Stop production in R-parity violating supersymmetry at Tevatron

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Abstract
Constraints for stop production in R-parity violating supersymmetry at Tevatron have been evaluated using the D0 limits for first generation leptoquarks. Such limits have been converted in constraints for the $\lambda_{131}$ R-parity violating coupling as a function of the stop mass for different Minimal Supersymmetric Standard Model (MSSM) scenarios and compared with Atomic Parity Violation and HERA results. The D0 limits have also been interpreted in terms of constraints on the parameters of the minimal Supergravity model. For a part of the considered MSSM parameter space and for stop mass less than 240 GeV, Tevatron results are the best to date.

PACS no: 11.30.Pb, 14.60.Cd, 14.80.Ly
1 Introduction

New exotic states connecting lepton and quark sectors naturally arise in grand unification theories [1] that arrange quarks and leptons in common multiplets (leptoquarks, LQ) or in supersymmetric (SUSY) models that violate $R$-parity [2] (squarks, $\tilde{q}$). These states should be produced by the same processes at the colliders but differ for the decay modes. Leptoquarks exclusively decay via a Yukawa coupling in a lepton and a quark while squarks have further gauge decay modes in a gaugino and a quark or in a squark of different flavor and a $W$. In proton-anti-proton collisions at Tevatron both leptoquarks and squarks should be pair produced via ordinary gauge couplings dominantly by quark-anti-quark annihilation and gluon-gluon fusion. A detailed description of stop phenomenology in $R$-parity violating SUSY at Tevatron can be found in [3].

The study presented here focuses on the stop ($\tilde{t}$, supersymmetric partner of the top-quark) production, since it is predicted to be the lightest sfermion in a large variety of possible supersymmetric scenarios. In $R$-parity violating SUSY a Yukawa coupling $\lambda'_{131}$ (where the subscripts are generation indices) rules the partial width of the reaction $\tilde{t} \to eq^2$ while the partial width of the gauge decays depend on the SUSY scenario considered. In this paper we evaluate 95% confidence level (CL) limits for the stop in $R$-parity violating SUSY at Tevatron, using recent D0 limits [4] (table I) on the mass of first generation leptoquarks as a function of the branching ratio to an electron and a quark. Such results have been obtained using Tevatron run II data corresponding to an integrated luminosity of $\simeq 250$ pb$^{-1}$. Similar limits have been previously evaluated using $\simeq 120$ pb$^{-1}$ of integrated luminosity collected during the Tevatron run I [3].

Constraints on stop production in $R$-parity violating SUSY have been already reported by the H1 [5] and ZEUS [6] collaborations at HERA, where the stop can be resonantly produced by electron-quark fusion via the $\lambda'_{131}$ coupling. Indirect limits also come from low-energy experiment on atomic parity violation (APV) [7, 8].

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1 The SUSY partners of the left- and right-handed top, $\tilde{t}_L$ and $\tilde{t}_R$, mix together in two mass eigenstates, $\tilde{t}_1$ and $\tilde{t}_2$, which are strongly non-degenerate due to the large top mass. Throughout the paper, with the symbol $\tilde{t}$ we always refer to the lightest stop, $\tilde{t}_1$.

2 Here and in the following we generically refer to both stop and anti-stop; $e$ hence denotes both a positron or an electron and $q$ a $d$- or an anti-$d$-quark. Throughout the paper we also use ”electron” to denote both an electron or a positron.

3 The D0 limits obtained assuming that both LQs decay to $eq$ (final states with two electrons and two jets) have been considered in this study. The combined limits, obtained looking also at the $\nu q$ decay of one of the two LQs (final states with one electron, two jets and missing transverse energy), cannot be applied to the stop.

4 First generation leptoquarks are assumed to couple only to quarks and leptons of the first family.
| $\text{Br}(LQ \to eq)$ | 0.5 | 0.6 | 0.7 | 0.8 | 0.9 | 1. |
|-------------------------|-----|-----|-----|-----|-----|-----|
| LQ mass limit (GeV)     | 158 | 180 | 203 | 220 | 232 | 241 |

Table 1: D0 95% CL exclusion limits for first generation leptoquark mass as a function of the branching ratio to an electron and a quark.

