The charm of charm

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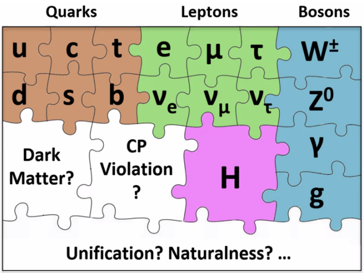
Outline:

1. Why are charm particles charming?
2. The first observation of *CP* violation in charm sector
3. Intriguing two-body D^0 decays
4. *CP* violation searches in charm baryons
5. Conclusions

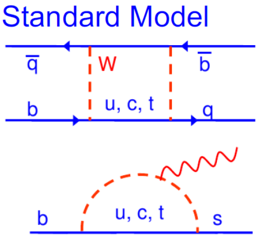
Standard Model - missing puzzles or new theory?



- The Standard Model (SM) is a theory of elementary particles and their interactions.
- The known value of *CP* violation is too small to explain the dominance of matter over antimatter in the universe.
- **The main goal of particle physics is to look for physics beyond the SM.**

How to find sign of new physics?

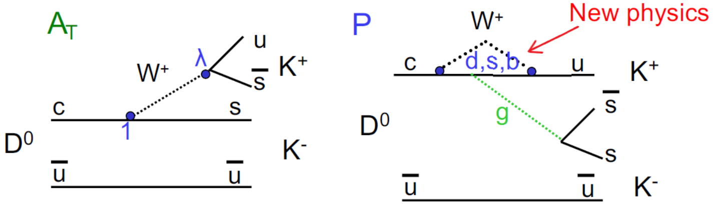
- ATLAS and CMS search for new processes and new particles directly produced in *pp* interactions.
- LHCb tests the SM in very precise measurements of known processes. Any disagreement with theoretical predictions will indicate in indirect way the existence of new phenomena.
- New particles might enter in the loops:



- ***CPV* in charm sector is particularly promising, why?** $\Longrightarrow$

Standard Model predictions in charm decays

- *CP* violation is expected to be $\sim 10^{-3}$ or less.
- Singly Cabibbo-suppressed decays are the **ONLY** place for *CP* violation in the SM.
- Small background from the SM makes a perfect place for searching new physics effects.
- To observe *CP* violation at least two amplitudes MUST interfere with different weak (ϕ) and strong phases (δ):



$$A_{CP} \sim |A_1||A_2| sin(\phi_1 - \phi_2) sin(\delta_1 - \delta_2)$$

- **So far, *CP* violation is not observed in ANY baryon decays.**

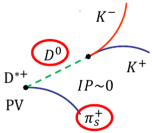
The first observation of *CPV* in charm sector

Phys. Rev. Lett. 122 (2019) 211803

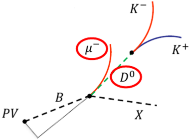
- $\sqrt{s} = 13$ TeV, $L \sim 6\,\text{fb}^{-1}$.

$$A_{CP}(t) = \frac{\Gamma(D^0(t) \to f) - \Gamma(\bar{D}^0(t) \to f)}{\Gamma(D^0(t) \to f) + \Gamma(\bar{D}^0(t) \to f)}$$

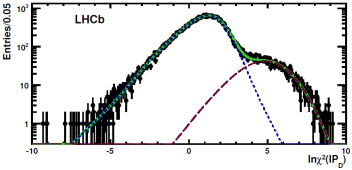
- The $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ decays are analysed.
- The LHCb uses two methods to identify D^0 flavour:



prompt D^0
π-tagged method



secondary D^0
(1/6 of prompt)
μ-tagged method



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The first observation of *CPV* in charm sector

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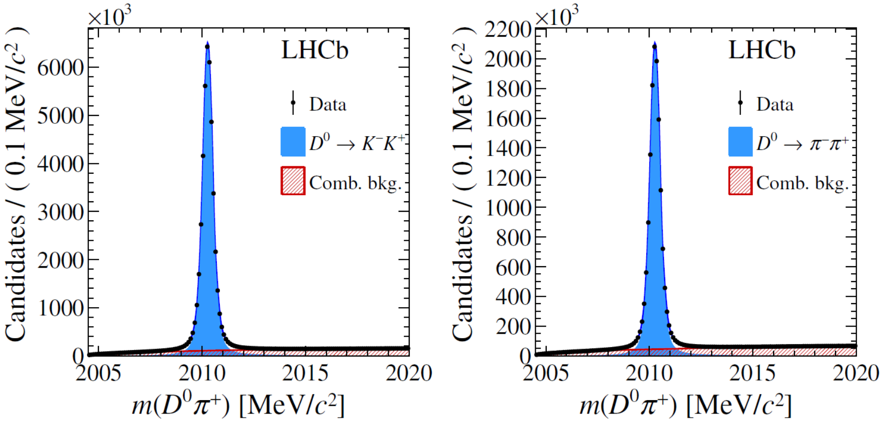


