# Study of CPV in *b* and charm systems at LHCb

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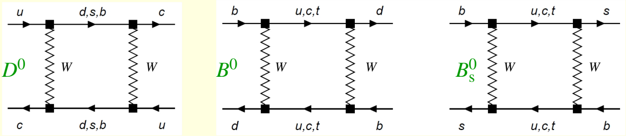
**Les Rencontres de Physique de la Vallée d'Aoste**
**La Thuile**

# OUTLINES

# PHENOMENOLOGY

## Mixing

In Standard Model, neutral mesons mix with their antiparticles via box diagrams




## CP violation

3 types of CP violation

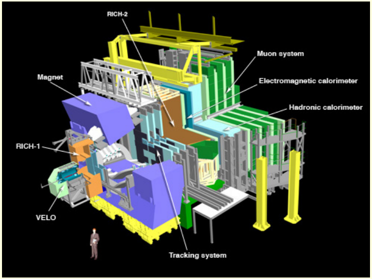
- Mixing: rates of $H^0 \to \overline{H}^0$ and $\overline{H}^0 \to H^0$ differ, with $H^0 = D^0, B^0, B_s^0$
- Decay: amplitudes from a process and its conjugate differ
- Interference between mixing and decay

# LHCb detector

## LHCb: CP violation and rare decays study in $b$ and charm sector

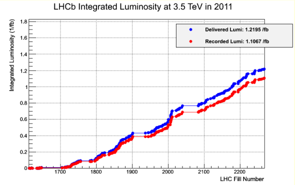
Single-arm forward spectrometer

- Excellent vertex resolution
  separation of primary and secondary vertices
- Precise tracking system
  IP resolution $\sim$ 15 $\mu$m (at high $p_T$), $\delta p/p \sim 0.5\%$
- Excellent particle identification
  $\pi/K/p$ separation over large momentum range
- Calorimeters:
  $\pi^0$, $\gamma$ reconstruction, $e$ identification
- High trigger efficiency (many BF $< 10^{-5}$)




## 2011 data taking, $\sqrt{s}$ =7 TeV

- Data taking efficiency: 91 %
- $\sim$1 fb$^{-1}$ of data recorded
- 99 % of data good for physics



# CP violation in charm with $D \to h^+h^-$

LHCb-PAPER-2011-023 to appear to PRL, $\mathcal{L} = 0.62\text{fb}^{-1}$

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

## CP violation and charm physics

- $D^0$ mixing is well established (no mixing excluded at $10.2\sigma$)
- CP violation expected to be very small in SM but significant hadronic uncertainties
- CP violation in D decays not yet seen

## Aim

Measure the difference of CP asymmetries

$$\Delta A_{CP} = A_{CP}(D^0 \to K^+K^-) - A_{CP}(D^0 \to \pi^+\pi^-)$$

$$\text{with } \mathrm{A_{CP}}(D^0 \to f) = \frac{\Gamma(D^0 \to f) - \Gamma(\overline{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\overline{D}^0 \to f)}$$

## Experimental challenges

- Initial flavor of $D^0$ tagged by slow pion : $D^{\star +} \to D^0 \pi_S^+$
- Experimental asymmetry:

$$A_{raw}(f) = \underbrace{A_{CP}(f)}_{\text{Physics CP}} + \underbrace{A_D(f)}_{\text{Detection of } D} + \underbrace{A_D(\pi_S)}_{\text{Detection of } \pi_S} + \underbrace{A_P(D^{\star +})}_{\text{Production}}$$

# CP VIOLATION IN $D^0 \to h^+h^-$

## What we measure

Raw asymmetries difference : $\Delta A_{CP} = A_{CP}(KK) - A_{CP}(\pi\pi) = A_{raw}(KK) - A_{raw}(\pi\pi)$

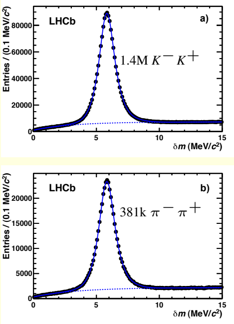
- Production and soft pion detection asymmetries cancel at 1st order
- No detection asymmmetry for $KK$ or $\pi\pi$ final states

