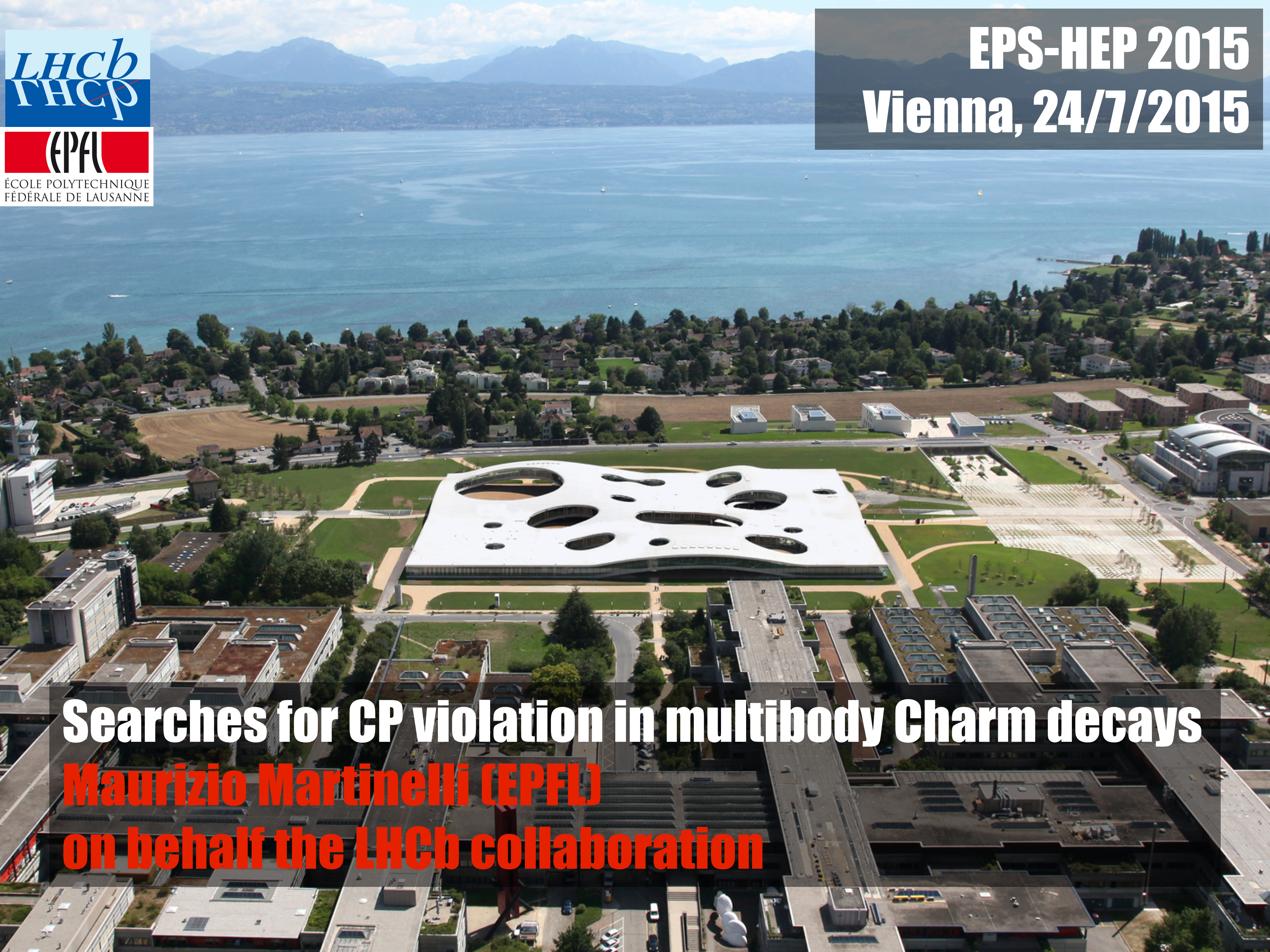


EPS-HEP 2015
Vienna, 24/7/2015

Searches for CP violation in multibody Charm decays

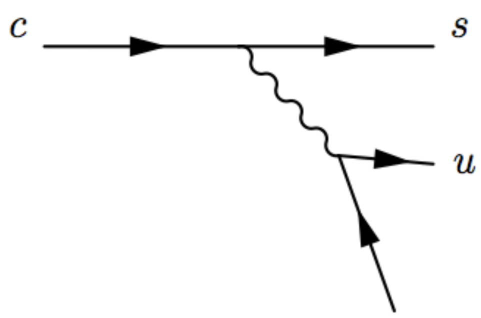
Maurizio Martinelli (EPFL)
on behalf the LHCb collaboration

