Abstract

In the presence of the T-parity violating Wess-Zumino-Witten (WZW) anomaly term, the otherwise stable heavy photon $A_H$ in the Littlest Higgs model with T-parity (LHT) decays to either Standard Model (SM) gauge boson pairs, or to SM fermions via loop diagrams. We make a detailed study of the collider signatures where the $A_H$ can be reconstructed from invariant mass peaks in the opposite sign same flavor dilepton or the four-lepton channel. This enables us to obtain information about the fundamental symmetry breaking scale $f$ in the LHT and thereby the low-lying mass spectrum of the theory. In addition, indication of the presence of the WZW term gives us hints of the possible UV completion of the LHT via strong dynamics. The crucial observation is that the sum of all production processes of heavy T-odd quark pairs has a sizeable cross-section at the LHC and these T-odd particles eventually all cascade down to the heavy photon $A_H$. We show that for certain regions of the parameter space with either a small $f$ of around 500 GeV or relatively light T-odd quarks with a mass of around 400 GeV, one can reconstruct the $A_H$ even at the early LHC run with $\sqrt{s} = 10$ TeV and a modest integrated luminosity of 200 pb$^{-1}$. At $\sqrt{s} = 14$ TeV and with an integrated luminosity of 30 fb$^{-1}$, it is possible to cover a large part of the typical parameter space of the LHT, with the scale $f$ up to 1.5 TeV and with T-odd quark masses almost up to 1 TeV. In this region of the parameter space, the mass of the reconstructed $A_H$ ranges from 66 GeV to 230 GeV.
1 Introduction

Little Higgs models [1, 2] have been proposed a few years ago to explain electroweak symmetry breaking and, in particular, to solve the so-called little hierarchy problem [3]. We can view the Standard Model (SM) as an effective field theory (EFT) with a cutoff \( \Lambda \) and parametrize new physics in terms of higher-dimensional operators which are suppressed by inverse powers of \( \Lambda \). Precision tests of the SM have not shown any significant deviations, which in turn translates into a cutoff of about \( \Lambda \sim 5 – 10 \) TeV which is more than an order of magnitude above the electroweak scale. Since radiative corrections to the Higgs mass are quadratically sensitive to the cutoff \( \Lambda \), some amount of fine-tuning is needed to get a Higgs which is lighter than about 200 GeV as indicated by electroweak precision data.

Little Higgs models suggest a way of stabilizing the mass of the Higgs in the presence of a cut-off \( \Lambda \) of the above kind of magnitude. Here the Higgs particle is a pseudo-Goldstone boson of a global symmetry \( G \) which is spontaneously broken at a scale \( f \) to a subgroup \( H \). This symmetry protects the Higgs mass from getting quadratic divergences at one loop. The electroweak symmetry is broken via the Coleman-Weinberg mechanism [4] and the Higgs mass is generated radiatively, which leads naturally to a light Higgs boson \( m_H \sim (g^2/4\pi)f \approx 100 \) GeV, if the scale \( f \sim 1 \) TeV. The little Higgs model can then be interpreted as an EFT up to a new cutoff scale of \( \Lambda \sim 4\pi f \sim 10 \) TeV.

Among the different versions of this approach, the littlest Higgs model [5] achieves the cancellation of quadratic divergences with a minimal number of new degrees of freedom. However, precision electroweak constraints imply that the mass scale of the new particles in such theories has to be of the order of \( f \gtrsim 5 \) TeV in most of the natural parameter space [6], thus necessitating fine-tuning once more. The problem is circumvented through the introduction of an additional discrete symmetry, the so-called T-parity [7, 8], whereby all particles in the spectrum are classified as T-even or T-odd. This allows one to have the Higgs mass protected from quadratic divergences, and at the same time see a spectrum of additional gauge bosons, scalars and fermions, in the mass range of a few hundred GeV, with the lightest T-odd particle (LTP), typically the heavy neutral partner of the photon, \( A_H \), being stable. In particular, for the Littlest Higgs model with T-parity (LHT) [8, 9, 10, 11] it was shown in Refs. [10, 12, 13], that a scale \( f \) as low as 500 GeV is compatible with electroweak precision data. Furthermore, if T-parity is exact, the LTP can also be a potential dark matter (DM) candidate [9, 12, 14].

The experimental signals at colliders of a scenario with exact T-parity have close resemblance with those of supersymmetry (SUSY) with conserved R-parity or universal extra dimensions (UED) with KK-parity. First of all, T-odd particles can only be produced in pairs. Furthermore, all T-odd particles cascade decay down to the LTP which then carries away substantial missing transverse momentum, accompanied by jets and / or leptons rendered hard through the release of energy in the decay of the heavy new particles.

It was later pointed out in Ref. [15] that T-parity can be violated in the EFT by topological effects related to anomalies in the underlying theory (UV completion of the LHT). This induces a Wess-Zumino-Witten (WZW) term [16] in the low-energy effective Lagrangian, similarly to the WZW term of odd intrinsic parity in the usual chiral Lagrangian for QCD. This term encodes the Adler-Bell-Jackiw chiral anomaly [17] within the EFT framework and describes, for instance, the decay \( \pi^0 \rightarrow \gamma\gamma \). The structure of the WZW term is thereby
uniquely determined by the symmetry breaking pattern $G \to H$ and the gauged subgroups, up to a multiplicative quantized constant. This constant is related to the representation of new fermions in the underlying theory, if we assume that it is strongly interacting and a fermion condensate forms which signals spontaneous symmetry breaking. Essentially, as in QCD, the prefactor of the WZW term is a function of the number of ‘colors’ in the underlying theory.

Of course, there is no such WZW term, if there are no chiral anomalies in the underlying theory, for instance, if the low-energy non-linear sigma model Lagrangian of the LHT derives from a linear sigma model with new heavy fundamental scalar fields which break the symmetry, see Ref. [18] for an explicit construction of such an UV completion with unbroken T-parity.

The phenomenology at colliders of the LHT with T-parity violation changes completely [15, 19, 21, 20]. Assuming that $A_H$ is the LTP, the T-violating terms will lead to its decay into SM particles either directly into two electroweak gauge bosons or via one-loop graphs into SM fermion pairs. The decay width will be very small, of the order of $\text{eV}$. This is due to the small prefactor in front of the WZW term which counts as order $p^4$ in the chiral expansion, i.e. it is of the same size as one-loop effects in the EFT. Nevertheless, $A_H$ will promptly decay inside the detector and one does therefore not expect events with large missing transverse energy. As we will see, this allows one to reconstruct the masses of the new particles, in particular of $A_H$ itself. On the other hand, since the T-violating couplings are very small, the production mechanism of T-odd particles is essentially unchanged from the case with exact T-parity and the T-odd particles will again cascade decay down to $A_H$. Of course, with T-parity violation, the unstable LTP will now no longer be a suitable DM candidate.

The phenomenology of the LHT with exact T-parity at the Large Hadron Collider (LHC) has been studied quite extensively [22, 23, 24, 25]. Efforts are also on to discriminate the LHT signals from those of other scenarios where large missing $E_T$ is predicted [26]. However, relatively few studies have taken place on the collider signals of the scenario with T-parity violation [19, 21, 20]. Although Ref. [20] gives a very comprehensive list of signals for several regions in the parameter space, definitely more detailed studies of this interesting possibility of New Physics are required, in particular, since the WZW term is a direct window into the UV completion of the LHT.

In this paper we study the decay of $A_H$ into a pair of light leptons (electrons, muons) or, via its decay into a pair of Z-bosons, eventually into four leptons. With appropriate cuts, in particular demanding a large effective mass $M_{\text{eff}} > 1 \text{ TeV}$, to reduce the SM background from $t\bar{t}$ for dileptons and $ZZ$ for four leptons, a clear peak in the dilepton or four-lepton invariant mass distribution emerges at $M_{A_H}$. Since $M_{A_H} \sim f$, this will therefore allow one to directly determine the symmetry breaking scale $f$ of the LHT with good precision. The crucial point of our analysis is the observation that since pairs of T-odd heavy quarks can be produced in strong interaction processes and since all of them eventually decay into a pair of $A_H$ bosons and various SM particles, we get a sizeable signal at the LHC running at 10 TeV or 14 TeV, if we add all production processes of heavy T-odd quark pairs and look at the inclusive signal of $2l + X$ or $4l + X$. For the decay chain $A_H \to ZZ \to 4l$, the idea to look at the sum of all processes of T-odd heavy quark production was already proposed in Ref. [21]. Based on some rough event and detector simulations it was argued there that
a signal can be seen at the LHC, in particular, if a tight cut is applied that the four-lepton invariant mass should lie in the narrow window \( M_{A_H} \pm 6 \) GeV in order to reduce the SM background from \( ZZ \). Our study will be much more detailed and we will also include the dilepton signal which will be important for \( A_H \) masses below about 120 GeV. In this respect our analysis also differs from Ref. [20] which looked into specific final states with multiple leptons and jets coming from various decay chains, but not at the total of all production processes leading to \( A_H \).

The important points that are emphasized in this work, and where we have gone beyond the earlier studies, are as follows:

- We have performed a detailed study of two-and four-lepton signals for the situation where the LTP (the heavy photon \( A_H \)) is liable to decay. The relevant backgrounds and ways of reducing them have also been investigated.

- Our simulation shows how the mass of the \( A_H \) can be reconstructed from peaks in the dilepton and four-lepton spectra in different regions of the parameter space. This allows us to determine the fundamental parameter \( f \) in the LHT and thus gain deeper insight into the model from its low-lying particle spectrum.

- The clear identification of a decaying \( A_H \) suggests the breaking of T-parity via the WZW terms, and thus a possible UV completion of the theory in the form of a strong dynamics at a higher scale.

- The confirmation of a decaying LTP sets the scenario clearly apart from R-parity conserving SUSY or UED with conserved KK-parity. Moreover, the observation of invariant mass peaks in dilepton and four-lepton channels is not expected in R-parity violating SUSY either.

This paper is organized as follows. In Sec. 2 we briefly review some basics about the Littlest Higgs model with exact T-parity and then sketch how T-parity is violated by the WZW anomaly term, leading to an unstable \( A_H \). Section 3 discusses the dilepton and four-lepton signal processes, starting with the parton-level production of heavy T-odd quark pairs and the decay modes and branching ratios of \( A_H \). We also argue why the \( A_H \) is different from the often considered \( Z' \) gauge boson or the first Kaluza-Klein excitation of the graviton and thus could have escaped detection, even with a low mass of the order of 100 GeV. Finally, we present our choice of benchmark points for several values for the heavy quark masses \( m_{qH} \) and for several values for the mass of the heavy photon \( M_{A_H} \). Section 4 gives details on our event generation for the signal and the background. We describe the main sources of backgrounds from the SM and from within the LHT. We then go on to present our event selection criteria for the dilepton and the four-lepton signal and the various cuts to reduce the backgrounds. In Sec. 5 we present our results, first for the dilepton signal and then for the four-lepton signature. In both cases, we give numbers for the expected signal and background cross-sections after the cuts for the LHC running at a center of mass energy of 10 TeV (14 TeV) and the number of signal and background events for an integrated luminosity of 200 pb\(^{-1}\) (30 fb\(^{-1}\)). In particular, we will show that in the case where the heavy T-odd quarks are not much above the bound of approximately \( m_{qH} > 350 \) GeV from Tevatron, as estimated...
in Ref. [20], even with a rather modest luminosity of 200 pb$^{-1}$, one will get a signal in the early run of the LHC at 10 TeV. On the other hand, for T-odd quarks with masses around 1000 GeV, a clear signal will be visible with 30 fb$^{-1}$ of integrated luminosity for the LHC running at 14 TeV. We summarize and conclude in Section 6.

