BESIII

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PANIC Lisbon Portugal

Hadronic decays of charmed hadrons at BESIII

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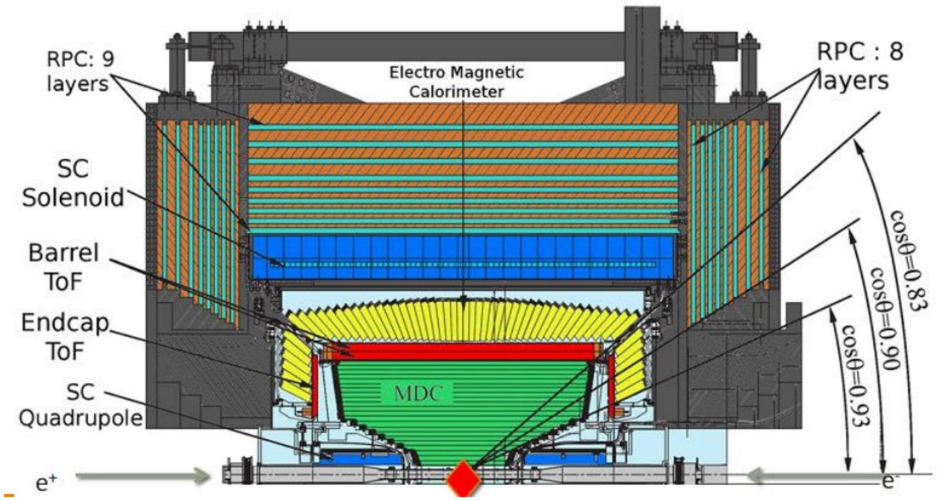
Outline

- Introduction
- Strong phase difference measurements
- Amplitude analyses of D_s decays
- Branching fraction results
- Summary

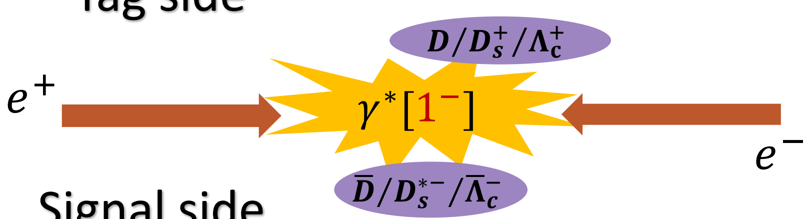
BESIII



Data samples	$\sqrt{s}$ (GeV)	Int. $\mathcal{L}$ (fb^{-1})
$D\bar{D}$	3.773	2.93
$D_s^+ D_s^{*-}$	4.178	3.19
$D_s^+ D_s^{*-}$	4.189-4.226	3.18
$\Lambda_c^+ \bar{\Lambda}_c^-$	4.599	0.567
$\Lambda_c^+ \bar{\Lambda}_c^-$	4.612-4.698	3.8

A Double-Tag(DT) event

Tag side



Signal side

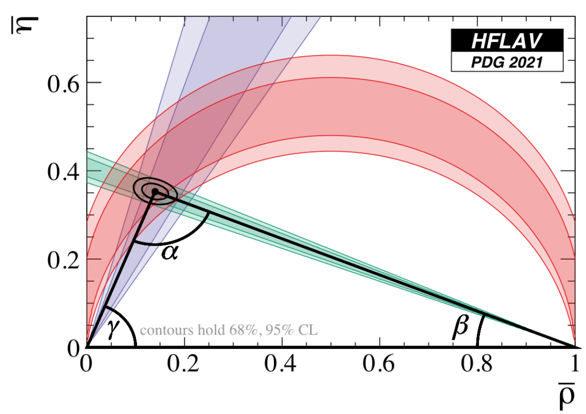
- $\Delta E = E_D - E_{Beam}$
- $M_{BC} = \sqrt{s/4 - |\vec{p}_D|^2}$
- $M_{rec} = \sqrt{[E_{cm} - (\vec{p}_{D_s}^{\,2} + m_{D_s}^2)^{\frac{1}{2}}]^2 - |\vec{p}_{D_s}|^2}$

