LHCb

EPFL ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

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Measurements of T-odd Observables

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on behalf the LHCb collaboration

Outline

Theoretical introduction

- *CPV* and *T*-odd correlations

Previous searches

- $D^0 \to K^+K^-\pi^+\pi^-$ and $D_{(s)}^+ \to K^+K^0_S\pi^+\pi^-$ decays at FOCUS, BaBar

Search at LHCb

- *CPV* search using *T*-odd correlations in $D^0 \to K^+K^-\pi^+\pi^-$ decays

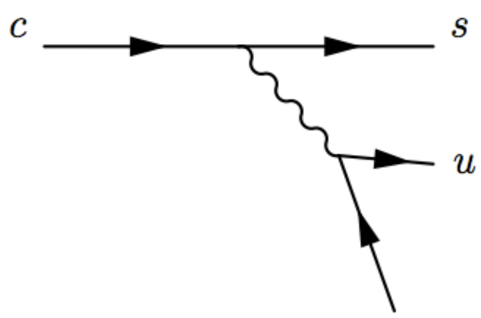
Conclusions

CP Violation in Charm Mesons Decays

G. Isidori et al., Phys. Lett. B711 (2012) 46

Small CKM contribution

- *CPV* is expected to be small in the charm sector since tree-level topology dominates the decay at scales $m_c < \mu < m_b$



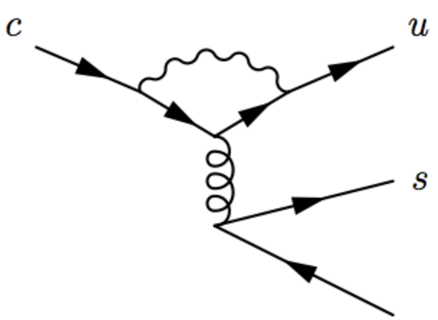
(a) *Tree diagram.*

New Physics

- May enhance this amplitude through the introduction of new processes and particles

Recently

- Mixing in charm is established within SM expectation
- Experiments have recorded enough statistics to probe *CPV* with sensitivities approaching 10^{-3}
- If any NP effect is out there we should start to be able to see it



(b) *Penguin diagram.*

CP Violation Observables

CPV in decay

$$\mathcal{A}_f \equiv \frac{\Gamma(M \to f) - \Gamma(\overline{M} \to \overline{f})}{\Gamma(M \to f) + \Gamma(\overline{M} \to \overline{f})}$$

- *CPV* is measured as the asymmetry between the decay rate of a meson and charge-conjugate state

$$\mathcal{A}_{f\pm} = -\frac{2|a_1 a_2| \sin(\delta_2 - \delta_1) \sin(\phi_2 - \phi_1)}{|a_1|^2 + |a_2|^2 + 2|a_1 a_2| \cos(\delta_2 - \delta_1) \cos(\phi_2 - \phi_1)}$$

CPV in mixing

$$\frac{q}{p} \neq 1, \quad \mathcal{A}_{SL}(t) \equiv \frac{d\Gamma/dt(\overline{M}^0_{\text{phys}}(t) \to l^+ X) - d\Gamma/dt(M^0_{\text{phys}}(t) \to l^- X)}{d\Gamma/dt(\overline{M}^0_{\text{phys}}(t) \to l^+ X) + d\Gamma/dt(M^0_{\text{phys}}(t) \to l^- X)}$$

- *CPV* measured from the mixing parameters

$$\mathcal{A}_{SL} = -\left|\frac{\Gamma_{12}}{M_{12}}\right| \sin(\phi_M - \phi_\Gamma)$$

CPV in interference between decay and mixing

$$Im(\lambda_f) \neq 0, \quad \lambda_f \equiv \frac{q}{p}\frac{\overline{A}_f}{A_f}, \quad \mathcal{A}_{f_{CP}}(t) \equiv \frac{d\Gamma/dt(\overline{M}^0_{\text{phys}}(t) \to f_{CP}) - d\Gamma/dt(M^0_{\text{phys}}(t) \to f_{CP}}{d\Gamma/dt(\overline{M}^0_{\text{phys}}(t) \to f_{CP} + d\Gamma/dt(M^0_{\text{phys}}(t) \to f_{CP}}$$

