EXPERIMENT LHCb AT THE LHC

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1. Introduction

The main physics goals of the LHCb experiment at the Large Hadron Collider (LHC) at CERN are studies of CP violation effects in various decays of *B* and *D* mesons and also searches for rare *B* decays suppressed in the Standard Model (SM). The PNPI group made important contributions to the design of the LHCb detector and especially to the design and construction of the LHCb Muon system, as it was described in the previous PNPI HEPD report for 2002–2006.

Below we describe shortly the performance of the LHCb Muon system and present some of the LHCb results from experimental data collected in 2010–2012, including the results of studies of the $B_s^0 \to \mu^+\mu^-$ decay, where the PNPI group took an active part.

2. Present status of the LHCb Muon system

Muon triggering is a major part of the LHCb lowest level trigger providing fast information on high transverse momentum muons. Prompt and accurate muon identification is an important part of the high level trigger and a strong requirement for most of branches in the off-line analysis. Muons are present in final states of many CP-sensitive *B* decays. Also, they play a major role in CP asymmetry and oscillation measurements since muons from semi-leptonic *b* decays provide a tag of the initial state flavour of the accompanying neutral *B* mesons. In addition, a study of rare *B* decays, such as the flavour-changing neutral current decay $B_s^0 \to \mu^+\mu^-$, may reveal new physics beyond the SM.

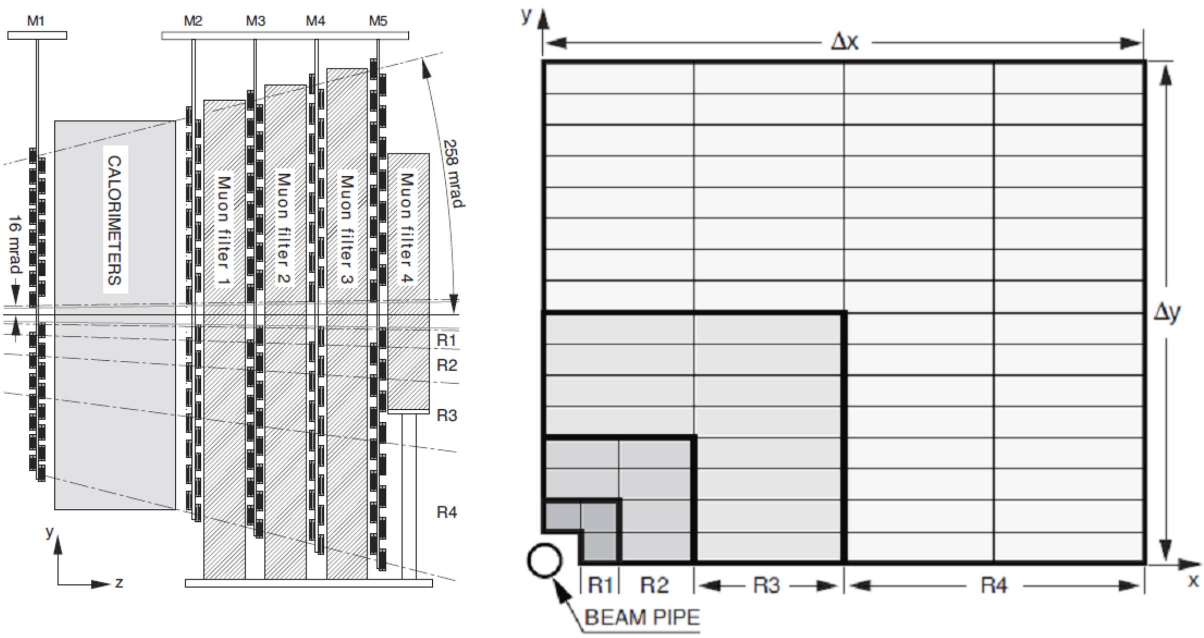

Fig. 1. Side view of the muon system (left). Front view of a quadrant of a muon station (right). Each rectangle represents one chamber. Each station contains 276 chambers

The muon system [1], shown in Fig. 1, consists of five stations M1–M5 of rectangular shape, placed along the beam axis. Each Muon station is subdivided into four regions, R1 to R4, with increasing distance from the beam axis. The linear dimensions of regions R1, R2, R3, R4 and their segmentations scale in the ratio 1 : 2 : 4 : 8. With this geometry, the particle flux and channel occupancy are expected to be roughly the same over the four regions of a given station. The full muon system comprises 12 GEMs (region M1R1) and 1368 four-gaps (two-gaps in M1) Multi-Wire Proportional Chambers (MWPCs), and it covers a total area of 435 m^2.

PNPI has constructed 660 MWPCs for region R4 in stations M2–M4. The sensitive areas of these chambers range from 120×25 cm^2 (M2R4) to 140×29 cm^2 (M4R4). The anode wires were wound along the short side of the chambers. In total, these chambers contain 1500000 anode wires with 2 mm wire spacing. The wires are grouped in wire pads. The wire pad size is constant within each region. For example, it is 5×4270 mm^2 for region M3R4. The MWPCs in region R3 contain cathode pads. The MWPCs in regions R2 and R1 have both anode and cathode pads, the crossovers of which determine “logical pads” of proper sizes. The chambers operate in the double-gap mode, where the pads from the neighbour gaps are joint together in one readout channel. The designed detection efficiency in a 20 ns time window should be at least 95 % for one double gap and at least 99 % for two double gaps at the nominal High Voltage (HV) around 2.6 kV.

An essential element of the Muon system is the multi-channel HV system. In total, the LHCb Muon system contains about 5000 MWPC gaps. For better redundancy, each of these gaps should have an independent HV line. In 2005, the LHCb Collaboration decided that the R3 and R4 regions in stations M2–M5 should be equipped with the HV system developed at PNPI. The total number of the MWPC gaps in these regions is about 4000. However, taking into account financial limitations, it was decided to build the HV system in two stages. At the first stage, a 2000-channel HV system was constructed at PNPI and installed in the LHCb detector in the end of 2007. The remaining 2000-channel system was constructed at PNPI in 2012 and prepared for installation during the LHC long shutdown period LS1 in 2013.

The PNPI group played a major role in assembling and commissioning of the LHCb Muon system. After initial start up of the LHC, the PNPI group participated in maintenance and technical support of the Muon system, as well as in the data analysis. The operational status of the Muon system is demonstrated in the efficiency plots from the 2011 data (Fig. 2). One can see that the measured efficiency in each station is close to 99 %. During the whole running period up to the LHC stop in February 2013, the Muon system showed a reliable operation, being one of the best operating subsystems in the LHCb detector.

