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Sensitivity Analysis for the Rare Decay $B_s^0 \to \mu^+\mu^-\phi$ with the DØ Detector*

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We present in this note a sensitivity analysis for the rare decay $B_s^0 \to \mu^+\mu^-\phi$ using about 300 pb^{-1} of Run II data collected with the DØ detector at the Fermilab Tevatron. Our search is based on a blind analysis hiding the signal region around the B_s^0 mass. The sideband regions below and above the blinded signal region are used to determine the shape and normalization of the background. In order to calculate a branching ratio or limit, the events are normalized to $B_s^0 \to J/\psi\phi$. The cuts have been optimized in a random grid search to enhance the signal sensitivity. Using the concept of a sensitivity, the *expected* upper limit on this branching ratio normalized to $B_s^0 \to J/\psi\phi$ at a 95% confidence level is given by $\frac{<\mathcal{B}(B_s^0\to\mu^+\mu^-\phi)>}{\mathcal{B}(B_s^0\to J/\psi\phi)} = 1.1\times10^{-2}$. When statistical and systematic uncertainties on background and signal efficiencies are included, the *expected* upper limit at 95% C.L. degrades to 1.3×10^{-2}. Using the present world average value for $\mathcal{B}(B_s^0 \to J/\psi\phi)$ without its uncertainty the absolute sensitivities for $\mathcal{B}(B_s^0 \to \mu^+\mu^-\phi)$ are then 1.0×10^{-5} and 1.2×10^{-5} at 95% C.L. The signal box was kept closed for this report.

Preliminary Results for Spring 2005 Conferences

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* In this note the charge conjugated states are included implicitly.

I. INTRODUCTION

The exclusive decay $B_s^0 \rightarrow \mu^+\mu^-\phi$ is a flavor-changing neutral current (FCNC) decay. In the Standard Model (SM) the related quark transition $b \rightarrow sl^+l^-$ is absent at tree level but proceeds at higher order through electroweak penguin and box diagrams. The investigations of rare FCNC B decay processes have received special attention since they open up the possibility of precision SM tests. In addition those decays are very sensitive to new physics. Within the SM the branching ratio of the exclusive decay $B_s^0 \rightarrow \phi\mu\mu$ is predicted to be at the order of $1.6 \cdot 10^{-6}$ [1] excluding long-distance effects. In models with a two Higgs-doublet the branching ratio of this decay might be enhanced [2], depending on the parameter values of $\tan\beta$ and the mass of the charged Higgs. Presently, the only existing experimental bound on $B_s^0 \rightarrow \mu^+\mu^-\phi$ is given by CDF from a Run I search [3]. They set an upper limit at a 95% C.L. of $\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-\phi) < 6.7 \times 10^{-5}$.

II. THE DØ DETECTOR

The sensitivity analysis uses a 300 pb^{-1} data set of $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV of Run II recorded by the DØ detector operating at the Fermilab Tevatron. The DØ detector is described elsewhere [4]. The main elements, relevant for this analysis, are the central tracking and muon detector system. The central tracking system consists of a silicon microstrip tracker (SMT) and a central fiber tracker (CFT), both located within a 2 T superconducting solenoidal magnet. The muon detector located outside the calorimeter consists of a layer of tracking detectors and scintillation trigger counters in front of toroidal magnets (1.8 T), followed by two more similar layers after the toroids, allowing for efficient detection out to pseudorapidity (η) of about 2.0.

The B_s^0 candidate event signature we are searching for contains two muons and two kaon candidate tracks which form a ϕ candidate. This signature is the same for the signal as well as for the normalization channel. The data selected in this analysis were triggered by four separate dimuon triggers. Trigger efficiencies for the signal and normalization samples were estimated using a trigger simulation software package. These efficiencies were also checked with data samples collected with unbiased or single muon triggers.

