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Search for the lepton-flavour-violating decays $B_s^0 \rightarrow \tau^\pm \mu^\mp$ and $B^0 \rightarrow \tau^\pm \mu^\mp$

LHCb collaboration

Abstract

A search for $B_s^0 \rightarrow \tau^\pm \mu^\mp$ and $B^0 \rightarrow \tau^\pm \mu^\mp$ decays is performed using data corresponding to an integrated luminosity of 3 fb^{-1} of proton-proton collisions, recorded with the LHCb detector in 2011 and 2012. For this search, the τ lepton is reconstructed in the $\tau^- \rightarrow \pi^- \pi^+ \pi^- \nu_\tau$ channel. No significant signal is observed. Assuming no contribution from $B^0 \rightarrow \tau^\pm \mu^\mp$ decays, an upper limit is set on the $B_s^0 \rightarrow \tau^\pm \mu^\mp$ branching fraction of $\mathcal{B}(B_s^0 \rightarrow \tau^\pm \mu^\mp) < 4.2 \times 10^{-5}$ at 95% confidence level. If instead no contribution from $B_s^0 \rightarrow \tau^\pm \mu^\mp$ decays is assumed, a limit of $\mathcal{B}(B^0 \rightarrow \tau^\pm \mu^\mp) < 1.4 \times 10^{-5}$ is obtained at 95% confidence level. These are the first limit on $\mathcal{B}(B_s^0 \rightarrow \tau^\pm \mu^\mp)$ and the world's best limit on $\mathcal{B}(B^0 \rightarrow \tau^\pm \mu^\mp)$.

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Lepton-flavour-violating B decays, such as $B_{(s)}^0 \rightarrow \tau^\pm \mu^\mp$ (the inclusion of charge-conjugate processes is implied throughout this Letter), may occur in the Standard Model (SM) via one-loop diagrams with neutrino oscillations, but are highly suppressed, with branching fractions, \mathcal{B} , expected to be of the order of 10^{-54} [1]. Hence they stand well beyond current and future experimental sensitivities. However, many models proposed to explain the recent experimental tensions mentioned below naturally allow for experimentally accessible rates for these processes. Among them, models containing a heavy neutral gauge boson (Z') could lead to a $B_s^0 \rightarrow \tau^\pm \mu^\mp$ branching fraction of up to 10^{-8} [2] or few 10^{-5} [3]. In models with either scalar or vector leptoquarks, the largest predictions for the $B_s^0 \rightarrow \tau^\pm \mu^\mp$ branching fraction range between 10^{-9} and 10^{-5} , depending on the assumed leptoquark mass [4, 5]. The three-site Pati–Salam gauge model favours values for this branching fraction in the range 10^{-4} to 10^{-6} [6, 7].

The SM predicts universal electroweak couplings for the three lepton families. Experimental tests of Lepton Flavour Universality (LFU) performed in $b \rightarrow s \ell^+ \ell^-$ and $b \rightarrow c \ell^- \bar{\nu}$ transitions show tensions with respect to the SM predictions in the observables $R_{K^{(*)}}$ [8, 9] and $\mathcal{R}(D^{(*)})$ [10], reaching, in the latter case, a discrepancy greater than 3σ from the SM expectations. Possible deviations from LFU reinforce the importance of Lepton Flavour Violation (LFV) searches, as scenarios beyond the SM departing from LFU usually imply LFV as well [11].

An upper limit $\mathcal{B}(B^0 \rightarrow \tau^\pm \mu^\mp) < 2.2 \times 10^{-5}$ at 90% confidence level (CL) has been set by the BaBar collaboration [12]. There are currently no experimental results for the $B_s^0 \rightarrow \tau^\pm \mu^\mp$ mode.

