Search for *CP* violation using T-odd observables in charm meson decays

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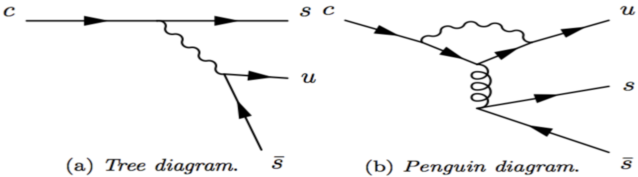
Physics Motivation

- *CPV* in charm decays is very suppressed in the SM: $\lesssim 0.1\%$. The first evidence of *CPV* in $D^0 \to K^+K^-,\pi^+\pi^-$ decays not confirmed by recent results.
- The study of *CPV* in singly Cabibbo-suppressed charm decays is uniquely sensitive to NP in $c \to us\bar{s}, ud\bar{d}$ transitions, in particular to new contribution to $\Delta C = 1$ *QCD* penguin and chromomagnetic dipole operators.



(a) *Tree diagram.* (b) *Penguin diagram.*

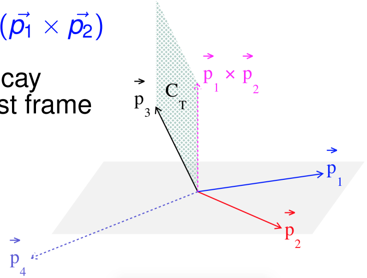
- The analysis of four-body charm decays probes for *CPV* in different phase space regions. Sensitivity enhanced due to several interfering amplitudes with different relative strong phases.

Experimental Technique

- T-odd triple products based on spin or momentum: I. Bigi arXiv:0902.3048

  $C_T = \vec{p}_3 \cdot (\vec{p}_1 \times \vec{p}_2)$

  4-body decay
  mother rest frame



- T-odd asymmetries built for CP conjugate decays:

  $$A_T = \frac{\Gamma(C_T > 0) - \Gamma(C_T < 0)}{\Gamma(C_T > 0) + \Gamma(C_T < 0)}$$

  $$\bar{A}_T = \frac{\Gamma(-\bar{C}_T > 0) - \Gamma(-\bar{C}_T < 0)}{\Gamma(-\bar{C}_T > 0) + \Gamma(-\bar{C}_T < 0)}$$

- True CP-violating observable cancel FSI effects

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

- Production asymmetry and charged track reconstruction asymmetry cancel by construction: low systematic uncertainty.

T-odd observables and sensitivity to *CPV* Phys. Rev. D39 (1989) 3339

- Invariant matrix element in $B(p) \to V_1(k,\epsilon_1)V_2(q,\epsilon_2)$: $S + D + P$
  $M = a\epsilon_1 \cdot \epsilon_2 + \frac{b}{m_1 m_2}(p\cdot\epsilon_1)(p\cdot\epsilon_2) + i\frac{c}{m_1 m_2}\epsilon^{\alpha\beta\mu\nu}\epsilon_{1\alpha}\epsilon_{2\beta}k_\mu p_\nu$
  $a = \sum_j |a_j|e^{i(\delta_{sj}+\phi_{sj})}$; $b = \sum_j |b_j|e^{i(\delta_{dj}+\phi_{dj})}$; $c = \sum_j |c_j|e^{i(\delta_{pj}+\phi_{pj})}$: δ strong phase, ϕ weak phase.
- Interference between P and other partial waves disappear, when integrate over full phase space:
  $$\sum_{\lambda_1\lambda_2}|M|^2 = \underbrace{|a|^2(2+x^2)}_{S-S} + \underbrace{|b|^2(x^2-1)^2}_{D-D} + \underbrace{|c|^2 2(x^2-1)}_{P-P} + \underbrace{2Re[ab^*]x(x^2-1)}_{S-D}$$
- A triple-product correlation wrt $\vec{k}\cdot\vec{\epsilon_1}\times\vec{\epsilon_2}$ is sensitive to the interference of $S-P$ waves ($\propto \mathrm{Im}[ac^*]$) and $D-P$ waves ($\propto \mathrm{Im}[bc^*]$)
  $$A_T = \frac{N_{events}(\vec{k}\cdot\vec{\epsilon_1}\times\vec{\epsilon_2}>0) - N_{events}(\vec{k}\cdot\vec{\epsilon_1}\times\vec{\epsilon_2}<0)}{N_{total}}$$
  $$\sim \mathrm{Im}[ac^*] = |ac|e^{i(\delta_s-\delta_p)}e^{i(\phi_s-\phi_p)} \sim |ac|\sin(\Delta\delta + \Delta\phi)$$
- For *CP* conjugate decay:
  $\bar{A}_T \sim |ac|e^{i(\delta_s-\delta_p)}e^{-i(\phi_s-\phi_p)} \sim |ac|\sin(\Delta\delta - \Delta\phi)$
- *CP*-violating observable: $a_{CP}^{T\text{-odd}} = \frac{1}{2}(A_T - \bar{A}_T) \approx \cos\Delta\delta\sin\Delta\phi$