III. PRE-SELECTION

The pre-selection starts by requesting that identified muons match a central track and build a vertex. For the resonant $B_s^0 \rightarrow J/\psi\phi$ candidates, the invariant mass of the muon pair is required to be within 250 MeV/c^2 of the J/ψ mass. For the non-resonant $B_s^0 \rightarrow \mu^+\mu^-\phi$ candidates, the J/ψ and ψ' resonances were excluded. The ranges were chosen to cover $\pm5\sigma$ ($\sigma = 75$ MeV/c^2) of the J/ψ resolution around the observed resonance masses. Both muons are requested to have at least the medium quality criterium fulfilled. The $\chi^2/d.o.f.$ of the two muon vertex is requested to be $\chi^2/d.o.f. < 10$. The transverse momentum of each of the muons is required to be greater than 2.5 GeV/c and their pseudorapidity has to be $|\eta| < 2.0$ in order to be well inside the fiducial tracking and muon region. Tracks that are matched to each muon leg need at least three hits in the SMT and four hits in the CFT. For surviving events, the two-dimensional decay length in the plane transverse to the beamline $L_{x,y}$ is calculated. The error on the transverse decay length $\delta L_{x,y}$ is calculated by taking into account the uncertainties on both the primary and secondary vertex positions. The primary vertex itself is found with a beam spot constrained fit. It is requested that $\delta L_{x,y}$ has to be smaller than 150 μm. The transverse momentum of the candidate event needs to be greater than 5 GeV/c to ensure a similar p_T behavior of the $\mu^+\mu^-$-system in signal events as well as in normalization channel events. The dimuons are then combined with another pair of oppositely charged tracks, each with $p_T > 0.5$ GeV/c, to a B_s candidate vertex with a $\chi^2 < 36$ with 5 d.o.f. In addition each of the kaon candidates needs at least 3 hits in the SMT, and the collinearity of the B_s^0 candidate with respect to the direction from the primary to the secondary vertex has to be greater than 0.95. Finally the the ϕ candidate is required to have an invariant mass between 1.008 and 1.032 GeV/c^2. The successive cuts and the remaining candidates surviving each cut are shown in Table I. The number of good vertex events is already restricted by having at least one additional two track particle in the invariant mass range 0.950 to 1.132 GeV/c^2.

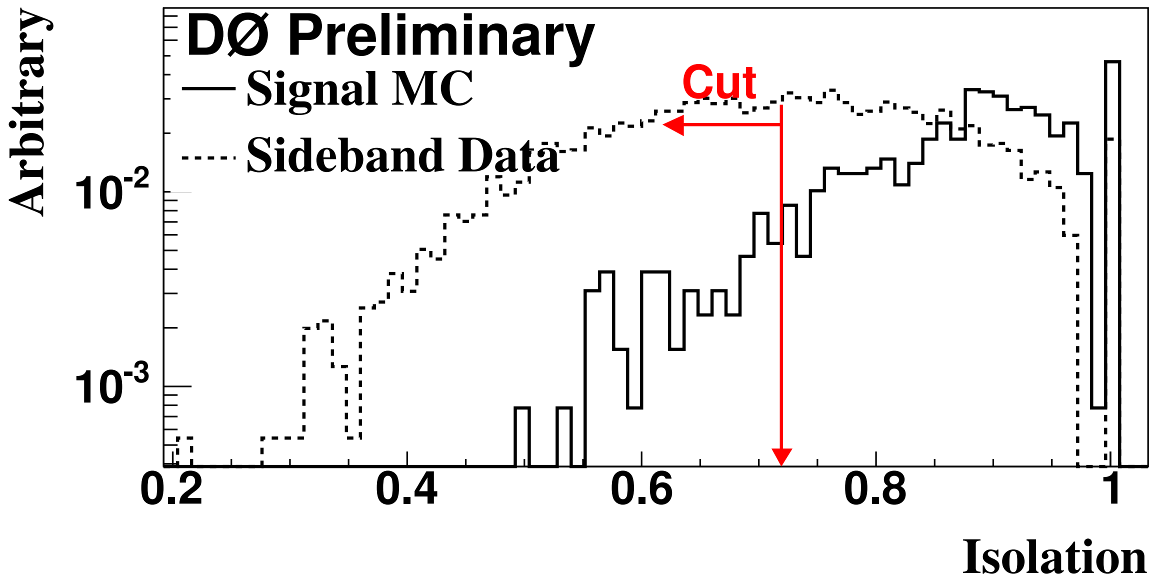

FIG. 1: Isolation variable after the pre-selection for data events from the sidebands and signal MC events

IV. DISCRIMINATING VARIABLES

For the final event selection we have used the same three discriminating variables that were already employed in the search for $B_s^0 \to \mu^+\mu^-$ [5]. The **isolation** variable I of the phi and muon pair is defined as:

$$I = \frac{|\vec{p}(\mu\mu\phi)|}{|\vec{p}(\mu\mu\phi)| + \sum\limits_{track\, i \neq B} p_i(\Delta R < 1)}$$

The $\sum\limits_{track\, i \neq B} p_i$, is the scalar sum over all tracks excluding the muon and kaon pair within a cone of $\Delta R < 1$ (where $\Delta R = \sqrt{(\Delta\Phi)^2 + (\Delta\eta)^2}$) around the momentum vector $\vec{p}(\mu^+\mu^-\phi)$ of the B_s^0 candidate.

