IL NUOVO CIMENTO Vol. 37 C, N. 1 Gennaio-Febbraio 2014
DOI 10.1393/ncc/i2014-11672-y

Colloquia: IFAE 2013

Rare decays at hadron colliders

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ricevuto l'1 Ottobre 2013

Summary. — Rare lepton decays of the $B^0_{(s)}$ mesons are sensitive probes of New Physics. The search for the decays $B^0_{(s)} \to \mu^+\mu^-$ may provide information on the presence of new (pseudo-) scalar particles. Also the study of the electroweak penguin processes are powerful probes for new physics, as physics beyond the Standard Model (SM) can enter via virtual particles at the same level as SM physics. The Tevatron collider opened the way to high precision Heavy Flavor physics at hadron collider experiments, while the LHCb experiment definitively proved the physics performances are competitive with the B-factories. This is a short review of the searches of rare decays performed at the hadron colliders.

PACS 13.20.-v – Leptonic, semileptonic, and radiative decays of mesons.
PACS 13.20.He – Decays of bottom mesons.
PACS 14.40.Nd – Bottom mesons ($|B| > 0$).

1. – Introduction

The study of rare decays in the Heavy Flavour sector is a complementary approach to detect New Physics (NP) with respect to the direct searches. While the latter approach aims to discover NP through the production of real new particles, the precise measurements of rare process can probe virtual new particles in loop diagrams. The effects of these particles can be observed as a deviation in the Standard Model (SM) expectation for observables such as branching fraction, angular distribution, either in CP-violating processes or in very rare decays involving Flavour-Changing Neutral Currents (FCNC). Since the effect of heavy new particles does not decouple in weak and Yukawa interactions, the precise measurement of FCNC can reveal NP that may be well above the TeV scale or can provide key information on the couplings and phases of these new particles if they are visible at the TeV scale.

2. – $B^0_{(s)} \to \mu^+\mu^-$

The search for $B^0_{(s)} \to \mu^+\mu^-$ is one of the most promising ways to constrain the parameters of any extended Higgs sector. These decays are highly suppressed in the SM because they are both FCNC and helicity suppressed. The SM model predictions for these decays are [1,2]

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-)_{SM} = (3.2 \pm 0.2) \times 10^{-9},$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-)_{SM} = (1.0 \pm 0.1) \times 10^{-10}.$$

NP enhancement of the $\mathcal{B}(B_{(s)}^0 \to \mu^+\mu^-)$ are already constrained by the recent searches done at the hadron collider experiments to be smaller or at the same level of the SM prediction. However, there still remains room for contributions from NP, for example a destructive interference between SM and NP process could lower the observed branching fractions.

In this review, I present the last results of the searches of $B_{(s)}^0 \to \mu^+\mu^-$ decays performed by different experiments at the hadron colliders.

At the Tevatron, the D0 experiment has recently published [3] an update of the $B_s^0 \to \mu^+\mu^-$ searches with $10.4\,\mathrm{fb}^{-1}$. In order to decrease the huge combinatorial background, two different BDT are used: one effective on the couple of muons coming from sequential decays such as $b \to \mu^- vc$ with $c \to \mu^+ vX$, and a second for the double semileptonic decays. To reduce the systematic uncertainties the result is normalized to $B^\pm \to J/\psi K^\pm$ decays. The CL_s method is used to evaluate the branching fraction upper limit. The expected limit $\mathcal{B}(B_{(s)}^0 \to \mu^+\mu^-) < 23 \times 10^{-9}$ at 95% CL and the observed $\mathcal{B}(B_{(s)}^0 \to \mu^+\mu^-) < 15 \times 10^{-9}$ at 95% CL.

Also ATLAS has published a blind analysis based on $2.4\,\mathrm{fb}^{-1}$ data, collected in 2011 [4]. The sample is divided into three regions of pseudo-rapidity (η) where the ATLAS Collaboration observes different resolution of the mass. Therefore the mass windows width ranges from 116 to $171\,\mathrm{MeV}/c^2$. The branching fraction is measured with respect to the decay $B^\pm \to J/\psi K^\pm$ in order to minimize systematic uncertainties in the evaluation of the efficiencies and acceptances. The observed upper limit evaluated with the CL_s method is $B_s^0 \to \mu^+\mu^- < 22 \times 10^{-9}$ at 95% CL.

