Searching for New Physics with $b\bar{b}\ell^+\ell^−$ Contact Interactions

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(Dated: December 3, 2019)

We study the impact of contact interactions involving two leptons (electrons or muons) and two $b$-quarks ($b\bar{b}\ell^+\ell^−$) on the high-mass di-lepton region at the LHC. We consider different selections of $b$-tagged jet multiplicities in the di-lepton final states: inclusive (no selection), 0, 1 and 2 $b$-tagged jets, and show that the single $b$-jet selection significantly improves the sensitivity to New Physics (NP) in the form of the $b\bar{b}\ell^+\ell^−$ contact term. We obtain a better sensitivity compared to the currently existing searches of NP in the di-lepton inclusive channel. In particular, the expected limits go beyond competitive bounds set by LEP (for electrons) on the scale of new physics, $Λ$, by a factor of $1.4 − 3.9$, depending on the chirality structure of the operator. In addition, the expected limits on $Λ$, set by using a non-resonant LHC di-lepton inclusive search, are expected to be improved by a factor of $1.3 − 1.4$ for both electrons and muons.

I. INTRODUCTION

The Standard Model (SM) of particle physics is believed to be a low-energy limit of a more fundamental high-energy theory. The non-observability of direct NP signals at the Large Hadron Collider (LHC) pushes the scale of the underlying high-energy theory to the multi-TeV regime. Thus, within its energy and luminosity limitations the NP is expected to show at the LHC in the tails of the distributions, where the NP signals can be modeled using effective field theory techniques, by integrating out the new degrees of freedom; in contrast to traditional NP searches of a lower scale (NP) in the form of the $b\bar{b}\ell^+\ell^−$ contact term. We obtain a better sensitivity compared to the currently existing searches of NP in the di-lepton inclusive channel. In particular, the expected limits go beyond competitive bounds set by LEP (for electrons) on the scale of new physics, $Λ$, by a factor of $1.4 − 3.9$, depending on the chirality structure of the operator. In addition, the expected limits on $Λ$, set by using a non-resonant LHC di-lepton inclusive search, are expected to be improved by a factor of $1.3 − 1.4$ for both electrons and muons.

While these EFT studies treat the quarks uniformly, summing over all quark flavors and using the inclusive di-lepton sample to derive constraints on flavor-specific operators, we will vary the $b$-jet multiplicity of the di-lepton events and show that the exclusive 1 $b$-jet selection can play a major role in deriving bounds on the strength of the $b\bar{b}\ell^+\ell^−$ operators. We have applied a similar approach in a previous work [35], where we demonstrated the importance of an extra $b$-jet selection for background rejection in studies of the NP effects due to a higher-dimensional $bs\ell^+\ell^−$ contact term. Other related studies include resonance type searches of associated $Z'$ and $W'$ production [25, 34], as well as direct searches for RPV SUSY in final states involving $b$-quarks [35].

The paper is organized as follows: in section I we present the EFT framework and discuss the relevant constraints, in section II we present our proposed analysis in order to maximize the sensitivity, and in section III we present the expected results for an analysis at the LHC. Finally, we conclude in section IV.

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II. THEORETICAL FRAMEWORK

Assuming that the NP is too heavy to be directly produced, we adopt an EFT approach where the heavy degrees of freedom of the underlying high-energy theory are integrated out. In this case, the SM Lagrangian is augmented by a series of higher dimensional operators involving the interactions of the SM light fields and are suppressed by inverse powers of the NP scale \( \Lambda \) [30,39]. In this work we will be interested in the subset of dimension six operators containing 4-fermion contact terms which involve the third generation \( b \)-quark and a pair of electrons and/or muons, that can be generated in the underlying theory by tree-level exchanges of a heavy vector boson. Focusing on the \( b \)-quark interaction\(^1\) it is convenient to cast the effective Lagrangian for the \( bb\ell^+\ell^- \) and \( b\mu^+\mu^- \) terms in the form\(^2\)

\[
\mathcal{L}_{\text{eff}} = \frac{g^2}{\Lambda^2} \sum_{i,j=L,R} (\eta_{ij} \bar{b}_i \gamma_{\mu} b_i)(\bar{\ell}_j \gamma^\mu \ell_j),
\]

