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TEVATRON SUSY RESULTS*

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Recent results on searches for SUSY particles at the Tevatron are presented.

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1. Introduction

Supersymmetry or SUSY [1], a proposed invariance of Nature for the interchange of fermionic and bosonic degrees of freedom, has many important features which justify an intensive research at the highest energy accelerators. To cite a few: it is the basic ingredient for unification of the four known forces, it is the only non-trivial extension of the Lorentz–Poincaré group and it provides an elegant solution to evade the fine tuning problem of the Standard Model (SM). In MSSM, the minimal extension of the SM, every SM particle has a partner differing in spin, S by $1/2$ unit. They are assigned an R-parity $R=(-1)^{3B+L+2S}=-1$, where B is the baryon and L is the lepton number of the particle, in contrast to the SM particles of $R=+1$. Another important feature of the MSSM is that a second Higgs doublet has to be introduced, which predicts 4 more Higgs particles which have $R=+1$. Here we shall report only on searches of the $R=-1$ partners, the additional Higgs sector is dealt with in a different talk.

If SUSY were an exact symmetry, one would need to introduce only one additional parameter, μ. However it is not the case, since the $R=-1$ partners have not yet been observed. The description of the symmetry breaking needs many new parameters, which can be reduced in certain models

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to a manageable number: for example to 5 (m_0, $\mathrm{m}_{1/2}$, $\tan\beta$, A_0 and the sign of μ) in the mSUGRA model [2] and to 6 (Λ, M_m, N_5, C_grav, $\tan\beta$ and the sign of μ) in the mGMSB model [3], treated here below.

In most cases R-parity is assumed to be conserved (RPC) since there are severe limits on B- and L-violating processes. Then, the SUSY partners are pair produced and the lightest SUSY particle (LSP) is neutral and weakly interacting, thus it escapes detection. Therefore, the basic experimental signature for SUSY is missing transverse energy (MET) and multiple jets and leptons originating from the cascade decay of the heavy $R = -1$ partners. The main SM backgrounds are $t\bar{t}$ production, gauge boson production either in pairs or accompanied by jets.

However R-parity violation (RPV) is not excluded. This would allow single resonant formation of SUSY particles, the production of even more jets or leptons in the final state from the B- or L-violating processes. In this case the theory contains 48 additional unknown Yukawa couplings. One usually assumes that only one of these couplings is non-zero at a time. At the Tevatron both RPC and RPV processes have been studied.

The Tevatron is a proton–antiproton collider with a collision energy of 1.96 TeV at the center of mass. It is situated at Fermilab near Chicago. Run IIa has ended in February of this year with a recorded dataset corresponding to an integrated luminosity of $\approx 1.3\ \mathrm{fb}^{-1}$. It represents about 10 times of the statistics collected in Run I. Run IIb has just started with the hope to reach minimum 4, possibly $8\ \mathrm{fb}^{-1}$ by the year 2009. Only results based on at least $0.3\ \mathrm{fb}^{-1}$ integrated luminosity are reported here. Details can be found on the corresponding web-sites [4, 5]. All limits are quoted at 95% C.L., if not stated otherwise.

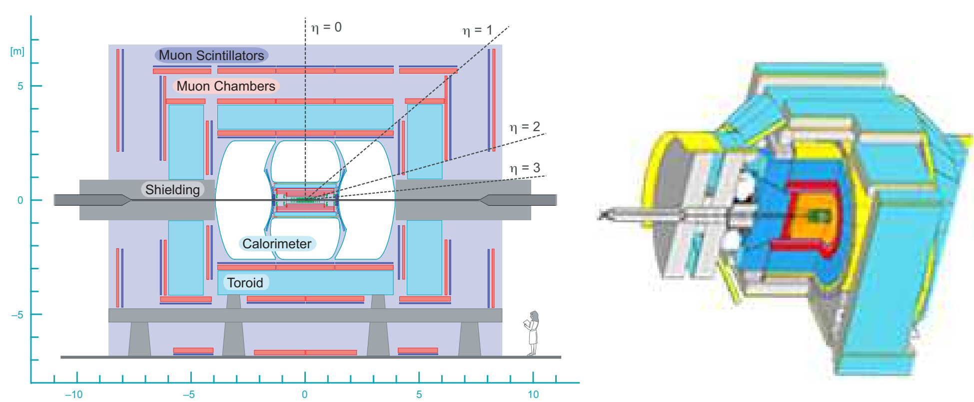

Fig. 1. The schematic view of the DØ (left) and CDF (right) detectors.

