CP violation in same-sign dilepton production at the LHC

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If the neutrino is a Majorana particle, low-energy lepton-number-violating (LNV) processes, such as neutrinoless double-beta ($0\nu\beta\beta$) decay, are possible. It may also be possible to observe high-energy $0\nu\beta\beta$-like LNV processes at the LHC. These are distinguished by the presence of same-sign dileptons in the final state (e.g., $\bar{u}d \to t\bar{b}e^-\mu^-$). In this paper, we show that *CP*-violating triple products (TPs) may be present in the process, and may be measurable at the LHC. If a nonzero TP were observed, it would give us much information about the underlying new physics (NP). We would know that there are (at least) two interfering NP amplitudes, with different weak phases and different Lorentz structures. And if we had some knowledge of the NP, e.g., by direct production of NP particles, we could get information about the magnitudes and relative phases of its couplings.

I. INTRODUCTION

One of the outstanding questions in particle physics is the nature of the neutrino. In particular, is it a Majorana particle? If it is, then lepton-number-violating processes, such as neutrinoless double-beta ($0\nu\beta\beta$) decay, are possible. A great deal of time and effort has been spent looking for $0\nu\beta\beta$ decay, but to date, no signal has been seen (for a review, see Ref. [1]).

The $0\nu\beta\beta$ process is $nn \to ppe^-e^-$, which at the quark level is $dd \to uue^-e^-$. While $0\nu\beta\beta$ decay is a low-energy process, $dd \to uue^-e^-$ could, in principle, also be observable at the LHC, given that pp collisions are involved. Furthermore, as this would now be a high-energy process, one or both of the final-state e^-'s could be a μ^- or a τ^-. So not only is the process lepton number violating, it could also be lepton flavor violating: $dd \to uu\ell^-\ell'^-$. In addition, pp collisions will also generate the related processes $d\bar{u} \to u\bar{d}\ell^-\ell'^-$ and $\bar{u}\bar{u} \to \bar{d}\bar{d}\ell^-\ell'^-$, as well as their *CP* conjugates. Finally, the d and u quarks can be down-type and up-type quarks of any family. Thus, what is studied at the LHC is really many processes: $d_id_j \to u_ku_l\ell^-\ell'^-$, $d_i\bar{u}_j \to u_k\bar{d}_l\ell^-\ell'^-$, $\bar{u}_i\bar{u}_j \to \bar{d}_k\bar{d}_l\ell^-\ell'^-$. We refer to all of these as

$0\nu\beta\beta$-like processes, which are identified by the presence of same-sign dileptons in the final state.

On the other hand, there is also a huge disadvantage at the LHC. Assuming that the neutrino masses are generated via the seesaw mechanism, the three ultralight neutrinos are Majorana (leading to lepton number violation) and mix among themselves (leading to lepton flavor violation). There are also three heavy neutrinos, which have little effect at low energy. The key point is that, in the standard model (SM) with Majorana neutrinos, the diagram for the process $dd \to uue^-e^-$ involves a neutrino propagator, with the result that the amplitude is proportional to m_ν, which is tiny, $O(10^{-2})$ eV. Low-energy experiments are approaching the sensitivity to observe $0\nu\beta\beta$ decay, even with such a suppression factor. However, if the amplitude is, in fact, proportional to m_ν, the process would be completely unobservable at the LHC.

Even so, there are many new-physics (NP) models in which $0\nu\beta\beta$-like processes can be generated *without* the amplitude being suppressed by a light neutrino mass. (For a review of NP models that can contribute to $0\nu\beta\beta$ decay, see Ref. [2].) If a $0\nu\beta\beta$-like process were observed at the LHC, it would point to the presence of one of these models of NP. The question is: which one?

Ultimately, this question can only be answered by the direct production of the NP particles themselves. In this paper, we show that there are indirect ways of learning about the NP: (i) $0\nu\beta\beta$-like processes potentially include *CP*-violating observables (triple products), and (ii) the measurement of such *CP* violation would give us important information about the underlying NP that cannot be easily obtained otherwise.

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We begin in Sec. II with an effective-field-theory (EFT) analysis of $0\nu\beta\beta$-like processes. We find that the interference of certain operators can give rise to CP-violating triple products. We illustrate this explicitly in Sec. III by constructing a toy model that produces such CP-violating effects. We show how the measurement of nonzero triple products can give us information about this model. In Sec. IV, we explore the experimental prospects for making such measurements at the LHC. We conclude in Sec. V.

