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Exclusion and discovery via Drell-Yan in the 4DCHM

Juri Fiaschi*
School of Physics & Astronomy, University of Southampton
E-mail: juri.fiaschi@soton.ac.uk

Elena Accomando
School of Physics & Astronomy, University of Southampton
E-mail: e.accomando@soton.ac.uk

Daniele Barducci
LAPTh, Université Savoie Mont Blanc
E-mail: daniele.barducci@lapth.cnrs.fr

Stefania De Curtis
INFN, Sezione di Firenze, and Dept. of Physics and Astronomy, University of Florence
E-mail: decurtis@fi.infn.it

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

Claire H. Shepherd-Themistocleous
Particle Physics Department, Rutherford Appleton Laboratory
E-mail: claire.shepherd@stfc.ac.uk

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Searches for Z' bosons are most sensitive in the dilepton channels at hadron colliders. Whilst finite width and interference effects do affect the modifications the presence of BSM physics makes to Standard Model (SM) contributions, generic searches are often designed to minimize these. The experimental approach adopted works well in the case of popular models that predict a single and narrow Z' boson allowing these effects to effectively be neglected. Conversely, finite width and interference effects may have to be taken into account in experimental analyses when such Z' states are wide or where several states are predicted. We explore the consequences of these effects in the 4-Dimensional Composite Higgs Model (4DCHM) which includes multiple new Z' bosons and where the decays of these resonances to non-SM fermions can result in large widths.

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*Speaker.

1. Introduction

Extra neutral massive gauge bosons, or Z's, are a common feature of Beyond the Standard Model (BSM) scenarios which can arise from general extensions of the Standard Model (SM) gauge group motivated by Grand Unified Theories (GUTs), Kaluza Klein (KK) excitations of SM gauge fields in models of extra dimensions, models of compositeness and some variants of Supersymmetric models to name but a few (see Ref. [1, 2] and references therein). Typically, such objects are searched for via Drell-Yan (DY) production into two leptons: $pp(\bar{p}) \to \gamma, Z, Z' \to \ell^+\ell^-$, where $\ell = e, \mu$, representing an ideal signature for these objects, owing to its substantial even rate, cleanliness and achievable precision.

The latest LHC limits of relevance here placed on a variety of Z' models are those obtained at around 2.5 TeV by CMS [3], with $\sqrt{\hat{s}} = 7, 8$ TeV data and full luminosity. Such limits are extracted by searching for a resonance (so-called 'bump search') in the invariant mass distribution of di-lepton events. These searches made the assumption that any resonance is narrow where the width of a Breit-Wigner (BW) used to model the signal is much smaller than the detector resolution. The results obtained may be interpreted in a variety of models where the resonance widths are consistent with this assumption. It was observed in [4, 5] that, by defining a cross section to be within a particular mass window ($|M_{ll} - M_{Z'}| \leq 0.05\ E_{\rm LHC}$ where $E_{\rm LHC}$ is the collider energy) around any such resonance, the cross sections for a wide variety of models correspond to those predicted by the NWA. By taking this approach the difference between a full cross section calculation including model dependent finite width (FW) and interference effects is kept to within $O(10\%)$. This procedure allows FW and interference effects to be treated in a consistent way and retains the advantages intrinsic to the NWA approach, through which model independent limits on the cross section are derived and in turn can be interpreted as constraints on the mass of the actual Z' pertaining to a specific model (i.e., the model dependence is only contained in the di-lepton BRs of the assumed Z').

All the above studies were performed in the case of single Z' models. The purpose of this paper is to analyze the above phenomenology in the case of scenarios with multiple Z's. In this case further challenges appear, as, in several well-motivated theoretical models, such Z' states can be quite close in mass and mix with each other. In this case the two such resonances may be close and wide enough to appear as a broad single resonance and they may interfere strongly with each other. The consequence of this is that standard approach to searching for a signal resonance does not model the deviation from SM expectations very well.

The content of our work is as follows. In Section II we introduce the multi-Z' model used as benchmark and present its phenomenology, a 4-Dimensional Composite Higgs Model (4DCHM), wherein three Z's are active in the DY process. In Section III we consider the case of a single Z' contribution and we compare the exclusion/discovery limits computed under NWA with the same obtained including FW and interference effects. In Section IV we discuss the case of the complete model, that is when multiple Z's are active and interfering (between themselves and with the SM). Finally in Section V we summarize and conclude.

