$R$ parity violating SUSY explanation for the CDF $Wjj$ excess

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Recently the CDF Collaboration has reported a statistically significant excess in the distribution of the dijet invariant mass between 120 −160 GeV in $Wjj$ event sample in 4.3 fb$^{-1}$ of data and later confirmed with 7.3 fb$^{-1}$ of data, which has generated considerable interest. We offer a possible explanation of this observation in the general framework of MSSM with $R$-parity violation through resonance production of $\tilde{\nu}_\tau$ decaying into the LSP $\tilde{\tau}_1$ and $W$ boson. We also give the predictions of this scenario for the LHC operating at 7 TeV center of mass energy.

The CDF Collaboration at the Fermilab has recently reported a 4.1$\sigma$ excess in the dijet invariant mass distribution (120 GeV < $M_{jj}$ < 160 GeV) in exclusive 2 jets + lepton + missing transverse energy ($E_T$) events in 7.3 fb$^{-1}$ of data from $p\bar{p}$ collisions at 1.96 TeV where the lepton ($\ell = e$, $\mu$) and $E_T$ are compatible with the decay of a real $W$. A Gaussian fit to the excess region of $M_{jj}$ indicates the peak to be around 147 GeV and it is wider than the $Z$ boson of the Standard Model (SM). There are few hundred events in the excess region of $M_{jj}$, which correspond to $\sigma(Wjj) \sim O$ (pb). Such a large cross-section immediately rules out the possibility of the indication of the SM Higgs boson $H$, because $\sigma(pp \rightarrow W^+H) \times BR(H \rightarrow bb) \simeq 12$ fb. The CDF analysis also reported no significant deviation from the SM expectation of $M_{jj}$ distribution in $Z$+jets and $bb\ell^-E_T$ samples. This result is in agreement with the earlier published one by the CDF Collaboration with 4.3 fb$^{-1}$ of data sample, increasing the significance of the previous result. The position of the $M_{jj}$ peak and the expected cross section for the process has not changed much.

This anomalous excess in the $Wjj$ event sample has naturally generated a lot of interest in the particle physics community, as this could be the long-anticipated direct signal of new physics beyond the SM. However, the DØ Collaboration, using their 4.3 fb$^{-1}$ of data sample, claimed that the distribution of $M_{jj}$ in such events is consistent with the SM prediction [3]. Nevertheless, one should be rather cautious in either believing or disbelieving the claims made by the CDF or the DØ Collaborations. Before coming to any concrete conclusion, one must take into account the different methodologies used by the CDF and the DØ Collaborations to analyze their data samples, estimations of different systematics in the SM backgrounds, especially the QCD background. The DØ Collaboration by simulating $p\bar{p} \rightarrow WH \rightarrow \ell\nu b\bar{b}$ process to model acceptance and efficiency, put an upper limit of 1.9 pb on the cross-section of anomalous dijet production at 95% CL for $M_{jj} = 145$ GeV [3]. As a result of this, their analysis does not rule out the possibility of new physics interpretation of the CDF dijet excess with a cross-section less than 1.9 pb [4]. On the other hand, one can argue that the CDF excess in dijet events could be due to some incorrect modeling of the QCD backgrounds in that mass window. To resolve this issue a joint task force has been formed [5] and till we reach a definitive settlement of the issue it might be interesting to explore the different theoretical avenues that could account for the dijet anomaly. Many such possibilities have been already discussed recently [4, 6–10].

To explain the intriguing CDF result, we propose a scenario in $R$-parity violating (RPV) supersymmetric (SUSY) model, where the lightest stau ($\tilde{\tau}_1$) is the lightest supersymmetric particle (LSP) and the next-to-lightest SUSY particle (NLSP) is the corresponding sneutrino, $\tilde{\nu}_\tau$. All the other superpartners are rather heavy (O (TeV)). The $\tilde{\nu}_\tau$ may be produced resonantly via $R$-parity violating coupling and subsequently decays into a real $\tilde{\tau}_1$ and an off-shell $W$ through $R$-parity conserving charged-current interaction. The real $\tilde{\tau}$ then decays into pair of jets via the same $R$-parity violating coupling and the off-shell $W$ decays into $\ell\nu$. Such resonant slepton production and decay has been briefly discussed in Ref. [2] in the context of CDF $Wjj$ anomaly with a smaller mass splitting between the sneutrino and the stau (only due to the D-term splitting). As a result of this, the lepton from the decay of the virtual $W$ is rather soft to satisfy the CDF criteria of lepton selection which arises from the decay of real $W$. In another analysis [3], authors assumed that the lepton and the sneutrino come from the decay of the LSP charged slepton involving $R$-parity violating couplings and not from the $W$-boson. The sleptons are produced in the decay of the pair produced neutral winos. In addition they assumed that the wino and the charged slepton are nearly degenerate in mass and showed that this scenario can explain the CDF dijet anomaly.