The CMS experiment has published a blind analysis using $5\,\mathrm{fb}^{-1}$ data collected in 2011 [5]. Also in this case the data sample is divided into two regions corresponding to two different background conditions. The first subsample containing only tracks with $|\eta| < 1.4$ and a mass resolution $\sim 36\,\mathrm{MeV}/c^2$ and a second subsample containing at least one track with $|\eta| < 1.4$ and a resolution of $\sim 86\,\mathrm{MeV}/c^2$. CMS performs a cut-based analysis optimized on MC signal and data-sidebands before the unblinding. The branching fraction is evaluated by measuring the ratio to a more abundant B-hadron decay $B^\pm \to J/\psi K^\pm$. The upper limits on the branching fractions are determined using the CL_s method. The combined upper limits for the barrel and endcap channels are $\mathcal{B}(B_{(s)}^0 \to \mu^+\mu^-) < 7.7 \times 10^{-9}$ at 95% CL. and $\mathcal{B}(B^0 \to \mu^+\mu^-) < 1.8 \times 10^{-9}$ at 95% CL.

The LHCb experiment, already in summer 2012, set the most restrictive upper limits [6] on the branching fractions, $\mathcal{B}(B_s^0 \to \mu^+\mu^-) < 4.5 \times 10^{-9}$ and $\mathcal{B}(B^0 \to \mu^+\mu^-) < 1.0 \times 10^{-9}$ at 95% CL by using only the data sample at 7 TeV center-of-mass energy collected during 2011.

Recently LHCb experiment updated this measurement including $1.1\,\mathrm{fb}^{-1}$ recorded during 2012 at $\sqrt{s} = 8\,\mathrm{TeV}$. Assuming a SM rate for these two decays at the end of the selection we expect ~ 24 $B_s^0 \to \mu^+\mu^-$ events and ~ 2.8 $B^0 \to \mu^+\mu^-$ events in the signal region.

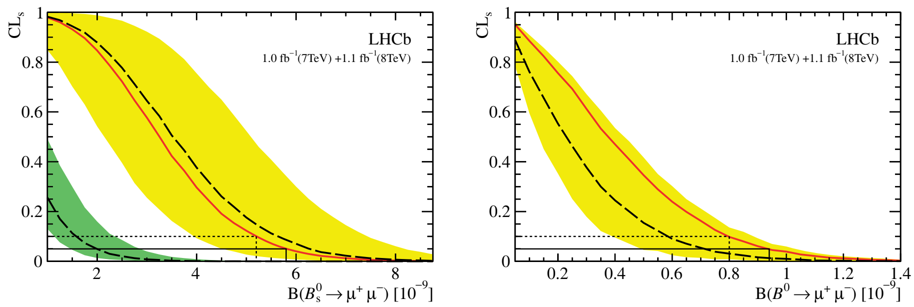

Fig. 1. – Expected CL_s (dashed black line) under the hypothesis of observing background-only (left) for the $B^0 \to \mu^+\mu^-$ and CL_s under background-plus-signal events according to the SM rate (right) for $B_s^0 \to \mu^+\mu^-$, with the yellow area covering the region of $\pm 1\sigma$ of compatible observations; the observed CL_s is given by the blue dotted line; the expected (observed) upper limits at 90% and 95% CL are also shown as dashed and solid grey (red) lines.

The events are classified in bins of the dimuon invariant mass $m_{\mu\mu}$ and bins of a multivariate classifier, BDT, based on kinematic and geometrical variables. In each bin the expected numbers of signal and background events are derived. The signal mass shape is assumed to be a Crystal Ball shape, where the mean and the resolution are obtained on data while the transition point is derived from simulations. The BDT shape is obtained on data by extracting with a fit to the mass distribution, in each BDT bin, the yields of $B^0_{(s)} \to h^+h^-$. For the combinatorial background, the mass and the BDT shape are obtained simultaneously by interpolating, in each BDT bin, the mass side-bands into the signal regions with an exponential function. The number of expected signal events, for a given branching fraction hypothesis, is evaluated by normalizing to the decays $B^0 \to K\pi$, $B^+ \to J/\psi K^+$ and $B_s^0 \to J/\psi\phi$. In order to avoid any bias, the mass region $m_{\mu\mu} = [m(B^0) - 60\,\mathrm{MeV}/c^2, m(B_s^0) + 60\,\mathrm{MeV}/c^2]$ is blinded until the analysis is finalized.

