

Flavor physics at the EIC with b -jet tagging

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We employ an approximate conserved quantum number [defined as “ b parity” in *Phys. Rev. Lett.* **86**, 3722 (2001)] of the Standard Model (SM): $b_p = (-1)^n$, where n is the number of produced b jets in the reaction $e + p/A \rightarrow n \cdot j_b + X$, to explore new TeV-scale flavor-changing interactions involving the third-generation quarks at the Electron-Ion Collider (EIC); simply by counting the number of b jets in the final state. In particular, the SM single and dijet production at the EIC, which occurs through charge current interactions, $e + p/A \rightarrow j + E_T$ and $e + p/A \rightarrow 2 \cdot j + E_T$, are b_p even since the b_p -violating (i.e., $b_p = -1$) SM signals for these processes are necessarily Cabibbo-Kobayashi-Maskawa suppressed and, therefore, have a vanishingly small production rate. In contrast, new flavor physics can generate $b_p = -1$ signals at the EIC whose only significant SM background is due to b -jet misidentification. We thus show that b_p can be used as a simple and sensitive probe of new flavor-violating physics; specifically, we find that counting single b -jet events in $e + p/A \rightarrow j + E_T$ at the EIC with a center-of-mass (c.m.) energy of $\sqrt{s} \sim 140$ GeV can probe scales of new physics up to $\Lambda \lesssim \mathcal{O}(5)$ TeV for a certain type of new chiral flavor-changing physics in third-generation interactions. This is remarkably more than 30 times larger than the assumed EIC c.m. energy and it critically depends on the b -tagging efficiency and purity as well as the feasibility of electron beam polarization. The sensitivity of the dijet process, $e + p/A \rightarrow 2j + E_T$, to these types of new physics is reduced compared to the single-jet channel.

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I. INTRODUCTION

Despite its enormous success, the Standard Model (SM) is widely regarded as a low-energy effective theory of a more fundamental framework. The nature of this underlying physics is currently being explored at the LHC and will be further probed by next-generation colliders. The Electron-Ion Collider (EIC) at the Brookhaven National Laboratory [1,2], which is expected to start taking data during the next decade, is probably going to be the only new high-energy collider worldwide in the next 20–30 years, so that exploiting its potential to address fundamental questions in particle physics is warranted. Indeed, in spite of the fact that the EIC is primarily designed for exploration of nuclear physics [1,2], there has been a growing interest in pointing out the EIC’s sensitivity and capability for precision tests of the SM [3–8] and for the search of beyond the SM (BSM) physics [8–30]. We note, in

particular, that the potential high polarization (expected to approach 80%) of the incoming electron beam at the EIC and its anticipated high integrated luminosity of $\mathcal{L} \sim \mathcal{O}(100)$ fb^{−1} is highlighted in many of these studies; for comparison, we recall that the HERA ep collider collected $\mathcal{O}(1)$ fb^{−1} of data and ran with about 30% of average electron beam polarization during its phase II [31,32].

In this paper we would like to promote the possibility of exploiting the EIC as a testing platform for the study of flavor-changing (FC) physics, which remains one of the fundamental unresolved matters in theoretical particle physics; a signal of TeV-scale FC interactions will be clear and unambiguous evidence for BSM physics. There are reasons to believe that FC interactions involving the third-generation quarks are likely to show the largest effect.¹ Following the idea introduced by the authors in [33], we propose here to test FC new physics (NP) effects in single- and dijet production at the EIC by simply counting the number of b jets in the final state (FS). As outlined in [33], this approach is best suited for lepton colliders, but in some cases it may be extended to hadron colliders or electron-

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¹Due to the very large number of investigations in this direction that have been carried out during the past several decades, an exhaustive citation list cannot be practically provided.

proton colliders if the b -quark content in the proton can be ignored. In particular, we will show in this work that it can be applied to the EIC in charge current (CC) interactions, by achieving a high purity of the b -jet sample and leveraging the polarization of the incoming electron beam.

Indeed, the combination of high luminosity, high b -jet identification efficiency, the availability of polarized beams, and the relatively low c.m. energy of the EIC (below the top-quark threshold) prove combined virtues leading to a rather impressive sensitivity of this collider to the kind of flavor physics investigated below. In particular, the expected EIC sensitivity is significantly better than that of HERA, despite the fact that HERA operated at more than twice the c.m. energy.

The physics behind the method we use is based on the observation that, in the limit where the Cabibbo-Kobayashi-Maskawa (CKM) parameters $V_{3j} = V_{j3} = 0$ ($j \neq 3$), the SM acquires an additional global $U(1)_b$ symmetry (“bottomness”), where b and $\bar{b}$ have opposite charges, and which holds to any order in perturbation theory. Specifically, since V_{j3}, V_{3j} ($j \neq 3$), though not zero, are small [$V_{31}, V_{13} \sim \mathcal{O}(\lambda^3)$ and $V_{32}, V_{23} \sim \mathcal{O}(\lambda^2)$, where $\lambda \sim 0.22$ is the Wolfenstein parameter], the quantum number associated with $U(1)_b$ is approximately conserved (in particular, the top quark decays almost exclusively into bW). Then, for example, given a reaction of the type

$$n_i \cdot b + X \rightarrow n_f \cdot b + Y, \quad (1)$$

where (i) X, Y denote sets of particles not containing b quark/jets; (ii) n_i, n_f are the number of b quark/jets in the initial and final states, respectively; and (iii) there are no top quarks in the initial state, and those in the final state have decayed via $t \rightarrow bW$; we have $(-1)^{n_i} = (-1)^{n_f}$ and we can define an approximately conserved flavor number for collider scattering processes, $b_p \equiv (-1)^{n_f - n_i}$, which was named b parity in [33]. Therefore, if there is no b -quark content in the initial state ($n_i = 0$), then an odd number of b -quark jets cannot be generated in the SM in scattering processes, as was pointed out in [33].

In this work we wish to apply the concept of b parity for searches of new BSM sources of FC physics in the third-generation quark sector at the EIC, in multijet production,

$$e + p/A \rightarrow n \cdot j_b + m \cdot j_\ell + X, \quad (2)$$

where n denotes the number of b and/or $\bar{b}$ jets in the FS,² m is the number of light jets, and X stands for leptons and/or missing energy. We assume below an EIC running phase with a c.m. energy $\sqrt{s} < m_t$, so that the production of b quarks via $t \rightarrow bW$ is vanishingly small, as it will occur only through an off-shell top quark in the FS. Thus, to the

²The method used here does not require differentiating between b - and $\bar{b}$ -quark jets.

extent that the b -quark content inside the proton can be ignored, the b -parity number for the reaction in Eq. (2) becomes

$$b_p = (-1)^n, \quad (3)$$

so that the measured quantum number reduces to the net number of detected b -quark jets, in which case it is convenient to use the derived quantity b_p . The only SM processes that violate b_p in these multijet production processes at the EIC necessarily involve the CC $u \rightarrow b$ and/or $c \rightarrow b$ interactions, which are suppressed by the corresponding small off-diagonal CKM element factors, $|V_{ub}|^2$ and $|V_{cb}|^2$, so that the SM is b_p even at the EIC to a good accuracy. Thus, to experimentally detect NP signals with $b_p = -1$ in the processes of the type shown in Eq. (2), one should simply measure/count the number of events with an odd number of b jets in the FS.

