CP Violation in Charm Decays at LHCb

Carla Göbel
Dept. de Física, PUC-Rio

on behalf of the LHCb Collaboration

LISHEP 2011
CBPF, Rio de Janeiro, July 04-10, 2011

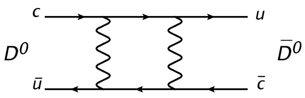
Outline

1. Introduction

Why study CP violation in charm?

★ Mixing and CPV

- $\not{C}P$ and mixing well established in K and B systems
- charm system is the only up-quark sector which can exhibit these phenomena
  $\rightarrow \pi^0$ is its own antiparticle and top does not hadronize....
- mixing in $D^0 - \bar{D}^0$ now verified with $\sim 10\sigma$
  (no single 5σ though)



mass eigenstates:

$$|D_1\rangle = p|D^0\rangle + q|\bar{D}^0\rangle$$
$$|D_2\rangle = p|D^0\rangle - q|\bar{D}^0\rangle$$

$$m = \frac{m_1+m_2}{2}, \quad \Gamma = \frac{\Gamma_1+\Gamma_2}{2}$$

$$\boxed{x = \frac{\Delta m}{\Gamma}} \qquad \boxed{y = \frac{\Delta\Gamma}{2\Gamma}}$$

- Indirect $\not{C}P$ arising through $D^0 - \bar{D}^0$ mixing estimated to be $\mathcal{O}(10^{-4})$ in the SM
  but up to $\mathcal{O}(10^{-2})$ in NP

Y. Grossman, A. L. Kagan, and Y. Nir, Phys. Rev. D 75, 036008 (2007)

Why study CP violation in charm?

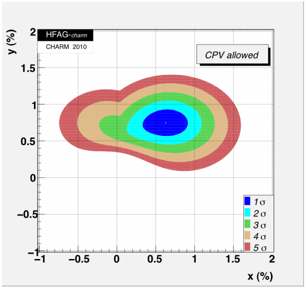
some mixing observables sensitive to $\not{C}P$

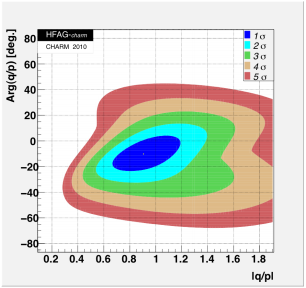
$$2y_{CP} = (|q/p| + |p/q|)\, y\cos\phi - (|q/p| - |p/q|)\, x\sin\phi$$
$$2A_\Gamma = (|q/p| - |p/q|)\, y\cos\phi - (|q/p| + |p/q|)\, x\sin\phi$$

with $\arg(q/p) = \phi$

In the absence of $\not{C}P$: $|q/p| = 1,\ \phi = 0,$
$y_{CP} = y,\ A_\Gamma = 0$

otherwise manifestation of $\not{C}P$!!

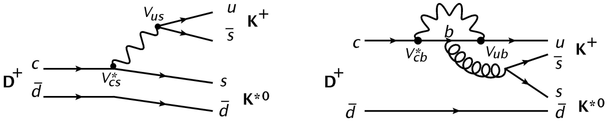




Why study CP violation in charm?

★ Direct $C\not{P}$

- in the SM, appears in single-Cabibbo suppressed channels:



both have $\mathcal{I}m(\mathcal{A}) \propto \lambda^5$ in the SM

$\Rightarrow$ asymmetries $\mathcal{O}(10^{-4} - 10^{-3})$

NP can enhance to $\mathcal{O}(10^{-3} - 10^{-2})$

- searches through time integrated measurements (both for neutral and charged D's)

