Establishing a search for $b \to s\ell^+\ell^-$ anomalies at the LHC

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ABSTRACT: One of the fundamental predictions of the Standard Model is Lepton Flavour Universality. Any deviation from this prediction would indicate the existence of physics beyond the Standard Model. Recent LHCb measurements present a pattern of deviations from this prediction in rare B-meson decays. While not yet statistically significant (currently $2.2 - 2.6\sigma$), these measurements show an imbalance in the ratio of B-meson decays to a pair of muons in association with a Kaon and decays to a pair of electrons in association with a Kaon. If the measured deviations are indeed present in nature, new physics may mediate interactions involving a pair of same flavour leptons, a b- and an s-quark. We present the prospect for a search of new physics in this type of interactions at the LHC, in a process that involves an s-quark, and a final state with two leptons and a b-jet. The proposed search can improve the sensitivity to new physics in these processes by a factor of four compared to current searches with in the total dataset expected at the LHC.

Contents

1 Introduction

One of the fundamental predictions of the Standard Model (SM) is Lepton Flavour Universality (LFU). The photon and the Z-boson, independently, couple with the same strength to all three generations of leptons. This property was tested extensively at LEP and SLD [1]. Any measured deviation from this prediction implies the existence of new physics, beyond the SM (BSM).

Over the past several years, measurements of rare B-meson decays have exhibited deviations from the SM prediction [2, 4–11]. These anomalies occur in the $b \to s\ell^+\ell^-$ transitions and are manifested by an imbalance in the ratio between the number of events measured in a final state with a pair of muons to a pair of electrons.

The value of this ratio is stated within a given range of the lepton pair mass squared, $[q^2_{\min}, q^2_{\max}]$. The q^2-dependent partial width of the decay is Γ. Currently there is a 2.6σ discrepancy with respect to the SM [3] in:

$$R_K = \frac{\int_{q^2_{\min}}^{q^2_{\max}} \frac{d\Gamma(B^+ \to K^+\mu^+\mu^-)}{dq^2} dq^2}{\int_{q^2_{\min}}^{q^2_{\max}} \frac{d\Gamma(B^+ \to K^+e^+e^-)}{dq^2} dq^2} \tag{1.1}$$

$$R_{K,[1.0,6.0]\mathrm{GeV}^2} = 0.745^{+0.090}_{-0.074} \pm 0.036$$

and a $2.1 - 2.5\sigma$ discrepancy in the related mode with the vector meson [4]:

$$R_{K^*} = \frac{\int_{q^2_{\min}}^{q^2_{\max}} \frac{d\Gamma(B^0 \to K^{0*}\mu^+\mu^-)}{dq^2} dq^2}{\int_{q^2_{\min}}^{q^2_{\max}} \frac{d\Gamma(B^0 \to K^{0*}e^+e^-)}{dq^2} dq^2} \tag{1.2}$$

$$R_{K^*,[0.045,1.1]\mathrm{GeV}^2} = 0.66^{+0.11}_{-0.07} \pm 0.03$$

$$R_{K^*,[1.1,6.0]\mathrm{GeV}^2} = 0.69^{+0.11}_{-0.07} \pm 0.05$$

These anomalies imply that new physics may lay between the initial common state (b-quark) and the final state that is common between the measurements (s-quark and two charged leptons). Many compelling UV-completions which aim to explain these anomalies include Z' models, where the $b \to s\ell^+\ell^-$ transition is mediated at tree level by an exchange of a new heavy vector boson with flavour violating couplings to b- and s-quarks, as well as couplings to either electrons [12] or muons [13–28]. The implications of such BSM models on proton-proton (pp) collisions have been examined by others [29, 30]. Alternatively, the anomalies may also be explained via tree-level exchanges of lepto-quarks [31–36]. In order to keep our analysis as general as possible, here we consider an Effective Field Theory (EFT) approach with a four-point interaction between b-quark, s-quark, and a pair of charged leptons that can address the aforementioned anomalies.