The particles produced in the collisions are detected by the DØ and CDF detectors. Both of them have adequate performance figures to search for SUSY in detecting/identifying electrons, photons, muons, taus, jets of light and heavy flavours. The schematic views of the DØ and CDF detectors are shown in Fig. 1.

2. Chargino–neutralino searches

The dominant production of charginos and neutralinos at the Tevatron along with their leptonic decays are depicted in Fig. 2.

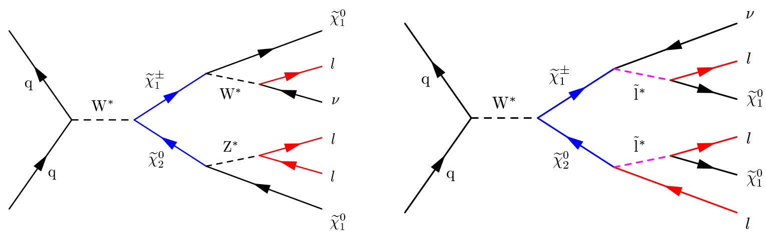

Fig. 2. Dominant production of charginos and neutralinos at the Tevatron and their decays.

The experimental signature searched for is three leptons, where the third lepton could be a charged track, accompanied by MET, or two leptons of same charge (SC) and MET. The SM background (Z/γ^*+jets, QCD (multi-jets), WW/WZ and $t\bar{t}$ production) is relatively small. This background is already well under control at the preselection stage, as for example Fig. 3 (left) shows.

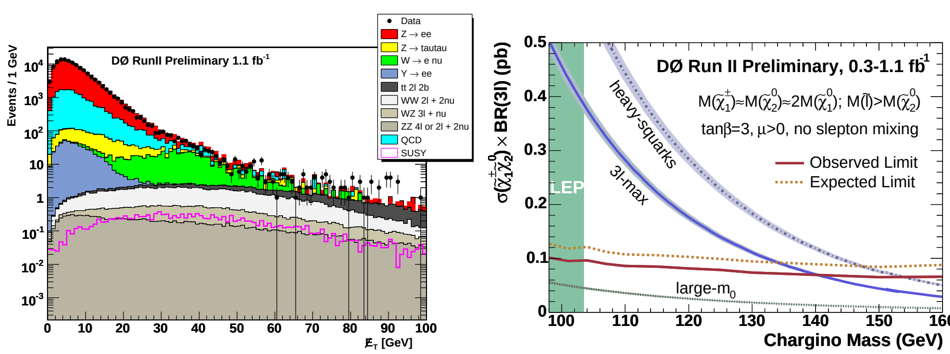

Fig. 3. MET distribution at the preselection stage of *eel* events selected by DØ (left). Cross section upper limits times branching fraction of chargino and neutralino production measured by DØ along with theoretical predictions (right).

Because of the small leptonic branching fractions several final states had to be studied and combined. Table I shows the different channels studied by the two collaborations. Since the observed numbers of events are in agreement in every channel with the predicted background, upper limits of cross-section times branching fraction were derived, as shown, *e.g.* in the case of DØ (see Fig. 3, right). The theoretical predictions are also shown for three cases within the framework of mSUGRA for mass relations indicated in the figure. From them, lower limits of the chargino mass have been derived: 140 GeV when the slepton mass is slightly above the mass of the second neutralino, thus allowing only 3-body decay, and 155 GeV for the case when squarks are heavy and therefore the destructive t-channel contribution is minimal. It should also be noted that in the 9 SC candidate events found by CDF the leading leptons have high transverse momentum, p_{T}, in 4 events it is above 60 GeV.

TABLE I

Three (two) lepton final states studied by the DØ and CDF collaborations.