The comparison of the distributions of observed events and expected background events, using the full (2011+2012) data sample, results in a p-value ($1 - CL_b$) of 11% for the $B^0 \to \mu^+\mu^-$ decay. From our data we constrain the $B^0 \to \mu^+\mu^-$ branching fraction to be less than 9.4×10^{-10} at 95% CL [7], which is the world-best limit from a single experiment. The expected and observed CL_s values are shown in fig. 1 for the $B^0 \to \mu^+\mu^-$ and $B_s^0 \to \mu^+\mu^-$ channels, each as a function of the assumed BF.

The probability that background processes can produce the observed number of $B_s^0 \to \mu^+\mu^-$ candidates or more is 5×10^{-4} and corresponds to a statistical significance of 3.5 σ. The value of the $B_s^0 \to \mu^+\mu^-$ branching fraction is obtained from an unbinned likelihood fit to the mass spectrum, performed simultaneously in different BDT bins. The invariant mass distribution of selected $B^0_{(s)} \to \mu^+\mu^-$ candidates with BDT > 0.7 is shown in fig. 2 with the fit results overlaid.

From the fit we obtain [7] $\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.2^{+1.4}_{-1.2}(\mathrm{stat})^{+0.5}_{-0.3}(\mathrm{syst})) \times 10^{-9}$, which is in agreement with the SM expectation. This is the first evidence for the decay $B^0_{(s)} \to \mu^+\mu^-$. In order to compare the upper limit on $\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ with the theoretical prediction, this value has to be multiplied by 0.911 ± 0.014, which takes into account the effective lifetime of the B_s meson [8].

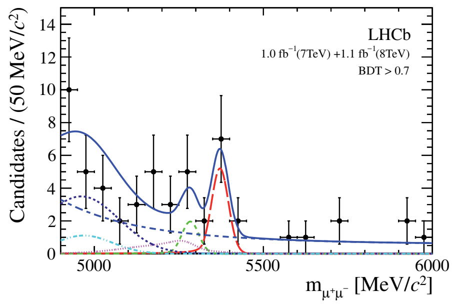

Fig. 2. – Invariant-mass distribution of selected $B^0_{(s)} \to \mu^+\mu^-$ candidates (black points) for combined 2011 and 2012 dataset and for BDT > 0.7. The result of the fit is overlaid (blue solid line) and the different components detailed: $B^0_s \to \mu^+\mu^-$ (red long dashed), $B^0 \to \mu^+\mu^-$ (green long dashed), $B^0_{(s)} \to h^+h^-$ (pink dotted), $B^0 \to \pi^-\mu^+v_\mu$ (black dashed), $B^{0(+)} \to \pi^{0(+)}\mu^+\mu^-$ (light blue dot dashed), and combinatorial (blue long dashed).

3. – $\mathcal{CP}$-asymmetry in $B^0 \to K^{0*}\mu^+\mu^-$

The direct $\mathcal{CP}$-asymmetry $\mathcal{A}_{\mathcal{CP}}$ is defined as $\mathcal{A}_{\mathcal{CP}} = \frac{\Gamma(\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-) - \Gamma(B^0 \to K^{*0}\mu^+\mu^-)}{\Gamma(\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-) + \Gamma(B^0 \to K^{*0}\mu^+\mu^-)}$ and it is predicted to be $\mathcal{O}(10^{-3})$ in the SM [9,10]. The theoretical prediction has a small uncertainty due to suppression of form factor uncertainties. This could be significantly enhanced in NP models up to 15% [11].

The analysis of $B^0 \to K^{*0}\mu^+\mu^-$ is performed with $1\,\text{fb}^{-1}$ of data recorded by LHCb during 2011. The resonant regions of the J/ψ and the $\psi(2S)$ are excluded. The decay is selected using a boosted decision tree and an event-by-event correction is applied to correct for experimental biases. The two $\mathcal{A}_{\mathcal{CP}}$ asymmetries, one for each polarity of the LHCb dipole magnet, are mediated with an equal weight. The production and interaction asymmetries are corrected for using the $B^0 \to J/\psi K^{*0}$ decay mode as a control channel. The $\mathcal{A}_{\mathcal{CP}}$ is extracted from simultaneous fit to B^0 mass in six bins of dimuon invariant mass, q^2, and is shown in fig. 3. The result integrated over q^2 is $\mathcal{A}_{\mathcal{CP}}(B^0 \to K^{*0}\mu^+\mu^-) = -0.072 \pm 0.040(\text{stat}) \pm 0.005(\text{syst})$ [12].

