Recent Charm Results at Belle and Belle II Experiments

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Nov 18 @USTC

Outline

1. Belle@KEKB and Belle II@SuperKEKB
2. Introduction to charm physics
3. Selected studies of charmed mesons at Belle
   - $\mathcal{B}/A_{CP}$ for $D^0 \to h^+h^-\eta$ $(h = K, \pi)$ and $D^0 \to \phi\eta$
   - $\mathcal{B}/a_{CP}^{T\text{-odd}}$ for $D^+_{(s)} \to K^\pm h^\pm \pi^+ \pi^0$
4. Selected studies of charmed baryons at Belle
   - $\mathcal{B}$ of $\Lambda_c^+ \to pK_S^0K_S^0$ and $\Lambda_c^+ \to pK_S^0\eta$
   - $\mathcal{B}/A_{CP}/\alpha/A_{CP}^{\alpha}$ of $\Lambda_c^+ \to \Lambda h^+$, $\Sigma^0 h^+$
5. Charm studies at Belle II
   - Measurement of charm lifetimes
   - Advanced tools for charm
   - Status and prospects at Belle II
6. Summary

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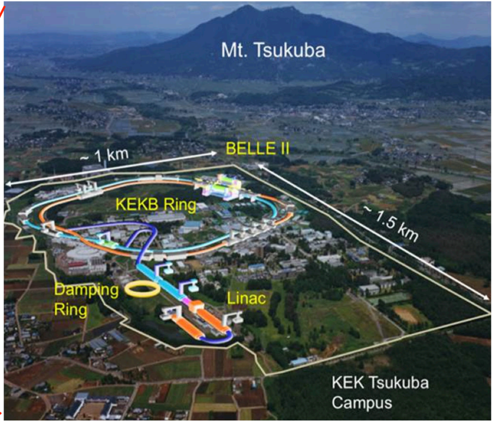
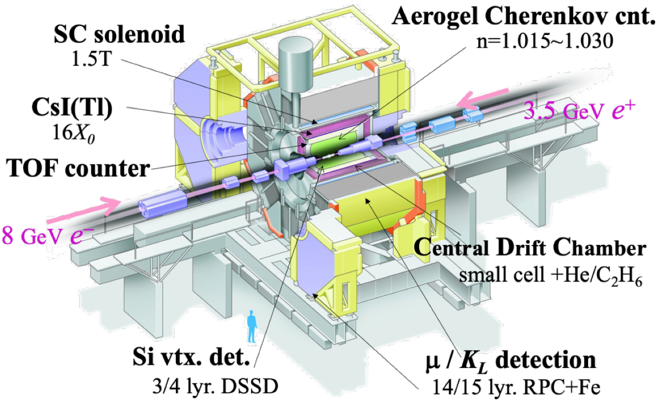
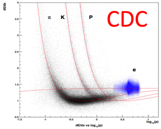
Belle at KEKB

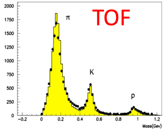
- KEK: 高エネルギー加速器研究機構，位于日本筑波市。
- KEKB: 第一代 B 介子工厂 [另一个位于 SLAC 的 PEP-II（BaBar 实验）]
  - 能量不对称的正负电子 (3.5 GeV×8 GeV) 对撞机。
  - 运行在10.58 GeV ($B\overline{B}$ 阈值上)。
  - 环周长3千米（历史），地下11米。
- 运行时间：1999--2010年，累计采集数据 $\sim 1\ \text{ab}^{-1}$。
- 最高瞬时亮度：$2.1 \times 10^{34}\ cm^{-2}s^{-1}$(曾经 W.R.)。
- 四个实验大厅：筑波、日光、富士、大穗。
  唯一探测器：Belle 探测器位于筑波大厅。
- 何谓 Belle? 绝世美女 $B = el + le$
- KEKB 升级为新一代 B 工厂 SuperKEKB
- Belle 探测器升级成新的探测器 Belle II (绝世美女二世)

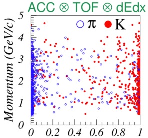


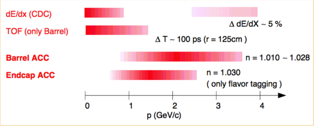
Belle detector and performance

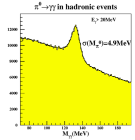


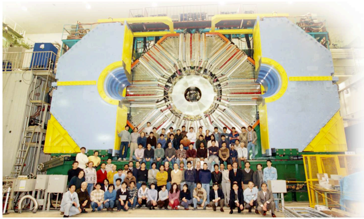


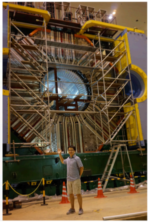










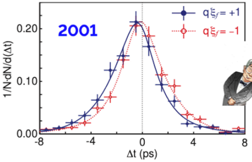


- Good momentum/vertex resolution
- Good K/π separation up to 3.5 GeV/c
- High efficiency for $\gamma/\pi^0/K_S^0$, high trigger efficiency

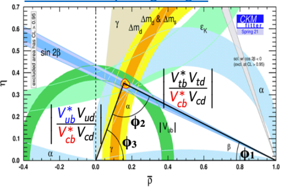
Highlights of Belle achievements （已发表近600篇文章，完成 >200篇博士论文）

CP violation/Unitarity Triangle

PRL 87, 091802 (2001)

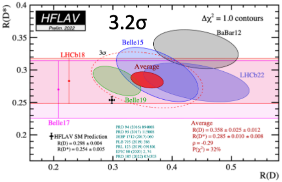


HFLAV: Unitarity triangle angles

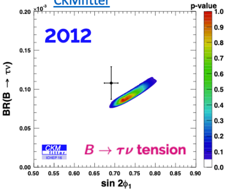


Flavor anomaly

HFLAV: SL B decays

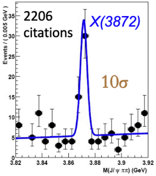


CKMfitter

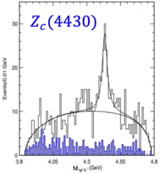


Exotic

PRL 91, 262001 (2003)

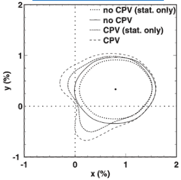


PRL 100, 142001 (2008)

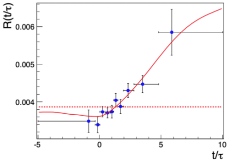


charm physics

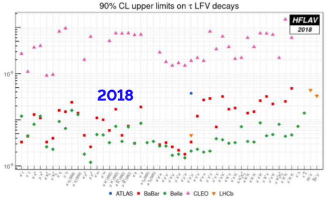
PRL 99, 131803 (2007)



PRL 112,111801 (2014)

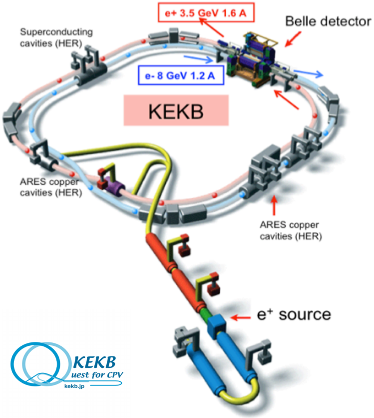


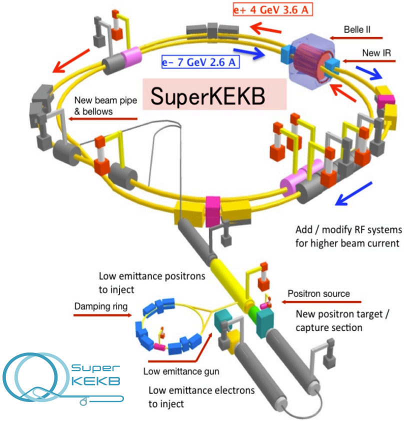
tau physics

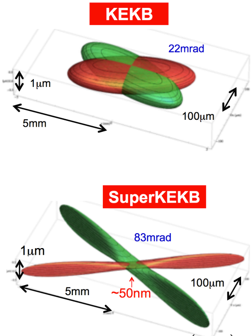


from KEKB to SuperKEKB

- As 1^{st} and 2^{nd} generation B-factories, KEKB and SuperKEKB have some similarities, but more differences:
  - Damping ring added to have low emittance positrons / use 'Nano-beam' scheme by squeezing the beta function (β) at the IP.
  - beam energy: admit lower asymmetry to mitigate Touschek effects / beam current ($I_{\pm}$): $\times 2$ to contribute to higher luminosity.
  - SuperKEKB achieved the luminosity record of $4.7 \times 10^{34}\ cm^{-2}s^{-1}$ (new W.R.).

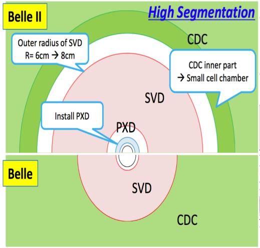


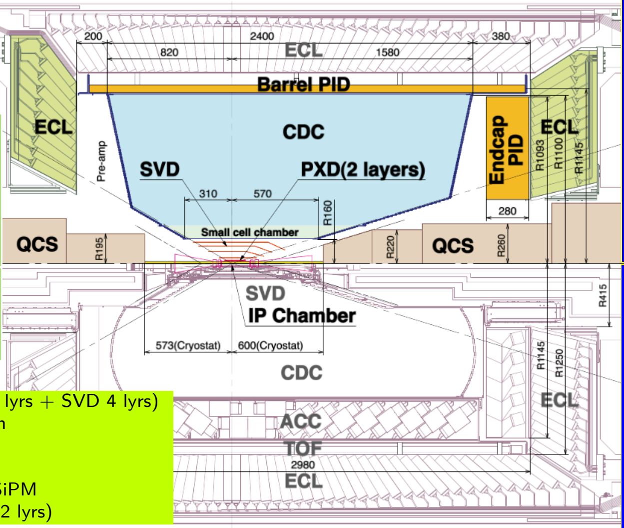




$$\mathcal{L} = \frac{\gamma_{\pm}}{2er_e}\left(1 + \frac{\sigma_y^*}{\sigma_x^*}\right)\frac{I_{\pm}\xi_{y\pm}}{\beta_{y\pm}^*}\left(\frac{R_L}{R_{\xi_y}}\right)$$

Belle II detector (Vs. Belle detector)





SVD: 4 lyrs → VXD=(PXD 2 lyrs + SVD 4 lyrs)
CDC: small cell, long lever arm
ACC+TOF → TOP+ARICH
ECL: waveform sampling
KLM: RPC → Scintillator + SiPM
(endcaps, barrel inner 2 lyrs)

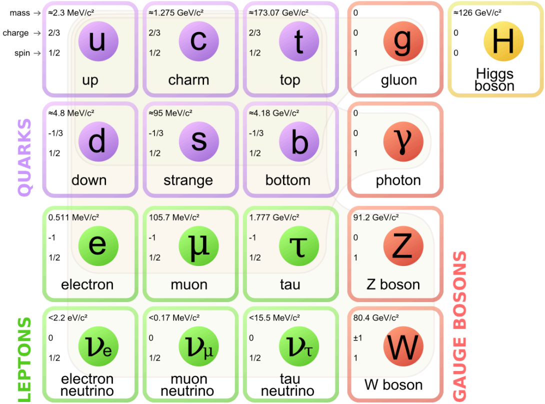
A big family at Belle and Belle II collaborations

- Belle II 合作组（中国大陆）：1155 个成员（7%），130（15）个单位，26个国家/地区。
  Belle 合作组：> 400 个成员，> 80 个单位，22个国家/地区。

Outline

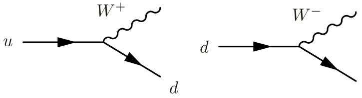
标准模型和 CKM

- 标准模型 (Standard Model)：基本粒子及其相互作用



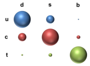
- 夸克之间味道改变的物理过程的描述：

$$\mathcal{L}_W = -\frac{g}{\sqrt{2}}\left(W_\mu^+ \bar{u}_i\gamma^\mu \frac{1-\gamma_5}{2} V_{ij} d_j + W_\mu^- \bar{d}_j\gamma^\mu \frac{1-\gamma_5}{2} V_{ij}^* u_i\right)$$



- CKM 矩阵元：描述着上下型夸克间味道改变的几率。

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$



- V_{CKM} 自由度为4。Wolfenstein 参数化形式，
  $\lambda \simeq \sin\theta_c \simeq 0.2253 \pm 0.0007$，相角 $\eta \neq 0$：唯一 CPV 源

$$\begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

Why *CP* violation and Charm Special?

- However, such CPV source in the SM is not large enough to explain the observed matter-antimatter asymmetry of the universe.⇒search for new CPV sources beyond the SM.
  - Sakharov (1967): CPV is one of the three conditions necessary to explain the matter-antimatter asymmetry of the universe.

- Among all open-flavored neutral meson systems, D^0 is only system made of up-type quark.
  - mixing: $K^0 \Leftrightarrow \overline{K}^0$, $B_d^0 \Leftrightarrow \overline{B}^0$, $B_s^0 \Leftrightarrow \overline{B}_s$, $D^0 \Leftrightarrow \overline{D}^0$.
  - provides a complimentary information on mixing and CPV.
- Charm CPV effects are very small (at level of $\mathcal{O}(10^{-3})$ or smaller [a b]), constrains New Physics models;
- New Physics may enhance the CPV [c d]. (An observation of charm CPV much larger than 10^{-3} indicates new physics.)
- The only observation of CPV via $\Delta A_{CP}(D^0 \to K^+K^-, \pi^+\pi^-)$ has been reported by LHCb [e].
- Recently, the first evidence for direct CPV in a specific D^0 decay ($D^0 \to \pi^+\pi^-$) is reported by LHCb [f].
- In order to understand the origin of the reported CPV result, we need to study more channels and improve the precision on the existing measurements.
- Study of charm physics helps to understand the SM, and is a sensitive probe to search for New Physics.

