Measurement of Branching Fractions and Search for *CP* Violation in $D^0 \to \pi^+\pi^-\eta$, $D^0 \to K^+K^-\eta$, and $D^0 \to \phi\eta$ at Belle

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Outline

Motivation

- Singly Cabibbo-suppressed (SCS) charm decays are important and special for studying weak interactions as they provide us a unique window on physics of the decay-rate dynamics and CP violation.
- The first and only observation of charm CP violation has been achieved at LHCb: $\Delta A_{CP}(D^0 \to K^+K^-, \pi^+\pi^-)$[a].
- Here we extend these SCS decays with an additional η meson in the final state, to measure their time-integrated CP asymmetries and branching fractions ($\mathcal{B}$).
  - For $D^0 \to \pi^+\pi^-\eta$: $\delta\mathcal{B}/\mathcal{B} \sim 6\%$[b]; $A_{CP} = (-9.6 \pm 5.7)\%$[c].
  - For $D^0 \to K^+K^-\eta$: no total $\mathcal{B}$ result; but having $\delta\mathcal{B}/\mathcal{B}(D^0 \to \eta(K^+K^-)_{\text{non}-\phi}) \sim 35\%$[d]; $\delta\mathcal{B}/\mathcal{B}(D^0 \to \phi\eta) \sim 20\%$[e, f].
  - Reference Cabibbo-favored (CF) mode $D^0 \to K^-\pi^+\eta$ is well-measured with $\delta\mathcal{B}/\mathcal{B} \sim 2\%$[b] and Dalitz-plot analysis result[g].
- Search for the intermediate processes, e.g. $D^0 \to \phi\eta, \rho\eta, a_0(980)\pi$, etc. None of these dominant intermediate processes has been observed to date. For example in $D^0 \to \pi^+\pi^-\eta$, due to statistics limit:
  - CLEO: "Surprisingly, there are no significant contributions from either $\eta\rho^0$ or $a_0(980)\pi^+$." [h]
  - BESIII: "there are no significant ρ and $a_0(980)$ signals in these Dalitz plots." [c]
  - Belle: any interesting observations benefiting from large charm samples (980 fb^{-1}, $\sigma(c\bar{c}) = 1.3$ nb).

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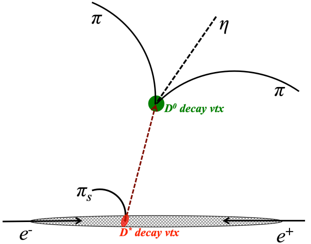
[a] LHCb, Phys. Rev. Lett. **122**, 211803 (2019)
[b] PDG2021, PTEP 2020 (2020) 083C01
[c] BESIII, Phys. Rev. D **101**, 052009 (2020)
[d] BESIII, Phys. Rev. Lett. **124**, 241803 (2020)
[e] Belle, Phys. Rev. Lett. **92**, 101803 (2004)
[f] BESIII, Phys. Lett. B **798**, 135017 (2019)
[g] Belle, Phys. Rev. D **102**, 012002 (2020)
[h] CLEO, Phys. Rev. D **77**, 092003 (2008)

