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Results from B Physics (LHCb, Belle)

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LHCb and Belle experiments have collected rich data on *b*-physics. We present an overview of recently performed measurements on B meson production cross-sections, lifetime, decay mode, branching ratios, angular distribution of decay products and CP violation which have been performed to cross-check predictions of the Standard Model and to search for New Physics (NP). Nearly all current results agree with the Standard Model expectations within measurement uncertainties.

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1. Introduction

This talk presents some results of the studies performed by LHCb [1] and Belle [2] experiments on *B*-meson spectroscopy, CP symmetry, Rare decays which might proceed with lepton flavor violation or could be mediated by charged Higgs bosons. The decays that are forbidden or rare within the Standard Model (SM) are sensitive to the New Physics. The results of recent measurements of differential cross-sections, branching ratios, forward-backward asymmetry compared with SM predictions are discussed here.

2. LHCb and Belle *B*-factories

The LHCb detector [1] is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$, designed for the study of particles containing b or c quarks. The detector includes a high-precision tracking system consisting of a silicon-strip vertex detector surrounding the pp interaction region, a large-area silicon-strip detector located upstream of a dipole magnet with a bending power of about 4 Tm , and three stations of silicon-strip detectors and straw drift tubes placed downstream. The combined tracking system provides momentum measurement with relative uncertainty that varies from 0.4% at 5 GeV/c to 0.6% at 100 GeV/c, and impact parameter resolution of 20 μm for tracks with high transverse momentum. Charged hadrons are identified using two ring-imaging Cherenkov detectors. Photon, electron and hadron are identified by a calorimeter system, an electromagnetic calorimeter and a hadronic calorimeter. Muons are identified by a system composed of alternating layers of iron and multiwire proportional chambers. The trigger [3] consists of a hardware stage, based on information from the calorimeter and muon systems, followed by a software stage, which applies a full event reconstruction. A multivariate algorithm is used for the identification of secondary vertices consistent with the decay of a b-hadron.

The data samples of Run1 (years 2010–2012) have been collected by the LHCb detector in pp collisions at $\sqrt{s} = 7$ and 8 TeV with integrated luminosities of 1.0 fb^{-1} and 2.0 fb^{-1}, respectively. Fig. 1 illustrates the principle of B meson event selection by triggering on b-hadron decay products.

The Belle Collaboration has built an excellent experimental setup [2] which allowed to extract clean samples of B mesons from (e^+e^-) collisions with a data set of 711 fb^{-1} at the $\Upsilon(4S)$

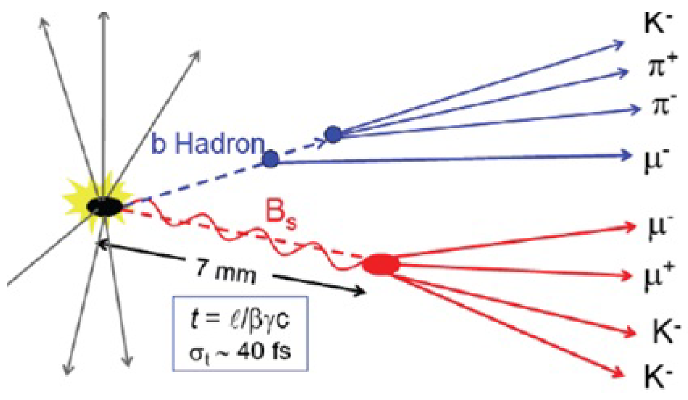

Figure 1: *B* meson event selection by reconstruction of secondary vertices.

resonance. The total data set acquired during 1999–2010 exceeded 1 000 fb^{-1}. The upgraded experiment Belle II [4] will run in the year 2016 at the luminosity of 8.0×10^{35} $cm^{-2}s^{-1}$ (40 times higher than at KEKB).

3. Precision measurements at *B*-Factories

3.1 Heavy Flavor Spectroscopy

After measurements performed by LHCb in the domain of the well-known resonances the studies of heavy flavored hadrons led to original observations and discoveries.

