



A new expected upper limit for the rare decay $B_s^0 \rightarrow \mu^+ \mu^-$ with the DØ detector

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We present in this note an update of our sensitivity of the rare decay $B_s^0 \rightarrow \mu^+ \mu^-$ using about 700 pb^{-1} of Run II data collected with the DØ detector at Tevatron. In order to calculate an expected branching ratio or expected limit, the events are normalized to reconstructed $B^\pm \rightarrow J/\psi K^\pm$ events. We obtain $\langle \mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) \rangle < 1.9 (2.3) \times 10^{-7}$ as a new expected upper limit at a 90% (95%) C.L. The signal box has not yet been examined.

Preliminary Results for Spring 2006 Conferences

I. DATA AND MC SAMPLES

The data used in the updated sensitivity analysis corresponds to data taken between June 29, 2004 and October 10, 2005 (called new data in this note). Thus, this sensitivity analysis is a continuation of the work presented in Ref. [1], which included all available $D\bar{O}$ data up to June 28, 2004 (called old data in this note).

For simulating the signal and normalization channels, the same Monte Carlo samples that were available in the previous analysis have been used and are described in [1].

II. EVENT SELECTION

For the selection, we require the events to have fired a dimuon trigger. As an additional Run selection criteria we verify in the data sets that the muon detector system was in a decent working condition.

The event pre-selection has been left unchanged and is described in detail in [1]. To further reduce the background three discriminating variables, *Isolation*, *Pointing angle* and *Transverse decay length significance* have been employed and are defined in Ref. [1].

A new optimization using the three discriminating variables was carried out in a Random Grid Search. The optimal set of cuts is found by maximizing an optimization criterion P proposed by G. Punzi [2]:

$$P = \frac{\epsilon_{\mu\mu}}{\frac{a}{2} + \sqrt{n_{back}}} \quad (1)$$

The constant a is the number of sigmas corresponding to the confidence level at which the signal hypothesis is tested. This number a should be defined before the statistical test and was set to 2.0, corresponding to about 95% C.L. The resulting cut values that were obtained from the maximized P are listed in Table I

The new optimization uses 400 pb^{-1} of new data for this sensitivity analysis and determines the expected number of background events, n_{back} , from sideband interpolations. This is in contrast to the optimization described in a previous publication [1], in which only one-third of the available data was used.

After a linear extrapolation of the sideband population for the whole data sample into the final signal region we obtain an expected number of background events of 2.2 ± 0.7 . The remaining background distribution is shown in Fig. 1.

III. THE NORMALIZATION CHANNEL $B^\pm \rightarrow J/\psi K^\pm$

The selection of the normalization events is unchanged and explained in detail in [1].

The mass spectrum of the reconstructed $B^\pm \rightarrow J/\psi K^\pm$ for the full data sample is shown in Fig. 2. A fit using a Gaussian function for the signal and a second order polynomial for the background yielded $899 \pm 37 \pm 24$ B^\pm events, where the first error is statistical and the second due to systematics estimated by varying the fit range and background shape hypothesis.

IV. CALCULATION OF THE SENSITIVITY

A. The expected upper limit on the branching ratio

Since the signal region (signal box) is still kept unexamined for this updated report, the number of candidate signal events for $B_s^0 \rightarrow \mu^+ \mu^-$ remains unknown. Hence, we present an “expected upper limit” that is the ensemble average of all expected limits in the absence of a signal for a hypothetical repetition of the experiment. This average upper limit is identical to the “sensitivity” [3] defined in the unified approach of classical confidence interval construction by Feldman and Cousins [5]. Assuming that there is only background n_{back} , we calculate for each possible value of observation n_{obs} a 95% C.L upper limit $\mu(n_{obs}, n_{back})$. The average upper limit on the signal events $\langle \mu(n_{back}) \rangle$ is then obtained by weighting each limit from the hypothetical ensemble by its Poisson probability of occurrence:

$$\langle \mu(n_{back}) \rangle = \sum_{n_{obs}=0}^{\infty} \mu(n_{obs}, n_{back}) \cdot \frac{(n_{back})^{n_{obs}}}{(n_{obs})!} \exp(-n_{back}). \quad (2)$$