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2. The 4DCHM

The recently presented 4DCHM of [6] is a scenario where the Higgs Boson arises as a pseudo Nambu-Goldstone Boson (pNGB) from the spontaneous breaking of a symmetry G to a subgroup H with the addition of the mechanism of partial compositeness. A minimal choice in the fermionic sector that can give rise to a finite Higgs potential, computable with the Coleman-Weinberg technique, is assumed. The main characteristic of this model is the presence of a large number of heavy spin-1 resonances, due to the extra gauge symmetry $SO(5) \otimes U(1)_X$, and new spin-1/2 ones.

In the 4DCHM we in fact have the following extra gauge and matter content (alongside SM states and the Higgs boson): 5 spin-1 neutral resonances, that are Z'; 3 spin-1 charged resonances, that are W'; 10 spin-1/2 with charge $2/3$ resonances, that are t'; 10 spin-1/2 with charge $-1/3$ resonances, that are b'; 2 spin-1/2 with charge $5/3$ resonances, that are T'; 2 spin-1/2 with charge $-4/3$ resonances, that are B'.

In particular, the masses of the gauge resonances are of order of fg_* for the three lightest neutral and the two lightest charged and of $\sqrt{2}fg_*$ for the two heaviest neutral and for the heaviest charged ones, where f is the strong sector (compositeness) scale of the model ($\simeq$ 1 TeV) and g_* is the common gauge coupling of $SO(5)$ and $U(1)_X$. The widths of these extra resonances are strongly dependent on the masses of the extra fermions: we can have a regime where the masses of the new fermions are too heavy to allow for the decay of a Z' and/or W' in a pair of heavy fermions, such that the widths of the heavy gauge bosons are small, typically well below 100 GeV, and we can have the opposite configuration where the widths of the heavy gauge bosons can become comparable with the masses themselves (when the extra fermions are light enough).

For the purpose of a DY analysis we have only three active Z' because Z_1 and Z_4 (that are the first and the fourth neutral gauge resonance in mass ordering) do not couple to the first two generations of quarks and leptons.

3. Limitations of the NWA

We now consider the direct production via DY of a Z' boson in the 4DCHM framework. Of the three active Z' states, to start with, we neglect the Z_2 and Z_5 states, this in order to establish a baseline for comparison with single Z' scenarios. Under this assumption we compare the results computed under NWA to those obtained following the inclusion of FW and interference effects.

The first thing to note is how interference effects modify the position of the resonance peak. In fig. 1 we show this effect for one point in the parameter space of the model. In this case the peak is shifted from the resonant mass pole by about 14 GeV, but there are regions in the parameter space of the model where the shift can grow up to 40-50 GeV.

In fig. 2a we show the deviations from the NWA results, as a function of the resonance width. In this particular case the cross sections are obtained by integrating from 2 TeV to effectively infinity. This means that we have not included a large part of the negative interference contribution stemming from the low mass region. Significant deviations from the NWA model are observed (dotted line compared with the dashed line) and can in general be larger if cross sections are integrated over all masses even leading to an overall signal cross section that is negative. This demonstrates that inclusion of FW and/or interference effects results in a non-trivial modification of the inte-

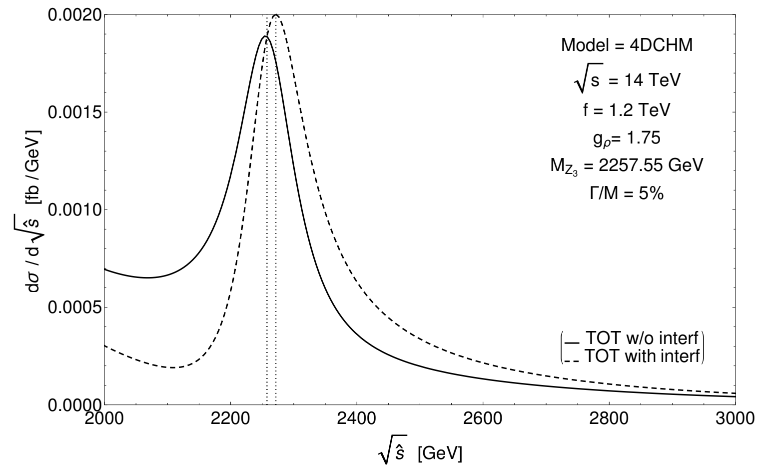

Figure 1: Differential cross section distribution for a particular configuration of the parameter in the 4DCHM where only the Z_3 boson is active. In the solid line we include the FW effects, in the dashed line we include both FW and interference effects. The two vertical dashed lines represent the position of the peak in the two cases.