CP Violation in Charm Mesons Decays

Small CKM contribution

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

- *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.*

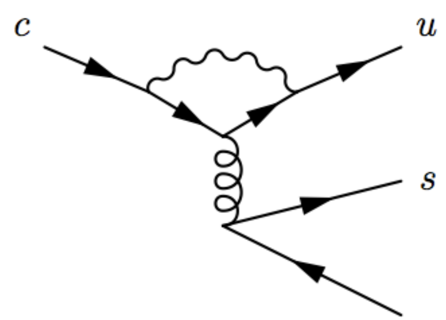
New Physics

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

CPV in Charm is a clean probe for NP!

Recent results

- 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.*

Multibody Charm decays

Interesting probes for CPV

- Allow to access a wide range of decays within the same final state that may have different contributing processes
- drawback: final state interactions introduce strong phase differences

Interpreting the results

- Many amplitudes can contribute to the same phase space region
  $\Longrightarrow$ Amplitude analysis is needed to clearly separate contributing amplitudes
- Other techniques are sensitive to CPV but are not able to identify its source
- Need to approach the topic from various sides

Techniques applied on LHCb data

- Energy Test: $D^0 \rightarrow \pi^+\pi^-\pi^0$
- S_{CP}: $D^+ \rightarrow \pi^+\pi^-\pi^+$, $D^0 \rightarrow \pi^+\pi^-\pi^+\pi^-$, $D^0 \rightarrow K^+K^-\pi^+\pi^-$
- kNN: $D^+ \rightarrow \pi^+\pi^-\pi^+$

} $\longrightarrow$ Discovery tools

- Amplitude analysis: $D^0 \rightarrow K^0_S K^\pm \pi^\mp$ $\longrightarrow$ Complete description
- Triple-product correlations: $D^0 \rightarrow K^+K^-\pi^+\pi^-$ $\longrightarrow$ Alternative observables

Energy Test on $D^0 \to \pi^+\pi^-\pi^0$

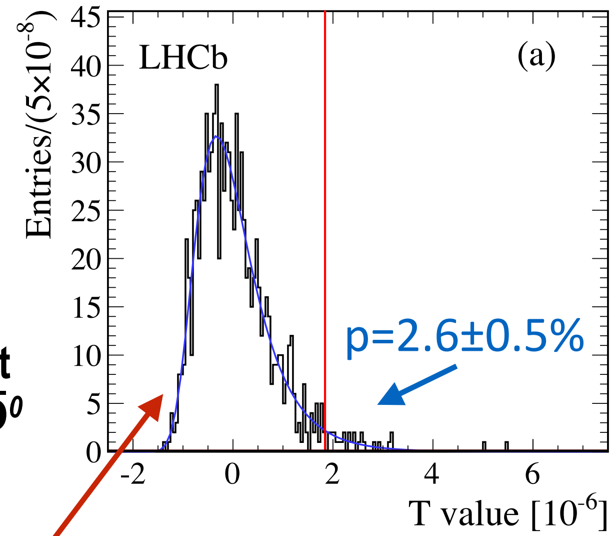
LHCb, Phys. Lett. B740 (2015) 158

Many first's

- First Charm analysis in LHCb using π^0's
- First analysis using "Energy test" method for CPV search

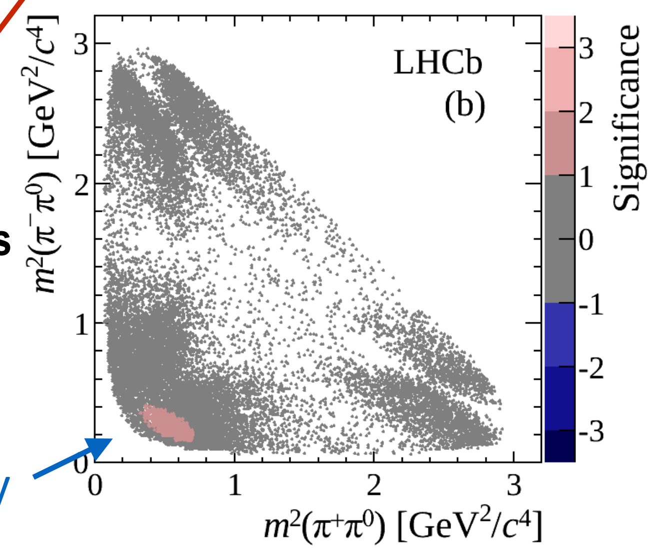
Energy Test

- Comparison of the average-pairwise distances on Dalitz plot among all D^0 events, all $\overline{D}^0$ events, and all D^0 events to all $\overline{D}^0$ events
- Test statistic T:
  T→0: equal distances among points ⟹ no asymmetry
  T>0: distances in D^0 Dalitz plane larger than those in $\overline{D}^0$