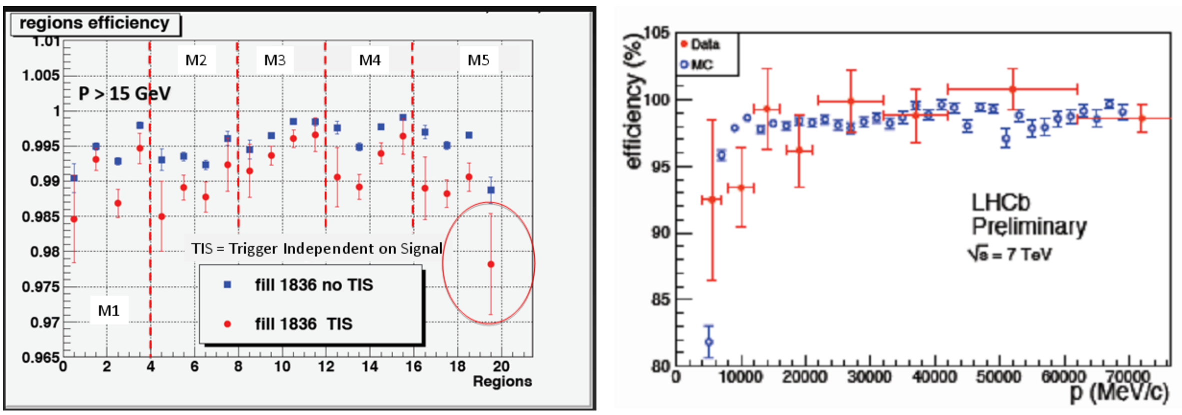

Fig. 2. Efficiency in Muon stations and regions ($p > 15$ GeV) (left). Efficiency of the whole Muon system versus momentum (right). The data are from 2011 runs

3. Plans for upgrades of the LHCb Muon system

The analysis of the data collected in 2010–2012 show that the LHCb detector is robust and is functioning well at the designed luminosity $L = 2 \cdot 10^{32}$ $cm^{-2}s^{-1}$. Moreover, it was demonstrated that LHCb can operate at higher luminosities up to $L = 4 \cdot 10^{32}$ cm^{-2}s^{-1}. This regime was kept during the 2012 running period until March 2013, and it will remain the same in 2015–2016 after the LS1 shutdown, when the energy of the colliding beams will be increased up to 7 TeV + 7 TeV. During the LS1 shutdown period in 2013–2014, the new PNPI 2000-channel HV system should be installed in the Muon detector. No other major upgrades in the LHCb Muon system are foreseen for this period.

The main goal of the second long shutdown LS2 in 2017 is to increase the LHC luminosity by an order of magnitude. All LHC detectors are preparing plans for upgrades, which could allow to use such high luminosities. Such a plan is under consideration also in the LHCb Collaboration. The aim is to operate the LHCb detector at luminosities up to $L = 2 \cdot 10^{33}$ cm^{-2}s^{-1}. To reach this goal, some subsystems of the LHCb detector should be essentially modified. Also, the readout electronics and the DAQ system should be rebuilt allowing to increase the maximal trigger rate from 1 MHz at present to 40 MHz.

For the Muon system, the planned upgrade consists mainly in changes of the off-detector electronics. Apart from these changes, some modifications of the muon chambers are under discussions. Running LHCb at the luminosities up to $L = 2 \cdot 10^{33}$ cm^{-2}s^{-1} brings station M1 and the central regions in stations M2 and M3 (M2R1, M2R2, and M3R1) to the rates exceeding the maximal permissible rate, which is 1 MHz per physical pad. As concerns station M1, the Muon system can operate without this station with slightly worth but still acceptable momentum resolution. Several solutions have been proposed to improve the situation in regions M2R1, M2R2, and M3R1. The most realistic ones are construction of new MWPCs for region M2R2 with smaller pad size and replacement of the MWPCs in regions M2R1 and M3R1 by GEM chambers.

4. Physics results

Figure 3 shows the integrated luminosities recorded by the LHCb detector during the running periods in 2010, 2011, and 2012. Note that the colliding beams energy was 3.5 TeV + 3.5 TeV in the 2010 and 2011 runs, and it was 4.0 TeV + 4.0 TeV in the 2012 runs. In total, LHCb has collected 3.19 fb^{-1} of data. An analysis of the data was continuously going on. About 100 papers had been published by the end of 2012, though only a part of the collected data had been analysed by that time. The intense analysis will be continued till the new start up of the LHC in 2015 with the colliding beams energy increased to 7.0 TeV + 7.0 TeV.

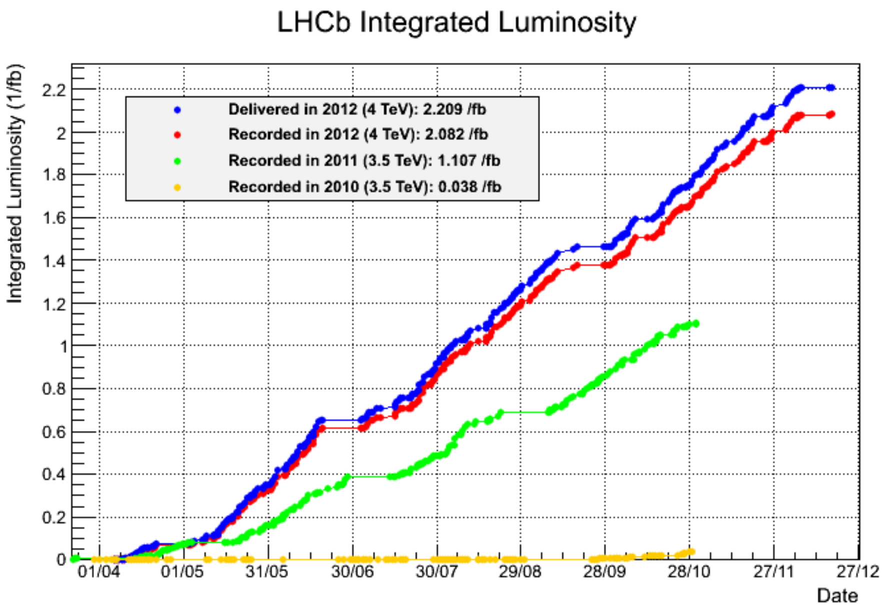

Fig. 3. Integrated luminosities delivered in 2012 (blue) and recorded by the LHCb detector during the running periods in 2010 (yellow), 2011 (green), and 2012 (red)

The excellent performance of the LHCb detector showed that it is the most powerful B-factory to date. The number of $b\bar{b}$ and $c\bar{c}$ pairs produced within the LHCb acceptance during this period was $2.6 \cdot 10^{11}$ and $5.9 \cdot 10^{12}$, respectively. A powerful particle identification system and a high mass resolution of the LHCb detector are important advantages of this detector. This helped the LHCb Collaboration to produce many new results on a record level of precision and sensitivity. Some of these results are presented below.

