IL NUOVO CIMENTO Vol. 35 C, N. 6 Novembre-Dicembre 2012
DOI 10.1393/ncc/i2012-11363-9

Colloquia: LaThuile12

Study of CPV in b and charm systems at LHCb

E. Maurice on behalf of the LHCb Collaboration
CPPM, Université Aix-Marseille, CNRS/IN2P3 - France

ricevuto il 7 Settembre 2012

Summary. — The LHCb experiment is a single-arm spectrometer designed to pursue an extensive study of CP violation in b and charm systems. In this contribution, three recent measurements are presented. First, the difference between CP asymmetries of $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ decays using $0.6\,\text{pb}^{-1}$ of 2011 data is detailled. Then an important milestones towards the measurement of the γ angle is presented with the study of $B^\pm \to DK^\pm$ decays using $1\,\text{fb}^{-1}$. Third, the measurement of the CP-violating phase ϕ_s in $B_s^0 \to J/\psi\phi$ and $B_s^0 \to J/\psi f_0$ is reported.

PACS `12.15.Ff` – Quark and lepton masses and mixing.
PACS `12.15.Hh` – Determination of Cabibbo-Kobayashi & Maskawa (CKM) matrix elements.

1. – Introduction

The LHCb experiment is dedicated to the study of charm and beauty flavour physics. Precise measurements in these sectors allow to test the CKM paradigm of flavour structure and CP violation. More precisely, LHCb investigate the possible New Physics effects in the loop-mediated processes. In this document, we present three recent LHCb results about CP violation in charm and beauty sectors. In sect. **2**, we present the difference in time-integrated CP asymmetries between $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$, using $0.6\,\text{pb}^{-1}$ of 2011 data. In sect. **3**, we detail the CP violation in $B^\pm \to DK^\pm$. In sect. **4**, we report on the measurement of the CP-violating phase ϕ_s.

2. – CP violation in charm

In the Standard Model, CP violation in charm sector is expected to be small [1, 2]. New Physics could enhance the rate of CP violation [3]. LHCb measures the difference in time-integrated CP asymmetries between $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$, using $0.6\,\text{pb}^{-1}$ of data collected in 2011 [4]. By requiring a $D^{*+} \to D^0\pi^+$ decay, the initial state, D^0 or $\overline{D}^0$, is tagged using the sign of the "slow" pion $\pi^\pm$.

The raw asymmetry for tagged D^0 decays to a final state f is defined as

$$A_{raw}(f) = \frac{N(D^{*+} \to D^0(f)\pi^+) - N(D^{*-} \to \overline{D}^0(\overline{f})\pi^-)}{N(D^{*+} \to D^0(f)\pi^+) + N(D^{*-} \to \overline{D}^0(\overline{f})\pi^-)},$$

with $N(X)$ the number of reconstructed events of decays X, and f the final state. This raw asymmetry can be written as the sum of various asymmetries,

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

where $A_{CP}(f)$ is the intrinsic physics CP asymmetry, $A_D(f)$ the asymmetry to select the D^0 decay into the final state f, $A_D(\pi_s)$ the detection asymmetry of the slow pion coming from the D^{*+} decay chain, and $A_P(D^{*+})$ the production asymmetry for prompt D^{*+} mesons.

For a two-body decay of a spin-0 particle to a self-conjugate final state there can be no D^0 detection asymmetry: $A_D(K^-K^+) = A_D(\pi^-\pi^+) = 0$. At first order, $A_D(\pi_s)$ and $A_P(D^{*+})$ cancel out in the difference $A_{raw}(K^-K^+) - A_{raw}(\pi^-\pi^+)$. Finally, the measurement of ΔA_{CP} corresponds to the difference of physics asymmetries:

$$\Delta A_{CP} = A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+) = A_{raw}(K^-K^+) - A_{raw}(\pi^-\pi^+).$$

In order to minimize second-order effects, the analysis is done in bins of kinematic variables, magnet polarity and running periods. In total, 216 independent measurements are made for each decay mode. The χ^2/ndf of these measurements is 211/215. The final time-integrated difference in CP asymmetry between $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ decays is the weighted average over 216 bins:

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

It is the first evidence of CP violation in charm sector, with a significance of 3.5σ. This measurement is consistent with the current HFAG world average [5].

