Generic tests of CP-violation in high-p_T multi-lepton 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 in not self-conjugate. Based on that, we propose a generic and model-independent search strategy for probing tree-level CP-violation in inclusive multi-lepton 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}.

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 paper we re-examine 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 in 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 tri-lepton and four-lepton signals:

$$pp \to \ell'^- \ell^+ \ell^- + X_3 \qquad (1)$$
$$pp \to \ell'^+ \ell^- \ell^+ + \bar{X}_3 \ , \qquad (2)$$
$$pp \to \ell'^+ \ell'^- \ell^+ \ell^- + X_4 \qquad (3)$$

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 3-flavor final state $pp \to e\mu\tau + X$. As an example, we will consider below CPV in the $e^\pm \mu^+ \mu^-$ tri-lepton signals, but it should be clear that it is equally important to search for CPV in multi-leptons final states with as many different combination of flavors as possible.

Multi-lepton 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 [9–11];[1] they are sensitive to many types of well-motivated underlying NP phenomena, such as lepton-flavor violation, lepton-universality violation, lepton-number violation [12–24] and CPV, which is the subject studied in this paper. These multi-leptons 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 [25–28] as well as in 4-top production $pp \to tt\bar{t}\bar{t}$ [29, 30] and searches for flavor-changing (FC) top physics [31–40].

The available momenta of the charged leptons in the final state of these multi-lepton 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 (PDF's) of the incoming partons may, therefore, have an asymmetric structure. This will be discussed below.

It should be emphasized that a sizeable, say $\mathcal{O}(\gtrsim 1\%)$ manifestation of CPV in multi-leptons events of the type (1), (2) or (3) will be strong evidence for NP, since the

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[1] We note that final states involving the τ have, in general, a lower experimental detection efficiency and are, therefore, expected to be less effective for our study.

CP-odd CKM-phase of the SM (which is responsible for CPV in the quark sector and has been measured [41]) is expected to yield negligible CP-violating effects in these processes, as it can only arise from EW processes at higher loop orders [42].[2] 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 [43, 44].

Finally, we recall that in the last several years a few σ deviations from the SM in B-decays [45–61] as well as in the muon $g-2$ [62–64] 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) [42, 65].

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 ($\ell \neq \ell'$):[3,4]

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

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

$$\begin{aligned} C(\mathcal{O}_{\tt CP}) = +\overline{\mathcal{O}_{\tt CP}} \ , \quad C(\overline{\mathcal{O}_{\tt CP}}) = +\mathcal{O}_{\tt CP} \ , \\ CP(\mathcal{O}_{\tt CP}) = -\overline{\mathcal{O}_{\tt CP}} \ , \ CP(\overline{\mathcal{O}_{\tt CP}}) = -\mathcal{O}_{\tt CP} \ . \end{aligned} \tag{5}$$

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

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

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

where $N\left(\mathcal{O}_{\tt CP} > 0\right)$ is the number of events for which sign$(\mathcal{O}_{\tt CP}) > 0$ 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) [42, 72, 73], 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:

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

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 tri-lepton 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:

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

and $d\bar{\hat{\sigma}} = d\hat{\sigma}(\Delta\phi \to -\Delta\phi, \mathcal{O}_{\tt CP} \to \overline{\mathcal{O}_{\tt CP}})$ for the CC channel, where $\Delta\phi = \phi_1 - \phi_2$, $\Delta\delta = \delta_1 - \delta_2$, $W \propto |M_1|^2, |M_2|^2$, $U \propto \text{Re}\left(M_1 M_2^\dagger\right)$ and the 3rd term in (10) arises from $\text{Im}\left(M_1 M_2^\dagger\right) \propto \mathcal{O}_{\tt CP}$ 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):

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

with

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

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

[2] Note that, although B-decays can be a source of sizeable CP-asymmetries in the SM, their effect in final states with 3 or more leptons of the type considered here is negligible. Moreover, leptons from B-meson decays can be strongly suppressed using a number of kinematic properties.