4.1. Study of $B_s^0 \leftrightarrow \bar{B}_s^0$, $B_d^0 \leftrightarrow \bar{B}_d^0$, and $D^0 \leftrightarrow \bar{D}^0$ oscillations

One of the goals of the LHCb experiment was to perform a precise measurement of the $B_s^0 \leftrightarrow \bar{B}_s^0$ oscillation frequency, that is the frequency with which the B_s^0 meson turns from particle to antiparticle and then back. The oscillation frequency in the $B_s^0 - \bar{B}_s^0$ system is given by the mass difference Δm_s between the heavy and light B_s mass eigenstates. For the first time, the $B_s^0 \leftrightarrow \bar{B}_s^0$ oscillation was observed by the D0 and CDF experiments. The oscillation frequency measured by CDF was Δm_s = 17.77 ± 0.10 ± 0.07 ps^{-1}. The LHCb experiment was able to reproduce this result already at an early stage with 36 pb^{-1} of data collected in 2010 in pp collisions at $\sqrt{s}$ = 7 TeV. The $B^0{}_s$ meson decays into $D^-{}_s\pi^+$ and $D^-{}_s\pi^+\pi^-\pi^+$ were used with $D^-{}_s$ decays into five different channels. All reconstructed decays are flavour-specific final states, thus the flavour of $B^0{}_s$ at the time of its decay is given by the charges of the final state particles of the decay. A combination of tagging algorithms was used to identify the $B^0{}_s$ flavour at production. A total of 1381 $B_s^0 \to D_s^- \pi^+$ and $B_s^0 \to D_s^- \pi^+\pi^-\pi^+$ decays were reconstructed with the average decay time resolution of 44 fs and 36 fs, respectively. An oscillation signal was observed, and the oscillation frequency was determined: Δm_s = 17.63 ± 0.11 (stat) ± 0.02 (syst) ps^{-1}, in agreement with the measurement reported by CDF. Later on, the analysis was repeated [2] with 1 fb^{-1} of data collected in 2011. In total, 34000 $B_s^0 \to D_s^- \pi^+$ signals were detected with the time distribution shown in Fig. 4.

***This analysis resulted in the highest-precision value of the oscillation frequency in the $B_s^0 - \bar{B}_s^0$ system*:**

$$\Delta m_s = 17.768 \pm 0.023 \pm 0.006 \text{ ps}^{-1}.$$

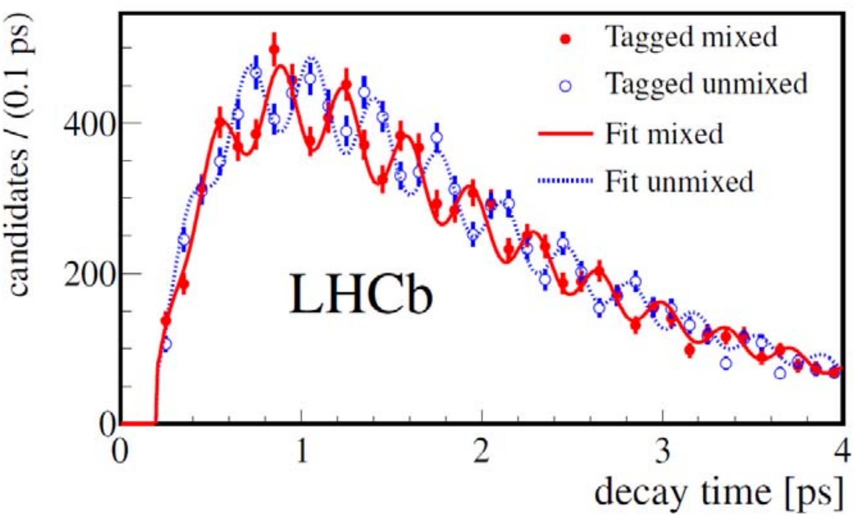

Fig. 4. Time dependence of $B_s^0 \to D_s^- \pi^+$ signals with two kinds of flavour tagging: when the production flavour is equal to the flavour at decay (tagged unmixed) and when the production flavour is opposite to the flavour at decay (tagged mixed)

***Also, the world's highest precision was achieved in the measurement of the oscillation frequency in the $B_d^0 \leftrightarrow \bar{B}_d^0$ system* [3].**

This measurement was based on an analysis of a data set corresponding to the integrated luminosity of 1 fb^{-1} of pp-collisions at $\sqrt{s}$ = 7 TeV using the decay channels $B^0 \to D^-\pi^+$ and $B^0 \to J/\psi\, K^*$.

Figure 5 shows the time dependent mixing asymmetry $A(t) = [N_{\text{unmixed}}(t) - N_{\text{mixed}}(t)] / [N_{\text{unmixed}}(t) + N_{\text{mixed}}(t)]$. The analysis of this time distribution gives the oscillation frequency Δm_d :

$$\mathbf{\Delta m_d = 0.5156 \pm 0.0051 \pm 0.0033\ ps^{-1}.}$$

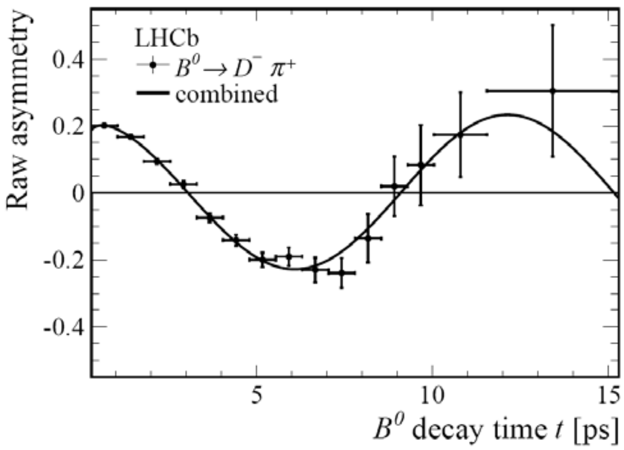

Fig. 5. Time dependence of the mixing asymmetry $A(t)$ in tagged $B^0 \to D^- \pi^+$ decays

From these two measurements it follows that $\mathbf{\Delta m_s / \Delta m_d = 34.4}$ with 1.2 % precision, this ratio being of special interest for theory.

