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Light stops emerging in WW cross section measurements?

Krzysztof Rolbiecki[a] **and Kazuki Sakurai**[b]

[a] *Instituto de Física Teórica, IFT-UAM/CSIC,*
C/ Nicolás Cabrera, 13-15, Cantoblanco, 28049 Madrid, Spain
[b] *DESY,*
Notkestrasse 85, D-22607 Hamburg, Germany

E-mail: krzysztof.rolbiecki@desy.de, kazuki.sakurai@desy.de

Abstract: Recent ATLAS and CMS measurements show a slight excess in the WW cross section measurement. While still consistent with the Standard Model within 1–2-σ, the excess could be also a first hint of physics beyond the Standard Model. We argue that this effect could be attributed to the production of scalar top quarks within supersymmetric models. The stops of $m_{\tilde{t}_1} \sim 200$ GeV has the right cross section and under some assumptions can significantly contribute to the final state of two leptons and missing energy. We scan this region of parameter space to find particle masses preferred by the WW cross section measurements. Taking one sample benchmark point we show that it can be consistent with low energy observables and Higgs sector measurements and propose a method to distinguish supersymmetric signal from the Standard Model contribution.

Keywords: Supersymmetry Phenomenology, Hadronic Colliders

Contents

1 Introduction

The W^+W^- diboson production process provides an important test of the electroweak (EW) interactions of the Standard Model (SM). Deviations from the SM predictions could arise due to new physics contributions, like anomalous triple gauge boson couplings or new particles decaying to the same final state as the electroweak gauge bosons.

The ATLAS and CMS experiments have performed measurements of the WW pair production cross section in pp collisions at $\sqrt{s} = 7$ TeV and 8 TeV in the fully leptonic channel. Using a full dataset at 7 TeV, ATLAS measured the cross section $\sigma = 51.9 \pm 2.0$ (stat) $\pm$ 3.9 (syst) $\pm$ 2.0 (lumi) pb [1], while quoting the SM prediction at next-to-leading (NLO) order of $\sigma = 44.7 \pm 2.0$ pb at $\sqrt{s} = 7$ TeV [2]. CMS measurements gave $\sigma = 52.4 \pm 2.0$ (stat) ± 4.5 (syst) ± 1.2 (lumi) pb [3], compared to the SM expectation of $\sigma = 47.0 \pm 2.0$ pb [4].[1] At $\sqrt{s} = 8$ TeV, only CMS has published the results using an integrated luminosity of 3.54 fb^{-1}. It reported $\sigma = 69.9 \pm 2.8$ (stat) $\pm$ 5.6 (syst) $\pm$ 3.1 (lumi) pb [5] compared to the electroweak theory prediction of $\sigma = 57.3^{+2.4}_{-1.6}$ pb [4].

While the above results are far from being conclusive, there is a clear tendency at both experiments and center-of-mass energies for a slightly higher measured rate than the SM predictions. Interestingly, other EW measurements tend to be in a far better agreement with the SM than the WW cross section measurement. This provokes us to speculate that the origin of the discrepancy could be attributed to physics beyond the Standard Model (BSM). Based on lepton kinematic distributions, ATLAS [1] imposes stringent limits on the anomalous WWZ and $WW\gamma$ couplings. This leaves us with an exciting possibility of new particles being produced that contribute to the same final state — two leptons and missing transverse energy — as WW pairs.

Production of supersymmetric (SUSY) particles could significantly affect measurement of WW cross section in the fully leptonic final state. It was suggested in ref. [6] that in scenarios with charginos as the next-to-lightest supersymmetric particle one could expect

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[1] CMS and ATLAS use different methods to calculate the SM cross section, hence slightly different result.

an excess in the WW cross section measurement, while avoiding constraints from searches in other channels. However, the size of enhancement is limited by the LEP limits [7] on the chargino mass. Nevertheless, the chargino contribution can be significant and would allow to decrease the tension between the prediction and measurement, provided charginos are light and close to the existing bounds, $m_{\tilde{\chi}_1^\pm} \sim \mathcal{O}(100\text{ GeV})$.

The other example of supersymmetric process that could contribute to the WW cross section measurement is pair production of top squarks, as we argue in this paper. Light stops, motivated by naturalness argument [8–11], are extensively searched for at the LHC [12–15]. Cross section is not a limiting factor here — for $m_{\tilde{t}_1} \sim 200$ GeV it easily exceeds 10 fb. On the other hand, since stops decay hadronically one has to suppress the number of jets in the final state, in order to contribute to the leptonic final state without jets. This can be achieved by placing a chargino with a mass only slightly lower than the stop mass. The b-jets produced in the two-body stop decay, $\tilde{t}_1 \to \tilde{\chi}_1^\pm b$, would be then too soft to be reconstructed. The chargino would further decay with on- or off-shell W, contributing to the dilepton final state,

$$\tilde{t}_1 \to \tilde{\chi}_1^\pm\, b \to \tilde{\chi}_1^0\, W^{(*)}\, b \to \tilde{\chi}_1^0\, \ell\, \nu\, b\,. \tag{1.1}$$

The other possibility could be provided by three- or four-body stop decays where kinematics also limits p_T of b-jets, however keeping in mind limits from the LHC searches [11, 16, 17]. The stop production with a subsequent two-body decay is on the other hand constrained by a dedicated ATLAS study [13]. However, because of the applied m_{T2} cut, sensitivity of this search does not significantly affect a part of parameter space where W becomes off-shell. Therefore, in section 3 we fit the signal of the stop pair production, followed by the decay chain eq. (1.1), in order to find the minimal supersymmetric standard model (MSSM) parameters compatible with the WW cross section measurement.

