PROCEEDINGS OF SCIENCE

B Hadron Properties at the LHC

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We present the prospects of measuring B hadron properties in the ATLAS, CMS and LHCb experiments at the LHC. The topics covered in this paper include the production of B^+, masses and lifetimes of B_s^0, B_d^0 and B_c, spin properties, CP and T violations of Λ_b. The analyses will start to produce results with an integrated luminosity of 10 pb^{-1} and continue until tens of fb^{-1}. During the early data taking period, the results will first assist us in understanding the performance of our detectors. With improved precisions as we accumulate data, these measurements will play a key role in testing the theoretical models and revealing new physics effects.

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1. B-physics at the LHC experiments

The Large Hadron Collider is a gigantic machine designed to collide protons or lead ions at a center-of-mass energy of up to 14 TeV with high luminosity. The total $b\bar{b}$ production cross-section from the 14 TeV proton-proton collisions is assumed to be 500 μb. ATLAS [1] and CMS [2] are two general-purpose experiments which are designed to operate all the way up to the maximum available luminosity of 10^{34} cm^{-2}s^{-1}. Both detectors cover the central rapidity region, $|\eta| < 2.5$ for tracking B decays. In view of trigger rates and pile-up, the initial running period will be most feasible for B-physics in these two experiments. The LHCb experiment [3] is dedicated to bottom and charm physics, with a forward single-arm spectrometer covering $1.9 < \eta < 4.9$. It is designed to perform B physics throughout its lifetime at an average luminosity, L = 2×10^{32} cm^{-2}s^{-1}.

The bunch crossing rate of the LHC will be 40 MHz. Trigger systems in the ATLAS and CMS detectors will reduce the event rate down to 200 Hz and the LHCb triggers will reduce it to 2 kHz. For most of the di-muon decays of B particles in ATLAS and CMS, low p_T muons are first identified by the hardware based level-1 triggers and then the events are fully reconstructed by the software high level triggers. In LHCb the hardware triggers reconstruct large E_T hadrons, electrons and photons as well as high p_T muons. Optionally pile-up events can be vetoed with the help of the vertex locator. The software high level triggers further select tracks with high p_T or large impact parameter and events with fully reconstructed charm or bottom hadrons.

Shortly the LHC will enter its initial running stage with the center-of-mass energy up to 7 TeV. At the very beginning, well known B-decay events are optimal candidates for understanding the performance of our detectors. Later measurements of the production cross-sections of the heavy quarkonia (J/ψ and Υ) and B hadrons will provide sensitive tests of QCD predictions at the LHC energy scale. It is also expected to study the properties of the B hadron family (B^+, B_d^0, B_s^0, B_c, Λ_b, Ξ_b^-, Ξ_b^0, Ω_b^-, etc.). Further, the high energy and high luminosity of the LHC will allow for the precise measurements of those weak decays of B-hadrons which are sensitive to various possible effects caused by physics beyond the Standard Model. Direct searches of rare decays (e.g. $B_s^0 \to \mu^+\mu^-$) will also be performed.

The focus of this paper is the feasibility of measuring B hadron properties in the ATLAS, CMS and LHCb experiments. Some of the investigations based on Monte Carlo samples will be presented in the following sections.

2. $B^+ \to J/\psi K^+$ with early data

Because of the large production rate, the $B^+ \to J/\psi K^+$ decay is expected to be one of the first fully-reconstructed B decays observed at the LHC. The mass, lifetime and production cross-section of B^+ will be measured with this channel in ATLAS, CMS and LHCb. Besides, the well known B^+ mass and lifetime can be used for detector calibration, alignment and other performance studies. It is also considered as a reference channel for some other B decays so that it can be used to estimate the systematic uncertainties and efficiencies of flavour tagging algorithms.