$\to$ Systematics suppressed at 1st order

## Results: $\mathcal{L} = 0.62\text{fb}^{-1}$, LHCb-PAPER-2011-023

Measurement of $\Delta A_{CP}$:

- from fits to $\delta m = m(D^\star) - m(D^0) - m(\pi^+)$
- in bins of : kinematics, magnet polarity, running periods
- measured asymmetries are consistent in all bins
- final $\Delta A_{CP}$ is a weighted average over 216 bins




First evidence of CP violation in charm sector ($3.5\sigma$):

$$\Delta A_{CP} = (-0.82 \pm 0.21(\text{stat}) \pm 0.11(\text{syst}))\%$$

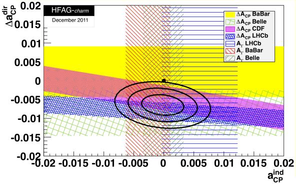
# CP violation in $D^0 \to h^+h^-$

## $\Delta A_{CP}$ interpretation [arXiv:1111.6515v2]

$$\Delta A_{CP} = \underbrace{\left(a_{CP}^{dir}(K^-K^+) - a_{CP}^{dir}(\pi^-\pi^+)\right)}_{\text{direct CP asymmetry}} + \underbrace{\frac{\Delta\langle t\rangle}{\tau_{D^0}} a_{CP}^{ind}}_{\text{indirect CP asymmetry}}$$

$\frac{\Delta\langle t\rangle}{\tau_{D^0}} = (9.8 \pm 0.9)\%$, with $\Delta\langle t\rangle$ difference of averages decay time for $KK$, $\pi\pi$ (experiment dependent)

## Current HFAG world-average




HFAG combination:
$a_{CP}^{ind} = (-0.019 \pm 0.232)\%$
$\Delta a_{CP}^{dir} = (-0.645 \pm 0.180)\%$
Consistency with NO CP violation : 0.128%

## New Physics or hadronic uncertainties ?

- Analyze more data (only 60% of 2011 is used)
- Look for direct CPV in other modes
- Search for indirect CPV
- Need more theory work

# Towards a measurement of the CKM angle $\gamma$

LHCb-PAPER-2012-001

# $\gamma$ MEASUREMENT

## Definition

$\gamma = \arg\left(-\frac{V_{ud}V_{ub}^{\star}}{V_{cd}V_{cb}^{\star}}\right)$ $\Longrightarrow$ Interference between $b \rightarrow u$ and $b \rightarrow c$ transitions

Indirect constraint: $\gamma = (67.1^{+4.6}_{-3.7})^{\circ}$ [CKMfitter]

## Towards a measurement of $\gamma$ at LHCb

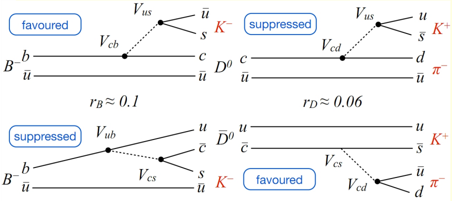
Many milestones passed :

- $B \rightarrow D(hh, hhhh)K$ : LHCb-CONF-2011-031, LHCb-CONF-2011-044
- $B \rightarrow DK^{\star}$ : Phys. Lett. B 706 (2011)32-39
- $B \rightarrow DK\pi\pi$ : LHCb-PAPER-2011-040
- $B_s^0 \rightarrow D_s K^{\pm}$ : LHCb-CONF-2011-057
- $B \rightarrow hh$ : LHCb-CONF-2011-042

Presentation of the first LHCb paper with 1 $fb^{-1}$, [LHCb-PAPER-2012-001], for submission to PLB
Direct CP violation in $B^{\pm} \rightarrow D K^{\pm}$ decays

# CP violation in $B^{\pm} \to Dh^{\pm}$ [LHCb-PAPER-2012-001]

## Simultaneous analysis of $B^{\pm} \to D_{CP}h^{\pm}$ and $B^{\pm} \to D_{ADS}h^{\pm}$




$B^{\pm} \to DK^{\pm}$ with $D$ decays to:

