Recent experimental results on Charm hadron decays

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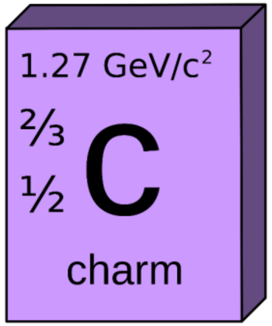
Outline

- **Motivations**
- **Selected results in the past year (earlier results can be found in Prasanth & Hailong's review talks at PIC2022)**
  - $D^0\overline{D}^0$ mixing & CP Violation
  - Lifetimes of Charm hadrons
  - QCD & Hadron structures
  - Rare decays
- **Summary & Prospect**

Spectroscopy results will be covered by Beijiang and Roberto's talk!

Introduction

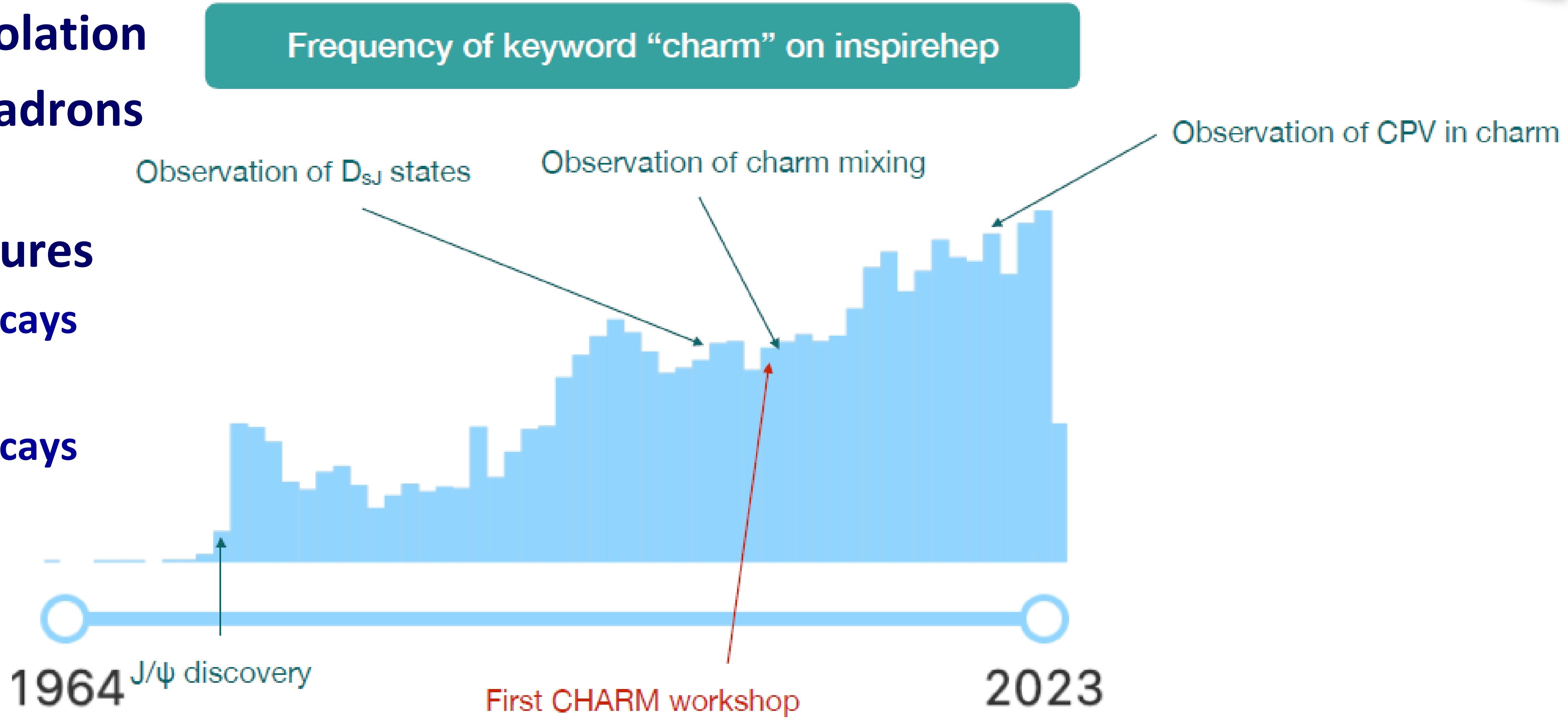


c-QUARK MASS	1.27 ± 0.02 GeV
m_c/m_s MASS RATIO	$11.76^{+0.05}_{-0.10}$
m_b/m_c MASS RATIO	4.58 ± 0.01
$m_b - m_c$ QUARK MASS DIFFERENCE	3.45 ± 0.05 GeV

- **Interactions in Standard Model**
  - **Strong interactions: Perturbative & non-Perturbative**
    - **QCD (Spectroscopy, Lattice QCD)**
    - **QCD corrections are large (difficult to calculate) $\Leftarrow$ Experimental input**
  - **Electroweak interactions: $SU(2)_L \times U(1)_Y$, $\Delta C = 1$, $\Delta C = 2$ processes**
- **A unique platform on searching for New physics**
  - **Up type quarks (Charm & Top) offer unique probes**
  - **Rare decays & CP violation suppressed in SM**

Covered experimental topics

- $D^0\overline{D}^0$ mixing & CP Violation
- Lifetimes of Charm hadrons
  - $D_s^+, \Xi_c^0, \Lambda_c^+, \Omega_c^0, \Xi_c^+$
- QCD & Hadron structures
  - (Semi)leptonic D decays
  - Hadronic D decays
  - Charmed baryon decays
- Rare decays



From Tara Nanut Petric's talk @Charm2023

Charm Facilities

Charm factory	B factory	Hadron collider
● Threshold production: No boost ● Small X-section : Lowest Statistics ● Quantum coherence ● Inclusive charm, neutrals and neutrinos ● Absolute BFs	● Low background ● Low statistics ● Low boost ● Good for neutrals and neutrinos ● Some Absolute BFs	● High background ● High statistics ● High boost ● Challenging for neutrals and neutrinos ● Complex and biasing triggers

$$e^+e^- \to \psi(3770) \to D\bar{D}$$
$$e^+e^- \to D_{(s)}^{(*)}\bar{D}_{(s)}^{(*)}$$
$$e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$$

BESIII, STCF in the future

$$e^+e^- \to c\bar{c}$$
+ some other Stuff

Belle / Belle II

$$p\bar{p} \to c\bar{c}$$
+ lots of other Stuff

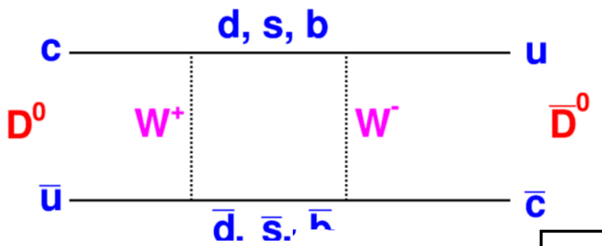
LHCb

$D^0\overline{D}^0$ mixing

$$x = \frac{m_2 - m_1}{\Gamma}; y = \frac{\Gamma_2 - \Gamma_1}{2\Gamma}$$

- New Physics can affect x
- Long range effects $\Leftarrow$ difficult to calculate
- Large uncertainties in SM mixing rate $\Leftarrow$ difficult to spot NP!

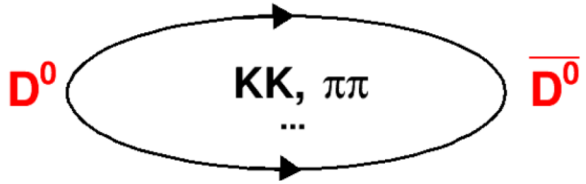
Short range quark-level mixing:



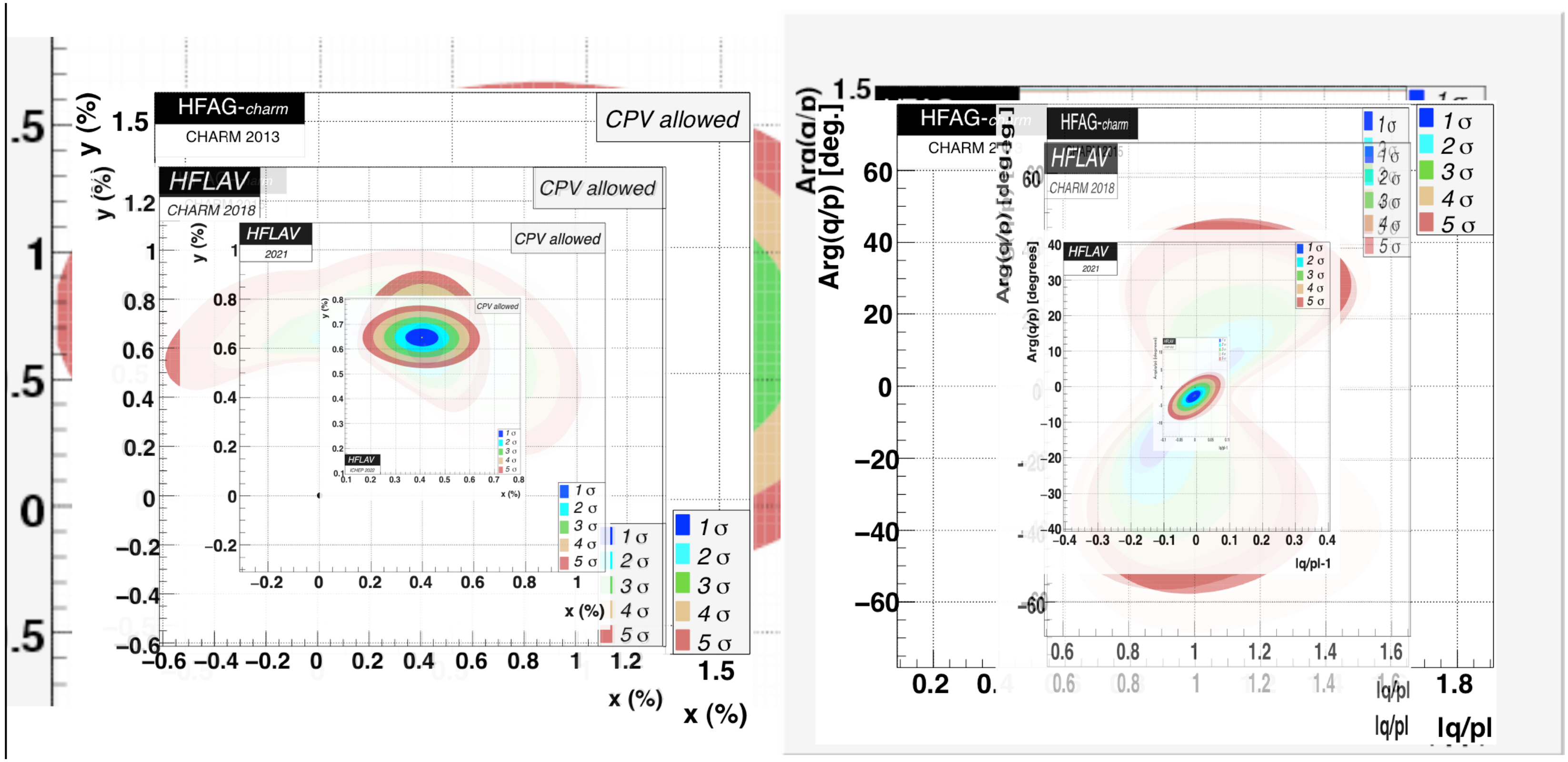
$x \sim 10^{-5}$

arXiv : hep – ph/0310076

Long range mixing via Final State Interactions:



$x, y \sim 1\%$



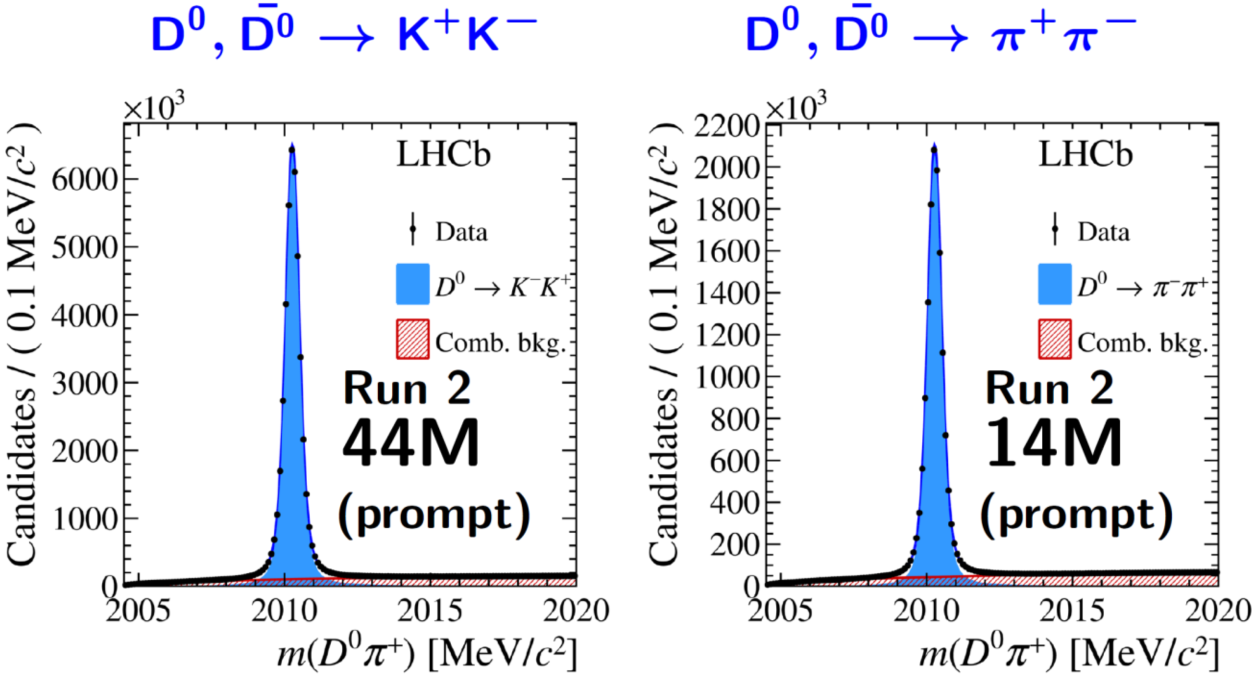
Discovery of CP violation in Charm in 2019

$$A_{\text{raw}} = A_{CP} + A_{\text{production}} + A_{\text{detection}}$$

PRL 122; 211803 (2019)

$$\Delta A_{CP} \equiv A_{\text{raw}}(K^+K^-) - A_{\text{raw}}(\pi^+\pi^-) \approx A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-)$$

- We measure the physical *CP* asymmetry plus asymmetries due to detection effects and production
- All nuisance asymmetries cancel out in the difference
- Full LHCb dataset (Run1 + Run2)
- First observation of CPV in charm decays



$\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}$ 5.3σ from zero!

