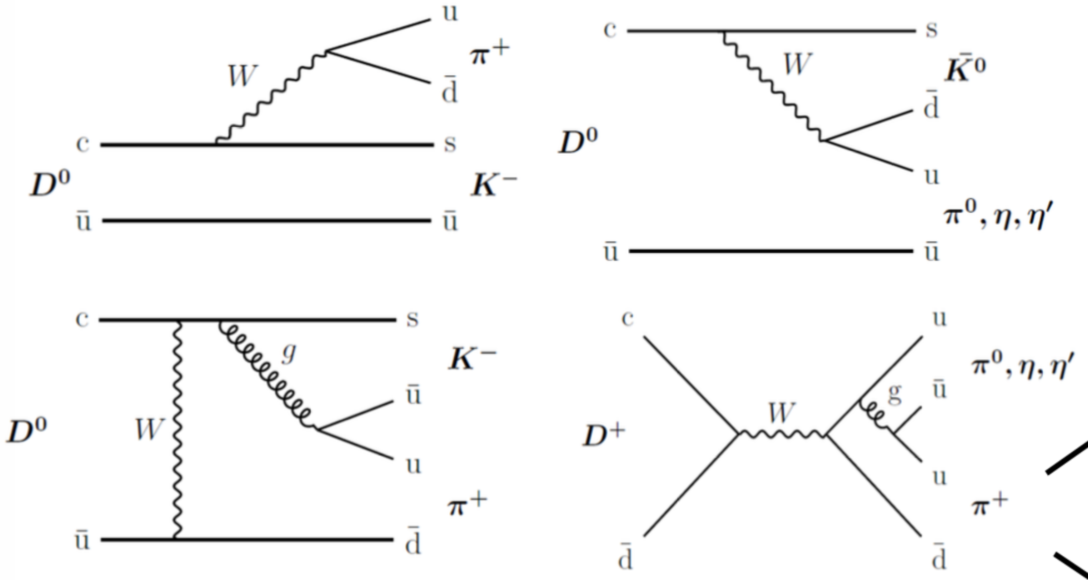
Beijing Spectrometer(BESIII)



Main Drift Chamber	Time Of Flight	Electromagnetic Calorimeter	Muon Counter
Small cell, 43 layer	Plastic scintillator	CsI(Tl): L=28 cm	RPC
σ_{xy}=130 μm	σ_T(barrel): 65 ps	Barrel σ_E=2.5%	Barrel: 9 layers
dE/dx~6%	σ_T(endcap): 110 ps (update to 60 ps with MRPC)	Endcap σ_E=5.0%	Endcap: 8 layers
σ_p/p= 0.5% at 1 GeV			$\sigma_{spatial}$: 1.48 cm

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

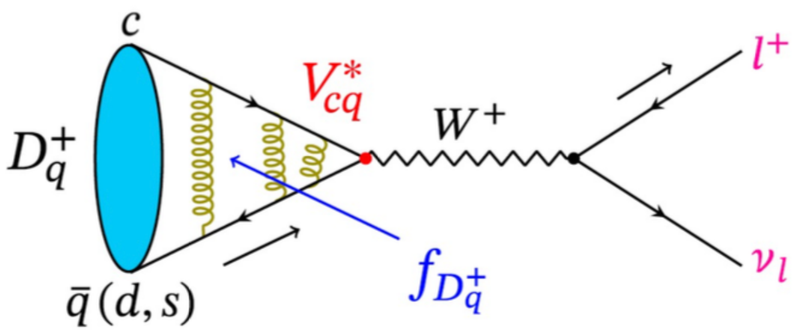
→ Get the information of $D \to VP, PP \ldots,$ where V and P denote vector and pseudoscalar, respectively.

Absolute BFs measurement

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

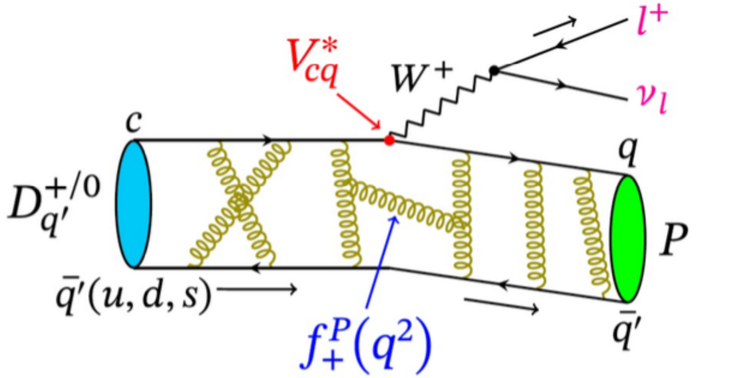
Why charm meson physics?

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

Data sets

- $20\ \mathrm{fb}^{-1}$ @ $\sqrt{s} = 3.773\ \mathrm{GeV}$

  $e^+e^- \to \psi(3770) \to D\bar{D}$

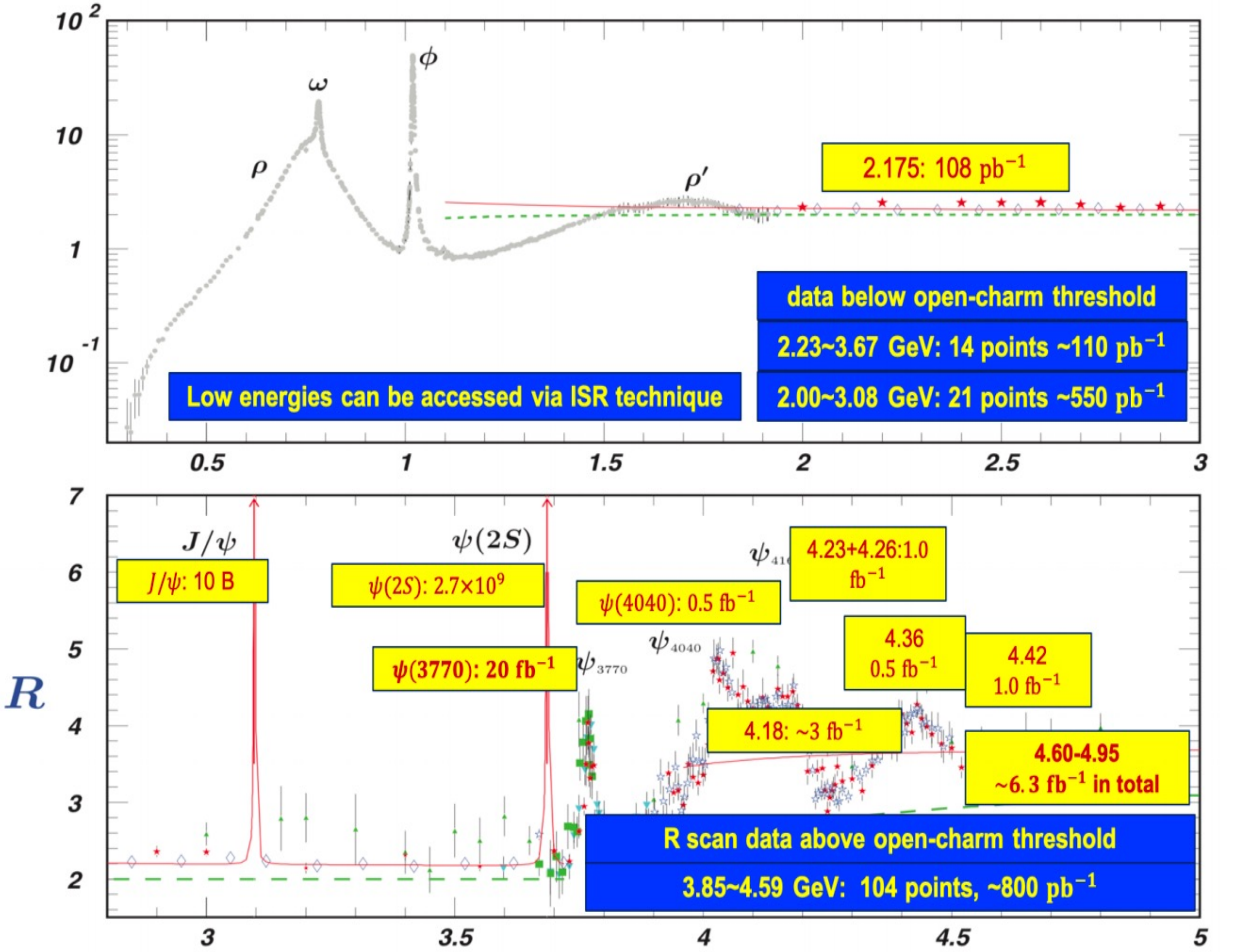
  $2.93\ \mathrm{fb}^{-1}$ in 2010-2011

- $7.33\ \mathrm{fb}^{-1}$ @ $\sqrt{s} = 4.128 - 4.226\ \mathrm{GeV}$

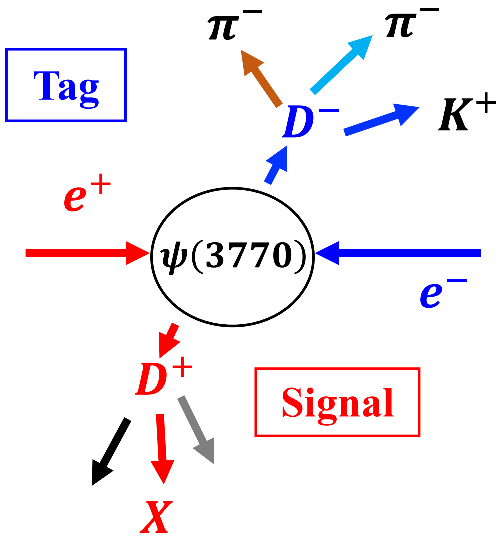
  $e^+e^- \to D_s^{*+}D_s^-$

- $10.6\ \mathrm{fb}^{-1}$ @ $\sqrt{s} = 4.237 - 4.699\ \mathrm{GeV}$

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



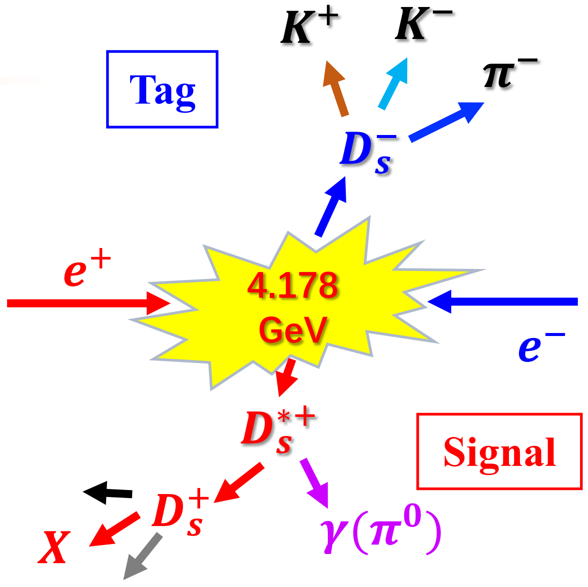
Analysis technique



Charge conjugated processes are implied

The signal branching fraction:

$$B_{\text{sig}} = \frac{N_{\text{DT}}^{\text{signal}}}{N_{D_{(s)}}^{\text{ST}} \times \bar{\epsilon}_{sig}}$$



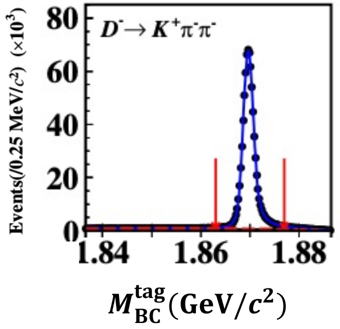
- **Single tag (ST):**

fully reconstruct one D^-

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

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

PRL124(2020)231801



- **Double tag (DT):**

in the recoil ST $D_{(s)}^-$,

analyze the signal $D_{(s)}^+$

$$\text{MM}^2 = E_{\text{miss}}^2 - |\vec{p}_{\text{miss}}|^2$$

$$E_{\text{miss}} = E_{\text{cm}} - \sqrt{\left|\vec{p}_{D_{(s)}^-}\right|^2 + M_{D_{(s)}}^2} - E_X$$

$$\vec{p}_{\text{miss}} = -\vec{p}_{D_{(s)}^-} - \vec{p}_X$$

$$U_{\text{miss}} = E_{\text{miss}} - |\vec{p}_{\text{miss}}|$$

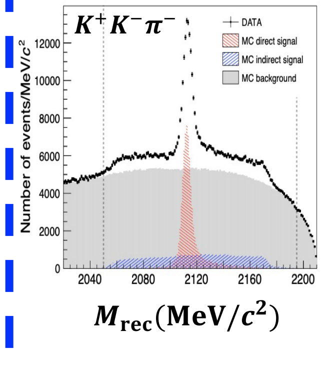
or other variables

- **Single tag (ST):**

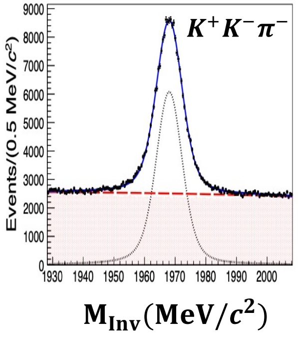
fully reconstruct one D_s^-

$$M_{\text{rec}} = \sqrt{\left(E_{\text{cm}} - \sqrt{|\vec{p}_{D_s^-}|^2 + m_{D_s^-}^2}\right)^2 - |-\vec{p}_{D_s^-}|^2}$$

PRD104(2021)052009



PRD 104 (2021) 012003



PWA method

- Closed source / hand coded
  - Tensor formulism: most of charm decays. [$D^+ \to K_S^0\pi^+\pi^0\pi^0$: JHEP09, 077(2023)]
  - Helicity formulism: [$e^+e^- \to \omega\pi^+\pi^-$: JHEP08,159(2023)]
- GPUPWA:
  - First PWA tool based on GPU
  - Used in many PWA of light mesons: [$J/\psi \to \gamma\eta\eta$: PRD87, 092009(2013); $J/\psi \to \gamma\eta\eta'$: PRD106, 072012(2022)]
- FDC-PWA:
  - Feynman Diagram Calculation
  - Used in some baryon final states [$\psi' \to p\bar{p}\eta$:PRD88, 032010(2013); $e^+e^- \to pK^-\bar{\Lambda}$: PRL131, 151901 (2023)]
- TF-PWA:
  - TensorFlow-based, configurable, GPU acceleration, AD
  - as an example: [$\Lambda_c^+ \to \Lambda\pi^+\pi^0$:JHEP12, 033(2022)]
- Other tools:
  - Amptools: [$\chi_{c1} \to \eta\pi^+\pi^-$: PRD95,032002(2017)]
  - PAWIAN: [$e^+e^- \to \phi K^+K^-$: PRD108, 032004 (2023)]
  - ComPWA: [$D^0 \to K_S K^+K^-$: arXiv:2006.02800]

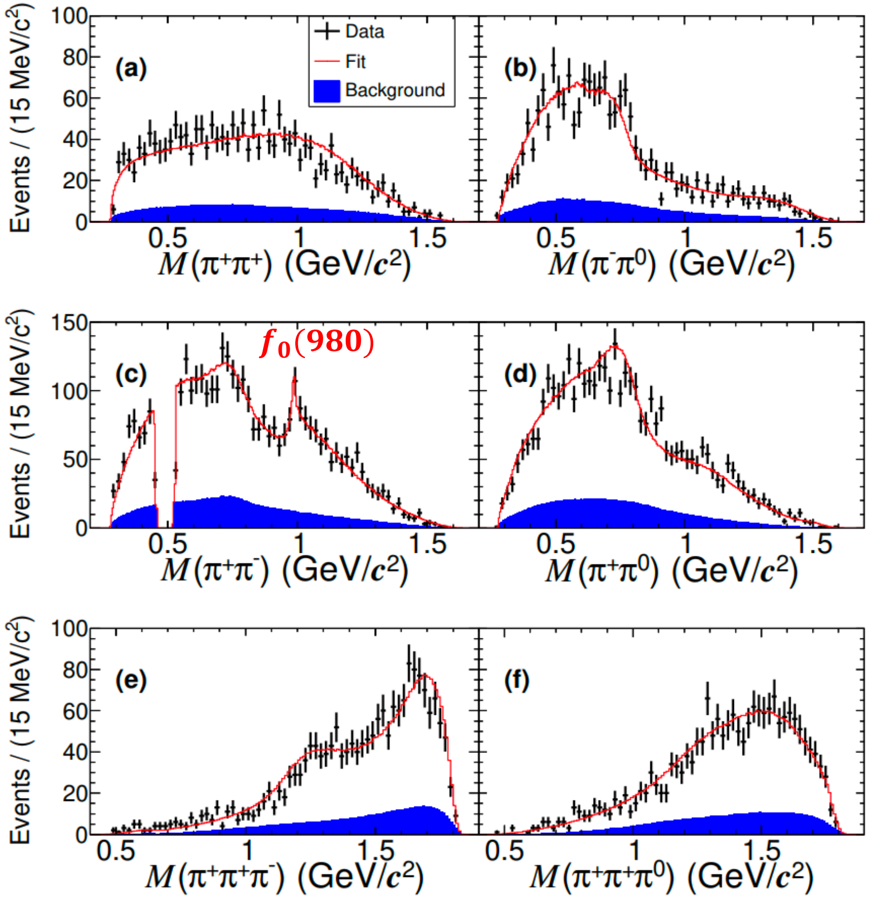
Hadronic decays

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

arXiv:2406.17452[hep-ex]

- $e^+e^- \to D_s^{*+}D_s^-$ with $7.33\ \mathrm{fb}^{-1}$ @ $\sqrt{s} = 4.128 - 4.226$ GeV
- $D_s^+ \to f_0(980)\,\rho^+$: mainly a W-external emission channel.
- $D_s^+ \to \omega\,\pi^+$: solely via the W-annihilation process.

