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Measurement of the B_c^\pm lifetime in the semileptonic decay $B_c^\pm \rightarrow J/\psi\mu^\pm + X$

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Using approximately 1.35 fb^{-1} of data collected by the DØ detector between 2002 and 2006, the lifetime of the B_c^\pm meson is studied in the $B_c^\pm \rightarrow J/\psi\mu^\pm + X$ final state. Using an unbinned likelihood simultaneous fit to $J/\psi + \mu$ invariant mass and lifetime distributions, a signal of 856 ± 80 (stat.) candidates is estimated and a lifetime measurement made of:

$$\tau(B_c^\pm) = 0.444_{-0.036}^{+0.039} \text{ (stat)}_{-0.034}^{+0.039} \text{ (sys) ps.}$$

I. INTRODUCTION

One of the most interesting mesons that can be studied at the Tevatron is the B_c^\pm meson. Unlike most other b hadrons the B_c^\pm meson comprises two heavy quarks that race each other to decay. The B_c^\pm meson is expected to have the shortest lifetime of all weakly decaying b hadrons, with a predicted lifetime of about one-third of the other B mesons, with explicit predictions of 0.55 ± 0.15 ps in an Operator Product Expansion (OPE) calculation and 0.48 ± 0.05 ps using QCD sum rules [1]. While the Charmonium ($c\bar{c}$) or Upsilon ($b\bar{b}$) mesons are also interesting with two heavy quarks, these both decay strongly and contain the same two quarks whereas the B_c^\pm contains one each of the quarks considered ‘heavy’: B_c^+ ($\bar{b}c$) and B_c^- ($b\bar{c}$). The B_c^\pm meson has three possible decay chains. The first involves the b quark acting as the spectator while the c quark decays dominated by $B_c^+ \rightarrow B_s^0\pi^+$, and $B_c^+ \rightarrow B_s^0\ell^+\nu$. Unless otherwise stated, charge-conjugate states are implied throughout this note. Similarly, the c quark can spectate while the b quark decays via the weak process, resulting in decays such as $B_c^+ \rightarrow J/\psi\pi^+$; $B_c^+ \rightarrow J/\psi D_s^+$; and $B_c^+ \rightarrow J/\psi\ell^+\nu$. A third option is the annihilation process: $B_c^+ \rightarrow \ell^+\nu$. This analysis examines the b quark decay, specifically examining the J/ψ +lepton final state with the decay $J/\psi \rightarrow \mu^+\mu^-$ and where the lepton is a muon. This three-muon final state takes advantage of the robust and high-acceptance DØ muon detectors.

After selecting a sample of $J/\psi \rightarrow \mu^+\mu^-$ decays in the data, a control sample is formed, with candidates where a vertex of the J/ψ with a single track is reconstructed. A subset of this sample is selected by demanding that this track is identified as a muon. Signal Monte Carlo (MC) samples and the data are studied to find selection criteria to enhance the signal. The invariant mass of the resulting three-muon system is taken as an estimate of the mass of the B_c^\pm . Data and Monte Carlo simulations are used to form templates of this mass distribution for both signal and background components. The decay length used to extract the B_c^\pm lifetime is measured as the distance between the reconstructed primary vertex and the secondary vertex formed by the J/ψ and the third muon.

After demonstrating the presence of the B_c^\pm signal and a making a qualitative estimate of its short lifetime compared with the other b hadrons, ‘ K -factors’ are used to correct the boost factor estimate due to the escaping neutrino, and models are constructed of the lifetime distributions of signal and background components. A log likelihood simultaneous fit to the three-muon invariant mass and lifetime distributions is made to measure the lifetime of the B_c^\pm meson.

This analysis differs from a previous preliminary DØ measurement of the B_c lifetime [2] that attempted to estimate the mass of the B_c meson at the same time. This analysis supercedes the previous preliminary DØ measurement, uses approximately six times more data, and uses precision measurements of the B_c mass as input in the construction of mass templates to help separate the signal from background.

II. DETECTOR

The DØ detector is described in detail elsewhere [3]. The detector components most important to this analysis are the central-tracking and muon systems. The central-tracking system consists of a silicon microstrip tracker (SMT) and a central fiber tracker (CFT), both located within a 2 T superconducting solenoidal magnet, with designs optimized for tracking and vertexing at pseudorapidities $|\eta| < 3$ and $|\eta| < 2.5$, respectively. An outer muon system, at $|\eta| < 2$, consists of a layer of tracking detectors and scintillation trigger counters in front of 1.8 T toroids, followed by two similar layers after the toroids [4].

III. DATA SAMPLE

The data sample used in the following analysis consists of approximately 1.35 fb^{-1} [5] of data collected at $\sqrt{s}=1.96$ TeV with the DØ detector at Fermilab between 2002 and 2006. An inclusive muon sample is used which is the union of a number of loose muon selections and triggers. While the majority of events selected in the inclusive muon sample satisfy single muon trigger requirements, it is possible to have events trigger only on lifetime-biasing triggers. To avoid lifetime biases, these events were removed from the event selection.

IV. MONTE CARLO SAMPLES

To simulate the B_c^\pm properties in this channel, and to determine appropriate selection criteria and cut values, signal Monte Carlo simulated samples of $B_c \rightarrow J/\psi\mu\nu$; $J/\psi \rightarrow \mu^+\mu^-$ were generated. The standard DØ simulation chain was used that includes the PYTHIA generator [6] interfaced with the EVTGEN decay package [7] followed by full GEANT [8] modeling of the detector response and the same event reconstruction as used for data.

For the Monte Carlo simulated signal samples used throughout the analysis, the Isgur-Wise semileptonic decay model [9] for B_c^\pm was used. A separate sample generated with a phase space decay model was generated for systematic study purposes. The mass of the B_c^\pm meson was set to 6.30 GeV [11] and its $c\tau$ set to 0.014 cm. Another viable decay of the B_c^\pm is $B_c \rightarrow \psi(2S)\mu + X$ where $\psi(2S) \rightarrow J/\psi X$. The representative decay $\psi(2S) \rightarrow J/\psi\pi^+\pi^-$ is used in the generation of the sample. See Section VI where this process is discussed in more detail.

To model one of the backgrounds, a large sample of QCD inclusive Monte Carlo was generated, only requiring a generator-level $J/\psi \rightarrow \mu^+\mu^-$ decay with kinematic cuts on the two muons coming from the J/ψ parent: $p_T(\mu) > 2.0$ GeV and $|\eta(\mu)| < 2.5$. It was important that this sample be generated including gluon splitting $g \rightarrow b\bar{b}$ so that the b and \bar{b} are not necessarily approximately back to back as is the case in a strictly $b\bar{b}$ Monte Carlo. The process $g \rightarrow b\bar{b}$ where the J/ψ arises from the decay of a b hadron and the muon from the other b hadron in the event results in the J/ψ and muon at small angles from each other.