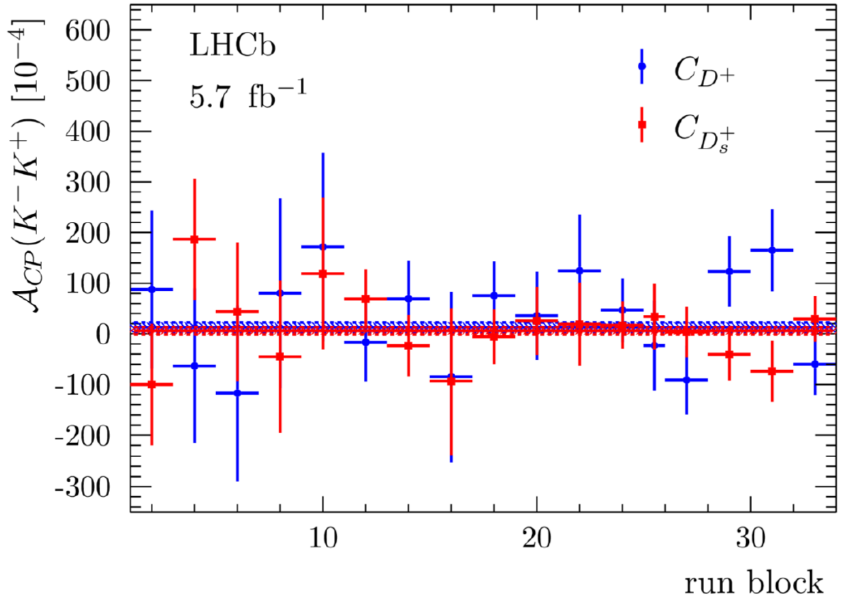
Individual asymmetries in $D^0 \to hh$ decays

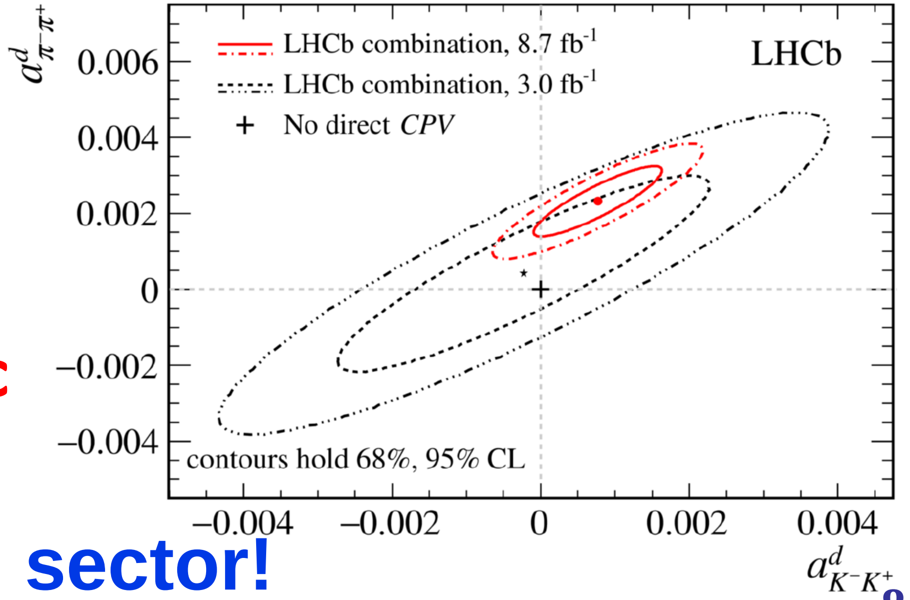
arXiv:2209.03179(2022)

- Control samples to cancel the detection and production asymmetries
- Control samples: no CPV is expected in Cabibbo Favor D^+, D_s^+ decays (Statistically independent)

$$a^d_{K^-K^+} = (7.7 \pm 5.7) \times 10^{-4}$$
$$a^d_{\pi^-\pi^+} = (23.2 \pm 6.1) \times 10^{-4}$$

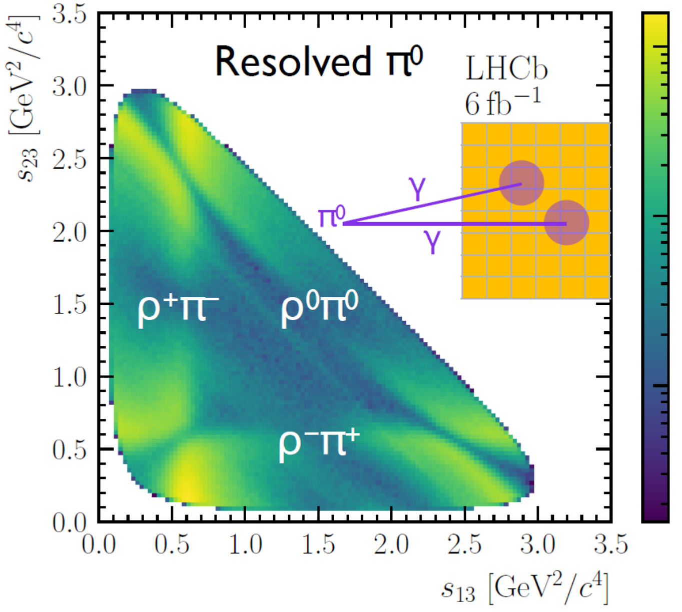
- Inconsistent with the CP symmetry hypothesis (3.8σ)
- First evidence for direct CP violation in a specific charm decay, $D^0 \to \pi^+\pi^-$

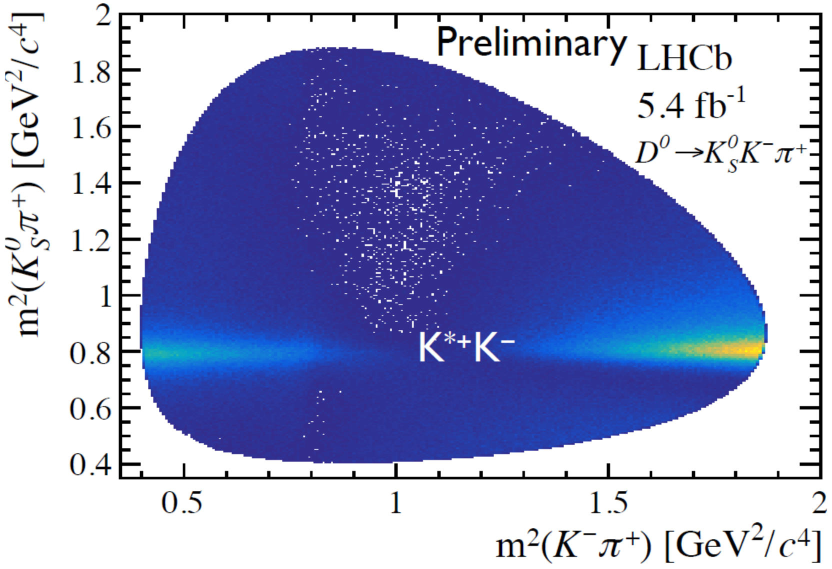


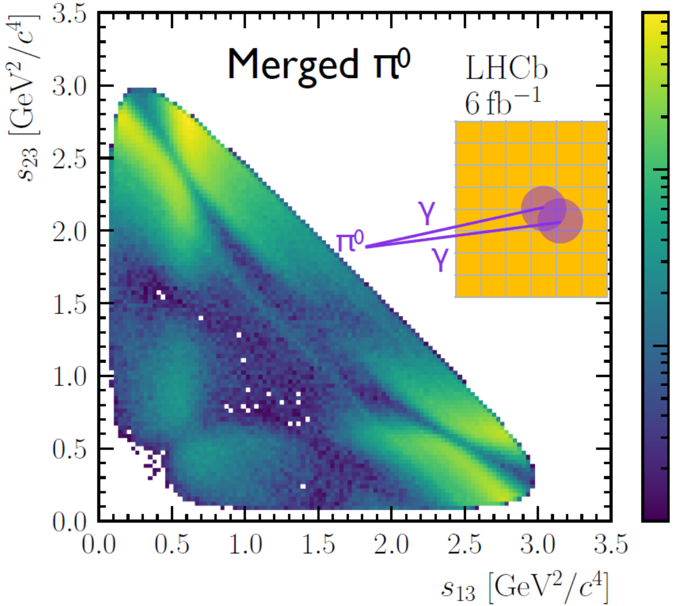


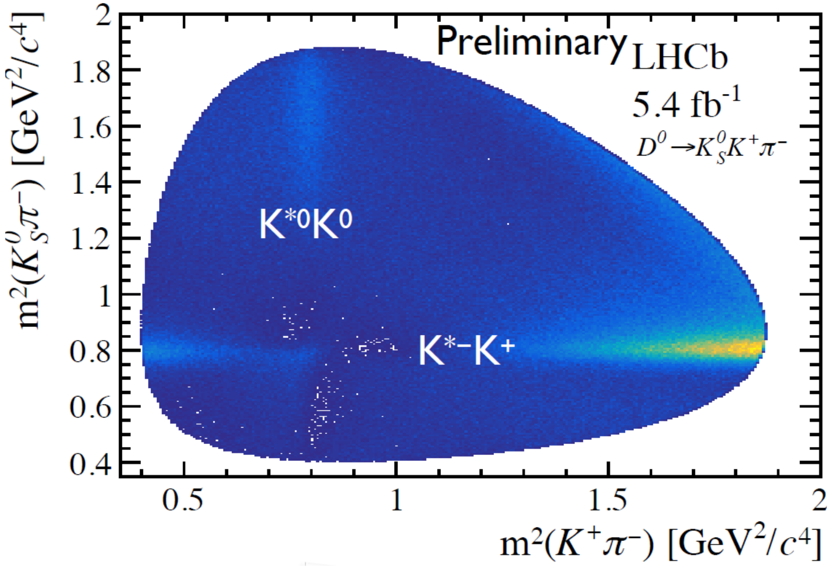
No other direct CPV observed yet in Charm sector!