The first search for the decay $B_s^0 \rightarrow \tau^\pm \mu^\mp$ is reported in this Letter, along with a search for the $B^0 \rightarrow \tau^\pm \mu^\mp$ decay. The analysis is performed on data corresponding to an integrated luminosity of 3 fb^{-1} of proton-proton (pp) collisions, recorded with the LHCb detector during the years 2011 and 2012 at centre-of-mass energies of 7 and 8 TeV, respectively. The τ leptons are reconstructed through the decay $\tau^- \rightarrow \pi^- \pi^+ \pi^- \nu_\tau$, which mainly proceeds via the production of two intermediate resonances, $a_1(1260)^- \rightarrow \pi^+ \pi^- \pi^-$ and $\rho(770)^0 \rightarrow \pi^+ \pi^-$ [13], which help in the signal selection. In this mode, the τ decay vertex can be precisely reconstructed, facilitating a good reconstruction of the B invariant mass despite the undetected neutrino. To avoid experimenter bias, the B meson invariant-mass signal region was not examined until the selection and fit procedures were finalised. The signal yield is determined by performing an unbinned maximum-likelihood fit to the reconstructed B invariant mass and is converted into a branching fraction using the decay $B^0 \rightarrow D^-(\rightarrow K^+ \pi^- \pi^-) \pi^+$ as a normalisation channel.

The LHCb detector [14, 15] is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$, designed for the study of particles containing b or c quarks. The detector includes a high-precision tracking system consisting of a silicon-strip vertex detector surrounding the pp interaction region, a large-area silicon-strip detector located upstream of a dipole magnet with a bending power of about 4 Tm, and three stations of silicon-strip detectors and straw drift tubes placed downstream of the magnet. The tracking system provides a measurement of the momentum, p , of charged particles with a relative uncertainty varying from 0.5% at low momentum to 1.0% at 200 GeV/ c . The minimum distance of a track to a primary vertex (PV), the impact parameter (IP), is measured with a resolution of $(15 + 29/p_T) \mu\text{m}$, where p_T is the component of the momentum transverse to the beam, in GeV/ c . Different types of charged hadrons are distinguished using information from two ring-imaging Cherenkov detectors. Photons,

electrons and hadrons are identified by a calorimeter system consisting of scintillating-pad and preshower detectors, an electromagnetic and a hadronic calorimeter. Muons are identified by a system composed of alternating layers of iron and multiwire proportional chambers.

The online event selection is performed by a trigger [16] consisting of a hardware stage based on information from the calorimeter and muon systems, followed by a software stage, which performs a full event reconstruction. At the hardware trigger stage, signal candidates are required to have a muon with high p_T , while, for the normalisation sample, events are required to have a hadron with high transverse energy in the calorimeters. The software trigger requires a two-, three-, or four-track secondary vertex with a significant displacement from any primary pp interaction vertex. A multivariate algorithm [17] is used for the identification of secondary vertices consistent with the decay of a b hadron. At least one charged particle must have a minimum transverse momentum $p_T > 1.0$ (1.6) GeV/ c for muons (hadrons), and be inconsistent with originating from a PV.

Simulation is used to optimise the selection, determine the signal model for the fit and obtain the selection efficiencies. In the simulation, pp collisions are generated using PYTHIA [18] with a specific LHCb configuration [19]. The τ decay is simulated using the TAUOLA decay library tuned with BaBar data [20], while the decays of all other unstable particles are described by EVTGEN [21]. Final-state radiation is accounted for using PHOTOS [22]. The interaction of the generated particles with the detector, and its response, are implemented using the GEANT4 toolkit [23], as described in Ref. [24].

Signal and normalisation candidates are built from tracks that are inconsistent with originating from any PV. Candidate $\tau^- \rightarrow \pi^- \pi^+ \pi^- \nu_\tau$ and $D^- \rightarrow K^+ \pi^- \pi^-$ decays are reconstructed from three tracks forming a good-quality vertex and with particle identification information corresponding to their assumed particle hypotheses. Candidate $B_{(s)}^0 \rightarrow \tau^\pm \mu^\mp$ decays are formed by combining a reconstructed τ lepton and an oppositely charged track identified as a muon. A sample of same-sign candidates, which are formed by a τ lepton and a muon with identical charges, is also selected to serve as a proxy for the background. For the normalisation mode, $B^0 \rightarrow D^- \pi^+$ candidates are made out of a reconstructed D meson and an oppositely charged track identified as a pion. The decay vertex of the signal or normalisation B candidate is determined through a fit to all reconstructed particles in the decay chain [25], that is required to be of good quality. The B -meson p_T is required to be greater than 5 GeV/ c for both signal and normalisation modes.