The four point interaction may be meaningful also for processes that do not necessarily include B-meson decays. For instance, the interaction may play a role in the direct production of a b-quark and two opposite sign and same flavour leptons in pp collisions. The correspondence of such an EFT model in these distinct energy scales has been previously studied [37], demonstrating the applicability of measurements made in pp collisions on the production mechanism on the physics of rare B-meson decays. Taking into account the stated four-point interaction, an imbalance between the SM prediction and the recorded data in a final state with two same flavour leptons and one b-jet can be expected. Therefore, this kind of interaction can be tested using the extensive dataset recorded at the LHC.

We propose a search based on final states with exactly one b-jet and two opposite sign and same flavour leptons. Any deviation from the SM prediction for this final state would imply that new physics lays in the interactions involved within this process. The proposed search differs significantly from the analyses that target B-meson decays, mainly in the higher momentum thresholds of the objects involved in the final state. In the following sections we test the feasibility and estimate the sensitivity of the search at the LHC.

2 Theoretical model

In order to have a model-independent analysis, we consider an EFT setup including 6-dimensional operators. Since the observed anomalies constitute a deviation in the number of muon pairs, only interactions between quarks and muons are considered (and not electrons). The phenomena at low energies, i.e. a deficit in the number of muon pairs in B-meson decays, may be explained by an interference between the new physics contribution and the SM, that is smaller and opposite to the SM contribution. However, here we consider higher energies and a parameter space where the resulting BSM contribution is significantly larger than the SM contribution that arise from electro-weak loop processes. We therefore assume a scenario where the LFU violation is dominated by the BSM contribution, and neglect the interference with the SM. This leads to an enhancement in the number of expected muon pairs produced in association with a b-jet at high di-muon masses due to BSM effects.
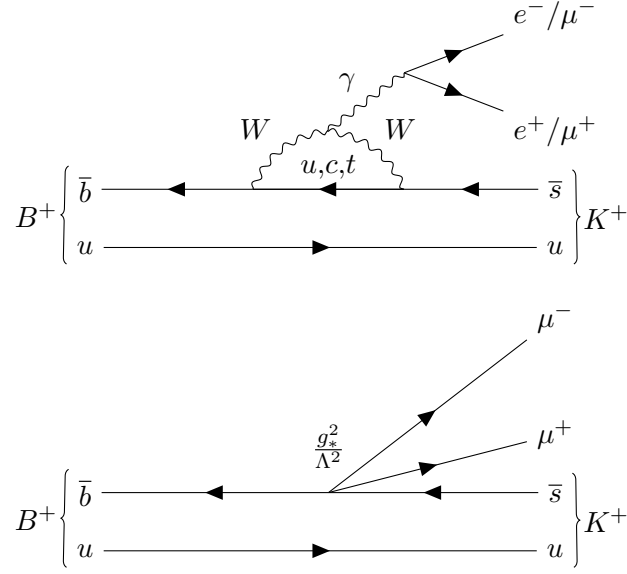
Figure 1. Representative Feynman diagrams for a decay of a B^+ meson to a K^+ meson in association with two leptons in the SM (upper) and in the EFT described in the text (bottom). Only muons are considered for the decay within the EFT approach.
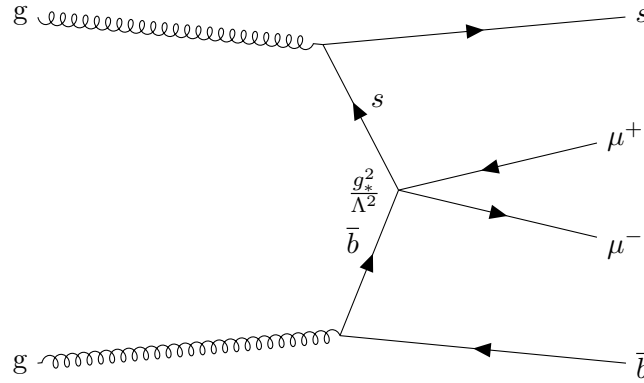

Figure 2. A representative Feynman diagram for a production of one b-jet in association with two muons within the EFT approach.