Results

- Produced data-permutation samples with no-CPV hypothesis to extract no-CPV T-value distribution (with GPUs)
- p-value = (2.6±0.5)%
- Best sensitivity to date for CPV in $D^0 \to \pi^+\pi^-\pi^0$



Method allows to visualise regions with larger asymmetry

S_{CP} (aka Miranda)

Bediaga et al., Phys. Rev. D80 (2009) 096006
BaBar, Phys. Rev. D78 (2008) 051102

Hunting for local asymmetries

- Decaying phase space divided in bins
- Compare the number of events for the two D flavours

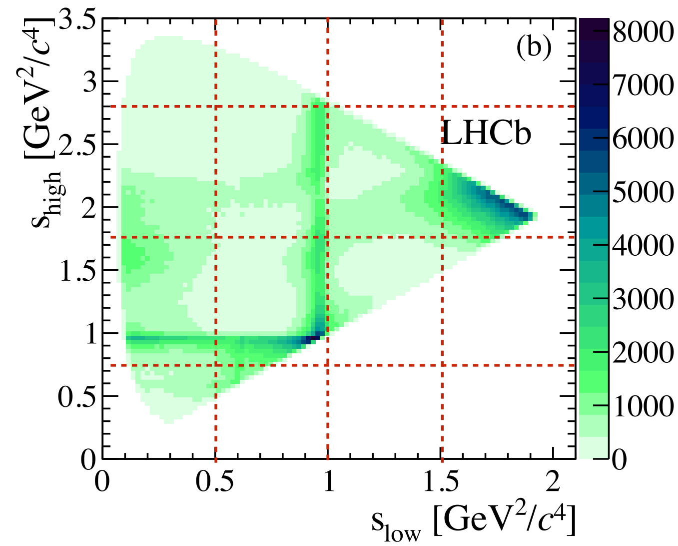
$$S_{CP}^{i} = \frac{n_i(D) - \alpha n_i(\bar{D})}{\sqrt{\sigma_i^2(D) + \alpha \sigma_i^2(\bar{D})}}, \alpha = \frac{\sum_i n_i(D)}{\sum_i n_i(\bar{D})}$$

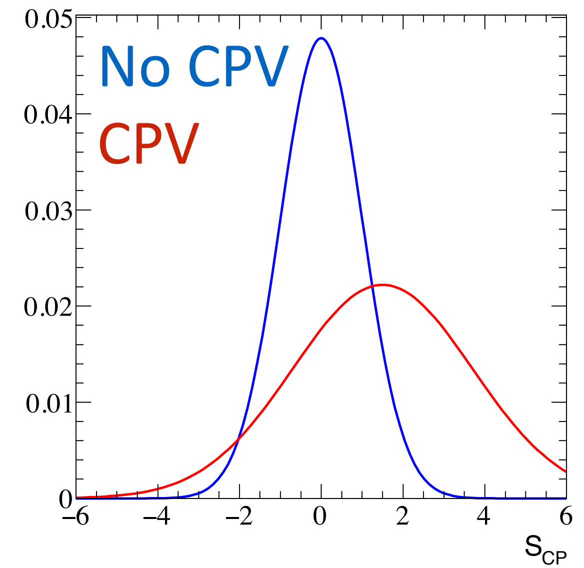
n_i = # events per bin, σ_i = error on n_i

- S_{CP} is distributed as Gaussian G(μ=0,σ=1) for CP conserving decays
- p-value from

$$\chi^2 = \sum_i (S_{CP}^{i})^2$$

- Method is tested on toy studies with different binning schemes (number of events, strong phase similarity)