ΔA_{CP} can be written at first order as the sum of CP asymmetries:

$$\Delta A_{CP} = \left(a_{CP}^{dir}(K^-K^+) - a_{CP}^{dir}(\pi^-\pi^+)\right) + \frac{\Delta\langle t\rangle}{\tau} a_{CP}^{ind},$$

with a_{CP}^{dir} the asymmetry coming from direct CP violation for the decay, $\langle \Delta t\rangle$ the difference in average decay time of the D^0 mesons in the K^-K^+ and $\pi^-\pi^+$ sample, τ the true D^0 lifetime, a_{CP}^{ind} the asymmetry from CP violation in the mixing. Using this result, the HFAG world-average combination in the plan $(\Delta a_{CP}^{dir}, a_{CP}^{ind})$ represented by the fig. 1 gives

$$a_{CP}^{ind} = (-0.019 \pm 0.232)\%, \qquad \text{and} \qquad \Delta a_{CP}^{dir} = (-0.645 \pm 0.180)\%.$$

This combination is consistent with no CP violation at 0.128%. To understand this 3.5σ effect, further analyses are ongoing at LHCb, and more theoretical precision is needed.

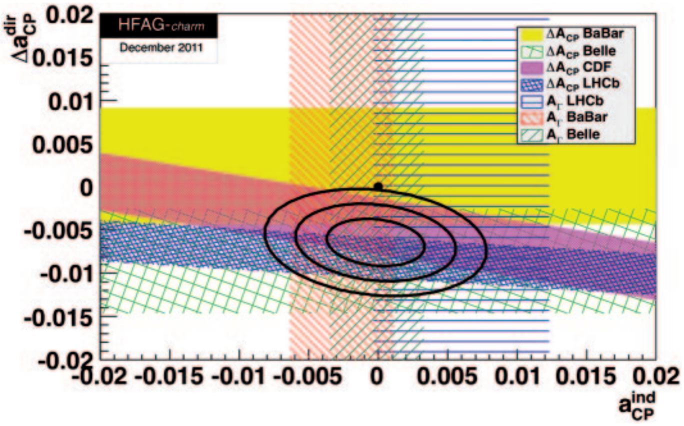

Fig. 1. – HFAG combination of the ΔA_{CP} and A_Γ measurements [5]. The bands represent $\pm 1\sigma$ intervals. No CP violation correspond to the black point at $(0,0)$, and the two dimensional 68% CL, 95% CL and 99.7% CL regions are the black ellipses.

3. – Toward a measurement of the CKM angle γ

The γ angle is the least accurately known parameter of the CKM unitarity triangle. In terms of CKM elements, γ is defined as: $\gamma = \arg(-\frac{V_{ud}V_{ub}^\star}{V_{cd}V_{cb}^\star})$. The indirect determination via global fits to experimental data gives $\gamma = (67.1^{+4.6}_{-3.7})$ [6]. One of the main goals of the LHCb experiment is to perform a precise direct measurement of this angle. It is extracted from the interference between $b \to u$ and $b \to c$ transitions. LHCb experiment has passed many milestones towards γ measurement with [7]. This contribution focuses on the first LHCb paper using the whole 2011 data: the direct CP violation in $B^\pm \to D^0 K^\pm$ decays with $1\,\text{fb}^{-1}$ [8].

The analyses of direct CP violation in $B^\pm \to D^0 K^\pm$ are time-integrated measurements, using only the self-tagging modes. The interference between decays to the same final products $(K^- K^+ \pi^-)$ by different intermediate states ($D^0 K^-$ or $\overline{D}^0 K^-$) gives access to γ. Depending of the D^0 decay, different measurement methods are availablable. The sensitivity to γ is given by the asymmetries between the decay and its conjugate, A, and the ratio of the sum compared to the favoured control mode $B^- \to D^0 h^-$, R.