Component	Phase (rad)	FF (%)	BF (10^{-3})
$f_0(1370)\rho^+$	0.0(fixed)	$24.9 \pm 3.8 \pm 2.1$	$5.08 \pm 0.80 \pm 0.43$
$f_0(980)\rho^+$	$3.99 \pm 0.13 \pm 0.07$	$12.6 \pm 2.1 \pm 1.0$	$2.57 \pm 0.44 \pm 0.20$
$f_2(1270)\rho^+$	$1.11 \pm 0.10 \pm 0.10$	$9.5 \pm 1.7 \pm 0.6$	$1.94 \pm 0.36 \pm 0.12$
$(\rho^+\rho^0)_S$	$1.10 \pm 0.18 \pm 0.10$	$3.5 \pm 1.2 \pm 0.6$	$0.71 \pm 0.25 \pm 0.12$
$(\rho(1450)^+\rho^0)_S$	$0.43 \pm 0.18 \pm 0.17$	$4.6 \pm 1.3 \pm 0.8$	$0.94 \pm 0.27 \pm 0.16$
$(\rho^+\rho(1450)^0)_P$	$4.58 \pm 0.16 \pm 0.09$	$8.6 \pm 1.3 \pm 0.4$	$1.75 \pm 0.27 \pm 0.08$
$\phi((\rho\pi) \to \pi^+\pi^-\pi^0)\pi^+$	$2.90 \pm 0.15 \pm 0.18$	$24.9 \pm 1.2 \pm 0.4$	$5.08 \pm 0.32 \pm 0.10$
$\omega((\rho\pi) \to \pi^+\pi^-\pi^0)\pi^+$	$3.22 \pm 0.21 \pm 0.09$	$6.9 \pm 0.8 \pm 0.3$	$1.41 \pm 0.17 \pm 0.06$
$a_1^+(\rho^0\pi^+)_S\pi^0$	$3.78 \pm 0.16 \pm 0.12$	$12.5 \pm 1.6 \pm 1.0$	$2.55 \pm 0.34 \pm 0.20$
$a_1^0((\rho\pi)_S \to \pi^+\pi^-\pi^0)\pi^+$	$4.82 \pm 0.15 \pm 0.12$	$6.3 \pm 1.9 \pm 1.2$	$1.29 \pm 0.39 \pm 0.24$
$\pi(1300)^0((\rho\pi)_P \to \pi^+\pi^-\pi^0)\pi^+$	$2.22 \pm 0.14 \pm 0.08$	$11.7 \pm 2.3 \pm 2.2$	$2.39 \pm 0.48 \pm 0.45$

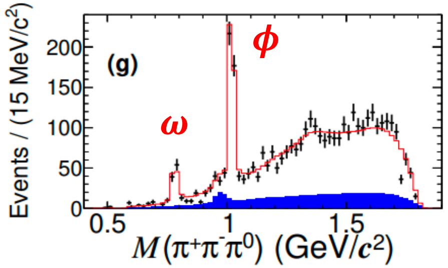


$$B_{D_s^+\to\pi^+\pi^+\pi^-\pi^0}|_{\text{non}-\eta} = (2.04 \pm 0.08_{\text{stat}} \pm 0.05_{\text{syst}})\%$$

First time

$$\frac{B_{\phi\to\pi^+\pi^-\pi^0}}{B_{\phi\to K^+K^-}} = (0.230 \pm 0.014_{\text{stat}} \pm 0.010_{\text{syst}})\%$$

> 4σ deviation from PDG value

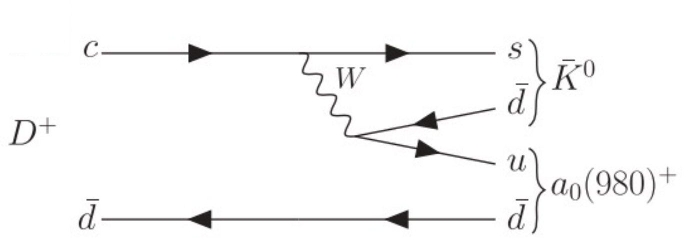


$D^+ \to K_S^0 \pi^+ \eta$

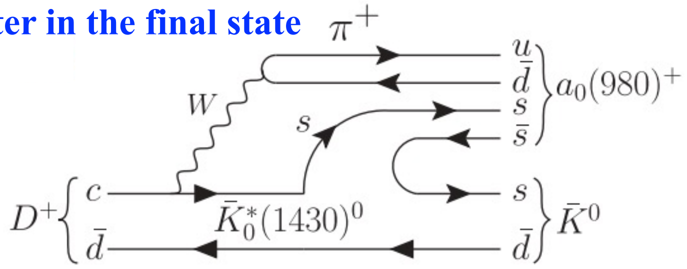
PRL132(2024)131903

- $e^+e^- \to \psi(3770) \to D\bar{D}$ with $2.93\ \mathrm{fb}^{-1}$@3.773 GeV
- $D^+ \to K_S^0\, a_0(980)$ is the only W-annihilation-free decay among D to $a_0(980)$ pseudoscalar, which is the ideal decay in extracting the contributions of the W-emission amplitudes involving $a_0(980)$ and to study the final-state interactions.

Internal W-emission



Rescatter in the final state

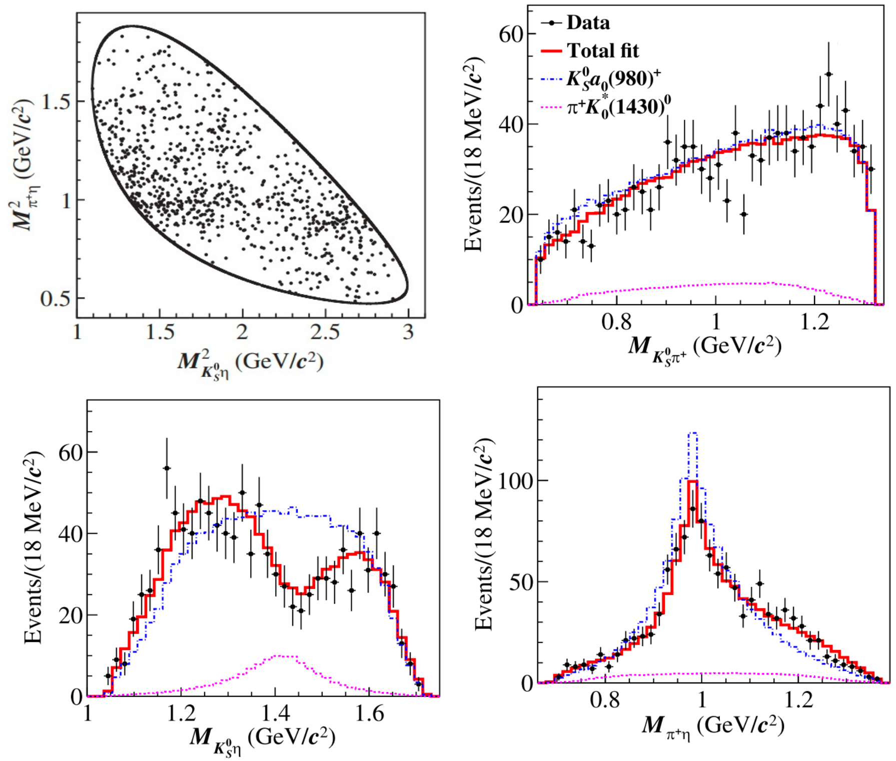


$$B_{D^+\to K_S^0\pi^+\eta} = (1.27 \pm 0.04_{stat} \pm 0.03_{syst})\%$$

$$B_{D^+\to K_S^0 a_0(980)^+(\to\pi^+\eta)} = (1.33 \pm 0.05_{stat} \pm 0.04_{syst})\%$$

$$B_{D^+\to \pi^+\bar{K}_0^*(1430)^0(\to K_S^0\eta)} = (0.14 \pm 0.03_{stat} \pm 0.01_{syst})\%$$

Amplitude	Phase ϕ (rad)	FF (%)	Significance
$D^+ \to K_S^0 a_0(980)^+$	0.0 (fixed)	$105.00 \pm 0.94 \pm 1.04 \pm 0.07$	$>10\sigma$
$D^+ \to \bar{K}_0^*(1430)^0\pi^+$	$2.58 \pm 0.06 \pm 0.09 \pm 0.01$	$10.83 \pm 1.50 \pm 1.27 \pm 0.08$	$>10\sigma$



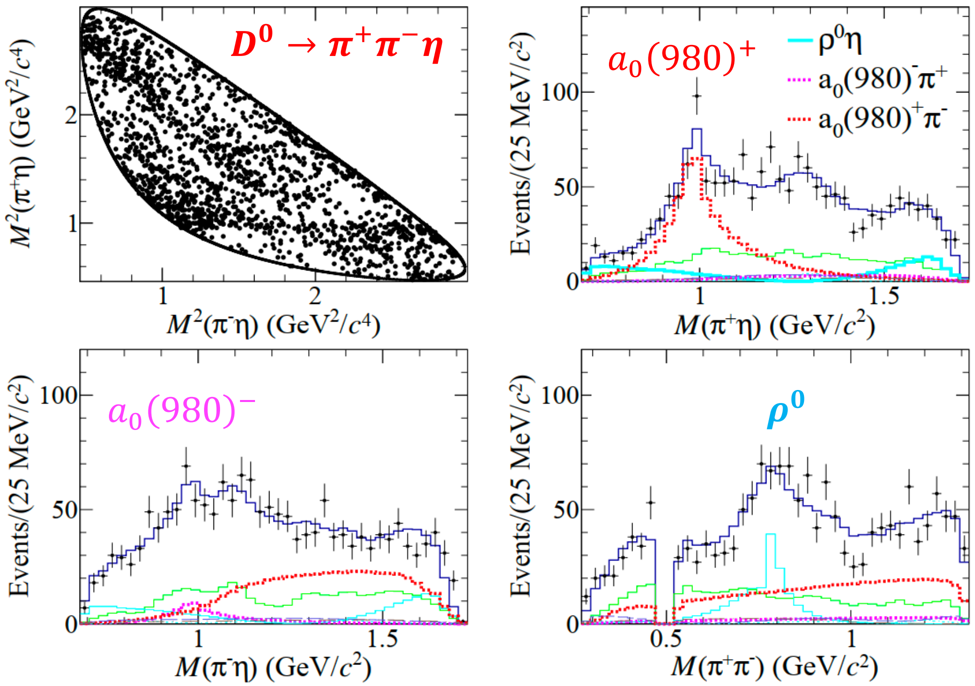
Destructive interference

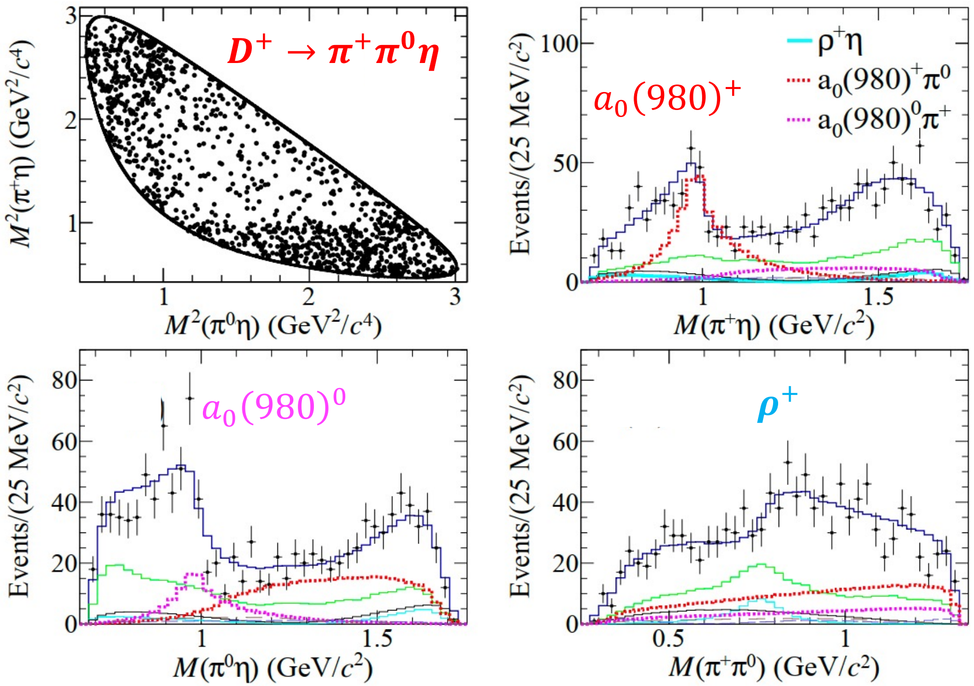
$D \to \pi\pi\eta$

- $e^+e^- \to \psi(3770) \to D\bar{D}$ with $7.9\ \mathrm{fb}^{-1}$@3.773 GeV

arXiv:2404.09219 [hep-ex]

- **The measurement of the branching fractions for $D \to \pi\, a_0(980)$ and the corresponding relative ratio can constrain the size and phase of the amplitude of the W-annihilation (W-exchange) process.**





$$\frac{FF_{D^0\to\pi^-a_0(980)^+}}{FF_{D^0\to\pi^+a_0(980)^-}} = 7.5^{+2.5}_{-0.8} \pm 1.7_{\mathrm{syst}}$$

Significantly higher than unity.