Total yields: $\sim 44\text{M}(D^0 \to K^- K^+)$ and $\sim 14\text{M}(D^0 \to \pi^- \pi^+)$

The first observation of *CPV* in charm sector

Phys. Rev. Lett. 122 (2019) 211803

- The difference in *CP* asymmetries between two decays:

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

$$A_{raw} = A_{CP}(f) + A_D(f) + A_P(D)$$

- $A_D(f)$ - the detector asymmetries.
- $A_P(D)$ - the production asymmetry.
- $A_D(f)$ and $A_P(D)$ are of the order of 2%, while $A_{CP} \leq 10^{-3}$.
- The detector asymmetries cancel since final states are charge symmetric (O(10^{-6})).
- The production asymmetries cancel in subtraction.

The first observation of *CPV* in charm sector

Phys. Rev. Lett. 122 (2019) 211803

- **The first observation of *CP* violation in charm hadrons:**

$$\boldsymbol{\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}\ (5.3\,\sigma)}$$

$$\Delta A_{CP} = [a_{CP}^{dir}(K^- K^+) - a_{CP}^{dir}(\pi^- \pi^+)] + \frac{\Delta\langle t\rangle}{\tau} a_{CP}^{ind}$$

JHEP 1106 (2011) 089

- Direct (majority) and indirect *CP* asymmetries contribute.
- Indirect *CP* asymmetries are smaller than 10%.

ΔA_{CP} - bittersweet result

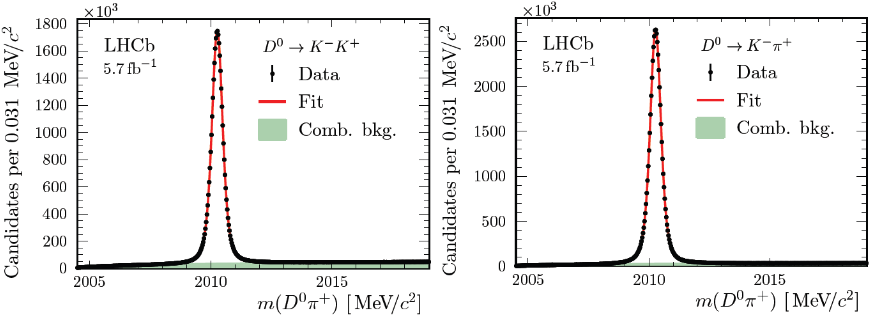
- Still, there are a few possibilities:
  - according to U-spin symmetry, a_{CP}^{dir} is roughly the same magnitude in K^-K^+ and $\pi^-\pi^+$,
  - or a_{CP}^{dir} might be significantly different, in $\pi^-\pi^+ >> K^-K^+$
    CP violation in D decays to two pseudoscalars: A SM-based calculation, E. Solomonidi, BEACH 2022.

- Nonetheless, to properly determine and investigate the source of potential *CP* violation, one has to examine **the single asymmetry.**

Measurement of *CPV* in $D^0 \to K^-K^+$

LHCb-PAPER-2022-024 in preparation

- Run 2 (2015 - 2018), $\sqrt{s} = 13$ TeV, $L \sim 6\,\text{fb}^{-1}$.



Total yields: $\sim 45\text{M}(D^0 \to K^-K^+)$ and $\sim 60\text{M}(D^0 \to K^-\pi^+)$

Measurement of *CPV* in $D^0 \to K^- K^+$

LHCb-PAPER-2022-024 in preparation

- The raw asymmetry can be written as:

$$A(K^-K^+) = \boldsymbol{A_{CP}(K^-K^+)} + A_{prod}(D/D^{*+}) + A_{det}(\pi^+_{soft})$$

- The nuisance asymmetries (A_{prod} and A_{det}) are removed by control channels with negligible *CP* asymmetry:

$$\begin{aligned} A(K^-\pi^+) &\approx A_{\rm prod}(D^{*+}) - A_{\rm det}(K^+) + A_{\rm det}(\pi^+) + A_{\rm det}(\pi^+_{\rm tag}), \\ A(K^-\pi^+\pi^+) &\approx A_{\rm prod}(D^+) - A_{\rm det}(K^+) + A_{\rm det}(\pi^+_1) + A_{\rm det}(\pi^+_2), \\ A(\overline{K}^0\pi^+) &\approx A_{\rm prod}(D^+) - A(K^0) + A_{\rm det}(\pi^+), \\ A(\phi\pi^+) &\approx A_{\rm prod}(D^+_s) + A_{\rm det}(\pi^+), \\ A(\overline{K}^0 K^+) &\approx A_{\rm prod}(D^+_s) - A(K^0) + A_{\rm det}(K^+). \end{aligned}$$