It is a known effect that the PYTHIA MC generation of b production does not model the true $p_T(b)$ distribution well when compared to data. In addition, the MC samples were not passed through a trigger simulation of the various muon triggers. To address this issue, an iterative weighting process is applied with weighting functions found from a detailed study of the kinematic properties of reconstructed J/ψ mesons from B hadrons in the data compared with those in observed in the MC [10].

V. EVENT SELECTION

Out of the single muon sample described earlier, a subsample of events each containing at least one J/ψ candidate is formed. To reconstruct $J/\psi \rightarrow \mu^+\mu^-$ candidates, events are selected with at least two muons of opposite charge reconstructed in the tracker and the muon system. The track of each muon candidate must either match hits in the muon system and have $p_T > 1.0$ GeV, or have calorimeter energies consistent with a minimum-ionizing particle along the direction of hits extrapolated from the tracking layers and have $p_T > 1.5$ GeV. For at least one of the muons, hits are required in all three layers of the muon detector, and each must have at least two hits in the CFT. The muon momenta are adjusted according to a mass-constrained fit to the known J/ψ mass [14].

Whenever a J/ψ has been found, an additional track that can be associated with the J/ψ vertex is sought, which will be referred to as the third track. The following are the selections applied that result in a J/ψ + track candidate: each muon from the J/ψ must have a least one hit in the SMT while the third track must have at least two to ensure tracks forming the vertex to have well-measured impact parameters, particularly for the third track; χ^2 of the three tracks with respect to pointing back to the correct primary vertex must be less than 49 (corresponding to 7σ , i.e., loose enough so as not to cause decay length biases); $p_T(\text{third track}) > 3$ GeV; $p(\text{third track}) > 4$ GeV; $p_T(J/\psi + \text{track}) > 5$ GeV; $\chi_{\text{vertex}}^2(J/\psi + \text{track}) < 16$ (corresponding to 4σ and a good-quality vertex); angle between the J/ψ and third track < 1 rad; and $\cos\theta < 0.99$ between any two muons, to remove problems with more than one central track being associated with a muon segment

If more than one J/ψ + track candidate is present in an event, the candidate with the lowest χ^2 of the J/ψ + track vertex is selected. Figure 1(a) shows the $\mu^+\mu^-$ invariant mass in the J/ψ + track sample, and Fig. 1(b) shows the same for the final $J/\psi + \mu$ sample, and the subsequent signal mass window region, $2.90 < M(\mu^+\mu^-) < 3.26$ GeV, is illustrated.

The final $J/\psi + \mu$ sample has three additional requirements, i.e., it is a subset of the J/ψ + track sample described above. The third track identified as a muon, will from this point be defined as the “third muon”, i.e., μ_3 . This muon must have the highest quality: have hits in all three layers of the muon detector, and have timing signals in the muon scintillator detectors within 10 ns of the beam crossing to reduce contamination from cosmic rays.

VI. CONTRIBUTIONS TO THE $J/\psi + \mu$ SAMPLE, MASS TEMPLATES

Due to the undetectable neutrino, reconstruction of an exclusive decay resulting in an invariant mass peak at the mass of the B_c^\pm is not possible; however, the invariant mass of the $J/\psi + \mu$, i.e., the trimuon invariant mass, can still be used to characterize and separate each of the components.

Each of the components described below contributes to the $J/\psi + \mu$ candidate sample. The mass templates that arise from these components will then be used in a simultaneous fit to the tri-muon invariant mass and lifetime distributions where they help constrain the normalization of each component. The modeling of the lifetime distributions will be discussed in Section IX.

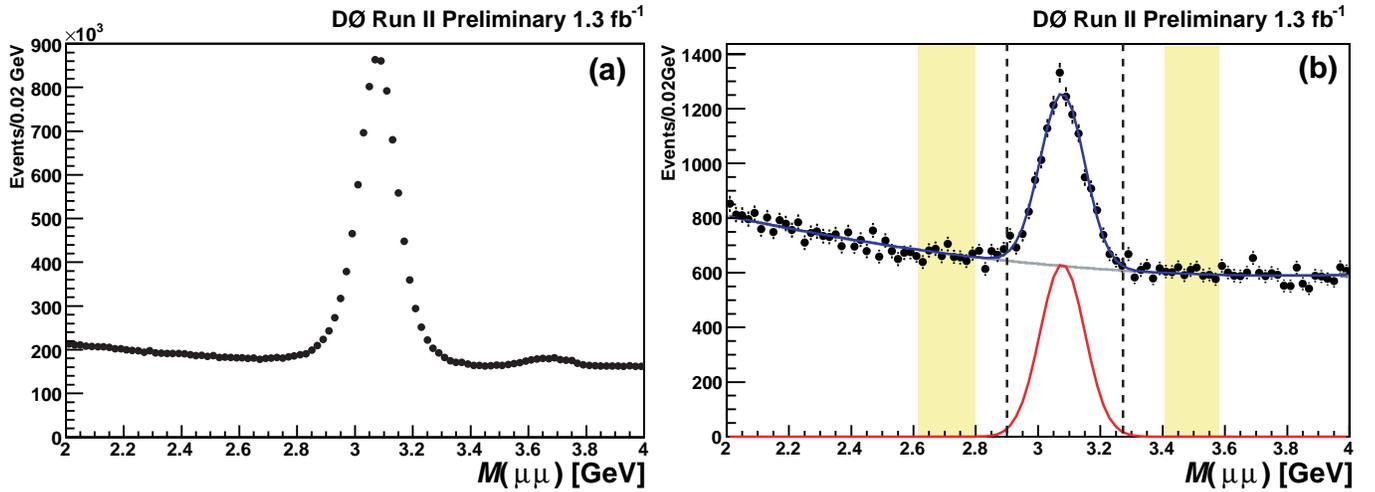


FIG. 1: (a) Invariant mass distribution $M(\mu^+\mu^-)$ in the J/ψ +track sample, and (b) in the $J/\psi + \mu$ sample showing a fit to the J/ψ mass peak as well as the signal mass window (dashed lines) and shaded sideband mass regions.

A. B_c^\pm Signal

The mass template for the B_c^\pm signal is shown in Fig. 2 as determined from the B_c^\pm signal Monte Carlo described in Section IV. The input mass is known to better than 0.1% [11] and this uncertainty is insignificant compared to the mass smearing of the tri-muon invariant mass due to the missing neutrino. Another signal decay channel is $B_c \rightarrow \psi(2S)\mu\nu$ where $\psi(2S) \rightarrow J/\psi\pi^+\pi^-$, (and the same general conclusions hold for $\psi(2S) \rightarrow J/\psi$ + neutrals) and some of the events in the $J/\psi + \mu$ sample could be arising from this feed-down channel. Theoretical estimates predict the $B_c \rightarrow J/\psi\mu + X$ branching fraction to be approximately 5 to 100 times larger than that of $B_c \rightarrow \psi(2S)\mu + X$ [1, 12]. To estimate the fraction of events due to this feed-down component, the efficiency of the selection for the two signal components was found to be $\epsilon(B_c \rightarrow J/\psi X) = 0.0443 \pm 0.0015$ (stat) and $\epsilon(B_c \rightarrow \psi(2S)X) = 0.0352 \pm 0.0017$ (stat) using the signal MC samples. The ratio of these efficiencies is 0.79 ± 0.04 (stat). Since the worst case scenario is that the $J/\psi\mu$ decay channel is only 5 times as likely as the feed-down channel, the feed-down channel can comprise a fraction up to $(0.79 \pm 0.04) \cdot 0.17 = 0.13 \pm 0.01$ of the signal. For the central value the fraction of this feed-down channel is taken to be one-half of this value, i.e., 6.5%, and it is later varied widely from 0% to 13% in the estimate of the systematic uncertainty due to this additional signal channel. The $B_c \rightarrow \psi(2S)\mu\nu$ MC is used to determine the shape of the $M(J/\psi\mu)$ distribution also shown in Fig. 2. This distribution is shifted down in mass as expected due to the pions not reconstructed in the decay $\psi(2S) \rightarrow J/\psi\pi^+\pi^-$. The $\pi^+\pi^-$ were not explicitly reconstructed due to reduced efficiency, the uncertainty on this additional reconstruction efficiency factor, and that the current treatment of this channel does not result one of the larger systematic uncertainties.