All tracks that are counted in the isolation sum have the additional requirement that the z distance of the track to the z-vertex of the muon pair has to be smaller than 5 cm in order to avoid overlapping events coming from the same bunch crossing. The distribution of the isolation variable for signal MC and data after pre-selection is shown in Fig. 1.

The **pointing angle** α is defined as the angle between the momentum vector $\vec{p}(\mu^+\mu^-\phi)$ of the muon pair and the ϕ meson and the vector $\vec{l}_{Vtx}$ pointing from the primary vertex to the secondary vertex. If the two muons and the ϕ are coming from the decay of a parent particle B_s^0, the vector $\vec{l}_{Vtx}$ should point into the same direction as $\vec{p}(\mu^+\mu^-\phi)$. The angle α is well-defined and used as a consistency between the direction of the decay vertex and the flight direction of the B_s^0 candidate. Fig. 2 shows the distributions of the angle α for signal MC and data after pre-selection.

In order to discriminate against short-lived background, we have used the **transverse decay length significance** $L_{xy}/\delta_{L_{xy}}$ since it gives a better discriminating power then the transverse decay length alone. This length L_{xy} is defined as the projection of the decay length vector $\vec{l}_{Vtx}$ on the transverse momentum of the B_s^0-meson:

$$L_{xy} = \frac{\vec{l}_{Vtx} \cdot \vec{p}_T^{\,B}}{p_T^B} \quad (1)$$

Its error $\delta_{L_{xy}}$ is calculated by the error propagation of the uncertainties on both the primary and secondary vertex positions. Figure 3 shows the distributions of the decay length significance for signal MC and data.

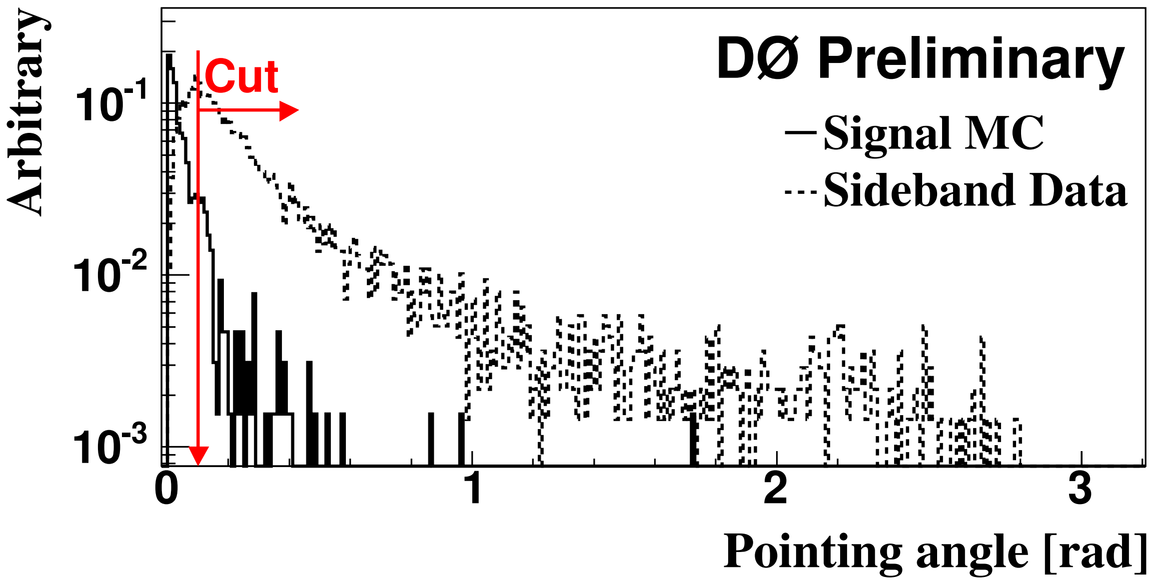

FIG. 2: The pointing angle α after the pre-selection for data events from the sidebands and signal MC events.

