Feasibility study for the measurement of B_c meson mass and lifetime with the general purpose detector at the LHC

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Abstract In this paper a feasibility study of the B_c meson to measure its mass and lifetime is described with the general purpose detector at the LHC. The study solely concentrated on the $J/\psi\pi^+$, $J/\psi \to \mu^+\mu^-$ decay channel of the B_c and it was concluded that about 120 events can be selected in the first fb^{-1} of data. With this data sample, the mass resolution was estimated to be 2.0(stat.) MeV/c^2 while the $c\tau$ resolution was found to be 13.1(stat.) μm, i.e. the lifetime resolution to be 0.044(stat.) ps.

Key words B_c, mass, lifetime, LHC, general purpose detector

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1 Introduction

The B_c meson is the ground state of $\bar{b}c$ system. In contrast to the common quarkonia, B_c in fact is the only one which carries different heavy flavors and decays through the weak interactions. This unique character provides a great opportunity for studying heavy quark dynamics, and helps to test the spin symmetry derived in the non-relativistic quantum chronmodynamics (NRQCD) and heavy quark effective theory (HQET) approaches[1—11].

The $\bar{b}c$ system has a rich spectroscopy of orbital and angular-momentum excitations. The majority of the B_c mesons at the LHC are produced indirectly via the decay of excited $\bar{b}c$ mesons. The excited states cascade down through the spectrum via a sequence of hadronic and electromagnetic transitions, until they reach the ground state $B_c(1s)$. The mass of B_c and other states can be calculated using the non-relativistic potential models[12—17]. The range of the resulting predictions for the B_c mass is 6.24 ± 0.05 GeV/c^2.

The decay of B_c ground state can be subdivided into three classes: the $\bar{b}$ quark decays with the c quark as a spectator, the c quark decays with the $\bar{b}$ quark as a spectator, and annihilation decay $\bar{b}c \to \ell^+\nu_\ell$, $c\bar{s}$, $u\bar{s}$, where $\ell =$ e, μ or τ. Modern theoretical tools used for the calculations of the fundamental B_c are the Operator Product Expansion (OPE), sum rules (SR) of QCD and NRQCD, and potential models (PM). Table 1[18] shows the results from the three different theoretical approaches. All predictions agree within the errors, and the inclusive OPE and exclusive PM approaches give the values consistent but with large errors. The same is true for the prediction of the lifetime[18]

$$\tau(B_c)_{\rm OPE,PM} = 0.55\pm0.15{\rm ps},$$
$$\tau(B_c)_{\rm SR} = 0.48\pm0.05{\rm ps}.$$

It should be noted that the SR's prediction is the most precise one for the lifetime.

Table 1. The branching ratios of the B_c decay modes calculated in the framework of inclusive OPE approach (OPE), by summing up the exclusive modes in the potential models (PM) and according to the semi-inclusive estimates in the sum rules of QCD and NRQCD (SR).

B_c decay mode	OPE (%)	PM (%)	SR (%)
$\Sigma\bar{b}\to\bar{c}$	25.0±6.2	25.0±6.2	19.6±1.9
$\Sigma c\to s$	64.3±16.1	65.6±16.4	72.0±7.2
$B_c^+\to c\bar{s}$	7.2±1.8	7.2±1.8	6.6±0.7

The first observation of the B_c meson was reported by the CDF Collaboration at Fermilab Tevatron col-

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lider in the semileptonic decay mode $B_c \to J/\psi\ell\nu$ with the J/ψ decaying into muon pairs[19, 20]. Values for the mass and the lifetime of the B_c meson were given as $M(B_c) = 6.40 \pm 0.39 \pm 0.13$ GeV/c^2 and $\tau(B_c) = 0.46^{+0.18}_{-0.16}$(stat.) $\pm$ 0.03(syst.) ps, repectively. Based on Tevatron Run II, recently new result by the CDF Collaboration for the mass of B_c meson from decay mode $B_c \to J/\psi\pi$, is 6.2857$\pm$ 0.0053(stat.) $\pm$ 0.0012(syst.) GeV/c^2 with errors significantly smaller[21], and for the lifetime from decay mode $B_c^+ \to J/\psi e^+\nu_e$ is $0.463^{+0.073}_{-0.065} \pm 0.036$ ps[22]. Also D0 Collaboration has observed the B_c in the semileptonic decay mode $B_c \to J/\psi\mu X$ and reported evidence that $M(B_c) = 5.95^{+0.14}_{-0.13} \pm 0.34$ GeV and $\tau(B_c) = 0.45^{+0.12}_{-0.10} \pm 0.12$ ps[23].