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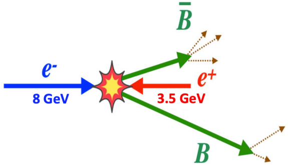
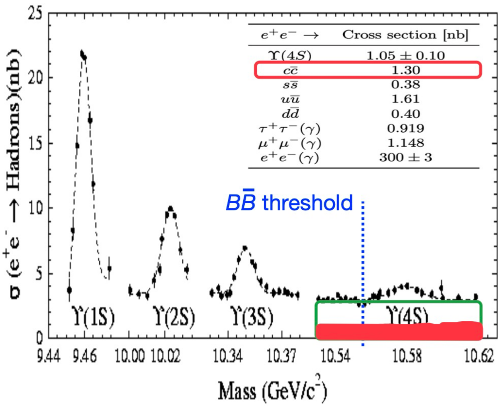
[a] H.-n. Li, C.-D. Lu, and F.-S. Yu, PRD 86, 036012 (2012)
[b] H.-Y. Cheng and C.-W. Chiang, PRD 104, 073003 (2021)
[c] A. Dery and Y. Nir, JHEP 12, 104 (2019)
[d] M. Saur and F.-S. Yu, Sci. Bull. 65, 1428 (2020)
[e] (LHCb Collaboration), PRL 122, 211803 (2019)
[f] (LHCb Collaboration), arXiv:2209.03179

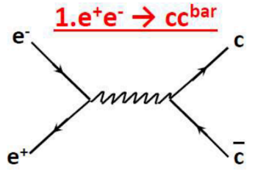
Charm production at Belle and Belle II

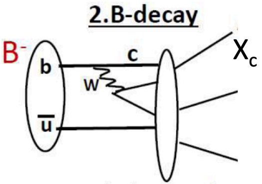
- In B-factories, e^+e^- collider at 10.58 GeV to make $\Upsilon(4S)$ resonance decaying into $B^0\bar{B}$ and B^+B^- in 96% of the time.
- Meanwhile, a large cross section for continuum processes $e^+e^- \to q\bar{q}$ ($q = u, d, s, c$).
- Thus, there are two ways to produce the charm sample at B-factories:



E_{cm}	On/Off(fb^{-1})	Number
$\Upsilon(1S)$	5.7/1.8	102M $\Upsilon(1S)$
$\Upsilon(2S)$	24.9/1.7	158M $\Upsilon(2S)$
$\Upsilon(3S)$	2.9/0.25	11M $\Upsilon(3S)$
$\Upsilon(4S)$ SVD1	140.0/15.6	152M $B\bar{B}$
$\Upsilon(4S)$ SVD2	571.0/73.8	620M $B\bar{B}$
$\Upsilon(5S)$	121.4/1.7	7.1M $B_s\bar{B}_s$
scan	0/27.6	







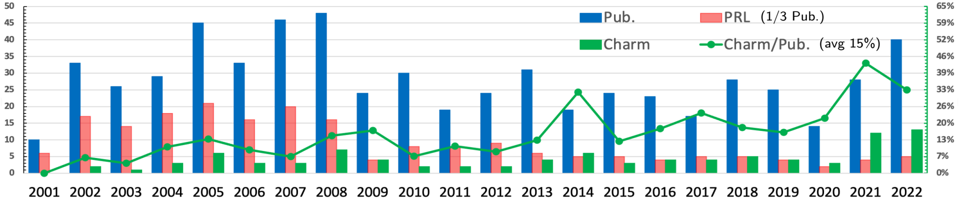
Available Charm samples from Charm factories, B-factories, hadron colliders

Experiment	Machine	Operation	C.M.	Lumin.	N(D^0)	efficiency	☺advantage/☹disadvantage
CLEO	CESR (e^+e^-)	2003-2008	3.77 4.18 GeV	0.8 fb^{-1} 0.6 fb^{-1}	2.9 M D^+: 2.3 M 0.6 M	~10-30%	☺ extremely clean environment ☺ pure D-beam, almost no bkg ☺ quantum coherence ☹ no CM boost, no T-dep analyses
BESIII	BEPC-II (e^+e^-)	2010-2011(2021-) 2016-2019 2014+2020	3.77 GeV 4.18-4.23 GeV 4.6-4.7 GeV	2.92($\rightarrow$ 20) fb^{-1} 7.3 fb^{-1} 4.5 fb^{-1}	10.5($\rightarrow$ 72) M D^+: 8.4 M 4.6 M Λ_c^+ : ? M ★	★★★	
Belle II	SuperKEKB (e^+e^-)	2019-	10.58 GeV	428+ fb^{-1}	0.6+ G D^+: 0.3 G	~5-10%	☺ clear event environment ☺ high trigger efficiency ☺ high-efficiency detection of neutrals ☺ many high-statistics control samples ☺ time-dependent analysis ☹ smaller cross-section than pp colliders
BELLE	KEKB (e^+e^-)	1999-2010	10.58 GeV	1000 fb^{-1}	1.4 G D^+: 0.8 G		
BaBar	PEP-II (e^+e^-)	1999-2008	10.58 GeV	500 fb^{-1}	0.65 G ★★	★★	
CDF	Tevatron ($p\bar{p}$)	2002-2011	1960	9.6 fb^{-1}	0.13 T	<0.5%	☺ very large production cross-section ☺ large boost ☺ excellent time resolution ☹ dedicated trigger required
LHCb	LHC (pp)	2011 2012 2015-2018	7 TeV 8 TeV 13 TeV	1.0 fb^{-1} 2.0 fb^{-1} 6 fb^{-1}	5.0 T ? ★★★	★	

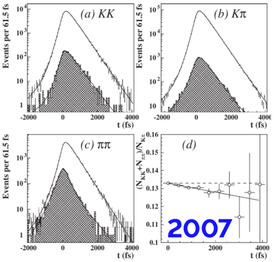
here $\sigma(D^0\bar{D}@3.77\,\text{GeV})$=3.61 nb, $\sigma(D^+D^-@3.77\,\text{GeV})$=2.88 nb, $\sigma(D^*D_s@4.17\,\text{GeV})$=0.967 nb, $\sigma(c\bar{c}@10.58\,\text{GeV})$=1.3 nb, and $\sigma(D^0@LHCb)$=1.661 nb are used. The table mainly refers to Int. J. Mod. Phys. A **29** (2014) 24, 14300518.

Highlights of Charm results at Belle

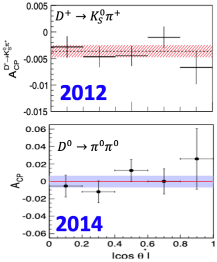
Belle journal publications per year



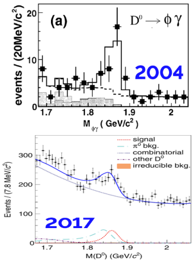
D^0-$\bar{D}^0$ mixing



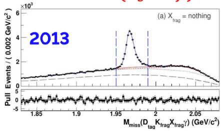
CP violation



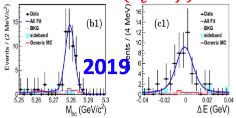
Rare D^0 decay



absolute $B(D_s^+ \to f)$



absolute $B(\Xi_c^0 \to f)$



Recent Charm results at Belle

- Although 12 years have passed since Belle finished the final data set accumulation, we are lasting to produce fruitful Charm results. The charm results since 2021 (here not covering charm spectroscopy results) are listed below:

BF of $\Lambda_c^+ \to pK_S^0K_S^0$ and $\Lambda_c^+ \to pK_S^0\eta$	arXiv:2210.01995 (accepted by PRD)
BF of $\Omega_c^0 \to \Xi^-\pi^+$, Ξ^-K^+, Ω^-K^+	arXiv:2209.08583 (accepted by JHEP)
BF/α of $\Lambda_c^+ \to \Sigma^+(\pi^0, \eta, \eta')$	arXiv:2208.10825 (submitted to PRD)
BF/$A_{CP}^{\rm dir}/\alpha/A_{CP}^{\alpha}$ of $\Lambda_c^+ \to \Lambda h^+$, $\Sigma^0 h^+$	arXiv:2208.08695 (submitted to Sci.Bull.)
BF/$a_{CP}^{T\text{-odd}}/A_{CP}$ of $D^0 \to K_S^0K_S^0\pi^+\pi^-$	arXiv:2207.07555 (submitted to PRD)
BF of $D^+ \to K^-K_S^0\pi^+\pi^+\pi^0$	arXiv:2207.06595 (submitted to PRD)
BF of $\Lambda_c^+ \to \Sigma^+\gamma$ and $\Xi_c^0 \to \Xi^0\gamma$	arXiv:2206.12517 (accepted by PRD)
BF of $\Xi_c^0 \to \Lambda_c^+\pi^-$	arXiv:2206.08527 (accepted by PRD)
BF of $D_{(s)}^+ \to K\pi\pi^+\pi^0$	arXiv:2205.02018 (accepted by PRD)
BF of $\Xi_c^0 \to \Lambda K_S^0$, $\Sigma^0K_S^0$, and Σ^+K^-	PRD **105**, L011102 (2022)
BF of $\Lambda_c^+ \to p\pi^0$, $p\eta$, $p\omega$, $p\eta'$	PRD **103**, 072004 (2021), PRD **104**, 072008 (2021), JHEP 03 (2022) 090
BF/A_{CP} in $D^0 \to \pi^+\pi^-\eta$, $K^+K^-\eta$, and $\phi\eta$	JHEP 09 (2021) 075
BF/$A_{CP}^{\rm dir}$ for $D_s^+ \to K^+\pi^0$, $K^+\eta$, $\pi^+\pi^0$, and $\pi^+\eta$	PRD **103**, 112005 (2021)
BF/α for $\Xi_c^0 \to \Lambda K^{*0}$, $\Sigma^0\overline{K}^{*0}$, and Σ^+K^{*-}	JHEP 06 (2021) 160
BF of $\Xi_c^0 \to \Xi^-\ell^+\nu_\ell$ and $\Omega_c^0 \to \Omega^-\ell^+\nu_\ell$	PRL **127**, 121803 (2021), PRD **105**, L091101 (2022)
BF of $\Xi_c^0 \to \Xi^0\phi$ and $\Xi_c^0 \to \Xi^0K^+K^-$	PRD **103**, 112002 (2021)
BF of $\Lambda_c^+ \to \Lambda\eta\pi^+$, $\Sigma^0\eta\pi^+$, $\Lambda(1670)\pi^+$, $\eta\Sigma(1385)$	PRD **103**, 052005 (2021)
Search for $\Omega_c^0 \to \pi^+\Omega(2012)^- \to \pi^+(\overline{K}^0\Xi)^-$	PRD **104**, 052005 (2021)

Recent Charm results at Belle

- Although 12 years have passed since Belle finished the final data set accumulation, we are lasting to produce fruitful Charm results. The charm results since 2021 (here not covering charm spectroscopy results) are listed below:

⇒ ⇒	BF of $\Lambda_c^+ \to pK_S^0K_S^0$ and $\Lambda_c^+ \to pK_S^0\eta$	arXiv:2210.01995 (accepted by PRD)
⇒	BF of $\Omega_c^0 \to \Xi^-\pi^+$, Ξ^-K^+, Ω^-K^+	arXiv:2209.08583 (accepted by JHEP)
⇒	BF/α of $\Lambda_c^+ \to \Sigma^+(\pi^0,\eta,\eta')$	arXiv:2208.10825 (submitted to PRD)
⇒ ⇒	BF/$A_{CP}^{\rm dir}$/α/A_{CP}^{α} of $\Lambda_c^+ \to \Lambda h^+$, $\Sigma^0 h^+$	arXiv:2208.08695 (submitted to Sci.Bull.)
	BF/$a_{CP}^{T\text{-odd}}$/A_{CP} of $D^0 \to K_S^0K_S^0\pi^+\pi^-$	arXiv:2207.07555 (submitted to PRD)
	BF of $D^+ \to K^-K_S^0\pi^+\pi^+\pi^0$	arXiv:2207.06595 (submitted to PRD)
⇒	BF of $\Lambda_c^+ \to \Sigma^+\gamma$ and $\Xi_c^0 \to \Xi^0\gamma$	arXiv:2206.12517 (accepted by PRD)
⇒	BF of $\Xi_c^0 \to \Lambda_c^+\pi^-$	arXiv:2206.08527 (accepted by PRD)
⇒ ⇒	BF of $D_{(s)}^+ \to K\pi\pi^+\pi^0$	arXiv:2205.02018 (accepted by PRD)
⇒	BF of $\Xi_c^0 \to \Lambda K_S^0$, $\Sigma^0K_S^0$, and Σ^+K^-	PRD **105**, L011102 (2022)
⇒	BF of $\Lambda_c^+ \to p\pi^0$, $p\eta$, $p\omega$, $p\eta'$	PRD **103**, 072004 (2021), PRD **104**, 072008 (2021), JHEP 03 (2022) 090
⇒ ⇒	BF/A_{CP} in $D^0 \to \pi^+\pi^-\eta$, $K^+K^-\eta$, and $\phi\eta$	JHEP 09 (2021) 075
⇒	BF/$A_{CP}^{\rm dir}$ for $D_s^+ \to K^+\pi^0$, $K^+\eta$, $\pi^+\pi^0$, and $\pi^+\eta$	PRD **103**, 112005 (2021)
⇒	BF/α for $\Xi_c^0 \to \Lambda K^{*0}$, $\Sigma^0\overline{K}^{*0}$, and Σ^+K^{*-}	JHEP 06 (2021) 160
⇒	BF of $\Xi_c^0 \to \Xi^-\ell^+\nu_\ell$ and $\Omega_c^0 \to \Omega^-\ell^+\nu_\ell$	PRL **127**, 121803 (2021), PRD **105**, L091101 (2022)
	BF of $\Xi_c^0 \to \Xi^0\phi$ and $\Xi_c^0 \to \Xi^0K^+K^-$	PRD **103**, 112002 (2021)
	BF of $\Lambda_c^+ \to \Lambda\eta\pi^+$, $\Sigma^0\eta\pi^+$, $\Lambda(1670)\pi^+$, $\eta\Sigma(1385)$	PRD **103**, 052005 (2021)
⇒	Search for $\Omega_c^0 \to \pi^+\Omega(2012)^- \to \pi^+(\overline{K}^0\Xi)^-$	PRD **104**, 052005 (2021)

- contributed by Chinese people (me) as first authors.