Denoting by t_j the light-jet mistagging probability (i.e., that of mistaking a light-quark jet or gluon jet for a b jet)³ and by ϵ_b the b -tagging efficiency, the probability (or cross section) for detecting precisely k b jets in the reaction of Eq. (2) is given by

$$\bar{\sigma}_{kj_b} = \sum_{u,v} P_u^n P_v^m [\epsilon_b^u (1 - \epsilon_b)^{n-u}] [t_j^v (1 - t_j)^{m-v}] \sigma_{nm} \delta_{u+v,k}, \quad (4)$$

where $P_j^i = i!/j!/(i-j)!$ and $\sigma_{nm} = \sigma(e + p/A \rightarrow n \cdot j_b + m \cdot j_\ell + X)$.

Clearly, the main obstacle in the search for b_p -odd NP signals is, therefore, the reducible SM background due to jet misidentification, which results from having a non-optimal b -tagging efficiency (ϵ_b) below 1 and/or having nonzero probabilities (t_j) of mistagging a light-quark jet for a b jet (also known as the purity of the b -jet sample). This type of background would of course disappear as $\epsilon_b \rightarrow 1$ and $t_j \rightarrow 0$, but even with the seemingly small $t_j \sim 0.01$ (and a relatively high b -tagging efficiency of $\epsilon_b \sim 0.8$) can produce a significant number of (misidentified) “fake” b_p -odd events in the detector.

In what follows, we will consider new flavor physics involving the third-generation quarks, which impacts single b -jet production at the EIC. We use effective field theory to describe the NP and find that the EIC will be sensitive to NP scales of $\Lambda \lesssim 1\text{--}3$ TeV and for a certain type of interaction up to $\Lambda \lesssim 5$ TeV. As will be shown, this will

³We do not differentiate between a light jet and a c -quark jet, since the contribution of c -quark jets in the reactions discussed below (although included) is negligible. In particular, the single- and dijet SM processes that lead to a c -jet in the final state contribute less than 1% in both these channels and, therefore, have a negligible effect on our analysis in the next sections.

TABLE I. The dim.6 effective operators that are PTG in the underlying heavy theory and that can mediate the CC interaction $e + p/A \rightarrow j_b + \nu_e$ and $e + p/A \rightarrow j_b + j_\ell + \nu_e$, where ℓ_1, q_1 are the lepton and quark SU(2) left-handed doublets of the first generation and e, u, d, b are the electron and u, d, b quarks right-handed SU(2) singlets; j, k are SU(2) indices. We list the chirality structure of the fermionic currents, possible types of underlying heavy physics that can generate these operators, and the additional $\ell\ell qq'$ contact terms that are generated by the four-Fermi operators due to SU(2) gauge invariance.

Effective operator	Chirality (type)	Interactions
$Q_{\ell q}^{(3)}(1113) = (\bar{\ell}_1 \gamma_\mu \tau^I \ell_1)(\bar{q}_1 \gamma^\mu \tau^I q_3)$	$(\bar{L}L)(\bar{L}L)$ (vector)	$eeu, eebd, e\nu_e bu$
$Q_{\ell equ}^{(1)}(1131) = (\bar{\ell}_1^j e) \epsilon_{jk} (\bar{q}_3^k u)$	$(\bar{L}R)(\bar{L}R)$ (scalar, tensor)	$eeu, e\nu_e bu$
$Q_{\ell equ}^{(3)}(1131) = (\bar{\ell}_1^j \sigma_{\mu\nu} e) \epsilon_{jk} (\bar{q}_3^k \sigma_{\mu\nu} u)$	$(\bar{L}R)(\bar{L}R)$ (scalar, tensor)	$eeu, e\nu_e bu$
$Q_{\ell edq}(1131) = (\bar{\ell}_1^j e) (\bar{b} q_1^j)$	$(\bar{L}R)(\bar{R}L)$ (scalar, vector)	$eebd, e\nu_e bu$
$Q_{\text{Hud}}(13) = i(\bar{H}^\dagger D_\mu H)(\bar{u} \gamma^\mu b) + \text{H.c.}$	$(\bar{R}R)$ (vector, fermion)	Wub
$Q_{Hq}^{(3)}(13) = i(H^\dagger i \overleftrightarrow{D}_\mu^\dagger H)(\bar{q}_1 \gamma^\mu \tau^I q_3)$	$(\bar{L}L)$ (vector, fermion)	Wub

require a relatively high purity of the b -jet sample and a substantial polarization of the electron beam.

$$\Lambda_{\text{eff}} \equiv \frac{\Lambda}{\sqrt{\alpha}}; \quad (6)$$

II. NEW THIRD-GENERATION FLAVOR PHYSICS AND THE EIC

With no indications of NP observed so far up to the TeV scale, it is useful to parametrize the impact of new heavy states by higher-dimensional, gauge-invariant effective operators $Q_i^{(n)}$ in the so-called SM effective field theory (SMEFT) framework, where the effective operators are constructed using the SM fields and their coefficients are suppressed by inverse powers of the NP scale Λ [34–38],

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \sum_{n=5}^{\infty} \frac{1}{\Lambda^{n-4}} \sum_i \alpha_i Q_i^{(n)}, \quad (5)$$

where here n is the mass dimension of $Q_i^{(n)}$ and we assume decoupling and weakly coupled heavy NP, so that n equals the canonical dimension. One can further divide the higher-dimension effective operators into those that can be potentially generated at tree-level (PTG) and those that are necessarily loop generated (LG) by the underlying heavy theory [39]. The dominating NP effects are then expected to be generated by contributing operators with the lowest dimension (smallest n) that are PTG in the underlying UV theory. The (Wilson) coefficients α_i depend on the details and dynamics of the underlying heavy theory and, therefore, they parametrize all possible weakly interacting and decoupling types of heavy physics. In particular, it is expected that $\alpha_i = \mathcal{O}(1)$ for the PTG operators (for favorable types of NP), and $\alpha_i \sim 1/(4\pi)^2$ for all LG operators; the effects of LG operators are thus *a priori* suppressed by a loop factor and, therefore, their effects at lower energies (i.e., $E < \Lambda$) are expected to be subleading.

