Measurements of Rare B Decays at Tevatron

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Both CDF and DØ experiments have been searching for evidence of physics beyond the standard model (SM) using the Tevatron $p\bar{p}$ collider at Fermilab. We report on recent searches in the B flavor sector, especially decays via flavor changing neutral current processes (FCNC), $B^0_{(s)} \to e^+\mu^-$ and $B^0_s \to \mu^+\mu^-$, at the Tevatron.

1 Introduction

The branching fraction of a rare decay mode is an interesting quantity to measure because the contribution from physics beyond the SM may be sizable in rare decay modes. In order to be able to observe rare heavy flavor decays it is essential to produce a sufficient number of bottom hadrons. The bottom anti-bottom production cross-section $\sigma(b\bar{b})$ at the Tevatron is $O(10^5)$ larger than production in e^+e^- colliders at the $\Upsilon(4s)$ or Z^0 energy scale. The large production of all kinds of b-hadrons at the Tevatron offers the opportunity to study rare decays also in the B^0_s and b-baryon sectors. On the other hand the inelastic cross section is 10^3 times higher than $\sigma(b\bar{b})$ requiring very selective and efficient triggers. Therefore, interesting events must be extracted from a high track multiplicity environment, and detectors need to have very good tracking, vertex resolution, wide acceptance, good particle identification and highly selective triggers.

In this article we report on searches for rare B decays via FCNC process, $B^0_{(s)} \to e^+\mu^-$ and $B^0_s \to \mu^+\mu^-$, using the Tevatron $p\bar{p}$ collider at Fermilab.

2 $B^0_{(s)} \to e^+\mu^-$ Decays

In the SM, lepton number and lepton flavor are conserved; therefore the decays such as $B^0_{(s)} \to e^+\mu^-$ are forbidden. However the observation of neutrino oscillations indicates that lepton flavor is not conserved while lepton flavor violating (LFV) decays in the charged sector have not been observed yet. The grand-unification theory by J. Pati and A. Salam predicts a new interaction to mediate transitions between leptons and quarks via exchange of spin-1 gauge bosons, which are called Pati-Salam leptoquarks (LQ), that carry both color and lepton quantum numbers [1]. The lepton and quark components of the leptoquarks are not necessarily from the same generation [2,3], and the decays $B^0_s \to e^+\mu^-$ and $B^0 \to e^+\mu^-$ can be mediated by different types of leptoquarks.

CDF reported on searches for the LFV decays $B^0_{(s)} \to e^+\mu^-$ using 2 fb^{-1} of Run II data [4]. Data sample used in the searches was taken with the two displaced-track trigger, in which two

oppositely-charged tracks are required to have a transverse momentum $p_T > 2$ GeV/c and an impact parameter[5] $0.1 < d_0 < 1$ mm, and it is also required that the scalar sum of the transverse momenta of the two tracks is greater than 5.5 GeV/c, the difference in the azimuthal angles of the tracks is $20° < \Delta\varphi < 135°$, and a transverse decay length[6] is $L_{xy} > 200$ μm. In the off-line analysis, additionally the $B^0_{(s)}$ isolation, the pointing angle and the transverse decay length were required to be consistent with those of $B^0_{(s)} \to e^+\mu^-$ decays. These thresholds were optimized in an unbiased way to obtain the best sensitivity for the searches[7]. To identify electrons, both the specific ionization (dE/dx)[8] measured in the central drift chamber and the transverse and longitudinal shower shapes as measured in the central electromagnetic calorimeter were used. The electron identification efficiency is $\sim 70\%$ while the muon identification is fully efficient with $p_T > 2$ GeV/c in the central muon detector. Search windows in $e^+\mu^-$ invariant mass were defined to be (5.262–5.477) GeV/c^2 for $B^0_s \to e^+\mu^-$ and (5.171–5.387) GeV/c^2 for $B^0 \to e^+\mu^-$. These correspond to a window around the nominal values of the B^0_s and B^0 masses[9] of approximately $\pm 3\sigma_m$. The background contributions considered include combinations of random track pairs and partial B decays that accidentally meet the selection requirement and hadronic two-body B decays in which both final particles are misidentified as leptons. The random track contribution was evaluated by extrapolating the normalized number of events found in the sidebands to the signal region. The double-lepton misidentification rate was determined by applying electron and muon misidentification probabilities to the number of two-body decays found in the search window. Figure 1 shows the invariant mass distribution for $e^+\mu^-$ candidates. One event in the B^0_s mass window, and two events in the B^0 mass window were observed. These numbers are consistent with the estimated total background of 0.8 ± 0.6 events in the B^0_s search window, and 0.9 ± 0.6 in the B^0 window. $B^0 \to K^+\pi^-$ decays were used as a reference channel to set a limit on $\mathcal{B}(B^0_{(s)} \to e^+\mu^-)$. Using the same selection criteria except lepton identification, 6387 ± 214 events of $B^0 \to K^+\pi^-$ decays were observed as shown in Fig. 1. Resulting upper limits were $\mathcal{B}(B^0_s \to e^+\mu^-) < 2.0\,(2.6) \times 10^{-7}$ and $\mathcal{B}(B^0 \to e^+\mu^-) < 6.4\,(7.9) \times 10^{-8}$ at 90% (95%) confidence level (C.L.). Using the limits on the branching fractions, the masses of the corresponding Pati-Salam leptoquarks were calculated to be $M_{LQ}(B^0_s \to e^+\mu^-) > 47.8\,(44.9)$ TeV/c^2 and $M_{LQ}(B^0 \to e^+\mu^-) > 59.3\,(56.3)$ TeV/c^2 at 90 (95)% C.L. These are the best limits in the world to date.
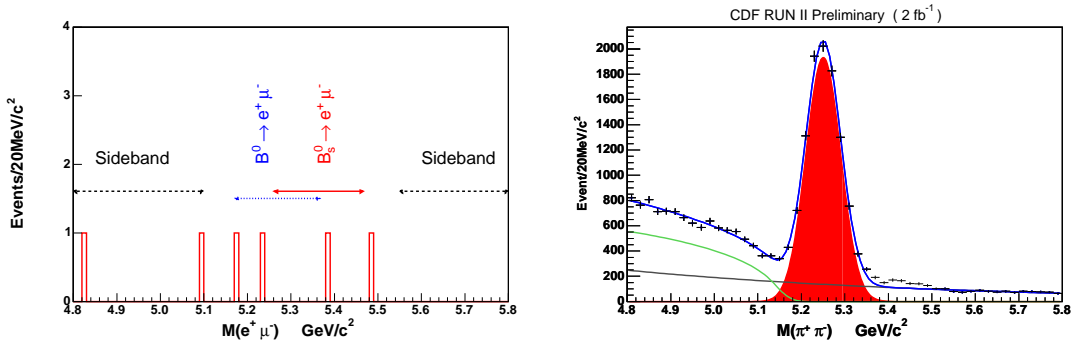