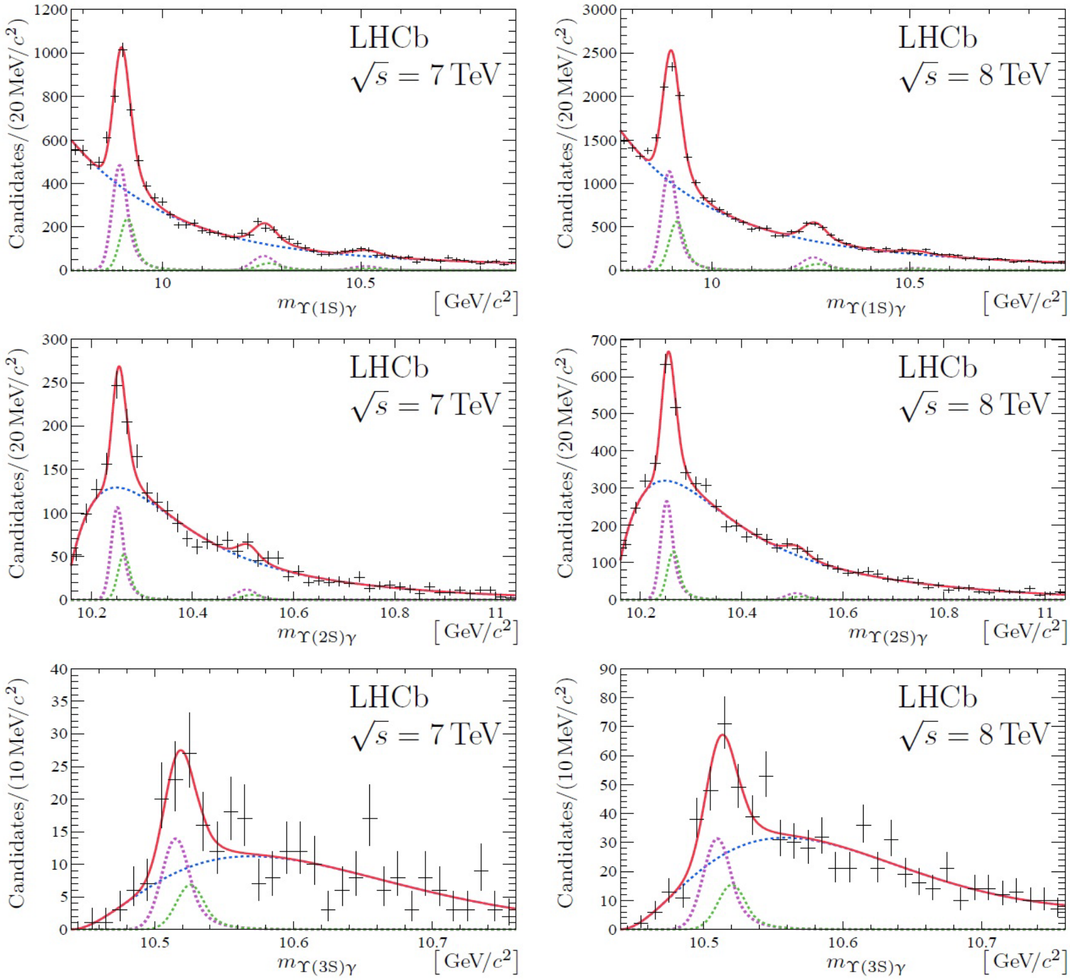

Figure 2: Distributions of the mass $m_{\Upsilon(nS)\gamma}$ for the selected χ_b candidates(black points) decaying into (top row) $\Upsilon(1S)$, (middle row) $\Upsilon(2S)$ and (bottom row) $\Upsilon(3S)$, for (left) $\sqrt{s} = 7$ TeV and (right) 8 TeV data [5]. Solid red line represents the result of the data fit (for signals and background see details in the text).

For instance, χ_b meson properties were studied in proton-proton collisions at the centre-of-mass energies $\sqrt{s} = 7$ and 8 TeV [5]. The χ_b signals are searched for in the invariant mass of $\Upsilon\gamma$ combinations. Fig. 2 shows the distributions of the masses $m_{\Upsilon(nS)\gamma}$ for $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$

candidates in the three ranges of the Υ transverse momentum ($14 < p_T^{\Upsilon(1S)} < 40$ GeV/c, $18 < p_T^{\Upsilon(2S)} < 40$ GeV/c and $24 < p_T^{\Upsilon(3S)} < 40$ GeV/c). Each plot shows also the result of the fit (solid red curve), including the background (dotted blue curve) and the signal (dashed green and magenta curves) contributions. The green dashed curve corresponds to the χ_{b1} signal and the magenta dashed curve to the χ_{b2} signal. The radiative transition of the $\chi_b(3P)$ meson to $\Upsilon(3S)$ was observed for the first time. The $\chi_{b1}(3P)$ mass is determined to be $10511.3 \pm 1.7(stat) \pm 2.5(syst)$ MeV/c^2.

The Belle Collaboration reported details about the observation of a narrow ($\sim$ 45 MeV) resonance at 4430 MeV in the $\psi'\pi^-$ mass distribution in $B^0 \to \psi' K^+\pi^-$ decays [6]. This resonance could be interpreted as the four quark state. The LHCb Collaboration performed an amplitude fit to a large sample of $B^0 \to \psi' K^+\pi^-$ decays and provided the first independent confirmation of the existence of the $Z(4430)$ resonance. Its spin-parity was determined to be 1^+ [7]. The Argand diagram obtained for the $Z(4430)$ amplitude is consistent with the resonant behavior.

