CDF/ANAL/EXOTIC/CDFR/2199
June 20, 1993

Constrained Regions of the SUSY Parameters within the MSSM

S. Mikamo

National Laboratory for High Energy Physics, KEK

In this note we briefly survey the current status of the SUSY parameter space. This note is written as a supporting document of the report CDF/PUB/EXOTIC/CDFR/1491 entitled " Search for the Radiative Decay of Neutralinos Produced in Proton-Antiproton Collisions at $\sqrt{s}$ = 1.8 TeV "[1] by refering to the existing phenomenological analyses[2-4].

The experimental data concerned here are the results of the search for supersymmetric (SUSY) particles made at mainly LEP[5,6] and Tevatron[1,7] although many useful results have been accumulated at other collider experiments. The SUSY model to be compared with the experiment at present is a minimal supersymmetric extension of the standard model which is called the MSSM. The MSSM is a two-Higgs doublet model, which possesses, in the Higgs sector, five physical Higgs bosons: a charged pair ($H^{\pm}$); two neutral CP-even scalars (h^0 and H^0); and a neutral CP-odd scalar (A^0), often called a pseudoscalar. Here $m_{H^0} > m_{h^0}$ by convention.

1.) Particle Masses in the MSSM

a) The mass of charged Higgs bosons

Dedicated searches have been performed in Z^0 decays to H^+H^-, in purely leptonic final states, purely hadronic final states and in mixed final states. Lower mass limits on charged Higgs bosons (within the MSSM) are shown in Table 1.

b) The mass of neutral Higgs bosons

Lower mass limits of h^0 and A^0 have been obtained from direct searches in the processes $Z^0 \rightarrow h^0Z^*$ and $Z^0 \rightarrow h^0A^0$ and from the Z^0 width measurement. The results valid in the framework of the MSSM are shown in Table 1.

c) The mass of scalar leptons

Non-observation of a significant number of events with acoplanar leptons of the same flavor at e^+e^- colliders yields lower limits on the masses of charged scalar leptons that are almost equal to the beam energy which is about $M_Z/2$ for LEP experiments. A lower mass limit on the sneutrinos has been obtained from the measurement of the Z^0 invisible width. (Table 1)

In the MSSM the masses and couplings of the charginos $\chi_i^{\pm}$ ($i = 1\sim2$) and neutralinos χ_i ($i = 1\sim4$) are determined by four parameters M_1, M_2, μ and $\tan\beta = v_2/v_1$, where M_1 and M_2 are the U(1) and SU(2) gaugino masses, μ is the supersymmetric mass term which mixes the two Higgs superfields, and v_2 and v_1 are the vacuum expectation values of the two Higgs doublets with Y = +1 and -1, respectively. M_1 and M_2 are related as will be discussed later. Charginos $\chi_1^{\pm}$ and $\chi_2^{\pm}$ are the mass eigen states of the charged winos $\tilde{w}^{\pm}$ and the charged higgsinos $\tilde{H}_1^+$ and $\tilde{H}_2^-$. The four neutralinos are the mass states of the linear combinations of the neutral gauginos: the photino $\tilde{\gamma}$ and the zino $\tilde{z}$; and the neutral higgsinos: $\tilde{H}_1^0$, $\tilde{H}_2^0$.

d) The mass of Charginos

The final state topology studied in this case is an acoplanar pair of leptons, an isolated lepton and missing energy in a hadronic event, or an acoplanar pair of jets. Non-observation of these events translates into a bound $m_{\chi_1^\pm} > 45$ GeV/c^2 (Table 1) , which is valid for all MSSM parameters assuming that the chargino only decays to the LSP such as $\chi^{\pm} \rightarrow f\bar{f}\chi_1$. (The LSP is the lightest supersymmetric particle, which is assumed to be χ_1 from mainly a cosmological point of view.)

e) The mass of Neutralinos

The LEP experiments have searched for neutralinos produced via $Z^0 \rightarrow \chi_1\chi_j$ ($j = 2, 3$), and $\chi_j\chi_j$ by looking for monojets and for acoplanar lepton or jet pairs. No observed events were turned into the limits on $Z\chi_1\chi_j$ and $Z\chi_j\chi_j$ couplings. The limit on $Z\chi_1\chi_1$ coupling is set from the Z^0 invisible width. These results also lead to the lower limits on the masses of χ_1 and χ_2 as a function of $\tan\beta$ as shown in Fig. 1.[5,6)]