2 Results

The constraints on stop production have been obtained using the program SUSYGEN 3 [9, 10] to describe different SUSY scenarios. The only $R$-parity violating Yukawa coupling different from zero was assumed to be $\lambda'_{131}$. A particular scenario is ruled out at 95% CL if it predicts for the stop a branching ratio to $eq$ already excluded by the D0 leptoquark analysis.

An unconstrained Minimal Supersymmetric Standard Model (MSSM) scenario was initially considered. The masses of the sfermions are free parameters of the model while the masses of the neutralinos, charginos and gluinos are determined by the following parameters: the mass term $\mu$ which mixes the Higgs superfields, the soft SUSY-breaking parameters $M_1$, $M_2$ and $M_3$ for the $U(1)$, $SU(2)$ and $SU(3)$ gauginos, respectively, and $\tan \beta$, the ratio of the vacuum expectation value of the two neutral scalar Higgs fields.

The mass of the lightest stop was varied in the range $150 - 280$ GeV while the masses of the other squarks and all the sleptons have been set at 1 TeV. In order to have a direct comparison between HERA and Tevatron sensitivities, we considered the same scenarios investigated by the ZEUS collaboration which published a search for stop production looking both at the $eq$ and $b\chi^+_1$ (where $\chi^+_1$ is the lightest chargino) decays [6]: $\tan \beta = 6, 300 \leq \mu \leq 300$ GeV and $100 \leq M_2 \leq 300$ GeV. Scenarios leading to a neutralino mass less than 30 GeV, already excluded by LEP results [11], were discarded. Figures 1 and 2 show limits on $\lambda'_{131}$ as a function of the stop mass for three choices of the parameter space. The lighter (darker) area denotes the region excluded by D0 for part of (all) the considered scenarios. The thick solid lines show the ZEUS limits; the region between the two lines (above the upper line) is excluded for part of (all) the considered scenarios. H1 published similar results [5]. Both D0 and ZEUS limits have a weak dependence of $\tan \beta$; D0 results for $\tan \beta = 2$ and 50 (dashed lines) are also reported. The dotted line is the indirect constraint from atomic parity violation (APV) [7, 8] measurements, the region above the line is excluded.

For low values of $M_2$ (fig. 1 a) or $|\mu|$ (fig. 1 b) D0 constraints are not competitive with ZEUS ones for stop masses larger than $\sim 150$ GeV. Indeed, in this region of the param-

\footnote{The gaugino masses are assumed to converge to a common mass $m_{1/2}$ at the GUT scale, leading to relations among $M_1$, $M_2$ and $M_3$. The SUSY scenario is thus defined by just one of the three soft SUSY-breaking masses.}
eter space, the first chargino is lighter than the stop and the gauge stop decay $\tilde{t} \to b\chi^+_1$ dominates over the $\tilde{t} \to eq$ decay.

Quite different is the high $M_2$ - high $|\mu|$ case (fig. 2) where, due to the high chargino mass, the stop branching ratio to $eq$ is dominant. Since at Tevatron, contrary to HERA, the stop production cross section is independent of the $\lambda'^{131}$ coupling, much lower coupling values can be probed in this case. It is interesting to note that, in this range of parameters, the excluded ZEUS region is almost completely superseded by D0 and APV limits.

In order to test the validity of the D0 constraints towards higher $|\mu|$ and $M_2$, a larger scan of the SUSY parameter space was performed for fixed stop mass and for two values of $\lambda_{131}' = 10^{-3}$ and $10^{-4}$. Fig. 3 a and b show the D0 exclusion limits for $\tan \beta = 6$ in the $\mu$-$M_2$ plane in the case of $M_{\text{stop}} = 200$ and 240 GeV, respectively. The darker area denotes the region excluded for a coupling $\lambda_{131}' = 10^{-4}$, the lighter area is the further exclusion region for $\lambda_{131}' = 10^{-3}$. The D0 constraints are still valid at the highest $|\mu|$ and $M_2$ values and show negligible dependence of $\tan \beta$ as shown by the limits for $\tan \beta = 50$ (dashed lines) which are also reported. The limits have also a small dependence of the

