Recent charm results from Belle

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Outline

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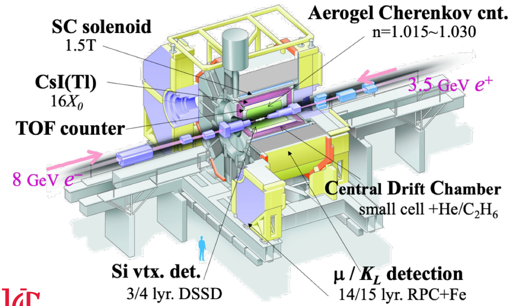
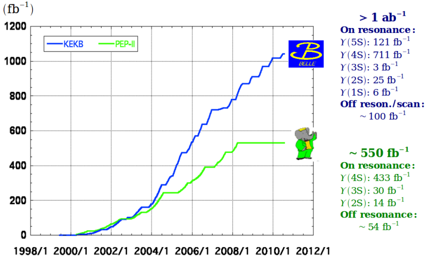
Belle experiment at KEKB

- KEKB is an asymmetric-energy ($\beta\gamma = 0.425$) e^+e^- collider operating near $\Upsilon(4S)$ mass peak (~ 10.58 GeV/c^2, above $B\bar{B}$ threshold).
- Belle detector is an advanced detector with good momentum and vertex resolution; K/π separation performance, etc.
- Although the full data set accumulation ($\sim 1\,\mathrm{ab}^{-1}$) has been finished for ten years, fruitful results on charm physics are lasting to be produced.
- 1.1×10^9 $B\bar{B}$ $\Rightarrow$ B-factory; 1.3×10^9 $c\bar{c}$ and 0.9×10^9 $\tau\tau$ $\Rightarrow$ tau-charm factory



Integrated luminosity of B factories



Outline

Introduction to D^0-$\bar{D}^0$ mixing and y_{cp} measurements

- open-flavor neutral meson transforms to its anti-meson, $K^0 \Leftrightarrow \bar{K}$, $B^0 \Leftrightarrow \bar{B}^0$, $B_s \Leftrightarrow \bar{B}_s$, $D^0 \Leftrightarrow \bar{D}^0$
- flavor eigenstates ($|D^0\rangle$, $|\bar{D}^0\rangle$) $\neq$ mass eigenstates $|D_{1,2}\rangle$ with $M_{1,2}$ and $\Gamma_{1,2}$ $\Rightarrow$ $|D_{1,2}\rangle \triangleq p|D^0\rangle \pm q|\bar{D}^0\rangle$ (CPT, $p^2+q^2=1$)

- charm-mixing parameters:

$$\mathbf{x} \triangleq 2\frac{M_1 - M_2}{\Gamma_1 + \Gamma_2}, \quad \mathbf{y} \triangleq \frac{\Gamma_1 - \Gamma_2}{\Gamma_1 + \Gamma_2}$$

- Considering $|x|$, $|y| \ll 1$, the decay-time dependence of $D^0 \to CP$ eigenstate is approximately exponential.

$$\left(d\Gamma(D^0 \to f_{cp}) + d\Gamma(\bar{D}^0 \to f_{cp})\right)/dt \propto e^{-\Gamma(1+\eta_f y_{cp})t}$$

where $\eta_f = \pm 1$ for CP-even or -odd decays.

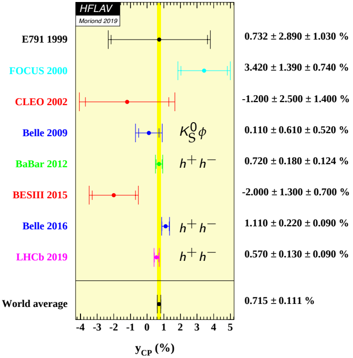
- Neglecting possible direct CP violation in decays,

$$y_{cp} = \frac{1}{2}\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right) y \cdot \cos\phi - \frac{1}{2}\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right) x \cdot \sin\phi$$

where $\phi = \arg(q/p)$. If CP conserves, $y_{cp} = y$.

- CP-odd decays: $\mathcal{B}(D^0 \to K_S^0[\omega \to \pi^+\pi^-\pi^0]) = 5 \times \mathcal{B}(D^0 \to K_S^0[\phi \to K^+K^-])$ in PDG
  $\Rightarrow$ measure y_{cp} in $D^0 \to K_S^0\omega$ for the first time.