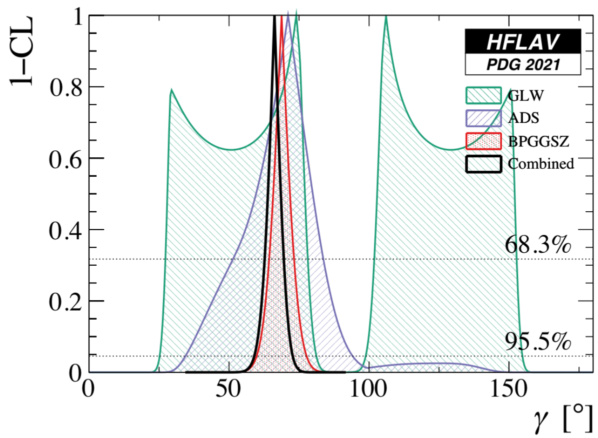
- $N_{ST} = 2 \cdot N_{D\bar{D}} \cdot \epsilon_{ST} \cdot B_{ST}$
- $N_{DT} = 2 \cdot N_{D\bar{D}} \cdot \epsilon_{DT} \cdot B_{Tag} \cdot B_{Sig}$

Quantum-coherent $D\bar{D}$

- Improving measurement result of γ in CKM unitarity triangle is one key to test SM and search NP
- Strong phases of $K^0\pi\pi$, K^0KK, $K^-\pi^+\pi^+\pi^-$ and $K^-\pi^+\pi^0$ are key inputs to γ measurement

$$\Gamma(F|G) \propto A_F^2\bar{A}_G^2 + \bar{A}_F^2A_G^2 - 2R_FR_GA_F\bar{A}_FA_G\bar{A}_G\cos(\delta_D^F - \delta_D^G)$$





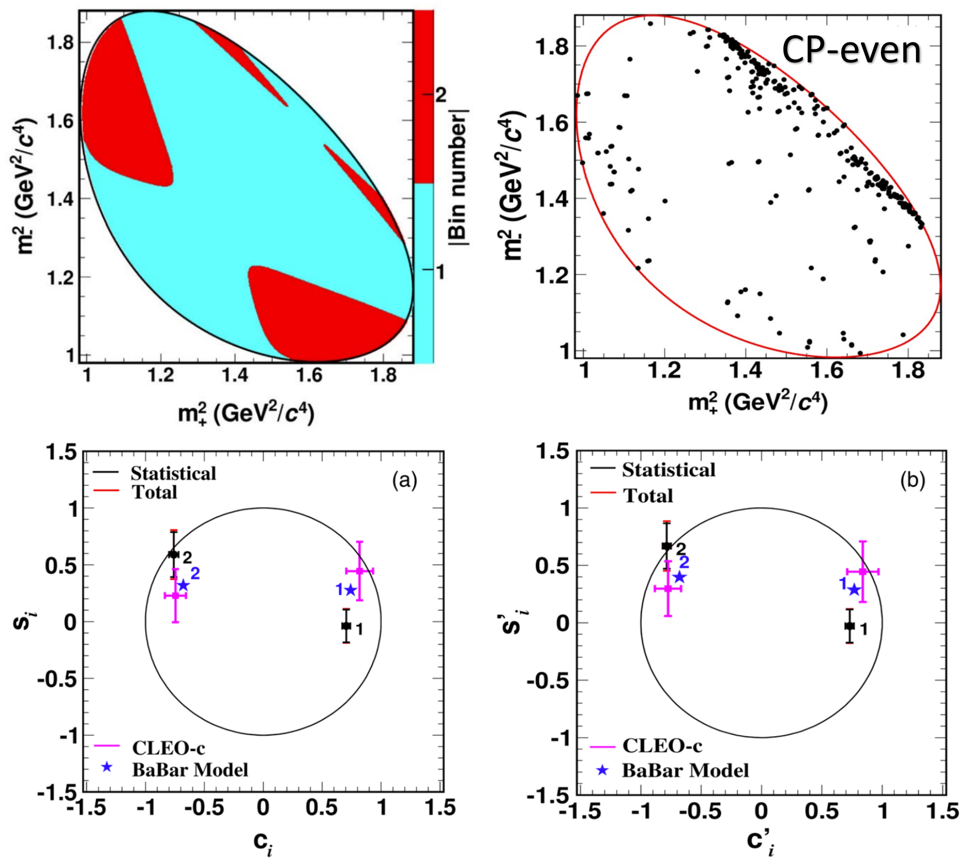
Method	γ
Direct[1]	$(66.2^{+3.4}_{-3.6})^\circ$
Indirect[2]	$(63.4^{+0.9}_{-0.9})^\circ$

