Discovering Heavy New Physics in Boosted Z Channels: $Z \to l^+l^-$ vs. $Z \to E_T$

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We propose a strategy for new physics searches in channels which contain a boosted $Z$ boson and a boosted massive jet in the final state. Our proposal exploits the previously overlooked advantages of boosted $Z \to \nu\bar{\nu}$ topologies, where collimated neutrinos result in signals with large missing energy. We illustrate the advantage of this channel in a case study of singly produced TeV scale charge $2/3$ fermionic top partners ($T'$) which decay to $t\bar{t}$ final states. A comparison with the di-leptonic channel reveals that, despite the large $t\bar{t}$ background, signals with missing energy combined with jet substructure techniques offer superior probes of new physics at TeV scales. The effect can be attributed to a factor of $\sim 3$ enhancement in the signal cross section, coming from the branching ratio of $Z \to \nu\bar{\nu}$. We exploit the unique event topology of singly produced top partners to suppress the $t\bar{t}$ background, as well as further improve on the existing proposals to detect $T'$ in the boosted di-lepton channel. Our conclusions on advantages of $Z \to \nu\bar{\nu}$ can be extended to most physics searches which utilize a boosted $Z$ boson in the final state.

New physics searches in channels containing a $Z$ boson in the final state are an important part of the LHC physics program, with $WZ$ and $hZ$ productions being some of the important probes of the Standard Model (SM). In the context of new physics searches, $Z$ boson production accompanied by a $h$, $W$ or top quark are also important. Such final states appear (for example) in the decays of charge $2/3$ vector-like top quark partners ($T'$), which emerge as generic features in many models that address the hierarchy problem within the framework of Naturalness [1–4].

At the dawn of LHC Run II, a natural question to ask is which of the $Z$ decay modes will be the most sensitive to new physics at the TeV scale? Conventional wisdom tells us that leptons offer clean signals with low backgrounds. For instance, $T'$ decaying into $t\bar{t}Z$ is a primary option for most experimental searches, where $Z$ decaying into di-leptons has so far been the most sensitive channel [5]. Recently, Ref. [6] also proposed a search strategy for singly produced $T'$ in a boosted di-lepton channel for Run II of the LHC. And while leptons are convenient final states, branching ratios of heavy SM states to leptons are usually small ($e.g.$ $\text{Br}(W \to l\nu) \approx 22\%$ and $\text{Br}(Z \to l^+l^-) \approx 6\%$), and there is always a lower limit on the signal production cross section (and hence an upper limit on the mass scale) which can be probed by leptons at fixed integrated luminosity.

In the initial stages of LHC Run II, it hence might be desirable to look for alternative search channels with larger signal cross section and reasonably small backgrounds, in order to improve the prospects of an early discovery. In this letter, we will show that $Z$ decaying to $E_T$ ($Z_{\text{inv}}$) accompanied by a boosted massive jet satisfies this criterion, when the mass scale of new physics is above 1 TeV.

The $Z_{\text{inv}}$ channel was not used in LHC Run I analyses, as exploration of the mass scales of $O(100)$ GeV focused on $Z$ events with low boost. The large angles between the neutrinos hence resulted in missing energy signals which were too low to be efficiently used for background discrimination. However, with a large enough boost of the $Z$, the $Z_{\text{inv}}$ channel becomes relevant for Run II. The utility of missing transverse energy has been discussed for the $VH$ production in a boosted regime [7] as well as the searches for Kaluza-Klein gravitons [8] in the $ZZ \to E_T l^+l^-$ channel. Here, we consider the $Zt$ channel where the top decays hadronically [25] and systematically compare the leptonic and the invisible $Z$ decay modes.

The core of our proposal is an observation of several important qualitative changes in the phenomenology of LHC Run II:

First, for mass scales $\gtrsim 1$ TeV, the SM decay products of heavy new particles become highly boosted. It follows that boosted $Z$s expected at Run II will decay into collimated neutrinos and hence large missing energy signatures ($i.e.$, in resonance searches one could expect signatures of $E_T \sim M_{\text{res}}/2$).

Second, standard jet reconstruction techniques and lepton isolations will not be adequate and tools of jet substructure and alternative lepton isolation variables will have to be employed.

Third, the boosted regime will be characterised by different efficiencies for reconstruction and tagging of the
t, Z, W, h decay channels. As a result, experimental sensitivity in different decay modes to new physics searches will change compared to Run I. At the same time, Standard Model backgrounds for signatures of very highly boosted objects (e.g. very high-pT jets, leptons, dileptons, large $E_T$, etc.) fall much faster than the signal, implying an altered background rejection power for the different channels.