Also the signal of $\chi_j \rightarrow \chi_1 \gamma$ was examined at LEP. The radiative decay of a neutralino is also the process studied at CDF[1]. The difference in between the experiments with electron colliders and hadron colliders is as follows. Electron collider experiments look at BR($Z^0 \rightarrow \chi_j \chi_1$) x BR($\chi_j \rightarrow \chi_1 \gamma$) whereas hadron collider experiments look at BR($\tilde{g} \rightarrow q\bar{q}\chi_j$) x BR($\chi_j \rightarrow \chi_1 \gamma$) or BR($\tilde{q} \rightarrow q\chi_j$) x BR($\chi_j \rightarrow \chi_1 \gamma$) and so on. In the case of LEP experiments the mass of χ_j is limited to be about a half of Z^0 mass, whereas in the case of Tevatron experiments there is essentially no limit on the χ_j (χ_2) mass. In fact, for a set of μ = -40 GeV and $\tan\beta = 1.5$ used in Ref.1 the mass of χ_2 is given to be heavier than 47 GeV/c^2 by ISASUSY program[7]. (Of course other necessary parameters are also fixed, but the effect to the χ_2 mass is small.) At the same time the mass of χ_1 is given when a set of parameters (μ, $\tan\beta$, $m_{\tilde{g}}$) is fixed.

f) The mass of the squark and gluino

Naturally the highest lower mass limits of the squark and gluino are obtained from the CDF group. The limits from the study[8] of multi-jets plus missing E_T are 126 GeV/c^2 for the squarks and 141 GeV/c^2 for the gluino. After taking into account the possible cascade decays of the squarks and gluino the asymptotic mass limit of squarks becomes about 100 GeV/c^2 for μ = -250 GeV and $\tan\beta = 2$. The asymptotic mass limit of gluino can not be set for this set of parameters because the LSP becomes too heavy and the corresponding branching fraction of the gluino decay to the LSP is small.

On the other hand, in the case of Ref.1 the production rate of χ_2 through the decays of squarks and/or gluino becomes large as increasing mass of these parent particles, keeping the radiative decay rate for χ_2 to be appreciable at a certain set of (μ, $\tan\beta$). This is the main reason why the the study of neutralino radiative decay can give asymptotic mass limits even including the cascade decay effect. It is to be noted that the asymptotic mass limit on the gluino obtained here is the direct measurement (though it depends on assumptions as described in Ref.1), not the one extracted from a lower mass limit on the chargino and so on as is seen in Ref. 4 (and shown in Table 1). The last column denoted " Theory[4]" in Table 1 is the mass limits of particles in the gaugino-higgsino sector extracted from the presently existing experimetal data by Hidaka[4]. This analysis was possible due to a new CDF limit on the gluino mass (i.e., 150 GeV/c^2, uncorrected for the cascade decay effect, reported as preliminary result elsewhere) in addition to the LEP data.

2) Constraints on the SUSY Parameter Space

Three parameters $\tan\beta$, μ and $m_{\tilde{g}}$(as one of the gaugino masses) are essential for the physics of charginos and neutralinos. These three parameters plus the masses of squarks, sleptons, top quark and charged-Higgs-bosons are the basic parameters of the MSSM which determine all the physics and enter into the ISASUSY program[7], for example, as input parameters.

a) The range of $\tan\beta$

Since the vacuum expectation values v1 and v2 may be taken to be real and positive we can restrict the range of β to be $0 \leq \beta \leq \pi/2$, then $\tan\beta > 0$. Usaually $\tan\beta$ is expected to lie in $1 < \tan\beta < 10 \sim 100$ depending on the mass of top quark. (It is however noted that the recent proton-decay constraint[9] favors a small $\tan\beta$, say ≤ 10 GeV.) The range $0.63 < \tan\beta < 1.6$ is once excluded by the MSSM Higgs search of ALEPH, but large radiative corrections to the mass of the lightest Higgs boson with a heavy top quark mass invalidates this bound, resulting in no bound on it .[10]

b) The range of μ

The higgsino mixing mass term μ in the superpotential can be both negative or positive when the SU(2) gaugino mass M_2 is chosen to be positive by convention.[2] Perhaps this customary choise may be needed a further explanation as follows. After the gaugino mass M_2 is chosen to be real and positive in the gaugino-higgsino sector there remains two-fold sign ambiguities for the product of $\mu\cdot\tan\beta$ which can be either positive or negative. Since we chose $\tan\beta$ to be positive as above the sign of μ can be both positive or negative.

