WG7 summary

Mixing and CP violation in the D system

Patricia Magalhaes, Tara Nanut Petric, Stefan Schacht

Outline

20’ + 10’ talks

Direct CPV

Direct CPV	**69 - Direct CPV in D mesons decays at LHCb**	*Jolanta B a*	*Sala Palatino*	14:45 - 15:15	MESONS	Exp.
	70 - CPV in D meson decays at Belle and Belle II	*Michel Bertemes*	*Sala Palatino*	15:15 - 15:45		
	71 - Charm CP Violation	*Prof. Ulrich Nierste*	*Sala Palatino*	15:45 - 16:15		Theory
	72 - BSM and direct CPV	*Hector Gisbert Mullor*	*Sala Palatino*	16:15 - 16:45		
	73 - CPV in charmed baryons (theory)	*Fu-Sheng Yu*	*Aula Magna*	14:45 - 15:15	Baryons	
	74 - CPV in charmed baryons (experimental)	*Dr Artur Ukleja*	*Aula Magna*	15:15 - 15:45		Exp
	76 - Earth mover’s distance as a measure of CP violation	*Ahmed Youssef*	*Aula Magna*	15:45 - 16:15	MESONS	
Mixing, indirect CPV & strong phases	**77 - HQE, mixing and lifetimes**	*Alexander Lenz*	*Aula Magna*	17:20 - 17:50		Theory
	78 - HFLAV Charm CPV and oscillations	*Jolanta Brodzicka*	*Aula Magna*	17:50 - 18:20		Exp
	79 - Mixing and indirect CPV in charm decays at LHCb	*Federico Betti*	*Aula Magna*	18:20 - 18:50		
	80 - Measurements of CPV and phases in charm decays at BESIII	*Yang Gao*	*Aula Magna*	18:50 - 19:20		

J. Brodzicka

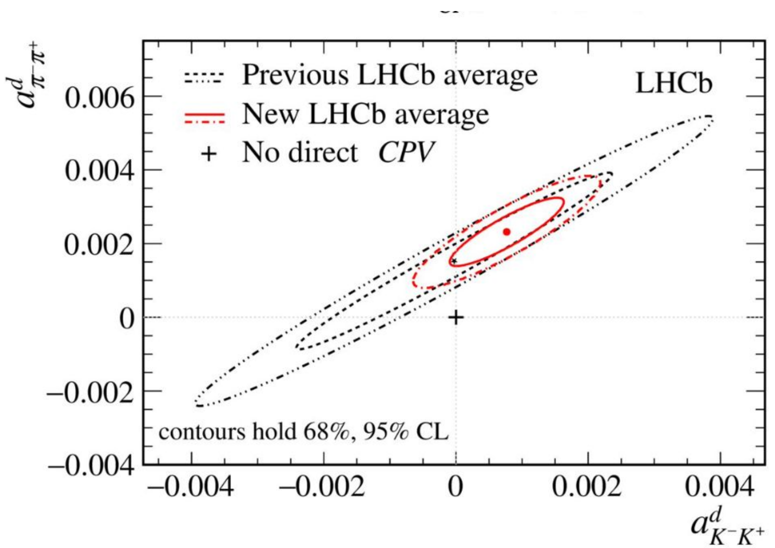
LHCb: CP asymmetry in $D^0 \rightarrow K^+K^-$ and $\pi^+\pi^-$

Measure A_{CP} in K^+K^-: first evidence of CPV in single channel ($\pi^+\pi^-$) when combining with ΔA_{CP}

Breaking U-spin symmetry!

$$a^{dir}_{K^+K^-} = (7.7 \pm 5.7) \times 10^{-4} \quad (1.4\sigma)$$

$$a^{dir}_{\pi^+\pi^-} = (23.2 \pm 6.1) \times 10^{-4} \quad (3.8\sigma)$$



PRL 131, 091802 (2023)

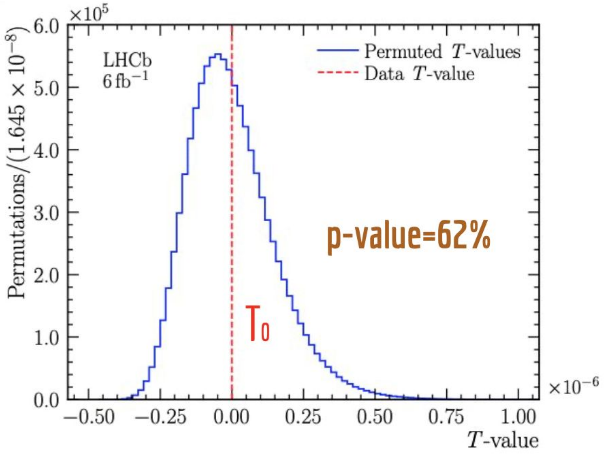
J. Brodzicka

LHCb: other results consistent with CP symmetry

- Search for CPV in $D_{(s)}^+ \to \eta^{(\prime)} \pi^+$ decays
- Search for CPV in $D_{(s)}^+ \to K^- K^+ K^+$ with Miranda technique
- Examining $D^0 \to \pi^+ \pi^- \pi^0$ and $D^0 \to K_S K \pi$ with Energy Test