[3] The TP's in (4) are defined in the laboratory frame and we expect that systematic uncertainties in the reconstruction of the momenta involved will be smaller then e.g., the case where the momenta are defined in a rest frame of some particle(s). Also, the kinematical cuts on the leptons involved should be CP-symmetric, e.g., same p_T cuts should be applied to all leptons.

[4] Useful TP correlations for CP studies in scattering processes at the LHC, which involve leptons with jets momenta, e.g., in $t\bar{t}$ and vector-bosons production, have been also suggested in [66–71].

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)):

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

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 PDF's), 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 [74]), 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 [75–78]:

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

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

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 SU(3) × SU(2) × U(1) SM gauge group.[5] Indeed, these scalar leptoquarks can address the $R_{D^{(*)}}$ anomaly [80–86], as well as the muon $g-2$ discrepancy [87, 88] (see also [89–98] and for an alternative scenario with R-Parity violating Supersymmetry see [99–102]).

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

$$|f_T(prst)| = \frac{1}{4}|f_S(prst)| \;, \quad (16)$$

universally for any given set of flavor indices $prst$ in (14) and (15), see [13]. We will use this relation as a benchmark scenario in the numerical calculations described below.

The scalar and tensor 4-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 [13], and can thus also give rise to tree-level CPV in both the tri-lepton and four-leptons production channels of (1)-(3).

In the following, we focus just on the FC $tu_i\ell\ell$ 4-Fermi interactions, which can modify (see also [12, 31]) and generate CPV in the tri-lepton 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 tri-lepton 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 least one of the corresponding Wilson coefficients is complex.[6]

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

[5] Note that the leptoquark R_2 is the only scalar leptoquark that does not induce proton decay [79].

[6] Equivalently, assuming that the underlying scattering processes/diagrams are generated by the tree-level exchanges of the two leptoquarks S_1 and R_2, the CP-violating effect arises from the interference between them (i.e., the amplitudes M_1 and M_2 in (9) are generated by S_1 and R_2, respectively) and if their couplings to a $t\ell$ and $u\ell$ (and/or $c\ell$) pairs carry a (different) CP-violating phase. Interesting examples of CPV leptons and quarks Electric Dipole Moments (EDM's), which are generated from S_1 and R_2 complex couplings can be found in [103, 104].

(15)):[7]

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

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

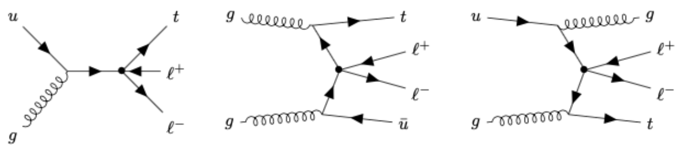

FIG. 1: Representative lowest order Feynman diagrams for $pp \to t\ell^+\ell^-$ and $pp \to t\ell^+\ell^- + j$ (j is a light jet), via the $tu\ell^+\ell^-$ 4-Fermi interaction (marked by a heavy dot).

In contrast to the numerators, the NP contributions to the denominators of our CP-asymmetries are proportional to the CP-conserving terms $\propto |f_S|^2, |f_T|^2, \mathtt{Re}(f_S \cdot f_T^\star)$, where the dominating term is the pure tensor contribution $|f_T|^2$. The SM tri-lepton production processes will also contribute to the total number of tri-lepton events which enter the denominators of A_{CP} and $T_N, \bar{T}_N$; the dominating SM tri-lepton process is $pp \to WZ + X$.[8]

To assess the feasibility of CP asymmetry measurements in multi-leptons final states at the LHC, we perform a simulation on the tri-lepton 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 multi-lepton 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 multi-lepton 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 [13, 31, 105–107]) 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 di-leptons involved, $m_{\mathtt{min}}(\ell^+\ell^-)$, which allows us to suppress the SM background without loss of generality. The input for the numerical calculations is further described in Appendix A.

