Recent Flavour-physics Results in Open Charm Decays

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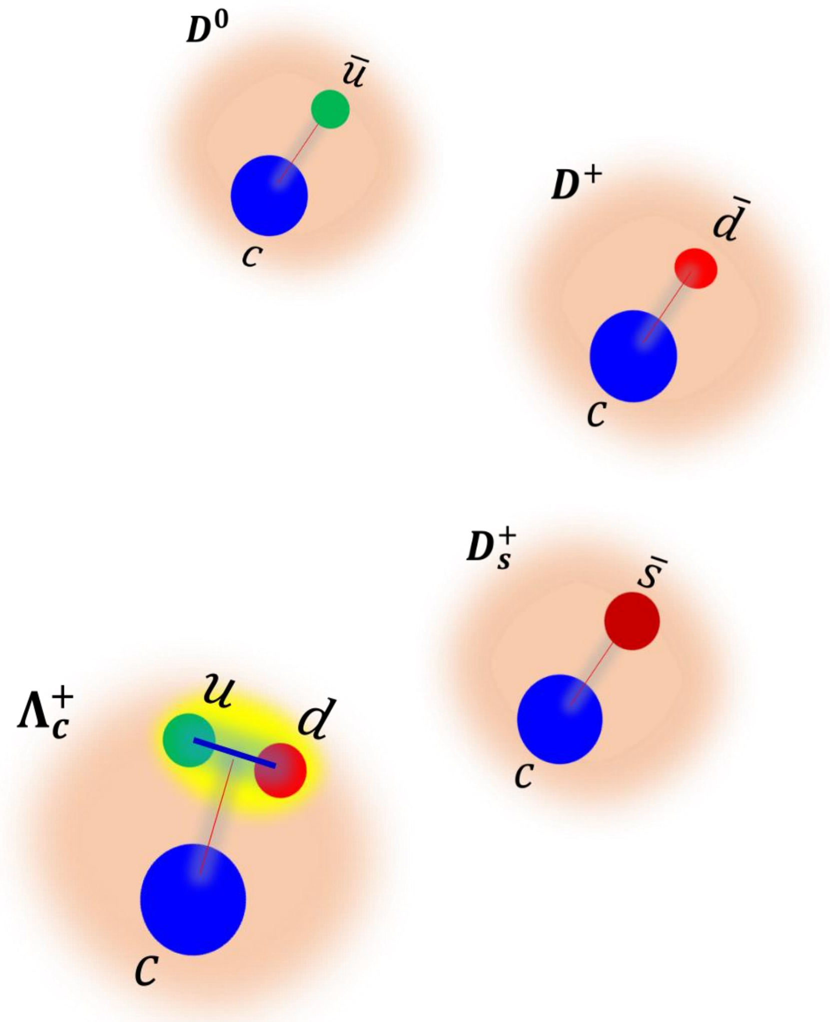
on behalf of the BESIII Collaboration

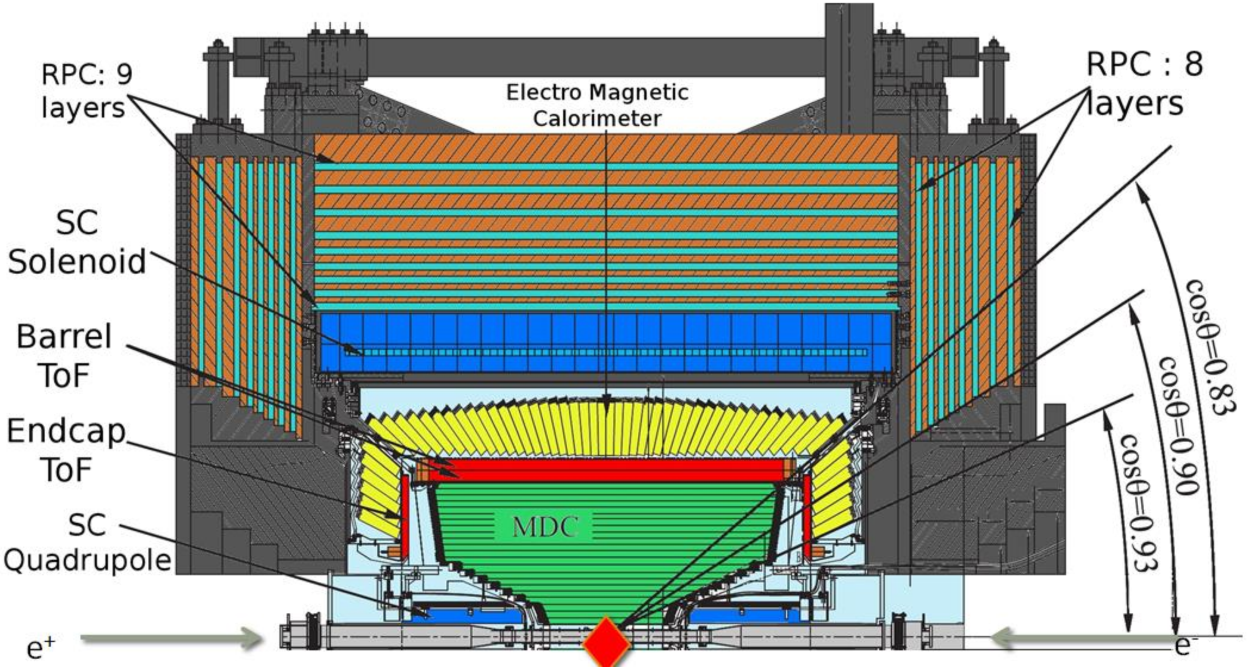
Outline

- Introduction to BESIII experiment
- Leptonic Decay
- Semileptonic Decay
- Hadronic Decay
- Summary and Prospect



Natl.Sci.Rev. 8 (2021) 11, nwab181

BESIII detector and Data Sample

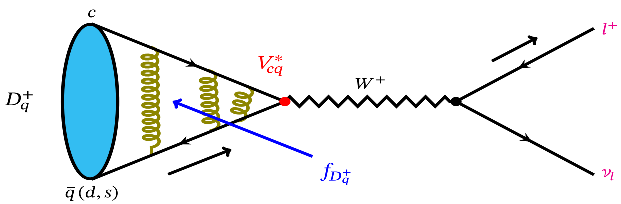


$\sqrt{s}$ (GeV)	Year	Luminosity (fb^{-1})	D^0 Yields	D^+Yields	D_s^+Yields	Λ_c^+Yields
3.773	2010 − 2011(+2023)	$2.93 \to 8$	2.5M(2.7×)	1.7M(2.7×)		
4.009	2011	0.5			13 K	
4.18 − 4.23	2016, 2017, 2014, 2019	7.3			1.5M	
4.6(4.61 − 4.7)	2014(+2020)	$0.6 \to 4.5$				15 K(8×)

Leptonic Decay

[Natl.Sci.Rev. 8 (2021) 11]

➢ $\Gamma(D_q^+ \to \ell^+\nu_\ell) = \frac{G_F^2}{8\pi} \mid V_{cq} \mid^2 f_{D_q^+} m_\ell^2 m_{D_q^+} \left(1 - \frac{m_\ell^2}{m_{D_q^+}}\right)^2$



- Helicity suppressed
- $f_{D_{(s)}^+}$ determination $\Leftarrow \left|V_{cd(s)}\right|$ from the CKM global fit
  - Calibration of LQCD
- $\left|V_{cd(s)}\right|$ determination $\Leftarrow f_{D_{(s)}^+}$ from the LQCD
  - Test of CKM unitary

Decay Mode	$\Gamma_{\ell\nu_\ell}/\Gamma_{\mu\nu_\mu}\ (D^+)$	$\Gamma_{\ell\nu_\ell}/\Gamma_{\mu\nu_\mu}\ (D_s^+)$
$\tau\nu_\tau$	2.67	9.74
$\mu\nu_\mu$	1	1
$e\nu_e$	2.35×10^{-5}	2.35×10^{-5}

➢ Test of lepton flavor universality

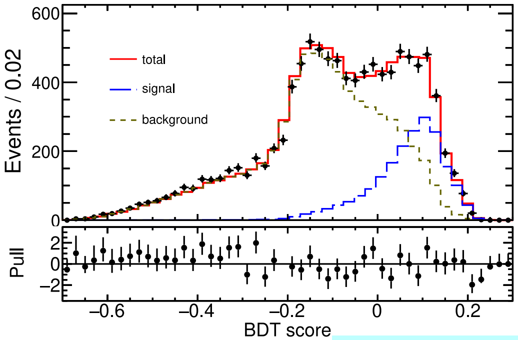
$$R_{D_q^+} = \frac{\Gamma(D_q^+ \to \tau^+\nu_\tau)}{\Gamma(D_q^+ \to \mu^+\nu_\mu)} = \frac{m_\tau^2\left(1 - \frac{m_{\tau^+}^2}{m_{D_q^+}^2}\right)^2}{m_\mu^2\left(1 - \frac{m_\mu^2}{m_{D_q^+}^2}\right)^2}$$

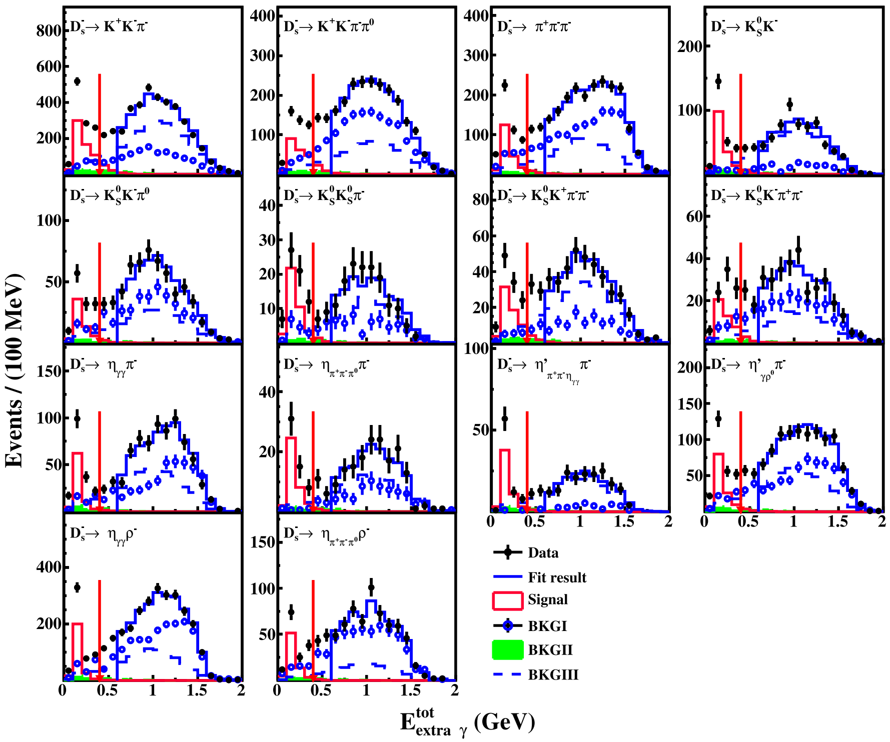
	R_{D^+}	$R_{D_s^+}$
SM predicted	2.67	9.74
Measured	3.21±0.64±0.43	9.98±0.52

Leptonic decay: $D_s^+ \to \tau^+\nu_\tau$ via $e^+e^- \to D_s^{*\pm}D_s^{\mp}$

τ Decay	$\mathcal{B}$ (%)	$f_{D_s}\|V_{cs}\|$ (MeV)	f_{D_s} (MeV)	$\|V_{cs}\|$
$e^+\nu_e\bar{\nu}_\tau$	$5.27 \pm 0.10 \pm 0.12$	$244.4 \pm 2.3 \pm 2.9$	$251.1 \pm 2.4 \pm 3.0$	$0.978 \pm 0.009 \pm 0.012$
$\mu^+\nu_\mu^+\bar{\nu}_\tau$	$5.34 \pm 0.16 \pm 0.10$	$246.2 \pm 3.7 \pm 2.5$	$252.7 \pm 3.8 \pm 2.6$	$0.984 \pm 0.015 \pm 0.010$
$\pi^+\bar{\nu}_\tau$	$5.41 \pm 0.17 \pm 0.13$	$247.6 \pm 3.9 \pm 3.2 \pm 1.0$	$254.3 \pm 4.0 \pm 3.3 \pm 1.0$	$0.991 \pm 0.015 \pm 0.013 \pm 0.004$

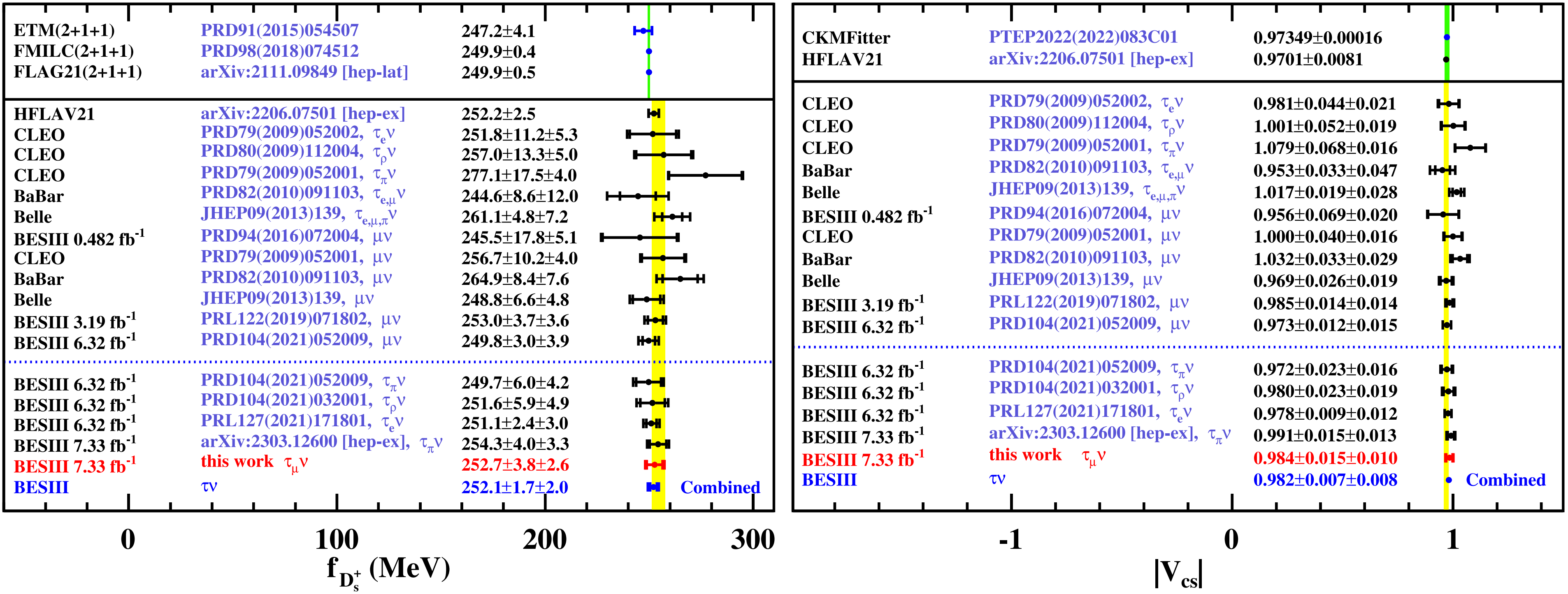
- $\tau^+ \to e^+\nu_e\bar{\nu}_\tau$ [Phys. Rev. Lett. 127, 171801 (2021)]
  - 6.32 fb^{-1} @ $\sqrt{s}$ between 4.178 and 4.226 GeV
- $\tau^+ \to \mu^+\nu_\mu\bar{\nu}_\tau$ [arXiv:2303.12468]
  - 7.33 fb^{-1} @ $\sqrt{s}$ between 4.128 and 4.226 GeV
- $\tau^+ \to \pi^+\bar{\nu}_\tau$ [arXiv:2303.12600]
  - 7.33 fb^{-1} @ $\sqrt{s}$ between 4.128 and 4.226 GeV