where here \( \ell = \mu, e, \) \( \Lambda \) is the NP scale and we have summed over all possible chirality structures with \( \eta_{ij} = \pm 1 \), which will be useful for accounting for constructive/destructive interference with the SM Drell-Yan process \( pp \to Z/\gamma^* \to \ell^+\ell^- \). Also, we set \( g = \sqrt{4\pi} \) following [45,46] and the analysis performed by the OPAL and ALEPH collaborations [47,48]. As previously stated, the effective interactions in eq. (1) naturally arise in the broader EFT extension of the SM, the so-called SMEFT [36–39]. Thus, the 4-fermion couplings defined in (1) are linearly related to the Wilson coefficients of the corresponding gauge invariant operators in the SMEFT framework (see e.g., [29]).

The operators in eq. (1) generate new tree-level di-lepton production modes at the LHC, in association with three different \( b \)-quark multiplicities, as depicted in Fig. 1. These contact interactions grow with energy as \( \mathcal{O}(s/\Lambda^2) \) and therefore a harder di-lepton spectrum is expected in the events originating from these operators.

![FIG. 1: Representative Feynman diagrams for a production of a lepton pair via the \( bb\ell^+\ell^- \) operator at the LHC, in association with 0 (left), 1 (center) and 2 (right) \( b \)-jets.](image)

Let us now briefly discuss the relevant constraints on our setup. It is useful to cast those in terms of a third generation \( Z' \) (i.e., a \( Z' \) which couples dominantly to the third generation quarks) which can UV-complete our EFT description in eq. (1). In that case the \( Z' \) mass is associated with the scale of NP up to some coupling, i.e., \( \Lambda \approx M_{Z'} \) and \( g^2 \approx \eta_{bb} g_{\ell \ell} \). Direct constraints on the flavor-diagonal \( bb\ell^+\ell^- \) interaction were derived by the OPAL and ALEPH collaborations at LEP [37,38] and are given in Tab. 1, where the operators were normalized as in eq. (1). Roughly the same bound was extracted recently on the \( bb\mu^+\mu^- \) operator in [29] from non-resonant LHC di-lepton searches. Constraints on the \( bb\mu^+\mu^- \) operators from lepton flavor universality tests in \( \Upsilon \)-meson turn out to be very weak as they only apply to the low-mass region [24]. One can also use the bounds on the flavor non-diagonal \( b\bar{b}\ell^+\ell^- \) operator to constrain the flavor diagonal \( bb\ell^+\ell^- \) ones, if the \( g_{bb} \) coupling is assumed to be related to the \( b - s \) admixture via \( g_{bs} = V_{ts}^* g_{bb} \), where \( V_{ts} \sim 0.04 \) is the \( t - s \) CKM element. In particular, it has been shown that the most stringent constraint on such \( Z' \) vector bosons comes from the low energy \( B_s - B_s \) mixing and reads \( g_{bs} \lesssim M_{Z'}/194 \text{ TeV} \) [22]. On the other hand, the \( Z' \) coupling to muons, \( g_{\mu\mu} \), which for left-handed muons need not be too large so as to evade the bound from neutrino trident \( \nu\mu\mu/\mu^+\mu^- \) production [24], induces subdominant constraints from \( Z \to 4\mu \) at the LHC which only excludes the low-mass region \( 5 \lesssim M_{Z'} \lesssim 70 \text{ GeV} \), whereas the dimuon resonance search in ATLAS [50] constrains \( Z' \) masses of up to 5 TeV.

Henceforth, we will only refer to the LEP and the non-resonant LHC searches for comparison, since those directly bound the diagonal contact interactions under consideration.

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1 Note that, due to gauge invariance, the operators involving the SU(2) lepton and quark doublets also contain 4-fermion contact interactions between the top-quark and the leptons as well as the charged interactions (\( b\bar{b}(e\ell) \)). These operators are studied in [40].