[1]: PDG 2021
[2]: JHEP03((2020) 112

$c_i^{(\prime)}, s_i^{(\prime)}$ of $D \to K_{S/L}KK$

$$c_i \equiv \frac{1}{\sqrt{F_i F_{-i}}} \int_i |f_D(m_+^2, m_-^2)||f_D(m_-^2, m_+^2)| \times \cos[\Delta\delta_D(m_+^2, m_-^2)] dm_+^2 dm_-^2,$$

$$s_i \equiv \frac{1}{\sqrt{F_i F_{-i}}} \int_i |f_D(m_+^2, m_-^2)||f_D(m_-^2, m_+^2)| \times \sin[\Delta\delta_D(m_+^2, m_-^2)] dm_+^2 dm_-^2.$$



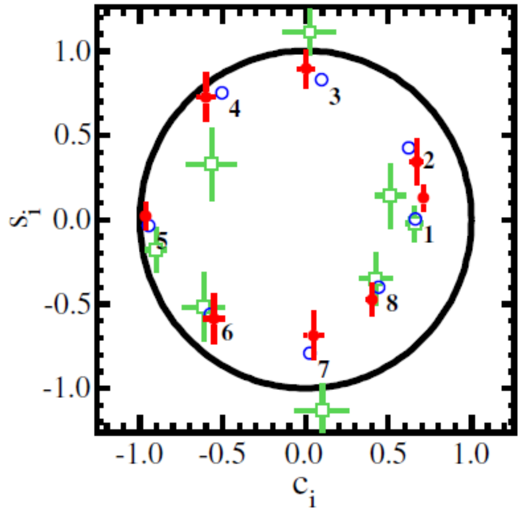
PhysRevD.102.052008

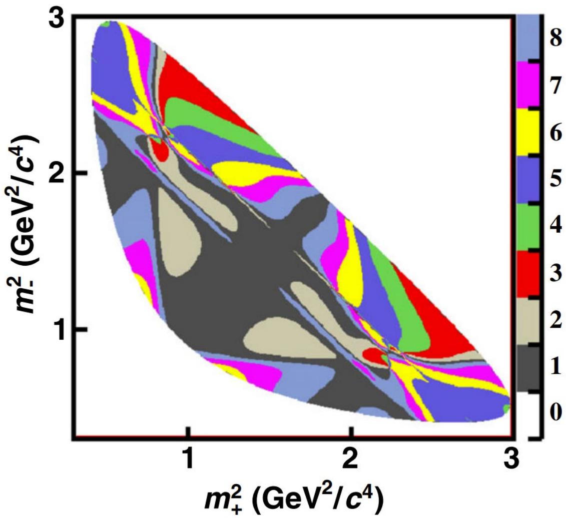
- Good agreement with the previous measurements by CLEO Collaboration
- Uncertainties on γ are $2.3°, 1.3°, 1.3°$ for N=2,3,4 binning schemes

$c_i^{(\prime)}, s_i^{(\prime)}$ of $D \to K_{S/L}\pi\pi$

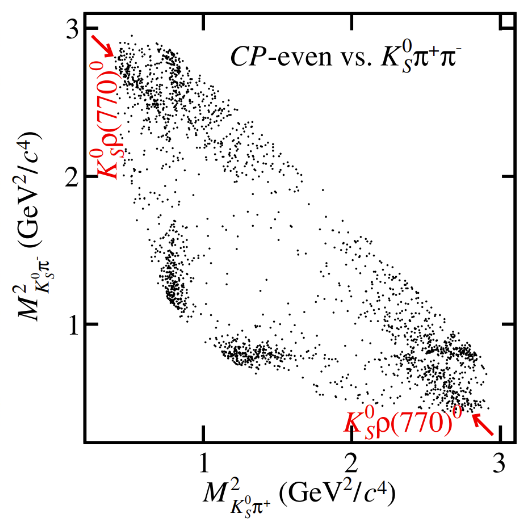
- A factor of ~2.5 (2.0) more precise for $c_i(s_i)$ than previous results
- The associated uncertainty on γ is reduced from ~3° to ~1° in $B^- \to D(K_S\pi\pi)K^-$[GGSZ]