No significant LFU violation

Status

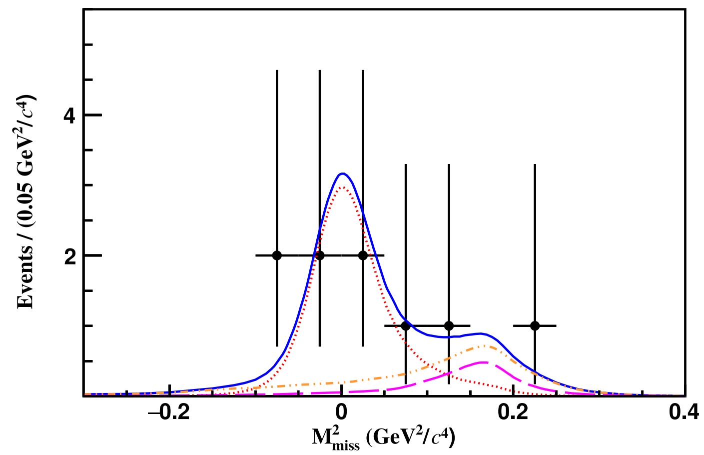


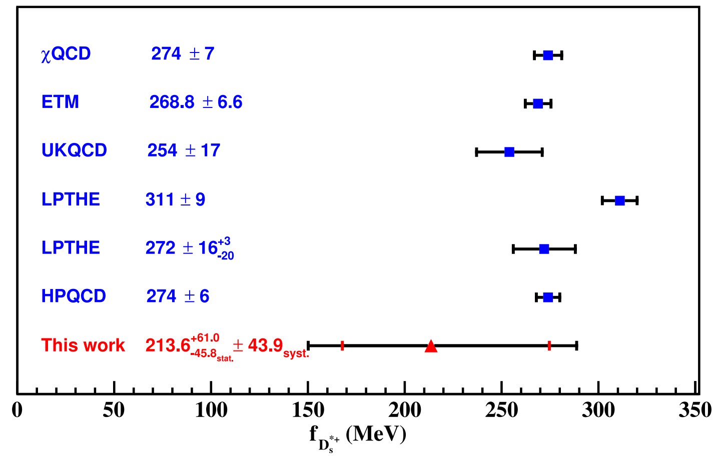
BESIII dominates the results

[arXiv:2303.12468]

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

- 7.33 fb^{-1} of data at $\sqrt{s}$ in [4.128, 4.226] GeV
- $\mathcal{B}(D_s^{*+} \to e^+\nu_e) = \left(2.1^{+1.2}_{-0.9}\text{stat.} \pm 0.2_{\text{syst.}}\right) \times 10^{-5}$
  - Statistical significance: 2.9σ
  - $< 4.0 \times 10^{-5}$ @ 90% C.L.
- Total width $\Gamma^{\text{tot}}_{D_s^{*+}} = (121.9^{+69.6}_{-52.2} \pm 11.8)\text{eV}$
  - $\Gamma^{\text{tot}} = 2.4 \times 10^{-3} \times \left(\frac{f_{D_s^{*+}}}{f_{D_s^+}}\right)^2 / \mathcal{B}(D_s^{*+} \to e^+\nu_e)\text{eV}$
  - Constrain the U.L. from MeV to KeV level
- $f_{D_s^{*+}} = \left(213.6^{+61.0}_{-45.8}\text{stat.} \pm 43.9_{\text{syst.}}\right)$ MeV
  - <353.8 MeV @ 90%
  - With input of $|V_{cs}|$ from the PDG



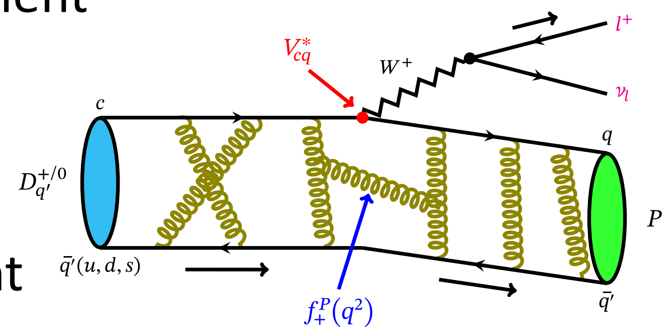


[arXiv:2304.12159] submitted to PRL

The first hint of leptonic decays of the excited D_s^+

Semileptonic decay

- $\frac{\mathrm{d}\Gamma(D\to P\ell^+\nu_\ell)}{\mathrm{d}q^2} = \frac{G_F^2}{24\pi^3}\left|V_{cq}\right|^2 |f_+^X(q^2)| p_P^3$
- Calibration of LQCD with $|f_+^P(q^2)|$ measurement
  - input of $\left|V_{cq}\right|^2$
- Test of CKM Unitarity with $\left|V_{cq}\right|^2$ measurement
  - with input of $|f_+^P(0)|$
- Test of LFU within different q^2 ranges
  - Ratio of the decay rate: $\mathcal{R}^{e/\mu}(q^2) = \frac{\Delta\Gamma/\Delta q^2(X\mu^+\nu_e)}{\Delta\Gamma/\Delta q^2\,(Xe^+\nu_e)}$
  - Ratio of Forward-backward asymmetry
    - $A_{FB}^{e/\mu}(q^2) = \frac{\frac{d\Gamma}{dq^2}(\text{ forward }) - \frac{d\Gamma}{dq^2}(\text{ backward })}{\frac{d\Gamma}{dq^2}}$

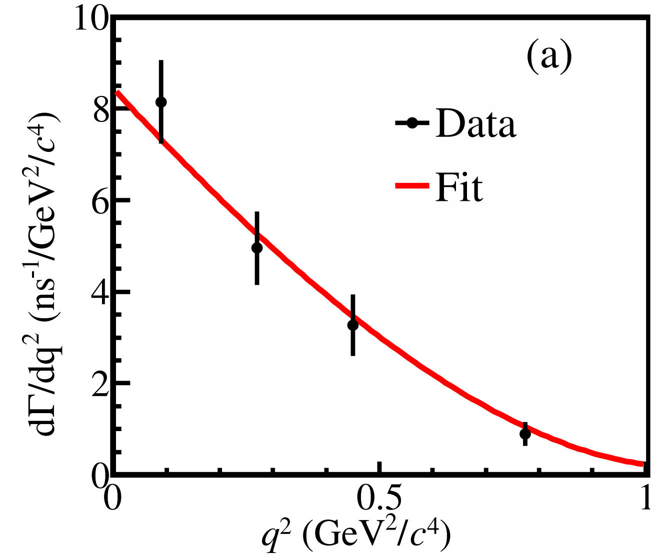


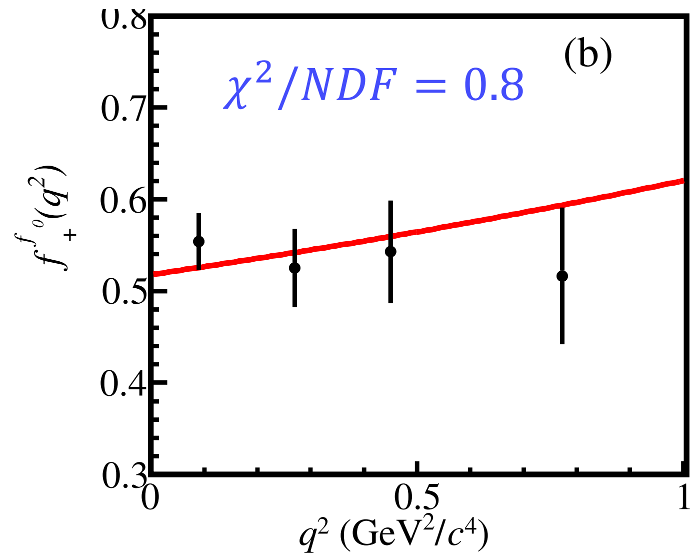
$D_s^+ \to f_0(980)e^+\nu_e$

[arXiv:2303.12927]

- 7.33 fb^{-1} of data at $\sqrt{s}$ in [4.128, 4.226] GeV
- $\mathcal{B}(D_s^+ \to f_0(980)e^+\nu_e) = (1.72 \pm 0.13_{stat} \pm 0.10_{syst}) \times 10^{-3}$
  - $s\bar{s}$ dominated with assumption of regular $q\bar{q}$
    - [Phys. Rev. D 80, 074030 (2009)]
- $f_+^{f_0}(0)|V_{cs}| = 0.504 \pm 0.017_{stat} \pm 0.035_{syst}$
  - With simple pole parametrization
- $f_+^{f_0}(0) = 0.518 \pm 0.018_{stat} \pm 0.036_{syst}$

	$f_+^{f_0(0)}$
This work	$0.518 \pm 0.018_{\rm stat} \pm 0.036_{\rm syst}$
CLFD [6]	0.45
DR [6]	0.46
QCDSR [7]	0.50 ± 0.13
QCDSR [8]	0.48 ± 0.23
LCSR. [9]	0.30 ± 0.03
LFQM [11]	0.24 ± 0.05
CCQM [12]	0.39 ± 0.02



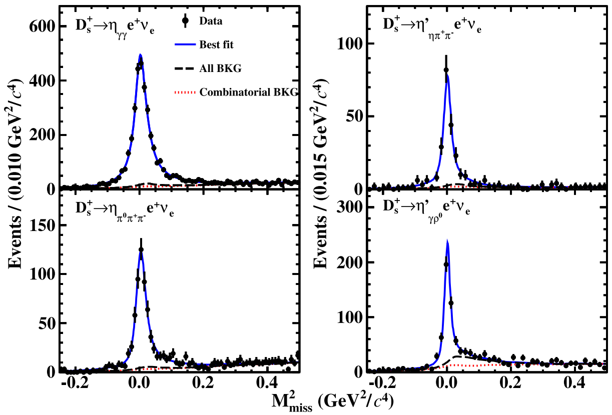


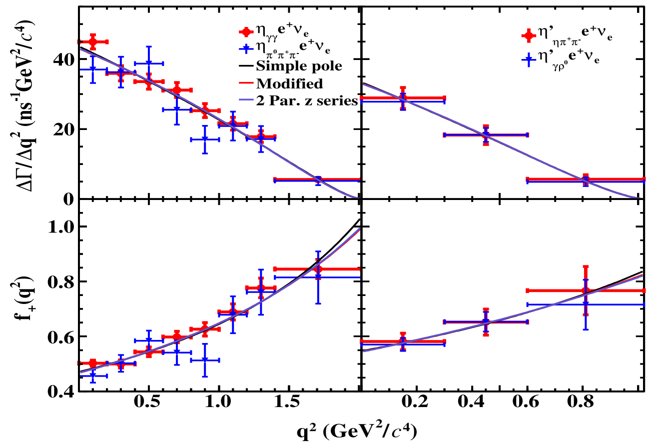
[6] Phys. Rev. D79, 076004 (2009). [7] Phys. Lett. B579, 59-66 (2004).
[8] EPL90, 61001 (2010). [9] Phys. Rev. D81, 074001 (2010).
[11] Phys. Rev. D80, 074030 (2009). [12] Phys. Rev. D102, 016013 (2020).

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

[arXiv:2306.05194]

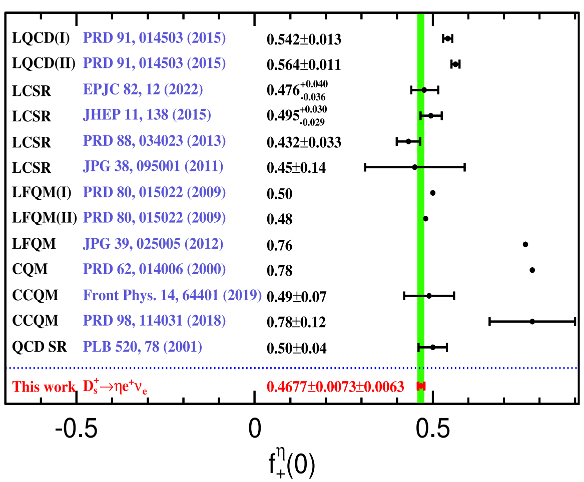
- 7.33 fb^{-1} of data at $\sqrt{s}$ in [4.128, 4.226] GeV

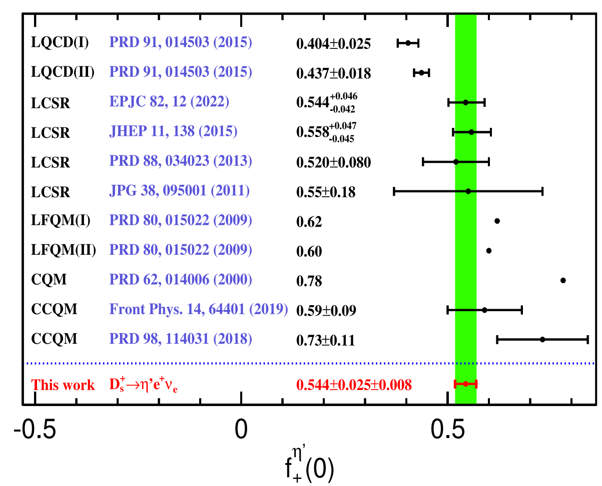




- $\mathcal{B}_{\eta e^+\nu_e}$: $(2.251 \pm 0.039_{stat.} \pm 0.051_{syst.})\%$
- $\mathcal{B}_{\eta' e^+\nu_e}$: $(0.810 \pm 0.038_{stat.} \pm 0.024_{syst.})\%$
- $\eta - \eta'$mixing angle:$\phi_P = (40.0 \pm 2.0_{stat.} \pm 0.6_{syst.})^\circ$

- $f_+^{\eta}(0)|V_{cs}| = 0.4553 \pm 0.0071_{\text{stat}} \pm 0.0061_{\text{syst}}$
- $f_+^{\eta'}(0)|V_{cs}| = 0.529 \pm 0.024_{\text{stat}} \pm 0.008_{\text{syst}}$





$\Lambda_c^+ \to \Lambda l^+ \nu_l (l = e, \mu)$

- Measurements based on data at $\sqrt{s}$ in [4.6, 4.7] GeV with $\mathcal{L} = 4.5\ fb^{-1}$

Measurement	$\Lambda e^+ \nu_e$	$\Lambda \mu^+ \nu_\mu$
$\mathcal{B}$	$(3.56 \pm 0.11_{stat.} \pm 0.07_{syst.})\%$	$(3.48 \pm 0.14_{stat.} \pm 0.10_{syst.})\%$
$\mathcal{T}$	$-0.021 \pm 0.041_{stat.} \pm 0.001_{syst.}$	$0.068 \pm 0.055_{stat.} \pm 0.002_{syst.}$
$\langle A^l_{FB} \rangle$	$-0.24 \pm 0.03_{stat.} \pm 0.01_{syst.}$	$-0.22 \pm 0.04_{stat.} \pm 0.01_{syst.}$
$\langle A^p_{FB} \rangle$	$-0.33 \pm 0.03_{stat.} \pm 0.01_{syst.}$	$-0.37 \pm 0.04_{stat.} \pm 0.01_{syst.}$
α_{Λ_c}	$-0.94 \pm 0.07_{stat.} \pm 0.03_{syst.}$	
$\lvert V_{cs} \rvert$	$0.937 \pm 0.014_{\mathcal{B}} \pm 0.024_{LQCD} \pm 0.007_{\tau_{\Lambda_c}}$	

