SUSY at the LHC without Missing $P_T$

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Abstract

We consider a specific class of events of the SUSY particle production at the LHC without missing $P_T$. Namely, we discuss the chargino pair production with a further decay into the W-boson and the neutralino when the masses of the chargino and neutralino differ by 80-90 GeV. In this case, in the final state one has two Ws and missing $E_T$ but no missing $P_T$. The produced neutralinos are just boosted along Ws. For a demonstration we consider the MSSM with non-universal gaugino masses. In this case, such events are quite probable in the region of parameter space where the lightest chargino and neutralino are mostly gauginos. The excess in the $W$ production cross-section reach about 10% over the Standard Model background. We demonstrate that the LHC experiments, which presently measure the $WW$ production cross section at the 8% level can probe chargino mass around 110 GeV within the suggested scenario, which is not accessible via other searches. If the precision of $WW$ cross section measurement at the LHC will achieve the 3% level, then it would probe chargino masses up to about 150 GeV within the no missing $P_T$ scenario.

Keywords: super partners, missing energy and momentum, LHC.

1 Introduction

Search for R-parity conserving Supersymmetry (SUSY) at colliders is traditionally based on the events with missing transverse momenta, $P_T$, which naturally appear due to the escape of the stable lightest supersymmetric particle - LSP. If the mass gap between decaying SUSY particles (either strongly or weakly produced) and the LSP is large enough, then the LSP, usually neutralinos, carry considerable momenta. The triggers which are sensitive to $P_T$ at the level of hundred GeV will illuminate this signature. Unfortunately,
there is no evidence for signals with $P_T$ so far. There are, however, two special cases for different SUSY signals coming from the long-lived particles and events with no missing transverse momentum.

The first case is related to charged particles like charginos which live long enough to produce the secondary vertex or even to escape the detector before decaying into the Standard Model (SM) particle(s) plus neutralino. In the framework of the MSSM with the SUGRA motivated SUSY breaking this might happen when the masses of the chargino and neutralino are degenerate [1]. The closer the masses the longer is the life time. To have the secondary vertex at a few mm or more, one needs the degeneracy smaller than few hundreds of MeV. The gauge mediated models are more favourable for the long-lived particles, and one can easily get the particle to escape the detector undecaying [2]. Both scenarios, however, require the proper fine-tuning of parameters especially in the SUGRA scenario.

The second case is less constrained. If the masses of, say, chargino and neutralino differ by 80-90 GeV, then the decay of the chargino into W and the neutralino is possible and goes with 100% probability. Due to the conservation of energy in the rest frame of the chargino, the decay products are produced almost at rest and in the laboratory frame they are boosted along W. As a result, the chargino pair production gives rise to an additional W pair production accompanied by boosted neutralinos. These neutralinos, being essentially back to back (at the leading order) along the direction of each W-boson carry the energy but do not contribute to missing transverse momentum of the event. Instead, one has the excess of the produced W boson pairs as compared to the Standard Model. Contrary to the usual case, here there will be virtually no contribution to $P_T$ from SUSY particles.

In this note, we study how probable these events are, how big the parameter space is where it happens, and what kind of excess in the W production one might expect for a reasonable interval of chargino masses. As an example, we consider the MSSM with non-universal gaugino masses. We would like to note that these events, where $P_T$ from SUSY particles does not occur at the tree level, in general could acquire a non-negligible $P_T$ in case of an extra hard jet radiated from the initial state quarks. In this case, two neutralinos will not be balancing each other and would give a contribution to missing energy. This $W^+W^-jet + P_T$ signature, which eventually will be suppressed in comparison with the $W^+W^-$ one, could be still potentially interesting in exploring the SUSY parameter space but is not in the scope of the current paper.

One should note that the LHC potential to probe the R-parity conserving SUSY without using the missing transverse momenta information has been discussed previously but in aspects different from the current study. For example, in [3] the authors have shown that high lepton multiplicity events coming from the cascade decays of the coloured SUSY partners could provide constraints on the SUSY parameter space without using $P_T$ information. In paper [4], which is closer in spirit to our study, the authors used the $W^+W^-$ signature to improve the limit on the light stop quarks production at the
LHC. Finally, one should mention the case when the mass gap between the LSP and the
next-to-lightest particle (NLSP) is small, the NLSP still decays promptly in the detector
and the pair production of the NLSP leads to the signature without $P_T$; actually such a
process leads to no signature in the detector at all. To probe such a scenario, it became
traditional now to consider the *monojet signature*, when high-$P_T$ jet is radiated from
the initial state quark or gluon and provides a monojet and $P_T$. In our paper we study
conceptually different scenario with no $P_T$ signature as a key to probe SUSY at the LHC.

