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Search for SUSY at the Tevatron

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Summary. — This report presents the most recent results on supersymetry searches in $p\bar{p}$ collisions at $\sqrt{s} = 1.96\,\text{TeV}$, in events with large missing transverse energy, leptons, photons, and multiple jets in the final state using data collected by the D0 and CDF Run-II detectors at Tevatron. No evidence of new physics is found and exclusions limits in several scenarios are extracted.

PACS 14.80.Ly – Supersymmetric partners of known particles.
PACS 12.60.Jv – Supersymmetric models.

1. – Introduction

Supersymmetry (SUSY) [1] is regarded as one of the most compelling theories to describe physics at arbitrarily high energies beyond the Standard Model (SM). In SUSY, a new spin-based symmetry turns a bosonic state into a fermionic state—and vice versa—postulating the existence of a superpartner for each of the known fundamental particles, with spin differing by 1/2 unit. The phenomenology is determined by the breaking mechanism of the symmetry and several constraints are assumed to reduce the vast SUSY parameter space. In mSUGRA [2], one of the most extensively studied models, symmetry breaking is achieved via gravitational interactions and only five parameters determine the low-energy phenomenology from the scale of Grand Unification (GUT). If R-parity(1) is conserved, SUSY particles have to be produced in pairs and ultimately decay into the lightest supersymmetric particle (LSP), usually identified as the lightest neutralino $\tilde{\chi}_1^0$, which constitutes a valid candidate for cold dark matter because it is colorless and neutral. Due to these properties the LSP escapes detection and it is identified as a large imbalance in transverse momentum historically called missing transverse energy ($\not\!\!E_T$).

(1) $R_P = (-1)^{3(B-L)+2S}$, where B is the baryon number, L is the lepton number, and S is the spin.

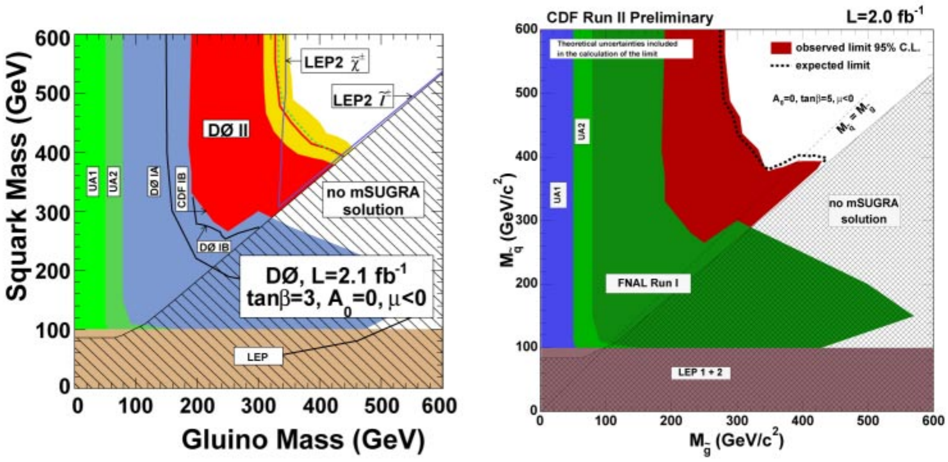

Fig. 1. – Exclusion limit at 95% CL in the squark-gluino mass plane by D0 (left) and CDF (right) experiments with $2.1\,\text{fb}^{-1}$ and $2.0\,\text{fb}^{-1}$ of data, respectively. Previous exclusion limits are also reported.

2. – Searches for SUSY particles

The experiments at Tevatron are performing searches for SUSY particles in low and high $\tan\beta$ scenarios. Squarks and gluino, sbottom, stop, and chargino+netralino searches are described in this section.