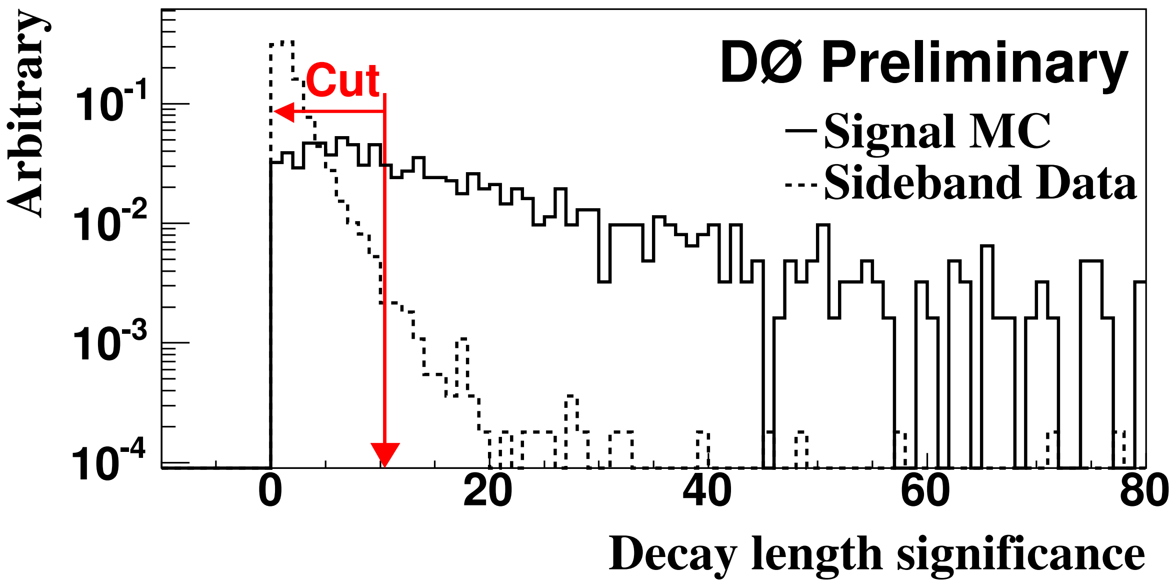

FIG. 3: The transverse decay length significance for data and signal MC events after the pre-selection.

Before optimizing the cuts on these discriminating variables, we restrict ourselves to a mass region of interest of $4.51 < M_{\mu^+\mu^-\phi} < 6.13$ GeV/c^2 containing the signal region around the PDG world average value of the B_s^0 mass of $m_{B_s^0} = 5369.6 \pm 2.4$ MeV/c^2 [6]. The whole mass region of interest is shifted downward with respect to the world average B_s^0 mass by 47 MeV/c^2 in order to correct the mass scale of the DØ tracker. The 47 MeV/c^2 mass shift was taken from the mean B_s^0 mass obtained from the fit to the $B_s^0 \to J/\psi\phi$ mass spectra without constraining the $\mu\mu$-pair to the J/ψ mass.

The signal box is blinded during the whole analysis and sufficiently far away from the sidebands. Table II defines the regions for the sidebands and the blinded signal box that have been used. The signal region corresponds to a window of ± 270 MeV/c^2 around the (shifted) world average mass value of the B_s^0. The expected mass resolution for $B_s^0 \to \mu^+\mu^-\phi$ in the MC is ≈ 75 MeV/c^2. The ± 270 MeV/c^2 corresponds therefore to $\pm 3.6\sigma$. After the cut optimization we shrink the blinded signal box to ± 225 MeV/c^2 for calculating the final sensitivity.

In order to find the optimal set of cuts we use a Random Grid Search (RGS) [7] and an optimization criterion proposed by G. Punzi [8]. The optimal set of cuts is found by maximizing the ratio P defined as:

$$P = \frac{\epsilon_{\mu\mu\phi}}{\frac{a}{2} + \sqrt{N_{Back}}}. \tag{2}$$

$\epsilon_{\mu\mu\phi}$ is the reconstruction efficiency of the signal MC after the pre-selection and N_{Back} is the expected number of background events extrapolated from the sidebands. 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 has been set to 2, corresponding to about 95% C.L.. The optimization has been performed on the complete set of signal MC including the charmonium resonances to increase the number of cut combinations. This can be justified, since the discriminating variables do not depend on the invariant dimuon mass. The resulting cut values that were obtained from the maximized P are listed in table III

The total signal efficiency relative to pre-selection of the three discriminating cuts turned out to be (52 ± 2)%. 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 5.1 ± 1.0. Figure 4 shows the remaining background events populating the lower and upper sidebands.