Search for CPV in $D \to \pi^+\pi^-\pi^0$, $D \to K_S K^{\mp}\pi^{\pm}$





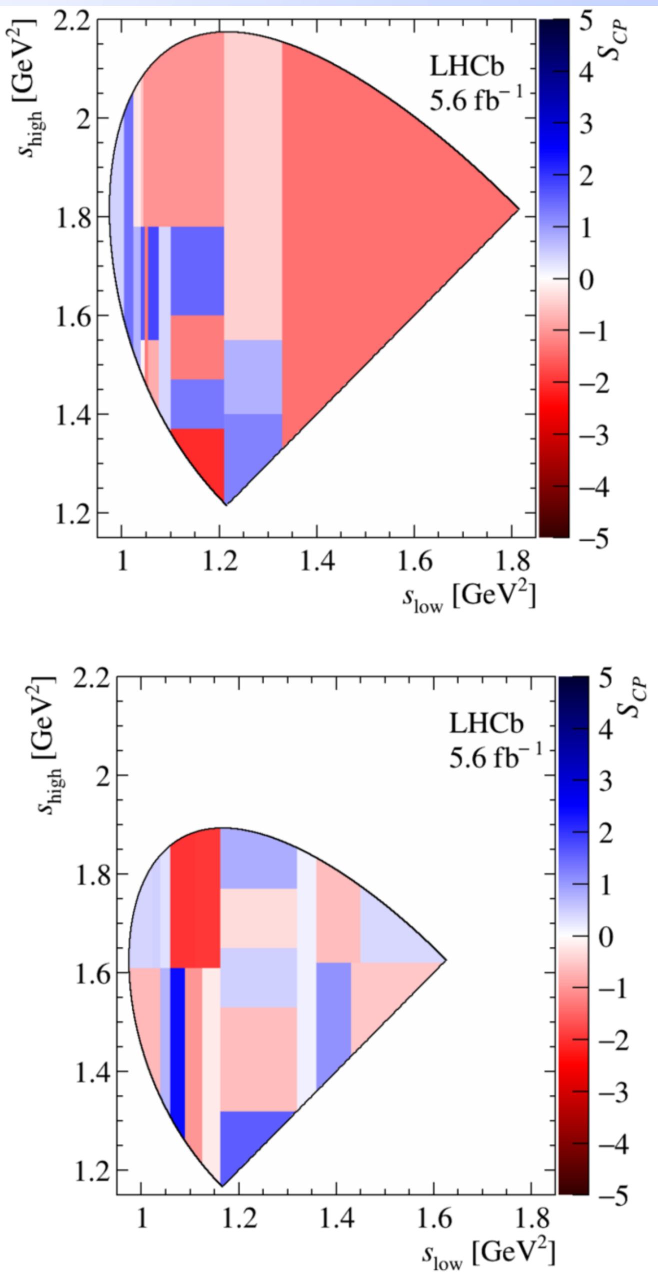




arXiv:2306.12746 (2023)
LHCb-PAPER-2023-019

- Energy test (~unbinned version of χ^2 test) reveals no significant difference between CP-conjugate Dalitz plots.
- Note however, that current sensitivity insufficient to discover CPV at level seen in 2-body decays.

Search for CPV in $D^+_{(s)} \to K^-K^+K^+$

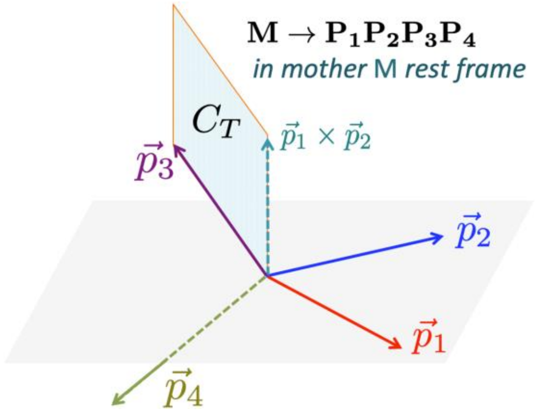


JHEP 2023, 67 (2023)

- Singly Cabibbo suppressed $D_s^+ \to K^-K^+K^+$; doubly Cabibbo suppressed $D^+ \to K^-K^+K^+$
- Signal purity 64% (D_s^+) and 78% (D^+)
- Control samples:
  - Phase space simulation
  - Background samples
  - CF modes： $D_s^+ \to K^-K^+\pi^+$ and $D^+ \to K^-\pi^+\pi^+$
- Stability checks:
  - different invariant mass fit models
  - different binning schemes
- No evidence for CP violation

Search for CPV in charm multi-body decays

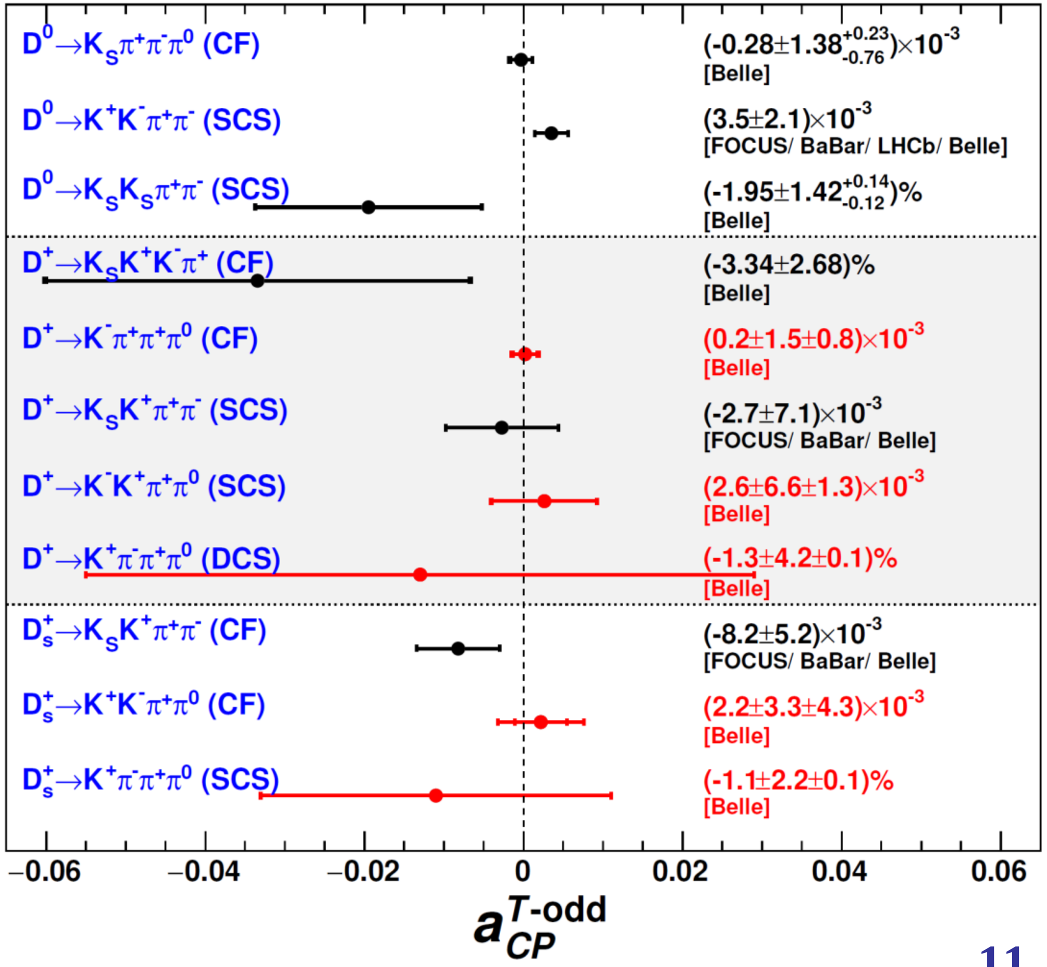
arXiv:2305.11405; 2305.12806; PRD107, 033003 (2023)



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

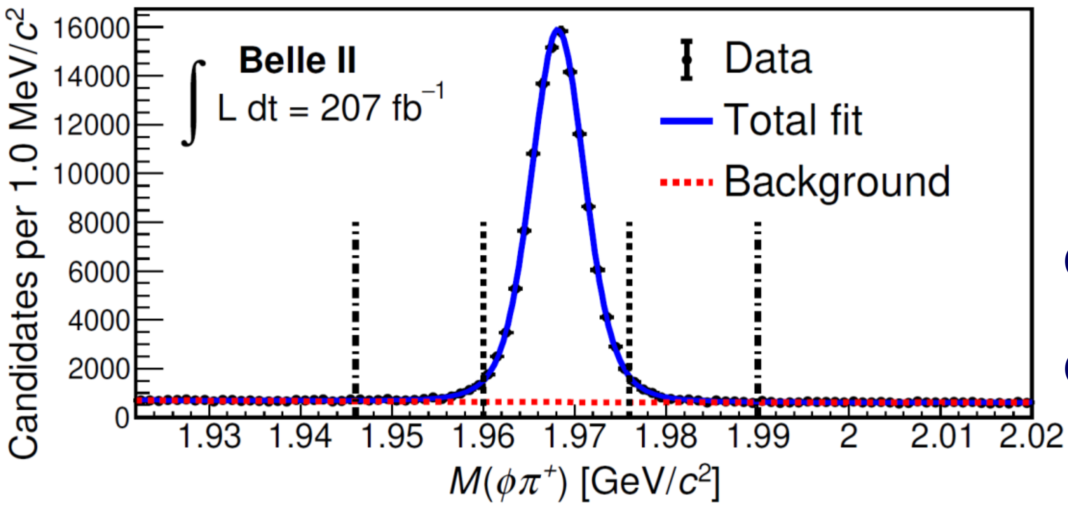
$$a_{CP}^{\text{T-odd}} = \frac{1}{2}\left(A_T - \overline{A}_T\right)$$

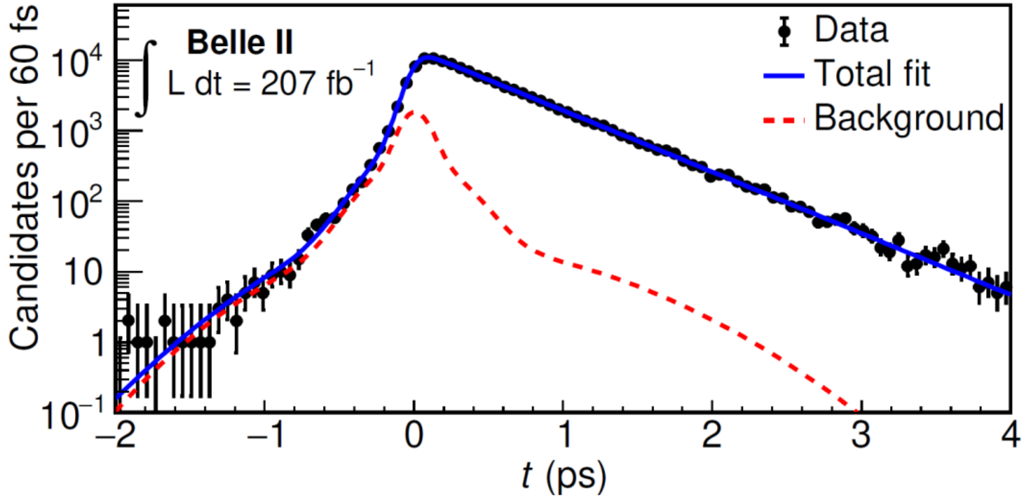
- **T-odd *CP* asymmetry can be nonzero if CPV**
- **No significant CPV observed**
- **Belle made the significant contributions to $a_{CP}^{T-\text{odd}}$ results for all measured charm decays.**
- **The precisions of $a_{CP}^{T-\text{odd}}$ for various decay modes have reached $\mathcal{O}(0.1\%)$.**



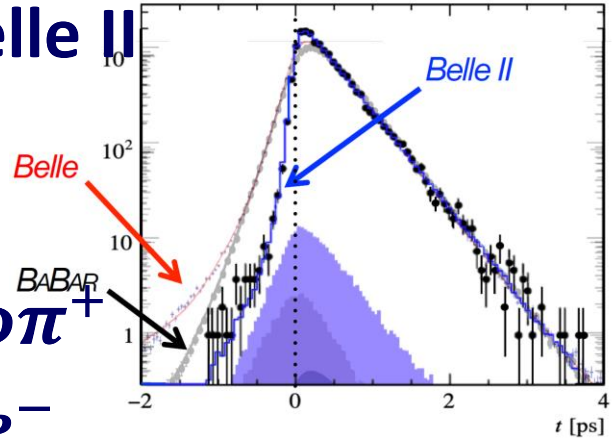
Charm meson Lifetimes @ Belle II

arXiv:2306.00365 (June 2023)





- Compared with Belle, Belle II vertex resolution is significantly improved.



