Generic Tests of *CP* Violation in High-p_T Multilepton Signals at the LHC and Beyond

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We introduce a modification to the standard expression for tree-level *CP* violation in scattering processes at the LHC, which is important when the initial state is not self-conjugate. Based on that, we propose a generic and model-independent search strategy for probing tree-level *CP* violation in inclusive multilepton signals. We then use TeV-scale 4-fermion operators of the form $tu\ell\ell$ and $tc\ell\ell$ with complex Wilson coefficients as an illustrative example and show that it may generate $\mathcal{O}(10\%)$ *CP* asymmetries that should be accessible at the LHC with an integrated luminosity of $\mathcal{O}(1000)$ fb^{-1}.

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The nature of *CP* violation (CPV), which is closely related to the flavor structure, is one of the major unresolved problems in particle physics. Indeed, the search for new *CP*-violating sources, beyond the standard model (SM), may be the key to a deeper understanding of particle physics and the evolution of the Universe, since CPV has far-reaching implications for cosmology [1–3]; in particular, the strength of CPV effects in the SM is insufficient to explain the observed baryon asymmetry of the universe (BAU), see, e.g., [4–6]. It is, for these reasons, that the search for CPV beyond the SM is a very important component of the on-going effort for unveiling the physics that underlies the SM, even if the latter has already been observed.

In this Letter we reexamine the formulation of tree-level *CP*-violating effects in scattering processes at the LHC, introducing a new term to the "master" CPV expression, which properly identifies the genuine *CP* violating signal and also takes into account "fake" *CP*-violating effects that arise when the initial state is not self-conjugate. We then present a generic test of CPV in scattering processes, which is potentially sensitive to a wide variety of underlying new physics (NP) scenarios. We are particularly interested in CPV in the inclusive trilepton and four-lepton signals:

$$pp \to \ell'^- \ell^+ \ell^- + X_3, \tag{1}$$

$$pp \to \ell'^+ \ell^- \ell^+ + \bar{X}_3, \tag{2}$$

$$pp \to \ell'^+ \ell'^- \ell^+ \ell^- + X_4, \tag{3}$$

where $\ell, \ell' = e, \mu, \tau$ (preferably $\ell \neq \ell'$, see below) and X_3, $\bar{X}_3$, and X_4 contain in general jets and missing energy. These include the $e^\pm \mu^+ \mu^-$ and $\mu^\pm e^+ e^-$ final states for $\ell, \ell' = e, \mu$ and similarly for the pairs $\ell, \ell' = e, \tau$ and $\ell, \ell' = \mu, \tau$, as well as the three-flavor final state $pp \to e\mu\tau + X$. As an example, we will consider below CPV in the $e^\pm \mu^+ \mu^-$ trilepton signals, but it should be clear that it is equally important to search for CPV in multilepton final states with as many different combination of flavors as possible.

Multilepton final states with high transverse momentum (p_T) particles have been extensively studied at the LHC, both in measurements of SM processes and in searches for NP. However, searches for *CP* asymmetries in such processes have been limited [7–9]. Indeed, high-p_{T} charged leptons are rather easily identifiable objects with excellent resolution and are, therefore, very useful probes of generic NP at the LHC [9–12]; they are sensitive to many types of well-motivated underlying NP phenomena, such as lepton-flavor violation, lepton-universality violation, lepton-number violation [13–25], and CPV, which is the subject studied in this Letter. These multileptons signatures are also useful channels for searching for NP in top-quark systems and this has led to experimental searches, e.g., in single-top and top-pair production processes $pp \to t\bar{t}V, t\bar{t}H, tV$ $(V = W, Z)$ [26–29] as well as in 4-top production $pp \to tt\bar{t}\bar{t}$ [30,31] and searches for flavor-changing (FC) top physics [32–41].

The available momenta of the charged leptons in the final state of these multilepton signals allow a straightforward construction of CPV observables in the laboratory frame, as will be shown below. We note, though, that special care is needed for CPV tests at pp colliders, where the initial state is not self-conjugate and the parton distribution functions (PDFs) of the incoming partons may, therefore, have an asymmetric structure. This will be discussed below.