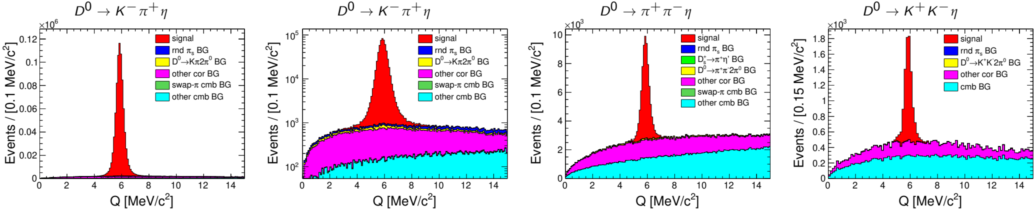
Event selections and optimization

Items	Requirements
charged tracks	at least two SVD hits in both $r\phi$ and z for tracks from D^0 $\mathcal{R} = \frac{\mathcal{L}_K}{\mathcal{L}_K+\mathcal{L}_\pi} > 0.6$ for kaon, others for pion eId < 0.95, μId < 0.95; $\lvert dr\rvert < 1$ cm and $\lvert dz\rvert < 3$ cm
$\eta \to \gamma\gamma$	$E_\gamma > 50$ or 100 MeV for barrel or endcup, and $e9o25 > 0.8$ $0.50 < M(\gamma\gamma) < 0.58$ GeV$/c^2$; mass constraint with $\chi^2_m < 8$ $p(\eta) > 0.7$ GeV$/c$; decay angle $\lvert\cos\theta\rvert < 0.85$ π^0-veto if both γ's meet $\lvert M(\gamma_\eta\gamma_{others}) - m_{\pi^0}\rvert < 10$ MeV$/c^2$
D^0 and D^*	$\lvert M(\pi^+\pi^-) - m_{K^0_S}\rvert > 10$ MeV$/c^2$ for $D^0 \to \pi^+\pi^-\eta$ vertex fit with two charged track; IP constraint fit for D^0; π_s refit at D^* vertex; these vertex fit qualities $\sum\chi^2_{\rm vtx} < 50$ $p^*(D^*) > 2.7$ GeV$/c$ $M \in m_D \pm 2\sigma$ and $0 < Q < 15$ MeV$/c^2$ (use Q to extract yields)
multi-candidates	BCS with smallest $\sum\chi^2_{\rm vtx} + \chi^2_m(\eta)$

e.g. $D^{*+} \to D^0\pi_s^+$, $D^0 \to \pi^+\pi^-\eta$

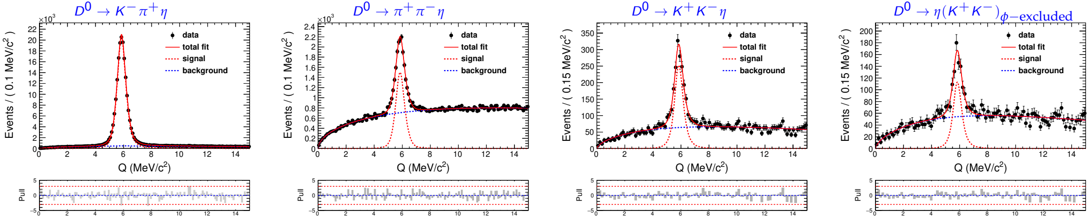


$Q = M(h^+h^-\eta\pi_s^+) - M(h^+h^-\eta) - m_{\pi_s^+}$



Extract signal yields

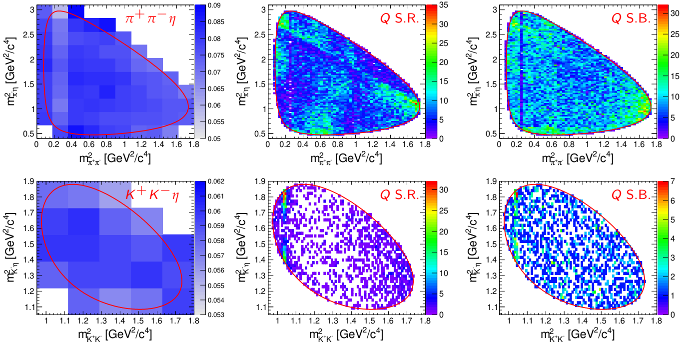
- We perform an unbinned extended maximum-likelihood fit on the Q distributions to extract the signal yields for these decay channels and also for $D^0 \to \eta(K^+K^-)_{\phi-\text{excluded}}$ with $|M_{KK} - m_\phi| > 20\ \text{MeV}/c^2$.