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 [31]. 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:

$$\mathrm{Im}\left(f_S \cdot f_T^\star\right) = 0.25 \;. \quad (18)$$

Our results are summarized in Fig. 2 and Table I. In Fig. 2 we show the dependence of A_{CP} on $m_{\mathtt{min}}(\ell^+\ell^-)$ and in Table I we give the resulting CP-violating and T_N-odd asymmetries for $m_{\mathtt{min}}(\ell^+\ell^-) = 400$ GeV. The expected inclusive tri-lepton cross-sections for the NP and the dominant SM background, after the event selection criteria have been applied, are given in Appendix B: for $m_{\mathtt{min}}(\ell^+\ell^-) = 400$ 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.

We see that the CP-asymmetry increases with the invariant mass cut on the same-flavor di-leptons, $m_{\mathtt{min}}(\ell^+\ell^-)$. This is due to the decrease of the SM contribution with $m_{\mathtt{min}}(\ell^+\ell^-)$ 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 w.r.t. the signal in this case (see the Appendix and discussion above).[9] On the other hand, the asymmetries $A_T, \bar{A}_T$ and A_{CP} decreases 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 Appendix B. Note also that $|A_T| >> |\bar{A}_T|$ in the ug-fusion case due to the difference between the incoming ug and $\bar{u}g$ PDF's, see (11).

[7] Note that for a given lepton flavor, anyone of the FC 4-Fermi operators has two coupling products contributing to $d\hat{\sigma}(CPV)$ in (17), which correspond to different quark indices. For example, in the case of the $tc\mu\mu$ interaction, we denote by $\mathrm{Im}(f_S f_T^\star)$ any one of the products $\mathrm{Im}\left(f_S(2232) \cdot f_T^\star(2232)\right)$ or $\mathrm{Im}\left(f_S^\star(2223) \cdot f_T(2223)\right)$; only one of the two will be "turned on" henceforward.

[8] Other irreducible SM background to the inclusive tri-lepton signals are $pp \to t\bar{t}V$ with $V = W, Z$ and $pp \to t\bar{t}t\bar{t}$. These, however, are more than an order of magnitude smaller than the WZ one in the inclusive channel. Note, though, that the $t\bar{t}V$ and $t\bar{t}t\bar{t}$ backgrounds may become important if specific selections are used, e.g., b-jet tagging.

[9] The uncertainty (numerical) in the reported asymmetries is of $\mathcal{O}(0.1\%)$. This is estimated by "turning off" the CP-violating NP contribution and calculating $A_T, \bar{A}_T$ and A_{CP} within the SM, where it is expected to vanish.

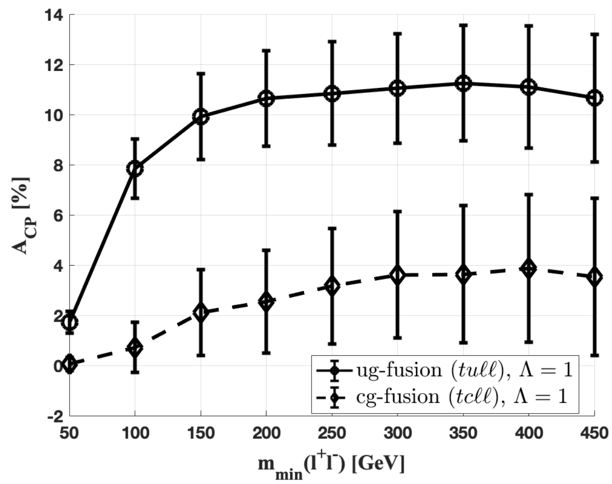

FIG. 2: A_{CP} as a function of $m_{min}(\ell^+\ell^-)$, for $\Lambda = 1$ TeV, $\mathrm{Im}\,(f_S f_T^\star) = 0.25$ and including the SM background. The dependence of the asymmetry on Λ is given in Appendix B. The error bars represent the expected statistical uncertainty with an integrated luminosity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

TABLE I: The expected T_N-odd and CP asymmetries in tri-lepton 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 $m_{min}(\ell^+\ell^-) = 400$ 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)%

Finally, it is possible to further refine this approach by defining the axis-dependent TP CP-asymmetries $\mathcal{O}^i_{\rm CP} = p^i_a \cdot (\vec{p}_b \times \vec{p}_c)^i$, where $i = x, y, z$. As shown in Appendix C, the $\mathcal{O}^{x,y,z}_{\rm CP}$ 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 multi-leptons 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 multi-lepton 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 tri-lepton 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 parameterization 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 $\mathcal{O}(TeV)$.