- *CPV* asymmetry is modified by mixing effects

$$\mathcal{A}_{f_{CP}}(t) = \eta_f \sin(\phi_M + 2\phi_f) \sin(\Delta m t)$$

ϕ: weak phases, from CKM
δ: unitarity (strong) phases

T-odd Observables

G. Valencia, Phys. Rev. D39 (1989) 3339

A different point of view

- **Describe invariant matrix element in the most general way (quasi two-body)** $B(p) \to V_1(k,\epsilon_1)V_2(q,\epsilon_2)$

$$M = a\epsilon_1 \cdot \epsilon_2 + \frac{b}{m_1 m_2}(p\cdot\epsilon_1)(p\cdot\epsilon_2) + i\frac{c}{m_1 m_2}\epsilon^{\alpha\beta\mu\nu}\epsilon_{1\alpha}\epsilon_{2\beta}k_\mu p_\nu$$

S+D+P

$$a = \sum_j |a_j| e^{i(\delta_{sj}+\phi_{sj})}; \quad b = \sum_j |b_j| e^{i(\delta_{dj}+\phi_{dj})}; \quad c = \sum_j |c_j| e^{i(\delta_{pj}+\phi_{pj})}$$

$$\bar{a} = \sum_j |a_j| e^{i(\delta_{sj}-\phi_{sj})}; \quad \bar{b} = \sum_j |b_j| e^{i(\delta_{dj}-\phi_{dj})}; \quad \bar{c} = \sum_j |c_j| e^{i(\delta_{pj}-\phi_{pj})}$$

- **A triple-product correlation arises in $|M|^2$ from terms involving the *c* amplitude (Im[ac*], Im[bc*]) wrt $\vec{k}\cdot(\vec{\epsilon}_1\times\vec{\epsilon}_2)$**

$$A_B = \frac{\Gamma(k\cdot\epsilon_1\times\epsilon_2>0)-\Gamma(k\cdot\epsilon_1\times\epsilon_2<0)}{N_B}$$
$$\approx \Im(ac^*) = |ac| e^{i(\delta_s-\delta_p)} e^{i(\phi_s-\phi_p)} = |ac|\sin(\Delta\delta+\Delta\phi)$$

- **The same observable on the charge-conjugate decay gives**

$$A_{\bar{B}} \approx |ac| e^{i(\delta_s-\delta_p)} e^{-i(\phi_s-\phi_p)} = |ac|\sin(\Delta\delta-\Delta\phi)$$

- **That allows the definition of the *CPV* observable**

$$a_{CP}^{T-\text{odd}} = A_B + A_{\bar{B}} \approx \cos\Delta\delta\sin\Delta\phi$$

Comparison to Direct CPV

A. Datta and D. London, Int.J.Mod.Phys. A19 (2004) 2505

They are complementary

- **The only difference is in the unitarity phases that enter differently in the game**

$$a_{CP} \propto \sin\Delta\delta \sin\Delta\phi$$
$$a_{CP}^{T-\text{odd}} \propto \cos\Delta\delta \sin\Delta\phi \qquad (*)$$

- **a_{CP} is more sensitive to *CPV* when the difference in the strong phases is large**

- **$a_{CP}^{T\text{-odd}}$ is more sensitive to *CPV* when the difference in the strong phases between the interfering amplitudes is small**

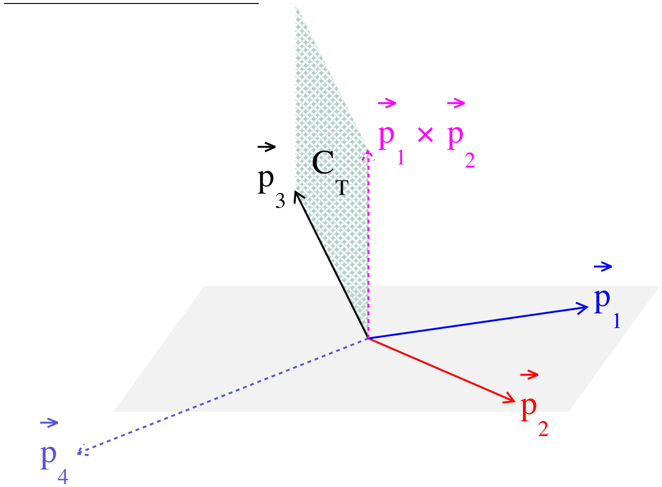
- **Datta and London demonstrated that a TP asymmetry can be also built with interference between decay and mixing, but it is proportional to sinΔδ as well.**