## 2 Phenomenology of the no-missing $P_T$ MSSM scenario

In this section, we study the MSSM scenario when $m_{\chi^\pm} - m_{\chi^0} \approx M_W$ and consider
chargino production at the LHC with a subsequent decay into $W$ and a neutralino in the
whole relevant parameter space. As an example we take the MSSM with non-universal
SUSY breaking parameters [5]. This does not limit our analysis since we do not rely on
particular properties of the MSSM but just try to demonstrate that the advocated events
are quite probable and the parameter space is not that much fine-tuned.

In what follows we impose the following constraint:

$$m_{\chi^\pm} - m_{\chi^0} \approx M_W + 0 \div 10 \text{ GeV}.$$  \hspace{1cm} (1)

It can be easily satisfied if both the lightest chargino and neutralino are higgsinos. Then
their masses are given essentially by $\mu$ and are close. However, in this case their interaction
with the light quarks in a proton is suppressed by the smallness of the Yukawa couplings,
and the production cross-section is small. Therefore, we choose the other option and
consider the case when both the lightest chargino and neutralino are gauginos. In this
case their masses are defined by $M_2$ and $M_1$, respectively, and one needs the latter to be
close. This practically excludes the universal scenario where $M_2 = M_1$ at the GUT scale
and run down to the EW scale reaching the ratio 2:1. For this reason we consider the
non-universal gaugino masses and treat them as free parameters at the EW scale.

All together we have the following set of parameters at the EW scale which are essential
for our analysis: $M_2$, $M_1$, $\mu$ and $\tan \beta$. We are interested in the region of parameter space
where the constraint \ref{eq:constraint} is satisfied. Besides, we check the chargino production cross-
section in comparison with the $W$ production in the SM and look for the regions, where
the former one gives a few percent enhancement.

We compare two processes of the $W$ production: the direct SM one and the one
via chargino decay. The corresponding Feynman diagrams are shown in Fig.1. The
leading order (LO) SM cross-section for the $W$ pair production at the LHC with the cm
energy of 8 TeV and 13 TeV is equal to 35.7 and 67.7 pb, respectively. To evaluate it
together with the $\chi^+\chi^-$ production, we use the CalcHEP 3.6.15 code [9] with the parton
distributions MRST2008lo68cl [10] linked to CalcHEP via LHAPDF6 [11] framework. For
In this evaluation, the renormalisation and factorisation scales were set to $\mu_R = \mu_F = M_W$ and the EW parameters were set to reproduce $G_F = 1.16639 \times 10^{-5}$ GeV$^{-2}$. Our LO results for the $WW$ production agree with those from [12], where the authors went up to the NNLO level. They found out that at the LHC energies the NLO order K-factor for the W production is about 1.5, while the NLO K-factor for chargino pair production for chargino masses of the order of 100 GeV is about 1.35 [13]. Hence, at the NLO the ratio of $\sigma_{\chi^+\chi^-}/\sigma_{WW}$ will be slightly reduced by a factor of $1.35/1.5 = 0.9$ as compared to the tree level result. We take it into account in our estimations:

$$\frac{\sigma_{\chi^+\chi^-}}{\sigma_{WW}} \equiv \frac{\sigma_{\chi^+\chi^-}^{NLO}}{\sigma_{WW}^{NLO}} = \frac{\sigma_{\chi^+\chi^-}^{LO}}{\sigma_{WW}^{LO}} \times \frac{K_{\chi^+\chi^-}^{NLO}}{K_{WW}^{NLO}} \simeq \frac{\sigma_{\chi^+\chi^-}^{LO}}{\sigma_{WW}^{LO}} \times 0.9$$  \hspace{1cm} (2)

For our analysis we use the MSSM model implemented into CalcHEP which is publicly available at High Energy Physics Model Database (HEPMDB) at [http://hepmdb.soton.ac.uk/hepmdb:0611.0028](http://hepmdb.soton.ac.uk/hepmdb:0611.0028). One should note that the present theoretical accuracy of $pp \rightarrow W^+W^-$ production at the LHC as defined by its NNLO results ($59.84_{-1.9}^{+2.2}$ pb [12]) is at about 2%, while ATLAS ($71.4 \pm 5.6$ pb [14]) and CMS ($60.1 \pm 4.8$ pb [15]) currently measure this process with the accuracy of about 8%. One can also see from the numbers given above that ATLAS observes about 2σ excess in $WW$ production. Eventually, this excess is not conclusive; however, it provides us with some source of speculation. In particular, we would like to verify if MSSM could provide enough contribution from $\chi^+_1\chi^-_1$ with no $P_T$ kinematics to explain this excess quantitatively.