DØ channels	$\mathcal{L}_{\mathrm{int}}$ (fb^{-1})	Background	Data
ee+track	1.2	0.82±0.66	0
$\mu\mu$+track	0.3	1.75±0.57	2
$e\mu$+track	0.3	0.31±0.13	0
$\mu^+\mu^+/\mu^-\mu^-$	0.9	1.1±0.4	1
$e\tau$+track	0.3	0.58±0.14	0
$\mu\tau$+track	0.3	0.36±0.13	1
CDF channels	**$\mathcal{L}_{\mathrm{int}}$ (pb^{-1})**	**Background**	**Data**
$e^\pm e^\pm, e^\pm\mu^\pm, \mu^\pm\mu^\pm$	710	6.80±1.00	9
$\mu\mu + e/\mu$ (low p_{T})	310	0.13±0.03	0
ee+track	610	0.48±0.07	1
$ee + e/\mu$	350	0.17±0.05	0
$\mu\mu + e/\mu$	750	0.64±0.18	1
$\mu e + e/\mu$	750	0.78±0.15	0

CDF and DØ have also studied chargino–neutralino pair-production in the case when the lightest neutralino was allowed to decay into leptons through the R-parity violating term $\lambda_{ijk}L_iL_j\bar{E}_k$. Here, L and E are lepton super fields and i, j, k are generation indices. It was assumed that only one coupling constant λ is non-zero at a time and its value is sufficiently large that no displaced vertex is produced. CDF has searched for events with 4 leptons and found none in a dataset of $\mathcal{L}_{\mathrm{int}} = 0.35$ fb^{-1} with an expected background of 0.008 ± 0.004. DØ searched in a similar size of data set for events with 3 well identified leptons in the eel, $\mu\mu l$ and $ee\tau$ channels, where l could be either an electron or a muon. No events have been found with an expected background of 0.9 ± 0.4, 0.4 ± 0.1 and 1.3 ± 1.8 in the 3 channels, respectively. By combining the 3 channels lower limits for the lightest chargino and neutralino masses were derived for $\lambda_{121}, \lambda_{122}$ and λ_{133}, respectively.

If λ_{122} is sufficiently small, the decay of the lightest neutralino may produce a displaced vertex. DØ has searched for opposite sign (OS) muon pairs with a reconstructed vertex between 5 and 20 cm away from the beamline in the transverse plane. No such pairs were found with an expected background of 0.75 ± 1.6 which allowed to set 95%(99%) C.L. upper limit of cross-section times branching fraction as a function of the neutral long lived particle's (NLL) mass and lifetime, respectively (see Fig. 4). These limits exclude the interpretation of the three events observed earlier by NuTeV as being long lived neutralinos.

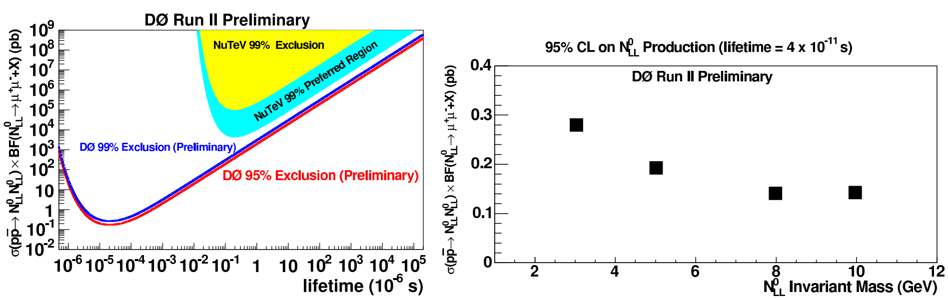

Fig. 4. 95%(99%) C.L. cross-section upper limits times branching fraction for neutral long lived (NLL) particles of mass 5 GeV as a function of its lifetime (left). The same quantity for 95% C.L. at fixed lifetime as a function of the mass of the NLL particle (right).

In the mGMSB scenario the LSP is the gravitino and in one of the variants the next-to-lightest SUSY particle (NLSP) is the lightest neutralino, which then decays to a gravitino and a photon. The lifetime of the NLSP depends on the $C_{\rm grav}$ parameter of the model. DØ and CDF have searched for two high energy prompt photons accompanied by large MET, caused by the gravitino. As one can see in Fig. 5 (left) the observed MET distribution is compatible with what one expects from the SM. With recent data, corresponding to 760 pb^{-1}, DØ has improved the previous limit on the Λ parameter (and thereby the lightest chargino and neutralino mass limits) obtained from combined measurements of CDF and DØ. The new limit is shown in Fig. 5 (right).