(*) **Caveat**: in a_{CP} the two phases are from different diagrams, in a_{CP}^{Todd} from different spin contributions

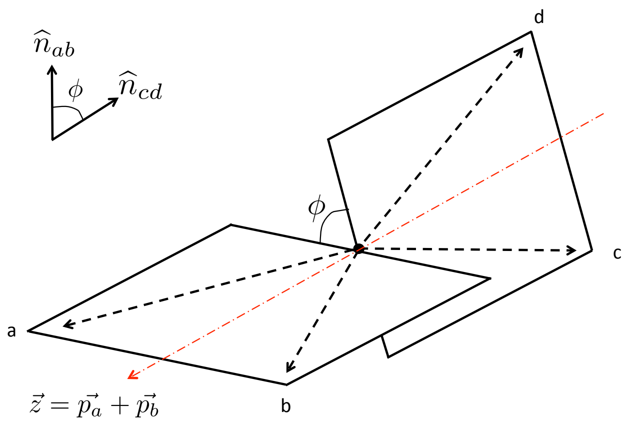
Defining a T-odd observable

- One needs at least 3 independent momentum or spin variables

4-body decay



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



$$\sin\phi = (\hat{n}_{ab} \times \hat{n}_{cd}) \cdot \hat{z}$$

- Momenta can be also used to define angles

T-odd Correlation Asymmetry

Asymmetries

- Two asymmetries are measured separately on the particle and charge-conjugate decays

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

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

- The *CP*-violating asymmetry is

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

Results From Previous Experiments

Used prompt D^0 and $D_{(s)}^+$ decays

- **FOCUS (2005) N_{ev}~1k**

Link et al., Phys. Lett. B662 (2005)239

$$a_{CP}^{T-\mathrm{odd}}(D^0) = (1.0 \pm 5.7(\mathrm{stat}) \pm 3.7(\mathrm{syst}))\%$$

$$a_{CP}^{T-\mathrm{odd}}(D^+) = (2.3 \pm 6.2(\mathrm{stat}) \pm 2.2(\mathrm{syst}))\%$$

$$a_{CP}^{T-\mathrm{odd}}(D_s^+) = (-3.6 \pm 6.7(\mathrm{stat}) \pm 2.3(\mathrm{syst}))\%$$

- **BaBar (2010-2011) N_{ev}~50k**

del Amo Sanchez et al., Phys. Rev. D81 (2010) 111103(R)
Lees et al., Phys. Rev. D84 (2011) 031103(R)

$$a_{CP}^{T-\mathrm{odd}}(D^0) = (1.0 \pm 5.1(\mathrm{stat}) \pm 4.4(\mathrm{syst})) \times 10^{-3}$$

$$a_{CP}^{T-\mathrm{odd}}(D^+) = (-12.0 \pm 10.0(\mathrm{stat}) \pm 4.6(\mathrm{syst})) \times 10^{-3}$$

$$a_{CP}^{T-\mathrm{odd}}(D_s^+) = (-13.6 \pm 7.7(\mathrm{stat}) \pm 3.4(\mathrm{syst})) \times 10^{-3}$$

- **BaBar provided significant statistical improvement (x10)**

Latest Results From LHCb - $D^0 \to K^+K^-\pi^+\pi^-$

JHEP10(2014)005

Semileptonic B decay

- $D^0 \to K^+K^-\pi^+\pi^-$ from semileptonic B decays, tagged from muon charge
  $B \to D^0\mu^- X$, $D^0 \to K^+K^-\pi^+\pi^-$
- Clean sample

