B_c^- at the Tevatron

W. Wester[a*]

[a]Fermi National Accelerator Laboratory,
P.O. Box 500, Batavia IL, U.S.A.

We report Tevatron results on the B_c^- meson in Run II. The B_c^- meson has been observed in semileptonic decays, $B_c^- \to J/\psi\ \ell^- \nu X$, by both the CDF and DØ collaborations at a significance greater than 5σ. For DØ, the candidate $B_c^- \to J/\psi\ \mu^- X$ events are used to extract measurements of the mass and lifetime of the B_c^- meson. For CDF, the $B_c^- \to J/\psi\ \ell^- \nu X$ observations have resulted in measurements of the relative production times branching ratio with respect to $B^- \to J/\psi\ K^-$ decays and a precise determination of the lifetime of the B_c^-: $c\tau(B_c^-) = 0.474\ ^{+0.073}_{-0.066}\ \pm\ 0.033$ ps. Also for CDF, an observation of $B_c^- \to J/\psi\ \pi^-$ decays at a significance exceeding 6σ results in a precise determination of the mass of the B_c^-: $\mathrm{M}(B_c^-) = 6275.2\ \pm\ 4.3\ \pm\ 2.3\ \mathrm{MeV}/c^2$.

1. INTRODUCTION

1.1. B Physics at Hadron Colliders

The study of the B_c^- meson [1] highlights the advantages of making B physics measurements at hadron colliders. There is a relatively large production cross section times integrated luminosity available for producing b-quarks, which are able to fragment into all species of B mesons including those not accessible at B-factories at the Υ(4S). While it is perceived that the hadron collider enviornment is "messy" with high backgrounds, there exist triggerable decay modes of B hadrons into "clean" final states with leptons or with a J/ψ. These samples typically have relatively small backgrounds that can be further reduced by the power of the multipurpose detectors that sit at the hadron collider interaction regions. The UA1 collaboration was able to measure the large b-quark cross section through semileptonic decays with a final state muon [2]. The CDF collaboration, even before being instrumented with a silicon vertex detector was able to indentify the fully reconstructed decay $B^- \to J/\psi\ K^-$ [3]. The study of the B_c^- meson relies on the large production cross section at hadron colliders, triggerable low background decay modes, and the powerful capabilities of the modern multipurpose collider detectors.

1.2. Tevatron in Run II

The Tevatron at Fermilab is currently operating the Run II physics program where protons and anti-protons collide at energy $\sqrt(s) =$ 1.96 TeV with over 1 fb^{-1} of integrated luminosity recorded. Two interaction regions are instrumented with the CDF [4] and DØ [5] detectors. For B physics, both CDF and DØ are instrumented with an inner silicon tracking system to provide high resolution hit positions close to the interaction point. This high resolution allows for the reconstruction of secondary vertices from B hadron decays at a small displacement $\mathcal{O}(50\mu\mathrm{m})$. In order to improve the impact parameter resolution even in the region where there is passive electronic material, the CDF detector consists of an inner layer of silicon detectors, Layer00 [6], that is mounted directly onto the beam pipe. In a future Run IIb upgrade, the DØ detector will similarly be instrumented with a silicon measurement layer attached to the beam pipe.

1.3. B_c^- properties

The B_c^- meson is a special B meson composed of two relatively heavy quarks with different flavors. The presence of both such quarks impacts the production, decay, and mass properties of the B_c^-. In terms of the production, theoretical work

*Presented on behalf of the CDF and DØ Collaborations with support from the U.S. Department of Energy.

using factorization with both the M_b and M_c mass scales and separating the contributions of color singlet and octet processes suggests the B_c^- meson will be produced with a softer P_T spectrum compared with the other B mesons [7]. With both the b and c quarks in the system, the B_c^- meson is expected to have decay properties [8] that include both a shorter c-like lifetime and a larger number of possible final states. Finally, the precision determination of the mass of the B_c^- meson is interesting for comparison with theoretical predictions that employ models for the potential [9] and that employ QCD calculations on the lattice [10]. All of these theoretical ideas require testing through experimental measurements.