B. Real J/ψ & Fake μ

One of the backgrounds in the sample is a real J/ψ associated with a fake muon. To model this component, the invariant mass of the vertex of the J/ψ and associated track in the $J/\psi + \text{track}$ data sample described earlier is used. Given the robust DØ muon detector system, the fake muon rate is small but not zero, and primarily due to decays in flight of $\pi^\pm \rightarrow \mu^\pm\nu$ and $K^\pm \rightarrow \mu^\pm\nu$. To find the fraction of events contributing to this component, the $B^+ \rightarrow J/\psi K^+$ decay is used. The K^+ meson will decay in flight to a muon and neutrino hence enter the $J/\psi + \mu$ final sample. A fit was made to the B^+ mass peak in both the $J/\psi + \mu$ sample and the $J/\psi + \text{track}$ sample and the ratio of the number of B^+ events in the $J/\psi + \mu$ sample to that found in the $J/\psi + \text{track}$ sample is taken as the fraction of events that are due to a real J/ψ but a fake μ . Contributions due to B^+ or $B_c^+ \rightarrow J/\psi\pi^+$ were estimated to be negligible. The mass distribution of this component is shown in Fig. 3(a); a peak due to $B^\pm \rightarrow J/\psi K^\pm$ can also clearly be seen in this distribution.

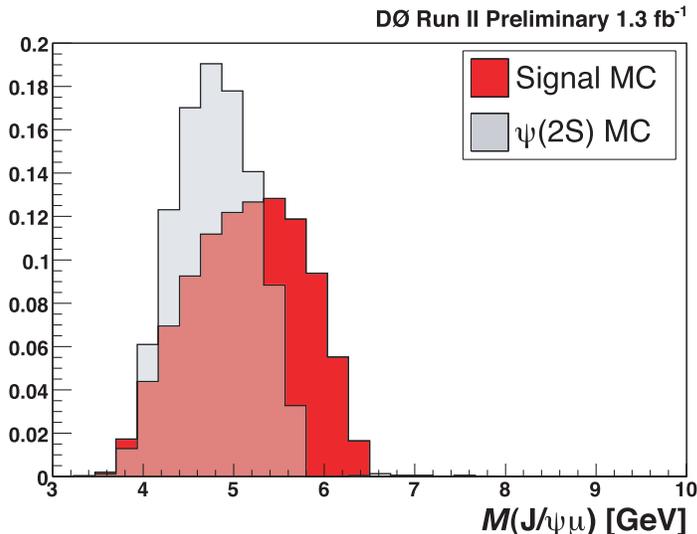


FIG. 2: Distribution of $M(J/\psi\mu)$ in the $B_c \rightarrow J/\psi\mu\nu$ and $B_c \rightarrow \psi(2S)\mu\nu$ signal Monte Carlo samples.

C. Fake J/ψ & Real μ

Another component within the $J/\psi + \mu$ sample are fake J/ψ mesons combined with real muons. Events containing an identified J/ψ candidate within the prescribed $M(\mu^+\mu^-)$ mass range but that are actually due to combinatorial background are covered by this component. A normalized mass template used to describe this component is formed from events that come from the J/ψ mass sidebands. Fitting to the J/ψ mass before all selections are applied, the sideband regions were defined to be 3σ on either side of the J/ψ peak, i.e., events within $2.62 < M(J/\psi\mu) < 2.80$ GeV or $3.40 < M(J/\psi\mu) < 3.58$ GeV. The signal region is defined to be $2.90 < M(\mu^+\mu^-) < 3.26$ GeV. As shown in Fig. 1(b), the ratio of events found by integrating the background function over the J/ψ signal mass region to the same integration of the signal plus background function, 0.667 ± 0.004 , is then taken as the fraction of number of candidates that comprises this background.

D. Real J/ψ & Real μ

A real physics background that arises is where both a real J/ψ and a real μ are produced, but neither comes from a B_c^\pm decay and they are used to incorrectly form a vertex. This component is dominated by $b\bar{b}$ backgrounds, where one b hadron decays to $J/\psi + X$ and the other decays semileptonically to a muon (or via a cascade decay $b \rightarrow c \rightarrow \mu$). The requirement that the J/ψ and μ_3 be close in angle increases the accepted fraction of $b\bar{b}$ production via gluon splitting. To model this background, the J/ψ QCD Monte Carlo is used. A requirement is placed that the parent of the J/ψ does not arise from prompt a B_c^\pm meson, B^\pm , or $c\bar{c}$ (the latter two are estimated using the data as separate components described below). The resulting distribution used is shown in Fig. 3(b).

E. B^+

The decay $B^+ \rightarrow J/\psi K^+$ followed by the decay in flight of the K to a muon results in a mass peak right in the middle of the signal mass region, so it was important to correctly and carefully model this component of the sample. A fit was made to the mass of the B^+ in the $J/\psi + \mu$ data sample. This fitted distribution, as shown in Fig. 4, was then used as a mass template for the B^+ component. Determining this mass distribution from the data itself removes any uncertainty in the modeling of the width of this mass distribution.

