Direct CPV Searches in charm at Belle

Long-Ke LI (李龙科)
On behalf of the Belle Collaboration
University of Cincinnati (UC)

11th International Workshop on the CKM Unitarity Triangle (CKM 2021)
Nov 22, 2021
Outline

1. Belle at KEKB
2. BF and $A_{CP}$ in $D^0 \rightarrow \pi^+ \pi^- \eta, K^+ K^- \eta$, and $\phi \eta$
3. BF and $A_{CP}$ in $D_s^+ \rightarrow K^+ \pi^0, K^+ \eta, \pi^+ \pi^0$, and $\pi^+ \eta$
4. Summary
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3. BF and $A_{CP}$ in $D_s^+ \rightarrow K^+ \pi^0, K^+ \eta, \pi^+ \pi^0$, and $\pi^+ \eta$
4. Summary
Belle at KEKB

- KEKB is an asymmetric-energy $e^+e^-$ collider operating near $\Upsilon(4S)$ mass peak ($\sim 10.58 \text{ GeV}/c^2$, $>B\bar{B}$ threshold).
- Belle detector has good performances on momentum/vertex resolution; particle identification, etc.
- Accumulated data set of $\sim 1 \text{ ab}^{-1}$: not only a large $B\bar{B}$ sample ($B$-factory); but also a large charm sample to study charm physics.

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Charm results at Belle this year

- Fruitful Charm results are lasting to produce, although the accumulation of final data set finished >10 years ago.
- Here I focus on two CPV-related analyses.

BF of $\Xi_0 \rightarrow \Lambda K^0, \Sigma^0 K^0$, and $\Sigma^+ K^-$
BF of $\Lambda_0^+ \rightarrow p\omega$
M and $\Gamma$ of $\Sigma_c(2455, 2520)^+$
BF and $A_{CP}$ in $D^0 \rightarrow \pi^+ \pi^- \eta, K^+ K^- \eta$, and $\phi \eta$
Search for $\Omega_0^0 \rightarrow \pi^+ \Omega(2012)^- \rightarrow \pi^+ (K \Xi)^-$
BF and $\alpha$ for $\Xi_0 \rightarrow \Lambda K^*0, \Sigma^0 K^*0$, and $\Sigma^+ K^*$
BF and $A_{CP}$ for $D_s^+ \rightarrow K^+ \pi^0, K^+ \eta, \pi^+ \pi^0$, and $\pi^+ \eta$
BF of $\Xi_0^0 \rightarrow \Xi^- \ell^+ \nu \ell$ and $\alpha(\Xi_0^0 \rightarrow \Xi^- \pi^+)$
Amplitude analysis for $\Xi_0^0 \rightarrow \Xi^0 K^+ K^-$
Determine spin-parity of $\Xi_c(2970)^+$
BF of $\Lambda_0^+ \rightarrow p\pi^0$ and $p\eta$
BF of $\Lambda_0^+ \rightarrow \Lambda \eta \pi^+, \Sigma^0 \eta \pi^+$, $\Lambda(1670) \pi^+$, and $\eta \Sigma(1385)$

arXiv:2111.08981
PRD 104, 072008 (2021)
PRD 104, 052003 (2021)
JHEP 2021, 75 (2021)
PRD 104, 052005 (2021)
JHEP 2021, 160 (2021)
PRD 103, 112005 (2021)
PRD 103, 112002 (2021)
PRD 103, L11101 (2021)
PRD 103, 072004 (2021)
PRD 103, 052005 (2021)
Measurement of time-integrated CP asymmetry

- Time-integrated CP asymmetry for $D \to f$ decays: $A_{CP} = \frac{B(D \to f) - B(D \to f)}{B(D \to f) + B(D \to f)}$

- Taking $D^0$ decays for example, for the decay chain $e^+e^- \to c\bar{c} \to D^{*-} \pi^+ \pi^0 \pi^+ \pi^0$, the raw asymmetry

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

where $A_{CP}$ is our physical goal CP asymmetry; $A_{FB}$ is forward-backward asymmetry arising from $\gamma$-$Z^0$ interference and higher-order QED effects; $A_{f}^{\pi^+}, A_{\pi s}^{\pi^+}$ are the reconstruction asymmetries for final state particles.