- current experimental y_{cp} results

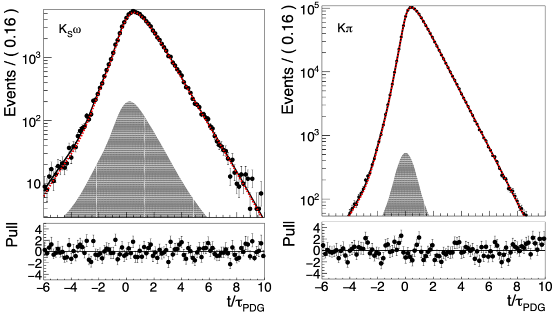


Measurement of y_{cp} in $D^0 \to K^0_S\omega$ decays arXiv:1912.10912 [hep-ex]

- Based on 976 fb^{-1} data set, large samples of $D^0 \to K^0_S\omega$ (91k) and (flavored eigenstate) $D^0 \to K^-\pi^+$ (1375k) are obtained from $M(D^0)$-ΔM with high purity 96.3% and 99.6%.
- The parameter y_{cp} is determined by (considering $d\Gamma(D^0 \to K^-\pi^+)/dt \propto e^{-\Gamma t}$),

$$y_{cp} = 1 - \tau(D^0 \to K^-\pi^+)/\tau(D^0 \to K^0_S\omega)$$

- A lifetime fitting is performed with resolution (triple Gaussians) and backgrounds (with nonzero- and zero-lifetime components), $PDF(t;\tau) = f_{\rm sig}/\tau e^{-t/\tau} \otimes {\rm Res}(t) + (1-f_{\rm sig})B(t)$.



- Finally, we have $y_{cp} = (0.96 \pm 0.91 \pm 0.62^{+0.17}_{-0.00})\%$, where the errors are statistical, systematic, and from possible CP-even decays in the final state.
- This result is consistent with previous result in $D^0 \to K^0_S\phi$, as well as with the W.A. value.
- In the future, comparing more precise measurements of y_{cp} with that of y may reveal new physics effects in charm sector.

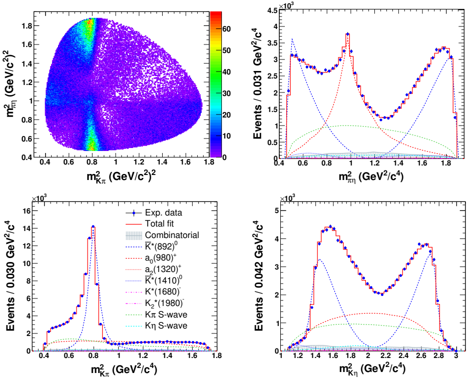
Outline

1. Belle and KEKB
2. Charm-mixing parameter y_{cp} in $D^0 \to K_S^0\omega$
3. Dalitz-plot analysis of $D^0 \to K^-\pi^+\eta$
4. Branching fractions of $\Lambda_c^+ \to \eta\Lambda\pi^+$, $\eta\Sigma^0\pi^+$, $\Lambda(1670)\pi^+$, and $\eta\Sigma(1385)^+$
5. Spin and Parity of a charmed-strange Baryon, $\Xi_c(2970)^+$
6. Summary

Dalitz-plot analysis of $D^0 \to K^-\pi^+\eta$ [PRD **102**, 012002 (2020)]

- Dalitz-plot analysis of $D^0 \to K^-\pi^+\eta$ for the first time is performed to study its dynamics, and also provides us a platform to study the decays of some excited kaons to $K\pi$ and $K\eta$.
- Using 953 fb^{-1} of data, we obtain 105k yields in M_{D^0}-Q signal region with purity 95%.
- 'Isobar model' is applied for amplitude of signal, $\mathcal{M} = a_{NR}e^{i\phi_{NR}} + \sum_R a_R e^{i\phi_R}\mathcal{M}_R(m^2_{K\pi}, m^2_{\pi\eta})$
- Dalitz-plot of background is obtained from M_{D^0} sidebands, the fraction of each signal event is determined by M_{D^0}-Q fit.
- Final optimal Dalitz mode includes five resonances with relativistic Breit-Wigner, $a_0(980)^+$ with Flatté, and two $K\pi$ and $K\eta$ S-waves with generalized LASS.
- Dalitz-plot fit result with fit fractions:

Component	Magnitude	Phase (°)	Fit fraction (%)
$\bar{K}^*(892)^0$	1	0	$47.61 \pm 1.32^{+0.24+3.64}_{-0.49-2.71}$
$a_0(980)^+$	2.779 ± 0.032	310.3 ± 1.1	$39.28 \pm 1.50^{+1.58+4.38}_{-0.51-3.30}$
$(K\pi)_{\text{S-wave}}$	10.82 ± 0.23	50.0 ± 5.7	$31.92 \pm 1.21^{+1.47+2.75}_{-0.53-2.87}$
$(K\eta)_{\text{S-wave}}$	1.70 ± 0.082	113.8 ± 13.6	$3.37 \pm 0.50^{+0.77+3.20}_{-0.27-1.21}$
$a_2(1320)^+$	1.27 ± 0.079	283.4 ± 4.7	$0.74 \pm 0.09^{+0.06+0.37}_{-0.04-0.17}$ (14σ)
$\bar{K}^*(1410)^0$	4.84 ± 0.36	352.7 ± 2.8	$6.94 \pm 0.85^{+0.55+2.37}_{-1.61-3.22}$ (15σ)
$K^*(1680)^-$	2.56 ± 0.18	232.2 ± 6.6	$1.07 \pm 0.16^{+0.11+0.58}_{-0.10-0.36}$ (16σ)
$K_2^*(1980)^-$	9.29 ± 0.69	207.7 ± 4.0	$1.13 \pm 0.15^{+0.05+0.88}_{-0.05-0.98}$ (17σ)
Sum			$132.1 \pm 3.4^{+1.6+8.3}_{-0.7-4.5}$



Discussion on Dalitz fit results of $D^0 \to K^-\pi^+\eta$ [PRD **102**, 012002 (2020)]

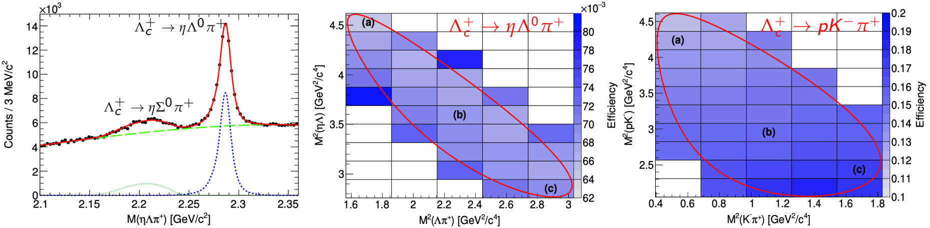
- Using normalized mode $D^0 \to K^-\pi^+$ with $\Upsilon(4S)$ data set, a relative branching ratio is determined via M_{D^0} fit, $\frac{\mathcal{B}(D^0\to K^-\pi^+\eta)}{\mathcal{B}(D^0\to K^-\pi^+)} = 0.500 \pm 0.002(\text{stat}) + 0.020(\text{syst}) \pm 0.003(\mathcal{B}_{\text{PDG}})$.
- using the world averaged $\mathcal{B}(D^0 \to K^-\pi^+)$, we have the branching fraction $\mathcal{B}(D^0 \to K^-\pi^+\eta) = (1.973 \pm 0.009(\text{stat}) \pm 0.079(\text{syst}) \pm 0.018(\mathcal{B}_{\text{PDG}}))\%$.
- A further discussion is performed based on Dalitz-plot fit results and above branching ratio:
  - $D^0 \to \bar{K}^*(892)^0\eta$ decay: $\mathcal{B} = (1.41^{+0.13}_{-0.12})\%$, consistent with, and more precise than, the current world averaged $(1.02 \pm 0.20)\%$. However it deviates from theoretical predictions of (0.51-0.92)% [a,b,c] with $> 3\sigma$.
  - $K^*(1680) \to K\eta$ decay: $\mathcal{B} = (1.44^{+0.98}_{-0.76})\%$ and $\frac{\mathcal{B}(K^*(1680)^-\to K^-\eta)}{\mathcal{B}(K^*(1680)^-\to K^-\pi^0)} = (0.11^{+0.07}_{-0.06})\%$. This ratio is not consistent with theoretical predictions (≈ 1.0) under the assumption that $K^*(1680)$ is a pure 1^3D_1 state[d,e].
  - $K_2^*(1980) \to K\eta$ decay: $\mathcal{B}(D^0 \to [K_2^*(1980)^- \to K^-\eta]\pi^+) = (2.2^{+1.7}_{-1.9}) \times 10^{-4}$ for the first time, which is strongly suppressed due to a limit of the phase-space region and yet allowed due to a large width of $K_2^*(1980)$.