Representative Feynman diagrams for the decay of a B-meson within the scope of the SM and within the EFT approach are shown at figure 1. A representative Feynman diagram for tree level production of this model at the LHC is shown at figure 2.

The effective Lagrangian of the benchmark model, as stated at [37], is:

$$\mathcal{L}_{\text{eff}} = \frac{C_{ij}^{U\mu}}{v^2}(\bar{u}_L^i \gamma_\mu u_L^j)(\bar{\mu}_L \gamma_\mu \mu_L) + \frac{C_{ij}^{D\mu}}{v^2}(\bar{d}_L^i \gamma_\mu d_L^j)(\bar{\mu}_L \gamma_\mu \mu_L), \tag{2.1}$$

where $C_{ij}^{U\mu}$ and $C_{ij}^{D\mu}$ are matrices that carry the flavour structure of the operators. For the off-diagonal elements only the $b - s$ admixtures are considered, since those are the ones

related to the observed anomalies. The matrices take the form:

$$C_{ij}^{U\mu} = \begin{pmatrix} C_{u\mu} & 0 & 0 \\ 0 & C_{c\mu} & 0 \\ 0 & 0 & C_{t\mu} \end{pmatrix}, C_{ij}^{D\mu} = \begin{pmatrix} C_{d\mu} & 0 & 0 \\ 0 & C_{s\mu} & C_{bs\mu}^* \\ 0 & C_{bs\mu} & C_{t\mu} \end{pmatrix} \quad (2.2)$$

The generality of eq. (2.1) stems from the fact that it can be accommadated by a plethora of new physics scenarios. Comprehensive EFT studies including the operators in eq. (2.1) have recently been performed in the context of B-meson decays in [38, 39]. The Wilson coefficients can then be matched to specific model realizations, including Z' and leptoquarks [40–47], Composite Higgs [48], Randall-Sundrum models [49, 50], Type III 2HDM [51], R-parity violating supersymmetry [52] and more.

As for the $b \to s\ell^+\ell^-$ transitions, the recent combined fit reported [53]:

$$\frac{\pi}{\alpha V_{tb} V_{ts}^*} C_{bs\mu} = -0.62 \pm 0.13 \quad (2.3)$$

Where α is the electromagnetic fine structure constant. The presumed scale of the new physics, Λ, is estimated by defining

$$C_{bs\mu} = g_*^2 v^2 / \Lambda^2. \quad (2.4)$$

Taking the CKM matrix elements to be $|V_{ts}| = (40.0 \pm 2.7) \times 10^{-3}$ and $|V_{tb}| = 1.009 \pm 0.031$ [54], and using result (2.3), the scale of new physics is: $\Lambda/g_* \approx 31^{+4}_{-3}$ TeV.

The present 95% CL limit from the 13 TeV ATLAS $pp \to \mu^+\mu^-$ analysis with 36 fb $^{-1}$ [55] and a prediction for 3000 fb^{-1} of luminosity as stated in [37] is:

$$\left| \frac{\pi}{\alpha V_{tb} V_{ts}^*} C_{bs\mu} \right| < 100(39), \quad (2.5)$$

which corresponds to $\Lambda/g_* > 2.5(3.9)$ TeV. The stated ATLAS analysis, however, is aimed for final states with a pair of electrons or a pair of muons. In contrast to the previous selection method, which is inclusive for a pair of electrons or a pair of muons, we add requirements on a few more variables, including the number of b-tagged jets. As a result, the background is being reduced significantly. Therefore, a selection dedicated to the presented model is expected to improve the sensitivity significantly.

3 Analysis

3.1 Simulated event samples

Monte Carlo (MC) simulated event samples of pp collisions at $\sqrt{s} = 13$ TeV were used to estimate the background SM processes as well as the EFT signal. The SM processes taken into consideration are: top pair production events ($t\bar{t}$); top pair production events in association with an electro-weak boson ($t\bar{t} + W/Z$); production of Z boson and Drell-Yan processes in association with jets ($Z/\gamma^* + jets$); and di-boson production (WZ, WW) processes. The background samples were uniformly generated at leading order using MAD-GRAPH5_AMC@NLO 2.6.1 [56] in the 5 flavour scheme with the NNPDF30LO PDF set

and interfaced with the PYTHIA 8.23 [57] parton shower. The MADSPIN interface was used to model the decay of top quarks and the electro-weak bosons.