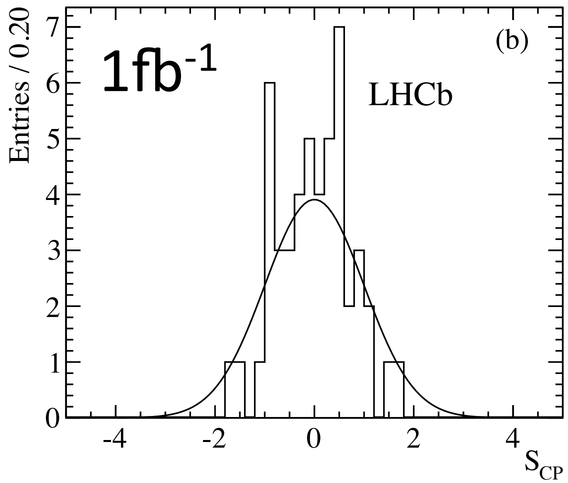




S_{CP} in three- and four-body D decays

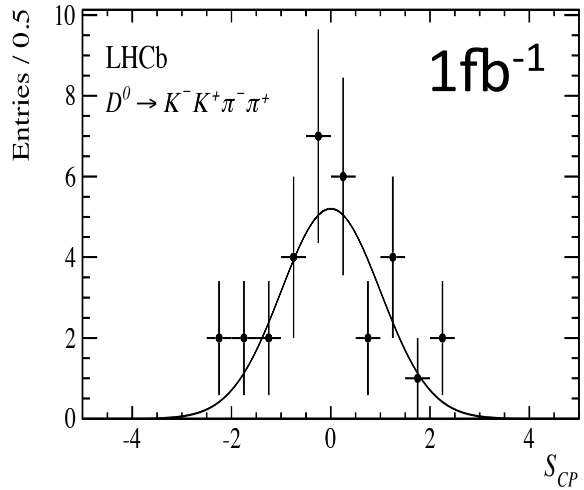
LHCb, Phys. Lett. B726 (2013) 623
LHCb, Phys. Lett. B728 (2014) 585

$D^+ \rightarrow \pi^+\pi^-\pi^+$



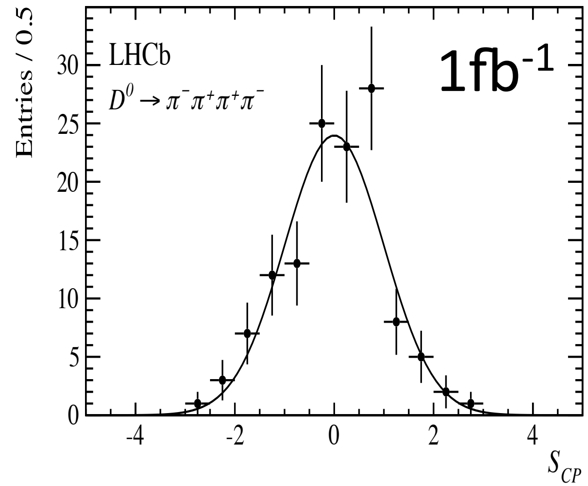
- **3.1M D^+ events**
- **49 adaptive bins of equal population**
- **Sensitivity**
  2° phase difference and 2% amplitude in $\rho(700)\pi^+$, $\sigma(500)\pi^+$, $f_2(1270)\pi^+$
- **p-value = 99.5%**

$D^0 \rightarrow K^+K^-\pi^+\pi^-$



- **57k D^0 events**
- **32 adaptive bins of equal population**
- **Sensitivity**
  10° phase difference and 10% amplitude in $\phi\rho$
- **p-value = 9.1%**

$D^0 \rightarrow \pi^+\pi^-\pi^+\pi^-$



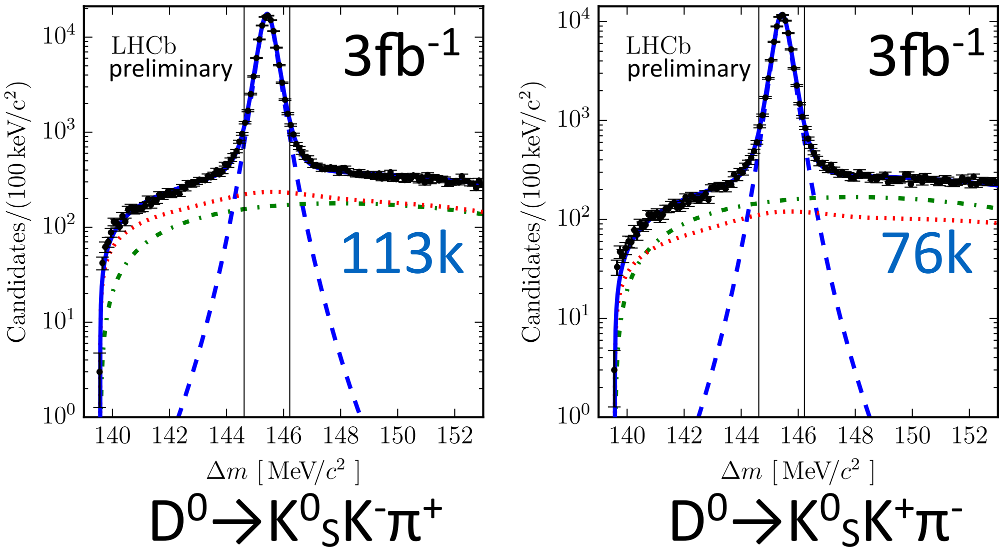
- **0.3M D^0 events**
- **128 adaptive bins of equal population**
- **Sensitivity**
  10° phase difference and 10% amplitude in $a_1(1260)\pi^+$
- **p-value = 41.0%**