The GLW method was proposed by Gronau, Wyler and London [9, 10]. It is a theoretically clean measurement of the angle γ from the rate and asymmetry measurement of $B^- \to D_{CP} K^-$ decays, where the D^0 meson decays to CP eigenstates: $D^0 \to K^+ K^-$, $D^0 \to \pi^+ \pi^-$. This method benefits from the interference between the dominant $b \to cu$ transition with the doubly CKM-suppressed $b \to uc$ transition. The asymmetry and ratio observables are defined by

$$R_{CP+} = 2\frac{\Gamma(B^- \to D_\pm K^-) + \Gamma(B^+ \to D_\pm K^+)}{\Gamma(B^- \to D^0 K^-) + \Gamma(B^+ \to D^0 K^+)} = 1 + r_B^2 \pm 2 r_B \cos\delta_B \cos\gamma,$$

$$A_{CP+} = \frac{\Gamma(B^- \to D_\pm K^-) - \Gamma(B^+ \to D_\pm K^+)}{\Gamma(B^- \to D_\pm K^-) + \Gamma(B^+ \to D_\pm K^+)} = \pm 2 r_B \sin\delta_B \sin\gamma / R_{CP+}$$

with the relative magnitude of suppressed amplitude $r_B = |A(b \to u)/A(b \to c)|$, the strong phase $\delta_B = \arg(A(b \to u)/A(b \to c)$ and the weak phase γ.

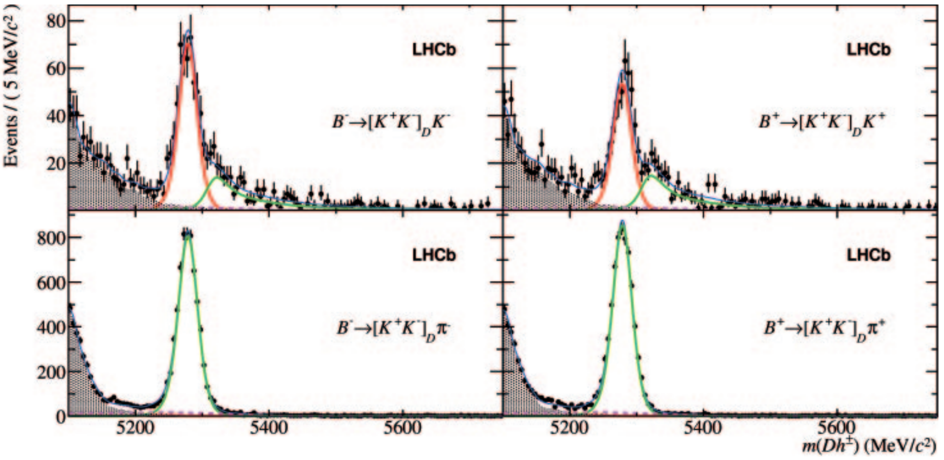

Fig. 2. – Invariant-mass distributions of selected $B^{\pm} \to [K^+K^-]_D h^{\pm}$ candidates [8]. The left plots are B^- candidates, B^+ are on the right. In the top plots, the bachelor track is assigned to be a kaon, although in the bottom plots it is a pion. The dark (red) curve represents the $B \to DK^{\pm}$ events, the light (green) curve is $B \to D\pi^{\pm}$. The shaded contribution are partially reconstructed events and the total PDF includes the combinatorial component. The contribution from $\Lambda_b \to \Lambda_c^{\pm} h^{\mp}$ decays is indicated by the dashed line.