2˙1. *Inclusive search for squark and gluino production.* – Squarks and gluinos are searched for in events with large $\not{E}_T$ and multiple jets in the final state. An R-parity conserved mSUGRA scenario is assumed, with the common soft trilinear SUSY breaking parameters $A_0 = 0$, the sign of the higgsino mass term $\mu < -1$, and the ratio of the Higgs vacuum expectation values at the electroweak scale $\tan\beta = 5$. The gluino-squark mass plane is scanned via variations of the parameters m_0 and $m_{1/2}$, common scalar and gaugino mass at the GUT scale, respectively. Light-flavor squark masses are considered degenerate, while 2-to-2 processes involving stop ($\tilde{t}$) and sbottom ($\tilde{b}$) production are excluded to avoid strong theoretical dependence on the mixing in the third generation. Depending on the relative masses of $\tilde{q}$ and $\tilde{g}$, different event topologies are expected. If squarks are significantly lighter than gluinos, $\tilde{q}\tilde{q}$ production is enhanced, and since the squark tends to decay according to $\tilde{q} \to q\tilde{\chi}_1^0$, a dijet topology is favoured, along with large $\not{E}_T$ due to the two neutralinos in the final state. If gluinos are lighter than squarks, $\tilde{g}\tilde{g}$ process dominates and the gluino decay via $\tilde{g} \to q\bar{q}\tilde{\chi}_1^0$ yields topologies containing a large number of jets (≥ 4) and moderate $\not{E}_T$. For $m_{\tilde{g}} \approx m_{\tilde{q}}$, a topology with at least three jets in the final state is expected to be dominant. Three different analyses are carried out, requiring at least 2, 3 or 4 jets in the final state, respectively.

No significant deviation from SM predictions is found in the analysis performed by the D0 [3] and CDF [4] Collaborations. The results are translated into 95% CL upper limits on the cross-section for squark and gluino production in different regions of the squark-gluino mass plane (fig. 1), using a Bayesian approach and including statistical and systematic uncertainties.

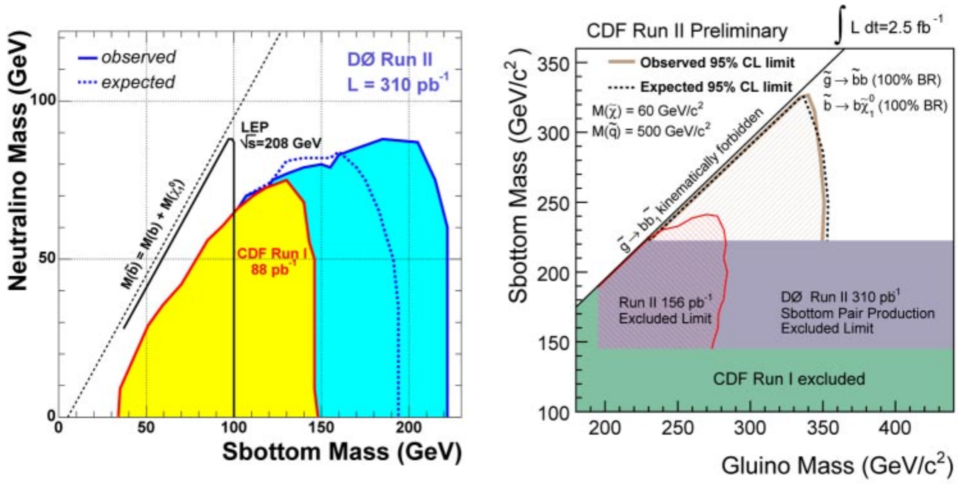

Fig. 2. – Exclusion limits at 95% CL in the neutralino-sbottom mass plane (left) for direct $\tilde{b}$ production and in the sbottom-gluino mass plane (right) for $\tilde{b}$ production through $\tilde{g}$ decays.

2˙2. *Sbottom searches.* – If $\tan\beta$ is large, then there can be a large mass splitting in the scalar bottom sector, yielding a mass to the lightest state ($\tilde{b}$) in the reach of the Tevatron center-of-mass energy. Assuming R-parity conservation the only particle lighter than the $\tilde{b}$ is the LSP.

At Tevatron, two different searches for sbottom are performed depending on its production mechanism. Direct $\tilde{b}$ production with the subsequent sbottom decay to a b-quark and the lightest neutralino ($\tilde{\chi}^0$), leads to the main signature for $\tilde{b}$ detection which includes two b-jets and $\not{E}_T$. The other one is the $\tilde{b}$ production through gluino ($\tilde{g}$) decays. Under the assumption that mass of the $\tilde{g}$ is smaller than mass of the $\tilde{q}$, but larger than mass of the $\tilde{b}$, the gluino pair production, $p\bar{p} \to \tilde{g}\tilde{g}$, is one of the dominant SUSY processes. After production the gluino decays to $\tilde{g} \to b\tilde{b}$ with the subsequent sbottom decay to a b-quark and $\tilde{\chi}^0$, $\tilde{b} \to b\tilde{\chi}^0$.

Although involving more particles and constraints in the SUSY spectrum, this last approach is stronly motivated by the fact that the gluino pair production cross-section is large ($\sigma(g\tilde{g}) \sim 10 \times \sigma(b\tilde{b})$) compared to direct sbottom pair production of similar mass.