It should be emphasized that a sizable, say $\mathcal{O}(\gtrsim 1\%)$ manifestation of CPV in multileptons events of the type (1), (2), or (3) will be strong evidence for NP, since the CP-odd CKM-phase of the SM (which is responsible for CPV in the quark sector and has been measured [42]) is expected to yield negligible CP-violating effects in these processes, as it can only arise from EW processes at higher loop orders [43,44]. Furthermore, new CP-violating effects in leptonic systems may shed light on Leptogenesis, where the BAU is generated from a lepton asymmetry via a decay of a heavy neutral lepton [45,46].

Finally, we recall that in the last several years a few σ deviations from the SM in B decays [47–63] as well as in the muon $g-2$ [64–66] have been measured, indicating a possible need for NP. The CPV searches in collider physics that are being suggested here are then especially timely since CP is not a symmetry of nature and, on general grounds, one expects new physics to entail beyond the SM CP-odd phase(s) [43,67].

Potential large tree-level CP asymmetries at the LHC in the tri- and four-lepton production processes (1), (2), and (3) can be searched for, using the following triple products (TP) of the lepton momenta ($\ell \neq \ell'$) [68]:

$$\mathcal{O}_{CP} = \vec{p}_{\ell'^-} \cdot (\vec{p}_{\ell^+} \times \vec{p}_{\ell^-}),$$
$$\overline{\mathcal{O}_{CP}} = \vec{p}_{\ell'^+} \cdot (\vec{p}_{\ell^-} \times \vec{p}_{\ell^+}), \tag{4}$$

which are odd under P and under naive time reversal (T_N): time → -time. Under C and CP they transform as

$$C(\mathcal{O}_{CP}) = +\overline{\mathcal{O}_{CP}}, \qquad C(\overline{\mathcal{O}_{CP}}) = +\mathcal{O}_{CP},$$
$$CP(\mathcal{O}_{CP}) = -\overline{\mathcal{O}_{CP}}, \qquad CP(\overline{\mathcal{O}_{CP}}) = -\mathcal{O}_{CP}. \tag{5}$$

Thus, to measure a nonzero TP correlation effect for the $\mathcal{O}_{CP}$'s defined in (4), the following T_N-odd (and also P-violating) asymmetries can be constructed:

$$A_T \equiv \frac{N(\mathcal{O}_{CP} > 0) - N(\mathcal{O}_{CP} < 0)}{N(\mathcal{O}_{CP} > 0) + N(\mathcal{O}_{CP} < 0)}, \tag{6}$$

$$\bar{A}_T \equiv \frac{N(-\overline{\mathcal{O}_{CP}} > 0) - N(-\overline{\mathcal{O}_{CP}} < 0)}{N(-\overline{\mathcal{O}_{CP}} > 0) + N(-\overline{\mathcal{O}_{CP}} < 0)}, \tag{7}$$

where $N(\mathcal{O}_{CP} > 0)$ is the number of events for which $\mathrm{sign}(\mathcal{O}_{CP}) > 0$ is measured, etc.

As will be shown below, a measurement of $A_T \neq 0$ and/or $\bar{A}_T \neq 0$ may indicate the presence of CPV [CP-odd phase(s)], but may also be a signal of some strong or generic CP-even phase, e.g., from final state interactions (FSI) [43,75,76], even if the underlying dynamics that drives the processes under consideration is CP conserving. Therefore, in order to better isolate the pure CPV effect, we use the following observable, sensitive to CPV:

$$A_{CP} = (A_T - \bar{A}_T)/2. \tag{8}$$

A_{CP} may, in fact, also be "contaminated" by CP-even phases when the initial state is not CP symmetric, as can be the case at the LHC or at pp colliders, in general. To see this, let us consider the underlying (hard) processes of the trilepton signals of (1) and (2) [the discussion below applies similarly to the four-lepton signals of (3)]: $ab \to \ell'^- \ell^+ \ell^- + X$ and $\bar{a}\,\bar{b} \to \ell'^+ \ell^- \ell^+ + \bar{X}$. We assume for simplicity that there are only 2 interfering amplitudes that contribute to these processes as follows (CPV requires at least two amplitudes with different phases for any given process):