In summary:

charm represents a unique sector for searches of $C\not{P}$ (both direct and through mixing)

clear windows for NP due to the low SM predictions

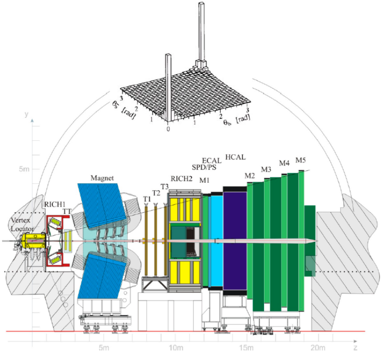
2. The LHCb Experiment and Charm

The LHCb Experiment

The LHCb Experiment

LHCb design

- a forward spectrometer:
  good acceptance for $b\bar{b}$
  $2 < \eta < 5$
- excellent vertexing and proper time resolution
  $\sigma_\tau = 50fs$ (compared to $\tau_D \sim 410\text{fs}$, $\tau_B \sim 1500\text{fs}$)

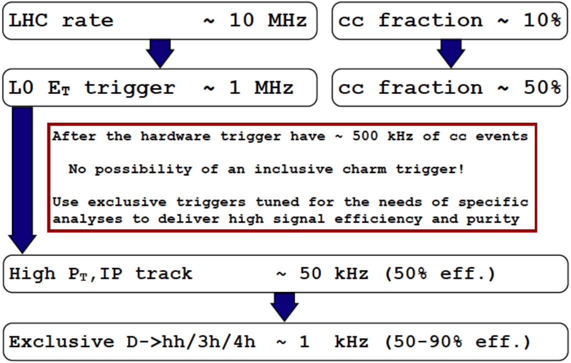


- very good tracking and momentum resolution
  $\sigma_p/p \sim 0.15 - 0.35\%$
- excellent particle ID (specially K/π discrimination)
  kaon ID eff $\sim 95\%$, misid $\sim 7\%$
- excellent features for charm physics too!!!

PUC RIO

Charm Production & Trigger in LHCb

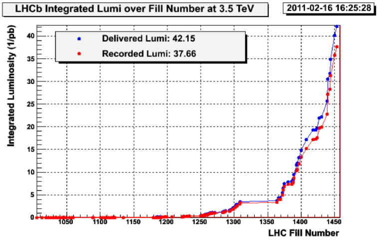
- Two types of charm production:
  - *prompt* - created at the PV
  - *secondary* - from B decay ($\mathcal{B} \sim 50\%$)
- $\sigma(c\bar{c}) \sim 20 \times \sigma(b\bar{b}) \Rightarrow$ much more prompt charm!
- Trigger

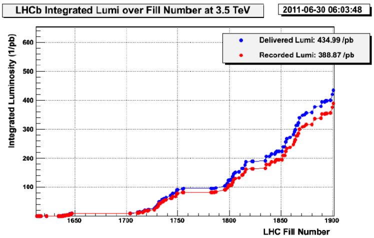


2010 – 2011 Data Taking

2010 data taking: 37 pb^{-1}

2011: $\sim$390 pb^{-1} collected so far





- currently running at $3 \times 10^{32} cm^{-2} s^{-1}$
- ~ 1 fb^{-1} expected by the end of 2011

... results shown here correspond to 2010 data

3. Time Integrated $\not{C}\not{P}$

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

- $D \to h^+h^-$ can manifest time-integrated asymmetries both from • indirect $\not{C}P$ (final-state independent)
  • direct $\not{C}P$ (final-state dependent)

$\Rightarrow$ Look for CP asymmetries in $D \to K^-K^+$ and $D \to \pi^-\pi^+$

$\Rightarrow$ $D \to K^-\pi^+$ as control channel

- CP asymmetry is defined by $A_{CP} = \frac{\Gamma(D^0 \to f) - \Gamma(\bar{D}^0 \to \bar{f})}{\Gamma(D^0 \to f) + \Gamma(\bar{D}^0 \to \bar{f})}$
- what we measure, instead, is

$$A_{RAW} = \frac{N(D^0 \to f) - N(\bar{D}^0 \to \bar{f})}{N(D^0 \to f) + N(\bar{D}^0 \to \bar{f})}$$

- A_{RAW} can have contributions from
  - production
  - detection (particle interaction and/or reconstruction)
  - and ... $\not{C}P$
- study *tagged* and *untagged* modes

tagged (*) : $D^{*+} \to D^0(h^+h^-)\pi_s^+$ and $D^{*-} \to \bar{D}^0(h^+h^-)\pi_s^-$