V. THE NORMALIZATION CHANNEL $B_s^0 \to J/\psi\phi$

In order to obtain a branching ratio limit for $B_s^0 \to \mu^+\mu^-\phi$, we have used $B_s^0 \to J/\psi\phi$ events with $J/\psi \to \mu^+\mu^-$ and $\phi \to K^+K^-$ as normalization. As mentioned above, the same cuts were applied to the $B_s^0 \to J/\psi\phi$ candidates. The contamination of muon pairs from the non-resonant $\mu^+\mu^-\phi$ decay in the resonant normalization region $J/\psi(\to \mu^+\mu^-)\phi$ is negligible. We therefore constrain the two muons to have an invariant mass equal to the J/ψ mass [6].

The mass spectrum of the reconstructed $B_s^0 \to J/\psi\phi$ for the full data sample is shown in Figure 5. A fit using a Gaussian function for the signal and a second order polynomial for the background yielded 74 ± 11 B_s^0 events, where only the statistical uncertainty is given. The obtained mass resolution of the B_s^0 is 27.3 MeV which compares very well to the resolution of the MC simulation of 26.2 MeV.

VI. CALCULATION OF THE SENSITIVITY

Since the box is still kept closed for this report, the number of candidate signal events for $B_s^0 \to \mu^+\mu^-\phi$ 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" defined in the unified approach of classical confidence interval construction by Feldman and Cousins [9].

Assuming that there is only background n_{back}, we calculate for each possible value of observation n_{obs} a 95% C.L upper limit $\mu(n_{obs}, n_{back})$ using the method by Feldman and Cousins [9]. The average upper limit on the signal events $< \mu(n_{back}) >$ is then obtained by weighting each limit from the hypothetical ensemble by its Poisson probability of occurrence:

$$< \mu(n_{back}) > = \sum_{n_{obs}=0}^{\infty} \mu(n_{obs}, n_{back}) \cdot \frac{(n_{back})^{n_{obs}}}{(n_{obs})!} \exp(-n_{back}) \tag{3}$$

In order to translate $< \mu(n_{back}) >$ into a 95% C.L. sensitivity limit we have used:

$$\frac{< \mathcal{B}(B_s^0 \to \mu^+\mu^-\phi) >}{\mathcal{B}(B_s^0 \to J/\psi\phi)} = \frac{< \mu(n_{back}) >}{N_{B_s^0}} \cdot \frac{\epsilon_{J/\psi\phi}}{\epsilon_{\mu\mu\phi}} \cdot \mathcal{B}(J/\psi \to \mu\mu) \tag{4}$$

where

- $\epsilon_{\mu\mu\phi}$ and $\epsilon_{J/\psi\phi}$ are the efficiencies of the signal and normalization channels, obtained from MC simulations, and
- $\mathcal{B}(J/\psi \to \mu\mu) = (5.88 \pm 0.1)\%$ [6].

The efficiencies $\epsilon_{\mu\mu\phi}$ and $\epsilon_{J/\psi\phi}$ 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 yielding an efficiency ratio of $\epsilon_{J/\psi\phi}/\epsilon_{J/\psi\mu\mu} = 2.19 \pm 0.13$, where the uncertainties are due to MC limiting statistics.

In order to avoid large uncertainties associated with the poorly known branching ratio of $B_s^0 \to J/\psi\phi$, we normalize the sensitivity to $\mathcal{B}(B_s^0 \to J/\psi\phi)$ as given in Eq. 4. For the calculation of $\frac{<\mathcal{B}(B_s^0 \to \mu^+\mu^-\phi)>}{\mathcal{B}(B_s^0 \to J/\psi\phi)}$ we have used the fixed cuts of Table III that were obtained with our optimization method performed on the data sample. Figure 4 shows the remaining background events in the lower and upper sidebands.