$$\mathcal{M}_{ab\to\ell'^-\ell^+\ell^-} = M_1 e^{i(\phi_1+\delta_1)} + M_2 e^{i(\phi_2+\delta_2)}, \tag{9}$$

where we have factored out the CP-odd phases, $\phi_{1,2}$, and CP-even phases $\delta_{1,2}$. The latter typically arise from FSI at higher loop orders. Also, M_i can be complex in general (as in our case below) and the amplitude for the charge-conjugate (CC) channel ($\bar{a}\,\bar{b} \to \ell'^+ \ell^- \ell^+$) is obtained from (9) by changing the sign of the CP-odd phases $\phi_i \to -\phi_i$ and replacing $M_i \to M_i^\star$.

The corresponding (hard) differential cross sections can then be schematically written as

$$d\hat{\sigma} = W + U \cdot \cos(\Delta\delta + \Delta\phi) + V \cdot \mathcal{O}_{CP} \cdot \sin(\Delta\delta + \Delta\phi), \tag{10}$$

and $d\bar{\hat{\sigma}} = d\hat{\sigma}(\Delta\phi \to -\Delta\phi, \mathcal{O}_{CP} \to \overline{\mathcal{O}_{CP}})$ for the CC channel, where $\Delta\phi = \phi_1 - \phi_2$, $\Delta\delta = \delta_1 - \delta_2$, $W \propto |M_1|^2, |M_2|^2$, $U \propto \mathrm{Re}(M_1 M_2^\dagger)$ and the 3rd term in (10) arises from $\mathrm{Im}(M_1 M_2^\dagger) \propto \mathcal{O}_{CP}$ and is where the tree-level CPV resides, i.e., when $\Delta\delta = 0$.

We then find for A_T and $\bar{A}_T$ in (6) and (7):

$$A_T = \mathcal{I}_{ab} \sin(\Delta\delta + \Delta\phi), \quad \bar{A}_T = \mathcal{I}_{\bar{a}\bar{b}} \sin(\Delta\delta - \Delta\phi), \tag{11}$$

with

$$\mathcal{I}_{ab} \propto \frac{\int_R d\Phi \cdot f_a f_b \cdot V \cdot \mathtt{sign}(\mathcal{O}_{CP})}{\int_R d\Phi \cdot f_a f_b \cdot (W + U \cdot \cos(\Delta\delta + \Delta\phi))}, \tag{12}$$

where $d\Phi$ is the phase-space volume element, R is the phase-space region of integration and f_a, f_b are the PDFs of the incoming particles a, b; similarly, for the CC channel, $\mathcal{I}_{\bar{a}\bar{b}}$ is obtained by replacing $f_a f_b \to f_{\bar{a}} f_{\bar{b}}$, $\mathcal{O}_{CP} \to \overline{\mathcal{O}_{CP}}$ and $\Delta\phi \to -\Delta\phi$.

As mentioned earlier, we see that $A_T \neq 0$ and/or $\bar{A}_T \neq 0$ can be observed even in the absence of CPV (i.e., when $\Delta\phi = 0$), due to the presence of CP-even phases ($\Delta\delta \neq 0$). Also, $|A_T| \neq |\bar{A}_T|$ is possible at the LHC, even with $\Delta\delta = 0$, due the different PDF's of the incoming particles in the process and its CC channel, i.e., due to $f_a, f_b \neq f_{\bar{a}}, f_{\bar{b}}$, when the initial state is not self conjugate. This affects the CP asymmetry A_{CP} of (8), which is given by [using (11)]:

$$A_{CP} = \frac{\mathcal{I}_{ab} + \mathcal{I}_{\bar{a}\bar{b}}}{2} \cos\Delta\delta \sin\Delta\phi + \frac{\mathcal{I}_{ab} - \mathcal{I}_{\bar{a}\bar{b}}}{2} \sin\Delta\delta \cos\Delta\phi. \tag{13}$$