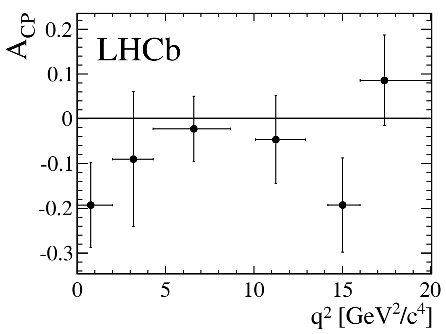

Fig. 3. – $\mathcal{CP}$-asymmetry of $B^0 \to K^{*0}\mu^+\mu^-$ as a function of dimuon invariant mass squared, q^2.

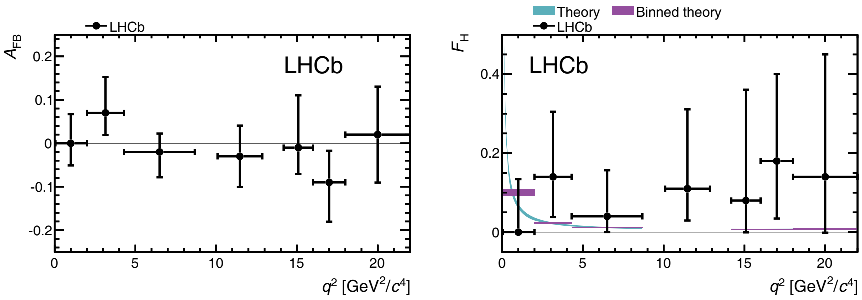

Fig. 4. – The forward-backward asymmetry A_{FB} and the flat parameter F_H in $B^+ \to K^+\mu^+\mu^-$ as a function of the dimuon invariant mass squared [13]. The theory predictions are taken from ref. [14] and [15]. A_{FB} is expected to be negligible in the SM for the full q^2 range.

4. – $B^+ \to K^+\mu^+\mu^-$

The analysis of $B^+ \to K^+\mu^+\mu^-$ is performed using $1\,\mathrm{fb}^{-1}$ data recorded during 2011 by the LHCb experiment. The differential branching fraction is evaluated using $B^+ \to J/\psi K^+$ as a normalization channel. This measurement is performed in 7 bins of q^2. The integrated branching fraction, taking the region of the excluded charmonium resonances into account, is $\mathcal{B}(B^+ \to K^+\mu^+\mu^-) = (4.36 \pm 0.15(\mathrm{stat}) \pm 0.18(\mathrm{syst})) \times 10^{-7}$ [13].

The differential decay rate of $B^+ \to K^+\mu^+\mu^-$ can be written as $\frac{1}{\Gamma}\frac{\mathrm{d}\Gamma(B^+\to K^+\mu^+\mu^-)}{\mathrm{d}\cos\theta_\ell} = \frac{3}{4}(1-F_H)(1-\cos^2\theta_\ell)+\frac{1}{2}F_H+A_{FB}\cos\theta_\ell$, where A_{FB} is the forward-backward asymmetry and F_H is a flat parameter. A_{FB} is predicted to be zero in the SM while $F_H \sim 0$. An event-by-event correction is applied to account for experimental effects. Also in that case A_{FB} and F_H are measured in 7 bins of q^2 by a likelihood fit in the invariant mass of $K\pi\pi$ system and $\cos\theta_\ell$. The distributions of A_{FB} and F_H are shown in fig. 4. The results are consistent with the SM expectations.

5. – $B^\pm \to K^\pm\mu^+\mu^-$

In the SM the $b \to \mathrm{d}\ell^+\ell^-$ transition is even more suppressed than $b \to s\ell^+\ell^-$, by a factor $|V_{td}|/|V_{ts}|$. Furthermore, this process has never been observed so far. The predicted SM branching fraction for $B^+ \to \pi^+\mu^+\mu^-$ is $(1.96 \pm 0.21) \times 10^{-8}$ [16]. However, many new physics models predict enhanced branching fractions for this decay [17]. The best limit has been published by Belle and it is $\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-) < 6.9 \times 10^{-8}$ at 90% of CL [18].

The analysis performed by LHCb is based on a sample of $1.0\,\mathrm{fb}^{-1}$ of data collected in 2011. The selection is based on a multivariate discriminant (BDT), trained using the kinematic properties of the daughters and the vertex quality of the B candidate. The J/ψ and $\psi(2S)$ resonances are excluded using a veto on the dimuon mass.

