Complementarity of Forward-Backward Asymmetry for discovery of Z' bosons at the Large Hadron Collider

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

Alexander Belyaev

School of Physics & Astronomy, University of Southampton
E-mail: a.belyaev@soton.ac.uk

Ken Mimasu

School of Physics & Astronomy, University of Sussex
E-mail: k.mimasu@sussex.ac.uk

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

The Forward-Backward Asymmetry (AFB) in Z' physics is commonly only perceived as the observable which possibly allows one to interpret a Z' signal by distinguishing different models of such (heavy) spin-1 bosons. In this article, we examine the potential of AFB in setting bounds on or even discovering a Z' at the Large Hadron Collider (LHC) and show that it might be a powerful tool for this purpose. We analyse two different scenarios: Z's with a narrow and wide width, respectively. We find that in both cases AFB can complement the conventional searches in accessing Z' signals.

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[*]Speaker.

1. Introduction

Extra gauge bosons are present in many Beyond Standard Model (BSM) theories. From a phenomenological point of view, the simplest case is an extra $U(1)$ symmetry group in addition to the SM group. Using this approach we can study the three main classes of models that predict a Z': E_6, Generalized Left-Right (*GLR*) symmetric and Generalized Standard Model (*GSM*) [1]. All these scenarios predict rather narrow Z's ($\Gamma_{Z'}/M_{Z'} \sim 0.5 - 12\%$).

Experimental searches optimized for such narrow resonances assume a very visible peak with a Breit-Wigner line-shape over the SM background, when looking at the invariant mass of the Z' decay products. On the basis of this assumption, the 95% Confidence Level (C.L.) upper bound on the cross section is derived and limits on the mass of the resonance are extracted within the above benchmark models. Theoretical cross section predictions are mostly calculated in the Narrow Width Approximation (NWA), although occasionally include Finite Width (FW) and interference effects. Putting an appropriate cut on in the invariant mass spectrum, those contribution can be kept under control (below 10%) in a model independent way [2].

However, there exist many scenarios where the NWA is not valid. Technicolor, Composite Higgs Models scenarios where the Z' couples differently to the first two fermion generations with respect to the third one or where the new gauge sector mixes with the SM neutral one are all frameworks where wide Z's are possible. Here, the ratio $\Gamma_{Z'}/M_{Z'}$ can reach 50% or more.

Experimental searches studying these "effectively" non-resonant cases are essentially counting experiments: an integration over the overall invariant mass spectrum beyond the control region seeks an excess of events spread over the SM background. The analysis, even if improved using optimized kinematical cuts, still maintains some fragile aspects as it relies on the good understanding of the SM background. Indeed the BSM signal might non-trivially interfere with the latter, affecting the Z' decay products invariant mass distribution also in the low mass region. For this reason the detection of a wide resonance turns out to be quite problematic.

In this article we study the effects of the inclusion of another observable into the analysis of heavy neutral resonances: the Forward-Backward Asymmetry (AFB). We explore the complementary potential of AFB with respect to the "bump" or "counting experiment" searches in both the narrow and broad Z' framework, respectively. Note that, in current literature, this observable is usually adopted as a post-discovery tool to interpret the experimental evidence of a peaked signal and to possibly disentangle between different theoretical models that would predict it. Our purpose is to show that AFB can be used not only for interpreting a possible discovery but also in the very same search process (see Ref. [3]). We focus on the golden channel for Z' discovery search at the LHC, *i.e.*, the Drell-Yan (DY) process $pp \to l^+l^-$ with $l = e, \mu$.

The article is organized as follows. In sect. 2 we derive current and projected bounds for Z' model benchmarks for the LHC at 7, 8 and 13 TeV. In sect. 3 we discuss the role of AFB in the context of either narrow or wide resonance searches. In sect. 4 we summarize and conclude.

2. Bounds on the Z' mass

In order to validate our analysis we reproduced current experimental limits obtained by, *e.g.*, the CMS collaboration after the 7 and 8 TeV runs with about 20 fb^{-1} of luminosity [6]. These lim-

Class	E_6					
$U'(1)$ Models	χ	ϕ	η	S	I	N
$M_{Z'}$ [GeV]	2700	2560	2620	2640	2600	2570
Class	GLR				GSM		
$U'(1)$ Models	R	$B-L$	LR	Y	SSM	T_{3L}	Q
$M_{Z'}$ [GeV]	3040	2950	2765	3260	2900	3135	3720

Table 1: Bounds on the Z' mass we have derived from the latest direct searches data performed by CMS at the 7 and 8 TeV LHC with integrated luminosity $\mathscr{L} = 20\,fb^{-1}$. They are in good agreement with the latest CMS published results [6].