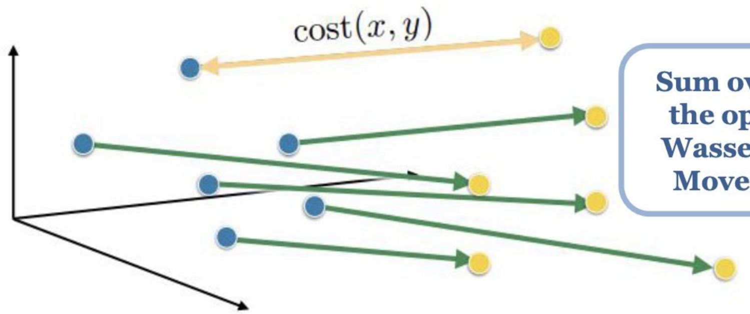
→ Binned / Unbinned — Discovery methods

Similar mechanism as $\pi^+\pi^-$



New method for CPV searches: Earth mover's distance

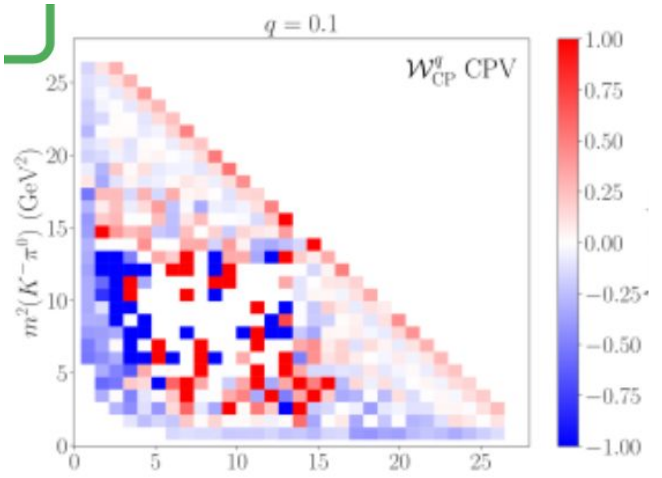
Another test statistics: aiming to match the energy test performance with added benefits in interpretability - pinpointing which part of the Dalitz plot the CPV originates from



Sum over the cost of the optimal path = Wasserstein (Earth Mover's) distance

EMD asymmetry:

$$\mathcal{W}^q_{\mathrm{CP}}(s_{12}, s_{13}) = \frac{\sum_{\bar{i}} \delta \bar{W}_q(\bar{i}) - \sum_i \delta W_q(i)}{\sum_{\bar{i}} \delta \bar{W}_q(\bar{i}) + \sum_i \delta W_q(i)}$$



For high statistics a modification can be applied to reduce computation cost: "sliced" EMD

M. Bertemes

Belle: all results consistent with CP symmetry

$A_{CP} \propto \sin(\phi)\sin(\delta)$

Measurement of BR and search for CPV in $D^0 \to K_S^0 K_S^0 \pi^+\pi^-$ decays

PRD 107, 052001 (2023)

Search for CPV in $D^+_{(s)} \to K^+ K^0_S h^+ h^-$ decays and observation of $D_s^+ \to K^+ K^- K^0_S \pi^+$

arXiv:2305.11405

First observation of decay D□⁺ → K⁺K⁻Ks⁰π⁺

$a_{CP}^{T-\mathrm{odd}} \propto \sin(\phi)\cos(\delta)$

Search for CPV using T-odd correlations in $D^+_{(s)} \to K^+K^-\pi^+\pi^0, K^+\pi^-\pi^+\pi^0$ and $D^+ \to K^-\pi^+\pi^+\pi^0$ decays

arXiv:2305.12806

$$a_{CP}^{T-\mathrm{odd}} = (0.34 \pm 0.87(\mathrm{stat.}) \pm 0.32(\mathrm{syst.}))\,\%$$

Measure also in subregions of phasespace:

- largest asymmetry found in $D_s^+ \to K^{*0}\rho^+$
- $a_{CP}^{T-\mathrm{odd}} = (6.2 \pm 3.0(\mathrm{stat}) \pm 0.4(\mathrm{syst}))\,\%$

Belle II: toward future measurements

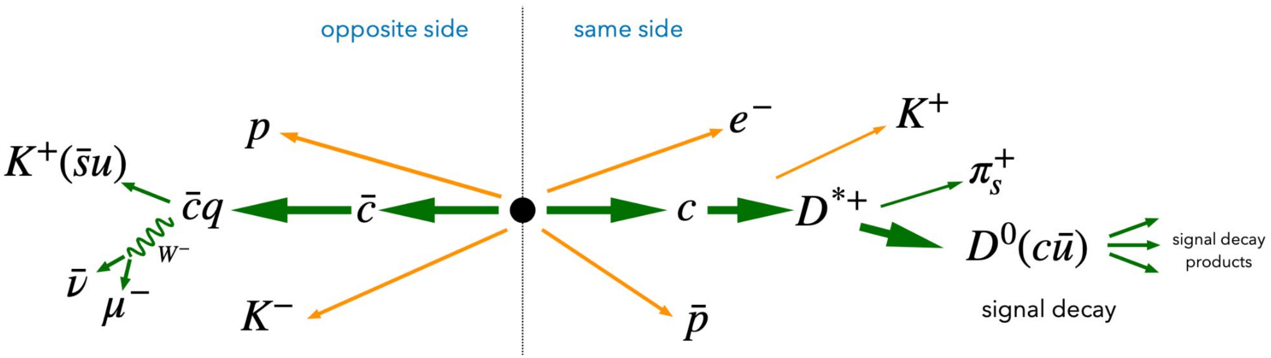
- excellent reconstruction of **final states with neutrals** e.g. $D^+ \to \pi^+\pi^0$, $D^0 \to \rho^0\gamma, \pi^0\pi^0, K_S^0K_S^0, K\pi\pi^0, \pi\pi\pi^0 \ldots$
- unique access to final states with invisible particles: e.g. decay into neutrinos

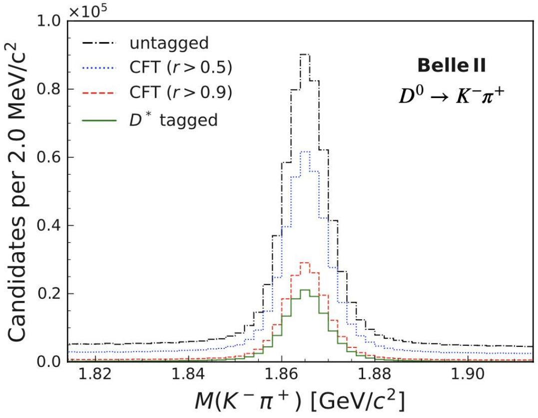
Some of these measurements are well under way already

Combine Belle + Belle II datasets

M. Bertemes

Belle II: new charm flavour tagger for D^0





- D* tag: loss in statistics (only ~25% of all charm quarks hadronize into D* at Belle (II))
- CFT: reconstruct particles most collinear with signal meson
- Doubles the signal wrt D* tag, but introduces more background (depending on channel)
- BDT-based decision based on kinematics and PID: predicts decision and dilution (*qr*)
- Future expansions possible

Direct CPV - theory

2022: $a_{CP}(D^0 \to K^+K^-)$

KCETA — Institut für Theoretische Teilchenphysik (KIT)

LHCb 2022: $a_{CP}(D^0 \to K^+K^-) = (7.7 \pm 5.7) \cdot 10^{-4}$.