- 116,000 prompt $D_s^+ \to \phi\pi^+$
- $p(D_s) > 2.5$ GeV in e^+e^- rest frame is required to remove D_s from $B \to D_s$
- Measured result:

$$\tau(D_s) = 498.2 \pm 1.7 \underbrace{{}^{+1.1}_{-0.8}}_{\pm 2 \text{ fs}} \text{ fs}$$

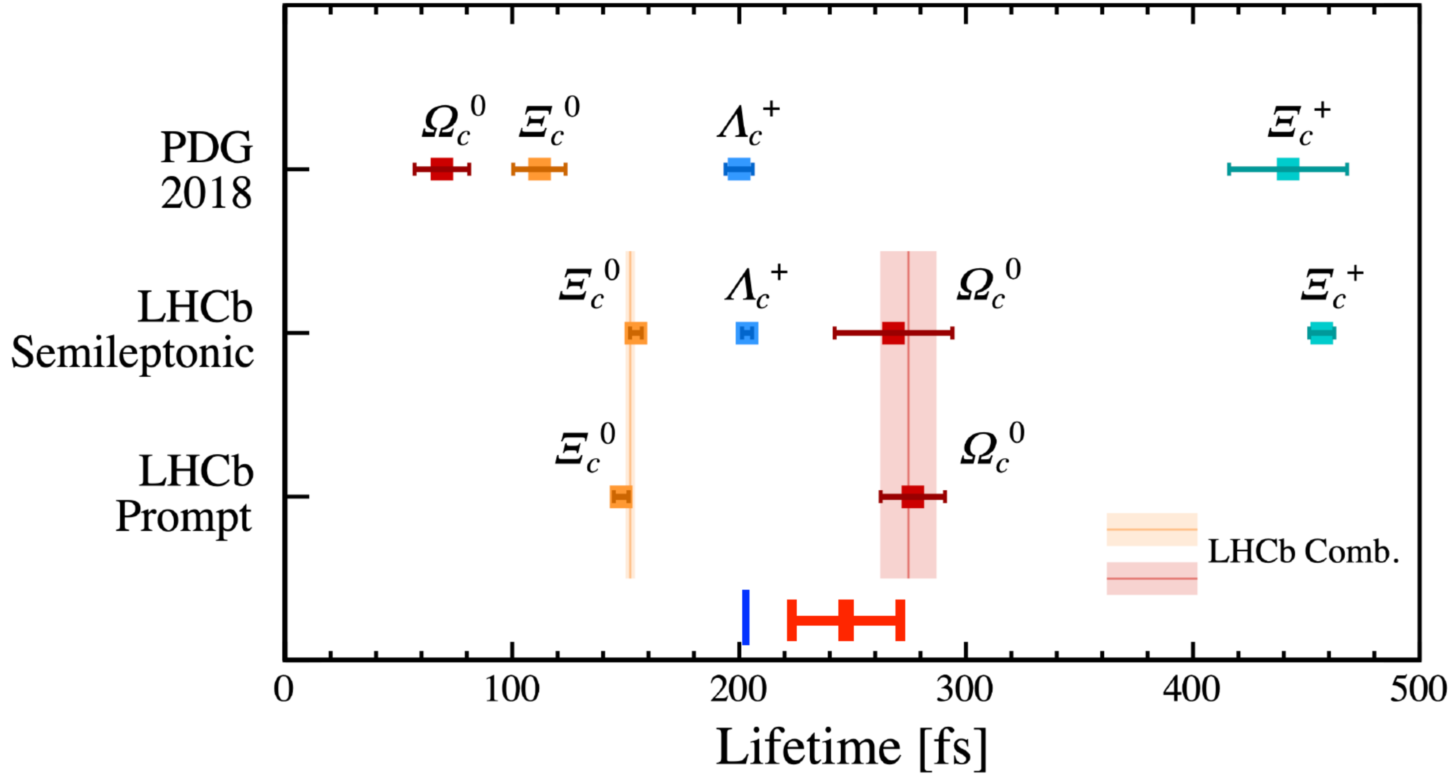
- previous word average:

$$\tau(D_s) = 504 \pm 4 \text{ fs}$$

Almost as precise as D^0, D^+ lifetimes @Belle II (PRL 127(2021)21,211801)

Charm Baryon Lifetimes

HQE (up to order $1/m^3$): $\tau(\Omega_c^0) < \tau(\Xi_c^0) < \tau(\Lambda_c) < \tau(\Xi_c^+)$



Adapted from Nisar Nellikunnummel @ ICHEP 2022

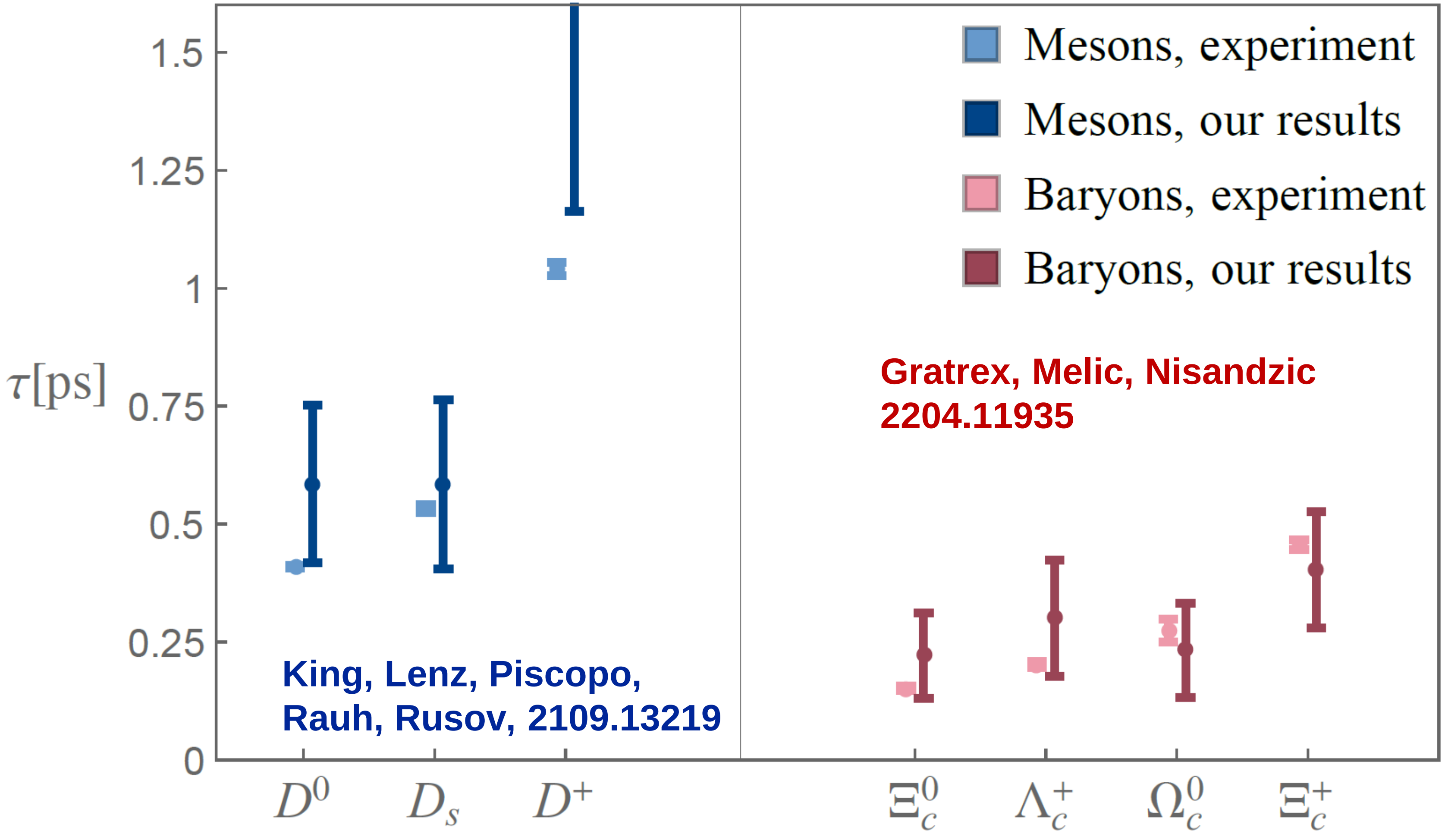
PRD 100 (2019) 3, 032001

Sci.Bull. 67 (2022) 5, 479-487

BELLE-II Ω_c^0: PRD 107 (2023) 3, L031103

BELLE-II Λ_c: PRL 130 (2023) 7, 071802

Charm lifetimes from HQE

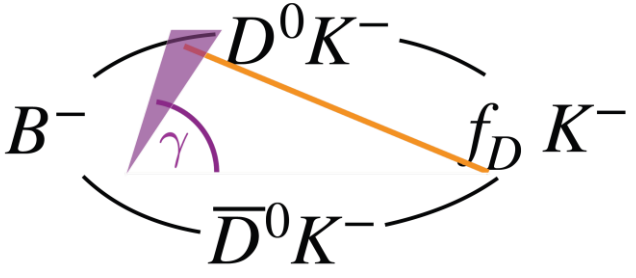


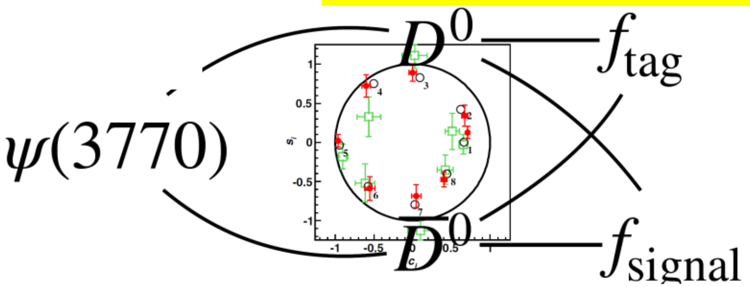
Another HQE-based calculation leading to compatible results:
Hai-Yang Cheng,
Science Bulletin 67 (2022) 445–447

Mannel, Moreno, ivovarov 2304.08964 : inclusion of newly calculated NLO corrections to μ_G^2 would probably significantly reduce uncertainty

Satisfactory agreement with the experiment!

New unbinned model-independent method to extract γ

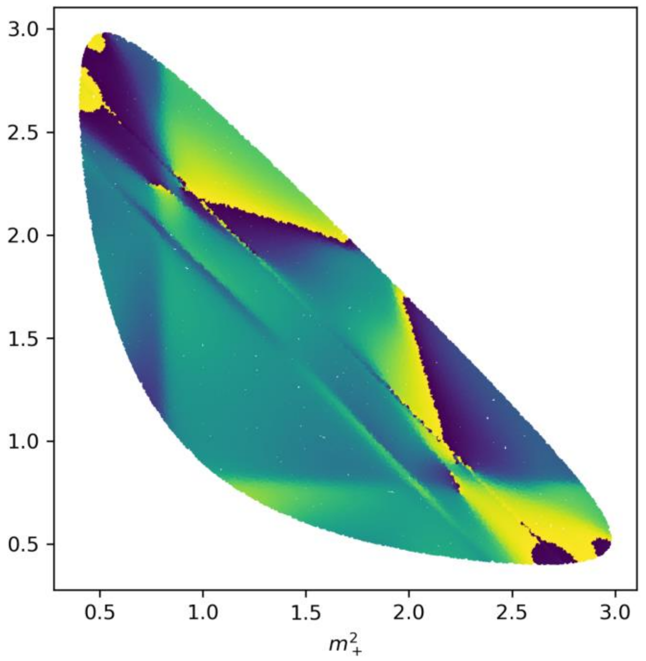




arXiv:2305.10787 (2023)

measures CKM angle γ ⇐ measures charm interference, especially strong phases

New, unbinned model-independent method



		$\sigma_\gamma(°)$		
Lumi		new QMI	Model-dependent	8 bins, fixed* ci, si
1xLHCb	1xBESIII	4.2	4.2	5.1
1xLHCb	10xBESIII	4.2		
100xLHCb	1xBESIII	0.45	0.42	0.52
100xLHCb	10xBESIII	0.43		

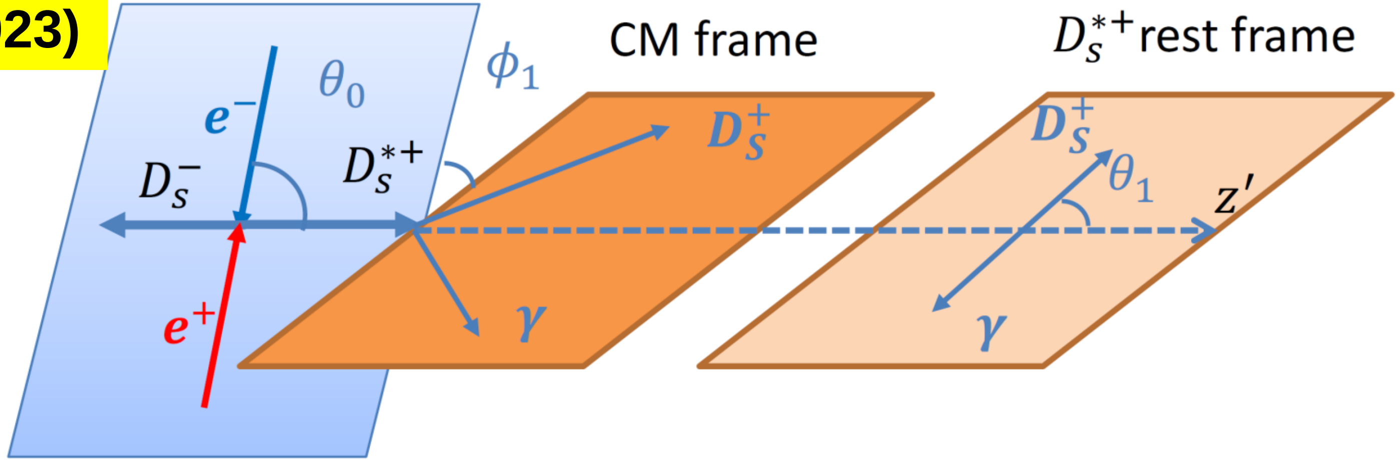
(average error reported in 100 pseudo experiments)

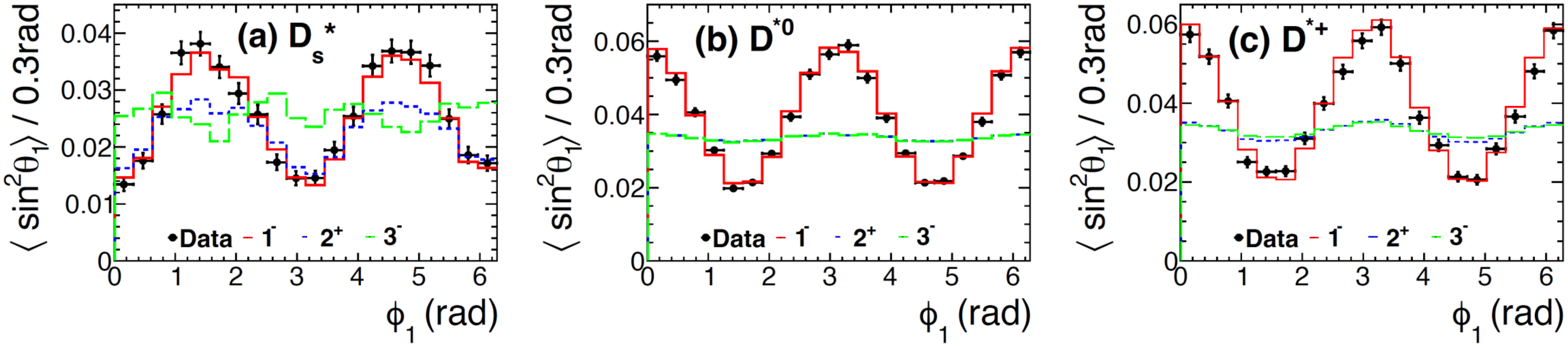
additional uncertainty on binned γ fit due to finite BESIII data for 1xBESIII: 1.2° PRD 101 (2020) 11200

New method do not do any integration, averaging or projection from 2D to 1D, and therefore do not suffer the associated information loss.