Measurements of the total and differential production cross-section as well as the lifetime from the $B^+ \to J/\psi K^+$ channel have been studied in ATLAS. The di-muon trigger suitable for this work requires one muon with $p_T > 4$ GeV and the other with $p_T > 6$ GeV. The study was performed with a fully simulated sample of inclusive $b\overline{b}$ decays corresponding to 10 pb^{-1} of data at 14 TeV [1]. The total cross-section is determined from the events selected offline in the region p_T^B >10 GeV, using a maximum-likelihood fit to the invariant mass distribution. The differential cross-sections are retrieved separately in 4 bins of p_T^B using the same fitting procedure. The results show that with the first 10 pb^{-1} of integrated luminosity the total production cross-section can be measured with a statistical precision better than 5% and the differential cross-section can reach a precision around 10%. The dominant systematic uncertainties are expected to come from the luminosity and branching ratio. On the other hand, the lifetime of B^+ is extracted from a simultaneous fit to the proper decay length and the invariant mass of the reconstructed B candidates taking into account the per-event proper decay time error. It is shown that the lifetime resolution could reach 0.088 ps with the first 10 pb^{-1} of data.

CMS has investigated the sensitivity of measuring the differential cross-section of B^+ and the lifetime ratio between B^+ and B^0 with the first 10 pb^{-1} of data for the 10 TeV scenario [4]. The events are first selected by a di-muon trigger requesting both muons with $p_T > 3$ GeV. A two-dimensional fit to the invariant mass and proper decay length of the reconstructed B candidates is applied in 7 bins of p_T^B to derive differential cross-sections. The lifetimes from $B^+ \to J/\psi K^+$ and $B^0 \to J/\psi K^{*0}$ are determined with similar fits in both samples in the range $p_T^B > 9$ GeV. The differential cross-section has been measured with a statistical precision of less than 10% and systematic uncertainties are mainly from the luminosity and branching ratio. Uncertainties due to detector misalignment and lifetime resolution cancel in the lifetime ratio of B^+ to B^0, thus its precision is dominated by the statistical uncertainty of 5%.

$B^+ \to J/\psi K^+$ is also a control channel to calibrate the opposite-side flavour taggers for CP measurements in the $B_s^0 \to J/\psi\phi$ channel. For instance, in LHCb, events are required to pass the L0 trigger and cover the same phase space as $B_s^0 \to J/\psi\phi$. After the trigger and offline selections, the total efficiency is found to be 2.6% and the event yield for the $B^+ \to J/\psi K^+$ channel is 942,000 corresponding to an integrated luminosity of 2 fb^{-1}. The combination of results from opposite side taggers in LHCb gives an effective tagging efficiency εD = 3.4 $\pm$ 0.1%, compatible with the efficiency from the $B_s^0 \to J/\psi\phi$ study [5].

3. B_s^0 and B_d^0 with early data

The decay of $B_s^0 \to J/\psi\phi$ is one of the promising channels at the LHC. Precise measurements of the parameters from the two weak eigenstates in the B_s^0 - $\overline{B_s^0}$ system such as Δm_s and $\Delta\Gamma_s$ will be valuable inputs for improving our knowledge of the elements of the CKM matrix. In the Standard Model, the CP-violating weak phase is predicted to be very small (of the order of 0.03). So observing an enhanced CP asymmetry would be the sign for physics beyond the Standard Model.

ATLAS will start with basic measurements of B masses and lifetimes from the earliest data. The decay of $B_s^0 \to J/\psi\phi$ will provide sensitive tests of the tracking system after 150 pb^{-1} of integrated luminosity [1]. A similar analysis will also be performed for the control channel $B_d^0 \to J/\psi K^{*0}$ after 10 pb^{-1} of data because of its larger cross-section. Studies from the fully simulated samples have shown that the statistical precisions of 10% on the lifetimes of B_s^0 and B_d^0 can be achieved at the early stage. Meanwhile the self-tagging decay $B_d^0 \to J/\psi K^{*0}$ will be used to cali-

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brate the jet charge tag which will serve for flavour tagging of $B_s^0 \to J/\psi\phi$. The invariant mass and decay time distributions for the reconstructed B_s^0 events are shown in Fig. 1.

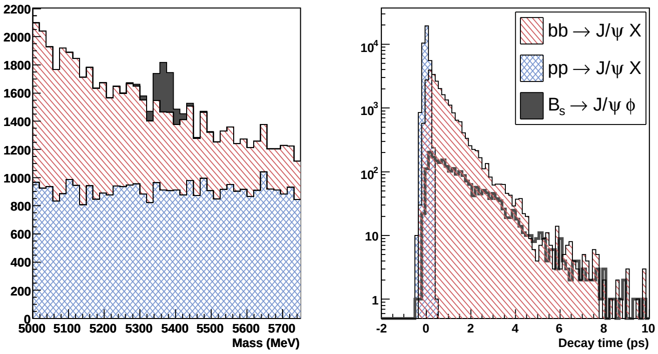


Figure 1: Distributions of the reconstructed B_s^0 mass and decay time expected with 150 pb^{-1} in ATLAS.