Because of the higher colliding energy, the production cross section of the B_c at the LHC is higher than the one at the Tevatron: $\sigma(B_c)^{\rm LHC} \sim 16\,\sigma(B_c)^{\rm Tevatron}$[5]. Since also the LHC luminosity will be higher, the experiments at the LHC poss the potential to collect much more B_c mesons and its excited states than the experiments at the Tevatron. The large sample allows the study of the spectroscopy and decays of B_c mesons, and open to full experimental investigation and systematic test of the theory on its mass, production rate and lifetime, etc.[18, 24, 25].

There have been some possibility studies on the B_c meson at the LHC[26, 27]. Former work in Ref. [28] gaves some estimation for such possibilities based on lepton trigger but not through real detector simulation.

In this paper the study of the B_c meson in the fully reconstructed decay chain $B_c \to J/\psi\pi$ followed by $J/\psi \to \mu^+\mu^-$ at the general purpose detector with the prototype of the Compact Muon Solenoid[29] at the LHC is proposed. The emphasis here is for the first 1 fb^{-1} data at the initial phase with the advantage of few pile-up events at the low luminosity mode below 2×10^{-33}cm^{-2}·s^{-1}. The signal and background event samples are discussed and given in Section 2, and event selection is described in Section 3. The mass and lifetime fitting of the B_c meson is presented in Section 4.

2 Monte Carlo data samples

A large amount of Monte Carlo events have been produced to study the measurement of B_c mass and lifetime for the detector described in Ref. [29] at the LHC by using the first fb^{-1} of recorded data.

2.1 The B_c signal event sample

There are two dedicated B_c generators, BCVEGPY[5, 11, 30] and Protvino[31, 32], both based on perturbative QCD and integrated in the SIMUB package[33]. PYTHIA[34] can also generate B_c events but consumes much more CPU time for this process. Fig. 1 gives a comparison of the B_c p_T distribution generated by them. It shows that the Protvino package produces a harder p_T spectrum, while PYTHIA and BCVEGPY agrees with each other. In order to save CPU time, the BCVEGPY generator was used, and for the optimization, in the generation process only signal events that satisfied the following requirements on transverse momentum p_T and pseudorapidity η are generated:

1) $p_T(B_c) > 10$ GeV/c and $|\eta(B_c)| < 2.0$

2) $p_T(\mu) > 4$ GeV/c and $|\eta(\mu)| < 2.2$

After these kinematic cuts the accepted cross section including the branching ratio is 1.78 pb. The produced 52 000 B_c events therefore correspond to 29.2 fb^{-1} of the integrated luminosity.

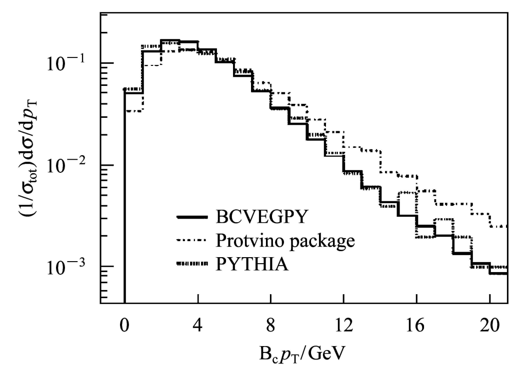

Fig. 1. Comparison of p_T distribution of B_c mesons, BCVEGPY (solid line) agrees with PYTHIA (dot line), while Protvino package (dash-dot line) generates higher p_T[28].