Spin-parity of D*(s)

BESIII: arXiv:2305.14631 (2023)





$J^P = 1^-$ for D_s^* , D^{*0} , and D^{*+}

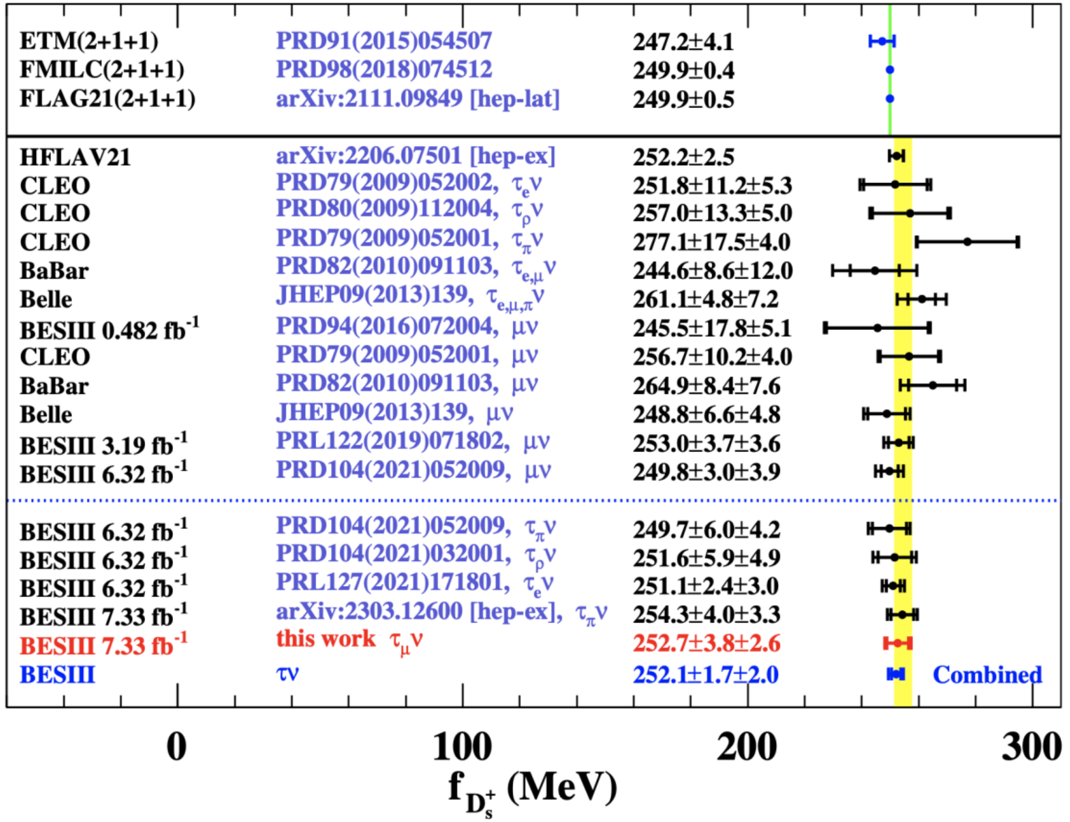
- Many people thought these quantum numbers had been measured, but we didn't!
- Prior to this measurement, only spin 0 for D^{*0} excluded : PRL 39,(1977) 262.

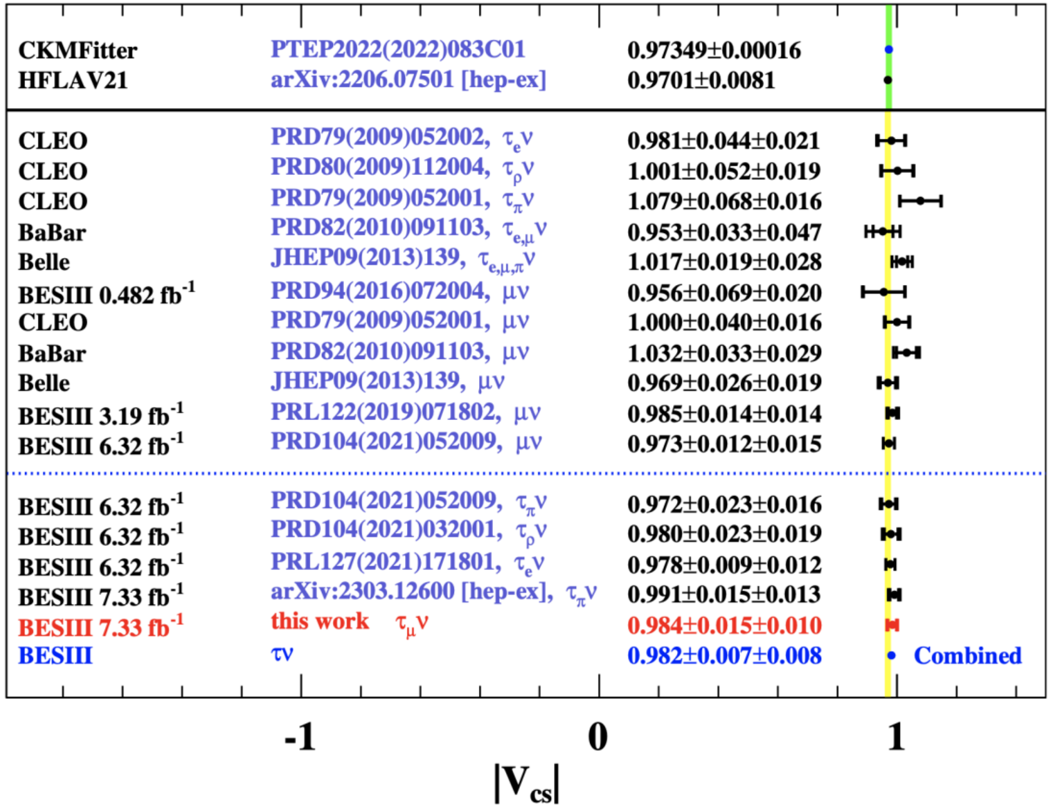
Leptonic decays: $D_s^+ \to \ell^+ \nu_\ell$

Lattice QCD

this work: 2303.12468(2023)

$$\Gamma(D_s^+ \to l^+\nu_l) = \frac{G_F^2 f_{D_s}^2}{8\pi} |V_{cs}|^2 m_l^2 m_{D_s} \left(1 - \frac{m_l^2}{m_{D_s}^2}\right)^2$$





1%

Leptonic decays: $D_s^{*+} \to e^+\nu_e$

arxiv: 2304.12159 (2023)

Motivated by theoretical prediction: EPJC 82, 1037 (2022); PRL 112, 212002 (2022)

- 7.33 fb^{-1} data @ 4.128-4.226 GeV

- **First measurement of BF and $f_{D_s^{*+}}$**

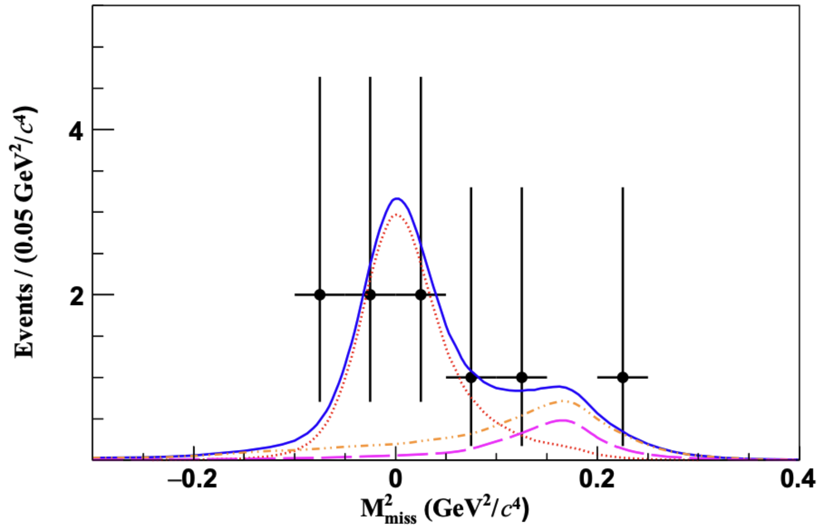
$$B(D_s^{*+} \to e^+\nu) = \left(2.1^{+1.2}_{-0.9\,stat} \pm 0.2_{syst}\right) \times 10^{-5}$$ **(2.9σ)**

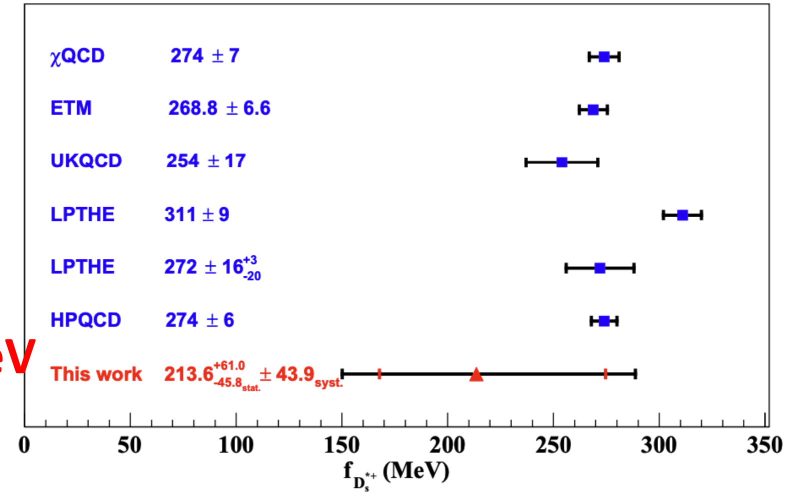
$$f_{D_s^{*+}} = (213.6^{+61.0}_{-45.8\,\mathrm{stat}} \pm 43.9_{\mathrm{syst}})$$ **MeV**

- **Combine** $\frac{f^+_{D_s^{*+}}}{f^+_{D_s^+}} = 1.12 \pm 0.01$ **from LQCD calculation:**

--> $\Gamma^{total}_{D_s^{*+}} = (121.9^{+69.6}_{-52.2} \pm 11.8)$ **eV agree with LQCD prediction** (70 ± 28) **eV**

--> **Indirectly constrains the upper limit on** $\Gamma^{total}_{D_s^{*+}}$ **from MeV to KeV level.**

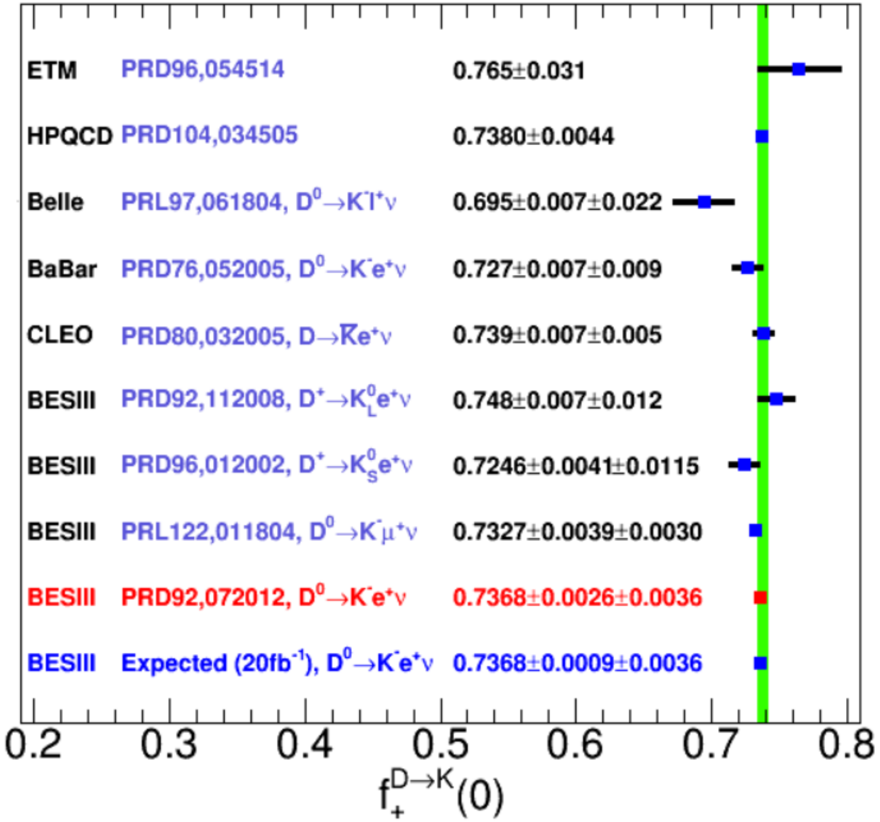




Semileptonic Decays

Lattice QCD

$$\Gamma(D_{(s)} \to P(S)\ell^+\nu_\ell)/dq^2 \propto |V_{cd(s)}|^2 |f_+(q^2)|^2$$