2 The Littlest Higgs model with T-parity and T-parity violation

2.1 The Littlest Higgs model with T-parity

In the LHT a global symmetry $SU(5)$ is spontaneously broken down to $SO(5)$ at a scale $f \sim 1$ TeV. An $[SU(2) \times U(1)]^2$ gauge symmetry is imposed, which is simultaneously broken to the diagonal subgroup $SU(2)_L \times U(1)_Y$, the latter being identified with the SM gauge group. This leads to four heavy gauge bosons $W^+_H, Z_H$ and $A_H$ with masses $\sim f$ in addition to the SM gauge fields. The SM Higgs doublet is part of an assortment of pseudo-Goldstone bosons which result from the spontaneous breaking of the global symmetry. This symmetry protects the Higgs mass from getting quadratic divergences at one loop, even in the presence of gauge and Yukawa interactions. The multiplet of Goldstone bosons contains a heavy $SU(2)$ triplet scalar $\Phi$ as well. In contrast to SUSY, the new states which cancel the quadratically divergent contributions to the Higgs mass due to the top quark, gauge boson and Higgs boson loops, respectively, are heavy fermions, additional gauge bosons and triplet Higgs states.

In order to comply with strong constraints from electroweak precision data on the Littlest Higgs model [6], one imposes T-parity [7] which maps the two pairs of gauge groups $SU(2)_i \times U(1)_i, i = 1, 2$ into each other, forcing the corresponding gauge couplings to be equal, with $g_1 = g_2$ and $g'_1 = g'_2$. All SM particles, including the Higgs doublet, are even under T-parity, whereas the four additional heavy gauge bosons and the Higgs triplet are T-odd. The top quark has two heavy fermionic partners, $T^+_i$ (T-even) and $T^-_i$ (T-odd). For consistency of the model, one has to introduce the additional heavy, T-odd vector-like fermions $u^i_H, d^i_H, e^i_H$ and $\nu^i_H$ ($i = 1, 2, 3$) for each SM quark and lepton field. For further details on the LHT, we refer the reader to Refs. [8, 9, 10, 11].

The masses of the heavy gauge bosons in the LHT are given by

$$M_{W_H} = M_{Z_H} = g f \left(1 - \frac{v^2}{8 f^2}\right) \approx 0.65 f,$$

$$M_{A_H} = \frac{f g'}{\sqrt{5}} \left(1 - \frac{5 v^2}{8 f^2}\right) \approx 0.16 f,$$  \hspace{1cm} (1)

where corrections of $\mathcal{O}(v^2/f^2)$ are neglected in the approximate numerical values. Thus these particles have masses of several hundreds of GeV for $f \sim 1$ TeV, although $A_H$, the heavy partner of the photon, can be quite light, because of the small prefactor, and is usually assumed to be the LTP. The masses of the heavy, T-odd fermions are determined by general $3 \times 3$ mass matrices in the (mirror) flavor space, $m'^{ij}_{qH} \sim \kappa^{ij}_{q} f$ with $i, j = 1, 2, 3$. We simplify our analysis by assuming that $\kappa^{ij}_{q} = \kappa_{q} \delta^{ij}$. The parameter $\kappa_{q} \sim \mathcal{O}(1)$ thus determines the masses of the heavy quarks in the following way:

$$m_{uH} = \sqrt{2} \kappa_q f \left(1 - \frac{v^2}{8 f^2}\right), \quad m_{dH} = \sqrt{2} \kappa_q f,$$  \hspace{1cm} (2)
thereby allowing the new heavy quarks to have masses ranging from several hundreds of GeV to a TeV, for $f \sim 1$ TeV. Similarly, the masses of the heavy leptons in the spectrum are determined by a common parameter $\kappa_l$. Note that these heavy quarks and leptons cannot be decoupled from the model as there is an upper bound $\kappa \leq 4.8$ (for $f = 1$ TeV) obtained from 4-fermion operators [10]. We will come back to lower limits on the masses of the heavy quarks and therefore on $\kappa_q$ in the context of the model with T-parity violation.

While they can act as a source of model background for our leptonic signals, the T-odd leptons do not otherwise play any important role in our analysis. We will therefore use $\kappa_l = 1$ throughout. In the section on background analysis, we discuss the model backgrounds in further detail. Thus $f$ and $\kappa_q$ determine the part of the LHT spectrum relevant for our study.

The mass of the triplet scalar $\Phi$ is related to the doublet Higgs mass by $m_\Phi = \sqrt{2}m_Hf/v$. We will take $m_H = 120$ GeV throughout this paper. Two more dimensionless parameters $\lambda_1$ and $\lambda_2$ appear in the top quark sector; the top mass being given by $m_t = (\lambda_1/\sqrt{1 + R^2})v$, where $R = \lambda_1/\lambda_2$. The masses of the two heavy partners of the top quark, $T^+_t$ and $T^-_t$, can be expressed as $m_{T^+_t} = \lambda_2\sqrt{1 + R^2}f$ and $m_{T^-_t} = \lambda_2 f$. We use $m_t = 175$ GeV in our analysis and set $R = 1$.

### 2.2 T-parity violation

T-parity violation in the LHT and thus the decay of the heavy photon $A_H$ arises via the so-called Wess-Zumino-Witten term [16], which, according to Ref. [15], can be written as follows:

$$\Gamma_{WZW} = \frac{N}{48\pi^2} \left( \Gamma_0[\Sigma] + \Gamma[\Sigma, A_l, A_r] \right).$$

(3)

The functional $\Gamma_0[\Sigma]$ is the ungauged WZW term which depends only on the non-linear sigma model field $\Sigma$. It cannot be expressed as a four-dimensional integral over a local Lagrangian. Instead, a closed form can be written as an integral over a five-dimensional manifold with ordinary spacetime as its boundary [16]. The term $\Gamma[\Sigma, A_l, A_r]$ is the gauged part of the WZW term. This part can be written as an ordinary four-dimensional integral over a local Lagrangian. The explicit expressions for the functionals and the relation of the fields $A_{l,r}$ to the gauge fields in the LHT can be found in Ref. [15]. While these functionals are uniquely given by the symmetry breaking pattern $SU(5) \rightarrow SO(5)$ and the gauged subgroups in the LHT, the integer $N$ in Eq. (3) depends on the UV completion of the LHT. In strongly coupled underlying theories it will be related to the representation of the fermions whose condensate acts as order parameter of the spontaneous symmetry breaking. In the simplest case, $N$ will simply be the number of ‘colors’ in that UV completion, as is the case for the WZW term in ordinary QCD. The overall coefficient $N/48\pi^2$ encapsulates the effect of the chiral anomaly, which is a one-loop effect in the corresponding high-scale theory.

As noted in Ref. [15], the WZW term in Eq. (3) is not manifestly gauge invariant. Gauge invariance is violated by terms with three or four gauge bosons with an odd number of T-odd gauge bosons, e.g. by a term like $\epsilon_{\mu\nu\rho\sigma}V_H^\mu V^\nu V^\rho V^\sigma$, where $V_H$ is a T-odd gauge boson and $V$ denotes a SM gauge boson. Such anomalous terms need to be cancelled to have a consistent theory and some mechanisms to achieve this are discussed in Ref. [15]. After this cancellation, the leading T-odd interactions appear only at order $1/f^2$. For instance, we get a vertex with
one T-odd gauge boson and two SM gauge bosons from $\epsilon_{\mu\nu\rho\sigma}(H^\dagger H/ f^2) V_{H}^{\mu\nu} V_{H}^{\rho\sigma}$, after the Higgs doublet $H$ gets a vacuum expectation value $v$.

To leading order in $1/f$, the part of the WZW term containing one neutral T-odd gauge boson is given, in unitary gauge, by

$$\Gamma_n = \frac{N g^2 g'}{48\pi^2 f^2} \int d^4 x (v + h)^2 \epsilon_{\mu\nu\rho\sigma} \times$$

$$\left[ -(6/5) A_H^\mu \left( c_w^2 Z^\nu \partial^\rho Z^\sigma + W^+ W^- D_A^\rho W^{-\sigma} + W^+ W^- D_\nu W^{+\sigma} + i (3 g x_w + g' s_w) W^+ W^- W^\sigma Z^\rho \right) 
+ t_w^{-1} Z_H^\mu \left( 2 c_w^2 Z^\nu \partial^\rho Z^\sigma + W^+ D_A^\rho W^{-\sigma} + W^+ D_\nu W^{+\sigma} - 2 i (2 g c_w + g' s_w) W^+ W^- W^\sigma Z^\rho \right) \right].$$

(4)

Here $h$ is the physical Higgs boson, $D_A^\mu W^\pm = (\partial^\mu \mp ie A^\mu) W^\pm$ and $s_w, c_w$ and $t_w$ denote the sine, cosine and tangent of the weak mixing angle, respectively. All T-violating vertices with up to four legs have been tabulated in Ref. [20] and implemented into a model file for CalcHEP 2.5 [27, 28].

If $A_H$ is heavy, the vertices in Eq. (4) lead to its decay into a pair of $Z$-bosons or into $W^+ W^-$ with a decay width of the order of eV [19]. On the other hand, if $M_{A_H} < 2 M_W$, the heavy photon cannot decay into on-shell SM gauge bosons. It could still decay into (one or two) off-shell SM gauge bosons, but for low masses loop induced decays into SM fermions will dominate. In fact, as discussed in Ref. [20], the T-violating vertices can couple the $A_H$ to two SM fermions via a triangle loop. But since the corresponding one-loop diagrams are logarithmically divergent, one needs to add counterterms to the effective Lagrangian of the form

$$\mathcal{L}_{ct} = f g_\mu \left( c_L P_L + c_R P_R \right) f A_H^\mu,$$

(5)

$$c_i^f = c_{t,\epsilon}^f \left( \frac{1}{\epsilon} + \log(\mu^2) + \mathcal{O}(1) \right),$$

(6)

where $P_{L,R} = (1 \mp \gamma_5)/2$. As shown in Ref. [20] the counterterms can also be written in a manifestly gauge invariant way. These counterterms are only some of the infinitely many terms which have to be included anyway at higher orders in the momentum and loop expansion in the EFT. This procedure to renormalize the EFT order by order is well known from chiral perturbation theory [29] and, as usually done there, dimensional regularization was used in Ref. [20] which preserves chiral and gauge invariance.\footnote{Of course, in view of the notorious problems with dimensional regularization in chiral gauge theories and the appearance of $\gamma_5$ and the Levi-Civita tensor $\epsilon_{\mu\nu\rho\sigma}$, for a consistent treatment of divergent loop integrals a more appropriate regularization scheme should be chosen like the proper-time method or zeta-function regularization, see Ref. [30].}

The coefficients $c_i^f(\mu)$ of the counterterms can be estimated by naive dimensional analysis [31] or naturalness arguments. Since the scale dependence of the loop diagrams is cancelled by the scale dependence of the counterterms $c_i^f(\mu)$, any change of order one in the renormalization scale should be compensated by a change of order one in $c_i^f(\mu)$. Therefore these coefficients are given, up to $\mathcal{O}(1)$ factors, by the coefficients of the leading $1/\epsilon$ divergence in dimensional regularization of the loop integrals. The coefficients $c_i^f(\epsilon)$ are explicitly listed in Ref. [20] and we have included the vertices from Eq. (5) in the CalcHEP model file.
The finite parts of the counterterms are determined by the underlying theory. For a given UV completion of the LHT, they can be obtained, in principle, by integrating out the new ‘resonances’ which lie above the cutoff $\Lambda$ of the LHT. Since the branching ratios (BR’s) into the different SM fermions depend on these coefficients, at least in principle, we could get information on the UV completion of the LHT by precisely measuring the BR’s of $A_H$. We will discuss below, how $O(1)$ changes (different for quarks and leptons) in the coefficients $c_{i,\ell}$ could affect these BR’s and thus our analysis. Note that the unknown constant $N$ from Eq. (4) cancels in the branching ratios. Actually, if we could measure the total decay width of $A_H$, we could even get information on $N$ itself, in the same way as the decay $\pi^0 \rightarrow \gamma\gamma$ yields information about the number of colors in ordinary QCD, however, the width of $O(\text{eV})$ for $A_H$ is too small to be measurable.