$T'$ models are an excellent example of studies where the boosted $Z$ regime will be relevant in the future LHC runs. Past studies of ATLAS [9] and CMS [10] established bounds on mass of the vector-like top partners, excluding states with mass lighter than $700 - 800$ GeV (with the precise bound depending on the $T'$ branching fractions). The Run II of the LHC will thus probe the TeV mass range, where the boosted regime will become important. For concreteness, here we consider $T'$ single-production with subsequent $T' \to tZ$ decay for which the process shown in Fig. 1 yields the dominant contribution.

In the following, we show that considerations of $E_T$ signals greatly extend the ability of Run II of the LHC to discover possible new physics in the boosted $Z$ channel. Although we use $T'$ searches for the purpose of illustration, our main conclusion that at sufficiently high boost $Z_{inv}$ searches will outperform the $Zll$ searches is valid in a more general sense and qualitatively applies to many physics searches which utilise a boosted $Z$ boson in the final state.

**Sample Model and Event Simulations** – For the purpose of event simulation, we use the Minimal Composite Higgs Model with a partially composite top (c.f. Ref. [11] for the model Lagrangian, parameter definitions and the detailed derivation of the interactions.) In the singlet-partner-limit, the model contains only one light vector-like top partner: an $SU(2)_L$ singlet with charge 2/3. The top-partner sector of the model is described by the effective Lagrangian

$$\mathcal{L} \supset \bar{t}' (i\not{D} - M_1) \tilde{T} + \bar{q}_L i\not{D} q_L + t_R i\not{D} t_R$$

$$- \left( \lambda_{rf} \cos(h/f)t_R \tilde{t}_L - \frac{\lambda_{lf} \sin(h/f)}{\sqrt{2}} t_L \tilde{t}_R + \text{h.c.} \right),$$

where $\tilde{h} = v + h$, $f$ is the Higgs compositeness scale and $M_1$ is the singlet mass scale.

We consider only $T'$ production, which dominates over $T'$ pair production for high $M_T$ due to larger phase space. For exactly what mass single production becomes dominant is model dependent, but in many models this occurs around $M_{T'} \approx 1$ TeV for natural parameter choices (i.e. only slightly above the scale up to which Run I is sensitive).

The results of our analysis depend on $M_{T'}$ and $\sigma_{T'} = \sigma(pp \to T'/T' + X) \times BR(T' \to tZ)$, the production cross section of the $T'$ times the branching fraction of $T' \to tZ$ (provided that the width of $T'$ is small), while the dependence of event kinematics on specific model parameters is small enough to be neglected. In the following, we keep $M_{T'}$ and $\sigma_{T'}$ a free parameter, in order to maintain a minimum of model dependence.

We simulate signal and backgrounds with leading order Madgraph 5 [12] (using NNPDF2.3LO1 PDFs [13] interfaced with Pythia 6 [14] for parton showering and hadronization, while we conservatively assume a $k$-factor of 2 for all background channels. We match the background samples to extra jets using the 5 flavour MLM [15] matching scheme.

On parton level, we generate the events with simple generation level cuts on leptons ($p_T > 10$ GeV, $|\eta| < 2.5$, $\Delta R_{lj} > 0.1$ (0.4)) for the $Zll$ ($Z_{inv}$) channel and quarks ($p_T > 15$ GeV, $|\eta| < 5$, $\Delta R_{lj} > 0.1$). We then cluster the showered events using the FastJet [16] implementation of the anti-kT algorithm [17], where we use $R = 1.0$ for “fat jets”, $r = 0.4$ for the light and $b$-jets and $r = 0.2$ for forward jets.

The main backgrounds for the $E_T$ channel are SM processes containing a $Z$ boson in the final state, as well as the SM $tt$ production. The “$Z$-containing” backgrounds include $Z + t$, characterised by a true $Z$ and a top quark, where we include $Zt$ and $Zt/\tilde{t}$ (with up to two extra jets) into our simulation. Similarly, we define $Z + X$ background to be SM events which contain a $Z$ and “fake” (hadronic) top signal. In this class, we include $Z, Zbb, Z + Z/W$ with up to two additional jets. Finally, we include $tt$ background with up to two additional jets.

Di-lepton channels are afflicted by similar SM backgrounds, with the exception of $tt$ which is effectively vetoed by requiring two hard leptons which reconstruct a $Z$ mass, small missing energy.