[a] Phys. Rev. D **81**, 074021 (2010)
[b] Phys. Rev. D **86**, 036012 (2012)
[c] Phys. Rev. D **89**, 054006 (2014)
[d] Phys. Rev. D **68**, 054014 (2003)
[e] Eur. Phys. J. C **77**, 861 (2017)

Outline

Measurement of $\mathcal{B}(\Lambda_c^+ \to \eta \Lambda \pi^+, \eta \Sigma^0 \pi^+)$ Preliminary result, to be submitted

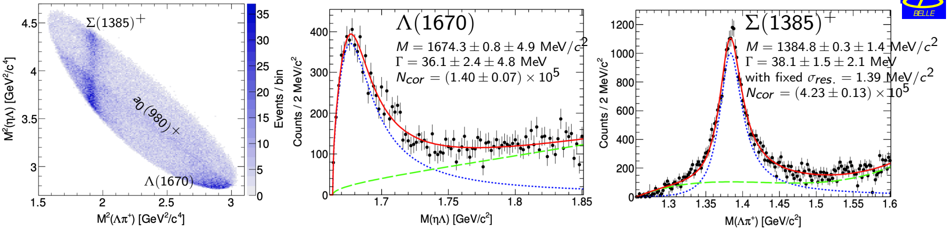
- The branching fractions of weakly decaying charmed baryons provide a way to study both strong and weak interactions. The $\Lambda_c^+ \to \eta \Lambda \pi^+$ is an ideal decay mode to study $\Lambda(1670)$ because the isospin is fixed for any combination of two particles in final state.
- Using 980 fb^{-1} data set, a large sample of $\Lambda_c^+ \to \eta \Lambda \pi^+$ is obtained on $M_{\eta\Lambda\pi^+}$ spectrum. Meanwhile, $\Lambda_c^+ \to \eta \Sigma^0 \pi^+$ is observed indirectly as a feed-down component and it has efficiency-corrected yield $N_{cor} = (3.05 \pm 0.16) \times 10^5$.



- Considering $\Lambda_c^+ \to \eta \Lambda \pi^+$ and $pK^- \pi^+$ have sufficiently large statistics, the yields in individual bins of Dalitz plots are determined. The total yields $N_{cor}(\eta\Lambda\pi^+) = (7.41 \pm 0.07) \times 10^5$ and $N_{cor}(pK^-\pi^+) = (1.005 \pm 0.001) \times 10^7$ are used to measure the branching fractions.
- Finally $\frac{\mathcal{B}(\Lambda_c^+ \to \eta\Lambda\pi^+)}{\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)} = 0.293 \pm 0.003 \pm 0.014$ and $\frac{\mathcal{B}(\mathcal{B}(\Lambda_c^+ \to \eta\Sigma^0\pi^+)}{\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)} = 0.120 \pm 0.006 \pm 0.006$.