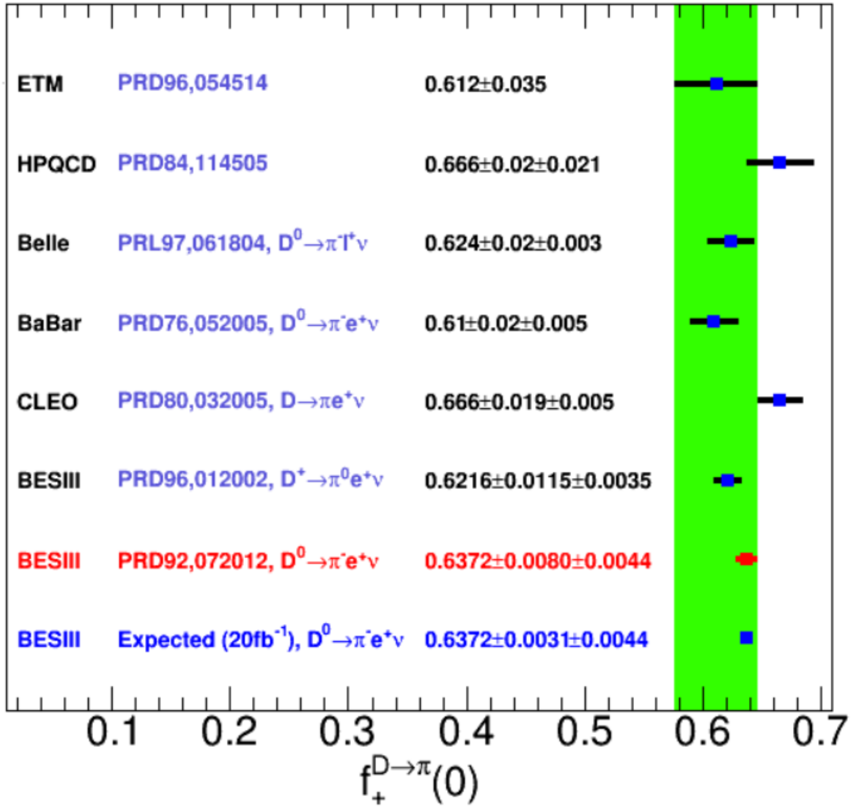
2010 (2.4%)

⇩

2021 (0.6%)

0.7%

<0.5%



>4%

1.4%

<1%

Experimental precision is comparable to the latest LQCD result

The measurements of the Cabibbo-suppressed decays are still dominated by statistical uncertainties

Semileptonic Decays: $D_s^+ \to K^+K^-\mu^+\nu_\mu$

BESIII

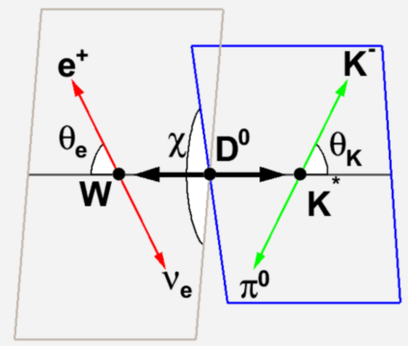
arxiv: 2307.03024 (2023)

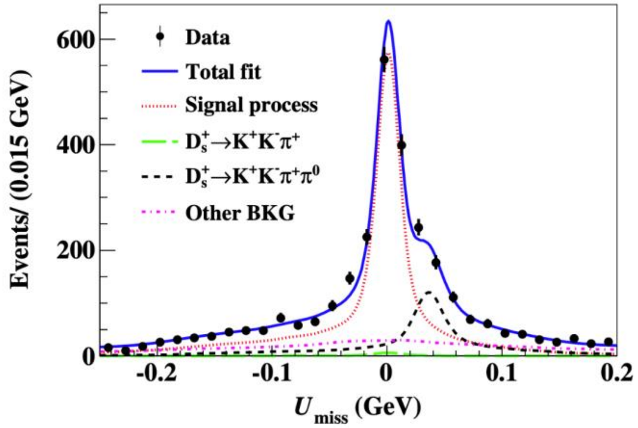
- **Partial wave analysis (PWA)**
- 7.33 fb^{-1} data @ **4.128-4.226 GeV**
- $N_{sig} = 1725 \pm 68$ for BF measurement

$\mathcal{B}(D_s^+ \to \phi\mu^+\nu_\mu) = (2.25 \pm 0.09 \pm 0.07) \times 10^{-2}$

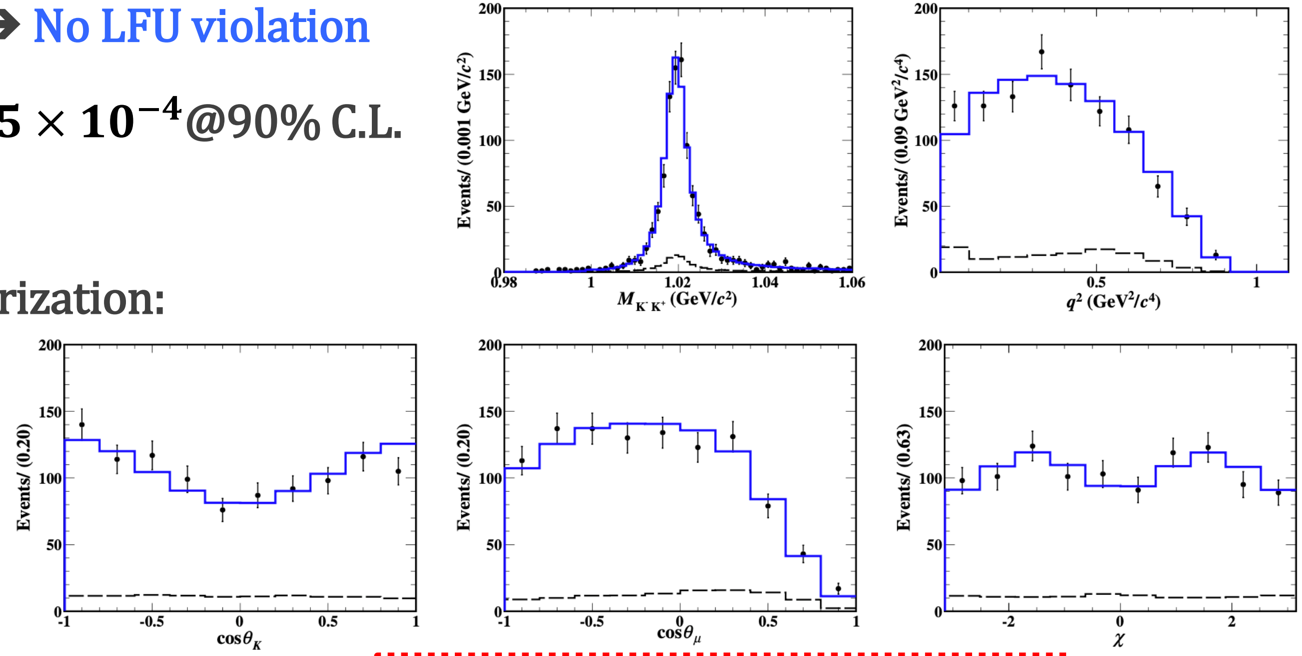
$\mathcal{B}(D_s^+ \to \phi\mu^+\nu_\mu)/\mathcal{B}(D_s^+ \to \phi e^+\nu_e) = 0.94 \pm 0.08$ ➔ No LFU violation

$\mathcal{B}(D_s^+ \to f_0(980)\mu^+\nu_\mu) \cdot \mathcal{B}(f_0(980) \to K^+K^-) < 5.45 \times 10^{-4}$@90% C.L. $\sim 2.2\sigma$





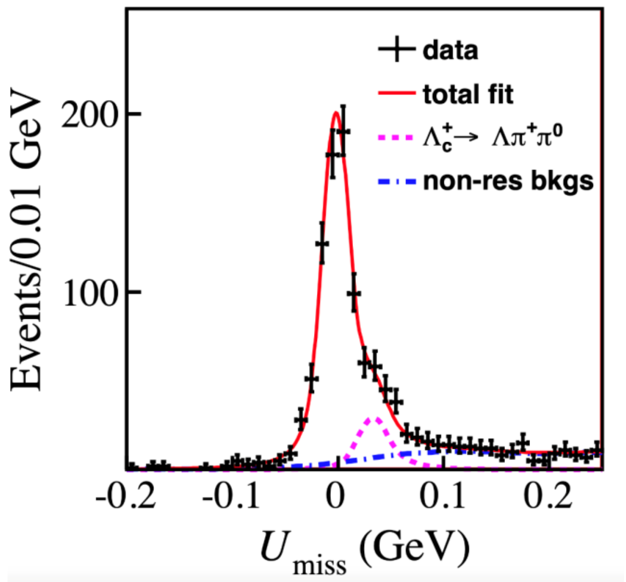
- First FF measurement based on single pole parameterization:
  - PWA is performed -> ϕ dominate
  - μ mass is considered in the formula



$|U_{miss}| < 0.02$ GeV
939 signal events with (9.8±0.7)% Bkg

Semileptonic Decays: $\Lambda_c^+ \to \Lambda\mu^+\nu_\mu$

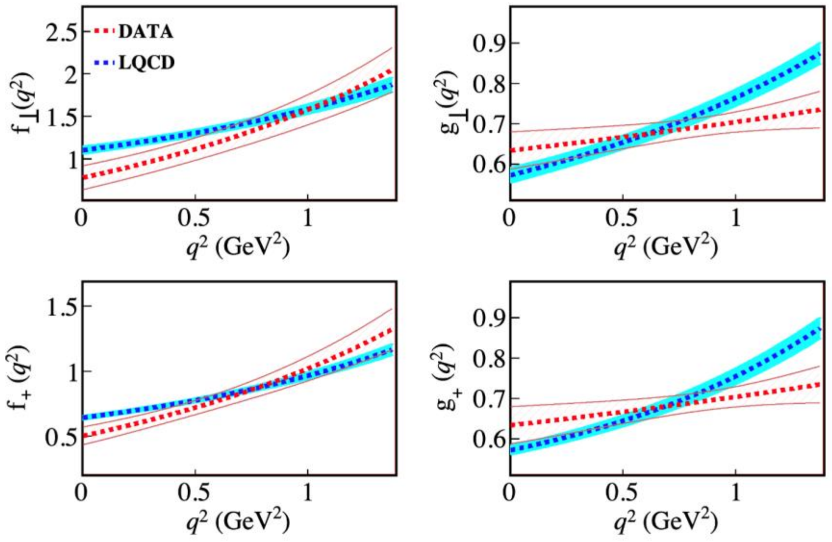
BESIII **Arxiv:2306.02624 (2023)**



- $4.5\ fb^{-1}$ data @ 4.600 - 4.699 GeV ➔ $N_{sig} = 752 \pm 31$
- **Updated BF and first FF measurement:**

  $\mathcal{B}(\Lambda_c^+ \to \Lambda\mu^+\nu_\mu) = (3.48 \pm 0.14 \pm 0.10)\%$ (~5%)

- $|V_{cs}| = 0.937 \pm 0.014_{\mathcal{B}} \pm 0.024_{\rm LQCD} \pm 0.007_{\tau_{\Lambda_c}}$
- $\mathcal{R}_{\mu/e} = 0.98 \pm 0.05 \pm 0.03$ **vs** SM: 0.97 --> **No LFUV**