To calculate the cross-section in the case of chargino decay, we actually calculate the chargino production cross-section and assume that the chargino is produced on shell.
and subsequently decays into $W$ and the neutralino provided $m_{\chi^\pm} \geq m_W + m_{\chi^0}$. In doing so we perform the scan of the whole relevant parameter space mentioned above: $M_1[-500-500 \text{ GeV}], M_2[10-500 \text{ GeV}], \mu[10-2000 \text{ GeV}]$ and $\tan \beta[10-50]$, imposing the constraint (II) and the LEP2 limits on chargino mass reaching 103.5 GeV. To evaluate the cross sections and SUSY mass spectrum, we use the standard CalcHEP subroutines. One should note that in the region (I) the LHC cannot set better limits than LEP2 in the generic scenario when sleptons, squarks and gluino are heavy because of very low $P_T$ (see e.g. [16]).

![Figure 2: $\sigma_{\chi^+\chi^-}$ at the LHC@8TeV versus chargino mass as a colour map of $M_1$ (left) and $\mu$ (right).](image)

The results of the scan are shown in Fig. 2, where we present the ratio $\frac{\sigma_{\chi^+\chi^-}}{\sigma_{WW}}$ at the LHC@8TeV versus chargino mass as a colour map of $M_1$ (left) and $\mu$ (right). One can see that the chargino can contribute up to about 10% to the $W^+W^-$ production at the LHC if chargino mass is of the order of 100 GeV and just above the LEP2 constraints. One can also see from this figure that $\sigma_{\chi^+\chi^-}$ achieves its highest value (for a given chargino mass) for minimal $M_2$ around 100 GeV and high values of $\mu$ parameter, $\mu \gtrsim 400 \text{ GeV}$. In this parameter space chargino has a large wino component and, respectively, large coupling to the $Z$-boson, the main mediator of the chargino pair production. The largest wino component of the chargino defines the upper band of its production cross section. On the contrary, when $\mu$ is small and $M_2$ is large, the chargino has a dominant higgsino component, suppressed coupling to $Z$-boson and, respectively, a low production cross section indicated by the lower band in Fig. 2.

In Fig. 3 we present the ratio $M_2/M_1$ versus $M_1$ as a scatter plot from our scan with the colour map indicating the ratio $\frac{\sigma_{\chi^+\chi^-}}{\sigma_{WW}}$. One can see from this plot that the value of the ratio $\frac{\sigma_{\chi^+\chi^-}}{\sigma_{WW}}$ above a few percent is achievable only for $M_2/M_1 > 3$ and reaches the maximum for $M_2/M_1 \simeq 5 - 6$ where $m_{\chi^+}$ is just above the LEP2 constraints and $m_{\chi^0}$ is about 20 GeV. It is clear that such a scenario cannot be realized for universal gaugino
masses at the GUT scale which gives $M_2/M_1 \simeq 2$ at the electroweak scale.

It is also very informative to look at the other 2-dimensional scatter plots for various pairs of the model parameters and physical masses presented in Fig.4. One can see that practically all the values of the parameters are allowed including the values of $\mu$ and $\tan \beta$; however, if one wants to increase the cross-section one is pushed to the edges of parameter space towards smaller values. These regions are favoured by small chargino and neutralino masses since the cross section of chargino production is inversely proportional to the latter. Note, however, that the ratio of $M_{\chi^+}/M_{\chi^0}$ is constrained to the narrow band where their mass difference satisfies the constraint (1). This band is linear but does not give the fixed mass ratio since it does not go through the origin of the coordinate plane. For small masses one finds that the neutralino mass is very small, which is still not excluded by modern data.

There is no real preference for any particular values of $\tan \beta$ coming from constraint (1). This preference will appear if one considers the other constraints, in particular, the amount of the Dark matter [6]. The $\mu$ parameter might also vary in a wide range but is typically bigger than $M_1$ and even $M_2$ that provides the gaugino origin of the lightest chargino and neutralino. Thus, one can see that the fulfillment of the requirement (1) is not that restrictive and does not require much fine-tuning. One has at least 4 free parameters which can be used to get into the desired region. Even more possibilities appear in extended models. We use here the MSSM as an illustration of the most constrained model. Of course, if one wants to apply more constraints, they might get into contradiction with this one. For instance, the LHC limits already excluded a large part of the parameter
Figure 4: The 2-dimensional scatter plots for various pairs of the model parameters and physical masses from the scan of the low energy MSSM parameter space assuming that constraint (1) is satisfied. The colour map indicates the ratio of the cross-sections of chargino production in the MSSM to the cross-section of W production in the SM at LHC@8TeV.