The paper is organised as follows. In the next section we briefly discuss the WW cross section measurements, the relevant top squark search and simulation procedure. In section 3 we perform a scan of the stop-neutralino masses to find a region consistent with the WW excess and discuss a method to distinguish SUSY signal from SM processes. Finally, we conclude in section 4.

2 WW and stop searches

Both ATLAS and CMS have published WW pair production searches. ATLAS measured the WW production cross section in pp collisions at $\sqrt{s} = 7$ TeV [1], while CMS published results for $\sqrt{s} = 7$ TeV [3] and 8 TeV [5] using $\mathcal{L}_{\text{int}} = 4.92\text{ fb}^{-1}$ and 3.54 fb^{-1}, respectively. As discussed in Introduction, in both cases there was an excess in the observed number of events compared to the SM prediction. The experiments were looking at the leptonic channel, where the final state consists of two oppositely charged leptons (the same or opposite flavour) and missing transverse energy, $\ell^+\ell^- + E_T^{\text{miss}}$. In the following we briefly recapitulate the ATLAS and CMS searches.

The main SM backgrounds for $pp \to W^+W^- \to \ell^+\ell^-\nu\bar{\nu}$ process originate from top quark production, Drell-Yan processes and other diboson pairs. In order to suppress top quark contribution a jet veto is applied. An event is rejected if there is at least one jet with $p_T > 25(30)$ GeV in ATLAS (CMS) search. Drell-Yan production is suppressed using a cut on the invariant lepton mass, $m_{\ell\ell}$, and a *projected (relative)* $E_{T,\mathrm{rel}}^{\mathrm{miss}}$ defined as

$$E_{T,\mathrm{rel}}^{\mathrm{miss}} = \begin{cases} E_T^{\mathrm{miss}} \times \sin \Delta\phi_{\ell,j} & \text{if } \Delta\phi_{\ell,j} < \pi/2 \\ E_T^{\mathrm{miss}} & \text{if } \Delta\phi_{\ell,j} \geq \pi/2 \end{cases}, \tag{2.1}$$

where $\Delta\phi_{\ell,j}$ is a difference in the azimuthal angle between $\mathbf{p}_T^{\mathrm{miss}}$ and the nearest lepton (jet). After the cuts one obtains relatively clean sample of WW events, with purity of $\sim 70\%$. The remaining background contribution is estimated using data-driven methods.[2]

Finally, we discuss the search for light stops performed by ATLAS [13], which covers a mass region relevant for our study. It targets the same final state as WW analyses, two leptons with missing transverse momentum, but using a different set of cuts. Crucially, the signal regions in this study require $m_{\mathrm{T2}} > 90$ GeV. The m_{T2} variable [18, 19] has a sharp kinematic edge at the W boson mass for $t\bar{t}$ production. For the supersymmetric $\tilde{t}_1\tilde{t}_1^*$ production the kinematics could significantly differ from that of the top pair production, because of an additional contribution to missing energy due to the lightest supersymmetric particles (LSP). Therefore, stop production would populate a region of high m_{T2}, where the SM backgrounds are suppressed. The situation changes for nearly-off-shell and off-shell W in eq. (1.1). In this case, the m_{T2} cut will also result in suppression of the supersymmetric signal and lost of sensitivity. Since ATLAS presented search results for a similar scenario with $m_{\tilde{t}_1} - m_{\tilde{\chi}_1^\pm} = 10$ GeV we can easily apply those exclusion bounds in our study.

In order to find a range of stop parameters consistent with experimental searches we simulate events using `Herwig++ 2.5.2` [20, 21] and process them using fast detector simulation `Delphes 2.0.3` [22]. We implement selection procedures and cuts for the relevant ATLAS and CMS searches discussed above. Furthermore, we validate the implementation by comparing efficiencies as reported by the collaborations and we find a good agreement. Nevertheless, whenever possible we use the event rates of WW and other SM processes given in the ATLAS and CMS notes. The stop signal is scaled to the NLO rate using `Prospino 2.1` [23]. With this setup, we perform a scan described in the next section.

