Overview of Charm Physics
(some recent experimental highlights)

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Outline

Charm physics and charm samples

- Why is charm physics so interesting?
  - ► It provides unique opportunities for probing the strong and weak interactions in the standard model and beyond, e.g. charm CP violation, D^0-$\bar{D}^0$ mixing, (semi)leptonic decays, rare or forbidden decays, etc. [arXiv:1503.00032]
- Available charm samples from Charm factories, B-factories, hadron colliders

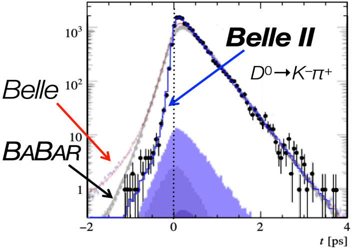
Experiment	Machine	Operation	C.M.	Luminosity	$N_{\rm prod}$	Efficiency	Characters
BESIII	BEPC-II (e^+e^-)	2010-2011 (2021-) 2016-2019 2014+2020	3.77 GeV 4.18-4.23 GeV 4.6-4.7 GeV	2.9 (8 → 20) fb^{-1} 7.3 fb^{-1} 4.5 fb^{-1}	$D^{0,+}$: $10^7(\to 10^8)$ D_s^+: 5×10^6 Λ_c^+ : 0.8×10^6 ★☆	~ 10-30% ★★★	☺ extremely clean environment ☺ quantum coherence ☺ pure D-beam, almost no background ☹ no CM boost, no time-dept analyses
Belle II	SuperKEKB (e^+e^-)	2019-	10.58 GeV	0.4 (→ 50) ab^{-1}	D^0: 6×10^8 $(\to 10^{11})$ $D_{(s)}^+$: 10^8 $(\to 10^{10})$ Λ_c^+: 10^7 $(\to 10^9)$	$\mathcal{O}$(1-10%) ★★	☺ clear event environment ☺ high trigger efficiency ☺ good-efficiency detection of neutrals ☺ time-dependent analysis ☹ smaller cross-section than LHCb
Belle	KEKB (e^+e^-)	1999-2010	10.58 GeV	1 ab^{-1}	D: 10^9 Λ_c^+: 10^8 ★★☆		
LHCb	LHC (pp)	2011,2012 2015-2018 (2022-2025,2029-)	7+8 TeV 13 TeV	1+2 fb^{-1} 6 fb^{-1} (→ 23 → 50)	5×10^{12} 10^{13} ★★★★	$\mathcal{O}$(0.1%) ★	☺ very large production cross-section ☺ large boost ☺ excellent time resolution ☹ dedicated trigger required

Belle/Belle II/BESIII/LHCb recently achieved ~ 80 papers on the charm physics, according to the arXiv records in 2022(3).
This indicates the charmers' hard working at different experiments

Charm lifetime measurements at Belle II

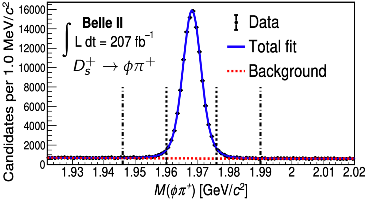
For more details, see Alan's talk tomorrow

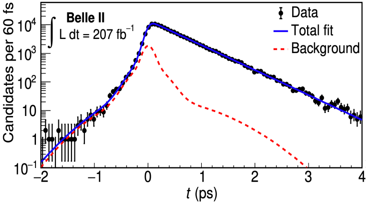
- Precise lifetime measurements provide excellent tests of strong-interaction theory e.g. HQE. Lifetimes are needed to compare measured $\mathcal{B}$'s to predictions for partial decay widths.
- As the first super B-factory experiment, Belle II has better ($\times 2$) time resolution than Belle/BaBar. Thus, it measured the charm lifetimes using its early dataset:
- Obtain the world-best charm lifetimes for $\tau(D^0) = 410.5 \pm 1.1 \pm 0.8$ fs and $\tau(D^+) = 1030.4 \pm 4.7 \pm 3.1$ fs [a], $\tau(\Lambda_c^+) = 203.20 \pm 0.89 \pm 0.77$ fs [b], and latest result of $\tau(D_s^+) = 499.5 \pm 1.7 \pm 0.9$ fs [c]. Their tiny systematic uncertainties demonstrate the excellent performance and understanding of the Belle II detector.
- Confirm the hierarchy of charm lifetimes: $\tau(\Omega_c^0) = 243 \pm 48 \pm 11$ fs [d] is consistent with LHCb, inconsistent with pre-LHCb average at 3.4σ.

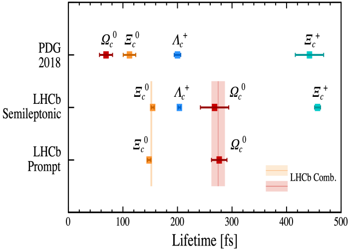


Sci. Bull. 67 (2022) 479

arXiv:2306.00365





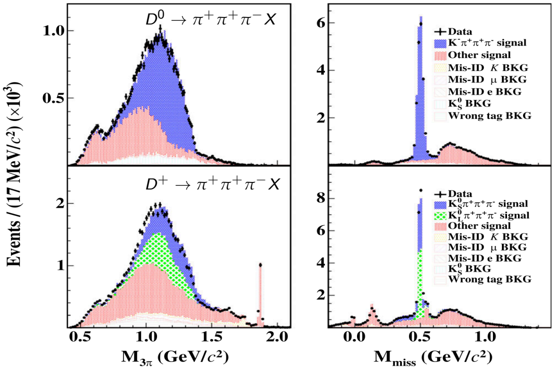


[a] (Belle II) PRL 127, 211801 (2021)
[b] (Belle II) PRL 130, 071802 (2023)
[c] (Belle II) arXiv:2306.00365 (2023)
[d] (Belle II) PRD 107, L031103 (2023)

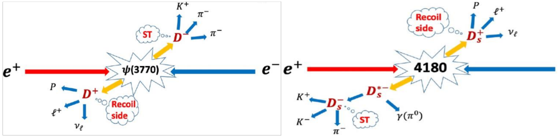
Hadronic decays of charmed hadrons — $\mathcal{B}(D^{0,+} \to \pi^+\pi^+\pi^- X)$ at BESIII

- Recently > 70 branching fractions ($\mathcal{B}$) of charmed hadron decays (a summary table in backup) were reported at Belle/BESIII/LHCb .
- BESIII charm samples are produced near $D\bar{D}/D_s D_s^*/\Lambda_c^+\bar{\Lambda}_c^-$ threshold. The exclusive decays involving K_L, n or ν_ℓ and the inclusive decays can be measured with the "double tag" technique.