$\mathcal{T}$:T asymmetry parameter, $\langle A^p_{\rm FB} \rangle$: forward-backward asymmetry, α_{Λ_c}: asymmetry parameter

- Comparison with theory model
  - CQM and CQM(HONR) are disfavored in terms of $\mathcal{B}$
  - $\mathcal{T}$ is consistent with 0 prediction by SM

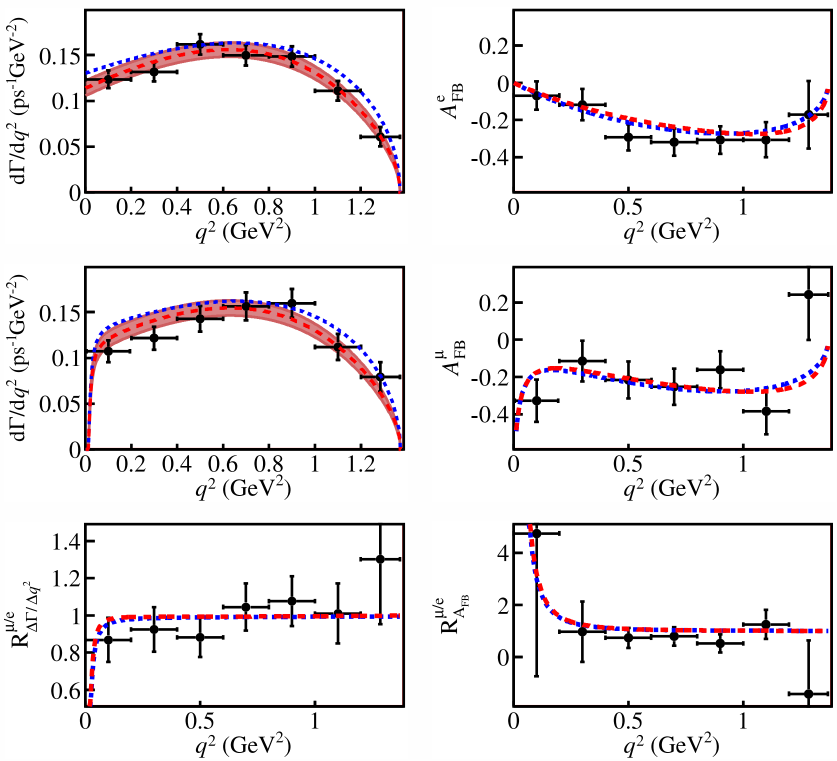
[Phys. Rev. Lett. 129, 231803 (2022)]

[ArXiv:2306.02624v1]

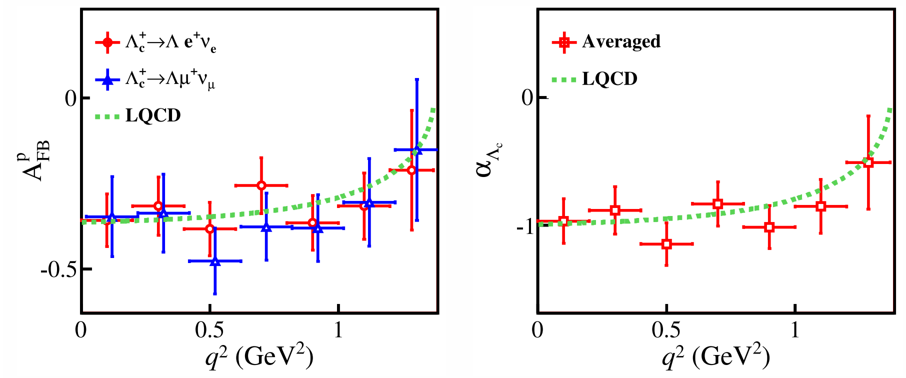
	$\mathcal{B}^e(\%)$	$\mathcal{B}^\mu(\%)$	$\langle A^e_{\rm FB} \rangle$	$\langle A^\mu_{\rm FB} \rangle$	$\langle \alpha_{\Lambda_c} \rangle$
Constituent quark model	2.78	2.69	-0.2	-0.21	-0.87
Relativistic quark model	3.25	3.14	-0.209	-0.242	-0.86
Homogeneous bag model	3.78 ± 25	3.67 ± 0.23	$-0.176(5)$	$-0.143(6)$	-0.826
Lattice QCD	3.80 ± 0.22	3.69 ± 0.22	$-0.201(6)$	$-0.169(7)$	$-0.874(10)$
SU(3)	3.6 ± 0.4	3.6 ± 0.4			$-0.86(4)$
Light-front constituent quark model	3.36 ± 0.87	3.21 ± 0.85			$-0.97(3)$
MIT bag model	3.48	3.38			-0.83
Light-front quark model	4.04 ± 0.75	3.90 ± 0.73	0.20(5)	0.16(4)	$-0.87(9)$
Constituent quark model (HONR)	4.25	4.25			
Non-relativistic quark model	3.84	3.72			
Light-cone sum rule	3.0 ± 0.3	3.0 ± 0.3			
Measurement	3.56 ± 0.13	3.48 ± 0.17	$-0.94(8)$	$-0.22(4)$	$-0.24(3)$

$\Lambda_c^+ \to \Lambda l^+ \nu_l (l = e, \mu)$

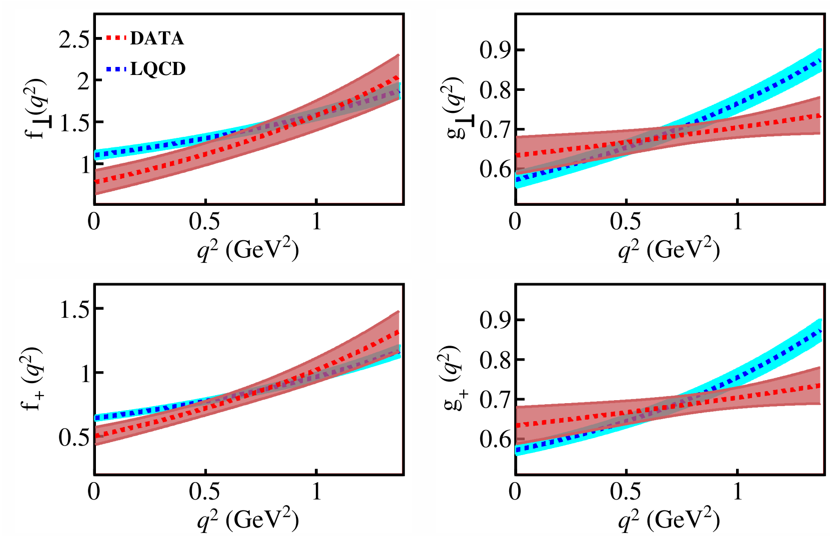
- Differential measurement



Test of LFU: no evidence of violation



A_{FB}^{p} and α_{Λ_c}: consistent with LQCD



Form factor: important for test and calibration of LQC

[ArXiv:2306.02624v1]

Hadronic Decay

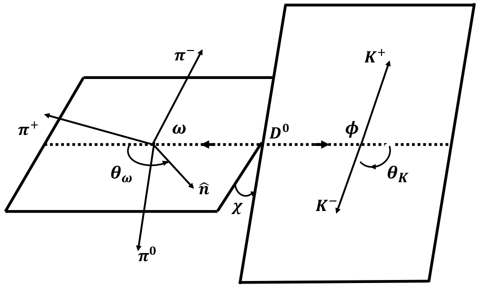
- Branching fraction measurement
  - Input for the measurement of bottom hadrons
  - Calibration for non-perturbative QCD
  - CP violation study, e.g. $A_{CP} = \frac{\Gamma(D\to f)-\Gamma(\bar{D}\to\bar{f})}{\Gamma(D\to f)+\Gamma(\bar{D}\to\bar{f})}$
  - SU(3) breaking, e.g. $K_S^0 - K_L^0$ asymmetry
  - ...
- Amplitude analysis
  - Light hadron spectroscopy
  - Optimization of binning scheme for the measurement of strong phase difference and CKM angle γ

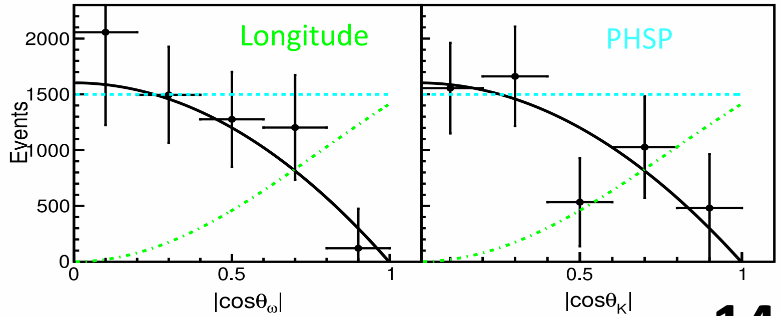
$D^0 \to \phi\omega$

- $\mathcal{B} = (6.48 \pm 0.96 \pm 0.40) \times 10^{-4}$ [Phys. Rev. Lett. 128, 011803 (2022)]
  - First observation with significance of $6.2\,\sigma$

Prediction	Mode
6.6×10^{-4}	Factorization model [PRD 81.114020(2010)]
3.5×10^{-5}	$\mathrm{SU}(3)$ symmetry with nonet symmetry [PRD 43, 843 (1991)]
$(1.41 \pm 0.09) \times 10^{3}$	Factorization-assisted topological-amplitude method [CPC 42, 063101 (2018)]
0.028 ± 0.004	Heavy quark effective Lagrangian and chiral perturbation theory [PRD 56.7207 (1997)]

- Polarization measurements
  - $\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_{\omega/K}} = \frac{3}{2}\left\{\frac{1}{2}(1-f_L)\sin^2\theta_{\omega/K} + f_L\cos^2\theta_{\omega/K}\right\}$
  - Transverse polarized
    - $f_L < 0.24$ @ 95% CL
  - Contradicts to the naive factorization and Lorentz invariant-based symmetry models
    - [Phys. Rev. D 81, 114020 (2010), JHEP 03(2014)042]
  - Consistent with explanation of FSI
    - [arXiv:2303.00535v2]



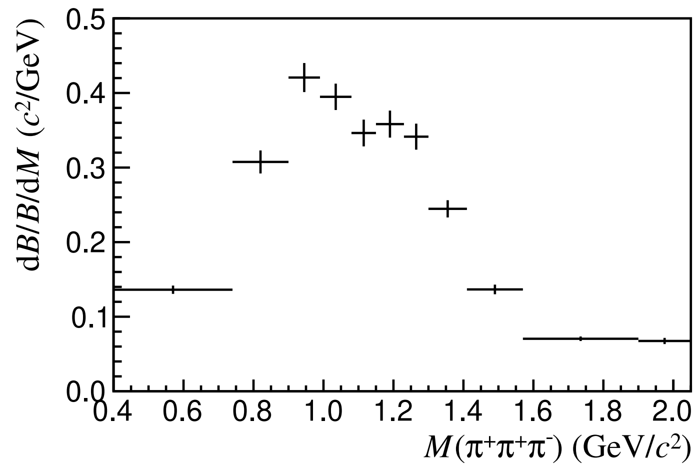


Inclusive Decays of D

Decay Mode	$\mathcal{B}$ (inclusive)	$\mathcal{B}_{sum}$ (exclusive)	Difference
$D^0 \to K_S^0 X$	$(32.78 \pm 0.13 \pm 0.27)\%$	$(31.68 \pm 0.32)\%$	$(1.10 \pm 0.41)\%$
$D^+ \to K_S^0 X$	$(20.54 \pm 0.12 \pm 0.18)\%$	$(18.16 \pm 0.72)\%$	$(2.38 \pm 0.75)\%$
$D^0 \to \pi^+\pi^+\pi^- X$	$(17.60 \pm 0.11 \pm 0.22)\%$	$(16.05 \pm 0.47)\%$	$(1.55 \pm 0.53)\%$
$D^+ \to \pi^+\pi^+\pi^- X$	$(15.25 \pm 0.09 \pm 0.18)\%$	$(14.74 \pm 0.53)\%$	$(0.51 \pm 0.53)\%$
$D_s^+ \to \pi^+\pi^+\pi^- X$	$(32.81 \pm 0.35 \pm 0.82)\%$	$(24.7 \pm 1.5)\%$	$(8.11 \pm 1.74)\%$

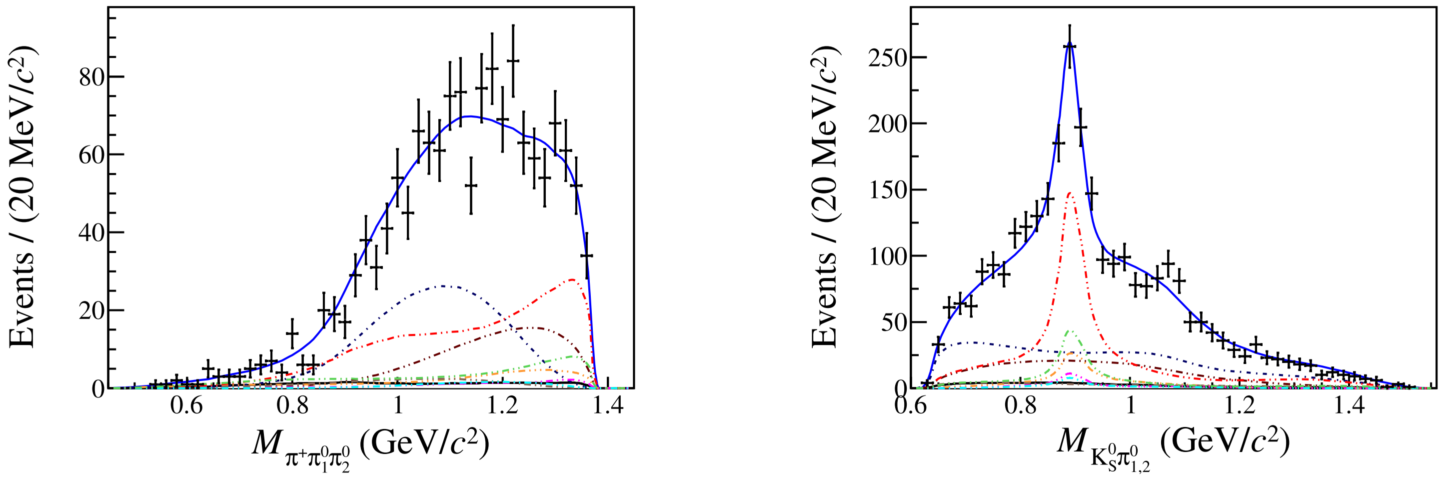
[arXiv:2302.14488]:accepted by PRD [Phys. Rev. D 107, 032002 (2023)] [arXiv:2212.13072]

- Results from Inclusive measurements are larger
- Indications of unobserved decay modes
- $D_s^+ \to \pi^+\pi^+\pi^- X$
  - The partial $\mathcal{B}$ as a function of $M(\pi^+\pi^-\pi^0)$ are measured to help study background $B^0 \to D^* D_s^+ (\to \pi^+\pi^+\pi^- X)$ for $B^0 \to D^* \tau^+ (\to \pi^+\pi^-\pi^+)$