While the neutrino from the τ decay escapes detection, its momentum vector can be constrained from the measured positions of the primary and τ decay vertices, the momenta of the muon and the three pions, and the trajectory of the muon. Imposing that the invariant mass of the three pions and missing neutrino corresponds to the true mass of the τ lepton, and requiring that the B decay vertex lies on the trajectories of the muon, of the τ lepton and of the B meson, the $B_{(s)}^0 \rightarrow \tau^\pm \mu^\mp$ candidate invariant mass can be determined analytically with a two-fold ambiguity. The solution whose distribution shows the largest separation between signal and background is used as the reconstructed B invariant mass, M_B , in the analysis. Due to finite measurement resolutions, 32% of selected signal in the simulated sample and 48% of same-sign candidates in data have nonphysical solutions and are removed, thereby improving the signal-to-background ratio. The distribution of M_B for the remaining candidates is shown in Fig. 1. To reduce the data to a manageable level and focus on the rejection of the most difficult backgrounds, the

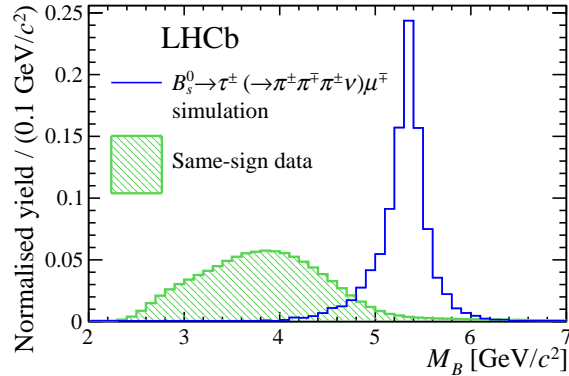


Figure 1: Distribution of the reconstructed B invariant mass for $B_s^0 \rightarrow \tau^\pm (\rightarrow \pi^\pm \pi^\mp \pi^\pm \nu_\tau) \mu^\mp$ simulated decays and same-sign candidates in data after initial selection (see text).

low-mass region with $M_B < 4 \text{ GeV}/c^2$ is discarded. The signal loss due to this requirement is negligible.

To further reduce the background, additional requirements, optimised with same-sign candidates and simulated samples, are applied to the selected $B_{(s)}^0 \rightarrow \tau^\pm \mu^\mp$ decays. Taking advantage of the resonant structure of the $\tau^- \rightarrow \pi^- \pi^+ \pi^- \nu_\tau$ decay, candidates with both combinations of oppositely charged pions with invariant-masses below $550 \text{ MeV}/c^2$ are removed. Candidates with a three-pion invariant mass greater than $1.8 \text{ GeV}/c^2$ are discarded to veto the background contribution due to $D^+ \rightarrow \pi^+ \pi^- \pi^+$ decays. A set of isolation variables is used to reduce background from decays with additional reconstructed particles. The first class of isolation variables exploits the presence of activity in the calorimeter to identify the contribution of neutral particles contained in a cone centred on the B or τ flight directions. The second class is based on the presence of additional tracks consistent with originating from the B or τ decay vertices, or uses a multivariate classifier, trained on simulated data, to discriminate against candidates whose decay products are compatible with forming good-quality vertices with other tracks in the event. These variables are combined using a Boosted Decision Tree (BDT) [26], trained on same-sign candidates and simulated $B_s^0 \rightarrow \tau^\pm \mu^\mp$ decays. Candidates with a BDT output compatible with that of background are discarded. A second BDT is used to reduce to a negligible level the contribution of combinatorial background, which extends over the whole mass range but dominates at higher masses. It uses variables related to vertex quality and reconstructed particle opening angles and is trained on samples of same-sign candidates with $M_B > 6.2 \text{ GeV}/c^2$ and simulated $B_s^0 \rightarrow \tau^\pm \mu^\mp$ decays. Specific background decays, such as $B_{(s)}^0 \rightarrow D_{(s)}^- (\rightarrow \mu^- \bar{\nu}_\mu) \pi^+ \pi^- \pi^+$, have M_B distributions peaking in the signal region. In these decays, the three pions come from the B decay vertex, and therefore the reconstructed B and τ decay vertices are very close. Discarding candidates with a reconstructed τ decay-time significance lower than 1.8 reduces this type of background to a negligible level while keeping $\sim 75\%$ of signal, according to studies performed on simulation. All previously described selection criteria also reject $\sim 96\%$ of a possible contribution from the $B^0 \rightarrow a_1(1260)^- \mu^+ \nu_\mu$ mode. Its rate is currently unmeasured, but, given that the largest known $b \rightarrow u$ semileptonic decay branching fractions are of the order of 10^{-4} , its branching fraction is not expected to be much higher. Events from the decay $\tau^- \rightarrow \pi^- \pi^+ \pi^- \pi^0 \nu_\tau$ passing the selection are also included as signal. After the selection