Amplitude analysis: $D^0 \to K^0_S K\pi$

LHCB-PAPER-2015-026

First LHC Charm amplitude analysis measurement!

- Yes, we can do that!
- Large statistics (~180k)
- Complex Dalitz plot structure
- Used GPU's



Not only CPV

- Tests of SU(3) flavour symmetry
- Isobar models of D^0 decays assuming *CP* conservation useful for mixing measurements and γ in $B^- \to D^0 K^-$
- Removing CP assumption, model-dependent search for CPV

Benchmark for future LHCb multibody analysis

- The experience gained is being used to perform amplitude analysis of other channels

  $D^0 \to K^0_S h^+ h^-$

  $D^+ \to h^+ h^- h^+$

$D^0 \to K^0_S K\pi$ Dalitz plot

LHCB-PAPER-2015-026

Resonance states

- $K^*(892)^{\pm}$, $(K\pi)^{0,+}_{\text{S-wave}}$, $K^*(892)^0$ and $K^*_{1,2}$

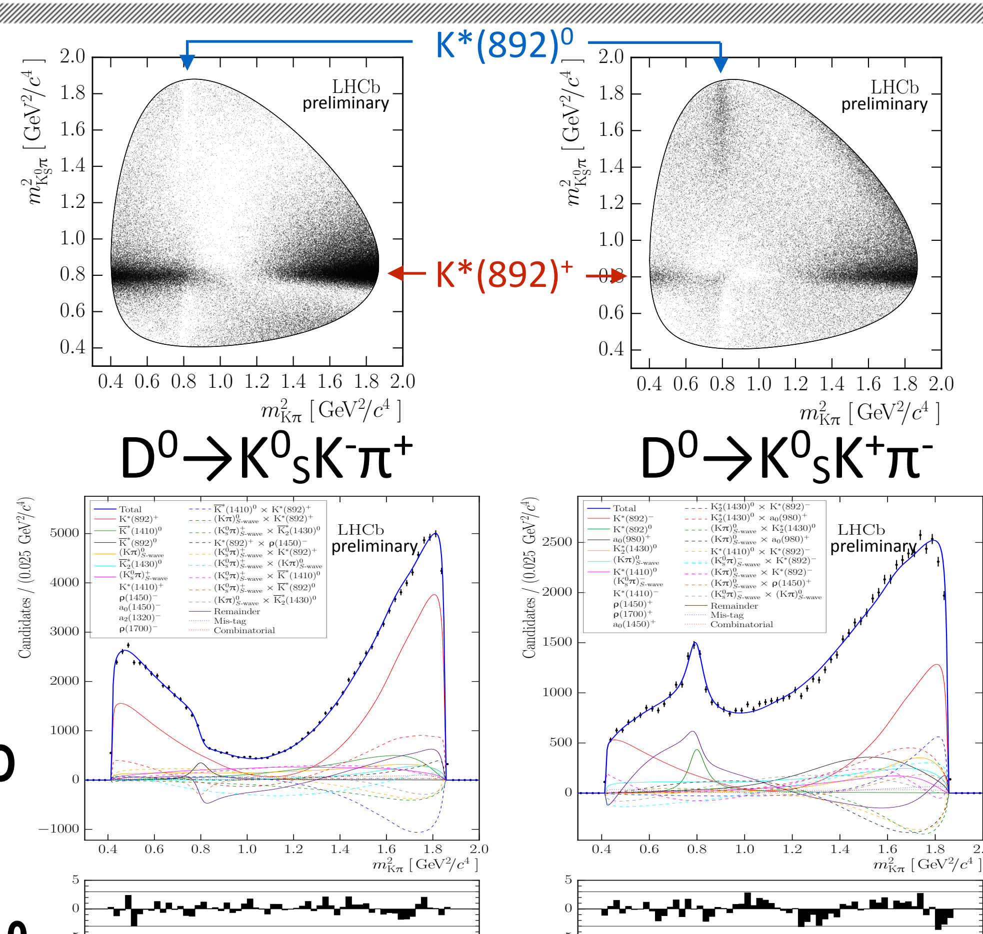
  ~50% ~10% ~1-5%

Model

- S-wave: GLASS vs. LASS give consistent results

Coherence factors

- $R_{K_S K\pi}$, R_{K^*K} improved factor 10 wrt CLEO
- Do not depend by S-wave parametrisation
- Strong phase difference consistent wrt 0



Variable	GLASS	LASS
$R_{K^0_S K\pi}$	$0.573 \pm 0.007 \pm 0.019$	$0.571 \pm 0.005 \pm 0.019$
R_{K^*K}	$0.831 \pm 0.004 \pm 0.010$	$0.835 \pm 0.003 \pm 0.011$
$\delta_{K^0_S K\pi} - \delta_{K^*K}$	$(0.2 \pm 0.6 \pm 1.1)^\circ$	$(-0.0 \pm 0.5 \pm 0.7)^\circ$