The prefactor of the WZW term, $N/48\pi^2$, is of the size of a one-loop effect, thus the coupling of $A_H$ and other T-odd gauge bosons to SM fermions via a triangle-loop is effectively 2-loop suppressed. Therefore these T-violating couplings will not affect the production mechanism of T-odd particles and their cascade decays at colliders, or EW precision observables [20]. In particular, T-parity violation should still satisfy the EW data with a rather small scale $f$. It is only in decays of the $A_H$ that the anomaly term acquires phenomenological importance. As we demonstrate in what follows, reconstruction of the $A_H$ mass becomes possible through such decays, thus confirming the bosonic nature of the LTP.

Since there is no stable LTP now, the collider signals in the LHT with T-parity violation are completely different from the LHT with exact T-parity. The LEP bounds of order 100 GeV still apply to all T-odd particles except for the $A_H$. In addition, based on an analysis of recent Tevatron data from CDF Vista on multijet events [32], it has been argued in Ref. [20] that a bound of $m_{q_H} > 350$ GeV applies to the LHT with broken T-parity.

3 The dilepton and four-lepton signal processes

3.1 Parton level production of heavy T-odd quark pairs

As the cross-section for direct single or pair production of $A_H$ is very tiny, this gauge boson can essentially only be produced via the decay of heavier T-odd particles. Hence, in principle, we should be considering the production of all such T-odd particle pairs and their subsequent decays. But owing to the substantial technical difficulties in simulating all such processes together, we restrict our attention to the production of heavy T-odd quarks in the initial parton level hard scattering. Needless to say, our cross-sections for the specific final states that we consider are then rather underestimated, and can be taken as lower bounds.

We consider the following processes for the production of T-odd quark pairs at the LHC:

$$pp \rightarrow q_H\bar{q}_H + X,$$

$$pp \rightarrow u_Hu_H + X, \quad \bar{u}_Hu_H + X, \quad d_Hd_H + X, \quad \bar{d}_H\bar{d}_H + X,$$

$$u_Hd_H + X, \quad \bar{u}_H\bar{d}_H + X, \quad u_H\bar{d}_H + X,$$

where $t_H$ denotes the lighter T-odd partner of the top quark. Since, $T_-$, the heavier T-odd partner of the top quark has a mass of 1013 GeV (for $f = 1$ TeV) and is thus heavier than $t_H$ (for most of our choices for $\kappa_q$ below), its cross-section is much smaller and we have
neglected its pair production. Of course, for lower values of \( f \), both \( T, \bar{T} \) and heavy T-odd gauge boson productions can have appreciable cross-section at the LHC.

In general, we expect the processes in Eq. (7) to be dominant because of the strong interaction production channels through gluon-gluon fusion and \( q\bar{q} \)-annihilation. But the electroweak processes from Eq. (8) also contribute significantly to the cross-section via \( t \)-channel T-odd gauge boson exchange, especially when the T-odd gauge bosons become relatively light, i.e. for low values of \( f \). For instance, for \( f = 1 \) TeV and \( \kappa_q = 0.5 \), we find \( m_{\text{qq}} \sim 700 \) GeV and the total production cross-section for a pair of heavy T-odd quarks is about 2.1 (0.7) \( \text{pb} \) for the LHC running at 14 (10) TeV. On the other hand, we can also obtain \( m_{\text{qq}} \sim 700 \) GeV by choosing \( f = 500 \) GeV and \( \kappa_q = 1 \). In this later case the cross-section goes up to 5.8 (2.3) \( \text{pb} \), where actually the electroweak processes from Eq. (8) are found to dominate. This fact has also been observed recently in Ref. [25].

The important fact is that the sum of the cross-sections of all T-odd quark pair production processes can be sizeable, in particular for not too large \( m_{\text{qq}} \). This will allow us to extract a clear signal after cuts are applied. Furthermore, since additional electroweak processes which can, for instance, produce pairs of T-odd gauge bosons \( V_H V_H \), finally also lead to two \( A_H \)'s, the given cross-sections, as mentioned before, are actually rather lower bounds.

The initially produced T-odd heavy quarks subsequently decay as \( q_H \to W_H q' \), \( Z_H V \), \( A_H q \) and then \( W_H \to A_H W \), \( \bar{q} q' \) and \( Z_H \to A_H Z \). At one point in such decay chains of a pair of \( q_H \)'s, we are left with two \( A_H \) bosons, which will further decay as discussed in the next subsection. There will also be several hard jets and leptons and some amount of missing \( E_T \), if there are decays of \( W^\pm \) and \( Z \) into neutrinos.

The initial parton level hard-scattering matrix elements and the relevant decay branching ratios for the signal in the LHT with T-parity violation are calculated with the help of CalcHEP (Version 2.5.1) [27]. We have used the CalcHEP model files for the LHT (with exact T-parity) from Ref. [23] and the one from Refs. [20, 28] for the T-violating terms. We have used the leading order CTEQ6L [34] parton distribution functions with NLO running of \( \alpha_s \) with \( \alpha_s(M_Z) = 0.118 \). The QCD factorization and renormalization scales were set equal to the sum of the masses of the particles which are produced in the initial parton level scattering process.

\[ A \text{ new } \text{CalcHEP model file has been written by the authors of Ref. [25] which includes some missing factors of order } v^2/f^2 \text{ in the couplings of T-odd fermions to the } Z \text{- and } W \text{-bosons, which were found in Ref. [33]. These changes in the Feynman rules will, however, not significantly affect our analysis, which focuses on the decays of the } A_H \text{ boson.} \]
3.2 Decay modes of $A_H$

A comprehensive list of possible final states in the LHT with T-parity violation after the decay of the $A_H$’s is given in Ref. [20]. Here we are interested in either dilepton or four-lepton signals from the decay of the two $A_H$’s. The advantage of these leptonic decay channels of $A_H$ is very apparent. As we will see, one can obtain clean signatures over the backgrounds with a minimal number of selection cuts and with luminosity building up, clear peaks in the invariant-mass distributions of dileptons or four leptons give us information about the $A_H$ mass and thus on the symmetry breaking scale $f$. The decay branching fractions of $A_H$ to either leptons (electron, muon) or to a pair of $Z$ bosons (one of which might be off-shell) are given in Table 1. Note that the BR for the further decay $ZZ \rightarrow l^+l^-l'^+l'^-$, where $l,l' = \{e,\mu\}$, is only $4.5 \times 10^{-3}$, but the signal in this channel is very clean and the SM backgrounds, primarily from $ZZ$ production, can be reduced efficiently as we will discuss below.

| $f$ (GeV) | $M_{A_H}$ (GeV) | BR($A_H \rightarrow \ell^+\ell^-$) + BR($A_H \rightarrow \mu^+\mu^-$) (%) | BR($A_H \rightarrow ZZ^{(*)}$) (%) |
|---------|----------------|---------------------------------|-------------------------------|
| 500     | 66             | 7.59                            | $\sim 0$                      |
| 750     | 109            | 7.40                            | 0.18                          |
| 1000    | 150            | 3.42                            | 11.03                         |
| 1100    | 166            | 0.99                            | 8.67                          |
| 1500    | 230            | 0.02                            | 22.45                         |

Table 1: Decay branching fractions of $A_H$ to leptons ($\ell = e, \mu$) or $ZZ^{(*)}$ as a function of the scale $f$, i.e. the mass $M_{A_H}$.

As already observed in Ref. [20], for lower masses ($M_{A_H} \lesssim 120$ GeV, $f \lesssim 800$ GeV) the decay of $A_H$ is dominated by the loop-induced two-body modes into fermions, whereas for higher masses ($M_{A_H} > 2M_W, f > 1070$ GeV) the two-body modes to gauge boson pairs dominate. For intermediate masses, both the two-body and three-body modes compete (in the three-body mode we have one on-shell $W^\pm$ or $Z$). The decay into two off-shell $Z$’s for low $f$ will have a very small branching-fraction, as the relative one-loop suppression is already compensated by the off-shellness of one vector boson.

As mentioned earlier, the decay rates of $A_H$ into fermions (quarks, charged leptons, neutrinos) via one-loop triangle diagrams depend on the values of the finite terms in the counterterms from Eq. (5). To obtain the results given in Table 1 we followed Ref. [20] and used naive dimensional analysis to fix the $O(1)$ constants from Eq. (6) to be exactly equal to one. These finite terms are determined by the UV completion of the LHT and could easily be different from one. In particular, one could imagine a situation, where the underlying theory couples differently to quarks and leptons. For instance, it could happen that all the couplings of the charged leptons could be bigger by a factor of two, which is well within the uncertainty of naive dimensional analysis. This would increase the partial decay width $\Gamma(A_H \rightarrow \text{all charged leptons})$ by a factor of four. The corresponding change of the branching ratio BR($A_H \rightarrow e^+e^-$) + BR($A_H \rightarrow \mu^+\mu^-$), which is relevant for our study, depends on the total decay width and therefore on the mass of $A_H$ or the scale $f$. 9
It increases by about a factor of three for $M_{A_H} = M_Z$, i.e. for $f = 650$ GeV. Such a scenario would of course require less luminosity to get a certain number of dilepton events in our analysis below. On the other hand, if the underlying theory increases the couplings of $A_H$ to only the quarks by a factor of two compared to naive dimensional analysis, then the $\text{BR}(A_H \to e^+e^-) + \text{BR}(A_H \to \mu^+\mu^-)$ would be smaller (by a factor of about three for $M_{A_H} = M_Z$) and we would need more luminosity. While the precise numbers for these fermionic branching ratios therefore crucially depend on the unknown $\mathcal{O}(1)$ coefficients in the counterterms, the overall results of our analysis are not expected to change. In particular, the required luminosity is not expected to change by more than a factor of three, up or down.

As already noted in Ref. [20] as soon as the $WW^{(*)}$ and $ZZ^{(*)}$ decay channels for $A_H$ open up for larger $M_{A_H}$ or $f$, they quickly dominate over the fermionic modes. Therefore the overall picture and the value of $f$ where this cross-over occurs, does not depend too sensitively on the precise values of the counterterms, as long as they vary only in a reasonably small window around the values as predicted by naive dimensional analysis.

3.3 Why is the $A_H$ different from a usual $Z'$ ?

Of course, the strategy to look for a resonance peak in the invariant mass distribution of dileptons is well known from the searches for a $Z'$ gauge boson which appears in many models of New Physics, see for instance the recent reviews [35] and references therein.

Low energy weak neutral current experiments are affected by $Z'$ exchange, which is mainly sensitive to its mass, and by $Z - Z'$ mixing. On the other hand, measurements at the $Z$-pole are very sensitive to $Z - Z'$ mixing, which lowers the mass of the $Z$ relative to the SM prediction and also modifies the $Zf\bar{f}$ vertices. For $e^+e^-$ colliders, like LEP2, a $Z'$ much heavier than the center of mass energy would manifest itself through induced four-fermion interactions, which then interfere with virtual $\gamma$ and $Z$ contributions for leptonic and hadronic final states. The primary discovery mode at hadron colliders, like the Tevatron, is from the direct Drell-Yan production of a dilepton resonance.