2 As previously stated, the EFT approach in di-lepton signals at the LHC has been extensively utilized in the past, in particular, using 4-fermion contact operators [25,31] and in \( b \)-decays [11,13]. In [29] it has been shown that 4-fermion operators of the form \( q\bar{q}\ell^+\ell^- \) can be probed via the high-\( p_T \) dimuon tail, while others have highlighted the importance of angular variables in disentangling the NP effects [31].
III. ANALYSIS

A. Simulated Event Samples

Monte Carlo (MC) simulated event samples of $pp$ collisions at $\sqrt{s} = 13$ TeV were used to estimate the SM contribution as well as the EFT signal. All MC samples have been generated at leading order, using a minimal requirement for $m_{\ell\ell}$, in order to have high statistics in the tail of the $m_{\ell\ell}$ distribution.

Background processes with $t\bar{t}$ events, as well as DY processes ($Z/\gamma^* + jets$), which are the dominant SM backgrounds, were generated with up to two extra partons. Other backgrounds which were taken into account are $t\bar{t} + W$, $t\bar{t} + Z$ (denoted in the text as "top" together with $t\bar{t}$ events) and $VV$ processes ($WW, WZ, ZZ$). For simplicity, events with fake electrons from $W + jets$ and multi-jet processes were neglected, as those are expected to be sub-dominant [28].

A valid MadGraph UFO model was built in order to generate signal events, using the EFT prescription presented in section II. The signal was generated with up to two extra partons, taking into account interference with the SM, as a combination of the pure NP contribution and the SM-NP interference term. While only discrete values of $\Lambda$ were generated for all possible chirality combinations, the yields of non discrete values of $\Lambda$ were derived by means of interpolation.

Furthermore, all of the samples were generated at leading order using MadGraph5_AMC@NLO 2.6.3 [51] in the 5 flavor scheme with the NNPDF30LO PDF set [52] and interfaced with the Pythia 8.23 [53] parton shower. The default MadGraph LO dynamical scale was used, which is the transverse mass calculated by a $k_T$-clustering of the final-state partons. Events of different jet-multiplicities are matched using the MLM scheme [54]. Finally, all simulated samples were processed through Delphes 3 [55] in order to simulate the detector effects and apply simplified reconstruction algorithms.

B. 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 [56]. In one of the recent analyses by the ATLAS collaboration [28], the relative background uncertainty for an inclusive selection was 8% for both final states (di-electron or di-muon) with $m_{\ell\ell} > 1200$ GeV. For a tighter cut of $m_{\ell\ell} > 1800$ GeV, the relative background uncertainty was estimated to be 16% (13%) for di-electron (di-muon) final states. Guided by this analysis and taking into account the possibility that an additional selection on the number of $b$-tagged jets will add systematic uncertainties, we take the total relative uncertainty on the background to be 25%, which is on the conservative side. The integrated luminosity was chosen to be 140 fb$^{-1}$, which is the approximate full LHC Run-2 integrated luminosity.

As a base-point, the selection contains two leptons, either electrons or muons, with opposite-sign charges (OS). The invariant mass of both leptons ($m_{\ell\ell}$) was used for optimization; the NP is expected to dominate at the tail of the $m_{\ell\ell}$ distribution whereas a small yield for the background is expected in that regime.

Different selections of $b$-tagged jet multiplicities in each event were tested: inclusive (no selection), 0, 1 and 2 $b$-tagged jets. We find that the selection with the highest sensitivity is the one with a single $b$-tagged jet, as can be observed from Fig. 2. Furthermore, the expected sensitivity is higher for final states with muons compared to final states with electrons. The reason for that is a higher detector acceptance in the $m_{\ell\ell}$ tail for the di-muon final states, as we get by using the Delphes 3 detector simulation. For example, for the $LL$ operator with $\Lambda = 5$ TeV and a constructive interference, in the 1 $b$-tagged jet selection and $m_{\ell\ell} > 1500$ GeV, the expected signal yield is 25 events for the muon operators and 16 events for the electron ones, while the corresponding cross sections are similar. The background for final states with muons comparing to electrons is higher as well for similar reasons. However, the sensitivity for the muons final state is still higher when combining both of the signal and background yields. In Fig. 3 we present the $m_{\ell\ell}$ distributions, for the two selections of lepton pair: an inclusive and one $b$-tagged jet selections.
FIG. 2: Expected $Z$-value for different signal hypotheses varied with respect to the NP scale value ($\Lambda$), for the selections of number of $b$-tagged jets discussed in the text, for electrons (left) and muons (right).