Figure 1: $e^+\mu^-$ invariant mass distribution(left) and the reference channel $B^0 \to K^+\pi^-$ (right) in data.

3 $B^0_s \to \mu^+\mu^-$ Decays

Branching fraction of the pure leptonic FCNC processes like $B^0_s \to \mu^+\mu^-$ in the SM is heavily suppressed[10]: $\mathcal{B}(B^0_s \to \mu^+\mu^-) = (3.35 \pm 0.32) \times 10^{-9}$. $B^0 \to \mu^+\mu^-$ decay is further suppressed by a factor $|V_{td}/V_{ts}|^2$ in the CKM matrix elements leading to a SM predicted branching fraction of $O(10^{-10})$. The decay amplitude of $B^0_s \to \mu^+\mu^-$ can be enhanced significantly in some extensions

of the SM. For instance, in the type-II two-Higgs-doublet-model (2HDM)[11] the branching fraction is proportional to $\tan^4\beta$, where $\tan\beta$ is the ratio between the vacuum expectation values of the two neutral Higgs fields. In the minimal super-symmetric SM (MSSM)[12] the dependence on $\tan\beta$ is even stronger, $\propto \tan^6\beta$. Current observation of this decay at the Tevatron would necessarily imply new physics.

Current world best limit on $\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ is given by CDF using 2 fb^{-1} of Run II data[13]. The sensitivity of the analysis was improved significantly from the previous result[14] by increasing the integrated luminosity of the event sample, using an enhanced muon selection, employing a neural network (NN) classifier to separate signal from background, and performing the search in a two dimensional grid in dimuon mass and NN space. The observed event rates were consistent with SM background expectations. Extracted 90% (95%) C.L. limit was $\mathcal{B}(B_s^0 \to \mu^+\mu^-) < 4.7\ (5.8) \times 10^{-8}$.