2.2 The B_c background event samples

B hadron decays containing J/ψ as well as the prompt J/ψ production are the most important backgrounds for the analysis. Other important background sources are $b\bar{b} \to \mu^+\mu^- X$, $c\bar{c} \to \mu^+\mu^- X$, W+jets and Z+jets. B hadrons containing J/ψ are generated with PYTHIA 6.228 utilizing similar kinematic cuts on final muons as were used for the B_c production. Prompt J/ψ events are generated with PYTHIA 6.324 including color-octet contributions.

Table 2. The cross section multiplied by the branching ratio after kinematic cuts and the number of events produced for B hadrons and prompt J/ψ and $c\bar{c} \to \mu^+\mu^- X$.

channel	$\sigma \cdot Br$/pb	$N_{\rm event}$
B^0	70.3	740 000
B^+	70.7	740 000
B_s	14.8	190 000
Λ_b	19.4	200 000
prompt J/ψ	240.3	500 000
$c\bar{c} \to \mu^+\mu^- X$	1690	210 000

Table 2 shows the cross sections multiplied by the branching ratio and number of produced events for the important background processes. Therefore, more than 10 fb^{-1} B hadrons, 2 fb^{-1} prompt J/ψ and 0.12 fb^{-1} $c\bar{c}\rightarrow\mu^+\mu^-X$ events were produced for this study. Furthermore about 950 000 QCD, 880 000 W+jets, 710 000 Z+jets and 100 000 $b\bar{b}\rightarrow\mu^+\mu^-X$ background events were also used for this analysis.

3 Event selection

Signal events for this analysis are characterized by a b-jet, a c-jet as well as a B_c meson in the final state. The B_c is supposed to decay in a pion and $J/\psi\rightarrow\mu^+\mu^-$. The selection of this topology starts from 2 muon tracks where the p_T of both muons must be larger than 4 GeV/c and their absolute value of η is required to be less than 2.2. Furthermore the two muons must have different charge, share the same vertex, and their invariant mass must be within the J/ψ mass window from 3.0 to 3.2 GeV/c^2.

The analysis continues by requiring an additional track at the J/ψ vertex. This track must not be a muon nor an electron candidate, with the conditions $p_T > 2$ GeV/c and $|\eta| < 2.4$.

The decay length, L_{xy}, and the proper decay length, L_{xy}^{PDL}, are calculated from the primary vertex and the J/ψ vertex candidate defined in the x-y plane. A Gaussian fit to the distribution of the difference of reconstructed and generated proper decay length yields a resolution of 25 μm for L_{xy}^{PDL}. It is interesting to note that this resolution is almost independent of the L_{xy}^{PDL} value.

In order to suppress the prompt J/ψ background, the secondary vertex must be displaced from the primary one significantly. Therefore, the significance of the decay length $L_{xy}/\sigma_{xy} > 2.5$ and $L_{xy}^{PDL} > 60$ μm is required. In addition, the cosine value of the opening angle between the direction from primary to second vertex and the reconstructed B_c momentum $\cos\theta_{sp}$ must be larger than 0.8.

The invariant mass of the J/ψ and pion candidate after all the cuts is shown in Fig. 2. The plot is normalized to the integrated luminosity 1 fb^{-1}. Already with this rather low luminosity a clear signal of the B_c meson in the mass region of 6.25 to 6.55 GeV/c^2 can be established.

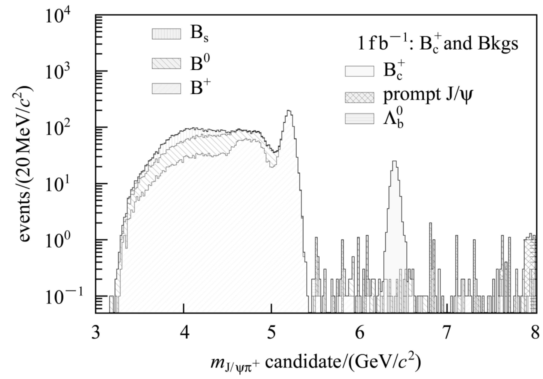

Fig. 2. The invariant mass of J/ψ and pion candidate for the B_c meson and its backgrounds.