$\mathcal{B}(\Lambda_c^+ \to \Lambda(1670)\pi^+/\eta\Sigma(1385)^+)$ in $\Lambda_c^+ \to \eta\Lambda\pi^+$

Preliminary result, to be submitted



- On the Dalitz plot of $\Lambda_c^+ \to \eta\Lambda\pi^+$, bands corresponding to $\Lambda_c^+ \to \Lambda(1670)\pi^+/\eta\Sigma(1385)^+$ resonant subchannels are seen, along with $\Lambda_c^+ \to \Lambda a_0(980)^+$.
- For every 2 MeV$/c^2$ bin of $M_{\eta\Lambda}$ and $M_{\Lambda\pi}$ distributions, Λ_c^+ signal yield is obtained by fitting $M_{\eta\Lambda\pi}$. Then, a relativistic Breit-Wigner is used for (S-wave) $\Lambda(1670)$ and (P-wave) $\Sigma(1385)$

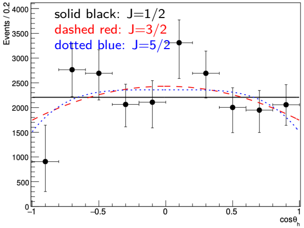
$$\frac{dN}{dm} \propto \frac{m\Gamma(m)}{(m^2 - m_0^2)^2 + m_0^2(\Gamma(m) + \Gamma_{\text{others}})^2}, \text{with partial width } \Gamma(m) = \Gamma_0 \frac{m_0}{m}(q/q_0)^{2L+1}F(q)$$

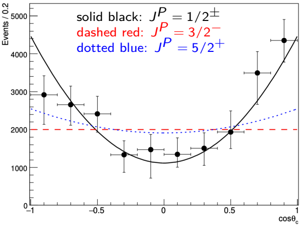
- $\frac{\mathcal{B}(\Lambda_c^+ \to [\Lambda(1670) \to \eta\Lambda]\pi^+)}{\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)} = (5.54 \pm 0.29 \pm 0.73)\%$ and $\frac{\mathcal{B}(\Lambda_c^+ \to \eta\Sigma(1385)^+)}{\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)} = 0.192 \pm 0.006 \pm 0.016$
- Finally, we have $\mathcal{B}(\Lambda_c^+ \to [\Lambda(1670) \to \eta\Lambda]\pi^+) = (3.48 \pm 0.19 \pm 0.46 \pm 0.18) \times 10^{-3}$, $\mathcal{B}(\Lambda_c^+ \to \eta\Sigma(1385)^+) = (1.21 \pm 0.04 \pm 0.46 \pm 0.10 \pm 0.06)\%$, after using the world averaged $\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)$.

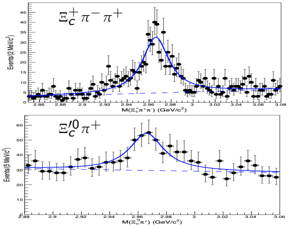
Outline

First determination of $J^P(\Xi_c(2970)^+)$ Preliminary result, to be submitted

- The unclear theoretical situation motivates an experimental determination of J^P of $\Xi_c(2970)$, which provides important info to test predictions and help decipher its nature.
- Spin is determined by angular analysis of $\Xi_c(2970)^+ \to \Xi_c(2645)^0 \pi^+ \to \Xi_c^+ \pi^- \pi^+$.
  - (1) helicity angle θ_h of $\Xi_c(2970)^+$: the background-subtracted and efficiency-corrected yields distribution is fitted with expected decay-angle distribution W_J for different spin hypotheses. $\Rightarrow$ the best fit is for J=1/2, while others are excluded with small significance. The result is inconclusive.
  - (2) helicity angle θ_c of $\Xi_c(2645)^0$: the expected angular correlation $W(\theta_c)$ with an assumption that lowest partial wave dominates, is used to to fit. $\Rightarrow$ the $J^P = 1/2^\pm$ hypothesis over the $3/2^-$ $(5/2^+)$ one at the level of 5.1σ (4.0σ).







- Parity is established from $\mathcal{B}(\Xi_c(2970)^+ \to \Xi_c(2645)^0 \pi^+)/\mathcal{B}(\Xi_c(2970)^+ \to \Xi_c'^0 \pi^+) = 1.67 \pm 0.29(\text{stat})^{+0.15}_{-0.09}(\text{syst}) \pm 0.25(\text{IS})$. This result favors $J^P = 1/2^+$ with the spin of the light-quark degrees of freedom $s_l = 0$.