The ADS method is a modification of the GLW approach, developed by Atwood, Dunietz and Soni [11]. In the $B^- \to D^0 K^-$ decays, the D^0 meson decays to flavour specific final states: $D^0 \to K\pi$. The favoured transition $b \to c$ is followed by the doubly CKM-suppressed D decay interfering with the supressed $b \to u$ transition followed by the CKM-favoured D decay. The asymmetry and ratio are given by

$$R_{ADS} = \frac{\Gamma(B^- \to D_{\pm}K^-) + \Gamma(B^+ \to D_{\mp}K^+)}{\Gamma(B^- \to D_{\mp}K^-) + \Gamma(B^+ \to D_{\pm}K^+)} = r_B^2 + r_D^2 + 2r_B r_D \cos(\delta_B + \delta_D)\cos\gamma,$$

$$A_{ADS} = \frac{\Gamma(B^- \to D_{\pm}K^-) - \Gamma(B^+ \to D_{\mp}K^+)}{\Gamma(B^- \to D_{\pm}K^-) + \Gamma(B^+ \to D_{\mp}K^+)} = \frac{2r_B r_D \sin(\delta_B + \delta_D)\sin\gamma}{R_{ADS}},$$

with r_B, δ_B, γ already defined for the GLW method, and r_D, δ_D the corresponding amplitude ratio and strong phase difference of the D meson decay amplitudes.

For this analysis, the strategy is to reconstruct every mass hypothesis combination, then to extract the ratios and asymmetries with a simultaneous fit. Figures 2 and 3 show, respectively, the invariant-mass distributions of $B^{\pm} \to D_{CP}\pi^{\pm}$ and $B^{\pm} \to D_{\pm}\pi^{\pm}$. In fig. 2, there is a clear asymmetry in $B^{\pm} \to [KK]_D K^{\pm}$, but no asymmetry in $B^{\pm} \to [KK]_D \pi^{\pm}$.

The measurements give

$$\begin{aligned} A_{CP+} &= 0.15 \pm 0.03 \pm 0.01 &\quad \text{and} \quad R_{CP+} &= 1.01 \pm 0.04 \pm 0.01,\\ A_{ADS(K)} &= -0.520 \pm 0.150 \pm 0.021 &\quad \text{and} \quad R_{ADS(K)} &= 0.0152 \pm 0.0020 \pm 0.0004,\\ A_{ADS(\pi)} &= 0.143 \pm 0.062 \pm 0.011 &\quad \text{and} \quad R_{ADS(\pi)} &= 0.0041 \pm 0.0003 \pm 0.0001. \end{aligned}$$

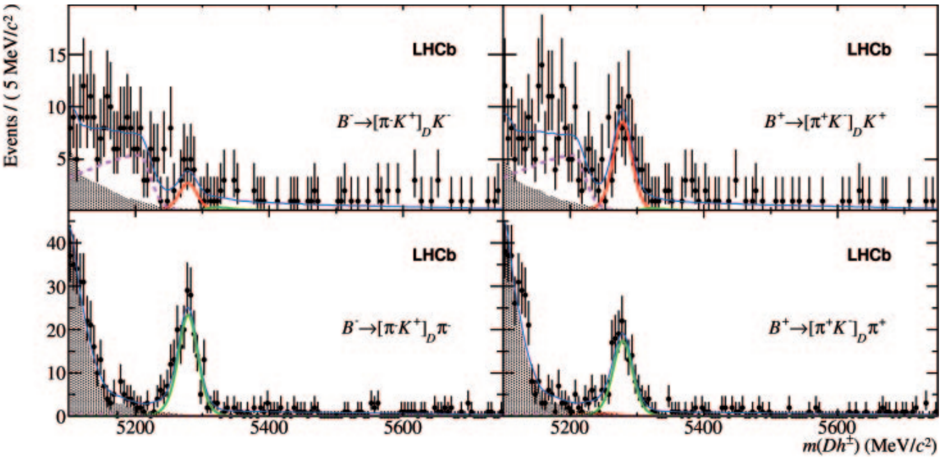

Fig. 3. – Invariant-mass distribution of selection $B^\pm \to [\pi^\pm K^\mp]_D h^\pm$ candidates [8]. See the caption of 2 for a full description. The dashed line here represents the partially reconstructed, but Cabbibo-favoured, $B_s \to \overline{D}^0 K^-\pi^+$ and $\overline{B}_s \to D^0 K^+\pi^-$ decays where the pions are lost. The pollution from favoured mode cross feed is drawn, but is too small to be seen.

These measurements are an important contribution to a future extraction of the γ angle. They are the most precise measurement and in good agreement with the B factories [5].