1.4. B_c^- in Run I

The observation by CDF in Run I [11] of a significant number of semileptonic candidates was hailed as the discovery of the last meson. From the observation of 20.4 $^{+6.2}_{-5.5}$ signal events in both the e and μ semileptonic channels, CDF made crude determinations of the mass, $M(B_c^-) = 6.4 \pm 0.39 \pm 0.13$ GeV$/c^2$, and lifetime, $c\tau(B_c^-) = 0.46 ^{+0.18}_{-0.16} \pm 0.03$ ps. In addition, the production cross section times branching ratio for $B_c^- \to J/\psi\, \ell^- \nu X$ relative to $B^- \to J/\psi\, K^-$ decays was determined with some assumptions on the production P_T spectrum. These measurements suggested that the study of B_c^- decays would be a fruitful enterprise in Run II.

2. Semileptonic B_c^- Decays

$B_c^- \to J/\psi\, \ell^- \nu X$ decays with $\ell = e$ or μ are not fully reconstructed due to the missing neutrino and possible missing particles, X. However, a $B_c^- \to J/\psi\, \ell^- \nu X$ signal can be identified over background and measurements of some of the B_c^- properties can be made. Understanding the background is a key component of the $B_c^- \to J/\psi\, \ell^- \nu X$ analyses with expected background contributions arising from $b\bar{b}$ events where one of the B mesons decays into a J/ψ and the other anti-B meson decays semileptonically. Backgrounds also include electrons and muon candidates that are "fake" in the sense that the lepton candidate comes from a hadronic track that happens to pass the lepton selection criteria. Fortunately, the study of the backgrounds can be performed both with Monte Carlo simulation and with the data itself. In particular, the larger J/ψ + *track* sample and the reference $B^- \to J/\psi\, K^-$ decay sample provide a means to help determine residual background.

3. $B_c^- \to J/\psi\, \mu^- X$ in DØ

The DØ experiment has reported a study of semileptonic B_c^- decays in the inclusive $B_c^- \to J/\psi\, \mu^- X$ channel [12]. In 0.21 fb^{-1} of collected data, DØ finds 231 $B_c^- \to J/\psi\, \mu^- X$ candidates which includes both a B_c^- signal and residual background. In a larger J/ψ + *track* control sample, the fraction of prompt and non-prompt backgrounds is studied. Monte Carlo methods are used to perform a combined likelihood fit that either includes or excludes a B_c^- signal component. In the case where the B_c^- signal component is included, a mass and lifetime measurement are extracted.

Figure 1 shows the mass distribution of the $B_c^- \to J/\psi\, \mu^- X$ candidates with super-imposed fits that highlight the contributions of the prompt and non-prompt backgrounds. In the fit where a B_c^- signal is added, the best likelihood is obtained with the inclusion of $95 \pm 12 \pm 11$ B_c^- signal candidates. The mass and lifetime are also extracted from the fit and determined to be the following:

$M(B_c^-) = 5.95\ ^{+0.14}_{-0.13} \pm 0.34$ GeV$/c^2$

$c\tau(B_c^-) = 0.448\ ^{+0.123}_{-0.096} \pm 0.121$ ps

4. $B_c^- \to J/\psi\, \ell^- \nu X$ in CDF

The CDF experiment has results of semileptonic B_c^- decays in both the final state μ [13] and e [14] channels. In the $B_c^- \to J/\psi\, \mu^- X$ channel, CDF uses 0.36 fb^{-1} of integrated luminosity in which over 2.7 M J/ψ decays into dimuons are identified. Both the general J/ψ + *track* and $B^- \to J/\psi\, K^-$ samples are used to understand the sample composition. Fake muon backgrounds for B_c^- are estimated from the number of ex-

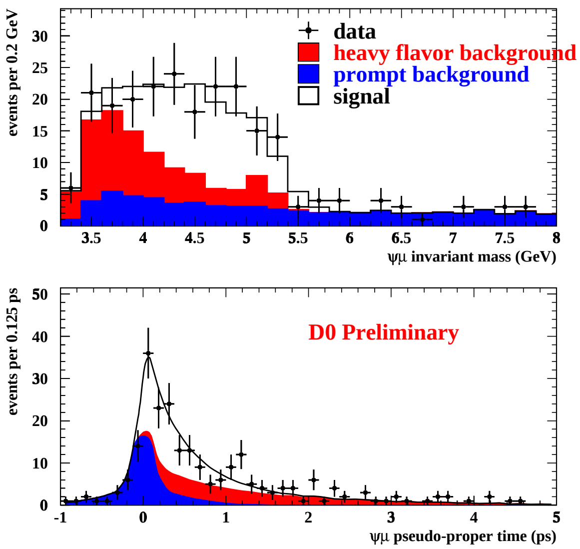

Figure 1. The mass (upper) and pseudo-proper time (lower) distributions of $B_c^- \rightarrow J/\psi\ \mu^- X$ candidates in the DØ Run II data for various backgrounds with and without and with a B_c^- signal contribution.