The bounds on the $Z'$ mass in a variety of popular models are usually obtained by assuming the $Z'$ coupling to SM fermions to be of electroweak strength and family universal. Then for some models the strongest bounds come from electroweak precision tests yielding $M_{Z'} \sim 1200 - 1400$ GeV at 95% confidence level. On the other hand, for a sequential $Z'$ model, the LEP2 lower bound is even around 1800 GeV. For other models, the bounds from direct searches at the Tevatron are better than those derived from electroweak data, typically one obtains $M_{Z'} \gtrsim 800 - 1000$ GeV for these models [35].

Why does this fact not rule out a $A_H$ with a mass around $50 - 250$ GeV which we will consider below? The crucial point is that although a light $A_H$ decays with a large BR into a pair of SM fermions, the actual coupling of $A_H$ to two SM fermions is very small. Essentially, the coupling is of the size of a two-loop effect as discussed above. Thus the couplings are very different from the most commonly considered $Z'$ models with couplings of electroweak strength for which the above limits apply. Therefore the direct production cross-section of such a low-mass $A_H$ in $e^+e^-$ colliders like LEP2 or at the Tevatron is tiny, of the order of $10^{-6}$ pb [20]. Also the four-fermion operators induced by $Z'$ at low energies have only a small coupling and will not affect low-energy weak observables. Furthermore, the coupling of $A_H$ to $WW$ or $ZZ$ which is directly induced by the WZW term, see Eq. (1),
is very small and thus the production cross-section for $A_H$ radiated off some $W$ or $Z$ boson is again very small. Therefore the $A_H$ cannot be produced directly, but only via the decay of heavier T-odd particles, which themselves have not yet been observed.

As far as the decay $A_H \to ZZ$ is concerned, again the small coupling of $A_H$ to SM fermions leads to a tiny $s$-channel production cross-section at LEP2 or the Tevatron. This is in contrast to the case of models with warped extra dimensions, like Randall-Sundrum (RS) [36], where the first Kaluza-Klein excitation of the graviton, $G_1$, can have a sizeable coupling to SM fermions and also often decays into $ZZ$ with a branching ratio of typically 5%. From the absence of any deviation from the SM signal in $e^+e^- \to ZZ$ at LEP2 it was concluded in Ref. [37] that $M_{G_1} > 700$ GeV. Recently, CDF [38] has searched for a new heavy particle decaying to $ZZ \to eeee$ in the mass range of $500 - 1000$ GeV. In $1.1 \text{fb}^{-1}$ of integrated luminosity, no event was observed after all the selection cuts, with an expected background of $0.028 \pm 0.014$ events. Within the RS-model, this translates into $\sigma(p\bar{p} \to G_1) \times \text{BR}(G_1 \to ZZ) < 4 \text{pb}$ at 95% C.L. for $M_{G_1} \sim 500$ GeV. Since the mass region below 400 GeV was used to control the background from hadrons faking electrons, a potential signal from a lighter resonance, like the $A_H$ with a mass around $150 - 250$ GeV, could not be observed. In any case, no signal is expected, since for a $A_H$ of mass $230$ GeV, $\sigma(p\bar{p} \to A_H) \times \text{BR}(A_H \to ZZ) = 0.03 \text{pb}$. This is well below the above bound. A light $A_H$ with a mass well below 1 TeV, giving a simultaneous signal in the dilepton and four-lepton channels (via $ZZ$), also sets the LHT with T-parity violation apart from R-parity violating SUSY models with an additional $Z'$ which can decay into four leptons via a slepton/sneutrino pair, as proposed in Ref. [39].

### 3.4 Choice of benchmark points

As discussed above, the production cross-section of heavy T-odd quark pairs decreases with increasing mass $m_{qH}$, up to the discussed enhancement of the electroweak processes from Eq. (8) for low $f$. We therefore will choose benchmark points (BP’s) with $m_{qH} \sim 400, 700, 1000$ GeV to see this effect. The point with the lightest mass is close to the bound $m_{qH} > 350$ GeV found in Ref. [20] from recent Tevatron data.

The intermediate mass region $120 \text{ GeV} < m_{A_H} < 165 \text{ GeV}$ ($800 \text{ GeV} < f < 1100 \text{ GeV}$) will be the most difficult to analyze, since neither the BR of $A_H$ into dileptons nor into four leptons (via $ZZ$) dominates as can be seen from Table 1. Therefore we first take a benchmark point from this region and choose $f = 1 \text{ TeV}$ which corresponds to $M_{A_H} = 150$ GeV. Later, we will also take $f = 500$ GeV, where the dilepton mode dominates and $f = 1500$ GeV, where the dilepton mode is negligible and the decay into $ZZ$ and thus into four leptons is important.

The first two BP’s with $f = 1 \text{ TeV}$ are chosen in order to illustrate the effect of low and heavy quark masses both at the production level and at the level of kinematical variables. We take for the first BP-1 $m_{qH} = 400 \text{ GeV}$ ($\kappa_q = 0.285$) and for the second BP-2 $m_{qH} = 700 \text{ GeV}$ ($\kappa_q = 0.5$), see Table 2.

As we will see below, BP-1 with a rather low $m_{qH}$ leads to a clean dilepton signal over the backgrounds with rather modest luminosity. Therefore such a scenario should be testable during the early run of the LHC with 10 TeV center of mass energy, even in the difficult
intermediate mass region for $M_{A_H}$. We expect the analysis to be easier for either lighter $M_{A_H}$ (lower $f$) or heavier $M_{A_H}$ (higher $f$), where one of the dilepton or four-lepton signals will clearly dominate.

For the further BP’s, we therefore restrict ourselves to the heavier quark masses $m_{q_H} \sim 700,1000 \text{ GeV}$. For $m_{q_H} \sim 700 \text{ GeV}$, we show the possible reconstruction of the $A_H$ mass in the invariant mass distributions of dileptons for a point with very low values of $f = 500 \text{ GeV}$ ($M_{A_H} = 66 \text{ GeV}$) (BP-3) and of four leptons for a point with a higher value of $f = 1500 \text{ GeV}$ ($M_{A_H} = 230 \text{ GeV}$) (BP-4), see Table 2. As the T-odd quarks become heavier, their production cross-section goes down. It then becomes increasingly difficult to obtain a reasonable number of signal events over the background. In such a scenario, in order to check the reach of the LHC, we choose the last two benchmark points such that $m_{q_H} \sim 1000 \text{ GeV}$. For reasons discussed above, here also we consider two different values of $f$, $f = 1000 \text{ GeV}$ ($M_{A_H} = 150 \text{ GeV}$) (BP-5) and $f = 1500 \text{ GeV}$ ($M_{A_H} = 230 \text{ GeV}$) (BP-6).

| Benchmark Point | $m_{d_H}$ (GeV) | $m_{u_H}$ (GeV) | $M_{A_H}$ (GeV) | $f$ (GeV) | $\kappa_q$ | $\sqrt{s} = 10 \text{ TeV}$ | $\sigma_{q_Hq_H}$ (fb) | $\sqrt{s} = 14 \text{ TeV}$ | $\sigma_{q_Hq_H}$ (fb) |
|----------------|----------------|----------------|----------------|----------|----------|-----------------------------|--------------------------|-----------------------------|--------------------------|
| BP-1           | 403            | 400            | 150            | 1000     | 0.285    | 12764.6                     | 35989.0                  | 2061.0                     | 5750.4                   |
| BP-2           | 707            | 702            | 150            | 1000     | 0.5      | 660.8                       | 2061.0                   | 5750.4                     | 2061.0                   |
| BP-3           | 707            | 686            | 66             | 500      | 1.0      | 2298.1                      | 5750.4                   | 2061.0                     | 5750.4                   |
| BP-4           | 742            | 740            | 230            | 1500     | 0.35     | 373.0                       | 1283.1                   | 2061.0                     | 5750.4                   |
| BP-5           | 1025           | 1018           | 150            | 1000     | 0.725    | 119.9                       | 421.0                    | 2061.0                     | 5750.4                   |
| BP-6           | 1008           | 1004           | 230            | 1500     | 0.475    | 66.3                        | 261.0                    | 2061.0                     | 5750.4                   |

Table 2: The different benchmark points (BP’s) for our study. These choices are made in view of the different scenarios that can arise in terms of production cross-sections, decay branching fractions and kinematic distributions. We also present the heavy quark pair production cross-section $\sigma_{q_Hq_H}$ for the sum of all parton-level processes from Eqs. (7) and (8) at the LHC with center of mass energies of 10 TeV and 14 TeV.

In Table 2 we have also listed the total production cross-section for the sum of all parton-level processes from the strong-interaction processes from Eq. (7) and the electroweak processes from Eq. (8) at the LHC with center of mass energies of 10 TeV and 14 TeV. For BP-2, the strong interaction processes dominate and yield about 1.47 pb, while the electroweak processes give only a contribution of 0.60 pb at 14 TeV, i.e. about 29%. On the other hand, for BP-3 with low $f = 500 \text{ GeV}$ and therefore rather light $A_H$, $Z_H$ (exchanged in the $t$-channel), the electroweak processes contribute 3.75 pb at a center of mass energy of 14 TeV, i.e. 65% of the total, compared to 2.0 pb from strong interaction processes. The biggest individual parton-level cross-section is $\sigma(pp \to u_Hd_H + X) = 2.39 \text{ pb}$. This has to be compared with the QCD process $\sigma(pp \to u_H\bar{u}_H + X) = 0.44 \text{ pb}$ from $q\bar{q}$-annihilation and gluon-fusion, the latter contributing about one third. The relative smallness of the QCD processes can be understood from the small value of $\alpha_s(\mu_R = 2m_{q_H} = 1.4 \text{ TeV}) = 0.084$ and the size of the various parton density functions for $\mu_F = 2m_{q_H} = 1.4 \text{ TeV}$ around $x \sim m_{q_H}/7 \text{ TeV} = 0.1$. 

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4 Event generation: backgrounds and signal event selection

As noted earlier, the initial parton level hard-scattering matrix elements in the LHT with T-parity violation were calculated and the events generated with the help of CalcHEP. These events, along with the relevant masses, quantum numbers and two-body and three-body decay branching fractions were passed on to PYTHIA (Version 6.421) [40] with the help of the SUSY Les Houches Accord (SLHA) (v1.13) SUSY/BSM spectrum interface [41] for their subsequent decays, showering, and hadronization. Initial and final state radiations from QED and QCD and multiple interactions were also taken into account in PYTHIA. The SM backgrounds, except for $Z^{(*)}/\gamma^*$ (Drell-Yan process), were simulated with ALPGEN [42] and then subsequently the unweighted event samples are passed onto PYTHIA for their showering and hadronization. The matching of matrix-element hard partons and shower-generated jets is performed using the MLM prescription [42]. This jet-parton matching allows us to generate inclusive samples of arbitrary jet multiplicity without any over-counting. Owing to the very large cross-section for the Drell-Yan process, it was not possible to generate statistically significant samples of events with additional hard jets using ALPGEN. Instead, the Drell-Yan background has been simulated with PYTHIA. As we will explain below, after appropriate cuts, the Drell-Yan background is reduced to a negligible level. We have again used the leading order CTEQ6L parton distribution functions (for PYTHIA we use the Les Houches Accord Parton Density Function (LHAPDF) interface [43]). The QCD factorization and renormalization scales are in general kept fixed at the sum of the masses of the particles which are produced in the initial parton level scattering process. For the production of $Z^{(*)}/\gamma^*$, we have chosen the scale to be $M_Z$. If we would decrease the QCD scales by a factor of two, the cross-section can increase by about 30%.