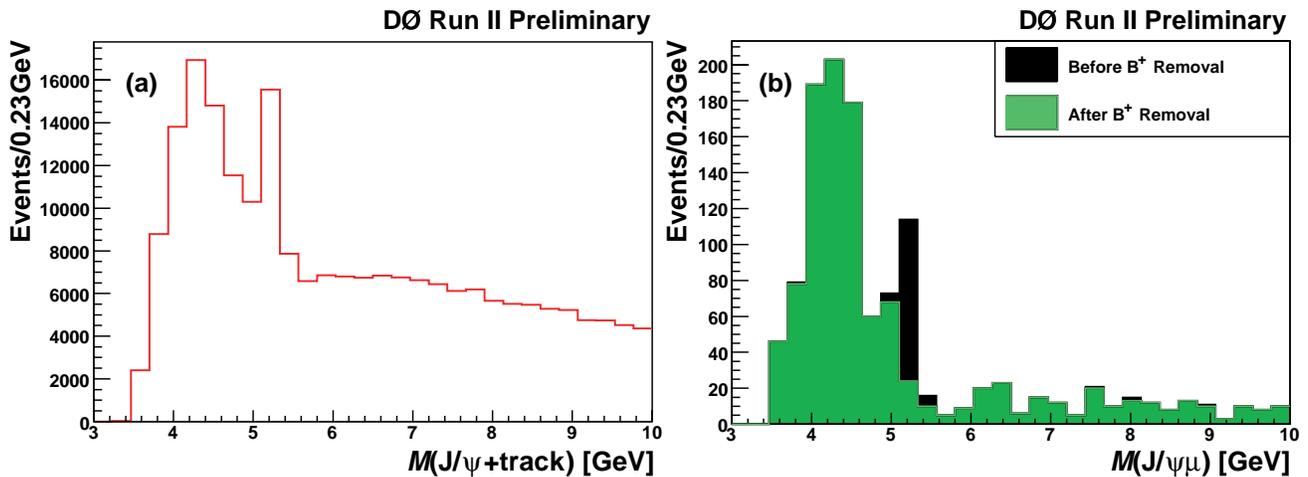


FIG. 3: (a) Distribution of $M(J/\psi\mu)$ within the $J/\psi + \text{track}$ sample; (b) and in the J/ψ QCD Monte Carlo before and after removing $B^+ \rightarrow J/\psi + K^+$ events. The filled green distribution is the one used as the mass template for this component throughout the analysis.

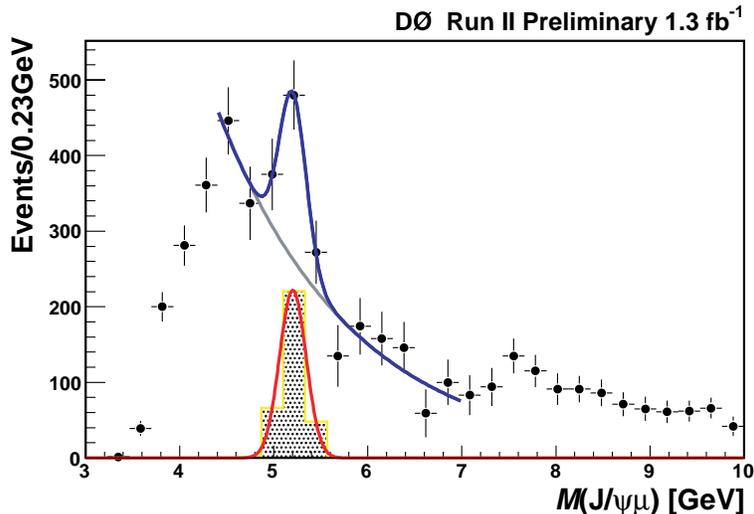


FIG. 4: Fit of the B^+ peak in the $J/\psi + \mu$ mass distribution. The yellow histogram is the mass template used in the full fit.

F. Prompt $J/\psi + \mu$

One also has to take into account the $c\bar{c}$ contribution to the signal where a prompt J/ψ is vertexed with a muon. Using the $J/\psi + \mu$ data sample, those events which have a negative decay length on the J/ψ vertex are used to estimate the mass template of the prompt background.

VII. PSEUDO-PROPER DECAY LENGTH AND K -FACTOR DISTRIBUTIONS

Models are now found for the lifetime distribution for each of the data components in order to quantify the lifetime in a measurement. The lifetime of the B_c^\pm , τ , is related to the transverse decay length by: L_{xy} , by $L_{xy} = c\tau p_T/m$, where p_T and m are the transverse momentum and rest mass of the B_c , respectively. L_{xy} is defined as the displacement of the B_c^\pm vertex from the primary vertex projected onto the direction of the transverse momentum vector of the $J/\psi \mu$

system. The primary vertex is determined using information from both the average x - y position of the beamspot and the other tracks in the event as described in Ref. [13]. When the B_c^\pm meson decays semileptonically, it cannot be fully reconstructed due to the escaping neutrino, and thus $p_T(B_c)$ is not determined. The p_T of the $J/\psi\mu$ system is used instead as the best approximation. A correction factor distribution, $K = p_T(J/\psi\mu)/p_T(B_c)$ is introduced to estimate the $p_T(B_c)$. To obtain the B_c^\pm lifetime, the pseudo-proper decay length (PPDL) is measured, represented by λ and defined as $\lambda = L_{xy}m(B_c)/p_T(J/\psi\mu) = c\tau/K$. The K -factor distribution, as shown in Fig. 5, is determined using signal Monte Carlo samples and is applied statistically by smearing the exponential decay distribution when extracting $c\tau(B_c)$ from the PPDL distribution in the lifetime fit. The mass of the B_c is taken from the CDF result $M(B_c) = 6274.1 \pm 3.2 \pm 2.6$ MeV [11]. Since part of the signal component contains the $\psi(2S)$ feed-down component, a separate K -factor distribution is needed for this component. As $M(J/\psi\mu)$ approaches the B_c mass, less energy and momentum is being carried off by the neutrino and the K -factor distribution is narrower and peaked more towards 1, i.e., provides better resolution on estimating the boost factor. To take advantage of these events with better resolution, the K -factor is applied in the analysis in six bins of $M(J/\psi\mu)$.

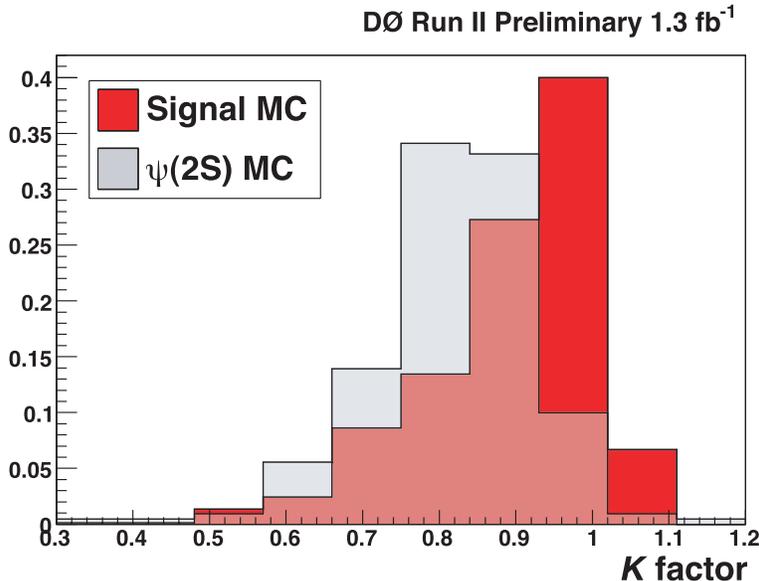


FIG. 5: K -factor distributions in the $B_c \rightarrow J/\psi\mu\nu$ and the $B_c \rightarrow \psi(2S)\mu\nu$ signal MC samples.