- Measurement is performed with **two methods**:

$$\boldsymbol{A_{CP}(K^-K^+)} = A(K^-K^+) - A(K^-\pi^+) + A(K^-\pi^+\pi^+) - A(\bar{K}^0\pi^+) - A(K^0)$$

$$\boldsymbol{A_{CP}(K^-K^+)} = A(K^-K^+) - A(K^-\pi^+) + A(\phi\pi^+) - A(\bar{K}^0K^+) - A(K^0)$$

Measurement of *CPV* in $D^0 \to K^- K^+$

LHCb-PAPER-2022-024 in preparation

- The resulting values for both methods:

$$A_{CP}(K^+K^-) = (13.6 \pm 8.8 \pm 1.6) \times 10^{-4}$$

$$A_{CP}(K^+K^-) = (2.8 \pm 6.7 \pm 2.0) \times 10^{-4}$$

  with a correlation corresponding to 0.06.

- **The time-integrated *CP* asymmetry (averaged):**

$$\boldsymbol{A_{CP}(K^+K^-) = [6.8 \pm 5.4 \pm 1.6] \times 10^{-4}}$$

- The time-integrated *CP* asymmetry is a sum of a direct and indirect components:

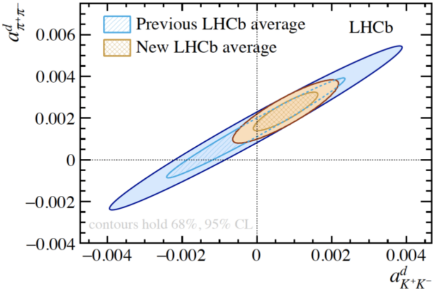
$$A_{CP}(f) \approx a_{CP}^{dir} + \frac{\langle t \rangle}{\tau_D} \Delta Y, \quad \Delta Y \equiv -x \sin\phi + y \cos\phi \, a_{CP}^{dir}$$

Breaking news!

LHCb-PAPER-2022-024 in preparation

- The combination, including result from Run 1:
  $a^{dir}_{K^-K^+} = (7.7 \pm 5.7) \times 10^{-4}$

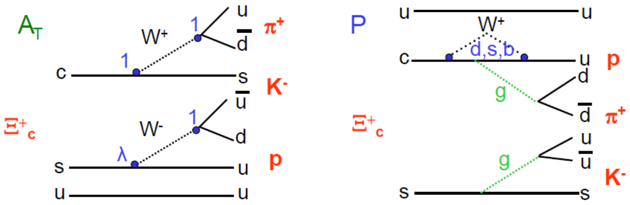
- Subtracting from ΔA_{CP}:
  $\boldsymbol{a^{dir}_{\pi^-\pi^+} = (23.2 \pm 6.1) \times 10^{-4}}$



- **The deviation from zero corresponds to $3.8\,\sigma$!**
- **The first evidence of direct *CPV* in single charm decay!**
- Agreement with the hypothesis of U-spin symmetry (i.e. quark s - quark d symmetry) - $2.7\,\sigma$

CPV searches in charm baryons

- So far, *CPV* has not been observed in any baryon decays.
- Searches are conducted in $\Xi_c^+ \to pK^-\pi^+$ decays.



- First search [Eur. Phys. J. C80 (2020) 986]:
  - Data collected in Run 1, $\sqrt{s} = 7$ and 8 TeV, $L = 3\,\text{fb}^{-1}$,
  - Two methods are used:
    - binned S_{CP} [Phys. Rev. D 80, 096006]
    - unbinned kNN [J. Am. Stat. Assoc. 81, 799 (1986)]
  - **Results are consisted with *CP* symmetry.**

The other approach: Energy test

Defined as the analogue of the potential energy of the field of charges.

$$T = \frac{1}{2}\iint (f_p(\vec{x}) - f_a(\vec{x}))(f_p(\vec{x}') - f_a(\vec{x}'))K(\vec{x},\vec{x}')d\vec{x}d\vec{x}'$$

$$K(\vec{x},\vec{x}') = exp(-\frac{(\vec{x}-\vec{x}')^2}{2\delta})$$

ET can be estimated without the need for any knowledge about the f_p or f_a:

$$T = \frac{1}{n(n-1)}\sum_{i,j>i}^{n} K(|\vec{x}_i - \vec{x}_j|) + \frac{1}{m(m-1)}\sum_{i,j>i}^{n} K(|\vec{x}'_i - \vec{x}'_j|) - \sum_{i=1}^{n}\sum_{j=1}^{m} K(|\vec{x}_i - \vec{x}'_j|)$$

Distribution for $H_0 : f_p = f_a$ is unknown - how to find **p-value**?