PRD **107**, 032002 (2023)



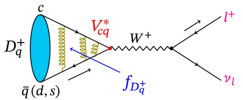
$$M_{miss} = (2E_{beam} - E_{\bar{D}} - E_{3\pi})^2/c^4 - |-\vec{p}_{\bar{D}} - \vec{p}_{3\pi}|^2/c^2$$

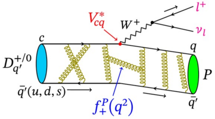


- $\mathcal{B}(D^{0,+} \to \pi^+\pi^+\pi^- X)$ values are important inputs for LFU tests for the semileptonic B decays.
  e.g. $B^0 \to D^{*+}\tau\nu_\tau, \tau \to 3\pi\bar{\nu}_\tau$ has (sub)leading background sources: $B^{0,+} \to DX, D \to \pi^+\pi^+\pi^- X$.
- The results: $\mathcal{B}(D^0 \to \pi^+\pi^+\pi^- X) = (17.60 \pm 0.11 \pm 0.22)\%$ and $\mathcal{B}(D^+ \to \pi^+\pi^+\pi^- X) = (15.25 \pm 0.09 \pm 0.18)\%$, are consistent with the sums of the $\mathcal{B}$'s of the known decay modes within 3σ.
  $\Rightarrow$ little room for possible missing $D^{0,+}$ decays containing $\pi^+\pi^+\pi^-$.

Charm (semi-)leptonic decays — $D_s^+ \to \ell^+\nu_\ell$ at BESIII

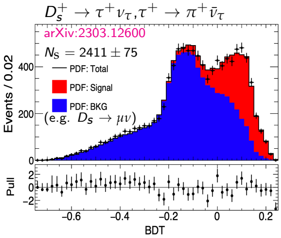
- BESIII plays a leading study of charm (semi-)leptonic decays, to measure the form factors and CKM matrix elements $|V_{cq}|$.

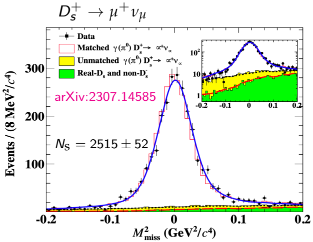




$$\Gamma(D_{(s)}^+ \to \ell^+\nu_\ell) = \frac{G_F^2 f_D^2}{8\pi}|V_{cd(s)}|^2 m_\ell^2 m_{D_{(s)}}\left(1-\frac{m_\ell^2}{m_{D_{(s)}}^2}\right)^2$$

- Precise measurement of $\mathcal{B}(D_s^+ \to \ell^+\nu_\ell)$ can help us to determine $f_{D_s^+}$ when taking the $|V_{cq}|$ from the SM global fit as input, thereby testing various theoretical predictions, especially from LQCD.
- Conversely determine $|V_{cd(s)}|$ by taking the LQCD calculation of f_D as input, thereby providing a stricter test of the CKM matrix unitarity.
- Measurement of $R_{\tau/\mu(e)} = \frac{\Gamma(D_s^+\to\tau\nu)}{\Gamma(D_s^+\to(\mu,e)\nu)}$ test the lepton flavor universality (LFU).
- BESIII recently updated $\mathcal{B}(D_s^+ \to \tau^+\nu_\tau, \mu^+\nu_\mu)$:





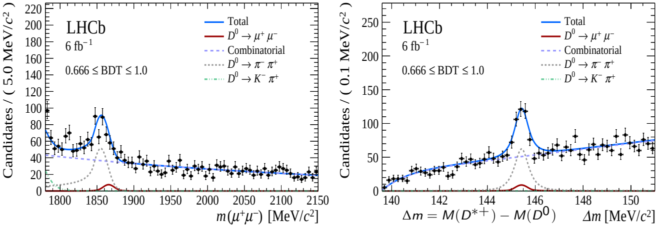
- $\mathcal{B}(D_s^+ \to \tau^+\nu) = (5.44 \pm 0.17 \pm 0.13)\%$ using 9 BDT variables, thereby determine $f_{D_s^+}|V_{cs}| = (284.3 \pm 3.9 \pm 3.0 \pm 1.0)$ MeV.
- $\mathcal{B}(D_s^+ \to \mu^+\nu) = (0.5294 \pm 0.0108 \pm 0.0085)\%$, thereby determine $f_{D_s^+}|V_{cs}| = (281.8 \pm 2.5 \pm 2.2 \pm 1.0)$ MeV.
- combining all BESIII results of $D_s^+ \to \tau\nu, \mu\nu$ channels has $|V_{cs}| = 0.9774 \pm 0.0056 \pm 0.0072$ ($\sigma_{stat} < \sigma_{syst}$), agrees well with the result given by the SM global fit.
- For more details, see Tengjiao's talk tomorrow.

Charm rare or forbidden decays

$D^0 \to \mu^+\mu^-$ at LHCb

- Rare decays of charmed hadrons are interested widely as a sensitive probe for new physics beyond Standard Model (SM). e.g. $c \to u\nu\bar{\nu}$ (strong GIM and CKM suppression). B-L violating decays, charmed baryon radiative decays.
- Recently about 10 publications on charm radiative, rare or forbidden decays were released, e.g. $D^0 \to \mu^+\mu^-$: fully leptonic and additionally suppressed by helicity reasons. In SM short-distance contribution: 10^{-18} and long-distance 10^{-13}.
- The $D^0 \to \mu^+\mu^-$ decay rate can be enhanced in many NP modes. One of the most sensitive FCNC processes in the up-quark sector.
- Experimentally, its searching is challenging. The main peaking background arises from $D^0 \to \pi^+\pi^-$ with pion's mis-identification as μ.
- To improve mass resolution, the prompt $D^{*+} \to D^0\pi^+$ sample is used. A multivariate selection based on BDT to suppress background.

PRL **131**, 041804 (2023)

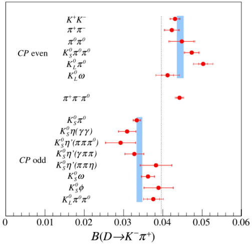


- LHCb (9 fb^{-1}) set an upper limit at a 90% C.L. $\mathcal{B}(D^0 \to \mu^+\mu^-) \leq 3.1 \times 10^{-9}$ the most stringent limit on the relevant FCNC couplings in the charm sector, allowing one to set additional constraints on physics models beyond the SM which predict the $\mathcal{B}(D^0 \to \mu^+\mu^-)$ and describe results from B physics measurements.
- For more details, see Paras's talk (LHCb) and Zhijun's talk (BESIII).