We will use below a more practical “effective” NP scale, which is the variable that enters the calculation

note that $\Lambda_{\text{eff}} \sim \Lambda$ for natural PTG couplings.

As mentioned above, in this work we characterize and exploit the possible manifestations of new flavor structures that involve the third-generation quarks, assuming a generic decoupling and weakly coupled underlying heavy NP and using the SMEFT framework. In particular, we examine below single- and dijet production at the EIC via $2 \rightarrow 2$ and $2 \rightarrow 3$ processes, focusing (for reasons explained below) on CC interactions comprising a single b quark in the FS. The relevant dimension-six (dim.6) operators that are PTG and that can mediate sizable new flavor physics effects in these reactions involve a FC $b \rightarrow u$ transition and are listed in Table I.

Let us make a few comments on the effective operators listed in Table I:

- (i) We focus only on the operators that mediate $b \rightarrow u$ flavor transitions, generating the $e\nu_e bu$ four-Fermi contact terms and the Wub charged currents, since these yield the dominant contribution to single b -jet production at the EIC, e.g., via $eu \rightarrow \nu_e b$ and $eu \rightarrow \nu_e bg$ (see next section). In particular, we find that the sensitivity to the corresponding operators that generate $b \rightarrow c$ transitions is significantly reduced, due to the suppressed c -quark content inside the proton.
- (ii) The operators $Q_{\ell edq}$, $Q_{\ell equ}^{(1)}$, and $Q_{\ell equ}^{(3)}$ are non-Hermitian and no symmetry applies to their indices, so that, for example, the (1131) entry is different from the (1113) one.⁴ We note that, for the CC reactions $e + p/A \rightarrow j_b + \nu_e$ and $e + p/A \rightarrow j_b + j_\ell + \nu_e$, only the (1131) entries of these operators contribute.

⁴The numbers denote the generation of the fermions as they appear in the operator label.

- (iii) The operator Q_{Hud} is also non-Hermitian and $\alpha_{\text{Hud}}(31) \neq \alpha_{\text{Hud}}(13)$; here also only $Q_{\text{Hud}}(13)$ contributes to $e + p/A \rightarrow j_b + \nu_e$ and $e + p/A \rightarrow j_b + j_\ell + \nu_e$.
- (iv) The operators $Q_{\ell q}^{(3)}$ and $Q_{Hq}^{(3)}$ are Hermitian, so that, for real Wilson coefficients, $\alpha_{\ell q}^{(3)}(1131) = \alpha_{\ell q}^{(3)}(1113)$ and $\alpha_{Hq}^{(3)}(13) = \alpha_{Hq}^{(3)}(31)$.

Bounds on the operators listed in Table I can be derived from Drell-Yan (DY) processes at the LHC, via the CC $\bar{b}u \rightarrow e^+\nu_e$ and neutral current (NC) $\bar{b}d \rightarrow e^+e^-$ interactions [40–44], from the b decays $b \rightarrow ue\nu_e$ and $b \rightarrow dee$ [40,42] and from $e^+e^- \rightarrow t\bar{u}$ at LEP2 [45–47] and $t\bar{t}$ production at the LHC followed by the FC top decay $t \rightarrow ue^+e^-$ [48–52]. While the latter (i.e., top-quark production and decays) gives the weakest bounds of $\Lambda_{\text{eff}} \gtrsim \mathcal{O}(1)$ TeV, analysis of the DY processes at the LHC mentioned above yield $\Lambda_{\text{eff}} \gtrsim 3\text{--}7$ TeV, depending on the type of operator and process. The bounds from b decays are the strongest, reaching in some cases $\Lambda_{\text{eff}} > \mathcal{O}(10\text{--}20)$ TeV when a single NP operator is turned on. As mentioned earlier and will be shown below, the sensitivity to these dim.6 effective operators at the EIC strongly depends on the b -tagging efficiency and purity and on the availability of polarized electron beams, where, for most operators, it is expected to be more sensitive to this type of NP than the top-quark systems (mentioned above) and, for a certain type of four-Fermi interaction, it is competitive with the current bounds from DY processes at the LHC.

III. b PARITY AND SINGLE-JET PRODUCTION AT THE EIC

Let us consider $2 \rightarrow 2$ processes from CC and NC interactions, which are potentially the most sensitive to new flavor physics,

$$\text{CC: } e + p/A \rightarrow j + E_T, \quad (7)$$

$$\text{NC: } e + p/A \rightarrow j + e, \quad (8)$$

where $j = j_b$ and $j = j_l$ for a b jet and light-quark jet, respectively, and E_T stands for missing energy from the outgoing electron-neutrino ν_e .

In the limit of a diagonal CKM, the CC parton-level process in Eq. (7) proceeds in the SM only via the t-channel W-boson exchanges $eu \rightarrow d\nu_e$ (this channel contributes more than 90% to the total CC $2 \rightarrow 2$ cross section in the SM), $ec \rightarrow s\nu_e$, $e\bar{d} \rightarrow \bar{u}\nu_e$, and $e\bar{s} \rightarrow \bar{c}\nu_e$, while the NC process in Eq. (8) proceeds via the t-channel γ and Z-boson exchanges $eq \rightarrow qe$ and $e\bar{q} \rightarrow \bar{q}e$, where $q = u, d, c, s, b$ (in this case, $eu \rightarrow eu$ and $ed \rightarrow ed$ contribute about 80% and 10%, respectively, of the total NC $2 \rightarrow 2$ SM cross section).

Note that a single b jet can be produced in the SM via the NC reaction in Eq. (8), even in the limit of a diagonal CKM mixing matrix, due to the presence of the b -quark in the proton via $eb \rightarrow eb$ and $e\bar{b} \rightarrow e\bar{b}$; this, however, accounts for a marginal fraction (about 0.3%) of the total $2 \rightarrow 2$ NC cross section. The total SM contribution to the single b -jet signal via the NC process of Eq. (8) is driven primarily by light jets mistagged as b jets, and we find that it is overwhelmingly large relative to the NP effects under consideration (see next section), even for a high purity $t_j \sim 0.001$ of the b -jet sample. In other words, the SM portion of the single b -jet signal in the NC process case of Eq. (8) (due to $t_j \neq 0$) dominates our b_p analysis, to the level that it cannot yield useful bounds on the new flavor physics involving the b quark.⁵