FIG. 3: Distribution of the invariant mass of both leptons for one constructive ($\eta_{LL} = +1$) and one destructive ($\eta_{LL} = -1$) $b\bar{b}\ell^+\ell^-$ operator (left) and for the signal and SM background at the distribution tail (right), with an inclusive (upper) and single $b$-tagged jet (bottom) selections. Final states with muons are presented.

For both inclusive and 0 $b$-tagged jet selections, the maximum sensitivity was found to be with $m_{\ell\ell} > 2$ TeV. On the other hand, for the 1 $b$-tagged jet selection, a value of $m_{\ell\ell} > 1.5$ TeV gives maximum sensitivity, whereas for the 2 $b$-tagged jets selection maximum sensitivity is obtained for $m_{\ell\ell} > 1.3$ TeV. The maximum sensitivity selections were found to be common between final states with electrons and muons. The results for all types of the number of
b-tagged jet selections are summarized in Tab. I.

| Observable | inclusive | 0 b-tag | 1 b-tag | 2 b-tag |
|------------|-----------|---------|---------|---------|
| $N_b$      | -         | =0      | =1      | =2      |
| $N_\mu/N_e$ | 2, OS    | 2, OS   | 2, OS   | 2, OS   |
| $m_{\ell\ell}$ [TeV] | > 2       | > 2     | > 1.5   | > 1.3   |

TABLE I: Summary of the maximum sensitivity ranges for the various selections of lepton pairs in association with b-tagged jets. See also text.

C. Ratio Analysis - a note

In case where the NP couples only to one lepton generation, either with constructive or destructive interference, a ratio analysis may be more effective for detecting a deviation from the SM prediction. In this case, the theoretical uncertainties can be minimized since they are expected to be similar in both the di-muon and di-electron final states, therefore reducing the total relative uncertainty. This is important in particular in the high energy regime of $m_{\ell\ell}$ where high theoretical uncertainties are expected. Such a ratio analysis is in particular useful for the study of lepton flavor non-universality and will be investigated in detail in [40], within a broader context including interactions involving the top-quark with the leptons.

IV. RESULTS

As can be seen from Fig. 2, a higher sensitivity for the 1 b-tagged jet selection is expected in comparison with the other selections. The 2 b-tagged jet selection yields better sensitivity then the inclusive and 0 b-tagged jet selections, but still not compatible with the 1 b-tagged jet selection. The reason the 1 b-tagged jet selection possesses the best sensitivity is that the $Z/\gamma^* + jets$ and $VV$ backgrounds dominate mostly the inclusive and the 0 b-tagged jet selections, so that the requirement to have a single b-tagged jet removes most of those backgrounds. For the 2 b-tagged jet selection the $Z/\gamma^* + jets$ and $VV$ backgrounds are reduced as well, however, the signal yield is lower compared to the 1 b-tagged jet selection.

In order to determine the sensitivity to the NP scale $\Lambda$, we calculated the $p$-value for each signal and background hypothesis using the BinomialExp function by RooFit [50]. After the $p$-value of the background-only and background+signal hypotheses for each point were calculated, a $CL_s$ [57] test was made in order to determine whether the corresponding signal point is expected to be excluded with 95% Confidence Level (CL). The expected upper limits for the inclusive and for the single b-jet selection for all possible chirality structures of the $bb\ell^+\ell^-$ interactions are presented in Fig. 4, where the current operating luminosity at the LHC was used. The $\pm 1\sigma$ ($\pm 2\sigma$) bands are derived by calculating the limits after pulling the background up and down with the corresponding background uncertainty, which we define as 25% for $1\sigma$ (50% for $2\sigma$). The bounds from LEP in the di-electron case are also plotted in Fig. 4 for comparison. We find, for example, that the sensitivity of the exclusive 1 b-tagged jet selection can extend the reach of this operator up to $\Lambda = 7.6^{+0.2}_{-0.2} (7.8^{+0.3}_{-0.3})$ TeV for electrons (muons) for the $LL$ constructive operator. In Fig. 5 we furthermore show, for the $LL$ constructive operator, the expected upper limit of the inclusive and the 1 b-tagged jet selections for different values of the total integrated luminosity, using two scenarios of the relative background uncertainty: 25% and 50%. We conclude that even in cases where the relative uncertainty of the 1 b-tag selection is significantly higher compared to the inclusive selection, better sensitivity can still be obtained using this channel.
Finally, the sensitivity to the NP scale $\Lambda$ for the operators with all types of chiralities are summarized in Tab. II
and III, where we also included the LEP bounds for comparison. The limits on similar operators which were obtained in [20], using an inclusive di-lepton ATLAS analysis [28] are not presented, since the authors of this work used a 2$\sigma$ method, while we choose a more conservative approach - $CL_s$. Thus, although the results of both works are not comparable, it is clear that better limits will be obtained by using the single $b$-tagged jet selection, regardless of the statistical method.