Class	E_6					
$U'(1)$ Models	χ	ϕ	η	S	I	N
$M_{Z'}$ [GeV]	4535	4270	4385	4405	4325	4290
$M_{Z'}$ [GeV]	5330	5150	5275	5150	5055	5125
Class	GLR				GSM		
$U'(1)$ Models	R	$B-L$	LR	Y	SSM	T_{3L}	Q
$M_{Z'}$ [GeV]	5175	5005	4655	5585	4950	5340	6360
$M_{Z'}$ [GeV]	6020	5855	5495	6435	5750	6180	8835

Table 2: Projection of discovery limits (first row) and exclusion limits (second row) on the Z' mass from direct searches at the forthcoming Run II of the LHC at 13 TeV. We assume $\mathscr{L} = 300\ fb^{-1}$.

its are computed through the ratio $R_\sigma = \sigma(pp \to Z' \to l^+l^-)/\sigma(pp \to Z, \gamma \to l^+l^-)$. Here R_σ has been calculated at the Next-to-Next-to-Leading Order (NNLO) in QCD. The resulting exclusion limits we compute include FW and interference effects. The values we obtain are summarized in Tab. 2: they match the reported limits by CMS for the benchmark models $GSM - SSM$ and $E_6 - \chi$ within the accuracy of 1-2 %. These models with extra $U(1)$ symmetry group indeed predict intrinsically narrow Z's, and in this context we expect interference effects to be small. This is why we have been able to match CMS results with great precision even though their results are calculated with NWA.

After having verified the reliability of our code, we have been able to project future discovery and exclusion limits for the next run of the LHC at 13 TeV and with a luminosity of 300 fb^{-1}. In both cases we have taken into account the published acceptance $\times$ efficiency corrections and a Poisson statistic approach has been used for computing the significance of the signal. Requiring for the latter a significance of 2 for exclusion and of 5 for discovery, we obtain the results summarized in Tab. 2. It is worth to stress that the significances we are computing here are purely statistical and they do not include systematic uncertainties.

3. The role of AFB in Z' searches: narrow and wide heavy resonances

We define A^*_{FB} as follows:

$$\frac{d\sigma}{d\cos\theta^*_l} \propto \sum_{spin,col} \left| \sum_i \mathscr{M}_i \right|^2 = \frac{\hat{s}^2}{3} \sum_{i,j} |P^*_i P_j|[(1 + \cos^2\theta^*_l)C^{ij}_S + 2\cos\theta^*_l C^{ij}_A] \qquad (3.1)$$

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where θ_l^* is the lepton angle with respect to the quark direction in the di-lepton Centre-of-Mass (CM) frame, which can be derived from the measured four-momenta of the di-lepton system in the laboratory frame. The AFB is indeed given by the coefficient of the contribution to the angular distribution linear in $\cos\theta_l^*$. In Eq. (3.1), $\sqrt{\hat{s}}$ is the invariant mass of the di-lepton system and P_i and P_j are the propagators of the gauge bosons involved in the process. At the tree-level, DY production of charged lepton pairs is mediated by three gauge bosons: the SM photon and Z-boson and the hypothetical Z′. These three vector boson exchanges all participate in the matrix element squared. The interferences amongst these three particles have to be take into account properly. Finally, the factors C_S^{ij} and C_A^{ij} in the angular distribution given in Eq. (3.1) are the parity symmetric and anti-symmetric coefficients which are functions of the chiral quark and lepton couplings, $q_{L/R}^i$ and $e_{L/R}^i$, to the i-boson with $i = \{\gamma, Z, Z'\}$:

$$C_S^{ij} = (q_L^i q_L^j + q_R^i q_R^j)(e_L^i e_L^j + e_R^i e_R^j), \quad C_A^{ij} = (q_L^i q_L^j - q_R^i q_R^j)(e_L^i e_L^j - e_R^i e_R^j). \quad (3.2)$$

Looking at these expressions it is clear that the analysis of AFB can give us complementary information with respect to the cross section distribution (which is proportional to the sum of the squared chiral couplings) about the couplings between the Z′ and the fermions. This feature has motivated several authors to study the potential of AFB in interpreting a possible Z′ discovery obtained in the usual cross section hunt.