- CP eigenstates (GLW): $K^+K^-$, $\pi^+\pi^-$
  $\to$ large BR, but small interference
  Phys. Lett. B 265 17 (1991)
- non CP eigenstates (ADS): $K^-\pi^+$, $K^+\pi^-$
  $\to$ combinations of favoured $\times$ suppressed decays lead to comparable amplitudes
  Phys. Rev. Lett. 78 (1997) 3257-3260
  $\Longrightarrow$ more sensitive to $\gamma$

## Observables related to $\gamma$

CP asymmetries and partial widths compared to the favoured control mode: $B^- \to D^0h^-$

$$R_{GLW} = 1 + r_B^2 + 2r_B \cos\delta_B \cos\gamma$$
$$A_{GLW} = 2r_B \sin\delta_B \sin\gamma / R_{GLW}$$

$$R_{ADS} = r_B^2 + r_D^2 + 2r_B r_D \cos(\delta_B + \delta_D)\cos\gamma$$
$$A_{ADS} = 2r_B r_D \sin(\delta_B + \delta_D)\sin\gamma / R_{ADS}$$

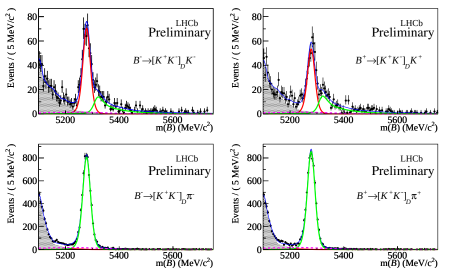
with the relative magnitude of suppressed amplitude $r_B$, weak phase $\gamma$, strong phase $\delta_B$

# ANALYSIS : $B^{\pm} \to Dh^{\pm}$ [LHCB-PAPER-2012-001]

## Strategy

- Reconstruction of every mass hypothesis combination : $B \to [hh']_D h''$, with $h, h', h'' = K, \pi$
- Extract ratios and asymmetries with a simultaneous fit
- Most systematic uncertainties cancel

## GLW : $B^{\pm} \to [KK]_D h^{\pm}$




Clear asymmetry in $B^{\pm} \to [KK]_D K^{\pm}$

No asymmetry in $B^{\pm} \to [KK]_D \pi^{\pm}$

**Preliminary results:**

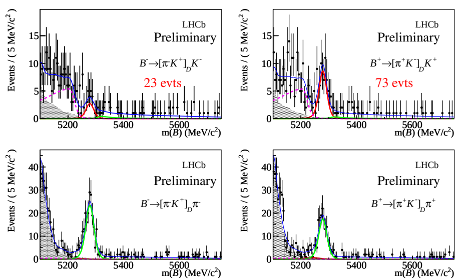
$$R_{CP+} = \frac{\langle R^{KK}_{K/\pi}, R^{\pi\pi}_{K/\pi} \rangle}{R^{K\pi}_{K/\pi}} = 1.01 \pm 0.04 \pm 0.01$$

$$A_{CP+} = \langle A^{KK}_{K}, A^{\pi\pi}_{K} \rangle = 0.15 \pm 0.03 \pm 0.01 \quad 4.5\sigma$$

Compatible results with B factories

# CP violation in $B^{\pm} \to Dh^{\pm}$ [LHCb-PAPER-2012-001]

## ADS : $B^{\pm} \to [\pi K]_D h^{\pm}$




First observation of $B^{\pm} \to [\pi K]_D K^{\pm}$

Using $R_K^{\mp} = \frac{\Gamma(B^{\mp} \to [\pi^{\mp} K^{\pm}]_D K^{\mp})}{\Gamma(B^{\mp} \to [K^{\mp} \pi^{\pm}]_D K^{\mp})} \Longrightarrow R_{ADS(K)} = \frac{R_K^- + R_K^+}{2}$ $\quad A_{ADS(K)} = \frac{R_K^- - R_K^+}{R_K^- + R_K^+}$