- Red: this work   Blue: expected values [PRD 98,110212(2018)]   Green: CLEO-c results





[Equal $\Delta\delta_D$]



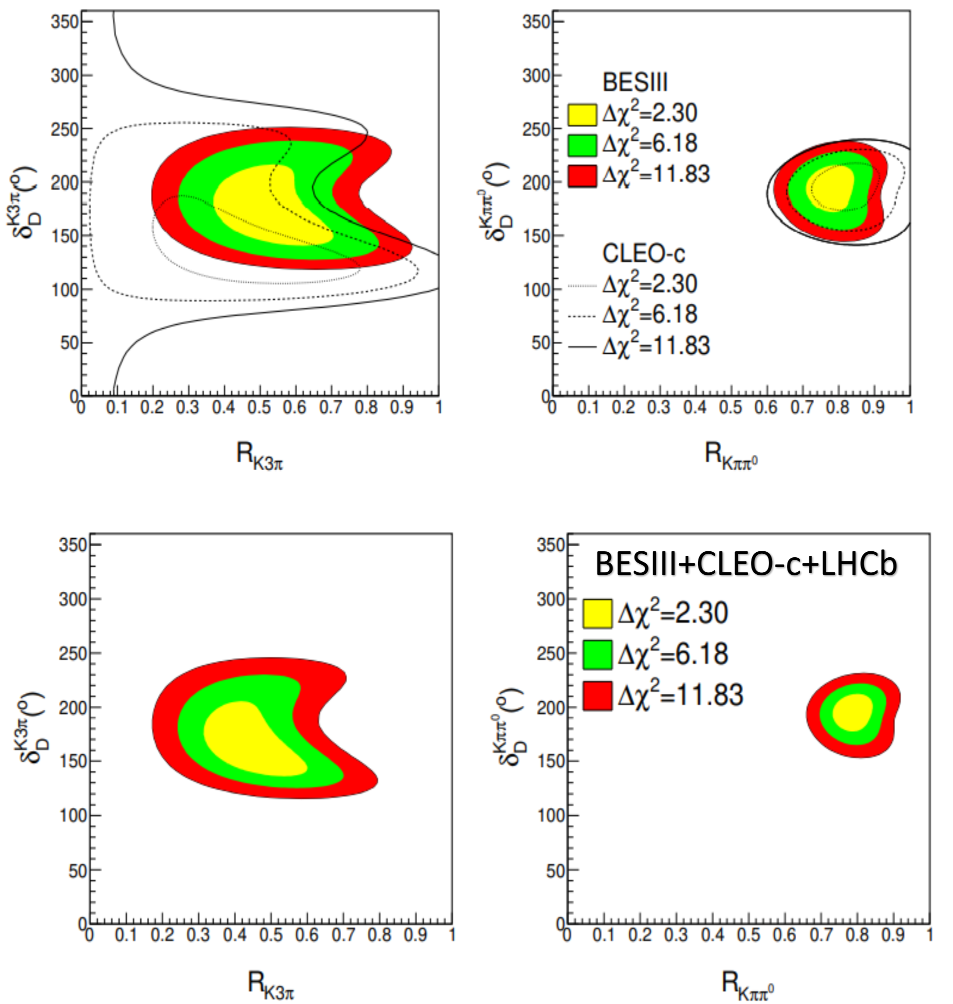
PhysRevD.101.112002
PhysRevLett.124.241802

Hadronic parameters δ_D and R_D

- The result is more precise than the existing world average values with more restricted allowed region planes