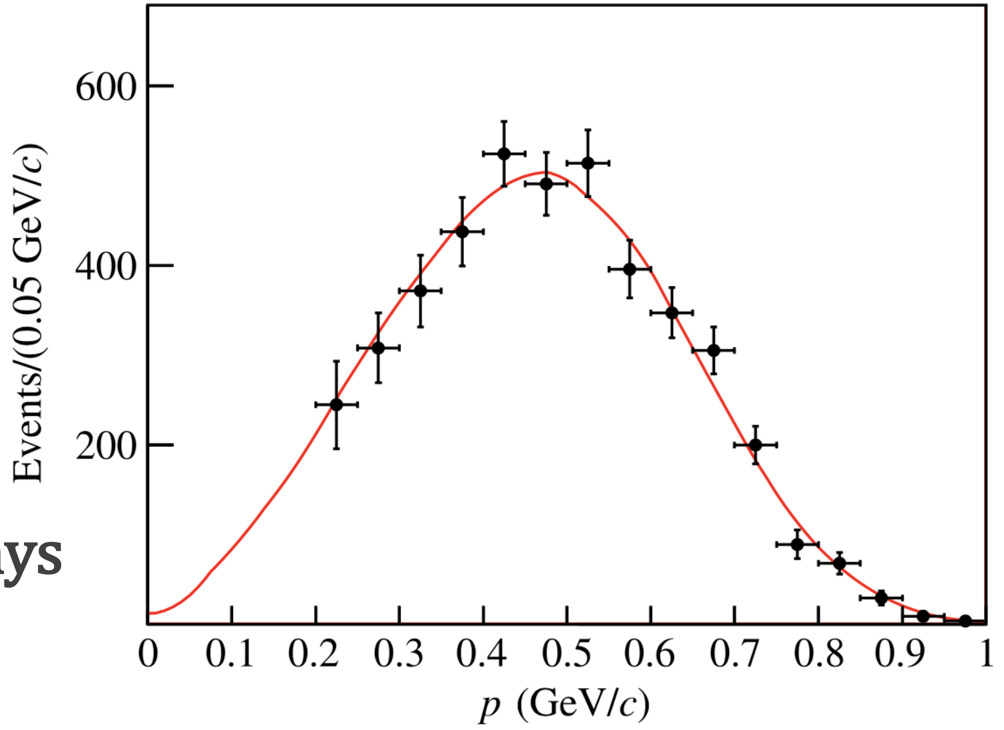


Inclusive semileptonic decays: $\Lambda_c^+ \to X e^+ \nu_e$

PRD. 107, 052005 (2023)

- **4.5** fb^{-1} **data @ 4.600-4.699 GeV** ➔ $N_{\mathrm{obs}} = 3706 \pm 71$
- $\mathcal{B}(\Lambda_c^+ \to X e^+ \nu_e) = (4.06 \pm 0.10 \pm 0.09)\%$ (~ 3%)

  ➔ Unknown decays: ~0.5%
- $\Gamma(\Lambda_c^+ \to X e^+ \nu_e)/\bar{\Gamma}(D \to X e^+ \nu_e)$ = **1.28 ± 0.05**
- Theoretical interest: distributions for inclusive decay rates relevant for HQE treatment of Semileptonic decays



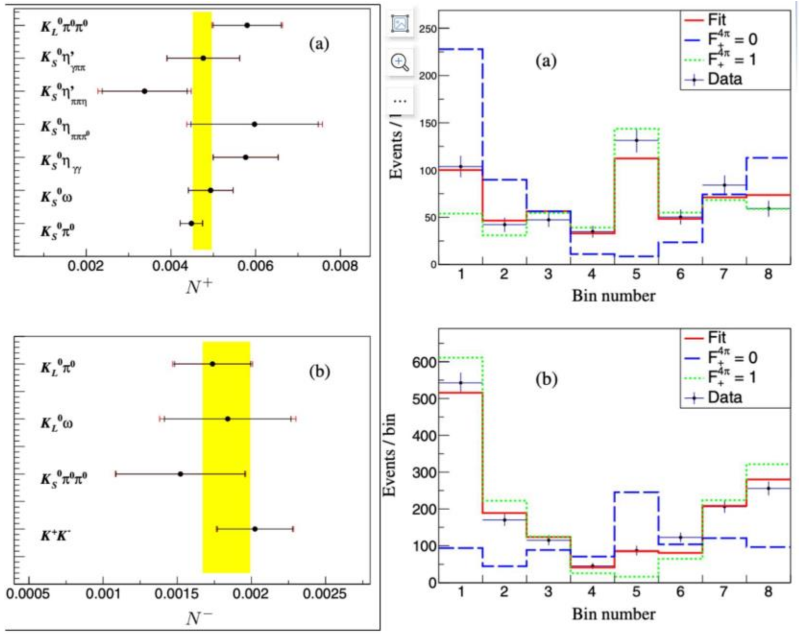
Phys. Lett. B 843, 137993 (2023)

- $\mathcal{B}(\Lambda_c^+ \to \Lambda \pi^+ \pi^- e^+ \nu_e) < 3.9 \times 10^{-4}$ **@90%C.L.**
- $\mathcal{B}(\Lambda_c^+ \to p K_S^0 \pi^- e^+ \nu_e) < 3.3 \times 10^{-4}$ **@90%C.L.**

Hadronic decays: CP-even fraction measurement

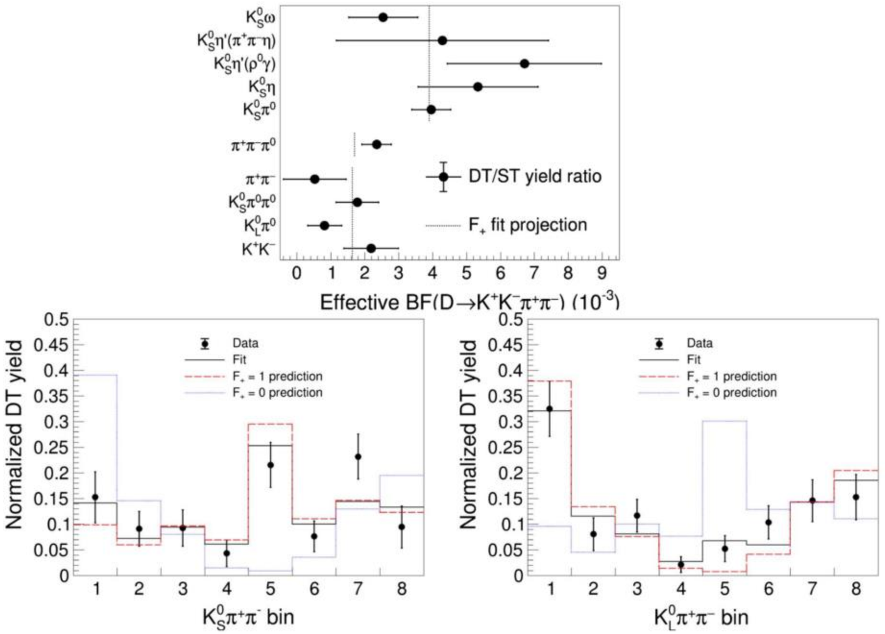
Quantum correlated $D^0\bar{D}^0 \Rightarrow$ CP-even fraction measurement

PRD 106 092004(2022)



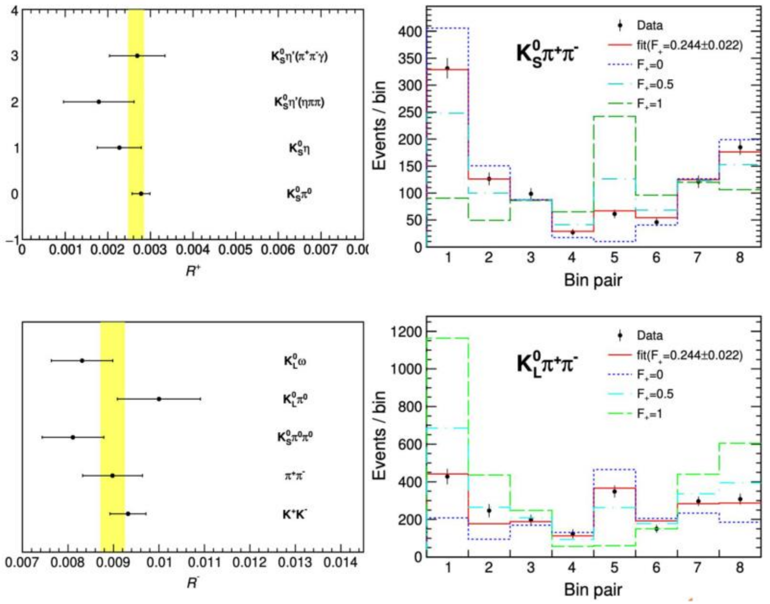
$$D^0 \to \pi^+\pi^-\pi^+\pi^-$$
$$F_+ = 0.735 \pm 0.015 \pm 0.005$$

PRD 107 032009(2023)



$$D^0 \to K^+K^-\pi^+\pi^-$$
$$F_+ = 0.730 \pm 0.037 \pm 0.021$$

arxiv:2305.03975



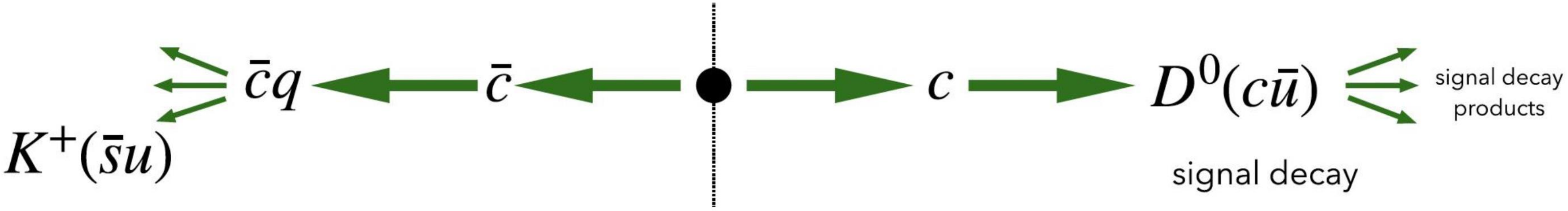
$$D^0 \to K_S^0\pi^-\pi^+\pi^0$$
$$F_+ = 0.235 \pm 0.010 \pm 0.002$$

Novel method for ID production flavor of D^0

- CPV/mixing measurement → flavor tagging
- Standard approach: exclusive reconstruction of strong decay $D^{*+} \to D^0\pi^+$
- New approach: exploit correlation between signal flavor and charge of particles reconstructed in the rest using BDT

# of tagged signal D^0: (125600 ± 350) + (127080 ± 280)

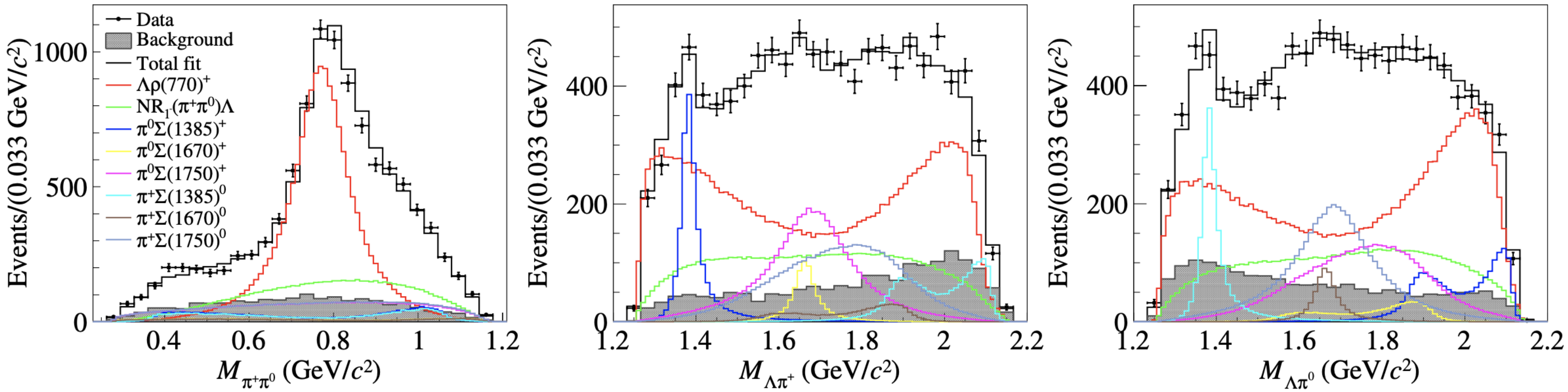
doubling the sample size!