Complementary approach to direct *CPV* searches

- Sensitive to different relative phases:

$$A_{CP} \propto \sin(\delta_1 - \delta_2)\sin(\phi_1 - \phi_2)$$
$$= \sin\Delta\delta\prime \sin\Delta\phi\prime : \text{1,2 different amplitudes}$$
$$a_{CP}^{T\text{-odd}} \propto \cos(\delta_s - \delta_p)\sin(\phi_s - \phi_p)$$
$$= \cos\Delta\delta \sin\Delta\phi : \text{s,p different partial waves}$$

- In contrast to the asymmetry between the phase-space integrated rates in a $D^0 \to V_1 V_2$ decay (V_i, vector meson), $a_{CP}^{T\text{-odd}}$ is sensitive to *CPV* in the interference between even- and odd- partial waves of the $V_1 V_2$ system.

Experimental status

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

$D^0 \to K^+K^-\pi^+\pi^-$	N_{sig}	$a_{CP}^{T\text{-odd}}$
FOCUS(2005)	800	$a_{CP}^{T\text{-odd}}(D^0) = (1.0 \pm 5.7 \pm 3.7)\%$ [1]
Babar(2010)	47k	$a_{CP}^{T\text{-odd}}(D^0) = (0.10 \pm 0.51 \pm 0.44)\%$ [2]
$D^+_{(s)} \to K^+K^0_S\pi^+\pi^-$		
FOCUS(2005)	500	$a_{CP}^{T\text{-odd}}(D^+) = (2.3 \pm 6.2 \pm 2.2)\%$ [1]
	500	$a_{CP}^{T\text{-odd}}(D^+_s) = (-3.6 \pm 6.7 \pm 2.3)\%$
BaBar(2011)	20k	$a_{CP}^{T\text{-odd}}(D^+) = (-1.20 \pm 1.00 \pm 0.46)\%$ [3]
	30k	$a_{CP}^{T\text{-odd}}(D^+_s) = (-1.36 \pm 0.77 \pm 0.34)\%$

[1] Phys. Lett. B622 (2005) 239 , [2] Phys. Rev. D 81 (2010) 111103 , [3] Phys. Rev. D 84 (2011) 031103 .

Measurements at LHCb

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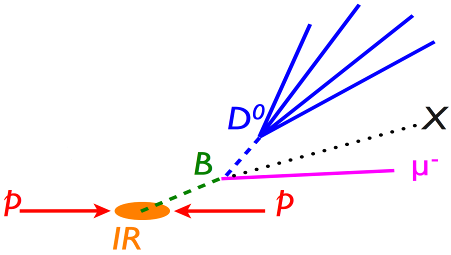
- D^0 flavor tagged using semileptonic B decays $B \to D^0 \mu^- X$.
- 171k $D^0 \to K^+ K^- \pi^+ \pi^-$ reconstructed using a data set of $3\,\text{fb}^{-1}$.
- Triple-products:

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



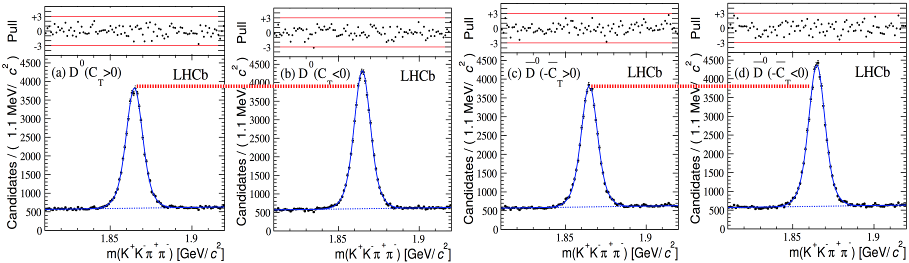
Analysis Strategy

- Dataset divided 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.

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

- Three measurements
  - Measurement integrated in the phase space.
  - Measurement in different regions of the phase space.
  - Measurement as a function of D^0 proper time (sensitive to indirect *CPV*).

Integrated measurement



$$A_T = (-7.18 \pm 0.41(\text{stat}) \pm 0.13(\text{syst}))\%$$

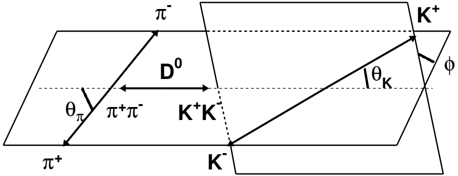
$$\bar{A}_T = (-7.55 \pm 0.41(\text{stat}) \pm 0.12(\text{syst}))\%$$

$$a_{CP}^{T\text{-odd}} = (0.18 \pm 0.29(\text{stat}) \pm 0.04(\text{syst}))\%$$

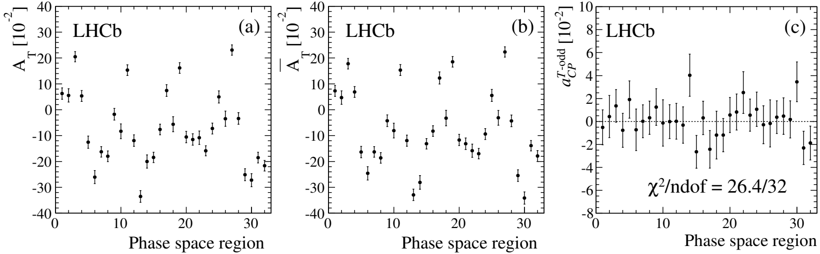
- deviation of A_T, $\bar{A}_T$ from zero not large but sizable due to re-scattering at low energy.
- $a_{CP}^{T\text{-odd}}$ consistent with no *CPV* hypothesis.

Measurement in phase space regions

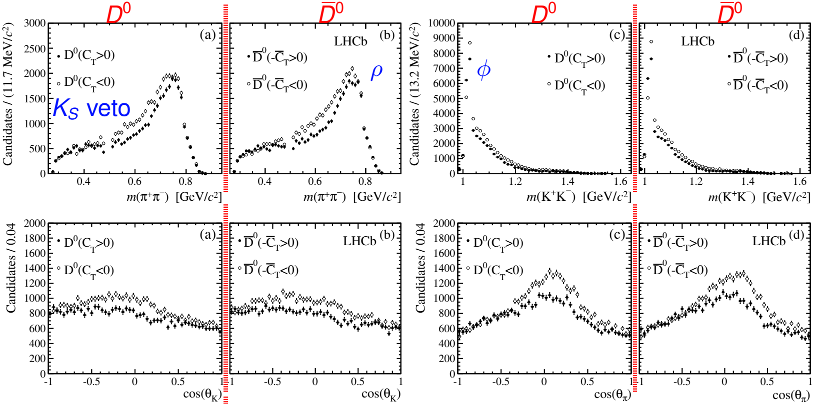
- The phase space is divided into 32 bins following a binning scheme based on the Cabibbo-Maksimowicz variables: Phys. Rev. 137 (1965) B438.
  $m^2_{\pi^+\pi^-}$, $m^2_{K^+K^-}$, $cos(\theta_\pi)$, $cos(\theta_K)$, and ϕ.