3.2 Lifetime measurements

Lifetime measurements for various b-hadrons have been performed at LHCb. An example of such measurements is shown in Fig. 3 where the lifetime of the B meson is compared with the lifetime of the Λ_b^0 baryon [8].

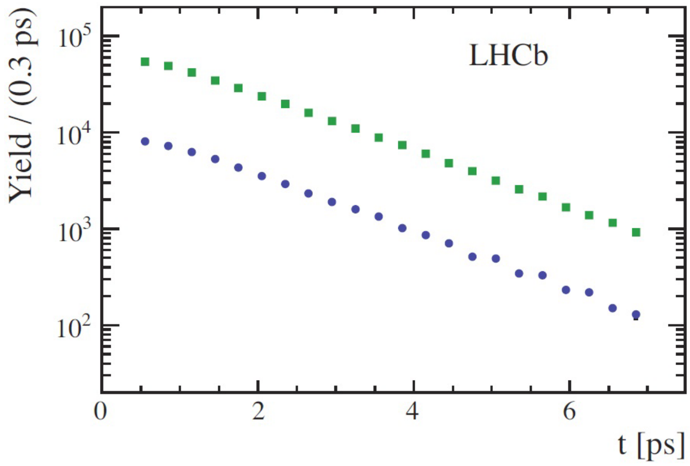

Figure 3: Evolution of the decay rates for $B^0 \to J/\psi K^*(892)$ (green squares) and $\Lambda_b^0 \to J/\psi p K^-$ (blue dots) [8]. Data of 3.0 fb^{-1} of integrated luminosity were measured in pp collisions at $\sqrt{s} = 7$ and 8 TeV.

The ratio of the Λ_b^0 baryon lifetime to that of the B^0 meson measured by LHCb using 3.0 fb^{-1} of integrated luminosity in 7 and 8 TeV center-of-mass energy pp-collisions is $0.974 \pm 0.006 \pm 0.004$. Using the known B^0 meson lifetime, the Λ_b^0 lifetime is found to be $1.479 \pm 0.009 \pm 0.010$ ps. In both cases the first uncertainty is statistical and the second systematic.

3.3 CP symmetry violation

As far as CP Violation (CPV) level in the SM is significantly lower than needed to explain baryon asymmetry in the Universe, the CPV measurements are considered as a potential probe of the New Physics. The CP violation may be observed directly in decays, indirectly—in mixing, and via interference of the above two processes. Mixing may proceed via loop diagrams with heavy particles beyond Standard Model.

3.3.1 CP Violation in Beauty Direct Decays

The direct CP violation in charmless charged two-body decays of neutral B mesons has been observed by Belle [9] and BaBar [10]. In particular, Belle has reported for B^0 decays large asymmetry $A_{CP} = -0.069 \pm 0.014 \pm 0.007$ (a significance of 4.4σ). This observation raised the question of whether the effect could be accommodated by the SM or it was due to non-SM physics. The LHCb Collaboration has determined CP-violation asymmetries from the data of 1 fb^{-1} integrated luminosity measured in pp collisions at 7 TeV for decays of neutral B_d as well as B_s mesons [11].

Fig. 4 shows a set of invariant mass spectra used for extraction of asymmetries. Invariant mass resolution is about 22 MeV/c^2. The measured by LHCb value of $A_{CP}(B^0 \to K\pi) = -0.080 \pm 0.007 \pm 0.003$ is the most precise and confirms the Belle result with significance of 10.5σ. The first observation of CP violation in the decays of B_s^0 mesons is characterized by the asymmetry value $A_{CP}(B_s^0 \to K\pi) = +0.27 \pm 0.04 \pm 0.01$, with significance of 6.5σ.

The first observation (a significance of 4.3σ) of the asymmetry in three-body charmless B decays has been also reported by the LHCb: $A_{CP} = -0.036 \pm 0.004 \pm 0.002 \pm 0.007$ [12]. The obtained results agree with SM expectation [13].