II. EFT ANALYSIS

CP violation arises due to the interference of (at least) two amplitudes with a relative weak (CP-odd) phase. The first step is therefore to identify all possible operators that can contribute to this process.

To this end, following the notation of Ref. [3], we list all of the dimension-nine operators that contribute to $d_i d_j \rightarrow u_k u_l \ell^- \ell'^-$ and the related $0\nu\beta\beta$-like processes. These operators take the form $\bar{u}\Gamma_1 d\bar{u}\Gamma_2 d\bar{\ell}'\Gamma_3 \ell^C$, where the Γ_i include all possible Lorentz structures (detailed below). Here we have suppressed the flavor indices, so that u, d and ℓ, ℓ' represent any of $\{u, c, t\}$, $\{d, s, b\}$ and $\{e, \mu, \tau\}$, respectively. All operators involve two hadronic currents J and one leptonic current j. Each of these has three types of Lorentz structure:

$$
\begin{aligned}
J_{L,R} &\equiv \bar{u}P_{L,R}d, & j_{L,R} &\equiv \bar{\ell}'P_{L,R}\ell^C, \\
J^{\mu}_{L,R} &\equiv \bar{u}\gamma^{\mu}P_{L,R}d, & j^{\mu}_{L,R} &\equiv \bar{\ell}'\gamma^{\mu}P_{L,R}\ell^C, \\
J^{\mu\nu}_{L,R} &\equiv \bar{u}\sigma^{\mu\nu}P_{L,R}d, & j^{\mu\nu}_{L,R} &\equiv \bar{\ell}'\sigma^{\mu\nu}P_{L,R}\ell^C,
\end{aligned} \quad (1)
$$

where the antisymmetric tensor is defined as $\sigma^{\mu\nu} = \frac{i}{2}[\gamma^{\mu}, \gamma^{\nu}]$.

Note that, if $\ell = \ell'$, the leptonic current must be antisymmetric under the exchange of the two identical leptons. This implies that

$$
\bar{\ell}\gamma^{\mu}\ell^C = 0, \qquad \bar{\ell}\sigma^{\mu\nu}\ell^C = 0. \quad (2)
$$

For simplicity, we consider only dimension-nine operators involving hadronic currents that are color singlets. The most general effective Lagrangian containing such dimension-nine operators is then given by

$$
\mathcal{L}_{eff} = \frac{1}{M^5} \sum_{X,Y,Z=L,R} \sum_{i=1}^{8} C_i^{(XY)Z}(O_i)_{(XY)Z} + \text{H.c.}, \quad (3)
$$

where M is the scale of NP, and

$$
\begin{aligned}
\text{SSS:} & \quad (O_1)_{(XY)Z} = J_X J_Y j_Z, \\
\text{TTS:} & \quad (O_2)_{(XY)Z} = (J_X)_{\mu\nu}(J_Y)^{\mu\nu}j_Z, \\
\text{VVS:} & \quad (O_3)_{(XY)Z} = (J_X)_{\mu}(J_Y)^{\mu}j_Z, \\
\text{TVV:} & \quad (O_4)_{(XY)Z} = i(J_X)_{\mu\nu}(J_Y)^{\mu}(j_Z)^{\nu}, \\
\text{SVV:} & \quad (O_5)_{(XY)Z} = J_X(J_Y)_{\mu}(j_Z)^{\mu}, \\
\text{VVT:} & \quad (O_6)_{(XY)Z} = i(J_X)_{\mu}(J_Y)_{\nu}(j_Z)^{\mu\nu}, \\
\text{STT:} & \quad (O_7)_{(XY)Z} = (J_X)_{\mu\nu}J_Y(j_Z)^{\mu\nu}, \\
\text{TTT:} & \quad (O_8)_{(XY)Z} = i(J_X)_{\mu\mu'}(J_Y)^{\mu\nu'}(j_Z)^{\mu'}_{\nu'}. \quad (4)
\end{aligned}
$$

Here we denote the scalar, vector and tensor currents as S, V and T, respectively. With this shorthand, we describe each operator as a product of these different Lorentz structures. For example, in the third entry, O_3 is VVS, where the first two labels (V) denote the hadronic currents, and the third (S) is the leptonic current. Furthermore, since the first two currents are both hadronic, the labels should be understood as being symmetric in these currents. That is, O_4 is both TVV and VTV, and similarly for operators O_5 and O_7. The operators $O_{4,6,8}$, which involve an odd number of tensor currents, include a prefactor of i to compensate the factor of i in $\sigma_{\mu\nu}$. The operators O_6–O_8 are nonzero only if $\ell \neq \ell'$ [see Eq. (2)].