In our analysis of the proposed signal $p\bar{p} \rightarrow \tilde{\nu}_\tau \rightarrow W^-\tilde{\tau}_1^+ \rightarrow \ell^-\bar{\nu}_\ell jj$, we consider a large mass splitting between the $\tilde{\nu}_\tau$ and $\tilde{\tau}_1$. This may be achieved if one considers the $\tilde{\tau}_1$ to be a mixture of left-chiral stau ($\tilde{\tau}_L$) and right-chiral stau ($\tilde{\tau}_R$) and hence the mass splitting between the $\tilde{\nu}_\tau$ and $\tilde{\tau}_1$ can be made significantly larger ($\sim 200$ GeV or so). To have $M_{jj}$ in the correct ball-park, we consider $M_{\tilde{\tau}_1}$ in the range 140 −150 GeV. Now, the sneutrino ($\tilde{\nu}_\tau$) produced through the $R$-parity violating coupling $\lambda'_{311}$...
decays into $\tilde{\tau}_1$ and an on-shell $W$, which then eventually lead to a pair of hard jets (from $\tilde{\tau}_1$ decay) and a charged lepton and neutrino (from real $W$ decay) in the final state.

In our numerical analysis, we use the CTEQ6L parton distribution function [11] with factorization scale $Q = \sqrt{s}/2$, where $\sqrt{s}$ is the parton level CM energy. We also smear lepton and jet energies according to

$$\frac{\sigma(E_j)}{E_j} = \frac{a_j}{\sqrt{E_j/GeV}} \oplus b_j$$

$$\frac{\sigma(E_{\ell})}{E_{\ell}} = \frac{a_{\ell}}{\sqrt{E_{\ell}/GeV}} \oplus b_{\ell}$$

where, $a_j = 13.5\%, b_j = 2\%, a_{\ell} = 75\%$ and $b_{\ell} = 3%$ . After smearing we apply the selection criteria used by the CDF Collaboration, viz.

- lepton ($\ell = e, \mu$) and $E_T$ due to the neutrino should be consistent with decay of a $W$ boson: $E_T(\nu_T) > 20$ GeV, $|\eta| < 1.0$ and $E_T > 25$ GeV with transverse mass $M_T(\ell\nu_T) > 30$ GeV.

- Two jets with $E_{j_T} > 30$ GeV, cone size $\Delta R = 0.4$; $|\eta| < 2.4$ such that $|\eta_j - \eta_W| < 2.5$ and $(p_T)_j > 40$ GeV.

- $|\Delta\phi(E_T,j_1)| > 0.4$ so that $E_T$ should not be due to mismeasurement of jet energy.

- lepton and the jets should be isolated, $\Delta R(j,\ell) > 0.52$.

With all these, we are now well equipped to explain the observations of CDF. We set $M_\sigma = 300$ GeV, $M_{\tilde{\tau}_1} = 145$ GeV. From this mass spectrum, one can see that $\tilde{\nu}_\tau$ can be produced in $s$ channel resonance via the $\chi'_{311}$ coupling, which then decay into the LSP $\tilde{\tau}_1$ and the gauge boson $W$. The LSP $\tilde{\tau}_1$ then decays into a pair of jets via the same $R$ parity violating coupling and the $W$ boson decays semileptonically, which eventually leads to $jj\tilde{\nu}_\tau$ final state with low invariant mass ($M_{jj} \approx 140-150$ GeV).