$T'$ Search Strategy for LHC Run II – We choose the cut-schemes for the $T'$ search in $t+j+Z_{inv}$ and the $t+j+Zll$ channels to be identical for cuts focussed on the $t+j$ part of the event in order to allow for a fair comparison. As a part of the “basic cuts”, we demand at least one fat jet with $p_T^j > 400$ GeV (600 GeV) for the $M_T = 1$ TeV (1.5 TeV) searches with $|\eta_j| < 2.5$ as well as $p_T^j > 25$ GeV for light, $b$, and forward jets. For the $Z_{inv}$ channel, we furthermore require the absence of any isolated leptons...
TABLE I: Example-cutflow for signal- and background events in the $Z \rightarrow ll$ channel with $p_{T} > 25$ GeV for the $Z_{ll}$ channel we instead follow a modified prescription of Ref. [6], where we require at least two isolated leptons with $p_{T} > 25$ GeV. The two hardest leptons are then required to reconstruct a leptonic $Z$ boson candidate, and demand $p_{T} > 225$ GeV and $|\eta| < 2.3$. Finally, for the $Z_{ll}$-channel, we demand $\Delta R_{ll} < 1.0$ and $m_{ll}-m_{Z} < 10$ GeV.

For the purpose of top-identification we follow a procedure analogous to Ref. [11], based on the TemplateTagger v.1.0[19] implementation of the Template Overlap Method [20–23]. For a $R = 1.0$ jet to be tagged as a “top,” we demand a 3 body top template overlap score of $O_{\ell_{1}} > 0.6$. We require every fat jet which passes the top selection criteria to also be b-tagged, whereby we define a “fat jet b-tag” as presence of at least one b-tagged $r = 0.4$ jet within the fat jet ($\Delta R_{tb} < 1.0$). For the purpose of this analysis, we use b-tagging efficiencies of 75% for every b jet to be tagged as a b, with a fake rate of 18% and 1% for c and light jets respectively.

We further utilise the fact that the spectator light jet in the signal events is typically emitted at low $|\eta|$, a very special feature of singly produced $T^{\prime}$ event topology. For the purpose of “forward jet tagging” we re-cluster the events with a cone-radius $r = 0.2$ and demand at least one forward jet with $p_{T} > 25$ GeV and $2.5 < \eta < 4.5$ (see Ref. [11] for a discussion and evaluation of this forward-jet-tagging procedure).

In the $Z_{ll}$ channel, we impose a strong cut of $E_{T} > 400$ GeV (600 GeV) for the $MT_{\ell}=1$ TeV (1.5 TeV) search. The $t\bar{t}$ background of the invisible $Z$ channel can be further suppressed by demanding the reconstructed $E_{T}$ to be isolated from any hard jets by $|\Delta \phi_{E_{T},j}| > 1$.

Note that our event selection in the di-lepton channel differs from that of Ref. [6] in that we also incorporate improvements in the form of forward jet and b jet tagging into the analysis.

### Results

We show our first main result in the example cut-flow Table I. The sample signal cross sections given in the table correspond to the parameter point ($f = 780$ GeV, $M_{l_{1}} = 183$ GeV, $\lambda_{l_{1}} = 2.77, \lambda_{R} = 0.517$) for the 1 TeV partner search and ($f = 780$ GeV, $M_{l_{1}} = 1.31$ TeV, $\lambda_{l_{1}} = 3.11, \lambda_{R} = 0.710$) for the 1.5 TeV partner search. These parameter points yield a large production cross section within the model defined by Eq. (1), and can therefore be considered as optimistic scenarios in the searches for $T^{\prime}$ channels.

Our analysis shows that jet substructure techniques ($O_{\ell_{1}}$) in conjunction with fat jet b-tagging efficiently diminish background channels which do not contain top quarks (e.g. $Z + X$). For the $Z_{ll}$ search, the $E_{T}$ cut becomes a crucial discriminant, in particular for $t\bar{t}$ background, with the factor of $\sim 10$ ($\sim 20$) improvement in signal to background ratio ($S/B$) in the 1 TeV (1.5 TeV) search. Forward jet tagging provides a significant improvement in both, $Z_{ll}$ and $Z_{ll}$ channels, where we find a factor of $\sim 4$ improvement in $S/B$. Notice that for $M_{T_{\ell}} = 1$ TeV, the performance of the $Z_{ll}$ channel is comparable to $Z_{ll}$, in terms of signal significance ($S/\sqrt{B}$), with former yielding a larger signal cross section, but the latter giving a better $S/B$. If we go to higher masses,
such as $M_{T'} = 1.5$ TeV, Table II already suggests that the $Z_{\text{inv}}$ channel outperforms di-leptons.