VIII. DEMONSTRATION OF B_c^\pm SIGNAL

To check the validity of the modeling of the $M(J/\psi\mu)$ mass distribution, a mass-only fit is first performed to check for both an adequate description of the data and for the presence of B_c signal. Taking the mass distributions of the six contributions described in the previous section, a fit is made to the mass distribution in the data sample. Since the sample without additional requirements is overwhelmingly background, additional cuts are placed in an effort to further suppress background and check for the presence of the signal. A requirement is placed on the transverse decay length significance: $L_{xy}/\sigma(L_{xy}) > 4$, where $\sigma(L_{xy})$ is the uncertainty on L_{xy} due to propagation of track parameter errors to the vertices. After subtracting the J/ψ sideband component and the B^+ components, Fig. 6 shows the fit to the mass distribution. At this point, the fitted number of the events due to the signal component is 242 ± 38 . The probability for the signal to fluctuate down to the background is equivalent to 6.4σ , and the probability for the background to fluctuate up to the total number of events or more is greater than 5σ . Such lifetime-biasing cuts will not be applied in the full simultaneous fit, and the signal significance will be greater.

To qualitatively demonstrate the relatively short lifetime of the signal, a test is made cutting progressively harder on the pseudo-proper decay length (PPDL) of the $J/\psi + \mu$ vertex. After J/ψ mass sideband subtraction, as shown in Fig. 7, when a cut of $\text{PPDL} > 0$ is applied, the prompt component is decreased by a factor of approximately two compared to no PPDL cut, as expected. The B_c meson is expected to have a shorter lifetime than the other b hadrons. As the cut value of PPDL is further increased, the relative fraction of the B_c signal increases. However, as

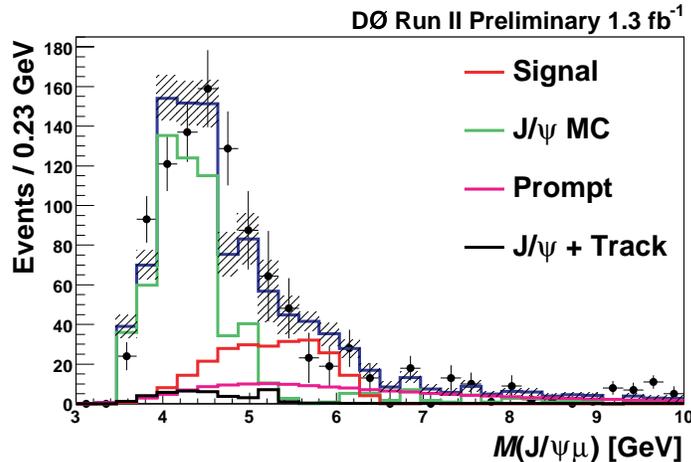


FIG. 6: Fit to the mass of the $J/\psi + \mu$ vertex with J/ψ mass sideband and B^+ component subtracted and decay length significance $L_{xy}/\sigma(L_{xy}) > 4$ required. Shading of the fit line indicates the estimated total systematic uncertainty (described later) on the shape of the mass templates (described later).

the cut value is increased to even larger values, the fraction of signal component drops and for large PDDL values, the only significant components are those due to the long-lived $b\bar{b}$ estimated from the J/ψ QCD MC and that due to the B^+ meson. This test demonstrates the validity of the modeling of the $M(J/\psi\mu)$ distributions, particularly in the important positive PDDL region, both at small and large values, and also provides qualitative evidence that the B_c meson has a significantly shorter lifetime than the other b hadrons.

IX. LIFETIME ANALYSIS

For the lifetime analysis, each component \mathcal{F}_j consists of a combination of a mass shape template and a lifetime functional model, described in the subsections below, to allow a simultaneous fit. The lifetime is extracted, and the fit to the tri-muon invariant mass distribution helps to constrain the normalization of each component. For the fit, the mass of the $J/\psi + \mu$ vertex is required to be in the range $3.0 < M(J/\psi\mu) < 10.0$ GeV, resulting in a sample containing 14753 events. An unbinned log likelihood fit is made minimizing the log likelihood:

$$\mathcal{L} = \prod_i (f_{jtrk} \mathcal{F}_{jtrk}^i + (1 - f_{jtrk}) \mathcal{F}_{j\mu}^i), \quad (1)$$

where f_{jtrk} is the fraction of the $J/\psi + \text{fake } \mu$ component and \mathcal{F}_{jtrk} is the PDF of the lifetime distribution from the $J/\psi + \text{track}$ sample, described later. The product is over all the events in the data signal sample. The term $\mathcal{F}_{j\mu}^i$ is defined as:

$$\mathcal{F}_{j\mu}^i = f_{sb} \mathcal{F}_{sb}^i + (1 - f_{sb}) (f_{sig} \mathcal{F}_{sig}^i + f_{jmc} \mathcal{F}_{jmc}^i + f_{bp} \mathcal{F}_{bp}^i + (1 - f_{sig} - f_{jmc} - f_{bp}) \mathcal{F}_{pr}^i), \quad (2)$$

where each term is defined below. The fraction $f_{jtrk} = 0.034 \pm 0.002$ is from fits to the B^+ peak. The fraction of fake J/ψ events, $f_{sb} = 0.667 \pm 0.004$, is found from J/ψ mass sideband fits. In the lifetime fit, these fractions are allowed to float within a Gaussian penalty function, where the width of the Gaussian function is the indicated error on each value.

A. Signal: \mathcal{F}_{sig}

The signal PDF lifetime function is comprised of an exponential function convoluted with a Gaussian resolution function \mathcal{R} and smeared with a normalized K -factor distribution $\mathcal{H}(K)$ (binned in $M(J/\psi\mu)$), defined as:

$$\mathcal{F}_{sig}^i(\lambda_j, \sigma(\lambda_j), s) = \int dK \mathcal{H}(K) \left[\frac{K}{c\tau(B_c)} e^{-K\lambda_j/c\tau(B_c)} \otimes \mathcal{R}(\lambda_j, \sigma(\lambda_j), s) \right]. \quad (3)$$