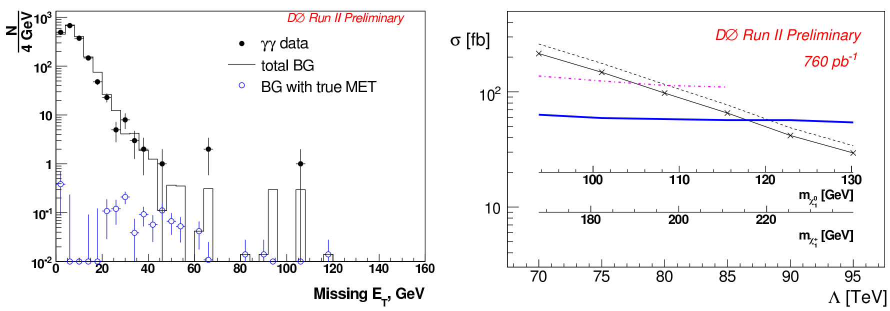

Fig. 5. MET distribution of recent DØ data (full circles), that of the background (histogram) and a part of the latter with true MET (open circles) of events containing 2 photons (left). Cross section upper limits (solid blue line) and theoretical LO (NLO) cross-section for the GMSB process (solid (dotted) black lines) (right).

CDF searched for similar events assuming long lifetime for the NLSP, by looking for "late" photons in the calorimeter. The Fig. 6 (left) shows that the arrival time distribution of photons accompanied by MET doesn't show significant excess at positive times where the GMSB signal is expected. One observed 10 events with 7.6 ± 1.9 background expected. This allowed to exclude a region in the plane of the neutralino lifetime *versus* its mass, as shown in Fig. 6 (right).

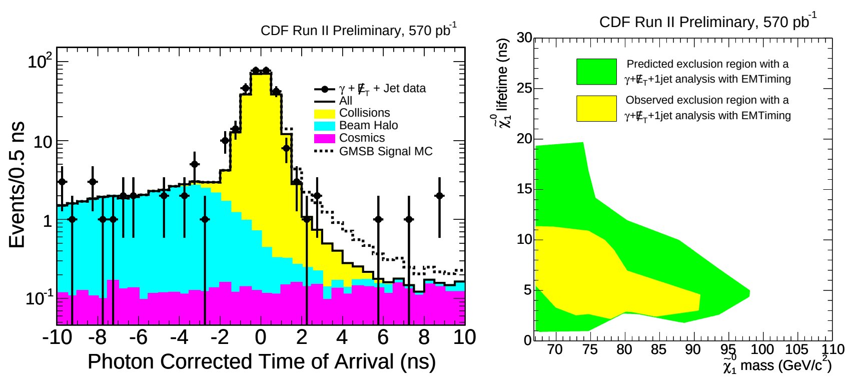

Fig. 6. Photon arrival time distribution in the CDF calorimeter (left). Excluded mass and lifetime values of the lightest neutralino (NLSP) (right).

DØ has studied chargino pair production assuming anomaly mediated symmetry breaking. In this case the mass difference of the lightest chargino and neutralino is expected to be small, say less than ≈150 MeV. Therefore, wino-like charginos possibly live long, appear as muons in the detector, but they are slower. The speed significance, defined as $s = (1 - v)/\sigma_v$, where v

is the speed of the chargino in units of the speed of light and σ_v is its error, is shifted toward positive values depending on the mass, as indicated in Fig. 7 (left) for heavy staus. Therefore two muons with $s > 0$ were searched for. The observed number of events was compatible with the expected background, determined by muon pairs from the $Z \to \mu^+\mu^-$ decay. An upper limit of the production cross-section was derived (see Fig. 7, right) which, by confronting with the theoretical cross-section, excludes wino-like charginos with mass less than 174 GeV.

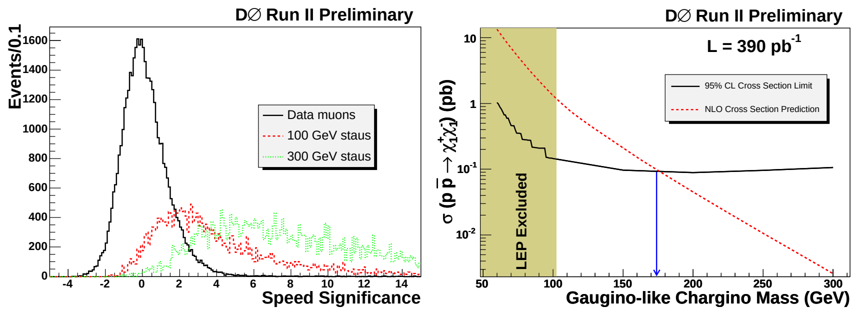

Fig. 7. Speed significance distributions of muons and of staus of two different masses. They are similar for charginos of the same mass (left). Cross section upper limit and theoretical cross-section for a gaugino-like chargino as a function of its mass (right).