4.1 Background from SM processes and within the LHT

The main SM backgrounds for the dilepton channel come from the Drell-Yan process via $Z^{(*)}/\gamma^*$ and the abundantly produced top quark pairs, whereas for the four-lepton channel, $ZZ$ is the dominant source of background. For the dilepton channel we have also considered the backgrounds coming from $ZZ, ZW, WW$ and $tW$. We have included additional multiple hard jets in the simulations as follows:

- $t\bar{t} + n$ jets, $0 \leq n \leq 4$
- $ZZ + n$ jets, $0 \leq n \leq 3$
- $ZW + n$ jets, $0 \leq n \leq 3$
- $WW + n$ jets, $0 \leq n \leq 3$

Although $t\bar{t}$ events can also give rise to four-lepton events, such backgrounds are relatively easily reduced with the requirement that among the four leptons, there are at least two opposite sign same flavor ones, whose invariant mass is around the $Z$ boson mass, followed by the effective mass cut, as shown in our subsequent analysis.
\begin{itemize}
\item $tW + n$ jets, $0 \leq n \leq 1$
\end{itemize}

For the other possible dilepton and four-lepton backgrounds, we have checked that their cross-sections are small compared to the above ones, for instance, for $t\bar{t}Z$, where $Z \rightarrow l^+l^-$, the cross-section is around 40 fb at $\sqrt{s} = 14$ TeV\footnote{In case of a jet faking a lepton, $W^+ +$ jets can also give rise to dilepton events. Although we do not consider the possibility of such fakes, we expect the large $M_{\text{eff}}$ cut to reduce this background significantly.}. After putting a large effective mass cut as described below, these backgrounds are not expected to be significant. Additional leptons coming from the photons radiated by charged particles, or from the decay of pions, are generally expected to be removed by the basic isolation cuts described later.

For the strongly produced process $t\bar{t} +$ jets, which has a long tail in the effective mass distribution, we have multiplied the leading order cross-sections from ALPGEN by appropriate K-factors wherever they are available in the literature. For $t\bar{t} + 0$ jet the K-factor used is 2.2 from next-to-leading order (NLO) and next-to-leading-log resummed (NLL) corrections according to the analysis in Ref. \cite{44}. For $t\bar{t} + 1$ jet we have used a K-factor of 1.29 according to the NLO calculation in Ref. \cite{45}, whereas for $t\bar{t} + 2$ jets we used 1.28 as inferred from the recent NLO calculation in Ref. \cite{46}.

\section{Event selection criteria}

In our analysis we demand for the dilepton signal that we have exactly one pair of opposite sign same flavor (OSSF) leptons from the decay $A_H \rightarrow l^+l^-$, with $l = \{e, \mu\}$. For the four-lepton signal from the decay $A_H \rightarrow ZZ(\ast) \rightarrow l^+l^-l'^+l'^-$, where $l, l' = \{e, \mu\}$, we demand that there should be four leptons, among which at least one OSSF lepton pair should have an invariant mass peaked around $M_Z$ (i.e., $M_Z - 20$ GeV \(\leq M_{ll} \leq M_Z + 20\) GeV). The last criterion is used because in the scenarios that we consider, at least one $Z$-boson is on-shell.

The following basic selection cuts (denoted by Cut-1 below) were applied for both the signal and the background \cite{48, 49}:

\textbf{Lepton selection:}
\begin{itemize}
\item $p_T > 10$ GeV and $|\eta| < 2.5$, where $p_T$ is the transverse momentum and $\eta$ is the pseudorapidity of the lepton (electron or muon).
\end{itemize}

\textbf{Lepton-lepton separation:} $\Delta R_{ll} \geq 0.2$, where $\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2}$ is the separation in the pseudorapidity–azimuthal angle plane.

\textbf{Lepton-jet separation:} $\Delta R_{lj} \geq 0.4$ for all jets with $E_T > 20$ GeV.

\footnote{Note that this K-factor has been obtained with a minimum $p_T$ of 50 GeV for the jets whereas we will employ a cut of only 20 GeV. Based on the observation in Ref. \cite{47}, that in many cases the K-factor diminishes for processes with more hard jets, the actual K-factor for $t\bar{t} + 2$ jets might be lower than 1.28.}
• The total energy deposit from all hadronic activity within a cone of $\Delta R \leq 0.2$ around the lepton axis should be $\leq 10$ GeV.

Jet selection:

• Jets are formed with the help of PYCELL, the inbuilt cluster routine in PYTHIA. The minimum $E_T$ of a jet is taken to be 20 GeV, and we also require $|\eta_j| < 2.5$.

We have approximated the detector resolution effects by smearing the energies (transverse momenta) with Gaussian functions. The different contributions to the resolution error have been added in quadrature.

• Electron energy resolution:

$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} + b + \frac{c}{E},$$

where

$$(a, b, c) = \begin{cases} (0.030 \text{ GeV}^{1/2}, 0.005, 0.2 \text{ GeV}), & |\eta| < 1.5, \\ (0.055 \text{ GeV}^{1/2}, 0.005, 0.6 \text{ GeV}), & 1.5 < |\eta| < 2.5. \end{cases}$$

• Muon $p_T$ resolution:

$$\frac{\sigma(p_T)}{p_T} = \begin{cases} a, & p_T < 100 \text{ GeV}, \\ a + b \log \frac{p_T}{100 \text{ GeV}}, & p_T > 100 \text{ GeV}, \end{cases}$$

with

$$(a, b) = \begin{cases} (0.008, 0.037), & |\eta| < 1.5, \\ (0.020, 0.050), & 1.5 < |\eta| < 2.5. \end{cases}$$

• Jet energy resolution:

$$\frac{\sigma(E_T)}{E_T} = \frac{a}{\sqrt{E_T}},$$

with $a = 0.5 \text{ GeV}^{1/2}$, the default value used in PYCELL.

Under realistic conditions, one would of course have to deal with aspects of misidentification of leptons.

An important cut will be imposed on the effective mass variable, defined to be the scalar sum of the transverse momenta of the isolated leptons and jets and the missing transverse energy,

$$M_{\text{eff}} = \sum p_T^{\text{jets}} + \sum p_T^{\text{leptons}} + E_T,$$

where the missing transverse energy is given by

$$E_T = \sqrt{\left(\sum p_x\right)^2 + \left(\sum p_y\right)^2}.$$
Here the sum goes over all the isolated leptons, the jets, as well as the ‘unclustered’ energy deposits. The energies of the ‘unclustered’ components, however, have not been smeared in this analysis.

In Fig. 1 we plot the distribution of the effective mass after the basic cuts (Cut-1) for dilepton events for the benchmark points BP-1 ($m_{q_H} \sim 400$ GeV), BP-2 ($m_{q_H} \sim 700$ GeV), BP-5 ($m_{q_H} \sim 1000$ GeV) and the SM background, dominantly from Drell-Yan and $t\bar{t}$ + jets. Recall that we have included appropriate K-factors for the latter process. The SM backgrounds are huge; however, the distributions peak around $2m_{q_H}$ for the signal and between $M_Z$ and $2m_t$ for the SM background. It is clear that the production of heavy particles in the initial hard-scattering will lead to a high $M_{\text{eff}}$ in most cases. Therefore, imposing the effective mass cut:

$$M_{\text{eff}} \geq 1 \text{ TeV} \quad \text{(Cut-2),}$$

will reduce the SM background substantially, although the distribution from SM processes with additional hard jets has a long tail towards larger values of $M_{\text{eff}}$. Note that the log-plot makes the differences between the curves look smaller than they actually are. Although this fixed cut also reduces the signal for the lighter $m_{q_H} \sim 400$ GeV from BP-1 by about half, the corresponding larger production cross-section makes up for this loss. In a more realistic analysis one would of course try to optimize the choice of the cut on $M_{\text{eff}}$, depending on the expected signal.

In addition to the effective mass cut from Eq. (16), we will also use the fact that we expect a peak in the invariant mass distribution of dileptons ($M_{ll}$) or four leptons ($M_{4l}$) near the mass of $A_H$. In our analysis, we will therefore impose the condition that the invariant mass should be in a window around $M_{A_H}$

$$M_{A_H} - 20 \text{ GeV} \leq M_{ll,4l} \leq M_{A_H} + 20 \text{ GeV} \quad \text{(Cut-3).}$$

As we will see, this condition will in particular help to reduce the background from leptons within the LHT model. Of course, in a realistic experimental analysis, where the mass of $A_H$ is unknown, one would scan the whole range of invariant masses and impose such a window around some seed-mass $M_{A_H}$, thereby looking for an excess of the signal over the SM and LHT model backgrounds, which are almost flat except near the $Z$-mass. Moreover, this excess should stand out in this window, as compared to the adjoining bins.

Unfortunately, the need to implement such a cut in our analysis will not allow us to detect a heavy photon $A_H$ with a mass very close to $M_Z$, since in that case the cut cannot free the peak from contamination by $Z$-production within the SM and in LHT cascades. In principle, by looking at the relative size of the branching fractions into charged leptons, including $\tau$, and hadrons (jets), one might still be able to distinguish the $A_H$ from the $Z$-boson. However, if we look at a heavy photon with $M_{A_H} = 92$ GeV, we get $R_{A_H} \equiv \text{BR}(A_H \rightarrow \text{quarks})/\text{BR}(A_H \rightarrow \text{all charged leptons}) = 6.27$, which is not much different from the corresponding ratio for the $Z$-boson, $R_Z = 6.92$. So the signature of $A_H$ in this situation might be difficult to distinguish at the LHC. On the other hand, if the effective couplings of all charged leptons with the $A_H$ are scaled up by a factor of two, as discussed above, we would get $R_{A_H} = 1.57$, which is quite different from the value for the $Z$-boson. Note that in this case $\text{BR}(A_H \rightarrow e^+e^-) + \text{BR}(A_H \rightarrow \mu^+\mu^-)$ changes from 7.58% for the original couplings to 22.66% for the rescaled leptonic couplings, i.e. it increases by a factor three and the required luminosity decreases correspondingly.
Figure 1: Effective mass distribution of dilepton events after the basic cuts (Cut-1) for BP-1 ($m_{qH} \sim 400$ GeV), BP-2 ($m_{qH} \sim 700$ GeV), BP-5 ($m_{qH} \sim 1000$ GeV) and the SM background, mostly Drell-Yan and $tt +$ jets, at $\sqrt{s} = 10$ TeV (top panel) and $\sqrt{s} = 14$ TeV (bottom panel).
5 Results

5.1 Dilepton signal

5.1.1 LHC with $\sqrt{s} = 10$ TeV

In Table 3 we list, for the opposite sign same flavor (OSSF) dilepton signal ($l = e, \mu$), the cross-sections of the dominant SM background processes after the basic cuts (Cut-1) and the effective mass cut $M_{\text{eff}} > 1$ TeV (Cut-2) for the LHC running at $\sqrt{s} = 10$ TeV. We can see that the effective mass cut reduces all the SM dilepton backgrounds significantly, in particular from the Drell-Yan process via $Z/\gamma^*$, which is the overwhelming background after the basic cuts. After the cut on $M_{\text{eff}}$, $t\bar{t}$ + jets is the largest background due to the long tail in the effective mass distribution, see Fig. 6.

| Background | Cut-1 (fb) | Cut-2 (fb) |
|------------|------------|------------|
| $Z/\gamma^*$ | 1247174 | $\sim 0.00$ |
| $tt$ + jets | 6278 | 84.03 |
| $ZZ$ + jets | 546 | 5.76 |
| $WW$ + jets | 946 | 9.58 |
| $ZW$ + jets | 624 | 13.39 |
| $tW$ + jets | 719 | 8.37 |
| **Total** | **1256287** | **121.13** |

Table 3: Dominant opposite sign same flavor dilepton ($l = e, \mu$) SM background cross-sections for $\sqrt{s} = 10$ TeV after the basic cuts (Cut-1) and after the cut $M_{\text{eff}} \geq 1$ TeV (Cut-2).