$$\frac{FF_{D^+\to\pi^0a_0(980)^+}}{FF_{D^+\to\pi^+a_0(980)^0}} = 2.6 \pm 0.6_{\mathrm{stat}} \pm 0.3_{\mathrm{syst}}$$

$$B_{D^0\to\pi^+\pi^-\eta} = (1.24 \pm 0.04_{\mathrm{stat}} \pm 0.03_{\mathrm{syst}})\times10^{-3}$$

$$B_{D^+\to\pi^+\pi^0\eta} = (2.18 \pm 0.12_{\mathrm{stat}} \pm 0.05_{\mathrm{syst}})\times10^{-3}$$

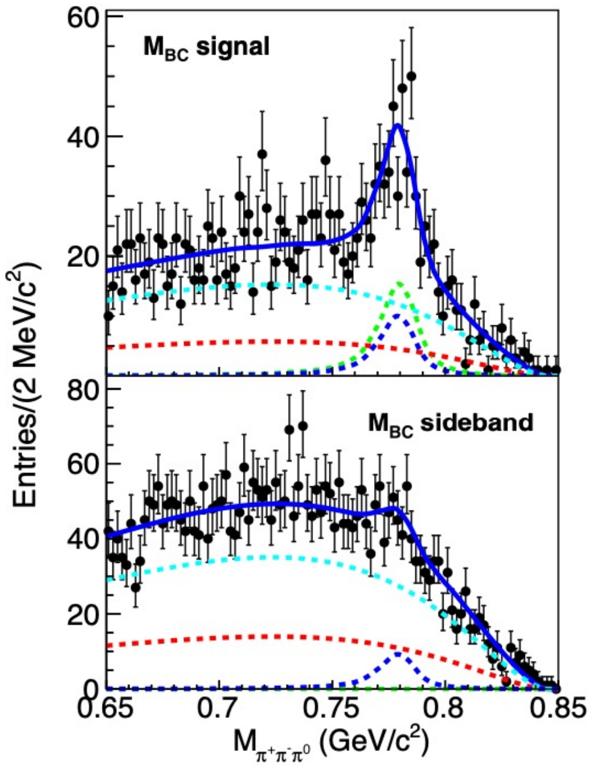
Polarization of $D^0 \to \omega\phi$

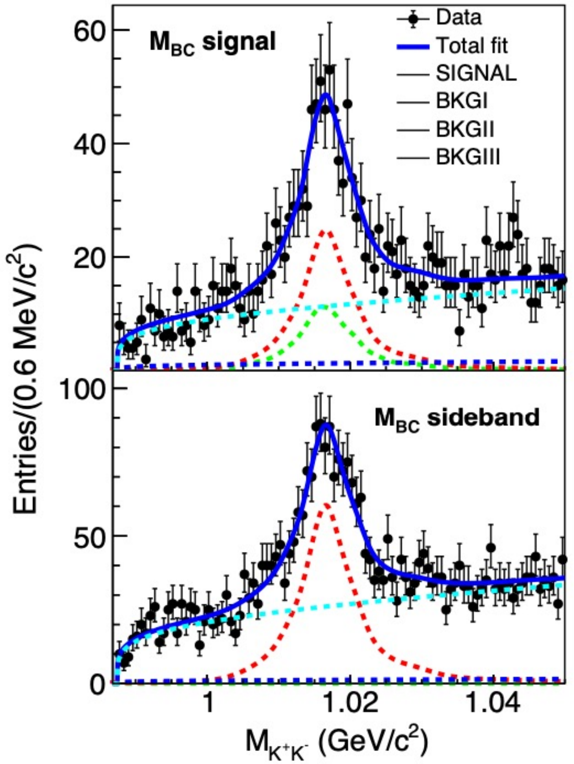
PRL128(2022)011803

- The polarization in the $D^0 \to VV$ decay is sensitive to the V-A structure of electroweak interactions in the SM, spin correlations, and the final state interactions, among other effects.
- 2-D unbinned maximum likelihood fit

$N_{sig} = 195.9 \pm 29.1$

$$B(D^0 \to \omega\phi) = (6.48 \pm 0.96 \pm 0.40)\times 10^{-4}$$

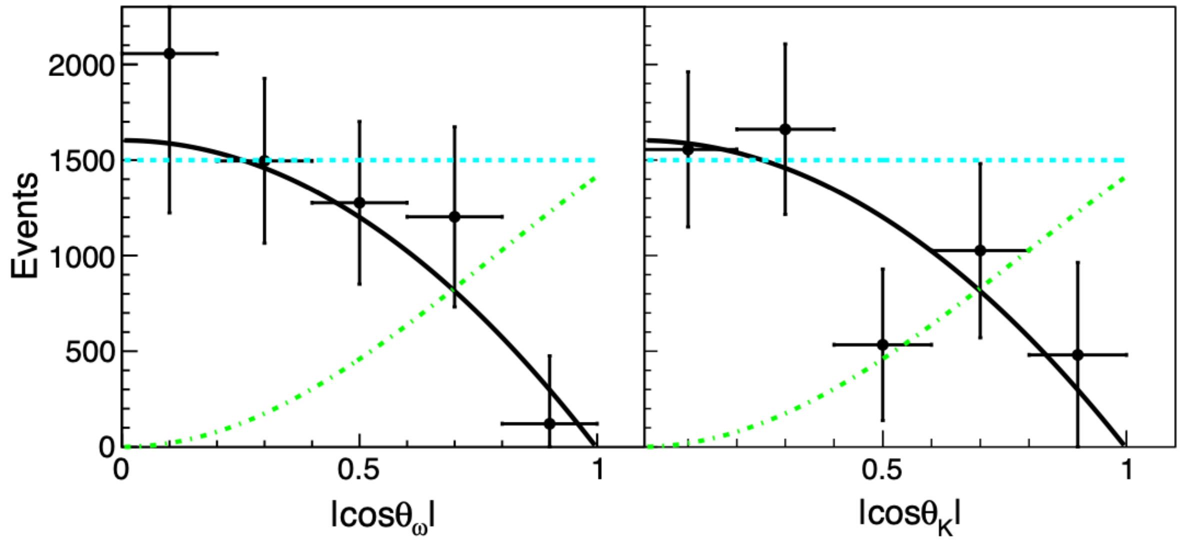




$f_L < 0.24$ @ 95% CL

PHSP

Longitudinal polarization



***ω* and *ϕ* are transversely polarized**

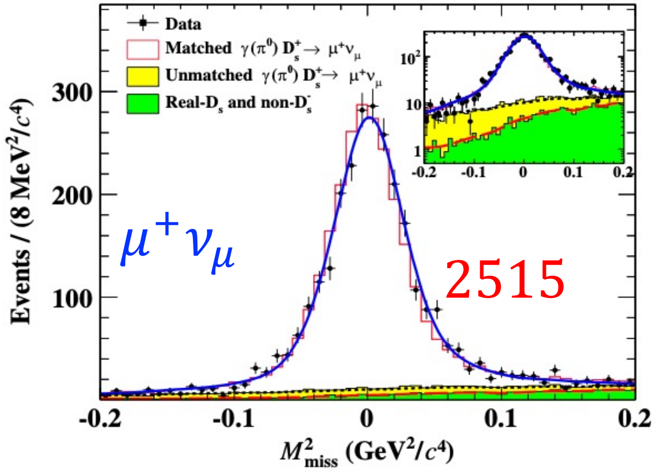
(Semi-) leptonic decays

$D_s^+ \to \ell^+ \nu_\ell \ (\ell = \mu, \tau)$

BESIII

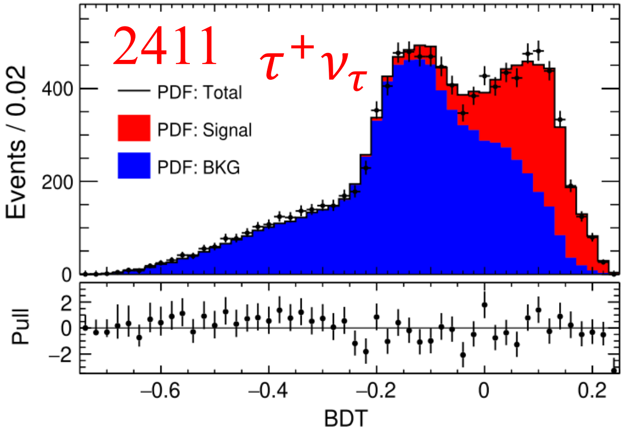
- $\mu^+\nu_\mu$, muon counter

$@4.128-4.226$ GeV PRD108(2023)112001



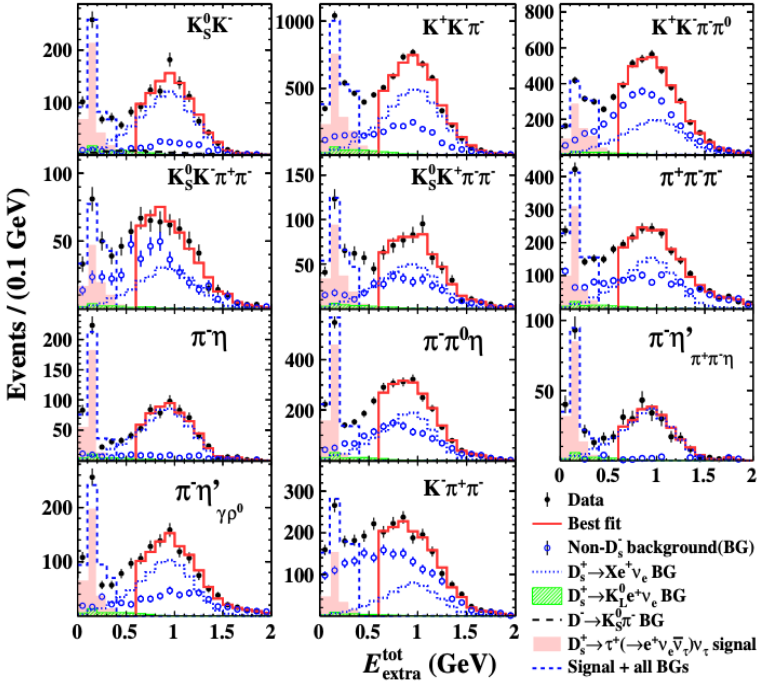
- $\tau^+ \to \pi^+ \bar{\nu}_\tau$ multivariate analysis

$@4.128-4.226$ GeV PRD108(2023)092014



- $\tau^+ \to e^+ \nu_e \bar{\nu}_\tau$ 4940

$@4.178-4.226$ GeV PRL127(2021)171801

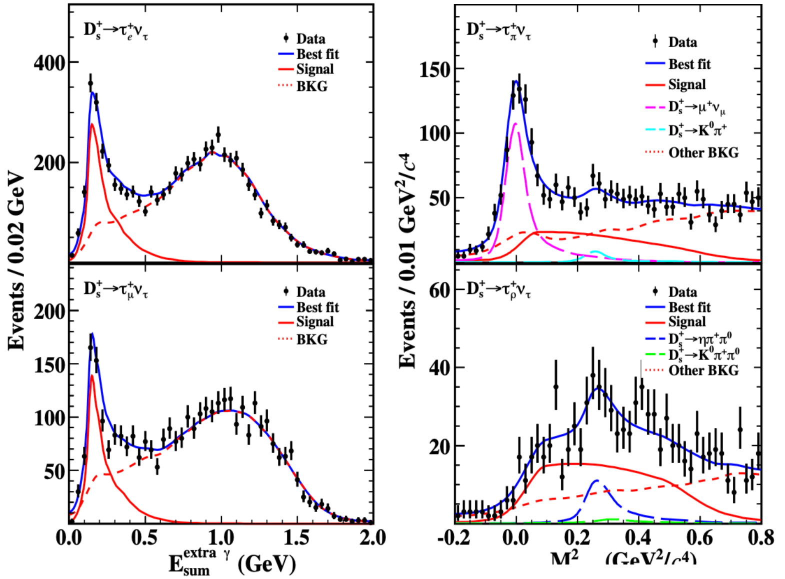


$\tau^+ \to e^+ \nu_e \bar{\nu}_\tau$	$(17.82 \pm 0.04)\%$
$\tau^+ \to \mu^+ \nu_\mu \bar{\nu}_\tau$	$(17.39 \pm 0.04)\%$
$\tau^+ \to \pi^+ \pi^0 \bar{\nu}_\tau$	$(25.49 \pm 0.09)\%$
$\tau^+ \to \pi^+ \bar{\nu}_\tau$	$(10.82 \pm 0.05)\%$

- $\tau^+\nu_\tau$ 2845

$@4.237-4.699$ GeV PRD110(2024)052002

$\tau^+ \to e^+ \nu_e \bar{\nu}_\tau$ $\tau^+ \to \mu^+ \nu_\mu \bar{\nu}_\tau$



$\tau^+ \to \pi^+ \bar{\nu}_\tau$ $\tau^+ \to \pi^+ \pi^0 \bar{\nu}_\tau$

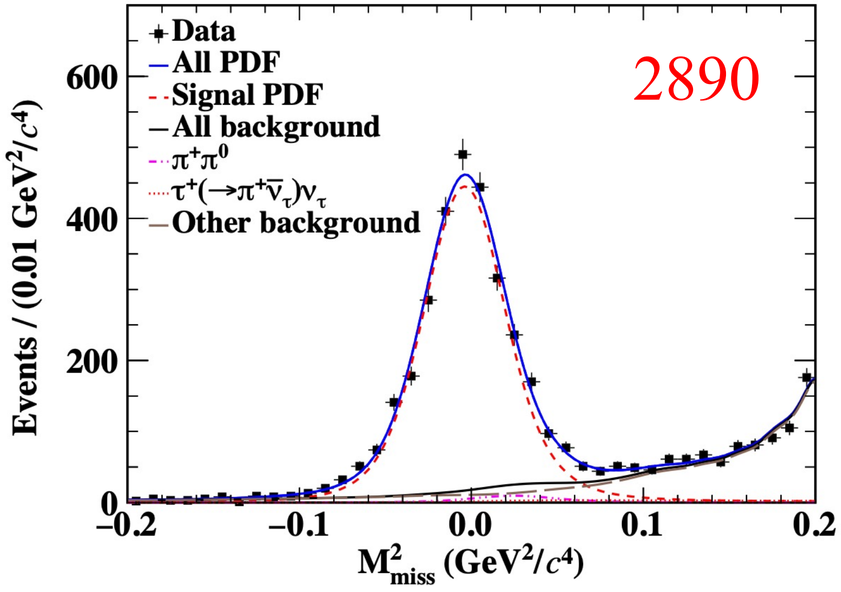
Simultaneous fit with the same BF

$D^+ \to \ell^+\nu_\ell \ (\ell = \mu, \tau)$

BESIII

- $\mu^+\nu_\mu$, muon counter

$20.3\ \mathrm{fb}^{-1}$@3.773 GeV arXiv:2410.07626



$B(D^+ \to \mu^+\nu_\mu) = (3.981 \pm 0.079 \pm 0.040)\times10^{-4}$

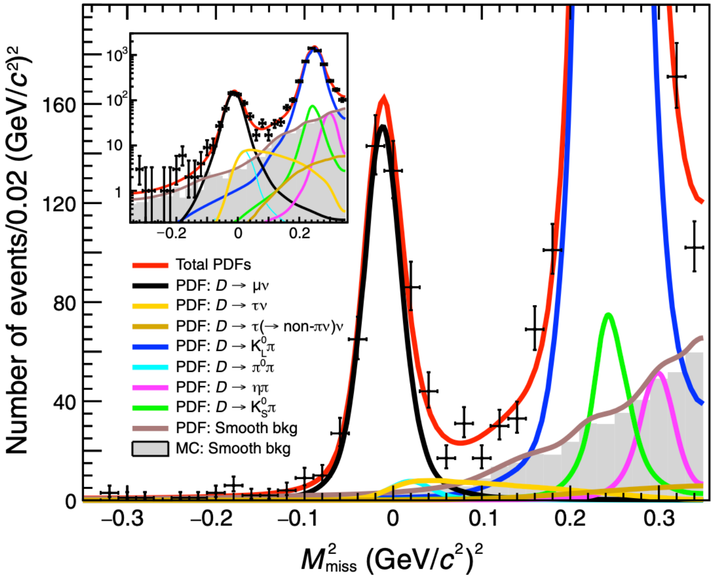
$f_{D^+}|V_{cd}|$ The most precise to date