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

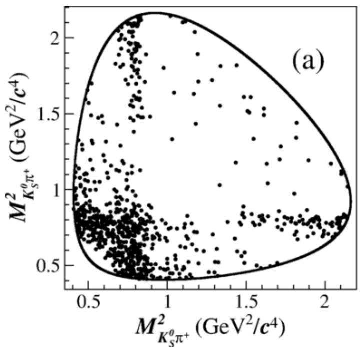
- 2.93 fb^{-1} of data at $\sqrt{s}$ =3.773 GeV
- $\mathcal{B}\left(K_S^0\pi^+\pi^0\pi^0\right) = (2.888 \pm 0.058_{stat.} \pm 0.069_{syst.})\%$
  - $\mathcal{B}\left(D^+ \to K_S^0 a_1(1260)^+(\to \rho^+\pi^0)\right) = (8.66 \pm 1.04_{stat.} \pm 1.39_{syst.}) \times 10^{-3}$
  - $\mathcal{B}(D^+ \to \bar{K}^{*0}\rho^+) = (9.70 \pm 0.81_{stat} \pm 0.53_{syst.}) \times 10^{-3}$

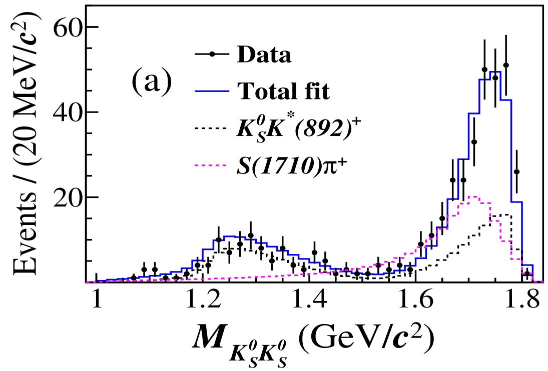


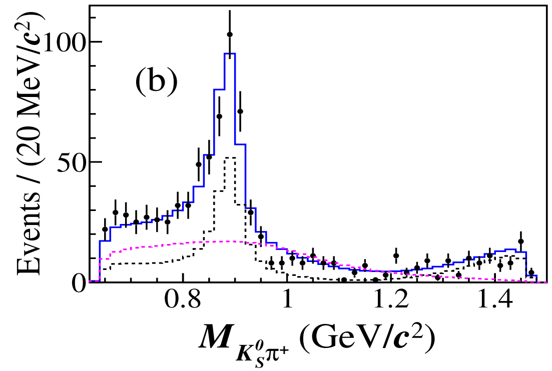
Amplitude Analysis :$D_s^+ \to K_S^0 K_S^0 \pi^+$

- A structure around 1.7 GeV, $S(1710)$, in $M_{K_S^0 K_S^0}$

	S(1710)	f_0(1710)PDG	difference
Mass (GeV/c^2)	$1.723 \pm 0.011 \pm 0.002$	1.704 ± 0.012	1.2σ
Width (GeV)	$0.140 \pm 0.014 \pm 0.004$	0.123 ± 0.018	0.7σ







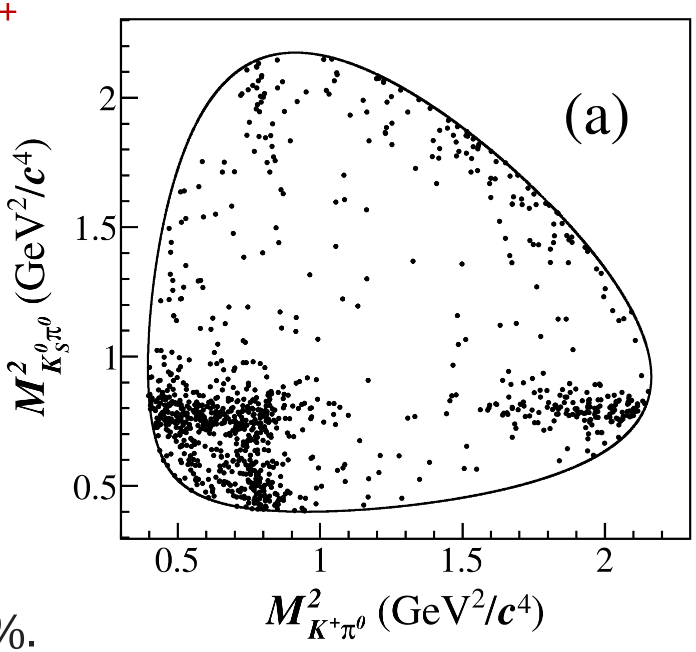
Decay mode	Branching fraction (10^{-3})
$D_s^+ \to K_S^0 K_S^0 \pi^+$	$6.8 \pm 0.4_{stat} \pm 0.1_{syst}$
$D_s^+ \to K_S^0 K^*(892)^+$	$3.0 \pm 0.3_{stat} \pm 0.1_{syst}$
$D_s^+ \to S(980)\pi^+, S(980) \to K_S^0 K_S^0$	< 0.18 @ 90% C.L.
$D_s^+ \to S(1710)\pi^+$	$(3.1 \pm 0.3_{stat} \pm 0.1_{syst}) \times 10^{-3}$

- The $S(980)$ is observed in the ($D_s^+ \to S(980)\pi^+, S(980) \to K^+K^-$) decay with significance $> 20\sigma$ [Phys. Rev. D 104, 012016 (2021)]
- Constructive interference between $a_0(980)^0$ and $f_0(980)^0$ for K^+K^-
- Destructive interference between $a_0(980)^0$ and $f_0(980)^0$ for $K_S^0 K_S^0$

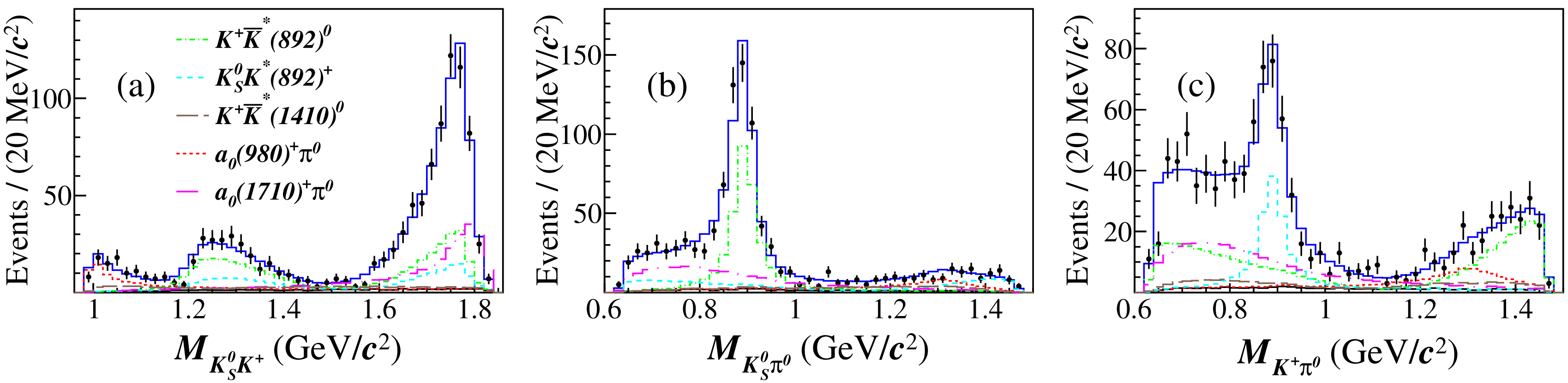
- One order of magnitude larger than expectation based on the isospin symmetry
- Constructive interference between $f_0(1710)$ and $a_0(1710)^0$
- A simultaneous amplitude analysis of $D_s^+ \to K^+K^-\pi^+$ and $D_s^+ \to K_S^0 K_S^0 \pi^+$ is desirable

Amplitude Analysis :$D_S^+ \to K_S^0 K^+ \pi^0$ [Phys. Rev. Lett. 129, 182001 (2022)]

- First observation of a_0-like state, $S(1817)^+$, in $M_{K_S^0 K^+}$
  - Mass: $(1.817 \pm 0.008 stat \pm 0.020 syst)$ GeV/c^2
  - Width: $\left(0.097 \pm 0.022_{stat} \pm 0.015_{syst}\right)$ GeV/c^2
  - Isospin-one partner of $f_0(1710)(\to K_S^0 K_S^0)$
    - ~100 MeV difference in mass
    - [Eur. Phys. J. C **82**, 225 (2022)]
  - Isospin-one partner of the $X(1812)$
    - [Phys. Rev. D 105, 114014(2022)]



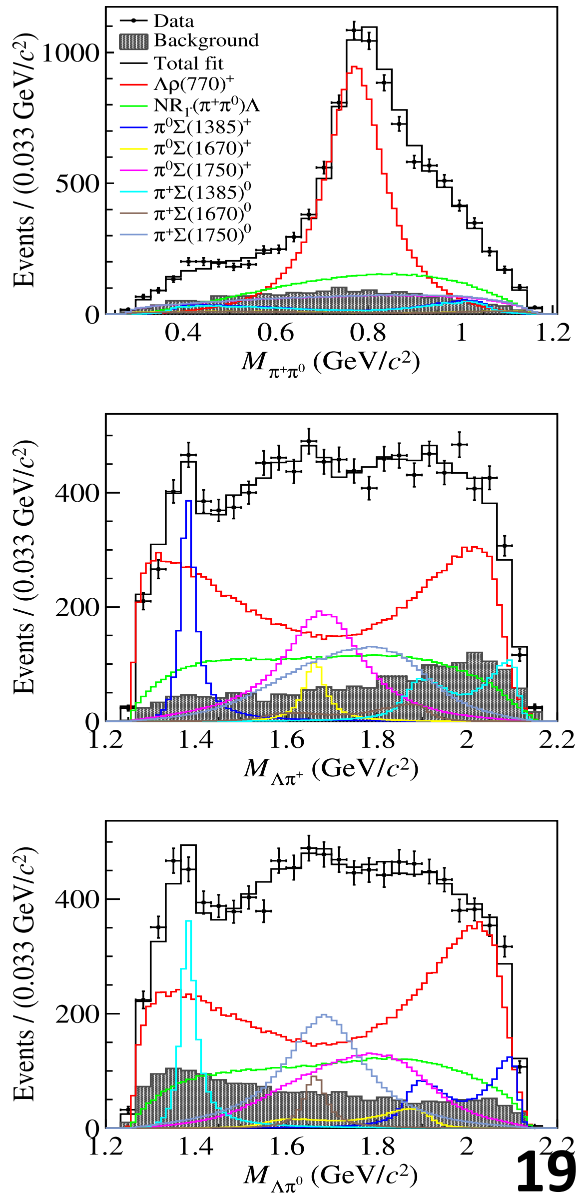
- $\mathcal{B}(D_S^+ \to K_S^0 K^+ \pi^0) = \left(1.46 \pm 0.06_{stat} \pm 0.05_{syst}\right)\%$.



Amplitude Analysis :$\Lambda_c^+ \to \Lambda\pi^+\pi^0$ [J. High Energy Phys. 12(2022)033]

	Theoretical calculation		This work	PDG
$10^2 \times \mathcal{B}(\Lambda_c^+ \to \Lambda\rho(770)^+)$	4.81 ± 0.58 [13]	4.0 [14, 15]	4.06 ± 0.52	< 6
$10^3 \times \mathcal{B}(\Lambda_c^+ \to \Sigma(1385)^+\pi^0)$	2.8 ± 0.4 [16]	2.2 ± 0.4 [17]	5.86 ± 0.80	—
$10^3 \times \mathcal{B}(\Lambda_c^+ \to \Sigma(1385)^0\pi^+)$	2.8 ± 0.4 [16]	2.2 ± 0.4 [17]	6.47 ± 0.96	—
$\alpha_{\Lambda\rho(770)^+}$	-0.27 ± 0.04 [13]	-0.32 [14, 15]	-0.763 ± 0.070	—
$\alpha_{\Sigma(1385)^+\pi^0}$	$-0.91^{+0.45}_{-0.10}$ [17]		-0.917 ± 0.089	—
$\alpha_{\Sigma(1385)^0\pi^+}$	$-0.91^{+0.45}_{-0.10}$ [17]		-0.79 ± 0.11	—

First observation



[13] C.Q. Geng, C.-W. Liu and T.-H. Tsai, *Charmed Baryon Weak Decays with Vector Mesons*, *Phys. Rev. D* **101** (2020) 053002 [arXiv:2001.05079] [INSPIRE].

[14] H.-Y. Cheng and B. Tseng, *Nonleptonic weak decays of charmed baryons*, *Phys. Rev. D* **46** (1992) 1042 [*Erratum ibid.* **55** (1997) 1697] [INSPIRE].

[15] H.Y. Cheng and B. Tseng, *Erratum: Nonleptonic weak decays of charmed baryons*, *Phys. Rev. D* **55** (1997) 1697.

[16] Y.K. Hsiao, Q. Yi, S.-T. Cai and H.J. Zhao, *Two-body charmed baryon decays involving decuplet baryon in the quark-diagram scheme*, *Eur. Phys. J. C* **80** (2020) 1067 [arXiv:2006.15291] [INSPIRE].

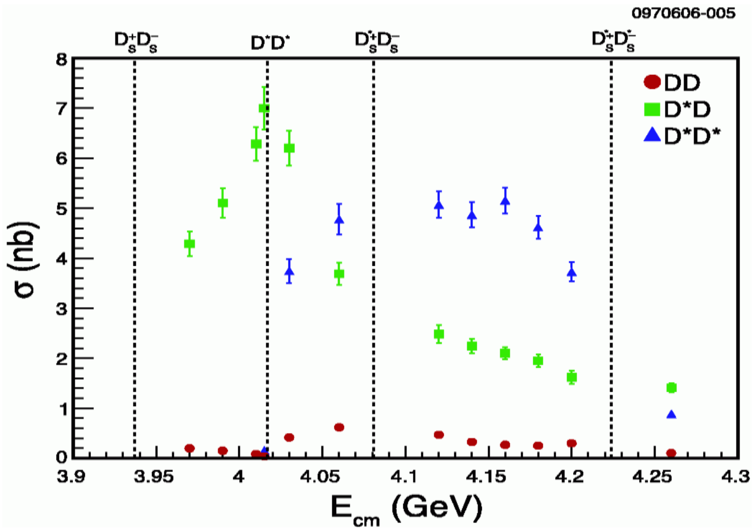
[17] C.-Q. Geng, C.-W. Liu, T.-H. Tsai and Y. Yu, *Charmed baryon weak decays with decuplet baryon and* SU(3) *flavor symmetry*, *Phys. Rev. D* **99** (2019) 114022 [arXiv:1904.11271] [INSPIRE].