Thus Δa_{CP} implies $a_{CP}(D^0 \to \pi^+\pi^-) = (23.1 \pm 6.1) \cdot 10^{-4}$.

- $a_{CP}(D^0 \to K^+K^-)$ complies with the calculation of Khodjamirian and Petrov.
- For approximate U-spin limit $a_{CP}(D^0 \to K^+K^-) \approx -a_{CP}(D^0 \to \pi^+\pi^-)$ to work, with future data $a_{CP}(D^0 \to K^+K^-)$ must flip sign.
- Will future data decrease $|\Delta a_{CP}|$ and will the 5σ discovery eventually go away?
- Or did LHCb discover new physics in 2019?

The challenge: low-energy QCD or genuine BSM physics?

Strategy: Use sum rules as a tool to probe for U-spin breaking beyond the SM.

$D^0, D^+_{(s)} \to$ two pseudoscalars

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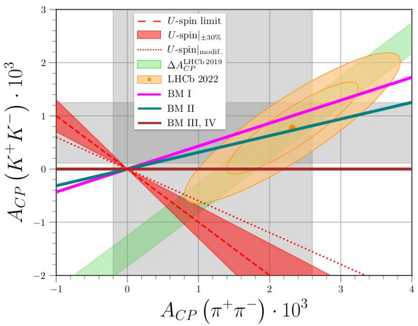
$\Delta U = 0$	$\Delta U = 1$
$a_{CP}(K^+K^-) + a_{CP}(\pi^+\pi^-) = 0$	$a_{CP}(K^+K^-) - a_{CP}(\pi^+\pi^-) = 0$
$a_{CP}(K^0\pi^+) + a_{CP}(\bar{K}^0K^+) = 0$	$a_{CP}(K^0\pi^+) - a_{CP}(\bar{K}^0K^+) = 0$
$a_{CP}(\eta\eta) + a_{CP}(\pi^0\pi^0) + 2a_{CP}(\eta\pi^0) = 0$	$a_{CP}(\eta\eta) - a_{CP}(\pi^0\pi^0) = 0$
$a_{CP}(\eta K^+) + a_{CP}(\eta\pi^+) + a_{CP}(\pi^0K^+) = 0$	$a_{CP}(\eta\eta) - a_{CP}(\eta\pi^0) = 0$
$3a_{CP}(\eta K^+) - 3a_{CP}(\pi^0K^+) + a_{CP}(K^0\pi^+) = 0$	two sum rules connecting four modes each

Direct CPV - BSM

What tells the new LHCb result? 2207.08539, 2210.16330



1. $a^d_{\pi^-\pi^+}$ is larger than $|\Delta A_{CP}|$. SM needs even more enhancement!

$$a^d_{\pi^-\pi^+}|_{SM} \sim 2\,\mathrm{Im}(\lambda_b/\lambda_s)\left(\frac{h}{t}\right) \sim 1.2\cdot 10^{-3}\left(\frac{h}{t}\right) \longrightarrow \boxed{\frac{h}{t}\sim 2}$$

2. Violation of U-spin, $a^d_{K^-K^+} + a^d_{\pi^-\pi^+} \neq 0$, at the level of $2.7\,\sigma$!

BSM CP & U-spin violation?

Prediction of a leptophobic, light Z' below O(20 GeV).

Large U-spin breaking can be explained in Z' models. Smoking gun predictions for BSM physics.

Anomaly-free $U(1)'$ models 2210.16330

$$2\langle\mathcal{F}_Q\rangle - \langle\mathcal{F}_u\rangle - \langle\mathcal{F}_d\rangle = 0\,,$$
$$3\langle\mathcal{F}_Q\rangle + \langle\mathcal{F}_L\rangle = 0\,,$$
$$\langle\mathcal{F}_Q\rangle + 3\langle\mathcal{F}_L\rangle - 8\langle\mathcal{F}_u\rangle - 2\langle\mathcal{F}_d\rangle - 6\langle\mathcal{F}_e\rangle = 0\,,$$
$$6\langle\mathcal{F}_Q\rangle + 2\langle\mathcal{F}_L\rangle - 3\langle\mathcal{F}_u\rangle - 3\langle\mathcal{F}_d\rangle - \langle\mathcal{F}_e\rangle - \langle\mathcal{F}_\nu\rangle = 0\,,$$
$$\langle\mathcal{F}_Q^2\rangle - \langle\mathcal{F}_L^2\rangle - 2\langle\mathcal{F}_u^2\rangle + \langle\mathcal{F}_d^2\rangle + \langle\mathcal{F}_e^2\rangle = 0\,,$$
$$6\langle\mathcal{F}_Q^3\rangle + 2\langle\mathcal{F}_L^3\rangle - 3\langle\mathcal{F}_u^3\rangle - 3\langle\mathcal{F}_d^3\rangle - \langle\mathcal{F}_e^3\rangle - \langle\mathcal{F}_\nu^3\rangle = 0\,.$$

$$\mathcal{F}_X = \mathrm{diag}(F_{X_1}, F_{X_2}, F_{X_3})$$
$$\langle\mathcal{F}_X\rangle = \mathrm{Tr}(\mathcal{F}_X)$$

