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RARE B AND CHARM DECAYS AT THE TEVATRON

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The measurements of rare decays are highly sensitive to physics beyond the standard model. In this article limits on the branching ratios of the decays $B^0_{(s)} \to \mu^+\mu^-$, $D^0 \to \mu^+\mu^-$ and $D^+ \to \pi^+\mu^+\mu^-$ are presented. Furthermore the first measurement of the branching fraction and CP asymmetry of $\Lambda^0_b \to p\pi^-$ and $\Lambda^0_b \to pK^-$ decays is described. Data samples with an integrated luminosity of up to 2 fb^{-1} collected at the Tevatron $p\bar{p}$-collider at $\sqrt{s} = 1.96$ TeV were used in these analyses. The results are consistent with the standard model predictions and tighten the constraints on new physics models.

1 Introduction

The branching ratio of a rare decay mode is an interesting quantity to measure because the contribution from physics beyond the standard model, which can be negligible compared to the standard model (SM) contribution in the dominant decay modes, may be sizable in the rare decay mode. Decays are suppressed in the SM for different reasons. One of them is that flavor-changing neutral current (FCNC) processes are forbidden at tree level. The FCNC decays discussed here are $B^0_{(s)} \to \mu^+\mu^-$, $D^0 \to \mu^+\mu^-$ and $D^+_{(s)} \to \pi^+\mu^+\mu^-$. Although the decays $\Lambda^0_b \to p\pi^-$ and $\Lambda^0_b \to pK^-$ are allowed at tree level in the SM, they are suppressed because the b to u quark transition involves the small CKM matrix element V_{ub}.

In order to be able to observe rare heavy flavor decays it is essential to produce a sufficient amount of bottom and charm hadrons. The large $b\bar{b}$ and $c\bar{c}$ cross section at the Tevatron, more than four orders of magnitude higher than at the B-factories, allows to probe very small branching ratios. Another advantage of the Tevatron is the production of all species of b hadrons so that rare decays of B^0_s mesons and b baryons can be studied.

On the other hand the inelastic cross section is 10^3 times higher than $\sigma(b\bar{b})$ requiring very selective and efficient triggers. For rare decays in particular triggers on pairs of muons or pairs of displaced tracks are used. Another challenge at the Tevatron is the high combinatorial background from fragmentation tracks. Sophisticated selection procedures based on kinematic, topologic and particle identification quantities are employed to extract the signal.

2 Rare decay measurements

2.1 $B^0_{(s)} \to \mu^+\mu^-$

The FCNC process $B^0_s \to \mu^+\mu^-$ is predicted to have a branching ratio of $\mathcal{B}(B^0_s \to \mu^+\mu^-) = (3.42 \pm 0.54) \times 10^{-9}$ in the SM[1]. The $B^0 \to \mu^+\mu^-$ decay is further suppressed compared to the B^0_s decay by $|V_{td}/V_{ts}|^2$. The SM prediction for the branching ratio is $\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.00 \pm 0.14) \times 10^{-10}$. A significant enhancement of the B^0_s and B^0 branching ratios is predicted by several new physics models. For example in the minimal super-symmetric standard model (MSSM) the B^0_s branching ratio is proportional to $\tan^6\beta$ where $\tan\beta$ is the ratio between the vacuum expectation values of the two neutral Higgs fields. In R-parity violating super-symmetric (SUSY) models an enhancement is possible even at low values of $\tan\beta$.

Both Tevatron experiments optimize the selection of $B_s^0 \to \mu^+\mu^-$ candidates using simulated signal events and background events from mass sidebands. While D0 combines the discriminant variables in a likelihood ratio, CDF uses a neural network (NN). It was checked on background samples that the NN does not introduce a selection bias. Both experiments estimate the combinatorial background by a fit to the mass sidebands. The contribution from decays of B mesons to two light hadrons, which could peak in the signal mass region, was estimated to be an order of magnitude lower than the combinatorial background. To obtain an absolute branching ratio the number of signal events is normalized to the high-statistics $B^+ \to J/\psi K^+$ mode. For the limit calculation CDF splits the data sample in three bins in NN output and five bins in mass which improves the sensitivity by 15% compared to using just one bin. Both experiments do not see a significant excess (Fig. 1). The 90% confidence level (CL) limits calculated with a Bayesian method for a data sample of 2 fb^{-1} per experiment are $\mathcal{B}(B_s^0 \to \mu^+\mu^-) < 7.5 \times 10^{-8}$ (D0)[2] and $\mathcal{B}(B_s^0 \to \mu^+\mu^-) < 4.7 \times 10^{-8}$ (CDF)[3]. Because of the good mass resolution of the tracking system CDF is able to separate B_s^0 and B^0 mesons and to quote a 90% CL limit on the B^0 decay of $\mathcal{B}(B^0 \to \mu^+\mu^-) < 1.5 \times 10^{-8}$.

