Z polarization in $e^+e^- \rightarrow ZWW$ for testing special interactions of massive particles.

F.M. Renard
Laboratoire Univers et Particules de Montpellier, UMR 5299
Université de Montpellier, Place Eugène Bataillon CC072
F-34095 Montpellier Cedex 5, France.

Abstract

We show that the $ZWW$ production process may give complementary informations about scale dependent heavy particle masses and possible final state interactions as compared to previously studied top quark production processes. We illustrate the $p_Z$ distribution of the rate of longitudinal $Z_L$ component showing its sensitivity to these effects which may arise from heavy particle substructure or a dark matter (DM) environment.
1 INTRODUCTION

Our basic motivation is the search for simple signals of the existence of special properties of heavy particles (t, Z, W, H, ... ) like a scale dependent mass [1, 2] or of final state interactions in multiparticle production (for example like in the hadronic case due to a substructure [3, 4, 5, 6, 7] or to a dark matter environment [8, 9, 10]).

Previous papers [11, 12, 13] were devoted to Zt̄ and Wtb production where the ”simple signal” is given by the longitudinal gauge boson (ZL or W± L ) rate of production. In SM it is, at high energy, equivalent to the rate of Goldstone boson G0,± production (up to corrections of order m2 Z,W /s) [14] for which the couplings to the particles involved in the considered process are indeed proportional to their masses. So finally the rate of longitudinal gauge boson would give a measurement of the effective mass of the accompanying particles. We have illustrated these properties for a set of interesting processes e+e−, γγ, gg → Zt̄, W−tb showing the sensitivity to the top mass and also to a final state (ZLt or WLt) interaction.

However in these processes the sensitivity to the top mass arises (as we can directly see from the Goldstone couplings) from the ratio mt/v or mt/mW. So one should consider the possibility of a simultaneous modification of the top and of the W (and Z) masses by scale dependence such that the resulting effective coupling is only weakly or not at all affected.

It is therefore important to look at effects for different mass combinations. This is the motivation for the present paper and the analysis of the Z polarization in the e+e− → ZWW process where only the W and Z masses are involved.

In Section 2 we present the basic SM properties and the details of the sensitivity to these masses. In Section 3 we consequently show the effects of a scale dependence of the heavy masses and we compare them to the case of the top quark in the previous processes. In Section 4 we also look at the effects of final state interactions among ZL and W L states which may have some similarities with those of the masses. Finally we summarize the possible implications of such observations and how other processes could help about our aim.

2 SM properties

We will first look at the sensitivity of the e+e− → ZWW process to the values of the Z and W masses.

In SM the Born diagrams are depicted in Fig.1. Each of these diagrams has a specific dependence due to its kinematical feature and to the involved couplings. In addition longitudinal polarization vectors have the peculiar 1/m dependence

\[ \epsilon_L = \left( \frac{p}{m}, \frac{E}{m} \hat{p} \right) \] (1)
An important SM feature is the equivalence of $Z_L$ amplitudes with the Goldstone boson $G^0$ ones in $e^+e^- \rightarrow G^0WW$. The corresponding diagrams are drawn in Fig.2. Apart from simple kinematical dependences, the mass dependence appear in the $H - WW$ and $\gamma, Z - GW$ couplings:

\[ g_{HWW} = \frac{em_W}{s_W} \quad g_{\gamma GW} = em_W \quad g_{ZW} = -e \frac{m_W s_W}{c_W} \]  

(2)

In a first study we will assume that the $m_W/m_Z$ ratio (i.e. $c_W$) is fixed. This leads to $G^0WW$ amplitudes proportional to the W mass. But the $G^0W_LW_L$ amplitudes get, in addition, $\frac{1}{m_W}$ factors which make them dominant at high energies and finally behaving like $\frac{1}{m_W}$.

Apart from various $m^2_{Z,W}/s$ corrections (arising for example from the difference between $p^0$ and $p$) these $Z_LWW$ amplitudes should be equivalent to the $G^0WW$ ones.