$= (47.53 \pm 0.48_{\mathrm{stat}} \pm 0.24_{\mathrm{syst}} \pm 0.12_{\mathrm{input}})$ MeV

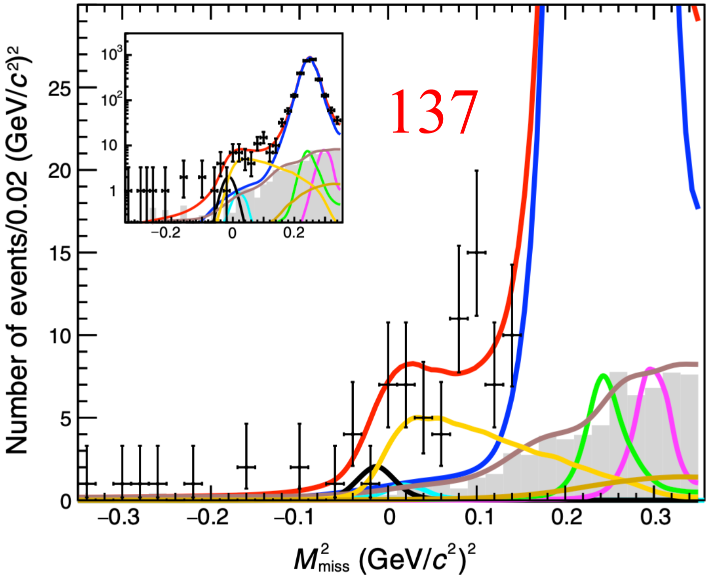
- $\tau^+\nu_\tau$ $2.93\ \mathrm{fb}^{-1}$@3.773 GeV

PRL123(2019)211802

μ-like: $E_{\mathrm{EMC}} \leq 0.3$ GeV



π-like: $E_{\mathrm{EMC}} > 0.3$ GeV



$B(D^+ \to \tau^+\nu_\tau) = (1.20 \pm 0.24 \pm 0.12)\times10^{-3}$

$$R_{\tau/\mu} = \frac{\bar{\Gamma}(D^+ \to \tau^+\nu_\tau)}{\bar{\Gamma}(D^+ \to \mu^+\nu_\mu)} = 3.02 \pm 0.68$$

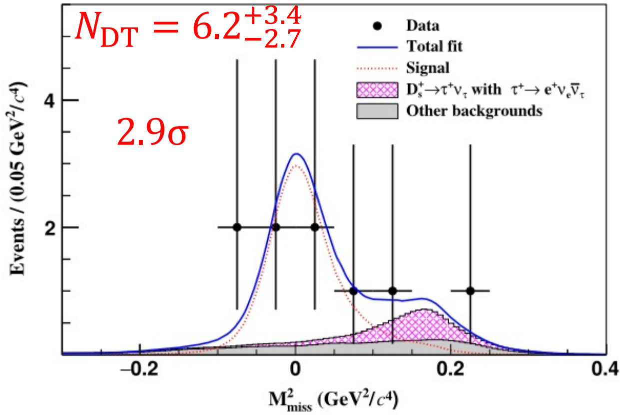
SM prediction: 2.67 ± 0.01

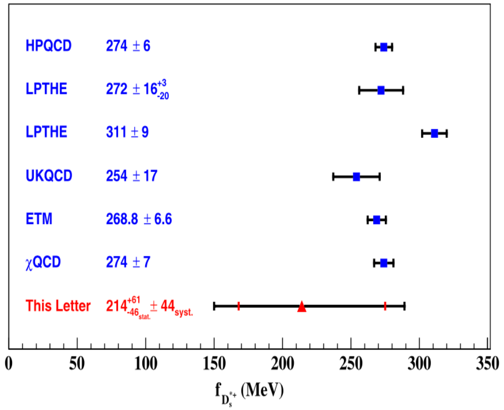
No LFU violation

$D_{(s)}^{*+} \to \ell^+\nu_\ell\ (\ell = e, \mu)$ Charmed vector meson

- $D_s^{*+} \to e^+\nu_e$ @4.128 – 4.226 GeV

PRL131(2023)141802





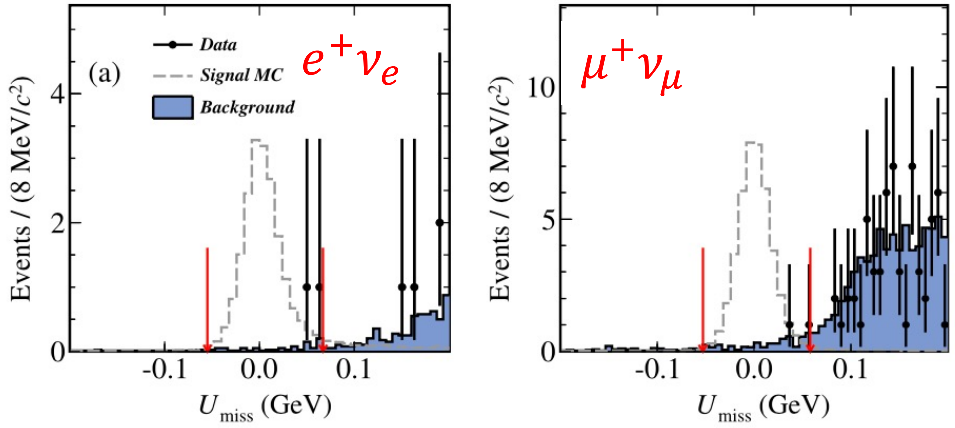
$B(D_s^{*+} \to e^+\nu_e) = \left(2.1^{+1.2}_{-0.9} \pm 0.2\right)\times 10^{-5}$

$f_{D_s^{*+}}|V_{cs}| = \left(208^{+59}_{-45} \pm 43\right)$ MeV

$f_{D_s^{*+}} = \left(214^{+61}_{-46} \pm 44\right)$ MeV For the first time

- $D^{*+} \to \ell^+\nu_\ell\ (\ell = e, \mu)$ @4.178 – 4.226 GeV

PRD110(2024)012003



No significant signal. Profile likelihood method.

$B(D^{*+} \to e^+\nu_e) < 1.1\times 10^{-5}$ @ 90% C. L.

$B(D^{*+} \to \mu^+\nu_\mu) < 4.3\times 10^{-6}$ @ 90% C. L.

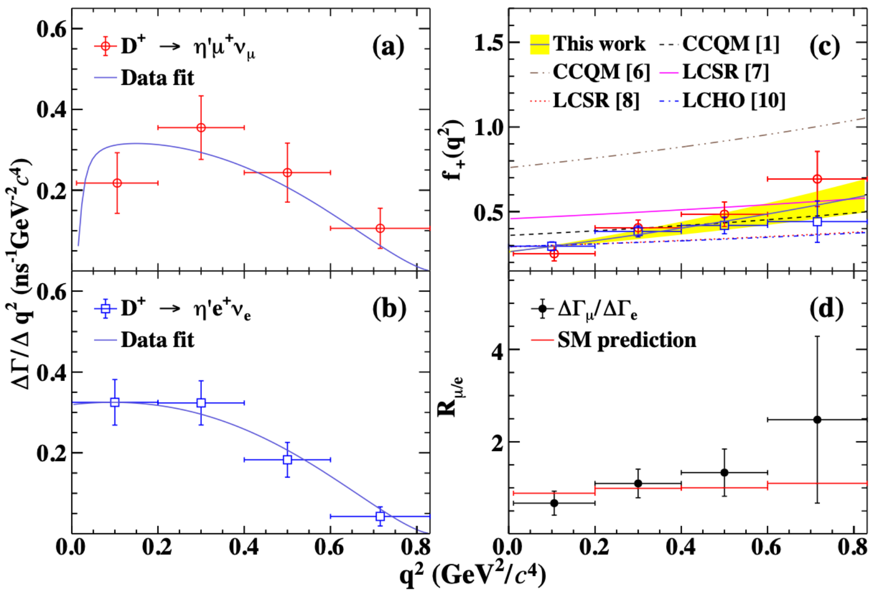
$D^+_{(s)} \to P\ell^+\nu_\ell$

BESIII

$e^+e^- \to \psi(3770) \to D\bar{D}$ with 20.3 fb^{-1}@3.773 GeV

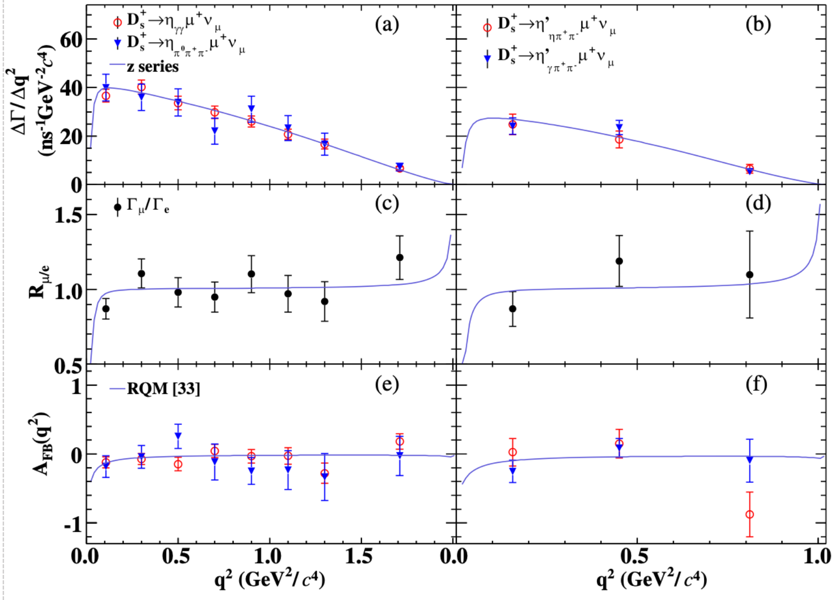
$e^+e^- \to D_s^{*+}D_s^-$ with 7.33 fb^{-1} @ $\sqrt{s} = 4.128 - 4.226$ GeV

- $D^+ \to \eta'\ell^+\nu_\ell$ arXiv:2410.08603



$B(D^+ \to \eta'\mu^+\nu_\mu) = (1.92 \pm 0.28_{stat} \pm 0.08_{syst})\times10^{-4}$. 8.6$\sigma$
$B(D^+ \to \eta' e^+\nu_e) = (1.79 \pm 0.19_{stat} \pm 0.07_{syst})\times10^{-4}$.
$f_+^{\eta'}(0)\,\lvert V_{cd}\rvert = (5.92 \pm 0.56_{stat} \pm 0.13_{syst})\times10^{-2}$.
The $\eta - \eta'$ mixing angle in the quark flavor basis is determined to be $\phi_P = (39.8 \pm 0.8_{stat} \pm 0.3_{syst})^{\circ}$

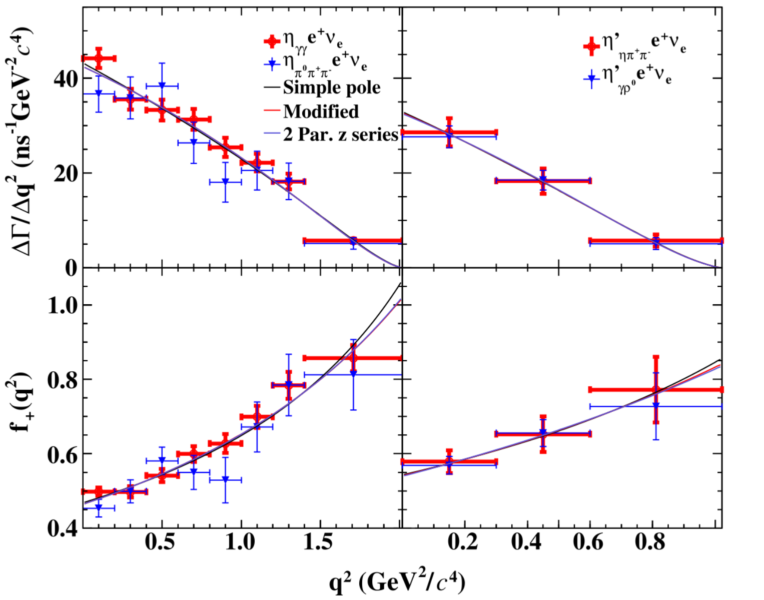
- $D_s^+ \to \eta^{(\prime)}\mu^+\nu_\mu$ PRL132(2024)091802



> 10σ

$B(D_s^+ \to \eta'\mu^+\nu_\mu) = (0.801 \pm 0.055_{stat} \pm 0.028_{syst})\%$.
$B(D_s^+ \to \eta\mu^+\nu_\mu) = (2.235 \pm 0.051_{stat} \pm 0.052_{syst})\%$.
$f_{+,0}^{\eta}(0)\,\lvert V_{cs}\rvert = 0.452 \pm 0.010_{stat} \pm 0.007_{syst}$.
$f_{+,0}^{\eta'}(0)\,\lvert V_{cs}\rvert = 0.504 \pm 0.037_{stat} \pm 0.012_{syst}$.