Quantum correlated $D^0\bar{D}^0$ studies — $\delta_D^{K\pi}$ and F_+ at BESIII

- BESIII produces its $D^0\bar{D}^0$ sample at the $\psi(3770)$ energy point. Thus it is able to perform some quantum correlated $D^0\bar{D}^0$ studies.
- Improved measurement of strong-phase difference $\delta_D^{K\pi}$ between DCS and CF decays EJPC **82**, 1009 (2022)
  - $\frac{\langle K^+\pi^-|D^0\rangle}{\langle K^+\pi^-|\bar{D}^0\rangle} = r_D^{K\pi}e^{-i\delta_D^{K\pi}}$; mixing in $D^0\to K^+\pi^-$: $y' = y\cos\delta_D^{K\pi} - x\sin\delta_D^{K\pi}$.
  - *CP* asymmetry in $B\to DK^-, D\to K^+\pi^-$: $\mathcal{A}_{CP} = \frac{2r_B r_D^{K\pi}\sin(\delta_B+\delta_D^{K\pi})\sin\gamma}{(r_B)^2+(r_D^{K\pi})^2+2r_B r_D^{K\pi}\cos(\delta+\delta_D^{K\pi})\cos\gamma}$.
  - An update of the asymmetry between *CP*-odd and *CP*-even eigenstate decays into $K^-\pi^+$.
    $$A_{K\pi} = \frac{\mathcal{B}(D_-\to K^-\pi^+)-\mathcal{B}(D_+\to K^-\pi^+)}{\mathcal{B}(D_-\to K^-\pi^+)+\mathcal{B}(D_+\to K^-\pi^+)} = \frac{-2r_D^{K\pi}\cos\delta_D^{K\pi}+y}{1+(r_D^{K\pi})^2} = 0.132\pm0.011\pm0.007$$
  - $\delta_D^{K\pi} = 187.6^{+8.9+5.4}_{-9.7-6.4}$, the most precise result obtained from quantum-correlated $D\bar{D}$ data.
- Measurements of the fractional *CP*-even content of self-conjugated multi-body decays F_+:
  - important inputs of γ measurements in $B\to DK$ with D decaying to pseudo-*CP* eigenstates.
  - $F_+ = 0.735\pm0.015\pm0.005$ for $D^0\to\pi^+\pi^-\pi^+\pi^-$ PRD **106**, 092004 (2022)
  - $F_+ = 0.730\pm0.037\pm0.021$ for $D^0\to K^+K^-\pi^+\pi^-$ PRD **107**, 032009 (2023)
  - all these results are dominated by statistical uncertainties.
- Many ongoing projects with eventually 20 fb^{-1} $\psi(3770)$ data samples. Their results are crucial in some methods: inputs, interpretations for mixing and CPV studies.
- For details, see Xiaokang's talk this afternoon and Yang's talk on Sep 21.

EJPC **82**, 1009 (2022)



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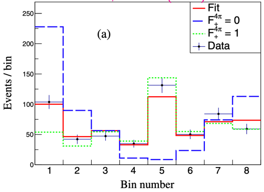
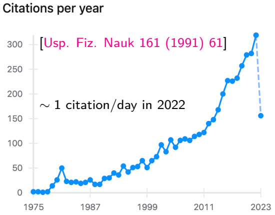


Why *CP* Violation and Charm CPV Special?

- Standard Model provides an only *CP* violation (CPV) source in quark sector: a complex phase in CKM matrix. But, such CPV source is not large enough to explain the observed matter-antimatter asymmetry of the universe.
  $\Rightarrow$ search for new CPV sources beyond SM, as a lasting hot topic.
  - Sakharov in 1967: CPV is one of the three conditions necessary to explain the matter-antimatter asymmetry of the universe.
  - In 1964, CPV in K meson decays was observed by Cronin, Fitch, *et al.* (Nobel 1980)
  - In 2001, BABAR and Belle observed a large *CP* asymmetry in B meson decays, providing strong experimental evidence for the theoretical predictions from Kobayashi and Maskawa (Nobel 2008).



- Charm CPV effect is very small ($\mathcal{O}(10^{-3})$ or smaller [a b]). New Physics may enhance it [c d].
- Study of charm CPV may help to understand the SM, and is a sensitive probe to search for New Physics.
- In 2019, *CP* violation in D^0 decays was found at LHCb: $\Delta A_{CP}(D^0 \to K^+K^-, \pi^+\pi^-) = (-15.4 \pm 2.9) \times 10^{-4}$ (5.3σ).
  $\Rightarrow$ to understand this CPV, we need to study more channels and improve the precision on the existing measurements.
- CPV has been observed in all the open-flavored meson sector, but not yet established in the baryon sector.
  $\Rightarrow$ discovering the CPV in charmed baryon is one of major targets of charm physics.

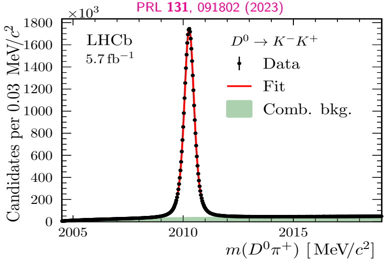
[a] H.-n. Li, C.-D. Lu, and F.-S. Yu, PRD 86, 036012 (2012)
[b] H.-Y. Cheng and C.-W. Chiang, PRD 104, 073003 (2021)
[c] A. Dery and Y. Nir, JHEP 12, 104 (2019)
[d] M. Saur and F.-S. Yu, Sci. Bull. 65, 1428 (2020)

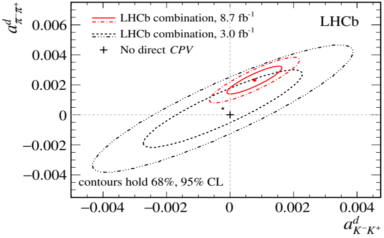
Time-integrated CP asymmetry in $D^0 \to K^+K^-$ at LHCb