Model	F_{Q_i}			F_{u_i}			F_{d_i}			F_{L_i}			F_{e_i}			F_{ν_i}		
BM I	0	0	0	9	-16	7	20	-11	-9	15	-6	-9	-16	0	16	6	12	-18
BM II	0	0	0	-19	9	10	20	-8	-12	4	1	-5	15	2	-17	8	2	-10
BM III	0	0	0	0	-1	0	1	0	0	0	0	0	0	0	1	0	0	-1
BM IV	0	0	0	$-\frac{985}{1393}$	$\frac{985}{1393}$	0	1	0	-1	0	0	0	$\frac{1}{1393}$	0	$-\frac{1}{1393}$	F_ν	$-F_\nu$	0

- **All these BMs survive the previous constraints!**
- **BMs feature U-spin and IB with signals in $\pi^+\pi^0$, $\pi^0\pi^0$:**

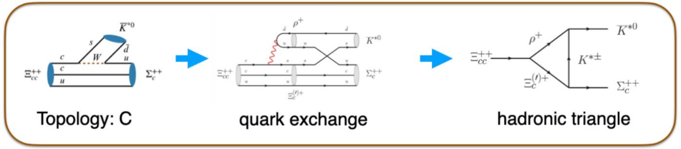
$$A_{CP}(\pi^0\pi^0) \simeq A_{CP}(\pi^+\pi^0) \simeq \left(1 - \frac{F_{u_1}}{F_{d_1}}\right)|\Delta A_{CP}| \simeq (1-2)\,10^{-3}$$

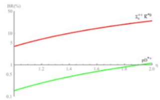
F.-S. Yu

Direct CPV baryons - theory

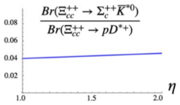
Rescattering mechanism

- Rescattering mechanism have been successfully used to predict the discovery channel of $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ [FSY, Jiang, Li, Lu, Wang, Zhao, '17]





- Theoretical uncertainty is under control in the **ratio** of branching fractions of different processes



1703.09086
2102.00961

- It deserves to develop the rescattering mechanism to study CPV of charmed baryons

Complementary observables with different dependence on the strong phase.

Many additional opportunities with baryons.

Models of underlying rescattering mechanism can be tested with future data.

Important guidance for experiment.

CPV induced by T-odd and T-even

$$a_{CP}^{\text{T-odd}} \propto \sum_{m,n} Im(A_m^* A_n - \bar{A}_m^* \bar{A}_n) \propto \cos \delta_s \sin \phi_w$$

$$a_{CP}^{\text{T-even}} \propto \sum_{m,n} Re(A_m^* A_n - \bar{A}_m^* \bar{A}_n) \propto \sin \delta_s \sin \phi_w$$

- Example: $\Lambda_c^+ \to \Lambda^0 K^+$, Lee-Yang decay-asymmetry parameter

T-even: $\vec{s}_i \cdot \vec{p}$ $\quad \alpha \propto Re[S^* P]$ $\quad a_{CP}^{\alpha} = \frac{\alpha + \bar{\alpha}}{\alpha - \bar{\alpha}} \propto \sin \delta$

T-odd: $(\vec{s}_i \times \vec{s}_f) \cdot \vec{p}$ $\quad \beta \propto Im[S^* P]$ $\quad a_{CP}^{\beta} = \frac{\beta + \bar{\beta}}{\beta - \bar{\beta}} \propto \cos \delta$

complimentary

Direct CPV baryons - theory

Charmed baryon decays

- Charmed baryon decays are the next opportunity and challenge of charm physics
- CP asymmetry sum rules based on SU(3) flavor symmetry are firstly obtained [Grossman and Schacht, PRD (2019)][Di Wang, EPJC (2019)]

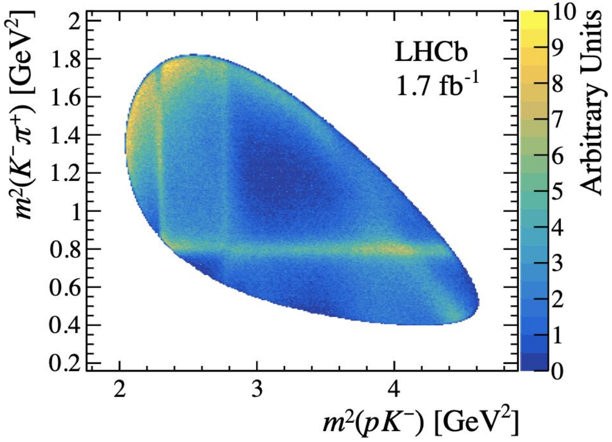
$$A_{CP}(\Lambda_c^+ \to pK^-K^+) + A_{CP}(\Xi_c^+ \to \Sigma^+\pi^-\pi^+) = 0,$$

$$A_{CP}(\Lambda_c^+ \to \Sigma^+\pi^-K^+) + A_{CP}(\Xi_c^+ \to pK^-\pi^+) = 0,$$

$$A_{CP}(\Lambda_c^+ \to p\pi^-\pi^+) + A_{CP}(\Xi_c^+ \to \Sigma^+K^-K^+) = 0.$$

- **No any numerical prediction on CPV of charm-baryon decays**

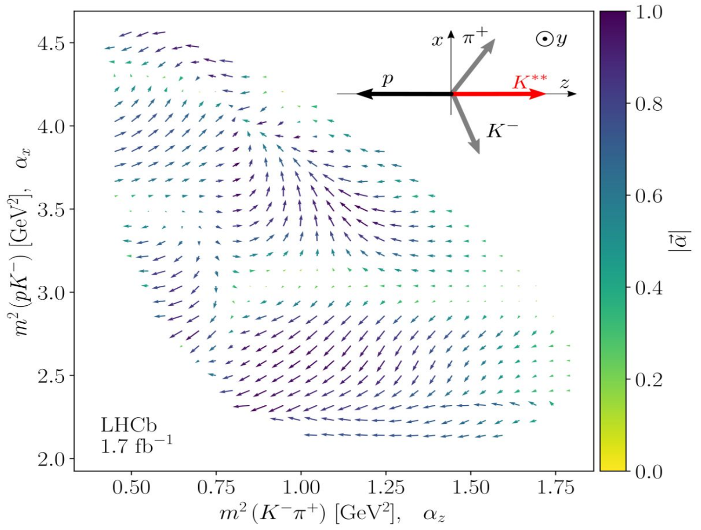
Direct CPV baryons - experimental



LHCb: amplitude analysis performed for $\Lambda_c^+ \rightarrow pK^-\pi^+$.