Using only these numbers without their uncertainties we obtain as a result for the sensitivity at 95% C.L. $\frac{<\mathcal{B}(B_s^0 \to \mu^+\mu^-\phi)>}{\mathcal{B}(B_s^0 \to J/\psi\phi)} = 1.1 \cdot 10^{-2}$. If the world average branching ratio [6] of $\mathcal{B}(B_s^0 \to J/\psi\phi) = 9.3 \pm 3.3 \cdot 10^{-4}$ is used, the sensitivity level to the rare decay is then $< \mathcal{B}(B_s^0 \to \mu^+\mu^-\phi) >= 1.0 \cdot 10^{-5}$.

VII. UNCERTAINTIES

The different sources of relative uncertainties that go into a sensitivity calculation of $< \mathcal{B} >$ are given in Table IV. Basically, the branching ratio of $B_s^0 \to J/\psi\phi$ has the largest uncertainty, but its uncertainty cancels due to our normalization. The second largest uncertainty of 20% is due to the background interpolation into the signal region. The uncertainty on the number of observed $B_s^0 \to J/\psi\phi$ events as the normalization channel is 14.8%. An additional uncertainty due to MC weighting is applied. Our MC for the normalization channel contained only CP-even states. Therefore another uncertainty concerning the CP odd-even eigenstates of the $B_s^0 \to J/\psi\phi$ events of 7% was assigned. This is a conservative systematic uncertainty and will be be reduced further during the review process.

The relative statistical uncertainties on the efficiencies $\epsilon_{\mu\mu\phi}^{B_s^0}$ and $\epsilon_{J/\psi\phi}$ are combined into one efficiency uncertainty number assuming no correlations.

The statistical and systematic uncertainties can be included into the sensitivity calculation by integrating over probability functions that parameterize the uncertainties. We have used a prescription [10] where we construct a frequentist confidence interval with the Feldman and Cousins [9] ordering scheme for the MC integration. The background was modeled as a Gaussian distribution with its mean value equal to the expected number of background events and its standard deviation equal to the background uncertainty. Including the statistical and systematic uncertainties, the sensitivity degrades to $< \mathcal{B}(B_s^0 \to \mu^+\mu^-\phi) > /\mathcal{B}(B_s^0 \to J/\psi\phi) = 1.3 \times 10^{-2}$. Using again the world average branching ratio [6] of $\mathcal{B}(B_s^0 \to J/\psi\phi)$, this sensitivity level corresponds to $< \mathcal{B}(B_s^0 \to \mu^+\mu^-\phi) >= 1.2 \cdot 10^{-5}$.

VIII. CONCLUSIONS

We have presented a sensitivity analysis of the search for the rare decay $B_s^0 \to \mu^+\mu^-\phi$ based on 300 pb^{-1} of data recorded with the DØ detector. The search is carried out as a blind analysis hiding the signal region around the B_s^0 and normalizing the events to $B_s^0 \to J/\psi\phi$. The sensitivity for the rare signal has been optimized by leaving the normalization channel untouched. For the data set the expected background extrapolated from the sidebands amounts to 5.1 $\pm$ 1.0 events. Using the concept of an expected upper limit on a 95% C.L. we obtain $< \mathcal{B}(B_s^0 \to \mu^+\mu^-\phi) > /\mathcal{B}(B_s^0 \to J/\psi\phi) = 1.1 \times 10^{-2}$. Using the world average value for $\mathcal{B}(B_s^0 \to J/\psi\phi)$ this corresponds to an absolute sensitivity of $< \mathcal{B}(B_s^0 \to \mu^+\mu^-\phi) >= 1.0 \times 10^{-5}$. If systematic uncertainties are included, the limit degrades to $< \mathcal{B}(B_s^0 \to \mu^+\mu^-\phi) > /\mathcal{B}(B_s^0 \to J/\psi\phi) = 1.3 \times 10^{-2}$ and $< \mathcal{B}(B_s^0 \to \mu^+\mu^-\phi) >= 1.2 \times 10^{-5}$, respectively.