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

- thus, A_{RAW} is expanded as

$$A_{RAW}(f) = \boxed{A_{CP}(f)} + \boxed{A_D(f)} + \qquad\qquad + \boxed{A_P(D^0)}$$

$$A_{RAW}(f)^* = \boxed{A_{CP}(f)} + \boxed{A_D(f)} + \boxed{A_D(\pi_s)} + \boxed{A_P(D^{*+})}$$

physics CP asymmetry

Detection asymmetry of D[0]

Detection asymmetry of soft pion

Production asymmetry

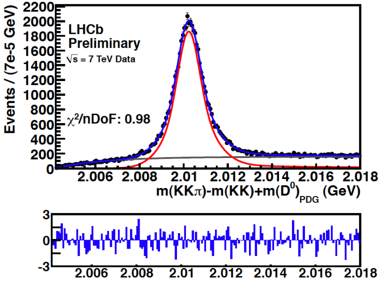
- construct observables for which unknown asymmetries cancel
- without external inputs:

$$A_{CP}(KK) - A_{CP}(\pi\pi) = A_{RAW}(KK)^* - A_{RAW}(\pi\pi)^*$$

  - indirect $\not{C}P$ expected to cancel (since it is final-state independent)
  - expect non-zero result if there is direct $\not{C}P$
  - complementary NP search to A_Γ
- also possible to get info on production asymmetry (discussed later)

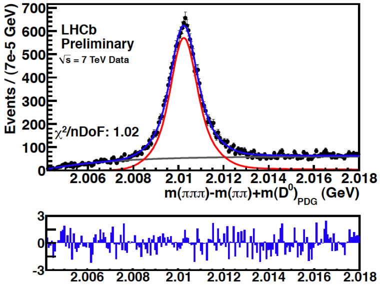
Getting $A_{CP}(KK) - A_{CP}(\pi\pi)$

tagged K^+K^-



yield=1.16×10^5 for 37 pb^{-1}

tagged $\pi^+\pi^-$



yield=0.36×10^5 for 37 pb^{-1}

- study also in bins of (p_T, η) and magnet polarities

Getting $A_{CP}(KK) - A_{CP}(\pi\pi)$

LHCb-CONF-2011-023

⇒ Results:

- systematic studies:
  D^0 mass window (0.20%), multiple candidates (0.13%), modeling lineshapes (0.06%), binning in (p_T, η) (0.01%),
- systematics dominated by conservative estimates due to large statistical uncertainties; expects to decrease with statistics

preliminary

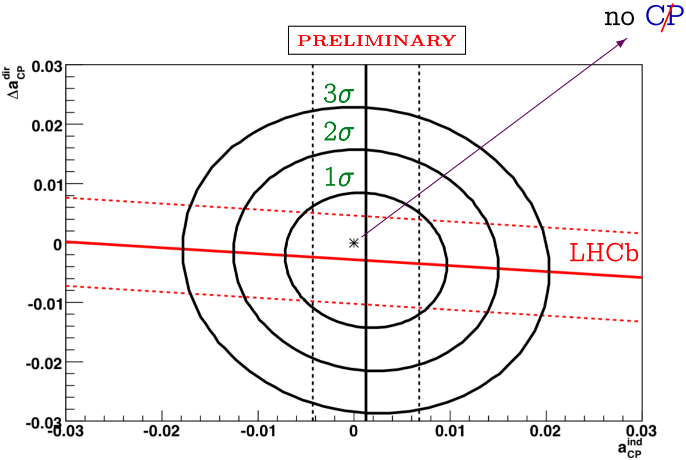
$$\boxed{A_{CP}(KK) - A_{CP}(\pi\pi) = (-0.28 \pm 0.70_{stat} \pm 0.25_{syst})\%}$$

Comparisons:

Experiment	$A_{CP}(KK)-A_{CP}(\pi\pi)$ in %	Reference
Belle	$-0.86\pm0.60_{stat}\pm0.07_{syst}$	Phys.Lett.B670 (2008) 190
BaBar*	$+0.24\pm0.62_{stat}$	Phys.Rev.Lett.100 (2008) 061803
CDF*	$-0.46\pm0.33_{stat}$	CDF note 10296 (preliminary)