In CMS, measuring the width difference in the B_s^0 system with untagged $B_s^0 \to J/\psi\phi$ decay has been tested by analyzing the time evolution of the full angular distributions [2]. A first measurement of the relative width difference $\Delta\Gamma_s/\overline{\Gamma}_s$ undertaken with 1.3 fb^{-1} of data could yield an uncertainty of 20%. More advanced $B_s^0 \to J/\psi\phi$ measurements starting from 10 fb^{-1} in both ATLAS and CMS are presented in a dedicated document in current proceedings.

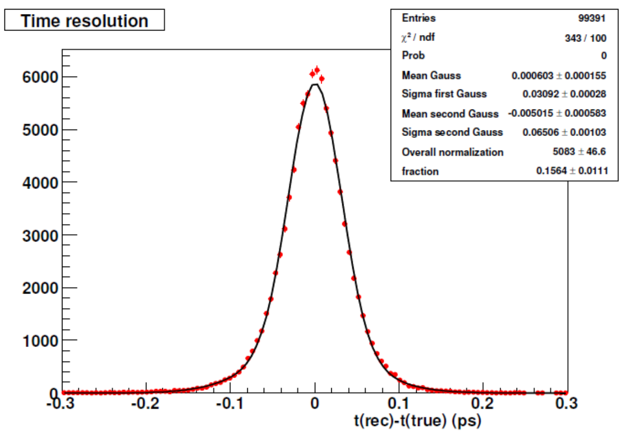


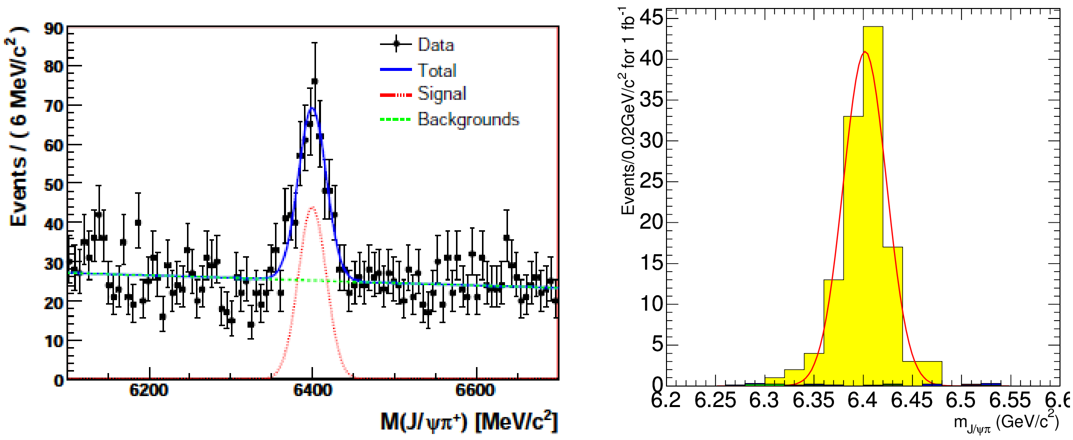
Figure 2: Distribution of the proper time residual for the decay $B_s^0 \to J/\psi\phi$ in LHCb.

LHCb will also perform the measurement of B_s^0 and B_d^0 decays with early data. For the channel $B_s^0 \to J/\psi\phi$, the average proper time resolution is expected to be 38 fs (Fig. 2) [5]. A full physics program for this channel in LHCb is described in a dedicated document in current proceedings. As mentioned in the first section, the LHCb triggers apply cuts on the impact parameters and transverse momenta of tracks, so the hadronic channels suffer from the lifetime bias introduced by the hadronic trigger. A lifetime fit method taking into account the trigger acceptance has been developed and well tested with $B_d^0 \to D^-(\pi^-\pi^-K^+)\pi^+$ [6]. This benchmark channel is intended for comparisons with other channels that are sensitive to new physics. The result shows that a precision of 0.009 ps on the B_d^0 lifetime could be reached with 2 fb^{-1} of data.