（原因之一：得益于国内越来越多的从事粲物理研究的理论学者，理论和实验更密切的交流。）

Outline

$\mathcal{B}/A_{CP}$ for $D^0 \to h^+h^-\eta$ and $D^0 \to \phi\eta$: Motivation (JHEP 09 (2021) 075)

- 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 $\delta\mathcal{B}/\mathcal{B}(D^0 \to \eta(K^+K^-)_{\mathrm{non-}\phi}) \sim 35\%$[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 our large charm sample?

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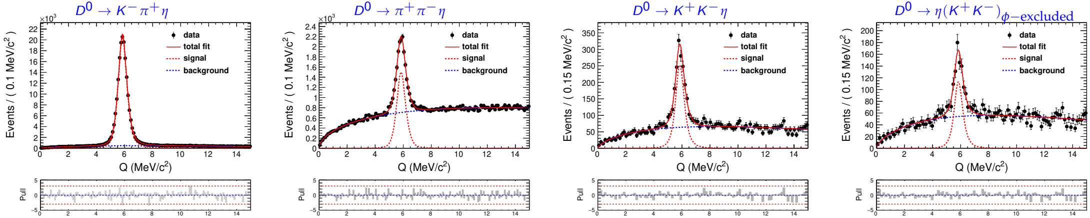
[a] LHCb, Phys. Rev. Lett. **122**, 211803 (2019)
[b] PDG2021, PTEP 2020 (2020) 083C01
[c] BESIII, Phys. Rev. D **101**, 052009 (2020)
[d] BESIII, Phys. Rev. Lett. **124**, 241803 (2020)
[e] Belle, Phys. Rev. Lett. **92**, 101803 (2004)
[f] BESIII, Phys. Lett. B **798**, 135017 (2019)
[g] Belle, Phys.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

$\mathcal{B}/A_{CP}$ for $D^0 \to h^+h^-\eta$ and $D^0 \to \phi\eta$: Signal Yields (JHEP 09 (2021) 075)

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

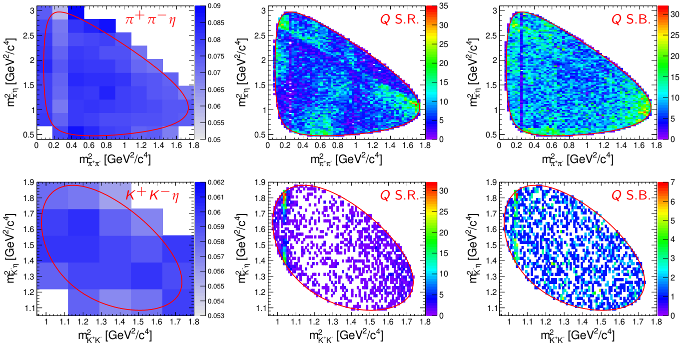


Region	Component	$D^0 \to K^-\pi^+\eta$	$D^0 \to \pi^+\pi^-\eta$	$D^0 \to K^+K^-\eta$	$D^0 \to \eta(K^+K^-)_{\phi-\text{excluded}}$
Fit region	signal	180369 ± 837	12982 ± 198	1482 ± 60	660 ± 49
	background	57752 ± 761	101011 ± 357	5681 ± 88	4804 ± 81
	fit quality	$\chi^2/(150-8) = 1.21$	$\chi^2/(150-6)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

- Measure the branching fraction via $\mathcal{B}_{\text{sig}}/\mathcal{B}_{\text{ref}} = (N_{\text{sig}}/\varepsilon_{\text{sig}})/(N_{\text{ref}}/\varepsilon_{\text{ref}})$.

$\mathcal{B}/A_{CP}$ for $D^0 \to h^+h^-\eta$ and $D^0 \to \phi\eta$ (JHEP 09 (2021) 075)

- 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

A very clear $\phi(1020)$ structure

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

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

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

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

Using the world average (W.A.) $\mathcal{B}(D^0 \to K^-\pi^+\eta)$[g,d], we have the absolute branching fractions:

$\mathcal{B}(D^0 \to \pi^+\pi^-\eta) = (1.22 \pm 0.02 \pm 0.02 \pm 0.02) \times 10^{-3}$

$\mathcal{B}(D^0 \to K^+K^-\eta) = (1.80^{+0.07}_{-0.06} \pm 0.04 \pm 0.03) \times 10^{-4}$

$\mathcal{B}(D^0 \to (K^+K^-)_{\rm ex.-\phi}\eta) = (0.99^{+0.08}_{-0.07} \pm 0.02 \pm 0.02) \times 10^{-4}$.

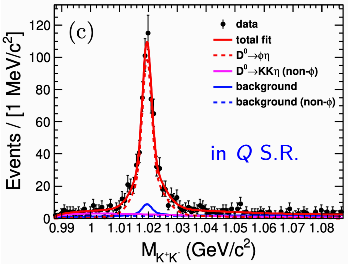
the last one is somewhat higher (but more precise) than a similar measurement by BESIII[d] $(0.59 \pm 0.19) \times 10^{-4}$.

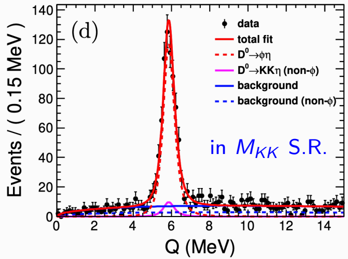
$\mathcal{B}/A_{CP}$ for $D^0 \to h^+h^-\eta$ and $D^0 \to \phi\eta$ (JHEP 09 (2021) 075)

- 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.
- First observation of $D^0 \to \phi\eta$ with large statistical significance ($> 10\sigma$).
- Based on $N_{sig} = 600 \pm 29$ and $\varepsilon = (5.262 \pm 0.021)\%$ in signal region, the relative branching fraction is determined.
  $\frac{\mathcal{B}(D^0\to\phi\eta,\phi\to K^+K^-)}{\mathcal{B}(D^0\to K^-\pi^+\eta)} = [4.82 \pm 0.23\,(\mathrm{stat}) \pm 0.16\,(\mathrm{syst})] \times 10^{-3}$.
- using well-measured $\mathcal{B}(D^0 \to K^-\pi^+\eta)$ and $\mathcal{B}_{\mathrm{PDG}}(\phi \to K^+K^-)$, we have

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

  which is consistent, but notably more precise than, previous results from Belle and BESIII.
- As a consistency check, we calculate $\mathcal{B}(D^0 \to (K^+K^-)_{\mathrm{non}-\phi}\eta)$ 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 $\mathcal{B}(D^0 \to K^+K^-\eta)_{\mathrm{ex.}-\phi}$.





Time-integrated CP asymmetry measurement

- Taking $D^0 \to f$ decays for example, for the decay chain $e^+e^- \to c\bar{c} \to D^{*+}X$, $D^{*+} \to D^0\pi_s^+$, 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 $A_{\rm FB}$ arises from the forward-backward asymmetry (FBA) of D^{*+} production due to γ-Z^0 interference and higher-order QED effects in e^+e^- collisions. The FBA is an odd function in $\cos\theta^*$, where θ^* is the D^{*+} production polar angle in the e^+e^- center-of-mass frame.

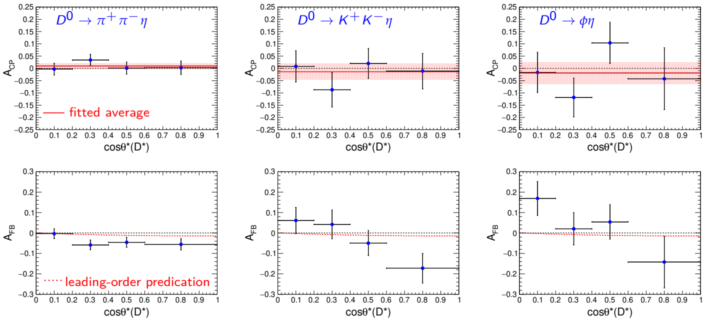
- To remove $A_\varepsilon^{\pi_s}$, $D^0/\bar{D}^0$ candidates are weighted by factors $w_{D^0/\bar{D}^0} = 1 \mp A_\varepsilon^{\pi_s}[\cos\theta(\pi_s), p_T(\pi_s)]$, where the map $A_\varepsilon^{\pi_s^+}$ is determined from large samples of tagged and untagged $D \to K^-\pi^+$ decays.
- For decays with self-conjugated final states ($A_\varepsilon^f = 0$), the π_s-corrected raw asymmetry: $A_{\rm corr}(\cos\theta^*) = A_{CP} + A_{\rm FB}(\cos\theta^*)$.
- 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.

$\mathcal{B}/A_{CP}$ for $D^0 \to h^+h^-\eta$ and $D^0 \to \phi\eta$ (JHEP 09 (2021) 075)

- Dividing 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_{KK}-Q distributions for D^0 and $\bar{D}^0$ samples, to extract the corrected raw asymmetry $A_{\rm corr}$: $N_{\rm sig}(D^0, \bar{D}^0) = N_{\rm sig}/2 \cdot (1 \pm A_{\rm corr})$.
- calculate four sets of A_{CP} and $A_{\rm FB}$ values from symmetric bin-pair of $\cos\theta^*$, as plotted in below figures.



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

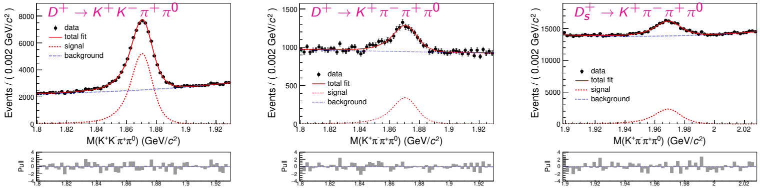
$$A_{CP}(D^0 \to \pi^+\pi^-\eta) = [0.9 \pm 1.2\,(\text{stat}) \pm 0.5\,(\text{syst})]\%,$$
$$A_{CP}(D^0 \to K^+K^-\eta) = [-1.4 \pm 3.3\,(\text{stat}) \pm 1.1\,(\text{syst})]\%,$$
$$A_{CP}(D^0 \to \phi\eta) = [-1.9 \pm 4.4\,(\text{stat}) \pm 0.6\,(\text{syst})]\%,$$

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

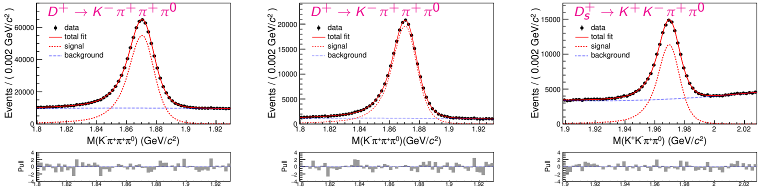
No evidence for CP violation is found in these SCS decays.

$\mathcal{B}/a_{CP}^{T\text{-odd}}$ of $D^+_{(s)} \to K^\pm h^\pm \pi^+ \pi^0$ (arXiv:2205.02018 (Accepted by PRD))

- The four-body decays of charged D mesons. e.g. three CS decays below



and their corresponding reference modes:



- Based on the efficiency-corrected yields and the W.A. $\mathcal{B}$ of reference mode, obtain relative $\mathcal{B}_{\rm sig}/\mathcal{B}_{\rm ref}$. e.g. $\left(\frac{\rm DCS}{\rm CF}\right) \frac{\mathcal{B}(D^+ \to K^+\pi^-\pi^+\pi^0)}{\mathcal{B}(D^+ \to K^-\pi^+\pi^+\pi^0)} = (1.68 \pm 0.11 \pm 0.03)\%$ corresponds to $(5.83 \pm 0.42)\tan^4\theta_C$. This is significantly larger than all other known DCS/CF ratios, but confirms BESIII's discovery.
- using the W.A. $\mathcal{B}_{\rm ref}$, we have three most precise results:
  $\mathcal{B}(D^+ \to K^+K^-\pi^+\pi^0) = (7.08 \pm 0.08 \pm 0.16 \pm 0.20) \times 10^{-3}$,
  $\mathcal{B}(D^+ \to K^+\pi^-\pi^+\pi^0) = (1.05 \pm 0.07 \pm 0.02 \pm 0.03) \times 10^{-3}$,
  $\mathcal{B}(D_s^+ \to K^+\pi^-\pi^+\pi^0) = (9.44 \pm 0.34 \pm 0.28 \pm 0.32) \times 10^{-3}$.

$\mathcal{B}/a_{CP}^{T\text{-odd}}$ of $D^+_{(s)} \to K^\pm h^\pm \pi^+ \pi^0$

- T-odd correlations provides a powerful tool to indirectly search for CP violation under CPT symmetry conservation:
- C_T observable defined by a triple mixed product $C_T = (\vec{p}_1 \times \vec{p}_2) \cdot \vec{p}_3$, satisfying $CP(C_T) = -C(C_T) = -\overline{C}_T$. Define T-odd asymmetries for $D^+_{(s)}$ or $D^-_{(s)}$ decays:

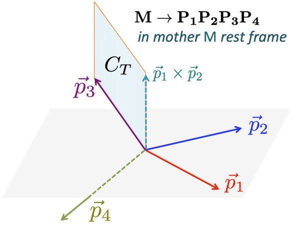
$$A_T = \frac{\Gamma_+(C_T > 0) - \Gamma_+(C_T < 0)}{\Gamma_+(C_T > 0) + \Gamma_+(C_T < 0)} \qquad \overline{A}_T = \frac{\Gamma_-(-\overline{C}_T > 0) - \Gamma_-(-\overline{C}_T < 0)}{\Gamma_-(-\overline{C}_T > 0) + \Gamma_-(-\overline{C}_T < 0)}$$

which are $\propto \sin(\phi + \delta)$ and $\propto \sin(-\phi + \delta)$, respectively [1].