To translate $\langle \mu(n_{back}) \rangle$ into a 95% C.L. upper limit on the $\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-)$ the number of reconstructed events $N_{B^\pm} = 899 \pm 37 \pm 24$ decaying into $J/\psi(\mu^+ \mu^-)K^\pm$ have been used as the normalization as explained in Section III. Thus, $\langle \mathcal{B}(B_s^0) \rangle$ can be calculated by:

$$\langle \mathcal{B}(B_s^0) \rangle \cdot \left(1 + R \cdot \frac{\epsilon_{\mu\mu}^{B_d^0}}{\epsilon_{\mu\mu}^{B_s^0}} \cdot \frac{b \rightarrow B_d^0}{b \rightarrow B_s^0} \right) = \quad (3)$$

$$\frac{\langle \mu(n_{back}) \rangle}{N_{B^\pm}} \cdot \frac{\epsilon_{\mu\mu K}}{\epsilon_{\mu\mu}^{B_s^0}} \cdot \frac{b \rightarrow B^\pm}{b \rightarrow B_s^0} \cdot \mathcal{B}(B^\pm \rightarrow J/\psi K^\pm) \cdot \mathcal{B}(J/\psi \rightarrow \mu\mu) \quad (4)$$

- $\epsilon_{\mu\mu}^{B_s^0}$ and $\epsilon_{\mu\mu K}$ are the efficiencies of the signal and normalization channels, obtained from MC simulations;
- $b \rightarrow B_s^0$, $b \rightarrow B^\pm$ and $b \rightarrow B_d^0$ are the fragmentation fractions of b or \bar{b} quark producing a B_s^0 , a B^\pm or a B_d^0 respectively. The ratio which enters in the equation has been calculated using the latest world average values [6] for the fragmentation for $B_{u,d}$ and B_s^0 mesons respectively. We assume for the error on the fragmentation ratio a full anti-correlation between the two and obtain $(b \rightarrow B_s^0)/(b \rightarrow B_{u,d}) = 0.270 \pm 0.034$
- $\mathcal{B}(B^\pm \rightarrow J/\psi K^\pm) = (1.00 \pm 0.04) \cdot 10^{-3}$ and $\mathcal{B}(J/\psi \rightarrow \mu\mu) = (5.88 \pm 0.1)\%$ [6]; and
- $R \cdot \epsilon_{\mu\mu}^{B_d^0}/\epsilon_{\mu\mu}^{B_s^0}$ is the branching fraction ratio $\mathcal{B}(B_d^0)/\mathcal{B}(B_s^0)$ of $B_{d,s}^0$ mesons decaying into two muons [7] multiplied with their efficiency ratio.

To simplify the calculation of the upper limit on the branching fraction $\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-)$ in Eq. 3, it is assumed that there are no contributions from $B_d^0 \rightarrow \mu^+ \mu^-$ decays ($R \approx 0$) in our search window centered around the B_s^0 mass. This assumption is acceptable since the decay is suppressed by $|V_{td}/V_{ts}|^2 \approx 0.04$. Any non-negligible contribution due to B_d^0 decays ($R > 0$) would make the obtained branching fraction $\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-)$ as given in Eq. 3 smaller. Thus, our presented limit for $\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-)$ is in that context conservative.

The efficiencies $\epsilon_{\mu\mu}^{B_s^0}$ and $\epsilon_{\mu\mu K}$ are the global signal efficiencies for the search signal and normalization channel respectively including the pre-selection cuts and the acceptance. They are determined from MC to be $\epsilon_{\mu\mu}^{B_s^0} = (4.9 \pm 0.1) \cdot 10^{-4}$ and $\epsilon_{\mu\mu K} = (4.2 \pm 0.12) \cdot 10^{-4}$, where the uncertainties are due to MC limiting statistics [9]. The mentioned efficiency numbers refer to triggered MC events in a trigger simulator only.