space. However, on the other hand, the LHC limits are based on the events with $P_T$ and might miss some opportunities. One can think of a model free case and just look for
Table 1: The cross-section of the chargino production at various benchmark points at the LHC at 8 and 13 TeV. The masses of the chargino and the neutralino as well as values for $M_1$, $M_2$ and $\mu$ parameters are given in GeV.

| BM# | $\tan \beta$ | $M_1$ | $M_2$ | $\mu$ | $m_{\chi^0}$ | $m_{\chi^\pm}$ | $\sigma_{WW}^8$ (pb) | $\sigma_{WW}^{13}$ (pb) |
|-----|--------------|-------|-------|-------|---------------|---------------|-----------------|-----------------|
| 1   | 20           | 20    | 100   | 400   | 19.02         | 105.1         | 3.73            | 7.19            |
| 2   | 40           | 22    | 100   | 1000  | 21.65         | 110.0         | 3.23            | 6.22            |
| 3   | 10           | 26    | 105   | 1400  | 25.33         | 115.0         | 2.74            | 5.32            |
| 4   | 10           | 32    | 110   | 1000  | 31.12         | 119.6         | 2.34            | 4.59            |
| 5   | 20           | 40    | 115   | 800   | 39.23         | 125.2         | 1.96            | 3.87            |
| 6   | 10           | 44    | 120   | 1000  | 43.00         | 130.4         | 1.68            | 3.35            |
| 7   | 10           | 48    | 125   | 800   | 46.80         | 135.0         | 1.47            | 2.94            |
| 8   | 20           | 54    | 130   | 600   | 52.85         | 140.0         | 1.27            | 2.55            |

Figure 5: The ratio of the W production cross-section via the chargino decay to the SM cross-section at the LHC for the cm energy of 8 and 13 TeV for various benchmark points from Table 1.

advocated events. The chargino production cross-section in its turn depends on its mass and the mixings. As an illustration, we calculate it for several benchmark points shown in Table 1 for the LHC energies of 8 and 13 TeV. The ratio $\frac{\sigma_{WW}}{\sigma_{WW}^8}$ for the benchmark points from Table 1 is visualised in Fig. 5, where one can see that the W production cross-section via the chargino decay varies between 9 and 4% for the chargino mass range between 105 and 140 GeV. The cross-section $\sigma_{WW}^8$ is close to its maximum when $\mu > M_2$. In this
case the $\sigma_{\chi^+\chi^-}/\sigma_{WW}$ is defined mainly by the chargino mass and its decrease is caused mainly by the parton distributions. Thus, taking higher masses one gets a smaller cross-section and hence a smaller excess in the W production.

We would like to stress once more that our calculations within the MSSM serve as an illustration of the possibility of the SUSY production process without missing $P_T$. Precise values of the cross section and the position of the benchmark points in parameter space are not essential. In a more complicated model these numbers may change but the very possibility of the advocated process remains.

3 Discussion

We have explored the contribution of SUSY particles to the WW production with no $P_T$ signature. We demonstrate that the LHC experiments which presently measure the WW production cross section at the 8% level can probe chargino masses around 110 GeV within the suggested scenario, which is not accessible via other searches. If the precision of the WW cross-section measurement at the LHC will achieve 3% level, then it would probe the chargino masses up to about 150 GeV within the no missing $P_T$ scenario.

This excess of Ws produced via the chargino decay might be noticeable. The recent data on the diboson production with a subsequent decay into muons has shown that all results are compatible with the theoretical expectation within the statistical and systematic uncertainties though some excess with respect to the SM expectations at the level of two $\sigma$ is observed by the ATLAS collaboration [14]. This might be the usual fluctuation but equally might indicate the manifestation of a new physics. The detailed analysis of these data as well as the new run results will clear the case. However, this kind of processes is precisely the one where one can expect the new physics to show up. Possible SUSY interpretation of this excess was considered in a sequence of papers [17] and it was shown that the data from both experiments can be better fitted with the inclusion of electroweak gauginos with masses of O(100) GeV. We have demonstrated that in the case of low energy supersymmetry, these processes are quite natural. The mass range of the electroweak gauginos might be even higher being well within the limits of the LHC searches. They might come with as well as without missing $p_T$. The latter possibility, which is the main concern of our paper, is less probable but is quite possible and should be taken into account in analysis.

Acknowledgements

DK and AS acknowledge financial support from the RFBR grant # 14-02-00494 and the Heisenberg-Landau Program, Grant # HLP-2014-07. AB acknowledges partial support from the STFC grant ST/L000296/1, the NExT Institute, Royal Society Leverhulme Trust Senior Research Fellowship LT140094 and Soton-FAPESP grant.
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