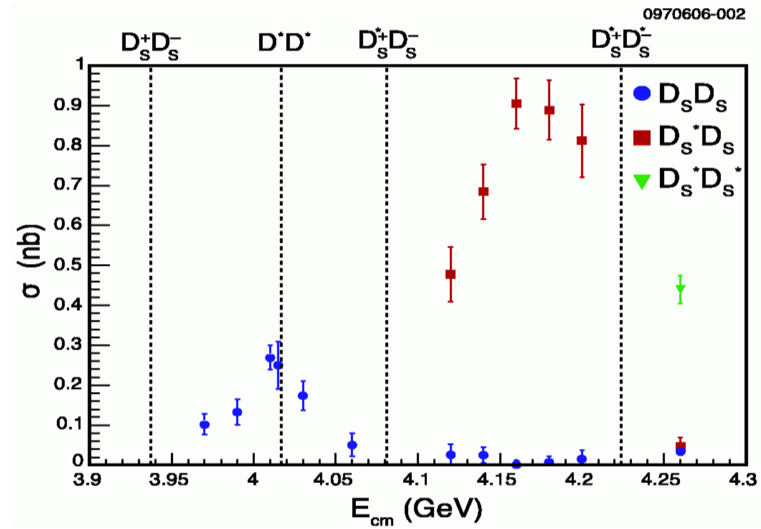
Summary and Prospect

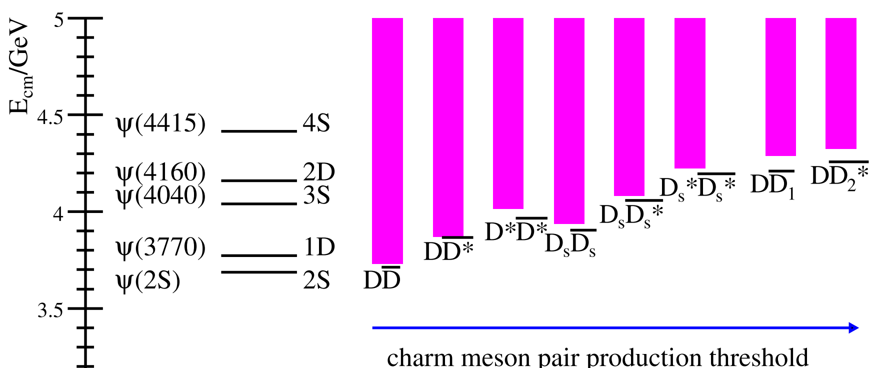
- Many results related to the charmed hadron decays are reported
  - Hint of leptonic decay of excited D_s^+
  - Observation of transverse polarized Decay $D^0 \to \phi\omega$
  - Observation of a structure $S(1710)$ in $M_{K_S^0 K_S^0}$ of $D_s^+ \to K_S^0 K_S^0 \pi^+$
  - Observation of a structure $S(1817)^+$ in $M_{K_S^0 K^+}$ of $D_s^+ \to K_S^0 K^+ \pi^0$
  - …
- Prospect
  - More data will be available
    - $8\ fb^{-1}$ data at 3.773 GeV has been released and 20 fb^{-1} data will be available in 2024
  - More progresses with higher precisions will be reported

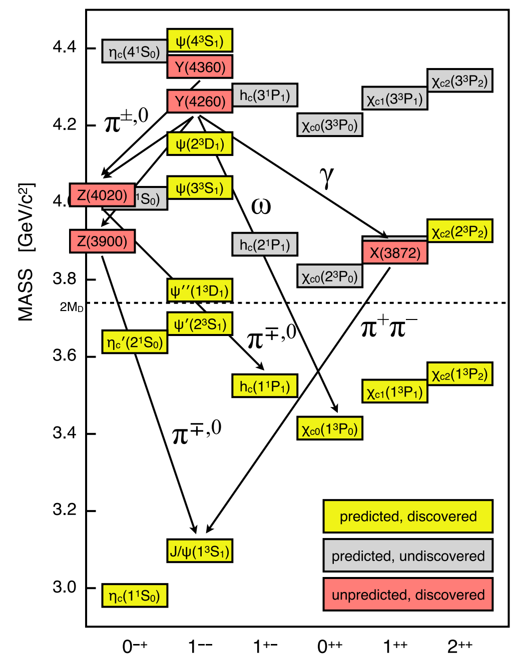
Backup

Charmed meson production







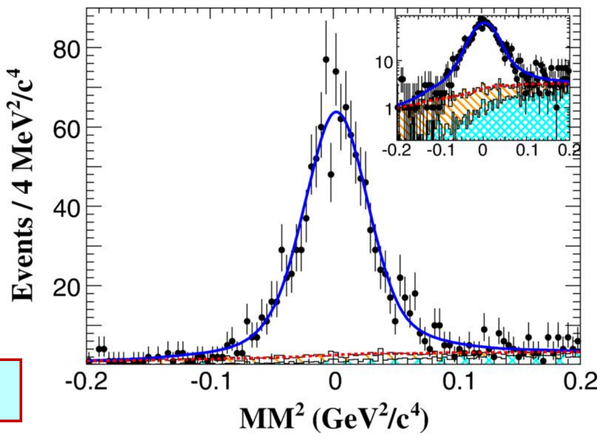


leptonic decay: $D_s^+ \to \mu^+\nu_\mu$ [Phys. Rev. Lett. 122, 071802 (2019)]

- 3.19 fb^{-1} data @ 4.178 GeV via $e^+e^- \to D_s^+$
- $\mathcal{B}(D_s^+ \to \mu^+\nu_\mu) = (5.49 \pm 0.16_{stat} \pm 0.15_{syst}) \times 10^{-3}$
  - $f_{D_s^+}|Vcs| = 246.2 \pm 3.6_{stat} \pm 3.5_{syst}$ MeV
  - $f_{D_s^+} = 252.9 \pm 3.7_{stat} \pm 3.6_{syst}$ MeV
  - $|V_{cs}| = 0.985 \pm 0.014_{stat} \pm 0.014_{syst}$

SM predicted $|V_{cs}|$

$f_{D_s^+}$ from LQCD calculation

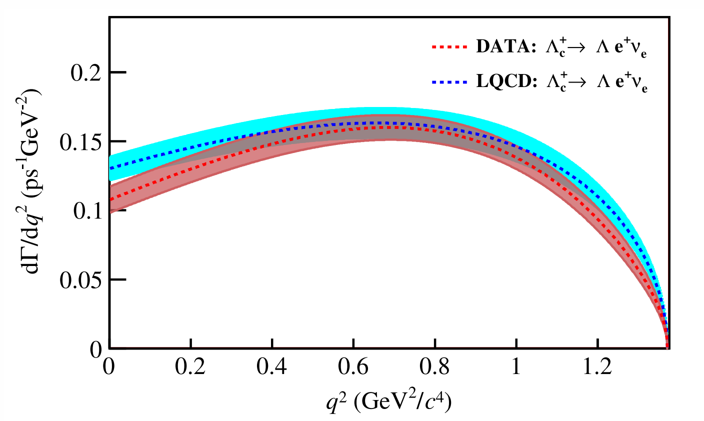


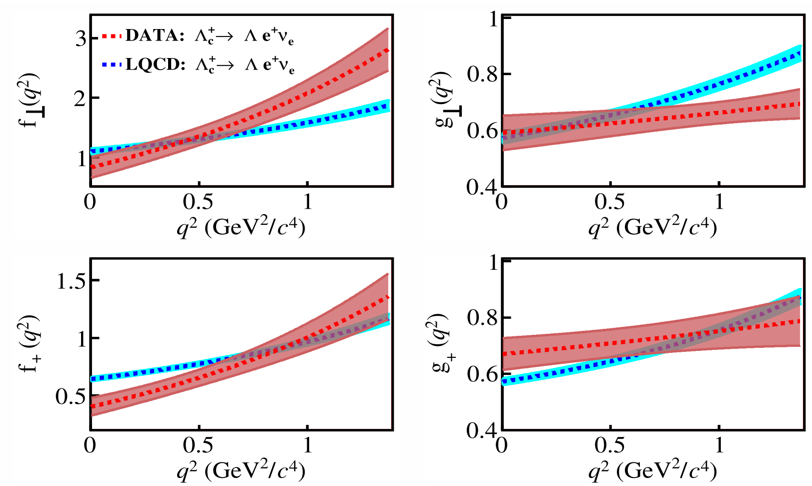
- LFU test
  - $\mathcal{B}(D_s^+ \to \tau^+\nu_\tau)/\mathcal{B}(D_s^+ \to \mu^+\nu_\mu) = 9.98 \pm 0.52$ consistent with SM predicted value of 9.74
- Search for the *CP* violation
  - $A_{CP} = \frac{\mathcal{B}(D_s^+\to\mu^+\nu_\mu)-\mathcal{B}(D_s^-\to\mu^-\nu_\mu)}{\mathcal{B}(D_s^+\to\mu^+\nu_\mu)+\mathcal{B}(D_s^-\to\mu^-\nu_\mu)} = (2.0 \pm 3.0_{stat} \pm 1.2_{syst})\%$
  - No significant violation

$\Lambda_c^+ \to \Lambda e^+ \nu_e$

- Data at $\sqrt{s}$ in $[4.6, 4.7]$ GeV with $\mathcal{L} = 4.5\ fb^{-1}$
- $\mathcal{B}(\Lambda_c^+ \to \Lambda e^+ \nu_e) = (3.56 \pm 0.11_{stat} \pm 0.07_{syst})\%$
  - The most precise measurement
- Measurement of differential rate and form factors
  - Measured for the first time

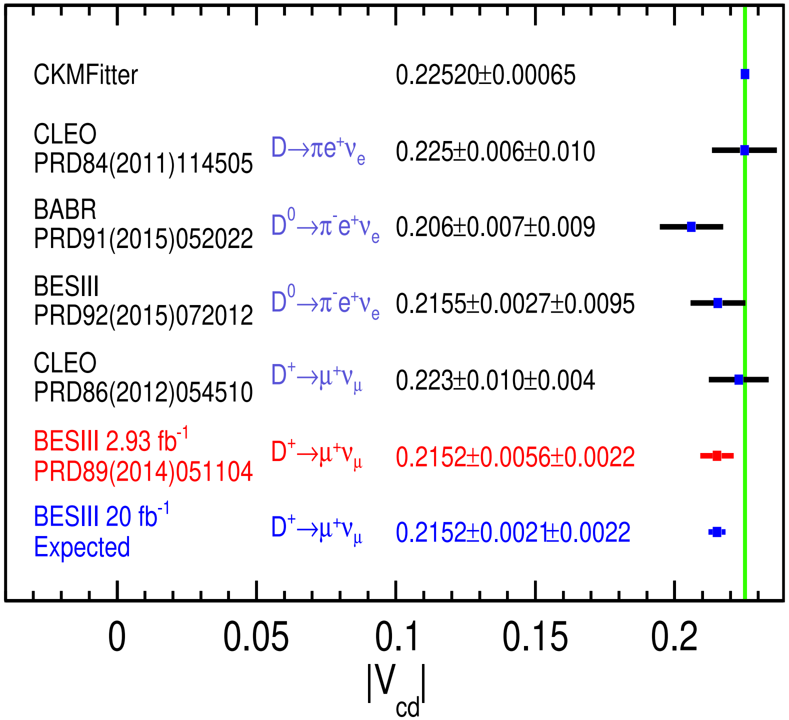
Model	prediction
Constituent quark model (HONR) [9]	4.25
Light-front approach [10]	1.63
Covariant quark model [11]	2.78
Relativistic quark model [12]	3.25
Non-relativistic quark model [13]	3.84
Light-cone sum rule [14]	3.0 ± 0.3
Lattice QCD [15]	3.80 ± 0.22
SU(3) [16]	3.6 ± 0.4
Light-front constituent quark model [17]	3.36 ± 0.87
MIT bag model [17]	3.48
Light-front quark model [18]	4.04 ± 0.75

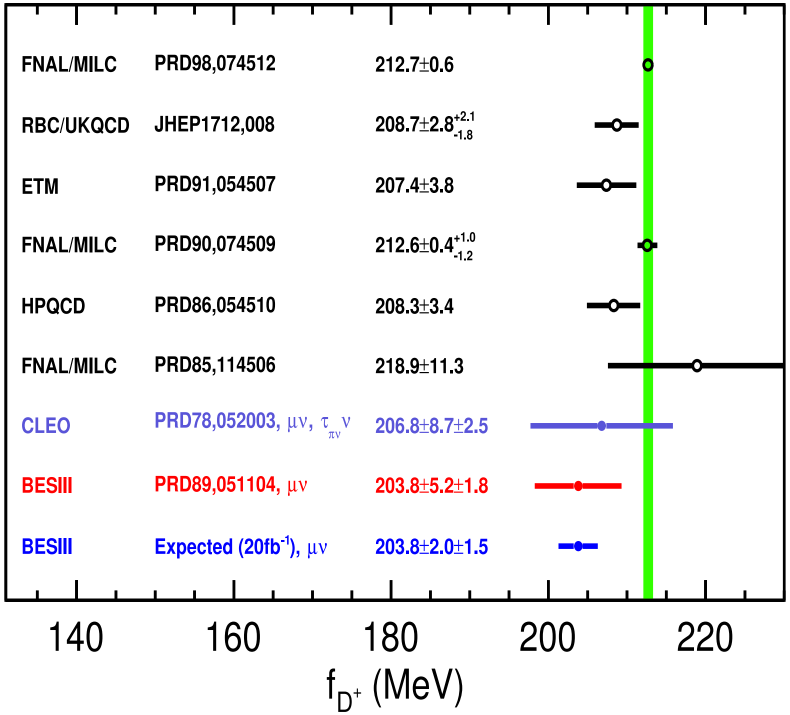




- $|V_{cs}|$ measurement: $0.936 \pm 0.017_{\mathcal{B}} \pm 0.024_{\text{LQCD}} \pm 0.007_{\tau_{\Lambda_c}}$
  - Consistent with $|V_{cs}|$ measured in $D \to K\ell\nu_\ell$ decays

Leptonic decay

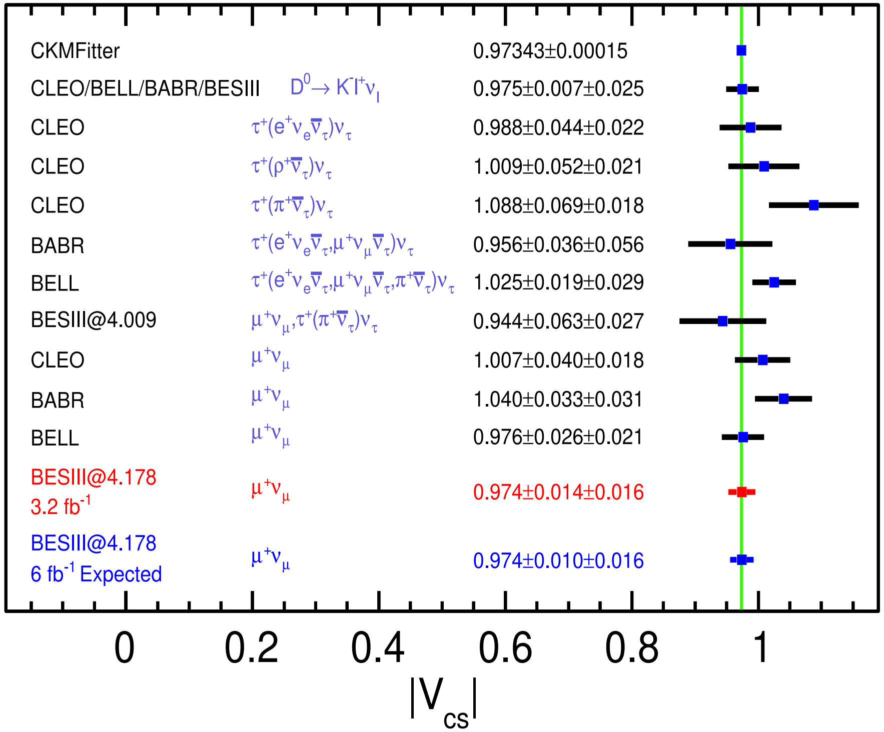


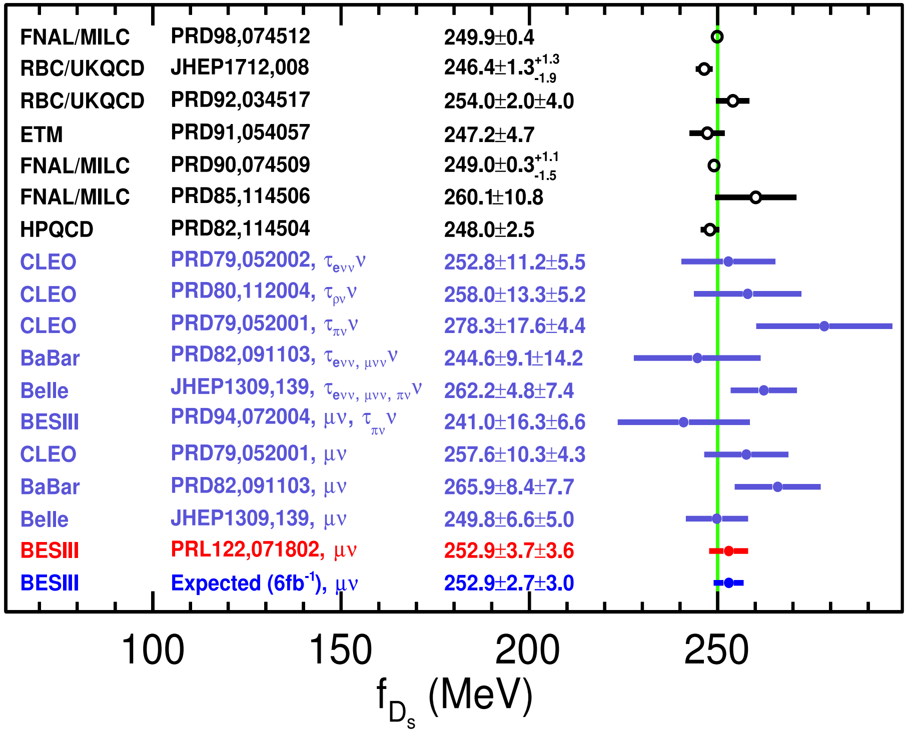


- Most precise result is from BESIII
  - Statistics dominated
  - Room to improvement of statistical uncertainty
- 2.5% ⇒ 1.0 % with future 20 fb^{-1} data

