PROCEEDINGS OF SCIENCE

Forward-Backward Asymmetry and Z' searches via Drell-Yan at the LHC

Elena Accomando[∗†]
School of Physics and Astronomy, University of Southampton
E-mail: e.accomando@soton.ac.uk

Alexander Belyaev
School of Physics and Astronomy, University of Southampton
E-mail: s.moretti@soton.ac.uk

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

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

Stefano Moretti
School of Physics and 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 di-lepton final states provide the greatest sensitivity in searches for Z'-bosons at the Large Hadron Collider (LHC). These additional neutral bosons are predicted by many theories. From a phenomenological point of view, they can be divided into two classes: narrow width and wide Z's. The experimental collaborations at the LHC have searched for narrow width Z'-bosons via the measurement of the di-lepton invariant mass. Wide scenarios have not yet been considered. Exclusion limits on the narrow-width Z'-boson mass have been determined using the data collected at centre-of-mass energies of $\sqrt{s}$ = 7, 8 TeV by the LHC experiments corresponding to integrated luminosities of approximately $\mathscr{L} \simeq 20 fb^{-1}$ for each experiment.

Here, we discuss the possibility of using an additional observable to complement the usual di-lepton invariant mass in order to maximize the LHC potential in searching for Z'-bosons. The observable we consider is the Forward-Backward Asymmetry (AFB). This variable is commonly proposed as a tool to be used for interpreting data and discriminating between different models in the event of a prior Z' observation. We propose that the AFB is also useful as an observable in the Z' search process.

The XXIII International Workshop on Deep Inelastic Scattering and Related Subjects
April 27 - May 1, 2015
Southern Methodist University
Dallas, Texas 75275

PoS(DIS2015)097

1. Introduction

Drell-Yan (DY) processes, giving rise to lepton pairs in the final state, are very powerful for discovering or bounding new physics involving heavy spin-1 gauge bosons. Several scenarios predict such exotic particles (for a review see Refs. [1, 2]). These models are particularly relevant now as the LHC has already accumulated $\mathscr{L} \simeq 20 fb^{-1}$ per experiment at the 7, 8 TeV Run I, and is now probing higher energies with much larger project luminosities. We thus address the search for extra Z's at the LHC. Our proposal is to use the Forward Backward Asymmetry (AFB) as a variable in search analyses, where a bump is being sought. This observable, traditionally proposed as a useful tool in the interpretation of data after a Z' discovery, could actually play a major role at the search stage. This is what we propose in the following. In Sec. 2, we review the present bounds on the Z'-boson mass derived from direct searches at the 7, 8 TeV LHC Run I, and we summarize both discovery and exclusion projections at the current Run II. In Sec. 3, we discuss the role of the AFB in interpreting the data giving an update of the optimal cuts to be used for this purpose. In Sec. 4, we present our proposal of promoting the AFB to be a primary variable alongside the cross section itself in the Z'-boson search. We summarize our findings in the conclusions.

2. Search strategies and exclusion limits on the Z'-boson mass

State-of-the-art of calculations and tools for DY processes at the LHC now includes computations at Next-to-Leading (NLO) and Next-to-leading-log (NLL). At NLO QCD, mass scale dependent K-factors are often included in the experimental analyses via different Monte Carlo Event Generators [3, 4]. A dedicated NLO + NLL computation has been recently performed in Ref. [5]. Also ElectroWeak (EW) radiative corrections can become sizeable at the energy scales, namely TeV, we are probing now. They can be of the same order of the QCD corrections, depending on the jet veto imposed. Recent implementations (see Ref. [6] and references therein) combine both the NLO EW and QED multiple photon corrections with the "default" NLO and Parton Shower QCD contributions, in order to provide the most accurate result.

As for the LO evaluation, recent progress has been made in taking into account Finite Width (FW) effects and interference between New Physics signal and SM background. Over the last few years interest has increased in these effects. They have been shown to be qualitatively and quantitatively important in many different environments like Higgs Physics [7, 8] and both W' [9] and Z'-boson searches [10, 11]. Following these theoretical studies, first attempts at dealing with FW and interference issues have been made in the experimental analyses at the LHC. The interference can be sizeable and model dependent, so different strategies are adopted. In the Z'-boson search, following the recipe from [10], CMS interprets results by defining cross sections within a di-lepton mass range of $|M_{ll} - M_{Z'}| \leq 0.05\ \ E_{LHC}$ where $E_{\rm LHC}$ is the collider energy. This definition is designed such that the error in neglecting the (model-dependent) Finite Width and interference effects (between γ, Z, Z') is kept below $O(10\%)$ for all models and for the full range of allowed Z' masses. This procedure allows for the consistent treatment of FW and interference

*Speaker.