A valid MADGRAPH model was built in order to generate signal events, using the model presented in section 2 as a benchmark. The signal samples were uniformly generated at leading order using MADGRAPH5_AMC@NLO 2.6.1 [56] in the 4 flavour scheme.[1] The signal samples were then normalized according to the total cross-section obtained in the 5 flavour scheme.

Finally, all simulated samples were processed through DELPHES 3 [58] in order to simulate the detector effects and apply simplified reconstruction algorithms.

3.2 Event reconstruction

The analysis relies on the reconstruction of hadronic jets, muons, and missing transverse energy ($E_{\mathrm{T}}^{\mathrm{miss}}$). Jets were reconstructed using the anti-k_t [59] clustering algorithm with a radius parameter $R = 0.4$ implemented in FastJet [60, 61], and are required to have transverse momentum $p_{\mathrm{T}} > 20\,\mathrm{GeV}$ and pseudo-rapidity $|\eta| < 2.5$. The identification of b-tagged jets was done by applying a p_{T}-dependent weight based on the jet's associated flavour, using truth information, and the MV2c20 tagging algorithm [62] in the 70% working point. Muons are reconstructed using truth-level muons after applying an artifical p_{T}- and η-dependent efficiency weight, with isolation requirements from other energy-flow objects applied in a cone of $R = 0.5$, and a minimum p_{T} requirement of $20\,\mathrm{GeV}$ for each muon. The missing transverse energy was calculated based on all energy-flow objets in the particle flow approach.

3.3 Event selection

An optimization was done by maximizing the sensitivity of the selection. The sensitivity was estimated as the expected Z-value using the `BinomialExpZ` function by `RooFit` [63]. Different scenarios for the total relative uncertainty on the background were tested: $25\%, 50\%, 100\%$. The integrated luminosity was chosen to be $120\,\mathrm{fb}^{-1}$, which is an evaluation for the full Run-2 integrated luminosity, expected to be available by the end of 2018.

As a base-point, the selection contains two muons with opposite-sign charges (OS). In addition, since the signal is expected to have exactly one b-jet, this selection was applied as well, using the medium working point of 70% ($\mathcal{N}_b$). Since the signal expected to have low missing transverse energy ($E_{\mathrm{T}}^{\mathrm{miss}}$), an upper selection on $E_{\mathrm{T}}^{\mathrm{miss}}$ was optimized. This is especially helpful in reducing the $t\bar{t}$ background, since in addition to the muons it contains two neutrinos that escape the detectors. The invariant mass of both muons ($m_{\mu\mu}$) was used for optimization where new physics is expected to enter at the tail of the $m_{\mu\mu}$ distribution while keeping a small yield for the background. The selection applied is summarized in table 1. The distributions of the observables described in the text, within the selection of the muon pair and the b-tagged jets, are presented in figure 3.

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[1]We find this choice suitable since the appearance of a massive b-quark in the final state is indicative of the signal.

Observable	Selection
$\mathcal{N}_b$	$=1$
$\mathcal{N}_\mu$	$=2$, OS
E_T^{miss} [GeV]	<180
$m_{\mu\mu}$ [GeV]	>1700