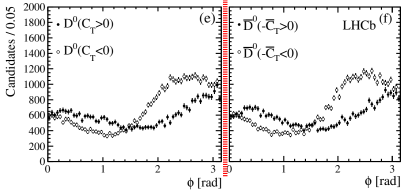


- $a_{CP}^{T\text{-odd}}$ consistent with no *CPV* hypothesis with a probability of 74%. A_T and $\bar{A}_T$ are significantly different among the different bins due to FSI effects.



Asymmetries over the phase space



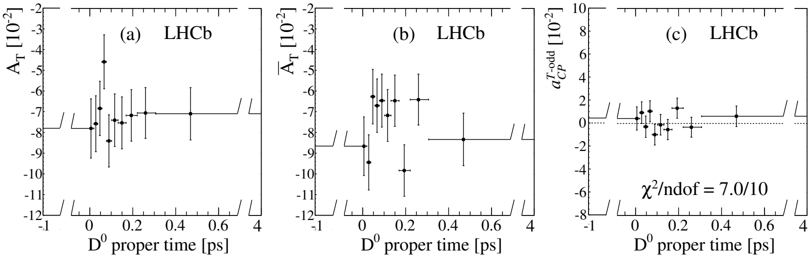


Difference between $C_T > 0$ and $C_T < 0$ ($-\bar{C}_T > 0$ and $-\bar{C}_T < 0$) is due to FSI.

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

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

- $a_{CP}^{T\text{-odd}}$ consistent with no time-dependent *CPV* hypothesis with a probability of 83%.
- A_T and $\bar{A}_T$ do not show any significant dependance on the proper time, compatible with a constant at 80% and 38% probability, respectively.



Systematic Uncertainties

Contribution	$\Delta A_T(\%)$	$\Delta \bar{A}_T(\%)$	$\Delta a_{CP}^{T\text{-odd}}(\%)$
Prompt bkg	± 0.09	± 0.08	± 0.00
Detector bias	± 0.04	± 0.04	± 0.04
C_T resolution	± 0.02	± 0.03	± 0.01
Fit Model	± 0.01	± 0.01	± 0.01
Flavor misid.	± 0.08	± 0.07	± 0.00
Total	± 0.13	± 0.12	± 0.04

- PID: $a_{CP}^{T\text{-odd}}$ not dependent on variation of PID.
- Reconstruction Efficiency: not dependent on C_T.
- C_T resolution: estimated accurately from MC.
- Prompt bkg: any contamination affects the asymmetry: $A \to A(1-f) + fA^d$. f-contamination fraction; A^d-asymmetry of the contamination sample; fA^d very small effect.
- Detector bias: conservative estimate from control sample $D^0 \to K^-\pi^+\pi^-\pi^+$ (Cabibbo favored decay).
- Flavor misID: wrongly identified muon candidates $\Rightarrow a_{CP}^{T\text{-odd}} \to a_{CP}^{T\text{-odd}} - \Delta\omega/2(A_T + \bar{A}_T)$, $\Delta\omega$-difference among the mistag probabilities, measured from control samples $B \to D^{*+}\mu^- X$ $(D^{*+} \to D^0\pi^+, D^0 \to K^+K^-\pi^+\pi^-)$

Summary

- $a_{CP}^{T\text{-odd}}$ analysis is a complementary approach for *CPV* searches.
- *CPV* is searched for in $D^0 \to K^+K^-\pi^+\pi^-$ using three methods:
  - measurement integrated over the phase space.
  - measurement in different regions of the phase space.
  - measurement as a function of the D^0 decay time for the first time.
- All results consistent with no *CPV*.
- Established an alternative approach for precision *CPV* searches at LHCb with very small systematic uncertainties.
- Technique is very promising also for LHCb upgrade.