Searches for *CP* violation in multibody D decays

Jinlin Fu

INFN Milano
On behalf of LHCb Collaboration

Beauty conference 2014
Edinburgh, 14 - 18 July 2014

Introduction

- *CPV* is an interference effect:
  at least two amplitudes with different strong and weak phases.
- *CPV* in charm decays is *CKM* suppressed in the SM, $\lesssim 0.1\%$.
- Multibody charm decays are a good place to search for *CPV*:
  very rich resonant structures of interfering amplitudes can give large effects.
  allow to probe *CPV* in different phase space regions.
- Searches at LHCb:
  $D^+ \to \pi^-\pi^+\pi^+$
  $D^0 \to \pi^+\pi^-\pi^+\pi^-$
  $D^0 \to K^+K^-\pi^+\pi^-$.
  Two model-independent methods are applied:
  Miranda and *T*-odd correlations (**New**)

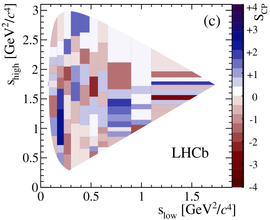
Miranda method

- Phase space splitted into different bins. Significance defined between *CP* conjugate decays for each bin:

$$S^i_{CP} = \frac{N_i(D^0) - \alpha N_i(\bar{D}^0)}{\sqrt{\alpha(\sigma_i^2(D^0) + \sigma_i^2(\bar{D}^0))}}, \quad \alpha = \frac{\sum_i N_i(D^0)}{\sum_i N_i(\bar{D}^0)}.$$

α, removes sensitivity of global production and detection asymetries.

σ_i, uncertainty of N_i determination



- A χ^2 statistic constructed, from which a *p*-value calculated with $N_{bins} - 1$ degree of freedom.

$$\chi^2 = \sum_i (S^i_{CP})^2$$

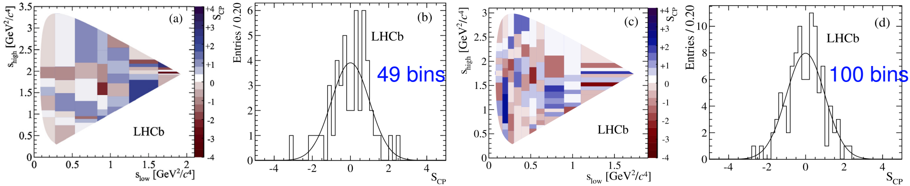
CP conserved: pass χ^2 test.
CPV: deviation from χ^2 distribution.

Miranda analysis $D^+ \to \pi^-\pi^+\pi^+$

[PLB 728 (2014) 585]

- Reconstructed with a data set of 1 fb^{-1}. Sensitive to 1^o in phase difference or 2% in amplitude difference.

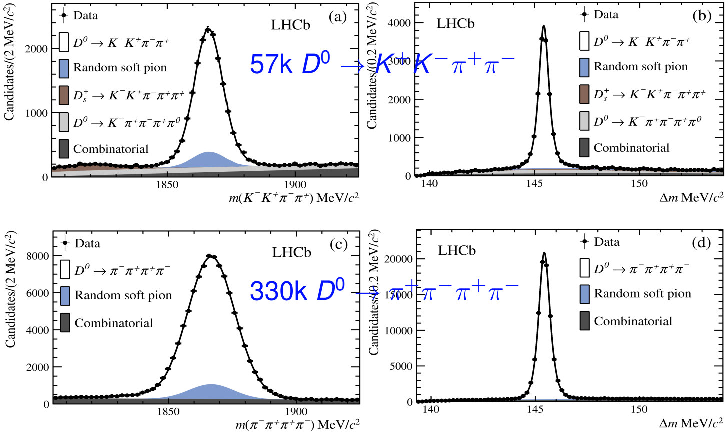
Control sample 2.7M $D_s^+ \to \pi^-\pi^+\pi^+$ 2.7M $D^+ \to \pi^-\pi^+\pi^+$



- Tested with adaptive binning schemes of 20, 30, 40, 49 and 100 bins. Results consistent with no *CPV* at current sensitivities with the *p*-values above 50%.
- Tested with uniform binning schemes of 20, 32, 52 and 98 bins. Results consistent with no *CPV* with the *p*-values above 90%.
- No single bin in any of the binning schemes presents an absolute S^i_{CP} value larger than 3.