Since both analyses have b-jets in the final state, applying a b-tagging algorithm is a mandatory tool to enhance the sensitivity by reducing backgrounds. The B-hadrons in jets coming from b-quark fragmentation have an average flight path of about 500 microns, yielding secondary vertices relative to the interaction point (primary vertex). The tagging algorithms are optimized to find these sencondary vertices using different approaches in each experiment.

The search for direct $\tilde{b}$ production [5] is performed by the D0 Collaboration using $310\,\text{pb}^{-1}$ of data while the search for $\tilde{b}$ production through $\tilde{g}$ decays [6] is performed by the CDF Collaboration using $2.5\,\text{fb}^{-1}$ of data. In both analyses the results are in good agreement with the SM prediction and no hints of sbottom have been found. They were used to extract exclusion limits for the cross-section of the described process. Figure 2 shows the exclusion limits at 95% CL in the neutralino-sbottom mass plane for direct $\tilde{b}$ production and in the sbottom-gluino mass plane for $\tilde{b}$ production through $\tilde{g}$ decays.

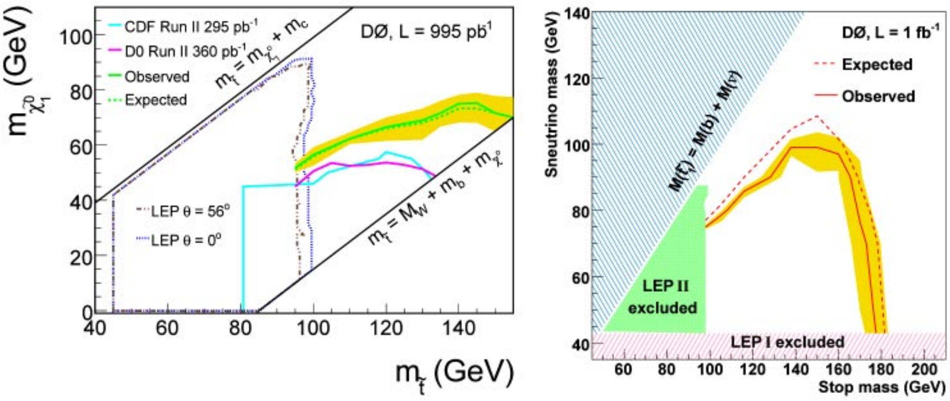

Fig. 3. – Exclusion limits at 95% CL in the neutralino-stop mass plane (left) for stop decaying into charm+neutralino at D0, and in the sneutrino-stop mass plane (right) for stop decaying into bottom+lepton+sneutrino at D0. Stop mass (right) for the stop decaying into bottom+neutralino+lepton+neutrino at CDF.

2·3. *Stop searches.* – Due to the large mass of the top quark, the mass splitting between the two stop quarks states $(\tilde{t}_1, \tilde{t}_2)$ may be large, allowing $\tilde{t}_1$ to possibly be the lightest squark, and possible even lighter than the top quark.

Three different seaches for $\tilde{t}_1$ particles are performed at Tevatron depending on their dacay mode.

The first scenario is accessible in the range $m_{\tilde{t}_1} < m_b + m_{\tilde{\chi}^+}$ and $m_{\tilde{t}_1} < m_W + m_b + m_{\tilde{\chi}^0}$. The dominant $\tilde{t}_1$ decay mode in this model is the flavor-changing process $\tilde{t}_1 \rightarrow c\tilde{\chi}^0$, which is typically assumed to occur with 100% branching fraction. The $\tilde{t}_1 \rightarrow t\tilde{\chi}^0$ decay is kinematically forbidden over the $\tilde{t}_1$ mass range currently accessible at Tevatron, and the tree level four-body decays $\tilde{t}_1 \rightarrow bff'\tilde{\chi}^0$ can be neglected. In this particular case the experimental signature consists of two c-jets and $\not{E}_T$ from the undetected $\tilde{\chi}^0$ [7].

In the second scenario we assume that $\mathrm{BR}(\tilde{t}_1 \rightarrow bl\tilde{\nu}) = 1$, where $\tilde{\nu}$ is the scalar neutrino (sneutrino). Among possible stop decays, this final state is one of the most attractive from the experimental point of view; in addition to a b-quark, it benefits from the presence of a lepton with high transverse momentum with respect to the beam axis. The sneutrino is either the LSP or decays invisibly: $\tilde{\nu} \rightarrow \nu\tilde{\chi}^0$ or $\nu\tilde{G}$, where the lightest neutralino, $\tilde{\chi}^0$, or the gravitino, $\tilde{G}$, is the LSP. The signal topology consists of two isolated leptons, $\not{E}_T$, coming mainly from undetected sneutrinos, and jets [8].