17 746 events are retained from the data sample. The selection efficiencies for the signal and normalisation modes, $\epsilon_{B_{(s)} \rightarrow \tau \mu}$ and $\epsilon_{B \rightarrow D \pi}$, respectively, are estimated using simulation or, whenever possible, data. The efficiency $\epsilon_{B_{(s)} \rightarrow \tau \mu}$ includes those for both $\tau^- \rightarrow \pi^- \pi^+ \pi^- \nu_\tau$ and $\tau^- \rightarrow \pi^- \pi^+ \pi^- \pi^0 \nu_\tau$ decays, where the latter is weighted by the ratio of the two branching fractions. The tracking and particle identification efficiencies are determined using data [27,28]. The trigger efficiency for the normalisation channel is estimated using a trigger-unbiased subsample made of events which have been triggered independently of the normalisation candidate. For the signal, muons from $B^+ \rightarrow J/\psi (\rightarrow \mu^+ \mu^-) K^+$ decays are used to evaluate the muon trigger efficiency and corrections are applied to the simulated signal samples. To account for differences between the control and the signal samples, the efficiency is computed as a function of the muon p_T and IP. Simulation as well as $B^+ \rightarrow J/\psi (\rightarrow \mu^+ \mu^-) K^+$ decays are used to determine the software-trigger efficiency and its systematic uncertainty.

The signal yield for the normalisation mode is obtained from a fit to the invariant-mass distribution of the $B^0 \rightarrow D^- \pi^+$ candidates. In the fit the signal is modelled by the sum of two Crystal Ball (CB) [29] functions, with tails on opposite sides, having common means and widths, but independent tail parameters. The tail parameters are fixed to values determined from a fit to a sample of $B^0 \rightarrow D^- (\rightarrow K^+ \pi^- \pi^-) \pi^+$ simulated decays, while all other parameters are left free. The small background contribution is described by an exponential function. The measured yield of the $B^0 \rightarrow D^- \pi^+$ mode is $N^{\text{norm}} = 22\,588 \pm 176$ where the uncertainty is statistical only.

The $B_{(s)}^0 \rightarrow \tau^\pm \mu^\mp$ branching fractions can be written as

$$\mathcal{B}(B_{(s)}^0 \rightarrow \tau^\pm \mu^\mp) = \alpha_{(s)}^{\text{norm}} \cdot N_{(s)}^{\text{sig}}, \quad (1)$$

where $N_{(s)}^{\text{sig}}$ is the number of observed $B_{(s)}^0 \rightarrow \tau^\pm \mu^\mp$ decays and $\alpha_{(s)}^{\text{norm}}$ a normalisation factor. The latter is defined by

$$\alpha_{(s)}^{\text{norm}} = \frac{f_{B^0}}{f_{B_{(s)}^0}} \cdot \frac{\mathcal{B}(B^0 \rightarrow D^- (\rightarrow K^+ \pi^- \pi^-) \pi^+)}{\mathcal{B}(\tau^- \rightarrow \pi^- \pi^+ \pi^- \nu_\tau)} \cdot \frac{\epsilon_{B \rightarrow D \pi}}{\epsilon_{B_{(s)} \rightarrow \tau \mu}} \cdot \frac{1}{N^{\text{norm}}}, \quad (2)$$