*naive difference from individual measurements of $A_{CP}(KK)$ and $A_{CP}(\pi\pi)$ ignoring systematics; all input measurements are dominated by statistical uncertainty

Getting $A_{CP}(KK) - A_{CP}(\pi\pi)$



kindly provided by M. Gersabeck

LHCb-CONF-2011-023

- also possible to get info on production asymmetry

$$A_{RAW}(f) = \boxed{A_{CP}(f)} + \boxed{A_D(f)} + \qquad + \boxed{A_P(D^0)}$$

$$A_{RAW}(f)^* = \boxed{A_{CP}(f)} + \boxed{A_D(f)} + \boxed{A_D(\pi_s)} + \boxed{A_P(D^{*+})}$$

physics CP asymmetry

Detection asymmetry of D^0

Detection asymmetry of soft pion

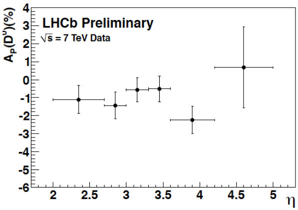
Production asymmetry

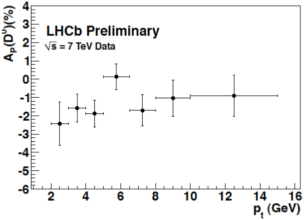
$$A_P(D^0) + A_{CP}(K^-K^+) =$$
$$A_{RAW}(K^-\pi^+) - A_{RAW}(K^-\pi^+)^* + A_{RAW}(K^-K^+)^*$$

- use measured (external) $A_{CP}(KK)$ to obtain $A_P(D^0)$

preliminary

$$\boxed{A_P(D^0) = (-1.08 \pm 0.32_{stat} \pm 0.12_{syst})\%}$$





PUC RIO

4. Time Dependent Studies for $D \to h^- h^+$

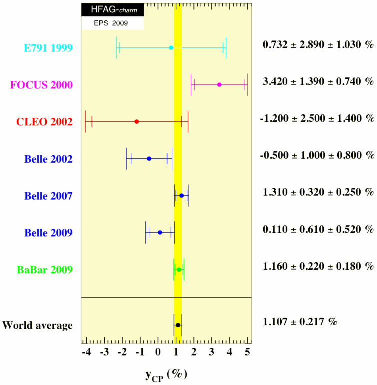
Time Dependent $\not{C}\not{P}$ from $D \to hh$

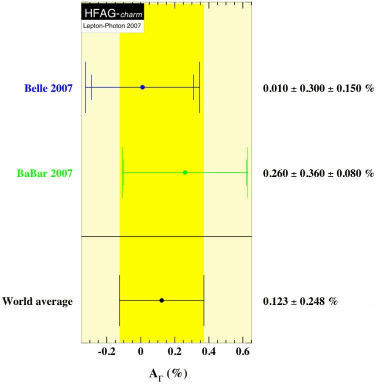
⋆ recall the quantities y_{CP} and A_Γ

$$y_{CP} \equiv \frac{\hat{\Gamma}(K^-K^+)}{\hat{\Gamma}(K^-\pi^+)} - 1 = \frac{\tau(K^-\pi^+)}{\tau(K^-K^+)} - 1$$

$$A_\Gamma = \frac{\tau(\bar{D}^0 \to K^-K^+) - \tau(D^0 \to K^-K^+)}{\tau(\bar{D}^0 \to K^-K^+) + \tau(D^0 \to K^-K^+)}$$

⇒ both measurements made through lifetime ratios

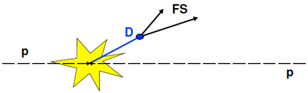


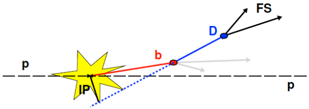


Time Dependent $\not{C}\not{P}$ from $D \to hh$

… Some analysis details …

- use decay chain $D^{*+} \to D^0(h^+h^-)\pi^+$ to tag the flavour of D^0 (and correspondingly for $\bar{D}^0$)
- for the Lifetime fit: mainly two concerns
  - charm can be produced promptly or from B decay