PRD 107,112010(2023)

Amplitude Analysis: $\Lambda_c^+ \to \Lambda\pi^+\pi^0$

JHEP12(2022)033 BESIII



Use new-developed Tensor Flow based package TF-PWA*
(*BESIII Preliminary: https://github.com/jiangyi15/tf-pwa)

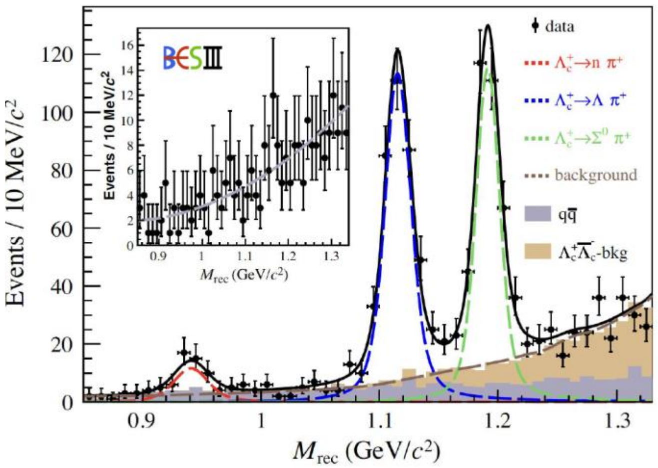
	Theoretical calculation		This work	PDG
$10^2 \times \mathcal{B}(\Lambda_c^+ \to \Lambda\rho(770)^+)$	4.81 ± 0.58 [13]	4.0 [14, 15]	4.06 ± 0.52	< 6
$10^3 \times \mathcal{B}(\Lambda_c^+ \to \Sigma(1385)^+\pi^0)$	2.8 ± 0.4 [16]	2.2 ± 0.4 [17]	5.86 ± 0.80	—
$10^3 \times \mathcal{B}(\Lambda_c^+ \to \Sigma(1385)^0\pi^+)$	2.8 ± 0.4 [16]	2.2 ± 0.4 [17]	6.47 ± 0.96	—
$\alpha_{\Lambda\rho(770)^+}$	-0.27 ± 0.04 [13]	-0.32 [14, 15]	-0.763 ± 0.066	—
$\alpha_{\Sigma(1385)^+\pi^0}$	$-0.91^{+0.45}_{-0.10}$ [17]		-0.917 ± 0.083	—
$\alpha_{\Sigma(1385)^0\pi^+}$	$-0.91^{+0.45}_{-0.10}$ [17]		-0.79 ± 0.11	—

Ref. [13]: PRD 101 (2020) 053002
Ref. [14,15]: PRD 46 (1992) 1042; 55 (1997) 1697
Ref. [16]: EPJC 80 (2020) 1067
Ref. [17]: PRD 99 (2019) 114022

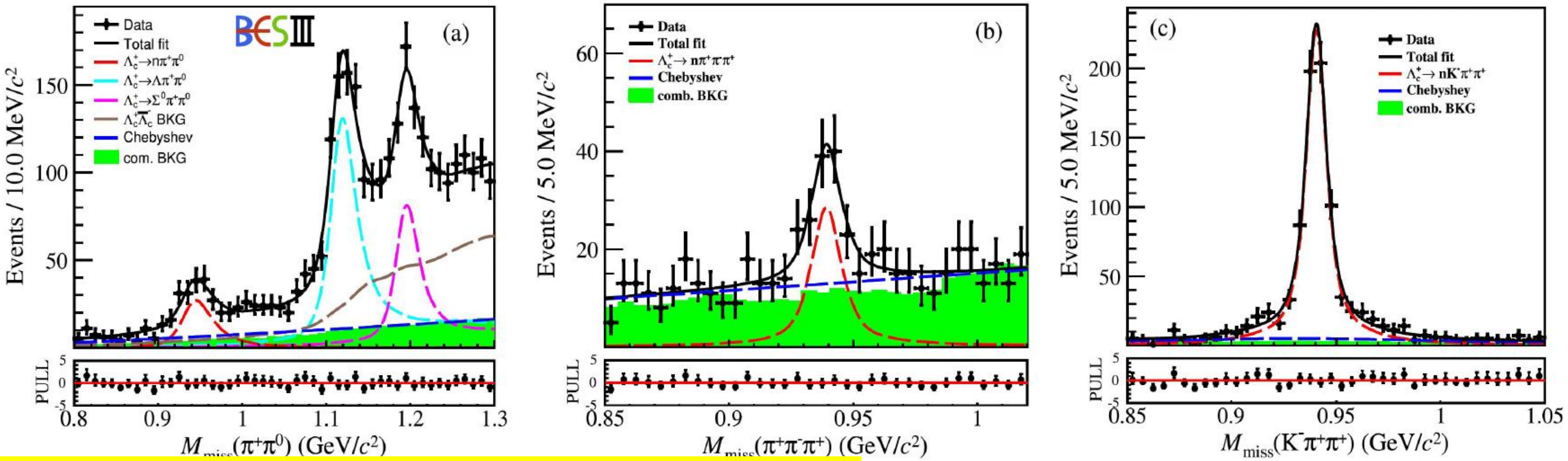
The first measurement of the decay asymmetry parameters for the relevant resonance

Charmed Baryon decays with n in final states

PRL 128,142001(2022)



CPC 47,023001(2023)



First measurement

Use recoil mass to access neutron

$\mathcal{B}(\Lambda_c^+ \to n\pi^+)$
$=(6.6 \pm 1.2 \pm 0.4) \times 10^{-4}$

$\mathcal{B}(\Lambda_c^+ \to \Lambda\pi^+)$
$=(1.31 \pm 0.08 \pm 0.05) \times 10^{-2}$

$\mathcal{B}(\Lambda_c^+ \to \Sigma^0\pi^+)$
$=(1.22 \pm 0.08 \pm 0.07) \times 10^{-2}$

$\mathcal{B}(n\pi^+)/(p\pi^0) > 7.2$ at 90% C.L.

Signal decay		$\mathcal{B}$ (%)
$\Lambda_c^+ \to n\pi^+\pi^0$		$0.64 \pm 0.09 \pm 0.02$
$\Lambda_c^+ \to n\pi^+\pi^-\pi^+$	First Observation	$0.45 \pm 0.07 \pm 0.03$
$\Lambda_c^+ \to nK^-\pi^+\pi^+$		$1.90 \pm 0.08 \pm 0.09$

One order larger than $\mathcal{B}(n\pi^+)$
$\mathcal{B}(\Lambda_c^+ \to p\pi^-\pi^+)/\mathcal{B}(\Lambda_c^+ \to n\pi^0\pi^+) = 0.72 \pm 0.11$

Disagrees with most predictions of the phenomenological models

More charmed baryon decays

- Measurements of branching fractions of $\Lambda_c^+ \to \Sigma^+\eta$ and $\Lambda_c^+ \to \Sigma^+\eta'$ and asymmetry parameters of $\Lambda_c^+ \to \Sigma^+\pi^0$, $\Lambda_c^+ \to \Sigma^+\eta$ and $\Lambda_c^+ \to \Sigma^+\eta'$

  PRD 107, 032003 (2023)

- Search for CP violation and measurement of branching fractions and decay asymmetry parameters for $\Lambda_c^+ \to \Lambda h^+$ and $\Lambda_c^+ \to \Sigma^0 h^+ (h = K, \pi)$

  Science Bulletin 68 (2023) 583–592

- Measurement of branching fractions of $\Lambda_c^+ \to pK_S^0K_S^0$ and $\Lambda_c^+ \to pK_S^0\eta$ at Belle

  PRD 107, 032004 (2023)

- First Search for the weak radiative decays $\Lambda_c^+ \to \Sigma^+\gamma$ and $\Xi_c^0 \to \Xi^0\gamma$

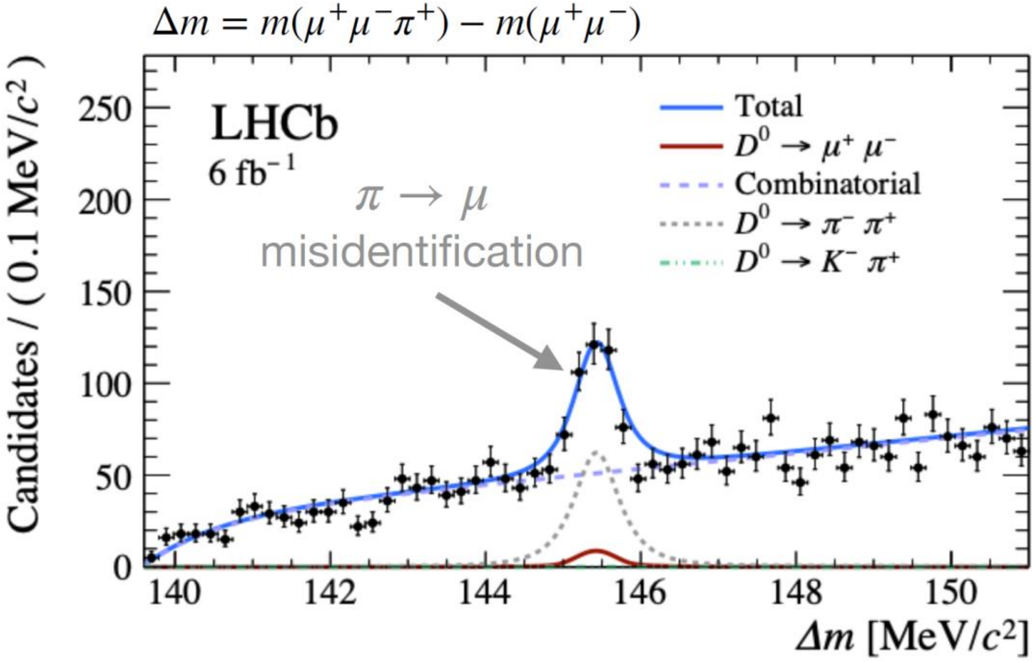
  PRD 107, 032001 (2023)

- Measurement of the branching fraction of $\Xi_c^0 \to \Lambda_c^+\pi^-$ at Belle

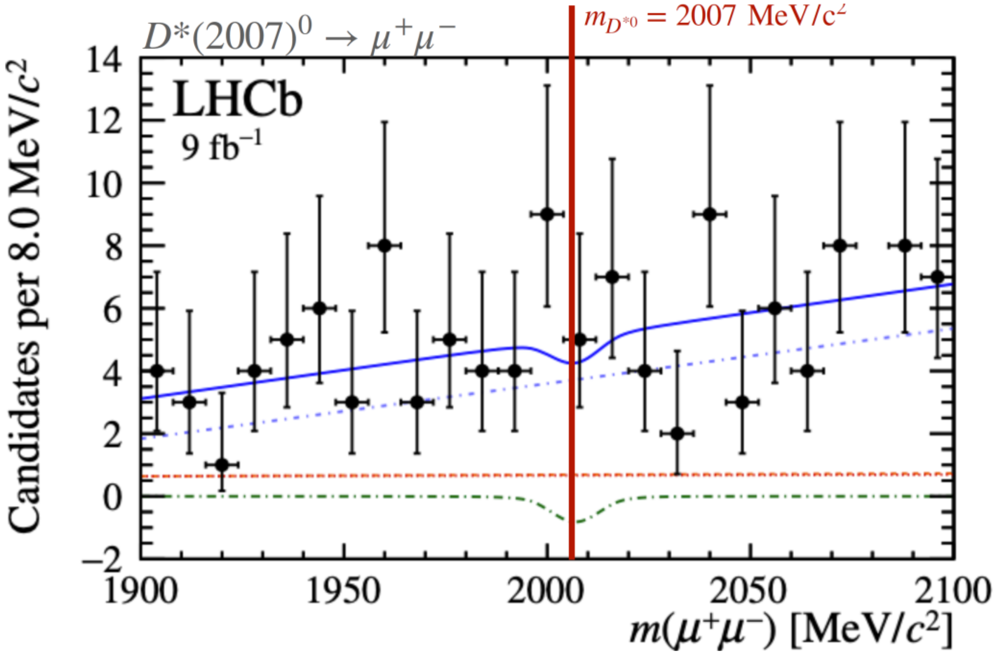
  PRD 107, 032005 (2023)

Rare decays: $D^{(*)0} \to \mu^+\mu^-$

arXiv:2212.11203 (2022)



arXiv:2304.01981 (2023)



- SM: short-distance: $\mathcal{O}(10^{-18})$
- SM: long-distance via γγ: $3 \times 10^{-13} - 2 \times 10^{-11}$

  G.Burdman et al, PRD 66(2002)014009,
  using limit $D^0 \to \gamma\gamma$ by Belle: PRD93 (2016) 051102
- No significant signal is observed
- Most stringent limit on leptonic charm decays:
  $\mathcal{B}(D^0 \to \mu^+\mu^-) \le 3.1 \times 10^{-9} (90\%CL)$

- First limit for $D^* \to \mu^+\mu^-$:

$$\mathcal{B}(D^*(2007)^0 \to \mu^+\mu^-) \le 2.6 \times 10^{-8} (90\%CL)$$

Super Tau-Charm Facility (STCF)

- E_{cm}=2-7GeV， L=0.5×10^{35} cm^{-2} s^{-1}
- Potential for upgrade to increase L and realize polarized beam
- Site area: 1 km^2

	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032-2042	2043-2046
Form collaboration																
Conception design CDR																
R&D (TDR)																
Construction																
Operation																
Upgrade																

Anhui provice and USTC have officially endorsed 420M RMB R&D project of STCF, and great progress is achieved; the site is preliminarily decided in Hefei, and geological exploration and engineering design is ongoing.

Will apply for the construction (~4.5B RMB) during the 15th five-year plan (2026-2030) from central government.

Summary & Prospect

- In the past year, many important results of charm decays were reported by BESIII, Belle, and LHCb.
- Non-perturbative QCD is the main challenge. The theoretical calculations are hard for the Hadronic charm decays.
  - Tools are improving.
  - Collaborations between theorists and experimentalists are crucial for accelerating research.
- The future of charm is promising. Lots of high quality data coming our way: LHCb, Belle II, BESIII(+upgrade)
- A dedicated charm facility, STCF, has been proposed in China. The R&D project with 420M RMB budget has been officially supported by Anhui province and USTC.

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