Restoration of Electroweak Symmetry in Single Gauge Boson Production at the LHC

CERN Summer Student Report

Taylor Sussmane
Advisor: Philip Sommer

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Abstract

Massive gauge bosons obtain their mass from absorbing a Goldstone boson from the Higgs field. Because they have mass, they have an extra degree of freedom which gives rise to a longitudinal polarization state. The Goldstone Boson Equivalence Theorem predicts that at high energies, the production cross section of a longitudinally polarized massive gauge boson will converge to the production cross section of the Higgs boson. Consequently, longitudinal gauge bosons encode valuable information about the Higgs mechanism. In VBF events, they also provide knowledge of boson-self interactions. This paper studies the energy dependence of VBF events, polarization fraction of the Z boson, and EFT effects to determine if a measurement of a longitudinally polarized Z boson is feasible at the LHC.

Contents

1 Introduction

It is widely accepted that the W and Z bosons get their mass from the Higgs mechanism in the absorption of a corresponding Goldstone boson. Because they have mass, they have an extra degree of freedom which gives rise to a longitudinal polarization state. This polarization state encodes valuable knowledge about the Higgs mechanism because of its origins.

The Goldstone Boson Equivalence Theorem (GBET) states that at high energies, the production rate of a longitudinally polarized gauge boson is equal to that of the Higgs boson. GBET can be studied at the LHC in vector boson fusion events (VBF). These are events in which two vector bosons radiate off the incoming quarks and then scatter to produce either a Higgs, W, or Z boson. Because no color in exchanged between the two quarks, the experimental event signature consists of two jets with high invariant mass which are produced in opposite hemispheres of the detector. Additionally, all decay products in VBF Z events can be reconstructed, making it a great candidate for studying longitudinally polarized Z bosons.

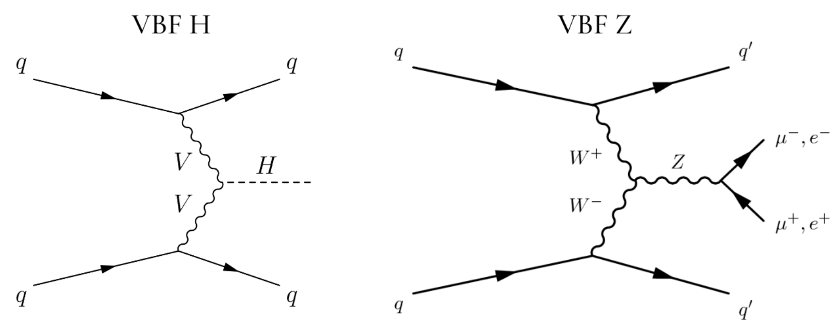

Figure 1: This figure shows the Feynman diagrams for VBF Higgs (left) and VBF Z (right) processes.

This paper will analyze the energy dependence of the production cross section for VBF events that create a Higgs, Z, or W boson. We hope to find a value of Z and W production that converges with VBF Higgs production, despite the complexity of GBET in VBF events. Furthermore, the polarization fraction of VBF Z events will be analyzed to determine the feasibility for a measurement at the LHC. With these two analyses, there will hopefully be enough information to determine whether longitudinal Z or W production that has converged to VBF Higgs can be measured. A measurement could experimentally confirm the Higgs mechanism implemented in the Standard Model or, perhaps, reveal deviations from the Standard Model.

2 Energy Dependence of Longitudinally Polarized Gauge Bosons

First, it is important to examine the production cross section behavior at high energy. As aforementioned, GBET suggests that the production of massive gauge bosons will converge to Higgs production at high energies. However, the theorem becomes more nuanced with VBF events. We began with a simple comparison of the production cross section behavior for different boson productions. To achieve this, VBF events were generated using the Monte Carlo event simulation software, MadGraph. The following processes were considered:

$pp \to h\ jj$	Higgs production
$pp \to Z_L\ jj$	Longitudinal Z production
$pp \to W_L^+\ jj$	Longitudinal W^+ production
$pp \to W_L^-\ jj$	Longitudinal W^- production

Each of these processes was generated with the following cuts, suggested in Ref. [1] to enhance signal: Invariant mass of jets >500 GeV, Rapidity seperation of jets >2. The resulting transverse momentum distibution is shown in Figure 2.

