Analysis of $\mathbf{B^0_{(s)}} \to \mu^+\mu^-$ decays with Run 3 data at the LHCb experiment

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An analysis of the very rare decays $B^0_{(s)} \to \mu^+\mu^-$ is presented using data collected by the LHCb experiment at CERN. The studied decays proceed through flavour-changing neutral currents (FCNCs), which do not occur at tree level in the Standard Model and can therefore only proceed through higher-order loop diagrams, resulting in a strong suppression of their decay rates.. In addition, these processes are suppressed by Cabibbo-Kobayashi-Maskawa (CKM) matrix elements and helicity suppression. At the same time, their theoretical predictions are particularly precise due to the purely leptonic final state. The combination of strong suppression, precise theoretical predictions and a distinct experimental signature makes these decays especially sensitive to possible contributions from physics beyond the Standard Model.
While the $B^0_s \to \mu^+\mu^-$ decay was already observed in a combined measurement of the CMS and LHCb collaborations in 2014 and has since been measured several times, $B^0 \to \mu^+\mu^-$ is much rarer and has not yet been observed. The analysis therefore aims both to improve the precision of the $B^0_s \to \mu^+\mu^-$ measurement and to search for evidence of the $B^0 \to \mu^+\mu^-$ decay.

A key aspect of the analysis is the Upgrade I LHCb detector and the new dataset collected with it. Following the upgrade after Run 2 of the LHC, most detector components were renewed and the detector now operates at a substantially higher instantaneous luminosity with a fully software-based trigger. The dataset used in the analysis is collected in 2024 and 2025 at a centre-of-mass energy of 13.6 TeV and corresponds to approximately 18 fb^{-1} of integrated luminosity. The early 2024 data suffered from suboptimal detector alignment, which is substantially improved by offline calibrations. After these corrections, the reconstructed mass resolution is found to be comparable to that of the previous detector.

The selection of candidate events consists of a dedicated trigger strategy, several requirements based on the reconstructed tracks, vertices, and particle identification, as well as a multi-level boosted decision tree (BDT) selection. Thanks to the new detector, the same trigger strategy can be used for the signal decays and the normalisation channel $B^0 \to K^+\pi^-$ which greatly simplifies the normalisation. To reduce the overwhelming amounts of background emerging from the random combination of unrelated tracks, machine learning methods are employed. In particular, a first BDT provides an initial background suppression, while a second, global BDT uses isolation information from track-based isolation BDTs to distinguish signal candidates from other tracks in the event. The output of the final BDT is transformed to be uniform for signal events, allowing the subsequent mass fit to be performed in different BDT bins, which enhances

the sensitivity.
Another important part of the analysis concerns the differences between simulated events and real detector data. Since the detector response and operating conditions are complex and can change with time, the simulation has to be corrected and calibrated. The analysis therefore applies corrections to the decay kinematics and event multiplicity, tracking efficiency, trigger efficiency and particle-identification efficiency using data-driven techniques. For example, simulated events are reweighted using control-mode data, while trigger and particle-identification efficiencies are calibrated directly from data. These corrections are necessary to obtain reliable efficiency estimates for the branching-fraction measurement.

The reliability of the analysis is verified using several control modes. Absolute and normalised branching fractions of $B^0_{(s)} \to h^+h'^-$ decays (with $h, h' \in [K, \pi]$) are studied, as well as the ratio of $B^0 \to K^+\pi^-$ to $B^+ \to J/\psi K^+$. The results of these cross-checks are consistent with the expected values and are used to validate the analysis strategy and identify possible systematic problems.

Finally, the expected sensitivity to the signal decays is assessed through a blinded fit to the dimuon invariant-mass distribution. The fit is performed simultaneously in different BDT regions. Especially in the high BDT regions, a particularly low background level is observed. The expected precision improves with the larger Run 3 dataset, and pseudo-experiments are used to study the sensitivity to the very rare $B^0 \to \mu^+\mu^-$ decay. The preliminary results indicate a good possibility of obtaining evidence for this decay.

Only selected aspects of the analysis are covered in this contribution, as the study is conducted by a large team of researchers from several institutes, with different members contributing to various aspects of the analysis. The discussion focuses on those aspects to which the author of this contribution makes a substantial contribution, while the full analysis encompasses a much broader range of topics. Overall, the analysis is well advanced, with the remaining work consisting mainly of finalisations. These developments and the new dataset of the LHCb Upgrade 1 detector place the experiment increasingly close to the sensitivity required to find evidence for $B^0 \to \mu^+\mu^-$.