LHCB POTENTIAL TO MEASURE/EXCLUDE THE BRANCHING RATIO OF THE DECAY $B_s \rightarrow \mu^+ \mu^-$

G. LANFRANCHI

*Laboratori Nazionali di Frascati dell'INFN
via E. Fermi 40, 00044 Frascati (Rome, Italy).
E-mail: Gaia.Lanfranchi@lnf.infn.it*

ON BEHALF OF THE LHCB COLLABORATION

We present the potential of the LHCb detector to measure/exclude the $B_s \rightarrow \mu^+ \mu^-$ branching ratio in pp collisions at $\sqrt{s} = 14$ TeV at LHC. LHCb can exclude the interesting region between 10^{-8} and Standard Model predictions with $\sim 0.5 \text{ fb}^{-1}$ and to claim a 3σ (5σ) observation (discovery) of the Standard Model prediction with $\sim 2 \text{ fb}^{-1}$ ($\sim 6 \text{ fb}^{-1}$) of integrated luminosity.

1. Introduction

Measurements at low energies may provide interesting indirect constraints on the masses of particles that are too heavy to be produced directly. This is particularly true for Flavour Changing Neutral Currents (FCNC) processes which are highly suppressed in the Standard Model (SM) and can only occur through higher order diagrams.

The SM prediction for the Branching Ratio (BR) of the FCNC decay $B_s \rightarrow \mu^+ \mu^-$ has been computed ¹ to be $BR(B_s \rightarrow \mu^+ \mu^-) = (3.4 \pm 0.5) \times 10^{-9}$ using the latest ΔM_s measurement at Tevatron ² which reduces significantly the uncertainty in the prediction.

However new physics contributions can significantly enhance this value. For example, in minimal supersymmetric extensions of the SM (MSSM) the $BR(B_s \rightarrow \mu^+ \mu^-)$ is found to be proportional ⁴ to $\sim \tan^6 \beta$, where $\tan \beta$ is the ratio of vacuum expectation values of the two neutral CP-even Higgs fields. Therefore it could be strongly enhanced for large values of $\tan \beta$.

A very interesting prediction comes from the constrained version of MSSM (CMSSM), where the constraint comes from the density of dark matter in the Universe ⁵. Within this framework, the anomalous magnetic moment of the muon $a_\mu = (g_\mu - 2)$ and the $BR(B_s \rightarrow \mu^+ \mu^-)$ have

been computed ⁶ as a function of few parameters: the universal gaugino mass $m_{1/2}$, the scalar mass m_0 , the trilinear soft supersymmetry-breaking parameter A_0 and $\tan\beta$. For large value of $\tan\beta$, e.g. $\tan\beta = 50$, the complete MSSM contributions to one loop to a_μ can easily account for the estimated discrepancy of 2.7σ between the SM predictions ⁷ and the experimental value ⁸ if the gaugino mass is in the interval 400-600 GeV. For this range of the gaugino mass the $BR(B_s \rightarrow \mu^+\mu^-)$ could be enhanced up to two orders of magnitude above the SM predictions.

The present experimental upper limit comes from CDF and D0 Collaborations ³ which claim $BR(B_s \rightarrow \mu^+\mu^-) < 7.5 \times 10^{-8}$ at 90% C.L. This upper limit is still a factor 21 above the SM prediction. Any improvement of the upper limit is therefore important for constraining new physics.

2. LHCb experimental conditions

The LHCb detector ⁹ will operate at the LHC collider with pp collisions at a center of mass energy $\sqrt{s} = 14$ TeV. At the nominal luminosity of $L = 2 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$, ~ 40 kHz of $b\bar{b}$ pairs will be produced in the LHCb acceptance ($1.9 < \eta < 4.9$).

Given the extremely low BR of the $B_s \rightarrow \mu^+\mu^-$ decay, the three main experimental requirements needed to perform such a measurement are a high efficient trigger, a good mass and vertex resolutions and an excellent muon identification capability for rejecting backgrounds.