1. **reference mode** to cancel same asymmetry sources, e.g. $\Delta A_{CP} = A_{CP}(D^{*-}\to \pi^0 \pi^+ \pi^0 \pi^0) - A_{CP}(D^{*-}\to \phi \pi^+ \pi^0 \pi^0)$ where the latter one is well-measured and $\pi^+$ tracks have similar kinematic info (i.e. $A_{\pi s}^{\pi^+}$ can be cancelled).

2. **correction method** for the charged track detection asymmetry. e.g. in $D^0$ self-conjugated decays $D^0 \to f$ ($A_{\pi s}^{\pi^+} = 0$),

- weight events with $A_{\pi s}^{\pi^+}$: $w_{D^0, B^0} = 1 \mp A_{\pi s}^{\pi^+}[\cos \theta(\pi_s), p_T(\pi_s)]$.
- determine the corrected raw asymmetry $A_{corr} = A_{CP} + A_{FB}(\cos \theta^*)$.
- Since $A_{CP}$ is independent on any kinematic variable and $A_{FB}(\cos \theta^*) = - A_{FB}(- \cos \theta^*)$, we determine the asymmetries in multiple symmetric bins of $\cos \theta^*$:

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

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.
Outline

1. Belle at KEKB
2. BF and $A_{CP}$ in $D^0 \rightarrow \pi^+ \pi^- \eta$, $K^+ K^- \eta$, and $\phi \eta$
3. BF and $A_{CP}$ in $D^+_s \rightarrow K^+ \pi^0$, $K^+ \eta$, $\pi^+ \pi^0$, and $\pi^+ \eta$
4. Summary
Motivation

- The first and only observation of charm CP violation is achieved at LHCb via $\Delta A_{CP}$ measurement in two SCS decays $D^0 \to K^+ K^-$ and $\pi^+ \pi^-$. [PRL 122, 211803 (2019)]
- Here we extend these singly Cabibbo-suppressed (SCS) decays with an additional $\eta$ meson in the final state, to measure their time-integrated CP asymmetries and branching fractions ($B$).
- Current experimental branching fractions ($B$) and $A_{CP}$ results of signal modes and the reference mode:

<table>
<thead>
<tr>
<th>Channel</th>
<th>experiment</th>
<th>$B$</th>
<th>Note</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^0 \to \pi^+ \pi^- \eta$</td>
<td>CLEO</td>
<td>$(1.09 \pm 0.16) \times 10^{-3}$</td>
<td></td>
<td>PRD 77, 002003 (2008)</td>
</tr>
<tr>
<td></td>
<td>BESIII ($\eta_{2\gamma}$)</td>
<td>$(1.20 \pm 0.08) \times 10^{-3}$</td>
<td></td>
<td>PRD 101, 052009 (2020)</td>
</tr>
<tr>
<td></td>
<td>BESIII ($\eta_{3\pi}$)</td>
<td>$(1.06 \pm 0.19) \times 10^{-3}$</td>
<td>$A_{CP} = (-9.6 \pm 5.7)%$</td>
<td>PRD 102, 052003 (2020)</td>
</tr>
<tr>
<td></td>
<td>Combined</td>
<td>$(1.16 \pm 0.07) \times 10^{-3}$</td>
<td>$\delta B/B \sim 6%$</td>
<td>PDG</td>
</tr>
<tr>
<td>$D^0 \to \eta(K^+ K^-)_{\phi}$</td>
<td>Belle ($\phi\eta$)</td>
<td>$(1.46 \pm 0.47) \times 10^{-4}$</td>
<td>$4.4\sigma$</td>
<td>[a] PRL 92, 101803 (2004)</td>
</tr>
<tr>
<td></td>
<td>BESIII ($\phi\eta$)</td>
<td>$(1.81 \pm 0.46) \times 10^{-4}$</td>
<td>$4.2\sigma$</td>
<td>[b] PLB 798, 135017 (2019)</td>
</tr>
<tr>
<td></td>
<td>Combined</td>
<td>$(1.64 \pm 0.33) \times 10^{-4}$</td>
<td>$\delta B/B \sim 20%$</td>
<td></td>
</tr>
<tr>
<td>$D^0 \to \eta(K^+ K^-)_{\text{non-}\phi}$</td>
<td>BESIII</td>
<td>$(0.59 \pm 0.19) \times 10^{-4}$</td>
<td>$\delta B/B \sim 35%$</td>
<td>[c] PRL 124, 241803 (2020)</td>
</tr>
<tr>
<td>$D^0 \to K^- \pi^+ \eta$</td>
<td>Belle</td>
<td>$(1.97 \pm 0.082)%$</td>
<td>Dalitz-plot analysis</td>
<td>[d] PRD 102, 012002 (2020)</td>
</tr>
<tr>
<td></td>
<td>BESIII</td>
<td>$(1.85 \pm 0.040)%$</td>
<td></td>
<td>[e] PRL 124, 241803 (2020)</td>
</tr>
<tr>
<td></td>
<td>Combined</td>
<td>$(1.88 \pm 0.05)%$</td>
<td>$\delta B/B \sim 2%$</td>
<td>PDG</td>
</tr>
</tbody>
</table>
Based on 980 fb\(^{-1}\) data set; the \(\eta\) candidates are reconstructed by two photons.