CPV search and other measurements

LHCB-PAPER-2015-026

Model dependent CPV

- Introduce CPV parameters in the model

$$A = \sum_R a_R e^{i\phi_R} A_R \Longrightarrow \sum_R a_R (1 \pm \Delta a_R) e^{i(\phi_R \pm \Delta\phi_R)} A_R$$

amplitude coefficient resonance CPV terms

- Sign depending on D0 flavour
- Perform a χ^2 test wrt to no CPV hypothesis fit (Δ=0)

  $\chi^2/n_{dof} = 32.3/32 = 1.01 \longrightarrow$ p-value = 0.45

Branching Ratio

$$\mathcal{B}_{K_S^0 K\pi} \equiv \frac{\mathcal{B}(D^0 \to K_S^0 K^+ \pi^-)}{\mathcal{B}(D^0 \to K_S^0 K^- \pi^+)} = 0.655 \pm 0.004(\mathrm{stat}) \pm 0.006(\mathrm{syst})$$

$$\mathcal{B}_{K^* K} = 0.370 \pm 0.003(\mathrm{stat}) \pm 0.012(\mathrm{syst})$$

SU(3) flavour symmetry test

- Results in agreement between LASS and GLASS and in favour of theoretical scenario with small η-η' mixing angle

Triple product correlations

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

Use momenta or spin vectors

- **Spinless particle → minimum 4-body**
- **Spin particle → minimum 3-body**

very small σ_{syst}:
no pid, prod. asym., reconstruction

Asymmetries

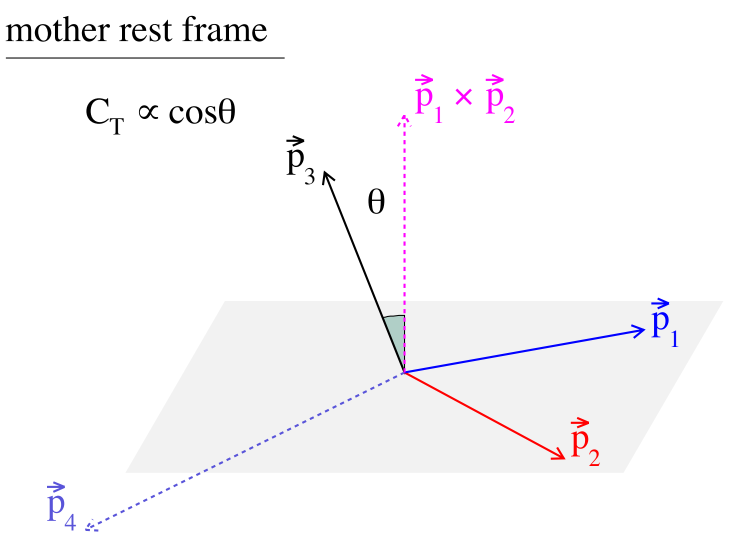
- **Built on the D and $\bar{\text{D}}$ sample separately**