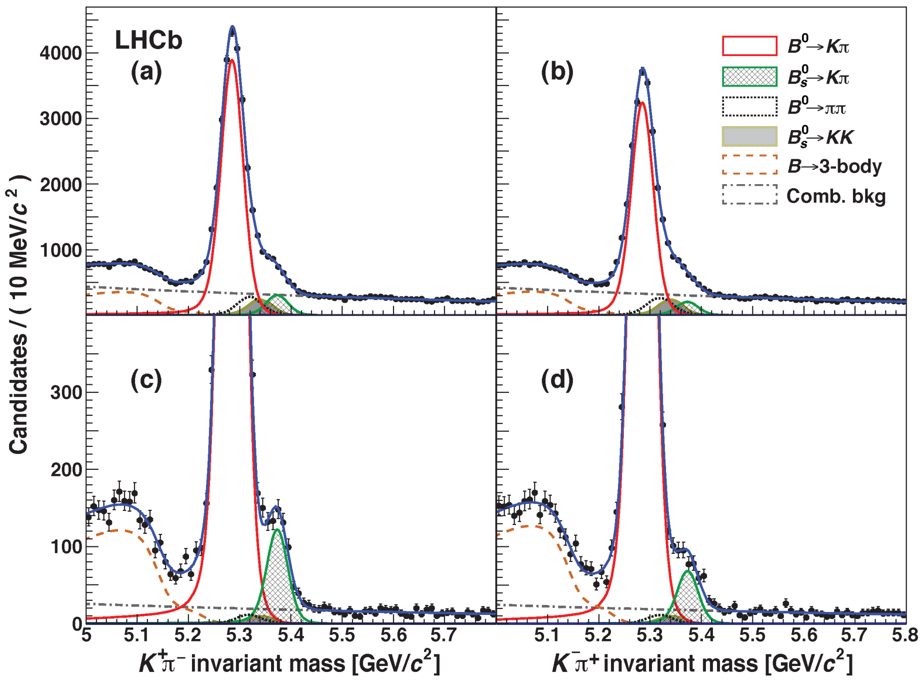

Figure 4: Invariant mass spectra. (a), (c) plots for $K^+\pi^-$ events; (b), (d)—for $K^-\pi^+$ events. Plots (a) and (b) illustrate the determination of the $A_{CP}(B^0 \to K\pi)$; plots (c) and (d) show event selections optimized for determination of $A_{CP}(B_s^0 \to K\pi)$. Dots—experimental data. Blue solid lines—the unbinned maximum likelihood fits. The main processes contributing to the fit model are shown by different color lines as indicated at the right upper corner of the (b) panel [11].

3.3.2 CP Violation in B_s Mixing

LHCb is able to measure the flavor evolution (mixing or oscillations) with an accuracy of ~ 40 fs due to VELO displaced vertex reconstruction with an accuracy of about 30 μm. The features of mixing, as the mass difference Δm (related to the frequency of mixing), width difference $\Delta\Gamma$, phase between the decay and mixing amplitudes ϕ_s define the evolution of the corresponding rates. The phase ϕ_s is sensitive to physics beyond the Standard Model that affects the loops in mixing and/or decay. A neutral meson mixing with its own antiparticle is well described in the SM which predicts oscillation frequencies for different hadrons ranging over several orders of magnitude. The frequency of oscillations extracted from combined studies of $B_d^0 \to D^-\pi^+$ and $B_d^0 \to J/\psi K^*$ decays has a value of $\Delta m_d = 0.5156 \pm 0.0051_{stat} \pm 0.0033_{syst}$ ps^{-1} [14], which is the most precise measurement of the oscillation frequency for B^0 mesons. Fig. 5 shows the LHCb measurement of B_s^0 oscillations. The oscillation frequency for the B_s^0 decay is: $\Delta m_s = 17.768 \pm 0.023_{stat} \pm 0.006_{syst}$ ps^{-1} [15].

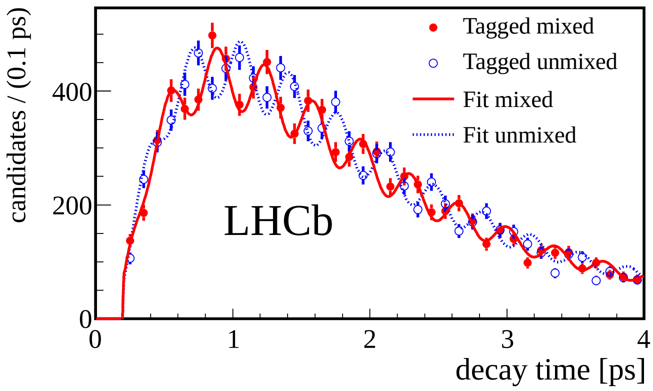

Figure 5: Time evolution of number of events for B_s^0 decays. Data of 1 fb^{-1} integrated luminosity were measured in pp collisions at $\sqrt{s} = 7$ TeV [15].

CP symmetry violation in the B_s^0 decays is treated as a result of interference between amplitudes of the neutral meson mixing and direct decay into the final state. The B_s^0 decay is sensitive also to mixing-induced CP violation where the CP-violating phase accordingly to the SM is very small ($\phi_s = -0.0363 \pm 0.0017$ rad). New physics contributing via box diagram could modify this phase. Time dependent decay studies for measuring CP violating parameters in B_s^0 mixing have been performed for $B_s^0 \to J/\psi K^+K^-$ and $B_s^0 \to J/\psi\pi^+\pi^-$.