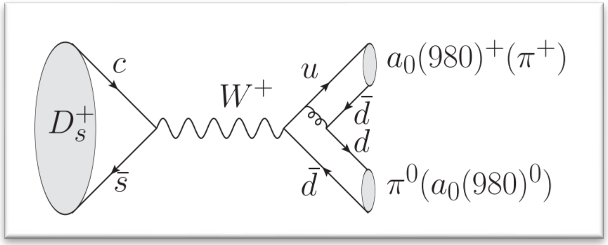
$$R_{K3\pi} = 0.52^{+0.12}_{-0.10}$$
$$\delta_D^{K3\pi} = (167^{+31}_{-19})^\circ$$
$$R_{K\pi\pi^0} = 0.78 \pm 0.04$$
$$\delta_D^{K\pi\pi^0} = \left(196^{+14}_{-15}\right)^\circ$$

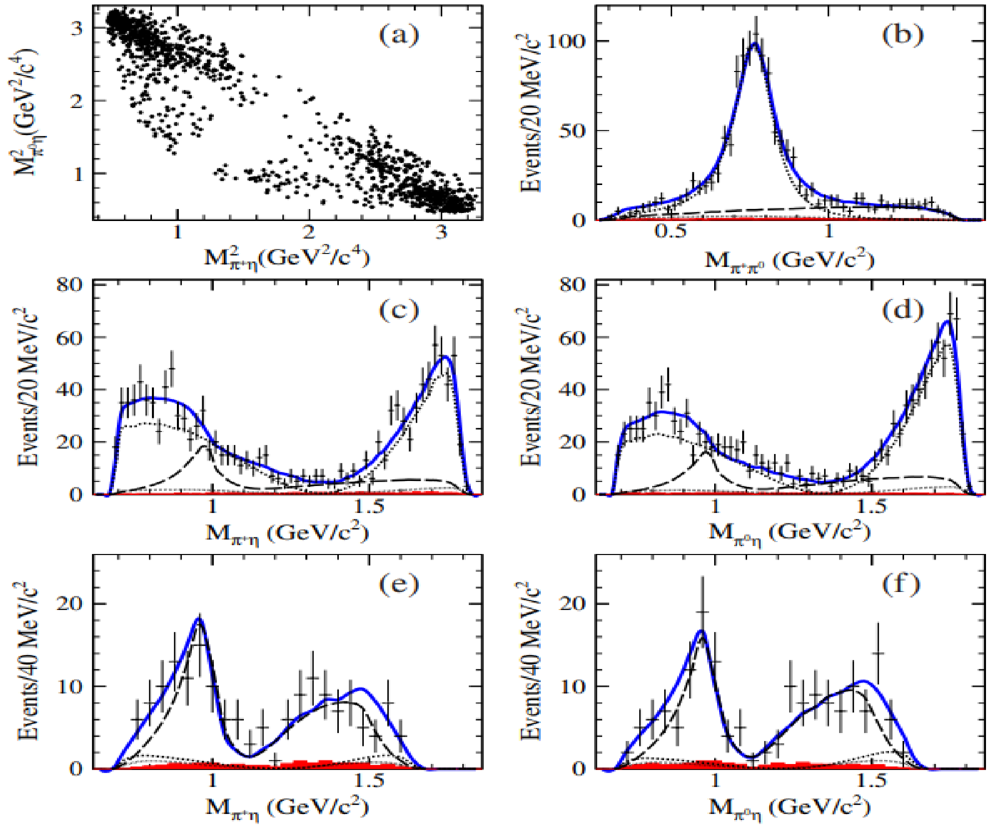
- Uncertainty on γ is around 6° (binned $K3\pi$)



JHEP05(2021)164

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





- Retaining 1239 signal event with a purity of $(97.7 \pm 0.5)\%$
- First observation of $D_s^+ \to a_0(980)^{+(0)}\pi^{0(+)}$, with a statistical significance of 16.2σ (4.178 GeV data only)
- Branching fraction is larger than other WA decays significantly

Amplitude	ϕ_n (rad)	FF$_n$
$D_s^+ \to \rho^+\eta$	0.0 (fixed)	$0.783 \pm 0.050 \pm 0.021$
$D_s^+ \to (\pi^+\pi^0)_V\eta$	$0.612 \pm 0.172 \pm 0.342$	$0.054 \pm 0.021 \pm 0.025$
$D_s^+ \to a_0(980)\pi$	$2.794 \pm 0.087 \pm 0.044$	$0.232 \pm 0.023 \pm 0.033$