Region	Component	$D^0 \to K^-\pi^+\eta$	$D^0 \to \pi^+\pi^-\eta$	$D^0 \to K^+K^-\eta$	$D^0 \to \eta(K^+K^-)_{\phi-\text{excluded}}$
Fit region	signal	180369 ± 837	12982 ± 198	1482 ± 60	660 ± 49
	background	57752 ± 761	101011 ± 357	5681 ± 88	4804 ± 81
	fit quality	$\chi^2/(150-8) = 1.21$	$\chi^2/(150-6) = 1.02$	$\chi^2/(150-6) = 1.00$	$\chi^2/(150-6) = 0.96$
Signal region	signal	162456 ± 754	12053 ± 184	1343 ± 54	599 ± 45
	background	7578 ± 100	11274 ± 40	678 ± 11	576 ± 10

Measurement of $\mathcal{B}(D^0 \to h^+h^-\eta)$ with efficiency map correction

- The efficiency-corrected yield on Dalitz-plot: $N^{\rm cor} = \sum_i \frac{N_i^{\rm tot} - N^{\rm bkg} f_i^{\rm bkg}}{\varepsilon_i}$ to consider bin-to-bin variations of ε, where ε_i is the efficiency in the $i^{\rm th}$-bin based on PHSP signal MC; $N^{\rm tot}$ is yield in Q signal region; and $N^{\rm bkg}$ is the fitted background yield in Q signal region; $f_i^{\rm bkg}$ is the fraction of background in the $i^{\rm th}$-bin, with $\sum_i f_i = 1$, obtaining from the Dalitz-plot in Q sideband.



S.R. = signal region;
S.B. = sideband region

Then we have $\frac{\mathcal{B}(D^0\to h^+h^-\eta)}{\mathcal{B}(D^0\to K^-\pi^+\eta)} = \frac{N^{\rm cor}(D^0\to h^+h^-\eta)}{N^{\rm cor}(D^0\to K^-\pi^+\eta)}$

$$\frac{\mathcal{B}(D^0\to\pi^+\pi^-\eta)}{\mathcal{B}(D^0\to K^-\pi^+\eta)} = [6.49 \pm 0.09\,({\rm stat}) \pm 0.12\,({\rm syst})] \times 10^{-2}$$

$$\frac{\mathcal{B}(D^0\to K^+K^-\eta)}{\mathcal{B}(D^0\to K^-\pi^+\eta)} = [9.57^{+0.36}_{-0.33}\,({\rm stat}) \pm 0.20\,({\rm syst})] \times 10^{-3}$$

$$\frac{\mathcal{B}(D^0\to K^+K^-\eta)_{\rm ex.-\phi}}{\mathcal{B}(D^0\to K^-\pi^+\eta)} = [5.26^{+0.45}_{-0.38}\,({\rm stat}) \pm 0.11\,({\rm syst})] \times 10^{-3}$$

Using $\mathcal{B}(D^0 \to K^-\pi^+\eta) = (1.877 \pm 0.036)\%$[g], we have the absolute branching fractions of $D^0 \to \pi^+\pi^-\eta$, $K^+K^-\eta$, and $\eta(K^+K^-)_{\rm ex.-\phi}$, respectively:

$[1.22 \pm 0.02\,({\rm stat}) \pm 0.02\,({\rm syst}) \pm 0.02\,(\mathcal{B}_{\rm ref})] \times 10^{-3}$

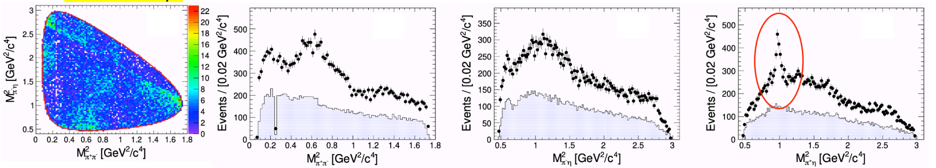
$[1.80^{+0.07}_{-0.06}\,({\rm stat}) \pm 0.04\,({\rm syst}) \pm 0.03\,(\mathcal{B}_{\rm ref})] \times 10^{-4}$