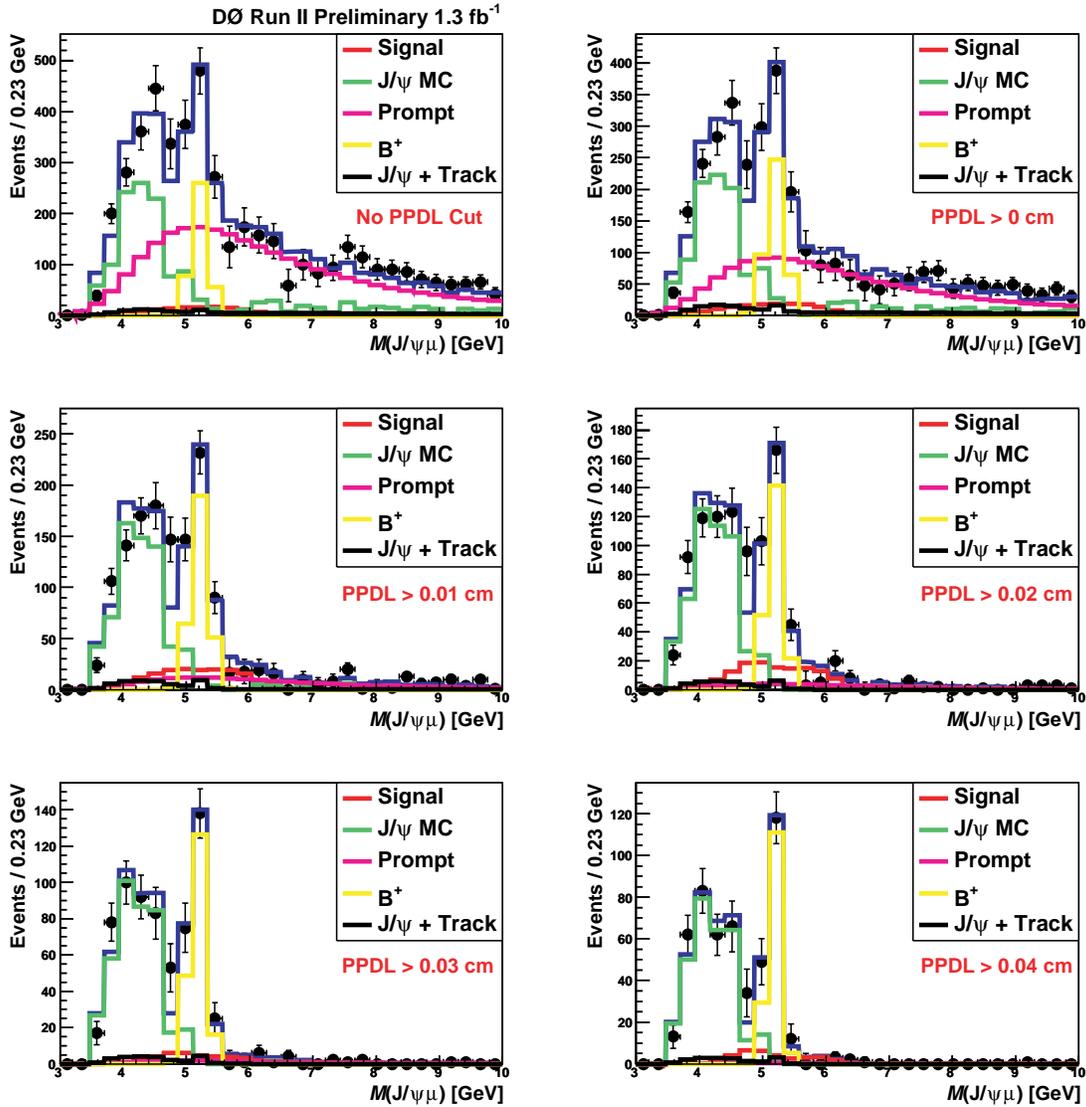


FIG. 7: Mass fits, after side-band subtraction, cutting progressively harder on the pseudo-proper decay length (PPDL) of the vertex. Note that there is still signal apparent at the lower PPDL cuts, but for very large values, the fit indicates the the components are dominated by the long-lived J/ψ QCD MC and the B^+ components. The prompt component has almost completely disappeared as has the signal.

The width of the Gaussian resolution function \mathcal{R} uses the event-by-event uncertainty $\sigma(\lambda_i)$ on the PPDL, multiplied by a floating scale factor s to take into account a systematic underestimate of this error due to tracking systematic uncertainties not being included in the errors on the track parameters. 6.5% of the events are randomly chosen to have come from the feed-down component as described previously, with appropriate mass template and K -factor distributions.

B. Prompt J/ψ ($c\bar{c}$): \mathcal{F}_{pr}

To validate the functional form of the lifetime PDF for the prompt J/ψ ($c\bar{c}$) \mathcal{F}_{pr} component, candidates with negative decay length were examined. From this and verifying with MC samples, the prompt lifetime distribution is expected to be symmetric around a PPDL of zero and could be modeled with a double (same mean) Gaussian function. The same Gaussian resolution functional form and scale factor s as for the signal was used, but allowing

for a wider second Gaussian with floating multiplicative width factor k and fraction $(1 - f_{g1})$:

$$\mathcal{F}_{pr}^i = f_{g1}\mathcal{R}(\lambda_j, \sigma(\lambda_j), s) + (1 - f_{g1})\mathcal{R}(\lambda_j, \sigma(\lambda_j) \cdot k, s). \quad (4)$$

This functional form was varied as systematic uncertainty.

C. Real J/ψ + fake μ : \mathcal{F}_{jtrk}

A fit was made to the PDDL distribution in the J/ψ + track sample to obtain the lifetime PDF for \mathcal{F}_{jtrk} . The empirical functional form for the lifetime PDF contains two negative-going exponentials, a central gaussian, and three positive-going exponentials to describe the fixed shape, and only the normalization, via the fraction f_{jtrk} , was allowed to float in the fit.

D. Fake J/ψ + Real μ : \mathcal{F}_{jsb}

The lifetime PDF in \mathcal{F}_{jsb} is obtained by fits to the PDDL J/ψ mass sideband sample. An empirical functional form is used of a double central gaussian, two negative-going exponentials and one positive-going exponential. The shape was kept fixed in the fit, and only its normalization was allowed to vary via f_{sb} . The shape was later varied within uncertainties as described in Section XI.

E. Real J/ψ + real μ : \mathcal{F}_{jmc}

The PDF that was used to model the lifetime distribution of this component is given by:

$$\mathcal{F}_{jmc}^i = (1 - f_L) \left(f_{R1} \frac{e^{\lambda/\lambda^{R1}}}{\lambda^{R1}} + (1 - f_{R1}) \frac{e^{\lambda/\lambda^{R2}}}{\lambda^{R2}} \right) + f_L \frac{e^{-\lambda/\lambda^{L1}}}{\lambda^{L1}}. \quad (5)$$

First a fit was made on the J/ψ QCD Monte Carlo sample to obtain the values that will be used as starting values in the final fit. The parameter f_L was kept fixed in the final fit, the parameters f_{R1} and λ^{R1} were allowed to vary within a Gaussian penalty function with a width of the error on the parameter, and λ^{R2} and λ^{L1} were allowed to float freely in the final fit. Further variations of these parameters were studied as a source of systematic uncertainty.

F. B^+ : \mathcal{F}_{bp}

The lifetime PDF for the B^+ component \mathcal{F}_{bp} is a single exponential function with slope taken from as the world average value [14], i.e., $\tau(B^+) = 1.638 \pm 0.011$ ps. This value was allowed to float but constrained within a Gaussian penalty function, the width of which was the indicated uncertainty. This lifetime was varied later and also allowed to float freely to assess systematic uncertainty. The PDDL values for this component were scaled to take into account the mass difference between the B^+ and the B_c mesons.

