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A New Upper Limit on the Rare Decay $B_s^0 \to \mu^+\mu^-$ with the DØ Experiment

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We present the new measurement of the rare decay branching ratio $B_s^0 \to \mu^+\mu^-$ using $6.1\ \text{fb}^{-1}$ of Run II data collected with the DØ detector at the Tevatron. When setting limits on the branching ratio, selected events are normalized to reconstructed $B^\pm \to J/\Psi K^\pm$ events in order to decrease the systematic uncertainty. With respect to previous DØ $B_s^0 \to \mu^+\mu^-$ analyses, this one uses a complete new data selection based on a multivariate classifier. The resulting observed upper limit is $\mathscr{B}(B_s^0 \to \mu^+\mu^-) = 5.1 \times 10^{-8}$ at the 95% C.L.

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1. Introduction

The $B_s^0 \to \mu^+\mu^-$ decay involves a Flavor Changing Neutral Current and it is furthermore helicity suppressed. It is therefore forbidden at the tree level within the Standard Model and can only occur through higher order short distances electroweak penguin and box diagrams with a predicted branching ratio of $(3.6 \pm 0.3) \times 10^{-9}$ [1]. Since enhancements by several orders of magnitude are expeceted in many extensions of the Standard Model, namely those involving new scalar operators which would allow to lift the helicity suppression, such a process provides sensitive signature to search for new physics. Current most stringent experimental constraint for this branching ratio is a preliminary result presented by CDF. With 3.7 fb^{-1} of data they observe a 95 % C.L. upper limit of 4.3×10^{-8} [2]. DØ has also presented and published limits [3]. This report presents an update [4] of the preliminary upper bound of 9.3×10^{-8} obtained at the 95% C.L. with 2 fb^{-1} [5]. It is based on an increased dataset and a completely refined analysis technique.

The Tevatron proton-antiproton collider produces large amounts of all kind of bottom hadrons, even those like the B_s^0 which are too heavy to be accessible at the $\Upsilon(4S)$ resonance. However the benefit of the high $b\bar{b}$ production rate and of the high luminosity delivered by the Tevatron is somehow reduced by the more challenging hadronic environment. Interesting events have to be extracted out of a huge background, 3 orders of magnitude higher than the $b\bar{b}$ production. And once an event is selected, the process we are interested in has to be extracted out of the high track multiplicity environment. Under these experimental conditions, and as far as b physics is concerned, the DØ detector takes benefit of its good muon identification with an especially wide acceptance, allowing highly selective triggers based on single- and di-muon triggers. The other detector component important to this analysis is the tracking system, which consists of a silicon microstrip vertex detector and a central fiber tracker, both located within a 2 T superconducting solenoidal magnet.

The data used in this analysis are the complete single- and di-muon triggered data collected by DØ up to June 2009, corresponding to an integrated luminosity of 6.1 fb^{-1}. These data are split and handled as 2 independent subsamples with luminosities of 1.3 and 4.8 fb^{-1}, called respectively Run IIa and Run IIb data. This separate treatment allows to take into account the dependence of the B reconstruction efficiency with the growing up instantaneous luminosity and thus with the increasing occupancy rate. Between the first and the second data sample, during the summer 2006, the DØ vertex detector has been upgraded by inserting an additional layer of silicon strip detectors close to the beam pipe. This Layer 0 counterbalances the degrading performances of the Layer 1 expected after 8 fb^{-1} of accumulated luminosity.

2. Measurement of the $B_s^0 \to \mu^+\mu^-$ branching ratio

The $\mathscr{B}(B_s^0 \to \mu^+\mu^-)$ branching ratio is measured through its normalization to the number of reconstructed $B^+ \to J/\Psi K^+$, with $J/\Psi \to \mu^+\mu^-$, following this formula:

$$\mathscr{B}(B_s^0 \to \mu\mu) = \frac{N(B_s^0 \to \mu\mu)}{N(B^+ \to J/\psi K^+)} \times \frac{\varepsilon(B^+)}{\varepsilon(B_s^0)} \times f\left(\frac{b \to B^+}{b \to B_s^0}\right) \times \mathscr{B}(B^+ \to J/\psi K^+, J/\psi \to \mu\mu)$$

where $N(B_s^0)$ and $N(B^+)$ are the number of observed B_s^0 and B^+ in the search mass window, and the reconstruction efficiencies ε are estimated from the simulation. The B^+ branching ratio is well known and its value is taken from [6], while the uncertainty on the fragmentation ratio f between $b \to B^+$ and $b \to B_s^0$ being the most limiting factor, its value is taken from [7] in order to be able to compare our result with those of previous analyses. To simplify the calculation, the $B^0 \to \mu^+\mu^-$ contribution is conservatively assumed to be negligible in the search mass window, as it is further suppressed by the CKM factor $|V_{td}/V_{ts}|^2$ with respect to the $B_s^0 \to \mu^+\mu^-$ decays.