pected J/ψ + *track* combinations that have an invariant mass, M($J/\psi\mu$), in the 4-6 GeV/c^2 signal region where the track is mis-identified as a muon. The π, K, and p composition as a function P_T is studied using dE/dx and time-of-flight particle identification capabilities of CDF. The fake rate can then be extracted using large samples of fully reconstructed $K_s^0 \rightarrow \pi^+\ \pi^-$, $D^0 \rightarrow K^-\ \pi^+$ and $\Lambda^0 \rightarrow p\ \pi^-$ decays. The $b\bar{b}$ background studies use Monte Carlo simulation normalized to $B^- \rightarrow J/\psi\ K^-$ decays. Finally, the sidebands of the J/ψ are used to estimate the contribution arisings from fake-J/ψ events. Of the 106 events in the signal region, the three backgrounds are estimated to contribute approximately 16 (fake μ), 13 ($b\bar{b}$), and 19 (fake J/ψ) events resulting in a 5.3σ signal consisting of 60.0 ± 12.6 B_c^- candidates. A measurement is made of the $\mathcal{R}$, the production times branching ratio relative to $B^- \rightarrow J/\psi\ K^-$ decays with $P_T(B) > 4$ GeV/c and $|y| < 1$:
$\mathcal{R} = 0.249 \pm 0.045 \pm 0.069\ ^{+0.082}_{-0.033}$.

CDF has also studied semileptonic decays $B_c^- \rightarrow J/\psi\ e^- X$ where backgrounds are further complicated by the presence of conversion photons. The conversion background as a function of M($J/\psi e$) is estimated by studing a sample of conversion photons and understanding the efficiency for identifying the electron track as a function of P_T. The conversion background contributes approximately 15 of the total 64 event background estimate. The remaining signal excess has a 5.9σ significance and contains 114.9 ± 15.5 ± 13.6 B_c^- candidates. In this channel, a measurement of $\mathcal{R}$ is made for $P_T(B) > 4$ GeV/c and $|y| < 1$:
$\mathcal{R} = 0.282 \pm 0.038 \pm 0.035 \pm 0.065$.

The $B_c^- \rightarrow J/\psi\ e^- X$ sample is also used to measure the lifetime of the B_c^- meson. Figure 2 shows the pseudo-proper decay length distribution with superimposed signal and background contributions. With relaxed requirements on the pseudo-proper decay length compared with the $\mathcal{R}$ analysis, the fit finds a total of 238 signal events over 545 ± 55 background events in the M(J/ψe) range between 4 and 6 GeV/c^2. From the fit, the B_c^- lifetime is measured to be: $c\tau(B_c^-) = 0.474\ ^{+0.073}_{-0.066} \pm 0.033$ ps.

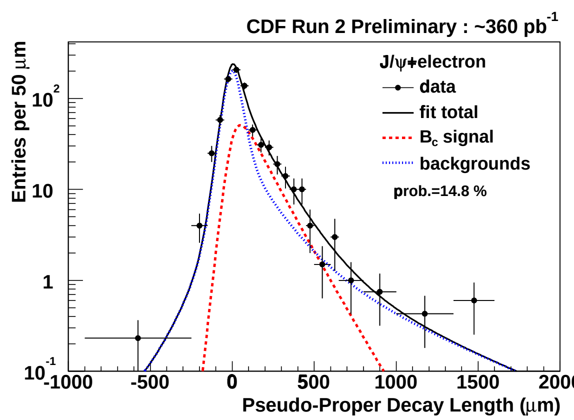

Figure 2. The pseudo proper lifetime distribution of $B_c^- \rightarrow J/\psi\ e^- X$ candidates in the CDF Run II data showing the contributions of background and B_c^- signal.

