IL NUOVO CIMENTO Vol. 32 C, N. 3-4 Maggio-Agosto 2009
DOI 10.1393/ncc/i2009-10431-7

Colloquia: IFAE 2009

Rare B decays at LHC

A. Sarti
Laboratori Nazionali di Frascati - Frascati, Italy

(ricevuto il 19 Settembre 2009; pubblicato online il 16 Ottobre 2009)

Summary. — The LHC collider will soon produce the largest sample of B mesons, opening several new paths to the discovery of New Physics processes through the study of their rare and very rare decays. The strategies for the data analysis and the expected performances for several key decay channels are reviewed and compared for the three LHC experiments that are ready to reconstruct and select the B mesons: LHCb, ATLAS and CMS.

PACS 13.20.He – Leptonic, semileptonic, and radiative decays of bottom mesons.
PACS 13.25.Hw – Hadronic decays of bottom mesons.

1. – Introduction

The Large Hadron Collider (LHC) experiments at CERN will soon start collecting data from proton-proton interactions with a center-of-mass energy greater than 5 TeV. A large fraction of the particles produced in the pp interactions will contain a b quark. In this perspective, given the very high design luminosity of the collider and the large $b\bar{b}$ production cross-section, the LHC experiments are going to analyze the largest B meson sample ever produced and collected. Even if the experimental environment is not as clean as in e^+e^- collider experiments the LHC experiments will contribute to a substantial improvement in the experimental knowledge of the rare B meson decays with respect to present B factories (BaBar, Belle) and hadron colliders (CDF, D0) results.

2. – Experimental set-up

Three detectors, LHCb [1], ATLAS [2] and CMS [3], are almost ready to acquire the data produced by the particles originating from the proton-proton collisions in the LHC interaction points every 25 ns. While LHCb is a forward spectrometer specifically designed and optimized for doing B meson physics studies, ATLAS and CMS are general purpose experiments covering nearly the 4π solid angle around the interaction point.

A very large number of B mesons and hadrons will be produced at the LHC. The expected cross-section for $b\bar{b}$ production at 14 TeV is $\sim 500\,\mu$b, yielding $5 \cdot 10^4$ $b\bar{b}$ pairs produced every second at a luminosity (L) of $10^{32}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. However the total pp cross-section is two orders of magnitude higher, $\sim$ 100 mb in the LHCb simulations, demanding an efficient trigger with a strong background rejection.

Since most of the interesting B meson decays have a large transverse momentum (p_T) and some of the key rare decays involve leptons (e, μ) as final states, the track reconstruction and particle identification (PID) performances play a central role in their selection. ATLAS and CMS achieve a p_T resolution less than 2%, a transverse impact parameter resolution of $10\,\mu$m and a μ reconstruction efficiency greater than 98% but cannot resolve kaons and pions in B meson decays. LHCb achieves a relative momentum resolution ~ 0.4, an impact parameter resolution of $30\,\mu$m and a reconstruction efficiency for tracks traversing the full detector larger than 95%. LHCb has also excellent PID capabilities achieving a μ identification efficiency greater than 95% with a misidentification smaller than 1% for tracks with $p > 3\,\mathrm{GeV}/c$ and a high kaon-pion discrimination power and identification efficiency in the 1–100 GeV/c momentum range.

The trigger of all the three experiments follows almost the same logic: after a hardware trigger, named L0 in LHCb and L1 in ATLAS and CMS, that uses the input of the fastest detectors such as the calorimeters and muon detectors, the affordable rate is obtained through a software trigger (HLT) that uses information from all the sub-detectors. In addition, in LHCb, a pile up veto is used in order to clean up the environment from multiple interactions, since the number of expected pp interactions for each beam crossing goes from ~ 1 to ~ 33 when increasing the luminosity from $2 \cdot 10^{32}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ (LHCb) to $10^{33}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ (ATLAS, CMS). The L0 and L1 rates are, respectively, $\sim 1\,\mathrm{MHz}$ and $< 100\,\mathrm{kHz}$. The LHCb HLT rate is 2 kHz, out of which 200 Hz is the bandwidth allocated for exclusive B selections and the remaining 1.8 kHz are used to acquire control samples and inclusive b samples for data mining. The ATLAS and CMS HLT rates are $\sim 200\,\mathrm{Hz}$, and $\sim 10\%$ of this rate can be used for doing B physics studies.

3. – Rare B meson decays overview

Rare B meson decays can be used as sensitive probes of Standard Model (SM) or SM extension (new physics or NP) predictions. Their properties are currently the less experimentally constrained: while some of the B_d rare decays have already been studied by the B factories experiments, the whole B_s sector is poorly constrained and thus opened for SM validation or NP discovery searches. Among the very large number of interesting decay modes that can be used to constrain NP models, in this paper we only consider two different approaches.

