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Searches for Supersymmetry at the Tevatron

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Abstract. Status of the searches for supersymmetric particles performed by the CDF and DØ collaborations using samples of data from $p\bar{p}$ collisions at a center-of-mass energy of 1.96 TeV with an integrated luminosity of $\approx 300\ pb^{-1}$ (talk given at the Hadron Collider Physics symposium 2005).

PACS. 14.80.Ly Supersymmetric partners of known particles – 13.85.Rm Limits on production of particles

1 Introduction

Supersymmetry (SUSY) postulates a symmetry between bosonic and fermionic degrees of freedom and predicts the existence of a supersymmetric partner for each Standard Model particle. A new quantum number R is introduced and the parity of R is equal to +1 for the ordinary particles, to -1 for their superpartners. In R-parity conserving modes, SUSY particles are produced in pairs and the lightest supersymmetric particle (LSP) is stable. In R-parity violating modes, a sparticle could be single produced and new coupling constants are added. One can write the R-Parity violating part of the lagrangian as follows: $\lambda_{ijk} L_i L_j E_k^c + \lambda'_{ijk} L_i Q_j D_k^c + \lambda''_{ijk} U_i^c D_j^c D_k^c$ where $L_i(Q_i)$ are the lepton (quark) SU(2) doublet superfields, E_j (D_j, U_j) are the electron (down and up quark) SU(2) singlet superfield, λ, λ' and λ'' are Yukawa couplings.
The CDF [1] and DØ [2] collaborations have general purpose detectors well understood and highly efficient, with excellent calorimeters and muon chambers coverage and a precision tracking including silicon vertex detectors. Results presented here describe searches for SUSY particles, covering the 2 cases where the R-parity is conserved (RPC) or violated (RPV).

2 Searches for Charginos, Neutralinos and Sleptons.

At Tevatron the ligthest chargino $\tilde{\chi}_1^{\pm}$ and the second-lightest neutralino $\tilde{\chi}_2^0$ could be produced in pair and are assumed to decay via sleptons $(\tilde{l})$ or vector boson exchange into the lightest neutralino $\tilde{\chi}_1^0$ and Standard Model (SM) fermions. The searches for charginos, in case of R-parity conservation, are described in sections 2.1 to 2.3.
In case of R-parity violation, the lightest SUSY particle, here the lightest neutralino $\tilde{\chi}_1^0$, is allowed to decay into a purely leptonic state. The events will then contain more leptons and jets and less missing transverse energy ($\not\!\!E_T$) that in the RPC case. The description of those analyses is given in section 2.4. Searches for single production of scalar muon $\tilde{\mu}$ or scalar neutrino $\tilde{\nu}$ are described in sections 2.5 and 2.6.

2.1 Searches for the associated production of Chargino and Neutralino in final states with three leptons.

Assuming RPC, the $\tilde{\chi}_1^0$ is stable and the final state is caracterized by 3 leptons and large $\not\!\!E_T$. DØ has made 6 analyses [3] looking for 2 identified leptons (e, μ, or τ), an isolated high quality track which is the third lepton, and requesting high $\not\!\!E_T$ value. A third isolated track is not required for same sign muons. The numbers of observed and expected events for each of the analyses are summarized in Tab. 1 together with the integrated luminosity used.

Table 1. Number of observed events and expected SM backgrounds in the searches for charginos and neutralinos in 3 leptons (RPC).

DØ	L(pb^{-1})	channel	data	exp. SM
	320	$ee + l(track)$	0	0.21 ± 0.12
	"	$e\mu + l(track)$	0	0.31 ± 0.13
	"	$\mu\mu + l(track)$	2	1.75 ± 0.57
	"	same sign $\mu\mu$	1	0.66 ± 0.37
	"	$e\tau + l(track)$	0	0.58 ± 0.14
	"	$\mu\tau + l(track)$	1	0.36 ± 0.13
CDF	L(pb^{-1})	channel	data	exp. SM
	346	$ee + l(e, \mu)$	0	0.16 ± 0.07
	224	$ee + l(track)$	2	0.36 ± 0.27

On Fig 1 the observed cross-section limit, obtained from a combination of the 4 first analyses [4], is compared

to three theoretical schemes. As an example, a mass below 117 GeV/c^2 is excluded for the $\tilde{\chi}_1^{\pm}$ in the "3l-max" scheme. When the two analyses with τ are included in the combination, the cross section limit improves by about 10 % for $\tan\beta = 3$ and this improvement is better at large $\tan\beta$ values where the τ's dominate the final state.
The results of two similar analyses done by CDF [5] are summarized in Tab. 1.