Note that the above operators are written at the level of weak effective theory, i.e., after electroweak symmetry breaking. That is, they are invariant only under $SU(3)_C \times U(1)_{em}$. When considering a particular operator, one must ensure that it is compatible with the SM effective field theory (SMEFT), i.e., it respects the full $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge symmetry. Only a subset of the above dimension-nine operators are already part of the SMEFT. The others must be generated in other ways, e.g., by dimension-11 operators containing the Higgs. The dimension-nine operator is obtained when the Higgs gets a vacuum expectation value [4,5].

As noted above, we propose to obtain information about the underlying NP through the measurement of CP-violating observables in this decay. These observables arise due to the interference of two of the above operators. In our analysis, we neglect the masses of all fermions, except for that of the top quark. Now, the interference of the left-handed and right-handed fermion fields f_L and f_R is proportional to m_f, so that it vanishes in the limit $m_f \rightarrow 0$. This implies that, in the two interfering amplitudes, each fermion field in one amplitude must have the same chirality as the corresponding fermion field in the other amplitude. (The only exception is if the final state includes two top quarks.) Clearly each current can interfere with another current of the same Lorentz structure. However, if we consider two different types, only S-T interference is allowed. The key point here is that, since only S-S, V-V, T-T and S-T interferences are allowed, we

can immediately see which operators interfere and which do not. For example, O_1 and O_2 interfere, but O_1 and O_3 do not.

III. TOY MODEL

Now, in Eq. (5) there are several pairs of operators that can interfere—SSS-TTS, VVS-VVT, etc.—and each pair has its own set of CP-violating effects. Furthermore, these effects depend on which $0\nu\beta\beta$-like process is used. In this paper, in order to clearly illustrate the various features of our method, we focus on a single pair of operators—SSS and STT—and examine the $0\nu\beta\beta$-like process $\bar{u}d \to t\bar{b}e^-\mu^-$, in which there are no identical particles. In this section, we construct a toy model to generate the SSS and STT operators. Note that we are not advocating this model; it is chosen only for illustrative purposes.

One question that may arise at this stage is: assuming that the NP particles are scalars, fermions or vectors, how can there be tensor operators? The answer is that these can be generated via Fierz transformations. As an example of how this can come about, suppose that $\bar{u}d \to t\bar{b}e^-\mu^-$ is produced as follows. We have $\bar{u}d \to H^-$, where H^- is a charged (scalar) Higgs boson, part of an $SU(2)_L$ doublet with $Y = 1/2$. We also have two scalar leptoquarks (LQs), $\tilde{R}_2$ and S_1 [6], that decay as follows: $\tilde{R}_2 \to \bar{b}_R e_L^-$ (fermion-number conserving) and $S_1 \to t_L \mu_L^-$ (fermion-number violating). Finally, we allow $H^- \to \tilde{R}_2 S_1$. This coupling conserves all SM quantum numbers, but it violates lepton number by 2 units. Thus, all couplings respect the full $SU(3)_C \times SU(2)_L \times U(1)_Y$ symmetry, so that this model is compatible with the SMEFT. The diagram of this process is shown in Fig. 1.

Note that, since the model generates $\Delta L = 2$ $0\nu\beta\beta$-like processes, it may also contribute to Majorana neutrino-mass terms at higher order (after electroweak symmetry breaking). In the present case, if the H^- also couples to $\bar{t}b$, it will produce a neutrino mass term at two loops. Since the present limits on neutrino masses are at the scale of $O(\mathrm{eV})$, this could be problematic: given that the scale of NP is $O(\mathrm{TeV})$, a two-loop suppression could still lead to a value of m_ν that is many orders of magnitude too large. Fortunately, here the problem can be evaded simply by
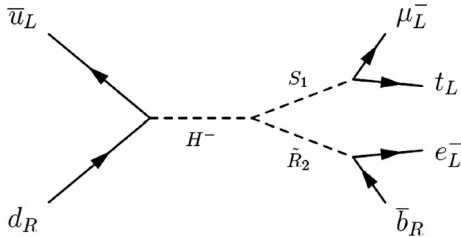
taking the $H^-\bar{t}b$ coupling $\simeq 0$, but these types of potential problems should be checked, even for a toy model.