Input can be used for model-independent CPV searches.

LHCb-PAPER-2022-044, JHEP 2023(2023) 228



- Λ_c polarization of O(65%) found.
- Can be used to probe b→c transitions in semileptonic Λ_b decays.

Charm Mixing and Lifetimes - Theory

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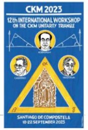
Cancellations



The charm system is theoretically more difficult than the b system since

$$\alpha_s(m_c) \approx 0.33 \qquad \text{and} \quad \frac{\Lambda_{QCD}}{m_c} \approx 3\frac{\Lambda_{QCD}}{m_b}$$

Nevertheless the **Heavy Quark Expansion** might still converge

But things will become very ugly, if in addition cancellations arising

A. No cancellations, e.g. $\Gamma(D^0)$
B. Strong cancellations, e.g. $\Gamma(D^+)$
C. Crazy cancellations, e.g. D-mixing

Is the charm quark heavy enough for the heavy quark expansion?

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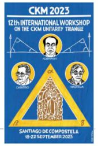
Theory for Charm

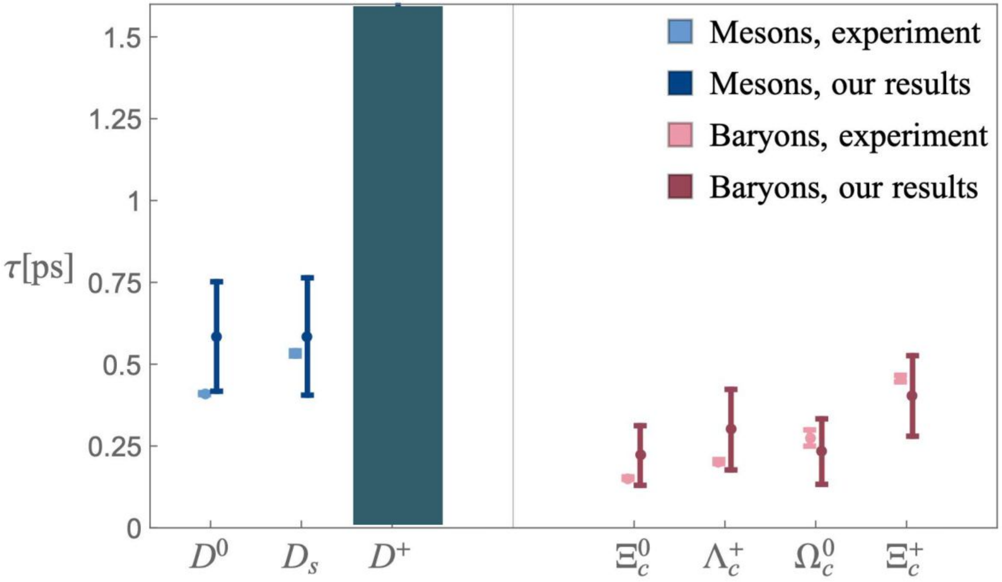


Theory for Charm Observable ≠ Theory for Charm Observable

- No cancellations, e.g. Lifetime of D^0 can be predicted, $1/m_c$ **works**
- Cancellations, e.g. Lifetime of D^+ lies in the right ball park, $1/m_c$ **might work**
- Crazy cancellations, e.g. Mixing of D^0 HQE might overlap with exp., $1/m_c$ **not excluded**
- Hadronic decays: **we have to first understand the B-system!**

More progress on the way.

Lifetime hierarchy



Lifetimes of singly charmed hadrons #17

James Gratrex (Boskovic Inst., Zagreb), Blaženka Melić (Boskovic Inst., Zagreb), Ivan Nišandžić (Boskovic Inst., Zagreb)

(Apr 25, 2022)

Published in: *JHEP* 07 (2022) 058, *JHEP* 07 (2022) 058 • e-Print: 2204.11935 [hep-ph]

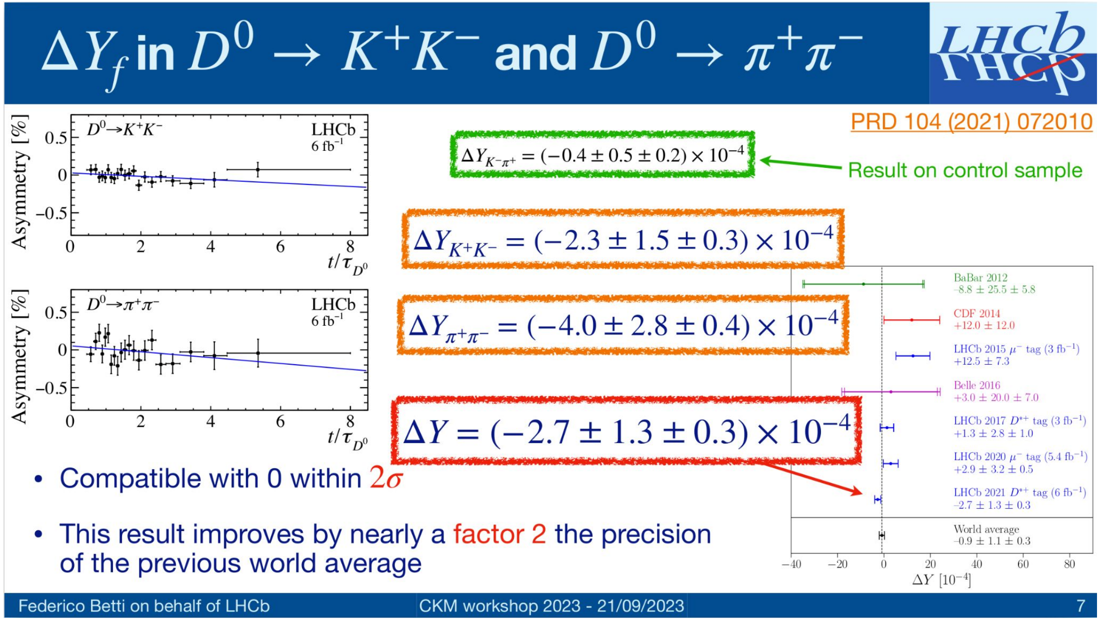
(Far) future: can theory/lattice predict the hierarchy?