It has been shown in [7] that the bound on $\chi'_{311}$ coupling from dijet resonance searches both at the CDF and UA2 experiments allows one to take a value of this coupling to be $\leq 0.3$. In our analysis we take the value to be 0.1. With these set of parameters, we estimate $\sigma_{LO}(p\bar{p} \rightarrow \tilde{\nu}_\tau \rightarrow W^- \tilde{\tau}_1^+ \rightarrow jjW) = 1.296$ pb, which is consistent with the 95% CL upper limit on $\sigma(Wjj)$ by the D0 Collaboration. This signal cross-section (1.296 pb) eventually comes down to 71 fb after taking into account the leptonic ($e$ & $\mu$) branching ratio of $W$ boson and imposing all the selection cuts mentioned above. There is no branching ratio suppression from $\tilde{\tau}_1 \rightarrow jj$ decay, as $\tilde{\tau}_1$ decays into a pair of jets with 100% probability, which we think is a rather good approximation given the fact that all other SUSY particles are heavy.

This cross-section corresponds to 518 (305) events with $L_{int} = 7.3$ fb$^{-1}$ (4.3 fb$^{-1}$). The $M_{jj}$ distribution according to our proposed scenario is shown in Fig. 1(a) (top plot). It is very clear that the signal histogram agrees reasonably well with the CDF data points. It may be

\begin{figure}
\centering
\includegraphics[width=\columnwidth]{Fig1}
\caption{The top plot shows the distribution of dijet invariant mass ($M_{jj}$) after the CDF selection criteria have been applied: the points with error bars are taken from CDF data ($L_{int} = 7.3$ fb$^{-1}$), the histogram (red) shows our proposed signal events and a Gaussian is fitted to the histogram (blue line). The bottom plot shows distribution of $M_{Wjj}$ from our signal events.}
\end{figure}

\begin{figure}
\centering
\includegraphics[width=\columnwidth]{Fig2}
\caption{The top plot shows the distribution of dijet invariant mass ($M_{jj}$) after the CDF selection criteria have been applied: the points with error bars are taken from CDF data ($L_{int} = 7.3$ fb$^{-1}$), the histogram (red) shows our proposed signal events and a Gaussian is fitted to the histogram (blue line). The bottom plot shows distribution of $M_{Wjj}$ from our signal events.}
\end{figure}

\footnote{Here, we assume only one $R$-parity violating coupling is dominant at a time.}
noted that detailed implementation of detector effects is beyond the scope of this letter. Hence, instead of quantitative comparison of the number obtained in this analysis, which is somewhat larger than that of the CDF, we restrict ourselves to a qualitative comparison of the features of the distributions obtained. In the top plot of Fig.1 we normalize the signal histogram by the ratio of CDF peak value over the signal peak value. We also fit the signal histogram by a Gaussian and the mean of the Gaussian is given by $M_{jj} = 145$ GeV. The CDF Collaboration has given plots for several kinematic variables from their $7.3 \text{ fb}^{-1}$ data in. In the bottom plot of Fig.1 we display the invariant mass distribution of $M_{\ell\nu jj}$ system. The longitudinal momentum ($p_z$) of the neutrino is obtained by constraining $(p_x + p_y)^2$ to $M_W^2$ and extracting the two possible solutions. To construct the $M_{\ell\nu jj}$ we take the smallest solution between the two. The CDF Collaboration has shown a plot of $M_{\ell\nu jj}$ after subtracting the SM background \cite{CDF}. The plot shows excess in the region of our interest (250 GeV - 300 GeV). However, in their earlier analysis with 4.3 fb$^{-1}$ data sample, this $M_{\ell\nu jj}$ distribution was compatible in shape with the SM background only hypothesis \cite{CDF}. As a result of this, one requires more statistics to reach a definite conclusion in $M_{\ell\nu jj}$ distribution.