using externally measured quantities: the ratio of b -quark hadronisation fractions to B_s^0 and B^0 mesons, $f_{B_s^0}/f_{B^0} = 0.259 \pm 0.015$ [30], $\mathcal{B}(B^0 \rightarrow D^- (\rightarrow K^+ \pi^- \pi^-) \pi^+) = (2.26 \pm 0.14) \times 10^{-4}$ [31] and $\mathcal{B}(\tau^- \rightarrow \pi^- \pi^+ \pi^- \nu_\tau) = (9.02 \pm 0.05)\%$ [31]. The measured values of $\alpha_{(s)}^{\text{norm}}$ for the B_s^0 and B^0 modes are, respectively,

$$\begin{aligned} \alpha_s^{\text{norm}} &= (4.32 \pm 0.19 \pm 0.45 \pm 0.36) \times 10^{-7} \text{ and} \\ \alpha^{\text{norm}} &= (1.25 \pm 0.06 \pm 0.13 \pm 0.08) \times 10^{-7}, \end{aligned}$$

where the three quoted uncertainties are the statistical uncertainty due to the sizes of the signal and normalisation simulated and data samples, the systematic uncertainty on the selection efficiencies (dominated by the trigger efficiency contribution, $\sim 11\%$) and the total uncertainty on the externally measured quantities.

A final BDT is built to split the selected candidates into four samples with different signal-to-background ratios. It combines 16 discriminating variables, which are not correlated with the B invariant mass. The most important ones are the invariant masses of the three-pion system and of the two combinations of oppositely charged pions, the

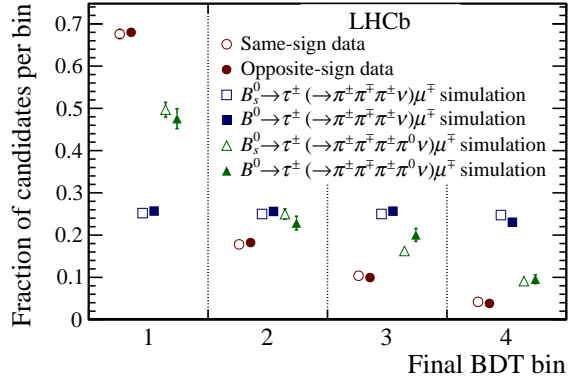


Figure 2: Final BDT output binned distributions for data and simulated signal samples. The markers are displaced horizontally to improve visibility.

B -meson IP and flight distance significances, and the output of the BDT based on isolation variables. The output of the BDT is transformed to have a uniform distribution between 0 and 1 for $B_s^0 \rightarrow \tau^\pm (\rightarrow \pi^\pm \pi^\mp \pi^\pm \nu_\tau) \mu^\mp$ simulated decays. As a consequence, its distribution for the background peaks at low BDT values. All samples are divided into four bins of equal width in BDT output. Their distributions are shown in Fig. 2.

The signal yield is evaluated by performing a simultaneous unbinned maximum-likelihood fit to the M_B distributions in the range $[4.6, 5.8]$ GeV/c^2 of the four samples corresponding to different BDT bins. In each bin, the data are described by the sum of a signal and a background component. The background shape is modelled by the upper tail of a reversed CB function, whose peak position and tail parameters are shared among BDT bins. For the determination of the systematic uncertainties, different sets of constrained parameters or alternative background models, such as the sum of two Gaussian functions, are considered. The signal shapes are described by double-sided Hypatia functions [32] whose parameters are initialized to the values obtained from a fit to the $B_s^0 \rightarrow \tau^\pm \mu^\mp$ and $B^0 \rightarrow \tau^\pm \mu^\mp$ simulated samples and allowed to vary within Gaussian constraints accounting for possible discrepancies between data and simulation. As the separation between $B_s^0 \rightarrow \tau^\pm \mu^\mp$ and $B^0 \rightarrow \tau^\pm \mu^\mp$ signal shapes is limited, two independent fits are performed assuming the contribution of either the B_s^0 or the B^0 signal only. The signal fractional yields in each BDT bin are Gaussian constrained according to their expected values and uncertainties. The fit result corresponding to the hypothesis of B_s^0 signal only is shown in Fig. 3. The fit procedure is validated by performing fits to a set of pseudoexperiments where the mass distributions are randomly generated according to the background model observed in the data. The pulls of all fitted parameters are normally distributed except those of the signal yields N^{sig} , which exhibit a very small bias of -3 ± 1 (2 ± 2) events for the B_s^0 (B^0) mode. This effect is accounted for by adding the bias to N^{sig} in the simultaneous fit. The obtained signal yields are

$$N_{B_s^0 \rightarrow \tau^\pm \mu^\mp}^{\text{sig}} = -16 \pm 38 \text{ and}$$

$$N_{B^0 \rightarrow \tau^\pm \mu^\mp}^{\text{sig}} = -65 \pm 58,$$

showing no evidence for any signal excess.