The statistical uncertainties on the background expectation as well as the uncertainties of signal and background efficiencies can be folded into the sensitivity calculation of Eq. 3 by integrating over probability functions which parameterize the uncertainties. We have used a prescription [10] constructing a frequentist confidence interval with the Feldman and Cousins ordering scheme for the MC integration. The background is modeled as a Gaussian distribution with its mean value equal to the expected number of background events and its sigma equal to the background uncertainty. The signal and background efficiency uncertainties are considered as Gaussian distributions assuming a full correlation among the two. The uncertainty on the number of B^\pm events is propagated into the signal and background efficiency uncertainties. The relative errors on the fragmentation ratio and on the branching ratios are taken into account. The resulting sensitivity including all the mentioned statistical and systematical uncertainties is then

$$\langle \mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) \rangle < 3.0 (3.7) \times 10^{-7}$$

at a 90% (95%) C.L.

We also quote the *single event sensitivity* (*ses*) of this analysis defined as the calculated value for $\langle \mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) \rangle$ in Eq. 3 in case of $\mu(n_{back}) = 1$. It is given by $ses = 6.7 \times 10^{-8}$ and represents an inverse measure for the acceptance and efficiency factors of the analysis, but does not include any background conditions.

Compared to the previous analysis of Ref. [1] the new *ses* is about 10% worse, due to the tighter cuts on the discriminating variables which in turn result in smaller efficiencies for signal and normalization channels. The improved background rejection however, is reflected in the expected limit, which is also the final result of this analysis. Its value is about 15% better than in the previous analysis. For a comparison between the previous old analysis and the new one, see Table III.

B. Uncertainties

All the relative uncertainties that go into the calculation of $\langle \mathcal{B} \rangle$ are given in Table II. Despite the background uncertainty, the largest error of almost 13% comes from the fragmentation ratio $(b \rightarrow B^\pm)/(b \rightarrow B_s^0)$. For the error on

the fragmentation ratio we have conservatively assumed that the individual fragmentations ($b \rightarrow B^\pm$) and ($b \rightarrow B_s^0$) are fully anti-correlated. The relative statistical uncertainties on $\epsilon_{\mu\mu}^{B_s^0}$ and $\epsilon_{\mu\mu K}$ are 2.0% and 2.9% respectively. They are combined into one efficiency uncertainty number assuming no correlations.

The value for the final efficiency ratio is then given by $\epsilon_{\mu\mu K}/\epsilon_{\mu\mu}^{B_s^0} = 0.277 \pm 0.01 \pm 0.02$, where the second error is due to systematics which arise from a different muon p_T distribution between J/ψ and B_s^0 decays (2.3%), an account of tracking inefficiency for the additional Kaon track with respect to MC (1%), the weighting procedure (6.3%), different mass resolutions (1.3%) and finally the uncertainty on trigger and muon identification between data and MC (0.7%). In addition this ratio was corrected for the observed mass resolution difference between data and MC.

The relative error on the number of remaining background events is 31.4% and the B^\pm normalization channel has a relative uncertainty of 4.9% including statistical and systematical error. For the limit calculation we have propagated the theoretical errors on the fragmentation and branching ratios as well as the normalization error of the B^\pm into global signal and background efficiency uncertainties assumed to be of Gaussian shapes. The modified probability function distributions are then obtained by integrating over those distributions. The limit calculation assumes a full correlation among the signal and background detection efficiencies. As previously mentioned we have used the program described in [10] for the calculation.

V. COMBINED EXPECTED LIMIT

The obtained expected limit for the new data set can be combined with the previous analysis of Ref. [1] using 300 pb^{-1} of older data. The previous finding yielded 4.3 ± 1.2 expected events while four events were finally observed in the signal region. The expected limit for the entire data set is thus a combination of two experiments: one actual measurement with observed events (old data) and one hypothetical experiment (new data) with all possible outcomes in the signal region weighted by their Poisson probability of occurrence, i.e., under the assumption of a background hypothesis only. We have used a Bayesian technique to combine the two experiments and include at this stage the uncorrelated uncertainties into the expected limit calculation. The background uncertainty, the uncertainty on the number of normalization events and the statistical error on the efficiencies are considered as uncorrelated.