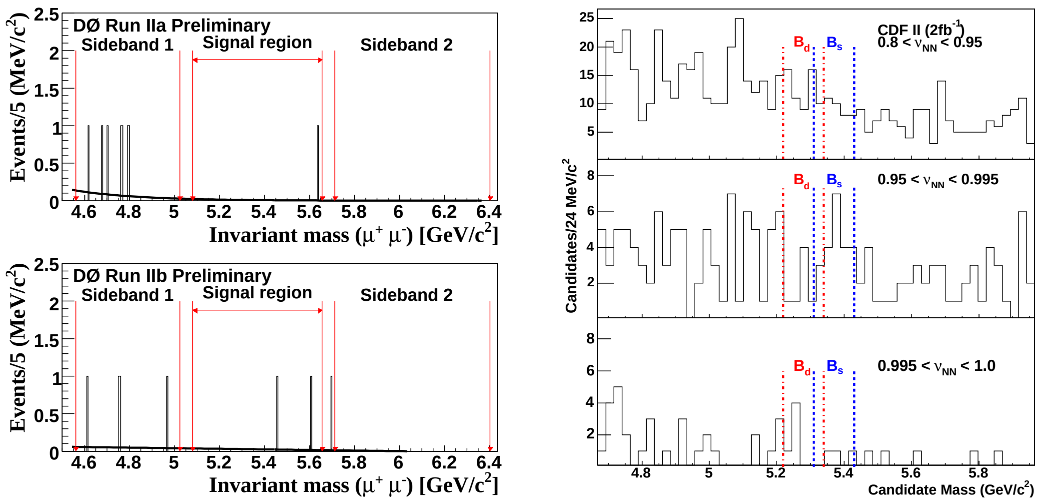

Figure 1: Invariant mass spectrum of $B_s^0 \to \mu^+\mu^-$ candidates measured by D0 in two run ranges (left) and by CDF in three bins of neural network output (right).

2.2 $D^0 \to \mu^+\mu^-$

The SM box and penguin processes of the $D^0 \to \mu^+\mu^-$ decay are much more suppressed by the GIM mechanism than in the $B_s^0 \to \mu^+\mu^-$ case. Therefore long distance processes like the decay via hadronic resonances and photons are dominant resulting in a predicted branching ratio[4] of $\mathcal{B}(D^0 \to \mu^+\mu^-) \geq 4 \times 10^{-13}$. While no significant enhancement is expected in R-parity conserving SUSY models, branching ratios up to 10^{-6} are possible if R-parity is violated.

CDF selects candidates of $D^0 \to \mu^+\mu^-$ decays by a trigger on displaced tracks which allows to use the $D^0 \to \pi^+\pi^-$ mode for normalization. Muons are identified using muon chambers in the pseudorapidity ranges $|\eta| < 0.6$ (CMU) and $0.6 < |\eta| < 1$ (CMX). Background events are reduced by requiring the D^0 to come from a D^* decay and by cutting on a lifetime information based probability ratio between signal events and $B \to \mu^+\mu^- X$ events, the dominant background. In a data sample of 360 pb^{-1} the observed numbers of events of 3, 0 and 1 in the acceptance regions CMU-CMU, CMU-CMX and CMX-CMX are consistent with the background expectations of

4.9 ± 1.5, 2.7 ± 1.0 and 1.0 ± 0.5, respectively (Fig. 2). The obtained 90% CL Bayesian limit[5] is $\mathcal{B}(D^0 \to \mu^+\mu^-) < 4.3 \times 10^{-7}$.

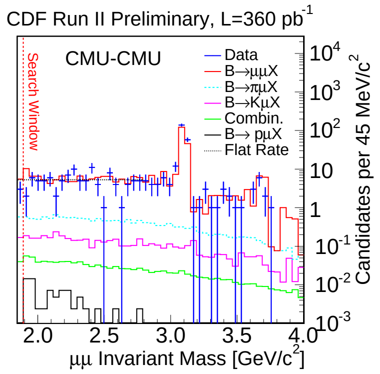

Figure 2: Invariant mass spectrum of $D^0 \to \mu^+\mu^-$ candidates in the CMU-CMU acceptance region.