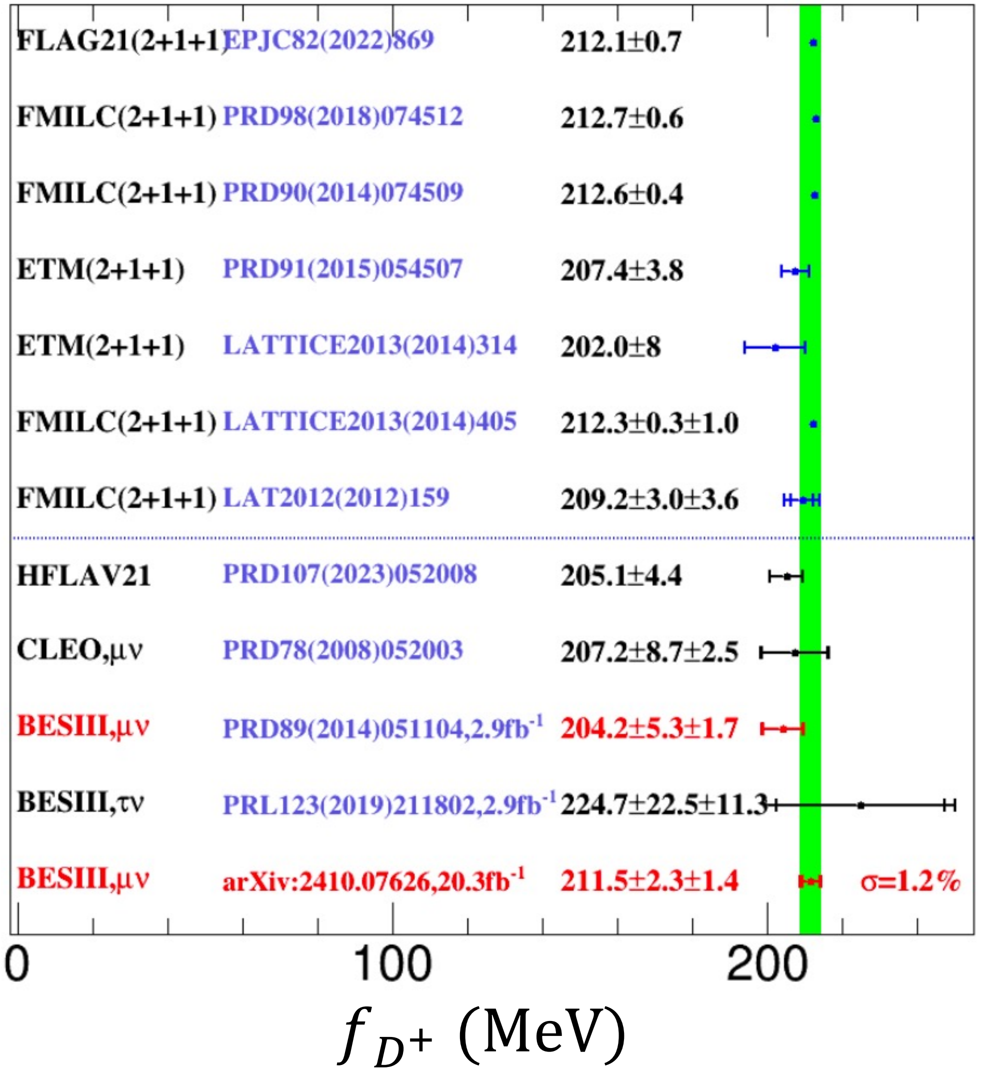
- $D_s^+ \to \eta^{(\prime)}e^+\nu_e$ PRD108(2023)092003



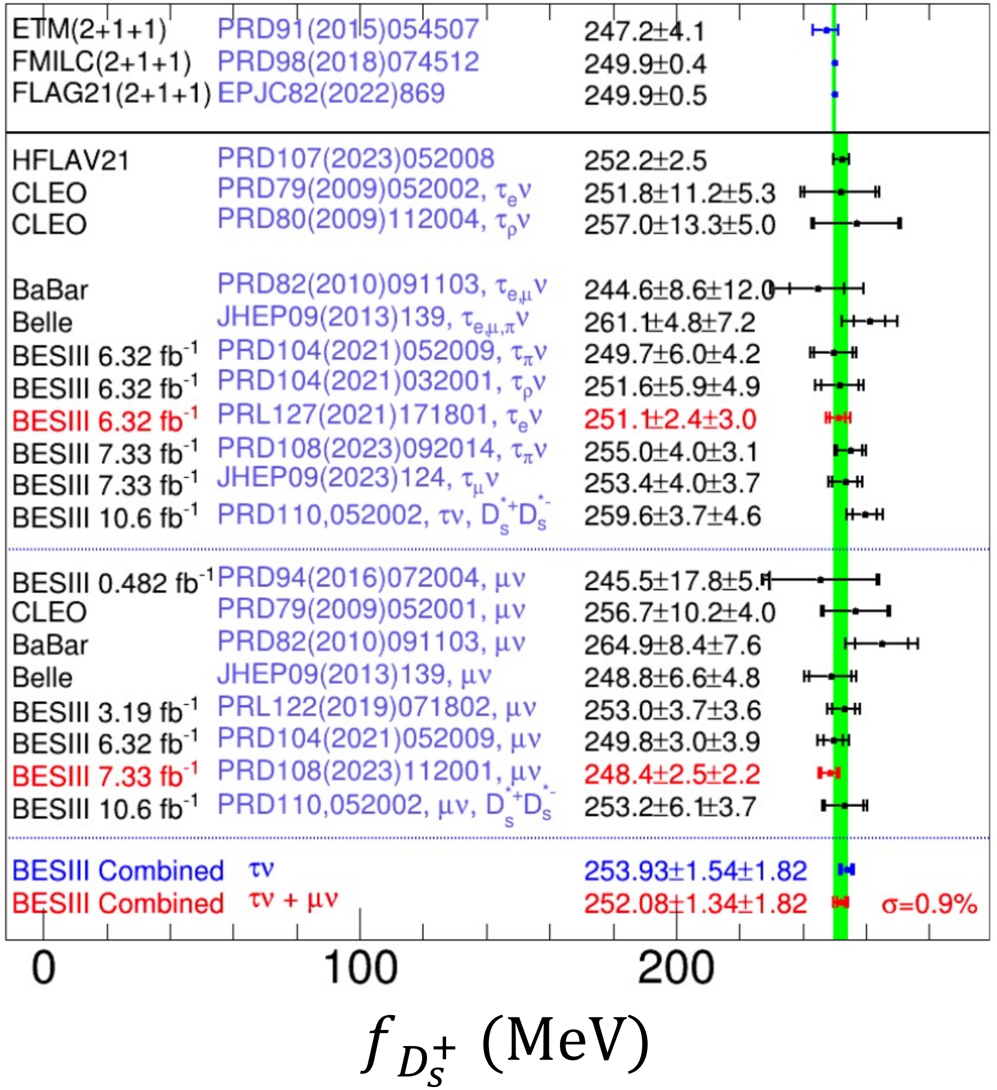
$B(D_s^+ \to \eta' e^+\nu_e) = (0.810 \pm 0.038_{stat} \pm 0.024_{syst})\%$.
$B(D_s^+ \to \eta e^+\nu_e) = (2.255 \pm 0.039_{stat} \pm 0.051_{syst})\%$.
$f_+^{\eta}(0)\,\lvert V_{cs}\rvert = 0.4519 \pm 0.0071_{stat} \pm 0.0065_{syst}$.
$f_+^{\eta'}(0)\,\lvert V_{cs}\rvert = 0.525 \pm 0.024_{stat} \pm 0.009_{syst}$.

Comparison of the $D_{(s)}^{+}$ decay constant

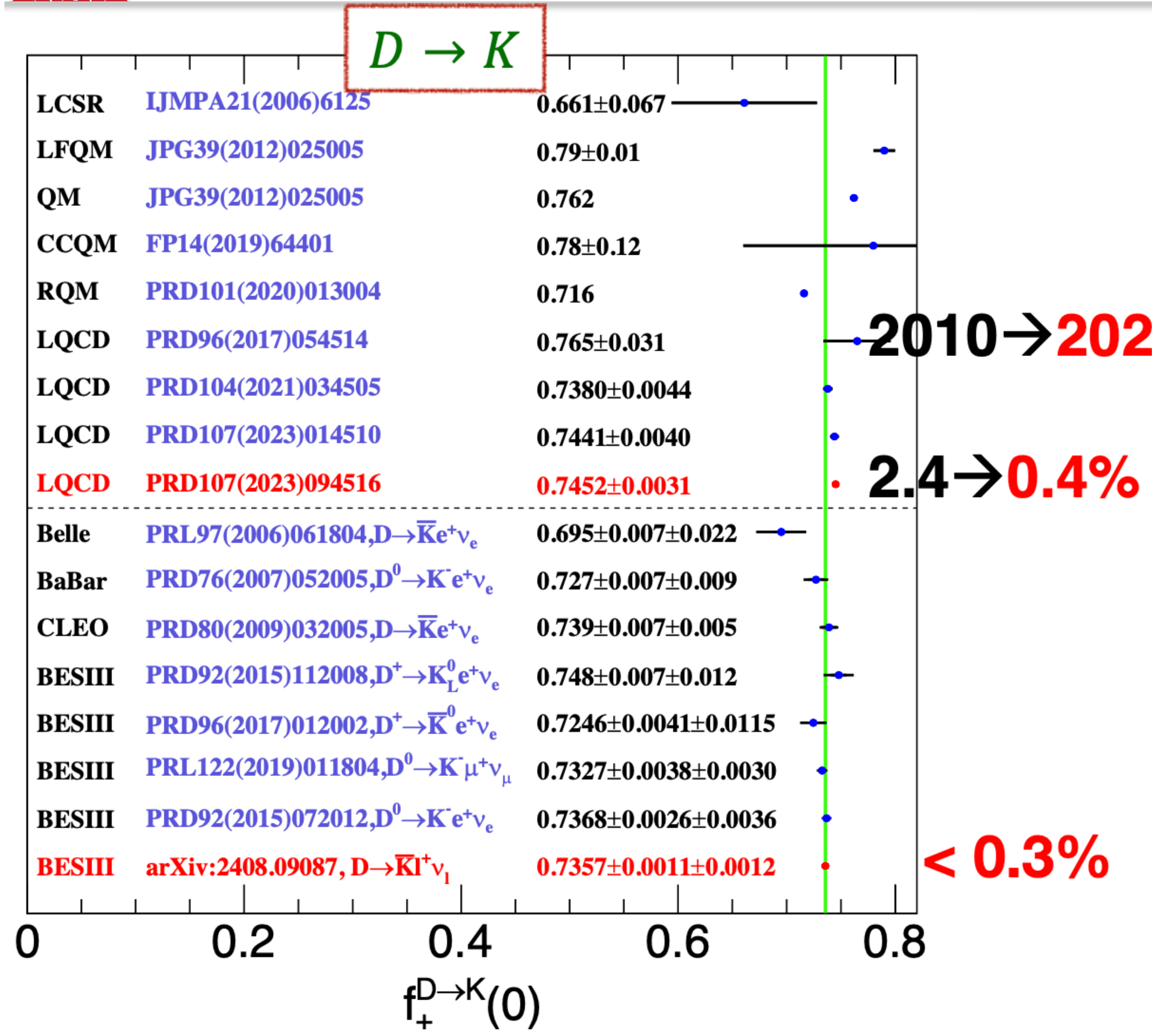
- **Input $|V_{cd}| = 0.22487 \pm 0.00068$ from CKM global fit**

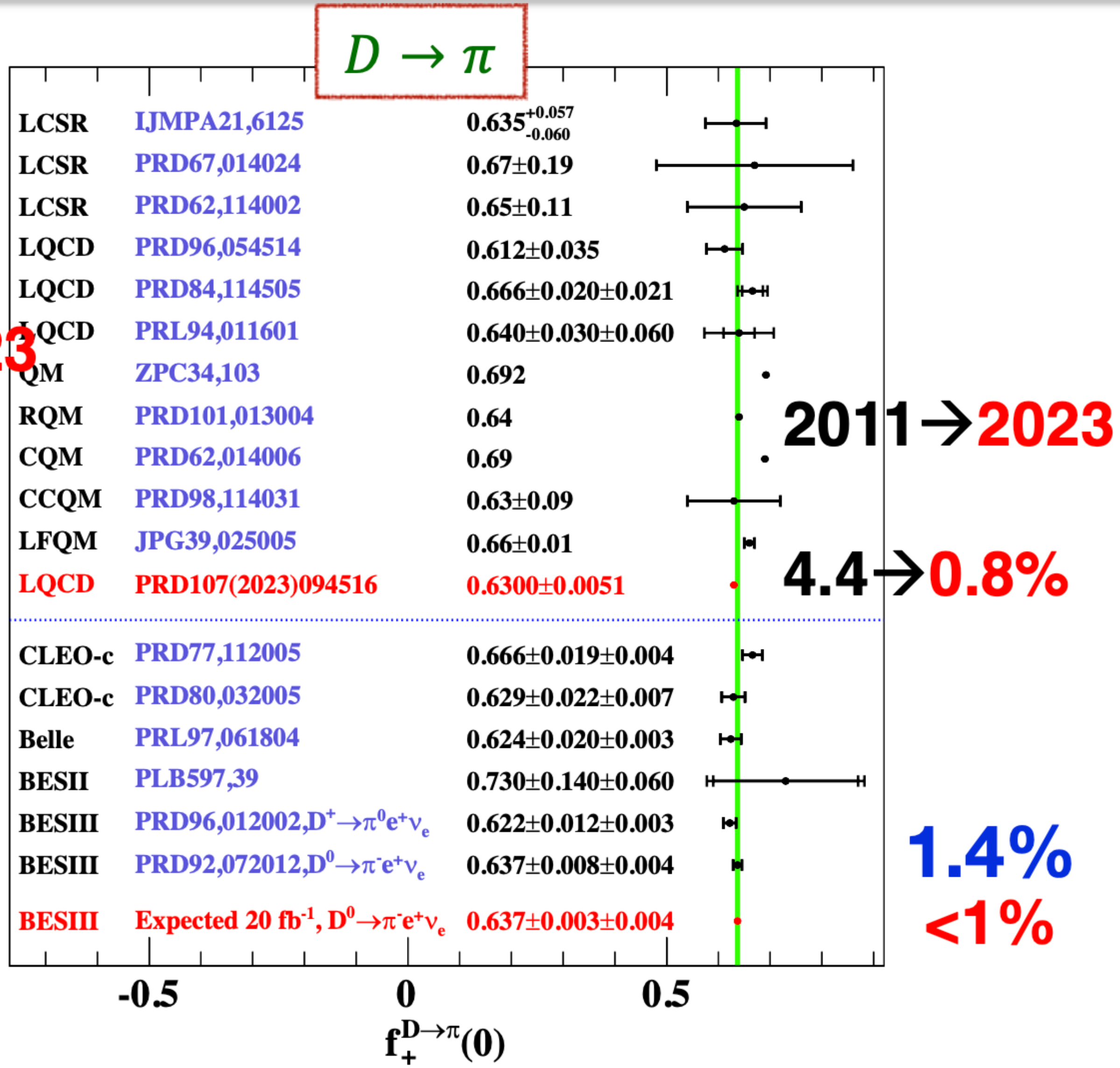


- **Input $|V_{cs}| = 0.97320 \pm 0.00011$ MeV from CKM global fit**



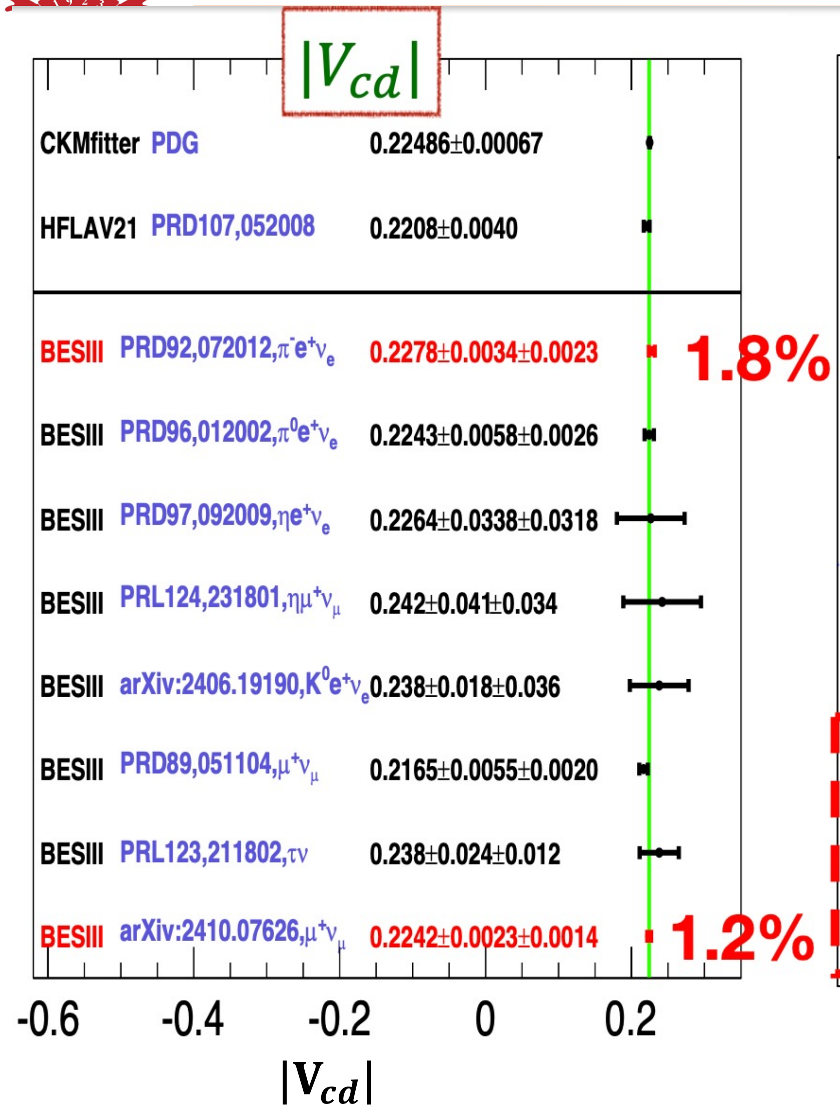
Comparison of form factor $D \to K(\pi)\ell^+\nu_\ell$