**Preliminary results:**

$R_{ADS(K)} = 0.0152 \pm 0.0020 \pm 0.0004$ $10\sigma$

$R_{ADS(\pi)} = 0.0041 \pm 0.0003 \pm 0.0001$

$A_{ADS(K)} = -0.520 \pm 0.150 \pm 0.021$ $4\sigma$

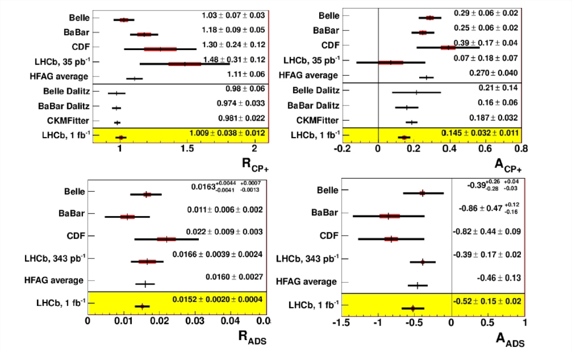
$A_{ADS(\pi)} = 0.143 \pm 0.062 \pm 0.011$ $2.4\sigma$

$\to$ Most precise measurements

# CP violation in $B^{\pm} \to Dh^{\pm}$ [LHCb-PAPER-2012-001]

## Conclusions

- $R_{CP}$, $R_{ADS}$ and $A_{CP}$, $A_{ADS}$ contain dependence on the weak phase $\gamma$ $\to$ important contribution to a future extraction of this parameter
- Good agreement with B-factories results




Important milestones towards $\gamma$ measurement

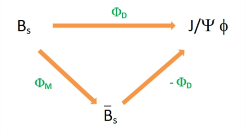
# $B_s^0$ mixing phase $\phi_s$

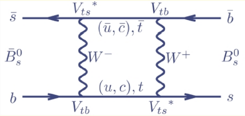
LHCb-PAPER-2011-021 accepted by PRL
LHCb-PAPER-2011-031, PLB 707(2012)497-505
LHCb-CONF-2011-056
LHCb-PAPER-2011-028

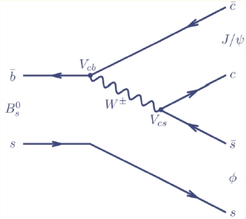
# PHENOMENOLOGY: $\phi_s$

## $\phi_s$: interference between mixing and decay

Interference between the direct amplitude and the amplitude via $B_s^0$-$\overline{B}_s^0$ oscillation gives rise to a CP violating phase $\phi_s = \Phi_M - 2\Phi_D$




## Standard Model

$$\phi_s^{SM} = -2\arg\left(-\frac{V_{ts}V_{tb}^\star}{V_{cs}V_{cb}^\star}\right) + \delta_{penguins}^{SM}$$

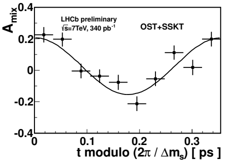
Penguins are expected to be small :
with $\delta_{penguins}^{SM} = 0 \Longrightarrow \phi_s^{SM} = -(0.0363 \pm 0.0017)$ rad [CKMfitter]
If New Physics: $\phi_s$ can be larger !

# $\phi_s$ EXPERIMENTAL CHALLENGES

## Fast oscillations and flavour tagging

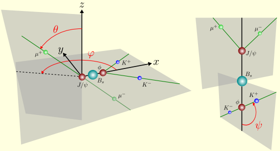
- $B_s^0$ system oscillates rapidly
  $\rightarrow$ Requires very good proper-time resolution
  $B_s^0 \rightarrow J/\psi\phi$: $\sigma_t = 50$fs
- Flavour tagging required :
  [LHCb-PAPER-2011-028, submitted to Eur. Phys. J. C]
  $B_s^0 \rightarrow J/\psi\phi$ OS tagging power : $(1.91 \pm 0.23)\%$
- Proof of principle: $\Delta m_s$ measurement
  LHCb-CONF-2011-050
  Analysis $B_s^0 \rightarrow D_s^- \pi^+$, $\mathcal{L} = 370\,\text{pb}^{-1}$ of 2011 data
  **Preliminary** $\Delta m_s = 17.725 \pm 0.041(stat) \pm 0.026(syst)\ \text{ps}^{-1}$
  $\rightarrow$ Most precise measurement