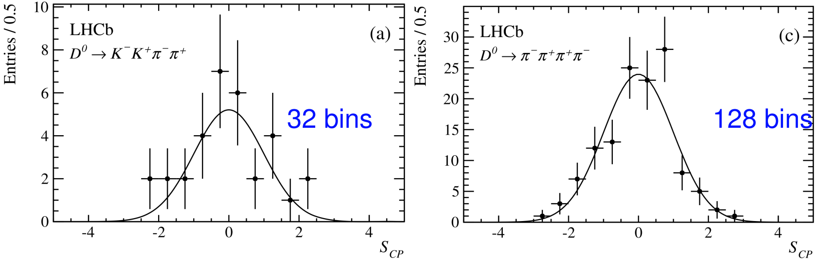
$D^0 \to K^+K^-\pi^+\pi^-$, $D^0 \to \pi^+\pi^-\pi^+\pi^-$ **[PLB 726 (2013) 623]**

- Reconstructed with a data set of 1 fb^{-1}. Sensitive to 10^o in phase difference or 10% in amplitude difference.
- Two-dimensional unbinned likelihood fits to $m(hhhh)$ and Δm , *s*Plot method for signal and background seperation.



Miranda analysis $D^0 \to K^+K^-\pi^+\pi^-$, $D^0 \to \pi^+\pi^-\pi^+\pi^-$ [PLB 726 (2013) 623]

- The phase space more complicated than 3-body decays, can be described with five invariant mass-squred combinations of final particles.
- An adaptive binning algorithm devised to partition the phase space into 5-dimensional hypercubes.

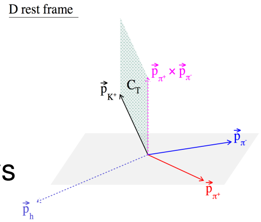


- Results consistent with no *CPV* with *p*-values of 9.1% for $D^0 \to K^+K^-\pi^+\pi^-$, and 41% for $D^0 \to \pi^+\pi^-\pi^+\pi^-$.
- Cross checked with 16, 64 and 256 binning schemes, all results consistent with no *CPV*.

T-odd correlations method: $D^0 \to K^+K^-\pi^+\pi^-$ (**New**)

- T-odd triple products: in D^0 ($\bar{D}^0$) rest frame.

  $C_T \equiv \vec{p}_{K^+} \cdot (\vec{p}_{\pi^+} \times \vec{p}_{\pi^-})$, for D^0
  $\bar{C}_T \equiv \vec{p}_{K^-} \cdot (\vec{p}_{\pi^-} \times \vec{p}_{\pi^+})$, for $\bar{D}^0$



- T-odd observable:

  $A_T \equiv \frac{\Gamma(C_T>0)-\Gamma(C_T<0)}{\Gamma(C_T>0)+\Gamma(C_T<0)}$, measured in D^0 decays

  $\bar{A}_T \equiv \frac{\Gamma(-\bar{C}_T>0)-\Gamma(-\bar{C}_T<0)}{\Gamma(-\bar{C}_T>0)+\Gamma(-\bar{C}_T<0)}$, measured in $\bar{D}^0$ decays

- True CP-violating observable: cancel FSI effects

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

W. Bensalem, A. Datta and D. London, Phys. Rev. D66, 094004 (2002)
W. Bensalem and D. London, Phys. Rev. D64, 116003 (2001)
W. Bensalem, A. Datta and D. London, Phys. Lett. B538, 309 (2002)
I. Bigi and H.-B. Li, Int. J. Mod. Phys. A24, 657 (2009)

Sensitivity using T-odd correlations

- Measurement of $a_{CP}^{T\text{-odd}}$ is different from S_{CP}:
  - Complementary approach to the search for *CPV*.
  - $a_{CP}^{T\text{-odd}} \propto \sin(\phi)\cos(\delta)$, $S_{CP} \propto \sin(\phi)\sin(\delta)$.
    ϕ weak phase, δ strong phase of two interfering amplitudes.
  - Different sensitivity to *CPV*:
    S_{CP} vanishes for $\delta = 0$, while $a_{CP}^{T\text{-odd}}$ is maximal.
- The measurement $a_{CP}^{T\text{-odd}}$ is affected by small systematic uncertainties:
  - $a_{CP}^{T\text{-odd}}$ is not sensitive to $D^0/\overline{D}^0$ production asymmetry.
  - $a_{CP}^{T\text{-odd}}$ is not sensitive to detector charge reconstruction asymmetry.