The first one is related to the study of b mesons and hadrons decaying into hh$'$ final states (where h, h$'$ stand for kaon and/or pion) that can be used [4] to make the first observation of the $B_s \to \mathrm{KK}$ transition, validate U-spin relations between B_d and B_s decays and extract the CKM angles γ and ϕ_s.

The second approach is related to the B semi-leptonic decays that can be theoretically described in terms of the Operator Product Expansion (OPE) with a parametrization of NP processes through modified Wilson coefficients and operators [5]. Different transitions, such as $\mathrm{b} \to \mathrm{sll}$ and $\mathrm{b} \to \mathrm{s}\gamma$, are sensitive to different operators and can be used to constrain NP models contributions. While the inclusive approaches represent a great challenge for hadron collider experiments, the exclusive decays can be addressed more easily, and observables can be found in which the theoretical hadronic uncertainties are well under control. For example, the $\mathrm{b} \to \mathrm{sll}$ forward-backward asymmetry (A_{FB}), its zero value (s_0) and the ratio of branching ratios of $\mu\mu$ and ee modes have SM [6] predictions that can be largely affected by NP contributions.

TABLE I. – *LHCb sensitivities with* $2\,\text{fb}^{-1}$ *to the most relevant physics measurements under study.*

Quantity	σ(stat.)	Quantity	σ(stat.)
$\mathcal{A}^{\mathcal{CP}}_{K^+\pi^-}$	0.0025	$\mathcal{A}^{\mathcal{CP}}_{\pi^+K^-}$	0.016
$\mathcal{A}^{\mathcal{CP}}_{p\pi^-}$	0.016	$\mathcal{A}^{\mathcal{CP}}_{pK^-}$	0.009
$\mathcal{A}^{\text{dir}}_{\pi^+\pi^-}$	0.04	$\mathcal{A}^{\text{mix}}_{\pi^+\pi^-}$	0.04
$\text{Corr}(\mathcal{A}^{\text{dir}}_{\pi^+\pi^-}, \mathcal{A}^{\text{mix}}_{\pi^+\pi^-})$	-0.03	$\mathcal{A}^{\text{dir}}_{K^+K^-}$	0.047
$\mathcal{A}^{\text{mix}}_{K^+K^-}$	0.035	$\text{Corr}(\mathcal{A}^{\text{dir}}_{K^+K^-}, \mathcal{A}^{\text{mix}}_{K^+K^-})$	0.02

4. – Non-leptonic two body decays

The analysis of non-leptonic decays is feasible only in the LHCb experiment, where the kaons and pions from the B mesons can be discriminated with high efficiency. Twelve different decay modes have been studied: B_d, B_s and Λ_b decays into $\pi\pi$, πK, Kπ and KK pairs. The selection has been designed in order not to use the PID information. Only kinematics and geometrical constraints have been imposed achieving nearly the same efficiencies for all the various modes. The cuts have been optimized maximizing the signal (S) over background (B) $\frac{S}{\sqrt{S+B}}$ ratio. The total selection efficiency is $\sim 1.3\%$ with an expected yield, assuming an integrated luminosity of $2\,\text{fb}^{-1}$, of nearly 380k events in total. LHCb will match the expected final CDF statistics ($L_{\text{int}} \sim 3\,\text{fb}^{-1}$), with $L_{\text{int}} \sim 100\,\text{pb}^{-1}$. The annual yield for signal, combinatorial and physical (mis-reconstructed three body decay) backgrounds at 95% confidence level are, respectively, [187,508]k, [44,255]k and [59,306]k events.

The CP parameters can be extracted from an Unbinned Maximum Likelihood Fit to all the Probability Density Functions (PDFs) of the various decay modes and backgrounds on the collected data sample. The signal decay modes invariant mass (IM) PDFs are modeled in terms of the reconstructed tracks momentum asymmetry $\left(\beta = \frac{p_+ - p_-}{p_+ + p_-}\right)$ taking into account the radiative tails modeled using QED calculations [7]. The combinatorial background IM PDF is going to be extracted from the IM side-bands.

The PID PDFs will be extracted from the control samples. The PDFs describing the time-dependent rates are known from theoretical calculations and do depend on the decay channel. Key ingredients common to all the decay modes are the proper time resolution, that is modeled as a sum of three Gaussians with sigmas 30, 55 and 120 fs respectively, and the effective tagging efficiencies ($\epsilon_{\text{eff}} = \epsilon_{\text{tag}} \cdot (1-2\omega)^2$) that depend on the decay mode and are in the 4.5–6.5% range.