In practice this equivalence results from cancellations at high $p_Z$ of several terms which individually explode like $p/m$. Except for the $H$ exchange which is directly equivalent to the corresponding one in the $G^0$ case and for the 2 diagrams of the second set in Fig.1 which almost cancel each other, the cancellation requires the addition of all other diagrams.

We will now compute the longitudinal $Z_L$ rate of production

\[ R_L = \frac{\sigma(Z_L WW)}{\sigma(Z_T WW) + \sigma(Z_L WW)} \]  

(3)

and the similar $R^G_L$ one with $Z_L$ replaced by $G^0$.

They are illustrated in Fig.3 for $\sqrt{s} = 5$ TeV and $\theta_Z = \frac{\pi}{4}$ and $\frac{\pi}{2}$, versus $p_Z$, where one can see the importance of the $m^2_Z$ terms in the accuracy of the equivalence.

3 Sensitivity to scale dependent $W, Z$ masses

We now want to see how this $m_W$ dependence will affect the observables when one replaces the fixed mass value by some scale dependence which may originate as mentioned in the introduction by some substructure (like in the hadronic case) or by some DM environment.

As in the previous analyzes we will use an effective scale dependence form

\[ m_W(s) = m_W \left( \frac{m^2_{th} + m^2_0}{s + m^2_0} \right) \]  

(4)

with $m_0 = 2, 4$ TeV, leading to curves "$m2$" and "$m4$" in the illustrations of the effects on the rates $R_L$ and $R^G_L$. 

3
In the $G^0WW$ case the above mentioned $\frac{1}{m_W}$ behaviour of the leading $G^0W_LW_L$ amplitudes is responsible for the results shown in Fig.4a,b.

First note the drastic difference with the top quark mass cases in $(Ztt, Wtb)$ production, [11, 12, 13], where the effects were exactly opposite.

The more subtle dependence of the $Z_LWW$ case is illustrated in Fig.5a,b. As explained above the result is a mixture of the effects of couplings, cancellations of exploding terms and $m_{Z,W}^2/s$ kinematical corrections. The main features of the Goldstone case are nevertheless reproduced with larger differences at low $p_Z$.

Note however that the Goldstone equivalence may not be valid beyond SM except for special models designed to preserve it.

4 Final state interactions

Independently of the possible presence of a scale dependent mass there could exist strong final interactions essentially between longitudinal $Z_L, W_L$ states. This may be due to their substructure (like in the case of hadrons) or to a DM environment.

We have already considered this possibility in $Ztt$ and $Wtb$ production, [11, 12, 13]. In the $ZW W$ case the 2 effects, effective mass and final state interaction, respectively shown in Fig.5 and in Fig.6, may be cumulative.

In our illustrations we will use the same final state forms as in the previous cases simply modifying the $Z_LW_L^+W_L^-$ amplitudes by the $(1+C(s_{ZW^+}))(1+C(s_{ZW^-}))(1+C(s_{W^+W^-}))$ "test factor" with

$$C(x) = 1 + \frac{m_Z^2}{m_0^2} \ln \frac{-x}{(m_Z + m_W)^2},$$

with the subenergies $x = s_{ZW^+}, s_{ZW^-}$ or $s_{W^+W^-}$ and $m_0 = 0.5$ TeV, like in [10]. The resulting $p_Z$ distributions are shown in Fig.6a,b.

In order to distinguish these effects from the ones of effective scale dependent masses detailed studies of their kinematical structures may have to be done; for example the subenergies and angle dependences. For this aim precise dynamical models should be considered.

5 Conclusions and prospectives

In this paper we have pursued our studies of possible effects of scale dependent masses (for example due to substructures) and of special interactions among heavy particles also generated by substructures or by a DM environment.
Previously we had essentially considered the case of the top quark, the effect of $m_t(s)$, its influence on the accompanying $Z_L$ or $W_L$ rate assuming no modification of the Higgs mechanism producing the $Z,W$ masses and generating these $Z_L,W_L$ states.