We therefore focus in the rest of this study on the CC process of Eq. (7) and define the corresponding effective SM and NP cross sections for producing a single b jet, which we denote by $\bar{\sigma}_{1j_b}$ [cf. Eq. (4)], which takes into account the nonideal b -jet-tagging efficiency and purity,⁶

$$\bar{\sigma}_{1j_b}^{\text{CC}}(\text{SM}) = t_j \cdot \sigma_{\text{SM}}^{\text{CC}}, \quad \sigma_{\text{SM}}^{\text{CC}} = \sigma(e + p/A \rightarrow j_l + E_T), \quad (9)$$

$$\bar{\sigma}_{1j_b}^{\text{CC}}(\text{NP}) = \epsilon_b \cdot \sigma_{\text{NP}}^{\text{CC}}, \quad \sigma_{\text{NP}}^{\text{CC}} = \sigma(e + p/A \rightarrow j_b + E_T), \quad (10)$$

so that, as noted above, the SM contribution to $e + p/A \rightarrow j_b + E_T$ arises due to mistagged light-quark jets as b jets in $e + p/A \rightarrow j_l + E_T$. We find that $\sigma_{\text{SM}}^{\text{CC}} \sim 13$ pb at the EIC with beam energies of $E_e = 18$ and $E_p = 275$ GeV (see also below), while the irreducible SM background from $e + p/A \rightarrow j_b + E_T$ arises from the parton-level $eu \rightarrow b\nu_e$ and $ec \rightarrow b\nu_e$ processes and, therefore, is CKM suppressed and negligibly small compared to $\sigma_{\text{SM}}^{\text{CC}}$. In particular, $\sigma_{\text{SM}}(eu \rightarrow b\nu_e) \sim \sigma_{\text{SM}}(eu \rightarrow d\nu_e) \times |V_{ub}|^2$ and $\sigma_{\text{SM}}(ec \rightarrow b\nu_e) \sim \sigma_{\text{SM}}(ec \rightarrow s\nu_e) \times |V_{cb}|^2$, and these two channels yield an overall single b jet + MET cross section of $\sigma_{\text{SM}}(e + p/A \rightarrow j_b + E_T) \sim 5 \times 10^{-4}$ pb, which is more than 4 orders of magnitude smaller than $\sigma_{\text{SM}}^{\text{CC}}$ in Eq. (9).

Another potential SM (reducible) background may arise from the $2 \rightarrow 2$ NC process $e + p/A \rightarrow j + e$, due to nonideal detector performance and event selection, when the electron is missed; in this case, such an event appears as a CC event, i.e., with a single jet and Missing Transverse Energy (MET) in the final state. We note, however, that this type of background is expected to be easier to control at the

⁵In the $2 \rightarrow 2$ NC case of single-jet production [$e + p/A \rightarrow j + e$, see Eq. (8)], we find that the SM effective cross section (i.e., the SM background) is about 3 orders of magnitude larger than the NP one even with $t_j \sim 0.001$: $\bar{\sigma}_{1j_b}^{\text{NC}}(\text{SM}) \sim \mathcal{O}(1000 \text{ fb})$, while $\bar{\sigma}_{1j_b}^{\text{NC}}(\text{NP}) \sim \mathcal{O}(1 \text{ fb})$, for $t_j \sim 0.001$ and $\epsilon_b \sim 0.8$. Thus, the expected 95% CL bound on Λ_{eff} in this case [see Eq. (13)] is of $\mathcal{O}(100 \text{ GeV})$ and, therefore, not useful.

⁶We neglect the effects of SM $\times$ NP interference for the processes being considered since it is CKM suppressed.

EIC (compared, e.g., to the LHC), since its initial state energy is relatively well known and so global energy-momentum conservation is easier to apply. Also, the electron-proton/ion collider (ePIC) detector is specifically designed with a very good forward coverage specifically for the scattered electron as well as a very good MET resolution (i.e., about an order of magnitude better than at the LHC), so that lost-electron backgrounds producing fake MET are expected to be much less problematic at the EIC (see Ref. [1] and subsequent ePIC studies); a detailed study of such detector simulations of fake MET signals is beyond the scope of this paper.

We, therefore, do not include below the SM background from the CKM suppressed channels and from fake MET signals due to missed electrons in the NC channel $e + p/A \rightarrow j + e$. In particular, for the total CC $j_b + E_T$ production cross section, we take

$$\bar{\sigma}_{1jb}^{\text{CC}}(\epsilon_b, t_j, \Lambda_{\text{eff}}) = \bar{\sigma}_{1jb}^{\text{CC}}(\text{SM}) + \bar{\sigma}_{1jb}^{\text{CC}}(\text{NP}), \quad (11)$$

which depends on the b tagging and purity factors as well as on the effective NP scale, Λ_{eff} [see Eq. (6)]. The projected performance for the tagging efficiencies at the EIC is still not known and, in the following, we will use values in the ranges $0.6 < \epsilon_b < 0.8$ and, depending on ϵ_b , $0.001 < t_j < 0.1$. Specifically, we consider below three representative benchmark choices for the pair (ϵ_b, t_j) , spanning from optimistic to conservative scenarios. We will also present in some instances results as a function of t_j over a broader interval, since, as discussed below, this parameter plays a central role in the analysis performed here. We hope that these setups will provide challenging yet interesting cases to investigate at the EIC.

In Table II, we list the NP cross sections $\sigma_{\text{NP}}^{\text{CC}} = \sigma(e + p/A \rightarrow j_b + \nu_e)$, corresponding to each of the operators in Table I, with beam energies $E_p = 275$ and $E_e = 18$ GeV, i.e., a c.m. energy of $\sqrt{s} = 141$ GeV. All cross sections (here and in the next sections) were calculated using MADGRAPH5_AMC@NLO [53] at leading-order (LO) parton level and with the SMEFTsim model of [54,55] for the effective field theory framework. The five-flavor scheme was used, with the CT18NNLO parton distribution functions [56] and the default MADGRAPH5_AMC@NLO LO dynamical scale. Also, the acceptance cuts of $p_{T_j} > 20$ GeV and $|\eta_j| < 3.5$ were applied on the transverse momentum and pseudorapidity distributions of the light-quark and/or b -quark jets in the final state.

To assess the sensitivity of the b_P -odd NP signal of our interest, we use the number of expected single b -jet events, which correspond to $\bar{\sigma}_{1jb}^{\text{CC}}(\epsilon_b, t_j, \Lambda_{\text{eff}})$ in Eq. (11),

$$N_{1jb}^{\text{CC}}(\epsilon_b, t_j, \Lambda_{\text{eff}}) = \mathcal{L} \cdot \mathcal{A} \cdot \bar{\sigma}_{1jb}^{\text{CC}}(\epsilon_b, t_j, \Lambda_{\text{eff}}), \quad (12)$$

and we will henceforward take $\mathcal{L} = 100 \text{ fb}^{-1}$ as the projected integrated EIC luminosity and $\mathcal{A}$ as the overall acceptance + efficiency factor which we will set below to $\mathcal{A} = 0.8$.