In the following sections we will describe the LHCb potential in measuring this decay by focusing mainly on the issues related to signal efficiency and background rejection. A detailed description of the analysis can be found in reference ¹⁰.

3. Trigger

The LHCb has a two-level trigger system ¹¹. The first level trigger (L0) is a hardware trigger based on calorimeter and muon chambers informations: it reduces the input rate from ~ 10 MHz to ~ 1 MHz by requiring a muon, an electron or an hadron with transverse momentum (p_t) or energy (E_t) above a certain threshold. The second level trigger (HLT) is a software trigger running on the online farm at ~ 1 MHz input rate.

$B_s \rightarrow \mu^+\mu^-$ events will pass the L0 trigger either if a single muon has $p_t > 1.1$ GeV/c and the event has just one interaction vertex, or if two muons have a total $p_t > 1.3$ GeV/c. Since in the latter case there is no constraint on the number of interaction vertices, the L0 trigger efficiency

for di-muon events is independent of the instantaneous luminosity.

The HLT requires either a single muon with $pt > 3$ GeV/c and impact parameter significance $IPS > 3$ or a di-muon event with invariant mass $M_{\mu\mu} > 2.5$ GeV/c². The total trigger efficiency for $B_s \rightarrow \mu^+\mu^-$ events is expected to be $> 90\%$.

4. Event Reconstruction

The offline reconstruction starts by identifying two muons candidates of opposite charge with a common vertex. Muon candidates are searched among the long tracks sample^a. Typically the efficiency to reconstruct a long track is $\sim 95\%$. The average momentum resolution is $\delta p/p \sim 0.37\%$, the vertex resolution is ~ 110 μm in the z-position while the average precision of the track impact parameter is ~ 40 μm . A gaussian fit on the invariant mass distribution for signal events gives a resolution of ~ 18 MeV. The invariant mass resolution is crucial to reduce the level of combinatorial background and the misidentified two-body decays. This resolution also allows a clear separation between B_d (5279.4 MeV/c²) and B_s (5367.5 MeV/c²) decays. In this respect LHCb has a big advantage with respect to other LHC experiments¹²: ATLAS achieves an invariant mass resolution of ~ 80 MeV/c² while CMS ~ 36 MeV/c².

Long tracks which release a certain number of hits within some *field of interest* in the muon stations are identified as muon candidates¹³. The probability that a muon candidate is a real muon is parametrised into a likelihood function which take into account all the informations from the Muon system, the Calorimeter and the RICH detectors. The differences of likelihoods between a muon and a pion ($\Delta LL_{\mu\pi}$) or a muon and a kaon ($\Delta LL_{\mu K}$) are used as discriminant variables. The $\mu/\pi/K$ separation is function of the momentum: for a b inclusive sample the average efficiency for muons with $p > 3$ GeV/c is $\sim 96\%$ while the average probability to misidentify a hadron in the same range is $\sim 2\%$. For hadrons coming from B two-body decays the misidentification is lower ($< 1\%$) since their momentum spectrum is harder.

5. Analysis Strategy

The analysis for the $B_s \rightarrow \mu^+\mu^-$ search is done in two steps: first a very efficient selection removes the biggest amount of the background while keeping

^aA track is *long* if it crosses the entire LHCb tracking system from VELO to T-Station.

most of the signal within the LHCb acceptance. Then each event is weighted by the probability to be signal or background estimated on some discriminant variables. The combined probability depends on the assumed value for the BR and it is used for setting limits for exclusion and observation.

5.1. *Event selection*

The selection requires two muon candidates of opposite charge, forming a vertex with a $\chi^2 < 14$. The B candidate is required to have an $IPS < 6$. The z-position of the secondary di-muon vertex (SV) is required to be downstream with respect to the reconstructed primary vertex (PV). If more than one PV is reconstructed in the event, the one which the B candidate has the smallest impact parameter is chosen. The angle between the SV and PV direction and the B momentum has to be smaller than 0.1 rad. Finally the reconstructed invariant mass should be within a window of 5368 ± 60 MeV/c². The total efficiency for signal due to the acceptance, detection, reconstruction and selection is 10.2% and corresponds to an event yield of ~ 36 signal events/fb⁻¹. The same selection on a b inclusive sample gives ~ 376 k per fb⁻¹ background events.