The expected upper limit at a 90% (95%) C.L. for the entire $D\bar{O}$ data set of 700 pb^{-1} is then given by

$$\langle \mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) \rangle < 1.9 (2.3) \times 10^{-7}.$$

VI. CONCLUSIONS

We have presented a sensitivity update of the search for the rare decay $B_s^0 \rightarrow \mu^+ \mu^-$. We have used the newly available p17 dimuon data set with only one dimuon trigger. For the new data set corresponding to about 400 pb^{-1} of data the expected background interpolated from the sidebands amounts to 2.2 ± 0.7 events. Calculating the expected average upper limit at a 90% (95%) C.L. for the new data set we obtain $\langle \mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) \rangle < 3.0 (3.7) \times 10^{-7}$ including the statistical and systematical background and signal efficiency uncertainties and using $B^\pm \rightarrow J/\psi K^\pm$ events as normalization. The expected upper limit is combined with the previous analysis exploiting 300 pb^{-1} of old data and using uncorrelated uncertainties only. The obtained expected upper limit at a 90% (95%) C.L. is then $\langle \mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) \rangle < 1.9 (2.3) \times 10^{-7}$ and corresponds to the present $D\bar{O}$ exclusion power/sensitivity for Run II with about 700 pb^{-1} of data.

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TABLE I: The optimized cuts after maximizing P compared to the old analysis.

cut parameter	New cut value	PRL cut value [1]
Opening angle (rad)	< 0.18	< 0.2
Decay length significance	> 19.5	> 18.5
Isolation	> 0.59	> 0.56

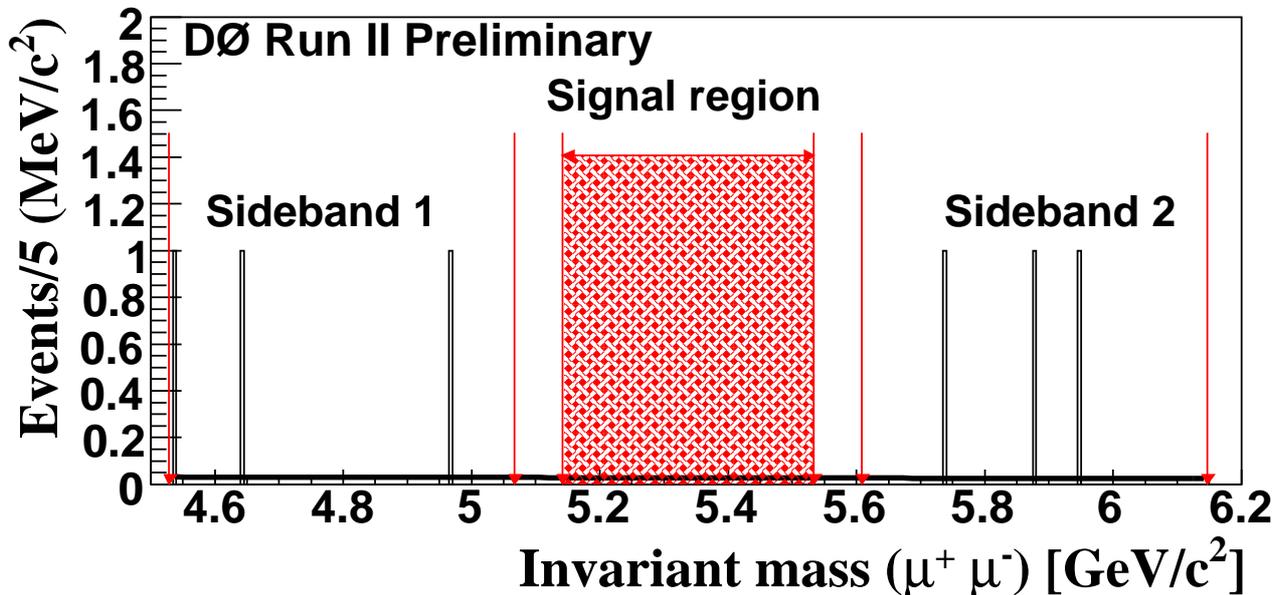


FIG. 1: The mass distribution for the new data sample with the standard discriminating variables.