In our simulation of the Drell-Yan process with PYTHIA, out of $10^6$ Monte-Carlo (MC) events, we did not see any dilepton event with $M_{\text{eff}} > 1$ TeV. Actually, in the simulation for the LHC running at 14 TeV, where the cross-section is higher and where we expect more events with larger $M_{\text{eff}}$, we did not get a single event with $M_{\text{eff}} > 1$ TeV out of $10^7$ simulated Drell-Yan events. A larger MC sample would be needed to put a definite number on the cross-section after Cut-2. If we simply assume an upper bound of one event after Cut-2, which is probably much bigger than the correct number, this leads to an upper bound on the dilepton cross-section from $Z/\gamma^*$ after Cut-2 of about 45 fb, i.e. quite sizeable compared to $t\bar{t}$. In the following we assume that we can neglect the SM background from $Z/\gamma^*$ after the effective mass cut. In any case, after the Cut-3, i.e. that the dilepton invariant mass should be in a narrow window around $M_{A_H}$, see Eq. (17), a further reduction of the cross-section and number of dilepton events from $Z/\gamma^*$ will occur anyway.

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6We should note that in the simulation with ALPGEN a substantial number of events in $t\bar{t}$ + 4 jets and $VV + 3$ jets ($V = W, Z$) pass the $M_{\text{eff}}$ cut. We can therefore not exclude the possibility that the inclusion of more hard jets might increase the total background cross-section after Cut-2 by some amount. Such a simulation is beyond the scope of our present study. At least part of the effects of these hard jets is taken into account by the PYTHIA showering and MLM matching of the ALPGEN samples with the highest jet multiplicity.
In Fig. 2 we plot the invariant mass distributions of OSSF dileptons for all the benchmark points and the corresponding SM background after the basic cuts (Cut-1) and the $M_{\text{eff}}$ cut (Cut-2). For BP-1, BP-2, BP-3 and BP-5, a peak emerges at the mass of $A_H$, in particular very clearly for BP-1 and BP-3. BP-1 has a large parton-level T-odd quark pair production cross-section because of the relatively small $m_{q_H} \sim 400$ GeV, compared to $m_{q_H} \sim 700$ GeV for BP-2. BP-3 has also $m_{q_H} \sim 700$ GeV, but a small value of $f = 500$ GeV. Therefore the T-odd quark production cross-section is strongly enhanced by electroweak contributions, as discussed earlier, see Table 2. Furthermore, the leptonic branching ratio for the light $M_{A_H} = 66$ GeV is also large, see Table 1, leading to more dilepton events. Note, however, that the ‘signal’ after Cut-2 also includes dileptons from within the LHT coming for instance from the decay via the $Z$-boson, leading to an enhancement in the peak at $M_Z$ for BP-1 and BP-2 in Fig. 2. Since for BP-3 with $f = 500$ GeV the branching ratio $A_H \rightarrow l^+l^-$ is higher than for BP-1 and BP-2, the $Z$-peak is much smaller compared to the $A_H$-peak.

The total integrated luminosity at the LHC running at 10 TeV will probably be around 200 pb$^{-1}$. For this integrated luminosity, there will be 73 dilepton ‘signal’ events for BP-1 and 33 events for BP-3, compared to a SM background of 24 events. Note, however, that there will be only 8 dilepton events for BP-2 and 1.5 events for BP-5.

As mentioned in Section 2.2, the total decay width of $A_H$ is only of the order of eV and therefore radiative corrections and detector effects will determine the observed width of the resonance peak in reality.

For BP-4 and BP-6 with $f = 1500$ GeV, the decay branching ratio $A_H \rightarrow l^+l^-$ is negligible compared to $A_H \rightarrow ZZ^{(*)}$, see Table 1, and therefore the four-lepton signal will be the relevant signature for discovery. Nevertheless, we get some dilepton events, in particular for BP-4, but the dilepton invariant mass distribution peaks at the $Z$-boson mass and not at $M_{A_H}$.

In order to reduce the SM background further, and also to eliminate the background from dileptons within the LHT which do not come from the decay $A_H \rightarrow l^+l^-$, we impose the additional constraint that the invariant mass of the dileptons should be in a window of $\pm 20$ GeV around $M_{A_H}$ (Cut-3), see Eq. (17). In Table 3 we give the cross-sections for OSSF dilepton events after the basic cuts (Cut-1) and after Cut-2 and Cut-3 for all the benchmark points for the LHC running at $\sqrt{s} = 10$ TeV. The total cross-section for the SM background after Cut-2 and Cut-3 is also given. We also list in Table 4 the number of signal and background events after Cut-2 and after Cut-3 for an integrated luminosity of 200 pb$^{-1}$.

We can see from Table 4 that with an integrated luminosity of 200 pb$^{-1}$, only BP-1 and BP-3 yield a clear signal over the SM background after Cut-2. The Cut-3 then reduces the SM background and the dilepton background from within the LHT model almost completely, with $S_3/B_3 = 15.7$ for BP-1 and $S_3/B_3 = 5.7$ for BP-3 with more that 10 signal events for both benchmark points. Although the high $M_{\text{eff}} \geq 1$ TeV cut (Cut-2) reduces the signal for BP-1 with a low mass $m_{q_H} = 400$ GeV by about a factor two, the larger production cross-section compensates for that. Therefore, at least for BP-1 and BP-3, one expects a clear dilepton signal from the decay of the $A_H$ in the LHT with T-parity violation at the early stage of the LHC run with low center of mass energy and modest luminosity. With the predicted number of signal events after Cut-3, it will presumably also be possible to reconstruct the mass of $A_H$ and determine the symmetry breaking scale $f$.

If we demand that we have at least 10 signal events, BP-2 yields not enough events
Figure 2: Invariant mass distribution of OSSF dilepton pairs ($l = e, \mu$) for $\sqrt{s} = 10$ TeV after the basic cuts (Cut-1) and the effective mass cut $M_{\text{eff}} \geq 1$ TeV (Cut-2) for all the benchmark points, with the corresponding SM background. Note that the ‘signal’ also includes dileptons within the LHT not coming from $A_H$, but, for instance through the decay of the $Z$-boson. This is in particular the case for BP-4 and BP-6 where we do not expect any dileptons from $A_H$. For an integrated luminosity of 200 pb$^{-1}$ there are 73 signal events for BP-1 and 33 events for BP-3, but only 8 signal events for BP-2 and 1.5 events for BP-5, compared to 24 events from the SM background. See Table 4 for more details.
Table 4: OSSF dilepton signal ($S$) from all T-odd quark-pair production processes and total SM background (BG) cross-sections at the LHC with $\sqrt{s} = 10$ TeV after the different cuts described in the text. The number of signal and background events after Cut-2 with an integrated luminosity of 200 pb$^{-1}$ are also given as $S_2$ and $B_2$, respectively. The corresponding numbers after Cut-3 are denoted by $S_3$ and $B_3$.

|      | Cut-1 [S] (fb) | Cut-2 [S] (fb) | Cut-2 [BG] (fb) | $S_2$ | $B_2$ | Cut-3 [S] (fb) | Cut-3 [BG] (fb) | $S_3$ | $B_3$ |
|------|---------------|---------------|----------------|-------|-------|---------------|---------------|-------|-------|
| BP-1 | 871.5         | 367.0         | 121.1          | 73.4  | 24.2  | 196.7         | 12.4          | 39.3  | 2.5   |
| BP-2 | 41.9          | 39.8          | 121.1          | 8.0   | 24.2  | 18.2          | 12.4          | 3.6   | 2.5   |
| BP-3 | 175.2         | 168.1         | 121.1          | 33.6  | 24.2  | 132.9         | 23.3          | 26.6  | 4.7   |
| BP-4 | 21.9          | 21.3          | 121.1          | 4.3   | 24.2  | 0.5           | 7.2           | 0.1   | 1.4   |
| BP-5 | 7.6           | 7.6           | 121.1          | 1.5   | 24.2  | 3.1           | 12.4          | 0.6   | 2.5   |
| BP-6 | 3.5           | 3.5           | 121.1          | 0.1   | 24.2  | 0.1           | 7.2           | 0.02  | 1.4   |

with an integrated luminosity of 200 pb$^{-1}$, in particular after Cut-3. Furthermore, with this luminosity there will be almost no dilepton events for BP-5, already after Cut-2, because of the small production cross-section for $m_{q_H} \sim 1$ TeV. Also the branching ratio of $A_H$ into dileptons is small for this benchmark point, since $f = 1$ TeV.

Note that the BP-4 with $M_{A_H} = 230$ GeV yields about half the dilepton events of BP-2 for the same mass $m_{q_H} \sim 700$ GeV of the heavy T-odd quarks. However, these dileptons for BP-4 are not coming from the decay $A_H \rightarrow l^+l^-$, but from other sources, mostly the Z-boson, as mentioned above. In Table 4 this is visible after imposing the Cut-3 which almost completely removes all dilepton events for BP-4, whereas about half the dilepton events survive for BP-2. For BP-6 there are essentially no dilepton events for 200 pb$^{-1}$. As for BP-4, we expect for this benchmark point, which has $f = 1500$ GeV and $M_{A_H} = 230$ GeV, the four-lepton mode to be relevant for discovery.

We should caution the reader about the numbers given in Table 4 for the SM background cross-sections and the number of BG events after Cut-2 and in particular after Cut-3. The total number of MC events in the OSSF channel we simulated (including all possible processes) is 350987 after Cut-1. After the cut on $M_{eff}$ (Cut-2), we have 4296 events in our MC sample and after Cut-3 there remain 644 MC events in the window of ±20 GeV around the $A_H$ mass (for the case $M_{A_H} = 66$ GeV). Therefore, there is an intrinsic uncertainty of about 4% on the numbers for $B_3$ given in the Table 4. A much larger MC simulation to pin down these numbers more precisely is beyond the scope of the present work. Note, however, that we have enough simulated events for the signal. For instance, for BP-2, we have 12041 MC events after Cut-2 and 5501 MC events after Cut-3.

5.1.2 LHC with $\sqrt{s} = 14$ TeV

In Table 5 we list, for the opposite sign same flavor (OSSF) dilepton signal ($l = e, \mu$), the cross-sections of the dominant SM background processes after the basic cuts (Cut-1) and the effective mass cut $M_{eff} > 1$ TeV (Cut-2) for the LHC running at $\sqrt{s} = 14$ TeV. As
for 10 TeV, we can see that the effective mass cut reduces all the SM dilepton backgrounds significantly, in particular from the Drell-Yan process via $Z/\gamma^*$ which is the main background after the basic cuts. Again, after the cut on $M_{\text{eff}}$, $t\bar{t}$ is the largest background due to the long tail in the effective mass distribution, see Fig. 1. As noted in the previous subsection, in our simulation of the Drell-Yan process with PYTHIA, we did not see any dilepton event with $M_{\text{eff}} > 1$ TeV out of $10^7$ MC events. There were 30048 OSSF dilepton MC events which passed the basics cuts. If we would simply assume an upper bound of one event after the Cut-2, which might be way off the correct number, this would lead to an upper bound on the dilepton cross-section from $Z/\gamma^*$ after Cut-2 of about 57 fb, i.e. again quite sizeable compared to $t\bar{t}$. In the following we assume again that we can neglect the SM background from $Z/\gamma^*$ after Cut-2.

| Background          | Cut-1 (fb) | Cut-2 (fb) |
|--------------------|------------|------------|
| $Z/\gamma^*$       | 1711746    | $\sim 0.00$ |
| $t\bar{t} + \text{jets}$ | 13854   | 344.33     |
| $ZZ + \text{jets}$  | 827        | 13.82      |
| $WW + \text{jets}$  | 1385       | 30.17      |
| $ZW + \text{jets}$  | 951        | 43.40      |
| $tW + \text{jets}$  | 1604       | 41.89      |
| **Total**          | **1730366**| **473.61** |

Table 5: Same as Table 3 for $\sqrt{s} = 14$ TeV.