The combined results for two processes are compatible with the SM: $\phi_s = 0.01 \pm 0.07_{stat} \pm 0.01_{syst}$ rad [16]. The measurement results of the ϕ_s by LHCb shown in Fig. 6 [18] together with measurements by the CDF, D0 and ATLAS collaborations demonstrate an agreement with the SM. The updated LHCb result [17] for the data set of 3 fb^{-1} gives a value of

$$\phi_s = (70 \pm 68 \pm 8) \text{ mrad}.$$

The average semileptonic flavor flavor specific asymmetry from e^+e^- B-factories measured in B^0 decays is $a_{sl}^d = (0.02 \pm 0.31)\%$ [18], in good agreement with the SM. D0 experiment published

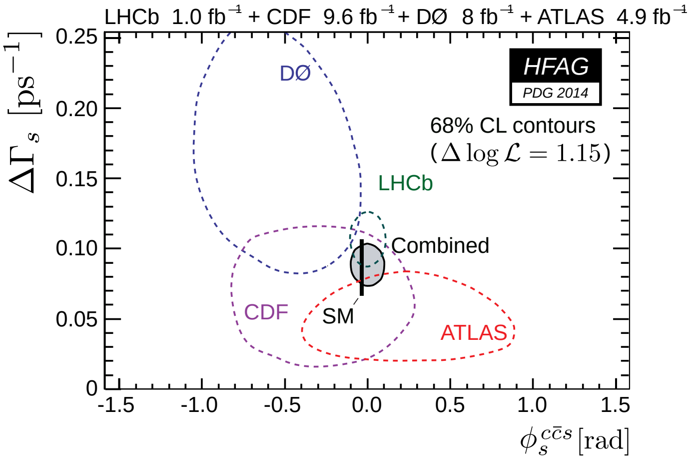

Figure 6: CP violating phase ϕ_s and differences in decay widths of the B_s^0 mass eigenstates in resonant and non-resonant decays measured by different experiments. The solid line—combination of all measurements. Thick vertical line—SM prediction [18].

measurements of $a_{sl}^d = (0.68 \pm 0.45 \pm 0.14)\%$ [19], and $a_{sl}^s = (-1.12 \pm 0.74 \pm 0.17)\%$ [20]. LHCb has recently performed similar measurements with high accuracy for a_{sl}^d and a_{sl}^s [21]. This LHCb result for a_{sl}^s is currently the most precise one and it could be treated as that physics beyond the SM does not influence flavour oscillations in the B_s^0 system within the reached accuracy of data.

4. CKM angles in the Unitarity Triangle

The measurements of the angles of the CKM Unitarity Triangle provide precision tests of the SM description of CP violation. The angle $\varphi_1(\beta)$ measured with the best precision by Belle from the whole data set is characterized by the value of $\sin 2\varphi_1(\beta) = 0.667 \pm 0.023 \pm 0.012$ [22]. The angle $\varphi_2(\alpha)$ is known with the highest precision also from Belle studies of the $B^0 \to \pi^+\pi^-$ decays with the value of $\varphi_2(\alpha) = (85.4^{+4.0}_{-3.8})^\circ$ [23]. The angle $\varphi_3(\gamma)$ measured by LHCb in B or B_s meson decays into D or D_s mesons (3 fb^{-1} data set) has a value of $(72.9^{+9.2}_{-9.9})^\circ$ at 68.3% confidence level [24]. The precision of this result which is better than the combination of the results of the experiments BaBar [25] and Belle [26] sets a new level of accuracy for searching contribution from processes different than tree-level ones. Due to the absence of loop contributions it is interpreted in a theoretically clean way.

5. Rare decays

Characterization of decays which are either forbidden or rare in the SM may provide evidence for NP. For instance, theories with additional Higgs bosons predict enhancements to the branching fractions [27, 28].

5.1 $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$

The SM prediction for these pure leptonic final states, which are flavor-changing neutral current (FCNC) and helicity suppressed, gives values for branching ratios as $Br(B_s^0 \to \mu^+\mu^-) = (3.65 \pm 0.23) \times 10^{-9}$ and $Br(B^0 \to \mu^+\mu^-) = (1.1 \pm 0.10) \times 10^{-10}$ [29]. LHCb has observed a signal at the level of 4σ for the B_s decay in the data set of 3 fb^{-1}. The measured branching fraction has a value of $Br(B_s^0 \to \mu^+\mu^-) = (2.9 \pm 0.7) \times 10^{-9}$. For the B^0 decay it is determinecd as $Br(B^0 \to \mu^+\mu^-) = (3.6^{+1.6}_{-1.4}) \times 10^{-10}$ at 95% CL. The LHCb results combined with results from the CMS experiment are shown in Fig. 7 [30] and are consistent with the SM. It looks that the New Physics requires the next digit of data accuracy, at least.