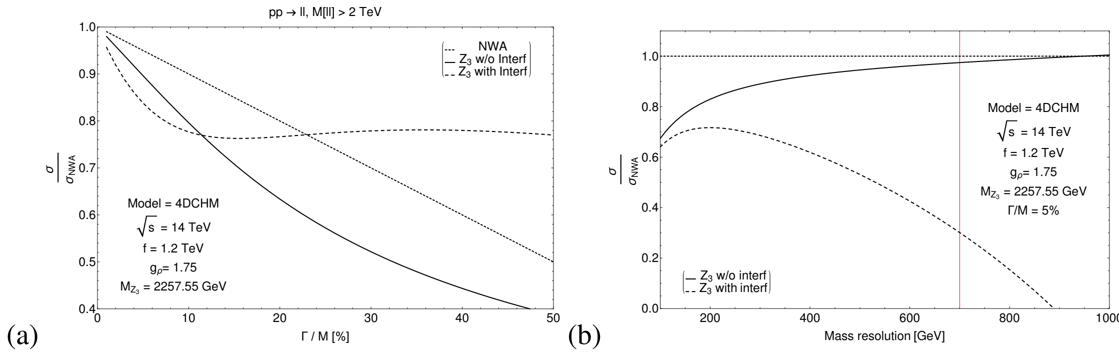

Figure 2: Ratio of the integrated cross section for the signal of a Z_3 boson in the 4DCHM over the NWA result. The dotted line is the Z_3 in NWA result, the solid line is the Z_3 contribution including FW effects and the dashed line is the Z_3 contribution including both FW and interference effects. (a) We start the integration at 2 TeV and the result is plotted as a function of the resonance width over its mass (in percentage). (b) We plot the integrated cross section as a function of the symmetric integration interval around the peak. The vertical red line represents the CMS adopted optimal cut which keeps the interference and FW effects below the 10% in the case of narrow single Z' models [4].

grated cross section that cannot be accounted for by a simple rescaling of the NWA results, nor do are there cancellations between FW and interference effects leading to anything close to the NWA results. This is in contrast to [7] where such effects are claimed to negligible.

The 4DCHM is indeed dominated by interference effects. This makes this scenario a representative example of a large variety of Z' models that share this particular feature like Extra Dimensional models [8, 9] and the recently published Custodial Vector Model [10]. Large negative contributions to the signal cross section coming from the interference in the region just below the resonance pole appear in many single Z' scenarios and can be particularly large in models with multiple Z' resonances. In these cases using the NWA is inappropriate, potentially leading to

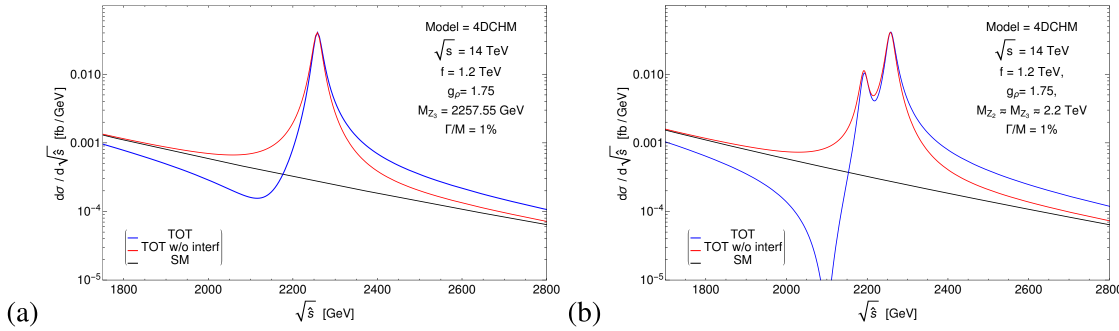

Figure 3: Cross section distribution for a specific point in the parameter space of the 4DCHM. (a) We have considered only the Z_3 contribution and its interference with the SM background. (b) The complete model is considered with the inclusion of the Z_2 boson exchange as well as its interference with the SM background and with the Z_3 boson.

significant overestimations of the cross section that may be observed in experiments.

The deviations from the naive NWA application with respect to the consistent inclusion of FW and interference effects are summarized in fig. 2b. Here we plot these differences as a function of the integrating region around the Z' peak (that is integrating $\pm$ the quoted mass resolution around the resonance pole).

The red solid vertical line represents the integration region (suggested in [4]) adopted by CMS in order to keep the FW and interference effects below 10% in the case of narrow single Z' models. Clearly, for the 4DCHM this prescription breaks down and we obtain substantial deviations from the NWA predictions. Moreover, the picture becomes even worse as we increase the resonance width. Again, scenarios where the (partially) integrated signal cross section turns negative are not uncommon.