Thus, when the initial state is self-conjuate and $\mathcal{I}_{ab} = \mathcal{I}_{\bar{a}\bar{b}}$ (i.e., the initial state and its CC state have the same PDFs), then the asymmetry appears with the conventional CP-even and CP-odd phase factors, $A_{CP} \propto \cos\Delta\delta \sin\Delta\phi$; in this case A_{CP} vanishes when the CP-odd phase vanishes. The second term in (13), which is $\propto \mathcal{I}_{\bar{a}\bar{b}} - \mathcal{I}_{ab}$, deals with the case when the initial state is not self-conjugate and $\mathcal{I}_{ab} \neq \mathcal{I}_{\bar{a}\bar{b}}$, as is the case for the LHC or other future hadron colliders that are being envisioned (see also below). This term is a new correction to the classic expression for tree-level CPV in scattering processes. It is a fake CP signal (being $\propto \cos\Delta\phi$) that can be generated in the presence of a CP-even phase. We note, though, that such a fake CP effect cannot be generated at tree-level in scattering processes at the LHC if there are no resonances involved (for situations involving resonances, see [77]), since then CP-even phases can only arise from FSI at higher loop orders, as opposed to the potentially large *tree-level* effects in A_{CP}, i.e., the 1st term in (13). It thus follows that, in the absence of resonances, if a large CP asymmetry is measured, say of $\mathcal{O}(10\%)$, (as shown below), then besides the fact that it will be strong evidence for NP, it will also be a signal of genuine CP-violating tree-level dynamics.

We use an effective field theory (EFT) approach to describe the underlying NP responsible for CPV and demonstrate our strategy using the following scalar and tensor 4-Fermi operators [78–81]:

$$\mathcal{O}_S(prst) = (\bar{l}_p^j e_r)\epsilon_{jk}(\bar{q}_s^k u_t), \tag{14}$$

$$\mathcal{O}_T(prst) = (\bar{l}_p^j \sigma_{\mu\nu} e_r)\epsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t), \tag{15}$$

where ℓ and q are left-handed SU(2) lepton and quark doublets, respectively; e and u are SU(2) singlet charged leptons and up-type quarks, respectively; and p, r, s, t are flavor indices. These 4-Fermi interactions can be generated by tree-level exchanges of heavy scalars and tensors in the underlying heavy theory. Interesting examples are the scalar leptoquarks S_1 and R_2, which transform as $(3, 1, -1/3)$ and $(3, 2, 7/6)$, respectively, under the $\mathrm{SU}(3) \times \mathrm{SU}(2) \times \mathrm{U}(1)$ SM gauge group. Indeed, these scalar leptoquarks can address the $R_{D^{(*)}}$ anomaly [82–88], as well as the muon $g-2$ discrepancy [89,90] (see also [91–100] and for an alternative scenario with R-parity violating supersymmetry see [101–104]).

In particular, tree-level exchanges of S_1 and R_2 among the lepton-quark pairs induce the operators in (14) and (15), where, in this case, the Wilson coefficients, f_i, of the operators in (14) and (15), satisfy

$$|f_T(prst)| = |f_S(prst)|/4, \tag{16}$$

universally for any given set of flavor indices $prst$ in (14) and (15), see [14]. We will use this relation as a benchmark scenario in the numerical calculations described below.

The scalar and tensor four-Fermi operators in (14) and (15) (or, equivalently, tree-level exchanges of the leptoquarks S_1 and R_2) generate $t\bar{t}\ell^+\ell^-$ as well as FC $t\bar{u}_i\ell^+\ell^-$ (and the charge-conjugate $\bar{t}u_i\ell^+\ell^-$) contact terms, where $\ell = e, \mu, \tau$ stands for any one of the SM charged leptons and $u_i = u$, c. The $tt\ell\ell$ interaction modifies the process $pp \to t\bar{t}\ell^+\ell^-$, as discussed in detail in [14], and can thus also give rise to tree-level CPV in both the trilepton and four-leptons production channels of (1)–(3).

