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High mass resonances - extra gauge bosons and other exotics

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Searches for extra heavy Z' and W' bosons in the leptonic Drell-Yan channel at the Large Hadron Collider (LHC) are favoured by present and future data. We focus on a common approximation used in theoretical and experimental analyses: neglecting interference between the new heavy gauge bosons and the Standard Model ones W, Z and gamma. We present the implications of adopting this approximation on the data interpretation and the extraction of exclusion limits on the W' mass, in particular. We also address the LLP search at the new CERN facilities.

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1. Introduction

Drell-Yan (DY) processes, producing lepton pairs in the final state, are very powerful for discovering or bounding new physics involving heavy spin-1 gauge bosons. Scenarios predicting such exotic particles are particularly relevant now as the Large Hadron Collider (LHC) has already collected a generous number of events, and will be soon probing higher masses. We thus address the search for extra W' and Z' bosons at the LHC, summarising the common approximations used in the theoretical and experimental analyses, and showing their impact on the data interpretation. We focus in particular on the effect of interference between the W' and Z' bosons with their corresponding SM ones, W and Z, γ respectively. While interference is commonly discussed in specific models, one still encounters incomplete statements regarding how large the effect can be depending on the imposed kinematical cuts. Presently, while this contribution is being considered in Z' searches, that is equally set aside when interpreting the available data for W' searches. In section 2, we summarise these effects for the Z' search and in section 3 for the W' search at the LHC. In section 4, we address aspects of the search for light long-lived particles, in particular the sensitivity to the trigger thresholds and the benefits of running the new facilities at CERN.

2. Z'-boson searches in DY channel at the LHC

The prediction of one extra neutral vector boson is a generic feature of models where the gauge group is extended compared to the SM. Scenarios falling in that category include Grand Unified Theories (GUT), theories of dynamical electroweak symmetry breaking and extra-dimensional theories [1]. In Ref.[2], we consistently analysed thirteen different models, split in three classes: GUT with an E6 gauge group, Generalised Left-Right symmetric models, and generalisations of the SSM benchmark scenario. For the Z' search at the LHC in DY channel, we consider the process

$$pp \to Z', \gamma, Z \to l^+ l^- \quad \text{with} \quad l = e, \mu. \tag{1}$$

Here the focus is on the interference between the extra Z'-boson and the SM Z, γ, and its impact on the experimental analysis. The interference is sizeable and model dependent. Within the SSM, it can reach up to O(200%), as can be argued from the right plot of Fig. 1, and it can also distort the shape of the resonant signal as shown in the left plot of Fig. 1. In order to keep the size of the interference below the current theoretical uncertainties and allow a (quasi) model independent analysis, we found that the simple but powerful kinematical cut on the di-lepton invariant mass

$$|M_{ll} - M_{Z'}|/\sqrt{s} \leq 0.05 \tag{2}$$

where $\sqrt{s}$ represents the collider energy, reduces the interference effect below O(10%) over almost the entire Z' mass range for all thirteen analysed models. The result is therefore quite robust. The CMS collaboration is implementing this strategy since 2014, including the latest Z' search [4]. The latter reached 95% C.L. exclusion bounds of $M_{Z'} \geq 4.5$ TeV on the least constrained Z'_ψ boson and $M_{Z'} \geq 5.1$ TeV on the Z'_{SSM}. The ATLAS collaboration is now imposing a similar cut on their search window, $|M_{ll} - M'_Z| \leq 2\Gamma_{Z'}$, obtaining an excellent agreement on the Z'_{SSM} mass bound [5]. Note that an increase of a factor of 10 in the luminosity, during the past decade, has extended the Z' mass bound by 1 TeV; in the thirteen models analysed, it goes from $Z'_\psi \geq 4.5$ TeV to $Z'_Q \geq 7$ TeV.

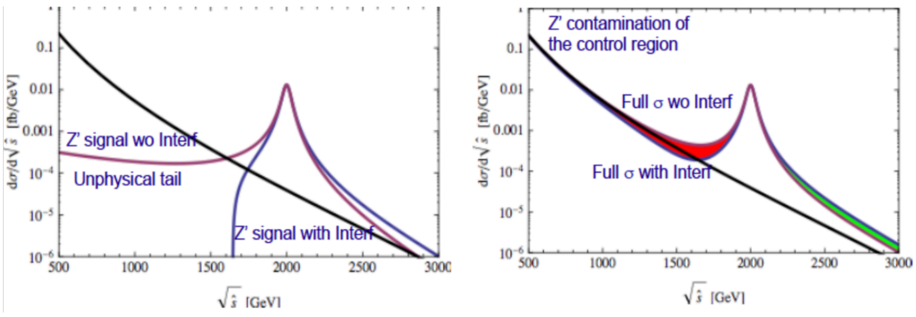

Figure 1: Invariant mass distribution in the presence of a Z'_{SSM} resonance, with and without interference between the signal and SM background. Left: signal only. Right: signal and SM background. LHC@8TeV with $M_{Z'}$=2 TeV is considered. No kinematical cuts are applied and the CT10 NLO PDF set is used.