4. B_c properties

The B_c meson is a bound state of bottom and charm quarks. Because of its bare flavour, it is constrained to decay weakly, offering a unique window onto heavy quark dynamics. The mass is predicted over a large range by non-relativistic potential models, perturbative QCD and lattice QCD. The ground state has been observed through semileptonic and hadronic decays at the Tevatron [7, 8]. At the LHC, the expected large production rate will allow us to test the theoretical models through precision measurements of B_c properties. For optimal mass resolution, the hadronic decay $B_c \to J/\psi\pi$ is selected in order to minimize dependence of the analysis upon the calibration of the calorimeter in the early data taking era.

In LHCb, the total reconstruction efficiency for $B_c \to J/\psi\pi$ including trigger efficiency was found to be (1.01 $\pm$ 0.02)% [9, 10]. In the signal region of M(B_c) $\pm$ 80 MeV, the ratio of background to signal events is 1 to 2 at 90% confidence level. Assuming the total production of B_c^+ is 0.4 μb and the branching ratio of this hadronic decay is 1.3×10^{-3}, one can expect about 310 signal events from 1 fb^{-1} of data. The B_c mass is extracted from a fit to the mass distributions of the fully simulated signal sample and the standalone simulated background sample as shown in Fig. 3(a). The result is 6399 $\pm$ 1.7 MeV with a resolution around 17 MeV, in agreement with the input value of 6400 MeV in the generator. To reduce dependency of lifetime precision on $p_T(B_c^+)$, the samples were divided into two $p_T(B_c^+)$ bins, 5-12 GeV and beyond. Event selections were re-optimized individually and a combined mass-lifetime fit was applied simultaneouly in the two $p_T(B_c^+)$ intervals. The lifetime obtained from the fit is 0.438 $\pm$ 0.027 ps, consistent with the input value of 0.46 ps.



(a) LHCb: the invariant mass of the selected B_c^+ candidates. (b) CMS: the invariant mass of the J/ψ and pion candidate of the selected B_c.

Figure 3: B_c mass measurements in the LHCb and CMS experiments.

In CMS, the signal sample was produced with the cross section of 1.78 pb after kinematic cuts applied [2]. After the offline selections, the number of $B_c \to J/\psi\pi$ events is expected to be 120 for 1 fb^{-1}. In Fig. 3(b), a fit to the mass distribution predicts a mean value of 6406 MeV with the resolution of 22 MeV. The result from a fit to the proper decay length with a fixed resolution is 148.8 $\pm$ 13.1 μm. With the first fb^{-1} data CMS is expected to measure the B_c mass with an uncertainty of $\pm$ 22.0(stat) $\pm$ 14.9(syst) MeV and the lifetime with $\pm$ 0.044(stat) $\pm$ 0.010(syst) ps.

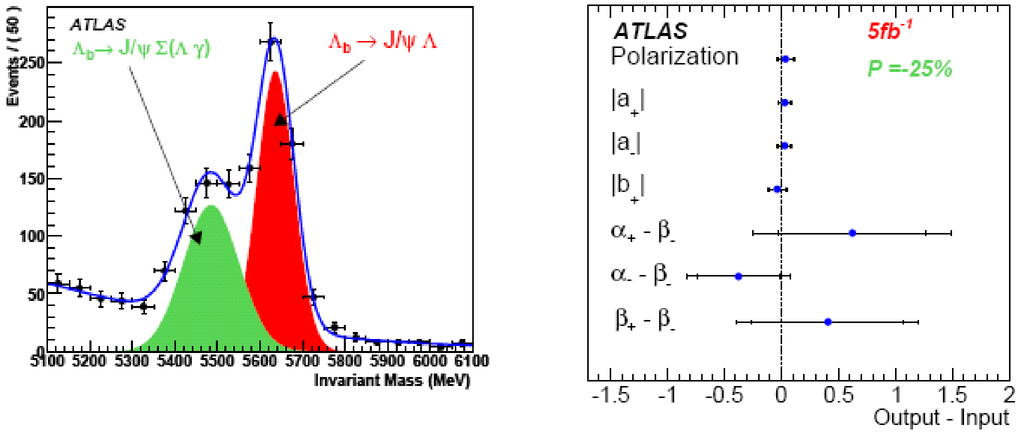
In ATLAS, the plan is also to retrieve the mass from $B_c \to J/\psi\pi$ after 1fb^{-1}. Once sufficient statistics have been accumulated, the work will move on to extract mass differences between excited and ground states which could be the constraints for the shape of strong potential models.