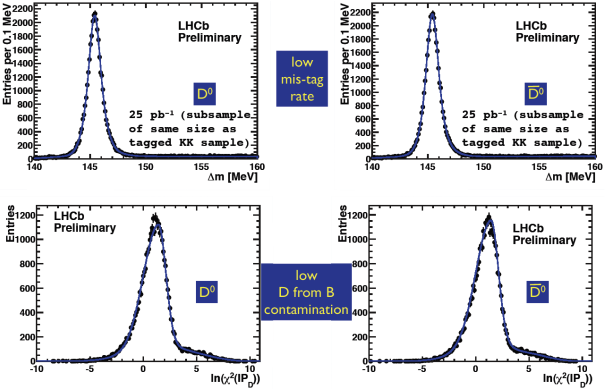


    important to discriminate these two sources for *production* and *time-dependent measurements*
    $\Rightarrow$ use the IP χ^2 of the D
  - lifetime distribution biased due to trigger & offline selection acceptances
    use an algorithm to obtain the per-event acceptance $\Rightarrow$ move the PV, rerun the trigger (possible due to software trigger)
    $\Rightarrow$ "swimming method"

Time Dependent $\not{C}P$ from $D \to hh$

KK and $\pi\pi$ measurements for A_Γ and y_{CP} underway and still "blind"

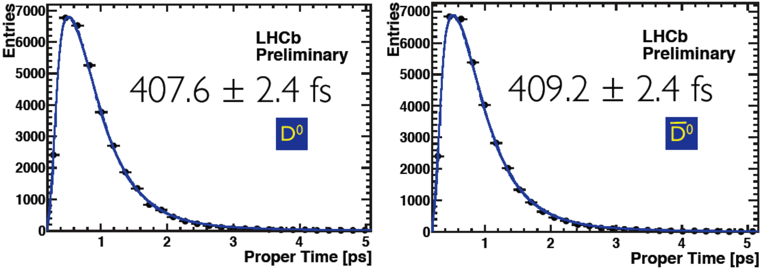
$\Rightarrow$ here the results for control channel $D^0 \to K^-\pi^+$



validation of the procedure:

no $\not{C}P$ expected in $K\pi$ $\Rightarrow$ $A_\Gamma^{K\pi} = 0$

Time Dependent $\not{C}P$ from $D \to hh$

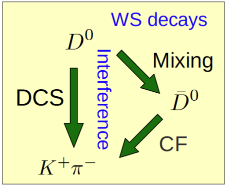


$$\bar{\tau}(D^0)_{\text{PDG}} = 410.1 \pm 1.5 \text{ ps}$$

preliminary

$$A_\Gamma^{K\pi,eff} = \frac{\tau^{eff}(\bar{D}^0) - \tau^{eff}(D^0)}{\tau^{eff}(\bar{D}^0) + \tau^{eff}(D^0)} = (-2 \pm 4) \times 10^{-3}$$

WS mixing analysis



- $D^0 \to K^+\pi^-$ - wrong-sing (WS) decay - can occur through DCS decay or mixing
- assuming no $\cancel{C}P$ ($\cos\phi = 1$, $|q/p| = 1$) the time evolution for WS is

$$WS(t) \propto e^{-\Gamma t}\left(\underbrace{R_D}_{\text{DCS}} + \underbrace{\sqrt{R_D}\, y'\Gamma t}_{\text{interference}} + \underbrace{\frac{x'^2 + y'^2}{4}(\Gamma t)^2}_{\text{Mixing}}\right)$$

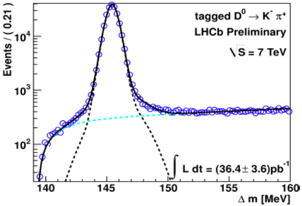
where $x' = x\cos\delta + y\sin\delta$, $y' = -x\sin\delta + y\cos\delta$; $x'^2 + y'^2 = x^2 + y^2$, $\delta \to$ strong phase between RS and WS

