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Z' signals in polarised top-antitop final states at the LHC

Lorenzo Basso
Physikalisches Institut, Albert-Ludwigs-Universität Freiburg
E-mail: lorenzo.basso@physik.uni-freiburg.de

Ken Mimasu*
School of Physics & Astronomy, University of Southampton
E-mail: k.mimasu@soton.ac.uk

Stefano Moretti
School of Physics & Astronomy, University of Southampton
Particle Physics Department, Rutherford Appleton Laboratory
E-mail: s.moretti@soton.ac.uk

We study the sensitivity of top pair production at the Large Hadron Collider (LHC) to the nature of an underlying Z' boson, including full tree level standard model background effects and interferences while assuming realistic final state reconstruction efficiencies. We demonstrate that exploiting asymmetry observables represents a promising way to distinguish between a selection of benchmark Z' models due to their unique dependences on the chiral couplings of the new gauge boson.

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*Speaker.

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1. Introduction

Z' bosons are a ubiquitous feature of theories beyond the Standard Model (SM) arising from various BSM scenarios such as $U(1)$ gauge extensions of the SM motivated by supersymmetry or grand unified theories, Kaluza-Klein excitations of SM gauge fields or excitations of composite exotic vector mesons in technicolor theories to name a few.

Typically, such resonances are searched for at hadron colliders via the Drell-Yan (DY) production of a lepton pair, i.e., $pp(\bar{p}) \to (\gamma, Z, Z') \to \ell^+\ell^-$, where $\ell = e, \mu$. The Tevatron places limits on the Z' mass, $M_{Z'}$, at around 1 TeV [1] (for a sequential Z') while the latest LHC limits lie around 2.3 TeV [2] from this channel. Several phenomenological studies on how to measure the Z' properties and couplings to SM particles in this clean DY channel have been performed.

These proceedings summarise a recently published paper [3] addressing the use of the top-antitop final state, i.e., $pp(\bar{p}) \to (\gamma, Z, Z') \to t\bar{t}$, to probe these Z' properties. While it may not have as much 'discovery' scope as the DY channel, owing to the large QCD background combined with the complex six-body final state and the associated reconstruction efficiency, it remains important to extract the couplings of new physics to the top quark. Furthermore, the fact that the top decays before hadronising, transmitting spin information to its decay products, allows for the definition of spin asymmetry observables which provide an extra handle on Z' couplings not present in non-decaying final states.

We study the scope of the LHC to profile a Z' boson mediating $t\bar{t}$ production, in both standard kinematic variables as well as spatial/spin asymmetries, by adopting some benchmark scenarios for several realisations of the sequential, Left-Right symmetric and E_6 based Z' models (specifically, the same as those in [4]). Specifically, the issue of distinguishability of various models using these observables is addressed.

2. Asymmetries and Z' couplings

We define the asymmetry observables considered with the aim of determining their power to discriminate between Z's. We refer the reader to our paper for a more detailed discussion on these as well as the selection of benchmark models, statistical uncertainties and definitions of significance. This study investigated charge (spatial) and spin asymmetries and their dependence on top couplings to profile and distinguish the models considered.

A selection of charge asymmetry variables were investigated with the most sensitive found to be A_{RFB}, defined by the rapidity difference of the top and antitop, $\Delta y = |y_t| - |y_{\bar{t}}|$, while also cutting on the boost of the $t\bar{t}$ system. This increases the contribution from the $q\bar{q}$ initial state by probing regions of higher partonic momentum fraction, x, where its parton luminosity is more important:

$$A_{RFB} = \left. \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)} \right|_{|y_{t\bar{t}}| > |y_{t\bar{t}}^{cut}} . \tag{2.1}$$

The two spin asymmetries considered, termed double (LL) and single (L), are defined as follows:

$$A_{LL} = \frac{N(+,+) + N(-,-) - N(+,-) - N(-,+)}{N_{Total}} \quad ; \quad A_L = \frac{N(-,-) + N(-,+) - N(+,+) - N(+,-)}{N_{Total}} \tag{2.2}$$

where N denotes the number of observed events and its first(second) argument corresponds to the helicity of the top (anti)quark. These observables are alternatively known as the spin correlation and spin polarisation asymmetries respectively and can be extracted as coefficients in differential angular distributions of the top decay products.