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Cut	Value	#candidates
Good vertex		2,582,267
Mass region (GeV/c^2)	$0.5 < m_{\mu^+\mu^-} < 4.4$ excl. J/ψ,Ψ'	1,107,585
Muon Quality	two medium	566,844
$\chi^2/d.o.f.$ of vertex	< 10	377,596
Muon p_T (GeV/c)	> 2.5	215,720
Muon $\lvert\eta\rvert$	< 2.0	212,309
Tracking hits	cft> 3, smt > 2	170,690
$\delta L_{x,y}$ (mm)	< 0.15	160,139
B_s^0 Candidate p_T (GeV/c)	> 5.0	159,736
B_s^0 χ^2 vertex	< 36	154,597
Kaon hits	smt > 2	141,610
B_s^0 collinearity	> 0.95	44,257
ϕ mass (GeV/c^2)	$1.008 < m_\phi < 1.032$	6,577

TABLE I: Number of candidate events surviving the cuts in data used in the pre-selection analysis.

Region	min Mass (GeV/c^2)	max Mass (GeV/c^2)
region of interest	4.5126	6.1326
blinded signal region during optimization	5.0526	5.5926
final blinded signal region for sensitivity	5.0976	5.5476
sideband I	4.5126	5.0526
sideband II	5.5926	6.1326

TABLE II: The four invariant mass regions for signal and sidebands used for background estimation.

cut parameter	cut value	MC signal efficiency (%)	MC normalization efficiency (%)
Opening angle (rad)	< 0.1	81	82
Decay length significance	> 10.5	71	76
Isolation	> 0.72	92	92

TABLE III: The optimized cuts and their relative MC efficiencies for signal and normalization channel after maximizing P.

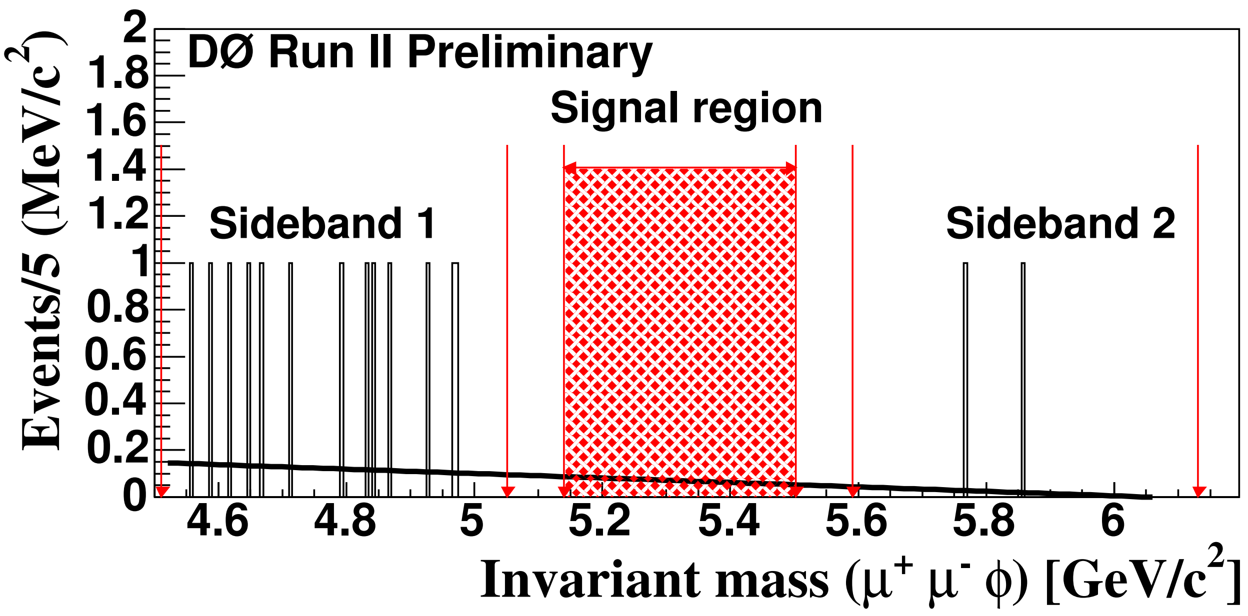

FIG. 4: The remaining background for the full data sample with our standard discriminating variables.