The B^+ decay channel offers the advantage of a high rate and it is reconstructed using the same set of sequential cuts as the searched B_s^0. This allows some systematics cancellation, namely we get rid of the dimuon efficiency uncertainty. It can be noticed that other quantities totally vanish through the ratio such as the integrated luminosity and the $b\bar{b}$ production rate. An additional track is required, as the Kaon candidate, to reconstruct the B^+. Therefore, the description of tracking efficiency in the simulation has been carefully calibrated, especially at high luminosity, by comparing simulated $B^0 \to J/\Psi K^{*0}$ decays followed by $J/\Psi \to \mu^+\mu^-$ and $K^{*0} \to K^+\pi^-$, which involve an additional track with respect to the normalization channel $B^+ \to J/\Psi K^+$. By performing a binned likelihood fit with the $J/\Psi K^+$ invariant mass distribution in data, and after having taken into account contributions from combinatorial and physicial background in the signal region, we observe 14340 ± 665 B^+ in Run IIa data and 32463 ± 875 in Run IIb data (see figure 1).

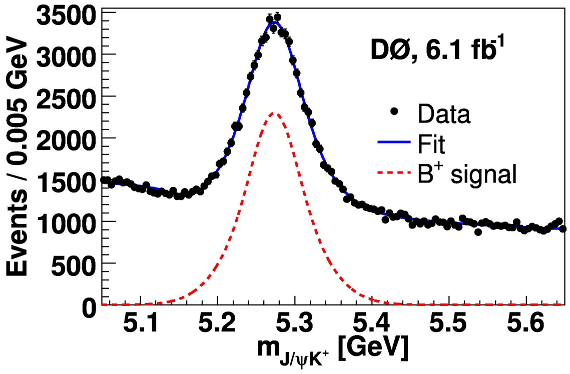

Figure 1: Fit to the $J/\Psi K^+$ invariant mass distribution in data. The red dashed line represents the B^+ signal distribution estimated from the fit.

To search for the $B_s^0 \to \mu^+\mu^-$ we further suppress the combinatorial background by using a multivariate classifier. It is built by combining 6 variables with a Bayesian Neural Network (BNN), which are, ranked with decreasing separation power between $B_s^0 \to \mu^+\mu^-$ signal distributions and combinatorial background distributions: the smaller impact parameter significance of the two muons, the pointing angle of the B_s^0 candidate, its decay vertex fit χ^2, its transverse decay length significance, its transverse momentum and the smaller transverse momentum of the two muons. The BNN is the same which has already been used in the recent single top observation by DØ [8]. To train it we use simulated signal events while the background templates are built with the data from the B invariant mass sidebands. The whole optimization procedure is done in an unbiased way by keeping the search window blind. The BNN output distributions are shown on figures 2.

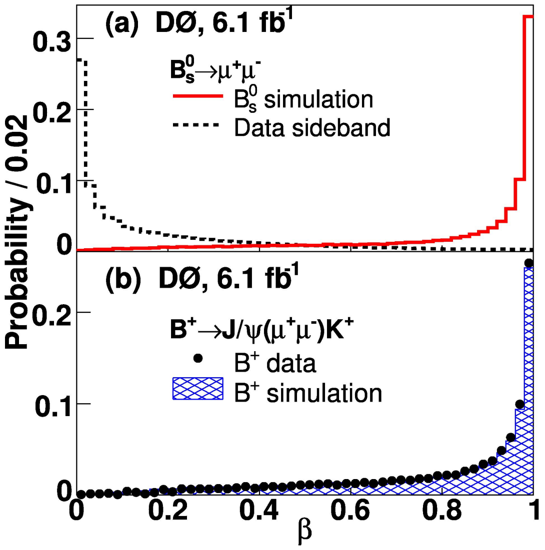

Figure 2: Output of the Bayesian Neural Network built to separate $B_s^0 \rightarrow \mu^+\mu^-$ signal from combinatorial background. On the top (figure (a)) is shown the $B_s^0 \rightarrow \mu^+\mu^-$ events distribution in red, well separated from the background events in dashed black. Figure (b) on the bottom illustrates the data versus simulation agreement with the $B^+ \rightarrow J/\Psi K^+$ decays used as a control sample.

The dominant source of background in the selected dimuon events is combinatorial, it is due to heavy flavours semi-leptonic decays. It can be categorized in two types. For the major contribution, the 2 muons are coming from different b-quarks, yielding dimuon invariant masses distributed over the entire signal region. Whereas in the second category the origin of the two muons is the same b-quark and their invariant masses distribute rather at low masses, below the B meson mass and only the tail of the distribution populates the signal region. These two sorts of combinatorial background are estimated separately by extrapoling into the signal region their dimuon invariant mass distribution fitted in the data sideband of the $B_s^0 \rightarrow \mu^+\mu^-$ candidates, for each BNN bin. In addition we include possible non-negligible contribution of B^0 and B_s^0 mesons decaying to two charged K or π, with the charged hadrons mis-identified as muons. The largest contribution is from $B_s^0 \rightarrow K^+K^-$ and it is found to be actually negligible, about 2000 times smaller than the combinatorial background contribution.