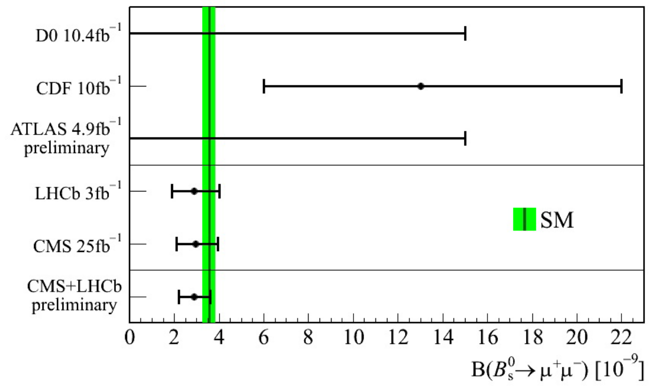

Figure 7: The results of experiments for the $Br(B_s^0 \to \mu^+\mu^-)$ are shown by points with error bars. SM prediction—shaded vertical band [30].

5.2 $B^0 \to K^+\pi^-\mu^+\mu^-$. Angular Distributions

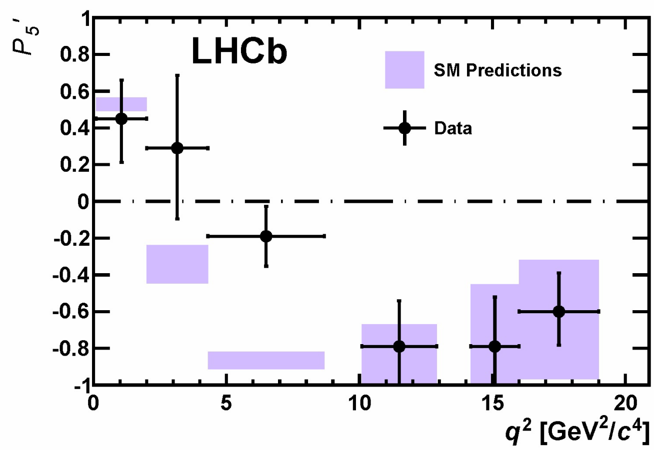

Figure 8: Measured values (points with error bars) of the observable $P_5{}'$ in $B^0 \to K^{*0}\mu^+\mu^-$. q^2 the effective mass squared of the dimuon system, the shaded areas—the SM predictions [31].

A possibility of modification of angular distributions of the B^0 decay products due to contribution of new particles via loop diagrams has motivated detailed studies of another FCNC process, namely $B^0 \to K^+\pi^-\mu^+\mu^-$. Four out of eight ($P_{1-8}$) parameters determining angular distribution of final state products have been measured by LHCb [31].

The form-factor independent $P_5{}'$ observable characterizing the angular distribution of K^* decay is shown in Fig. 8 as a function of the $\mu^+\mu^-$ invariant mass squared (q^2). The 3.7σ deviation of data from the Standard Model prediction is observed for the q^2 range between 4.3 and 8.68 GeV^2/c^4. In total, 24 independent measurements have been performed, the probability of such deviation does not exceed 0.5%.

5.3 Search for Lepton Flavor and Baryon number Violation

Lepton flavor violation (LFV) in some extensions of the Standard Model gives the enhancement of branching fractions for τ^- lepton decay into three leptons up to 10^{-7}, the level which is accessible at B-factory experiments. The best limit on the branching fraction for the $\tau^- \to \mu^-\mu^+\mu^-$ process was established by Belle: $R < 2.1 \times 10^{-8}$ (90% confidence level) [32]. LHCb (3 fb^{-1} data set) has found that this branching fraction is less than 4.6×10^{-8} (90% confidence level). Consistency of the LHCb result with the SM expectation is illustrated in Fig. 9 [33].

LHCb searched also for the decays of $\tau^- \to \bar{p}\mu^+\mu^-$ and $\tau^- \to p\mu^-\mu^-$, which violate baryon number (B) and lepton number (L), as well as lepton flavor. Using the 1 fb^{-1} data LHCb has set the first limits on branching fractions $Br(\tau^- \to \bar{p}\mu^+\mu^-) < 3.3 \times 10^{-7}$ and $Br(\tau^- \to p\mu^-\mu^-) < 4.4 \times 10^{-7}$, both at 90% CL [34] which are consistent with the SM expectations.