Referring to Fig. 1, when the heavy NP particles are integrated out, one obtains the dimension-nine operator

$$\frac{M'}{M^6} \bar{u} P_R d \bar{e} P_R b \bar{t} P_R \mu^C. \tag{5}$$

The prefactor M'/M^6 arises from two sources. First, the $H^- - \tilde{R}_2 - S_1$ coupling is proportional to a mass, M'. Second, the propagator of each of H^-, $\tilde{R}_2$ and S_1 provides a factor $1/M_{\mathrm{part}}^2$. Taking the masses of all virtual particles to be the same size, one arrives at a prefactor M'/M^6. In order to maximize the effect of this contribution, we take M to be as small as possible, given the present experimental limits from direct searches. This means that $M = O(\mathrm{TeV})$.

Performing a Fierz transformation of Eq. (5), one obtains

$$\frac{M'}{M^6} \left[\frac{1}{2} \bar{u} P_R d \bar{t} P_R b \bar{e} P_R \mu^C + \frac{1}{8} \bar{u} P_R d \bar{t} \sigma_{\mu\nu} P_R b \bar{e} \sigma^{\mu\nu} P_R \mu^C \right]. \tag{6}$$

Thus, with only scalar NP particles, this model produces both SSS (O_1) and STT (O_7) operators.

Note that, since these two operators have the same weak phase, their interference does not generate CP violation. [This is obvious, since there is basically only a single operator, Eq. (5).] In order to produce a CP-violating effect, we must interfere two operators with different weak phases. This is done below.

Turning to CP violation, the most common CP-violating observable is the direct CP asymmetry, which is the difference in the rates of the process and the CP-conjugate process. A nonzero direct CP asymmetry requires not only a weak-phase difference between the two interfering amplitudes, but also a strong-phase difference. In the present case, if the two interfering amplitudes were, for example, VVS and VVT, the two amplitudes would have the same hadronic structures. We would therefore expect the strong phases to also be the same, resulting in a vanishing direct CP asymmetry. And even with SSS-STT interference, although the Lorentz structures are different, the QCD structure (i.e., the placement of the quark fields) is the same in the two amplitudes, so that the strong phases should be similar. The upshot is that we do not expect a sizable direct CP asymmetry in $d_i d_j \to u_k u_l \ell^- \ell'^-$.[1]

Another type of CP-violating observable involves triple product (TP) correlations [8,9]. These take the form $\vec{v}_1 \cdot (\vec{v}_2 \times \vec{v}_3)$, where the $\vec{v}_i$ are momenta or polarizations. Technically, while the TP is T-odd, it is not CP violating, as it can be generated by strong phases. A true CP-violating observable can be obtained by comparing the TPs in a

FIG. 1. Contribution to $\bar{u}d \to t\bar{b}e^-\mu^-$ involving no virtual neutrinos.

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[1]A possible loophole is if one of the interfering amplitudes involves a resonant decay. In this case, the strong phase can be generated by the absorptive part of the amplitude; see Ref. [7].

process and its *CP*-conjugate process. However, if the strong phases are negligible, as is expected here, then a nonzero TP in a single process is an indication of *CP* violation.

To illustrate how TPs can arise, we return to the model above [Eqs. (5) and (6)]. Suppose that $\tilde{R}_2$ has two decay modes, $\tilde{R}_2 \to \bar{b}_R e_L^-$ and $\tilde{R}_2 \to \bar{b}_R \mu_L^-$, with different (complex) couplings. Similarly, $S_1 \to t_L \mu_L^-$ and $S_1 \to t_L e_L^-$, also with different couplings. There are now two amplitudes contributing to $\bar{u}d \to t\bar{b}e^-\mu^-$:

$$(i): A_1 = c_1 \frac{M'}{M^6} \bar{u}P_R d\bar{e}P_R b\bar{t}P_R \mu^C, \qquad (7)$$

$$(ii): A_2 = c_2 \frac{M'}{M^6} \bar{u}P_R d\bar{\mu}P_R b\bar{t}P_R e^C. \qquad (8)$$

The coefficients c_1 and c_2 are each products of four couplings:

$$c_1 = c_H^{\bar{u}d} c_H^{\tilde{R}_2 S_1} c_{\tilde{R}_2}^{\bar{b}e} c_{S_1}^{t\mu}, \qquad c_2 = c_H^{\bar{u}d} c_H^{\tilde{R}_2 S_1} c_{\tilde{R}_2}^{\bar{b}\mu} c_{S_1}^{te}, \qquad (9)$$

where c_P^{ij} is the coupling of the scalar P (H^-, $\tilde{R}_2$ or S_1) to particles i and j.