The sensitivity is then determined by comparing the theoretical shift due to the underlying b_P -odd interactions with the expected error (Δ) in measuring the given quantity. Thus, requiring a signal of at least N_{SD} standard deviations, we have

$$|N_{1jb}^{\text{CC}}(\epsilon_b, t_j, \Lambda_{\text{eff}}) - N_{1jb}^{\text{CC}}(\text{SM})| \geq N_{\text{SD}} \cdot \Delta, \quad (13)$$

where $N_{1jb}^{\text{CC}}(\text{SM}) = \mathcal{L} \cdot \mathcal{A} \cdot \bar{\sigma}_{1jb}^{\text{CC}}(\text{SM})$ [see Eq. (9)] is the expected number of $e + p/A \rightarrow j_b + E_T$ events in the SM due to light-jet misidentification as b jets. We include three contributions in the overall expected error Δ :

- (i) Statistical error: $\Delta_{\text{stat}} = \sqrt{N_{1jb}^{\text{CC}}(\epsilon_b, t_j, \Lambda_{\text{eff}})}$.
- (ii) Systematic error: $\Delta_{\text{sys}} = N_{1jb}^{\text{CC}}(\epsilon_b, t_j, \Lambda_{\text{eff}}) \cdot \delta_s$.
- (iii) Theory error: $\Delta_{\text{theor}} = N_{1jb}^{\text{CC}}(\epsilon_b, t_j, \Lambda_{\text{eff}}) \cdot \delta_t$.

We combine these in quadrature: $\Delta^2 = \Delta_{\text{stat}}^2 + \Delta_{\text{sys}}^2 + \Delta_{\text{theor}}^2$, where the δ_s, δ_t denote the statistical and theoretical errors per event; δ_s is usually estimated using experimental values from related processes and δ_t is derived from the errors in the Monte Carlo integration used in calculating the various cross sections. Unless stated otherwise, we will use below $\delta_s = \delta_t = 0.02$.

In Fig. 1 we plot the 95% confidence level (CL) bounds on Λ_{eff} for the tensor operator $Q_{\ell\text{equ}}^{(3)}(1131)$, as a function of the light-jet mistagging purity factor t_j and for three values of the b -jet-tagging efficiency $\epsilon_b = 0.6, 0.7, 0.8$. In Table III we give the 95% CL bounds on Λ_{eff} for all the operators in Table I, where we consider three representative tagging efficiency/purity scenarios: loose, $(\epsilon_b, t_j) = (0.8, 0.03)$; medium, $(\epsilon_b, t_j) = (0.7, 0.01)$; and tight, $(\epsilon_b, t_j) = (0.6, 0.001)$. We see from both Fig. 1 and Table III that the critical parameter in our case is the purity factor, i.e., the tight b -tagging setup is by far the most advantageous. This is indeed expected when the background from light-quark jets is large (as in our case),

TABLE II. The NP cross sections (fb) at the EIC for the CC production of a single b quark, $\sigma_{\text{NP}}^{\text{CC}} = \sigma(e + p/A \rightarrow j_b + \nu_e)$, that each of the operators in Table I yield. The cross sections are calculated with beam energies $E_p = 275$ and $E_e = 18$ GeV, see also text.

	$Q_{\ell q}^{(3)}(1113)$	$Q_{\ell\text{equ}}^{(1)}(1131)$	$Q_{\ell\text{equ}}^{(3)}(1131)$	$Q_{\ell\text{edq}}^{(1)}(1131)$	$Q_{\text{Hud}}(13)$	$Q_{Hq}^{(3)}(13)$
$\sigma(e + p/A \rightarrow j_b + \nu_e)$	76.4	1.5	176	1.5	4.2	45.4

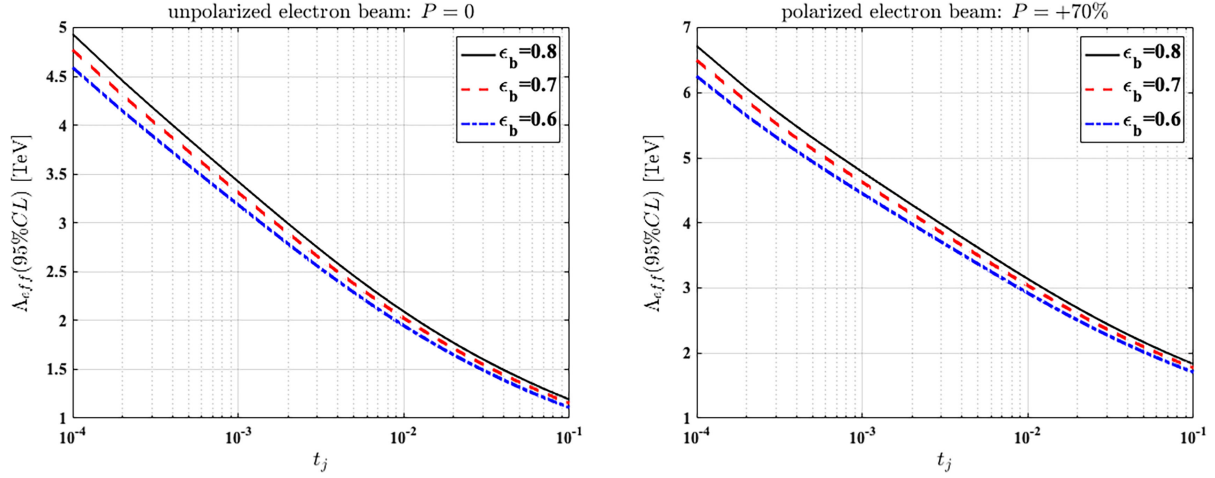


FIG. 1. Expected 95% CL bounds on Λ_{eff} (TeV) from the CC single-jet signal, $e + p/A \rightarrow j + E_T$, for the tensor operator $Q_{\ell\text{equ}}^{(3)}(1131)$, as a function of the light-jet mistagging purity factor t_j , for three values of the b -tagging efficiency $\epsilon_b = 0.6, 0.7, 0.8$. Left: without electron beam polarization. Right: with $P_e = 0.7$, i.e., +70% right-handed electron beam polarization.

so that the analysis benefits more from purity rather than from a higher b -tagging efficiency.

A. Effects of beam polarization

Let us next discuss the effects of beam polarization at the EIC. As mentioned earlier, an important feature of the EIC is the possibility of electron beam polarization, which is particularly useful for improving the sensitivity to NP with chiral couplings, as in our case. The polarized cross section is

$$\sigma(P_e) = \frac{1}{2}[(1 - P_e)\sigma_- + (1 + P_e)\sigma_+], \quad (14)$$

where P_e is the percentage longitudinal polarization, so that $\sigma_- = \sigma(P_e = -1)$ and $\sigma_+ = \sigma(P_e = +1)$ are the purely left- and right-handed cross sections, respectively. In Fig. 1 and Table III, we also show the expected 95% CL bounds on Λ_{eff} with $P_e = +70\%$, i.e., a 70% right-handed

incoming electron beam. We see that beam polarization will significantly improve the sensitivity to NP contributing to right-handed incoming electrons by up to $\sim 50\%$, since the SM contribution to these single-jet events arises from left-handed incoming electrons.