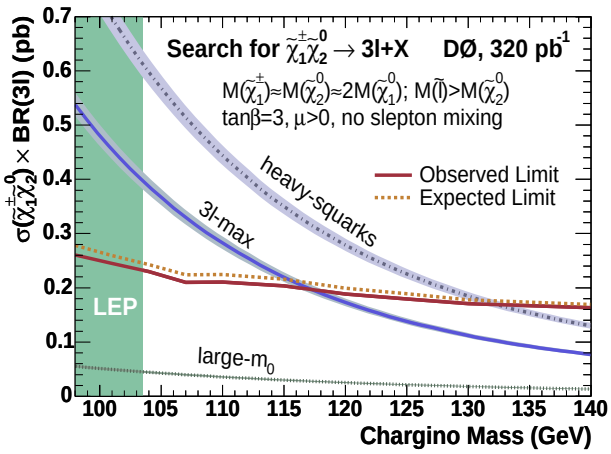

Fig. 1. Limit on $\sigma\times$ BR(3l) as a function of chargino mass, in comparison with expectation for several SUSY scenarios

2.2 Searches for the associated production of Chargino and Neutralino in final states with 2 γ and large $\not{E}_T$

Both CDF [6] and DØ [7] have reported a search for an excess of events containing two high-P_T γ and large $\not{E}_T$. The results have been interpreted in the framework of Gauge-Mediated Supersymmetry-Breaking (GMSB). In this model the $\tilde{\chi}_1^0$ is the next-to-lightest SUSY particle and decays into a gravitino and a photon. To select the candidates, CDF and DØ request two photons with E_T above 13 and 20 GeV and $\not{E}_T$ above 45 and 40 GeV respectively. CDF observes no event for an expected Standard Model (SM) background equal to 0.3 ± 0.1 event and DØ 2 events when the expected background is 3.7 ± 0.6 events. On Fig. 2 the combined experimental cross section limit [8] is compared to the theoretical cross section. The mass limit for the $\tilde{\chi}_1^{\pm}$ is 209 GeV/c^2 which translates to a mass limit of 114 GeV/c^2 on the $\tilde{\chi}_1^0$.

2.3 Search for Charged Massive Stable Particles

A search for Charged Massive Particles having a lifetime long enough to escape the entire detector before decaying (CMSP) has been performed at DØ using 390 pb^{-1} of data [9]. Several possible models could result in a CMSP. In the Anomaly-Mediated SUSY Breaking model, when the mass difference between the $\tilde{\chi}_1^{\pm}$ and the $\tilde{\chi}_1^0$ is less than about 150 MeV, the $\tilde{\chi}_1^{\pm}$ could be a CMSP. The selection

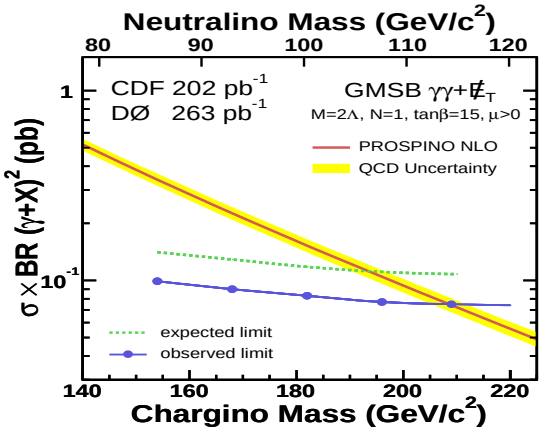

Fig. 2. The next-to-leading-order cross section and combined experimental limits as a function of chargino and neutralino mass.

requests two isolated muons with P_T >15 GeV and moving with a speed significantly slower than the light speed. No event has been found and the instrumental background has been determined to be 0.66 ± 0.6 event. This result could be interpreted such that a stable chargino must be heavier than 140 GeV/c^2 if it is higgsino-like and heavier than 174 GeV/c^2 if it is gaugino-like.