The measurement of such $\mathcal{O}(10\%)$ CP-asymmetry in multi-lepton 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 [108]) bearing in mind that such CP-violating effects in the SM are un-observably small in multi-lepton events. Indeed, we estimate the statistical uncertainty in measuring the CP-asymmetry, based on the expected number of tri-lepton events in our NP scenario (see Appendix) 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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Appendix A: Numerical calculations

All event samples (NP signal and SM background) were generated using MadGraph5_aMC@NLO [109] at LO parton-level and with the SMEFTsim model of [110, 111] for the EFT framework. The 5-flavor scheme was used to generate all samples, with the `NNPDF30_lo_as_0130` PDF set [112] and the default MadGraph5_aMC@NLO LO dynamical scale.

Both the NP and the SM tri-lepton production cross-sections were calculated with an additional jet. In particular, for the NP: $pp \to t(\bar{t})\ell^+\ell^-$ and $pp \to t(\bar{t})\ell^+\ell^- + j$ followed by the top(anti-top) decay $t(\bar{t}) \to b\ell'^+\nu_{\ell'}(\bar{b}\ell'^-\bar{\nu}_{\ell'})$, while for the SM: $pp \to ZW^\pm$ and $pp \to ZW^\pm + j$ followed by $Z \to \ell^+\ell^-$ and $W^\pm \to \ell'^\pm\nu_{\ell'}$.

Leptons were required to have transverse momentum of $p_T > 10$ GeV and pseudo-rapidity $|\eta| < 2.5$, while for jets we used $p_T > 20$ GeV, $|\eta| < 5.0$ and an angular separation of $\Delta R = 0.4$.

In Table II we list the estimated cross-sections for the NP with $\Lambda = 1$ TeV (note that the NP cross-section scales as Λ^{-4}) and the SM contributions to the inclusive $pp \to \ell'^\pm\ell^+\ell^- + X$ processes for $m_{min}(\ell^+\ell^-) = 200,\ 300$ and 400 GeV, where $m_{min}(\ell^+\ell^-)$ is the lower cut on the invariant mass of the same-flavor di-leptons. In particular, the $m_{min}(\ell^+\ell^-)$-dependent cross-sections are defined as:

$$\sigma_{m_{min}(\ell^+\ell^-)} \equiv \int_{m(\ell\ell)\geq m_{min}(\ell^+\ell^-)} dm(\ell\ell)\frac{d\sigma}{dm(\ell\ell)} \ . \quad \text{(A1)}$$

We note that the simulations were made without parton showering and jet matching, which has no effect on our CP-asymmetry (we confirmed that the calculated CP-asymmetry with and without the extra jet in the tri-lepton final state is the same within the numerical error). Also, we did not perform any detector simulation which is beyond the scope of this work and is left for a dedicated analysis. Thus, the cross-sections reported in Table II should be viewed as an estimate; a more realistic calculation of the expected total cross-sections for this type of NP and SM background can be found in [31].

Appendix B: Dependence of the CP-asymmetry on the NP scale

In Fig.3 we show the dependence of A_{CP} on the NP scale Λ, with parameters as indicated in the caption of the figure. We see that the asymmetry in the ug-fusion case falls rather slowly in the range $\Lambda \sim 1-4$ TeV, whereas in the cg-fusion case it drops steeply in this range, approaching $1/\Lambda^4$ where the SM contribution to the inclusive tri-lepton background dominates.

TABLE II: The estimated cross-sections in [fb], for the NP tri-lepton signals and the SM tri-lepton background. Values are given for the NP parameters $\text{Im}\,(f_S f_T^\star) = 0.25$, $\Lambda = 1$ TeV and for three values of $m_{min}(\ell^+\ell^-)$ as indicated. Also, all acceptance cuts (e.g., p_T and η of the leptons) have been applied, see also description in the text.