![Expected upper limit on $\Lambda$ for all possible chirality structures of the $b\bar{b}\ell^+\ell^-$ operator.](image)

**FIG. 4:** Expected upper limit on $\Lambda$ for all possible chirality structures of the $b\bar{b}\ell^+\ell^-$ operator. The cases where no $b$-jets requirement are used (inclusive, lower bands) and exactly one $b$-tagged jet is required (upper bands) are presented for comparison, all with 25% background uncertainty. Left: $b\bar{b}\ell^+\ell^-$ operators; right: $b\bar{b}\mu^+\mu^-$ operators.

| Chirality Structure | $LL$ const | $LL$ dest | $RR$ const | $RR$ dest | $LR$ const | $LR$ dest | $RL$ const | $RL$ dest |
|---------------------|------------|-----------|------------|-----------|------------|-----------|------------|-----------|
| OPAL [TeV]          | 4.0        | 4.8       | 2.9        | 1.7       | 2.4        | 2.0       | 1.8        | 2.8       |
| ALEPH [TeV]         | 5.6        | 4.9       | 3.9        | 1.9       | 3.0        | 2.3       | 1.9        | 3.6       |
| Inclusive [TeV]     | 5.5$^{+0.2}_{-0.3}$ | 5.4$^{+0.2}_{-0.3}$ | 5.5$^{+0.2}_{-0.3}$ | 5.5$^{+0.2}_{-0.3}$ | 5.5$^{+0.2}_{-0.3}$ | 5.5$^{+0.2}_{-0.3}$ | 5.5$^{+0.2}_{-0.3}$ | 5.5$^{+0.2}_{-0.3}$ |
| 0 $b$-tag [TeV]     | 4.9$^{+0.2}_{-0.2}$ | 4.9$^{+0.2}_{-0.2}$ | 4.9$^{+0.2}_{-0.2}$ | 4.9$^{+0.2}_{-0.2}$ | 4.9$^{+0.2}_{-0.2}$ | 4.9$^{+0.2}_{-0.2}$ | 4.9$^{+0.2}_{-0.2}$ | 4.9$^{+0.2}_{-0.2}$ |
| 1 $b$-tag [TeV]     | 7.6$^{+0.2}_{-0.2}$ | 7.6$^{+0.2}_{-0.2}$ | 7.6$^{+0.2}_{-0.2}$ | 7.6$^{+0.2}_{-0.2}$ | 7.6$^{+0.2}_{-0.2}$ | 7.6$^{+0.2}_{-0.2}$ | 7.6$^{+0.2}_{-0.2}$ | 7.6$^{+0.2}_{-0.2}$ |
| 2 $b$-tag [TeV]     | 6.0$^{+0.2}_{-0.2}$ | 5.7$^{+0.2}_{-0.2}$ | 5.8$^{+0.2}_{-0.2}$ | 5.8$^{+0.2}_{-0.2}$ | 5.8$^{+0.2}_{-0.2}$ | 5.8$^{+0.2}_{-0.2}$ | 5.8$^{+0.2}_{-0.2}$ | 5.8$^{+0.2}_{-0.2}$ |

**TABLE II:** Summary of the limits on the $b\bar{b}\ell^+\ell^-$ operators for constructive ($\eta_{ij} = +1$) and destructive ($\eta_{ij} = -1$) interference with the SM.