In Fig. 3 we plot the invariant mass distributions of OSSF dileptons for all the benchmark points and the corresponding SM background after the basic cuts (Cut-1) and the cut on $M_{\text{eff}}$ (Cut-2). Again for BP-1, BP-2, BP-3 and BP-5, a peak emerges at the mass of $A_H$, in particular very clearly for BP-1, BP-2 and BP-3. With an integrated luminosity of 30 fb$^{-1}$, there are 36088 signal events for BP-1, 3723 events for BP-2 and 2135 events for BP-3, compared to 14208 SM background events. Again, for BP-1 and BP-2 we have a non-negligible amount of dilepton background from within the LHT, in particular from the decays via the $Z$-boson, as can be clearly seen in the Fig. 3.

As mentioned before, for BP-4 and BP-6 with $f = 1500$ GeV, the decay branching ratio $A_H \to l^+l^-$ is negligible compared to $A_H \to ZZ^{(*)}$, see Table 1 and therefore the four-lepton signal will be the relevant signature for discovery. Nevertheless, we get many dilepton events even for these two benchmark points, but there is a peak at the $Z$-boson mass and not at $M_{A_H}$.

In order to reduce the SM background further, but also to eliminate the background from dileptons within the LHT which do not come from the decay $A_H \to l^+l^-$, we impose again the additional constraint that the invariant mass of the dileptons should be in a window around $M_{A_H}$ (Cut-3), see Eq. (17). In Table 6 we give the cross-sections for OSSF dilepton events after the basic cuts (Cut-1) and after Cut-2 and Cut-3 for all the benchmark points for the LHC running at $\sqrt{s} = 14$ TeV. The total cross-section for the SM background after Cut-2 and Cut-3 is also given. We also list in Table 6 the number of signal and background.
Figure 3: Same as Fig. 2 for $\sqrt{s} = 14$ TeV.

The qualitative features of the benchmark points for the LHC running at $\sqrt{s} = 14$ TeV are very similar to the case of $\sqrt{s} = 10$ TeV, but now we have higher event rates. First of all, after the Cut-2, all the signal and background cross-sections are about a factor of three bigger, see Tables 4 and 6. Furthermore, we assume that we have now much more integrated luminosity of $30 \text{ fb}^{-1}$. Events after Cut-2 and after Cut-3 for an integrated luminosity of $30 \text{ fb}^{-1}$.
luminosity, 30 fb\(^{-1}\) compared to 200 pb\(^{-1}\) earlier. The Cut-2 again removes about half of the signal events for BP-1. For all benchmark points, we now get more than 10 signal events even after Cut-3 and also the number of background events is much larger than 100. It makes therefore sense to consider the signal significance by looking at \(S/\sqrt{B}\) which is also given in Table 6 for the number of events after Cut-3.

|      | Cut-1 [S] (fb) | Cut-2 [S] (fb) | Cut-2 [BG] (fb) | S\(_2\) | B\(_2\) | Cut-3 [S] (fb) | Cut-3 [BG] (fb) | S\(_3\) | B\(_3\) | S\(_3\)/\(\sqrt{B}\)_3 |
|------|----------------|----------------|----------------|--------|--------|----------------|----------------|--------|--------|----------------------|
| BP-1 | 2341.8         | 1202.9         | 473.6          | 36088  | 14208  | 642.9         | 50.3          | 19286  | 1508   | 496.6                 |
| BP-2 | 129.1          | 124.1          | 473.6          | 3723   | 14208  | 55.5          | 50.3          | 1665   | 1508   | 42.9                 |
| BP-3 | 428.9          | 413.3          | 473.6          | 12398  | 14208  | 322.9         | 95.8          | 9686   | 2873   | 180.7                |
| BP-4 | 72.7           | 71.2           | 473.6          | 2135   | 14208  | 1.9           | 27.0          | 56     | 809    | 2.0                  |
| BP-5 | 26.1           | 26.0           | 473.6          | 781    | 14208  | 10.3          | 50.3          | 308    | 1508   | 7.9                  |
| BP-6 | 13.4           | 13.4           | 473.6          | 401    | 14208  | 0.4           | 27.0          | 11     | 809    | 0.4                  |

Table 6: Same as Table 4 for \(\sqrt{s} = 14\) TeV and an integrated luminosity of 30 fb\(^{-1}\).
even easier for the same \( m_{3H} \) or, conversely, for lower \( f \), we get a larger reach in \( m_{3H} \), if we demand a 5\( \sigma \) signal with 30 fb\(^{-1}\).

Again we should caution the reader about the numbers given in Table 6 for the SM background cross-sections and the number of BG events after Cut-2 and in particular after Cut-3, because of the limited statistics in the Monte-Carlo simulation. The total number of MC events in the OSSF channel we simulated (including all possible processes) is 139429 after Cut-1. After the cut on \( M_{\text{eff}} \) (Cut-2), we have 4170 events in our MC sample and after Cut-3 there remain 730 MC events in the window of ±20 GeV around the \( A_H \) mass (for the case \( M_{A_H} = 66 \) GeV). Therefore, there is an intrinsic uncertainty of about 4\% on the numbers for \( B_3 \) given in the Table 6 and correspondingly about 2\% uncertainty on the significance \( S_3/\sqrt{B_3} \). In particular, the required luminosity for a 5\( \sigma \) statistical significance for BP-5 should be taken with a grain of salt. A much larger MC simulation to pin down these numbers more precisely is again beyond the scope of the present work. Note, however, that we have enough simulated events for the signal. For instance, for BP-5, we have 12365 MC events after Cut-2 and 4880 MC events after Cut-3.

### 5.2 Four-lepton signal

#### 5.2.1 LHC with \( \sqrt{s} = 10 \text{ TeV} \)

The biggest SM background for the four-lepton signal, as defined in Section 4.1, arises from the production of \( ZZ + \) jets and the subsequent fully leptonic decays. For the LHC running at \( \sqrt{s} = 10 \) TeV, the corresponding cross-section after the basic cuts (Cut-1) is 13.78 fb. It is drastically reduced to 0.14 fb by the cut on the effective mass \( M_{\text{eff}} \geq 1 \) TeV (Cut-2). The second largest SM background is from \( t\bar{t} + \) jets, but after the basic cuts and the requirement that at least two OSSF leptons among the total four have an invariant mass in a window of ±20 GeV around \( M_Z \), it is only 0.53 fb and it is completely removed by the effective mass cut.

In Table 7 we list for all the benchmark points, except BP-3, the cross-sections for the four-lepton signal for the LHC running at a center of mass energy of 10 TeV, successively after the basic cuts (Cut-1), Cut-2 on the effective mass and Cut-3, i.e. the condition that the four-lepton invariant mass should be in a window of ±20 GeV around the mass of \( A_H \), see Eq. (17). The total SM background after Cut-2 and Cut-3 is also given. Note that for BP-3 with \( f = 500 \) GeV, the BR of \( A_H \) into \( ZZ^{(*)} \) is essentially zero, see Table 11 and therefore we have not included that benchmark point in the table.

Unfortunately, although the four-lepton signal cross-sections are larger than the SM background after Cut-2 for all the benchmark points considered in the table, there will be always less than 10 signal events for an integrated luminosity of 200 pb\(^{-1}\). Therefore we will not be able to see a clear \( A_H \) mass peak in the early stages of the LHC run.

#### 5.2.2 LHC with \( \sqrt{s} = 14 \text{ TeV} \)

The biggest SM background for the four-lepton signal comes again from \( ZZ + \) jets production. For the LHC running at \( \sqrt{s} = 14 \) TeV, the corresponding cross-section after the basic

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7 For details on a method to normalize the production rate of ZZ from data see Ref. [50].
Table 7: Four-lepton signal cross-sections (S) for $\sqrt{s} = 10$ TeV after the basic cuts (Cut-1), after Cut-2 and after Cut-3. For BP-3 there is no signal. The total SM background (BG) cross-section (mostly from ZZ) after Cut-2 and Cut-3 is also given. Note that we always demand that among the four leptons, there is always at least one OSSF lepton pair with its invariant mass being around ±20 GeV of $M_Z$. 

|       | Cut-1 S (fb) | Cut-2 S (fb) | Cut-2 BG (fb) | Cut-3 S (fb) | Cut-3 BG (fb) |
|-------|--------------|--------------|---------------|--------------|---------------|
| BP-1  | 21.70        | 6.45         | 0.14          | 1.53         | 0.003         |
| BP-2  | 1.21         | 1.07         | 0.14          | 0.19         | 0.003         |
| BP-4  | 1.34         | 1.26         | 0.14          | 0.33         | 0.010         |
| BP-5  | 0.23         | 0.23         | 0.14          | 0.02         | 0.003         |
| BP-6  | 0.18         | 0.18         | 0.14          | 0.04         | 0.010         |

cuts (Cut-1) is 18.79 fb. It is drastically reduced to 0.40 fb by the cut on the effective mass $M_{eff} \geq 1$ TeV. The second largest SM background is from $t\bar{t} +$ jets. After the basic cuts and the requirement that at least two OSSF leptons among the total four have an invariant mass around $M_Z$, it is 0.26 fb, but it is again completely removed by the effective mass cut.

In Fig. 4 we show the four-lepton invariant mass distributions for all the benchmark points, except BP-3, and the corresponding SM background for the LHC running at $\sqrt{s} = 14$ TeV after the basic cuts (Cut-1) and the cut of $M_{eff}$ (Cut-2).

As can be seen from Fig. 4 after the effective mass cut (Cut-2) the signal is larger than the SM background, except for BP-5 and BP-6. But for all benchmark points a clear peak emerges at the mass of $A_H$. Note that we do not observe any four-lepton events with an invariant mass of less than 100 GeV, which reflects the fact that we demand at least one OSSF lepton pair to have an invariant mass around $M_Z$.

In Table 8 we list for all the benchmark points, except BP-3, the cross-sections for the four-lepton signal for the LHC running at a center of mass energy of 14 TeV after the basic cuts (Cut-1), after Cut-2 on the effective mass and after Cut-3. The total SM background after Cut-2 and Cut-3 is also given. In addition, we give the number of events for an integrated luminosity of 30 fb$^{-1}$ after Cut-2 and after Cut-3.

We can see from the table that Cut-2, as for the dilepton signal, removes about half of the four-lepton events for BP-1, but this is compensated by the large parton-level cross section for $m_{\mu\mu} \sim 400$ GeV. The Cut-3 reduces the signal by a factor of six for BP-2, by a factor of four for BP-4 and by a factor of three for BP-1.

It is obvious that with essentially no background, we have a very clear signal and many events after Cut-3 for BP-1 and BP-4 with 30 fb$^{-1}$ of integrated luminosity. This should allow the reconstruction of the peak of the $A_H$ boson and the determination of the mass $M_{A_H}$. For BP-2 we have about 14 events after Cut-3, therefore the reconstruction of the peak might not be so precise.