$\Longrightarrow$




## $B_s^0 \rightarrow J/\psi\phi$ angular analysis

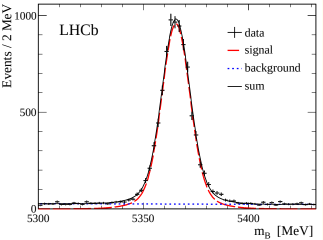
- P$\rightarrow$VV decay: mixture of CP odd and CP even states
  $\rightarrow$ need angular analysis to disentangle statistically the 3 polarization amplitudes: $A_0, A_{\parallel}$ (CP even), $A_{\perp}$ (CP-odd)
- *KK* S-wave component : add a CP odd polarization $A_S$

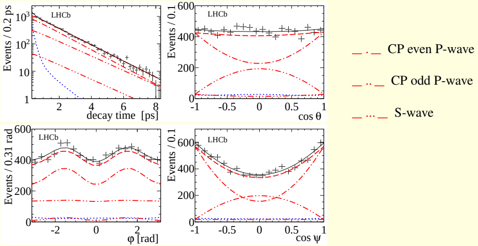



$J/\psi$ rest frame    $\phi$ rest frame

# FIT PROJECTIONS, LHCB-PAPER-2011-021

## $\mathcal{L} = 370\text{pb}^{-1}$: $8276 \pm 94$ $B_s^0 \to J/\psi\phi$ signal events




## Results

Most precise measurements:

$\Gamma_s = 0.656 \pm 0.009$ (stat)$\pm 0.008$ (syst) $\text{ps}^{-1}$

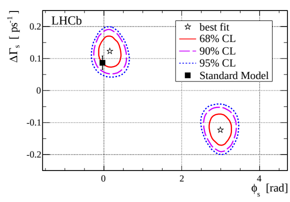
$\phi_s = 0.15 \pm 0.18$ (stat)$\pm 0.07$ (syst) rad

$\Delta\Gamma_s = 0.123 \pm 0.029$ (stat)$\pm 0.011$ (syst) $\text{ps}^{-1}$

First direct evidence of non-zero $\Delta\Gamma_s$

2 solutions, 1 in agreement with SM prediction

$\to$ Current uncertainties still leave room for New Physics



# $\phi_s$: SOLVING THE AMBIGUITY, LHCb-PAPER-2011-028

## Why 2 solutions ?

Invariance of the differential decay rate :

$$(\phi_s, \Delta\Gamma_s, \delta_{\|} - \delta_0, \delta_{\perp} - \delta_0, \delta_s - \delta_0) \leftrightarrow (\pi - \phi_s, -\Delta\Gamma_s, \delta_0 - \delta_{\|}, \delta_0 - \delta_{\perp}, \delta_0 - \delta_s)$$

## How to solve this ambiguity ?

Ambiguity is solved by studying the interferences between S-wave and P-wave: following similar method as BaBar $\cos 2\beta$ measurement (Phys. Rev. D 71 (2007) 032005)

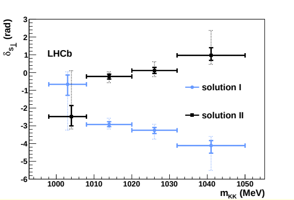
- P-wave strong phases: $\delta_0, \delta_{\|}, \delta_{\perp}$ $\rightarrow$ P-wave phase increases rapidly as a function of $m_{KK}$ going through $\phi$ resonance
- S-wave strong phase: $\delta_S$ $\rightarrow$ S-wave phase $\delta_S$ varies slowly as a function of $m_{KK}$

## Solution

$\delta_S - \delta_{\perp}$:

- extracted from a simultaneous fit in 4 bins of $m_{KK}$
- expected to decrease as a function of $m_{KK}$
  $\rightarrow$ Solution 1 is correct