Lepton flavor violating decays of B mesons are allowed in several NP models [35, 36, 37]. No signal was observed in LHCb data set of 1 fb^{-1} at 7 TeV for two decay channels of B^0 mesons. The world best limits on the branching fractions were set: $Br(B_s^0 \to e^\pm\mu^\mp) < 1.1 \times 10^{-8}$ and $Br(B^0 \to e^\pm\mu^\mp) < 2.8 \times 10^{-9}$, both at 90% CL. The $B^0 \to e^\pm\mu^\mp$ limit is used to set a limit on the mass scale of leptoquarks ($MLQ > 135$ TeV at 90% CL) [38]. To perform the test of the lepton

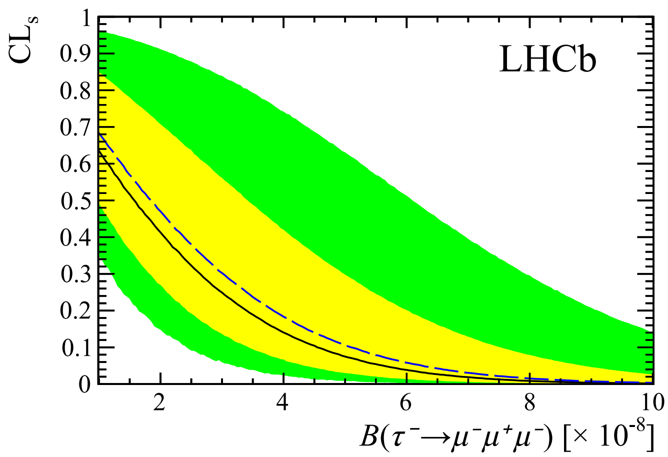

Figure 9: Branching fraction of the $\tau^- \to \mu^-\mu^+\mu^-$. Dashed line—SM prediction; Solid line—observed, with yellow band showing 68% CL and green one—95% CL [33].

universality LHCb studied B^+ decays to $(\mu^+\mu^-)$ and (e^+e^-) channels. With the 3 fb^{-1} data set the value of the ratio of branching fractions was measured to be: $0.745^{+0.090}_{-0.074}{}_{stat} \pm 0.036_{syst}$ for the q^2 (dilepton invariant mass squared) range between 1 and 6 GeV^2/c^4 [39].

Searches have been performed for LFV decays of the tau-lepton as well as heavy meson that would be mediated by Majorana neutrinos. The probability of the decay $B^- \to \pi^+\mu^-\mu^-$ could be enhanced for Majorana neutrino masses between 250 and 5000 MeV. LHCb has used its full 3 fb^1 data set (sensitive for neutrino lifetimes up to 1 ns) to look for this process. The limit has been set for branching fraction: $Br(B^- \to \pi^+\mu^-\mu^-) < 4 \times 10^{-9}$ at 95% CL for a neutrino lifetime of 1 ps [40].

6. Charged Higgs bosons search at *B*-factories

The idea of charged Higgs boson search at B-factories relies upon the fact that B-decays with heavy τ-lepton in final state may evolve with additional decay modes not present with light leptons. New physics contribution might change branching ratios observable in final states. Averaged over hadronic and semileptonic tagging experimental results published by BaBar [41] and Belle [42] give the value of $Br(B \to \tau\nu) = (1.15 \pm 0.23) \times 10^{-4}$. Some tensions with SM predictions [43] were observed in $B \to D^*\tau\nu$ decays. To reduce experimental and theoretical uncertainties the ratios $R = Br(B \to D^*\tau\nu)/Br(B \to D^*\ell\nu)$ were determined. The measured value for $R(D) = Br(B \to D\tau\nu)/Br(B \to D\ell\nu) = 0.430 \pm 0.091$ deviates from the SM by 1.4σ. For $R(D^*) = Br(B \to D^*\tau\nu)/Br(B \to D^*\ell\nu) = 0.405 \pm 0.047$ the deviation is at the level of 3.0σ. It has been shown that these deviations depend strongly on the SM parameters and cannot be explained simultaneously in frames of 2HDModel (Type II). The 2HDModel (Type III) introducing suitable flavor violation in the up-sector provides reasonable agreement with the observations [44].