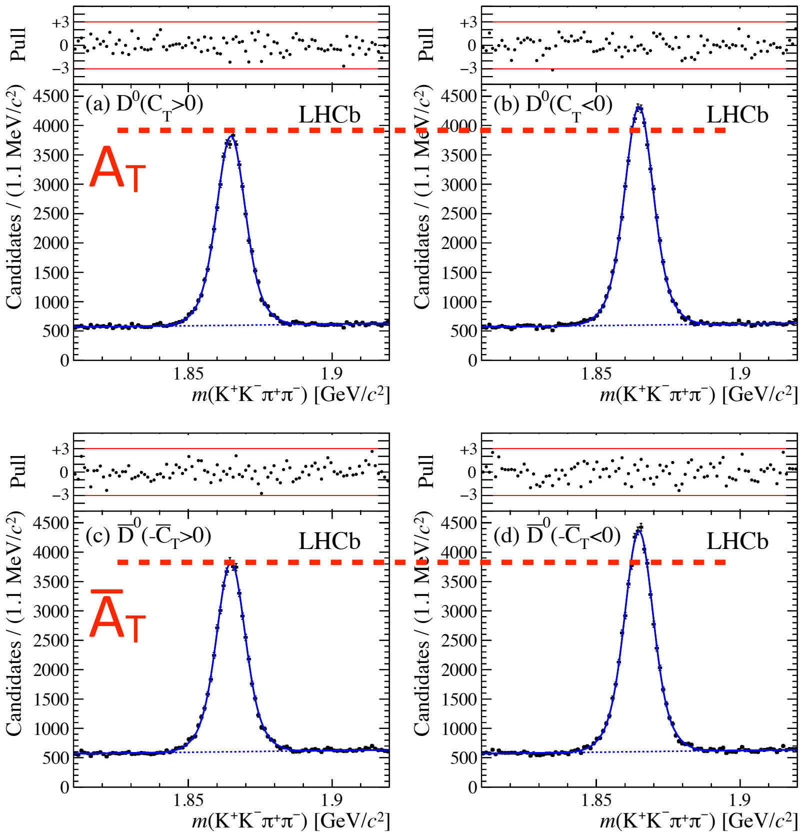
Data Sample

- 2011+2012: $3 fb^{-1}$

Fit Model

- Samples simultaneously fit to a model of two Gaussian distributions over an exponential shape
- Asymmetry parameters extracted from the fit