The third scenario happens when $\tilde{t}_1 \rightarrow b\tilde{\chi}^+ \rightarrow b\tilde{\chi}^0 l\nu$ assuming a 100% branching ratio of the stop squark into a b-quark and chargino, and allowing for the chargino to decay through a variety of channels to the dilepton decay mode. These stop events produce signatures similar to those of SM top quark decays, and could potentially be hiding in the top samples of the Tevatron data.

No significant deviation from the SM prediction was observed in any of the previous searches, the results were used to extract exclusion limits for the cross-section of the described process. Figure 3 shows the exclusion limits at 95% CL in the neutralino-stop mass plane for stop decaying into charm+neutralino, the exclusion limits at 95% CL in the sneutrino-stop mass plane for stop decaying into $\tilde{b}l\tilde{\nu}$. The stop invariant mass for the stop decaying into $b\tilde{\chi}^0 l\nu$ is shown in fig. 4.

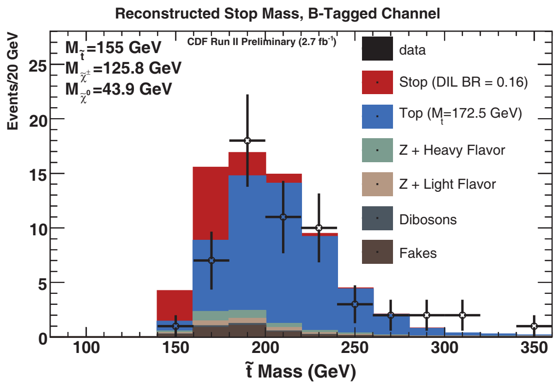

Fig. 4. – Stop mass for the stop decaying into $b\tilde{\chi}^0 l\nu$ at CDF.

2·4. *Chargino+neutralino in the trilepton final state*. – In $p\bar{p}$ collisions, charginos and neutralinos can be produced in pairs via an off-shell W-boson or the exchange of squarks. They decay into fermions and the lightest neutralino $\tilde{\chi}_1^0$, which is assumed to be the LSP and to escape undetected. The analysis shown describes the search for $p\bar{p} \to \tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ in purely leptonic decay modes in final states with $\not\!\!E_T$ and three charged leptons (e, μ or τ). This signature of three leptons can be particularly challenging in regions of parameter space where lepton momenta are very soft due to small mass differences of the SUSY particles. The analyses performed by D0 [9] are based on data corresponding to an integrated luminosity of $2.3\,\text{fb}^{-1}$, with the exception of the analysis using identified hadronic τ lepton decays, which is based on $1\,\text{fb}^{-1}$ of data.

The final state with three leptons plus $\not\!\!E_T$ is a very clean signature at hadron colliders, however the huge amount of backgrounds, from jets faking leptons, Drell-Yan and electroweak bosons production, makes the search challenging.

The analysis combines five separate final states depending on the final lepton combination: ee lepton, $\mu\mu\ l$, $e\mu\ l$, $\tau\mu\ l$, and $\mu\tau\tau$, where l is any other kind of lepton. The invariant mass of the dimuon system is shown in fig. 5 for the $\mu\mu$ lepton channel.

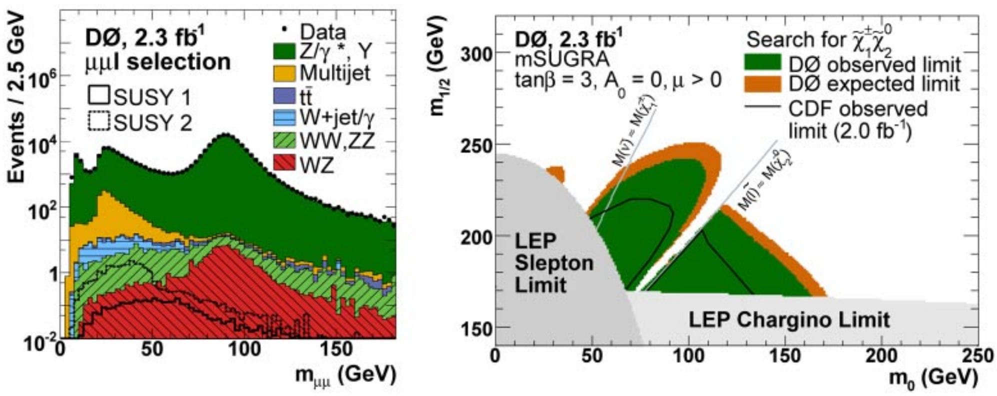

Fig. 5. – Invariant mass (left) of the dimuon sistem in the $\mu\mu$ lepton channel. Exclusion limit at 95% CL in the $(m_{1/2}, m_0)$-plane (right).