To get a better assessment of the potential effects of electron beam polarization (P_e) on the sensitivity to NP with specific chiral couplings, we depict in Fig. 2 the 95% CL bound on Λ_{eff} [denoted by $\Lambda_{\text{eff}}(95\text{CL})$ in the plot], as a function of P_e for the tensor and vector four-Fermi operators, $Q_{\ell\text{equ}}^{(3)}(1131)$ and $Q_{\ell q}^{(3)}(1113)$, in the three loose, medium, and tight b -tagging scenarios. In order to understand the behavior of the curves in Fig. 2, we recall that, for the CC process $e + p/A \rightarrow j_b + E_T$ of our interest here, the tensor operator $Q_{\ell\text{equ}}^{(3)}(1131)$ contributes to $e_R + p/A \rightarrow j_b + E_T$ (i.e., incoming right-handed electron beam), while the contribution from the vector operator $Q_{\ell q}^{(3)}(1113)$ (as well as the SM background) involves left-

TABLE III. The expected 95% CL bounds on the effective scale $\Lambda_{\text{eff}} = \Lambda/\sqrt{\alpha}$ for the operators in Table I. Numbers are given for the three b -tagging efficiency setups: loose, medium, and tight and for unpolarized and +70% [$P_e = +0.7$, see Eq. (14)] polarized incoming electron beam. See also text.

95% CL bounds on $\Lambda_{\text{eff}}(Q)$ (TeV) with electron beam polarization $P_e = 0(+0.7)$			
Q	Tight setup (ϵ_b, t_j) = (0.6, 0.001)	Medium setup (ϵ_b, t_j) = (0.7, 0.01)	Loose setup (ϵ_b, t_j) = (0.8, 0.03)
$Q_{\ell q}^{(3)}(1113)$	2.6 (2.4)	1.7 (1.6)	1.3 (1.3)
$Q_{\ell\text{equ}}^{(1)}(1131)$	1.0 (1.4)	0.6 (0.9)	0.5 (0.8)
$Q_{\ell\text{equ}}^{(3)}(1131)$	3.2 (4.6)	2.0 (3.1)	1.6 (2.5)
$Q_{\ell\text{edq}}^{(1)}(1131)$	1.0 (1.4)	0.6 (0.9)	0.5 (0.8)
$Q_{\text{Hud}}(13)$	1.3 (1.2)	0.8 (0.7)	0.6 (0.6)
$Q_{\text{Hq}}^{(3)}(13)$	2.3 (2.1)	1.5 (1.4)	1.2 (1.1)

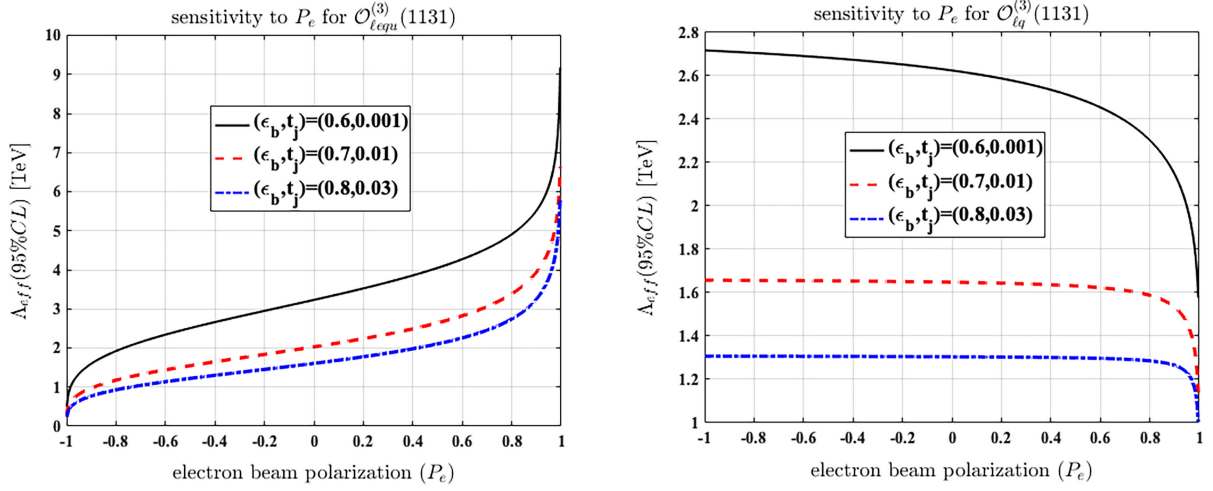


FIG. 2. Expected 95% CL bounds on Λ_{eff} (TeV) from the CC single-jet signal, $e + p/A \rightarrow j + E_T$, as a function of the electron beam polarization P_e for the loose, medium, and tight b -tagging scenarios. Results are shown for the tensor operator $\mathcal{Q}_{\ell \text{equ}}^{(3)}(1131)$ (left) and the vector operator $\mathcal{Q}_{\ell q}^{(3)}(1113)$ (right).

handed incoming electrons, i.e., $e_L + p/A \rightarrow j_b + E_T$. In particular, notice that with $P_e \rightarrow +100\%$ one would be able to probe $\Lambda_{\text{eff}} \rightarrow \mathcal{O}(10)$ TeV for the tensor operator; although not realistic, it is still quite remarkable bearing that the c.m. energy used for the EIC in this simulation

is $E_{\text{c.m.}} \sim 140$ GeV, so that this collider will approach a sensitivity to Λ_{eff} of up to $\sim 70 \times E_{\text{c.m.}}$ (EIC) if $P_e \rightarrow +100\%$.

One can further define a polarization asymmetry, which turns out to be a useful sensitive probe of chiral NP effects,

$$\mathcal{A}_{P_e}^{\text{CC}}(\epsilon_b, t_j, \Lambda_{\text{eff}}) = \frac{N_{1j_b}^{\text{CC}}(\epsilon_b, t_j, \Lambda_{\text{eff}}; P_e) - N_{1j_b}^{\text{CC}}(\epsilon_b, t_j, \Lambda_{\text{eff}}; -P_e)}{N_{1j_b}^{\text{CC}}(\epsilon_b, t_j, \Lambda_{\text{eff}}; P_e) + N_{1j_b}^{\text{CC}}(\epsilon_b, t_j, \Lambda_{\text{eff}}; -P_e)}, \quad (15)$$