The signal yields for each channel are extracted via the \(Q\) fit, where \(Q\) is the released energy of \(D^{*+}\) decay:

\[
Q = [M(h^+h^-\eta \pi_s) - M(h^+h^-\eta) - m(\pi_s)]c^2
\]

Signal is described by a combination of bifurcated Student t-function + several \(G_{\text{asym}}\)

Background uses \(f(Q) = Q^\alpha \exp(-\eta^Q\)) with floated parameters, except a fixed small peaking background in reference mode and fixed to MC.

\(> 10k\) and \(> 1k\) yields of SCS decays are obtained.

We also check \(D^0 \rightarrow \eta(K^+K^-)\phi\) excluded with \(|M_{KK} - m_{\phi}| > 20\) MeV/c\(^2\), and achieve statistical significance 20\(\sigma\).
Measurement of branching fractions of $D^0 \rightarrow \pi^+ \pi^- \eta$ and $K^+ K^- \eta$  

- The efficiency-corrected yield on Dalitz-plot: 
  
  $N^\text{cor} = \sum_i N_i^\text{tot} - N_i^\text{bkg} f_i^\text{bkg}$ 
  
  to consider bin-to-bin variations of $\varepsilon_i$.

where $\varepsilon_i$ is the efficiency in the $i^{th}$-bin based on PHSP signal MC; $N_i^\text{tot}$ is yield in $Q$ signal region; and $N_i^\text{bkg}$ is the fitted background yield in $Q$ signal region; $f_i^\text{bkg}$ is the fraction of background in the $i^{th}$-bin, with $\sum_i f_i = 1$, obtaining from the Dalitz-plot in $Q$ sideband.

We have 
  
  $\frac{B(D^0 \rightarrow h^+ h^- \eta)}{B(D^0 \rightarrow K^+ \pi^- \eta)} = \frac{N^\text{cor}(D^0 \rightarrow h^+ h^- \eta)}{N^\text{cor}(D^0 \rightarrow K^+ \pi^- \eta)}$ 

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

- $[1.22 \pm 0.02 \text{ (stat)} \pm 0.02 \text{ (syst)} \pm 0.02 \text{ (B}_{\text{ref}}) \text{]} \times 10^{-3}$
- $[1.80 \pm 0.07 \pm 0.06 \text{ (stat)} \pm 0.04 \text{ (syst)} \pm 0.03 \text{ (B}_{\text{ref}}) \text{]} \times 10^{-4}$
- $[0.99 \pm 0.08 \pm 0.07 \text{ (stat)} \pm 0.02 \text{ (syst)} \pm 0.02 \text{ (B}_{\text{ref}}) \text{]} \times 10^{-4}$

the last one is somewhat higher (but more precise) than a similar measurement by BESIII$[c] (0.59 \pm 0.19) \times 10^{-4}$.
Measurement of $B(D^0 \to \phi \eta)$  

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-$\phi$ $D^0 \to K^+K^-\eta$ component.