For details, see Jolanta's talk

- The measured asymmetry is defined as
  $A(K^+K^-) \equiv \frac{N(D^{*+}\to D^0\pi^+)-N(D^{*-}\to \bar{D}^0\pi^-)}{N(D^{*+}\to D^0\pi^+)+N(D^{*-}\to \bar{D}^0\pi^-)} \approx A_{CP}(K^-K^+) + A_{\rm P}(D^{*+}) + A_{\rm D}(\pi^+_{\rm tag})$
- The later two sources are estimated and removed through two calibration procedures:
  (1) C_{D^+}: $D^{*+} \to D^0(\to K^-\pi^+)\pi^+$, $D^+ \to K^-\pi^+\pi^+$, and $D^+ \to \bar{K}^0\pi^+$;
  (2) $C_{D_s^+}$: $D^{*+} \to D^0(\to K^-\pi^+)\pi^+$, $D_s^+ \to \phi(\to K^-K^+)\pi^+$, and $D_s^+ \to \bar{K}^0K^+$.
  All these decays are CF modes, their CP asymmetries are assumed to be negligible.
  C_{D^+}: $A_{CP}(K^+K^-) = A(K^+K^-) - A(K^-\pi^+) + A(K^-\pi^+\pi^+) - A(\bar{K}^0\pi^+) + A(\bar{K}^0)$
  $C_{D_s^+}$: $A_{CP}(K^+K^-) = A(K^+K^-) - A(K^-\pi^+) - A(\phi\pi^+) - A(\bar{K}^0\pi^+) + A(\bar{K}^0)$
- finally $A_{CP}(D^0 \to K^+K^-) = (6.8 \pm 5.4 \pm 1.6) \times 10^{-4}$.
- Combing with $\Delta A_{CP}(D^0 \to K^+K^-, \pi^+\pi^-)$ (and $A_{CP} \approx a_f^d + \frac{\langle t\rangle_f}{\tau_D}\Delta Y_f$) gives the direct CP asymmetries: $a^d_{K^+K^-} = (7.7 \pm 5.7) \times 10^{-4}$, and $a^d_{\pi^+\pi^-} = (23.2 \pm 6.1) \times 10^{-4}$ (3.8σ) $\Rightarrow$ first evidence for direct CPV in a specific D^0 decay.
- $a^d_{K^+K^-} + a^d_{\pi^+\pi^-} = (30.8 \pm 11.4) \times 10^{-4}$: a departure from U-spin symmetry of 2.7σ.

PRL **131**, 091802 (2023)





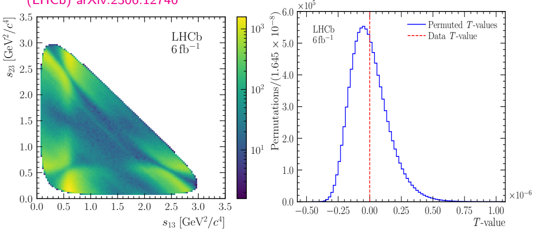
CPV in D three-body decays — Model-independent results at LHCb

- CPV searches in multi-body decays have been reported via different methods. e.g binned-χ^2, energy test, Dalitz-plot, T-odd, etc.
- LHCb (2.0 fb^{-1}) reported the local CPV in $D^0 \to \pi^+\pi^-\pi^0$ with a p-value of $(2.6 \pm 0.5)\%$ for the hypothesis of CP symmetry via a model-independent unbinned method "energy test": $T \equiv \frac{1}{n(n-1)} \sum_{i,j>i}^{n} \psi_{ij} + \frac{1}{\bar{n}(\bar{n}-1)} \sum_{i,j>i}^{\bar{n}} \psi_{ij} - \frac{1}{n\bar{n}} \sum_{i,j}^{n,\bar{n}} \psi_{ij}$ [PLB **740**, 158 (2015)]
- Recently a predecessor analysis (6 fb^{-1}) yields a p-value of 0.62, giving no indication of CPV in localised PHSP regions. [arXiv:2306.12746]
- LHCb reported a CPV search in $D^+_{(s)} \to K^-K^+K^+$ (with 10^6 yields) via a model-independent binned technique [JHEP **07**, 067 (2023)]

$$\mathcal{S}^i_{CP} = (N^i(D) - \alpha N^i(\bar{D})) / \sqrt{\alpha\left(\sigma^2_{N^i(D)} + \sigma^2_{N^i(\bar{D})}\right)}$$

with $\alpha = \frac{\sum_i N^i(D)}{\sum_i N^i(\bar{D})}$ is a global asymmetry arising in the production and the detection of the final-statue particles. Search for CPV by checking the difference between $\mathcal{S}^i_{CP}$ distribution and the normal Gaussian distribution: p-value= 13.3% and 31.6%, respectively: No evidence for CP violation. (For more details, see Jolanta's talk this afternoon.)

(LHCb) arXiv:2306.12746



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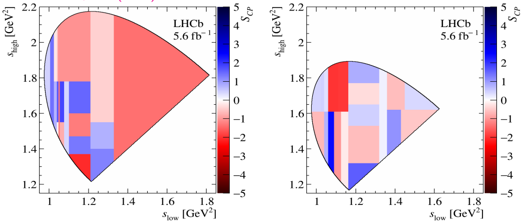


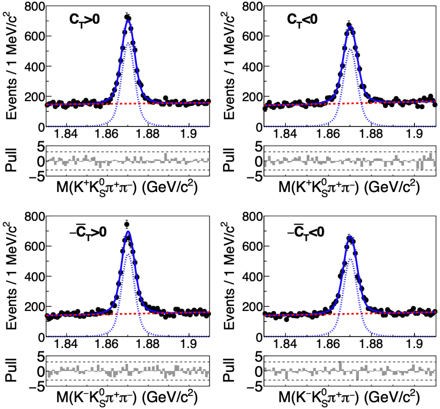
CPV in D four-body decays — T-odd asymmetry results from Belle

- Belle recently searched for CPV with T-odd correlations in charm decays of $D^0 \to K_S^0 K_S^0 \pi^+\pi^-$ [a], $D^+_{(s)} \to K_S^0 h^+\pi^+\pi^-$ [b], and $D^+_{(s)} \to K h \pi^+\pi^0$ [c].
- In D rest frame, a triple product $C_T = (\vec{p}_1 \times \vec{p}_2)\cdot \vec{p}_3$ satisfies $CP(C_T) = -C(C_T) = -\overline{C}_T$.
- The T-odd asymmetries for D or $\bar{D}$ decays are defined as

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

- T-odd CP asymmetry $\boxed{a_{CP}^{T\text{-odd}} = \frac{1}{2}(A_T - \bar{A}_T)}$ to remove FSI effects. With some conditions, $a_{CP}^{T\text{-odd}} \propto \sin\phi\cos\delta$ has largest value when $\delta = 0$ ($A_{CP}^{\rm dir} \propto \sin\phi\sin\delta \neq 0$ needs $\delta \neq 0$) $\Rightarrow$ an observable complementary to $A_{CP}^{\rm dir}$.
- All these recent $a_{CP}^{T\text{-odd}}$ results are first or most precise measurement.
- Belle II/LHCb may improve the precision utilizing increased samples, and apply this method to charmed baryons.
- For more details, see Michel's talk this afternoon.