$m_{min}(\ell^+\ell^-)[GeV] \Rightarrow$	200	300	400
$\sigma_{NP}(pp_{ug} \to \ell'^-\ell^+\ell^- + X)$	12.43	11.65	10.84
$\sigma_{NP}(pp_{\bar{u}g} \to \ell'^+\ell^-\ell^+ + X)$	0.98	0.87	0.76
$\sigma_{NP}(pp_{cg} \to \ell'^-\ell^+\ell^- + X)$	0.37	0.32	0.27
$\sigma_{NP}(pp_{\bar{c}g} \to \ell'^+\ell^-\ell^+ + X)$	0.37	0.32	0.27
$\sigma_{SM}(pp \to \ell'^-\ell^+\ell^- + X)$	0.33	0.11	0.05
$\sigma_{SM}(pp \to \ell'^+\ell^-\ell^+ + X)$	0.56	0.21	0.10

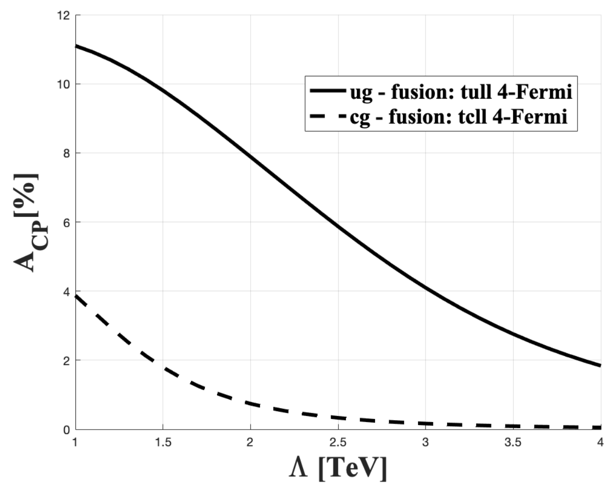

FIG. 3: The expected CP-asymmetry A_{CP}, as a function of the NP scale Λ, for $m_{min}(\ell^+\ell^-) = 400$ GeV and $\text{Im}\,(f_S f_T^\star) = 0.25$. Results are shown for the cases of NP from ug and cg-fusion, which arise from the $tu\ell\ell$ and $tc\ell\ell$ 4-Fermi operators, respectively. The SM background is calculated from $pp \to ZW^\pm + X$.

Appendix C: Axis-dependent CP-violating triple product observables

The triple products considered in the paper:[10]

$$\mathcal{O}_{\texttt{CP}} = \vec{p}_a \cdot (\vec{p}_b \times \vec{p}_c) \ , \quad \text{(C1)}$$

[10] The triple products are defined in the laboratory frame and we expect that systematic uncertainties in the reconstruction of the momenta involved will be smaller then e.g., the case where the momenta are defined in a rest frame of some particle(s). Also, the kinematical cuts on the leptons involved should be CP-symmetric, e.g., same p_T cuts should be applied to all leptons.

TABLE III: The expected T_N-odd and CP asymmetries A_T, $\bar{A}_T$, A_{CP} and the corresponding axis-dependent asymmetries A_T^i, $\bar{A}_T^i$, A_{CP}^i ($i = x, y, z$), for the tri-lepton events $pp \to \ell'^{\pm}\ell^+\ell^- + X$ at the LHC with $m_{min}(\ell^+\ell^-) = 400$ GeV. Results are given for both the ug-fusion and cg-fusion production channels (and the CC ones). Numbers are presented for $\Lambda = 1$ TeV, $\text{Im}\,(f_S f_T^\star) = 0.25$ and the dominant SM background from $pp \to ZW^\pm + X$ is included. The cases where an asymmetry is $\lesssim 0.5\%$ is marked by an X.