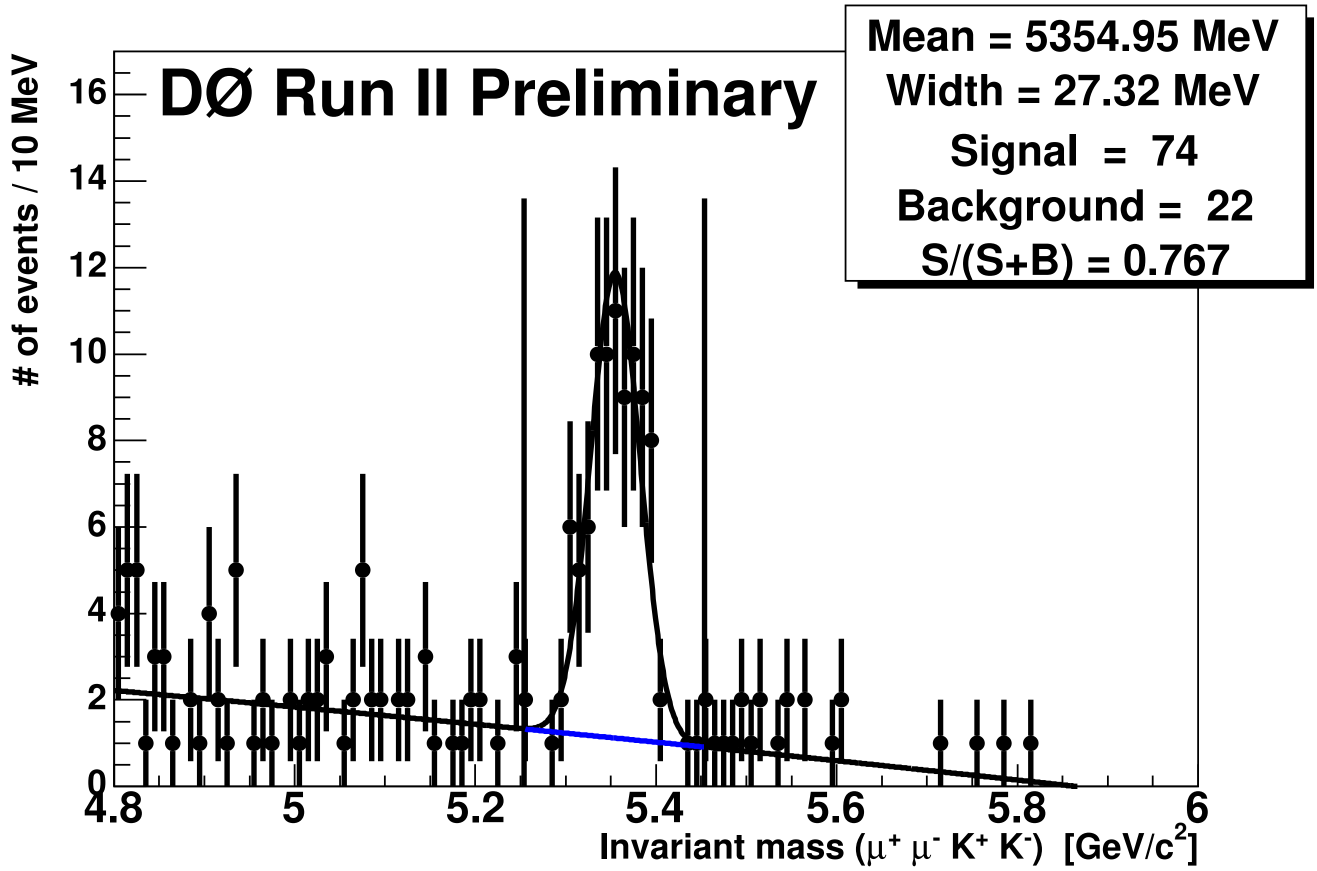

FIG. 5: The normalization channel $B_s^0 \to J/\psi\phi$ for the full data sample.

TABLE IV: The relative uncertainties for calculating an upper limit of $\mathcal{B}$. Note that the first uncertainty is not taken into account since we normalize the sensitivity to $\mathcal{B}(B_s^0 \to J/\psi\phi)$.

Source	Relative Uncertainty [%]
$\mathcal{B}(B_s^0 \to J/\psi\phi)$	35.5
$\mathcal{B}(J/\psi \to \mu\mu)$	1.7
$\epsilon_{J/\psi\phi}/\epsilon_{\mu\mu\phi}$	6.1
# of $B_s^0 \to J/\psi\phi$	14.8
MC weighting	3.8
tracking & trigger simulation	2.0
CP odd-even lifetime differences	7.0
Total	18.0
background uncertainty	19.6