2.4 Searches for Charginos, Neutralinos assuming RPV.

In case of RPV, the $\tilde{\chi}_1^0$ pair produced in the $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_2^0$ decays could decay itself in 4 leptons plus $\not{E}_T$. DØ has analyzed final states with at least 3 leptons corresponding to three Yukawa couplings: the final states with $eeee$, $eee\mu$, or $ee\mu\mu$ + 2 ν linked to λ_{121} [10], with $\mu\mu\mu\mu$, $\mu\mu\mu e$, or $\mu\mu ee$ + 2 ν for the coupling λ_{122} [11] and the final states $\tau\tau\tau\tau$, $\tau\tau\tau e$ or $\tau\tau ee$ + 2 ν connected to the coupling λ_{133} [12]. They select events with 3 isolated leptons with a low P_T cut on the third lepton and loose $\not{E}_T$ cuts. In Tab. 2 the observed and expected numbers of events for each analysis are shown together with the integrated luminosity used and the limit obtain on the $\tilde{\chi}_1^{\pm}$ mass in the framework of the mSUGRA model for different sets of parameters.

Table 2. Number of observed events and expected SM backgrounds in the searches for charginos and neutralinos in case of RPV.

L(pb^{-1})	channel	data	exp. SM	M($\tilde{\chi}_1^{\pm}$) > GeV
238	$eel(l = e, \mu)$	0	0.5 ± 0.4	181
160	$\mu\mu l(l = e, \mu)$	2	0.6 ± 1.9	165
200	$ee\tau_{had}$	0	1 ± 1.4	118

The parameters set used for the 2 first analyses is $m0$=250 GeV and $\tan\beta$=5. For the third analysis the values $m0$=80 GeV and $\tan\beta$=10 have been used, where $m0$

is the common scalar mass and $\tan\beta$ the ratio of Higgs vacuum expectation values. In both cases A_0 the trilinear coupling is taken equal to 0 and the sign of μ the Higgsino mass term positive.

2.5 Search for single production of $\tilde{\mu}$

Using 154 pb^{-1} of data , DØ has searched for $\tilde{\mu}$ which would be produced as $\bar{u}d \rightarrow \tilde{\mu}$ and decays in $\tilde{\chi}_1^0\mu \rightarrow \mu\mu u\bar{d}$ [13]. The cross section of this process is a function of the coupling constant λ'_{211} which occurs at the production and decay levels. The events with 2 jets and 2 isolated muons (applying on the 4 objects a P_T cut $\approx$ 20 GeV) are selected. Two candidates have been found and the expected SM background is equal to 1.1 $\pm$ 0.4 events. Cross section limits or limits on the value of λ'_{211} as a function of the mass of $\tilde{\chi}_1^0$ and $\tilde{\mu}$ are given. As an example, assuming $\lambda'_{211} = 0.07$ and a $\tilde{\chi}_1^0$ mass equal to 75 GeV/c^2, a $\tilde{\mu}$ mass below $\approx$ 252 GeV/c^2 is excluded.

2.6 Searches for single production of $\tilde{\nu}$

CDF, using an integrated luminosity of 344 pb^{-1}, have searched for $d\bar{d} \rightarrow \tilde{\nu}_\tau$ production (via the coupling constant λ'_{311}) with a $\tilde{\nu}$ decay in an electron and a muon of opposite charges (via λ_{132}). Cuts on the P_T of the two leptons ($P_T > 20$ GeV) and on their invariant mass ($M(e\mu) >$ 100 GeV) are applied. Five events are selected and the expected SM background is equal to 8 $\pm$ 1.1 events. On Fig 3 the experimental limit on the cross section is shown together with the theoretical NLO prediction calculated assuming $\lambda_{132} = 0.05$ and $\lambda'_{311} = 0.16$. A $\tilde{\nu}$ mass below 460 GeV/c^2 is excluded.

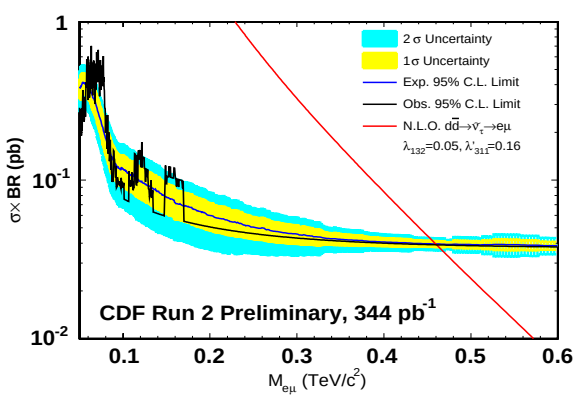

Fig. 3. Experimental $\tilde{\nu}_\tau$ cross section $\times$ BR limit as a function of the invariant $M(e\mu)$ mass and theoretical NLO cross section.