$B \to D^0\mu^- X$, $D^0 \to K^+K^-\pi^+\pi^-$



$3 fb^{-1}$: $N_{ev} \sim 170k$

Results From LHCb

JHEP10(2014)005

Three Measurements

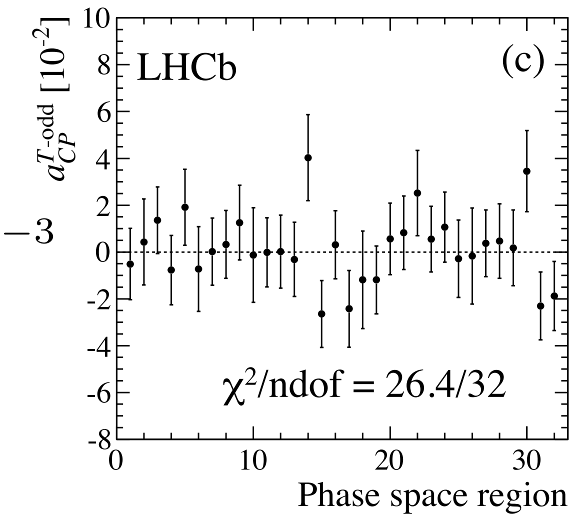
1. **Integrated**

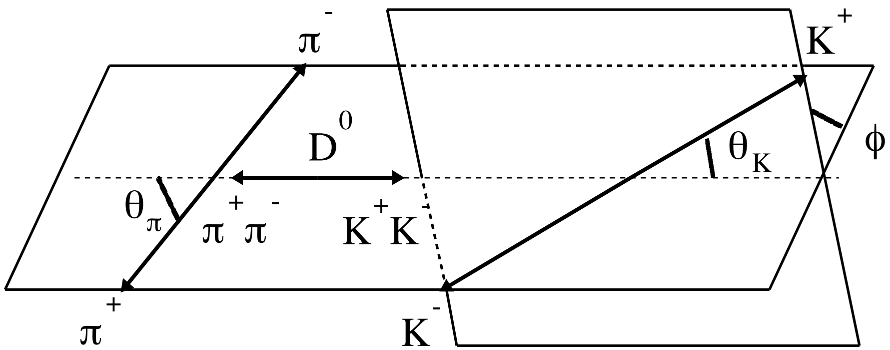
$$a_{CP}^{T-\text{odd}}(D^0) = (1.8 \pm 2.9(\text{stat}) \pm 0.4(\text{syst})) \times 10^{-3}$$

2. **Bins of phase-space**

   No significant deviation from 0 observed

   CP conservation tested with P(χ^2)=74%

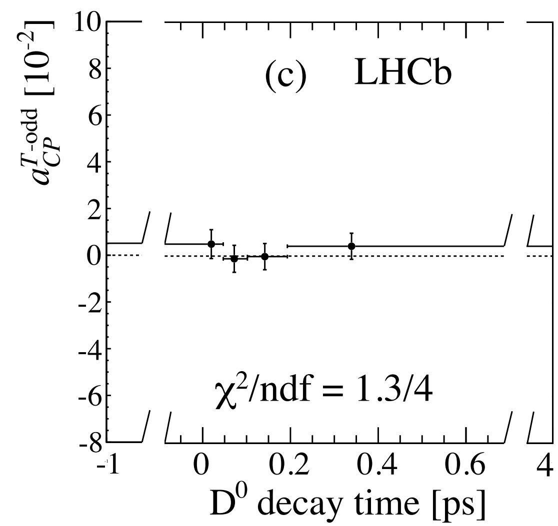




3. **Bins of D^0 decay time**

   No significant deviation from 0 observed

   CP conservation tested with P(χ^2)=83%



Results From LHCb - A_T and $\bar{A}_T$

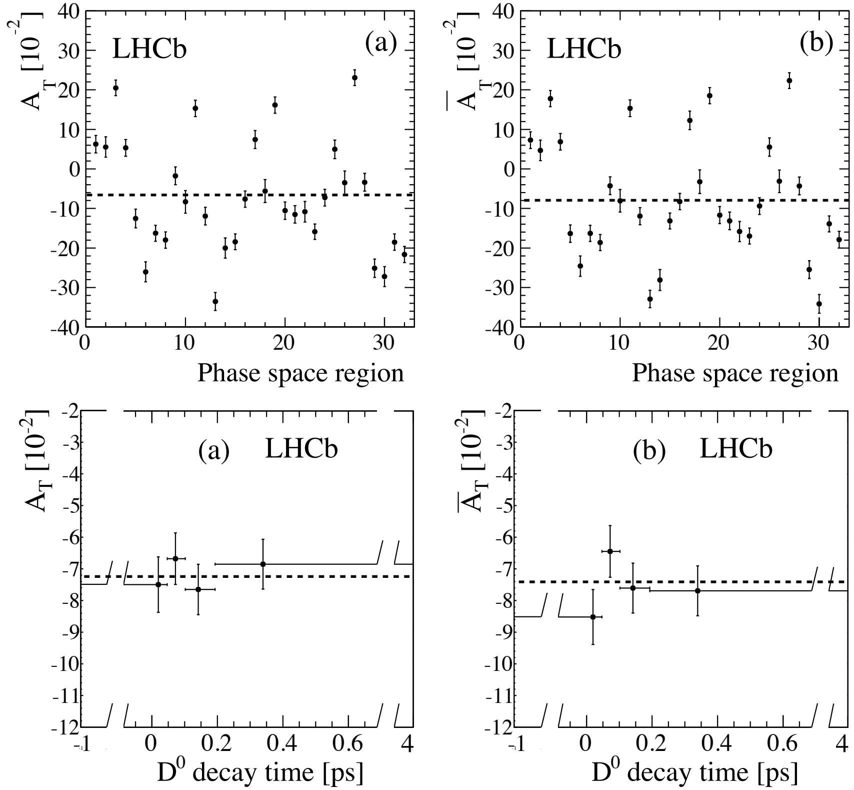
JHEP10(2014)005

$B \to D^0 \mu^- X$, $D^0 \to K^+ K^- \pi^+ \pi^-$

Local asymmetries up to 30%

FSI Effects?