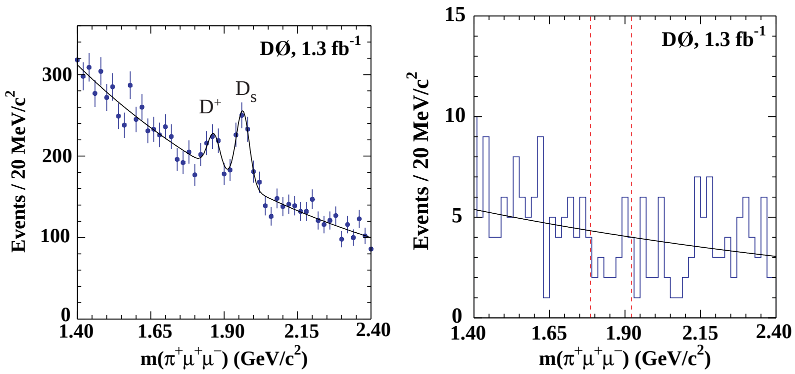

Figure 3: Invariant $\pi^+\mu^+\mu^-$ mass spectrum of for $\mu^+\mu^-$ candidates in the ϕ mass region (left) and outside the ϕ mass region (right).

2.3 $D^+_{(s)} \to \pi^+\mu^+\mu^-$

The $D^+_{(s)} \to \pi^+\mu^+\mu^-$ decay is, like the $D^0 \to \mu^+\mu^-$ decay, dominated by long distance processes. But the size of this contribution depends on the dimuon mass. The selection of non-resonant dimuon masses therefore increases the sensitivity to new physics contributions, in particular from R-parity violating SUSY.

In the first part of the analysis D0 selects events with $m(\mu^+\mu^-)$ in the ϕ meson mass region to establish a resonant decay signal. In the $m(\pi^+\mu^+\mu^-)$ spectrum a D_s^+ signal and a D^+ signal are observed (Fig. 3) with a statistical significance of 8σ for both combined and 4.1σ for the D^+ alone. The measured value[6] of $\mathcal{B}(D^+ \to \phi\pi^+ \to \mu^+\mu^-\pi^+) = (1.8 \pm 0.5 \pm 0.6) \times 10^{-6}$, using the resonant D_s^+ decay as normalization, is in good agreement with[7] $\mathcal{B}(D^+ \to \phi\pi^+) \cdot \mathcal{B}(\phi \to \mu^+\mu^-) = (1.86 \pm 0.26) \times 10^{-6}$.

For the search for the non-resonant decay events with $m(\mu^+\mu^-)$ in the ϕ mass region are excluded. The observed number of 19 events in the $m(\pi^+\mu^+\mu^-)$ search window is consistent with the background expectation of 25.8 ± 4.6 events (Fig. 3). By normalizing to the resonant D^+ decay a 90% CL Bayesian limit of $\mathcal{B}(D^+ \to \pi^+\mu^+\mu^-) < 3.9 \times 10^{-6}$ is determined from a data sample of 1.3 fb^{-1}.

2.4 $\Lambda_b^0 \to p\pi^-$ *and* $\Lambda_b^0 \to pK^-$

The decays $\Lambda_b^0 \to p\pi^-$ and $\Lambda_b^0 \to pK^-$ are allowed at tree level in the SM, but are suppressed by the small value of the involved CKM matrix element V_{ub}. Therefore loop diagram processes can contribute at a magnitude that is comparable to the tree diagram process. The interference of these amplitudes can lead to a sizeable direct CP violation. In the SM an A_{CP} value of $\mathcal{O}(10\%)$ is predicted. While R-parity violating SUSY processes would enhance the branching ratio from $\mathcal{O}(10^{-6})$ up to $\mathcal{O}(10^{-4})$ they would at the same time reduce A_{CP} by one order of magnitude.