Table 1. Summary of the selection for muon pairs. The object definition and common selection described in the text are applied.
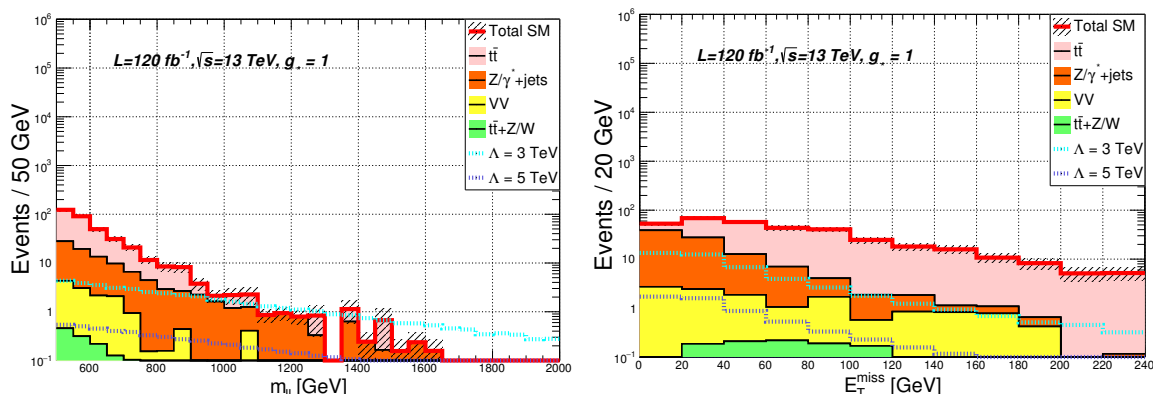
Figure 3. Distribution of the invariant mass of both muons $m_{\mu\mu}$ (left) and the missing transverse energy E_T^{miss} (right). The selection of two opposite sign muons and exactly one b-jet are applied. The signal scenarios of $\Lambda = (3,5)\,\mathrm{TeV}$ are presented as well, using $g_* = 1$. The requirement on the invariant mass of both muons $m_{\mu\mu} > 500\,\mathrm{GeV}$ is applied.

The expected Z-value for the total integrated luminosity of $120\,\mathrm{fb}^{-1}$, using the selections presented at table 1, is shown at figure 4. The expected Z-value as a function of the total integrated luminosity, for different parameter choice of the signal, using the selections presented at table 1, is shown at figure 5.

4 Ratio analysis

Keeping in mind the LHCb measurements [2, 3, 5–11], which hinted a deficit in the number of muon pairs with respect to the number of electron pairs, we suggest a ratio method as a complementary analysis. While an increase in the number of muon pairs can be observed over the expected background if the increase is of certain significance, a deficit can only be observed if the background is well known and the deficit is larger than the background resolution (this statement is also true for an increase but an increase is in principle unlimited). Hence, in order for our model to also accommodate a deficit at the higher muon pair invariant mass regime, a ratio method is proposed. This method has the advantage that the SM background does not need to be known to high precision as the systematical uncertainties associated with it vanish. Here too, we depart from the LHCb
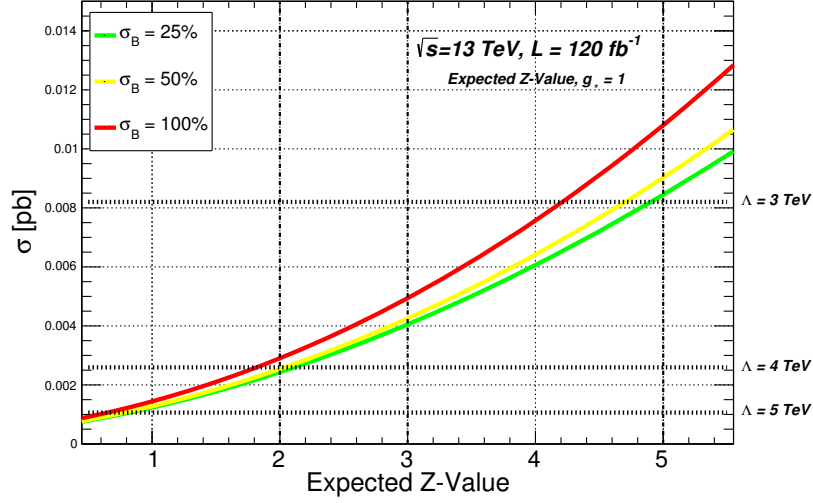
Figure 4. The signal cross-section as a function of the expected Z-value, using the selections presented at table 1. The cross-sections corresponding to $\Lambda = (3, 4, 5)\,\text{TeV}$ are presented, using $g_* = 1$.
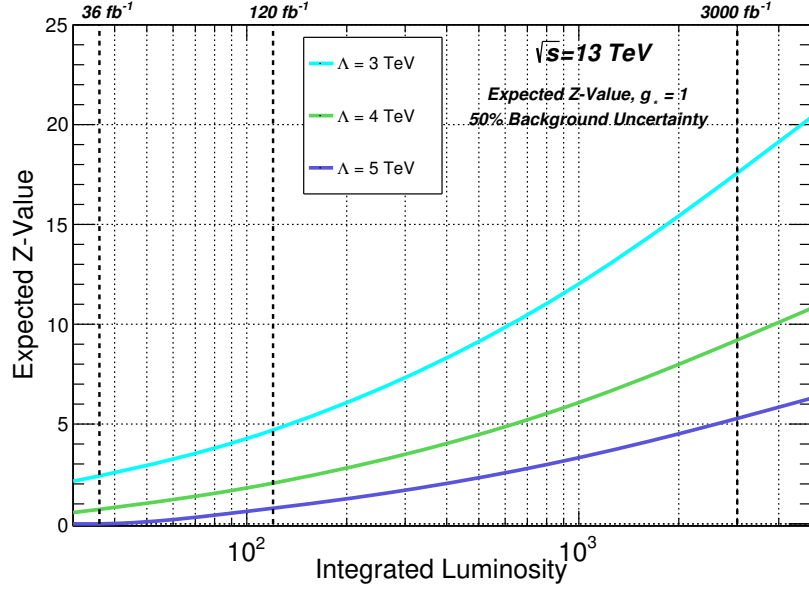