$D^+ \to K_S^0 K^+\pi^+\pi^-$ ($N_s = 18.6k$)



$a_{CP}^{T\text{-odd}}(D^+ \to K_S^0 K^+\pi^+\pi^-) = (0.34 \pm 0.87 \pm 0.32)\%$

[a] (Belle) PRD 107, 052001 (2023)
[b] (Belle) arXiv:2305.11405
[c] (Belle) arXiv:2305.12806

CPV in charmed baryon decays

$\Lambda_c^+ \to \Lambda K^+, \Sigma^0 K^+$ at Belle

- The raw asymmetry of $\Lambda_c^+ \to \Lambda K^+$ includes several asymmetry sources:
  $A_{\rm raw}(\Lambda_c^+ \to \Lambda K^+) \approx A_{CP}^{\Lambda_c^+ \to \Lambda K^+} + A_{CP}^{\Lambda \to p\pi^-} + A_\varepsilon^{\Lambda} + A_\varepsilon^{K^+} + A_{\rm FB}^{\Lambda_c^+}$
  - $A_{CP}^{\Lambda_c^+ \to \Lambda K^+}$ ($A_{CP}^{\Lambda \to p\pi^-}$): direct CP asymmetry associated with Λ_c^+ (Λ) decay,
  - A_ε^{Λ} ($A_\varepsilon^{K^+}$): detection asymmetry arising from efficiencies between Λ (K^+) and its anti-particle $\bar{\Lambda}$ (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 $\cos\theta^*$.
- using CF mode $\Lambda_c^+ \to \Lambda\pi^+$ to remove the common asymmetry sources.
- $\Delta A_{\rm raw} = A_{\rm raw}^{\rm corr}(\Lambda_c^+ \to \Lambda K^+) - A_{\rm raw}^{\rm corr}(\Lambda_c^+ \to \Lambda\pi^+) =$
  $A_{CP}^{\rm dir}(\Lambda_c^+ \to \Lambda K^+) - A_{CP}^{\rm dir}(\Lambda_c^+ \to \Lambda\pi^+) = A_{CP}^{\rm dir}(\Lambda_c^+ \to \Lambda K^+)$
  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.

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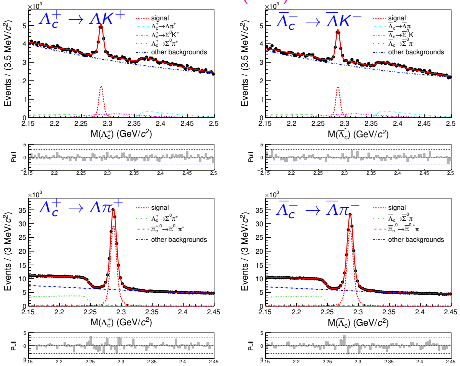


- $A_{CP}^{\rm dir}(\Lambda_c^+ \to \Lambda K^+) = (+2.1 \pm 2.6 \pm 0.1)\%$
- $A_{CP}^{\rm dir}(\Lambda_c^+ \to \Sigma^0 K^+) = (+2.5 \pm 5.4 \pm 0.4)\%$

First $A_{CP}^{\rm dir}$ for SCS two-body decays of charmed baryons.

For more information on CPV in charmed baryons, see Fu-Sheng's talk (theory) and Artur's talk (experiment) tomorrow.

Summary and prospects

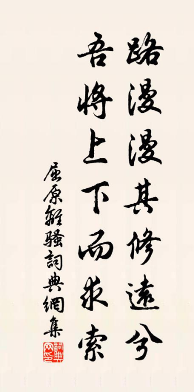
- In 2022(3), Belle(II)/BESIII/LHCb made significant contributions to obtain fruitful results of charm physics.
  - improve charm lifetimes [Belle II]
  - observe several new modes of charm hadronic decays [Belle/BESIII/LHCb]
  - measure (semi-)leptonic decays precisely to improve the V_{cq} [BESIII]
  - determine the strong-phase difference δ and CP-even fractions [BESIII]
  - measure D^0-$\bar{D}^0$ mixing parameters and CPV parameters [LHCb]
  - search for CPV in charmed meson decays [Belle/BESIII/LHCb]
  - search for CPV in charmed baryon decays [Belle]
  - ......
- Belle II/LHCb detectors and techniques are improving. e.g. charm flavor tagging way (see Michel's talk); Belle II's improved resolution w.r.t Belle/BaBar; LHCb's Run3 improved trigger, etc. Thus, It might not always be reliable for future predictions by scaling results of old machines with luminosity.
- Increasing charm sample at Belle II/BESIII/LHCb will bring more important and fruitful charm results.

  For some more info on prospects, see next talks: James's talk (e^+e^-) and Yasmine's talk (hadron machine).
- *"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." — From Alexander and Guy in [Ann. Rev. Nucl. Part. Sci. 71 (2021) 59]*

Homework of charm physics in my personal superficial opinion

- first observation of charm CPV in singly decay channel and more channels of D mesons
  $\Delta A_{CP}(D^0 \to K^+K^-, \pi^+\pi^-)$ ($> 5\sigma$) and $A_{CP}^{\rm dir}(D^0 \to \pi^+\pi^-)$ (3.8σ)
  CP asymmetry in many SCS decay channels have been studied but with statistics limited.
- first evidence of indirect CPV in D^0 decays [Long term]
  still no signs for non-zero result in $|q/p| - 1$ and $\arg(q/p)$.
- first evidence of CPV in charmed baryon sector [Long term]
  currently only three studies $\Lambda_c^+ \to ph^+h^-$, $\Lambda_c^+ \to (\Lambda, \Sigma^0)K^+$, $\Xi_c^+ \to pK^-\pi^+$
- first observation of Ξ_{cc}^+ and Ω_{cc}^+ and their hadronic decays
- first observation of radiative decays of charmed baryons
- precise/first absolute $\mathcal{B}$ of the decays of charmed baryons (Ξ_c and Ω_c)
- more precise $\mathcal{B}$ results of charmed baryon SL decays
  e.g $\mathcal{B}(\Xi_c \to \Xi\ell\nu)$ and $\mathcal{B}(\Omega_c \to \Omega\ell\nu)$ results are not understood or to be improved precisely.
- $\mathcal{B}$ (and α) measurements for more charm decays or with improved precision
- amplitude analyses of charmed baryon decays with current/increased available datasets
- more sensitive searches for rare or forbidden charm decays [Long term]
- ......

Lots of jobs to do for our charmers...



"The road ahead is long and endless; yet high and low we'll search with our will unbending."

Back up

Thank you for your attention.

谢谢！

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Recent publications on hadronic, (semi)leptonic, and rare decays of charmed hadrons

- Recently experiments reported > 70 branching fractions ($\mathcal{B}$) of charmed hadron decays.