To further illustrate the performance of the $Z_{\text{inv}}$ channel, we extend the results in Table I to more general $\sigma_T$ and integrated luminosity for a given $M_{T'}$. Fig. 2 illustrates the results in a more complete fashion. Results for the $Z_{\text{inv}}$ and $Z_{\ell\ell}$ searches are given in the top and bottom panel for $M_{T'} = 1$ TeV (left) and $M_{T'} = 1.5$ TeV (right). In each plot, the solid contours show $S/\sqrt{B}$, while the dotted lines show the number of signal events after cuts, as a function of luminosity and $\sigma_{T'}$. The shaded areas show regions where we expect $S/\sqrt{B} \geq 5$ and at least 10 signal events. Both the $Z_{\text{inv}}$ and the $Z_{\ell\ell}$ channels yield comparable discovery potential for top partners with masses of $\sim 1$ TeV, assuming efficient forward jet tagging from the previous section. For a luminosity of 35 fb$^{-1}$ (dashed horizontal line), optimistic cross sections of $\sigma_{T'} \gtrsim 140$ fb can be probed at $S/\sqrt{B} \geq 5$ with $N > 10$ signal events. A comparison of shaded areas in the left panels of Fig. 2 shows that the missing energy channel becomes important at $M_{T'} \sim 1$ TeV, where inclusion of the $Z_{\text{inv}}$ channel in this mass range would greatly complement the di-lepton searches.

Probing masses higher than 1 TeV, yields a different scenario, as shown in the right panels of Fig. 2 for the case of $M_{T'} = 1.5$ TeV. A partner of mass $M_{T'} = 1.5$ and an optimistic cross section $\sigma_{T'} = 24$ fb$^{-1}$ can be discovered in the $Z_{\text{inv}}$ channel with 100 fb$^{-1}$, whereas approximately 200 fb$^{-1}$ would be required in the $Z_{\ell\ell}$ channel to become sensitive to the same cross section. Considerations of lower signal cross section yield the same conclusion, as the $Z_{\text{inv}}$ channel gives both better sensitivity and a higher number of signal events at a fixed luminosity over the entire space of reasonable signal cross sections.

Conclusions – In this letter we discussed the LHC Run II potential to discover new heavy-physics in the boosted $Z + \text{jet}$ channel. As an illustration, we focused on $t + j + E_T$ and the $t + j + \ell\ell$ di-lepton search channels for a vector-like top partner $T'$ decaying into $tZ$ which occurs in a large class of SM extensions.

Our main conclusion is that future considerations of the $Z_{\text{inv}}$ channel in searches for new physics in the $Z + t, h, W$ channel will greatly extend the ability of the early LHC Run II to discover possible new particles at
the TeV scale. The di-lepton channel maintains competitive sensitivity for $M_{T'} \approx 1$ TeV, with a higher $S/B$ but lower signal cross section. The situation changes rapidly above 1 TeV. At $M_{T'} \approx 1.5$ TeV, we show that the $Z_{\text{inv}}$ channel displays clear superior performance in prospects for discovering the $T'$ states, with both larger signal significance and number of events. The di-lepton channel still remains important (especially in case of signal discovery), as the event reconstruction capability using leptons has an advantage over large missing energy, while the discovery reach can be further improved by combining the two channels. Furthermore, we show that the discovery potential can be substantially improved by demanding a high-energy forward-jet tagging in both $Z_{\text{inv}}$ and $Z_{tt}$ channels.

Our results are a direct consequence of the fact that for $M_{T'} \gtrsim 1$ TeV, kinematics of boosted $Z$ decays allow for efficient use of channels with high $E_T$. A high $E_T$ cut efficiently removes the $t\bar{t}$ background in the $t + E_T$ channel (with a weak effect on the signal), while addition of forward jet tagging into the analysis greatly improves the performance in both channels.

We base our conclusions on an example study of searches for charge 2/3 vector-like quarks, but the qualitative argument applies more broadly to new physics searches in channels containing a boosted $Z$ boson in the final state.

Effects of pileup contamination should be considered in future analyses, especially considering the high instantaneous luminosity expected for Run II. However, works of Refs. [11, 23] have already shown that effects of pileup on $E_T$ have a weak effect on the signal, while addition of forward jet tagging into the analysis greatly improves the performance in both channels.

We expect our conclusions to be robust even when considering high pileup levels.

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[25] This channel is more challenging than the previously discussed examples because the ATLAS Collaboration has no hard, isolated leptons in the final state and a potentially large background.
[26] We have confirmed that the signal efficiencies are mildly sensitive to variations of underlying model parameters (as long as $M_{T'}$ is kept fixed).