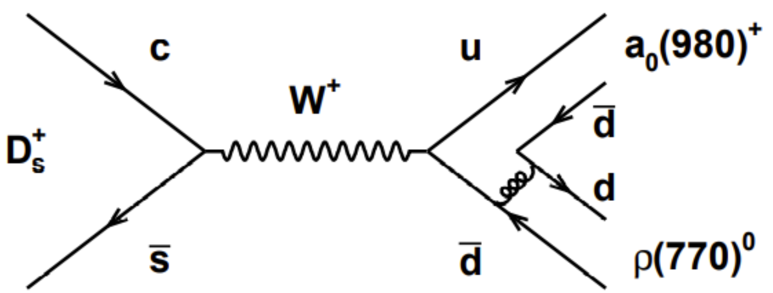
$$B(D_s^+ \to \pi^+\pi^0\eta) = (9.5 \pm 0.28 \pm 0.41)\%$$

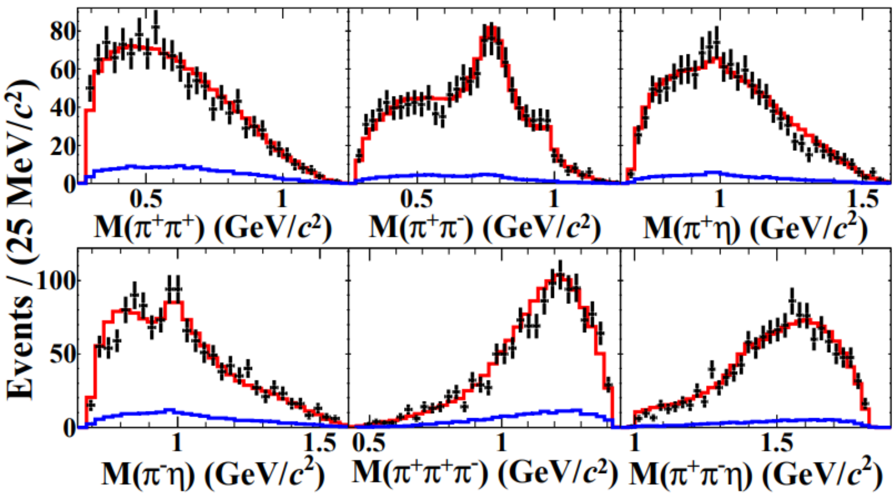
$$B\left(D_s^+ \to a_0(980)^{+(0)}_{\pi\eta}\pi^{0(+)}\right) = (1.46 \pm 0.15 \pm 0.23)\%$$

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

arXiv:2106.13536

- Signal purity is greater than 85% after selections
- $D_s^+ \to \eta 2\pi^+\pi^-$ is observed for the first time, BF is $(3.12 \pm 0.13 \pm 0.09)\%$
- $D_s^+ \to a_0(980)^+_{\pi\eta}\rho(770)^0$ is observed, BF is $(0.21 \pm 0.08 \pm 0.05)\%$
- First study of WA process with VS final state
- Provide useful input to reduce sys of R(D*)
  - → Improve LFU result