The chosen solution is the one compatible with SM



# $\phi_s$ MEASUREMENT IN $B_s^0 \to J/\psi f_0$ , LHCB-PAPER-2011-031

## History

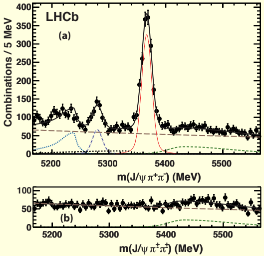
- 2008: Prediction of S-wave interference in $B_s^0 \to J/\psi\phi$ decay (arXiv:0812.2832)
  $\to$ S-wave could manifest as $f_0(980)$, CP odd eigenstate
- Feb. 2011: 1st observation of $B_s^0 \to J/\psi f_0$ decays at LHCb, then Belle, CDF, D0

$$R_{f_0/\phi} = \frac{\Gamma(B_s^0 \to J/\psi f_0)}{\Gamma(B_s^0 \to J/\psi\phi)} = 0.252^{+0.046+0.027}_{-0.032-0.033},$$ (Phys. Lett. B698:115-122, 2011)

## Analysis

- $f_0$ is a spin-0 resonance $\to$ no angular analysis
- $\mathcal{L} = 378\,\text{pb}^{-1}$ (2010 + 2011 data),
  1428±47 signal $B_s^0 \to J/\psi f_0$ events
- Constraining $\Delta\Gamma_s$ and $\Gamma_s$ to $B_s^0 \to J/\psi\phi$ values

$\phi_s = -0.44 \pm 0.44$ (stat) $\pm 0.02$ (syst) rad



# $\phi_s$: COMBINATION OF $B_s^0 \to J/\psi\phi$ AND $B_s^0 \to J/\psi f_0$

## Combination of the 2 $\phi_s$ measurement [LHCb-CONF-2011-056]

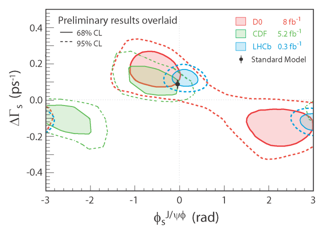
Simultaneous fit with common $\phi_s, \Gamma_s, \Delta\Gamma_s, \Delta m_s$:

$\phi_s = 0.03 \pm 0.16(\text{stat}) \pm 0.07(\text{syst})$ rad

Main systematics come from:

- Decay angle acceptance
- CP in mixing and decay
- Background modelling

Artist's view




CDF update (Lake Louise), $\mathcal{L} = 9.6\text{pb}^{-1}$:

$\phi_s \in [-\pi, -2.52] \cup [-0.60, 0.12] \cup [3.02, \pi]$ at 68% CL

## $\phi_s$ prospects

- Use the whole 2011 statistics ($1\,\text{fb}^{-1}$) $\Longrightarrow$ Expected $\sigma_{\phi_s} \sim 0.10$ rad for $B_s^0 \to J/\psi\phi$ only
- Add tagging information: Same Side kaon
- Add new channels as $B_s^0 \to J/\psi\pi\pi$
- Control penguin pollution with $B_s^0 \to J/\psi K^{*0}$ [arXiv:0810-4248]

# CONCLUSIONS AND PROSPECTS

## Conclusions

2011 has been an excellent year for LHCb

Selected CPV results:

- CP violation in charm:
  First evidence of CPV at $3.5\sigma$ with $\Delta A_{CP}$ measurement in $D \to KK$, $D \to \pi\pi$
- Towards a measurement of the CKM angle $\gamma$
  Important milestones with the measurements of $R_{CP}, A_{CP}, R_{ADS}, A_{ADS}$
- Measurement of the $B_s^0$ mixing phase: $\phi_s$
  Most precise measurement :
  $\Delta\Gamma_s = 0.123 \pm 0.029$ (stat)$\pm 0.011$ (syst) ps$^{-1}$
  $\phi_s = 0.03 \pm 0.16$ (stat)$\pm 0.07$ (syst) rad
  $\rightarrow$ Compatible with Standard Model but still room for New Physics

## Prospects

Use the full 2011 statistics

Much more results are in the pipeline for 2012 !