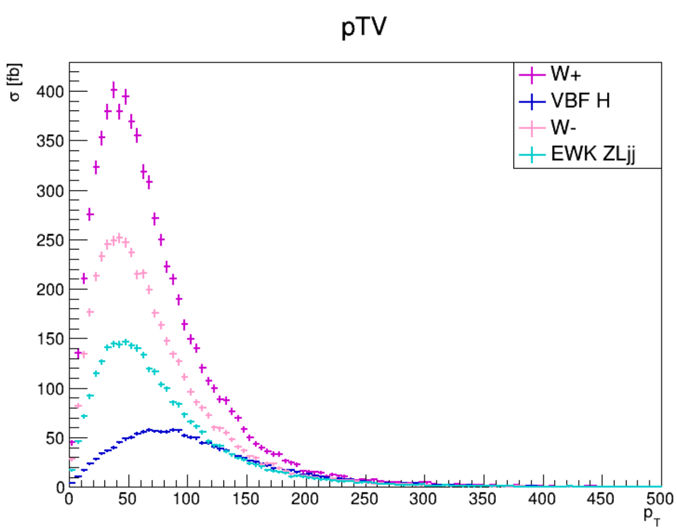

Figure 2: Transverse momentum distribution of boson producted in various VBF processes. Shown is longitudinal W and Z production, as well as Higgs production. $p_{\mathrm{T}}(V)$ is in units of GeV.

To verify GBET, the behavior of the gauge bosons in relation to VBF Higgs production should be studied. As shown in Figure 3, the production cross sections of W and Z bosons produced in VBF are not equivalent to those of the Higgs boson.

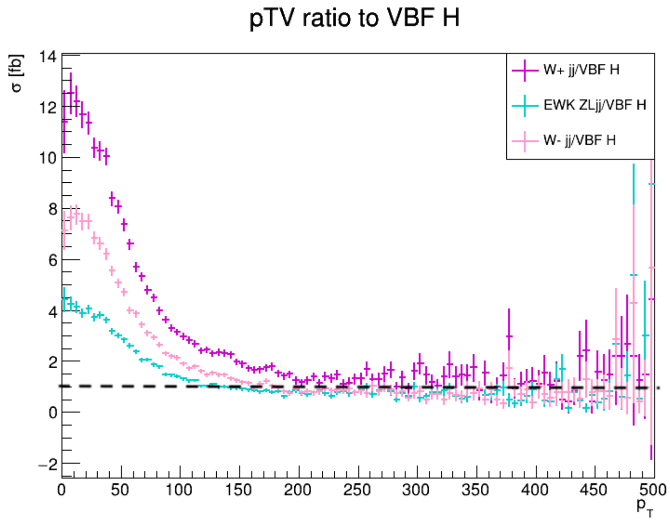

Figure 3: Transverse momentum distribution of longitudinal W and Z production as a ratio of Higgs production. $p_{\mathrm{T}}(V)$ is in units of GeV.

Figure 3 shows that W^{+} production converges above VBF Higgs production, while Z and W^{-} converge below VBF Higgs production.

The behavior of the cross sections was further examined by studying different initial and final states separately. In the total proton-proton to longitudinal Z events, there are twelve dominating processes:

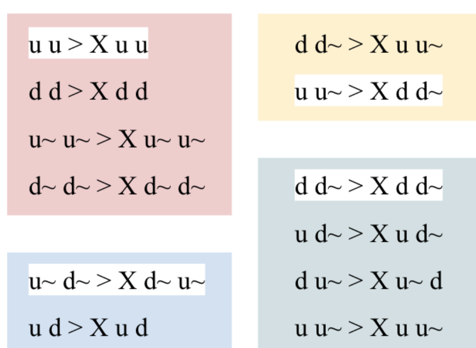

Figure 4: Sub processes of VBF Higgs and longitudinal Z production. X denotes a Higgs boson or longitudinally polarized Z boson. The processes are grouped into 4 grouped, denoted by the background color. Processes in the same group are analagous.