At this stage it is also important to look at some other interesting predictions of this scenario in the context of Tevatron. For example, the pair production of $\tilde{\tau}_1$ and subsequent decay of individual $\tilde{\tau}_1$ via $\lambda'_{311}$ coupling can lead to four-jet final state. We find that the leading order cross-section for 145 GeV $\tilde{\tau}_1$ pair production is of the order of $(\sim 4 - 5 \text{ fb})$, which is rather small to be seen at the Tevatron with the available statistics. The $\tilde{\tau}_1$ can also be produced in association with Z and Higgs bosons $H^\pm, h^0, H^0, A^0$ via $\lambda'_{311}$ coupling. As before, $\tilde{\tau}_1$ decays into a pair of jets via the same $R$-parity violating coupling, while Z and Higgs bosons can have several possible decay modes, which eventually lead to some spectacular signatures. Once again, for our scenario, the production cross-sections for these processes are too small to have any relevance at the Tevatron energy. For example, we find that the leading order cross-section $\sigma_{LO}(p\bar{p} \rightarrow \tilde{\tau}_1 + Z) \sim 10^{-2} \text{ pb}$ and we expect that the cross-section for $\sigma(p\bar{p} \rightarrow \tilde{\tau}_1 \Phi^0)$, $(\Phi = H^\pm, h^0, H^0, A^0)$ would be of the same order or even smaller (for heavier Higgs bosons) than $10^{-2} \text{ pb}$. In addition to these, one can have associated production of a $\tilde{\nu}_\tau$ and $\tilde{\tau}_1$ and this can lead to the $W + 4j$ signal where two pairs of jets will show peaks in their invariant mass distributions. Note that in this case the $2 \rightarrow 2$ production process is not suppressed by the small $R$-parity violating coupling. Similarly, pair-produced $\tilde{\nu}_\tau$s can lead to $WW + 4j$ signal at the Tevatron. Note that, with the mass spectrum considered here to explain the CDF dijet anomaly, one should not expect any significant number of events from those two processes with the present luminosity at the Tevatron.

In conclusion in this letter we have analyzed the recently reported dijet invariant mass excess at $4.1\sigma$ in $M_{jj} \sim 120 - 160$ GeV by the CDF Collaboration in $Wjj$ events with $7.3 \text{ fb}^{-1}$ data. We have proposed an $R$-parity violating scenario with $\lambda'_{311}$ as the dominant coupling, where $\tilde{\nu}_\tau$ and $\tilde{\tau}_1$ are the NLSP and the LSP respectively. In this scenario, the mass splitting between the NLSP and the LSP is of the order of hundred GeV, such that NLSP can decay into the LSP and a real $W$ boson. The resonant production of the NLSP can lead to a final state $\ell\nu jj$ where, the pair of jets coming from the $R$-parity violating decay of the LSP, show a peak at $M_{jj} \sim 145$ GeV with a rather good agreement with the dijet invariant mass distribution as shown by the CDF Collaboration at $7.3 \text{ fb}^{-1}$ data. We have also found an $s$ channel resonance at $M_{\ell\nu jj} \sim 300$ GeV, corresponding to our chosen value of the NLSP mass. This result also appears to be very close to the CDF plot of $M_{\ell\nu jj}$ after subtracting the SM background. However, for a definitive conclusion one requires higher luminosity. We note in passing that apart from the possible excess observed in $M_{\ell\nu jj}$ distribution around 250 GeV - 300 GeV, the CDF excess in $Wjj$ events in $4.3 \text{ fb}^{-1}$ as well as $7.3 \text{ fb}^{-1}$ data samples are almost consistent with each other. We have also discussed other possible signatures of this scenario at the Tevatron.

Let us also comment briefly on the implications of this scenario at the LHC, which is accumulating $pp$ collision data at $\sqrt{s} = 7$ TeV. We have found that the production cross-section for $Wjj$ from $pp \rightarrow \tilde{\nu}_\tau \rightarrow \tilde{\tau}_1 + W$ is $7.3 \text{ pb}$. At the LHC, the major SM background processes for this signal comes from the $W + n$ jets process ($n \geq 2$). In the wake of the CDF result the ATLAS Collaboration performed a similar analysis with data from $pp$ collisions at $\sqrt{s} = 7$ TeV \cite{ATLAS}. They have analyzed $33 \text{ pb}^{-1}$ of data collected in 2010 and did not observe any significant difference between SM expectation and observation in the mass range of interest. The estimated $W + n$ jets background is approximately 20 times higher than the rate measured at the Tevatron \cite{ATLAS}. After applying the same set of cuts as discussed before, the signal and the SM background cross-sections are 1.2 pb and 34 pb respectively. As a result of this, the signal significance of our scenario is $\lesssim 1\sigma$ at $33 \text{ pb}^{-1}$ of data. We know that both CMS and ATLAS have already collected $L_{\text{int}} > 1 \text{ fb}^{-1}$ of data per experiment and are likely to collect a few $\text{ fb}^{-1}$ of data by 2012. Hence we may expect that with the increase of luminosity it might be possible to have a definitive conclusion on this issue from both CMS and ATLAS Collaborations.

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