Finally, the LHCb Collaboration reported [4] on the first observation of $D^0 \leftrightarrow \overline{D}^0$ oscillations by measuring the time dependence of the ratio of $D^0 \to K^+ \pi^-$ to $\overline{D}^0 \to K^- \pi^+$ yields (Fig. 6). The oscillation rate in this case proved to be very low. Nevertheless, it was observed on a high confidence level.

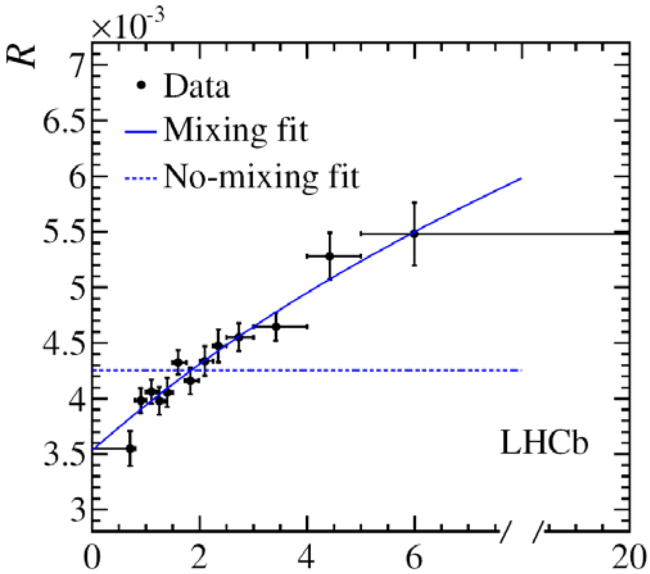

Fig. 6. Decay-time evolution of the ratio of the $D^0 \to K^+ \pi^-$ to $D^0 \to K^- \pi^+$ yields. The horizontal dotted line represents the prediction for the case with no mixing. This hypothesis is excluded at 9.1 standard deviations

4.2. CP violation in decays of *B* mesons

One of the main goals of the LHCb experiment was to study CP violation in *B* meson decays. The CP violation was discovered in 1964 in decays of neutral *K* mesons and was rewarded with the 1980 Nobel Prize in Physics for James Cronin and Val Fitch. In 1973, M. Kobayashi and T. Maskawa proposed a mechanism which could incorporate CP violation within the Standard Model with not less than 6 quarks. In 2001, CP violation was observed in the decay of B^0 mesons. The SM mechanism of CP violation was confirmed, and therefore Kobayashi and Maskawa were rewarded with the 2008 Nobel Prize in Physics. The LHCb Collaboration extended these studies for other *B* decays.

4.2.1. CP asymmetries in decays of charged *B* mesons

In March 2012, the LHCb Collaboration reported an observation of CP violation in charged $B^{\pm}$ meson decays into $DK^{\pm}$ with 5.8 σ significance [5]. Large CP asymmetries were observed also in three-body charmless decays of charged *B* mesons, $B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}$ and $B^{\pm} \to \pi^{\pm}K^{+}K^{-}$:

$$\boldsymbol{A_{\mathrm{CP}}(B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}) = +\,0.120 \pm 0.020 \pm 0.019,}$$
$$\boldsymbol{A_{\mathrm{CP}}(B^{\pm} \to \pi^{\pm}K^{+}K^{-}) = -\,0.153 \pm 0.046 \pm 0.019.}$$

A remarkable feature of these results is that the CP violation effects appear to arise in some special kinematical regions that are not dominated by contributions from narrow resonances. For example, in $B^{\pm} \to \pi^{\pm}K^{+}K^{-}$ decays the CP asymmetry is especially large at $m^2_{K^+K^-} < 1.5$ GeV^2, as one can see in Fig. 7. This points to some interesting hadronic dynamics that could generate the observed direct CP violation. The results from these analyses will also establish whether the observed CP violation is consistent with the expectations of the Standard Model or it has a more exotic origin.

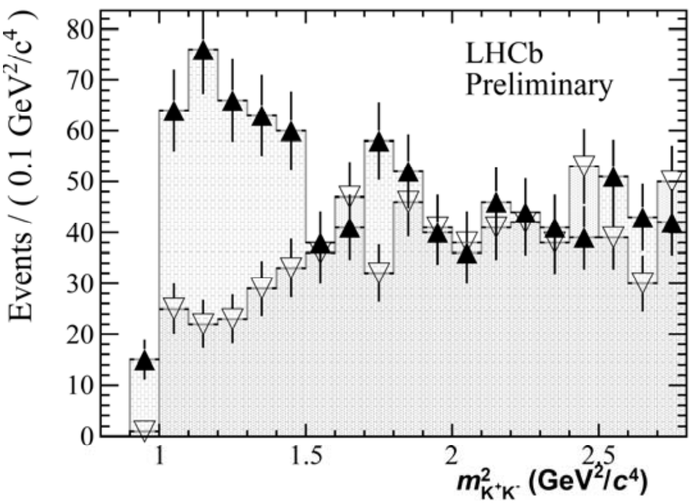

Fig. 7. Invariant mass $m^2_{K^+K^-}$ distribution of $B^{+} \to \pi^{+}K^{+}K^{-}$ decays (filled triangles) and $B^{-} \to \pi^{-}K^{+}K^{-}$ decays (open triangles)

4.2.2. First observation of CP violation in decays of B^0_s mesons

The direct CP violation in the $B^0 \to K^{+}\pi^{-}$ decay was first observed in 2004 in the BaBar experiment. This observation raised the question of whether the effect could be accommodated by the SM or it was due to non-SM physics. The answer to this question was expected from comparison with the direct CP violation in $B^0_s \to K^{-}\pi^{+}$ decay. Several attempts to perform such measurements were made, but only the LHCb experiment could observe this effect with more than 5 σ significance. In this experiment, the CP asymmetry was measured simultaneously in $B^0 \to K^{+}\pi^{-}$ and $B^0_s \to K^{-}\pi^{+}$ decays. Figure 8a – d shows the invariant mass spectra obtained for the $B^0 \to K^{+}\pi^{-}$ and $B^0_s \to K^{-}\pi^{+}$ decays. The analysis was based on the data corresponding to an integrated luminosity of 1 fb^{-1} of *pp*-collisions at $\sqrt{s} = 7$ TeV. The mass resolution was 22 MeV in these measurements. The number of the detected events was 41420 ± 300 for the $B^0 \to K^{+}\pi^{-}$ decay and 1065 ± 55 for the $B^0_s \to K^{-}\pi^{+}$ decay. As a result, the CP asymmetries were determined [6]:

$$\boldsymbol{A_{\mathrm{CP}}\,(B^0 \to K^{+}\pi^{-}) = -\,0.080 \pm 0.007 \pm 0.003,}$$
$$\boldsymbol{A_{\mathrm{CP}}\,(B^0_s \to K^{-}\pi^{+}) = +\,0.27 \pm 0.04 \pm 0.01.}$$