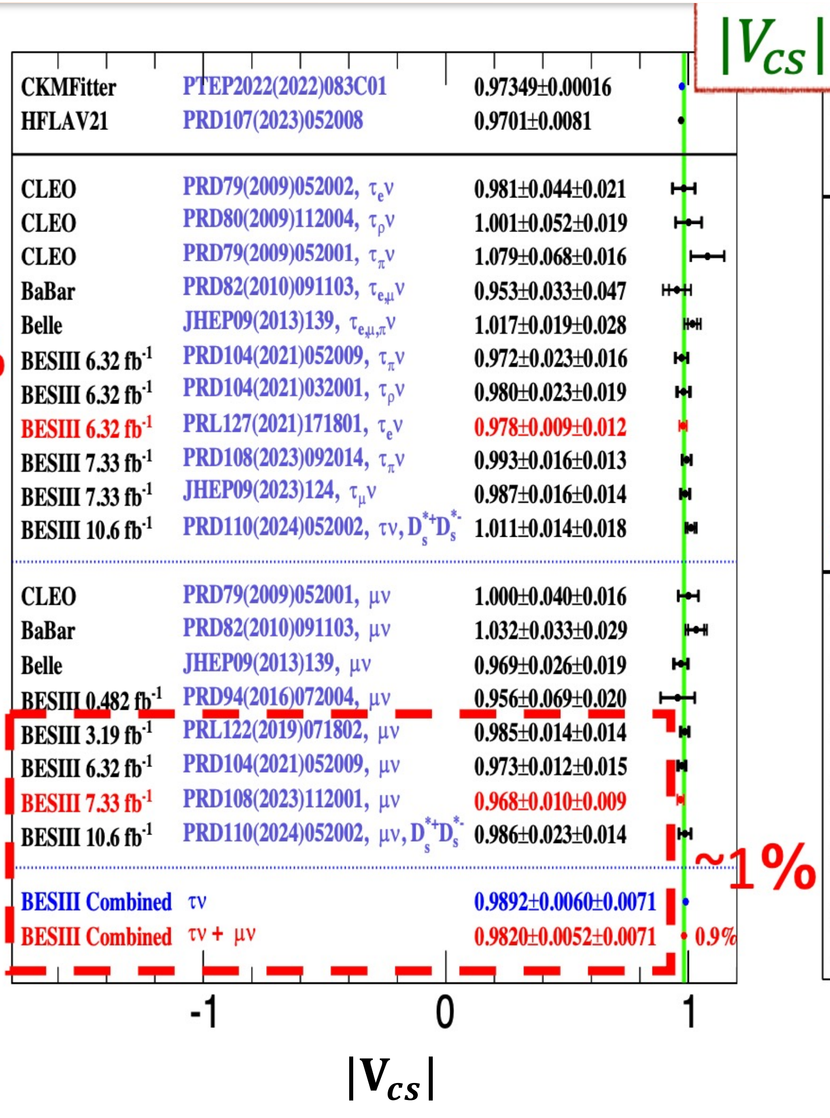




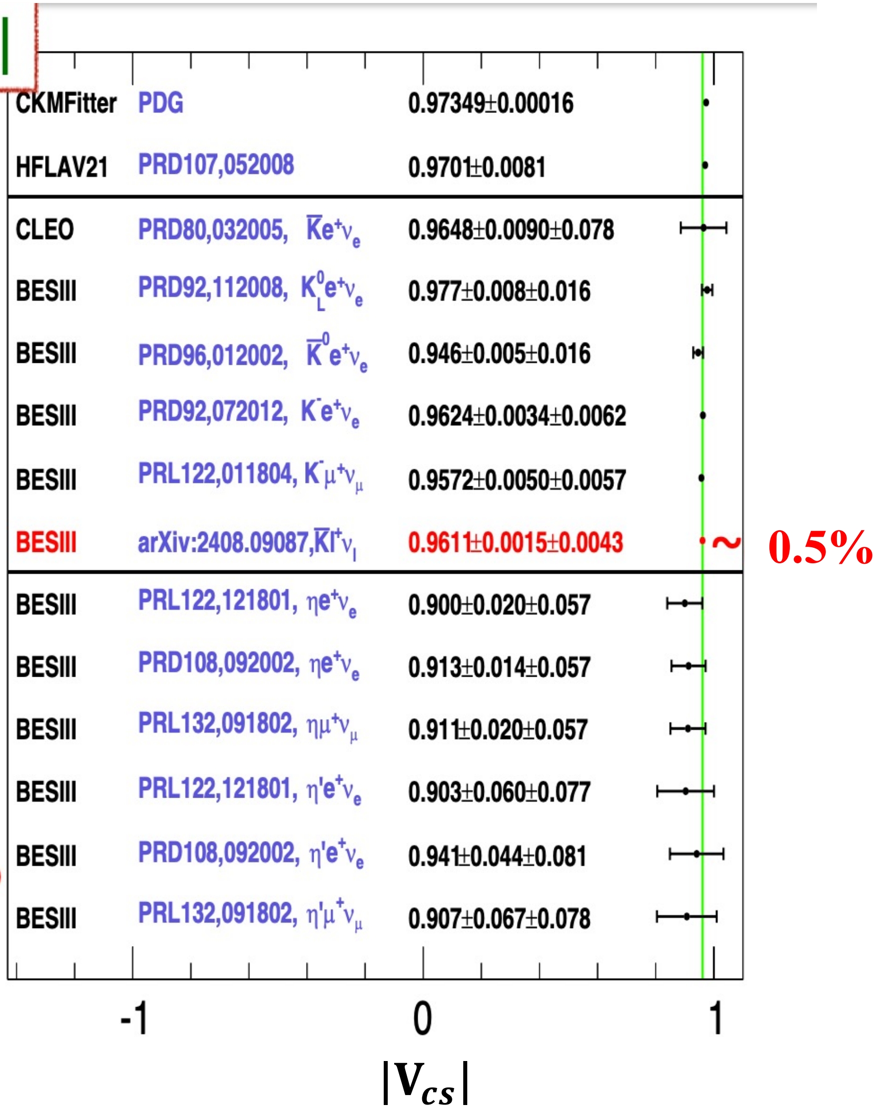
Experimental precision is comparable to the latest QCD result.

Comparison of $|V_{cd(s)}|$





pure leptonic D_s^+ decay



Semi-leptonic D_s^+ decay

Rare decays

$D_s^+ \to h^+(h^0)e^+e^-$

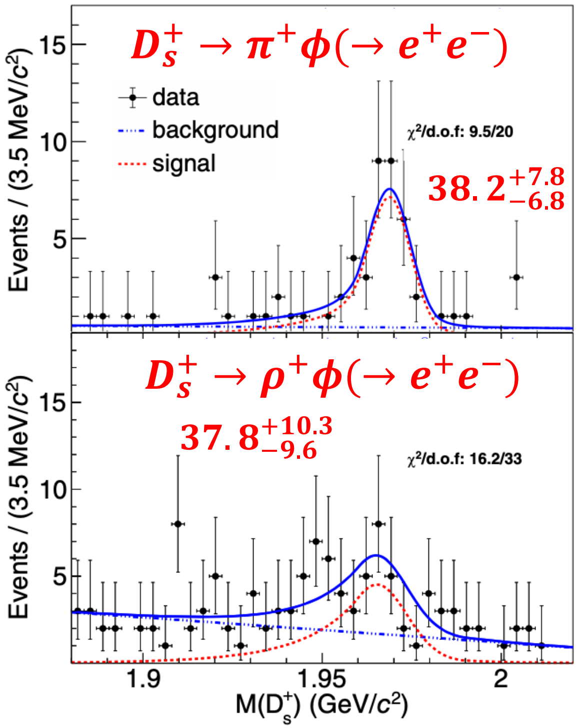
$e^+e^- \to D_s^{*+}D_s^-$ with $7.33\ \mathrm{fb}^{-1}$ @ $\sqrt{s} = 4.128 - 4.226$ GeV

PRL133(2024)121801

- In the SM, the $D_s^+ \to h^+(h^0)e^+e^-$ involve both short-distance (SD) and long-distance (LD) contribution.
- SD: FCNC, suppressed by GIM mechanism.
- LD: through a radiated photon or an intermediate meson decaying to dileptons, can enhance the BFs to 10^{-6}.

$B(D_s^+ \to \pi^+\phi(\to e^+e^-)) = (1.17^{+0.23}_{-0.21} \pm 0.03_{syst})\times 10^{-5}$ 7.8σ

$B(D_s^+ \to \rho^+\phi(\to e^+e^-)) = (2.44^{+0.67}_{-0.62} \pm 0.16_{syst})\times 10^{-5}$ 4.4σ



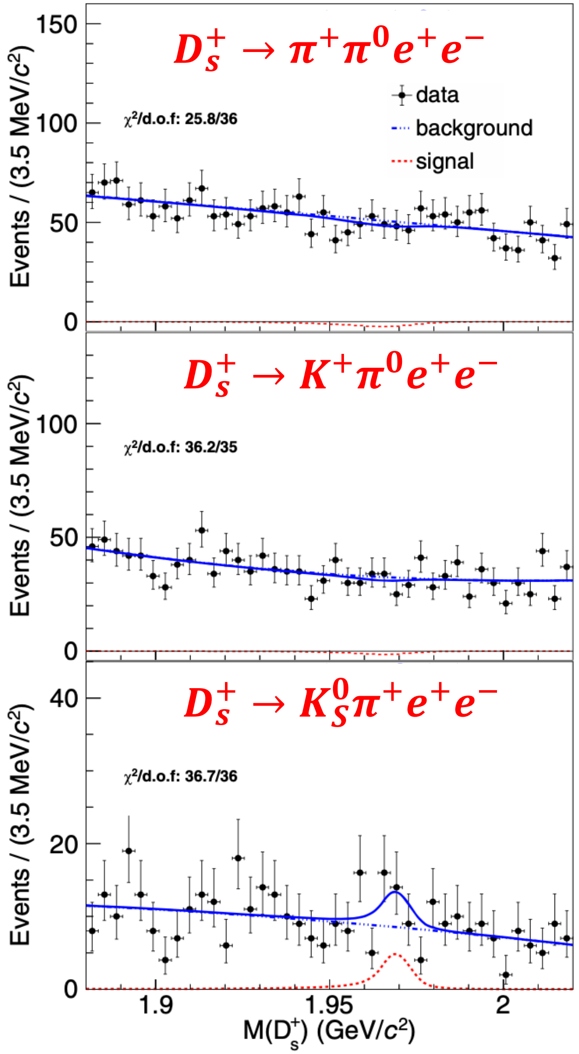
$B(D_s^+ \to \pi^+\pi^0 e^+e^-) < 7.0\times 10^{-5}$ @ 90% C.L.

$B(D_s^+ \to K^+\pi^0 e^+e^-) < 7.1\times 10^{-5}$ @ 90% C.L.

$B(D_s^+ \to K_S^0\pi^+ e^+e^-) < 8.1\times 10^{-5}$ @ 90% C.L.

Out of ϕ mass window to reject potential LD effect.

First upper limits on the BFs



$D_s^+ \to \gamma\, \rho(770)^+$

$e^+e^- \to D_s^{*+} D_s^-$ with $7.33\ \text{fb}^{-1}$ @ $\sqrt{s} = 4.128 - 4.226$ GeV

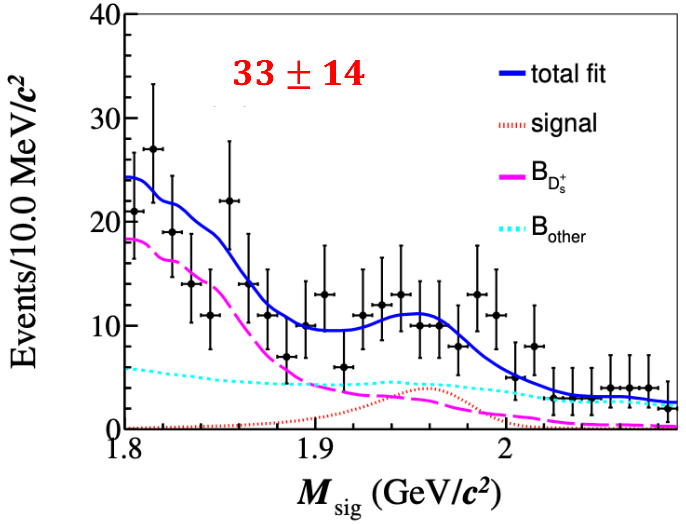
arXiv:2408.03980 [hep-ex]

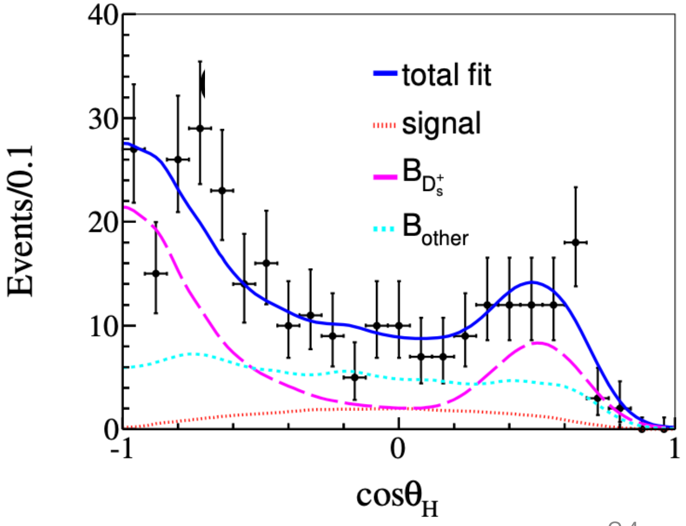
- **In the rare radiative decays of charmed mesons, the short distance interaction of the $c \to u\gamma$ process make a negligible contribution.**
- **The long distance, non-perturbative processes dominate these decays, potentially enhancing BFs up to 10^{-3}.**
- **To test the QCD-based calculation of the long-distance dynamics.**

$$B(D_s^+ \to \gamma\rho(770)^+) = (2.2 \pm 0.9_{stat} \pm 0.2_{syst})\times 10^{-4}$$

3.8σ smaller than the theoretical calculation of weak annihilation.

$$B(D_s^+ \to \gamma\rho(770)^+) < 6.1\times 10^{-4}\ @90\%\ \text{C.L.}$$



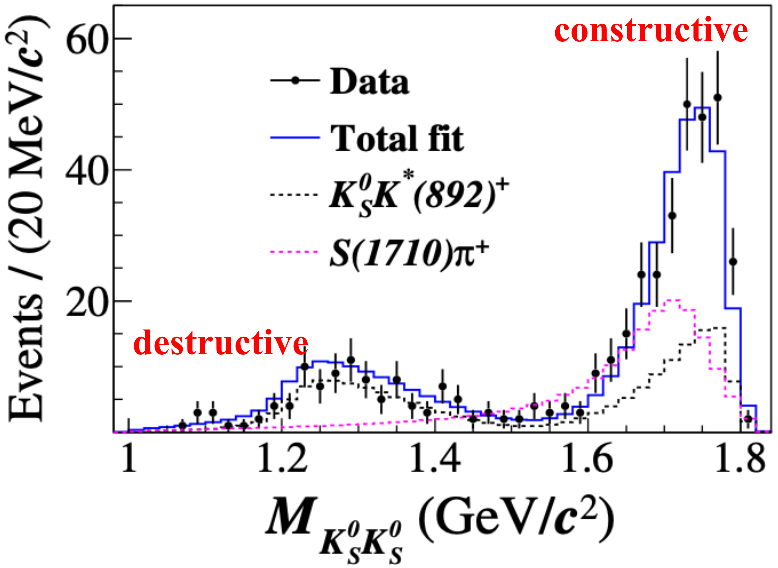


Summary

- Based on 20 fb^{-1} $\psi(3770)$ data and $7.33\ \mathrm{fb}^{-1}$ @ $\sqrt{s} = 4.128 - 4.226$ GeV data, BESIII have reported many important results on the charmed mesons: the amplitude analysis for the hadronic decays, dynamic studies for the semi-leptonic decays, precision measurements on the pure leptonic decays, the rare decays, DCS decays, and so on.
- More precise measurements for about $D^{0(+)}$ decays are coming soon based on the 20 fb^{-1} $\psi(3770)$ data.