3. Slepton searches

Sleptons are searched for at the Tevatron mainly by RPV resonant production, as indicated in Fig. 8 (left).

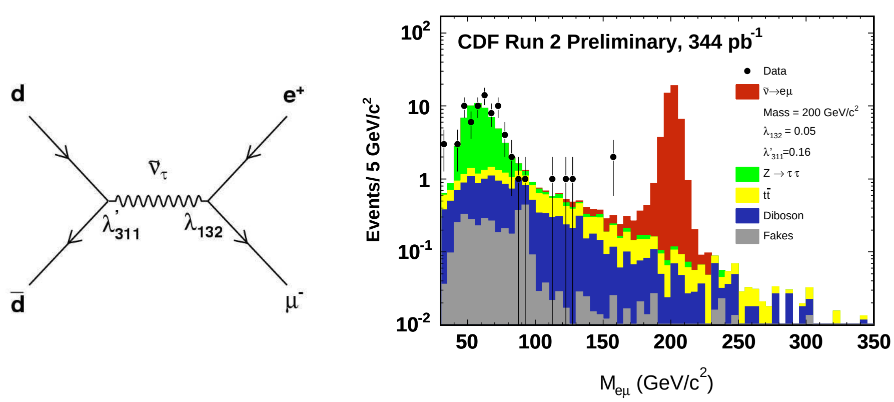

Fig. 8. RPV production and decay of $\tilde{\nu}_\tau$ (left). Invariant mass distribution of the electron–muon pair obtained by CDF (right).

Here, a $\tilde{\nu}_\tau$ is produced with a λ'_{311} Yukawa coupling which subsequently decays to a pair of OS electron–muon pair via a non-zero λ_{132}. As indicated in Fig. 8 (right), if such a process would exist, a clear peak in the electron–muon invariant mass would be seen. CDF searched for such electron–muon pairs, but has seen no indication for an enhancement in their mass distribution (*cf.* Fig. 8, right). Therefore exclusion limits as a function of the $\tilde{\nu}_\tau$ mass and the two Yukawa couplings are derived as shown in Fig. 9 (left).

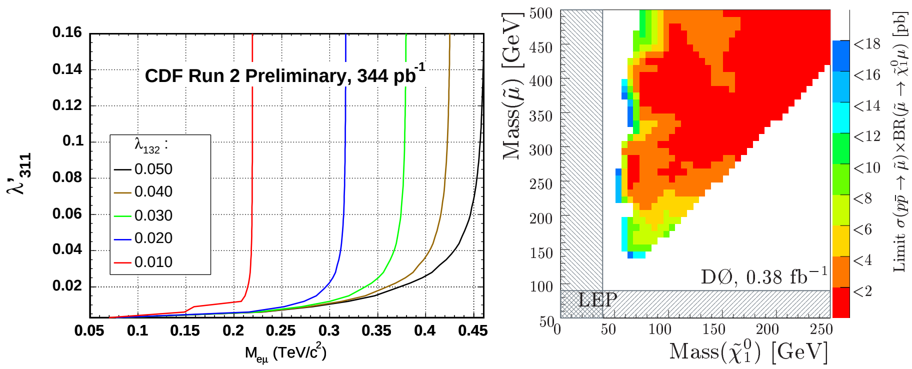

Fig. 9. Excluded regions on the plane λ'_{311} vs the $\tilde{\nu}_\tau$ mass obtained by CDF (left). Cross section upper limits for the slepton mass versus the neutralino mass obtained by DØ (right).

DØ has searched for resonant production of $\tilde{\nu}_\mu$ and $\tilde{\mu}$ assuming that only λ'_{211} is non zero and is large enough that the RPV decay of the lightest neutralino at the end of the decay change would not produce displaced vertex. The event topology searched for was 2 isolated muons and at least 2 jets. Using the leading muon and the two leading jets one would be able to reconstruct the lightest neutralino, and a peak in the invariant mass of the 2 muons and all jets would indicate the presence of the slepton. No evidence has been found for the existence of this process. The obtained cross-section upper limits as a function of the neutralino and slepton mass are shown in Fig. 9 (right). Having confronted these cross-section limits with the theoretical cross-sections one obtained 210, 340 and 363 GeV lower limits for the slepton mass for λ'_{211} values of 0.04, 0.06 and 0.10, respectively.