Defining a generic neutral current interaction with the Feynman rule

$$i\gamma^{\mu}(g_V - g_A\gamma^5) \equiv i\gamma^{\mu}(P_L\, g_L + P_L\, g_R)\ , \tag{2.3}$$

we can calculate the dependence of the asymmetries in terms of its vector and axial couplings g_V and g_A or alternatively, the left and right handed couplings g_L and g_R. These were obtained using the helicity formulae from [6] in the case of the spin asymmetries (also derived independently with the guidance of [7]), where i and t denote the initial state and the top quark respectively:

$$\begin{aligned} A^i_{FB} &\propto g^i_V\, g^i_A\, g^t_V\, g^t_A \\ &\equiv \left((g^i_R)^2 - (g^i_L)^2\right)\left((g^t_R)^2 - (g^t_L)^2\right), \end{aligned} \tag{2.4}$$

$$\begin{aligned} A^i_{LL} &\propto \left((g^i_V)^2 + (g^i_A)^2\right)\left(3\,(g^t_A)^2\beta^2 + (g^t_V)^2(2+\beta^2)\right) \\ &\equiv \left((g^i_L)^2 + (g^i_R)^2\right)\left((g^t_L + g^t_R)^2 + 2\left((g^t_L)^2 - g^t_L g^t_R + (g^t_R)^2\right)\beta^2\right), \end{aligned} \tag{2.5}$$

$$\begin{aligned} A^i_{L} &\propto \left((g^i_V)^2 + (g^i_A)^2\right) g^t_A\, g^t_V\, \beta \\ &\equiv \left((g^i_R)^2 + (g^i_L)^2\right)\left((g^t_R)^2 - (g^t_L)^2\right), \end{aligned} \tag{2.6}$$

for a neutral gauge boson exchanged in the s-channel, with $\beta = \sqrt{1-4m_t^2/\hat{s}}$. The charge asymmetry depends on the product of the vector and axial couplings of both the initial and final state particle and can only be generated when all of these are non-vanishing. Alternatively it is a function of the relative magnitudes of their right and left handed couplings. For the spin asymmetries, A_{LL} depends on the couplings in a similar way to the total cross section becoming maximal in the limit $\beta \to 1$, while A_L is only non-vanishing for non-zero vector and axial couplings of the final state tops and is additionally sensitive to their relative sign. This is equivalent to measuring their relative handedness but only for the final state. Note that A_L allows for the direct measurement of this feature of the top couplings while this information is lost in the charge asymmetry due to the identical dependence on the initial state couplings.

With these unique coupling dependences, it is our aim to show that asymmetries can provide extra information to distinguish Z' models and ultimately contribute to extracting the couplings of an observed neutral resonance.

3. Results

We present a selection of results profiling the spatial and spin asymmetry distributions of the benchmark Z' models compared to the SM including interference effects. The set of benchmarks are split into two categories: those with a vanishing vector or axial coupling (the E_6 models with the 'B-L' generalised left-right symmetric model) are classed as the 'E_6' type while the rest, with both couplings non-zero, are referred to as the 'generalised' models. The variables described in section 2 were computed as a function of the $t\bar{t}$ invariant mass within $\Delta M_{t\bar{t}} = |M_{Z'} - M_{t\bar{t}}| < 500$ GeV and compared to the tree-level SM predictions. The code exploited for our study is based on helicity amplitudes, defined through the HELAS subroutines [8], and built up by means of MadGraph [9]. CTEQ6L1 [10] Parton Distribution Functions (PDFs) were used, with the factorisation/renormalisation scale at $Q = \mu = 2m_t$. VEGAS [11] was used for numerical integration.

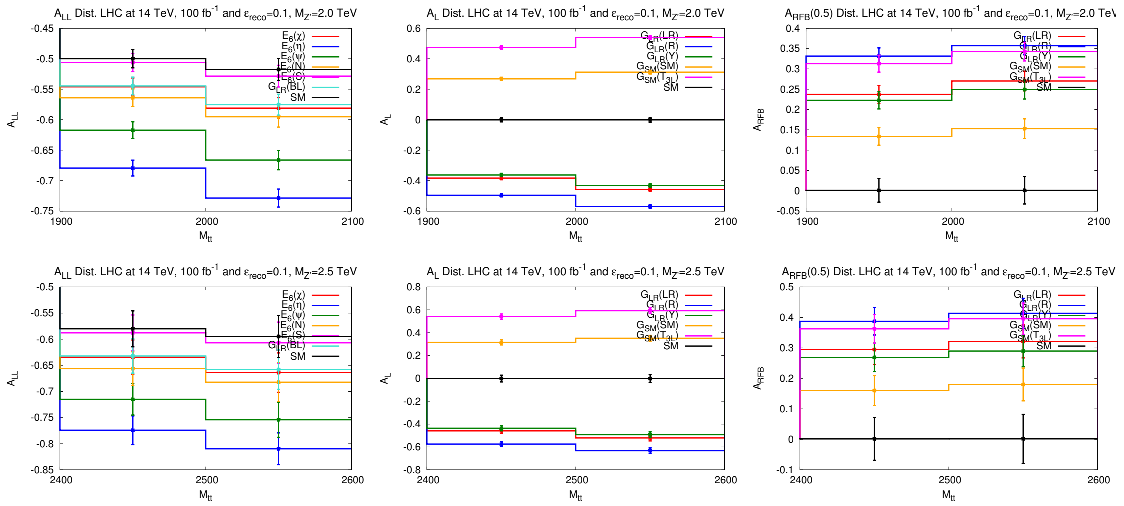

Figure 1: Upper[lower] plots show A_{LL} for the E_6-type models and A_L and $A_{RFB}(|y_{t\bar{t}}| > 0.5)$ for the generalised models binned in $M_{t\bar{t}}$ 100 GeV either side of $M_{Z'}$ =2[2.5] TeV for the LHC at 14 TeV assuming 100 fb^{-1} of integrated luminosity.