CDF has also studied the case where the $\tilde{\nu}$ decays in e^+e^-, $\mu^+\mu^-$ or $\tau^+\tau^-$ using a sample of data corresponding to an integrated luminosity of $\approx$ 200 pb^{-1}. For the 2 first channels [14], a cut of $\approx$ 20 GeV is applied on the P_T of the 2 leptons and the invariant mass of the 2 leptons has to be greater then 500 GeV/c^2 . No event has been observed in the ee channel and the expected SM background is 0.5 $\pm$ 0.1 event. One candidate is selected in the $\mu\mu$ channel and the SM background is 1.2 $\pm$ 0.1 event. A combination of these two results give a $\tilde{\nu}$ mass limit equal to 725 GeV/c^2. In the $\tau\tau$ analysis [15] 4 events with at least one identified hadronic tau decay and a e or a μ are selected. The expected SM background is equal to 2.8 $\pm$ 0.5 events. This analysis excludes a $\tilde{\nu}$ with a mass below 377 GeV/c^2. In both analyses the assumption is done that the square of the coupling constant times the branching ratio is equal to 0.01.

3 Searches for squarks and gluinos.

At hadron colliders, the most copiously produced SUSY particles should be, if sufficiently light, squarks and gluinos. The topologies of the events are a large number of jets and $\not{E}_T$ and therefore the multijet background is huge. Searches made by CDF and DØ for gluinos and squarks are reported in section 3.1 and more specific searches for squarks, in which the b-tagging plays a crucial role, are described in sections 3.2 to 3.4.

3.1 Searches for squarks and gluinos.

At low m_0 the gluino is heavier than the squark and the process with the dominant cross section is the $\tilde{q}\bar{\tilde{q}}$ production. As an important decay mode of the squark is $\tilde{q} \rightarrow q\tilde{\chi}$, the final topology will be acoplanar dijet event with $\not{E}_T$ coming from the two neutralinos LSP. At high m_0, the squarks are much heavier than the gluino. The process with the highest cross section is therefore $\tilde{g}\tilde{g}$. As $\tilde{g} \rightarrow q\bar{q}\tilde{\chi}$ is an important decay mode of the gluino, their pair production will lead to a large number of jets and $\not{E}_T$. Finally for intermediate m_0 region, all squark-gluino production processes contribute to the total cross section. DØ has reported a search for squarks and gluinos [16], using 310 pb^{-1} of data, and adressing the different possibilities for the m_0 value in 3 analyses which differ by the number of jets required (see Tab.3).

Table 3. Number of observed events and expected SM backgrounds in the searches for gluinos and squarks. m_0 is the common scalar mass.

DØ (310 pb^{-1})	#jets(P_T GeV)	data	exp. SM
Low m_0	2 jets(60,50)	12	12.8 $\pm$ 5.4
Int. m_0	3 jets(60,40,25)	5	6.1 $\pm$ 3.1
High m_0	4 jets(60,40,30,25)	10	7.1 $\pm$ 0.9
CDF (254 pb^{-1})	#jets(P_T GeV)	data	exp. SM
	3 jets(125,75,25)	3	4.2 $\pm$ 1.1

Cuts on the scalar sum of the transverse energies of the jets and $\not\!\!E_T$ are also applied. The observed number of events and the SM background expectations are summarized in Tab. 3 and are in good agreement. On Fig. 4 are shown the regions excluded at the 95% C.L. in the squark and gluino mass plane in the mSUGRA framework. Assuming $m_0 = 25\ GeV/c^2$ the $\tilde{q}$ must be heavier than 318 GeV/c^2. For a m_0 mass equal to 500 GeV/c^2, the $\tilde{g}$ mass will be greater than 233 GeV/c^2 and finally if the masses of the $\tilde{q}$ and the $\tilde{g}$ are of the same order, they should be heavier than 333 GeV/c^2. CDF, using data coresponding to a luminosity equal to 254 pb^{-1}, selects events with at least 3 jets, a scalar sum of the transverse jet energies above 350 GeV and large $\not\!\!E_T$ ($\not\!\!E_T > 165 GeV$) (Tab.3). 3 candidates survived to the cuts and the SM background is equal to 4.2 ± 1.1 events.