Of course there are other processes involved, but because they involve higher generations of quarks, they are conceptually identical to those involving only the first quark generation. We are just trying to understand where the discrepancy in convergence is originating. The twelve dominating processes can be divided into four groups, differentiated by the colors, which have nothing to do with QCD. All processes within these groups have the same tree level diagrams, subtract the initial and final states. That is, the part of the diagrams involving the creation of the boson in VBF are the same. Therefore, it is not necessary to generate events for all twelve processes. Instead, we chose the highlighted processes to generate events for. To further simplify this check, we have chosen to only generate these processes for Higgs and Z boson production. Longitudinal W production is more difficult to compare to Higgs production because it is electrically charged, so it would be impossible for the initial/final states of W and Higgs production to agree. We will study W production more with more appropriate checks. For each of the four chosen processes, events were generated with the same cuts used to generate the proton-proton events and an additional $p_{\mathrm{T}} > 200$ GeV cut to observe the high p_{T} behavior more closely.

After generation, the transverse momentum of the samples was plotted. The resulting plots are shown in Figure 5.

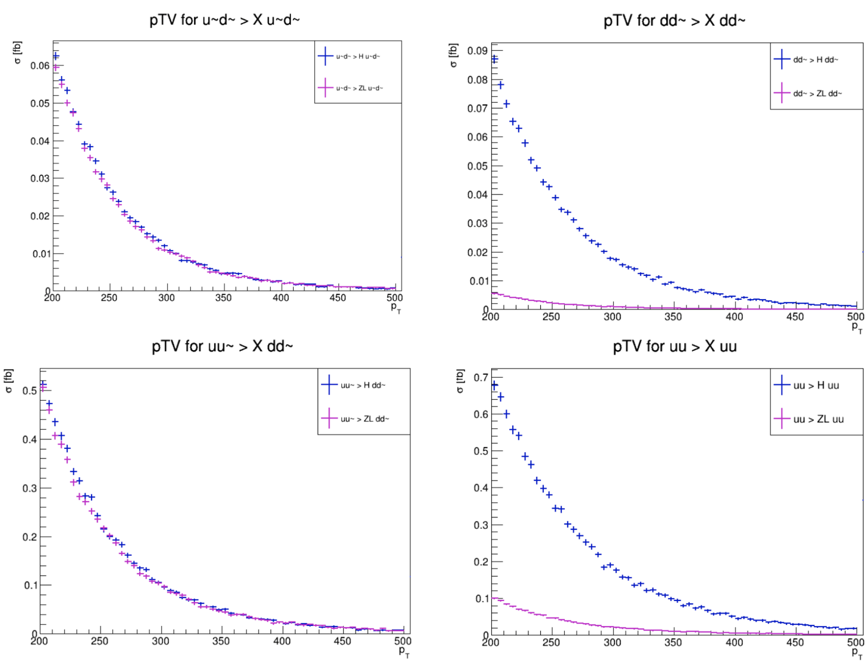

Figure 5: Transverse momentum distribution for sub processes considered. Each plot shows Higgs production (blue) and longitudinal Z production (pink). p_{T} is in units of GeV.

These plots show that only two of these four processes converge with Higgs production at high transverse momentum. It can be assumed that the other processes in the same group have the same behavior. Therefore, eight out of the total twelve processes do not converge to Higgs production. Additionally, these non converging processes converge to a value lower than Higgs production, similar to the overall proton-proton to longitudinal Z production. Experimentally, it is not possible to differentiate between the different sub processes, but this check provided valuable insight into the convergence of longitudinal Z production.

Interestingly, in the processes that do converge to Higgs production, a Higgs can be produced through fusion of ZZ and WW. However, in the non converging processes, a Higgs can only be produced through fusion of ZZ, and not WW. It is likely that in VBF events, GBET becomes more complicated to verify because only a single boson is being produced, meaning that each boson production has a unique set of initial/final states.

Finally, it may be enlightening to look at the behavior of the sum of W and Z production. Because we now know that individually, the massive vector boson productions do not converge to Higgs production, ideally, the sum would be measured instead. Events were generated again with the same cuts as suggested in Ref. [1]. The resulting transverse momentum ratio to Higgs production is shown, in Figure 6.