- It's possible that FSI are producing effects in all the three measurements
- Significant differences in bins of phase space
- Average consistent wrt D^0 decay time
- Wide spectrum of resonances and rescattering among the final state particles



$$A_T(D^0) = (-71.8 \pm 4.1(\text{stat}) \pm 1.3(\text{syst})) \times 10^{-3}$$
$$\bar{A}_T(D^0) = (-75.5 \pm 4.1(\text{stat}) \pm 1.2(\text{syst})) \times 10^{-3}$$

A Rich Resonant Structure

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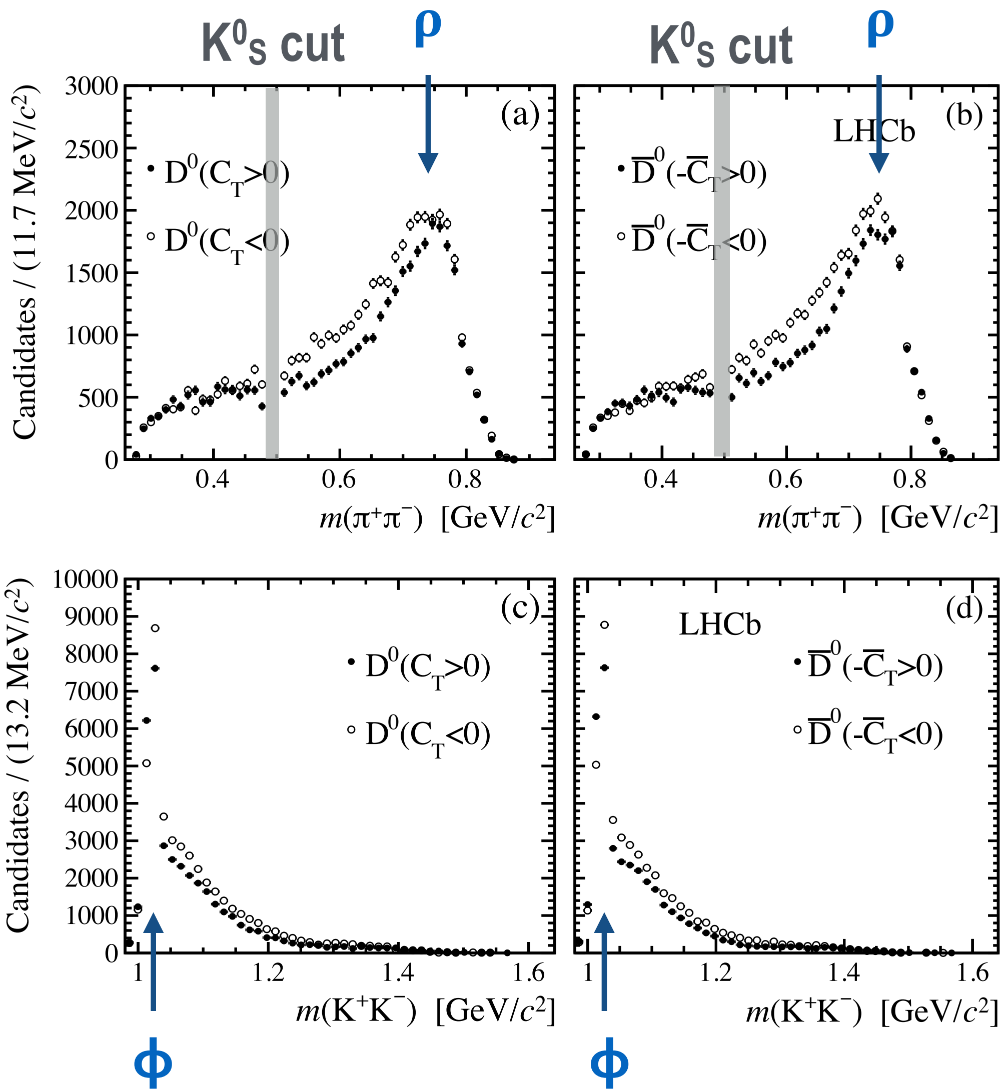
Resonant structure in $D^0 \rightarrow K^+K^-\pi^+\pi^-$