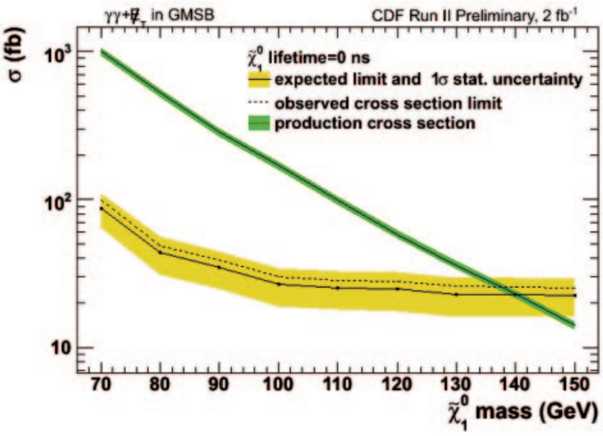

Fig. 6. – Exclusion limit at 95% CL in terms of cross-section as a function of the neutralino mass at a lifetime of 0 ns.

No evidence for a signal is observed, and upper limits on the product of production cross-section and leptonic branching fraction have been set. Within the mSUGRA model with $\tan\beta = 3$, $A_0 = 0$, and $\mu > 0$, this result translates into excluded regions in the $m_{1/2}$-m_0 plane as is shown in fig. 5, that significantly extend beyond previously existing limits from direct searches for supersymmetric particles.

3. – Searches with photons

An example of a theory that would produce these high-energy photon events is gauge-mediated supersymmetry breaking (GMSB) with $\tilde{\chi}_1^0 \to \gamma\tilde{G}$ where the $\tilde{\chi}_1^0$ is the lightest neutralino and the next-to-lightest supersymmetric particle (NLSP) and $\tilde{G}$, a gravitino as the LSP. At the Tevatron gaugino pair-production dominates and the decays produce $\tilde{\chi}_1^0$'s in association with jets, with each $\tilde{\chi}_1^0$ decaying into a $\tilde{G}$, giving rise to $\not{E}_T$, and a photon. Depending on how many of the two $\tilde{G}$'s decay inside the detector, due to their large decay length, the event has the signature $\gamma\gamma + \not{E}_T$ or $\gamma + \not{E}_T$ with one or more additional jets.

Using $2.0\,\text{fb}^{-1}$ of CDF data, one event is found which is consistent with the background estimate of 0.62 ± 0.29 events from the SM expectations. A limit on GMSB models with a $\tilde{\chi}_1^0$ mass reach of $138\,\text{GeV}/c^2$ at a $\tilde{\chi}_1^0$ lifetime of 0 ns is set as is shown in fig. 6.

4. – Searches for MSSM Higgs

One of the outstanding questions in modern particle physics is the dynamics of electroweak (EW) symmetry breaking and the origin of particle masses. In the SM, EW symmetry is spontaneously broken through the Higgs mechanism, by the introduction of a doublet of self-interacting complex scalar fields with non-zero vacuum expectation values. The physical manifestation of this scenario is the existence of a massive scalar Higgs boson h_{SM}. Theoretical difficulties related to divergent radiative corrections to the h_{SM} mass have natural solution in SUSY models and, in this context, the MSSM is