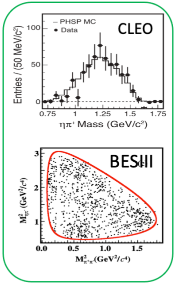
$[0.99^{+0.08}_{-0.07}\,({\rm stat}) \pm 0.02\,({\rm syst}) \pm 0.02\,(\mathcal{B}_{\rm ref})] \times 10^{-4}$.

the last one is somewhat higher (but more precise) than a similar measurement by BESIII[d] $(0.59 \pm 0.19) \times 10^{-4}$.

Dalitz plots and projections with some interesting observations

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

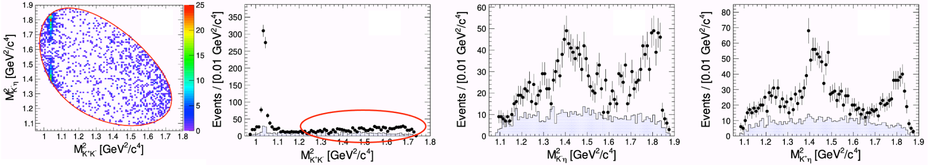




- Clear rho(770) and a0(980)+ (no visible intermediate process in CLEO and BESIII results due to the statisitcs limit.) => amplitude analysis is needed. But not included in this analysis.

Comparison Decay	theoretical Amplitude	$\mathcal{B}_{\rm naive}$	$\mathcal{B}_{\rm FSI}$	Experimental $\mathcal{B}_{\rm exp}$
$D^0 \to a_0(980)^+\pi^-$	$V_{cd}V^*_{ud}(T'+E)$	1.7×10^{-7}	6.5×10^{-5}	$(4.5 \pm 3.0) \times 10^{-3}$
$D^0 \to a_0(980)^-\pi^+$	$V_{cd}V^*_{ud}(T+E)$	1.3×10^{-3}	1.3×10^{-3}	$(1.0 \pm 1.1) \times 10^{-3}$
$\frac{\mathcal{B}(D^0\to a_0(980)^+\pi^-)}{\mathcal{B}(D^0\to a_0(980)^-\pi^+)}$		0.00013	0.05	4.5 ± 5.8

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

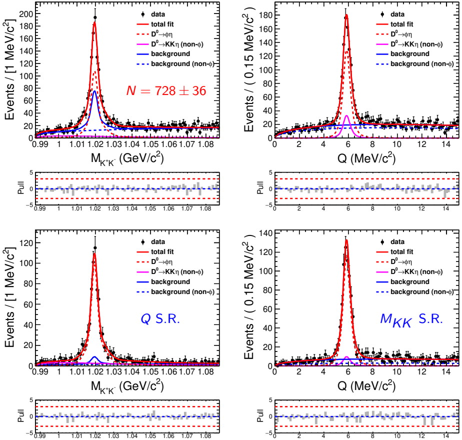


Dalitz-plot analysis is suggested by several colleagues at Belle.

- Clear phi(1020) signal (=>measure B(D0->ϕη) as next step), and visible non-phi component.
- an asymmetric helicity distribution of K in KK system in phi(1020) region, it indicates some interference due to $a_0/f_0(980)$ and ϕ(1020).

Measurement of $\mathcal{B}(D^0 \to \phi\eta)$

- To extract the yield of this SCS and color-suppressed decay $D^0 \to \phi\eta$, we perform M_{KK}-Q 2D fit instead of Q 1D fit, considering there is a Q-peaking background from non-ϕ $D^0 \to K^+K^-\eta$ component.