First observation	Publication
$D^0 \to K_L^0 P\ (P = \omega, \phi, \eta^{(\prime)})$	BESIII, PRD **105**, 092010 (2022)
$D_s^+ \to \omega\pi^+\eta$	BESIII, PRD **107**, 052010 (2023)
$D_s^+ \to K_S^0 K^+ K^- \pi^+$	Belle, arXiv:2305.11405
$\Lambda_c^+ \to n\pi^+$	BESIII, PRL **128**, 142001 (2022)
$\Lambda_c^+ \to n\pi^+\pi^0, n\pi^+\pi^+h^-$	BESIII, CPC **47**, 023001 (2023)
$\Lambda_c^+ \to p\eta'$	Belle, JHEP **03**, 090 (2022)
$\Lambda_c^+ \to pK_S^0K_S^0$	Belle, PRD **107**, 032004 (2023)
$\Omega_c^0 \to \Xi^-\pi^+, \Omega^-K^+$	LHCb, arXiv:2308.08512

Improved $\mathcal{B}$	Publication
$\Lambda_c^+ \to p\eta$	BESIII, arXiv:2307.09266
$\Lambda_c^+ \to \Sigma^+K^+\pi^-$	BESIII, arXiv:2304.09405
$\Lambda_c^+ \to (\Lambda, \Sigma^0)K^+$	Belle, Sci. Bull. **68**, 583 (2023)
$\Lambda_c^+ \to \Sigma^+(\eta, \eta')$	Belle, PRD **107**, 032003 (2023)
$\Lambda_c^+ \to pK_S^0\eta$	Belle, PRD **107**, 032004 (2023)
$D^+ \to K_S^0\pi^+\eta$	BESIII, arXiv:2309.05760
$D_s^+ \to K_S^0K_S^0\pi^+$	BESIII, PRD **105**, L051103 (2022)
$D_s^+ \to K_S^0K^+\pi^0$	BESIII, PRL **129**, 182001 (2022)
$D_{(s)}^+ \to K^+h^-\pi^+\pi^0$	Belle, PRD **107**, 033003 (2023)
$\Xi_c^0 \to \Lambda_c^+\pi^-$	Belle, PRD **107**, 032005 (2023)
$D_s^{*+} \to D_s^+\pi^0$	BESIII, PRD **107**, 032011 (2023)
$D^{0,+} \to \pi^+\pi^+\pi^-X$	BESIII, PRD **107**, 032002 (2023)
$D^{0,+} \to K_S^0X$	BESIII, PRD **107**, 112005 (2023)
$D_s^+ \to \pi^+\pi^+\pi^-X$	BESIII, PRD **108**, 032001 (2023)
$\bar{\Lambda}_c^- \to \bar{n}X$	BESIII, PRD **108**, L031101 (2023)
......	......

(Semi-)leptonic decay	Publication
$D_s^+ \to \mu^+\nu_\mu$	BESIII, arXiv:2307.14585
$D_s^+ \to \tau^+\nu_\tau, \tau \to \pi^+\bar{\nu}_\tau$	BESIII, arXiv:2303.12600
$D_s^+ \to \tau^+\nu_\tau, \tau \to \mu^+\nu_\mu\bar{\nu}_\tau$	BESIII, arXiv:2303.12468
$D_s^+ \to \eta^{(\prime)}\mu^+\nu_\mu$	BESIII, arXiv:2307.12852
$D_s^+ \to \eta^{(\prime)}e^+\nu_e$	BESIII, arXiv:2306.05194
$D_s^+ \to \pi^+\pi^-e^+\nu_e$	BESIII, arXiv:2303.12927
$D_s^+ \to K^+K^-\mu^+\nu_\mu$	BESIII, arXiv:2307.03024
$D_s^+ \to \pi^0e^+\nu_e$	BESIII, PRD **106**, 112004 (2022)
$D_s^+ \to (K_1(1270)^0, b_1(1235)^0)e^+\nu_e$	BESIII, arXiv:2309.04090
$D_s^{*+} \to e^+\nu_e$	BESIII, arXiv:2304.12159
$\Lambda_c^+ \to \Lambda\mu^+\nu_\mu$	BESIII, PRD **108**, L031105 (2023)
$\Lambda_c^+ \to \Lambda e^+\nu_e$	BESIII, PRL **129**, 231803 (2022)
$\Lambda_c^+ \to pK^-e^+\nu_e$	BESIII, PRD **106**, 112010 (2022)
$\Lambda_c^+ \to (\Lambda\pi^+\pi^-, pK_S^0\pi^-)e^+\nu_e$	BESIII, PLB **843**, 137993 (2023)
$\Lambda_c^+ \to Xe^+\nu_e$	BESIII, PRD **107**, 052005 (2023)

Rare dcays	Publication
$D^0 \to \mu^+\mu^-$	LHCb, PRL **131**, 041804 (2023)
$D^0, \bar{D}^0 \to p\ell$	Belle, Preliminary
$D^0 \to \bar{p}e^+, D^0 \to pe^-$	BESIII, PRD **105**, 032006 (2022)
$D^\pm \to (n, \bar{n})e^\pm$	BESIII, PRD **106**, 112009 (2022)
$D^0 \to \pi^0\nu\bar{\nu}$	BESIII, PRD **105**, L071102 (2022)
$D^*(2007)^0 \to \mu^+\mu^-$	LHCb, EJPC **83**, 666 (2023)
$\Lambda_c^+ \to \Sigma^+\gamma, \Xi_c^0 \to \Xi^0\gamma$	Belle, PRD **107**, 032001 (2022)
$\Lambda_c^+ \to \Sigma^+\gamma$	BESIII, arXiv:2212.07214
$\Lambda_c^+ \to p\gamma'$	BESIII, PRD **106**, 072008 (2022)

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

- Open-flavored neutral meson transforms to anti-meson:

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

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

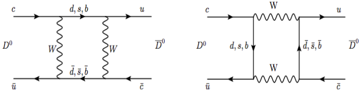
$$|D_{1,2}\rangle \equiv p|D^0\rangle \pm q|\bar{D}\rangle \text{ (CPT: } p^2+q^2=1)$$

- D^0-$\bar{D}^0$ mixing parameters: $\mathbf{x} \equiv 2\frac{M_1 - M_2}{\Gamma_1 + \Gamma_2}, \quad \mathbf{y} \equiv \frac{\Gamma_1 - \Gamma_2}{\Gamma_1 + \Gamma_2}$

- Time-dependent amplitude of $D^0 \to f$ (here $t[\tau_{D^0}]$ and $\lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f}$):

$$\Gamma(D^0(t) \to f) \propto |\mathcal{A}_f|^2 e^{-t}\left(\frac{1+|\lambda_f|^2}{2}\cosh(yt) - Re(\lambda_f)\sinh(yt)\frac{1-|\lambda_f|^2}{2}\cos(xt) + Im(\lambda_f)\sin(xt)\right)$$

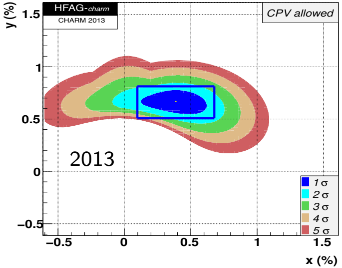
- Unique system: only up-type meson for mixing. SM predicts $\sim \mathcal{O}(1\%)$.