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

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

- **Combined to get the CPV asymmetry**

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



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

Sensitivity

- **Complementary to direct CPV observables wrt to strong phase contribution**

$$a_{CP} \propto \sin\Delta\delta \sin\Delta\phi$$

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

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

TP correlations in $D^0 \to K^+K^-\pi^+\pi^-$

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**

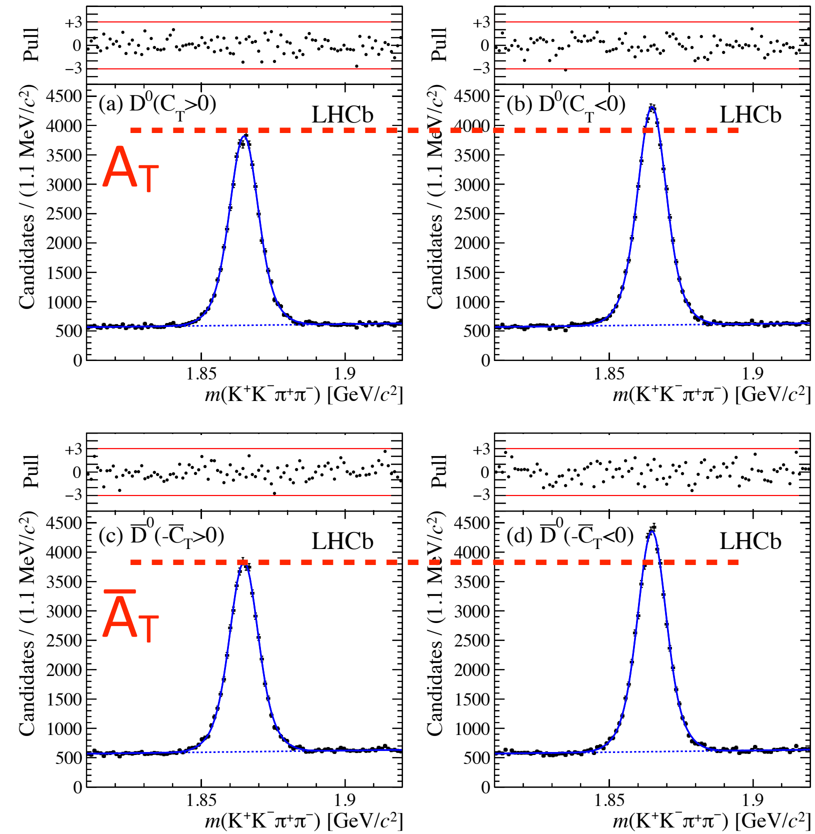
Data Sample

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

Fit Model

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

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



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

$D^0 \to K^+K^-\pi^+\pi^-$ Results

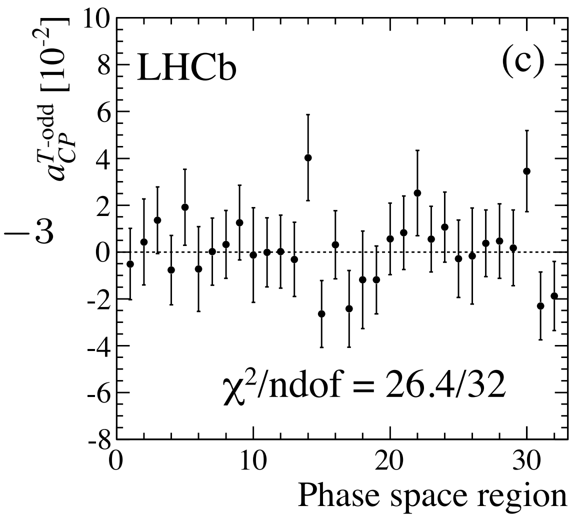
JHEP10(2014)005

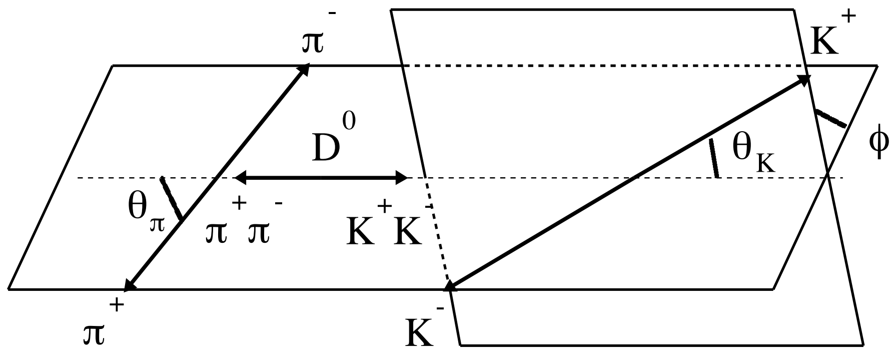
Three Measurements

1. **Integrated**

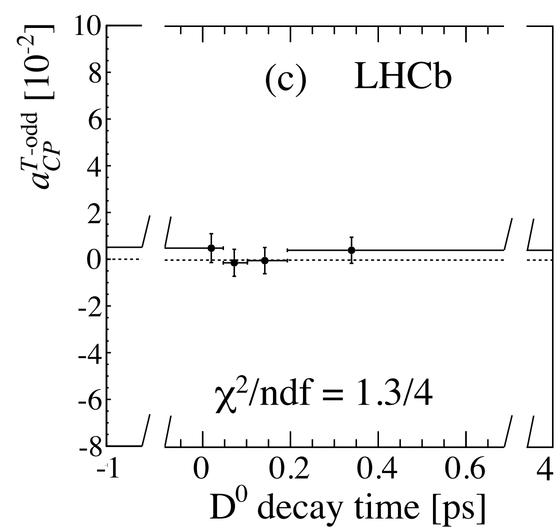
$$a_{CP}^{T-\text{odd}}(D^0) = (1.8 \pm 2.9(\text{stat}) \pm 0.4(\text{syst})) \times 10^{-3}$$

2. **Bins of phase-space**
   No significant deviation from 0 observed