G. Check for Lifetime Bias

Before examining the fit to the data, checks were made for possible lifetime biases. Three signal Monte Carlo samples were generated with different lifetimes (default lifetime, approximately 50% shorter and 50% longer). Fits were performed to the true decay lengths of the sample and to the PDDL distributions and compared. A linear fit to these values indicates a slope consistent with 1.0, i.e., no evidence of bias. Ensemble tests indicate the validity of the extracted statistical uncertainty and also show no evidence of a lifetime bias. Finally efficiency of the selection criteria were checked to be have no significant variation with decay length.

X. FIT RESULTS

A simultaneous fit to the invariant mass and PPDL distributions is performed using all the components described in previous sections. The fitted lifetime of the B_c meson is found to be:

$$\tau(B_c^\pm) = 0.444_{-0.036}^{+0.039} \text{ (stat)},$$

with an estimated signal sample of 856 ± 80 (stat) candidates. When the fit is repeated removing the signal mass and lifetime model, the resulting observed change in likelihood value is equivalent to a signal significance of 11.4σ . The fitted value of the scale factor is $s = 1.35 \pm 0.03$. Figures 8 and 9 show the PPDL and $M(J/\psi\mu)$ distributions, respectively, of the $J/\psi + \mu$ sample with projections of the fit result overlaid. Figure 9 also displays the observed variation of bin contents over the systematic uncertainty sources studied (discussed below, and including the statistical error on the large sideband component).

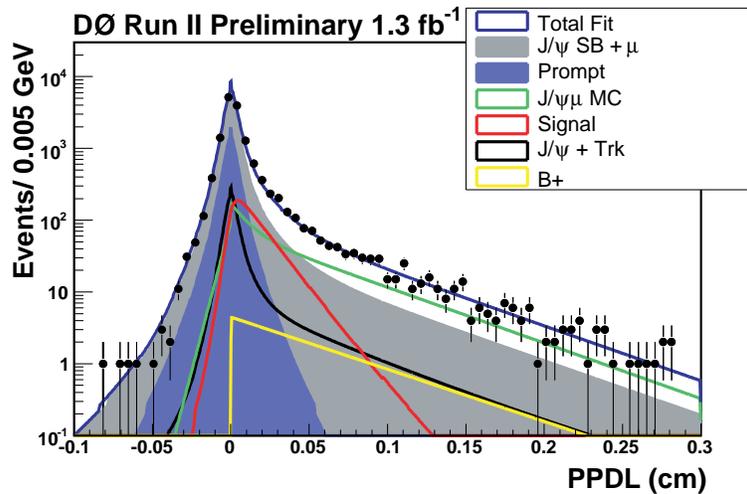


FIG. 8: PPDL distribution of the $J/\psi + \mu$ sample with the projected components of the fit overlaid.

XI. SYSTEMATIC UNCERTAINTIES

To check the stability of the measurement, values of important variables were chosen so as to split the data sample roughly in half in each case, i.e., positive and negative $\eta(B_c)$ and $\eta(\mu_3)$, forward and central η of μ_3 , high and low $p_T(B_c)$ and $p_T(\mu_3)$, top and bottom ϕ of μ_3 , and early and late halves of the data-taking run. The lifetime was then found separately for each split sample and the difference in number of standard deviations calculated. Since none of these split samples tests resulted in differences larger than 2σ , i.e., all variations were consistent within statistical uncertainty, no systematic uncertainties were assigned due to these checks.

Systematic uncertainties considered are discussed in detail below. Table I collates the resulting assigned systematic uncertainties.

Another sample of B_c signal Monte Carlo was generated, but with a phase space decay model rather than the ISGW2 decay model used for the default analysis. The lifetime fit was then rerun with a distribution for the mass template and K -factor distributions determined from this new MC sample, and the difference observed assigned as a symmetric systematic uncertainty due to the signal decay model. Variations of the B_c mass within its measurement uncertainties [11] made negligible difference on the lifetime.

The fraction of the feed-down $B_c \rightarrow \psi(2S)X$ signal component was varied from its default value of 6.5% down to 0% and then doubling to 13%. The differences in lifetime observed were assigned as systematic uncertainties due to uncertainty on this feed-down fraction.

There is an uncertainty on the MC simulation of $p_T(B_c)$. Weightings of this p_T distribution were determined to vary it between the distributions predicted by Ref. [15] when the factorization scale μ was varied between half and twice its default value. The observed variation in lifetime was assigned as the systematic uncertainty due to uncertainty

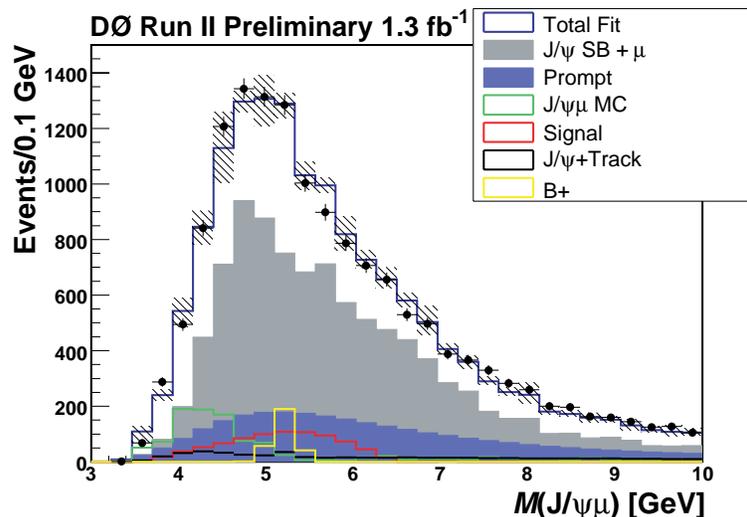


FIG. 9: The mass distribution of the $J/\psi + \mu$ sample with the projected components of the fit overlaid. Shading of the fit line indicates the variation in bin contents across the described checks for systematic uncertainties (including statistical uncertainty of the sideband component).

on $p_T(B_c)$. Other sources of uncertainty on $p_T(B_c)$ could arise from uncertainty on the initial parton distributions; however, variations in overall $p_T(b)$ described below are estimated to cover this source.

There is an uncertainty on the overall $p_T(b)$ distributions predicted by MC, including the background components. The weighting factor described in Section IV to improve the simulation and to include the effects of the triggers was removed and the lifetime fit repeated with the new mass templates and K -factor distributions determined from MC samples. The resulting change in lifetime was assigned as a symmetric systematic uncertainty due to modelling of the $p_T(b)$ distribution.

To assess the systematic uncertainty due to the uncertainty on the J/ψ QCD MC mass distribution, instead of using all events from the J/ψ QCD MC sample, only those events where the parent of the J/ψ is either a B^+ or a B^0 are taken. This drastic measure of removing all B_s^0 mesons and b baryons should be roughly equivalent to conservatively large variations of decay branching ratios. There are possible uncertainties in the modeling of and the fraction of gluon splitting in the J/ψ QCD MC sample. However, Figs. 6 and 7 show good modeling of the data in regions with little signal. Previous measurements [16] also indicate that data is consistent with PYTHIA for b hadrons with small angular separations typical of gluon splitting.

The shape of the mass template for the prompt component was varied within statistical errors of the fit used to fix the shape, and the observed variation in lifetime assigned as a systematic error due to this source.