- T-odd CP-violating asymmetry is defined as (to veto FSI effects):

$$\boxed{a_{CP}^{T\text{-odd}} = \frac{1}{2}(A_T - \overline{A}_T)}$$ can be nonzero if CPV

which is $\propto \sin\phi \cos\delta$ (largest value when $\delta = 0$, Vs. $A_{CP}^{\rm dir} \neq 0$ requires $\delta \neq 0$),



- Status of $a_{CP}^{T\text{-odd}}$ measurements in charmed mesons decay-rates:

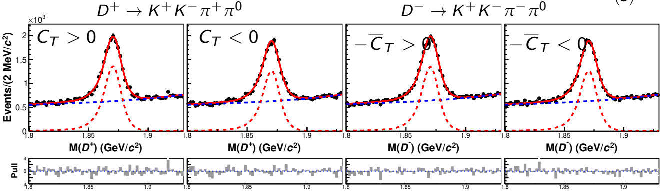
$D^0 \to K^0_S \pi^+\pi^-\pi^0$	$a_{CP}^{T\text{-odd}} = (-0.28 \pm 1.38^{+0.23}_{-0.76}) \times 10^{-3}$	Belle[2]
$D^0 \to K^+K^-\pi^+\pi^-$	$a_{CP}^{T\text{-odd}} = (+1.7 \pm 2.7) \times 10^{-3}$	LHCb[3], BaBar[4], Focus[5]
$D^+ \to K^0_S K^+\pi^+\pi^-$	$a_{CP}^{T\text{-odd}} = (-1.10 \pm 1.09) \times 10^{-2}$	BaBar[6], Focus[5]
$D^+_s \to K^0_S K^+\pi^+\pi^-$	$a_{CP}^{T\text{-odd}} = (-1.39 \pm 0.84) \times 10^{-2}$	BaBar[6], Focus[5]

Belle and Belle II may improve these $a_{CP}^{T\text{-odd}}$ results or obtain more precise results and results in more channels benefited from the increasing dataset.

[1] A. Datta, D. London, Int. J. Mod. Phys. A **19** (2004) 2505
[2] K. Prasanth *et al.*(Belle Collab.), Phys. Rev. D **95**, 091101(R) (2017)
[3] R. Aaij *et al.*(LHCb Collab.), JHEP **10**, 5 (2014)
[4] P. del Amo Sanchez *et al.*(BaBar Collab.), Phys. Rev. D **81**, 111103(R) (2010)
[5] J.M. Link *et al.*(FOCUS Collab.), Phys. Lett. B **622**, 239 (2005)
[6] J.P. Lees *et al.*(BaBar Collab.), Phys. Rev. D **84**, 031103(R) (2011)

$\mathcal{B}/a_{CP}^{T\text{-odd}}$ of $D^+_{(s)} \to K^\pm h^\pm \pi^+ \pi^0$ under internal review

- Simultaneous fit on four C_T sub-samples to extract $a_{CP}^{T\text{-odd}}$ for five $D^+_{(s)}$ decays.

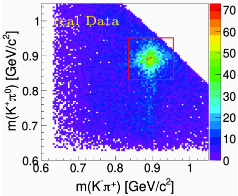


- Similar measurement in the subregion of phase space corresponding to dominant resonances.

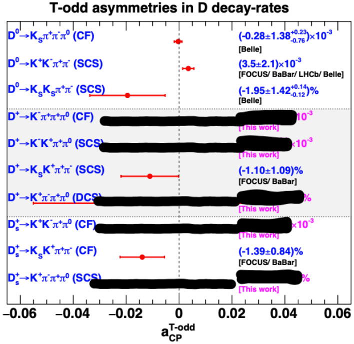
Index	$D \to VV$	PHSP subregion	$a_{CP}^{T\text{-odd}}$ $(\times 10^{-2})$
(1) SCS	$D^+ \to \phi\rho^+$	ϕ-SR, ρ^+-SR	[redacted] $\pm 0.95^{+0.07}_{-0.24}$
(2) SCS	$D^+ \to \bar{K}^{*0}K^{*+}$	$K^{*0,+}$-SR, veto ϕ-SR	[redacted] $\pm 1.26^{+0.02}_{-0.13}$
(3) CF	$D^+ \to \bar{K}^{*0}\rho^+$	K^{*0}-SR, ρ^+-SR	[redacted] $\pm 0.25^{+0.00}_{-0.13}$
(4) SCS	$D_s^+ \to K^{*0}\rho^+$	K^{*0}-SR, ρ^+-SR	[redacted] $\pm 2.99^{+0.09}_{-0.40}$
(5) SCS	$D_s^+ \to K^{*+}\rho^0$	K^{*+}-SR, ρ^0-SR	[redacted] $\pm 6.14^{+0.99}_{-1.29}$
(6) CF	$D_s^+ \to \phi\rho^+$	ϕ-SR, ρ^+-SR	[redacted] $\pm 0.40^{+0.00}_{-0.43}$
(7) CF	$D_s^+ \to \bar{K}^{*0}K^{*+}$	$K^{*0,+}$-SR, veto ϕ-SR	[redacted] $\pm 0.76^{+0.02}_{-0.37}$

$|M_{KK} - m_\phi| < 10$ MeV/c^2 as ϕ-SR
$|M_{K\pi} - m_{K^*}| < 60$ MeV/c^2 as $K^{*0,+}$-SR
$-90 < M_{\pi^+\pi^0} - m_\rho < 60$ MeV/c^2 as $\rho^{0,+}$-SR

e.g. $D^+ \to \bar{K}^{*0}K^{*+}$



- Final results in this work compared with that in other channels.



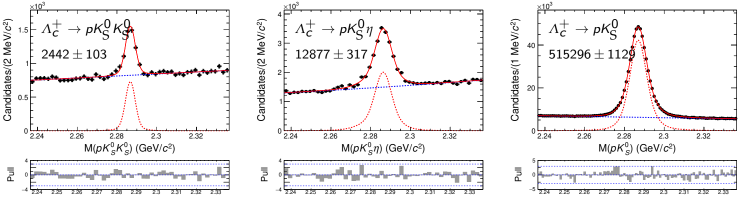
- ▶ All D mesons reach 10^{-3} level.
- More charm $a_{CP}^{T\text{-odd}}$ results will be released in one or two months.

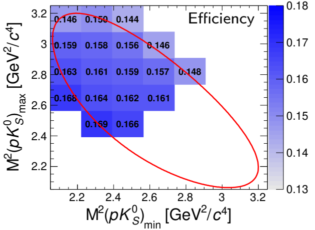
Outline

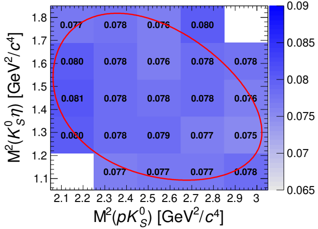
$\mathcal{B}$ of $\Lambda_c^+ \to pK_S^0K_S^0$ and $\Lambda_c^+ \to pK_S^0\eta$ (arXiv:2210.01995, accepted by PRD)

$$\frac{\mathcal{B}_{\rm sig}}{\mathcal{B}_{\rm ref}} = \frac{N_{\rm sig}/\varepsilon_{\rm sig}}{N_{\rm ref}/\varepsilon_{\rm ref}}$$

- The weak decays of charmed baryons provide an excellent platform for understanding QCD with transitions involving the charm quark.
- Their decay amplitudes consist of factorizable and non-factorizable contributions, the latter approached by various models: covariant confined quark model, current algebra, $SU(3)_F$ symmetry, etc.
- Experimentally, the investigation of charmed baryons is more challenging than that of charmed mesons. (mainly due to lower production rates).
- $\mathcal{B}(\Lambda_c^+ \to pK_S^0\eta)$ with uncertainty 22%. $\Lambda_c^+ \to pK_S^0K_S^0$ to be observed.







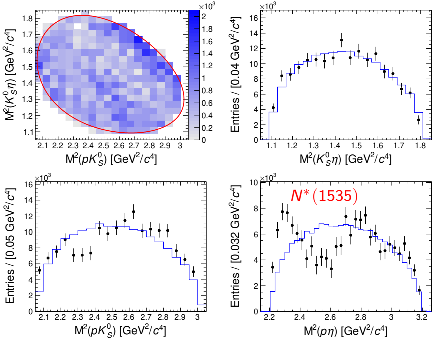
$\mathcal{B}(\Lambda_c^+ \to pK_S^0K_S^0) = (2.35 \pm 0.12 \pm 0.12) \times 10^{-4}$ (First observation)

$\mathcal{B}(\Lambda_c^+ \to pK_S^0\eta) = (4.35 \pm 0.10 \pm 0.22) \times 10^{-3}$ (vs PDG $(4.15 \pm 0.90) \times 10^{-3}$)

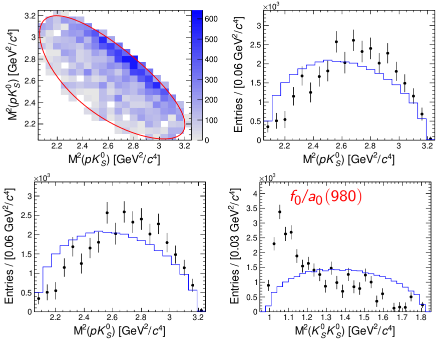
$\mathcal{B}$ of $\Lambda_c^+ \to pK_S^0K_S^0$ and $\Lambda_c^+ \to pK_S^0\eta$ (arXiv:2210.01995, accepted by PRD)

- We examine the Dalitz plots after background subtraction and efficiency correction, for intermediate resonances.
  - The mass of $N^*(1535)_{1/2-}$ is larger than that of $N^*(1440)_{1/2+}$, in opposition to predictions of classical constituent quark models. Secondly, the $N^*(1535)$ also couples strongly to channels with strangeness, such as ηN and $K\Lambda$, which is difficult to explain within the naive constituent quark models. The inclusion of five-quark components gives a natural explanation for these properties.
  - The nature of $f_0/a_0(980)$ remains not fully understood and continues to cause controversy, but they are often interpreted as compact tetraquark states or $K\overline{K}$ bound states.

$\Lambda_c^+ \to pK_S^0\eta$



$\Lambda_c^+ \to pK_S^0K_S^0$



► A proposal of amplitude analysis:
It is possible at BESIII or Belle II based on increasing data sets, may help understand the nature of such interesting resonances.

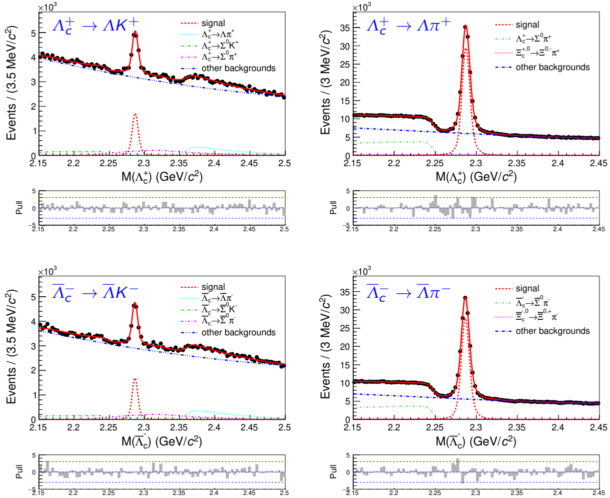
► Charmed baryon decays provide a good platform to study the light scalars and light flavor baryons.

► My focus has moved to the charmed baryon studies, including PWA of $\Lambda_c^+/\Xi_c^{+,0}$ three-body decays.

$\mathcal{B}/A_{CP}^{\rm dir}/\alpha/A_{CP}^{\alpha}$ of $\Lambda_c^+ \to \Lambda h^+$, $\Sigma^0 h^+$ at Belle (arXiv:2208.08695, submitted to Sci. Bull.)

- To date, CPV has been observed in the open-flavored meson sector (i.e. K, D and B mesons), but not yet established in the baryon sector. While, Baryogenesis, the process by which the baryon-antibaryon asymmetry of the universe developed, is directly related to baryon CPV.
- Experimentally, no direct CPV searches in two-body SCS decays of charm baryons have been made to date.
- The raw asymmetry in the decays $A_{\rm raw} = \frac{N_{\rm sig}(\Lambda_c^+ \to f) - N_{\rm sig}(\overline{\Lambda}_c^- \to \overline{f})}{N_{\rm sig}(\Lambda_c^+ \to f) + N_{\rm sig}(\overline{\Lambda}_c^- \to \overline{f})}$
- Several sources contribute to the raw asymmetry: $A_{\rm raw}(\Lambda_c^+ \to \Lambda K^+) \approx A_{CP}^{\Lambda_c^+ \to \Lambda K^+} + A_{CP}^{\Lambda \to p\pi^-} + A_\varepsilon^{\Lambda} + A_\varepsilon^{K^+} + A_{\rm FB}^{\Lambda_c^+}$
  - $A_{CP}^{\Lambda_c^+ \to \Lambda K^+}$ ($A_{CP}^{\Lambda \to p\pi^-}$) is the direct CP asymmetry associated with the Λ_c^+ (Λ) decay,
  - A_ε^{Λ} ($A_\varepsilon^{K^+}$) is the detection asymmetry arising from efficiencies between Λ (K^+) and its anti-particle $\overline{\Lambda}$ (K^-),
  - $A_{\rm FB}^{\Lambda_c^+}$ arises from the forward-backward asymmetry (FBA) of Λ_c^+ production due to γ-Z^0 interference and higher-order QED effects in $e^+e^- \to c\bar{c}$ collisions. The FBA is an odd function in $\cos\theta^*$, where θ^* is the Λ_c^+ production polar angle in the e^+e^- center-of-mass frame, but due to asymmetric acceptance, small residual asymmetry remains after integrating over $\cos\theta^*$.
- $A_{\rm raw}^{\rm corr}(\Lambda_c^+ \to \Lambda K^+) - A_{\rm raw}^{\rm corr}(\Lambda_c^+ \to \Lambda\pi^+) = A_{CP}^{\rm dir}(\Lambda_c^+ \to \Lambda K^+) - A_{CP}^{\rm dir}(\Lambda_c^+ \to \Lambda\pi^+) = A_{CP}^{\rm dir}(\Lambda_c^+ \to \Lambda K^+)$
  The reference mode $\Lambda_c^+ \to \Lambda\pi^+$ and signal mode have nearly the same Λ kinematic distributions, including the Λ decay length, the polar angle with respect to the direction opposite the positron beam and the momentum of the proton and pion in the laboratory reference frame.