In the following, we focus just on the FC $tu_i\ell\ell$ four-Fermi interactions, which can modify (see also [13,32]) and generate CPV in the trilepton signals of (1) and (2), via the underlying single-top hard processes $u_i g \to t\ell^+\ell^-$ and the CC channel (see Fig. 1), followed by the t and $\bar{t}$ decays $t \to b\ell'^+\nu_\ell$ and $\bar{t} \to \bar{b}\ell'^-\bar{\nu}_\ell$.

As discussed below, the contribution of the FC $tu_i\ell\ell$ effective operators to the trilepton signal does not interfere with the SM diagrams, so that the CPV in this case is a pure NP effect; it arises from the imaginary part of the interference between the scalar and the tensor operators, if at east one of the corresponding Wilson coefficients is complex [105]. In particular, the numerator of A_{CP} (and of A_T and $\bar{A}_T$) is proportional to the CP-violating part of the cross section for $u_i g \to t\ell^+\ell^- \to \ell'^+\ell^+\ell^- + X$ [hereafter we suppress the flavor indices of the operators in (14) and (15)]:

$$d\hat{\sigma}(\mathrm{CPV}) \propto \epsilon(p_{u_i}, p_{\ell'^+}, p_{\ell^+}, p_{\ell^-}) \cdot \mathrm{Im}(f_S f_T^\star), \tag{17}$$

and similarly for the CC channel $\bar{u}_i g \to \bar{t}\ell^-\ell^+ \to \ell'^-\ell^-\ell^+ + \bar{X}$ by replacing $\epsilon(p_{u_i}, p_{\ell'^+}, p_{\ell^+}, p_{\ell^-})$ with $\epsilon(p_{\bar{u}_i}, p_{\ell'^-}, p_{\ell^-}, p_{\ell^+})$, where $\epsilon(p_1, p_1, p_3, p_4) = \epsilon_{\alpha\beta\gamma\delta} p_1^\alpha p_2^\beta p_3^\gamma p_4^\delta$

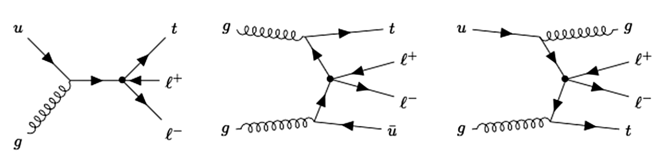

FIG. 1. Representative lowest order Feynman diagrams for $pp \to t\ell^+\ell^-$ and $pp \to t\ell^+\ell^- + j$ (j is a light jet), via the $tu\ell^+\ell^-$ four-Fermi interaction (marked by a heavy dot).

and $\epsilon_{\alpha\beta\gamma\delta}$ is the Levi-Civita tensor. In contrast to the numerators, the NP contributions to the denominators of our CP asymmetries are proportional to the CP-conserving terms $\propto |f_S|^2, |f_T|^2, \mathrm{Re}(f_S \cdot f_T^\star)$, where the dominating term is the pure tensor contribution $|f_T|^2$. The SM trilepton production processes will also contribute to the total number of trilepton events which enter the denominators of A_{CP} and $T_N, \bar{T}_N$; the dominating SM trilepton process is $pp \to WZ + X$ [108].

To assess the feasibility of CP asymmetry measurements in multilepton final states at the LHC, we perform a simulation on the trilepton signal processes described above, together with the relevant SM background processes, which do not include detector effects other than those modeled by simple threshold and acceptance requirements. Although more elaborated analysis approaches might also be useful, for simplicity, we follow an approach that is completely generic and provides a model-independent test of CPV in multilepton final states, which would be designed to be sensitive to any type of underlying CP-violating NP involving charged leptons. We therefore define the asymmetries for the inclusive multilepton signals, with no further event selections on the types or kinematic properties of the other objects in the final state, i.e., X_i in (1)–(3). Indeed, in general it is possible to use additional useful selections, e.g., in our case a selection of one b jet (see [14,32,109–111]) will essentially eliminate the dominating $pp \to W^\pm Z + X \to \ell'^\pm \ell^+ \ell^- + X$ SM contribution to the denominators of our asymmetries. Nonetheless, we use only a selection on the minimum invariant mass of the dileptons involved, $m_{\mathrm{min}}(\ell^+\ell^-)$, which allows us to suppress the SM background without loss of generality. The input for the numerical calculations is further described in the Supplemental Material [112].