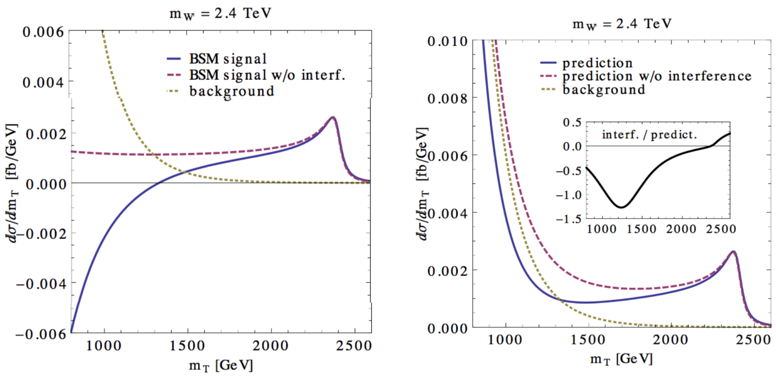

Figure 2: Transverse mass distribution in the presence of a W'_{SSM} resonance, with and without interference between the signal and SM background. Left: signal only. Right: signal and SM background. LHC@8TeV with $M_{W'}$=2.4 TeV is considered. No kinematical cuts are applied and the CT10 NLO PDF set is used.

3. W'-boson searches in DY channel at the LHC

Heavy charged W'-bosons arise in a number of theories that extend the SM gauge group. The Left-Right symmetric class of models [6, 7], based on the enlarged symmetry $SU(2)_L \times SU(2)_R \times U(1)$, is an old and popular example. A second class is represented by extra-dimensional theories [8, 9], where W'-bosons emerge as Kaluza-Klein excitations of the SM gauge bosons. Within the ADD model, the phenomenology of signals from extra charged gauge bosons at the LHC have been discussed in Refs. [10, 11]. In the RS1 model with gauge bosons in the 5D bulk and fermions on the UV brane, analogous results are published in Refs. [12, 13]. Here again the focus is on the signal shape and the search strategies. The cleanest process to be considered at the LHC is

$$pp \to W', W \to l\nu_l \quad \text{with} \quad l = e, \mu. \tag{3}$$

In this case, the effect of the interference between the W' signal and the SM background is even more dramatic, compared to the Z'-boson scenario. In Fig.2, we can observe the distortion of the signal shape (left plot) and the depletion of events when considering the complete differential cross-section in the dilepton transverse mass M_T (right plot). The low mass region, assumed to be new physics free and used to estimate the SM background and extrapolate it to higher masses, is also

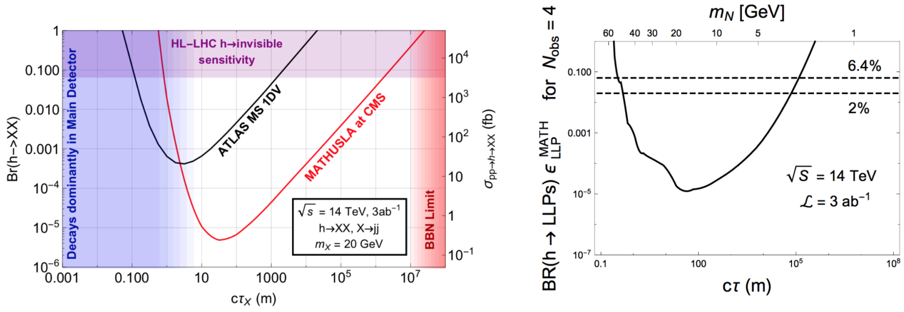

Figure 3: Left: Sensitivity to a hidden sector model with a SM-like Higgs decaying into two neutral scalar LLPs. Right: Sensitivity to the $U(1)_{B-L}$ model from the process $pp \to h \to \sum_i \nu_{iR}\nu_{iR}$.

highly altered. If an appropriate M_T cut is not applied, the interpretation of the LHC data would be highly impacted thus preventing a direct comparison between theory and experiment. Within the SSM, the signal cross section would be 6 times smaller, including the interference, pushing back the mass bound by roughly 1 TeV. Presently, the experimental analyses at the LHC are conducted setting aside the interference [14]. A 95% C.L. bound on the W' mass has been extracted but this is strictly valid only for a right-handed W'_R boson uniquely interacting with right-handed leptons. In this case, the interference is indeed null. All the other models cannot be easily compared to.

4. Long-lived right-handed neutrinos at the LHC

The minimal $B-L$ model based on the group $SU(2)_L \times U(1)_Y \times U(1)_{B-L}$ predicts a Z' boson accompanied by an extra Higgs singlet and three heavy long-lived right-handed neutrinos [15–17]. These neutrinos acquire a Majorana mass and naturally implement the Type I see-saw mechanism. If close to degeneracy, they can also give rise to a low-scale resonant leptogenesis, explaining the matter-antimatter asymmetry. The striking signature is the production of a right-handed neutrino pair, mediated either by the Z' or the Higgs(es), consequently decaying into three different categories: 2μ giving rise to two separated tracks, 3μ generating 1 displaced vertex (DV) and 1 separate track and finally 4μ producing 2 DVs. The trigger thresholds are crucial for this analysis [16]. With a transverse momentum cut, $P_T \geq 26$ GeV on the two most energetic muons and $P_T \geq 5$ GeV for all the others, the efficiency drops down to $\epsilon \simeq 4\%$. The ideal option to detect light neutral LLPs decaying into leptons and jets with low transverse momentum would be the nearly background free Mathusla and Faser. Fig.3 compares the sensitivity to light neutral LLPs, scalar (left-plot) and fermion (right-plot), that one could obtain in ATLAS and Mathusla at the projected HL-LHC. The difference is nearly one order of magnitude on the branching ratio of the Higgs into a LLP pair [18].

5. Conclusions

For Z' searches, a common strategy has been settled to interpret the LHC data within a variety of theoretical models. A similar approach should be applied to W' searches, to maximise the link between theory and experiment. We gave also an example within the U_{B-L} model of the capability of the new facilities at CERN in improving the sensitivity to LLPs.

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