[Chin.Phys.C 44 (2020) 4, 040001]

Leptonic decay



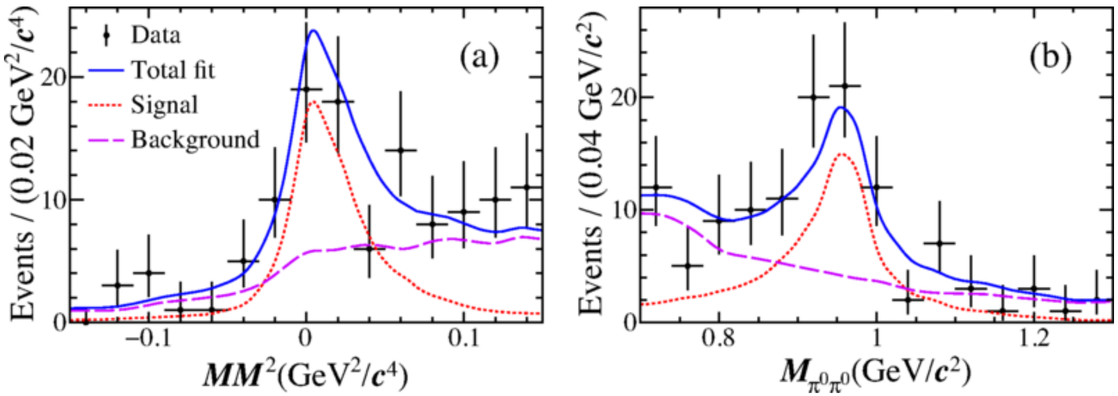


- Most precise result is from BESIII
- Systematic uncertainty is comparable with statistical uncertainty

[Chin.Phys.C 44 (2020) 4, 040001]

$D_s^+ \to \pi^0\pi^0 e^+\nu_e$ and $K_S^0 K_S^0 e^+\nu_e$ [PhysRevD.105.L031101]

- First measurement of $\mathcal{B}(D_s^+ \to f_0(980)e^+\nu_e) \times \mathcal{B}(f_0(980) \to \pi^0\pi^0)$:$\left(7.9 \pm 1.4_{stat} \pm 0.4_{syst}\right) \times 10^{-4}$
  - Consistent with $0.5 \times \mathcal{B}(D_s^+ \to f_0(980)e^+\nu_e) \times \mathcal{B}(f_0(980) \to \pi^+\pi^-)$ according to isospin symmetry



- $\mathcal{B}(D_s^+ \to f_0(500)e^+\nu_e) \times \mathcal{B}(f_0(500) \to \pi^0\pi^0) < 7.3 \times 10^{-4}$ @ 90% C.L.
- $\mathcal{B}\left(D_s^+ \to K_S^0 K_S^0 e^+\nu_e\right) < 3.8 \times 10^{-1}$@ 90% C.L.

Isospin for two body decay

$$\langle \overline{K}^0 \pi^+ | H_w^{n.L} | D^+ \rangle = A_{3/2} ,$$

$$\langle K^- \pi^+ | H_w^{n.L} | D^0 \rangle = \tfrac{1}{3} A_{3/2} + \tfrac{2}{3} A_{1/2} ,$$

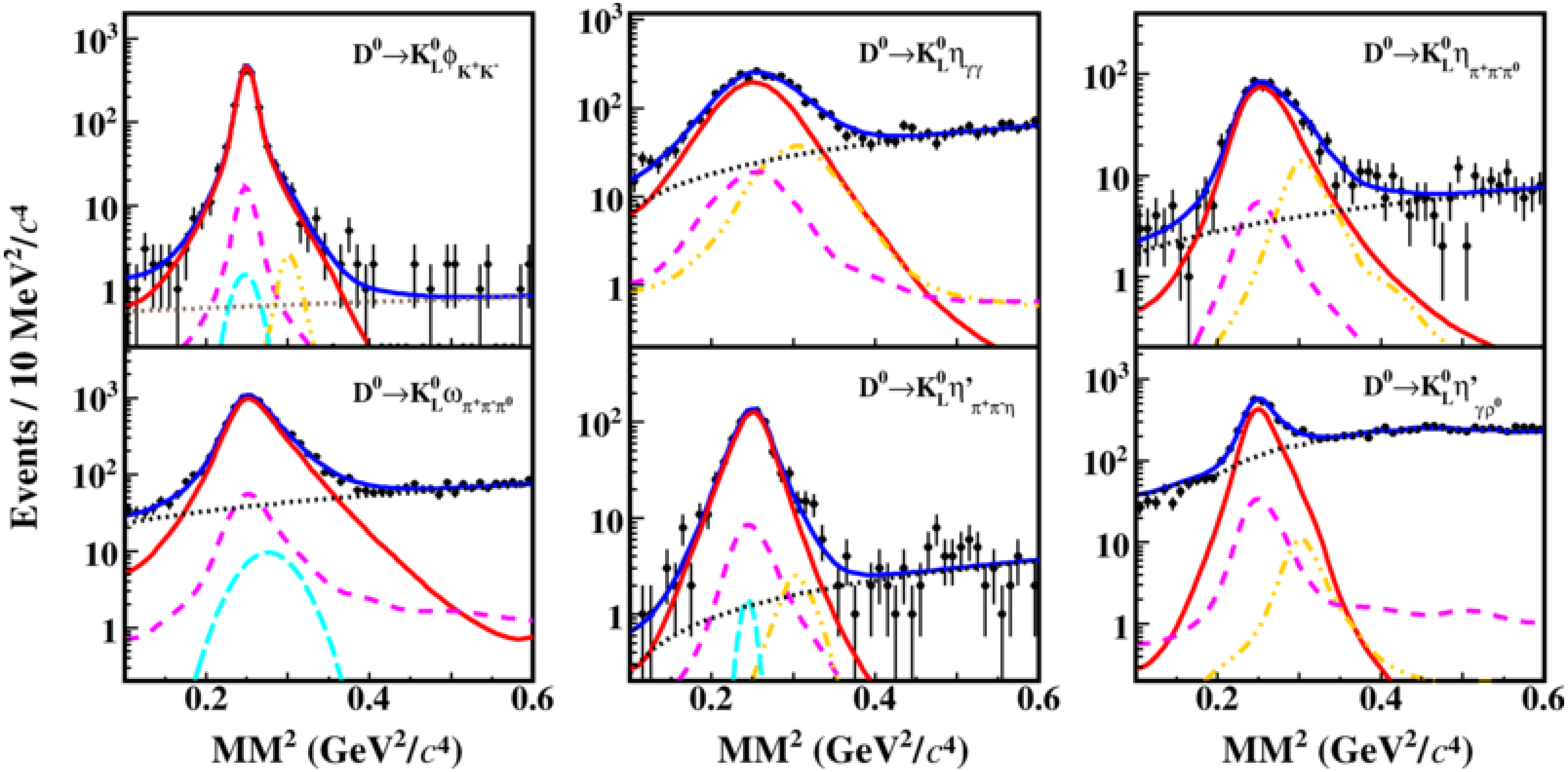
$$\langle \overline{K}^0 \pi^0 | H_w^{n.L} | D^0 \rangle = \tfrac{1}{3}\sqrt{2}(A_{3/2} - A_{1/2}) ,$$

Nuclear Physics B122 (1977) 144-169

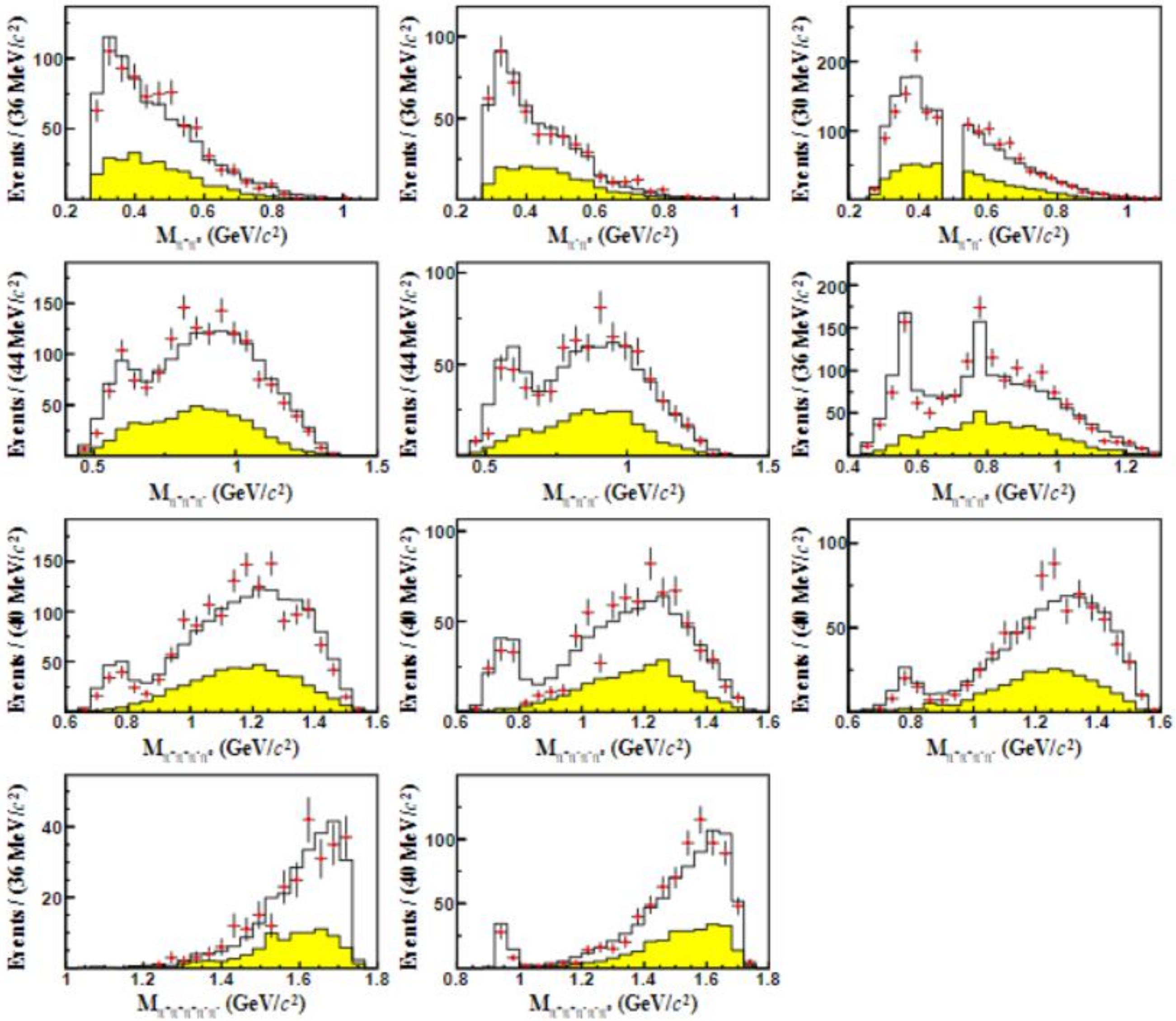
The charm-changing weak current is assumed to induce the quark transition *

$$c \leftrightarrow s \cos\theta_c - d \sin\theta_c , \qquad (1)$$

Signal yields of $D^0 \to K_L^0 X$



Intermediates for $D^+ \to 3\pi^+ 2\pi^- \pi^0$



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

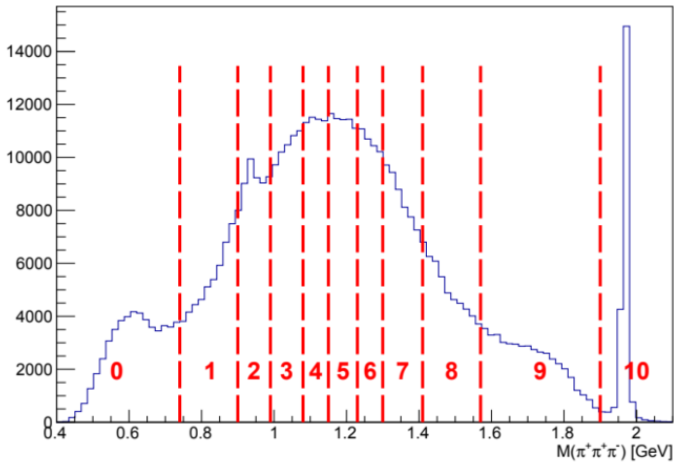
M(πππ) bins

- We measure partial branching fraction of $D_s \to \pi\pi\pi X$ in 11 bins of M(πππ)