Experimental status

- Previous measurements of $a_{CP}^{T\text{-odd}}$ consistent with no *CPV*.

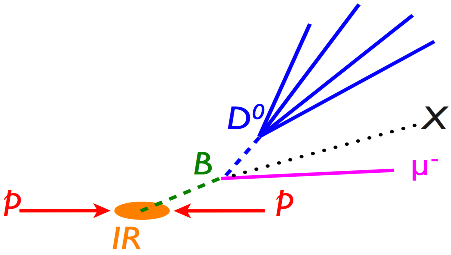
$D^0 \to K^+K^-\pi^+\pi^-$	N_{sig}	$a_{CP}^{T\text{-odd}}$
FOCUS(2005)	800	$a_{CP}^{T\text{-odd}}(D^0) = (1.0 \pm 5.7 \pm 3.7)\%$
Babar(2010)	47k	$a_{CP}^{T\text{-odd}}(D^0) = (0.10 \pm 0.51 \pm 0.44)\%$
$D^+_{(s)} \to K^+K^0_S\pi^+\pi^-$		
FOCUS(2005)	500	$a_{CP}^{T\text{-odd}}(D^+) = (2.3 \pm 6.2 \pm 2.2)\%$
	500	$a_{CP}^{T\text{-odd}}(D^+_s) = (-3.6 \pm 6.7 \pm 2.3)\%$
BaBar(2011)	20k	$a_{CP}^{T\text{-odd}}(D^+) = (-1.20 \pm 1.00 \pm 0.46)\%$
	30k	$a_{CP}^{T\text{-odd}}(D^+_s) = (-1.36 \pm 0.77 \pm 0.34)\%$

Phys. Lett. B622 (2005) 239 , Phys. Rev. D81 (2010) 111103 , Phys. Rev. D 84, 031103 .

T-odd correlations analysis: $D^0 \to K^+K^-\pi^+\pi^-$ (**New**)

[LHCb-PAPER-2014-046 in preparation]

- D^0 tagged using semileptonic B decays $B \to D^0\mu^- X$.
- 171k $D^0 \to K^+K^-\pi^+\pi^-$ reconstructed with a data set of $3\,\mathrm{fb}^{-1}$.
- Preliminary results, LHCb-PAPER-2014-046 is in preparation.



Analysis Strategy

- Dataset splitted into 4 samples depending on D^0 flavor and C_T value, the number of signal events retrieved by simultaneous fit to the four distributions of $m(K^+K^-\pi^+\pi^-)$. Asymmetry parameters A_T, $\bar{A}_T$ extracted from the fit.

$$N_{D^0,C_T>0} = \frac{1}{2}N_{D^0}(1+A_T),$$
$$N_{D^0,C_T<0} = \frac{1}{2}N_{D^0}(1-A_T),$$
$$N_{\bar{D}^0,-\bar{C}_T>0} = \frac{1}{2}N_{\bar{D}^0}(1+\bar{A}_T),$$
$$N_{\bar{D}^0,-\bar{C}_T<0} = \frac{1}{2}N_{\bar{D}^0}(1-\bar{A}_T).$$