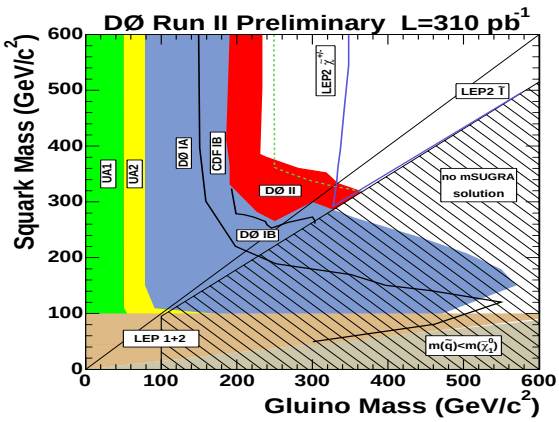

Fig. 4. In the squark and gluino mass plane, excluded regions at the 95% C.L. in the mSUGRA framework.

3.2 Searches for gluino decaying in $\tilde{b}b$.

CDF has searched for $\tilde{b}$ quarks in events with b-jets and $\not\!\!E_T$ using 156 pb^{-1} of data [17]. In a scenario where the $\tilde{b}$ is lighter than the $\tilde{g}$, $\tilde{b}$ could be produced through the decay $\tilde{g} \rightarrow \tilde{b}b$. The final state, then, will be 4 b-jets and $\not\!\!E_T$. The preselection cuts consist on requesting at least 3 jets ($P_T > 15 GeV$), $\not\!\!E_T > 80 GeV$, angular cuts between jets and $\not\!\!E_T$ and no leptons. The sample is then subdivided into exclusive single and inclusive double b-tagged events. For the exclusive single tag, 21 events are selected and it is in good agreement with the SM background expectation of 16.4 ± 3.7 events. Four events are observed in the double b-tag sample and 2.6 ± 0.7 SM events are expected. The exclusion regions, as a function of the $\tilde{b}$ and the $\tilde{g}$ mass, are shown on Fig. 5.

At 95 % C.L. $\tilde{g}$ with a mass smaller than 280 GeV/c^2 or $\tilde{b}$ with a mass smaller than 240 GeV/c^2 are excluded.

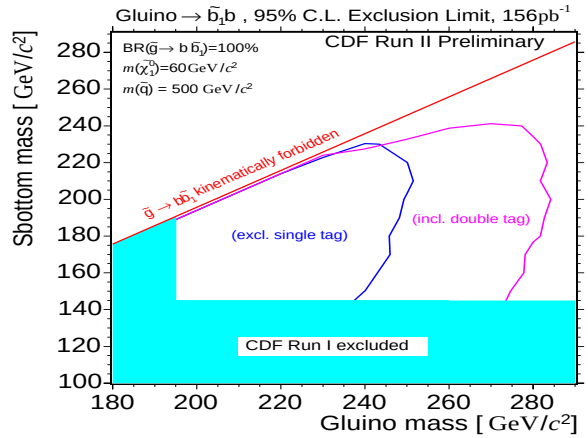

Fig. 5. 95 % C.L. exclusion contours in the $\tilde{g}$ and $\tilde{b}$ mass plane.

3.3 Search for direct production of $\tilde{b}\bar{\tilde{b}}$.

DØ has performed a search for direct pair production of sbottom $\tilde{b}$ with 310 pb^{-1} of data [18]. The $\tilde{b}$ decays into a b quark and a $\tilde{\chi}_1^0$. The topology of the events for this process corresponds to a final state with two acoplanar b-jets and $\not\!\!E_T$. Different analyses cover different assumptions on the $\tilde{b}$ mass value and the cuts are described in Tab. 4.

Table 4. Number of observed events and expected SM backgrounds in the searches for direct production of $\tilde{b}$.

M($\tilde{b}$)	Low val.	Med. val.	High Val.
E_T(j1,j2) (GeV)	>(40,15)	>(40,15)	>(70,40)
$\not\!\!E_T$ (GeV)	>60	>80	>100
Data	36	15	2
SM exp.	38.6 ± 2.8	19.6 ± 1.7	4.4 ± 0.4

Lepton veto and single b-tag are also requested. The number of observed events and expected SM backgrounds are summarized in Tab. 4. They are in good agreement and the resulting exclusion contour in the $\tilde{b}$ and $\tilde{\chi}_1^0$ mass plane is shown in Fig. 6.