Amplitude	Phase	FF(%)
$a_1(1260)^+(\rho(770)^0\pi^+)\eta$	0.0(fixed)	$55.4 \pm 3.9 \pm 2.0$
$a_1(1260)^+(f_0(500)\pi^+)\eta$	$5.0 \pm 0.1 \pm 0.1$	$8.1 \pm 1.9 \pm 2.1$
$a_0(980)^+\rho(770)^0$	$2.5 \pm 0.1 \pm 0.1$	$6.7 \pm 2.5 \pm 1.5$
$\eta(1405)(a_0(980)^-\pi^+)\pi^+$	$0.2 \pm 0.2 \pm 0.1$	$0.7 \pm 0.2 \pm 0.1$
$\eta(1405)(a_0(980)^+\pi^-)\pi^+$	$0.2 \pm 0.2 \pm 0.1$	$0.7 \pm 0.2 \pm 0.1$
$f_1(1420)(a_0(980)^-\pi^+)\pi^+$	$4.3 \pm 0.2 \pm 0.4$	$1.9 \pm 0.5 \pm 0.3$
$f_1(1420)(a_0(980)^+\pi^-)\pi^+$	$4.3 \pm 0.2 \pm 0.4$	$1.7 \pm 0.5 \pm 0.3$
$[a_0(980)^-\pi^+]_S\pi^+$	$0.1 \pm 0.2 \pm 0.2$	$5.1 \pm 1.2 \pm 0.9$
$[a_0(980)^+\pi^-]_S\pi^+$	$0.1 \pm 0.2 \pm 0.2$	$3.4 \pm 0.8 \pm 0.6$
$[f_0(980)\eta]_S\pi^+$	$1.4 \pm 0.2 \pm 0.3$	$6.2 \pm 1.7 \pm 0.9$
$[f_0(500)\eta]_S\pi^+$	$2.5 \pm 0.2 \pm 0.3$	$12.7 \pm 2.6 \pm 2.0$

Branching fractions

- D decays
  - New decay: $D^+ \to K^+\pi^+\pi^-\pi^0$ [PhysRevLett.125.141802]
  - Absolute BF: 14 exclusive D decays to η [PhysRevLett.124.241803]
  - New method: Semileptonic tagged $D^+ \to K^+\pi^+\pi^-\pi^0$ [arXiv: 2105.14310]

Decay mode	$\mathbf{N_{signal}}$	$\mathbf{B_{sig}}(\times 10^{-4})$	
$D^+ \to K^+\pi^+\pi^-\pi^0$	350(22)	11.3(8)(3)	Evidence for CPV X Evidence for $D^+ \to K^+\omega$ √
Semileptonic tag $D^+ \to K^+\pi^+\pi^-\pi^0$	112(12)	10.3(12)(6)	Consistent with previous result, method verified
$D^0 \to K^-\pi^+\eta$	6126(82)	185.3(25)(31)	Consistent with Belle's
$D^0 \to K_S\pi^0\eta$	1093(35)	100.6(34)(30)	Better precision
Total $D^0 \to \eta X$	--	$(8.62 \pm 0.35)\%$	≈inclusive rate $(9.5 \pm 0.9)\%$
Total $D^+ \to \eta X$	--	$(4.68 \pm 0.18)\%$	≈inclusive rate $(6.5 \pm 0.7)\%$

Branching fractions

- Absolute measurement with higher precision
  - D_s decays: 7 $D_s^+ \to PP$ decays [JHEP08(2020)146]
  - Λ_c decays (4.599 GeV data only): $\Lambda_c^+ \to pK_S\eta$ [PhyLettB 817 (2021) 136327],

Decay mode	$\mathrm{N_{signal}}$	$\mathrm{B_{sig}}(\times 10^{-3})$	
$D_s^+ \to K^+\eta'$	675(43)	2.68(17)(17)(8)	Higher precision than CLEO's results
$D_s^+ \to \pi^+\eta'$	9912(113)	37.8(4)(2)(1)	
$D_s^+ \to K^+\eta$	1841(114)	1.62(10)(3)(5)	
$D_s^+ \to \pi^+\eta$	19519(192)	17.41(18)(27)(54)	
$D_s^+ \to K^+K_S$	35977(206)	15.02(10)(27)(47)	
$D_s^+ \to \pi^+K_S$	2724(83)	1.109(34)(23)(35)	
$D_s^+ \to K^+\pi^0$	2275(149)	0.748(49)(18)(23)	
$\Lambda_c^+ \to pK_S\eta$	42(9)	4.14(84)(28)	Observed with 5.3σ significance

Summary

- Improved strong phase difference measurement results of $K_S\pi\pi, K_S KK, \mathrm{K}3\pi, K\pi\pi^0$, their uncertainties on γ measurement have been reduced
- More amplitude analyses of D_s^+ have been done
  - WA processes are studied in VP and SP final states
  - Observe $D_s^+ \to a_0(980)\pi$ for the first time
- Enhance branching fraction results of charmed hadron decays with higher precision, helping deepen theoretical understandings
- More results will come soon based on the large dataset at high energy

THANK YOU!