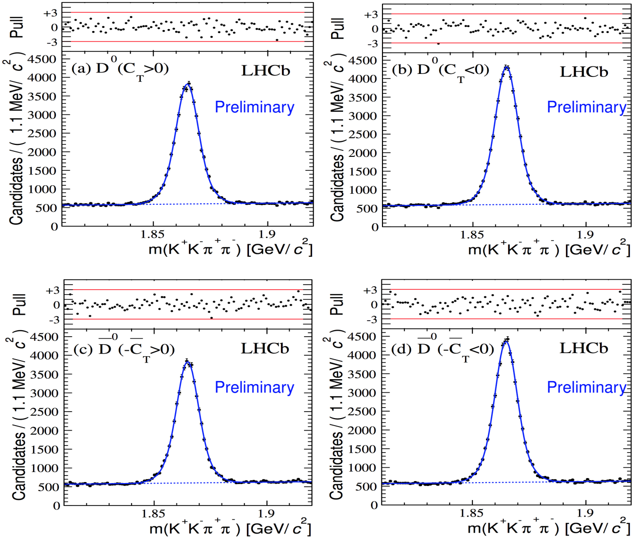
- Measurements of asymmetry parameters in different regions of the phase space by dividing the 5-dimensional Dalitz plots.
  The compatibility with no *CPV* hypothesis tested by $\chi^2 = X^T V^{-1} X$,
  X, array of $a_{CP}^{T\text{-odd}}$ residuals of each bin w.r.t 0.
  V, sum of the statistical and the systematic error matrix.
  $a_{CP}^{T\text{-odd}}$, Gaussian distributed variables, systematic errors are mainly Gaussian.

- Measurements of asymmetry parameters as a function of D^0 proper time.

Phase space integrated measurement (1) (**New**)

[LHCb-PAPER-2014-046 in preparation]

The simultaneous fit to the full data sample for the integrated measurement.



Phase space integrated measurement (2) (**New**)

[LHCb-PAPER-2014-046 in preparation]

- Asymmetries parameters: Preliminary

$$A_T = (-7.18 \pm 0.41(\text{stat}) \pm 0.13(\text{syst}))\%$$
$$\bar{A}_T = (-7.55 \pm 0.41(\text{stat}) \pm 0.12(\text{syst}))\%$$
$$a_{CP}^{T\text{-odd}} = (0.18 \pm 0.29(\text{stat}) \pm 0.04(\text{syst}))\%$$

consistent with measurements at Babar[1], with a precision improved by more than a factor of 2.

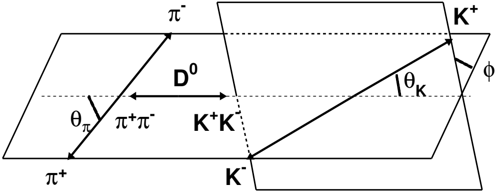
- Large asymmetries observed in A_T and $\bar{A}_T$ are due to FSI effect[2].

[1]: Phys. Rev. D81 (2010) 111103
[2]: arXiv:hep-ph/0107102, Phys. Rev. D 84 (2011) 096013

Phase space binning

[LHCb-PAPER-2014-046 in preparation]

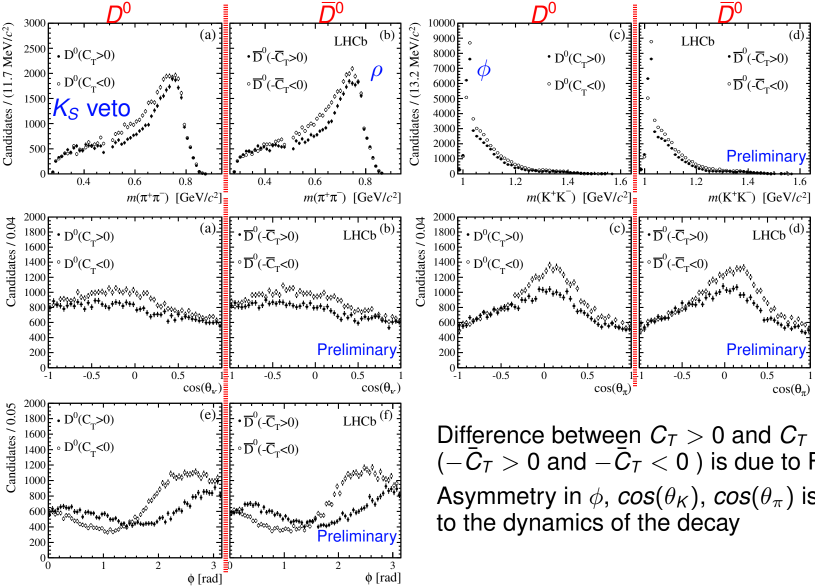
- The phase space is divided into 32 bins following a binning scheme based on the Cabibbo-Maksimowicz variables:
  $m^2_{\pi^+\pi^-}$, $m^2_{K^+K^-}$, $cos(\theta_\pi)$, $cos(\theta_K)$, and ϕ.