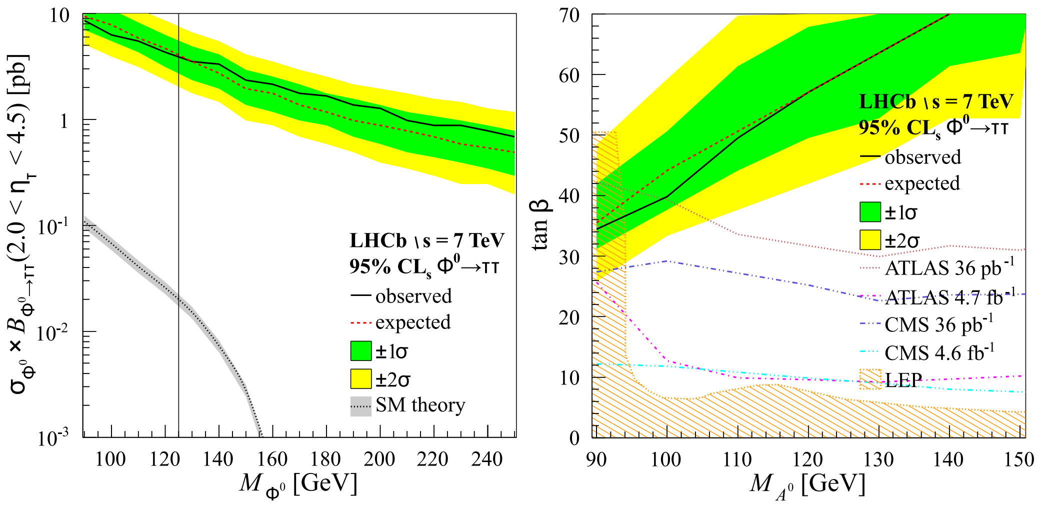

Figure 10: Left: Model independent combined limit for a Higgs boson decaying to two tau leptons as a function of M_{Φ^0}. The background only expected limits (dashed red) are compared with the observed limit (solid black) and the expected SM theory (dotted black). **Right**: The combined MSSM upper limit on $\tan\beta$ as a function of M_{A^0}. The results of other experiments are also shown [45]

The LHCb experiment well instrumented in the forward direction provides complementary data to the ATLAS and CMS studies of Higgs boson at central values of pseudorapidity. A model independent search for a Higgs boson decaying to two tau leptons has been made in data set of 1 fb^{-1} [45]. Bounds were set at the 95% confidence level on the cross-section times branching fraction: $0.7 < (\sigma \times BF) < 8.6$ pb for a Higgs boson mass range of $90 < M_H < 250$ GeV/c^2. The upper limit on the cross-section times branching fraction is presented on the left plot in Fig. 10 as a function of the Higgs boson mass, M_{Φ^0}. The upper limit on $\tan\beta$ for the production of neutral MSSM Higgs bosons, as a function of the CP-odd Higgs boson mass M_{A^0}, is presented in the right plot of Fig. 10. This plot illustrates exclusion of $\tan\beta$ values between 32 and 70 for the mass range of M_{A^0} between 90 and 150 GeV/c^2 at 95% CL.

Exploring the model BV48 (mSUGRA with baryon number violation and parameters:
114 GeV/c^2—h^0, 48 Gev/c^2—$\tilde{X}^0$, 10 ps—$\tau(X^0)$ and analyzing 35.8 pb^{-1} data set the LHCb has set an upper limit for the Higgs-like boson production cross-section of 32 pb at 95% CL [46]. To identify the background in searches for massive particles (such as the Higgs boson) decaying into b quarks it is necessary to know the inclusive b production rate from QCD processes. The production cross section for b-$\bar{b}$ pairs measured by LHCb (1fb^{-1} data set, pp collisions at $\sqrt{s} = 7$ TeV) has a value of $7.7 \pm 0.12_{stat} \pm 0.84_{syst}$ μb [47]. The analysis of events with two b jets, one of which is flavor tagged by the presence of a displaced muon with high momentum, yields the value of the forward-central asymmetry for $b\bar{b}$-events: $A = (0.5 \pm 0.5_{stat} \pm 0.5_{syst})\%$ [47], consistent with SM estimate [48]. Further data analysis is in progress.

7. Summary and Outlook

B physics studies have been successfully carried out at the leptonic and hadronic *B*-factories. Substantial data sets with *B*-matter samples were collected and analyzed at the LHCb and BELLE experiments. Measurements of physics observables at new energies of collisions up to 8 TeV at LHC have been performed with unprecedented accuracy (CP violation, rare decays) or for the first time ($B_s \to \mu^+\mu^-$, CPV in B_s^0, new resonances). Efforts to find signals beyond the Standard Model are being undertaken. Most of the results obtained so far were in agreement with the Standard Model predictions. Some tensions in the data space sensitive to New Physics are under studies. LHCb will continue data taking in 2015–2017 planning the upgrade for running in 2019 at luminosity up to 2 times 10^{33} cm^{-2}s^{-1}. BELLE II after upgrade aims to collect 50 ab^{-1} data set. New Physics must exist! It might require new tools and methods to be developed for its observation. New energy valley opened at LHC is certainly rich by new phenomena.

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