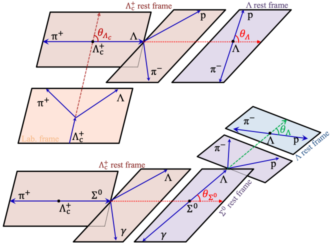
$\mathcal{B}/A_{CP}^{\rm dir}/\alpha/A_{CP}^{\alpha}$ of $\Lambda_c^+ \to \Lambda h^+$, $\Sigma^0 h^+$ at Belle (arXiv:2208.08695, submitted to Sci. Bull.)



- Simultaneous fit on the $A_\xi^{h^+}$-weighted $\Lambda_c^\pm$ samples gives
  $A_{CP}^{\rm dir}(\Lambda_c^+ \to \Lambda K^+) = (+2.1 \pm 2.6 \pm 0.1)\%$
  $A_{CP}^{\rm dir}(\Lambda_c^+ \to \Sigma^0 K^+) = (+2.5 \pm 5.4 \pm 0.4)\%$,
  first CPV result of charmed baryon SCS two-body decays.
- Based on $M(\Lambda_c^+)$ fit on the combined $\Lambda_c^\pm$ sample and the efficiencies based on signal MC produced with our measured angular distribution, we measure $\frac{\mathcal{B}_{\rm sig}}{\mathcal{B}_{\rm ref}} = \frac{N_{\rm sig}/\varepsilon_{\rm sig}}{N_{\rm ref}/\varepsilon_{\rm ref}}$.
  $$\frac{\mathcal{B}(\Lambda_c^+ \to \Lambda K^+)}{\mathcal{B}(\Lambda_c^+ \to \Lambda \pi^+)} = (5.05 \pm 0.13 \pm 0.09)\%;$$
  (Vs. PDG: 4.7 ± 0.9)%; BESIII recent result: $(4.78 \pm 0.39)\%$.)
  $$\frac{\mathcal{B}(\Lambda_c^+ \to \Sigma^0 K^+)}{\mathcal{B}(\Lambda_c^+ \to \Sigma^0 \pi^+)} = (2.78 \pm 0.15 \pm 0.05)\%.$$
  (Vs. PDG: $(4.0 \pm 0.6)\%$; BESIII recent result: $(3.61 \pm 0.73)\%$.)
- Using the W.A. $\mathcal{B}(\Lambda_c^+ \to (\Lambda, \Sigma^0)\pi^+)$, we have
  $\mathcal{B}(\Lambda_c^+ \to \Lambda K^+) = (6.57 \pm 0.17 \pm 0.11 \pm 0.35) \times 10^{-4}$
  $\mathcal{B}(\Lambda_c^+ \to \Sigma^0 K^+) = (3.58 \pm 0.19 \pm 0.06 \pm 0.19) \times 10^{-4}$.
  (Vs. PDG: 6.1 ± 1.2)% and 5.2 ± 0.8)%)
  Both are consistent with W.A. but with significantly improved precision.

$\mathcal{B}/A^{\rm dir}_{CP}/\alpha/A^{\alpha}_{CP}$ of $\Lambda_c^+ \to \Lambda h^+$, $\Sigma^0 h^+$ at Belle (arXiv:2208.08695, submitted to Sci. Bull.)

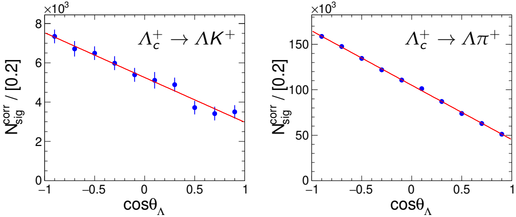
- The decay asymmetry parameter α was introduced by Lee and Yang to study the parity-violating and parity-conserving amplitudes in weak hyperon decays.
- In $1/2^+ \to 1/2^+ + 0^-$, $\boxed{\alpha \equiv 2 \cdot {\rm Re}(S^* P)/(|S|^2 + |P|^2)}$, where S and P denote the parity-violating S-wave and parity-conserving P-wave amplitudes, respectively.
- For $\Lambda_c^+ \to \Lambda h^+$ decays, the differential decay rate depends on α parameters and one helicity angle as: $\boxed{\frac{dN(\Lambda_c^+ \to \Lambda h^+)}{d\cos\theta_\Lambda} \propto 1 + \alpha_{\Lambda_c^+}\alpha_- \cos\theta_\Lambda}$
- For $\Lambda_c^+ \to \Sigma^0 h^+$ decays, considering $\alpha(\Sigma^0 \to \gamma\Lambda)$ is zero due to parity conservation for an electromagnetic decay, the differential decay rate related to the α parameters and helicity angles is given by
$$\boxed{\frac{dN(\Lambda_c^+ \to \Sigma^0 h^+)}{d\cos\theta_{\Sigma^0}\, d\cos\theta_\Lambda} \propto 1 - \alpha_{\Lambda_c^+}\alpha_- \cos\theta_{\Sigma^0}\cos\theta_\Lambda}$$



- Since α is CP-odd, the α-induced CP asymmetry: $\boxed{A^{\alpha}_{CP} \equiv \frac{\alpha_{\Lambda_c^+} - \widehat{CP}\alpha_{\Lambda_c^+}\widehat{CP}^\dagger}{\alpha_{\Lambda_c^+} + \widehat{CP}\alpha_{\Lambda_c^+}\widehat{CP}^\dagger} = \frac{\alpha_{\Lambda_c^+} + \alpha_{\overline{\Lambda}_c^-}}{\alpha_{\Lambda_c^+} - \alpha_{\overline{\Lambda}_c^-}}}$
- In the case that $A^{\rm dir}_{CP}$ is zero, A^{α}_{CP} is given by the CPV in ${\rm Re}(S^*P)$. Therefore, A^{α}_{CP} provides an observable complementary to the $A^{\rm dir}_{CP}$ induced by decay widths.

$\mathcal{B}/A^{\rm dir}_{CP}/\alpha/A^{\alpha}_{CP}$ of $\Lambda_c^+ \to \Lambda h^+$, $\Sigma^0 h^+$ at Belle (arXiv:2208.08695, submitted to Sci. Bull.)

- $\cos\theta_\Lambda$ distributions of $\Lambda_c^+ \to \Lambda h^+$ after efficiency correction, fitted with $1 + \alpha_{\Lambda_c^+}\alpha_- \cos\theta_\Lambda$

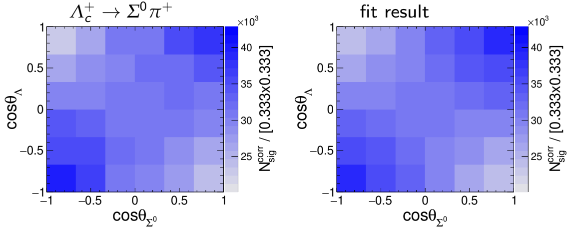


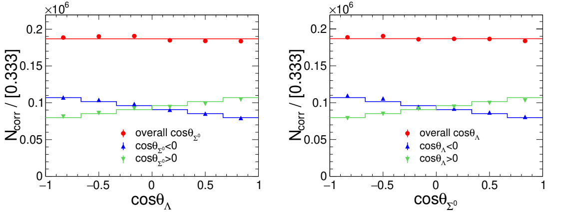
- Using the fitted slope factors and the average α_-, we have

$\alpha_{\rm avg}(\Lambda_c^+ \to \Lambda K^+) = -0.585 \pm 0.049 \pm 0.018$
$\alpha_{\rm avg}(\Lambda_c^+ \to \Lambda \pi^+) = -0.755 \pm 0.005 \pm 0.003$
(vs. PDG: -0.84 ± 0.09)
$\alpha_{\rm avg}(\Lambda_c^+ \to \Sigma^0 K^+) = -0.55 \pm 0.18 \pm 0.09$
$\alpha_{\rm avg}(\Lambda_c^+ \to \Sigma^0 \pi^+) = -0.463 \pm 0.016 \pm 0.008$
(vs. PDG: -0.73 ± 0.18)

- First α results of SCS decays for charm baryons; and significantly improved results of CF Λ_c^+ decays.

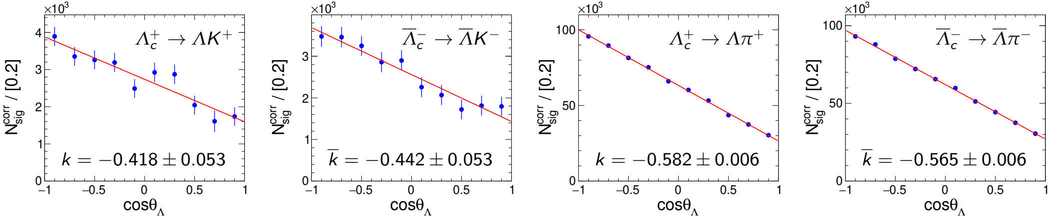
- $(\cos\theta_\Lambda, \cos\theta_{\Sigma^0})$ 2D distributions of $\Lambda_c^+ \to \Sigma^0 h^+$ after efficiency correction, fitted with $1 - \alpha_{\Lambda_c^+}\alpha_- \cos\theta_{\Sigma^0}\cos\theta_\Lambda$





$\mathcal{B}/A_{CP}^{\rm dir}/\alpha/A_{CP}^{\alpha}$ of $\Lambda_c^+ \to \Lambda h^+$, $\Sigma^0 h^+$ at Belle (arXiv:2208.08695, submitted to Sci. Bull.)

- Measure α values for Λ_c^+ and $\overline{\Lambda}_c^-$ decays separately. We obtain the first or most precise α and $A_{CP}^{\alpha}(\Lambda_c^+)$ results.



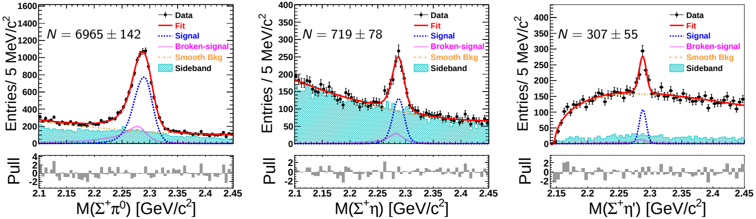
Channel	$k = \alpha_{\Lambda_c^+}\alpha_-$	$\overline{k} = \alpha_{\overline{\Lambda}_c^-}\alpha_+$	$\alpha_{\Lambda_c^+}$	$\alpha_{\overline{\Lambda}_c^-}$	A_{CP}^{α}	W.A. A_{CP}^{α}	our $A_{CP}^{\alpha}(\Lambda \to p\pi^-)$
$\Lambda_c^+ \to \Lambda K^+$	-0.418 ± 0.053	-0.442 ± 0.053	$-0.566 \pm 0.071 \pm 0.028$	$0.592 \pm 0.070 \pm 0.079$	$-0.023 \pm 0.086 \pm 0.071$	–	–
$\Lambda_c^+ \to \Lambda \pi^+$	-0.582 ± 0.006	-0.565 ± 0.006	$-0.784 \pm 0.008 \pm 0.006$	$0.754 \pm 0.008 \pm 0.018$	$+0.020 \pm 0.007 \pm 0.013$	-0.07 ± 0.22	$+0.017 \pm 0.007 \pm 0.012$
$\Lambda_c^+ \to \Sigma^0 K^+$	-0.43 ± 0.18	-0.37 ± 0.21	$-0.58 \pm 0.24 \pm 0.09$	$0.49 \pm 0.28 \pm 0.14$	$+0.08 \pm 0.35 \pm 0.14$	–	–
$\Lambda_c^+ \to \Sigma^0 \pi^+$	-0.340 ± 0.016	-0.358 ± 0.017	$-0.452 \pm 0.022 \pm 0.023$	$0.473 \pm 0.023 \pm 0.035$	$-0.023 \pm 0.034 \pm 0.030$	–	$-0.026 \pm 0.034 \pm 0.030$

combined: $+0.013 \pm 0.007 \pm 0.011$

- For our CF Λ_c^+ decay chains, $A_{CP}^{\alpha}(\text{total}) \equiv \frac{\alpha_{\Lambda_c^+}\alpha_- - \alpha_{\overline{\Lambda}_c^-}\alpha_+}{\alpha_{\Lambda_c^+}\alpha_- + \alpha_{\overline{\Lambda}_c^-}\alpha_+}$. Under the SM with $\alpha_{\Lambda_c^+} = -\alpha_{\overline{\Lambda}_c^-}$ for these CF Λ_c^+ decays, $A_{CP}^{\alpha}(\text{total}) = A_{CP}^{\alpha}(\Lambda \to p\pi^-)$. $\Rightarrow$ search for hyperon CPV in charm CF decays for the first time.
- No evidence of CPV in baryon decays (charmed baryon Λ_c^+ and hyperon Λ) is found.