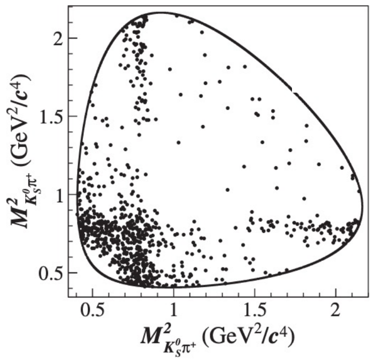
Backup

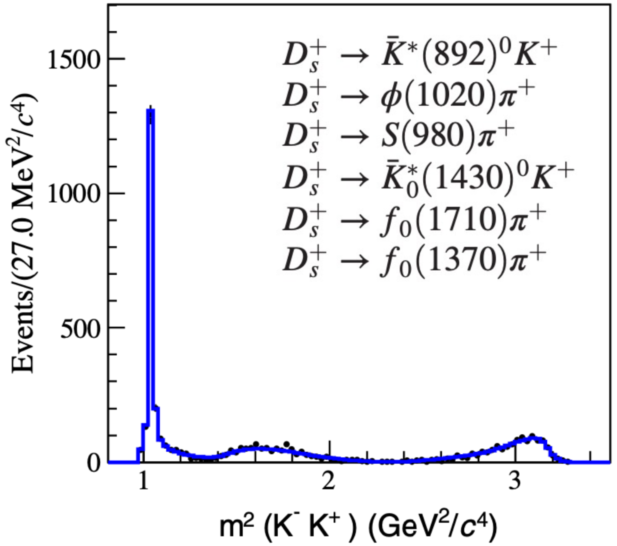
Observation of $a_0(1817)$ in D_s^+ decay



PRD105(2022)L051103

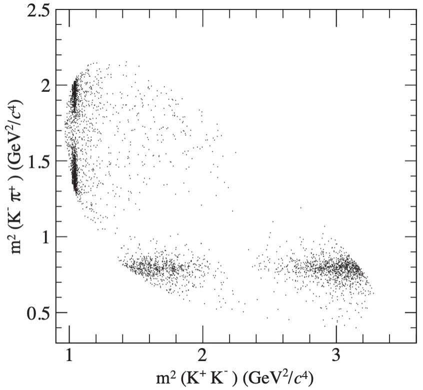
- $D_s^+ \to K_S^0K_S^0\pi^+$

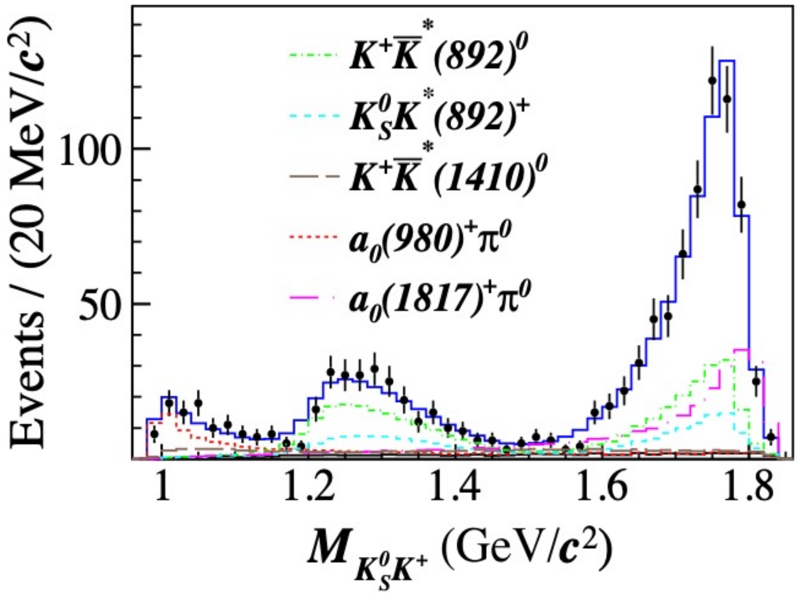




PRD104(2021)012016

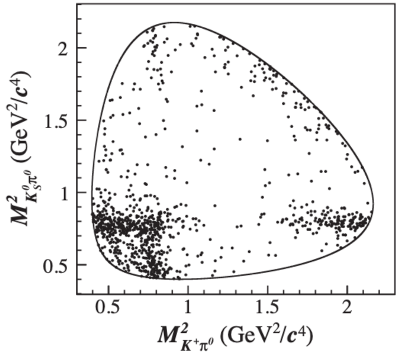
- $D_s^+ \to K^+K^-\pi^+$





PRL129(2022)182001

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



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

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

$$B(D_s^+ \to a_0(1817)^+\pi^0) = (3.44 \pm 0.52 \pm 0.32)\times 10^{-3},$$

Stat. significance: $> 10\sigma$

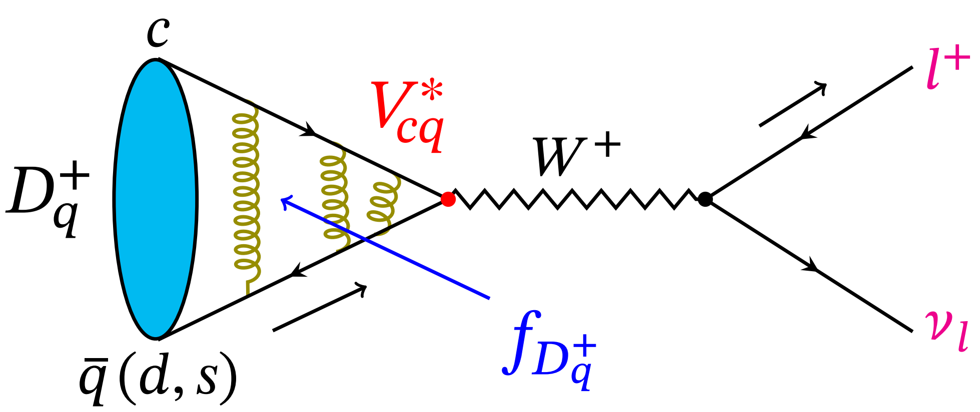
$a_0(1817)^+$: the isovector partner of $f_0(1710)$ or X(1812)?

Pure leptonic $D_{(s)}^+$ decays

- **Axial current (nonperturbative)**

$$< 0|\bar{s}\,\gamma_\mu\,\gamma_5\,c\,|D_s^+> = i\,p_\mu\,f_{D_{(s)}^+}$$

($f_{D_{(s)}^+}$: $D_{(s)}^+$ decay constant)



- **$V_{cd(s)}$: CKM matrix element, fundamental SM parameter, measured from experiments.**

- **In the SM, ignoring radiative corrections, the decay width:**

$$\Gamma = \frac{G_F^2}{8\pi} f_{D_{(s)}^+}^2 \left|V_{cd(s)}\right|^2 m_\ell^2\, m_{D_{(s)}^+} \left(1 - \frac{m_\ell^2}{m_{D_{(s)}^+}^2}\right)^2 \quad (\ell = e, \mu, \tau)$$

- **Branching fraction:** $Br(D^+_{(s)} \to \ell^+ \nu_\ell) = \Gamma \cdot \tau_{D^+_{(s)}}$ ($\tau_{D^+_{(s)}}$: lifetime)

$$Br(D^+_{(s)} \to \ell^+ \nu_\ell) \propto \left[f_{D^+_{(s)}} \cdot |V_{cd(s)}| \right]^2$$

Input $f_{D^+_{(s)}}$ from LQCD calculations → **Extract $|V_{cd(s)}|$**

Input $|V_{cd(s)}|$ from SM global fit → **Extract $f_{D^+_{(s)}}$**

(Direct measurements)

- **The decay constants $f_{D^+_{(s)}}$: help to calibrate the LQCD calculations;**
- **The CKM matrix elements $|V_{cd(s)}|$: help to test the unitarity of CKM.**

On the other side, although the $f_0(1710)$ is well established in the PDG [4], its quark structure is still unclear. The two most possible candidates are a glueball or a vector-vector, i.e., $K^*\bar{K}^*$, molecule [1,5,6]. If the $f_0(1710)$ is a $K^*\bar{K}^*$ molecule, there should be an isovector partner $a_0(1710)$, just as the nearly degenerate $f_0(980)$ and $a_0(980)$ for the case of $K\bar{K}$ molecules. If it is a glueball, a second state as pure glueballs must be isoscalar. Therefore, whether $a_0(1710)$ exists is crucial to understand the picture of $f_0(1710)$.

Both $a_0(980)$ and $f_0(980)$ decays to K^+K^-. Impossible to sepatate them here

Isospin configurations:

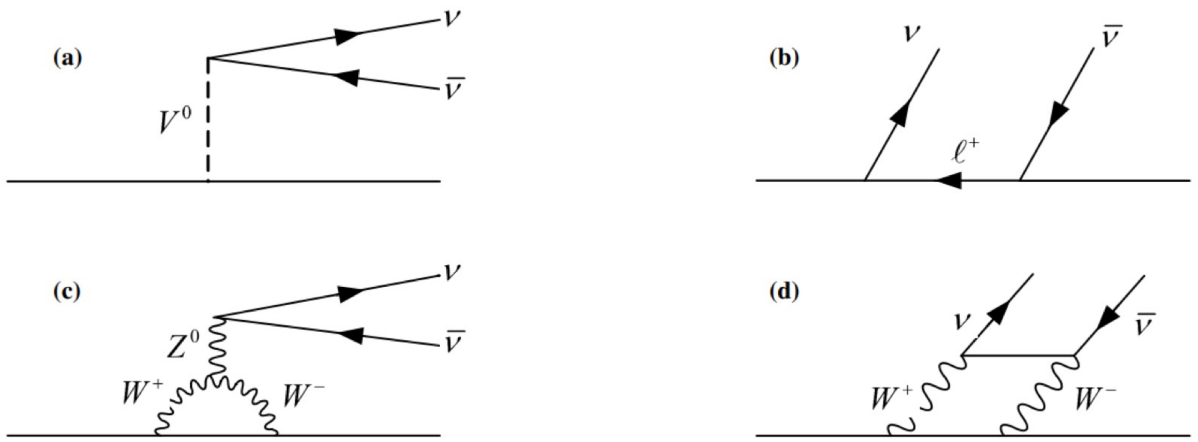
$a_0(980)$ I=1 $\rightarrow$ ($|K^+K^->$ - $|K^0\overline{K^0}>$)

$f_0(980)$ I=0 $\rightarrow$ ($|K^+K^->$ + $|K^0\overline{K^0}>$)

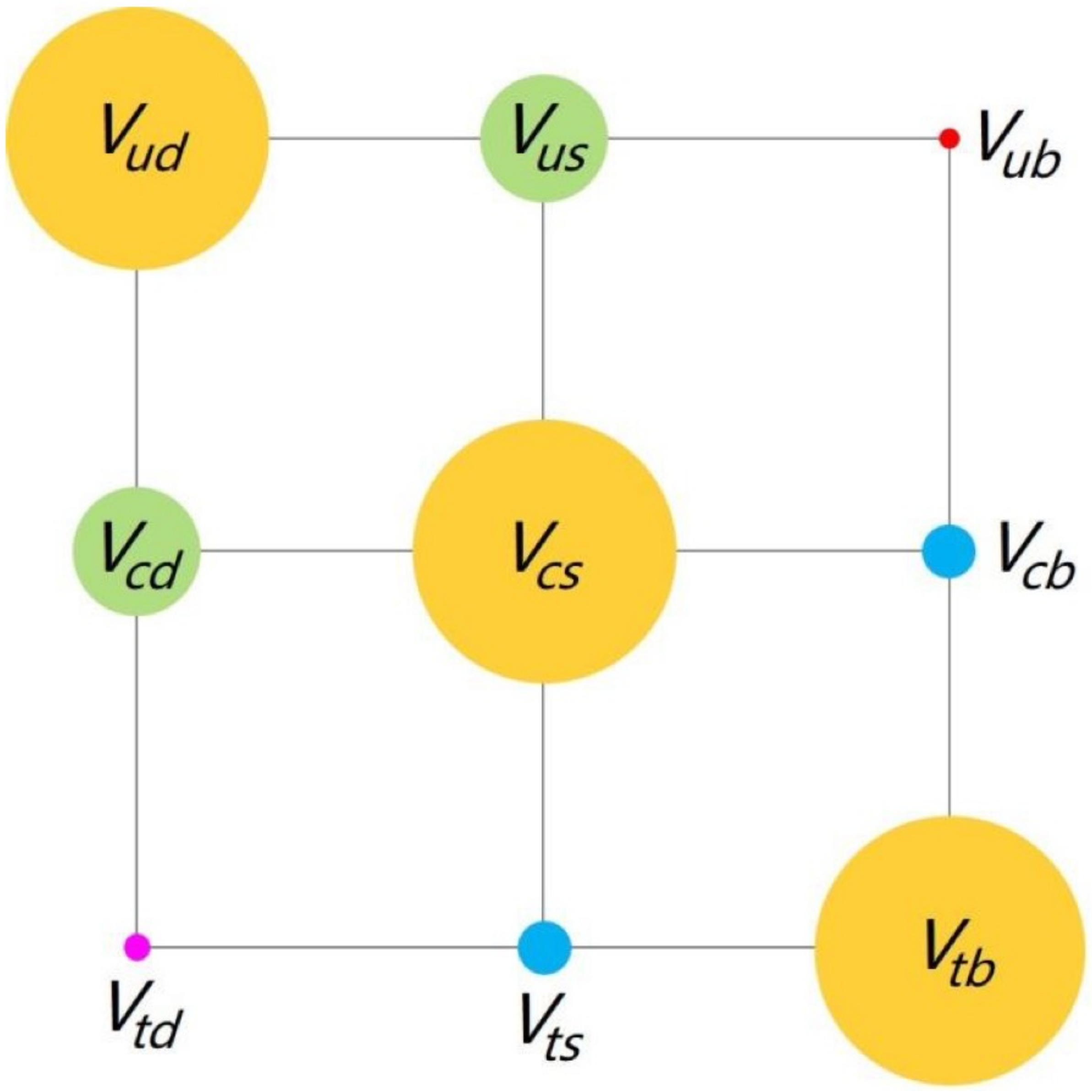
The comparison of K^+K^- and $K_S^0K_S^0$ spectrum will reveal more information!