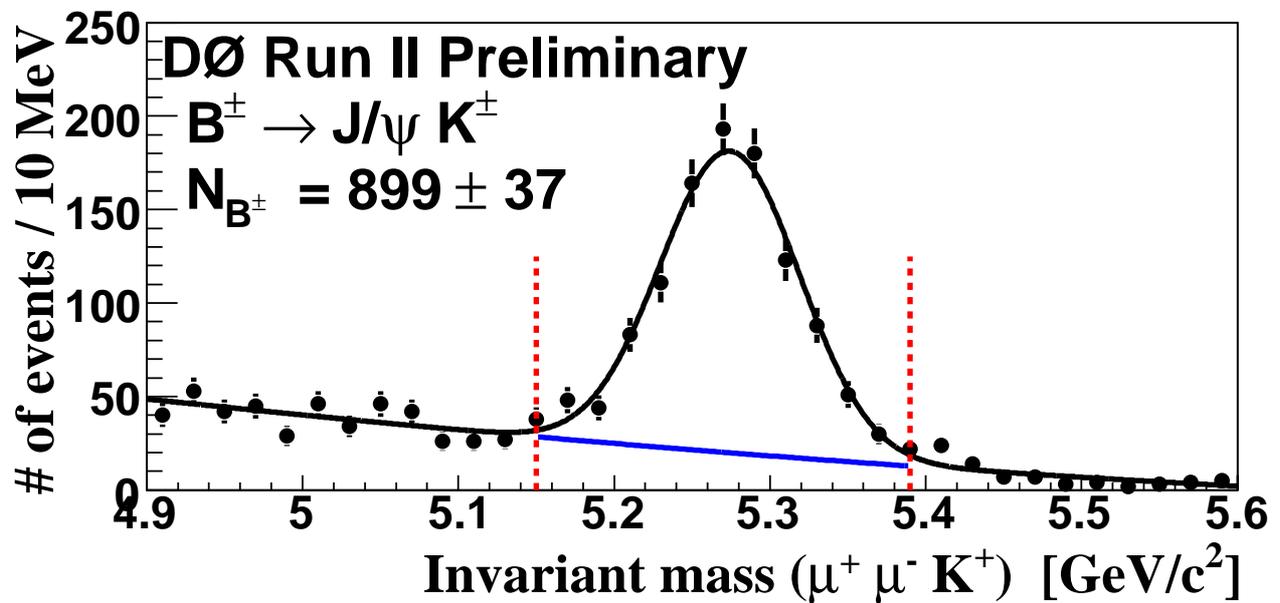
FIG. 2: The normalization channel $B^\pm \rightarrow J/\psi K^\pm$ for the new data sample.

TABLE II: The relative uncertainties for calculating an upper limit of \mathcal{B}

Source	Relative Uncertainty [%]
$\epsilon_{\mu\mu K} / \epsilon_{\mu\mu}^{B_s^0}$	7.8
# of $B^\pm \rightarrow J/\psi K^\pm$	4.9
$\mathcal{B}(B^\pm \rightarrow J/\psi K^\pm)$	4.0
$\mathcal{B}(J/\psi \rightarrow \mu\mu)$	1.7
$f_{b \rightarrow B_s^0} / f_{b \rightarrow B^\pm}$	12.7
background uncertainty	31.4

TABLE III: Summary information on the previous [1] (old) and this (new) $B_s^0 \rightarrow \mu^+ \mu^-$ analysis.

	old	new
Luminosity	300 pb ⁻¹	400 pb ⁻¹
$\frac{\epsilon_{\mu\mu K}^{B^\pm}}{\epsilon_{\mu\mu}^{B_s^0}}$	0.247 ± 0.019	0.277 ± 0.02
N_{B^\pm}	906 ± 35 ± 22	899 ± 37 ± 24
N_{back}	4.3 ± 1.2	2.2 ± 0.7
N_{obs}	4	–
ses	0.59×10^{-7}	0.67×10^{-7}
expect. limit 90% C.L.	3.5×10^{-7}	3.0×10^{-7}
expect. limit 90% C.L.	1.9×10^{-7} (DØ comb.)	