Figure 5. The expected Z-Value as a function of the total integrated luminosity, using the selections presented at table 1. The Z-Values corresponding to $\Lambda = (3, 4, 5)\,\text{TeV}$ are presented, using $g_* = 1$.

exclusive analysis and target the high invariant mass of the lepton pairs regime in the presence of a b-jet.

An evaluation of the signal cross-section as a function of the sensitivity was done, by using the selections presented at table 1. Figure 4 presents the signal cross-section as a function of the expected corresponding Z-value. The expected Z-value was calculated using different relative uncertainties assumptions on the background. In general, small differences observed between different values of the relative background uncertainty. For this reason, looking at the ratio between final states with a muon pair and with an electron
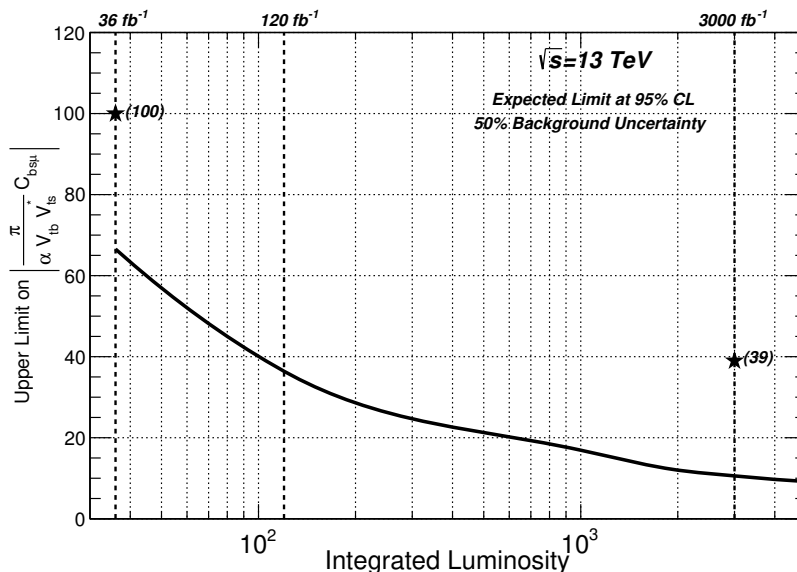
Figure 6. Predicted upper limit on the term presented at equation (2.5), as a function of the total integrated luminosity. The dashed lines correspond to integrated luminosity of $(36, 120, 3000)\,\mathrm{fb}^{-1}$. The upper limit for integrated luminosity of $36\,(3000)\,\mathrm{fb}^{-1}$, corresponding the a value of $100(39)$ using the latest ATLAS public analysis, are also marked.

pair will not improve our sensitivity. On the other hand, if we decide to look only at muon pairs in the final state, we can use similar selection for electron pairs as a CR, in order to normalise the expected SM yield.