- T for overall samples - **nominal T**.
- Set of T calculated for samples with random sign - **permuted T**.

$$\boldsymbol{p}-\text{value} = \frac{\text{number of permuted } \boldsymbol{T} \text{ values grater than nominal } \boldsymbol{T}}{\text{total number of permuted } \boldsymbol{T} \text{ values}}$$

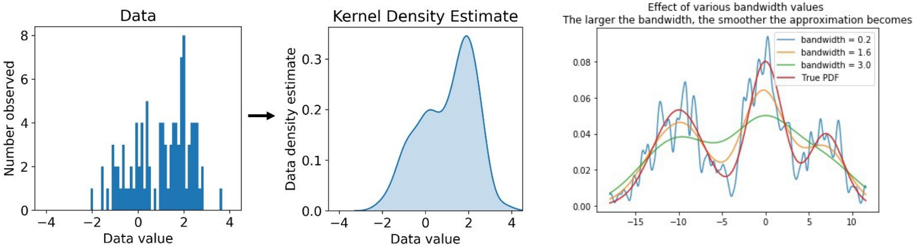
ET in LHCb: Phys. Lett. B740 (2015) 158, Phys. Lett. B769 (2017) 345, Phys. Rev. D102 (2020), 051101 , but only in mesons.

New approach: Kernel Density Estimation

a non parametric way to estimate the pdf of a random variable.

$$\hat{f}(x) = \frac{1}{n}\sum_{i=1}^{n}\frac{1}{h}\left(1-\frac{|x|}{h}\right), |x| < h,$$

- $h^i_{opt} = \frac{k\hat{S}N^{-0.2}}{\sqrt{f(x_i)}}$, $k = 1.06$, $\hat{S}$ - std of the sample, N - sample size



Never used for *CPV* searches: Szumlak T., *Performance of the LHCb Vertex locator and the measurement of the forward-backward asymmetry in $B^0_d \to K^{*0}(892)\mu^+\mu^-$ decay channel as a probe of New Physics*, Krakow (2013)

Conclusions

- The searches for *CPV* in the charm sector have been intensified.
- The difference between *CP* asymmetries in $D^0 \to K^-K^+/\pi^-\pi^+$:

$$\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}$$

- New measurements of *CPV*:

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

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

  - **The *CP* asymmetry is different from zero at 3.8σ level!**
  - **The first evidence of direct *CPV* in single charm decay!**
- Searches for *CPV* in charmed baryons are continuing...(Run 3 ...)

Back-up

Raw asymmetries and kinematic weighting

- The raw asymmetries are calculated from the least-square fit to mass distributions of the selected mesons,
- The decays channels must have the same kinematic distributions to cancel nuisance asymmetries,
- $A_{det}(\bar{K}^0)$ is estimated using the material map of LHCb, the mixing and scattering amplitudes of the neutral kaon system and validated on downstream $D^+ \to K^0_s \pi^+$,,

	$D^+ \to K^0_S \pi^+_{trig} \|^w$	$D^+ \to K^- \pi^+ \pi^+_{trig} \|^w$	$D^0 \to K^- \pi^+ \|^w$	$D^0 \to K^- K^+ \|^w$
	A^{blind} $[10^{-4}]$	A^{blind} $[10^{-4}]$	A^{blind} $[10^{-4}]$	A^{blind} $[10^{-4}]$
15 Dw	34.4 ± 44.5	-25.9 ± 11.5	-96.0 ± 14.3	37.3 ± 12.3
16 Dw	71.1 ± 20.3	-7.8 ± 4.2	-128.6 ± 6.3	4.9 ± 5.2
17 Dw	48.2 ± 20.3	-6.5 ± 4.0	-116.6 ± 5.8	-9.5 ± 5.2
18 Dw	60.2 ± 19.8	-22.5 ± 3.9	-117.7 ± 5.7	-1.1 ± 5.1
15 Up	-6.1 ± 54.1	-92.4 ± 15.5	-299.0 ± 18.0	-155.1 ± 15.5
16 Up	-39.2 ± 22.1	-81.7 ± 4.8	-287.4 ± 8.3	-166.2 ± 5.7
17 Up	-37.3 ± 20.3	-99.3 ± 4.2	-308.9 ± 5.9	-167.1 ± 5.3
18 Up	-31.0 ± 19.1	-79.2 ± 3.8	-294.8 ± 5.5	-173.2 ± 4.9