The plots shown in figure 1 of A_{LL}, A_L and A_{RFB} distributions are binned in 100 GeV either side of the Z' peak. They include statistical uncertainties and fold in an estimated 10% reconstruction efficiency of the $t\bar{t}$ pair assuming the use of all possible decay channels. Systematic uncertainties may also be important but would require a study beyond parton level. The figures show that the majority of benchmark models can be distinguished from one another using these variables, noting in particular the sensitivity of A_L to the relative sign of the vector and axial couplings which allows for a clear distinction between the G_{SM} (sequential) and G_{LR} (left-right symmetric) models in the 'generalised' category as described in equation (2.6).

A_{LL} depends on the couplings in the same way as the total cross section and therefore models that cannot be distinguished in the invariant mass spectrum will remain so in this observable. It is clear that A_L is the most powerful observable in that it provides the best distinguishing power along with the extra feature of being sensitive to the handedness of the top couplings. A_{RFB} provides some distinction but the handedness sensitivity is not present for reasons discussed in the previous section. Increasing the Z' mass increases the statistical uncertainties but also slightly raises the central values, both as a consequence of the lower SM background. Table 1 is an example of the statistical studies made where the significance of an observable (in this case A_L) is examined assuming 100 fb^{-1} of integrated luminosity. Here, the significance between various models is a measure of how well they can be distinguished. In almost all cases the significances are important, showing that this variable would certainly be effective in disentangling the 'generalised' models with the discrimi-

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nation decreasing slightly for higher masses. Although not shown in these proceedings, a similar statistical analysis was performed in determining how much integrated luminosity would be required to achieve a significance of 3σ between models in the various observables. We showed that in most cases, the models can be distinguished at the relatively early stages of the LHC (~ 100 fb^{-1} at 14 TeV) even for the higher mass of 2.5 TeV. The cases where this is not possible reflect mostly instances where the couplings are too similar and would be difficult to disentangle.

A_L	SM	$GLR(LR)$	$GLR(R)$	$GLR(Y)$	$GSM(SM)$	$GSM(T_{3L})$
SM	–	31.9(11.1)	40.6(18.3)	30.1(11.2)	22.1(9.8)	38.7(22.5)
$GLR(LR)$	16.9(7.7)	–	10.0(6.6)	2.0(0.1)	62.2(21.7)	81.3(34.5)
$GLR(R)$	21.3(11.5)	4.6(4.0)	–	12.0(6.5)	72.2(30.4)	91.3(44.1)
$GLR(Y)$	16.3(7.8)	1.0(0.1)	5.8(3.9)	–	60.2(21.8)	79.3(34.6)
$GSM(SM)$	11.8(6.3)	33.1(14.8)	38.8(18.8)	33.0(14.9)	–	19.1(13.7)
$GSM(T_{3L})$	20.1(13.9)	42.5(23.0)	48.5(27.2)	42.7(23.2)	9.7(7.8)	–

Table 1: Significance for A_L values around the Z' peak of generalised models, for the LHC at 14 TeV only. Upper triangle for $M_{Z'} = 2.0$ TeV and lower triangle for $M_{Z'}$=2.5 TeV. Figures refer to $\Delta M_{t\bar{t}} < 100(500)$ GeV.

4. Conclusion

We have presented an overview of a phenomenological study on classes of Z' models in both spin and spatial asymmetries of $t\bar{t}$ production and showed that there is much scope to observe deviations from the SM and even distinguish between various models, particularly for spin asymmetries. This suggests that the $t\bar{t}$ channel would certainly be a useful complement to the more popular DY channel in the aim of profiling a Z' resonance should one be observed in the near future.

It is worth noting that the classes of models studied are benchmarks put forward to set bounds on Z' masses best probed in the di-lepton channels. Other models could be better suited to the $t\bar{t}$ channel, such as leptophobic/top-phillic Z's occurring in composite/multi-site and extra-dimensional models. The profiling techniques discussed in this study would be increasingly more applicable in these scenarios.

Finally, although not addressed in the paper to which these proceedings refer, one can ask whether more can be done in profiling an observed resonance with the view of extracting its fermionic couplings. A previous study attempting to do this in the light lepton sector [12] finds a degeneracy in determining the quark and lepton couplings which can be solved by considering asymmetries in an alternate final state. In a more recent paper [13], we show that asymmetry observables in the $t\bar{t}$ provide independent information which would break this degeneracy and allow for a fit to all couplings in the 'minimal' framework of 5 independent couplings used in many benchmarks.

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