The likelihood difference between with and without including signal component $\Delta \ln L = 464.8$ corresponds to a very high statistical significance (31$\sigma$) ⇒ 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.

$$\frac{B(D^0 \to \phi \eta, \phi \to K^+K^-)}{B(D^0 \to K^-\pi^+\eta)} = [4.82 \pm 0.23 \text{ (stat)} \pm 0.16 \text{ (syst)}] \times 10^{-3}.$$  

using $B(D^0 \to K^-\pi^+\eta)^{d,e}$ and $B_{PDG}(\phi \to K^+K^-)$, we have

$$B(D^0 \to \phi \eta) = [1.84 \pm 0.09 \text{ (stat)} \pm 0.06 \text{ (syst)} \pm 0.04 \text{ (}B_{\text{ref}}) \text{}] \times 10^{-4},$$

which is consistent, but notably more precise than, previous results at Belle$^a$ and BESIII$^b$.

As a consistency check, we calculate $B(D^0 \to K^+K^-\eta)_{\text{non-}\phi}$ by

$$B(D^0 \to K^+K^-\eta) - B(D^0 \to \phi \eta, \phi \to K^+K^-) = (0.90 \pm 0.08) \times 10^{-4}$$

which is very close to our measurement of $B(D^0 \to K^+K^-\eta)_{\text{ex-}\phi}$. 

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[a] Long Ke Li (李龙科), Univ. of Cincinnati; [b] Direct CPV Searches in charm at Belle

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To correct for an asymmetry in $\pi^+_s$ reconstruction efficiencies, we weight events with factors $w_{D^0/D^0} = 1 \pm A_{\pi^+_s}$, where $A_{\pi^+_s}(\cos \theta, \rho_T)$-map is obtained from tagged and untagged $D^0 \rightarrow K^- \pi^+$ samples (because $A_{\text{untag}} = A_{\text{FB}} + A_{CP} + A_{\phi \pi} + A_{\pi^+_s}$ and $A_{\text{tag}} = A_{\text{FB}} + A_{CP} + A_{\phi \pi} + A_{\pi^+_s}$).

We divide the weighted samples into eight bins of $\cos \theta^*$: [0, 0.2], [0.2, 0.4], [0.4, 0.6], [0.6, 1] and symmetric intervals for negative region.

We perform a simultaneous fit in each $\cos \theta^*$ bin on the $Q$ or $M_{K^-Q}$ distributions for $D^0$ and $\bar{D}^0$ samples, to extract the corrected raw asymmetry $A_{\text{corr}}$: $N_{\text{sig}}(D^0, \bar{D}^0) = N_{\text{sig}}/2 \cdot (1 \pm A_{\text{corr}})$.

### Summary

**CP asymmetries of $D^0 \rightarrow \pi^+ \pi^- \eta$, $K^+ K^- \eta$, and $\phi \eta$**

**JHEP 2021, 75 (2021)**

- **Belle at KEKB**
- **ACP** of $D^0 \rightarrow h \eta$ and $h \phi$
- **Summary**
Then, using the formula below, we calculate four $A_{CP}$ values and four $A_{FB}$ values, as plotted in below figures.

$$A_{CP} = \frac{A_{corr}(\cos \theta^*) + A_{corr}(-\cos \theta^*)}{2}$$

$$A_{FB} = \frac{A_{corr}(\cos \theta^*) - A_{corr}(-\cos \theta^*)}{2}$$

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 fourfold improvement in precision over BESIII result; the later two are the first such measurements.