- The likelihood difference with and without including signal component $\Delta \ln \mathcal{L} = 464.8$ corresponds to a very high statistical significance (31σ) $\Rightarrow$ First observation
- Based on $N_{sig} = 600 \pm 29$ and $\varepsilon = (5.262 \pm 0.021)\%$ in signal region, the relative branching fraction is determined.
$$\frac{\mathcal{B}(D^0 \to \phi\eta, \phi \to K^+K^-)}{\mathcal{B}(D^0 \to K^-\pi^+\eta)} = [4.82 \pm 0.23\,(\text{stat}) \pm 0.16\,(\text{syst})] \times 10^{-3}.$$
- using $\mathcal{B}(D^0 \to K^-\pi^+\eta)$[g] and $\mathcal{B}_{\text{PDG}}(\phi \to K^+K^-)$, we have
$$\mathcal{B}(D^0 \to \phi\eta) = [1.84 \pm 0.09\,(\text{stat}) \pm 0.06\,(\text{syst}) \pm 0.04\,(\mathcal{B}_{\text{ref}})] \times 10^{-4},$$
which is consistent, but notably more precise than, previous results at Belle[e] and BESIII[f].
- As a consistency check, we calculate $\mathcal{B}(D^0 \to K^+K^-\eta)_{\text{non}-\phi}$ by $\mathcal{B}(D^0 \to K^+K^-\eta) - \mathcal{B}(D^0 \to \phi\eta, \phi \to K^+K^-) = (0.90 \pm 0.08) \times 10^{-4}$ which is very close to our measurement of $\mathcal{B}(D^0 \to K^+K^-\eta)_{\text{ex.}-\phi}$.

Introduction to time-integrated CP asymmetry measurement

- Time-integrated CP asymmetry for $D \to f$ decays: $A_{CP} = \frac{\mathcal{B}(D\to f)-\mathcal{B}(\bar{D}\to \bar{f})}{\mathcal{B}(D\to f)+\mathcal{B}(\bar{D}\to \bar{f})}$
- Taking D^0 decays for example, for the decay chain $e^+e^- \to c\bar{c} \to D^{*+}X$, $D^{*+} \to [D^0 \to f]\pi_s^+$, the raw asymmetry:

$$A_{\rm raw} = \frac{N_{\rm rec}(D^{*+}) - N_{\rm rec}(D^{*-})}{N_{\rm rec}(D^{*+}) + N_{\rm rec}(D^{*-})} = A_{\rm FB}^{D^{*+}} + A_{CP}^{D^0\to f} + A_{\varepsilon}^{f} + A_{\varepsilon}^{\pi_s},$$

  where forward-backward asymmetry $A_{\rm FB}$ is arising from γ-Z^0 interference and higher-order QED effects.

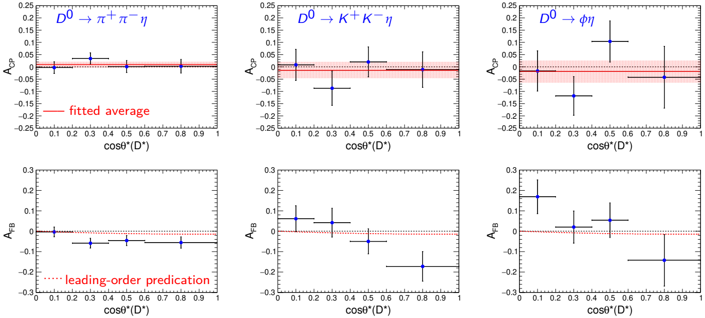
- Method (1): reference mode (CF or A_{CP} well-measured mode) to cancel same asymmetry sources, e.g. $\Delta A_{CP} = A_{CP}(D_s^+ \to \pi^0\pi^+) - A_{CP}(D_s^+ \to \phi\pi^+)$ where the latter one is well-measured.
- Method (2): correction method for the charged track detection asymmetry. e.g. in our decays, we weight events to correct the slow pion asymmetry: $w_{D^0,\bar{D}^0} = 1 \mp A_{\varepsilon}^{\pi_s}[\cos\theta(\pi_s), p_T(\pi_s)]$
- In our decay ($A_{\varepsilon}^{f} = 0$), the weighted samples give the π_s-corrected raw asymmetry: $\boxed{A_{\rm corr}(\cos\theta^*) = A_{CP} + A_{\rm FB}(\cos\theta^*)}$.
- Since A_{CP} is independent on $\cos\theta^*$ and $A_{\rm FB}(\cos\theta^*) = -A_{\rm FB}(-\cos\theta^*)$, we determine the asymmetries in multiple symmetric bins of $\cos\theta^*$:

$$A_{CP} = \frac{A_{\rm corr}(\cos\theta^*) + A_{\rm corr}(-\cos\theta^*)}{2}, \qquad A_{\rm FB} = \frac{A_{\rm corr}(\cos\theta^*) - A_{\rm corr}(-\cos\theta^*)}{2}.$$

  Finally, fitting these A_{CP} values to a constant gives the final measurement of $A_{CP}^{D^0\to f}$ that we are interested in.

Measurement of *CP* asymmetries

- Dividing samples into eight bins of $\cos\theta^*$, we perform a simultaneous fit on the Q or M_{KK}-Q distributions for D^0 and $\bar{D}^0$ samples in each $\cos\theta^*$ bin, giving the corrected raw asymmetry $A_{\rm corr}$: $N_{\rm sig}(D^0, \bar{D}^0) = N_{\rm sig}/2 \cdot (1 \pm A_{\rm corr})$.
- Then, using the formula in previous slide, we calculate four A_{CP} values and four $A_{\rm FB}$ values, as plotted in below figures.



Fitting these A_{CP} values to a constant gives:

$$A_{CP}(D^0 \to \pi^+\pi^-\eta) = [0.9 \pm 1.2\,(\text{stat}) \pm 0.5\,(\text{syst})]\%,$$
$$A_{CP}(D^0 \to K^+K^-\eta) = [-1.4 \pm 3.3\,(\text{stat}) \pm 1.1\,(\text{syst})]\%,$$
$$A_{CP}(D^0 \to \phi\eta) = [-1.9 \pm 4.4\,(\text{stat}) \pm 0.6\,(\text{syst})]\%,$$

where the first result represents a significant improvement in precision over previous result[c]; the later two are the first such measurements.

No evidence for *CP* violation is found in these SCS decays.

Systematic uncertainties on BR and A_{CP} measurements

Table: Relative systematic uncertainties on the branching ratio measurements.

Syst. sources	$\frac{\mathcal{B}(D^0 \to \pi^+\pi^-\eta)}{\mathcal{B}(D^0 \to K^-\pi^+\eta)}$	$\frac{\mathcal{B}(D^0 \to K^+K^-\eta)}{\mathcal{B}(D^0 \to K^-\pi^+\eta)}$	$\frac{\mathcal{B}(D^0 \to \phi\eta)\mathcal{B}(\phi \to K^+K^-)}{\mathcal{B}(D^0 \to K^-\pi^+\eta)}$
PID efficiency correction	1.8%	1.9%	1.9%
signal PDF	0.3%	0.5%	0.9%
background PDF	0.0%	0.0%	0.1%
mass resolution calibration	0.1%	0.3%	0.0%
yield correction with efficiency	0.3%	0.7%	–
MC statistics	0.3%	0.4%	0.4%
K_S^0 veto	0.1%	–	–
interference in $M(KK)$	–	–	2.5%
Total syst. error	1.9%	2.1%	3.3%
Vs. stat. error	1.6%	4.0%	6.6%

Table: The main systematic uncertainties for A_{CP} measurement.