Search for FCNC decays

- **Search for the flavor changing neutral current decay $D^0 \to \pi^0 \nu\bar{\nu}$**



LD and SD contributions (a, c, d) to neutral D decays (a, c, d) and charged D decays (a, b, c, d).


V_{ud}
V_{us}
V_{ub}
V_{cd}
V_{cs}
V_{cb}
V_{td}
V_{ts}
V_{tb}

Why charm meson physics?

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

➡ 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

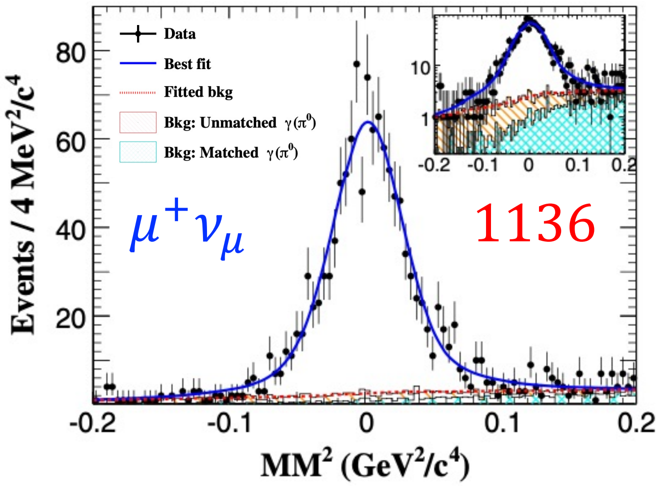
- GLW : D decaying to CP eigenstates
- ADS : D decaying to CF/DCS eigenstates
- GGSZ : D decaying to self-conjugate eigenstates

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	$K^0_S\pi^+\pi^-$, $K^0_SK^+K^-$, ...

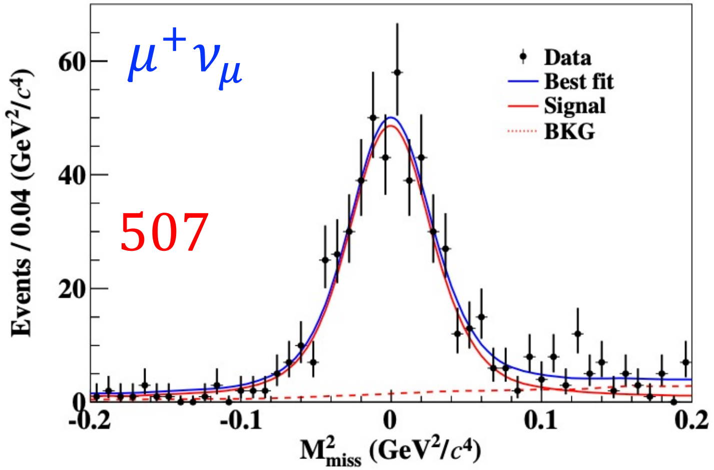
$D_s^+ \to \ell^+ \nu_\ell \ (\ell = \mu, \tau)$

- $\mu^+\nu_\mu$, muon counter

@4.178 GeV PRL122(2019)071802



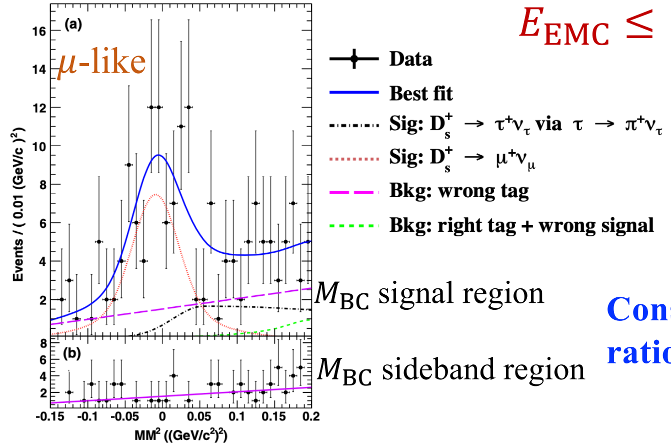
@4.237 – 4.699 GeV arXiv:2407.11727 [hep-ex]



- $\mu^+\nu_\mu$, $\tau^+(\to \pi^+\bar{\nu}_\tau)\ \nu_\tau$

@4.009 GeV PRD94(2016)072004

$\mu(\pi)$-like: $E_{EMC} \le (>) 0.3$ GeV

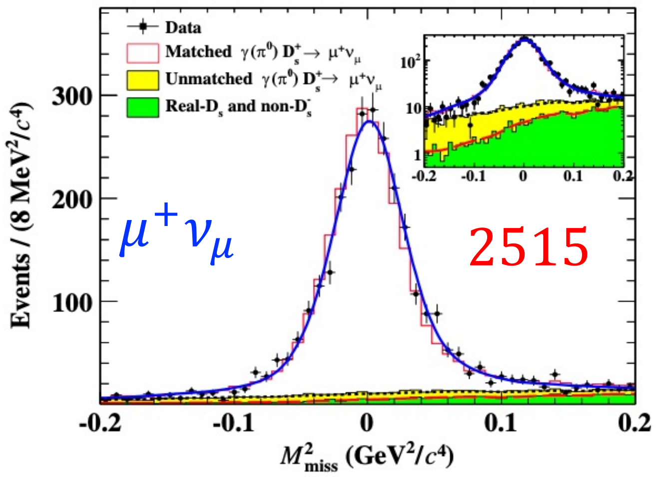


μ^+: 70

τ^+: 33

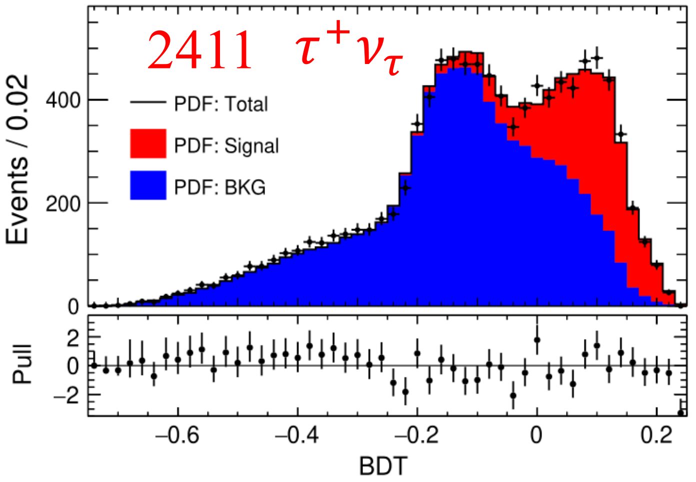
Constrain τ- μ ratio to SM

@4.128 – 4.226 GeV PRD108(2023)112001

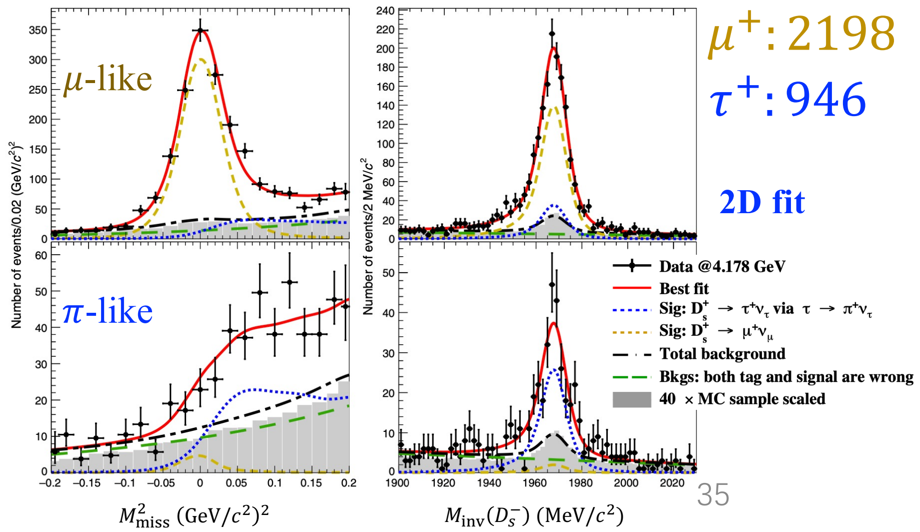


- $\tau^+ \to \pi^+\bar{\nu}_\tau$ multivariate analysis

@4.128 – 4.226 GeV PRD108(2023)092014



@4.178 – 4.226 GeV PRD104(2021)052009



μ^+: 2198

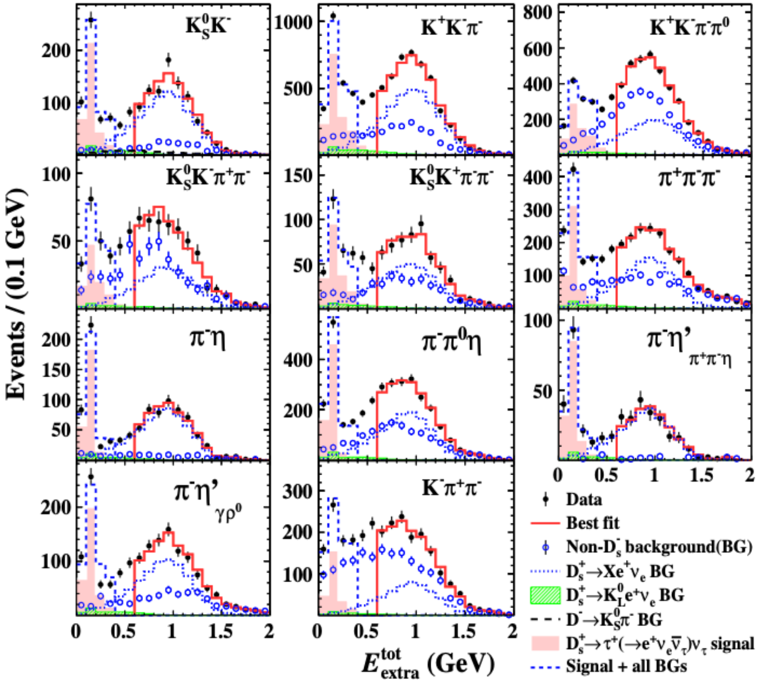
τ^+: 946

2D fit

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

- $\tau^+ \to e^+ \nu_e \bar{\nu}_\tau$

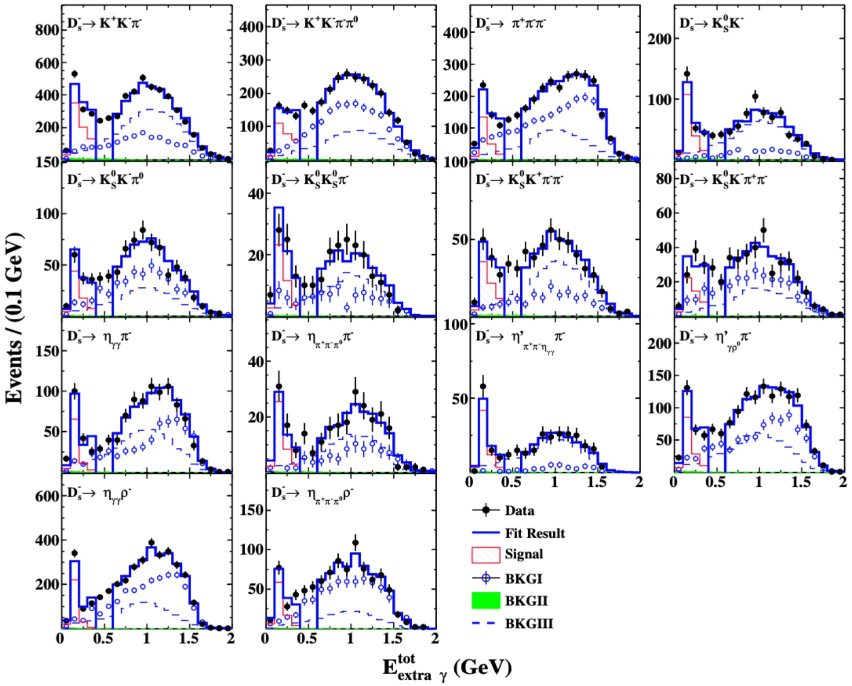
@4.178 – 4.226 GeV PRL127(2021)171801



Separated fit 4940

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

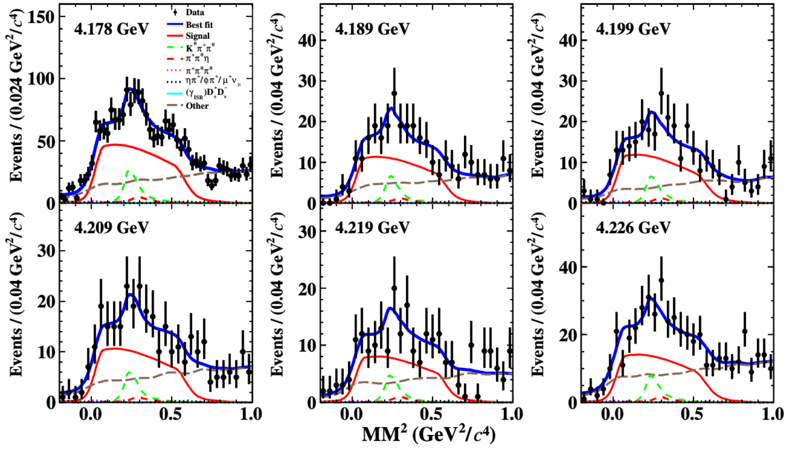
@4.128 – 4.226 GeV JHEP09(2023)124



Separated fit 2281

- $\tau^+ \to \pi^+ \pi^0 \bar{\nu}_\tau$

@4.178 – 4.226 GeV PRD104(2021)032001



Simultaneous fit, same BF. 1745

$\tau^+ \to e^+ \nu_e \bar{\nu}_\tau$	$(17.82 \pm 0.04)\%$
$\tau^+ \to \mu^+ \nu_\mu \bar{\nu}_\tau$	$(17.39 \pm 0.04)\%$
$\tau^+ \to \pi^+ \pi^0 \bar{\nu}_\tau$	$(25.49 \pm 0.09)\%$
$\tau^+ \to \pi^+ \bar{\nu}_\tau$	$(10.82 \pm 0.05)\%$

$E_{\text{extra}}^{\text{tot}}$: The total energy of the extra showers excluding those used in the tag side and $\gamma(\pi^0)$ from D_s^{*+}.

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

$e^+e^- \to D_s^{*+} D_s^{*-}$@4.237 − 4.699 GeV

Simultaneous fit with the same BF

PRD110(2024)052002

$E_{\rm cm}$ (GeV)	$\mathcal{L}$ (pb^{-1})	$M_{\rm BC}$ (GeV/c^2)	$N_{\rm ST}$
4.237	530.3	(2.107, 2.117)	6477±163
4.246	593.9	(2.107, 2.118)	11944±246
4.260	828.4	(2.107, 2.118)	21550±320
4.270	531.1	(2.107, 2.118)	13319±244
4.280	175.7	(2.106, 2.119)	4063±152
4.290	502.4	(2.106, 2.119)	9316±221
4.310-4.315	546.3	(2.106, 2.119)	5758±228
4.400	507.8	(2.106, 2.119)	1855±87
4.420	1090.7	(2.106, 2.121)	14890±443
4.440	569.9	(2.106, 2.121)	9699±443
4.470-4.699	4768.3	(2.104, 2.123)	25156±762
Sum			124027±1121

$N_{\rm DT} = 2845 \pm 83$

$B_{D_s^+ \to \tau^+ \nu_\tau} = (5.60 \pm 0.16 \pm 0.20\,)\%$