**Figure 1:** 95% CL exclusion limits for $\lambda_{131}'$ as a function of the stop mass for low $M_2$ (a) and low $|\mu|$ (b) MSSM scenarios. The lighter (darker) area denotes the region excluded by D0 for part of (all) the considered scenarios for $\tan \beta = 6$. The thick solid lines show the ZEUS limits for $\tan \beta = 6$; the region between the two lines (above the upper line) is excluded for part of (all) the considered scenarios. D0 results for $\tan \beta = 2$ and 50 (dashed lines) are also reported. The dotted line is the indirect constraint from APV measurements.
slepton masses, the scan was repeated lowering the mass of all sleptons from 1 TeV to 100 GeV, as expected no remarkable variations were observed.

Even if we focused on the coupling $\lambda_{131}'$ in order to have a direct comparison with HERA constraints, Tevatron limits are largely independent of the flavor of the quark coming from stop decay. The limits hence apply to the generic coupling $\lambda_{13j}'$ with $j = 1, 2, 3$.

Respect to the previously reported Tevatron limits on stop in $R$-parity violating SUSY [3] our results are based on a twofold integrated luminosity, further a larger scan of MSSM parameter space has been performed.

Besides $\lambda_{13j}'$, also $R$-parity violating MSSM scenarios involving the coupling $\lambda_{23j}'$ have been investigated using Tevatron Run II dimuon data [12].
Figure 3: 95% CL D0 exclusion limits in the $\mu$-$M_2$ plane for MSSM scenarios with $\tan\beta = 6$ in the case of $M_{stop} = 200$ (a) and 240 GeV (b). The darker area denotes the region excluded for a coupling $\lambda'_{131} = 10^{-4}$, the lighter area is the further exclusion region for $\lambda'_{131} = 10^{-3}$. Limits for $\tan\beta = 50$ (dashed lines) are also reported.

The study has been also extended to the minimal Supergravity model (mSUGRA) [13–15]. In this model the number of free parameters is further reduced by assuming, beside the common gaugino mass $m_{1/2}$, also a common sfermion mass $m_0$ at the GUT scale. Radiative corrections are assumed to drive the electroweak symmetry breaking (REWSB), leading to consistency relations that allow the complete model to be fixed by only five parameters: $m_0$, $m_{1/2}$, $\tan\beta$, the sign of $\mu$ and the common trilinear coupling $A_0$. The mSUGRA scenario was modelled by SUSYGEN 3 [9, 10] which makes use of the SUSPECT 2.1 [16] program to solve the REWSB consistency relations that determine the sparticle masses at the electroweak scale. The same scenarios analysed by the ZEUS [6] collaborations ($\tan\beta = 6$, $\lambda'_{131} = 0.3$, $A_0 = 0$, $m_0 \leq 300$ GeV, $m_{1/2} \leq 180$ GeV) were studied. In this case Tevatron limits are not competitive with HERA results, since, being the chargino always lighter than the stop, the gauge decays of the stop are dominant for all the scenarios considered.

3 Conclusions

Limits at 95% CL for stop production in $R$-parity violating SUSY at Tevatron have been evaluated using D0 constraints for first generation leptoquarks obtained using data col-
lected in run II and corresponding to an integrated luminosity of $\simeq 250 \text{ pb}^{-1}$.

Both unconstrained MSSM and mSUGRA scenarios have been considered. For the considered mSUGRA scenarios ($\tan \beta = 6, \chi'_{131} = 0.3, A_0 = 0, m_0 \leq 300 \text{ GeV}, m_{1/2} \leq 180 \text{ GeV}$), Tevatron limits are weaker than HERA ones. In the MSSM case, for large $M_2$ ($280 < M_2 < 300 \text{ GeV}$) and $|\mu|$ ($270 < |\mu| < 300 \text{ GeV}$), Tevatron results, for stop masses less than 240 GeV, are the best to date. The Tevatron limits remain competitive also for higher $|\mu|$ and $M_2$ and have a negligible dependence of $\tan \beta$ and slepton masses. For lower values of $M_2$ or $|\mu|$ HERA limits are stronger.

4 Acknowledgements

We would like to thank M. Corradi, E. Gallo and M. Kuze for critical reading of the manuscript and helpful comments.

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