†The speaker is very grateful to the Organizing committee for the invitation and the wonderful hospitality. This research is supported in part through the NExT Institute.

Class	E_6						GLR				GSM
$U'(1)$	χ	ψ	η	S	I	N	R	$B-L$	LR	Y	SM
$M_{Z'}$ [GeV]	2700	2560	2620	2640	2600	2570	3040	2950	2765	3260	2900
$M_{Z'}$ [GeV]	4535	4270	4385	4405	4325	4290	5175	5005	4655	5585	4905
$M_{Z'}$ [GeV]	5330	5150	5275	5150	5055	5125	6020	5855	5495	6435	5750

Table 1: The first row summarizes the bounds on the Z'-boson mass derived from the latest direct searches performed by CMS at the 7, 8 TeV LHC Run I with integrated luminosity $\mathscr{L} \simeq 20 fb^{-1}$. The second and last row present the projection of discovery and exclusion limits, respectively, from direct searches at the LHC Run II at 13 TeV with project luminosity $\mathscr{L} = 300 fb^{-1}$. From left to right, the columns indicate the $M_{Z'}$ limit in GeV within the E_6, GLR and GSM class of models.

effects whilst taking advantage of the useful properties of the Narrow Width Approximation (NWA) where the model dependence is only contained in the di-lepton BRs of the assumed Z'. In this way model independent limits on the cross section are derived and in turn they can be interpreted as constraints on the mass of the actual Z' for any specific model.

The CMS experiment has derived Z' mass bounds at the 7, 8 TeV LHC Run I [12]. These limits are summarized in the first row of Table 1. They have been used to validate our code which we then employed to project the limits to the current LHC Run II at 13TeV. The projections for discovery and exclusion are shown in the second and last row of Table 1. It is thus clear that the search window at Run II for the models explored during Run I is: 2.5 TeV $\leq M_{Z'} \leq$ 6.5 TeV. Over the next two years, the collected luminosity will be $\mathscr{L} \simeq 30 fb^{-1}$. At this rather low luminosity, one could aim at a 3σ effect, which would not provide grounds for claiming a discovery of a Z'-boson. With increasing the luminosity, the significance would increase, but the error on the Parton Distribution Functions (PDFs) could spoil the theoretical interpretation of any experimental excess found in the data. A great deal of effort is now being dedicated to the improvement of the knowledge of PDFs at large-x. Nevertheless, our finding is that the AFB could provide valuable additional evidence of a Z'-boson and we summarize this in the next two sections.

3. AFB as a tool for data interpretation

The Forward Backward Asymmetry is traditionally proposed as a tool for distinguishing between different Z' models once the discovery of a Z'-boson has been claimed using di-lepton spectra. A number of papers present the AFB along these lines (see for instance Refs. [13, 14, 15]). The AFB is defined as the difference between forward and backward cross sections, with respect to the initial quark direction, normalized to the total cross section:

$$A_{FB} = \frac{d\hat{\sigma}_F - d\hat{\sigma}_B}{d\hat{\sigma}_F + d\hat{\sigma}_B}. \tag{3.1}$$

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 our analysis, we follow the criteria of Ref. [16] and estimate the quark direction by making use of the boost of the di-lepton system with respect to the beam axis

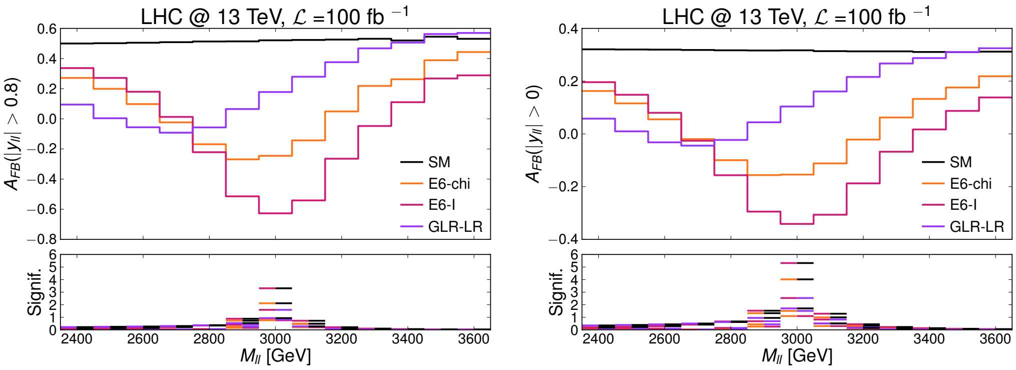

Figure 1: Left: Reconstructed A^*_{FB} as a function of the di-lepton invariant mass as predicted by the SM (black), the $E_6(\chi)$ (orange), the $E_6(I)$ (magenta) and the $GLR-LR$ (purple) models for a 3 TeV Z'-boson. The results are for the 13 TeV LHC with $\mathscr{L} = 100 fb^{-1}$. No cut on the di-lepton rapidity is imposed: $|y_{l\bar{l}}| \geq 0$. Lower plot: Significance in distinguishing models. Right: Same as left plot with $|y_{l\bar{l}}| \geq 0.8$.