5. Λ_b properties

The Λ_b is the lightest B baryon that has drawn a great deal of interest. There are still many puzzles and questions involved with Λ_b such as the direct search for CP and Time Reversal asymmetries, polarization, weak radiative decays, lifetime measurement and so on.

ATLAS has studied the measurements of the polarization and the parity-violating parameter α_{Λ_b} for the decay of $\Lambda_b \to J/\psi(\mu^+\mu^-)\Lambda(p\pi^-)$. The QCD calculations predict rather small polarizations on both b and s quark. However, when compared to the observed Λ polarization, these predictions are found to be an order of magnitude too small [11]. So a significant polarization of Λ_b might be observed and could be a sign for new physics. The measurement of the α_{Λ_b} parameter could be used to test factorization models and perturbative QCD. In order to test the sensitivity of measuring certain spin properties of Λ_b in the ATLAS detector, a Monte Carlo sample of $\Lambda_b \to J/\psi(\mu^+\mu^-)\Lambda(p\pi^-)$ was generated with a polarization of -25% and then fully simulated with the ATLAS geometry [1]. The overall selection efficiency including the di-muon trigger is around 6.1%. With an integrated luminosity of 30 fb^{-1}, it is expected to observe 13000 signal events. From the full decay angular distributions, the polarization and seven complex helicity amplitudes which are related to α_{Λ_b} could be obtained. Figure 4(a) shows the mass distribution after offline selections and Fig. 4(b) shows the fit result from the decay angular distributions including statistical and systematic uncertainties. It confirms that for polarizations up to 25%, a measurement with a statistical uncertainty of a few percent is affirmative with 30 fb^{-1} of data.

In LHCb, the overall efficiency for $\Lambda_b \to J/\psi(\mu^+\mu^-)\Lambda(p\pi^-)$ reaches 0.57% based on the Monte Carlo studies [12]. The dominant background is inclusive $b\overline{b}$ pair events and the ratio of background to signal events is 0.4 at 90% confidence level in the worst case scenario. The direct CP asymmetry is measured by observing the production difference between Λ_b and $\overline{\Lambda_b}$ from the decays of $\Lambda_b \to \Lambda J/\psi$ and $\overline{\Lambda_b} \to \overline{\Lambda} J/\psi$. The systematic error is estimated to be 1%. The CP asymmetry is expected to be weak (10^{-4}), whilst an experimental limit of 1.6% is accessible for 10 fb^{-1} of data observed in LHCb. T violation is investigated by constructing T-odd observables in the decay products. The asymmetry depends strongly on the polarization density matrix. It is forseen that after 2 fb^{-1} a Λ_b polarization $\geq$ 50% could be put into evidence. From 10 fb^{-1}, the asymmetry will achieve > 1% and supply crucial proofs for a direct test of Time Reversal symmetry.



(a) Invariant mass distribution from Λ_b candidates identified in $b \rightarrow J/\psi\Lambda X$ Monte Carlo sample. A fit to the fully reconstructed events after vertexing requirement is shown.

(b) Comparison of fit outputs for polarization of -25 % with respect to input values from Monte Carlo generation at 5 fb^{-1}.The statistical and systematic uncertainties are included.

Figure 4: Measurement of the spin properties of Λ_b from the decay $\Lambda_b \rightarrow J/\psi(\mu^+\mu^-)\Lambda(p\pi^-)$ in ATLAS.

6. Summary

The ATLAS, CMS and LHCb experiments will start to explore B-physics phenomena once the LHC starts colliding protons. At the early stage, some of the B hadron properties could contribute to assess our detector performance. During the main B-physics data taking phase, we expect high-precision measurements of the properties of B mesons and baryons. We also expect some of the measurements will be sensitive to uncover the effects from physics beyond the Standard Model. More B-physics studies from these three experiments could be found on the publication pages [13].

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