F. Betti

Charm Mixing and time-dep. CPV - experimental

- ΔY_f in $D^0 \to h^+h^-$
- $y_{CP}^{f} - y_{CP}^{K\pi}$
- $D^0 \to K_s^0 \pi^+ \pi^-$

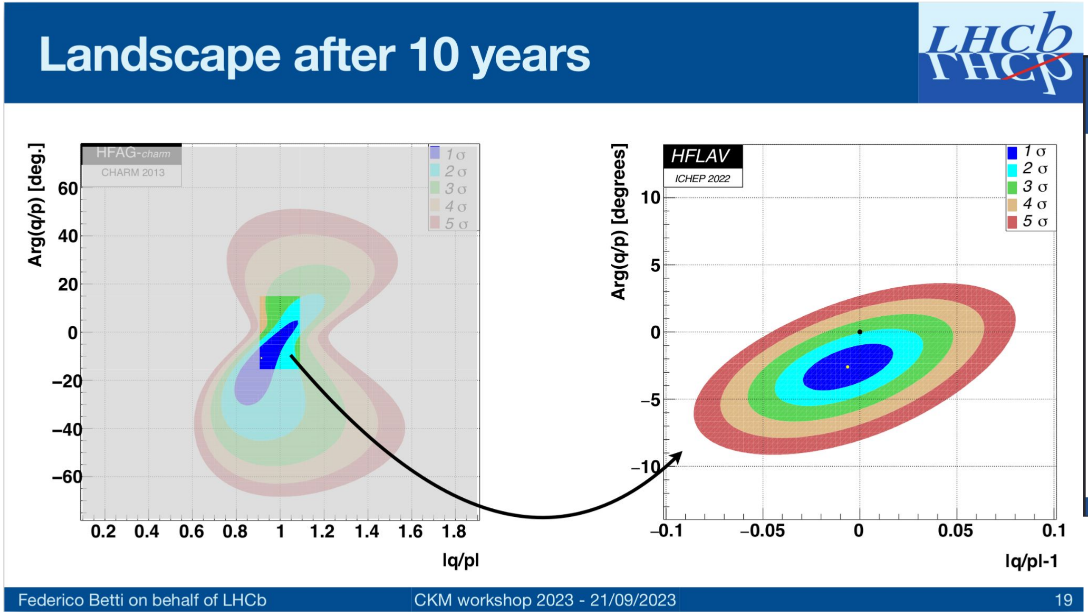
$$A_{CP}(D^0 \to f, t) = a_f^d(D^0 \to f) + \Delta Y_f \frac{t}{\tau_{D^0}}$$

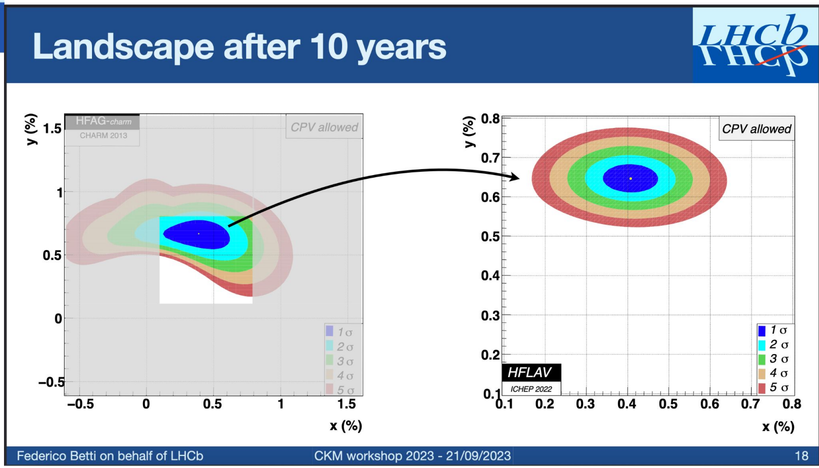


F. Betti

Charm Mixing and time-dep. CPV - experimental

We came a long way :





HFLAV Charm CPV and mixing

Recent experimental additions

- A_Γ with $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$, LHCb Run2, (π-tag)

  PRD 104, 072010 (2021)
- x_{CP}, y_{CP}, Δx, Δy in $D^0 \to K_S\pi^+\pi^-$, LHCb Run2, (π-tag) + (μ-tag)

  PRL 127, 111801 (2021) PRD108, 052005 (2023)
- y_{CP}-$y_{CP}(K\pi)$ with $D^0 \to K^+K^-$, $D^0 \to \pi^+\pi^-$, Run2, [π-tag]

  PRD 105, 092013 (2022)
- $A_{CP}(D^0 \to K^+K^-)$, $A_{CP}(D^0 \to \pi^+\pi^-)$, LHCb Run2, ($\pi$-tag)