Furthermore, for the NP contribution we study the dependence on the NP scale up to $\Lambda\sim$ few TeV; the typical bounds on the natural scale of the operators under investigation, in (14) and (15), are $\Lambda \gtrsim \mathcal{O}(1)$ TeV, see [32]. Guided by the relation between the scalar and tensor couplings in (16), we set $|f_S| = 1$, $|f_T| = 0.25$ with a maximal CP-odd phase for the $tu\ell\ell$ and $tc\ell\ell$ operators, so that

$$\mathrm{Im}(f_S \cdot f_T^\star) = 0.25. \tag{18}$$

Our results are summarized in Fig. 2 and Table I. In Fig. 2 we show the dependence of A_{CP} on $m_{\mathrm{min}}(\ell^+\ell^-)$ and in Table I we give the resulting CP-violating and T_N-odd asymmetries for $m_{\mathrm{min}}(\ell^+\ell^-) = 400$ GeV. The expected inclusive trilepton cross sections for the NP and the dominant SM background, after the event selection criteria have been applied, are given in the Supplemental Material [112]: for $m_{\mathrm{min}}(\ell^+\ell^-) = 400$ GeV and an integrated luminosity of 1000 fb^{-1}, we expect an $\mathcal{O}(100)$ $\ell'^\pm\ell^+\ell^-$ from the SM $pp \to ZW^\pm$ background, whereas the new $tu\ell\ell$ and $tc\ell\ell$ 4-Fermi operators yield $\sim 10^4$ and ~ 500 $\ell'^\pm\ell^+\ell^-$ events, respectively, if $\Lambda \sim 1$ TeV.

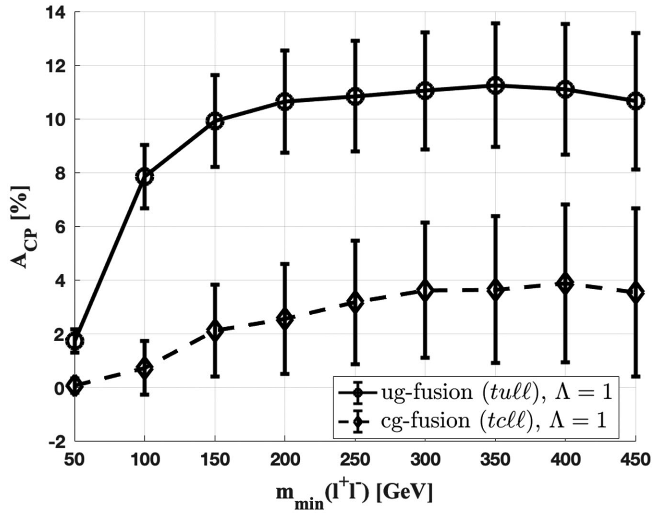

FIG. 2. A_{CP} as a function of $m_{\mathrm{min}}(\ell^+\ell^-)$, for $\Lambda = 1$ TeV, $\mathrm{Im}(f_S f_T^\star) = 0.25$ and including the SM background. The error bars represent the expected statistical uncertainty with an integrated luminosity of 1000(3000) fb^{-1} for the ug-fusion(cg-fusion) case.