5.2. *N-counting method*

Events surviving the selection are used to build three discriminant variables: the Geometry Likelihood, the Muon Identification Likelihood and the Invariant Mass Likelihood.

The Geometry Likelihood contains most of the informations related to the geometry of the event, such as the B_s lifetime, the minimum impact parameter of the two muons, the distance of closest approach of the two tracks, the B_s impact parameter and the isolation from other secondary vertices. These variables are combined in an optimal way by taking their correlations properly into account. A detailed description of this method can be found in reference ¹⁰. A similar method is described also in reference ¹⁴. The distribution of the Geometry Likelihood (GL) for signal, b inclusive and $b \rightarrow \mu X$, $\bar{b} \rightarrow \mu X$ samples is shown in Figs. 1.

The Muon Identification Likelihood contains the informations related to particle identification while the Invariant Mass Likelihood is just the invariant mass of the di-muon candidates.

In the sensitive region, defined as $GL > 0.5$ and ± 60 MeV/c² around the B_s mass, where the signal-to-background ratio is more relevant, the background is dominated by events with two real muons from different b

Figure 1. Distribution of the Geometry Likelihood for signal (solid black line), b inclusive (solid grey line) and $b \rightarrow \mu X$, $b \rightarrow \mu X$ (dashed black line) samples.

which combine to form a signal candidate. Background from two-body modes, as $B_{d,s} \rightarrow \pi\pi, \pi K, KK$, is instead very small: LHCb expects in the sensitive region ~ 1 events/fb $^{-1}$.

The three likelihoods are divided in bins and for each bin the expected number of signal (S_i) and background (B_i) events is computed. S_i depends on the assumed BR value. Both S_i and B_i depend on the integrated luminosity. In order to take into account the statistical uncertainty in the background predictions due to limited Monte Carlo statistics, each B_i is shifted upward such that the total number of background events has a 90% probability to be below the shifted value. In the real data the evaluation of the background levels will be done by using the huge amount of events from side bands and/or control samples.

The sensitivity to a given BR is computed with the same method used extensively at LEP in the search for the Higgs boson¹⁵. The BR exclusion at 90% CL is obtained by solving the equation:

$$CL_s = \frac{Poisson(N_{expected}^{S+B}(BR) \leq N_{observed})}{Poisson(N_{expected}^B \leq N_{observed})} = 10\%.$$

The formula gives the compatibility with the signal+background (S+B) hypothesis normalised to the compatibility to the background hypothesis¹⁵. Following the same reference¹⁵, the 3σ (5σ) sensitivity to a given BR is obtained from the equation $1-CL_B = 2.7 \times 10^{-3}$ (5.7×10^{-7}).

The BR exclusion at 90% CL as a function of the integrated luminosity

L is shown in Fig.2, left. This plot is made under the hypothesis that only background is observed. The band takes into account the statistical uncertainty in the background prediction. The BR observation (3σ) or discovery (5σ) is shown in Fig.2, right as a function of L . The shifted background is assumed to evaluate the significance.

From these plots we see that LHCb has the potential to exclude the interesting region between 10^{-8} and the SM prediction with very little L ($\sim 0.5 \text{ fb}^{-1}$) and to observe (discover) it, if SM value, with $\sim 2 \text{ fb}^{-1}$ ($\sim 6 \text{ fb}^{-1}$) of data.

Figure 2. $BR (\times 10^{-9})$ exclusion at 90% CL (left) and observation (3σ) or discovery (5σ) (right) as a function of integrated luminosity.

6. Conclusions

Simulations show that the LHCb experiment has the potential to exclude the $BR(B_s \rightarrow \mu^+ \mu^-)$ down to the SM prediction with the first 0.5 fb^{-1} and to observe this decay, if it has the SM value, in the first few years of data taking. This would allow to set strong constraints on new physics contributions, if any. The challenge will be to realize this potential with real data.

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