The AFB is obtained by integrating the lepton angular distribution forward and backward with respect to the quark direction. As in pp collisions the original quark direction is not known, one has to extract it from the kinematics of the di-lepton system. In this analysis, we follow the criteria of Ref. [7] and simulate the quark direction from the boost of the di-lepton system with respect to the beam axis (z-axis).

In the following we are going to show the impact of AFB on the significance of the signal. For this purpose we give the general definition of significance α for a generic observable:

$$\alpha = \frac{|O_1 - O_2|}{\sqrt{\delta O_1^2 + \delta O_2^2}}, \quad (3.3)$$

where the O_is ($i = 1, 2$) are the value of the observable in two hypothesis scenarios with uncertainty δO_i. In the case of AFB we will use the statistical uncertainty:

$$\delta A_{FB} = \sqrt{\frac{4}{\mathscr{L}} \frac{\sigma_F \sigma_B}{(\sigma_F + \sigma_B)^3}} = \sqrt{\frac{(1 - A_{FB}^2)}{\sigma \mathscr{L}}} = \sqrt{\frac{(1 - A_{FB}^2)}{N}}, \quad (3.4)$$

where $\mathscr{L}$ is the integrated luminosity and N the total number of events. Since the significance is proportional to the root of the total number of events, the imposition of a stringent cut on the boost variable, $y_{l\bar{l}}$, in spite of guiding the AFB spectrum towards its true line shape, will decrease the statistics and, by consequence, the resulting significance of the signal.

For this reason in the following we are not going to impose any rapidity cut and we are going to show how AFB can be used also as a powerful tool to search for new physics.

3.1 Narrow heavy resonances

We start comparing the shape of the AFB distribution as a function of the di-lepton invariant mass $\sqrt{\hat{s}}$ with the differential cross section distribution. We are showing here the cases of the $E_6 - S$ model (Fig. 1).
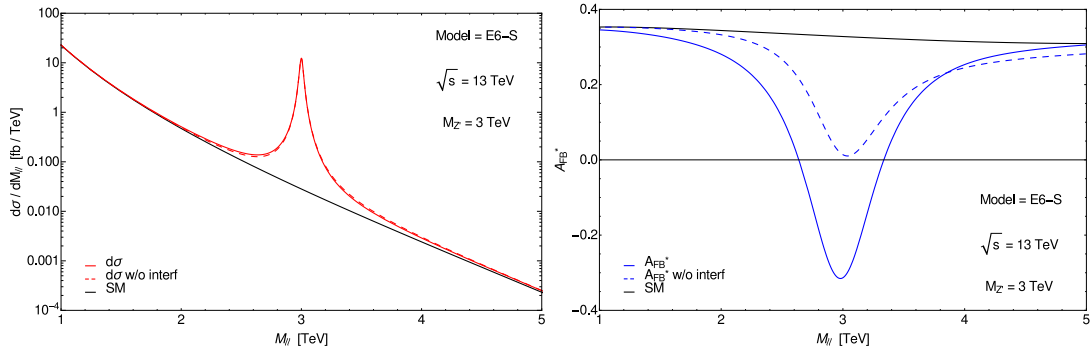
Figure 1: Hypothetic signal in the cross section (Left) and A_{FB}^* (Right) distributions produced by a Z' with mass $M_{Z'} = 3$ TeV, as predicted by the $E_6 - S$ model, at the LHC at $\sqrt{s} = 13$ TeV. No cut on the di-lepton rapidity is imposed: $|y_{l\bar{l}}| \geq 0$.