The total amplitude is the sum of these two amplitudes: $A_{\text{tot}} = A_1 + A_2$. When we compute $|A_{\text{tot}}|^2$, these two interfere. In the interference of Eqs. (7) and (8), one finds a term of the form

$$\text{Re}[(c_1 c_2^*)\text{Tr}[\not{p}_{\bar{u}}\not{p}_d]\text{Tr}[\not{p}_e\not{p}_{\bar{b}}\not{p}_\mu\not{p}_t\gamma_5]]$$
$$\propto \text{Im}(c_1 c_2^*) p_{\bar{u}} \cdot p_d \epsilon_{\mu\nu\rho\sigma} p_e^\mu p_{\bar{b}}^\nu p_\mu^\rho p_t^\sigma. \qquad (10)$$

This is a TP term. The 4-momenta of each of the final-state particles can be measured, so that $\epsilon_{\mu\nu\rho\sigma} p_e^\mu p_{\bar{b}}^\nu p_\mu^\rho p_t^\sigma$ includes four different TPs: $E_t \vec{p}_{\bar{b}} \cdot (\vec{p}_e \times \vec{p}_\mu)$, $E_{\bar{b}} \vec{p}_t \cdot (\vec{p}_e \times \vec{p}_\mu)$, $E_e \vec{p}_{\bar{b}} \cdot (\vec{p}_t \times \vec{p}_\mu)$, $E_\mu \vec{p}_{\bar{b}} \cdot (\vec{p}_e \times \vec{p}_t)$. However, individually these terms are not Lorentz invariant. It is only the original term, $p_{\bar{u}} \cdot p_d \epsilon_{\mu\nu\rho\sigma} p_e^\mu p_{\bar{b}}^\nu p_\mu^\rho p_t^\sigma$, that is Lorentz invariant. From here on, we refer to this as the Lorentz-invariant triple product (LITP).

Using this, one can now construct the TP asymmetry. For each event, the LITP is computed. This information can then be used to obtain

$$A_{TP} = \frac{\#\text{events}(\text{LITP} > 0) - \#\text{events}(\text{LITP} < 0)}{\text{total} \# \text{events}}. \qquad (11)$$

If $A_{TP} \neq 0$, this indicates a nonzero LITP, which is a signal of *CP* violation.

IV. EXPERIMENTAL PROSPECTS

At this stage, the question is: could this be measured at the LHC? To explore this, we implemented the model in FeynRules [10] and used MADGRAPH [11] to generate events.

We considered three versions of the LHC: (i) the high-luminosity LHC (HL-LHC, $\sqrt{s} = 14$ TeV, peak $\mathcal{L} = 3$ ab^{-1}), (ii) the high-energy LHC (HE-LHC, $\sqrt{s} = 27$ TeV, peak $\mathcal{L} = 15$ ab^{-1}) [12], and (iii) the future circular collider (FCC-hh, $\sqrt{s} = 100$ TeV, peak $\mathcal{L} = 30$ ab^{-1}) [13].

We fix the parameters of the model. We take the $H\bar{u}d$ coupling to be $|c_H^{\bar{u}d}| = 0.1$ and the LQ couplings to be $|c_{\tilde{R}_2}^{\bar{b}e}| = |c_{S_1}^{t\mu}| = |c_{\tilde{R}_2}^{\bar{b}\mu}| = |c_{S_1}^{te}| = 1$, with the relative weak phase of c_1 and c_2 [Eq. (9)] equal to $\pi/2$. We take the $H^- - S_1 - \tilde{R}_2$ coupling to be $M' = 1$ TeV.

Turning to the masses of the NP particles, we must check that these parameters respect the experimental bounds:

(1) The charged Higgs mass is constrained by the search for dijet resonances. In Ref. [14], it was found that $M_H = 1$ TeV is allowed, as long as $\sigma \mathcal{B} \lesssim 1$ pb, where σ is the $H^\pm$ production cross section, and $\mathcal{B}$ is the branching ratio of the $H^\pm$ to two jets. In our case, $\mathcal{B} = 1$, and $\sigma = 0.6$ pb for $|c_H^{\bar{u}d}| = 0.1$. So our value of $M_H = 1$ TeV is allowed. (Note that the dijet constraint is actually stronger for heavier resonances, so the data easily allow a lighter charged Higgs.)