BACKUP

Strong phase formalism

- The strong phase δ_D and coherence factor R are defined as:

$$r_D^S = A_{\bar{S}}/A_S. \qquad A_S^2 = \int |\mathcal{A}_S(\mathbf{x})|^2 \mathrm{d}\mathbf{x},$$

$$R_S e^{-i\delta_D^S} = \frac{\int \mathcal{A}_S^\star(\mathbf{x}) \mathcal{A}_{\bar{S}}(\mathbf{x}) \mathrm{d}\mathbf{x}}{A_S A_{\bar{S}}}$$

- Equations:

$$\Gamma(S|CP) = A_S^2 A_{CP}^2 \left(1 + (r_D^S)^2 - 2\lambda R_S r_D^S \cos\delta_D^S\right)$$

$$\Gamma(S|S) = A_S^2 A_{\bar{S}}^2 \left[1 - R_S^2\right].$$

$$Y_i^S = H\left(K_i + \left(r_D^S\right)^2 K_{-i} - 2 r_D^S R_S \sqrt{K_i K_{-i}} \left[c_i \cos\delta_D^S - s_i \sin\delta_D^S\right]\right)$$

$$M_{ij} = h_{\mathrm{corr}}\left[K_i K_{-j} + K_{-i} K_j - 2\sqrt{K_i K_{-j} K_{-i} K_j}(c_i c_j + s_i s_j)\right]$$

Amplitude analysis method

- Amplitude model for each intermediate state:

$$A_n = P_n^1 P_n^2 S_n F_n^1 F_n^2 F_n^3,$$

- Amplitude model of total decay:

$$M = \sum c_n A_n, \qquad c_n = \rho_n e^{i\phi_n}$$

- Signal PDF:

$$f_S(p_j) = \frac{\epsilon(p_j)|M(p_j)|^2 R_4(p_j)}{\int \epsilon(p_j)|M(p_j)|^2 R_4(p_j) dp_j},$$

Amplitude analysis results

- D_s^+ decay:
  - $D_s^+ \to K_S\pi^+\pi^0$ [JHEP06(2021)181]
  - $D_s^+ \to K^+K^-\pi^+\pi^0$ [PhysRevD.104.032011]
  - $D_s^+ \to K^+K^-\pi^+$ [PhysRevD.104.012016]
  - $D_s^+ \to K_SK^-\pi^+\pi^+$[PhysRevD.103.092006]
- D decay:
  - $D^+ \to K_SK^+\pi^0$ [PhysRevD.104.012006]
  - $D^0 \to K_SK^+K^-$ [arXiv:2006.02800]

Branching fraction results

- D and Λ_c^+ decays:

Mode		$B(\times 10^{-3})$	Ref
D^0	$K^+K^-\pi^+\pi^-$	0.69(7)(4)	PhysRevD.102.052006
	$K_SK_S\pi^+\pi^-$	0.53(9)(3)	
	$K_SK^-\pi^+\pi^0$	1.32(14)(7)	
	$K_SK^+\pi^-\pi^0$	0.65(7)(2)	
D^+	$K^+K^-\pi^+\pi^0$	6.62(20)(25)	
	$K_SK^+\pi^0\pi^0$	0.58(12)(4)	
	$K_SK^-\pi^+\pi^+$	2.27(12)(6)	
	$K_SK^+\pi^+\pi^-$	1.89(12)(5)	
	$K_SK_S\pi^+\pi^0$	1.34(20)(6)	
$D^0 \to \omega\pi^+\pi^-$		1.33(16)(12)	PhysRevD.102.052003
$D^+ \to \omega\pi^+\pi^0$		3.87(83)(25)	
$D^0 \to \omega\pi^0\pi^0$		<1.10	
$D^+ \to \eta\eta\pi^+$		2.96(24)(10)	PhysRevD.101.052009
$D^+ \to \eta\pi^+\pi^0$		2.23(15)(10)	
$D^0 \to \eta\pi^+\pi^-$		1.20(7)(4)	
$\Lambda_c^+ \to K_SX$		99(60)(40)	EurPhysJC(2020)80:935