(z-axis). As a measure of the boost, we define the di-lepton rapidity

$$y_{l\bar{l}} = \frac{1}{2} \ln \left[\frac{\mathrm{E}+\mathrm{P_z}}{\mathrm{E}-\mathrm{P_z}} \right] \tag{3.2}$$

where E and P_z are the energy and the longitudinal momentum of the di-lepton system, respectively. We identify the quark direction through the sign of $y_{l\bar{l}}$. In this way, one can define the reconstructed AFB, from now on called A^*_{FB}. As the AFB reconstruction procedure relies on the correlation between the boost variable, $y_{l\bar{l}}$, and the direction of the incoming valence quark, it is therefore more likely to pick up the true direction of the quark for higher values of $y_{l\bar{l}}$. Increasing the probability of identifying the direction of the quark would lead to an observed value of A^*_{FB} that is closer to the 'true' AFB value if one were able to access the partonic CM frame. The trade-off occurs in the reduction of statistics which impacts the significances the other way. The statistical uncertainty on the AFB is given by

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

where $\mathscr{L}$ is the integrated luminosity and N the total number of events. One can thus see that the significance is proportional to the root of the total number of events. Imposing a stringent cut on $y_{l\bar{l}}$ would then improve the A^*_{FB} pushing it towards its true line shape, but it will decrease the statistics. In this subtle balance between line shape gain and statistics loss, our finding is that it is better to abandon the cut $y_{l\bar{l}} \geq$ 0.5-0.8 proposed in the literature up to now. This cut was appropriate for $M_{Z'} \leq$1.8 TeV. At energy scales above 2.5 TeV which will be analysed at Run II, in order to maximize the significance, the di-lepton rapidity cut should be zero [17]. This is shown in Fig. 1 where we present the power of the A^*_{FB} in discriminating between different $U'(1)$ models, comparing the old cut $y_{l\bar{l}} \geq 0.8$ with the newly proposed setup $y_{l\bar{l}} \geq 0$.

4. AFB as a tool for the Z'-boson search in DY

The AFB is the observable where the effects of the interference between new physics and SM background are maximal. For this reason, the AFB is an intrinsically model dependent variable and

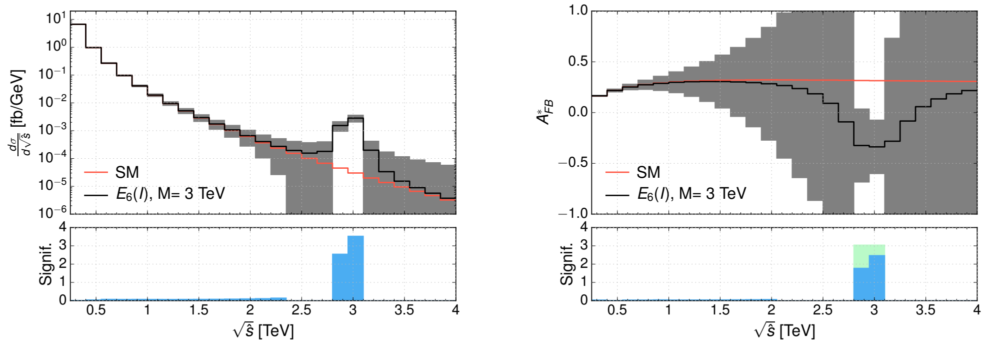

Figure 2: Left: Binned differential cross section as a function of the di-lepton invariant mass as predicted by the $E_6(I)$ model for a 3 TeV Z'-boson. Error bars are included. Right: Binned A^*_{FB} as a function of the di-lepton invariant mass as predicted by the $E_6(I)$ model for a 3 TeV Z'. Error bars are included. Both results are for the 13 TeV LHC with $\mathscr{L} = 30 fb^{-1}$. CMS acceptance cuts are imposed. In the lower plots, the blue histogram shows the significance bin by bin. The green area in the bottom right plot indicates the total significance integrated over that invariant mass range.