(2) Bounds on LQs are given in Ref. [15]. There are two sources: (i) pair production of LQs, and (ii) *t*-channel contribution of LQs to $pp \to \ell^+\ell^-$ ($\ell = \mu, \tau$). For S_1, it is found that its mass can be 950 GeV if its branching ratio to $t\mu$ is 50% (as it is in our model). $\tilde{R}_2$ was not discussed in Ref. [15], but R_2 was. Assuming similar bounds, the mass of $\tilde{R}_2$ can be as low as 1160 GeV if its branching ratio to $\bar{b}\mu$ is 50% and its coupling to $\bar{b}\mu$ is 1 (as it is in our model). This limit can be weakened if other decays are allowed. In light of all this, we take the LQ masses to be $M_{S_1} = M_{\tilde{R}_2} = 1$ TeV.

In addition to the process $\bar{u}d \to t\bar{b}e^-\mu^-$, there is also the *CP*-conjugate process, $u\bar{d} \to \bar{t}be^+\mu^+$. The amplitude for the antiprocess is obtained from that for the process by simply changing the sign of the weak-phase difference. Now, one can show that the TP in the *CP*-conjugate process is equal to that in the process: there is a minus sign coming from the weak phase, and another minus sign coming from the parity-odd angular function [9]. So one can combine both processes in measuring the TP asymmetry.

Using this NP model, MADGRAPH generates $pp \to t\bar{b}e^-\mu^-$ events, giving the 4-momenta of the final-state particles for each event. Using energy-momentum conservation, $p_{\bar{u}} + p_d = p_e + p_{\bar{b}} + p_\mu + p_t$, so that

$$p_{\bar{u}} \cdot p_d = \frac{1}{2}(p_{\bar{u}} + p_d)^2 = (p_e + p_{\bar{b}} + p_\mu + p_t)^2. \qquad (12)$$

With this, the LITP $p_{\bar{u}} \cdot p_d \epsilon_{\mu\nu\rho\sigma} p_e^\mu p_{\bar{b}}^\nu p_\mu^\rho p_t^\sigma$ is computed. Doing this for all events, the LITP asymmetry A_{TP}

TABLE I.   Summary for $pp \to t\bar{b}e^-\mu^-$ (top) and $pp \to \bar{t}be^+\mu^+$ (bottom). The LITP asymmetry is calculated using MADGRAPH with a simulated sample of 10^6 events.

Machine ($\sqrt{s}$)	Peak $\mathcal{L}$	σ(fb)	Expected # events	A_{TP}
HL-LHC (14 TeV)	3 ab^{-1}	0.005	15	14%
HE-LHC (27 TeV)	15 ab^{-1}	0.03	450	9.2%
FCC-hh (100 TeV)	30 ab^{-1}	0.24	7.2K	5.1%

Machine ($\sqrt{s}$)	Peak $\mathcal{L}$	σ(fb)	Expected # events	A_{TP}
HL-LHC (14 TeV)	3 ab^{-1}	0.01	30	12.3%
HE-LHC (27 TeV)	15 ab^{-1}	0.05	750	7.3%
FCC-hh (100 TeV)	30 ab^{-1}	0.32	9.6K	4.2%

[Eq. (11)] is calculated. This procedure is repeated for the *CP*-conjugate process $pp \to \bar{t}be^+\mu^+$.

The results are shown in Table I. There are three patterns that should be explained.

(1) For each machine, the cross section for the process is smaller than that for the antiprocess. Explanation: The process $pp \to t\bar{b}e^-\mu^-$ and antiprocess $pp \to \bar{t}be^+\mu^+$ involve $\bar{u}d$ and $u\bar{d}$ annihilation, respectively. But there are more u quarks in a proton than d quarks.

(2) A_{TP} decreases as the energy increases. Explanation: The TP is produced in SSS-STT interference, and the STT amplitude can be generated via a Fierz transformation of an SSS amplitude. These effective operators are produced by the exchange of virtual particles. But in some events, the final state is produced by the decay of (at least) one *on-shell* LQ. In this case, there is no effective operator, which means no Fierz transformation, and hence no TP. The number of events with an on-shell LQ increases with increasing energy, resulting in a smaller A_{TP}.