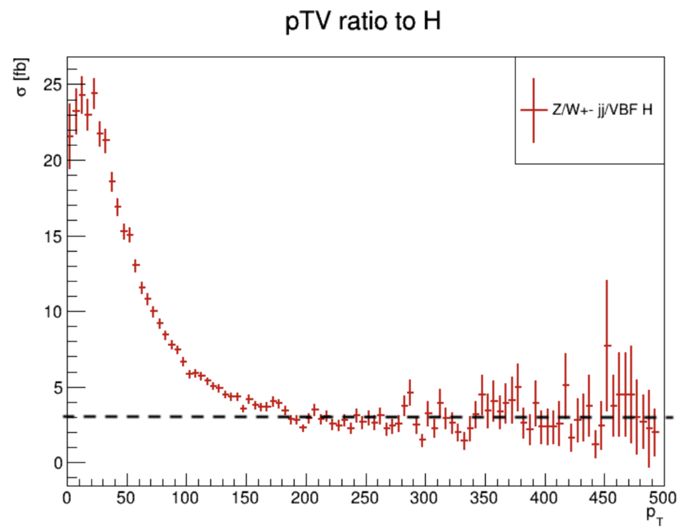

Figure 6: Transerve momentum distibution of the sum of W and Z production, expressed as a ratio of Higgs production. p_{T} is in units of GeV.

As shown in Figure 6, we see that the sum of W and Z converges to a value that is three times the Higgs production. Examining the results, GBET certainly holds true, but not trivially. Different processes dictate the productions of Higgs, Z, and W, so they cannot converge to the same production cross section at high p_{T}. If the inital quarks are considered, the GBET holds for isospin doublets of quarks but not for individual quark flavours. As a result, the sum of $W^{\pm}$ and Z production cross sections converge to an integer number relative to Higgs production, but the individual processes do not. Ultimately, this is an interesting outcome that would benefit from being examined further.

3 Polarization Fraction Analysis

To further study whether a measurement of a longitudinally polarized Z is feasible, the polarization fractions of Z production are examined. Naturally, not every Z produced in a VBF Z event will be longitudinally polarized, but it is important to know what fraction of VBF Z events produce a longitudinally polarized Z. To do this, the following processes were generated in MG:

$$pp \to Z_L\ jj$$
$$pp \to Z_T\ jj$$
$$pp \to Z\ jj$$

These processes were generated with the same cuts as aforementioned. Here, we do not assume that total Z production is equal to the sum of longitudinal and transverse Z production due to possible interference between polarization states, which is likely negligible. This is done simply for completion.

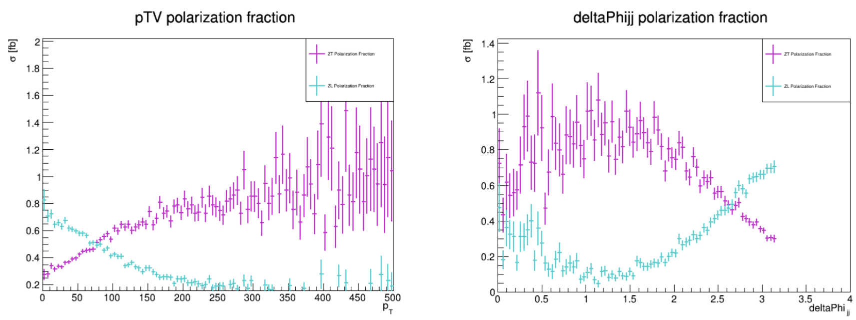

Figure 7: Polarization fraction plots for transverse momentum and $\Delta\phi_{jj}$. Shown is tranverse and longitudinal Z production. p_T is in units of GeV, and $\Delta\phi_{jj}$ is unitless.

As shown, the polarization fraction of longitudinal Z is unfortunately quite low at high transverse momentum. However, it does increase at high values of $\Delta\phi_{jj}$, the azimuthal separation of the two outgoing quarks. So, perhaps adding a delta phi cut to the events will improve the polarization fraction as a function of transverse momentum. The polarization fractions after this $\Delta\phi_{jj}$ >2 cut are shown in Figure 8.

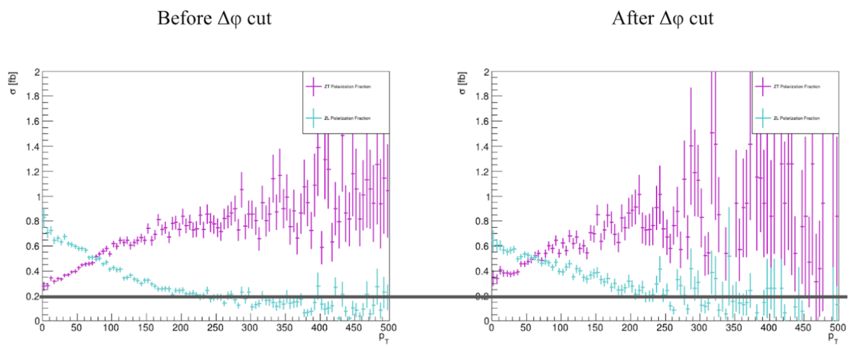

Figure 8: Polarization fraction for transverse momentum before (left) and after (right) the cut on $\Delta\phi_{jj}$. p_{T} is in units of GeV.