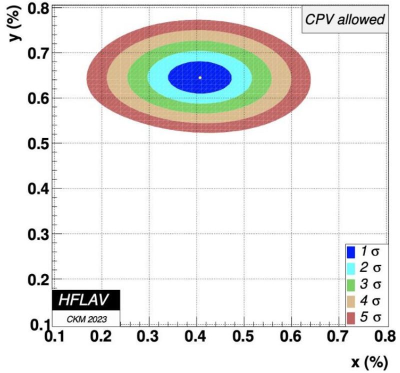
  PRL 131, 091802 (2023)
- $A_{CP}[K\pi]$ [$\to \delta_{K\pi}$], BESIII

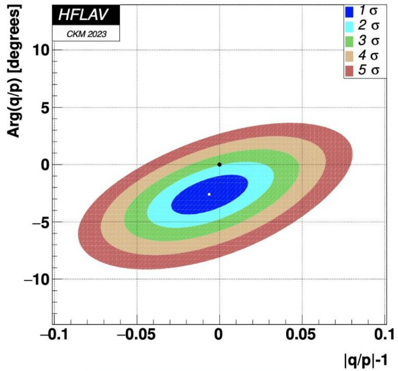
  Eur. Phys. J. C 82, 1009 (2022)

Included in global fit for CKM2023

[Thanks to Alan Schwartz]

Mixing fit with all CPV allowed





$$x = (0.407 \pm 0.044)\%$$
$$y = (0.645^{+0.024}_{-0.023})\ \%$$

$$\phi = (-2.6^{+1.1}_{-1.2})^\circ$$
$$|q/p| = 0.994^{+0.016}_{-0.015}$$

- Mixing well established, no indirect CPV, but ϕ non-zero at 2.2σ

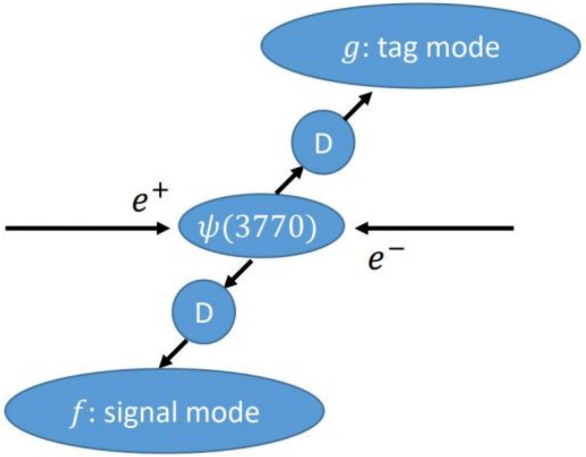
- Hence ΔA_{CP} *equivalent* for baryons would be:

$$\Delta\Delta A_{CP} \equiv \left(A_{CP}(\Lambda_c^+ \to pK^+K^-) - A_{CP}(\Lambda_c^+ \to p\pi^+\pi^-)\right) - \left(A_{CP}(\Xi_c^+ \to \Sigma^+K^+K^-) - A_{CP}(\Xi_c^+ \to \Sigma^+\pi^+\pi^-)\right)$$

- $\Delta\Delta A_{CP}$=0 in U-spin limit

CPV and strong phases at BESIII

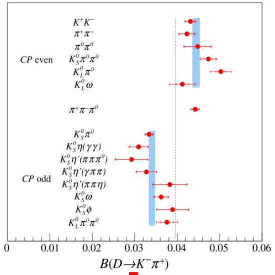
- BESIII can uniquely explore the quantum coherence of the initial $D^0\bar{D}^0$ state produced at $\psi(3770)$ to provide constraints on the mixing and CPV parameters.



Strong phase measurements

Improved measurement of the strong-phase difference $\delta_D^{K\pi}$ in quantum-correlated $D^0\bar{D}^0$ decays.

Eur. Phys. J. C (2022) 82:1009



- Pure CP tag channels: $\mathcal{A}_{K\pi} \equiv \frac{\mathcal{B}(D_- \to K^-\pi^+) - \mathcal{B}(D_+ \to K^-\pi^+)}{\mathcal{B}(D_- \to K^-\pi^+) + \mathcal{B}(D_+ \to K^-\pi^+)}$

  Which to $\mathcal{O}(x, y, (r_D^{K\pi})^2)$ has the following relationship to the physics parameters: $\mathcal{A}_{K\pi} = \frac{-2r_D^{K\pi}\cos\delta_D^{K\pi} + y}{1 + (r_D^{K\pi})^2}$.

- Similarly, CP Mixing tag channels:

$$\mathcal{A}_{K\pi}^{\pi\pi\pi^0} \equiv \frac{\mathcal{B}(D_X \to K^-\pi^+) - \mathcal{B}(D_+ \to K^-\pi^+)}{\mathcal{B}(D_X \to K^-\pi^+) + \mathcal{B}(D_+ \to K^-\pi^+)}, \Rightarrow \mathcal{A}_{K\pi}^{\pi\pi\pi^0} = \frac{(-2r_D^{K\pi}\cos\delta_D^{K\pi} + y)\, F_+^{\pi\pi\pi^0}}{1 + (r_D^{K\pi})^2 + (1 - F_+^{\pi\pi\pi^0})\,(2r_D^{K\pi}\cos\delta_D^{K\pi} + y)}.$$

- $K_{S,L}^0\pi^+\pi^-$:

$$Y(K^-\pi^+|K_S^0\pi^+\pi^-)_i = H(K_i + (r_D^{K\pi})^2K_{-i} - 2r_D^{K\pi}\sqrt{K_iK_{-i}}[c_i\cos\delta_D^{K\pi} - s_i\sin\delta_D^{K\pi}])$$

$$Y(K^-\pi^+|K_L^0\pi^+\pi^-)_i = H'(K'_i + (r_D^{K\pi})^2K'_{-i} - 2r_D^{K\pi}\sqrt{K'_iK'_{-i}}[c'_i\cos\delta_D^{K\pi} - s'_i\sin\delta_D^{K\pi}])$$

$\mathcal{A}_{K\pi} = 0.132 \pm 0.011 \pm 0.007$, $\mathcal{A}_{K\pi}^{\pi\pi\pi^0} = 0.130 \pm 0.012 \pm 0.008$

$r_D^{K\pi}\cos\delta_D^{K\pi} = -0.0634 \pm 0.0048 \pm 0.0030 \pm 0.0004$

$r_D^{K\pi}\cos\delta_D^{K\pi} = -0.0562 \pm 0.0081 \pm 0.0050 \pm 0.0010$

$r_D^{K\pi}\sin\delta_D^{K\pi} = -0.011 \pm 0.012 \pm 0.007 \pm 0.003$

$\delta_D^{K\pi} = (187.6^{+8.9+5.4}_{-9.7-6.4})°$

More details: Inputs from BESIII for γ, XiaoKang Zhou, WG5, CKM2023.