6 Double tag

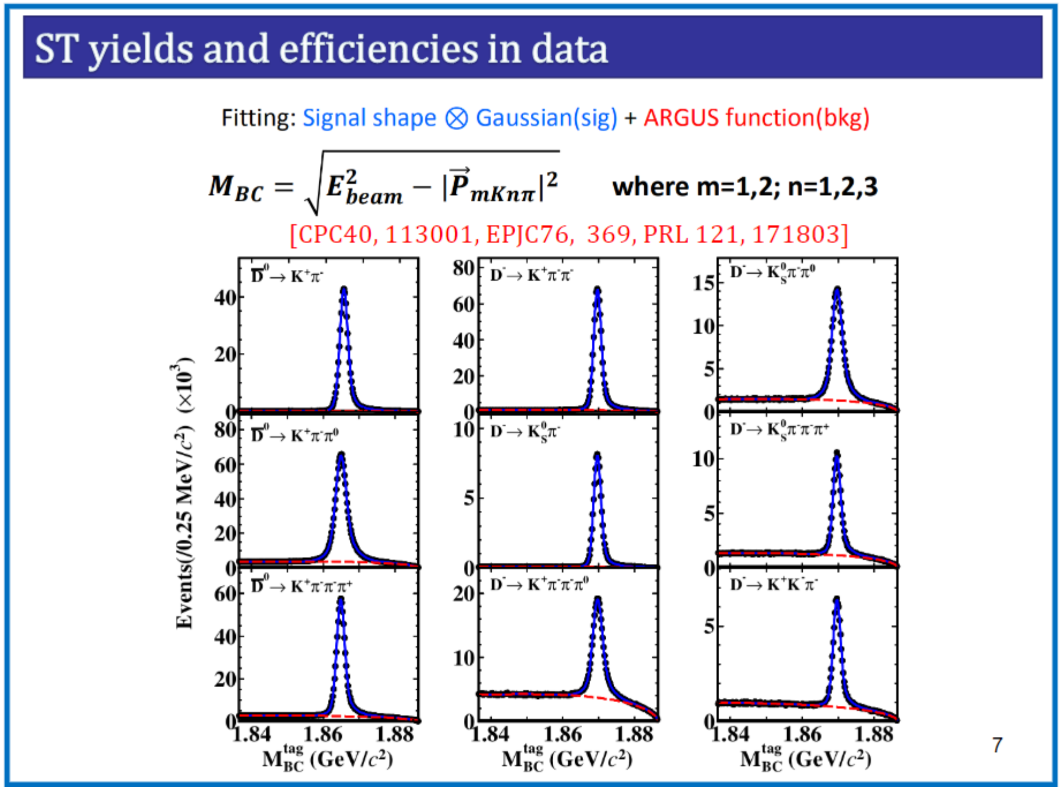
6.1 Selection of three charged pions from the signal side

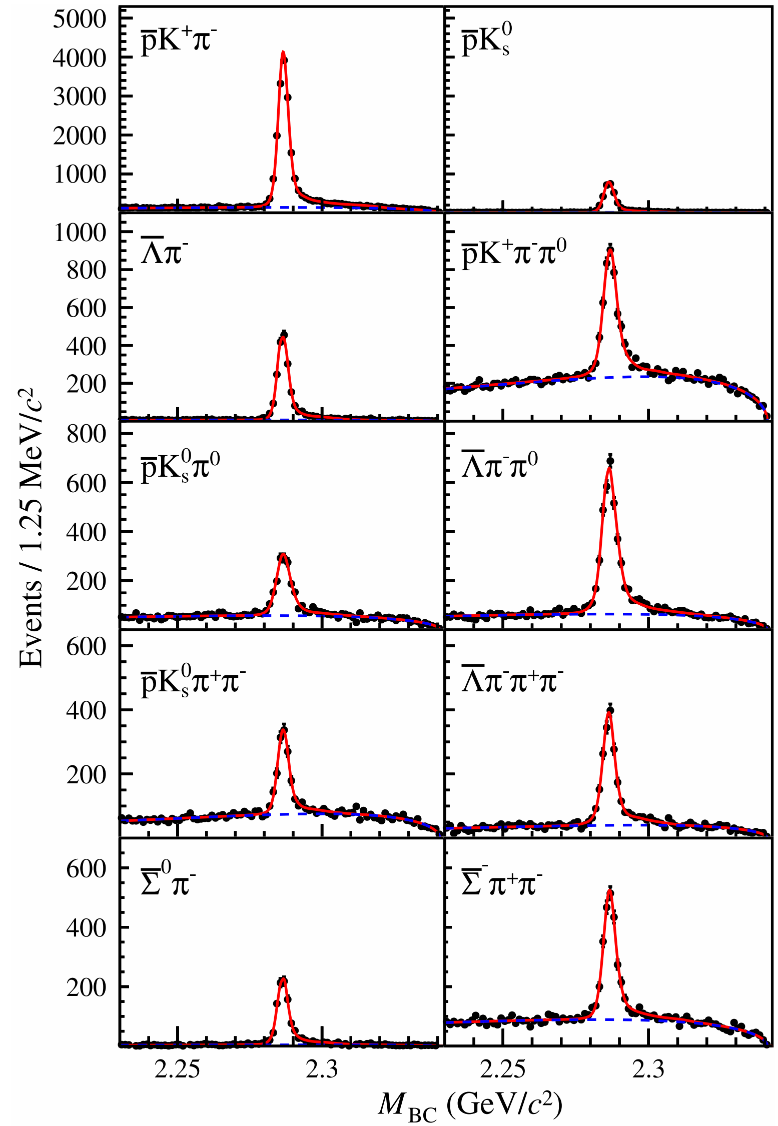
For one event, in the presence of the selected ST D_s^- candidates as described in the previous section, we look at the rest of the event for one π^- and two π^+ (or c.c.) for the inclusive decay of $D_s^+ \to \pi^+\pi^+\pi^- X$. The tracking and PID requirements on the selection pions are the same as those in §5.1. Also, charge pion candidates with momenta below 100 MeV/c are rejected to suppress soft pion backgrounds from $D^{*+} \to D^0\pi^+$. In case that more than one π^- is reconstructed at the signal side, we select the one with the largest $|p|$. When more than two π^+ is present at the signal side, we select the pion pairs with the largest and second largest $|p|$ values.



https://indico.ihep.ac.cn/event/10988/contributions/6719/attachments/3032/3462/ds2pipipiX_20200922.pdf

Single tag mode

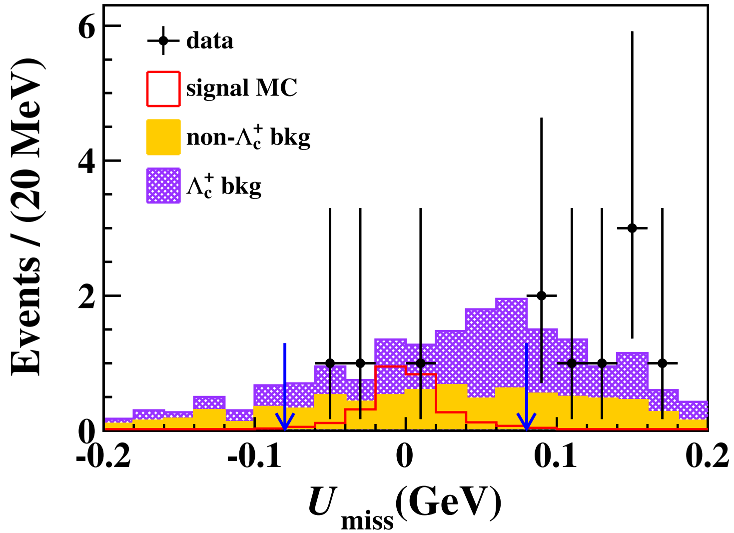




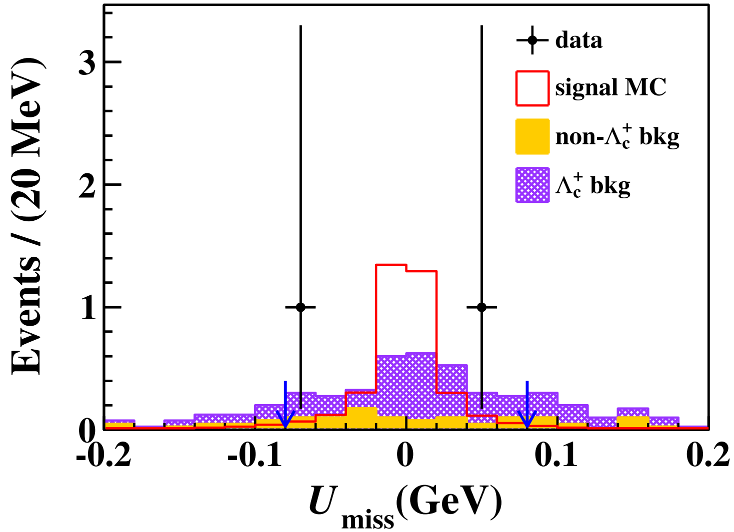
$\Lambda_c^+ \to \Lambda\pi^+\pi^-e^+\nu_e$ and $\Lambda_c^+ \to pK_S^0\pi^-e^+\nu_e$

- Data: 4.5 fb^{-1} at $\sqrt{s}$ in $[4.6, 4.7]$ GeV
- $\mathcal{B}(\Lambda_c^+ \to \Lambda\pi^+\pi^-e^+\nu_e) < 3.9 \times 10^{-4}$
- $\mathcal{B}\left(\Lambda_c^+ \to pK_S^0\pi^-e^+\nu_e\right) < 3.3 \times 10^{-4}$

[arXiv:2302.07529]: accepted by PLB



$\Lambda_c^+ \to \Lambda\pi^+\pi^-e^+\nu_e$



$\Lambda_c^+ \to pK_S^0\pi^-e^+\nu_e$

Branching Fraction: Kaonic

- $D^{0/+} \to Kn\pi$ PRD 106, 032002 (2022)

Decay mode	$\mathcal{B}(10^{-3})$
$D^0 \to K_S^0\pi^0\pi^0\pi^0$	$7.64 \pm 0.30 \pm 0.29$
$D^0 \to K^-\pi^+\pi^0\pi^0\pi^0$	$9.54 \pm 0.30 \pm 0.31$
$D^0 \to K_S^0\pi^+\pi^-\pi^0\pi^0$	$12.66 \pm 0.45 \pm 0.43$
$D^+ \to K_S^0\pi^+\pi^0\pi^0$	$29.04 \pm 0.62 \pm 0.87$
$D^+ \to K_S^0\pi^+\pi^+\pi^-\pi^0$	$15.28 \pm 0.57 \pm 0.60$
$D^+ \to K_S^0\pi^+\pi^0\pi^0\pi^0$	$5.54 \pm 0.44 \pm 0.32$
$D^+ \to K^-\pi^+\pi^+\pi^0\pi^0$	$4.95 \pm 0.26 \pm 0.19$

- $D^{0/+} \to K\pi\omega$ PRD 105, 032009 (2022)

	Measured	predicted
$\mathcal{B}(D^0 \to K^-\pi^+\omega)$ (%)	$3.392 \pm 0.044 \pm 0.085$	Improved by a factor 7
$\mathcal{B}(D^0 \to K_S^0\pi^0\omega)$ (%)	$0.848 \pm 0.046 \pm 0.031$	
$\mathcal{B}(D^+ \to K_S^0\pi^+\omega)$ (%)	$0.707 \pm 0.041 \pm 0.029$	
$\frac{\mathcal{B}(D^0\to K_S^0\pi^0\omega)}{\mathcal{B}(D^0\to K^-\pi^+\omega)}$	$0.23 \pm 0.01 \pm 0.01$	0.4
$\frac{\mathcal{B}(D^+\to K_S^0\pi^+\omega)}{\mathcal{B}(D^0\to K^-\pi^+\omega)}$	$0.21 \pm 0.01 \pm 0.01$	0.9

- $D^0 \to K_L^0 X$ PRD 105, 092010 (2022)

Decay	$\mathcal{B}_{\text{exp}}(\%)$	$\mathcal{R}(D^0)$
$D^0 \to K_L^0\phi$	$0.414 \pm 0.021 \pm 0.010$	-0.001 ± 0.047
$D^0 \to K_L^0\eta$	$0.433 \pm 0.012 \pm 0.010$	0.080 ± 0.022
$D^0 \to K_L^0\omega$	$1.164 \pm 0.022 \pm 0.028$	-0.024 ± 0.031
$D^0 \to K_L^0\eta'$	$0.809 \pm 0.020 \pm 0.016$	0.080 ± 0.023

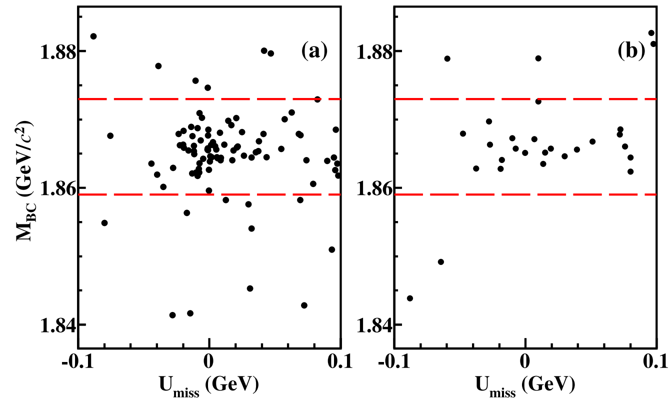
- Asymmetry between $\mathcal{B}(D^0 \to K_S^0 X)$ and $\mathcal{B}(D^0 \to K_L^0 X)$
  - $\mathcal{R}(D^0, X) = \frac{\mathcal{B}(D^0\to K_S^0X)-\mathcal{B}(D^0\to K_L^0X)}{\mathcal{B}(D^0\to K_S^0X)+\mathcal{B}(D^0\to K_L^0X)}$
  - Indications $K_L^0 - K_S^0$ asymmetry($\mathcal{R}$) for $K_L^0\eta$ and $K_L^0\eta'$

- Based on statistical isospin model Nucl.Phys.B 122 (1977) 144-169
- Large deviation from measured value
- Potential final-state interaction

Branching Fraction: Doubly Cabibbo-suppressed(DCS) Decay

➢ $D^0 \to K^+\pi^-\pi^0\ (\pi^0)$ PRD 105, 112001 (2022)

- Previous results are from the $D^0 - \bar{D}^0$ mixing or coherent factor measurement
- $\mathcal{B}(K^+\pi^-\pi^0) = [3.13^{+0.60}_{-0.56}(\text{ stat }) \pm 0.15(\text{ syst })] \times 10^{-4}$
- $\mathcal{B}(K^+\pi^-\pi^0\pi^0) < 3.6 \times 10^{-4}$ @ 90% CL.
  - $[1.84^{+1.19}_{-1.00}(stat)] \times 10^{-4}$



(a):$K^+\pi^-\pi^0(7\sigma)$, (b):$K^+\pi^-\pi^0\pi^0(1.9\sigma)$

➢ $D^+ \to K^+\pi^0\pi^0$ and $K^+\pi^0\eta$ JHEP09(2022)107

Decay mode	$\mathcal{B}_{\text{sig}}\ (\times 10^{-4})$	Significance
$D^+ \to K^+\pi^0\pi^0$	$2.1 \pm 0.4 \pm 0.1$	8.8σ
$D^+ \to K^+\pi^0\eta$	$2.1 \pm 0.5 \pm 0.1$	5.5σ
$D^+ \to K^{*+}\pi^0$	$3.4^{+1.4}_{-1.3} \pm 0.1$	3.2σ
$D^+ \to K^{*+}\eta$	$4.4^{+1.8}_{-1.5} \pm 0.2$	2.7σ

Ignoring interference between the K^* and $K^+\pi^0$

Decays	Measured($\tan^4\theta_C$)	Predicted($\tan^4\theta_C$)
$\frac{\mathcal{B}(D^+\to K^+\pi^0\pi^0)}{\mathcal{B}(D^+\to K^-\pi^+\pi^+)}$	0.77 ± 0.14	$2/3$
$\frac{\mathcal{B}(D^+\to K^+\pi^0\eta)}{\mathcal{B}(D^+\to \bar{K}^0\pi^+\eta)}$	2.64 ± 0.68	1