The polarization fractions only marginally improve, if anything. This result shows that $\Delta\phi_{jj}$ is not a very useful variable in isolating longitudinal Z production. Because of the low polarization fraction, it is unclear whether a longitudinally polarized Z produced in a VBF event could be measured up to high energy. This would benefit from further study. At first glance, it doesn't seem impossible.

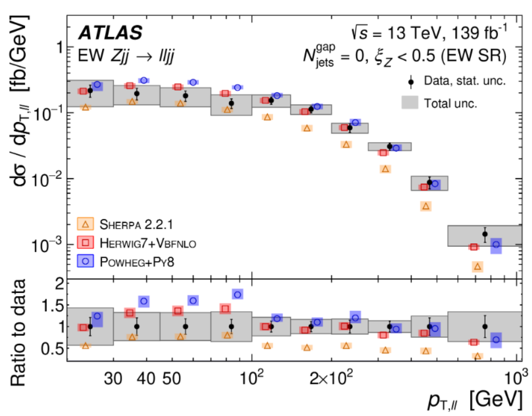

Figure 9: This plot from Ref. [2] shows the ATLAS detector's current sensitivity to electroweak Z production.

Figure 9 shows the ATLAS detector's current sensitivity to electroweak Z production. Based on this plot, it may be possible to detect a longitudinally polarized Z boson, despite the low polarization fraction. However, this would benefit from further study as the samples produced in this analysis do not include the leptonic decay of the Z boson, as the ATLAS plot does.

4 EFT Predictions

Finally, we are interested in analyzing these processes with an EFT approach. This will show which, if any, BSM effects contribute to longitudinally polarized Z production. To do this analysis, events are generated for each of the BSM operators considered. The full set of operators in this EFT analysis can be found in Ref. [3]. Each time events are generated, all operators are set to zero except for one, and the cross section is calculated. Operators that give a non-zero value for the production cross-section imply that the production is affected by that BSM effect. Table 1 shows the results of this analysis.

Table 1. MG EFT Predictions

This table shows the production cross section of Higgs and Z boson production for various BSM operators. The cross section is given in pb, with a symmetric uncertainty.