After having finalized the selection criteria we observe 256 events in Run IIa data and 823 events in Run IIb data, in the signal region, to be compared to the estimated background yields: 264 ± 13 events and 827 ± 23 events respectively. Using the standard model prediction of the branching ratio we expect 0.74 ± 0.17 $B_s^0 \rightarrow \mu^+\mu^-$ decays in Run IIa data and 1.95 ± 0.42 decays in Run IIb data. As the observed numbers of events are consistent with the background expectations, we will only be able to put a limit on the $B_s^0 \rightarrow \mu^+\mu^-$ branching ratio. Our final sensitivity will be improved by using 2-dimensional histograms of the dimuon mass versus the BNN output. On figure 3 are shown the observed dimuon mass and BNN output distributions of the selected events in the highest sensitivity region, which groups a couple of 2-dimensional bins.

The obtained semi-frequentist CL$_s$ 95 % C.L. upper limit is extracted separately for the lower and the higher luminosity data subsamples: 8.2×10^{-8} observed in Run IIa data for an expected upper limit of 8.5×10^{-8}, and 6.5×10^{-8} observed in Run IIb data for an expected upper limit

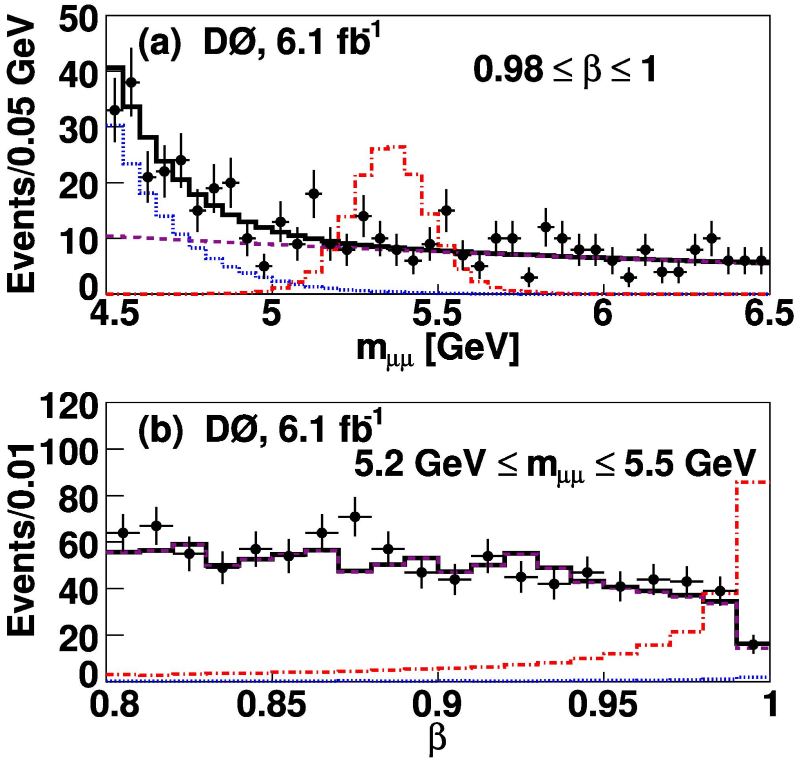

Figure 3: Dimuon invariant mass distribution (a) and BNN output distribution (b) of the selected events in the highest sensitivity region.

of 4.6×10^{-8}. The combined 95 % C.L. upper limit is 5.1×10^{-8} with an expected sensitivity of 4.0×10^{-8}. The main limitation to the sensitivity, after the statistics, comes from the uncertainty on the fragmentation ratio between B^0 and B_s^0.

3. Conclusion

The sensitivity reached by this analysis, of the order of 5×10^{-8} at the 95 % C.L., is the best published one up to now. It has been obtained with 6.1 fb^{-1} of data and improves the previous DØ bound by a factor of 2.4. The Tevatron collider operates very well and twice as much data, that is to say between 11 and 16 fb^{-1} of analyzable data, are expected until the end of Run II, depending on the 3-years extension of its running. Moreover the sensitivity reached at the Tevatron for this measurement has improved up to now better than the luminosity thanks to new analysis developments.

Current Tevatron limits are one order of magnitude above the Standard Model expectation, still leaving an opportunity to search for new physics effects. However even without any observation, this mode allows classes of models to be favored or ruled out. New models parameter space should be further reduced significantly by next year, with the LHC experiments, and above all LHCb, entering the race.

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