We see that the CP-asymmetry increases with the invariant mass cut on the same-flavor dileptons, $m_{\mathrm{min}}(\ell^+\ell^-)$. This is due to the decrease of the SM contribution with $m_{\mathrm{min}}(\ell^+\ell^-)$ in the denominators of the asymmetries. Also, the asymmetry is larger in the ug-fusion case, since the SM background in this case is considerably smaller with respect to the signal in this case (see Supplemental Material [112] and discussion above) [117]. On the other hand, the asymmetries $A_T, \bar{A}_T$, and A_{CP} decrease with Λ, as expected. For example, in the $tu\ell\ell$ 4-Fermi case, the CP asymmetry drops from $A_{CP} \sim 11\%$ if $\Lambda = 1$ TeV to $A_{CP} \sim 8\%$ if $\Lambda = 2$ TeV (see Table I). A plot of $A_{CP}(\Lambda)$ is given in the Supplemental Material [112]. Note also that $|A_T| \gg |\bar{A}_T|$ in the ug fusion case due to the difference between the incoming ug and $\bar{u}g$ PDFs, see (11).

Finally, it is possible to further refine this approach by defining the axis-dependent TP CP asymmetries

TABLE I. The expected T_N-odd and CP asymmetries in trilepton events, $pp \to \ell'^\pm\ell^+\ell^- + X$, via the ug-fusion and cg-fusion production channels (and the CC ones) at the LHC, for $m_{\mathrm{min}}(\ell^+\ell^-) = 400$ GeV. Values are given for $\Lambda = 1(2)$ TeV, $\mathrm{Im}(f_S f_T^\star) = 0.25$ and the SM background from $pp \to ZW^\pm + X$, as explained in the text.

	ug-fusion: $\Lambda = 1(2)$ TeV	cg-fusion: $\Lambda = 1(2)$ TeV
A_{CP}	11.1% (7.9)%	3.9% (0.7)%
A_T	16.4% (13.5)%	3.1% (0.5)%
$\bar{A}_T$	−5.8% (−2.3)%	−4.7% (−1.0)%

$\mathcal{O}^i_{CP} = p^i_a \cdot (\vec{p}_b \times \vec{p}_c)^i$, where $i = x, y, z$. As shown in the Supplemental Material [112], the $\mathcal{O}^{x,y,z}_{CP}$ can be useful for a deeper understanding of the origin of the underlying CP-violating NP; in the case of the 4-Fermi effective interactions studied here, they allow us to distinguish between the $tu\ell\ell$ and the $tc\ell\ell$ CP-violating dynamics.

To summarize, we have investigated the possible detection of tree-level CPV in scattering processes at the LHC and introduced a modification to the standard formula for such CP-violating effects, which is relevant when the initial state in not self-conjugate. We focused specifically on multilepton signals and their sensitivity to new TeV-scale sources of CPV. In particular, we have constructed CP-violating triple-product correlations out of the momenta of the charged leptons in multilepton events, which can be used as model-independent tests of tree-level (and therefore large) CPV from any source of underlying CP-violating physics. We have calculated the expected CP asymmetry in trilepton events at the LHC from new TeV-scale FC $tu\ell\ell$ and $tc\ell\ell$ 4-Fermi interactions, which can be viewed as an EFT parametrization of tree-level TeV-scale leptoquark exchanges in these channels. We showed that an $\mathcal{O}(10\%)$ CP asymmetry is naturally expected in this case, if the EFT operators carry a CP-odd phase and the NP scale is of $\mathcal{O}(\text{TeV})$.

The measurement of such $\mathcal{O}(10\%)$ CP asymmetry in multilepton events is challenging, but if observed, it should stand out as an unambiguous signal of NP that may shed light on the fundamental issue of BAU. We believe that it is quite feasible provided the experimental uncertainties can be kept at the level of $\mathcal{O}(1\%)$ (see [118]) bearing in mind that such CP-violating effects in the SM are unobservably small in multilepton events. Indeed, we estimate the statistical uncertainty in measuring the CP asymmetry, based on the expected number of trilepton events in our NP scenario (see Supplemental Material) to be $\sim 1\% - 2\%$ with an integrated luminosity of $\mathcal{L} \sim 1000(3000)$ fb^{-1} in the $tu\mu\mu(tc\mu\mu)$ NP cases (see Fig. 2).

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