Using $\alpha_{(s)}^{\text{norm}}$ and Eq. 1, the signal yield obtained from the likelihood fit is translated to an

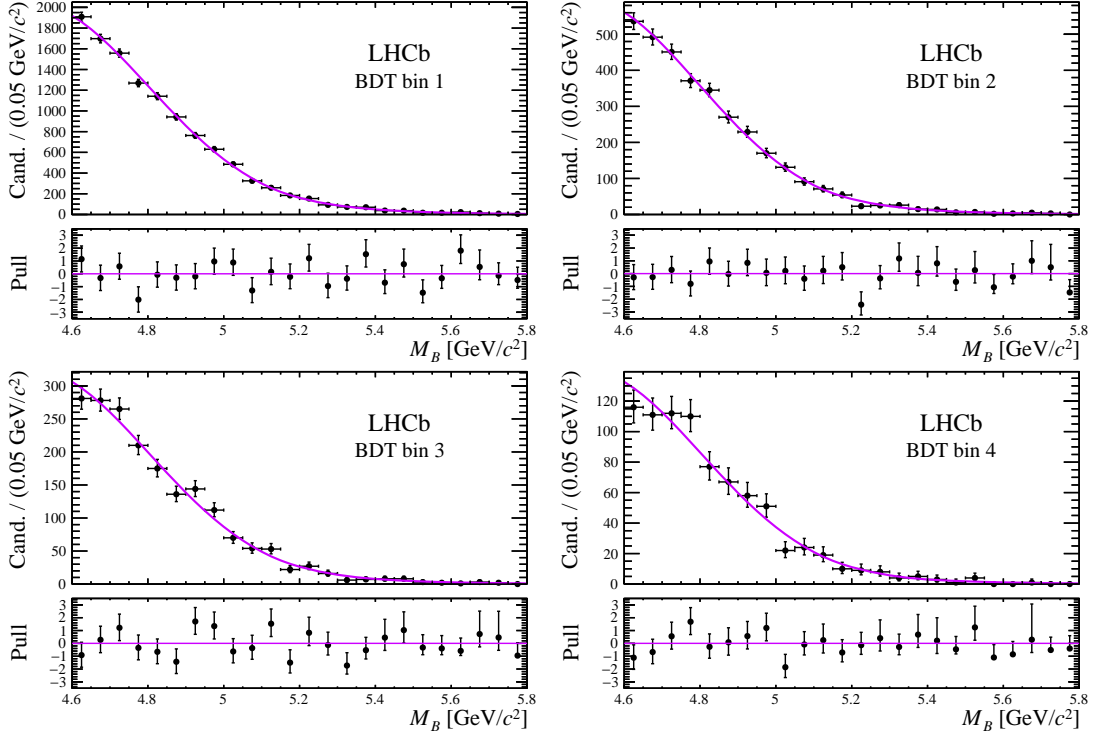


Figure 3: Distributions of the reconstructed B invariant-mass in data in the four final BDT bins with the projections of the fit for the B_s^0 signal-only hypothesis overlaid. The lower-part of each figure shows the normalised residuals.

Table 1: Expected and observed 90% and 95% CL limits on the $B_{(s)}^0 \rightarrow \tau^\pm \mu^\mp$ branching fraction.