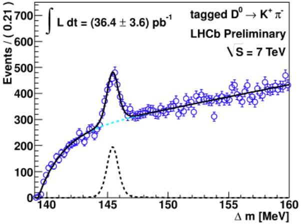
$\Rightarrow$ due to the limited 2010 statistics, we measure the time-integrated ratio

$$R = \frac{\int_0^\infty WS(t)}{\int_0^\infty RS(t)} = R_D + \sqrt{R_D}\, y' + \frac{x'^2 + y'^2}{2}$$

WS mixing analysis

- $N(RS) = 214,523 \pm 494$
- $N(WS) = 948 \pm 70$
- $R_{meas} = (0.442 \pm 0.033)\%$
- corrections: since $\frac{WS(t)}{RS(t)}$ increases with time the acceptance function requires a correction of the measured ratio
- final result:





	WS/RS of $D^0 \to K\pi$ decays (%)
R_{corr} preliminary	$0.409 \pm 0.031_{stat} \pm 0.039_{syst}$
R (PDG)	0.380 ± 0.018

5. Prospects for 2011/2012

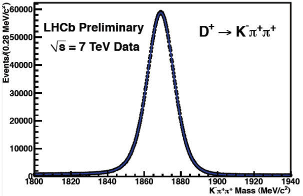
Direct CP Violation in $D^+ \to K^- K^+ \pi^+$

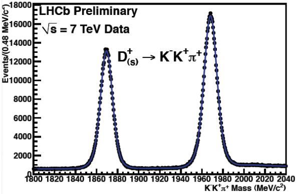
$\Rightarrow$ Search for $C\!\!\!/P$ signs by a direct comparison of $\boldsymbol{D^+}$ and $\boldsymbol{D^-}$ Dalitz plots

- Use *Mirandizing* method to search for $C\!\!\!/P$ (PRD **80** 096006 2009)

$$\mathcal{S}_{CP}(i) = \frac{N_{\mathrm{obs}}(i) - \alpha \bar{N}_{\mathrm{obs}}(i)}{\sqrt{N_{\mathrm{obs}}(i) + \alpha^2 \bar{N}_{\mathrm{obs}}(i)}}$$

- not sensitive to global asymmetries
- need careful control of non- $C\!\!\!/P$ sources of local asymmetries
- control channels $D^+ \to K^- \pi^+ \pi^+$ and $D_s \to K^- K^+ \pi^+$
- 2010 data sample:
  - 390K $D^+ \to K^- K^+ \pi^+$
  - 550K $D_s^+ \to K^- K^+ \pi^+$
  - 4M $D^+ \to K^- \pi^+ \pi^+$



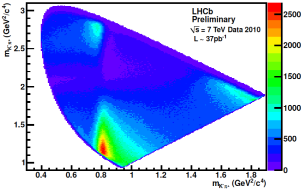


Direct CP Violation in $D^+ \to K^-K^+\pi^+$

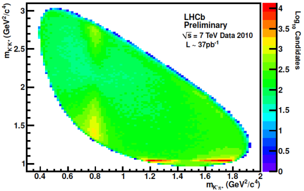
Analysis in progress

- 2010 data set is $\sim 20\times$ Cleo's (PRD D 78, 072003(2008))
- several studies to shown the absence of local asymmetries
  - sidebands
  - control channels
- toy studies on binning choice to improve sensitity (given our statistics)
- blind analysis until all controlled
- with 1fb^{-1} expects a few millions $KK\pi$ events!

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



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



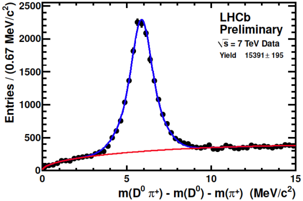
CP violation in $D^0 \to K_S h^+ h^-$

$\Rightarrow$ Very rich environment

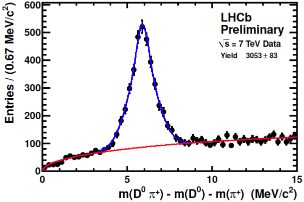
- CP eigenstates as intermediate states
- rich Dalitz plot structure
- both Cabibbo-favored and DCS final states
- promising D^0 $\not{C}P$ and mixing studies
  - time dependent amplitude analysis
  - direct access to $\not{C}P$ and mixing parameters (strong phases measured!)
- current results from BaBar and Belle with $\sim$ 540K for $K_S\pi\pi$
- explicit trigger implemented for 2011