The former is the most precise measurement of $A_{\mathrm{CP}}\,(B^0 \to K^{+}\pi^{-})$ to date, whereas the latter represents the first observation of CP violation in decays of B^0_s mesons with the significance exceeding 5 σ.

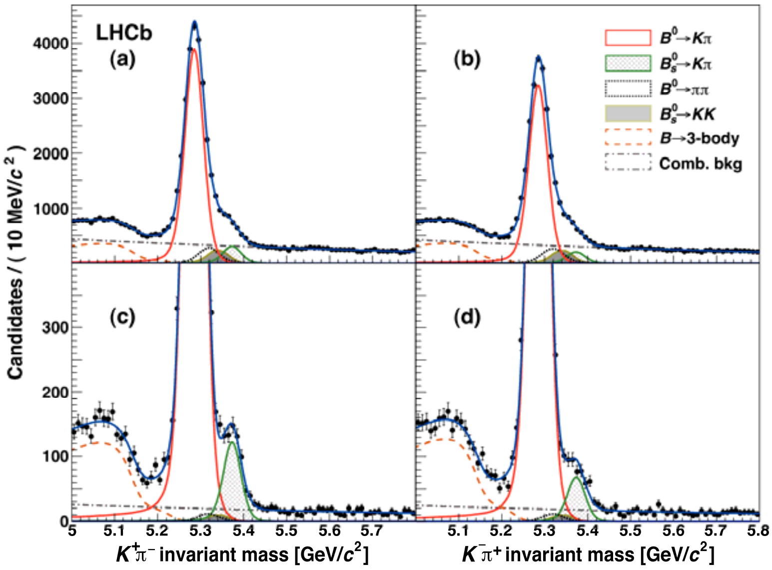

Fig. 8. Invariant mass spectra obtained using the event selection optimal for the $B^0 \to K^+\pi^-$ decay {plots (a) and (b)} and for $B^0{}_s \to K^-\pi^+$ decay {plots (c) and (d)}

These results allow a stringent test of validity of the relation between $A_{CP}(B^0 \to K^+\pi^-)$ and $A_{CP}(B^0{}_s \to K^-\pi^+)$ given in the SM: $\Delta_{SM} = A_{CP}(B^0 \to K^+\pi^-) / A_{CP}(B^0{}_s \to K^-\pi^+) + \mathcal{B}(B^0{}_s \to K^-\pi^+)\tau_d]$ / $/ \mathcal{B}(B^0 \to K^+\pi^-)\tau_s = 0$, where $\mathcal{B}(B^0 \to K^+\pi^-)$ and $\mathcal{B}(B^0{}_s \to K^-\pi^+)$ are CP-averaged branching fractions, and τ_d and τ_s are the B^0 and $B^0{}_s$ mean lifetimes, respectively. The experimental value of Δ_{SM} proved to be quite close to this prediction:

$$\boldsymbol{\Delta_{exp} = -\,0.02 \pm 0.05 \pm 0.04},$$

where the first uncertainty is from the measurements of the CP asymmetries and the second one is from the input values of the branching fractions and the lifetimes.

The observation of CP violation in the B_s decays was recognized at CERN as "an important milestone in the history of particle physics", extending the family of subatomic particles known to exhibit such behaviour.

4.3. Search for CP violation in charm decays

In the Standard Model, CP violation in the charm sector is expected to be very small, whereas new physics effects could generate essential enhancements. The LHCb Collaboration studied the CP asymmetry $A_{CP} = [N(D^0 \to f) - N(\overline{D}^0 \to f)]/[N(D^0 \to f) + N(\overline{D}^0 \to f)]$, where f is the CP eigenstate K^-K^+ or $\pi^-\pi^+$. As a matter of fact, it was decided to measure the difference in the asymmetries $\Delta A_{CP} = A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+)$ to eliminate some systematic errors, while the effect of new physics should be doubled as the induced asymmetries should have opposite signs in these two decay modes. The first result reported by the LHCb Collaboration in November 2011 showed a 3.5 σ evidence for CP violation in the charm sector: $\Delta A_{CP} =$ $= (-\,0.82 \pm 0.21 \pm 0.11)$ %. This result triggered an intensive theoretical and experimental activity. The CDF and Belle Collaborations presented their results: $\Delta A_{CP} = (-\,0.62 \pm 0.21 \pm 0.10)$ % and $\Delta A_{CP} = (-\,0.87 \pm 0.41 \pm$ $\pm\, 0.06)$ %, respectively, thus supporting the LHCb result.

In all these studies, $D^{*+} \to D^0\pi^+$ decays were used as the source of the D^0 sample, and the emitted pion was used to determine the flavour of the neutral meson. Later, the LHCb Collaboration repeated this analysis with a larger data set and with better background rejection [7]. The obtained result was $\Delta A_{CP} = (-\,0.34 \pm 0.15 \pm 0.10)$ %, which is much closer to zero than the previous ones. In addition, the LHCb Collaboration presented results of a second independent analysis in which the D^0 and $\overline{D}^0$ mesons were selected using the semileptonic B decays, $B^{+(-)} \to \mu^{+(-)}\,\nu\, D^0\,(\overline{D}^0)$. In this analysis, the flavour of the D^0 meson was identified by the sign of the detected muons. The second analysis resulted in the following value of the asymmetry: ΔA_{CP} = (+ 0.49 ± 0.30 ± 0.14) %. A combination of the two LHCb results gives:

$$\mathbf{\Delta A_{CP} = (-\,0.15 \pm 0.16)\ \%.}$$

The two new LHCb results are consistent with each other at the 2σ level and do not confirm the previous evidence for CP violation in the charm sector.