Syst. sources	$\sigma_{A_{CP}}(D^0 \to \pi^+\pi^-\eta)$	$\sigma_{A_{CP}}(D^0 \to K^+K^-\eta)$	$\sigma_{A_{CP}}(D^0 \to \phi\eta)$
signal and bkg shape	0.4%	1.0%	0.6%
$\cos\theta^*$ Binning	0.2%	0.4%	0.2%
$\mathcal{A}_\epsilon(\pi_s)$ map (56 bins)	0.1%	0.1%	0.1%
Total syst. error	0.5%	1.1%	0.6%
Vs. stat. error	1.2%	3.0%	4.4%

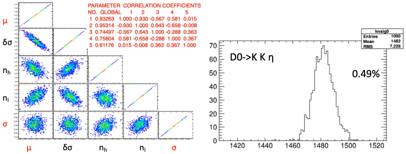


Figure: Sampling parameters with the covariance matrix; RMS/Mean of 1000 fitted yields as relative syst. error.

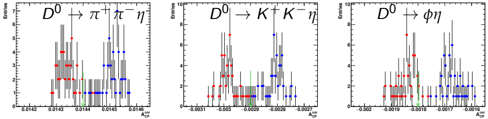


Figure: The distributions of 112 fitted $\mathcal{A}_{\rm corr}$ values after new 56 (56) $\mathcal{A}_\epsilon^{\pi_s}$ maps for $+1\sigma$ (-1σ) shift for bins one-by-one for red points (blue points). The resulting deviations from the nominal fit result (green arrows) are summed in quadrature, for $+1\sigma$ and -1σ separately, to give the syst uncertainty.

Summary

- Based on 980 fb^{-1} of data set at Belle experiment, we measure the branching fractions of three SCS decays (using reference mode $D^0 \to K^-\pi^+\eta$), and also their time-integrated CP asymmetries:

$$\mathcal{B}(D^0 \to \pi^+\pi^-\eta) = (1.22 \pm 0.02 \pm 0.02 \pm 0.02) \times 10^{-3} \qquad \mathcal{A}_{CP}(D^0 \to \pi^+\pi^-\eta) = (0.9 \pm 1.2 \pm 0.5) \times 10^{-2}$$
$$\mathcal{B}(D^0 \to K^+K^-\eta) = (1.80^{+0.07}_{-0.06} \pm 0.04 \pm 0.03) \times 10^{-4} \qquad \mathcal{A}_{CP}(D^0 \to K^+K^-\eta) = (-1.4 \pm 3.3 \pm 1.1) \times 10^{-2}$$
$$\mathcal{B}(D^0 \to \phi\eta) = (1.84 \pm 0.09 \pm 0.06 \pm 0.04) \times 10^{-4} \qquad \mathcal{A}_{CP}(D^0 \to \phi\eta) = (-1.9 \pm 4.4 \pm 0.6) \times 10^{-2}$$

- All these results are either world best or first of their measurements. No sign of CP violation is found.
- The SCS and Color-suppressed decay $D^0 \to \phi\eta$ is observed (31σ) for the first time.
- The non-ϕ $D^0 \to K^+K^-\eta$ component is observed (20σ) with achieved yields ~ 700 (50 times of BESIII)
- A much clearer sign for $D^0 \to a_0(980)^+\pi^-$ than $a_0(980)^-\pi^+$ is found, not following theoretical prediction.

► Prospects or proposals:

- First observation of (SCS) $D^0 \to K^0_S K^0_S \pi^0/\eta$ at Belle; *(predicted $A_{CP}(D^0 \to K^0_S K^{*0}) \sim \mathcal{O}(0.1\%)$ [arXiv:2104.13548])*
- Dalitz-plot analysis of $D^0 \to \pi^+\pi^-\eta$ at Belle (II), mainly target on $\mathcal{B}(D^0 \to \rho^0\eta)$ and $\mathcal{B}(D^0 \to a_0(980)^\pm\pi^\mp)$;
- Precise measurement of CP asymmetries in $D^0 \to h^+h^-\eta$ at Belle II.

Back up

Thank you for your attentions.

谢谢!

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