4. – B_s^0 mixing phase ϕ_s

The interference between B_s^0 decays to $J/\psi\phi$ either directly or via B_s^0-$\overline{B}_s^0$ oscillation gives rise to a CP-violating phase ϕ_s. In the Standard Model, this phase is predicted to be $\simeq -2\beta_s$, where $\beta_s = \arg(-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*)$. The indirect determination via global fits to experimental data gives $2\beta_s = (0.0364 \pm 0.0016)$ rad [6], within the Standard Model. ϕ_s is one of the CP observables with the smallest theoretical uncertainty in the Standard Model, neglecting the penguins contributions, and New Physics could significantly modify this prediction.

The decays $B_s^0 \to J/\psi\phi$ are pseudo-scalar to vector-vector transitions. Morever, the K^+K^- non-resonant state, the S-wave, is taken into account. Thus the final state is a mixture of CP odd and CP even states. It is described by a four time-dependent decay amplitudes corresponding to transitions in which the J/ψ and ϕ or K^+K^- have a relative orbital momentum L of 0, 1, or 2. In the transversity formalism [12], the initial amplitudes at time $t = 0$, $A_0(0)$ and $A_\parallel(0)$ describe the decays with $L = 0, 2$ while $A_\perp(0)$ and A_S describes the $L = 1$ final states. The arguments of these complex amplitudes are strong phases denoted δ_0, $\delta_\parallel$, $\delta_\perp$ and δ_S.

The measurement of ϕ_s phase requires a very good proper-time resolution to resolve the fast B_s^0 oscillations. It has been measured in $B_s^0 \to J/\psi\phi$ channel: $\sigma_t = 50\,\text{fs}$. Another key step towards the ϕ_s measurement is the tagging of the initial B-flavour. The tagging algorithm exploits charged tracks originating from the b-hadron opposite to the signal B-meson (kaon, muon, electron and vertex charge) and also tracks close to the signal B-meson (same-side tagging). The opposite side algorithm is optimized using $B^0 \to D^{*-}\mu^+\nu_\mu$ and $B^+ \to J/\psi K^+$ events and calibrated using $B^+ \to J/\psi K^+$,

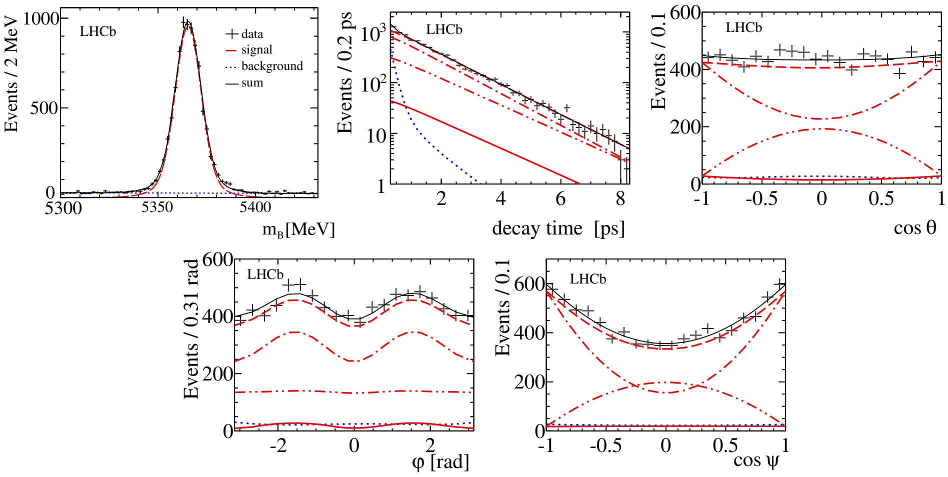

Fig. 4. – Data points overlaid with fit projections for the reconstructed invariant mass, decay time and transversity angle distributions of selected $B^0_s \to J/\psi\phi$, candidates, in a mass range of $\pm 20\,\mathrm{MeV}/c^2$ around the reconstructed B^0_s mass except for the invariant mass distribution [13]. The total fit result is represented by the black line. The signal components are represented by the red lines, and the background component by the blue line.