- θ_C: Cabibbo mixing angle
- $\frac{\mathcal{B}(D^+\to K^+\pi^0\eta)}{\mathcal{B}(D^+\to \bar{K}^0\pi^+\eta)}$ inconsistent with prediction based on isospins symmetry by 2.4σ Nucl.Phys.B 122 (1977) 144-169

First observation

Branching Fraction: Pionic

➢ D^{0+} decay with multiple pions(CS) PRD 106, 092005 (2022)

- First absolute measurement of 20 decay modes

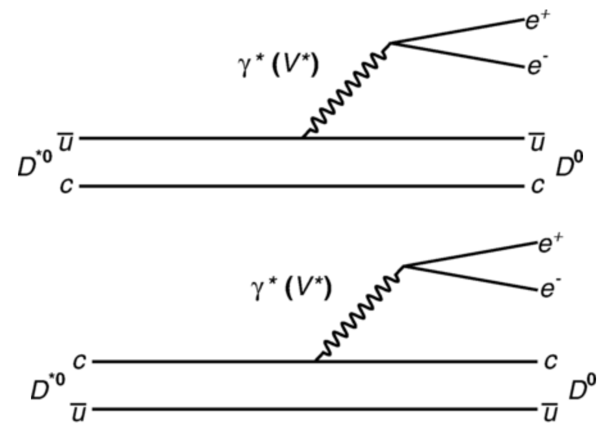
Decay	$\mathcal{B}_{\rm sig}$ $(\times 10^{-4})$
$D^0 \to \pi^+\pi^-\pi^0$	$134.3 \pm 13 \pm 16$
$D^0 \to \pi^+\pi^-2\pi^0$	$100.2 \pm 19 \pm 24$
$D^0 \to \pi^+\pi^-2\eta$	$8.5 \pm 13 \pm 04$
$D^0 \to 4\pi^0$	$7.6 \pm 09 \pm 07$
$D^0 \to 3\pi^0\eta$	$23.6 \pm 22 \pm 17$
$D^0 \to 2\pi^+2\pi^-\pi^0$	$34.6 \pm 15 \pm 15$
$D^0 \to 2\pi^+2\pi^-\eta$	$6.0 \pm 10 \pm 06$
$D^0 \to \pi^+\pi^-3\pi^0$	$15.3 \pm 17 \pm 13$
$D^0 \to 2\pi^+2\pi^-2\pi^0$	$47.7 \pm 31 \pm 21$
$D^+ \to 2\pi^+\pi^-$	$32.7 \pm 07 \pm 05$
$D^+ \to \pi^+2\pi^0$	$46.1 \pm 12 \pm 09$
$D^+ \to 2\pi^+\pi^-\pi^0$	$116.5 \pm 21 \pm 21$
$D^+ \to \pi^+3\pi^0$	$41.7 \pm 22 \pm 13$
$D^+ \to 3\pi^+2\pi^-$	$18.2 \pm 11 \pm 10$
$D^+ \to 2\pi^+\pi^-2\pi^0$	$107.4 \pm 40 \pm 30$
$D^+ \to 2\pi^+\pi^- - \pi^0\eta$	$38.8 \pm 32 \pm 12$
$D^+ \to \pi^+4\pi^0$	$19.5 \pm 36 \pm 23$
$D^+ \to \pi^+3\pi^0\eta$	$28.9 \pm 40 \pm 22$
$D^+ \to 3\pi^+2\pi^-\pi^0$	$23.4 \pm 22 \pm 15$
$D^+ \to 2\pi^+\pi^-3\pi^0$	$34.2 \pm 31 \pm 16$

- $\mathcal{A}_{CP} = \frac{\mathcal{B}^+ - \mathcal{B}^-}{\mathcal{B}^+ + \mathcal{B}^-}$ are measured
  - $\mathcal{B}^{\pm}$: branching fraction of $D \to f$ and $\bar{D} \to \bar{f}$
  - No significant *CP* violation is observed

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

Excited Charmed Meson Decays

- $D^{*0} \to D^0 e^+ e^-$ PRD 104, 112012 (2021)
  - Observed for the first time with significance of 13.2σ
  - $\frac{\mathcal{B}(D^{*0}\to D^0 e^+ e^-)}{\mathcal{B}(D^{*0}\to D^0 \gamma)} = (11.08 \pm 0.76 \pm 0.49) \times 10^{-3}$
    - Deviated from VMD model prediction of 6.7×10^{-3} by 4.8σ
  - $\mathcal{B}(D^{*0} \to D^0 e^+ e^-) = (3.91 \pm 0.27 \pm 0.17 \pm 0.10) \times 10^{-3}$

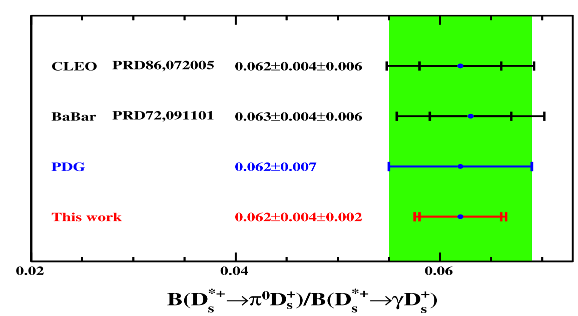


- $D_s^{*+} \to D_s^+ \gamma$ and $D_s^{*+} \to D_s^+ \pi^0$ PRD 107, 032011 (2023)

TABLE IV. Comparisons of the partial widths (Γ) and BFs (in brackets). The decay widths are in units of keV. The first two rows are from this work and the Particle Data Group, while the others are from various theoretical predictions. The superscript ^{a} denotes the value corresponding to $g = 0.52$, $\beta = 2.6$ GeV^{-1}, and $m_c = 1.6$ GeV; ^{b} denotes the values for a linear model; ^{c} denotes the value for $\kappa^q = 0.55$; and ^{d} denotes the values for (a) model.

	$\Gamma[\mathcal{B}]_{D_s^* \to D_s^+ \gamma}$	$\Gamma[\mathcal{B}]_{D_s^* \to D_s^+ \pi^0}$	$\mathcal{B}_{D_s^{*+} \to D_s^+ \pi^0} / \mathcal{B}_{D_s^{*+} \to D_s^+ \gamma}$
This work	$\ldots[(93.57 \pm 0.38 \pm 0.22)\%]$	$\ldots[(5.76 \pm 0.38 \pm 0.16)\%]$	$(6.16 \pm 0.43 \pm 0.18)\%$
PDG [17]	$\ldots[(94.2 \pm 0.7)\%]$	$\ldots[(5.9 \pm 0.7)\%]$	$(6.2 \pm 0.8)\%$
CM [14]	$3.53\ [(92.7 \pm 0.7)\%]$	$0.277^{+0.028}_{-0.026}\ [(7.3 \pm 0.7)\%]$	$(7.9 \pm 0.8)\%$
χPT [2][a]	4.5	$\ldots$	$\ldots$
χPT [3]	$\ldots$	$\ldots$	$8 \times 10^{-5} / \mathcal{B}(D^{*+} \to D^+ \gamma)$
χPT [4]	0.32 ± 0.30	$\ldots$	
χPT [5]	$\ldots$	$0.0081^{+0.0030}_{-0.0026}$	
LFQM [6][b]	0.18 ± 0.01	$\ldots$	
RQM [7][c]	$0.321^{+0.009}_{-0.008}$	$\ldots$	
QCDSR [8]	0.25 ± 0.08	$\ldots$	
QCDSR [9]	0.59 ± 0.15	$\ldots$	
NJLM [10]	0.09	$\ldots$	
LQCD [11]	0.066 ± 0.026	$\ldots$	
NRQM [12]	0.21	$\ldots$	
NRQM [13][d]	0.40	$\ldots$	

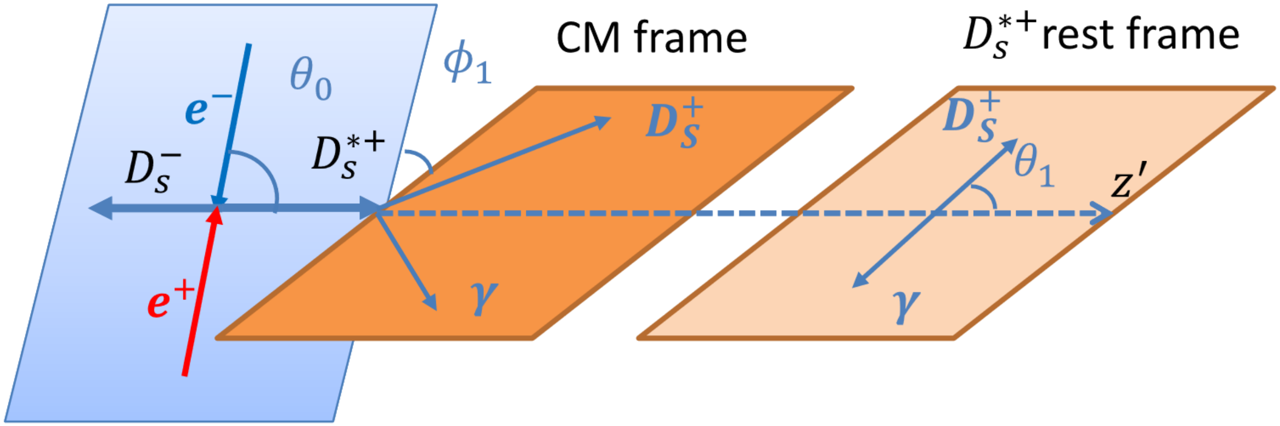
Covariant model
Eur. Phys. J. C 76, 19 (2016)

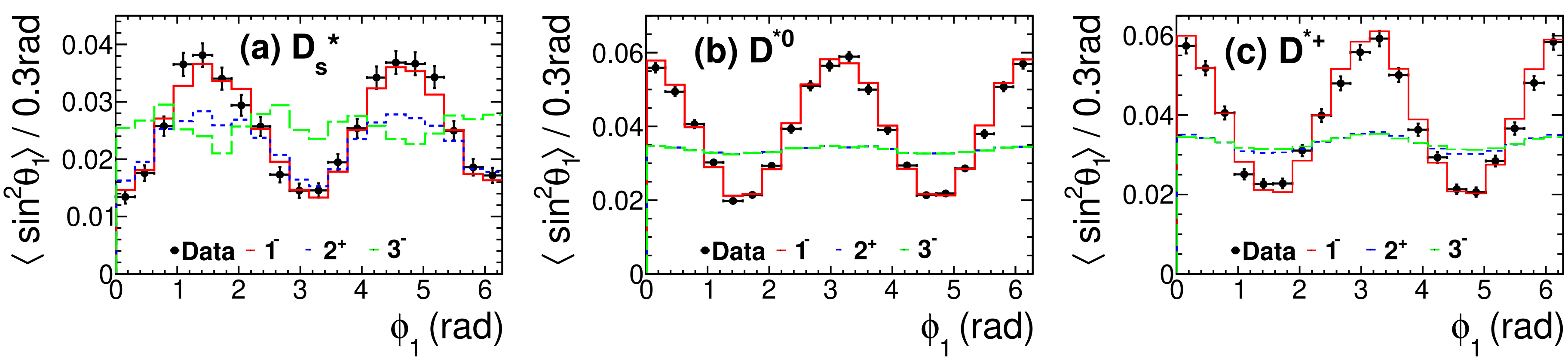


The most precise measurement

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

- 3.19 fb^{-1} of data at 4.178 GeV
- Determined $J^P = 1^-$ for $D^*_{(s)}$ Via $D_s^{*+} \to D_s^+\gamma, D^{*0} \to D^0\pi^0, \text{and} D^{*+} \to D^+\pi^0$



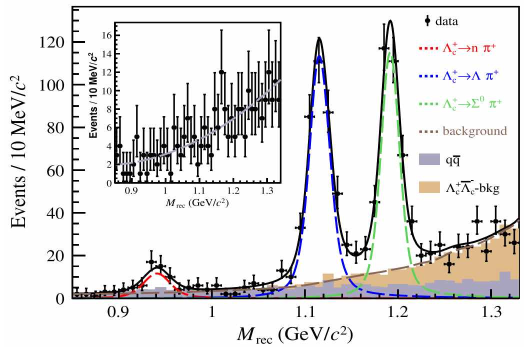


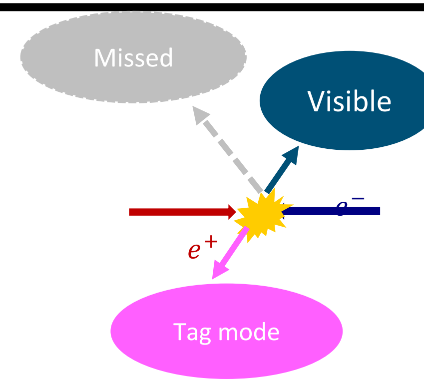
Λ_c Decay

➢ $\Lambda_c^+ \to n\pi^+$(SCS) PRL 128, 142001 (2022)

$\mathcal{B}(\Lambda_c^+ \to n\pi^+) \times 10^{-4}$	$\frac{\mathcal{B}(\Lambda_c^+ \to n\pi^+)}{\mathcal{B}(\Lambda_c^+ \to p\pi^0)}$	Reference
4	2	PRD 55, 7067 (1997)
9	2	PRD 93, 056008 (2016)
11.3 ± 2.9	2	PRD 97, 073006 (2018)
8 or 9	4.5 or 8.0	PRD 49, 3417 (1994)
2.66	3.5	PRD 97, 074028 (2018)
6.1 ± 2.0	4.7	PLB 790, 225 (2019)
7.7 ± 2.0	9.6	JHEP 02 (2020) 165
$6.6 \pm 1.2 \pm 0.4$	> 7.2 @ 90% C.L.	this work

topological-diagram approach





➢ $\Lambda_c^+ \to n\pi^+\pi^0, n\pi^+\pi^-\pi^+$(CS) and

$\Lambda_c^+ \to nK^-\pi^+\pi^+$ (CF) Chin. Phys. C47, 023001 (2023)

Decay Mode	$\mathcal{B}(\%)$	Sig.(σ)
$\Lambda_c^+ \to n\pi^+\pi^0$	$(0.64 \pm 0.09 \pm 0.02)$	7.9
$\Lambda_c^+ \to n\pi^+\pi^-\pi^+$	$(0.45 \pm 0.07 \pm 0.03)$	7.8
$\Lambda_c^+ \to nK^-\pi^+\pi^+$	$(1.90 \pm 0.08 \pm 0.09)$	>10

- $\frac{\mathcal{B}(\Lambda_c^+ \to n\pi^+\pi^-\pi^+)}{\mathcal{B}(\Lambda_c^+ \to nK^-\pi^+\pi^+)} = 0.24 \pm 0.04$
- Consistent with $|V_{cd}|/|V_{cs}| =$ (0.224 ± 0.005)

➢ $\bar{\Lambda}_c^- \to \bar{n} + X$ arXiv:2210.09561

- $\bar{n}$ identification
  - Most energetic shower in the EMC
  - A data driven method for the better simulation of $\bar{n}$ Nucl.Instrum.Meth.A 1033 (2022) 166672
- $\mathcal{B}(\bar{\Lambda}_c^- \to \bar{n} + X) =$ $(33.5 \pm 0.7 \pm 1.2)\%$
- $\mathcal{B}(\Lambda_c^+ \to n + X) =$ $(33.5 \pm 0.7 \pm 1.2)\%$
  - Ignoring CPV
- $\mathcal{B}^{sum}_{exclusive} \approx 25\%$
- 1/4 decay channels are not observed