(3) While A_{TP} is similar for process and antiprocess, it is always a bit smaller for the antiprocess. Explanation: As noted above, the events are generated by $\bar{u}d$ or $u\bar{d}$ annihilation. This means that they do not all have the same energy. Because the proton contains two valence u quarks, but only one valence d quark, the average u-quark energy is a bit larger than the average d-quark energy. As a result, on average, the antiprocess events have a larger energy, which results in more on-shell LQs, and hence a smaller A_{TP}.

Adding the results from both tables, we see that the expected number of events at the HL-LHC, HE-LHC and FCC-hh are about 45, 1200 and 17 000, respectively. Now, given an LITP asymmetry A_{TP}, the number of events required to show that it is nonzero at $n\sigma$ is

$$N = \frac{n^2}{A_{TP}^2 \epsilon}, \tag{13}$$

where ϵ is the experimental efficiency. Using this, we see that (i) $A_{TP} \simeq 13\%$ is not measurable at the HL-LHC, (ii) depending on the value of ϵ, $A_{TP} \simeq 8\%$ may be measurable at the HE-LHC at the level of $\simeq 2\sigma$, and (iii) $A_{TP} \simeq 4.5\%$ is certainly measurable at the FCC-hh at the 3σ level.

Of course, the above analysis is purely "theoretical," i.e., it does not take into account the issues an actual experiment will have to deal with. A complete analysis would include a full Monte Carlo simulation, but this is beyond the scope of this paper. Instead, we list below several things that will have to be taken into account in a real analysis, along with a discussion of the implications.

First, there is the question of backgrounds. Both the ATLAS and CMS collaborations have searched for NP at the LHC using same-sign dilepton events, and have had to deal with backgrounds. Consulting Ref. [16], we find that the background most relevant for us is $t\bar{t}W^-$, in which $\bar{t} \to \bar{b}W^-(\to \ell^-\bar{\nu}_\ell)$ and $W^- \to \ell'^-\bar{\nu}_{\ell'}$, with $\ell = e$ and $\ell' = \mu$ or vice versa. The background process is therefore $pp \to t\bar{b}e^-\mu^-$ + missing transverse energy, to be compared with our process $pp \to t\bar{b}e^-\mu^-$. Using MADGRAPH, we find that the cross section for this background process and its antiprocess at the 100 TeV FCC-hh is $\sim$60 fb. With a luminosity of 30 ab^{-1}, this corresponds to 1.8×10^6 events, to be compared with our 1.7×10^4 signal events. Using $S/\sqrt{B}$ as a measure of significance (S and B are the number of signal and background events, respectively), we find $S/\sqrt{B} = 12.7$, which is excellent. And if cuts on the missing transverse energy are applied, the background can be considerably reduced.

Second, in order to construct the LITP, it is necessary the measure the 4-momenta of all the final-state particles. For the e^- and μ^-, this is no problem. However, how well can p_t and $p_{\bar{b}}$ be measured?

We begin with p_t. The dominant decay is $t \to bW^+$, with the W^+ decaying to $q\bar{q}$ or $\ell^+\nu_l$. In either case, p_W can be found (even though the neutrino is not detected in $W^+ \to \ell^+\nu_l$, its 4-momentum can be deduced from the constraint that $p_W^2 = M_W^2$). Similarly, p_B can be deduced from $(p_B + p_W)^2 = m_t^2$, so that p_t can be obtained. The only potential difficulty is that there is an ambiguity due to the fact that one cannot distinguish the b from t decay from the $\bar{b}$ in the final state. However, similar problems arise when the t-quark mass is measured in a $t\bar{t}$ final state. In this case, there are statistical methods to deal with the ambiguity, so that the measurement can be made, with some smearing of the result [17].

The measurement of p_b is more challenging. Roughly 30% of b decays are semileptonic and include (undetected) neutrinos, which impacts the precision with which p_b can be measured. Also, for jets in general, the precision of the measurement of the 4-momenta improves with larger p_T, suggesting that it may be more difficult to measure p_b as

the LHC energy increases. On the other hand, b-jet resolution is extremely important for the ATLAS and CMS collaborations in order to be able to observe $H \to b\bar{b}$, so that there is a good deal of work in this area. For example, it has been found that it is possible to correct the b-jet energy when a muon is found inside the jet [17].