$B^0 \to J/\psi K^{*0}$ events [14]. An additional test is performed in [15], by measuring the B^0_s-$\overline{B}^0_s$ mixing frequency using $B^0_s \to D_s^-(3)\pi^+$ events using $370\,\mathrm{pb}^{-1}$:

$$\Delta m_s = 17.725 \pm 0.041(\mathrm{stat.}) \pm 0.026(\mathrm{syst.})\,\mathrm{ps}^{-1},$$

which is compatible and competitive with the world best measurement [16].

The physical parameters are extracted from a maximum likelihood fit to the mass, proper time and angles distributions of the fully reconstructed candidates as shown in fig. 4. In $370\,\mathrm{pb}^{-1}$, $8\,276 \pm 94\, B^0_s \to J/\psi\phi$ signal events are extracted [13]. Two solutions are available in the plan $(\Delta\Gamma_s, \phi_s)$, due to the invariance of the differential decay rate under the transformation $(\phi_s, \Delta\Gamma_s, \delta_\parallel - \delta_0, \delta_\perp - \delta_0, \delta_s - \delta_0) \leftrightarrow (\pi - \phi_s, -\Delta\,\Gamma_s, \delta_0 - \delta_\parallel, \delta_0 - \delta_\perp, \delta_0 - \delta_s)$. LHCb has recently solved this ambiguity [17] by studying the interferences between the S-wave and the P-wave, following similar method as BaBar $\cos(2\beta)$ measurement [18]. In the $B^0_s \to J/\psi\phi$ channel, we measure [13]:

$$\begin{aligned}
\phi_s &= 0.15 \pm 0.18 \pm 0.06\,\mathrm{rad},\\
\Gamma_s &= 0.656 \pm 0.009 \pm 0.008\,\mathrm{ps}^{-1},\\
\Delta\Gamma_s &= 0.123 \pm 0.029 \pm 0.011\,\mathrm{ps}^{-1},\\
|A_\perp(0)|^2 &= 0.237 \pm 0.015 \pm 0.012,\\
|A_0(0)|^2 &= 0.497 \pm 0.013 \pm 0.030,\\
|A_S|^2 &= 0.042 \pm 0.015 \pm 0.018,\\
\delta_\parallel &= 2.95 \pm 0.37 \pm 0.12,\\
\delta_S &= 2.98 \pm 0.36 \pm 0.12,
\end{aligned}$$

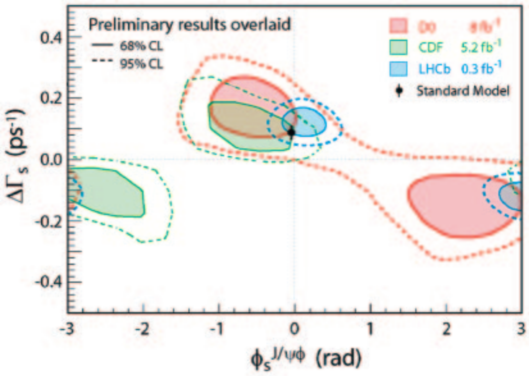

Fig. 5. – Artist's view of the $\Delta\Gamma_s$ and ϕ_s measurements at the end of 2011. CDF update is missing: $\phi_s \in [-\pi, -2.52] \cup [-0.60, 0.12] \cup [3.02, \pi]$ at 68% CL, with $9.6\,\text{pb}^{-1}$ [19].

where the first error is the statistical error from the fit and the second error is the systematic uncertainty. It the first direct evidence of non-zero $\Delta\Gamma_s$.

The ϕ_s phase is extracted from the decay $B_s^0 \to J/\psi f_0$ too [20]. A simultaneous fit in these two channels with common ϕ_s, Γ_s, $\Delta\Gamma_s$ and Δm_s gives [21]:

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

It is the most precise measurement of the ϕ_s phase, as illustrated by the artist's view in fig. 5. This value is compatible with the Standard Model, but there is still room for New Physics.