Both rare Λ_b decays were first observed in a CDF analysis of rare B meson decays to two light hadrons[8]. The analysis technique developed there is reused here. It involves an unbinned likelihood fit of invariant mass under dipion hypothesis (Fig. 4 left), relations between daughter particle momenta, and particle identification information provided by the specific ionization energy loss in the tracker. With the decay $B^0 \to K^+\pi^-$ as normalization the quantities $\mathcal{B}(\Lambda_b^0 \to p\pi^-)/\mathcal{B}(B^0 \to K^+\pi^-) \cdot f_{\Lambda_b^0}/f_{B^0} = 0.0415 \pm 0.0074 \pm 0.0058$ and $\mathcal{B}(\Lambda_b^0 \to pK^-)/\mathcal{B}(B^0 \to$

$K^+\pi^-) \cdot f_{\Lambda_b^0}/f_{B^0} = 0.0663 \pm 0.0089 \pm 0.0084$ are measured[9] in a data sample of 1 fb^{-1} where $f_{\Lambda_b^0}/f_{B^0}$ is the Λ_b^0 to B^0 production ratio. Taking the production ratio measured by CDF[10] and the known $B^0 \to K^+\pi^-$ branching ratio[7] one obtains absolute branching ratios of $\mathcal{B}(\Lambda_b^0 \to p\pi^-) = (1.4 \pm 0.3^{+0.9}_{-0.5}) \times 10^{-6}$ and $\mathcal{B}(\Lambda_b^0 \to pK^-) = (2.2 \pm 0.3^{+1.4}_{-0.8}) \times 10^{-6}$ which are in good agreement with the SM predictions of 1×10^{-6} and 2×10^{-6}, respectively[11].

To measure the CP asymmetry $A_{CP}(\Lambda_b^0 \to p\,h^-, h = \pi \text{ or } K) = [\mathcal{B}(\Lambda_b^0 \to p\,h^-) - \mathcal{B}(\bar{\Lambda}_b^0 \to \bar{p}\,h^+)]/[\mathcal{B}(\Lambda_b^0 \to p\,h^-) + \mathcal{B}(\bar{\Lambda}_b^0 \to \bar{p}\,h^+)]$ the relative efficiencies are determined from inclusive $\Lambda^0 \to p\pi^-$ and $\bar{\Lambda}^0 \to \bar{p}\pi^+$ decays. While the result of $A_{CP}(\Lambda_b^0 \to p\pi^-) = 0.03 \pm 0.17 \pm 0.05$ is well consistent with no CP asymmetry, the value of $A_{CP}(\Lambda_b^0 \to pK^-) = 0.37 \pm 0.17 \pm 0.03$ is about 2σ away from zero. Fig. 4 illustrates the asymmetry as well as the good description of the data by the fit and the powerful $\Lambda_b^0/\bar{\Lambda}_b^0$ separation.

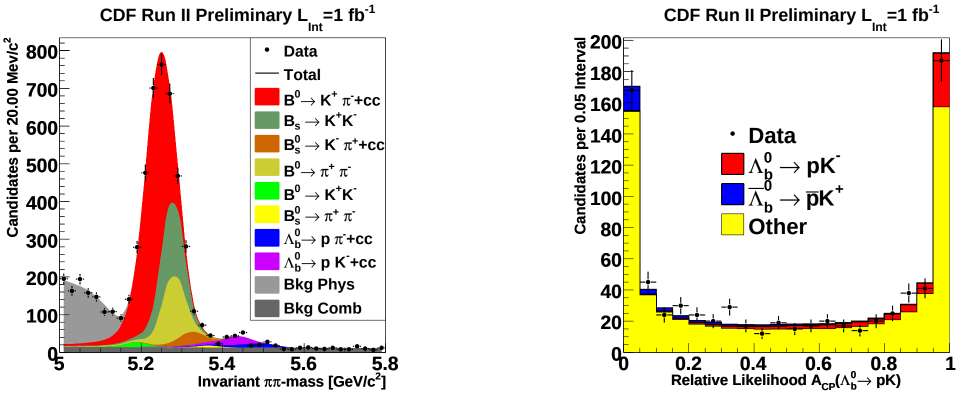

Figure 4: Invariant mass spectrum for $\pi^+\pi^-$ mass assignment (left) and relative probability density function (pdf) of $\Lambda_b^0 \to pK^-$: $\mathrm{pdf}(\Lambda_b^0)/[\mathrm{pdf}(\Lambda_b^0) + \mathrm{pdf}(\bar{\Lambda}_b^0)]$ (right).

3 Conclusions

New world's best limits on the branching ratio of the rare decays $B_s^0 \to \mu^+\mu^-$, $B^0 \to \mu^+\mu^-$, $D^0 \to \mu^+\mu^-$ and $D^+ \to \pi^+\mu^+\mu^-$ were presented. Furthermore the first branching ratio and CP asymmetry measurement of charmless hadronic Λ_b decays were shown. These Tevatron results can impose stringent constraints on physics beyond the SM. A further significant reduction of the new physics models parameter space can be expected as more data is taken and analyzed.

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