- The number of events is consistent in different bins. Other phase space divisions with 8 and 16 bins have been considered for control checks.

Asymmetries over the phase space (**New**)

[LHCb-PAPER-2014-046 in preparation]



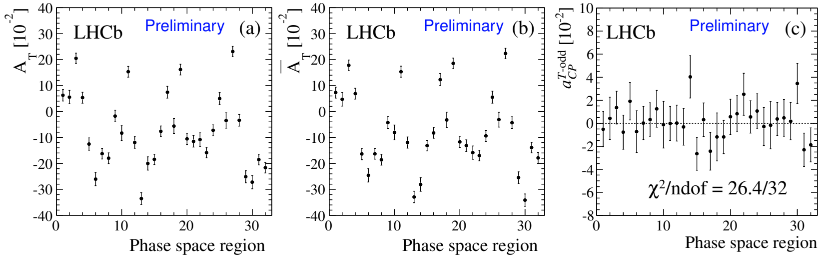
Difference between $C_T > 0$ and $C_T < 0$ ($-\bar{C}_T > 0$ and $-\bar{C}_T < 0$) is due to FSI.

Asymmetry in ϕ, $cos(\theta_K)$, $cos(\theta_\pi)$ is due to the dynamics of the decay

Results over phase space regions (**New**)

[LHCb-PAPER-2014-046 in preparation]

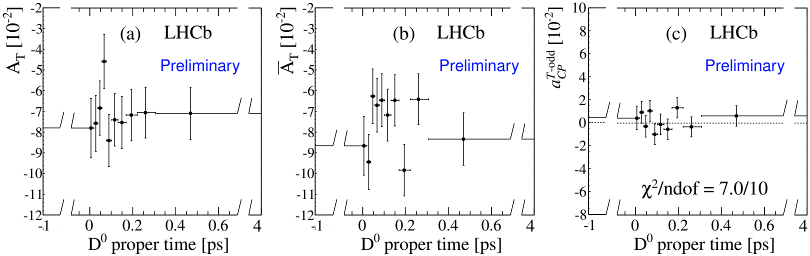
- Results consistent with no *CPV* hypothesis with a probability of 74% based on $\chi^2/\mathrm{ndof} = 26.4/32$.
- Control checks: results are compatible with no *CPV* hypothesis at 24% probability for the case of 8 bins and at 28%, 62%, 82% probability for cases of three different 16 bins.
- A_T and $\bar{A}_T$ are significantly different among the different bins: rich resonant structure produce different FSI effects.



Measurement of $a_{CP}^{T\text{-odd}}$ as a function of D^0 proper time

New **[LHCb-PAPER-2014-046 in preparation]**

- First time measurement of $a_{CP}^{T\text{-odd}}$ as a function of D^0 proper time.
- Proper time divided into 10 bins with similar signal events. Asymmetries measured in each bin.
- The compatibility with no *CPV* hypothesis verified by means of the χ^2 test.
- $a_{CP}^{T\text{-odd}}$ is consitent with no indirect *CPV* at 72% probability.
- A_T and $\bar{A}_T$ do not show any significant dependance on the proper time, compatible with a constant at 80% and 34% probability, respectively.



Summary

- A search for *CP* violation using the Miranda method is performed with a data set of 1 fb^{-1}:
  $D^+ \to \pi^-\pi^+\pi^+$
  $D^0 \to \pi^+\pi^-\pi^+\pi^-$
  $D^0 \to K^+K^-\pi^+\pi^-$
- A search for *CP* violation using the *T*-odd correlations method is performed in $D^0 \to K^+K^-\pi^+\pi^-$ decays with a data set of 3 fb^{-1}. Search for *CPV* in different regions of five dimensional phase space and as a function of D^0 proper time are also presented for the first time. (**New**)
- All results are consistent with no *CPV* in *D* decays.
- Further improvements expected with more statistics at the LHCb.