The signal yields extracted from the fit is $25.3^{+6.7}_{-6.4}$. This result corresponds to an excess of $5.2\,\sigma$ with respect to the null hypothesis and consequently it represents the first observation of a $b \to d\ell^+\ell^-$ decay. Normalizing the observed signal to the $B^+ \to J/\psi K^+$ decay, LHCb obtained [19]

$$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-) = (2.4 \pm 0.6(\mathrm{stat}) \pm 0.2(\mathrm{syst})) \times 10^{-8},$$

which is in agreement with the SM expectation.

6. – Conclusions

The Tevatron collider opened the way to high-precision Heavy Flavor physics at hadron collider experiments, both through detector and trigger strategies and through advanced analysis techniques. It is well demonstrated that Heavy flavour physics at the hadron collider can be fully competitive especially for hadronic modes and very rare decays. We have presented the search of $B^0_{(s)} \to \mu^+\mu^-$ decays at Tevatron and LHC. The LHCb experiment has set the first observation of the $B^0_s \to \mu^+\mu^-$ decay: $\mathcal{B}(B^0_s \to \mu^+\mu^-)$ is measured to be equal to $(3.2^{+1.4}_{-1.2}(\mathrm{stat})^{+0.5}_{-0.3}(\mathrm{syst})) \times 10^{-9}$ with a 3.5 σ significance. Also the study of rare electroweak penguin decays are a very active research area. Up to now all measurements are compatible with the SM and set strong constraints on a broad range of new physics models.

REFERENCES

[1] Buchalla G. and Buras A. J., *Nucl. Phys. B*, **548** (1999) 309.
[2] Buras A. J., arXiv:1012.1447; Gamiz E. *et al.*, *Phys. Rev. D*, **80** (2009) 014503; Buras A. J., *Phys. Lett. B*, **566** (2003) 115; Buras A. J. *et al.*, *Eur. Phys. J. C*, **72** (2012) 2172.
[3] Abazov V. M. *et al.* (D0 Collaboration), *Phys. Rev. D*, **87** (2013) 072006 arXiv:1301.4507 [hep-ex].
[4] Aad G. *et al.* (ATLAS Collaboration), *Phys. Lett. B*, **713** (2012) 387 arXiv:1204.0735 [hep-ex].
[5] Chatrchyan S. *et al.* (CMS Collaboration), *JHEP*, **04** (2012) 033 arXiv:1203.3976 [hep-ex].
[6] Aaij R. *et al.* (LHCb Collaboration), *Phys. Rev. Lett.*, **108** (2012) 231801 arXiv: 1203.4493v2 [hep-ex].
[7] Aaij R. *et al.* (LHCb Collaboration), *Phys. Rev. Lett.*, **110** (2013) 021801
[8] de Bruyn K. *et al.*, arXiv:1204.1735 [hep-ex].
[9] Bobeth C., Hiller G. and Piranishvili G., *JHEP*, **07** (2008) 106 arXiv:0805.2525 [hep-ph].
[10] Altmannshofer W., Ball P., Bharucha A., Buras A. J., Straub D. M. and Wick M., *JHEP*, **01** (2009) 019 arXiv:0811.1214 [hep-ph].
[11] Alok A. K., Datta A., Dighe A., Duraisamy M., Ghosh D. and London D., *JHEP*, **11** (2011) 122 arXiv:1103.5344 [hep-ph].
[12] Aaij R. *et al.* (LHCb Collaboration), arXiv:1210.4492 [hep-ex].
[13] Aaij R. *et al.* (LHCb Collaboration), arXiv:1209.4284 [hep-ex].
[14] Bobeth C., Hiller G., van Dyk D. and Wacker C., *JHEP*, **01** (2012) 107 arXiv:1111.2558 [hep-ph].
[15] Bobeth C., Hiller G. and van Dyk D., *JHEP*, **07** (2011) 067 arXiv:1105.0376 [hep-ph].
[16] Song H.-Z., Lü L.-X. and Lu G.-R., *Commun. Theor. Phys.*, **50** (2008) 696.
[17] Wang J.-J., Wang R.-M., Xu Y.-G. and Yang Y.-D., *Phys. Rev. D*, **77** (2008) 014017 arXiv:0711.0321 [hep-ph].
[18] Wei J.-T. *et al.* (Belle Collaboration), *Phys. Rev. D*, **78** (2008) 011101 arXiv: 0804.3656 [hep-ex].
[19] RAaij *et al.* (LHCb Collaboration), *JHEP*, **12** (2012) 125 arXiv:1210.2645 [hep-ex].