	A_{CP}	A_{CP}^x	A_{CP}^y	A_{CP}^z
ug-fusion:	11.1%	8.1%,	8.1%	X
cg-fusion:	3.9%	X	X	5.6%

	A_T	A_T^x	A_T^y	A_T^z
ug-fusion:	16.4%	11.3%,	10.7%	3.8%
cg-fusion:	3.1%	5.0	X	X

	$\bar{A}_T$	$\bar{A}_T^x$	$\bar{A}_T^y$	$\bar{A}_T^z$
ug-fusion:	-5.8%	-5.0%	-5.6%	3.1%
cg-fusion:	-4.7%	-6.3%	X	X

can be divided into three axis-sensitive triple-products:

$$\mathcal{O}_{\text{CP}}^i = p_a^i \cdot (\vec{p}_b \times \vec{p}_c)^i \ , \tag{C2}$$

where $i = x, y, z$ denotes the x, y, z components of the momenta, e.g., p_a^z and $(\vec{p}_b \times \vec{p}_c)^z$ are the z-components of the momenta $\vec{p}_a$ and $(\vec{p}_b \times \vec{p}_c)$, respectively. Note that only three out of the four $\mathcal{O}_{\text{CP}}$ and $\mathcal{O}_{\text{CP}}^{x,y,z}$ in (C1) and (C2) are independent, since $\mathcal{O}_{\text{CP}} = \sum_{i=x,y,z} \mathcal{O}_{\text{CP}}^i$. Furthermore, the axis-sensitive $\mathcal{O}_{\text{CP}}^{x,y,z}$ transform under P,C,CP and T_N the same as $\mathcal{O}_{\text{CP}}$, so that all the discussion and formulae for $\mathcal{O}_{\text{CP}}$ in the paper applies also to $\mathcal{O}_{\text{CP}}^{x,y,z}$. In particular, the axis-dependent CP-asymmetries can be similarly defined as:

$$A_{CP}^{x,y,z} = \frac{1}{2}\left(A_T^{x,y,z} - \bar{A}_T^{x,y,z}\right) \ , \tag{C3}$$

where $A_T^{x,y,z}$ and $\bar{A}_T^{x,y,z}$ are the axis-dependent T_N-odd asymmetries.

In Table III we show a sample of our results for all T_N-odd and CP-asymmetries including the axis dependent ones, for the tri-lepton events $pp \to \ell'^{\pm}\ell^+\ell^- + X$ at the LHC, which are considered in this paper. The asymmetries are calculated for both the ug-fusion and cg-fusion production channels (and the CC ones), with $m_{min}(\ell^+\ell^-) = 400$ GeV , $\Lambda = 1$ TeV and $\text{Im}\,(f_S f_T^\star) = 0.25$, and the dominant SM background from $pp \to ZW^\pm + X$ is considered. We see that a measurement of the axis-dependent asymmetries can be used to distinguish between the $tu\ell\ell$ and the $tc\ell\ell$ CP-violating dynamics. In particular, in the $tu\ell\ell$ case we obtain $A_{CP}^z \to 0$ and $A_{CP}^{x,y} \sim 8\%$, while for the $tc\ell\ell$ operator we find $A_{CP}^z \sim 5.5\%$ and $A_{CP}^{x,y} \to 0$. Note also that the axis-dependent asymmetries may yield a larger effect, e.g., in the cg-fusion case we find that $A_{CP}^z > A_{CP}$.

Appendix D: Differential distributions: signal vs. background

In Figs. 4 and 5, we plot the di-muon invariant mass and the triple-product differential distributions, respectively, for an integrated luminosity of $\mathcal{L} = 1000$ fb^{-1}. We show these distributions for the ug-fusion and the CC $\bar{u}g$-fusion NP cases and the corresponding SM backgrounds, assuming a NP scale of $\Lambda = 1$ TeV and/or $\Lambda = 2$ TeV. Note that the NP signals scale as Λ^{-4} and are calculated with our benchmark value for the CPV coupling $\text{Im}\,(f_S f_T^\star) = 0.25$. Also, the triple-product distributions in Fig. 5 are calculated with $m_{min}(\ell^+\ell^-) = 300$ GeV.