5. $B_c^- \to J/\psi\ \pi^-$ in CDF

CDF reported initial evidence of $B_c^- \to J/\psi\ \pi^-$ decays with 0.36 fb^{-1} [15]. We now describe an independent analysis [16] using the full 0.8 fb^{-1} of collected and processed data available for analysis at the end of 2005. This search for $B_c^- \to J/\psi\ \pi^-$ uses a strategy that studies the effects of various selection criteria on the reference $B^- \to J/\psi\ K^-$ decay and the side-band background events below 5.5 GeV/c^2. The selection requirements include requiring the K candidate track to have an impact parameter that is significantly displaced from the primary vertex while pointing to a displaced J/ψ secondary vertex defined by the two muons. Only after the selection was approved internally by CDF was the K hypothesis changed to a π and the region of interest in M($J/\psi\pi$) examined. A small excess is observed in this analysis with 0.36 fb^{-1} of data and has become more signifiant with the full 0.8 fb^{-1} where a fit to a Gaussian signal and linear background gives 38.9 B_c^- signal events and 26.1 background events in the mass range between 6.24 and 6.30 GeV/c^2 - an observation with a significance greater than 6σ based upon simulations that include random fluctuations over a wide search window. Figure 3 shows the invariant mass distribution of $J/\psi\pi$ candidates in the range between 5.6 and 7.2 GeV/c^2. An unbinned likelihood fit is used to measure the mass of the B_c^-: M(B_c^-) = 6275.2 $\pm$ 4.3 $\pm$ 2.3 MeV/c^2.

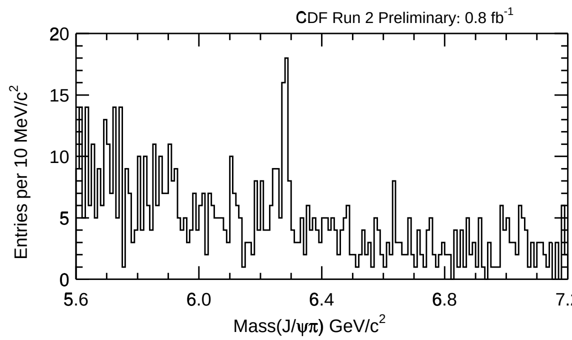

Figure 3. Invariant mass distribution of $J/\psi\ \pi^-$ in 0.8 fb^{-1} of CDF data.

6. Summary and Conclusions

Measurements of the B_c^- meson are happening at CDF and DØ using Run II data. The B_c^- is an unique system whose properties are currently best studied at the Tevatron collider where relatively large production rates, triggerable decays modes, and powerful detectors combine to provide the current best measurements of this meson. In particular, new precise measurements of the lifetime and mass of the B_c^- are challenging theoretical predictions.

REFERENCES

1. Charge conjugate modes are implied.
2. C. Albajar *et al.*, Phys. Lett. **B213**, 405 (1988).
3. F. Abe *et al.*, Phys. Rev. Lett. **68**, 3403 (1992).
4. D. Acosta *et al.*, Phys. Rev. **D71**, 032001 (2005).
5. V. M. Abazov *et al.*, submitted to Nucl. Instrum. Methods, physics/0507191.
6. C. S. Hill *et al.*, Nucl. Instrum. Methods **A530**, 1 (2004).
7. C. H. Chang and X. G. Wu, Eur. Phys. J. C. **38** (2004) 267.
8. V. V. Kislev, Phys. Atom. Nucl. **67**, 1559 (2004).
9. S. Godfrey, Phys. Rev. **D70**, 054017 (2004); E. J. Eichten and C. Quigg, Phys. Rev. **D49**, 5845 (1994); W. K. Kwong and J. L. Rosner, Phys Rev **D**44, 212 (1991).
10. I. F. Allison *et al.*, Phys. Rev. Lett. **94**, 172001 (2005).
11. F. Abe *et al.*, Phys. Rev. Lett. **81**, 2432 (1998) and F. Abe *et al.*, Phys. Rev. **D58**, 112004 (1998).
12. DØ Collaboration, DØ note 4539-CONF.
13. CDF Collaboration, CDF Note 7649.
14. CDF Collaboration, CDF note 7926.
15. CDF Collaboration, hep-ex/0505076.
16. CDF Collaboration, CDF note 8004.