Because of the large cross section, the number of produced QCD Monte Carlo events is not sufficient to directly determine the QCD background which is therefore estimated in 3 steps. At first the efficiency to select two muons ($\epsilon_{\mu^+\mu^-}$) is obtained directly from the QCD sample, then the efficiency to reconstruct two muons into a J/ψ candidate (ϵ_{rec}) is calculated from the $c\bar{c}\rightarrow\mu^+\mu^-X$ sample, and finally the efficiency for a J/ψ candidate plus a charged track to be taken as a fake B_c meson (ϵ_{prompt}) is obtained from the prompt J/ψ sample. The so estimated number of background events for QCD is shown in Table 3. Other processes as W+jets, $c\bar{c}\rightarrow\mu^+\mu^-X$ and $b\bar{b}\rightarrow\mu^+\mu^-X$ are presented in Tables 4, 5 and 6 respectively. All numbers are normalised to 1 fb^{-1}.

Table 7 summarises the number of selected B_c events and background events after all analysis cuts. The total background is dominated by $B\rightarrow J/\psi X$ decays and amounts to 2.6 ± 0.4 events for 1 fb^{-1}. For the same integrated luminosity 120 ± 11 signal events are expected.

Table 3. QCD backgrounds estimation at 1 fb^{-1} with different $\hat{p_T}$ bins.

source	σ/mb	$\epsilon_{\mu^+\mu^-}$	ϵ_{rec}	ϵ_{prompt}	N_{event}
QCD 0—15	55.22	$(1.7\pm0.2)\times10^{-7}$	$(1.3\pm0.1)\times10^{-3}$	$(6.2\pm1.2)\times10^{-6}$	0.08 ± 0.01
QCD 15—20	1.5	$(7.4\pm0.1)\times10^{-6}$	$(1.3\pm0.1)\times10^{-3}$	$(6.2\pm1.2)\times10^{-6}$	0.09 ± 0.00
QCD 20—30	0.64	$(4.4\pm2.2)\times10^{-5}$	$(1.3\pm0.1)\times10^{-3}$	$(6.2\pm1.2)\times10^{-6}$	0.23 ± 0.07
QCD 30—50	0.16	$(1.3\pm0.4)\times10^{-4}$	$(1.3\pm0.1)\times10^{-3}$	$(6.2\pm1.2)\times10^{-6}$	0.16 ± 0.02
QCD 50—80	0.02	$(6.3\pm0.6)\times10^{-4}$	$(1.3\pm0.1)\times10^{-3}$	$(6.2\pm1.2)\times10^{-6}$	0.11 ± 0.01
QCD 80—120	0.0029	$(1.6\pm0.1)\times10^{-3}$	$(1.3\pm0.1)\times10^{-3}$	$(6.2\pm1.2)\times10^{-6}$	0.04 ± 0.00
QCD 120—170	5.0×10^{-4}	$(3.5\pm0.2)\times10^{-3}$	$(1.3\pm0.1)\times10^{-3}$	$(6.2\pm1.2)\times10^{-6}$	0.01 ± 0.00
QCD 170—230	1.0×10^{-4}	$(6.1\pm0.4)\times10^{-3}$	$(1.3\pm0.1)\times10^{-3}$	$(6.2\pm1.2)\times10^{-6}$	0.01 ± 0.00
QCD 230—470	2.4×10^{-5}	$(1.5\pm0.1)\times10^{-2}$	$(1.3\pm0.1)\times10^{-3}$	$(6.2\pm1.2)\times10^{-6}$	0.00 ± 0.00

Table 4. W+jets backgrounds estimation at 1 fb^{-1} with different $\hat{p_T}$ bins.