No evidence for CPV is found in these decays.
Outline

1. Belle at KEKB
2. BF and $A_{CP}$ in $D^0 \rightarrow \pi^+ \pi^- \eta$, $K^+ K^- \eta$, and $\phi \eta$
3. BF and $A_{CP}$ in $D_s^+ \rightarrow K^+ \pi^0$, $K^+ \eta$, $\pi^+ \pi^0$, and $\pi^+ \eta$
4. Summary
Both $D^{+}_{s}$-tagged and untagged $D^{±}_{s}$ samples from 921 fb$^{-1}$ data set are used to measure the $B$'s relative to $D^{±}_{s} \rightarrow [\phi \rightarrow K^+K^-]\pi^{±}$.

To suppress backgrounds, we use a neural network (NN) based on input variables: $p(D^{±}_{s})$, $|d_{xy}|$, or $dr$, $\theta_{hel}(h^{±})$, $N(K)$, $\theta_{thrust}$, and $\theta(p(D^{±}_{s}), r_{vtx})$. The NN output is required to be greater than some minimum value, which is determined optimally.

Simultaneous fit on tagged and untagged samples for $M_{D^{±}_{s}}$ distribution to extract signal yield, and $B_{\text{sig}} = N_{\text{sig}} / N_{\phi\pi} \cdot \varepsilon_{\phi\pi} / \varepsilon_{\text{sig}} \cdot B_{\phi\pi}$.

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>$\varepsilon$ (%)</th>
<th>Fitted yield</th>
<th>$B/B_{\phi\pi}$ (%)</th>
<th>$B$ (10$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^{±}_{s} \rightarrow K^{+}\pi^{0}$</td>
<td>8.10 ± 0.04</td>
<td>11978 ± 846</td>
<td>3.28 ± 0.23 ± 0.13</td>
<td>0.735 ± 0.052 ± 0.030 ± 0.026</td>
</tr>
<tr>
<td>$D^{±}_{s} \rightarrow K^{+}\eta\gamma$</td>
<td>7.42 ± 0.05</td>
<td>10716 ± 429</td>
<td>8.04 ± 0.32 ± 0.35</td>
<td>1.80 ± 0.07 ± 0.08 ± 0.06</td>
</tr>
<tr>
<td>$D^{±}<em>{s} \rightarrow K^{+}\eta</em>{3\pi}$</td>
<td>4.04 ± 0.02</td>
<td>3175 ± 121</td>
<td>7.62 ± 0.29 ± 0.33</td>
<td>1.71 ± 0.07 ± 0.08 ± 0.06</td>
</tr>
<tr>
<td>$D^{±}_{s} \rightarrow K^{+}\eta$</td>
<td>–</td>
<td>–</td>
<td>7.81 ± 0.22 ± 0.24</td>
<td>1.75 ± 0.05 ± 0.06</td>
</tr>
<tr>
<td>$D^{±}_{s} \rightarrow \pi^{+}\pi^{0}$</td>
<td>6.63 ± 0.04</td>
<td>491 ± 734</td>
<td>0.16 ± 0.25 ± 0.09</td>
<td>0.037 ± 0.055 ± 0.021 ± 0.001</td>
</tr>
<tr>
<td>$D^{±}_{s} \rightarrow \pi^{+}\eta\gamma$</td>
<td>10.84 ± 0.02</td>
<td>166696 ± 1173</td>
<td>85.54 ± 0.64 ± 3.32</td>
<td>19.16 ± 0.14 ± 0.74 ± 0.68</td>
</tr>
<tr>
<td>$D^{±}<em>{s} \rightarrow \pi^{+}\eta</em>{3\pi}$</td>
<td>6.50 ± 0.03</td>
<td>56132 ± 407</td>
<td>83.55 ± 0.64 ± 4.37</td>
<td>18.72 ± 0.14 ± 0.98 ± 0.67</td>
</tr>
<tr>
<td>$D^{±}_{s} \rightarrow \pi^{+}\eta$</td>
<td>–</td>
<td>–</td>
<td>84.80 ± 0.47 ± 2.64</td>
<td>19.00 ± 0.10 ± 0.59 ± 0.68</td>
</tr>
<tr>
<td>$D^{±}_{s} \rightarrow \phi\pi^{+}$</td>
<td>22.05 ± 0.13</td>
<td>1005688 ± 2527</td>
<td>1</td>
<td>–</td>
</tr>
</tbody>
</table>