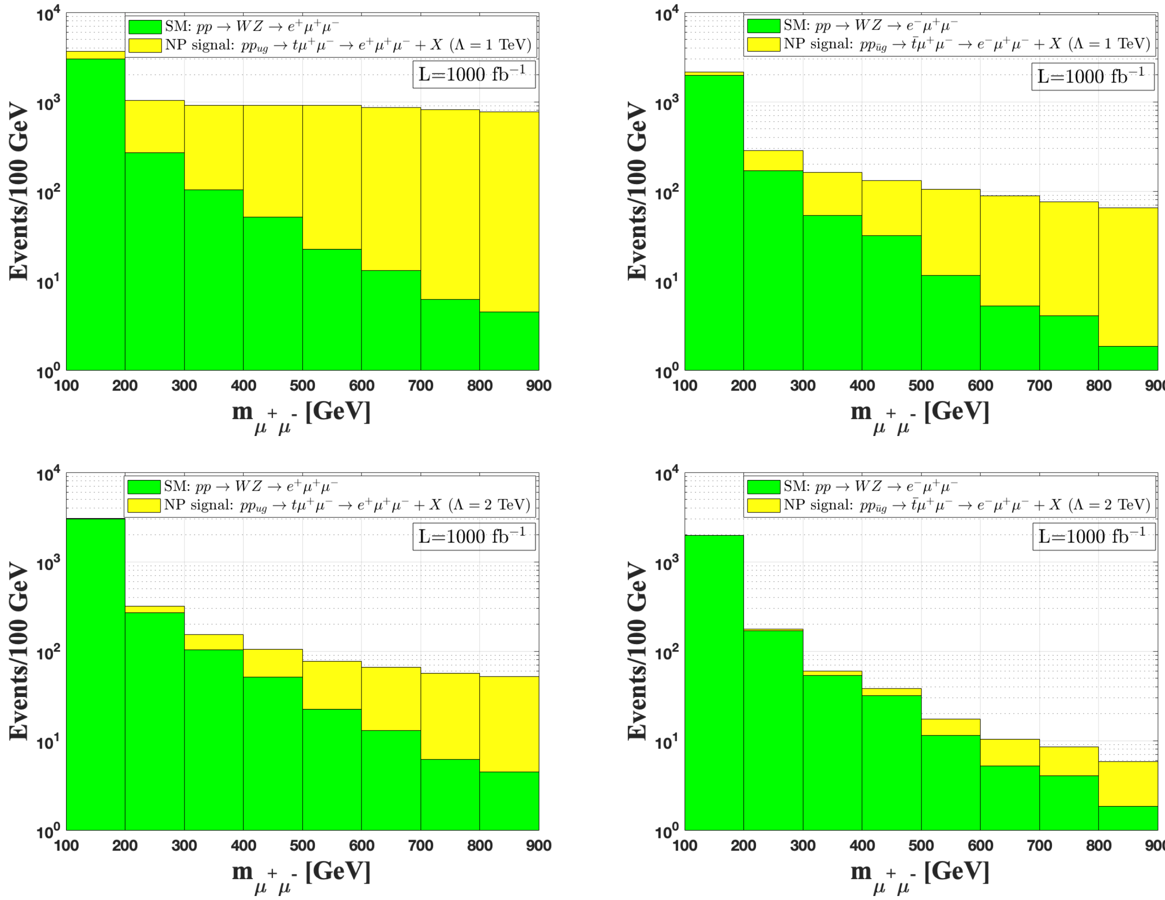

FIG. 4: Di-muon invariant mass distribution (stacked) for the tri-lepton $e^+\mu^+\mu^-$ (left figures) and $e^-\mu^+\mu^-$ (right figures) signals, from ug-fusion and $\bar{u}g$-fusion NP processes, respectively, and the corresponding SM backgrounds. The distributions are shown per integrated luminosity of $\mathcal{L} = 1000$ fb^{-1}, for $\Lambda = 1$ TeV (upper figures) and $\Lambda = 2$ TeV (lower figures).