The CP sensitivities have been obtained from a large number of unbinned likelihood fits to MC samples generated with input from the full MC simulation and a number of events corresponding to different values of L_{int}. Results for $L_{\text{int}} = 2\,\text{fb}^{-1}$ are reported in table I. By combining the CP observables it is possible to extract the sensitivities on the γ and ϕ_s CKM angles: a resolution of 7 degrees on γ and a 10% relative resolution on ϕ_s, for a large NP ϕ_s value: ~ 0.7, are obtained with $L_{\text{int}} = 2\,\text{fb}^{-1}$.

5. – Semi-leptonic and radiative decays

The LHCb and ATLAS experiments have studied the reconstruction and selection of several b $\to$ sll modes like $B_d \to K^{0*}\mu^+\mu^-$, $B_s \to \phi\mu^+\mu^-$, $B^+ \to K^+\mu^+\mu^-$, $B^+ \to$

$K^{+*}\mu^+\mu^-$ and $\Lambda_b \to \Lambda^0\mu^+\mu^-$. The expected yields are of the order of few thousand events in one (LHCb) or three (ATLAS) nominal years, to be compared with the one thousand events collected by Tevatron and B factory experiments together. The main sources of background are the combinations of tracks from two semi-leptonic b decays and from a semi-leptonic b decay and a muon from the $b \to c \to \mu$ decay chain. By measuring the A_{FB} as a function of the $\mu\mu$ invariant mass LHCb will be able to measure s_0 with an absolute uncertainty of $0.5\,\mathrm{GeV}^2$ with the data collected in one nominal year of running while ATLAS is going to achieve a 4% statistical error on s_0 in three nominal years. Slightly larger statistical uncertainties are expected from the analysis of $\Lambda_b \to \Lambda^0\mu^+\mu^-$ (6%). LHCb also expects to reconstruct 10k ee and 20k $\mu\mu$ events, achieving a relative resolution on $R_k \sim 4\%$ with $10\,\mathrm{fb}^{-1}$ L_{int}.

The LHC experiments can also reconstruct and select the radiative $B_s \to \phi\gamma$ and $\Lambda_b \to \Lambda^0\gamma$ decays, performing the time-dependent analysis of the decay rates. Few thousand events are expected in a nominal year of LHCb running (3 years for ATLAS) with $S/B \sim O(1)$. The expected resolution on CP parameters is of the order of 10% for the tagged analysis and 20% for the untagged one (current results from B factories on B_d mesons have a 40% uncertainty).

6. – Conclusions

Three LHC experiments are getting ready to reconstruct and analyze the largest B meson sample ever collected. The pp interactions will open several new windows on the b meson physics allowing the first accurate study of B_s meson and Λ_b hadrons to be cross-checked with known results from the already deeply studied B_d mesons system. Exciting new results from the study of B to hh′ decays (LHCb) and semi-leptonic and radiative decays (all the three experiments) will be available, with performances that are competitive, since the first years, with results already obtained from the B factories or Tevatron experiments.

Using the unified offline selection of all the b $\to$ hh′ decays, LHCb is going to collect nearly 100k signal events with an integrated luminosity of $0.5\,\mathrm{fb}^{-1}$ (first year of data taking), achieving a sensitivity on CP observables of the order of 3–5%. An uncertainty on γ of $\sim 7°$ can be achieved taking into account an U-spin breaking at the level of $\sim 20\%$. An uncertainty $\sigma(s_0)$ of $\sim 0.5\,\mathrm{GeV}^2$ is expected after a nominal year of LHCb data taking ($2\,\mathrm{fb}^{-1}$) studying the A_{FB} spectrum as a function of the $\mu\mu$ invariant mass in the $B_d \to K^*\mu\mu$ decay mode. After three nominal years of data taking the ATLAS experiment is going to be able to see deviations from SM predictions and set strong limits on NP models. CMS studies on this channels are ongoing and the expected performances will be published soon. The radiative b $\to$ sγ decays have also been studied. The expected resolutions on the CP parameters in a nominal year of data taking are at the 10–20% level.

REFERENCES

[1] Alves A. A. *et al.* (LHCb Collaboration), *JINST*, **3** (2008) S08005.
[2] Aad G. *et al.* (ATLAS Collaboration), *JINST*, **3** (2008) S08003.
[3] Chatrchyan S. *et al.* (CMS Collaboration), *JINST*, **3** (2008) S08004.
[4] Carbone A. *et al.*, *Charmless charged two-body B decays at LHCb*, CERN-LHCB-2008-052.
[5] Hiller G., *Phenomenology of New Physics* [hep-ph/0308180].
[6] Beneke M. *et al.*, *Eur. Phys. J. C*, **41** (2005) 173.
[7] Baracchini E. and Isidori G., *Phys. Lett. B*, **633** (2006) 309.