4.4. Measurement of the CP-violating phase φ_s and the difference in the lifetimes of B_s mass eigenstates

The mass difference $\Delta m_s = m_H - m_L$ between the B_s mass eigenstates B_H and B_L was determined with high precision from the $B_s^0 \leftrightarrow \overline{B}_s^0$ oscillation frequency. Also, it was known from previous measurements that there is some difference $\Delta\Gamma_s \equiv \Gamma_L - \Gamma_H$ in the lifetimes of the B_H and B_L states, though the sign of this difference was not determined. The CP properties of the B_H and B_L states depend on the value of the CP-violating phase φ_s. The previous studies (dominated by the LHCb experiment) of the $B_s \to J/\psi\varphi$ decays showed that the CP violation effect in the B_s system is rather small. The value of φ_s proved to be close to zero or to π, depending on the unknown sign of $\Delta\Gamma_s$. So, there were two options: $\Delta\Gamma_s > 0$, $\varphi_s \approx 0$, and $\Delta\Gamma_s < 0$, $\varphi_s \approx \pi$. To resolve this ambiguity, the LHCb Collaboration investigated interference between the K^+K^- S-wave and P-wave amplitudes in $B_s \to J/\psi K^+K^-$ decays with the K^+K^- pairs in the regions around the φ(1020) resonance. It was concluded from this analysis [8] that $\Delta\Gamma_s > 0$ with high significance, and the most precise results on φ_s, Γ_s and $\Delta\Gamma_s$ were presented:

$$\boldsymbol{\varphi_s = 0.07 \pm 0.09 \pm 0.01\ \text{rad},}$$
$$\boldsymbol{\Gamma_s = (\Gamma_L + \Gamma_H)/2 = 0.663 \pm 0.005 \pm 0.006\ \text{ps}^{-1},}$$
$$\boldsymbol{\Delta\Gamma_s = \Gamma_L - \Gamma_H = 0.100 \pm 0.016 \pm 0.003\ \text{ps}^{-1}.}$$

These results are plotted in Fig. 9 together with the results from the D0 and CDF experiments. One can see that LHCb not only has resolved the ambiguity but also has improved considerably the precision of the measurements.

The obtained results show that the lightest B_s mass eigenstate B_L decays faster and its state is almost CP = +1, while the heavier B_s mass eigenstate B_H is almost CP = –1 and it lives longer.

The LHCb results proved to be close to the SM predictions:

$$\varphi_s = -\,0.036 \pm 0.002\ \text{rad},\ \ \Delta\Gamma_s = 0.082 \pm 0.021\ \text{ps}^{-1}.$$

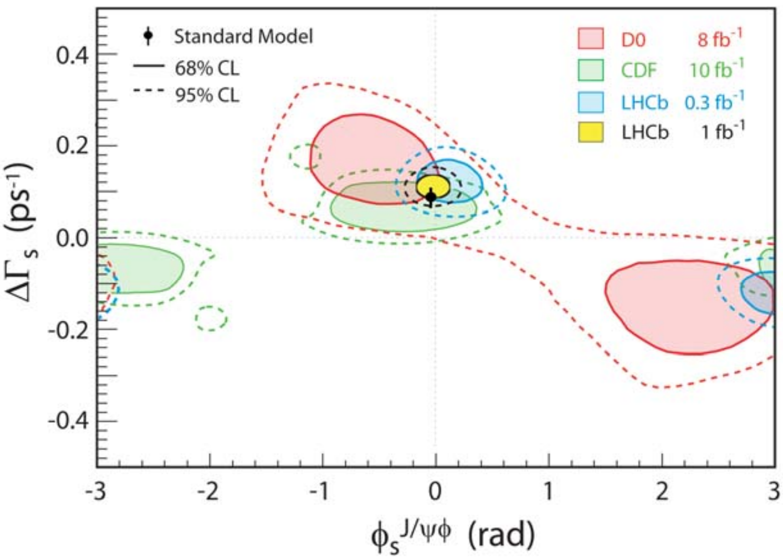

Fig. 9. Results of CDF, D0, and LHCb on measurements of the difference $\Delta\Gamma_s$ in the lifetimes of the B_s mass eigenstates B_H and B_L and determination of the CP-violating phase φ_s. The LHCb results have resolved the ambiguity and also have improved considerably the precision of the measurements, confirming the Standard Model

4.5. Study of exotic hadronic states

An important advantage of the LHCb experiment is a possibility to study exotic hadronic states with various quark combinations. This is not only because proton-proton collisions at the LHC energies are a rich source of such states, but also due to a powerful particle identification system and a high momentum resolution of the LHCb detector. Below we present two examples of such studies.

4.5.1. First observation of excited states of Λ_b

The excited states were previously observed for the $\Lambda(uds)$ and $\Lambda_c(udc)$ baryons. The LHCb Collaboration has made first observations [9] of two excited states of $\Lambda_b(udb)$.

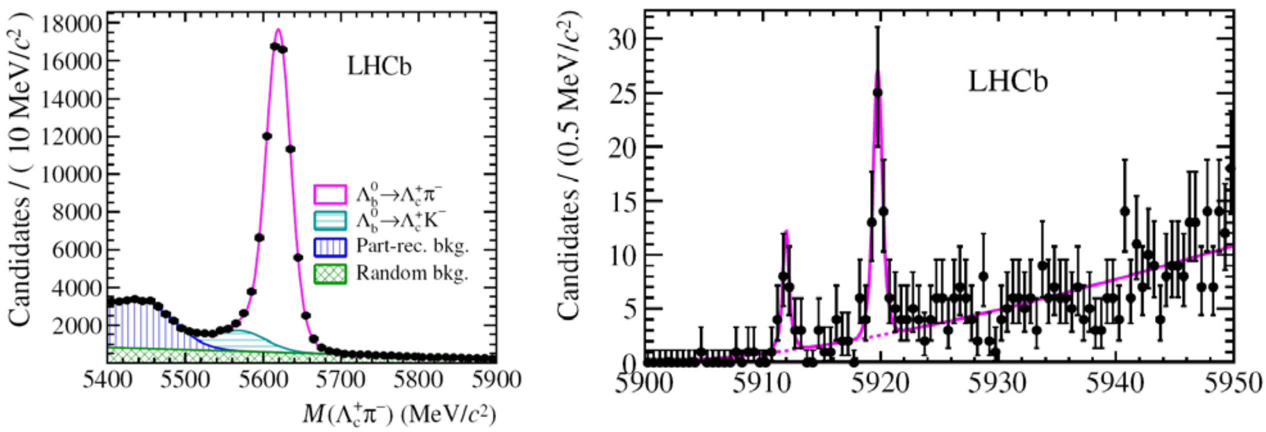

Fig. 10. Observation of Λ_b ground state (left panel) and two Λ_b excited states (right panel)

The Λ_b excited states were reconstructed in three steps. In the first step, the Λ_c^+ particles were reconstructed through their decay into a proton p, a negative K^- meson and a positive π^+ meson. In the second step, the Λ_c particles were combined with negative π^- mesons in order to form the Λ_b particles. The Λ_b signal is clearly seen as an enhancement in the left panel of Fig. 10 showing the $\Lambda_c^+\pi^-$ invariant mass spectrum. Finally, the Λ_b particles were combined with a pair of opposite sign pions $\pi^+\pi^-$. In the right panel of Fig. 10, two enhancements are clearly seen, corresponding to two Λ_b excited states with masses of 5912 MeV and 5920 MeV.