DØ reported a new expected upper limit on $\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ using approximately 5 fb^{-1} of dimuon trigger data[15]. The data sample was split into three subsamples, Run IIa, Run IIb-I and Run IIb-II, based on the data taking period. Roughly the integrated luminosity of Run IIa data is 1.3 fb^{-1}, Run IIb-I is 1.9 fb^{-1} and Run IIb-II is 1.6 fb^{-1}. The three subsamples were treated as three different and independent analyses, but the final upper limit was combined from the separate analyses. To separate signal from background a boosted decision tree (BDT)[16] classifier was constructed, where five input variables of the B_s^0 meson (isolation, transverse momentum, transverse decay length significance, impact parameter significance and logarithm of vertex χ^2 probability) were used. Figure 2 shows the dimuon invariant mass distributions after applying the BDT cut, where only events not in the blinded region $\pm 3\sigma_m$ ($\sigma_m = 0.115$ GeV/c^2) around the B_s^0 mass are shown. The same BDT cut was applied on the normalization channel, $B^+ \to J/\psi K^+$, and the following numbers of events were found: $1847 \pm 49(stat.) \pm 115(syst.)$ events in Run IIa data, $2188 \pm 52(stat.) \pm 123(syst.)$ events in Run IIb-I data and $1683 \pm 46(stat.) \pm 112(syst.)$ events in Run IIb-II data. The systematic uncertainty is coming from our parametrization of the B^+ mass shape. The random track contribution in the signal region $\pm 2.5\sigma_m$ was estimated by extrapolating events in the sideband region to the signal region. In addition, possible non-negligible contributions of misidentified $B_s^0 \to K^+K^-$ and $B^0 \to K^+\pi^-$ were estimated. The total background events in the search window in Run IIa, Run IIb-I, and Run IIb-II data sets were estimated to be 2.16 ± 0.62, 3.73 ± 1.07 and 2.15 ± 0.63, respectively. The expected SM yields of $B_s^0 \to \mu^+\mu^-$ events in Run IIa, Run IIb-I, and Run IIb-II data sets are 0.192 ± 0.034, 0.193 ± 0.034 and 0.139 ± 0.025, respectively. Aside from the background uncertainty, the largest uncertainty common to the three data sets, 15.2%, comes from the fragmentation ratio between B^+ and B_s^0. Assuming no signal counts (background only) in the signal region, an expected upper limit on the branching fraction at the 90%(95%) C.L was computed. The number of observed events was set to the number of background events, 2 events for Run IIa, 4 events for Run IIb-I and 2 events for Run IIb-II. In this calculation, it was assumed that there are no contributions from $B^0 \to \mu^+\mu^-$ decays, where the decay is suppressed by $|V_{td}/V_{ts}|^2 \approx 0.04$. The expected 90%(95%) upper limits for the branching fraction were $7.6\ (9.4) \times 10^{-8}$ for Run IIa data, $9.9\ (11) \times 10^{-8}$ for Run IIb-I data and $10\ (13) \times 10^{-8}$ for Run IIb-II data. The combined upper limit is then $4.3\ (5.3) \times 10^{-8}$ at the 90%(95%) C.L. This sensitivity is comparable with the best published upper limit from CDF[13], and improves the previous DØ result[17] by a factor of two. Further work to understand and reduce the background as well as to include more data is ongoing before opening the search box.

4 Conclusion

CDF has reported new upper limits on $\mathcal{B}(B_{(s)}^0 \to e^+\mu^-)$ using 2 fb^{-1} of data, and DØ has reported an new expected upper limit on $\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ using approximately 5 fb^{-1} of data.
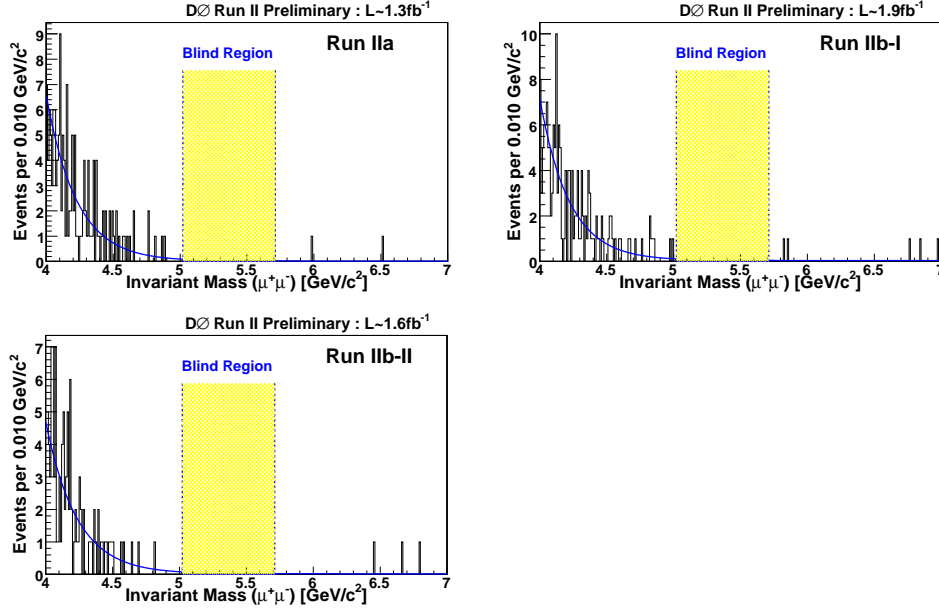
Figure 2: Dimuon invariant mass distributions. Search box remains blinded.

With the continuously increasing amount of data provided by the Tevatron and improvements of the analyses measurements of rare B decays provide new insight into the properties of the FCNC decays, which allows for improved tests of the SM that could guide us to new physics scenarios.

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