As one can see, the role played by the interference is extremely important. In this case for instance the AFB peak is strongly accentuated by interference effects. In contrast, the cross section distribution is almost interference free if the $|M_{l\bar{l}} - M_{Z'}| \leq 0.05 \times E_{\text{LHC}}$ cut is imposed. In interpreting the experimental data coming from AFB measurements instead it is mandatory to include the interference independently on any kinematical cut.
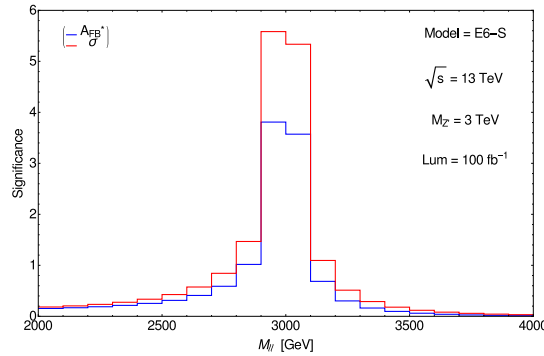
Figure 2: Binned significance of an hypothetic signal produced by a Z' with mass $M_{Z'} = 3$ TeV, as predicted by the $E_6 - S$ model, at the LHC at $\sqrt{s} = 13$ TeV and $\mathscr{L} = 100 fb^{-1}$, for the two observables: cross section and A_{FB}^*.

In terms of significance of the signal (Fig. 2), in the $E_6 - S$ case we find that what we get from the cross section is comparable with what we get from the A_{FB}^* observable. This means that it can be used as a valid alternative as the AFB observable is very reliable in terms of systematic uncertainties: since it comes from the ratio of cross sections, strong cancellations happen between the uncertainties on the forward and backward cross sections, upon taking into account their mutual correlations.

3.2 Wide heavy resonances

Here, we discuss the role of A_{FB}^* in searches for a new Z' characterized by a large width. Such a heavy and wide particle is predicted by various models, like strongly interacting models or non-universal models. Here we will consider an example of the latter, well described in the literature

[4, 5]. The large parameter space of the model allows to explore the phenomenology of a wide Z' boson. Indeed we are going to consider the case in which the Z' is more coupled with the fermions third generation, resulting in a quite large resonance width, and at the same time satisfying current exclusion limits due to the weaker coupling with electrons and muons.

In this case, the invariant mass distribution of the two final state leptons does not show a resonant (or peaking) structure around the physical mass of the Z' standing sharply over a smooth background, but just a broad shoulder spread over the SM background. This result is plotted in Fig. 3, where we consider a Z' with mass $M_{Z'} = 5.5$ TeV and width $\Gamma_{Z'}/M_{Z'} = 20\%$. The line shape of the resonance is not well defined but the shape of the A^*_{FB} distribution could help to interpret a possible excess of events. The peak in the AFB distribution is very shifted to lower invariant mass region with respect to the Z' pole. In terms of significance of the signal, this is translated into an interval with a high significance in the low invariant mass region (Fig. 4), that appears much before the cross section positive contribution.
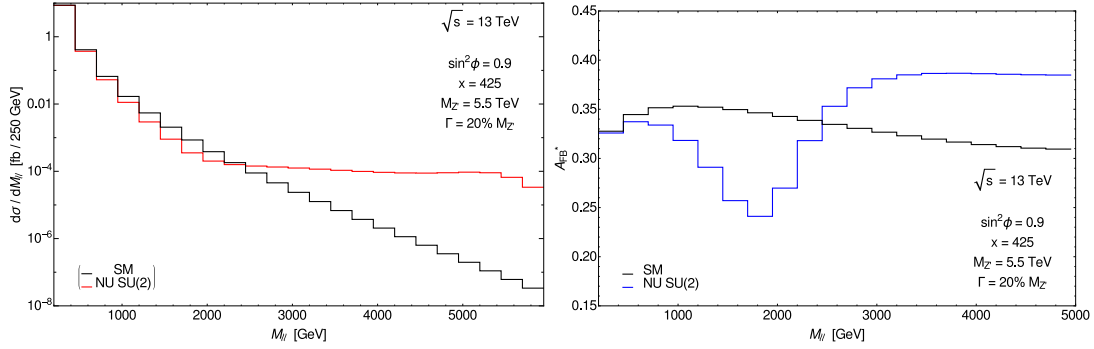
Figure 3: Binned differential cross section (Left) and A^*_{FB} (Right) distributions as a function of the di-lepton invariant mass as predicted by a Non-Universal $SU(2)$ model for a Z' with mass $M_{Z'} = 5.5$ TeV and $\Gamma_{Z'}/M_{Z'} = 20\%$. The results are for the LHC at $\sqrt{s} = 13$ TeV and no rapidity cuts are applied.
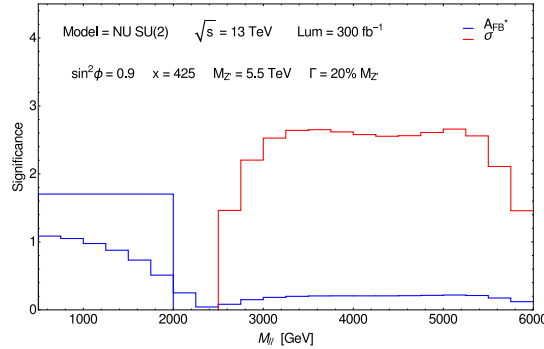
Figure 4: Binned significance for the Non-Universal $SU(2)$ model with a Z' with mass $M_{Z'} = 5.5$ TeV and $\Gamma_{Z'}/M_{Z'} = 20\%$. The results are for the LHC at $\sqrt{s} = 13$ TeV and $\mathscr{L} = 300 fb^{-1}$, for the two observables: cross section and A^*_{FB}.