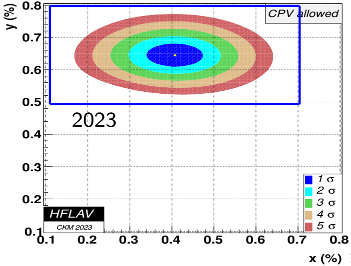


(1) short distance ($< 0.1\%$)

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

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

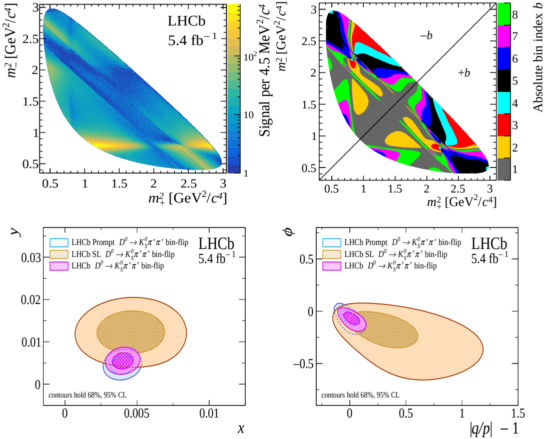




Model-independent measurement of D^0-$\bar{D}^0$ mixing

For details, see Federico's talk on Sep 21

- $D^0 \to K_S^0\pi^+\pi^-$: a golden channel of mixing measurement because of plentiful interferences between mixing and decay amplitudes.
- Belle/BaBar: model-dependent measurement [a b c]
- LHCb: 'bin-flip' method (model-indept.), mixing contribution mainly in upper half part of Dalitz-plot (DCS, mixing+CF). The ratio upper/lower is sensitive to mixing.
- The bins refer to the strong phase from CLEO/BESIII [d e].
- LHCb: first observation of non-zero x-parameter in 2021 using $D^{*+} \to [D^0 \to K_S^0\pi^+\pi^-]\pi^+$. [f]
- Recently an analysis with $\bar{B} \to D^0\mu^-\bar{\nu}_\mu X$ sample complements previous measurement. [g]
- Combined: $x_{CP} = (4.01 \pm 0.45 \pm 0.20) \times 10^{-3}$ (8.1σ), $y_{CP} = (5.51 \pm 1.16 \pm 0.59) \times 10^{-3}$

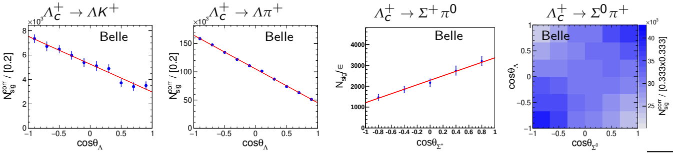


The larger the dataset, the more significant the advantage of bin-flip vs. model-dept method.

[a] (Belle) PRL 99, 131803 (2007)
[b] (Belle) PRD 89, 091103 (2014)
[c] (BABAR) PRL 105, 081803 (2010)
[d] (CLEO) PRD 82, 112006 (2010)
[e] (BESIII) PRL 124, 241802 (2020)
[f] (LHCb) PRL 127, 111801 (2021)
[g] (LHCb) (LHCb) arXiv:2208.06512

Decay asymmetry parameter α of charmed baryon decays

- 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 $1/2^+ \to 1/2^+ + 0^-$, $\alpha \equiv 2 \cdot \mathrm{Re}(S^* P)/(|S|^2 + |P|^2)$, where S and P denote the parity-violating S-wave and parity-conserving P-wave amplitudes.
- The charmed baryons are produced with negligible polarization averagely at Belle (II)/CLEO-II, different with BESIII/LHCb.
- For $\Lambda_c^+ \to \Lambda h^+, \Sigma^+ h^0$ decays, $\frac{dN(\Lambda_c^+ \to \Lambda h^+)}{d\cos\theta_\Lambda} \propto 1 + \alpha_{\Lambda_c^+}\alpha_- \cos\theta_\Lambda$
- For $\Lambda_c^+ \to \Sigma^0 h^+$ decays, $\frac{dN(\Lambda_c^+ \to \Sigma^0 h^+)}{d\cos\theta_{\Sigma^0}\, d\cos\theta_\Lambda} \propto 1 - \alpha_{\Lambda_c^+}\alpha_- \cos\theta_{\Sigma^0} \cos\theta_\Lambda$



- Since α is CP-odd, the α-induced CP asymmetry $A_{CP}^{\alpha} \equiv \frac{\alpha+\bar{\alpha}}{\alpha-\bar{\alpha}}$, which presents CPV in $\mathrm{Re}(S^* P)$ when $A_{CP}^{\mathrm{dir}} = 0$. $\Rightarrow$ A_{CP}^{α} provides an observable complementary to A_{CP}^{dir} (example shown later).

- No approaches based on various theories could successfully predict all the experimental α values. $\Rightarrow$ needs a joint effort from theory and experiment.

Decay	recent α results	W.A.
$\Lambda_c^+ \to p K_S^0$	–	0.18 ± 0.45 [a]
$\Lambda_c^+ \to \Lambda K^+$	-0.585 ± 0.052 [b]	–
$\Lambda_c^+ \to \Sigma^0 K^+$	-0.54 ± 0.20 [b]	–
$\Lambda_c^+ \to \Lambda \pi^+$	-0.755 ± 0.006 [b]	-0.84 ± 0.09
$\Lambda_c^+ \to \Sigma^0 \pi^+$	-0.463 ± 0.018 [b]	-0.73 ± 0.18 [c]
$\Lambda_c^+ \to \Sigma^+ \pi^0$	-0.480 ± 0.028 [d]	-0.55 ± 0.11
$\Lambda_c^+ \to \Sigma^+ \eta$	-0.990 ± 0.058 [d]	–
$\Lambda_c^+ \to \Sigma^+ \eta'$	-0.460 ± 0.067 [d]	–
$\Lambda_c^+ \to \Xi^0 K^+$	0.01 ± 0.16 [e]	–
$\Lambda_c^+ \to \Lambda \rho^+$	-0.76 ± 0.07 [f]	–
$\Lambda_c^+ \to \Sigma'^+ \pi^0$	-0.92 ± 0.09 [f]	–
$\Lambda_c^+ \to \Sigma'^0 \pi^+$	-0.79 ± 0.11 [f]	–
$\Xi_c^0 \to \Xi^- \pi^+$		-0.64 ± 0.05 [g]
$\Xi_c^0 \to \Lambda \bar{K}^{*0}$		$+0.15 \pm 0.22$ [h]
$\Xi_c^0 \to \Sigma^+ K^{*-}$		-0.52 ± 0.30 [h]