source	σ/mb	$\epsilon_{\mu^+\mu^-}$	ϵ_{rec}	ϵ_{prompt}	N_{event}
W+jets 0—20	1.1×10^{-4}	$(5.1\pm0.6)\times10^{-4}$	$(1.3\pm0.1)\times10^{-3}$	$(6.2\pm1.2)\times10^{-6}$	0.00 ± 0.00
W+jets 20—50	2.7×10^{-5}	$(1.4\pm0.1)\times10^{-3}$	$(1.3\pm0.1)\times10^{-3}$	$(6.2\pm1.2)\times10^{-6}$	0.00 ± 0.00
W+jets 50—85	1.0×10^{-5}	$(2.8\pm0.1)\times10^{-3}$	$(1.3\pm0.1)\times10^{-3}$	$(6.2\pm1.2)\times10^{-6}$	0.00 ± 0.00
W+jets 85—150	6.3×10^{-6}	$(4.5\pm0.1)\times10^{-3}$	$(1.3\pm0.1)\times10^{-3}$	$(6.2\pm1.2)\times10^{-6}$	0.00 ± 0.00
W+jets 150—400	1.4×10^{-6}	$(1.1\pm0.1)\times10^{-2}$	$(1.3\pm0.1)\times10^{-3}$	$(6.2\pm1.2)\times10^{-6}$	0.00 ± 0.00

Table 5. $c\bar{c}\to\mu^+\mu^-X$ backgrounds estimation at 1 fb^{-1}.

source	σ/mb	ϵ_{rec}	ϵ_{prompt}	N_{event}
$c\bar{c}$	1.69×10^{-6}	$(9.1\pm0.7)\times10^{-4}$	$(6.2\pm1.2)\times10^{-6}$	0.01 ± 0.00

Table 6. $b\bar{b}\to\mu^+\mu^-X$ backgrounds estimation at 1 fb^{-1}.

source	σ/mb	ϵ_{rec}	ϵ_{prompt}	N_{event}
$b\bar{b}$	4.8×10^{-6}	$(4.2\pm0.6)\times10^{-4}$	$(6.2\pm1.2)\times10^{-6}$	0.01 ± 0.00

Table 7. The number of signal and background events estimation at 1 fb^{-1}.

B_c	B^+	B_s	B^0	prompt J/ψ	Λ_b	$c\bar{c}$	$b\bar{b}$	QCD
120 ± 11	0.7 ± 0.2	0.1	0.8 ± 0.3	0.1	0.1	0.01	0.01	0.7 ± 0.1

For this study any potential issues related to a dedicated trigger strategy for the B_c events have not been considered. However, for the first fb^{-1} of data the machine luminosity is expected to be low and, therefore, the muon p_T trigger threshold could be as low as 2.5 GeV/c for the endcap and 3.5 GeV/c for the barrel. In addition more sophisticated high level trigger algorithms like a J/ψ mass window cut can be utilised to keep the trigger rate at an acceptable level.

4 B_c mass and lifetime fitting

A kinematic fit was performed to impose the J/ψ mass constraint as well as to require that the two muons and the pion candidate stem from one common vertex. Fig. 3 shows the invariant mass of J/ψ and pion after the kinematic fit. The plot contains 120 signal events as well as the background from B hadrons and prompt J/ψ. A Gaussian fit to the mass distribution results in a center mass of 6402.0±2.0 MeV/c^2, and a mass resolution, the standard deviation of the Gaussian at the central value, of 22.0 MeV/c^2. The input mass of the B_c for the Monte Carlo event generation was 6400 MeV/c^2.

A binned likelihood fitting was done on the proper decay length distribution of the selected B_c events. The likelihood function $\mathscr{L}$ is the product of the Poisson distribution $\mathscr{P}(n_i,\mu_i)$, n_i is the number of events observed, and μ_i is the number of events predicted in the i-th bin.

$$\mu=N\cdot\epsilon(x)\cdot\exp(-x/c\tau)\otimes G(x,\sigma),$$

where x represents the proper decay length, N and $c\tau$ are the parameters to be fitted, $G(x,\sigma)$ is the Gaussian smear-function, while σ is the resolution of the proper decay length to be 25 μm in the fitting as discussed above. $\epsilon(x)$ is the efficiency obtained from the large B_c sample.