The experimental method based on the counting experiment is based on the assumption that the control region is new physics free. But this might not the case for wide Z's. In these scenarios, the interference between the extra Z' and the SM γ, Z can be sizable enough to invade the control

region. If not correctly interpreted, these interference effects could induce an underestimation of the SM background with the consequence of overestimating the extracted mass bounds. Having all these uncertainties to deal with, the support of a second observable like AFB is crucial for wide Z' searches.

4. Conclusions

In this paper we have considered the scope of using AFB in Z' searches at the LHC in the neutral DY channel. Such a variable has traditionally been used for diagnostic purposes in presence of a potential signal previously established through a standard resonance search via the cross section. However, based on the observation that it is affected by systematics less than cross sections, we have studied the possibility of using AFB as a search tool for a variety of Z' models, E_6, *GLR*, *GSM*, embedding either a narrow or wide resonance. The focus was on determining whether such a resonance could be sufficiently wide and/or weakly coupled such that an usual peak search may not fully identify it and, further, whether the AFB could then provide a signal of comparable or higher significance to complement or even surpass the scope of more traditional analyses.

We have found promising results. In the case of narrow width Z's, we have proven that the significance of AFB based searches can be comparable with the usual bump search. In the case of wide Z', the AFB search could have again a comparable sensitivity to the cross section studies thanks to a more peculiar line-shape. Furthermore, we have emphasized the fact that the AFB distribution mapped in di-lepton invariant mass can present features amenable to experimental investigation not only in the peak region but also significantly away from the latter. In essence, here, AFB in specific regions of the invariant mass of the reconstructed Z' could be sensitive to broad resonances much more than the cross section, wherein the broad distribution of the signal seemingly merges with the background.

References

[1] E. Accomando, A. Belyaev, L. Fedeli, S.F. King, C. Shepherd-Themistocleous, *Z' physics with early LHC data*, *Phys. Rev.* (D83) 075012 2011 [`hep-ph/1010.6058`].

[2] E. Accomando, D. Becciolini, A. Belyaev, S. Moretti, C. Shepherd-Themistocleous, *Z' at the LHC: Interference and Finite Width Effects in Drell-Yan*, *JHEP* (1310) 153 2013 [`hep-ph/1304.6700`].

[3] E. Accomando, A. Belyaev, J. Fiaschi, K. Mimasu, S. Moretti, C. Shepherd-Themistocleous, *Forward-Backward Asymmetry as a Discovery Tool for Z' Bosons at the LHC*, [`hep-ph/1503.02672`].

[4] E. Malkawi, C.P. Yuan, *New physics in the third family and its effect on low-energy data*, *Phys. Rev.* (D61) 015007 2000 [`hep-ph/9906215`].

[5] Y.G. Kim, K.Y. Lee, *Direct search for heavy gauge bosons at the LHC in the nonuniversal SU(2) model*, *Phys. Rev.* (D90) 117702 2014 [`hep-ph/1405.7762`].

[6] CMS Collaboration, *Search for physics beyond the standard model in di-lepton mass spectra in proton-proton collisions at $\sqrt{s}$ = 8 TeV*, *CMS-EXO-12-061* 2014 [`hep-ex/1412.6302`].

[7] M. Dittmar, *Neutral current interference in the TeV region: The Experimental sensitivity at the LHC*, *Phys. Rev.* (D55) 161-166 1997 [`hep-ph/9606002`].