3 Stop contribution

3.1 Fitting a simplified model

Given that the stop pair production events followed by the decay chain eq. (1.1) contribute to the signal regions of the WW measurements, the following questions should be addressed:

- Which mass region can fit each experimental result well?
- Are those mass regions consistent with each other?
- Are those mass regions consistent with direct stop searches?

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[2] At this point the Higgs boson contribution, $h \to WW$, is not taken into account.

- How one can distinguish the stop contribution from genuine WW events?

Postponing the last question to the next subsection, we address the first three in this subsection based on the simplified model approach.

Our simplified model considers exactly the same process as given by eq. (1.1). As discussed in Introduction, the mass difference between the stop and chargino has to be small, otherwise the b-quark from the stop decay would be reconstructed as a high-p_T jet and the event would be rejected by jet veto. We therefore fix the chargino mass by $m_{\tilde{t}_1} - m_{\tilde{\chi}_1^\pm} = 10$ GeV. With this assumption, the model is defined by two parameters: $m_{\tilde{t}_1}$ and $m_{\tilde{\chi}_1^0}$. As mentioned in the previous section, ATLAS has recently presented the light stop search results using exactly the same simplified model. Therefore, one can simply apply their exclusion limit to our simplified model parameter space.

To find out which mass region fits the experimental results, we estimate the χ^2 variable for each measurement as a function of the stop and neutralino masses:

$$\chi_i^2(m_{\tilde{t}_1}, m_{\tilde{\chi}_1^0}) = \frac{\left[N_{\rm obs}^{(i)} - N_{\rm SM}^{(i)} - N_{\rm SUSY}^{(i)}(m_{\tilde{t}_1}, m_{\tilde{\chi}_1^0})\right]^2}{\sigma_i^2}, \tag{3.1}$$

where i specifies the measurement (i = ATLAS7 [1], CMS7 [3], CMS8 [5]), $N_{\rm obs}^{(i)}$ is the number of observed events in the signal region, $N_{\rm SM}^{(i)}$ and $N_{\rm SUSY}^{(i)}$ are the predicted contributions from the Standard Model and SUSY, respectively, and σ_i is the quadrature sum of the systematic and statistical errors. The $N_{\rm SM}^{(i)}$ includes not only the WW contribution but also the other SM contributions such as $t\bar{t}$ and $h \to WW^*$ processes. All the factors, except for the $N_{\rm SUSY}^{(i)}$, are provided in refs. [1, 3, 5].

We estimate $N_{\rm SUSY}^{(i)}(m_{\tilde{t}_1}, m_{\tilde{\chi}_1^0})$ in the following procedure. We generate a grid in the $(m_{\tilde{t}_1}, m_{\tilde{\chi}_1^0})$ plane with a 10 GeV × 10 GeV step size. In each grid point, 10^5 events of $\tilde{t}_1\tilde{t}_1^*$ followed by the decay eq. (1.1) are generated using `Herwig++ 2.5.2` [20, 21]. The events are processed by `Delphes 2.0.3` [22] in order to take detector effects into account. We then apply the cuts used in the WW cross section measurement and estimate the efficiency, $\epsilon_i(m_{\tilde{t}_1}, m_{\tilde{\chi}_1^0})$. The NLO cross section of the stop pair production, $\sigma_{\tilde{t}}(m_{\tilde{t}_1})$, is calculated using `Prospino 2.1` [23]. Finally, the SUSY contribution to the signal region is obtained by $N_{\rm SUSY}^{(i)}(m_{\tilde{t}_1}, m_{\tilde{\chi}_1^0}) = \mathcal{L}_{\rm int} \cdot \sigma_{\tilde{t}}(m_{\tilde{t}_1}) \cdot [{\rm BR}(\tilde{t}_1 \to \ell\nu\tilde{\chi}_1^0)]^2 \cdot \epsilon_i(m_{\tilde{t}_1}, m_{\tilde{\chi}_1^0})$, where $\mathcal{L}_{\rm int}$ is an integrated luminosity.

Figures 1 (a)–(c) show the χ^2 in the $(m_{\tilde{t}_1}, m_{\tilde{\chi}_1^0})$ plane for the ATLAS7, CMS7 and CMS8 measurements, respectively. The area below a black line is excluded by the ATLAS direct stop search [13]. In the white top-left region chargino becomes the LSP. Near the boundary of the chargino LSP region, the leptons from the $\tilde{\chi}_1^\pm \to \ell\nu\tilde{\chi}_1^0$ decay become too soft to be detected, leading to $N_{\rm SUSY}^{(i)} \to 0$. Therefore in the vicinity of the boundary the χ^2 approaches to the SM value.

As can be seen, the best fit regions of the three measurements form a similar arc-shaped area, which is roughly symmetric with respect to the dashed green line. The dashed green line shows the kinematical threshold of the $\tilde{\chi}_1^\pm \to W^\pm\tilde{\chi}_1^0$ decay. In the region above this line, the W becomes off-shell and the lepton from the three-body decay, $\tilde{\chi}_1^\pm \to \ell\nu\tilde{\chi}_1^0$,