4. Gluino–squark searches

DØ has carried out a generic search for gluinos and squarks requiring a minimum number of jets, N_j, and a minimum value of MET and H_T, the scalar sum of the jet transverse energies for the following three cases: (*i*) $N_\mathrm{j} = 2$ if $M_\mathrm{sq} < M_\mathrm{gl}$, (*ii*) $N_\mathrm{j} = 3$ if $M_\mathrm{sq} \approx M_\mathrm{gl}$, (*iii*) $N_\mathrm{j} = 4$ if $M_\mathrm{sq} > M_\mathrm{gl}$, where $M_{\rm sq}$ and $M_{\rm gl}$ is the mass of the squark and that of the gluino, respectively. One observed a general agreement between data and the expected background in all stages of selection, as can be seen *e.g.* in Fig. 10 (left), where the MET distribution is displayed in case of (*iii*). The obtained exclusion region in the $(M_{\rm gl}, M_{\rm sq})$ plane is shown in Fig. 10 (right). Also shown is the excluded region obtained by CDF using 3-jet event topology. The absolute lower mass limits are $M_{\rm sq}$ >325 GeV, $M_{\rm gl}$ >241 GeV, and $M_{\rm gl}$ >387 GeV, if $M_{\rm sq} \approx M_{\rm gl}$.

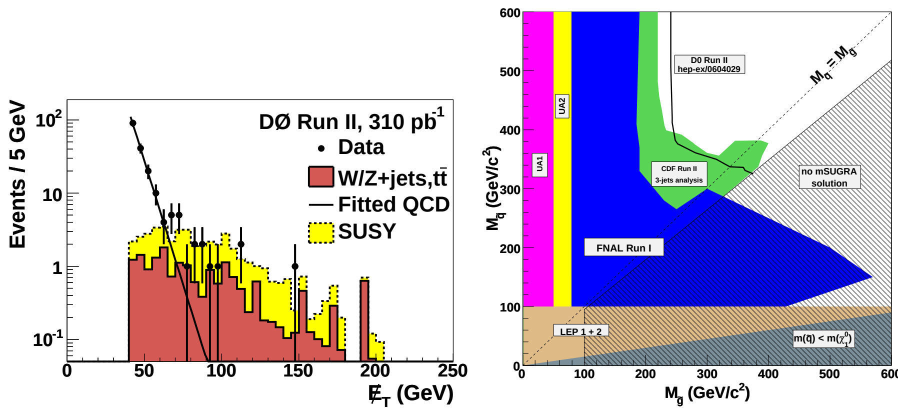

Fig. 10. MET distribution obtained by DØ for the 4-jet event topology and compared with the SM background and the expected SUSY signal (left). Excluded regions in the $(M_{\rm gl}, M_{\rm sq})$ plane obtained by CDF and DØ (right). It should be noted that DØ has used conservatively a theoretical cross-section reduced by its uncertainty.

Squarks and gluinos, however, may not have equal masses. For example, in the so-called "Split-SUSY" model squarks and sleptons are very heavy, whereas gluinos are light, so the latter are produced copiously. Moreover, they can have a long lifetime, enough to hadronize into R-hadrons. R-hadrons can have electric charge, in this case they lose energy, and eventually stop in the calorimeter and decay. These decays may happen even after several bunch crossings. DØ has searched for stopped gluinos in the $\tilde{g} \to g + \chi_1^0$ decay channel by looking for randomly oriented jets without underlying event. The background consists mainly of cosmic and beam-halo muon induced jets where the muon escaped reconstruction. It has been studied using the data. Fig. 11 (left) shows the energy distribution of the observed jets, along with that of the estimated background. As can be seen the data does not show any excess above the expected background. The derived cross-section upper limits are shown in Fig 11 (right) as a function of the gluino mass for different mass values of the χ_1^0. The theoretical cross-section is also shown, from which gluino masses below ≈300 GeV can be excluded if the mass of the χ_1^0 is less than 90 GeV.