$\mathcal{B}$ and α of $\Lambda_c^+ \to \Sigma^+(\pi^0, \eta, \eta')$ (arXiv:2208.10825 contributed by FDU, submitted to PRD)

- $\mathcal{B}$ measurement using $\Lambda_c^+ \to \Sigma^+\pi^0$ ($\mathcal{B} = (1.25 \pm 0.10)\%$) as reference mode.



$$\frac{\mathcal{B}(\Lambda_c^+ \to \Sigma^+\eta)}{\mathcal{B}(\Lambda_c^+ \to \Sigma^+\pi^0)} = 0.25 \pm 0.03 \pm 0.01$$

$$\frac{\mathcal{B}(\Lambda_c^+ \to \Sigma^+\eta')}{\mathcal{B}(\Lambda_c^+ \to \Sigma^+\pi^0)} = 0.33 \pm 0.06 \pm 0.02$$

$$\frac{\mathcal{B}(\Lambda_c^+ \to \Sigma^+\eta')}{\mathcal{B}(\Lambda_c^+ \to \Sigma^+\eta)} = 1.34 \pm 0.28 \pm 0.08$$

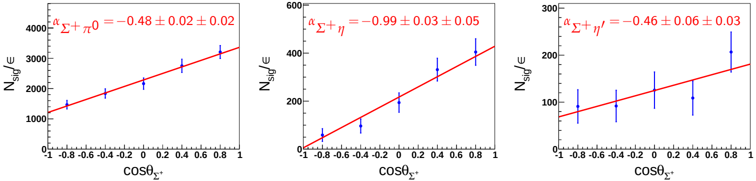
▶ Using $\mathcal{B}$ of reference mode, we have

$\mathcal{B}(\Lambda_c^+ \to \Sigma^+\eta) = (3.14 \pm 0.35 \pm 0.17 \pm 0.25) \times 10^{-3}$

$\mathcal{B}(\Lambda_c^+ \to \Sigma^+\eta') = (4.16 \pm 0.75 \pm 0.25 \pm 0.33) \times 10^{-3}$

which are the most precise results to date.

- perform $M(\Lambda_c^+)$ fits in five bins of $\cos\theta_{\Sigma^+}$ distribution, then plot and fit the efficiency-corrected $\cos\theta_{\Sigma^+}$ distributions.

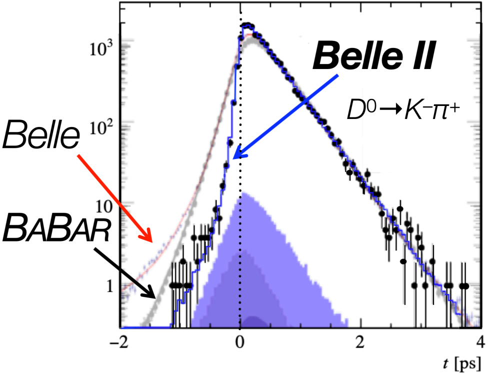


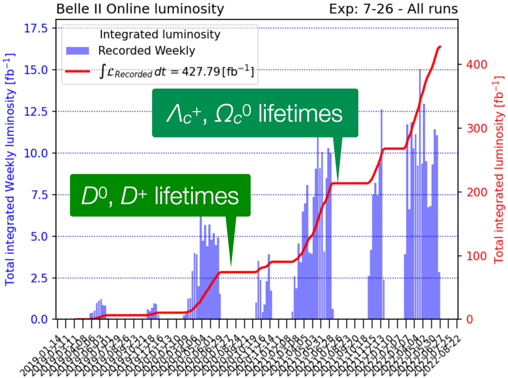
- This $\alpha_{\Sigma^+\pi^0}$ agrees with W.A. but with precision improved by threefold; the other two measured for the first time.
- Comparing $\alpha_{\Sigma^+\pi^0}$ with aforementioned $\alpha_{\Sigma^0\pi^+} = -0.463 \pm 0.016 \pm 0.008$, their agreement within 1σ shows consistency with the prediction from the isospin symmetry [PLB **794**, 19 (2019)].

Outline

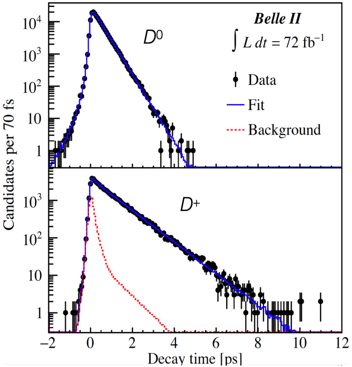
High precision vertex ⇒ charm lifetimes at Belle II

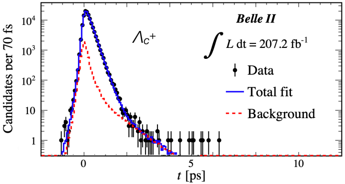
- The impact parameter resolution is $\times 2$ better than Belle/BaBar, which shows up in decay-time distribution.
- Benefited from this, the charm lifetimes are measured using the early data set, as listed in luminosity plot.
- We (Belle II) totally have accumulated 428 fb^{-1} of data set in. Now we are under the long-shut one.

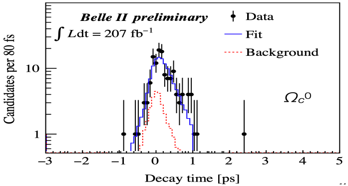


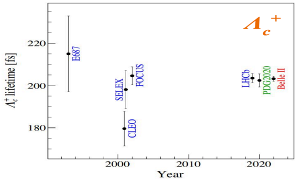


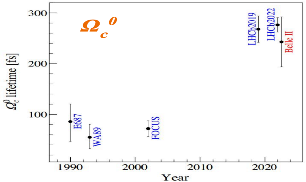
charm lifetimes at Belle II (PRL 127, 211801 (2021), arXiv:2206.15227 (PRL), arXiv:2208.08573 (PRD(L)))







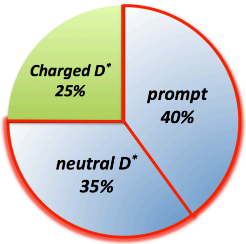


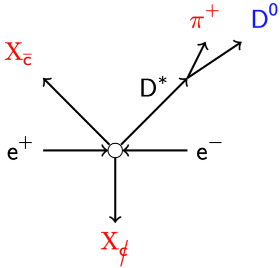


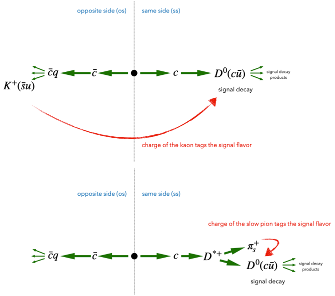
- We obtain the world-best charm lifetimes: $\tau(D^0) = 410.5 \pm 1.1 \pm 0.8$ fs, $\tau(D^+) = 1030.4 \pm 4.7 \pm 3.1$ fs, and $\tau(\Lambda_c^+) = 203.20 \pm 0.89 \pm 0.77$ fs (first Belle II precision measurements), Their tiny systematic uncertainties demonstrate the excellent performance and understanding of the Belle II detector.
- $\tau(\Omega_c^0)$ result, $243 \pm 48 \pm 11$ fs, is consistent with LHCb, inconsistent with pre-LHCb average at 3.4σ.
  $\Rightarrow$ the Ω_c^0 is not the shortest-lived weakly decaying charmed baryon.

Charm Flavor Tagger & Charm Tagger with Full Event Reconstruction & ...

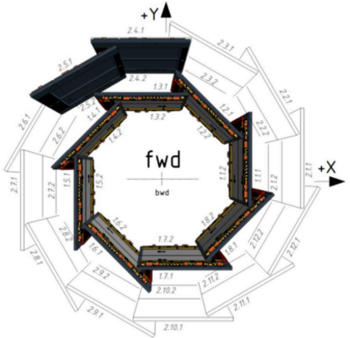
- Current Belle II date set (428 fb^{-1}) is only half of Belle (980 fb^{-1}). The first wave, the measurement of charm lifetimes (benefited from the significantly improved time resolution), will walk away soon.
- We need more papers. Now the Belle+Belle II datasets are recommended, although the task will be doubled.
- The advanced techniques for charm are developed. 攻克难点，勇于创新.
  - Charm Tagger using full event information with $e^+e^- \to X_c X_{\bar{c}} X_{\not{c}}$ (where $X_{\not{c}}$ indicates the fragment part)
    - although the reconstruction efficiency is quite low, absolute $\mathcal{B}$, leptonic and SL decays, invisible decays, etc. are available.
  - Charm flavor tagger for neutral D mesons (using BDT): considering the $c \to s$ CF process.
    - roughly double the effective tagged D^0 sample size. That will have big effects on many measurements of mixing and CPV.



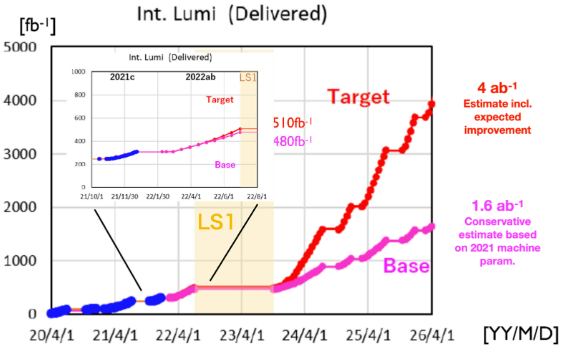




Status of Belle II: under Long-Shutdown1 (LS1) now



- PXD2 installation (fully re-installed)
  Due to problems in ladder gluing, only half of designed PXD (full L1+2 L2 ladders) was installed in 2018/2019
- TOP MCP-PMT replacement
- Additional shields for BG mitigation
- Collimator system upgrade (LER)
- Beam pipe upgrade at injection point (HER)



- Except the charm lifetime measurements, more charm analyses are on-going based on full LS1 data set. (some of them use Belle+Belle II data sets.)
  - CPV asymemtry in charmed mesons and baryons
  - D^0-$\bar{D}^0$ mixing with model-independent method
  - Branching fraction of charmed baryon decays
  - ......

Outline

Summary

- Belle is still producing unique results in flavor physics although Belle finished data-taking 12 years ago. Today the recent charm results contributed by me are reviewed.
  - charmed mesons: $\mathcal{B}$, CP asymmetry, T-odd CP asymmetry,
  - charmed baryons: $\mathcal{B}$, direct CP asymmetry, α and A^{α}_{CP}, $\Rightarrow$ leading the updated theoretical predictions (e.g. arXiv:2210.12728)
  - not covering charm mixing, (semi-)leptonic decays, rare or forbidden decay, amplitude analysis, charm spectroscopy, etc.

Summary

- Belle is still producing unique results in flavor physics although Belle finished data-taking 12 years ago. Today the recent charm results contributed by me are reviewed.
  - charmed mesons: $\mathcal{B}$, CP asymmetry, T-odd CP asymmetry,
  - charmed baryons: $\mathcal{B}$, direct CP asymmetry, α and A^{α}_{CP}, $\Rightarrow$ leading the updated theoretical predictions (e.g. arXiv:2210.12728)
  - not covering charm mixing, (semi-)leptonic decays, rare or forbidden decay, amplitude analysis, charm spectroscopy, etc.
- Belle II has already joined the game. Current dataset is 428 fb^{-1} before Long Shutdown 1.
  - the world best $\tau(D^0)$, $\tau(D^+)$, $\tau(D_s^+)$, and $\tau(\Lambda_c^+)$ (first Belle II precision measurements),
  - a confirmation of $\tau(\Omega_c^0)$ is not short-lived weakly decaying charmed baryon.
  - My focus: the studies on the charmed baryon CF decays based on the current dataset are potential publications.
- Advanced tools for charm analyses are under development at Belle II, e.g.
  - Charm Flavor Tagger: win an additional $\sim$100% tagged D^0 sample ▶ affect many measurements of CPV and mixing.
  - Charm Tagger with Full Event Reconstruction using ROE ▶ to measure the invisible decay, SL decays, absolute $\mathcal{B}$, etc.
  - My focus: CPV in charmed baryon decays with more methods proposed by theorists. eg. arXiv:2209.13196, 2211.07332, etc.

Summary

- Belle is still producing unique results in flavor physics although Belle finished data-taking 12 years ago. Today the recent charm results contributed by me are reviewed.
  - charmed mesons: $\mathcal{B}$, CP asymmetry, T-odd CP asymmetry,
  - charmed baryons: $\mathcal{B}$, direct CP asymmetry, α and A^{α}_{CP}, $\Rightarrow$ leading the updated theoretical predictions (e.g. arXiv:2210.12728)
  - not covering charm mixing, (semi-)leptonic decays, rare or forbidden decay, amplitude analysis, charm spectroscopy, etc.
- Belle II has already joined the game. Current dataset is 428 fb^{-1} before Long Shutdown 1.
  - the world best $\tau(D^0)$, $\tau(D^+)$, $\tau(D_s^+)$, and $\tau(\Lambda_c^+)$ (first Belle II precision measurements),
  - a confirmation of $\tau(\Omega_c^0)$ is not short-lived weakly decaying charmed baryon.
  - My focus: the studies on the charmed baryon CF decays based on the current dataset are potential publications.
- Advanced tools for charm analyses are under development at Belle II, e.g.
  - Charm Flavor Tagger: win an additional $\sim$100% tagged D^0 sample ▶ affect many measurements of CPV and mixing.
  - Charm Tagger with Full Event Reconstruction using ROE ▶ to measure the invisible decay, SL decays, absolute $\mathcal{B}$, etc.
  - My focus: CPV in charmed baryon decays with more methods proposed by theorists. eg. arXiv:2209.13196, 2211.07332, etc.
- More charm results from Belle II are on the road in the coming years. With larger and larger dataset, Belle II will make essential contributions to the flavor physics. This game will last for $>$(10+10) years.
- *"Charm is now a fast-moving discipline—one that can be considered complementary to beauty for its potential to test the CKM paradigm and to probe for New Physics effects. For flavor physicists, this is truly the age of charm."*
  粲物理现在是快速发展的领域——它是对美物理的补充，具有潜力来检验 CKM 和探索新物理。对味物理学家来说，这正是粲物理的时代（充满魅力的时代）。
  —from [Ann. Rev. Nucl. Part. Sci. 71 (2021) 59]

Back up

Thank you for your attentions.