5. – Epilogue

While completing these proceedings, CDF has confirmed the ΔA_{CP} measurement from LHCb with: $\Delta A_{CP} = (-0.62 \pm 0.21 \pm 0.10)\%$ [22]. LHCb has released its results on ϕ_s [23] using $1\,\text{fb}^{-1}$: $\phi_s = -0.001 \pm 0.101 \pm 0.027\,\text{rad}$, still compatible with the Standard Model.

6. – Conclusions

2011 has been an excellent year for LHCb with many measurements related to CP violation. Among all these measurements, LHCb made the first evidence of CP violation at 3.5σ in charm. Important milestones have been achieved to measure the CKM angle γ with the determination of R_{CP}, A_{CP}, R_{ADS}, A_{ADS} using $1\,\text{fb}^{-1}$. In the B_s^0, system, LHCb made the first direct evidence of a non-zero $\Delta\Gamma_s$, using $0.4\,\text{fb}^{-1}$, and the CP-violating phase ϕ_s has been measured: $\phi_s = 0.03 \pm 0.16(\text{stat}) \pm 0.07(\text{syst})\,\text{rad}$, consistent with the Standard Model.

* * *

I wish to thanks the organizers of the "Rencontres de Physique de la valle d'Aoste", for the nice atmosphere during the conference, and the LHCb collaboration for this beautiful opportunity.

REFERENCES

[1] Grossman Y., Kagan A. L. and Nir Y., *Phys. Rev. D*, **75** (2007) 036008.
[2] Bobrowski M., Lenz A., Riedl J. and Rohrwild J., *JHEP*, **03** (2010) 009.
[3] Bigi I. I., Blanke M., Buras A. J. and Recksiegel S., *JHEP*, **07** (2009) 097.
[4] The LHCb Collaboration, *Phys. Rev. Lett.*, **108** (2012) 111602.
[5] Asner D. *et al.* (Heavy Flavour Averaging Group), arXiv:1010.1589 [hep.ex].
[6] Charles J. *et al.* (CKMfitter group), *Eur. Phys. J. C*, **41** (2005) 1, hep-ph/0406184, updated results and plots available at `http://ckmfitter.in2p3.fr/`.
[7] See for example LHCb-CONF-2011-031, LHCb-CONF-2011-057, LHCb-CONF-2011-042, etc.
[8] The LHCb Collaboration, "Observation of CP violation in $B^{\pm} \to DK^{\pm}$ decays", LHCb-PAPER-2012-001.
[9] Gronau M. and London D., *Phys. Lett. B*, **253** (1991) 483.
[10] Gronau M. and Wyler D., *Phys. Lett. B*, **256** (1991) 172.
[11] Atwood D., Dunietz I. and Soni A., *Phys. D*, **63** (2001) 036005.
[12] The LHCb Collaboration, "Roadmap for selected key measurements of LHCb.", LHCB-PUB-2009-029, arXiv:0912.4179.
[13] The LHCb Collaboration, "Measurement of the CP-violating phase ϕ_s in the decay $B_s^0 \to J/\psi\phi$", LHCb-PAPER-2011-021.
[14] The LHCb Collaboration, "Opposite-side flavour tagging of the B mesons at the LHCb experiment", LHCb-PAPER-2011-027.
[15] The LHCb Collaboration, LHCb-CONF-2011-050.
[16] Abulencia A. *et al.* (CDF Collaboration), *Phys. Rev. Lett.*, **97** (2006) 242003.
[17] The LHCb Collaboration, "Determination of the sign of the decay width difference in the B_s^0 system", LHCb-PAPER-2011-028.
[18] BaBar Collaboration, *Phys. Rev. D*, **71** (2007) 032005.
[19] CDF Collaboration, Public Note 10778, 2012.
[20] The LHCb Collaboration, "Measurement of the CP-violating phase ϕ_s in $B_s^0 \to J/\psi f_0$", LHCb-PAPER-2011-031.
[21] The LHCb Collaboration, LHCb-CONF-2011-056.
[22] CDF Collaboration, Public Note 10784, 2012.
[23] The LHCb Collaboration, LHCb-CONF-2012-002.