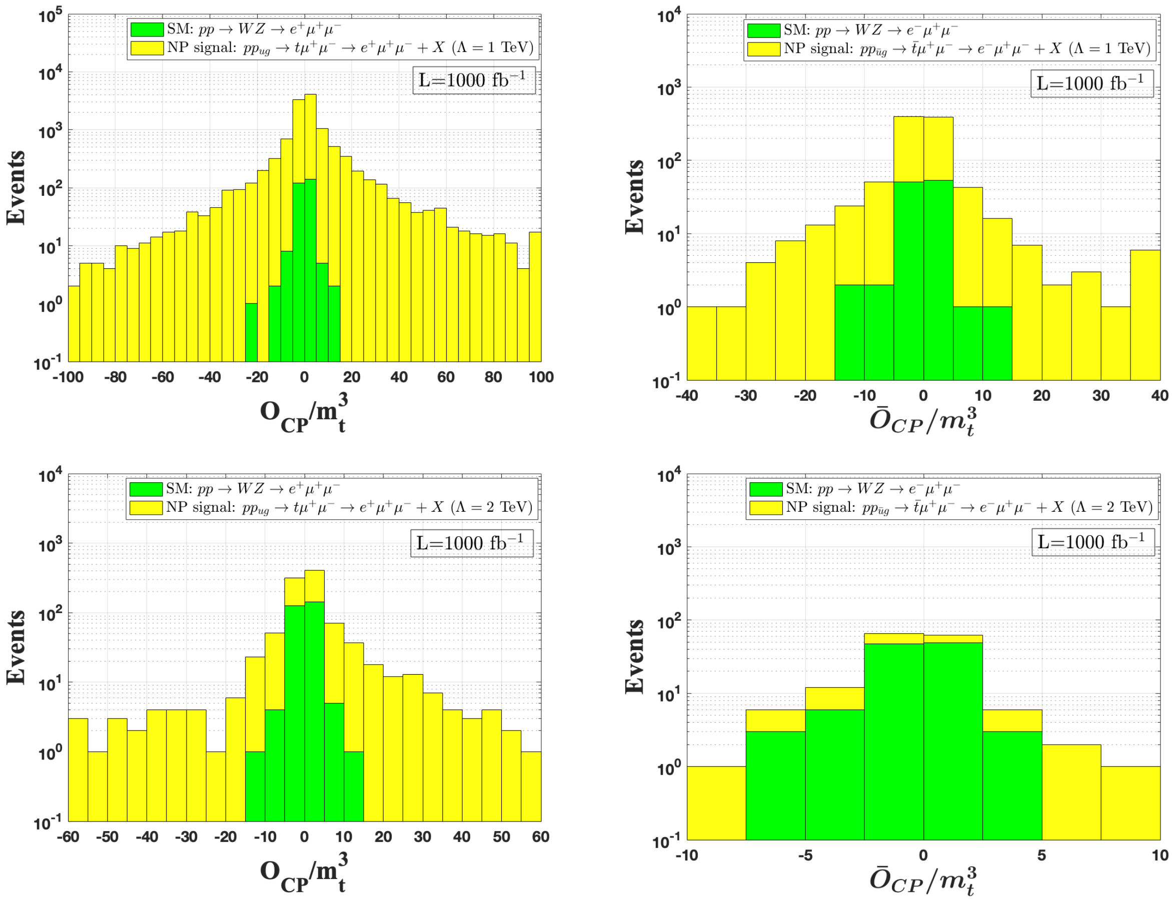

FIG. 5: Differential distribution (stacked) of the triple products $\mathcal{O}_{CP}$ (left figures) and $\bar{\mathcal{O}}_{CP}$ (right figures) in the tri-lepton NP signals and corresponding backgrounds. The NP is from $ug \to t\mu^+\mu^- \to e^+\mu^+\mu^-$ (left figures) and $\bar{u}g \to \bar{t}\mu^+\mu^- \to e^-\mu^+\mu^-$ (right figures) with $\Lambda = 1$ TeV (upper figures) and $\Lambda = 2$ TeV (lower figures). The distributions for both signal and background are calculated with the cut on the di-muon invariant mass of $m_{min}(\ell^+\ell^-) = 300$ GeV and per integrated luminosity of $\mathcal{L} = 1000$ fb^{-1}. See also text.

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