| Chirality Structure | $LL$ const | $LL$ dest | $RR$ const | $RR$ dest | $LR$ const | $LR$ dest | $RL$ const | $RL$ dest |
|---------------------|------------|-----------|------------|-----------|------------|-----------|------------|-----------|
| Inclusive [TeV]     | 5.6$^{+0.2}_{-0.3}$ | 5.5$^{+0.2}_{-0.3}$ | 5.6$^{+0.2}_{-0.3}$ | 5.5$^{+0.2}_{-0.3}$ | 5.6$^{+0.2}_{-0.3}$ | 5.6$^{+0.2}_{-0.3}$ | 5.6$^{+0.2}_{-0.3}$ | 5.6$^{+0.2}_{-0.3}$ |
| 0 $b$-tag [TeV]     | 5.0$^{+0.2}_{-0.3}$ | 4.9$^{+0.2}_{-0.3}$ | 5.0$^{+0.2}_{-0.3}$ | 5.0$^{+0.2}_{-0.3}$ | 5.0$^{+0.2}_{-0.3}$ | 5.0$^{+0.2}_{-0.3}$ | 5.0$^{+0.2}_{-0.3}$ | 5.0$^{+0.2}_{-0.3}$ |
| 1 $b$-tag [TeV]     | 7.8$^{+0.2}_{-0.3}$ | 7.6$^{+0.2}_{-0.3}$ | 7.6$^{+0.2}_{-0.3}$ | 7.6$^{+0.2}_{-0.3}$ | 7.6$^{+0.2}_{-0.3}$ | 7.6$^{+0.2}_{-0.3}$ | 7.6$^{+0.2}_{-0.3}$ | 7.6$^{+0.2}_{-0.3}$ |
| 2 $b$-tag [TeV]     | 6.2$^{+0.2}_{-0.2}$ | 5.9$^{+0.2}_{-0.2}$ | 6.1$^{+0.2}_{-0.2}$ | 6.0$^{+0.2}_{-0.2}$ | 6.1$^{+0.2}_{-0.2}$ | 6.1$^{+0.2}_{-0.2}$ | 6.1$^{+0.2}_{-0.2}$ | 6.0$^{+0.2}_{-0.2}$ |

**TABLE III:** Summary of the limits on the $b\bar{b}\mu^+\mu^-$ operators, for constructive ($\eta_{ij} = +1$) and destructive ($\eta_{ij} = -1$) interference with the SM.
FIG. 5: Expected upper limit on $4\pi/\Lambda^2$ for final states with $b$-quarks and electrons (left) or muons (right), as a function of the total integrated luminosity, for operators with the $LL$ chirality that have constructive interference with the SM ($\eta_{LL} = +1$). The cases where no $b$-jets requirement are used (inclusive) and exactly one $b$-tagged jet is required are presented for comparison, with 25% and 50% background uncertainty.

V. SUMMARY

We have used EFT techniques to carefully analyze the LHC di-lepton TeV scale spectrum in the presence of new $b\bar{b}\ell^+\ell^-$ contact interactions with a typical scale of $\Lambda \sim O(1-10)\,\text{TeV}$. We have considered pair production of either electrons or muons in association with $b$-quarks and studied the high energy behavior of these new interactions. We find that this form of NP is highly sensitive to the $b$-jet multiplicity in the final state, and that a selection of a single $b$-tagged jet allows to extract improved bounds compared to prior constraints from LEP and to constraints from non-resonant LHC di-lepton searches. In particular, applying an exclusive 1 $b$-jet selection on the inclusive di-electron (di-muon) sample extends the reach on the scale of the $b\bar{b}\ell^+\ell^-$ operator from $\Lambda \sim 5.5\,(5.6)$ to $\Lambda \sim 7.6\,(7.8)\,\text{TeV}$, assuming 25% uncertainty for the SM background.

ACKNOWLEDGMENTS

We thank Gauthier Durieux for a useful discussion regarding the choice of the flavor scheme. This research was supported by a grant from the United States-Israel Binational Science Foundation (BSF), Jerusalem, Israel, and by a grant from the Israel Science Foundation (ISF).

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