2010 data

$D^{*+} \to D^0(K_S\pi^+\pi^-)\pi^+$

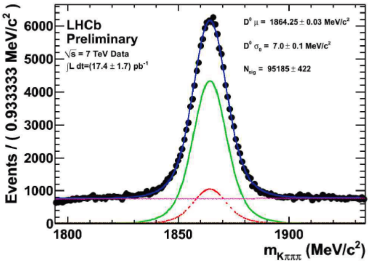


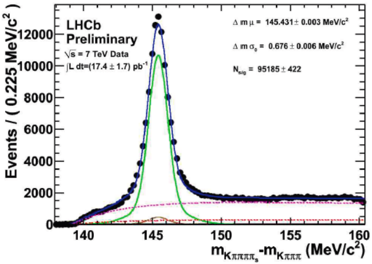
$D^{*+} \to D^0(K_S K^+K^-)\pi^+$



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

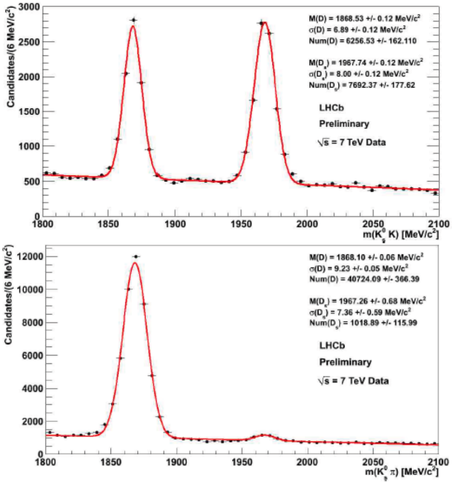
- one of the largest $\not{C}\!P$ effect was observed through T-odd observable
  angle between planes $\pi^+\pi^-$ and e^+e^- in $K_L \to \pi^+\pi^-e^+e^-$
- similar mechanism can be at work in $D^0 \to K^+K^-\pi^+\pi^-$
- look for asymmetry in the distribution of the angle between K^+K^- and $\pi^+\pi^-$ planes
  FOCUS (2005) pioneered this study; BaBar with 47K events measured $A_T^{CP} = (0.10 \pm 0.51 \pm 0.44)\%$
- LHCb competitive by the end of 2011





$D^\pm_{(s)} \to K_S h^\pm$

- CF and DCS decays: $D^+ \to K_S\pi^+$, $D_S^+ \to K_S K^+$
- CS decays: $D^+ \to K_S K^+$, $D_s \to K_S \pi^+$
- $\not{C}\!P$ through $K^0 - \bar{K}^0$ in the SM: expect asymmetries $\sim 0.3\%$
- values of $\mathcal{O}(1\%)$ would sign for NP
- no evidence so far of $\not{C}\!P$ (Belle)



Conclusions

Conclusions

- LHCb has a broad program on charm physics
- mainly focused on mixing and CPV

  but also spectroscopy and rare decays (not covered here)
- First (preliminary) results presented here :

$$A_{CP}(KK) - A_{CP}(\pi\pi) = (-0.28 \pm 0.70_{stat} \pm 0.25_{syst})\%$$

$$R_{corr}(WS/RS) = (0.409 \pm 0.031_{stat} \pm 0.039_{syst})\%$$

- dedicated triggers for many modes aiming to search for $\not{C}\!P$: $D^0 \to h^+h^-$, $D^+ \to 3h$, $D^0 \to 4h$, $D^0 \to K_S hh$, $D^+ \to K_S h$, etc
- plenty of charm foreseen for 2011

  for instance $\sim$ 200K $D^0 \to K^-\pi^+$ per pb^{-1} being recorded !
- great potential to search for New Physics in an environment with low SM $\not{C}\!P$ "background"