谢谢!

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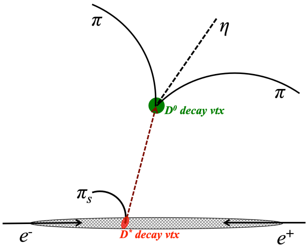
$\mathcal{B}/A_{CP}$ for $D^0 \to h^+h^-\eta$ and $D^0 \to \phi\eta$: Event selection (JHEP 09 (2021) 075)

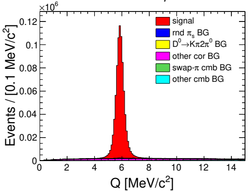
Items	Requirements
charged tracks	at least two SVD hits in both $r\phi$ and z for tracks from D^0 $\mathcal{R} = \frac{\mathcal{L}_K}{\mathcal{L}_K+\mathcal{L}_\pi} > 0.6$ for kaon, others for pion eId < 0.95, μId < 0.95; $\lvert dr\rvert < 1$ cm and $\lvert dz\rvert < 3$ cm
$\eta \to \gamma\gamma$	$E_\gamma > 50$ 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. $D^{*+} \to D^0\pi_s^+$, $D^0 \to \pi^+\pi^-\eta$

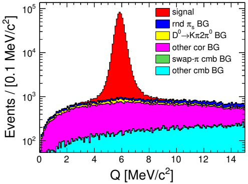


$Q = M(h^+h^-\eta\pi_s^+) - M(h^+h^-\eta) - m_{\pi_s^+}$

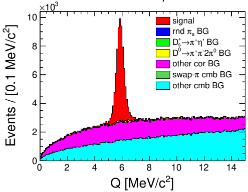
$D^0 \to K^-\pi^+\eta$



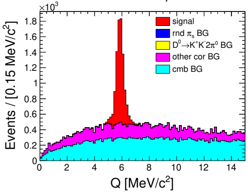
$D^0 \to K^-\pi^+\eta$



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

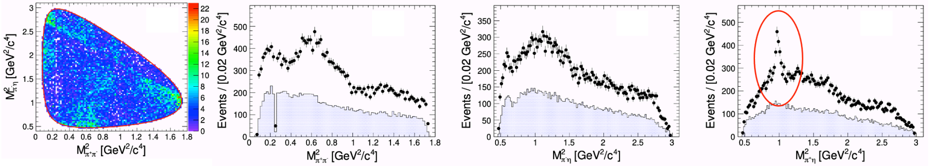


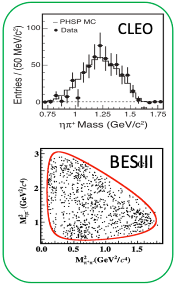
$D^0 \to K^+K^-\eta$



$\mathcal{B}/A_{CP}$ for $D^0 \to h^+h^-\eta$ and $D^0 \to \phi\eta$: Dalitz-plot projections

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

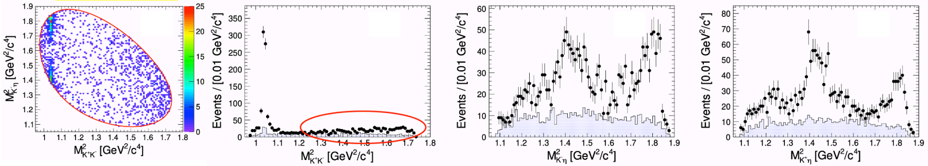




- Clear rho(770) and a0(980)+ (no visible intermediate process in CLEO and BESIII results due to the statisitcs limit.) => amplitude analysis is needed. But not included in this analysis.

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}	$(4.5\pm3.0)\times10^{-3}$
$D^0 \to a_0(980)^-\pi^+$	$V_{cd}V_{ud}^*(T+E)$	1.3×10^{-3}	1.3×10^{-3}	$(1.0\pm1.1)\times10^{-3}$
$\frac{\mathcal{B}(D^0\to a_0(980)^+\pi^-)}{\mathcal{B}(D^0\to a_0(980)^-\pi^+)}$		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).

Formalism of D^0-$\bar{D}^0$ mixing

- Open-flavor neutral meson transforms to its anti-meson and vice versa:

$$K^0 \Leftrightarrow \bar{K}^0,\ B_d^0 \Leftrightarrow \bar{B}^0,\ B_s^0 \Leftrightarrow \bar{B}_s,\ D^0 \Leftrightarrow \bar{D}^0$$

- Flavor eigenstate ($|D^0\rangle$, $|\bar{D}^0\rangle$) $\neq$ mass eigenstate $|D_{1,2}\rangle$ with $M_{1,2}$ and $\Gamma_{1,2}$)

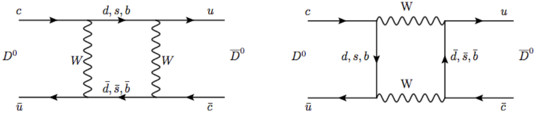
$$|D_{1,2}\rangle \equiv p|D^0\rangle \pm q|\bar{D}^0\rangle \text{ (CPT: p}^2\text{+q}^2\text{=1)}$$

- Mixing parameters definition:

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

- under phase convention $CP|D^0\rangle = |\bar{D}^0\rangle$, $CP|\bar{D}^0\rangle = |D^0\rangle$,
- with CP conservation ($q = p = 1/\sqrt{2}$): $|D_{1,2}\rangle = |D_{+,-}\rangle$ (CP eigenstates)

- Unique: only the up-type meson for mixing
- Standard Model predicts: $\sim \mathcal{O}(1\%)$



(1) short distance (< 0.1% by CKM and GIM)

(2) long distance ($\sim$ 1%)

- Precise measurement of x, y: effectively limit New Physics(NP) modes;
- search for NP, eg: $|x| \gg |y|$

Formalism for time evolution

- Time evolution of D^0-$\bar{D}^0$ system:

$$i\frac{\partial}{\partial t}\begin{pmatrix} D^0(t) \\ \bar{D}^0(t) \end{pmatrix} = (M - \frac{i}{2}\Gamma)\begin{pmatrix} D^0(t) \\ \bar{D}^0(t) \end{pmatrix}$$

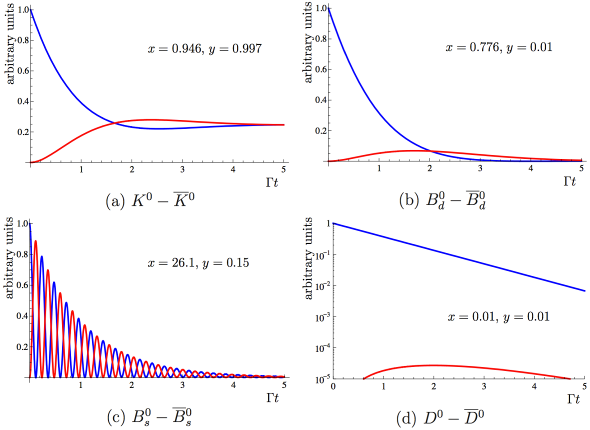
diagonal: $D \to D$,non-diagonal: $D \to \bar{D}$.

- time evolution related to (x,y) and (q/p)

$$|D^0(t)\rangle = g_+(t)|D^0\rangle + \frac{q}{p}g_-(t)|\bar{D}^0\rangle$$
$$|\bar{D}^0(t)\rangle = \frac{p}{q}g_-(t)|D^0\rangle + g_+(t)|\bar{D}^0\rangle$$
$$g_+(t) = e^{(-iM-\frac{1}{2}\Gamma)t}\cosh\left(-\frac{i\mathbf{x}+\mathbf{y}}{2}\Gamma t\right)$$
$$g_-(t) = e^{(-iM-\frac{1}{2}\Gamma)t}\sinh\left(-\frac{i\mathbf{x}+\mathbf{y}}{2}\Gamma t\right)$$

- Probability that the flavor is/is not changed at time t with a pure flavor state $|D^0\rangle$

$$|\langle D^0|D^0(t)\rangle|^2 = \frac{1}{2}e^{-\Gamma t}(\cosh(y\Gamma t) + \cos(x\Gamma t))$$
$$|\langle D^0|\bar{D}^0(t)\rangle|^2 = \frac{1}{2}\left|\frac{q}{p}\right|^2 e^{-\Gamma t}(\cosh(y\Gamma t) - \cos(x\Gamma t))$$



y effects lifetime in amplitude; x: brings a sine oscillating.

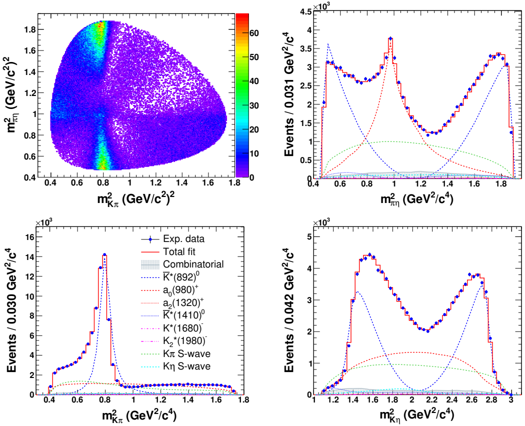
- ▶ D^0-$\bar{D}^0$ mixing measurement is most difficult.

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': $\mathcal{M} = a_{NR}e^{i\phi_{NR}} + \sum_R a_R e^{i\phi_R}\mathcal{M}_R(m^2_{K\pi}, m^2_{\pi\eta})$
- 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.

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			$132.1 \pm 3.4^{+1.6+8.3}_{-0.7-4.5}$

- $\frac{\mathcal{B}(K^*(1680)^- \to K^-\eta)}{\mathcal{B}(K^*(1680)^- \to K^-\pi^0)} = (0.11^{+0.07}_{-0.06})\%$: not consistent with predictions (≈ 1.0) under the assumption that $K^*(1680)$ is a pure 1^3D_1 state[a, b].



[a] Phys. Rev. D **68**, 054014 (2003)
[b] Eur. Phys. J. C **77**, 861 (2017)

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, $\frac{\mathcal{B}(D^0 \to K^- \pi^+ \eta)}{\mathcal{B}(D^0 \to K^- \pi^+)} = 0.500 \pm 0.002(\mathrm{stat}) + 0.020(\mathrm{syst}) \pm 0.003(\mathcal{B}_{\mathrm{PDG}})$.
- using the world averaged $\mathcal{B}(D^0 \to K^- \pi^+)$, we have the branching fraction $\mathcal{B}(D^0 \to K^- \pi^+ \eta) = (1.973 \pm 0.009(\mathrm{stat}) \pm 0.079(\mathrm{syst}) \pm 0.018(\mathcal{B}_{\mathrm{PDG}}))\%$.
- 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 $K_2^*(1980)$.

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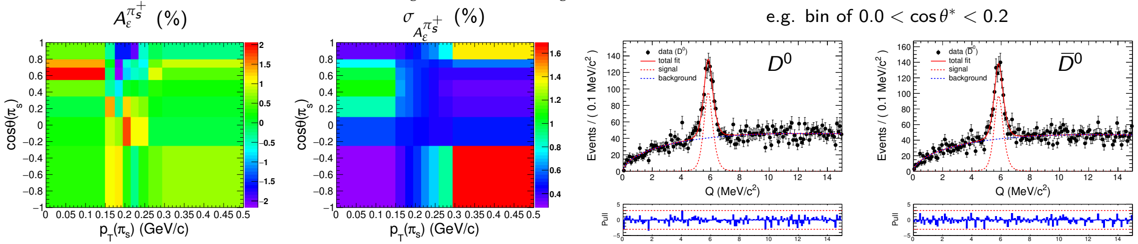
[a] Phys. Rev. D **81**, 074021 (2010)
[b] Phys. Rev. D **86**, 036012 (2012)
[c] Phys. Rev. D **89**, 054006 (2014)
[d] Phys. Rev. D **68**, 054014 (2003)
[e] Eur. Phys. J. C **77**, 861 (2017)

CP asymmetries of $D^0 \to \pi^+\pi^-\eta$, $K^+K^-\eta$, and $\phi\eta$ JHEP 2021, 75 (2021)

- To correct for an asymmetry in $\pi_s^\pm$ reconstruction efficiencies, we weight events with factors $w_{D^0/\bar{D}^0} = 1 \mp A_\varepsilon^{\pi_s^+}$ where $A_\varepsilon^{\pi_s}(\cos\theta, p_T)$-map is obtained from tagged and untagged $D^0 \to K^-\pi^+$ samples (because $A^{\rm untag} = A_{\rm FB}^D + A_{CP}^{K\pi} + A_\varepsilon^{K\pi}$ and $A^{\rm tag} = A_{\rm FB}^D + A_{CP}^{K\pi} + A_\varepsilon^{K\pi} + A_\varepsilon^{\pi_s}$).
- 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_{KK}-Q distributions for D^0 and $\bar{D}^0$ samples, to extract the corrected raw asymmetry $A_{\rm corr}$: $N_{\rm sig}(D^0, \bar{D}^0) = N_{\rm sig}/2 \cdot (1 \pm A_{\rm corr})$.