   CP conservation tested with $P(\chi^2)=74\%$





3. **Bins of D^0 decay time**
   No significant deviation from 0 observed
   CP conservation tested with $P(\chi^2)=83\%$



A_T and $\bar{A}_T$?

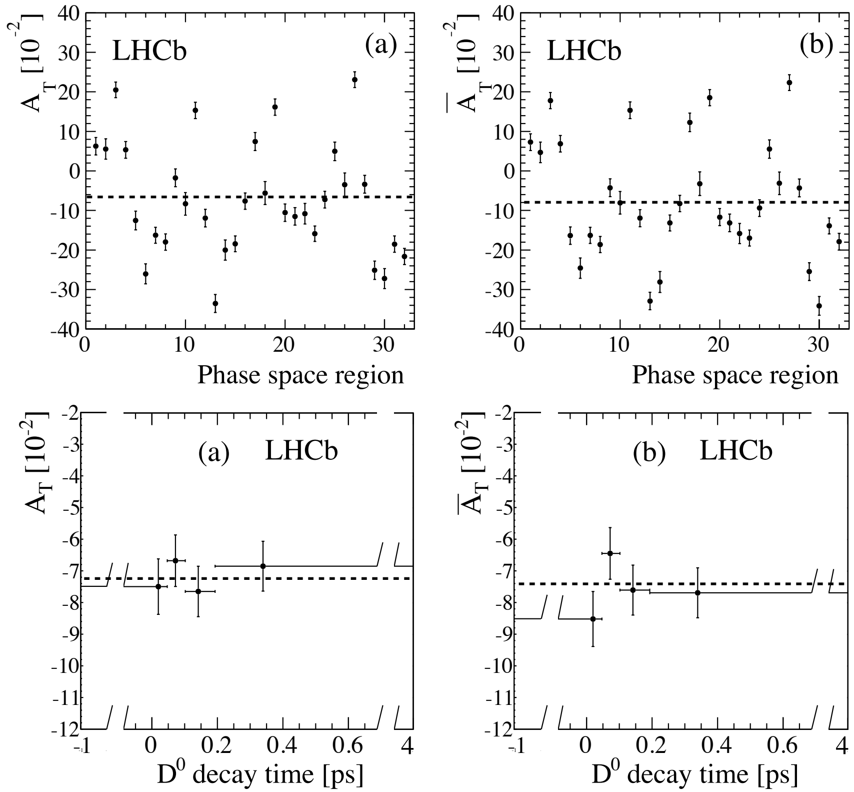
JHEP10(2014)005

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

Parity violation or FSI Effects?

- A_T and $\bar{A}_T$ are P-odd observables
- 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

Local asymmetries up to 30%



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

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

Conclusions

Multi body Charm and CPV

- The rich final state structure is excellent for studying different decay processes at once
- CPV can hide in specific corners of phase space

Techniques

- Model-independent searches as a discovery tool
- Amplitude analysis provide full understanding of the decay process
- Multi-body decays allow to study other observables such as triple products

Status and Outlook

- LHCb has just started to probe CPV in multi-body decays with sensitivities ~0.3%
- Many techniques have been developed during Run1 and are being refined for Run2
- In particular, model-dependent studies of large Charm data samples are on their way