However if these $Z_L,W_L$ states are also affected, then the ratios $m_t/m_W$ controlling the $Z_L,W_L$ (or Goldstone) couplings to the top quark may be very differently (weakly or even not at all) modified.

In such a situation the study of the $ZWW$ production processes could give essential and even decisive complementary informations as they will only depend on the $Z,W$ masses. In practice, because of an easier experimental measurement, we have only considered the effects on the $Z_L$ rate (and not shown the individual $W_L^\pm$ ones).

We have made illustrations showing the mentioned effects and their specificities (scale dependent masses, final state interactions) on the $p_Z$ distribution of the $Z_L$ rate in the $e^+e^- \rightarrow ZZW$ process. For experimental possibilities see [15].

Other production processes may also be interesting for our aim. One set is $ZWW$ production from different initial states like $\gamma - \gamma$, see [16], or gluon-gluon in hadronic collisions; for LHC possibilities see [17, 18]. Another possibility is $HWW$ or $HZZ$ production which will also directly depend on $Z,W$ masses but the identification of the $H$ may be more delicate than for a $Z$.

References

[1] G.J. Gounaris and F.M. Renard, arXiv: 1611.02426.

[2] F.M. Renard, arXiv: 1708.01111.

[3] H. Terazawa, Y. Chikashige and K. Akama, Phys. Rev. D15, 480 (1977); for other references see H. Terazawa and M. Yasue, Nonlin.Phenom.Complex Syst. 19,1(2016); J. Mod. Phys. 5, 205 (2014).

[4] D.B. Kaplan and H. Georgi, Phys. Lett. 136B, 183 (1984).

[5] K. Agashe, R. Contino and A. Pomarol, Nucl. Phys. B719, 165 (2005); hep/ph 0412089.

[6] G. Panico and A. Wulzer, Lect.Notes Phys. 913,1(2016).

[7] R. Contino, T. Kramer, M. Son and R. Sundrum, J. High Energy Physics 05(2007)074.
[8] B. Penning, arXiv: 1712.01391. We also thank Mike Cavedon for interesting informations about this subject.

[9] F.M. Renard, arXiv: 1712.05352.

[10] F.M. Renard, arXiv: 1801.10369.

[11] F.M. Renard, arXiv: 1803.10466.

[12] F.M. Renard, arXiv: 1805.06379.

[13] F.M. Renard, arXiv: 1807.00621.

[14] J.M.Cornwall, D.N.Levim and G.Tiktopoulos, Phys. Rev.D10(1974)1145; D11(1975) 972E; C.E.Vayonakis, Lett. Nuovo Cimento17(1976) 383; B.W.Lee, C.Quigg and H.Thacker, Phys. Rev.D16(1977) 1519; M.S.Chanowitz and M.K.Gaillard, Nucl. Phys.B261(1985) 379; M.S.Chanowitz, Ann.Rev.Nucl.Part.Sci.38(1988)323; G.J.Gounaris, R.Koegerler and H.Neufeld, Phys. Rev.D34(1986) 3257.

[15] G. Moortgat-Pick et al, Eur. Phys. J.C75, 371 (2015), arXiv: 1504.01726.

[16] V.I. Telnov, Nucl.Part.Phys.Proc. 273(2016)219.

[17] R. Contino et al, arXiv: 1606.09408.

[18] F. Richard, arXiv: 1703.05046.
Figure 1: Diagrams for $e^+e^- \to ZWW$. 
Figure 2: Diagrams for $e^+e^- \rightarrow G^0WW$. 
Figure 3: $e^+e^- \rightarrow Z_LWW$ ratio in SM case compared to the Goldstone $G^0WW$ case.
Figure 4: $e^+e^- \rightarrow G^0WW$ ratio for 2 cases of scale dependent mass compared to the SM case.
Figure 5: $e^+e^- \rightarrow Z_L WW$ ratio for 2 cases of scale dependent mass compared to the SM case.
Figure 6: $e^+e^- \rightarrow Z_LWW$ ratio for 2 cases of final state interaction compared to the SM case.