4.5.2. Study of the exotic state *X*(3872)

Some 10 years ago, the BELLE Collaboration observed a narrow state at the mass 3872 MeV. It was discovered in B^+ meson decay into an X(3872) and a K^+ meson. Its existence was confirmed later by the CDF, D0, and BaBar experiments. An analysis of the CDF Collaboration has limited possible values for the quantum numbers J^{PC} of X(3872) to either 1^{++} or 2^{-+}. The LHCb experiment has observed the X(3872) particle in the decay of a B^+ meson into an X(3872) and a K^+ meson. A peak at the mass of 3872 MeV was observed in the invariant mass of a J/ψ particle and a $\pi^+\pi^-$ pair, J/ψ being identified from its decay into a $\mu^+\mu^-$ pair. Figure 11 presents the difference between the invariant mass of the $\pi^+\pi^- J/\psi$ combination and J/ψ showing clearly the X(3872) and $\psi(2S)$ enhancements over the smooth background distribution. These results were obtained in an analysis of the 2011 data.

A sophisticated analysis [10] of the whole B^+ decay chain in 5 dimensions allowed to determine unambiguously the quantum numbers of X(3872) to be 1^{++}. The other previously allowed assignment of 2^{-+} was rejected with the statistical significance over 8 σ. The exotic nature of X(3872) would be unambiguously determined if its quantum numbers could not be described by the quark-antiquark combination. However, this is not the case. In fact, the mass of 3872 MeV is located in a region in which many charm quark-antiquark states (of charmonium) are present. X(3872) has the quantum numbers of an as yet unobserved charmonium state called $\chi_{c1}(2^3P_1)$. However, the charmonium spectrum is very well understood and the mass of 3872 MeV makes this assignment very unlikely**.**

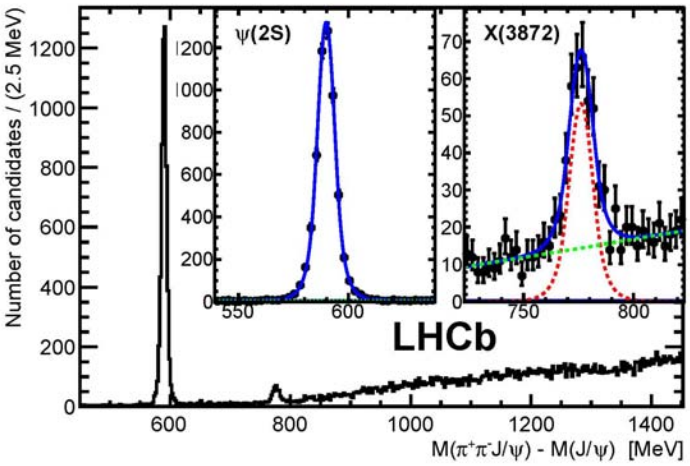

Fig. 11. Observation of the $X(3872)$ state in the B^+ decay into J/ψ and $\pi^+\pi^-$

Possible explanations of the X*(3872) *nature include the observation of a tetraquark state.

4.6. First evidence for the $B^0_s \to \mu^+\mu^-$ decay

Flavour changing neutral current processes are highly suppressed in the Standard Model. There are precise SM predictions for the branching fractions of the $B_{s(d)} \to \mu^+\mu^-$ decays: $\mathrm{Br}(B_s \to 2\mu) = (3.2 \pm 0.2) \cdot 10^{-9}$, $\mathrm{Br}(B_d \to 2\mu) = (1.0 \pm 0.1) \cdot 10^{-10}$. This makes these modes stringent probes in the search for deviations from the SM, since contributions from some new processes or new heavy particles can significantly modify these values. The search of the $B_{s(d)} \to 2\mu$ decays was initiated at the Tevatron at FNAL. The upper limits for the branching fraction of the $B_s \to 2\mu$ decays reached in these experiments by 2012 exceeded the SM value by more than an order of magnitude, thus leaving some room for «new physics». The CDF Collaboration even declared a possible observation of the $B_s \to 2\mu$ signals on a level of $\mathrm{Br}(B_s \to 2\mu) = (18^{+11}/_{-9}) \cdot 10^{-9}$, giving some hopes for observation of "new physics". However, these results were disproved by the LHCb experiment. The analysis of the experimental data collected in 2011 with the integrated luminosity of 1 fb^{-1} of *pp*-collisions at $\sqrt{s}$ = 7 TeV allowed to push down these upper limits to $\mathrm{Br}(B_s \to 2\mu) < 4.5 \cdot 10^{-9}$ and $\mathrm{Br}(B_d \to 2\mu) < 1.0 \cdot 10^{-9}$. These results were published in June 2012 [11]. The further analysis included a part of the data collected in 2012. The data sample comprised 1.1 fb^{-1} of *pp*-collisions at $\sqrt{s}$ = 8 TeV and 1.0 fb^{-1} at $\sqrt{s}$ = 7 TeV. The events were selected with the BDT method to classify data into bins with different ratios of $B^0_s \to 2\mu$ decays and background contributions. The $\mu^+\mu^-$ invariant mass spectrum for the bins with the smallest background contribution is shown in Fig. 12. The solid blue line shows that the data distribution presented as black dots is well understood and can be separated into different components presented with the help of different colour lines. The dashed red narrow distribution shows the $B^0_s \to 2\mu$ contribution around the B^0_s mass of 5366 MeV/c^2. The green dashed distribution shows a possible $B^0_d \to 2\mu$ contribution around the B^0_d mass of 5280 MeV/c^2.