- Clear evidence for ϕ and ρ resonances
- Significant difference in the distributions vs C_T
- Visible effects in angular variables as well
- $D^0 \rightarrow K^0_S K^+K^-$ removed by $\pi^+\pi^-$ invariant mass cut



An Almost Systematic Free Measurement

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Reconstruction Efficiency ☺

- Does not affect at all the result: A_T and $\bar{A}_T$ asymmetries are calculated separately on the same final state

Particle Identification ☺

- The same considerations apply to particle identification

C_T Resolution ✌

- Estimated accurately from Monte Carlo, almost cancels in a_{CP}^{Todd}

Systematic uncertainty estimates

Contribution	$\Delta A_T(\%)$	$\Delta \bar{A}_T(\%)$	$\Delta a_{CP}^{T\text{-odd}}(\%)$
Prompt background	±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 misidentification	±0.08	±0.07	±0.00
Total	±0.13	±0.12	±0.04

Peaking Backgrounds under $D^0/\bar{D}^0$ signal ✌

- Any contamination affects the asymmetry as $A \rightarrow A(1 - f) + f A^d$ ← very small effect

  f - contamination fraction; A^d - asymmetry of the contamination sample

Flavour Mistag ✌

- Considering the events with flavour mistag as a contamination $a_{CP}^{T\text{-odd}} \rightarrow a_{CP}^{T\text{-odd}} - \Delta\omega/2(A_T + \bar{A}_T)$

  $\Delta\omega = \omega^+ - \omega^-$ — difference among the mistag probabilities, measured from control samples

  $B \rightarrow D^{*+}\mu^- X$, ($D^{*+} \rightarrow D^0\pi^+$, $D^0 \rightarrow K^+K^-\pi^+\pi^-$); $B \rightarrow D^0\mu^- X$ ($D^0 \rightarrow K^-\pi^+\pi^+\pi^-$)

Detector bias ✌

- Conservative estimate from control sample of CF $D^0 \rightarrow K^-\pi^+\pi^+\pi^-$

LHCb Summary

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Results

- ***CPV* is searched for in $D^0 \to K^+K^-\pi^+\pi^-$ using:**
  1. A measurement integrated over the phase space
  2. Measurements in different regions of the phase space
  3. Measurements as a function of the D^0 decay time

1[st] time!

- **No *CPV* found**
- **Interesting information in the phase space of the decay: local A_T asymmetries up to 30%**
  These results are interpreted as possible effects of FSI produced by the rich resonant structure of the decay

Remarks

- **Systematic uncertainties are found to be very small (as expected) in these observables**
  High statistics control samples, toy studies

LHCb Potential

- **The full LHCb potential is not exploited yet**
  A similar measurement on $D^{*+} \to D^0(\to KK\pi\pi)\pi^+$ decays is ongoing and will roughly double the statistics
- **Run2 just behind the corner**
  Improved trigger and selections promise 2.5 data per fb^{-1} wrt to Run1
- **The rich resonant structure awaits detailed investigation**
  Model-dependent and -independent approaches under study
- **Other triple product correlations can be studied**
  See talk tomorrow from A. Bevan (hep-ph/1408.3813)

Conclusions

Alternative and Complementary CPV Tests

- Searches for *CPV* through asymmetries in *T*-odd moments are alternative and complementary to "standard" *CPV* measurements
- Applicable to many possible particle decays

Low Systematics

- Analyses have demonstrated that the systematic uncertainties are very small

Outlook

- Given the very low systematic uncertainties, such measurements could become extremely competitive at LHCb (10fb^{-1}) and at future experiments (Belle-II, LHCb Upgrade,…)