in the literature has therefore traditionally been considered to be useful for disentangling different Z' models. Its role has therefore been confined so far to the interpretation of a possible Z' discovery obtained via the default search for a narrow resonance. In Ref. [17], we show that the A^*_{FB} is also useful for searches alongside the cross section itself. Within particular $U'(1)$ models, the true AFB can give rise to a significance much larger than that found using the resonant peak in a mass spectrum alone. The reconstruction of the AFB reduces the significance, but nonetheless the significance remains sizeable. An example of such a model occurs in the E_6 class of theories and it is called $E_6(I)$. For this representative model, even for integrated luminosities of $\mathscr{L} = 30 fb^{-1}$ the AFB significance can be comparable to that found using the cross section from a binned mass distribution. This is illustrated in Fig. 2, where we compare the di-lepton invariant mass distribution to the A^*_{FB} for a 3 TeV Z'-boson. In this case, the evidence of new physics from the bump search alone would be insufficent to demonstrate the presence of a new Z'. But, it could be reinforced by a further comparable evidence in the independent variable A^*_{FB}, leading to a much more robust result.

Even after the objective of an integrated luminosity of $\mathscr{L} = 300 fb^{-1}$ is achieved for the current LHC Run II, the AFB may provide additional evidence of new physics and be very useful in the interpretation of the origin of this new physics. The reason now is the PDF's uncertainty which will dominate the theoretical error on the prediction of a new Z'-boson appearing as a resonant peak in the di-lepton invariant mass distribution. One of the methods for computing the PDF's error makes use of the Hessian formalism [18]. For Hessian PDF sets, both a central set and error sets are given. For the CTEQ6.6 PDF that we use, the number of error sets (twice the number of the eigenvectors) is equal to 40. Defining $X_i^{\pm}$ the value of the variable using the PDF error set corresponding to the "$\pm$" direction for the eigenvector i, the symmetric error on the variable X is given by:

$$\Delta X = \frac{1}{2}\sqrt{\sum_{i=1}^{N} |X_i^+ - X_i^-|^2}. \tag{4.1}$$

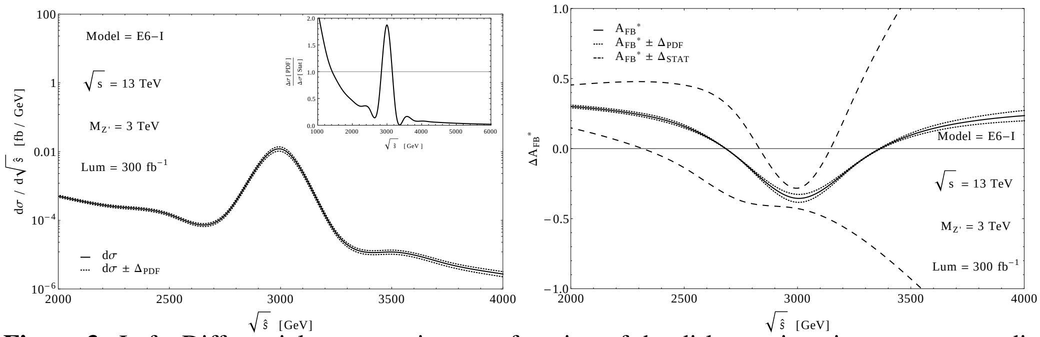

Figure 3: Left: Differential cross section as a function of the di-lepton invariant mass as predicted by the $E_6(I)$ model for a 3 TeV Z'-boson. The results are for the 13 TeV LHC with $\mathscr{L} = 300 fb^{-1}$. The solid line shows the central value, the dotted line the PDF uncertainty. The inset plot displays the ratio between PDF and statistical errors. Right: A^*_{FB} as a function of the di-lepton invariant mass as predicted by the $E_6(I)$ model for a 3 TeV Z'-boson. The results are for the 13 TeV LHC with $\mathscr{L} = 300 fb^{-1}$. The dotted lines show the PDF error band, while the dashed lines define the statistical error band.