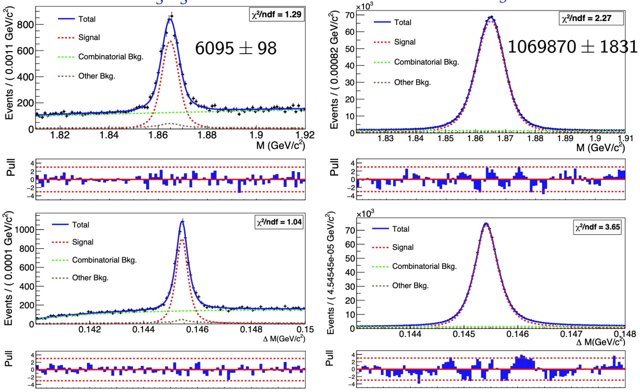


$\mathcal{B}/A_{CP}/a_{CP}^{T\text{-odd}}$ of $D^0 \to K_S^0 K_S^0 \pi^+\pi^-$ at Belle (arXiv:2207.07555)

- We measure the $\mathcal{B}$ (relative to reference mode $D^0 \to K_S^0\pi^+\pi^-$) and its time-integrated A_{CP} for $D^0 \to K_S^0 K_S^0 \pi^+\pi^-$.

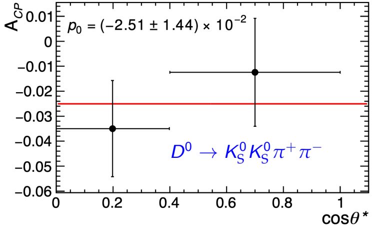
$$\mathcal{B}(D^0 \to K_S^0 K_S^0 \pi^+\pi^-) = \frac{N_{K_S^0 K_S^0\pi^+\pi^-}/\varepsilon_{K_S^0 K_S^0\pi^+\pi^-}}{N_{K_S^0\pi^+\pi^-}/\varepsilon_{K_S^0\pi^+\pi^-}} \frac{\mathcal{B}(D^0 \to K_S^0\pi^+\pi^-)}{\mathcal{B}(K_S^0 \to \pi^+\pi^-)}$$

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



- Self-conjugated decay, using same method in previous analysis] Extract signal yield on the weighted sample ($w = 1 \mp A_\varepsilon^{\pi_s}$) in four bins of $\cos\theta^*$ distribution.

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



- we obtain the most precise $\mathcal{B}$ and the first A_{CP} result for $D^0 \to K_S^0 K_S^0 \pi^+\pi^-$:

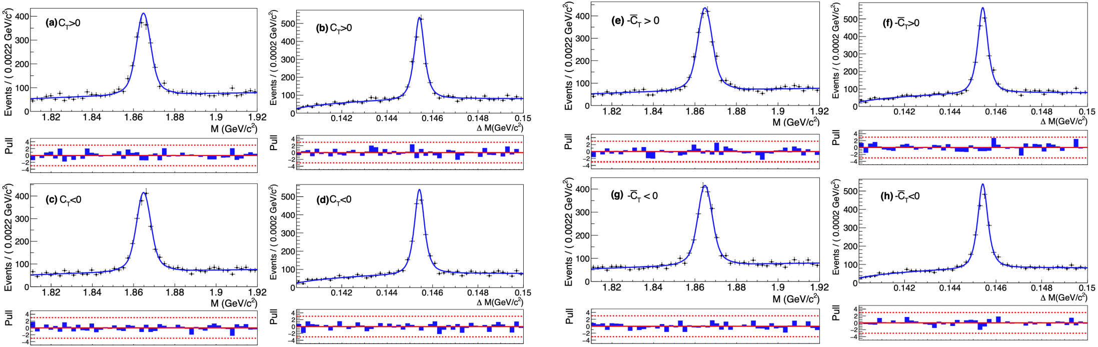
$\Rightarrow \mathcal{B} = (4.82 \pm 0.08^{+0.10}_{-0.11} \pm 0.31) \times 10^{-4}$

$\Rightarrow A_{CP} = (-2.51 \pm 1.44^{+0.35}_{-0.52})\%$

$\mathcal{B}/A_{CP}/a_{CP}^{T\text{-odd}}$ of $D^0 \to K_S^0 K_S^0 \pi^+\pi^-$ at Belle (arXiv:2207.07555)

- We divide the data into four subsamples (D flavor, C_T sign), and perform a simultaneous fit to extract $a_{CP}^{T\text{-odd}}$.

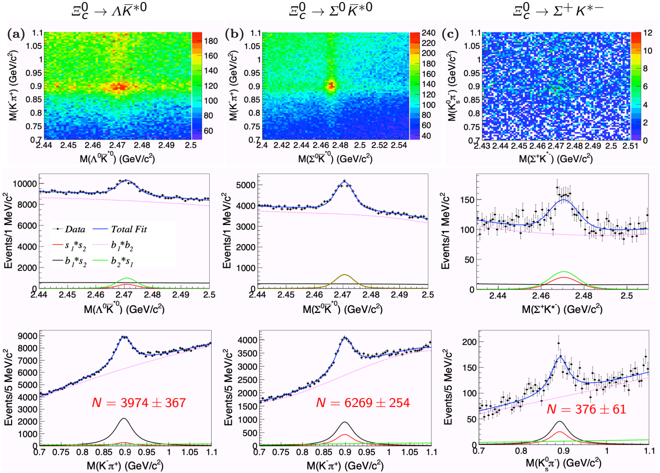
$D^0 \to K^0_{S\,\text{fast}} K^0_{S\,\text{slow}} \pi^+\pi^-$ $\qquad$ $\bar{D}^0 \to K^0_{S\,\text{slow}} K^0_{S\,\text{fast}} \pi^-\pi^+$



- Finally we have $a_{CP}^{T\text{-odd}}(D^0 \to K_S^0 K_S^0 \pi^+\pi^-) = (-1.95 \pm 1.42^{+0.14}_{-0.12})\%$ for the first time.
- Similar measurements of charged D decays, e.g $D^+_{(s)} \to K\pi\pi^+\pi^-$ and $D^+_{(s)} \to K_S^0 K^+\pi^+\pi^-$, are on the road.

$\mathcal{B}$ and α of $\Xi_c^0 \to (\Lambda, \Sigma^0)\overline{K}^{*0}$ and $\Sigma^+ K^{*-}$ at Belle (JHEP 06 (2021) 160)

- We measure $\mathcal{B}$ and α of three CF Ξ_c^0 decays of which the final state is a combination of a hyperon and a vector particle.
- The signal yields are extracted via $M_{\Xi_c^0}$-M_{K^*} 2D fit. See the figures with achieved signal yields.
- Then we have their $\mathcal{B}$'s relative to that of $\Xi_c^0 \to \Xi^-\pi^+$ after considering the efficiency.
  $\mathcal{B}(\Xi_c^0 \to \Lambda\overline{K}^{*0})/\mathcal{B}(\Xi_c^0 \to \Xi^-\pi^+) = 0.18 \pm 0.02 \pm 0.01$
  $\mathcal{B}(\Xi_c^0 \to \Sigma^0\overline{K}^{*0})/\mathcal{B}(\Xi_c^0 \to \Xi^-\pi^+) = 0.69 \pm 0.03 \pm 0.03$
  $\mathcal{B}(\Xi_c^0 \to \Sigma^+ K^{*-})/\mathcal{B}(\Xi_c^0 \to \Xi^-\pi^+) = 0.34 \pm 0.06 \pm 0.02$
- Finally, using the W.A. $\mathcal{B}(\Xi_c^0 \to \Xi^-\pi^+)$, we have absolute $\mathcal{B}$'s below for the first time:
  $\mathcal{B}(\Xi_c^0 \to \Lambda\overline{K}^{*0}) = (3.3 \pm 0.3 \pm 0.2 \pm 1.0(\mathcal{B}_{\rm ref})) \times 10^{-3}$
  $\mathcal{B}(\Xi_c^0 \to \Sigma^0\overline{K}^{*0}) = (12.4 \pm 0.5 \pm 0.5 \pm 3.6(\mathcal{B}_{\rm ref})) \times 10^{-3}$
  $\mathcal{B}(\Xi_c^0 \to \Sigma^+ K^{*-}) = (6.1 \pm 1.0 \pm 0.4 \pm 1.8(\mathcal{B}_{\rm ref})) \times 10^{-3}$

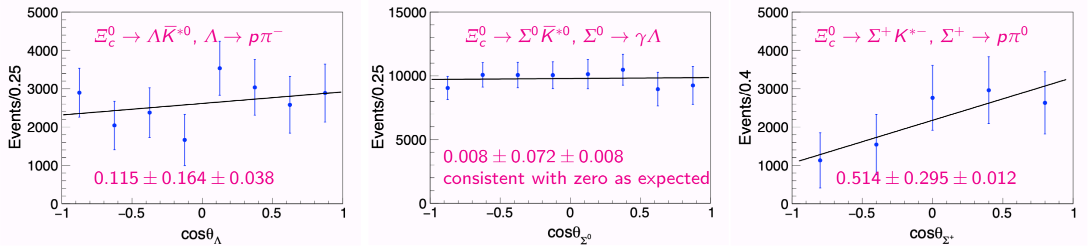


$\mathcal{B}$ and α of $\Xi_c^0 \to (\Lambda, \Sigma^0)\overline{K}^{*0}$ and $\Sigma^+ K^{*-}$ at Belle (JHEP 06 (2021) 160)

- Taking $\Xi_c^0 \to \Lambda \overline{K}^{*0}$ for example, the differential decay rate depends on decay asymmetry parameters and $\cos\theta_\Lambda$

$$\frac{dN}{d\cos\theta_\Lambda} \propto 1 + \alpha(\Xi_c^0 \to \Lambda\overline{K}^{*0})\alpha(\Lambda \to p\pi^-)\cos\theta_\Lambda$$

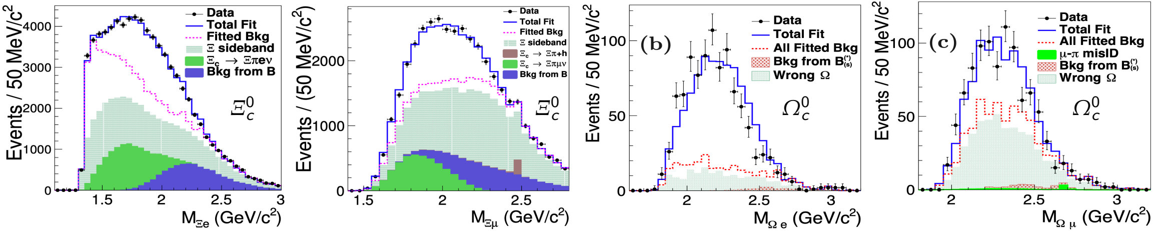
- We extract the $\alpha_{\Xi_c^0}\alpha_{(\Lambda,\Sigma^{0,+})}$ via the fits on the efficiency-corrected $\cos\theta_\Lambda$ or $\cos\theta_\Sigma$ distributions:



- The $\alpha(\Xi_c^0 \to \Sigma^0\overline{K}^{*0})$ can not be measured via 1D $\cos\theta_{\Sigma^0}$ distribution due to $\alpha(\Sigma^0 \to \gamma\Lambda) = 0$ in an electromagnetic decay.
- Using the W.A. $\alpha(\Lambda \to p\pi^-) = 0.747 \pm 0.010$ and $\alpha(\Sigma^+ \to p\pi^0) = -0.980 \pm 0.017$, we finally, for the first time, have $\alpha(\Xi_c^0 \to \Lambda\overline{K}^{*0}) = 0.15 \pm 0.22 \pm 0.05$ and $\alpha(\Xi_c^0 \to \Sigma^+ K^{*-}) = -0.52 \pm 0.30 \pm 0.02$.

$\mathcal{B}$ of $\Xi_c^0 \to \Xi^- \ell^+ \nu_\ell$ and $\Omega_c^0 \to \Omega^- \ell^+ \nu_\ell$ at Belle (PRL **127**, 121803 (2021), PRD **105**, L091101 (2022))

- Semileptonic (SL) decay of charm baryons is an ideal test of QCD in transition region of (non-)perturbation; cleanest processes among charm decays; test lepton flavor universality (LFU).
- Currently experimental results (from BESIII, ARGUS, CLEO) have large uncertainties.
- We measure the $\mathcal{B}$ of $\Xi_c^0 \to \Xi^- \ell^+ \nu_\ell$ and $\Omega_c^0 \to \Omega^- \ell^+ \nu_\ell$ with detailed study of backgrounds by data-driven method.



- $\mathcal{B}(\Xi_c^0 \to \Xi^- e^+ \nu_e) = (1.31 \pm 0.39)\%$, $\mathcal{B}(\Xi_c^0 \to \Xi^- \mu^+ \nu_\mu) = (1.27 \pm 0.39)\%$, and their ratio is $1.03 \pm 0.05 \pm 0.07$.
- $\frac{\mathcal{B}(\Omega_c^0 \to \Omega^- e^+ \nu_e)}{\mathcal{B}(\Omega_c^0 \to \Omega^- \pi^+)} = 1.98 \pm 0.13 \pm 0.08$, $\frac{\mathcal{B}(\Omega_c^0 \to \Omega^- \mu^+ \nu_\mu)}{\mathcal{B}(\Omega_c^0 \to \Omega^- \pi^+)} = 1.94 \pm 0.18 \pm 0.10$, and $\frac{\mathcal{B}(\Omega_c^0 \to \Omega^- e^+ \nu_e)}{\mathcal{B}(\Omega_c^0 \to \Omega^- \mu^+ \nu_\mu)} = 1.02 \pm 0.10 \pm 0.02$.
- Both ratios of SL decays are consistent with the expectation of lepton flavor universality.