3.4 Search for $\tilde{t}$ decaying in $b\tau$.

CDF has searched for pair production of scalar top $\tilde{t}$ in a RPV scenario in 200 pb^-1 of data [19]. Each $\tilde{t}$ decays into a τ lepton and a b quark. The final state is either an electron or a muon from the leptonic decay of one of the τ, as well as a hadronically decaying τ, and two or more jets. P_T cuts of 10 GeV and 15 GeV are applied on the lepton and the hadronic τ respectively. To remove the W background, a cut on the transverse lepton-$\not\!\!E_T$ mass ($M_T(l, \not\!\!E_T) < 35$ GeV) is applied. A SM background equal to 4.8 ± 0.7 events is expected and 5 candidates have been selected. Fig. 7 shows the experimental cross section limit as a function of the $\tilde{t}$ mass together with the theoretical

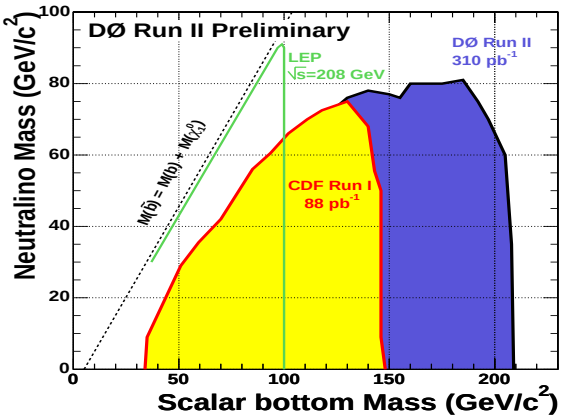

Fig. 6. 95 % C.L. exclusion contour, after all selections, including single b tagging and combining the 3 sets of cutoffs in $\not\!\!E_T$ and jet P_T.

prediction. At 95 % C.L. the $\tilde{t}$ should be heavier than 129 GeV/c^2, assuming that the branching ratio of the $\tilde{t}$ in $b\tau$ is equal to 100 %.

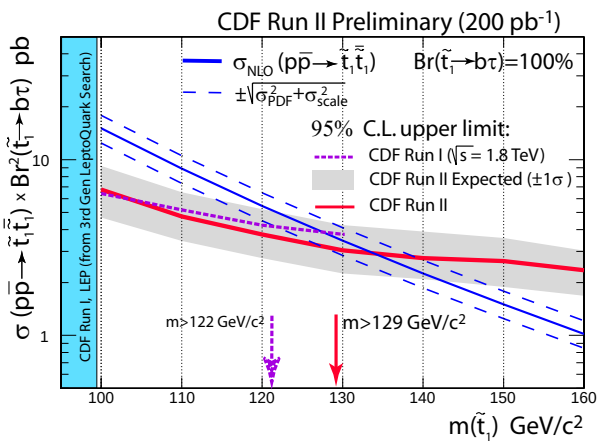

Fig. 7. Cross section exclusion limit as a function of the $\tilde{t}$ mass.

4 Searches for $B_s^0 \to \mu^+\mu^-$ decays

In the Standard Model, the branching ratio of the decay of B_s^0 in $\mu^+\mu^-$ is very small ($\approx 3.510^{-9}$). But in many SUSY models, an enhancement of this branching ratio varying as $(\tan\beta)^6$ is expected. So, for large $\tan\beta$, this measurement is a sensitive probe of new physics. Both CDF [20] and DØ [21] has search for this decay. They select events with a μ^+ and a μ^- coming from displaced vertices and count how many events have an invariant $M(\mu\mu)$ mass in a mass window around the B_S mass. The upper limit is then normalized to the number of $B^\pm \to J/\Psi K^\pm$ events and transform in an upper limit on the branching ratio. CDF uses a sample of data corresponding to a luminosity equal to 364 pb^{-1} and obtain an upper limit: BR$(B_s^0 \to \mu^+\mu^-)$ $< 210^{-7}$ at 95% C.L. Using a sample of data of 300 pb^{-1}, DØ gives an upper limit equal to 3.710^{-7} at 95% C.L.

5 Conclusion

The CDF and DØ collaborations have both covered many SUSY particles searches using a sample of data corresponding to an integrated luminosity of the order of 300 pb^{-1}. In all analyses, the number of observed events is consistent with the expected number of SM background events. Hence limits have been derived. The analyses of data samples, corresponding to a luminosity of $\approx 1\ fb^{-1}$, are underway and will provide either a discovery or a substantial improvement of the limits.

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