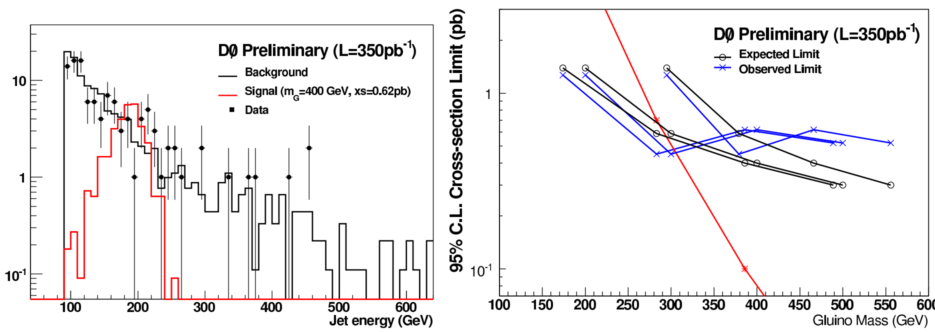

Fig. 11. Energy distribution of the selected jets (dots with error bars), that of the background (black histogram) and of a gluino of mass 400 GeV decaying into a gluon and a neutralino of mass of 90 GeV (left). Expected and observed cross-section upper limits as a function of the gluino mass for neutralino masses of 50, 90 and 200 GeV (right). Also shown is the theoretical cross-section (red star).

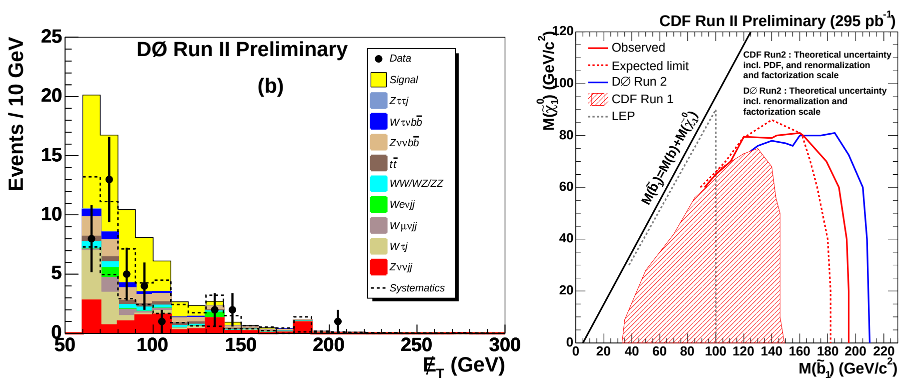

Fig. 12. MET distribution of events with at least one b-tagged jets observed by DØ together with the SM background and expected signal (left). Mass values of the sbottom and neutralino excluded by DØ and CDF (right).

Squarks of the 3rd generation deserve special attention since due to large mixing between the scalar partners of the left and right handed quarks one of them may be light and easily accessible at the Tevatron. Both DØ and CDF have searched for direct pair production of the lightest sbottom quark assuming that it decays 100% into a b-quark and the lightest neutralino. The experimental signature is two acoplanar b-jets and MET. In both analyses at least one of the jets was required to have a b-tag. The cut value of the MET and that of the E_{T} of the jets were optimized according to the mass value of the sbottom to be detected.

The data did not show any significant excess over the expected SM background as can be seen *e.g.* in Fig. 12 (left), where the MET distribution obtained by DØ is shown. The excluded mass values of the sbottom and the neutralino are shown in Fig. 12 (right).

If the mass M_{st} of the lightest stop quark $\tilde{t}_1$ satisfies the relation

$$M_c + M_{\chi_1^0} < M_{\mathrm{st}} < M_b + M_W + M_{\chi_1^0}\,,$$

where M_c, M_b, $M_{\chi_1^0}$, and M_W are the masses of the c-, b-quark, lightest neutralino, and the W, respectively, its dominant decay mode is $\tilde{t}_1 \to c + \chi_1^0$, and similar search strategy can be applied as for the sbottom outlined above, except that jets should satisfy a c-tag instead of a b-tag criterion. Again, data observed by DØ and by CDF showed agreement with SM expectation (see *e.g.* Fig. 13, left) which allowed to extend the earlier excluded regions of M_{st} and $M_{\chi_1^0}$, as shown in Fig. 13 (right).