where $N_{1j_b}^{\text{CC}}(\epsilon_b, t_j, \Lambda_{\text{eff}}; P_e)$ is the number of expected single b -jet $+E_T$ events from initial electron beam with polarization P_e which is extracted from the corresponding polarized cross section using Eq. (14). For the SM (and/or for any type of NP that contributes only to left-handed incoming electron beam, i.e., only to $e_L + p/A \rightarrow j + E_T$) we have $\mathcal{A}_{P_e}^{\text{CC}}(\text{SM}) = -P_e$, whereas, in general, we find

$$\mathcal{A}_{P_e}^{\text{CC}}(\epsilon_b, t_j, \Lambda_{\text{eff}}) = P_e \cdot \frac{\epsilon_b \cdot \sigma_{\text{NP}}^{\text{CC}} - t_j \cdot \sigma_{\text{SM}}^{\text{CC}}}{\epsilon_b \cdot \sigma_{\text{NP}}^{\text{CC}} + t_j \cdot \sigma_{\text{SM}}^{\text{CC}}}, \quad (16)$$

where $\sigma_{\text{SM}}^{\text{CC}}$ and $\sigma_{\text{NP}}^{\text{CC}}$ are the cross sections for the production of $j_l + E_T$ and $j_b + E_T$ at the EIC, respectively, without the tagging efficiencies, see Eqs. (9) and (10); note that $\sigma_{\text{NP}}^{\text{CC}} \propto 1/\Lambda_{\text{eff}}^4$.

In Fig. 3 we plot the resulting polarization asymmetry for the SM case (i.e., no NP insertion) and for the case where the tensor operator $\mathcal{Q}_{\ell \text{equ}}^{(3)}(1131)$ is turned on with $\Lambda_{\text{eff}} = 1$ TeV, as a function of P_e and for the three loose, medium, and tight b -tagging scenarios. As mentioned above, $\mathcal{A}_{P_e}^{\text{CC}}(\text{SM}) = -P_e$, so that the SM case is

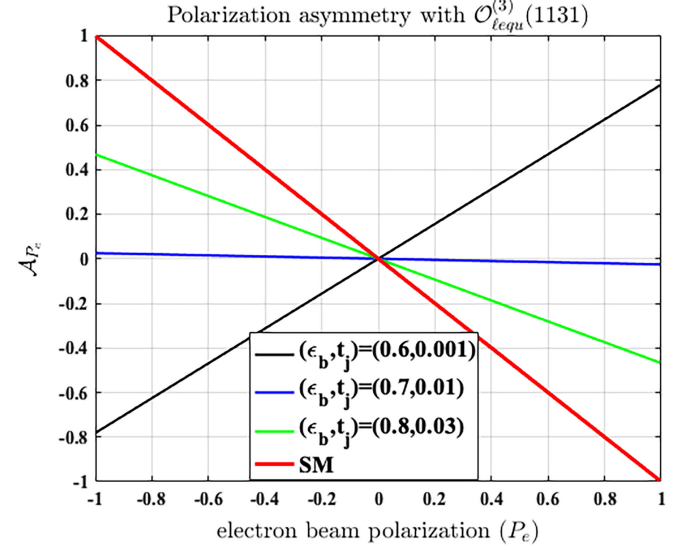


FIG. 3. The polarization asymmetry $\mathcal{A}_{P_e}^{\text{CC}}(\epsilon_b, t_j, \Lambda_{\text{eff}})$ of Eq. (15) when the tensor operator $\mathcal{Q}_{\ell \text{equ}}^{(3)}(1131)$ is turned on with $\Lambda_{\text{eff}} = 1$ TeV, as a function of the electron beam polarization P_e . The asymmetry is plotted for the loose, medium, and tight b -tagging scenarios and also for the SM case. See also text.

independent of the b -tagging and purity factors. We see that the asymmetry is very sensitive to the purity factor t_j and, in particular, it approaches its SM value as t_j grows. This is due to the growth of the SM background in the single b -jet production rate as t_j increases, to the level that it dominates the single b jet + missing energy signal. We find that the sensitivity of $\mathcal{A}_{P_e}^{\text{CC}}(\epsilon_b, t_j, \Lambda_{\text{eff}})$ to the operators that mediate $e_R + p/A \rightarrow j_b + E_T$ (i.e., with a right-handed electron beam) is comparable to what we found above simply by counting single b -jet events, cf. Eq. (13).

IV. b PARITY AND DIJET PRODUCTION AT THE EIC

The dijet production at the EIC can also be separated into the CC and NC interactions

$$\text{CC: } e + p/A \rightarrow 2 \cdot j + E_T, \quad (17)$$

$$\text{NC: } e + p/A \rightarrow 2 \cdot j + e, \quad (18)$$

where within the SM in the limit of a diagonal CKM, the parton-level processes contributing to the CC reaction in Eq. (17) are the electron-gluon fusion $eg \rightarrow d\bar{u}\nu_e, s\bar{c}\nu_e$ and $eu \rightarrow dg\nu_e, ec \rightarrow sg\nu_e, e\bar{d} \rightarrow \bar{u}g\nu_e, e\bar{s} \rightarrow \bar{c}g\nu_e$; the latter

group correspond to the $2 \rightarrow 2$ CC interactions with a gluon radiated off the initial or FS quarks. Here also, we find that the dominant contribution originates from the process $eu \rightarrow dg\nu_e$, which consists of more than 95% of the total $2 \rightarrow 3$ CC cross section.

The NC $2 \rightarrow 3$ reaction in Eq. (18) proceeds via the electron-gluon fusion processes $eg \rightarrow q\bar{q}e$ and electron-quark scattering $eq \rightarrow qge$ and $e\bar{q} \rightarrow \bar{q}ge$, where $q = u, d, c, s, b$ and $eq \rightarrow qge, e\bar{q} \rightarrow \bar{q}ge$ correspond to the NC $2 \rightarrow 2$ processes considered earlier with an additional gluon radiation off the initial and FS quarks. Notice that direct production of a single b jet in the $2 \rightarrow 3$ NC case is possible in the SM via $eb \rightarrow bge$ and $e\bar{b} \rightarrow \bar{b}ge$, though giving a negligibly small contribution to the dijets cross section of about 0.1% (as in the NC $2 \rightarrow 2$ case discussed earlier). Thus, the dominant SM background contribution to $e + p/A \rightarrow j_b + j_\ell + e$ arises from a light jet misidentified as a b jet in $e + p/A \rightarrow 2 \cdot j + e$, where we find that the parton-level $eu \rightarrow uge$ is responsible for about 80% of the corresponding total SM cross section. However, as in the $2 \rightarrow 2$ case, the $2 \rightarrow 3$ NC configuration exhibits noticeably lower sensitivity to the new flavor physics considered.