No significant signal for $D^{±}_{s} \rightarrow \pi^{+}\pi^{0}$ is observed, thus, an upper limit is set: $B(D^{±}_{s} \rightarrow \pi^{+}\pi^{0}) < 1.2 \times 10^{-4}$ at 90% C.L., which is the most stringent constraint to date.

Only $D^{±}_{s}$ samples are shown here for example.
Simultaneous fit on four $M(D_s^\pm)$ distributions from $D_s^+$ and $D_s^-$ tagged and untagged samples to extract the raw asymmetry $A_{\text{raw}}$.

For $D_s^+ \rightarrow \pi^+ \eta$, we use reference mode $D_s^+ \rightarrow \phi \pi^+$ to remove $A_{\text{FB}}(D_s^+)$ and $A_{\pi^+}$:

$$\Delta A_{\text{raw}} = A_{\text{raw}}^{\eta\pi} - A_{\text{raw}}^{\phi\pi} = A_{\text{CP}}^{\eta\pi} - A_{\text{CP}}^{\phi\pi} \Rightarrow A_{\text{CP}}^{\eta\pi} = \Delta A_{\text{raw}} + A_{\text{CP}}^{\phi\pi}$$

where $A_{\text{CP}}^{\phi\pi} = (-3.8 \pm 2.6 \pm 0.8) \times 10^{-3}$ in PDG.

For $D_s^+ \rightarrow K^+(\pi^0, \eta)$, we firstly perform simultaneous fit for six bins of $\cos \theta^*$, individually, to obtain $A_{\text{raw}}$; and then subtract $A_{K^+\epsilon}$ (obtained from signal MC with $A_{K^+\epsilon}(\cos \theta, p)$) to obtain $A_{\text{corr}}$ in each bin.

Finally, fitting these $A_{\text{CP}}$ values in several bins of $\cos \theta_{CM}$ to a constant gives the final measurements of $A_{\text{CP}}$:

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>$A_{\text{raw}}$</th>
<th>$A_{\text{CP}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_s^+ \rightarrow K^+\pi^0$</td>
<td>$0.115 \pm 0.045$</td>
<td>$0.064 \pm 0.044 \pm 0.011$</td>
</tr>
<tr>
<td>$D_s^+ \rightarrow K^+\eta\gamma\gamma$</td>
<td>$0.046 \pm 0.027$</td>
<td>$0.040 \pm 0.027 \pm 0.005$</td>
</tr>
<tr>
<td>$D_s^+ \rightarrow K^+\eta_{3\pi}$</td>
<td>$-0.011 \pm 0.033$</td>
<td>$-0.008 \pm 0.034 \pm 0.008$</td>
</tr>
<tr>
<td>$D_s^+ \rightarrow K^+\eta$</td>
<td>$-0.021$</td>
<td>$0.021 \pm 0.021 \pm 0.004$</td>
</tr>
<tr>
<td>$D_s^+ \rightarrow \pi^+\eta\gamma\gamma$</td>
<td>$0.007 \pm 0.004$</td>
<td>$0.002 \pm 0.004 \pm 0.003$</td>
</tr>
<tr>
<td>$D_s^+ \rightarrow \pi^+\eta_{3\pi}$</td>
<td>$0.008 \pm 0.006$</td>
<td>$0.002 \pm 0.006 \pm 0.003$</td>
</tr>
<tr>
<td>$D_s^+ \rightarrow \pi^+\eta$</td>
<td>$-0.002 \pm 0.003 \pm 0.003$</td>
<td></td>
</tr>
<tr>
<td>$D_s^+ \rightarrow \phi\pi^+$</td>
<td>$0.002 \pm 0.001$</td>
<td>$-0.002 \pm 0.003 \pm 0.003$</td>
</tr>
</tbody>
</table>