A small excess of data around the B^0_d mass over the background and the Standard Model rate is observed, but it is consistent with the SM expectation. This gives an upper limit for the branching fraction of the $B_d \to 2\mu$ decays. LHCb has set the following limit for this branching ratio:

$$\mathbf{Br(B^0_d \to 2\mu) < 9.4 \cdot 10^{-10}\ \text{at 95\% CL.}}$$

On the other hand, the excess of signals in the region of the B^0_s mass is interpreted as the first observation of the $B^0_s \to 2\mu$ decay with the branching fraction

$$\mathbf{Br(B^0_s \to 2\mu) = (3.2^{+1.5}_{-1.2}) \cdot 10^{-9}.}$$

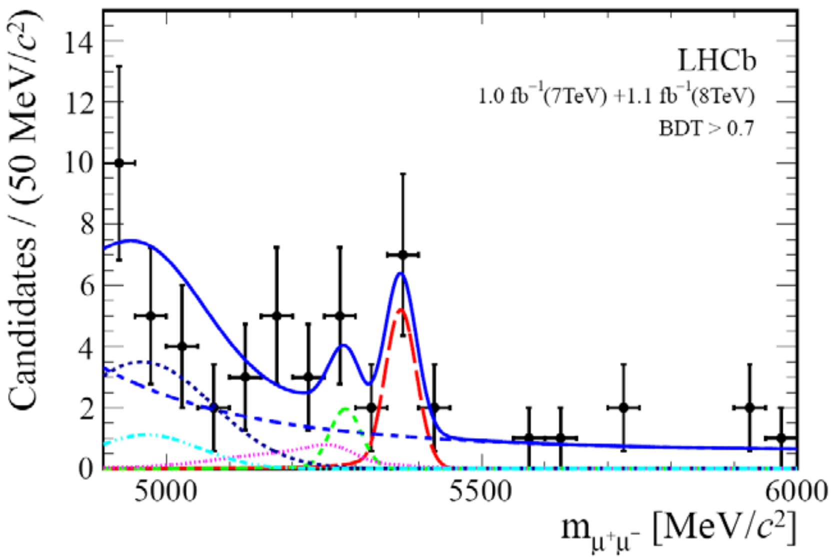

Fig. 12. The $\mu^+\mu^-$ invariant mass distribution of the selected ($B^0_s \longrightarrow 2\mu$) candidates

The significance of this measurement is 3.5 σ, and therefore this result is classified as ***the first evidence for the $B^0_s \rightarrow \mu^+\mu^-$ decay***, in agreement with the Standard Model.

These results were first presented at the Kioto conference in November 2012 and then published in PRL [12].

At CERN, these results are considered among the most important achievements of the LHC experiments, while the editorial board of PRL selected this article into the category of "exceptional research". The obtained results put quite strong limits for existence of supersymmetric partners in certain regions of the SSM parameters.

Figure 13 illustrates this statement for the case of the Constrained Minimal Super Symmetric Model (CMSSM). This figure shows a two-dimensional plot of the CMSSM parameters $\{m_0, m_{1/2}\}$ with the other two parameters fixed to $\tan\beta = 50$ and $A_0 = 0$. One can see that in this particular case the limits coming from the LHCb data are much stronger than those from the direct search. Note, however, that this statement is valid only for $\tan\beta > 30$.

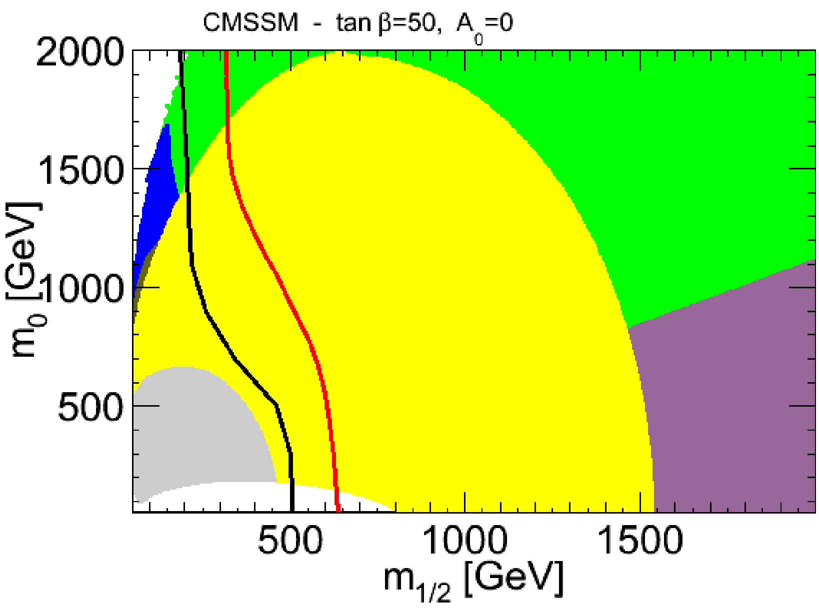

Fig. 13. The regions in the two-dimensional plot of the CMSSM parameters $\{m_0, m_{1/2}\}$ excluded by the LHCb $B^0_s \longrightarrow 2\mu$ data (yellow) and by the direct search in the CMS experiment (to the left from the red line)

5. Summary

The LHCb experiment demonstrated that it is the most powerful B-factory to date. Already during the first years of operation in 2010–2012, most of the previous results in this domain were exceeded in precision and many new observations were reported. The main outcome of these studies was strong quantitative confirmation of the validity of the Standard Model in various aspects including CP violation in the B sector. Also, some stringent limits were set on possible contributions from "new physics" (in particular, from some supersymmetry models) in the energy region explored by the LHC. Very promising areas for the LHCb experiment proved to be rare decay studies, as well as studies of exotic states of mesons and baryons.

The LHCb detector showed a very effective and reliable performance. This made it possible to perform measurements at the luminosity of $L = 4 \cdot 10^{32}$ cm^{-2} s^{-1}, twice exceeding the designed value. Plans for further upgrades of the LHCb detector are under considerations at present. The goal is to increase the luminosity up to $L = 2 \cdot 10^{33}$ cm^{-2} s^{-1}. This will require some serious modifications in various subsystems of the detector including the Muon system and the Tracking system. PNPI will take an active part in this upgrade program.

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In total, the LHCb Collaboration has published 116 physics papers in the period 2011 – June 2013. The list of the authors includes the following members of the PNPI team: G.D. Alkhazov, N.F. Bondar, A.A. Dzyuba, O.E. Maev, N.R. Sagidova, Yu.A. Shcheglov, A.A. Vorobyev.