CPV and strong phases at BESIII

Looking Forward

- For CPV, the decay of $D^0\overline{D}^0$ to the same CP final states has been studied based on blind analysis and will open data after finishing data taking plan.
- The CPV from polarization from Λ_c decay is in preparation.

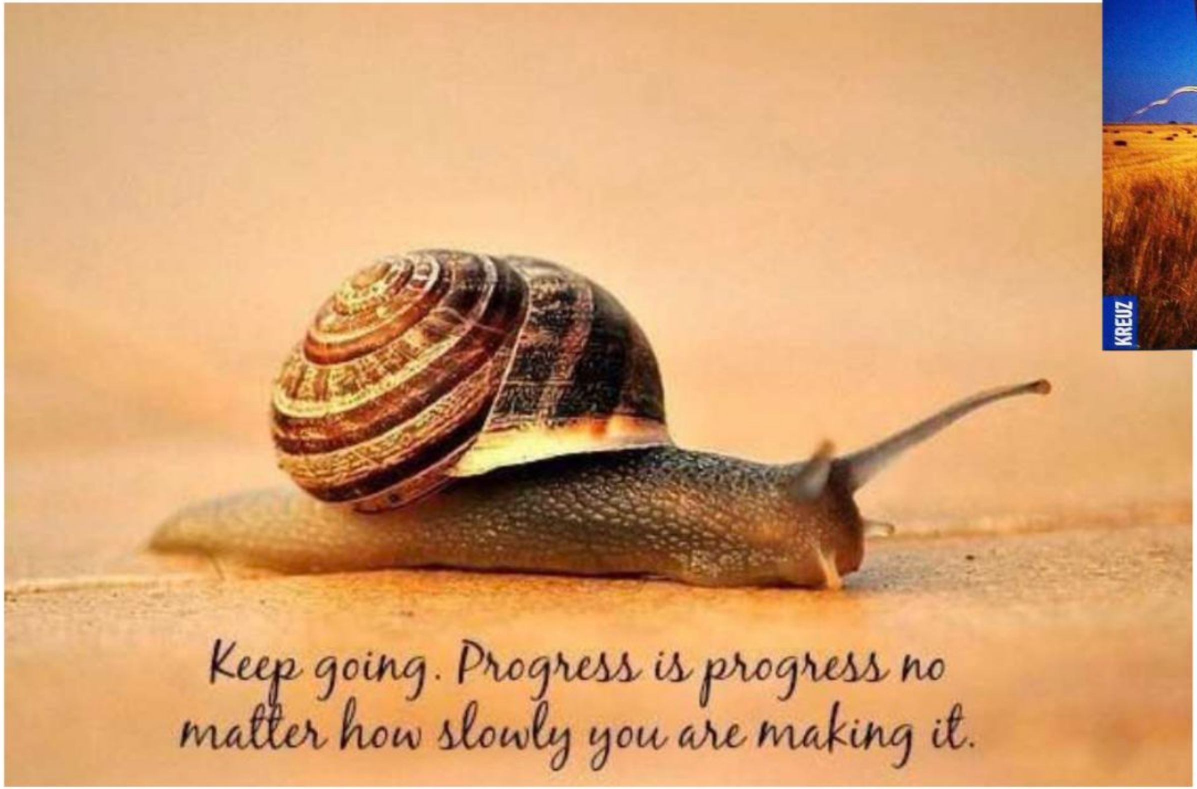
- For some flavor decays, the strong phases would be updated using 20 fb^{-1}.

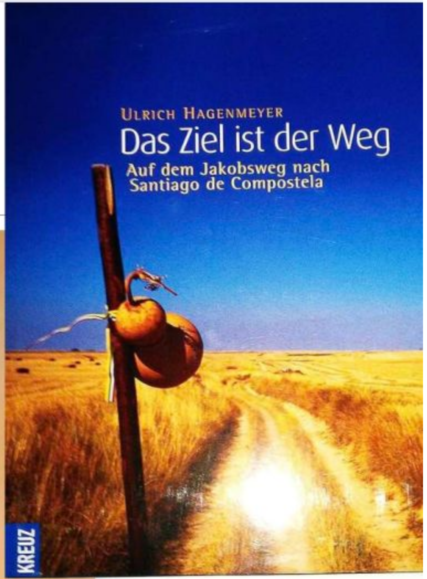
- For $\pi^+\pi^-\pi^0$ and $K^+K^-\pi^0$, the precision of F_+ would be improve with a factor more than 2 compared with CLEO-c's measurement. (~8 fb^{-1} in preparation)
- An optimized binning scheme and a precise c_i and s_i would be determined. (~8 fb^{-1}, ~20 fb^{-1})

- More precise c_i and s_i for $K_S^0\pi^+\pi^-$ and $K_L^0\pi^+\pi^-$, it is worthwhile to explore other binning. (~20 fb^{-1})

- A strong phase analysis of $K^+K^-\pi^+\pi^-$ is performed to measure the strong phase differences in bins of phase space. (~8 fb^{-1} in preparation) This would be the first binned analysis of this decay.
- The statistical uncertainty would be reduce significantly with 20 fb^{-1}.

A BIG THANKS TO THE ORGANIZERS!!!!





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