Since the observable physics are determined by a combined set of parameters (μ, $\tan\beta$, $m_{\tilde{g}}$) the range of μ is not independently constrained. Experiments at e^+e^- colliders usaually give a three dimensional bound in (μ-$m_{\tilde{\gamma}}$) plane or (μ-M_2) plane with parameter $\tan\beta$. The electron collider experiments can not directly give a limit on the gluino mass. However, since there is a relation between the mass of the gluino and photino at the grand unification scale the bound in (μ - $m_{\tilde{\gamma}}$) plane is often translated into (μ - $m_{\tilde{g}}$) plane with using the following GUT relations.

By assuming the equality of gaugino masses at the GUT scale and solving renormalization group equation the relation between the three masses at low energy is given as follows [2, 11].

$$(3/5)M_1/\alpha_1 = M_2/\alpha_2 = M_3/\alpha_3 \quad (1)$$

,where $\alpha_i = g_i^2/4\pi$ (i = 1,2,3) and $g_{1,2,3}$ are the gauge couplings of U(1), SU(2) and SU(3) gauge groups, respectively. Using an appropriate choise of numerical values for α_1, α_2 and α_3 at the electroweak scale and with using another GUT assumption $M_3 = M_{\tilde{g}}$ (i.e., the color symmetry is not broken) we get[2]

$$M_2 \approx 0.3\ M_{\tilde{g}}. \quad (2)$$

On the other hand since the photino parameter is a mixture of SU(2) and U(1) gauginos, its mass is related to that of gluino by the following [4]:

$$M_{\tilde{g}} = (3/8)(\alpha_3/\alpha_2)\ \sin^2\theta_W\ M_{\tilde{\gamma}}$$

$$\approx\ 5.76\ M_{\tilde{\gamma}}. \quad (3)$$

This is the relation that one usually uses to extract a lower mass limit on the photino parameter (sometimes assumed to be a main component of the LSP) from a lower mass limit on the gluino.

Figure 2 and 3 show contours of the parameters which indicate the presently excluded regions for various sets of ($m_{\tilde{g}}$, μ, tanβ).[12] The region excluded by CDF[1] for tanβ = 1.5 is shown In Fig. 4, which is based on the data in Table 1 of Ref. 1(Table 2 in this report). We see that this bound extends slightly the excluded region set by LEP. Most of other sets of parameters fall into the LEP region. This is due to the fact that the branching ratio for $\chi_j \rightarrow \chi_1\gamma$ decreases with increasing $|\mu|$ and tanβ[13].

As we see above, the choise of (μ, tanβ, $m_{\tilde{g}}$) imposes severe restrictions for the physics within the MSSM. Once proposed interesting process is a channel of high E_T Z^0 plus missing E_T[14].

The process is due to the decay of a heavy neutralino (χ_4 or χ_3) into Z^0 and χ_1. We have checked using ISASUSY program that the prominent production rate is limited only in the small μ region where the LEP experiments have already excluded. (It seems however to be interesting to check whether there is an excess in the E_T distribution of Z^0 's. If we have some events with high missing E_T and no explanation other than the SUSY, the simple version of the MSSM might be in a big trouble with an inconsistent interrelation between LEP and Tevatron data.)

We may reach about 200 GeV/c^2 of the gluino mass with an integrated luminosity of 100 pb^{-1}. However the masses of squarks and gluino accessible at the Tevatron are far low compared to those expected as " upper limits " on such sparticle masses; i.e., around 1 TeV/c^2 at which the standard model description is considered to break down. There is however one channel which does not depend on the heavy squark and gluino in production. That is direct associated production of charginos and neutralinos via s-chanell W (or off-shell W*) exchange. The resulting signal is triple-lepton, whose production rate is appreciable with the present luminosity and relatively background free.[15] This process is open for a wide range of the parameter space, even beyond the reach of LEP200.

These are some examples of the feature that we concern with the MSSM.

Perhaps it should be noted that the MSSM is not the only SUSY model. It is known that the SUSY phenomenology is largely changed in even slight extension of the MSSM. However it is often said that the MSSM should be treated as the first and necessary step to explore the SUSY models.

We thank H. Haber, K. Hagiwara, X. Tata and R. Settles (ALEPH group) for their useful conversations.