Recall that from the dilepton signature, we had a significant signal over the background for BP-1 and BP-3 at $\sqrt{s} = 10$ TeV and with 200 pb$^{-1}$ of integrated luminosity. In addition,
Figure 4: Four-lepton invariant mass distribution for all the benchmark points, except BP-3, where we do not expect any signal, after the basic cuts (Cut-1) and after the cut on $M_{eff} \geq 1$ TeV (Cut-2) for $\sqrt{s} = 14$ TeV.

at $\sqrt{s} = 14$ TeV and with $30 \text{ fb}^{-1}$, we could also cover BP-2 and BP-5. Now, with four-lepton events, we get a very clear signal after Cut-3 for BP-4 (34 events compared to about 1 background event) and, for an integrated luminosity of about $59 \text{ fb}^{-1}$, we would get at least
Table 8: Same as Table 7 for $\sqrt{s} = 14$ TeV. The number of signal and background events after Cut-2 with an integrated luminosity of $30 \text{ fb}^{-1}$ are also given as $S_2$ and $B_2$, respectively. The corresponding numbers after Cut-3 are denoted by $S_3$ and $B_3$.

|       | Cut-1 $[S]$ (fb) | Cut-2 $[S]$ (fb) | Cut-2 $[BG]$ (fb) | $S_2$ | $B_2$ | Cut-3 $[S]$ (fb) | Cut-3 $[BG]$ (fb) | $S_3$ | $B_3$ |
|-------|-----------------|-----------------|-------------------|-------|-------|-----------------|-------------------|-------|-------|
| BP-1  | 58.85           | 28.80           | 0.40              | 864.0 | 12    | 9.18            | 0.01              | 275.4 | 0.3   |
| BP-2  | 3.12            | 2.89            | 0.40              | 86.7  | 12    | 0.47            | 0.01              | 14.1  | 0.3   |
| BP-4  | 4.25            | 4.02            | 0.40              | 120.6 | 12    | 1.12            | 0.03              | 33.6  | 0.9   |
| BP-5  | 0.79            | 0.79            | 0.40              | 23.7  | 12    | 0.10            | 0.01              | 3.0   | 0.3   |
| BP-6  | 0.67            | 0.66            | 0.40              | 19.8  | 12    | 0.17            | 0.03              | 5.1   | 0.9   |

10 signal events even for BP-6, with around 2 background events. Both of these benchmark points have $f = 1500$ GeV and the branching fraction $A_H \to ZZ$ is 22.5% and thus it is enhanced compared to BP-1 and BP-2, where for $f = 1000$ GeV it is only about 11%, see Table 1. This allows us to use the four-lepton signal for discovery for BP-4 and, maybe, BP-6.

Of course, it would be a convincing cross-check on the LHT model with T-parity violation, if one could see the $A_H$ peak in the dilepton and in the four-lepton channel at the same mass. At least for BP-1 and BP-2 this will be possible with the LHC running at 14 TeV and with $30 \text{ fb}^{-1}$. For BP-5, we would need $100 \text{ fb}^{-1}$ to get 10 four-lepton signal events after Cut-3. Note that other New Physics models which have such a $Z'$-type boson like the $A_H$ might lead to a different pattern in the invariant mass distributions or the relative number of events in the dilepton and four-lepton channels might be very different from the ones in the LHT.

As suggested in Ref. [21], looking at the angular distributions of the two lepton pairs coming from $ZZ$-decays, one might be able to determine whether the decay $A_H \to ZZ$ is really described by a vertex which originates from the WZW-term. At least for BP-1 with 275 four-lepton events after Cut-3, such an analysis seems to be feasible.

6 Summary and Conclusions

In this work we have analyzed dilepton and four-lepton events (here lepton means electron or muon) at the LHC originating from the decay of the heavy photon $A_H$ in the Littlest Higgs model with T-parity violation. These decays of $A_H$, assumed to be the lightest T-odd particle, are induced by T-violating couplings from the Wess-Zumino-Witten anomaly term.

Since the WZW term reproduces, within the EFT, the chiral anomalies in the UV completion of the LHT, its prefactor $N/48\pi^2$ corresponds to a one-loop effect. Furthermore, because of gauge invariance, the actual coupling of $A_H$ to SM gauge bosons has an additional suppression factor of $v^2/f^2$. For larger masses $M_{A_H} > 150$ GeV, $A_H$ predominantly decays into $WW^{(*)}$ and $ZZ^{(*)}$. On the other hand, for smaller masses, loop-induced decays into SM fermions are possible. The corresponding one-loop diagrams in the EFT are, however, UV divergent and one needs counterterms with a priori unknown coefficients. Following
Ref. [20] these coefficients have been fixed by naive dimensional analysis. The couplings of $A_H$ to SM fermions are then effectively of the size of two-loop effects. Due to the tiny coupling of $A_H$ to SM particles, its direct production at $e^+e^-$ or hadron colliders only has a cross-section of the order of $10^{-6}$ pb. On the other hand, the production of the other T-odd particles is not affected by the presence of the WZW term. Therefore, these particles are still pair-produced and cascade decay down to $A_H$ by the T-conserving interactions in the LHT and finally the two $A_H$’s decay promptly in the detector. The crucial observation, already made in Ref. [21], is that summing all production processes of heavy T-odd quark pairs leads to a sizeable cross-section at the LHC, of the order of several pb, and this corresponds to a lower bound on the production cross-section of $A_H$ pairs.

We have studied the dilepton and four-lepton signals for six benchmark points, see Table 2 which have different values for the heavy quark mass $m_{qH} \sim 400, 700, 1000$ GeV and different values for the mass of the heavy photon $M_{A_H} = 66, 150, 230$ GeV ($f = 500, 1000, 1500$ GeV). The values of the heavy quark mass essentially determine the parton-level pair-production cross-section via strong interaction processes, although the effects of electroweak contributions from $t$-channel exchanges of $A_H$ and $Z_H$ can be very important and even dominate for low values of $f$, i.e. light $A_H$ and $Z_H$. On the other hand, the mass of $A_H$ determines the expected signal because of the different branching ratios into leptons or $ZZ$, see Table 1. For low and intermediate masses of $A_H$, the dilepton decays are sizeable, whereas for $M_{A_H} = 230$ GeV the decay into $ZZ$ and then into four-leptons is relevant.

We have studied the case of the LHC running at a center of mass energy of $\sqrt{s} = 10$ TeV with a modest integrated luminosity of 200 pb$^{-1}$ and the case of $\sqrt{s} = 14$ TeV with an integrated luminosity of 30 fb$^{-1}$.

In order to reduce the SM background from $Z/\gamma^*$ and $t\bar{t}$ + jets for the dilepton signal and from $ZZ$ + jets for the four-lepton signal, we have imposed a large cut on the effective mass of the events of $M_{eff} > 1$ TeV, since in general $M_{eff}$ approximately peaks at the sum of the masses of the initially produced particles. Essentially, this cut removes a considerable fraction of the SM backgrounds, except for processes with multiple additional hard jets, which have a long tail in the effective mass distribution (see Figure 1). On the other hand, there are many sources of leptons in the decay cascades leading to $A_H$ and in general we also get many events with leptons which do not originate from the decay of $A_H$. We have reduced the corresponding background from within the LHT by imposing the condition that the invariant mass of dileptons or four leptons should lie in a window of ±20 GeV around $M_{A_H}$.

For the dilepton signal, the main conclusion is that for regions of the parameter space where either the T-odd quarks are relatively light, $m_{qH} \sim 400$ GeV (BP-1 with $f = 1000$ GeV) or the scale $f$ is rather low, $f = 500$ GeV (BP-3 with $m_{qH} \sim 700$ GeV), we get after all the cuts a clear signal above the background for the early run of the LHC with center of mass energy of 10 TeV and integrated luminosity of 200 pb$^{-1}$. More details can be found in Table 1. For the LHC with $\sqrt{s} = 14$ TeV and 30 fb$^{-1}$ luminosity, also BP-2 ($m_{qH} \sim 700$ GeV, $M_{A_H} = 150$ GeV) and BP-5 ($m_{qH} \sim 1000$ GeV, $M_{A_H} = 150$ GeV) yield a significant signal with $S/\sqrt{B} = 42.9$ for the former and $S/\sqrt{B} = 7.9$ for the latter benchmark point, see Table 3 for details.

The four-lepton channel is very clean and the signal cross-sections are larger than the SM backgrounds after all the cuts, with the exception of BP-3 with small $f = 500$ GeV,
where we do not expect a four-lepton signal. Unfortunately, for the LHC running at 10 TeV and with 200 pb$^{-1}$ of integrated luminosity, we always get less than 10 signal events. For $\sqrt{s} = 14$ TeV and 30 fb$^{-1}$, the background is again negligible ($< 0.9$ events) and we can easily cover again BP-1 and BP-2. In addition, we now also get a clear signal for BP-4 ($m_{q_H} \sim 700$ GeV, $M_{A_H} = 230$ GeV). We would need 59 fb$^{-1}$ to get 10 signal events for BP-6 ($m_{q_H} \sim 1000$ GeV, $M_{A_H} = 230$ GeV). Note that these BP’s with large $f = 1500$ GeV can only be covered in the four-lepton channel. Details can be found in Table 8.

Therefore, with the LHC running at 14 TeV and an integrated luminosity of 30 fb$^{-1}$, we can cover with the dilepton and/or the four-lepton signal a large part of the typical parameter space of the LHT with values of $f$ up to 1500 GeV and with T-odd quark masses up to about 1000 GeV. In general, a clear peak emerges at $M_{A_H}$, if one plots the invariant mass distributions for dileptons, see Fig. 2 for the LHC running at 10 TeV, and Fig. 3 for $\sqrt{s} = 14$ TeV. The four-lepton invariant mass distribution for the LHC at 14 TeV is shown in Fig. 4. For all the studied benchmark points we have enough signal events after all the cuts, therefore it should be easy to reconstruct the mass peak of $A_H$, maybe with the exception of BP-6.

Note that the reconstruction of the peak and the measurement of $M_{A_H}$ directly determines the symmetry breaking scale $f$ in the LHT, which is one of the fundamental parameters of any Little Higgs model. Together with the $M_{eff}$ distribution which peaks around $2m_{q_H}$, this would then allow a rough determination of the parameter $\kappa_q$ as well.

Of course, it would also be an important cross-check on the LHT model with T-parity violation, if we could see the $A_H$ peak in both the dilepton and the four-lepton channel at the same mass. This, including the ratio of events in the two channels, distinguishes the case of $A_H$ in the LHT from other models of New Physics, like most $Z'$ models. At least for benchmark points with intermediate values of $f = 1000$ GeV, which yield both enough dilepton and four-lepton events, this could be achieved. For BP-1 and BP-2 this will be possible for the LHC running at 14 TeV and with 30 fb$^{-1}$. For BP-5 we would need 100 fb$^{-1}$ to get 10 four-lepton events (with essentially very low background).

Finally, we should stress again that the WZW term offers a unique window into the UV completion of the LHT. The parameter $N$ determines the total decay width of $A_H$, but since the width is only a few eV, it cannot be measured experimentally. Furthermore, in the decay branching ratios, the factor $N$ drops out. On the other hand, the finite parts of the counterterms needed to renormalize the one-loop diagrams in the EFT are determined by the underlying theory. In principle, measuring the branching ratios of $A_H$ would therefore yield information on the more fundamental theory. As briefly discussed, if these branching ratios of the decays into leptons or quarks differ substantially from those of the $Z$-boson, one might even be able to see a signal from $A_H$ with a mass close to $M_Z$.

Note added. After this manuscript was first submitted, the LHC schedule was revised, targeting a run at 7 TeV with about $1 - 2$ fb$^{-1}$ luminosity, followed by a direct upgrade to 14 TeV. Since the 14 TeV run maximizes our reach in the parameter space, we have presented the results corresponding to this energy in detail. However, we have also retained the results for 10 TeV.
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