Mode	Limit	90% CL	95% CL
$B_s^0 \rightarrow \tau^\pm \mu^\mp$	Observed	3.4×10^{-5}	4.2×10^{-5}
	Expected	3.9×10^{-5}	4.7×10^{-5}
$B^0 \rightarrow \tau^\pm \mu^\mp$	Observed	1.2×10^{-5}	1.4×10^{-5}
	Expected	1.6×10^{-5}	1.9×10^{-5}

upper limit on the branching fraction with the CLs method [33,34]. The total uncertainty on the normalisation factor is accounted for as an additional Gaussian constraint in the simultaneous fit. The expected and observed CLs values as a function of the branching fraction are shown in the Supplemental Material [35]. The corresponding limits on the B_s^0 and B^0 branching fractions at 90% and 95% CL are given in Table 1 assuming negligible contribution from the $B^0 \rightarrow a_1(1260)^- \mu^+ \nu_\mu$ mode. A possible residual contribution of this background would lower the expected limits by $\sim 16\% \times (\mathcal{B}(B^0 \rightarrow a_1(1260)^- \mu^+ \nu_\mu)/10^{-4})$.

The impact of systematic uncertainties on the final limits is about 35%, dominated by the uncertainty on the background model.

These results represent the best upper limits to date. They constitute a factor ~ 2 improvement with respect to the BaBar result for the B^0 mode [12] and the first measurement for the B_s^0 mode. The allowed range on the $B_s^0 \rightarrow \tau^\pm \mu^\mp$ branching fraction preferred by the three-site Pati–Salam model [6, 7] is significantly reduced by the results

presented in this Letter.

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Supplemental material for LHCb-PAPER-2019-016

Figures 4 and 5 show the expected and observed CLs values as a function of the $B_s^0 \rightarrow \tau^\pm \mu^\mp$ and $B^0 \rightarrow \tau^\pm \mu^\mp$ branching fractions.

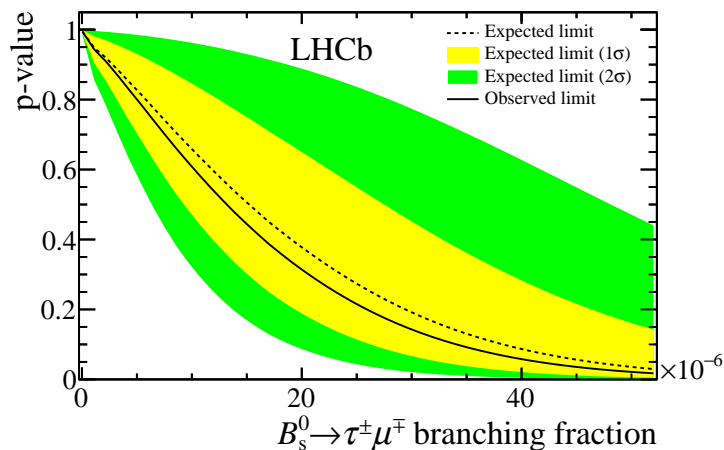


Figure 4: The expected and observed p-values derived with the CLs method as a function of the $B_s^0 \rightarrow \tau^\pm \mu^\mp$ branching fraction.

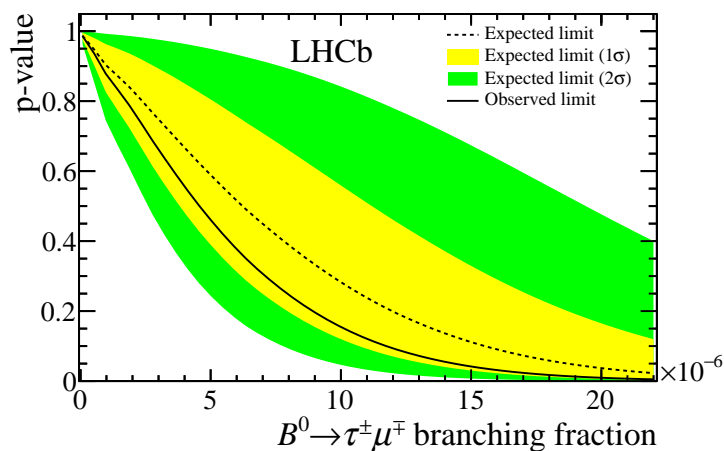


Figure 5: The expected and observed p-values derived with the CLs method as a function of the $B^0 \rightarrow \tau^\pm \mu^\mp$ branching fraction.

LHCb collaboration

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