It is clear that a full Monte Carlo simulation is required to determine how well the LITP signal of Table I can be measured. However, there are two additional points. First, the H^--$\tilde{R}_2$-S_1 coupling of the toy model has dimensions of mass, with $M' = O(\text{TeV})$. The LITP events were generated taking $M' = 1$ TeV. But another value of M' could have been reasonably chosen, say $M' = 2$ TeV. Since the cross section is proportional to M'^2, this would increase the number of events in Table I by 4. Thus, rather than asking how well the LITP signal of Table I can be measured, a better question would be: what size of LITP can be determined to, say, 3σ? Second, while we have focused on $\bar{u}d \to t\bar{b}e^-\mu^-$, other processes are also possible: $\bar{u}d \to tjete^-\mu^-$, $\bar{u}d \to \text{jet}\,\bar{b}e^-\mu^-$ and $\bar{u}d \to \text{jet}\,\text{jet}\,e^-\mu^-$, where jet represents a light quark. LITPs should be searched for in all of these processes.

V. CONCLUSIONS

If the neutrino is a Majorana particle, this means that lepton-number-violating (LNV) processes are possible. These typically contain a pair of same-sign leptons in the final state. At low energies, there are experiments looking for neutrinoless double-beta ($0\nu\beta\beta$) decay, $nn \to ppe^-e^-$, or $dd \to uue^-e^-$ at the quark level. It is also possible to search for LNV processes at high energies, at the LHC. One advantage at the LHC is that there are many LNV processes, including those in which the final-state leptons have different flavors, i.e., there is also lepton flavor violation. We referred to all of these as $0\nu\beta\beta$-like processes.

There is also an important disadvantage: the $0\nu\beta\beta$ decay amplitude is suppressed by a light neutrino mass. If such a suppression were present in LHC processes, they would be unobservable. Fortunately, there are many NP models in which $0\nu\beta\beta$-like processes can be generated without the amplitude being suppressed by a light neutrino mass. If such a process were observed at the LHC, it would imply that one of these NP models is present. Can we figure out which one?

In this paper, we used an effective-field-theory analysis to show that, if certain pairs of NP operators contribute to a

$0\nu\beta\beta$-like process, when one squares the total amplitude, their interference generates a term of the form $\epsilon_{\mu\nu\rho\sigma}p_1^\mu p_2^\nu p_3^\rho p_4^\sigma$, where the p_i are the 4-momenta of the final-state particles. This is a CP-violating LITP. In order to illustrate this, we focused on $\bar{u}d \to t\bar{b}e^-\mu^-$. We constructed a toy model involving a charged Higgs (H^-) and two types of leptoquark ($\tilde{R}_2$ and S_1), all with masses of 1 TeV. There is a $H^- - \tilde{R}_2 - S_1$ coupling that violates L by 2 units and leads to the LNV process $\bar{u}d \to t\bar{b}e^-\mu^-$. The couplings are chosen such that a LITP is generated.

Using FeynRules [10] and MADGRAPH [11], we examined the prospects for measuring the LITP at the LHC. To be specific, we considered the HL-LHC (14 TeV), the HE-LHC (27 TeV) and the FCC-hh (100 TeV). For each machine, we generated the $\bar{u}d \to t\bar{b}e^-\mu^-$ events. For each set, we calculated the TP asymmetry A_{TP}, defined as the difference of the percentage of events with LITP > 0 and LITP < 0. If $A_{TP} \neq 0$, this is a signal of CP violation. We found that the predicted A_{TP} is not measurable at the HL-LHC, may be measurable at the HE-LHC, and is certainly measurable at the FCC-hh.

What would we learn from such a measurement? This depends on what we already know at the time of the measurement. If no NP particles have been found via direct production, the observation of $pp \to t\bar{b}e^-\mu^-$ would be an indirect confirmation of the presence of NP, and the measurement of a nonzero TP asymmetry would indicate that there are two interfering amplitudes with different Lorentz structures and a nonzero weak-phase difference. And if NP particles have already been found, this will provide information about their properties. In the case of the above model, with masses of 1 TeV, it is likely that the H^-, $\tilde{R}_2$ and S_1 will already have been discovered, and some of their couplings to ordinary particles measured. But it may not be known that there is a $H^- - \tilde{R}_2 - S_1$ coupling that has $\Delta L = 2$. And the measurement of the TP asymmetry gives phase information about the NP couplings that would be difficult to obtain otherwise.

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