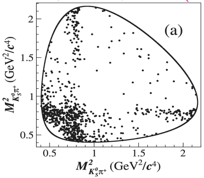
[a] BESIII, PRD **100**, 072004 (2019)
[b] Belle, Sci. Bull. **68**, 583 (2023)
[c] BESIII, PRD **100**, 072004 (2019)
[d] Belle, PRD **107**, 032003 (2023)
[e] BESIII, arXiv:2309.02774
[f] BESIII, JHEP **12**, 033 (2022)
[g] Belle, PRL **127**, 121803 (2021)
[h] Belle, JHEP **06**, 160 (2021)

Amplitude analysis of hadronic decays of charmed hadrons

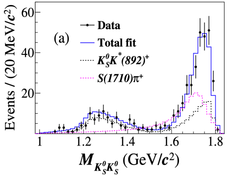
- The charm hadronic multi-body decays provide an ideal platform to study the light hadron spectroscopy, determine spin-parity of resonance, etc., using amplitude analysis.

Decays	Highlight or dominant res.	Publications
$D^+ \to K_S^0\pi^+\eta$	$K_S^0 a_0(980)^+$	BESIII, arXiv:2309.05760
$D_s^+ \to K_S^0 K_S^0 \pi^+$	observe $S(1710) \to K_S^0 K_S^0$	BESIII, PRD **105**, L051103 (2022)
$D_s^+ \to K_S^0 K^+ \pi^0$	observe $a_0(1817)^+ \to K_S^0 K^+$	BESIII, PRL **129**, 182001 (2022)
$D_s^+ \to \pi^+\pi^+\pi^-$	$\pi^+\pi^-$ S-wave	LHCb, JHEP **07**, 204 (2023)
$D^+ \to \pi^+\pi^+\pi^-$	$\pi^+\pi^-$ S-wave	LHCb, JHEP **06**, 044 (2023)
$D_s^+ \to K^+\pi^+\pi^-$	$K^+\rho^0$, $K^{*0}\pi^+$	BESIII, JHEP **08**, 196 (2022)
$D_s^+ \to \pi^+\pi^0\eta'$	$\rho^+\eta'$	BESIII, JHEP **04**, 058 (2022)
$D^+ \to K_S^0\pi^+\pi^0\pi^0$	$K_S^0 a_1(1260)^+$, $\bar{K}^{*0}\rho^+$	BESIII, arXiv:2305.15879
$D_s^+ \to K^+\pi^+\pi^-\pi^0$	$K^{*0}\rho^+$	BESIII, JHEP **09**, 242 (2022)
$D_s^+ \to K^-K^+\pi^+\pi^+\pi^-$	$a_1(1260)^+\phi$	BESIII, JHEP **07**, 051 (2022)
$\Lambda_c^+ \to pK^-\pi^+$	pK^{*0}, $\Delta^{++}K^-$, $pK_0^*(1430)^0$	LHCb, PRD **108**, 012023 (2023)
$\Lambda_c^+ \to pK^-\pi^+$	observe $\Lambda\eta$ cusp	Belle, PRD **108**, L031104 (2023)
$\Lambda_c^+ \to \Lambda\pi^+\pi^+\pi^-$	observe $\Sigma(1435)^\pm$ or $\bar{K}N$ cusp	Belle, PRL **130**, 151903 (2023)
$\Lambda_c^+ \to \Lambda\pi^+\pi^0$	$\Lambda\rho^+$, $\Lambda + NR_{1^-}$	BESIII, JHEP **12**, 033 (2022)

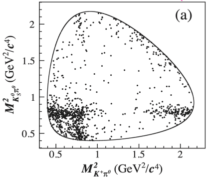
BESIII, PRD **105**, L051103 (2022)



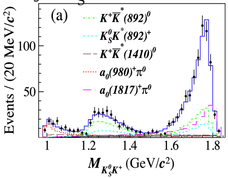
$D_s^+ \to K_S^0 K_S^0 \pi^+$



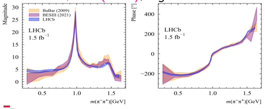
BESIII, PRL **129**, 182001 (2022)



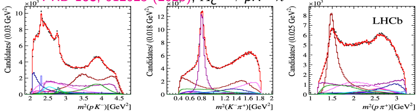
$D_s^+ \to K_S^0 K^+ \pi^0$



JHEP **07**, 204 (2023), $D_s^+ \to \pi^+\pi^+\pi^-$

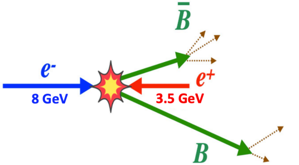


PRD **108**, 012023 (2023), $\Lambda_c^+ \to pK^-\pi^+$



Charm production at Belle and Belle II

- Belle (II) has two ways to produce the charm sample: $e^+e^- \to c\bar{c}$ ($\sigma = 1.3$ nb) and $b \to c$ transition.
- Belle accumulated a dataset of ~ 1 ab^{-1}, which provides a large $B\bar{B}$ sample (772 millions), and also a large charm sample to study charm physics, e.g. $N^{D^+}_{\rm prod} \sim \mathcal{O}(10^9)$, $N^{\Lambda_c^+}_{\rm prod} \sim \mathcal{O}(10^8)$, etc.



$E_{c.m}$	On/Off (fb^{-1})	Number
$\Upsilon(1S)$	5.7/1.8	102 M $\Upsilon(1S)$
$\Upsilon(2S)$	24.9/1.7	158 M $\Upsilon(2S)$
$\Upsilon(3S)$	2.9/0.25	11 M $\Upsilon(3S)$
$\Upsilon(4S)_{\rm SVD1}$	140.0/15.6	152 M $B\bar{B}$
$\Upsilon(4S)_{\rm SVD2}$	571.0/73.8	620 M $B\bar{B}$
$\Upsilon(5S)$	121.4/1.7	8.3 M $B_s\bar{B}_s$
Scan	0/27.6