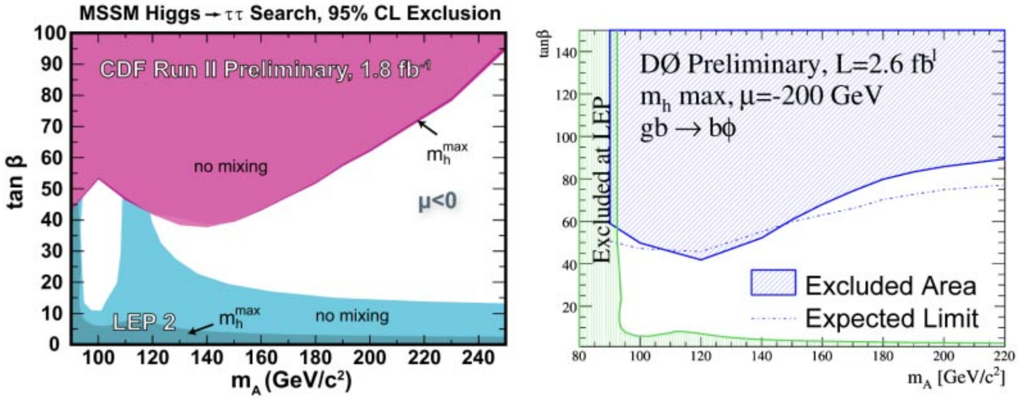

Fig. 7. – Exclusion limits at 95% CL in the $(\tan\beta, m_A)$-plane for the $\phi \to \tau\tau$ (left), and $\phi \to b\bar{b}$ (right) analyses.

the simplest realistic SUSY theory. It requires two Higgs doublets resulting in a Higgs sector with two charged and three neutral scalar bosons. Assuming CP-invariance, one of the neutral bosons (A) is CP-odd, and the other two (h, H) are CP-even. The usual notation uses h (H) for the lighter (heavier) CP-even neutral Higgs boson, and ϕ to denote any of h, H, A. At tree level, the MSSM Higgs bosons are described by two free parameters, chosen to be the mass of A (m_A), and $\tan\beta = v_2/v_1$, where v_2, v_1 are the vacuum expectation values of the neutral Higgs fields that couple to up-type and down-type fermions, respectively. The Yukawa couplings of A to down-type fermions (such as the b quark and τ) are enhanced by a factor of $\tan\beta$ relative to the SM. For large $\tan\beta$ one of the CP-even bosons is nearly mass-degenerate with A and has similar couplings. There are two dominant production mechanisms of neutral MSSM Higgs bosons at hadronic colliders: gluon fusion and $b\bar{b}$ fusion. The leading decay modes of A and the corresponding mass-degenerate CP-even Higgs boson are $\phi \to b\bar{b}$ ($\sim 90\%$) and $\phi \to \tau\tau$ ($\sim 10\%$). Despite the smaller branching fractions, Higgs searches in the ditau channel have advantages because they do not suffer from the large di-jet and multi-jet backgrounds as $\phi \to b\bar{b}$. The LEP experiments have excluded $m_A \leq 93\,\mathrm{GeV}/c^2$, and higher-mass A for small $\tan\beta$. Searches at hadron colliders are complementary, providing sensitivity in the large $\tan\beta$ region.

At Tevatron, both Collaborations D0 and CDF perform searches for $b\phi \to bb\bar{b}$ and $\phi \to \tau\tau$. One more channel: $b\phi \to \tau\tau$ complements previous searches and it is performed by D0 Collaboration. Since no significant deviation from the SM prediction was observed in any of the performed analyses the results were used to extract exclusion limits in the $(\tan\beta, m_A)$-plane as shows fig. 7.

5. – Conclusions

The most recent results on searches for SUSY at the Tevatron in events with large missing transverse energy, leptons, photons and multiple jets in the final state have been presented. No evidence of New Physics has been found yet and stringent exclusion limits have been extracted for the production of particles predicted in supersymetric extension of the SM, especially for squarks, gluinos, charginos, neutralinos, and higgses. With more than $4\,\mathrm{fb}^{-1}$ of data already collected, CDF and D0 Collaborations could reveal hints of New Physics, or place more severe limits on the SUSY parameter space before the start-up of the LHC.

REFERENCES

[1] Wess J. and Zumino B., *Nucl. Phys. B*, **70** (1974) 39.
[2] Chamseddine A. H., Arnowitt R. and Nath P., *Phys. Rev. Lett.*, **49** (1982) 970.
[3] Abazov V. *et al.*, *Phys. Lett. B*, **660** (2008) 449.
[4] Aaltonen T. *et al.*, *Phys. Rev. Lett.*, **102** (2009) 121801.
[5] Abazov V. M. *et al.*, *Phys. Rev. Lett.*, **97** (2006) 171806.
[6] Aaltonen T. *et al.*, hep-ex/0903.2618.
[7] Abazov V. M. *et al.*, *Phys. Lett. B*, **665** (2008) 1.
[8] Abazov V. M. *et al.*, *Phys. Lett. B*, **675** (2009) 289.
[9] Abazov V. *et al.*, hep-ex/0901.0646.