5   Results

In order to quantitatively evaluate the gained sensitivity of the presented analysis, a calculation of the expected upper limit was done. Figure 6 presents the expected upper limit on the term presented in equation (2.5), as a function of the total integrated luminosity. Figure 7 presents the expected value of the term presented in equation (2.5) for a discovery, as a function of the total integrated luminosity.

The upper limit was calculated using the CL_s [64] method. Data was randomly chosen as an integer of a poisson distribution, with an average of the expected background yield. The background only (signal+background) hypothesis was randomly chosen from a gaussian distribution with a mean of the background (signal+background) yield. Small differences were observed between different standard deviation assumptions on the background yield, so only the case of 50% was considered. The uncertainty on the signal was not considered. The expected upper limit for an integrated luminosity of $(36, 120, 3000)\,\mathrm{fb}^{-1}$ is $\left|\frac{\pi}{\alpha V_{tb} V_{ts}^*} C_{bs\mu}\right| < (67, 36, 11)$, assuming 50% of background uncertainty. One can conclude that the dedicated analysis presented in this section improves the sensitivity significantly, compared to the limit presented in [37].
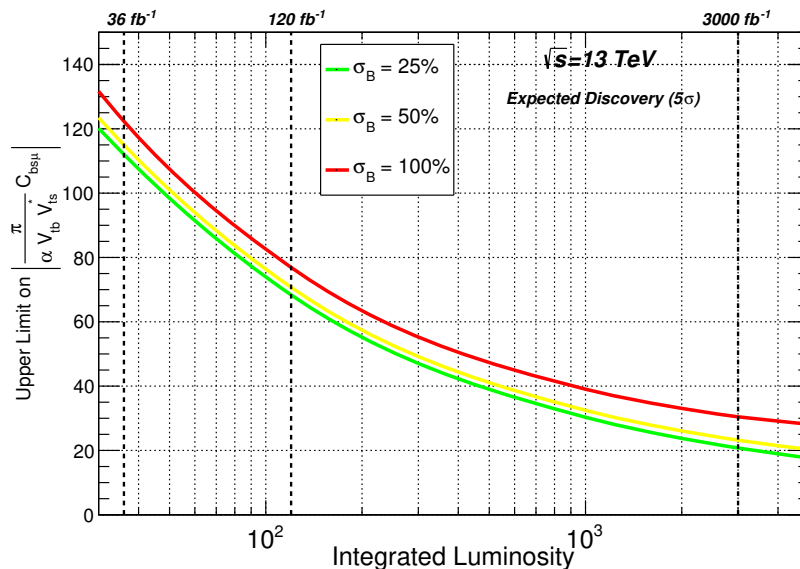
Figure 7. Predicted discovery (5σ) on the term presented at equation (2.5), as a function of the total integrated luminosity. The dashed lines correspond to integrated luminosity of (36, 120, 3000) fb^{-1}.

6 Conclusion

Recent anomalies observed in the decays of B-mesons imply a new physics interaction that may lay between initial and final states involving a b-quark, a s-quark and a pair of opposite sign muons. The interaction can be described in the scope of an EFT for a four-fermion interaction of a b-quark, an s-quark and a pair of muons. The four point interaction may play a role in the direct production of a b-quark and two opposite sign and same flavour leptons in pp collisions. We propose a search at the LHC for this type of interaction using final states with a pair of opposite sign muons and one b-jet. The search differs significantly from the analyses that target B-meson decays, mainly in the higher momentum thresholds of the objects involved in the final state. When compared to previous ATLAS analysis, the search significantly improves the sensitivity to new physics laying in this four-fermion interaction.

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