To compute the PDF uncertainty for the differential cross section, we apply Eq. 4.1 directly. For the AFB, the computation is slightly more involved. We consider as independent variables the forward and backward (differential) cross sections: σ_F and σ_B. The PDF degrees of freedom of these two observables are correlated, that is the quantity

$$\cos\phi = \frac{1}{4\Delta\sigma_F\Delta\sigma_B}\sum_{i=1}^{N}(\sigma_{F_i}^{+} - \sigma_{F_i}^{-})(\sigma_{B_i}^{+} - \sigma_{B_i}^{-}) \tag{4.2}$$

is equal to 1. Under this condition, by applying the error chain rule, we get

$$\Delta A^*_{FB} = \frac{1}{2}(1 - {A^*_{FB}}^2)\left|\frac{\Delta\sigma_F}{\sigma_F} - \frac{\Delta\sigma_B}{\sigma_B}\right|. \tag{4.3}$$

The sign appearing in the above formula is crucial for the A^*_{FB}. It indeed clearly shows that there is a partial cancellation of the PDF's error on this observable due to the fact that it is a ratio of (differential) cross sections. Compared to the differential cross section, A^*_{FB} is then more robust against PDF's uncertainties. This is shown in Fig. 3 where we compare the effect of PDF and statistical errors on the shape of the di-lepton invariant mass distribution and of the A^*_{FB} for the reference model $E_6(I)$.

As one can see, if we naively summed up the statistical and PDF's systematic errors linearly, the theoretical error on the binned cross section on peak would sizably increase while the uncertainty on A^*_{FB} would remain almost unaltered. To be more quantitative, if we take Fig. 2 and rescale the significances by a factor $\sqrt{10}$ we get the results at $\mathscr{L} = 300 fb^{-1}$. There, owing to the decreased statistical error, we have an a priori significance $S \simeq 12$ around the peak of the binned cross section which would allow to claim for a new physics discovery. However, the total theoretical error does not improve much with $\mathscr{L}$, being dominated by PDF's uncertainties. Indeed, in this case, it would be three times the statistical one. The capability of interpreting the results of an experiment is thus significantly reduced by PDF's errors in the bump search. This result should be compared with the outcome from an A^*_{FB} measurement. Here, the experimental significance would be rescaled to $S \simeq 7$, owing to the higher luminosity, and it would be followed by a proportional reduction of the theoretical error that in this case is purely dominated by statistics. For these reasons, even if the large-x

PDF's uncertainties are considerably improved in the future, it is likely that an A^*_{FB} measurement will prove to be useful evidence in any claims of Z' discoveries using the LHC data.

5. Conclusions

We have examined the possible use of the reconstructed A^*_{FB} in experimental analyses searching for Z'-bosons in both high ($\mathscr{L} \sim 300$ fb^{-1}) and low ($\mathscr{L} \sim 30$ fb^{-1}) integrated luminosity scenarios. This has been done in the context of a variety of models: E_6, GLR, GSM. This variable is normally only considered to be of major interest once a Z' has been discovered. At low luminosities we have shown that the statistical significance of an A^*_{FB} measurement can be comparable to that of a cross section measurement, an example being for E_6-type Z's, hence making it a useful observable in searches.
At high luminosities the significance of an observed bump type of structure can be large. However the knowledge of the predicted cross section in any particular model is subject to the large-x PDF errors. Current knowledge of PDFs is such that this results in large uncertainties. The A^*_{FB} on the other hand benefits from the partial cancellation of the uncertainties on cross sections making it much more insensitive to PDF's errors. This increases the importance of A^*_{FB} measurements in the interpretation of any observations. Progress is being made on improving the uncertainties of large-x PDFs through the inclusion of additional data and the use of new refitting procedures.

References

[1] P. Langacker, Rev. Mod. Phys. 81 (2009) 1199.

[2] E. Accomando et al., Phys. Rev. D83 (2011) 075012.

[3] Stefano Frixione, Paolo Nason, Carlo Oleari, JHEP 0711 (2007) 070.

[4] Simone Alioli, et al., JHEP 1006 (2010) 043.

[5] Tomas Jezo et al., JHEP 1412 (2014) 092.

[6] L. Barzé et al., Eur.Phys.J. C73 (2013) 6, 2474.

[7] E. Accomando, Phys.Lett. B661 (2008) 129-133.

[8] Nikolas Kauer, Giampiero Passarino, JHEP 1208 (2012) 116.

[9] Elena Accomando et al, Phys.Rev. D85 (2012) 115017.

[10] Elena Accomando et al., JHEP 1310 (2013) 153.

[11] Elena Accomando et al., PoS DIS2013 (2013) 125.

[12] CMS Collaboration, JHEP 1504 (2015) 025.

[13] Michael Dittmar et al., Phys.Lett. B583 (2004) 111-120.

[14] F. Petriello and S. Quackenbush, Phys. Rev. D77 115004 (2008).

[15] T. G. Rizzo, JHEP 0908, 082 (2009).

[16] M. Dittmar, Phys. Rev. D55 (1997).

[17] Elena Accomando et al., arXiv:1503.02672.

[18] Sergey Alekhin et al., arXiv:1101.0536.