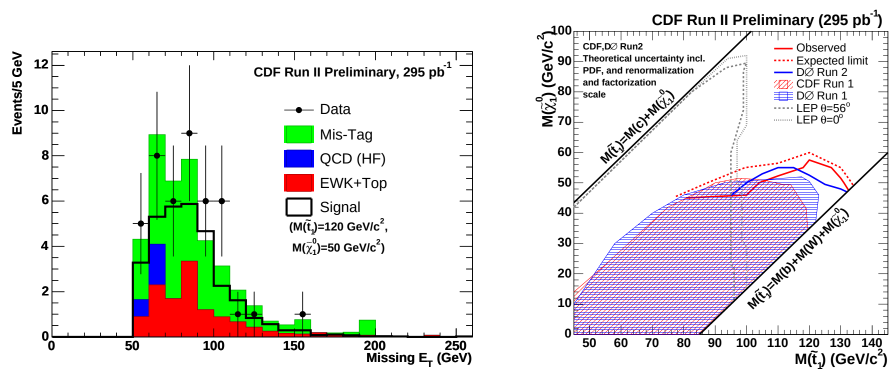

Fig. 13. MET distribution of events with at least one c-tagged jets observed by CDF together with the SM background and expected signal (left). Mass values of the lightest stop and neutralino excluded by DØ and CDF (right).

DØ has also searched for pair production of heavier $\tilde{t}_1$-quarks assuming that they decay into a b-quark and a lepton and sneutrino via a virtual chargino. Two cases were considered: (i) both $\tilde{t}_1$ decays into a muon, and (ii) one $\tilde{t}_1$ decays into a muon, the other one into an electron. In neither cases has one observed significant signal for the presence of the $\tilde{t}_1$-quark. Therefore, the two analyses have been combined to exclude masses of the $\tilde{t}_1$-quark and the sneutrino. As Fig. 14 (left) shows, the mass region excluded by earlier experiments has been significantly extended.

Finally, CDF has searched for pair production of stop quarks, where both of them decayed promptly into a b-quark and a τ via R-parity violating non-zero λ'_{333} Yukawa coupling, and one of the τ's decayed leptonically, the other one into hadrons. 2 events have been found with an isolated electron (or muon), a hadronic tau decay and two additional jets whereas $2.26^{+0.46}_{-0.22}$ SM background events have been expected. The derived upper limit of cross-section times branching fraction as a function of the stop mass, together with the theoretical function, is displayed in Fig. 14 (right). A lower limit of 155 GeV for the stop mass has been obtained.

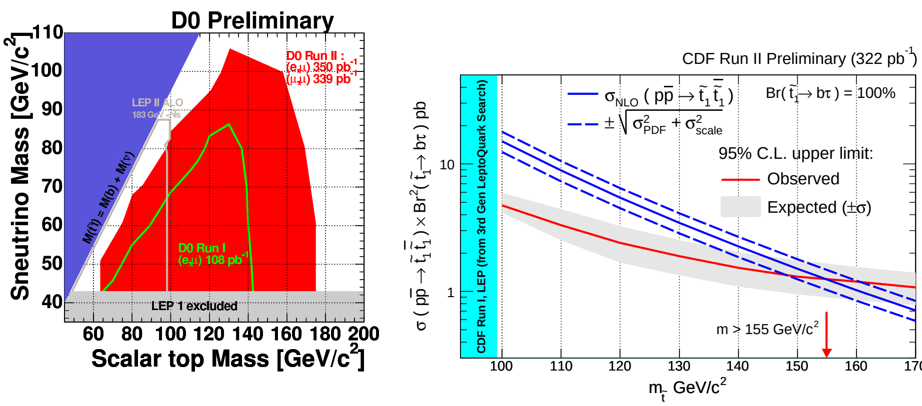

Fig. 14. Excluded regions of the stop and sneutrino masses obtained by DØ assuming the decay $\tilde{t}_1 \to l + b + \tilde{\nu}$, $(l = e, \mu)$ (left). Upper limits of cross-section times branching fraction as a function of the stop mass obtained by CDF assuming the decay $\tilde{t}_1 \to b + \tau$ (right). Also shown is the theoretical function.

5. Conclusion

Supersymmetry is still to be discovered. However, thanks to numerous experiments at the Tevatron the regions where there is no need to search for SUSY any more have increased considerably. The former LEP and Run I mass limits have been significantly extended. The searches continue in many cases with an order of magnitude more luminosity, with recently upgraded detectors, applying methods and exploring event topologies of ever increasing sophistication.

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[5] `http://www-cdf.fnal.gov/physics/exotic/exotic.html`