It is assumed that the modeling of the J/ψ combinatoric background can be approximated by taking the average of an upper and lower mass sideband. To test this assumption, the fit is performed using only the lower mass sideband, and then only the higher mass sideband, and a systematic uncertainty of one-half the resultant shifts in lifetime is assigned.

The B^+ mass template was re-determined using a fit to the background over a larger range in mass. The resulting variation in lifetime was taken as a symmetric systematic uncertainty.

The s scale factor was fixed to values of 1.2 and 1.4 as observed as typical fit values in other lifetime analyses [17], and the largest change in lifetime assigned as a symmetric systematic uncertainty due to this source.

In the modeling of the prompt lifetime PDF, a single Gaussian function rather than a double Gaussian was used to describe the zero lifetime events. Since all the parameters defining the empirical functional form for the sideband lifetime model are fixed, the shape was changed by varying the fit parameters within their uncertainties. For the parameters defining the J/ψ QCD MC lifetime model that are constrained by Gaussian penalty functions, their central values are changed by $\pm 1\sigma$. In all these cases, the observed variations in lifetime were assigned as systematic uncertainties due to uncertainties of these lifetime models.

For the B^+ lifetime model, since the lifetime is constrained within a Gaussian penalty function, the central value was changed by $\pm 1\sigma$ keeping the width the same. As an additional check, the B^+ lifetime was allowed to float, finding a value of 1.877 ± 0.19 ps, consistent with the world average value of 1.638 ± 0.011 ps [14]. In both cases, the change

in lifetime was assigned as the systematic uncertainty due to uncertainty in the B^+ lifetime model.

To estimate the systematic uncertainty due to alignment uncertainties, the signal MC was re-reconstructed using a SMT geometry file where the silicon sensors are physically moved from their nominal positions within the current alignment precision. The lifetime is measured in the original sample, and then again in the same sample using the different SMT geometry file, and the observed difference assigned as a symmetric systematic uncertainty.

TABLE I: Summary of estimated systematic uncertainties.

Systematic Source	$-\Delta\tau$ (ps)	$+\Delta\tau$ (ps)
Signal Decay Model	0.0104	0.0104
Signal Feed-Down Fraction	0.0032	0.0037
$p_T(B_c)$ Distribution	0.0025	0.0219
$p_T(b)$ Distribution	0.0087	0.0087
J/ψ MC Mass Distribution	0.0197	0.0197
J/ψ Sideband Mass Distribution	0.0144	0.0130
Prompt Mass Distribution	0.0048	0.0050
B^+ Mass Distribution	0.0060	0.0060
Scale Factor s	0.0040	0.0040
Prompt Lifetime Model	0.0069	0.0069
J/ψ SB Lifetime Model	0.0114	0.0096
J/ψ MC Lifetime Model	0.0042	0.0036
B^+ Lifetime Model	0.0002	0.0002
B^+ Float Lifetime	0.0067	0.0067
Alignment	0.0059	0.0059
Total	0.0338	0.0393

XII. CONCLUSIONS

Using approximately 1.35 fb^{-1} of data collected by the DØ detector between 2002 and 2006, the lifetime of the B_c^\pm meson is studied in the $B_c^\pm \rightarrow J/\psi\mu^\pm + X$ final state. Using an unbinned likelihood simultaneous fit to the $J/\psi + \mu$ invariant mass and lifetime, a signal of 856 ± 80 (stat.) candidates is estimated as well as making a lifetime measurement of:

$$\tau(B_c^\pm) = 0.444_{-0.036}^{+0.039} \text{ (stat)}_{-0.034}^{+0.039} \text{ (sys) ps.}$$

This result is consistent with and supercedes a previous preliminary DØ result of $\tau(B_c) = 0.448_{-0.095}^{+0.123} \pm 0.121$ ps [2]. It is also consistent with the most precise theoretical prediction of 0.48 ± 0.05 ps [1], as well as the latest CDF result of $\tau(B_c) = 0.463_{-0.065}^{+0.073} \pm 0.036$ ps [18], but with significantly better precision, making this DØ measurement currently the most precise in the world.

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- [1] V. Kiselev, *Decays of the B_c Meson*, hep-ph/0308214 (2003), and references therein.
- [2] DØ Note 4539-CONF, *Observation of the B_c Meson and a Study of its Properties in the $J/\psi\mu X$ Final State*, Aug. 2004; <http://www-d0.fnal.gov/Run2Physics/WWW/results/prelim/B/B12/>.
- [3] V.M. Abazov *et al.* [D0 Collaboration], *Nucl. Instr. and Meth. A* **565**, 463 (2006).
- [4] V.M. Abazov *et al.*, *Nucl. Instr. and Meth. A* **552**, 372 (2005).
- [5] T. Andeen *et al.*, *The D0 experiment's integrated luminosity for Tevatron Run IIa*, FERMILAB-TM-2365 (2007).
- [6] T. Sjöstrand *et al.*, *Comp. Phys. Commun.* **135**, 238 (2001).
- [7] D.J. Lange, *Nucl. Instrum. Methods* **462**, 152 (2001);
EVTGEN package home page <http://hep.ucsb.edu/people/lange/EvtGen/>.
- [8] R. Brun *et al.*, CERN Report No. DD/EE/84-1, 1984.
- [9] D. Scora and N. Isgur, *Phys. Rev. D* **52**, 2783 (1995).
- [10] V. M. Abazov *et al.* [D0 Collaboration], *Phys. Rev. Lett.* **98**, 121801 (2007) [arXiv:hep-ex/0701012].
- [11] A. Abulencia *et al.* [CDF Collaboration], *Phys. Rev. Lett.* **96**, 082002 (2006) [arXiv:hep-ex/0505076];
CDF Public Note 8004, $B_c \rightarrow J/\psi\pi$ with 2.2 fb^{-1} , July 22, 2007.

- [12] D. Ebert *et al.*, Phys. Rev. **D68**, 094020 (2003), and references therein.
- [13] J. Abdallah *et al.* [DELPHI Collaboration], Eur. Phys. J. **C32**, 185 (2004).
- [14] W.-M. Yao *et al.*, Journal of Physics G **33**, 1 (2006) and 2007 partial update for edition 2008.
- [15] K. M. Cheung and T. C. Yuan, Phys. Rev. D **53**, 3591 (1996) [arXiv:hep-ph/9510208].
- [16] D. Acosta *et al.* [CDF Collaboration], Phys. Rev. D **71**, 092001 (2005) [arXiv:hep-ex/0412006].
- [17] V. M. Abazov *et al.* [D0 Collaboration], Phys. Rev. Lett. **97**, 2418010 (2006) [arXiv:hep-ex/0604046];
V. M. Abazov *et al.* [D0 Collaboration], Phys. Rev. Lett. **94**, 102001 (2005) [arXiv:hep-ex/0410054].
- [18] A. Abulencia *et al.* [CDF Collaboration], Phys. Rev. Lett. **97**, 012002 (2006) [arXiv:hep-ex/0603027].