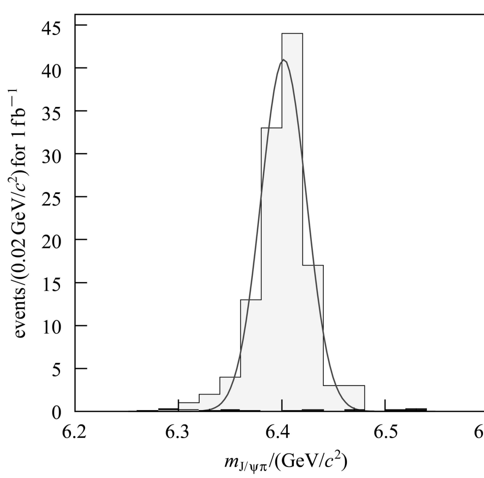

Fig. 3. The invariant mass of J/ψ and pion candidate for the selected B_c events at 1 fb^{-1}. The mean value is 6402 MeV/c^2, and the σ is 22 MeV/c^2 from a Gaussian fit.

After the fitting, $c\tau$ was obtained to be 148.8± 13.1 μm shown in Fig. 4. This result can be compared to the input value for the Monte Carlo event generation of 150 μm. Similar to the mass determination, the extraction of $c\tau$ shows no evidence for a systematic bias.

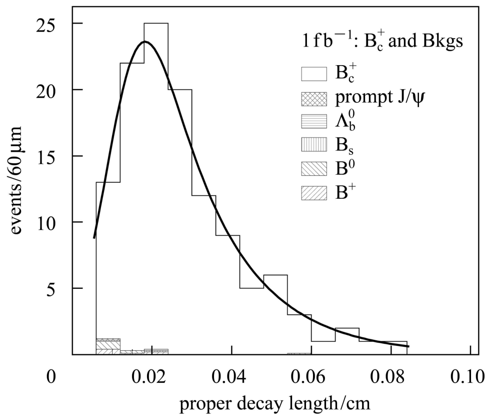

Fig. 4. The B_c proper decay length distribution at 1 fb^{-1}, the $c\tau$ was fitted to be $148.8\pm 13.1\mu$m.

5 Conclusion

With the first fb^{-1} of data, the general purpose detectors at the LHC are able to reconstruct roughly 120 $B_c{}^+ \rightarrow J/\psi\pi^+$ with $J/\psi \rightarrow \mu^+\mu^-$ events. With this data sample the B_c mass can be measured with an uncertainty of 2.0(stat.) MeV/c^2 and $c\tau$ can be extracted with a precision of 13.1(stat.) μm, corresponding lifetime uncertainty 0.044(stat.) ps, which is better than the present experimental results from the detectors at Tevatron. At the moment, the theoretical calculation is at the leading order without considering other possible additional production mechanism[35], the P-wave[36]and the color-octet contribution[37]. Therefore the theoretical uncertainty on the total cross section and the p_T distribution are large.

For the systematic uncertainties, the muon tracks as well as the vertex reconstruction will suffer from misalignment which affects the B_c measurement in the momentum scale of muons and pions, the momentum resolution[38] and the vertex determination[39]. It's expected to correct the misalignment and use the inclusive $J/\psi \rightarrow \mu^+\mu^-$ decays to calibrate the momentum scale of tracking system, especially in real data analysis. Deviations from the well-measured world averages in the $\psi' \rightarrow \mu^+\mu^-$ and $\Upsilon \rightarrow \mu^+\mu^-$ high statistics samples can be used to determine the uncertainty of the momentum scale. Other uncertainties include these from the theoretical uncertainty on B_c production mentioned above, trigger efficiency, detection efficiency, momentum resolution, and the robustness cut and selections in the analysis, etc. With the misalignment correction and detailed calibration of the detector, a high precision measurement of B_c meson with the detectors at the LHC is anticipated.

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