Outline

Summary

- Based on the large charm sample at Belle, some selected recent charm results are presented today.
  - D^0-$\bar{D}^0$ mixing: y_{cp} in $D^0 \to K_S^0\omega$
  - CP violation in charm sector
  - charm hadronic decays: $D^0 \to K^-\pi^+\eta$, $\Lambda_c^+ \to \pi^+\eta\Lambda/\pi^+\eta\Sigma^0$.
  - charm rare and radiative decays.
  - charm leptonic and semileptonic decays.
  - charm baryon properties and spectroscopy: $J^P(\Xi_c(2970)^+)$
  - ......
- Some other topics above are not included in my talk. (For charmonium or related results at Belle, please see Dr. Sen Jia's talk on July 31.[link])
- More charming charm results from Belle will be presented in near future.
- As a summary, I will say, "Belle is not only keeping alive but still keeping energetic, together with its upgraded experiment Belle II who is under a rapid growth."

Back up

Thank you for your attentions.

谢谢！

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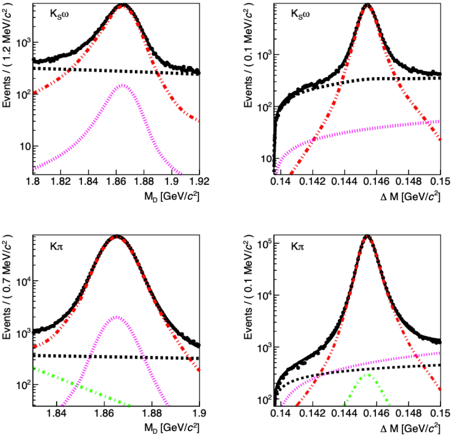
Measurement of y_{cp} in $D^0 \to K_S^0\omega$ decays arXiv:1912.10912 [hep-ex]

- Utilizing 976 fb^{-1} data set, a 2D unbinned maximum-likelihood fit to $M(D^0)$-ΔM ($\Delta M = M_{D^*} - M_{D^0}$) is performed to obtain yields for (CP-odd) $D^0 \to K_S^0\omega$ and flavored eigenstate process $D^0 \to K^-\pi^+$.

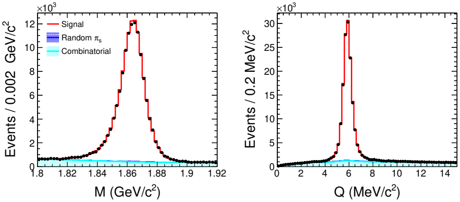
$K_S^0\omega$ components	Full region	Signal region
Signal	107978±455	90930
Random $\pi_{\rm slow}$ background	3238±346	918
Combinatorial background	27793±447	3554
$K^-\pi^+$ components	Full region	Signal region
Signal	1507830±1310	1375245
Random $\pi_{\rm slow}$ background	42899±459	13380
Combinatorial background	33828±384	4620
Multibody background	6769±415	1686

- Events in signal region with high purity 96.3% ($K_S^0\omega$) and 99.6% ($K^-\pi^+$) are used to perform the lifetime fitting.



Dalitz-plot analysis of $D^0 \to K^-\pi^+\eta$ [PRD **102**, 012002 (2020)]

- The understanding of hadronic charmed-meson decay is theoretically challenging due to the significant non-perturbative contributions, and input from experimental measurements thus plays an important role.
- A Dalitz-plot analysis is performed to study the dynamics of $D^0 \to K^-\pi^+\eta$ for the first time. It provides us a fruitful platform to study the decays of some excited kaons to $K\pi$ and $K\eta$.
- using 953 fb^{-1} of data, we obtain 105 thousands yields in M_{D^0}-Q (Q=$\Delta M - m_{\pi_s}$) signal region with purity 95%.



- Besides, using normalized mode $D^0 \to K^-\pi^+$, we determine the ratio of branching fraction via M_{D^0} fitting, $\frac{\mathcal{B}(D^0\to K^-\pi^+\eta)}{\mathcal{B}(D^0\to K^-\pi^+)} = 0.500 \pm 0.002(\text{stat}) + 0.020(\text{syst}) \pm 0.003(\mathcal{B}_{\text{PDG}})$.
- using the world averaged $\mathcal{B}(D^0 \to K^-\pi^+)$, we have $\mathcal{B}(D^0 \to K^-\pi^+\eta) = (1.973 \pm 0.009(\text{stat}) \pm 0.079(\text{syst}) \pm 0.018(\mathcal{B}_{\text{PDG}})$.