These results are the most precise and show no evidence of CP violation. (PS: nearly at same time, LHCb reported $A_{\text{CP}}$ results for these decays with competitive precision in JHEP06 (2021) 019.)
Outline

1. Belle at KEKB
2. BF and $A_{CP}$ in $D^0 \rightarrow \pi^+ \pi^- \eta, K^+ K^- \eta$, and $\phi \eta$
3. BF and $A_{CP}$ in $D_s^+ \rightarrow K^+ \pi^0, K^+ \eta, \pi^+ \pi^0$, and $\pi^+ \eta$
4. Summary
Belle is still lasting to produce lots of charm results this year. The $CP$ asymmetries in several $\pi^0/\eta$-involved channels (five SCS + one CF) are presented here, along with precise measurements of their branching fractions.

### Summary

- All these $A_{CP}$ results in SCS decays are at $O(\%)$; $B$'s are measured for the first time or with best precision.
- More charm $CP$ violation results are on the road, especially involving neutral particle in the final state.
  - $T$-odd asymmetry $CP$-violating parameters in several multi-body decays,
  - $CP$ asymmetries in charmed baryon decays, and more channels of $D$ decays.
- As a summary, I would like to say, "Our Belle is not only keeping alive but still keeping energetic with fruitful charm results, although its final full data set was achieved more than 10 years ago."

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<table>
<thead>
<tr>
<th>Decay channel</th>
<th>$A_{CP}$ (%)</th>
<th>Note</th>
<th>$B \times 10^{-3}$</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^0 \rightarrow \pi^+\pi^-\eta$</td>
<td>$+0.9 \pm 1.2 \pm 0.5$</td>
<td>improved fourfold</td>
<td>$1.22 \pm 0.02 \pm 0.02 \pm 0.02$</td>
<td>most precise</td>
</tr>
<tr>
<td>$D^0 \rightarrow K^+K^-\eta$</td>
<td>$-1.4 \pm 3.3 \pm 1.1$</td>
<td>first result</td>
<td>$0.180^{+0.007}_{-0.006} \pm 0.004 \pm 0.003$</td>
<td>first result</td>
</tr>
<tr>
<td>$D^0 \rightarrow \phi\eta$</td>
<td>$-1.9 \pm 4.4 \pm 0.6$</td>
<td>first result</td>
<td>$0.184 \pm 0.009 \pm 0.006 \pm 0.004$</td>
<td>first observation</td>
</tr>
<tr>
<td>$D_s^+ \rightarrow \pi^+\pi^0$</td>
<td>$+6.4 \pm 4.4 \pm 1.1$</td>
<td>$\sim \sigma_{LHCb}$</td>
<td>$&lt; 0.12$</td>
<td>most stringent UL</td>
</tr>
<tr>
<td>$D_s^+ \rightarrow K^+\pi^0$</td>
<td>$+2.1 \pm 2.1 \pm 0.4$</td>
<td>best result</td>
<td>$0.735 \pm 0.052 \pm 0.030 \pm 0.026$</td>
<td>most precise</td>
</tr>
<tr>
<td>$D_s^+ \rightarrow K^+\eta$</td>
<td>$+0.2 \pm 0.3 \pm 0.3$</td>
<td>best result</td>
<td>$1.75 \pm 0.05 \pm 0.05 \pm 0.06$</td>
<td>most precise</td>
</tr>
<tr>
<td>$D_s^+ \rightarrow \pi^+\eta$ (CF)</td>
<td>$+0.2 \pm 0.3 \pm 0.3$</td>
<td>best result</td>
<td>$19.00 \pm 0.10 \pm 0.59 \pm 0.68$</td>
<td>indep. another result</td>
</tr>
</tbody>
</table>
Thank you for your attentions.

谢谢！

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