4. Results for the complete 4DCHM

Here we consider the complete 4DCHM where the Z_2 contribution is also included, together with the Z_3. The other active resonance, the Z_5, as already mentioned, is much heavier and thus difficult to produce, ultimately giving a negligible contribution to the cross section distribution in the invariant mass region we are interested in (around the Z_2 and Z_3 poles). For these reasons and for ease of computation, here, we neglect the Z_5 resonance.

In fig. 3 we compare the cross section distribution in the case of the single Z_3 boson (a) and of the complete 4DCHM (b). As in the previous section the negative contribution below the resonance peak coming from the interference term spoils the NWA result: while already visible in the case of the single Z_3 boson, it is even more evident in the complete 4DCHM.

Thus all the conclusions presented in the previous section are also valid in the case of the complete model, where the deviations from the naive NWA approach are even more remarkable. In order to show these effects in the multi-Z' scenario, in fig. 4 we have repeated the exercise of the previous section, plotting the integrated cross section as a function of the integration interval.

Last thing to mention is about the double peak structure that we expect in the complete model case. In the particular example we examine here the double peak structure is clearly visible at

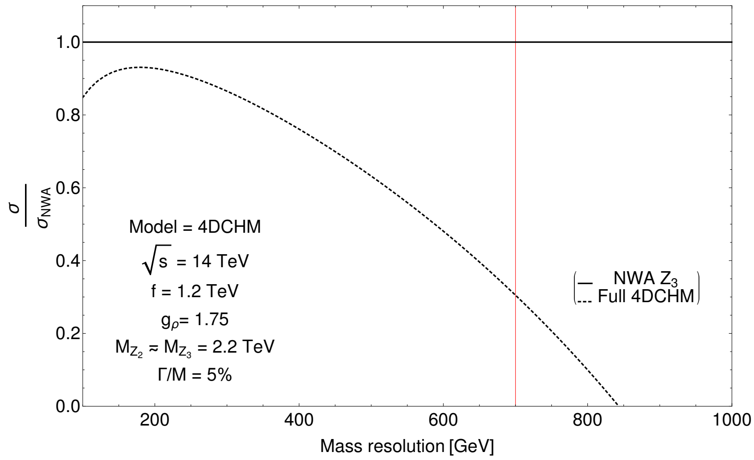

Figure 4: Ratio of the integrated cross section in the full 4DCHM scenario over the NWA result as a function of the symmetric integration interval around the peak. The vertical red line represent the CMS adopted optimal cut which keeps the interference and FW effects below 10% in the case of narrow single Z' models [4].

least before any detector resolutions are applied. Unfortunately this conclusion is not valid over the entirety of the model parameter space. The two resonances Z_2 and Z_3 can be very close in mass and it is therefore often very difficult to separate them, especially as their widths increase.

5. Conclusions

We have explored the phenomenology of the 4DCHM which is a realistic and representative example of the class of multi-Z' scenarios. We have examined the consequences of large interference effects which are not included in the NWA prescription and make this approach invalid, even in the case where we only consider the dominant resonant contribution, which comes from the Z_3 boson. When we consider the complete model, that is, also including the contribution of the Z_2 boson as well as its interference (the other active resonance, the Z_5, can be neglected as much heavier), the picture gets even worse in terms of NWA validity. The total cross section is significantly overestimated by the NWA approach. Any experimental interpretation of observations in the context of this type of model should take this dynamics into account and appropriately adapt the methodologies used.

We have also seen that FW effects can be sizable, since there are regions in the parameter space of the 4DCHM where the neutral resonances can become very broad, due to the opening of new decay channels into extra fermions. These features are quite common in models with multiple-Z', therefore it may be difficult to extract realistic bounds on a specific model using NWA assumptions. These drawbacks have been overlooked in several phenomenological analyses.

In summary, we have here reviewed the main effects which ought to be taken into account in search analyses for multi-Z' scenarios. These are the FW and interference effects, which generally manifest themselves as a substantial (negative) dip below the usual Z' peak(s). We expect this dynamics to be common to generic Composite Higgs Models.

Finite Width and Interference effects have already been taken into account by the CMS collaboration in a sophisticated and dedicated way for the W'-boson search at the LHC [11 – 13]. The analysis of the LHC data at 8 TeV has shown that the extracted limits on the W' mass have changed sizeably. We suggest that a similar approach should be adopted for the multi-Z' search in Run II.

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