Therefore, for the dijet case as well we concentrate below on the CC process of Eq. (17), where here the effective SM and NP single b -jet cross sections are [see Eq. (4)]

$$\bar{\sigma}_{1jb}^{\text{CC}}(\text{SM}) = 2t_j(1 - t_j) \cdot \sigma_{\text{SM}}^{\text{CC}}, \quad \sigma_{\text{SM}}^{\text{CC}} = \sigma(e + p/A \rightarrow 2 \cdot j_l + E_T), \quad (19)$$

$$\bar{\sigma}_{1jb}^{\text{CC}}(\text{NP}) = [\epsilon_b(1 - t_j) + t_j(1 - \epsilon_b)] \cdot \sigma_{\text{NP}}^{\text{CC}}, \quad \sigma_{\text{NP}}^{\text{CC}} = \sigma(e + p/A \rightarrow j_b + j_\ell + E_T), \quad (20)$$

and we find that $\sigma_{\text{SM}}^{\text{CC}} \sim 109.5$ fb (dominated by $eu \rightarrow dg\nu_e$, as noted above) and, e.g., $\sigma_{\text{NP}}^{\text{CC}} \sim 1.6$ fb for the tensor operator $\mathcal{O}_{\ell\text{equ}}^{(3)}(1131)$, at the EIC with beam energies of $E_e = 18$ and $E_p = 275$ GeV. The total effective cross section for the $2 \rightarrow 3$ CC single b -jet production process $e + p/A \rightarrow j_\ell + j_b + E_T$ is given by the sum of the SM and NP contributions, i.e., $\bar{\sigma}_{1jb}^{\text{CC}}(\epsilon_b, t_j, \Lambda_{\text{eff}})$ of Eq. (11), where the term $\propto \epsilon_b(1 - t_j)$ dominates the NP part $\bar{\sigma}_{1jb}^{\text{CC}}(\text{NP})$ when $t_j \ll \epsilon_b$.

In Fig. 4 we depict the 95% CL bound on Λ_{eff} that can be expected from a search of single b -jet events in dijet signals at the EIC $e + p/A \rightarrow 2 \cdot j + E_T$, as a function of P_e for the tensor operator $\mathcal{Q}_{\ell\text{equ}}^{(3)}(1131)$. Here also we present results for the loose, medium, and tight b -tagging scenarios defined above. Evidently, the dijet CC signal analyzed in this section is less sensitive to the scale of the FC operator $\mathcal{O}_{\ell\text{equ}}^{(3)}(1131)$ than the single-jet process discussed previously. This lower sensitivity also persists for the other FC operators examined throughout this study.

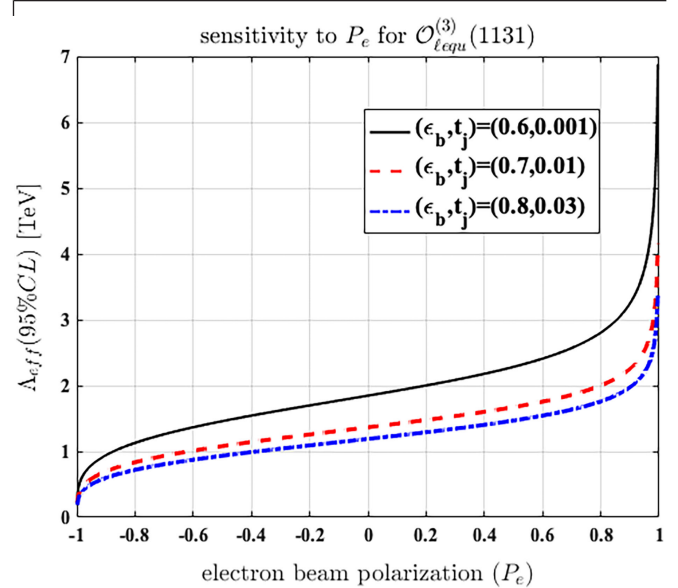


FIG. 4. Expected 95% CL bounds on Λ_{eff} (TeV) from the CC dijet production process, $e + p/A \rightarrow 2 \cdot j + E_T$, as a function of the electron beam polarization P_e for the loose, medium, and tight b -tagging scenarios, for the tensor operator $\mathcal{Q}_{\ell\text{equ}}^{(3)}(1131)$.

V. SUMMARY

We suggest that single- and dijet production at the EIC via the CC interactions $e + p/A \rightarrow j + E_T$ and $e + p/A \rightarrow 2 \cdot j + E_T$ ($j = j_\ell$ and $j = j_b$ for a light- and b -quark jet, respectively) will be a valuable environment for testing new BSM TeV-scale sources of flavor violation involving the third-generation quarks. In particular, these reactions are even under b parity in the SM, defined by $b_P = (-1)^n$ [33], where n is the number of b -quark jets in the final state, since the b_P -odd signals of single b -jet events (i.e., $b_P = -1$ for $n = 1$), $e + p/A \rightarrow j_b + E_T$ and $e + p/A \rightarrow j_b + j_l + E_T$, are necessarily proportional to the off-diagonal CKM factors $|V_{ub}|^2$ and/or $|V_{cb}|^2$ in the SM and are, therefore, unobservably small [more precisely, in the limit $V_{j3}, V_{3j} \rightarrow 0, j \neq 3$, the SM possesses an additional global $U(1)_b$ symmetry, bottomness, that holds to any order in perturbation theory]. Thus, the only significant source of SM background to b_P violation (for our purpose in the CC reactions $e + p/A \rightarrow j + E_T$ and $e + p/A \rightarrow 2 \cdot j + E_T$) arises from misidentifying a light jet for a b jet, i.e., from nonideal purity of the b -jet sample.

Conversely, we show that new types of TeV-scale flavor physics involving the third-generation quark fields can mediate the b_P -odd single b -jet $j_b + E_T$ and $j_b + j_\ell + E_T$ events at the EIC via CC interactions, where we use the SMEFT framework and examine the sensitivity of the EIC

to dim.6 flavor-changing $\ell\ell qq'$ four-Fermi contact terms, as well as operators that modify the Wqq' vertex; both types involving $b \rightarrow u$ transitions. In particular, since the SM is essentially b_P even, we show that b -jet counting offers a useful discriminator for new flavor physics effects, where the b -tagging efficiency and, more importantly, the purity of the b -jet sample become critical factors for this type of analysis.

Capitalizing on the different behaviors of the SM and the new flavor physics under b parity, we find that, by counting single b -jet events in CC reactions at the EIC, one will be able to probe new flavor-violating physics with a scale in the range $\Lambda \sim 1\text{--}5$, depending on the underlying heavy dynamics; notably, reaching a sensitivity to NP scales which are 10–30 times larger than the EIC c.m. energy considered ($E_{\text{c.m.}} \sim 140$ GeV). This represents a substantial improvement over what could have been achieved at the HERA ep collider and it will require a high purity of the b -jet sample and, for some types of NP, also a highly polarized electron beam.

DATA AVAILABILITY

The data that support the findings of this article are not publicly available. The data are available from the authors upon reasonable request.

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