Production cross section (pb)			
Operator	Higgs	Longitudinal Z	Transverse Z
SM	1.32 +- 0.0044	1.525 +- 0.0067	3.613 +- 0.011
cW (lin)	0.0 +- 0.0	0.09778 +- 0.00045	0.03858 +- 0.0012
cW (quad)	0.0 +- 0.0	0.004077 +- 1.7e-05	0.03194 +- 0.00014
cHbox (lin)	0.1512 +- 0.00043	0.0 +- 0.0	0.0 +- 0.0
cHbox (quad)	0.004813 +- 1.8e-05	0.0 +- 0.0	0.0 +- 0.0
cHDD (lin)	-0.01278 +- 0.00016	0.0398 +- 0.00017	0.09076 +- 0.00034
cHDD (quad)	0.001524 +- 3.9e-06	0.0005947 +- 2.5e-06	0.001627 +- 5.1e-06
cHG (quad)	0.0 +- 0.0	0.004825 +- 1.8e-05	9.369e-05 +- 3.5e-07
cHW (lin)	-0.1257 +- 0.0012	0.0 +- 0.0	0.0 +- 0.0
cHW (quad)	0.04663 +- 0.00018	0.0 +- 0.0	0.0 +- 0.0
cHB (lin)	-0.001746 +- 0.00018	0.0 +- 0.0	0.0 +- 0.0
cHB (quad)	0.02083 +- 8e-05	0.0 +- 0.0	0.0 +- 0.0
cHWB (lin)	0.02896 +- 0.0003	0.1164 +- 0.00064	0.2367 +- 0.00091
cHWB (quad)	0.01655 +- 4.4e-05	0.004158 +- 1.7e-05	0.01055 +- 3.4e-05
cHu (lin)	-0.02599 +- 9.6e-05	0.0007294 +- 7.3e-06	0.002273 +- 2.5e-05
cHu (quad)	0.01005 +- 2.7e-05	0.0002394 +- 1e-06	0.0007358 +- 2.1e-06
cHd (lin)	0.008656 +- 2.8e-05	5.554e-05 +- 1.3e-06	0.0001862 +- 4e-06
cHd (quad)	0.006347 +- 2.5e-05	8.378e-05 +- 3.2e-07	0.0002519 +- 8.1e-07
cuu1 (lin)	0.0 +- 0.0	-0.002832 +- 1.2e-05	-0.007984 +- 3.6e-05
cuu1 (quad)	0.0 +- 0.0	0.0123 +- 4e-05	0.03058 +- 0.00011
cdd1 (lin)	0.0 +- 0.0	-6.777e-05 +- 2.7e-07	-0.0001866 +- 1e-06
cdd1 (quad)	0.0 +- 0.0	0.0009902 +- 3e-06	0.002492 +- 8.6e-06
cud1 (lin)	0.0 +- 0.0	0.0005712 +- 3e-06	0.00162 +- 7.3e-06
cud1 (quad)	0.0 +- 0.0	0.006927 +- 2.3e-05	0.01626 +- 4.9e-05
cud8 (lin)	0.0 +- 0.0	-2.64e-20 +- 1.5e-22	-7.492e-20 +- 4.4e-22
cud8 (quad)	0.0 +- 0.0	0.001507 +- 4.9e-06	0.003637 +- 1.7e-05
cHl3 (lin)	-0.4534 +- 0.0013	-0.536 +- 0.0024	-1.272 +- 0.0037
cHl3 (quad)	0.04367 +- 0.00015	0.05043 +- 0.00022	0.1195 +- 0.00036

All other operators are set to zero.

There are a few important things to notice in Table 1. First, there are several operators that are only sensitvite to Higgs boson production: cHbox, cHW, and cHB. The measurement of the cross section ratio of VBF Z and VBF Higgs production could therefore be used to constrain these operators with reduced assumptions on the other operators.

Additionally, there are several operators that have enhanced sensitivity to longitudinal Z production, mainly the cW and cHG operators. We can also use cW operator to enhance longitudinal Z in the linear term which allows constraining these operators with fewer assumptions on the validity of the EFT expansion. If a measurement of a longitudinal Z is successful, we could learn about these specific operators, and possibly confirm or deny certain BSM theories.

5 Conclusions

A summer is but a short amount of time. Naturally, not every detail could be thoroughly analyzed, as wished. Although, hopefully, this paper serves as a good starting point for future analyses concerning longitudinally polarized gauge bosons produced in VBF events.

In the energy dependence study, it was found that in VBF events, the Goldstone Boson Equivalence Theorem holds. However, when including initial state quarks, vector-boson production from any combination of quarks from an isospin doublet have to be considered. Only one boson is produced in these VBF processes, so without the consideration of isospin symmetry, the production channels of the bosons will be different which prevents the longitudinal bosons from converging to Higgs production.

The polarization fraction analysis showed that the polarization fraction of longitudinal Z is quite low which is a somewhat discouraging outcome. The polarization fraction was also not improved with cuts on any of the variables in this analysis. However, it still may be possible to detect a longitudinally polarized Z boson at the ATLAS detector because of its sensitivity to electroweak Z events.

The EFT analysis showed that there are several operators that are partial to VBF Higgs or Z production, so measuring these processes can tell us about BSM effects of these specific operators.

For further studies, it would be beneficial to further study the convergence of the W and Z bosons to the Higgs, and, perhaps, confirm that these production cross sections converge when considering isospin doublets. Additionally, the polarization fraction calculations should be compared to the efficiency of appropriate detectors at the LHC to determine if it could reasonably be measured. Perhaps there is supplemental cuts on other variables that would more substantially increase the polarization fraction of longitudinally polarized Z bosons. Furthermore, it may be helpful to conduct the polarization fraction studies with samples that include the leptonic decay of the Z boson, as this will open the door to more, potentially interesting, variables. Finally, more rigorous EFT analysis could be done to further study the BSM effects on longitudinal Z production.

6 Acknowledgements

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7 References

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