References

1) F. Abe et al., CDF/PUB/EXOTIC/CDFR/1491(1992).
2) L. Roszkowski, Phys. Lett. **B252**, 471 (1990).
3) M. Drees and X. Tata, Phys. Rev. **D43**, 2971 (1991).
4) K. Hidaka, Phys. Rev. **D44**, 927 (1991).

5) ALEPH Collaboration, D. Decamp et al., Phys. Rep. **216C**, 253 (1992).
6) G. Wormser, presented at the XXVI International Conference on High Energy Physics, Dallas, Texas, 1992, Orsay Preprint LAL 92-56 (1992).
7) H. Baer, unpublished (1992).
8) F. Abe et al., Phys. Rev. Lett. **69**, 3439 (1992).
9) R. Arnowitt and Pran Nath, Phys. Rev. Lett. **69**, 725 (1992).
10) J. Ellis, G. Ridolfi and F. Zwirner, Phys. Lett. **257B** 83 (1991); H.E. Haber and R. Hempfling, Phys. Rev. Lett. **66** 1815 (1991).; Y. Okada, M. Yamaguchi and T. Yanagida, Prog. Theor. Phys. Lett. **85** 1 (1991).
11) J. Ellis and G. Ross, Phys. Lett. **117B**, 397 (1982).
12) H. Baer et al., presented at the 1990 Snowmass Summer Study on High Energy Physics, FSU-HEP-901110.
13) H. Haber, unpublished (1992).
14) H. Baer, X. Tata and J. Woodside, Phys. Rev. **D42,** 1450 (1990).
15) For example, Y. Kato and S. Mikamo, proposed at the CDF Collaboration Meeting on September, 1992 based on the discussion with H. Baer. Formal discussions can be seen in Florida preprint FSU-HEP-920907 (1992) by H. Baer and X. Tata.

Figure Captions

Fig. 1 (a), (b) : Lower mass limits for the masses of χ_1 and χ_2 as a function of tanβ from ALEPH[5]. (c) : The same from DELPHI[6] and L3[6]. χ' in Fig. 1(b) means a neutralino heavier than χ_1.

Fig. 2 Region of μ vs $m_{\tilde{g}}$ plane excluded due to LEP searches.[13]

Fig. 3 Region of μ vs $m_{\tilde{g}}$ plane excluded due to LEP searches for various allowed values of tanβ.[13]

Fig. 4 Region of μ vs $m_{\tilde{g}}$ plane excluded due to CDF experiment[1] for tanβ =1.5 shown by solid circles. The solid curve indicates the contour of $m_{\chi_1^\pm}$ = 45 GeV/c^2. The dashed curve is derived from the Z^0 width measurement and the dotted curve is from the non-observation of neutralinos at LEP.

Table 1 Lower Mass Limits on the MSSM Particles

	ALEPH(91)[5]	LEP(92)[6]	CDF	Theory[4]
H^0 Higgs	51.0			
$H^{\pm}$	41.7	45.2(DELPHI) 44.5(L3)		
h^0	41	43 (ALEPH) 42(L3,DELPHI)		
A^0	20	21		
$\tilde{\nu}$	41.1			
$\tilde{e}$, $\tilde{\mu}$	45.1			
$\tilde{\tau}$	45.0			
$\chi_1^{\pm}$	45.2			
$\chi_2^{\pm}$				99
χ_1	13 (at $\tan\beta = 2$)			18.4
χ_2	40 (at $\tan\beta = 2$)			45
χ_3				70
χ_4				108
$\tilde{q}$	45		100[a] 110[b]	
$\tilde{g}$			100[c] 140[b]	132

Note :
The mass is in GeV/c^2 units.
(a) at $m_{\tilde{g}} = 410$, $\mu = -250$ and $\tan\beta = 2$, (Ref. 8).
(b) at $m_{\tilde{g}} = 4000$, $\mu = -40$ and $\tan\beta = 1.5$ (Ref.1).
(c) at $m_{\tilde{q}} = 5000$, $\mu = -250$ and $\tan\beta = 2$ (Ref. 8).
(d) at $m_{\tilde{q}} = 4000$, $\mu = -40$ and $\tan\beta = 1.5$ (Ref.1)

Table 2. Asymptotic lower mass limits on the squarks and gluino for six different sets of SUSY parameters (μ, $\tan\beta$) given in Ref. 1. (NL) means that no limit can be set.[1]

	$\tan\beta = 1.5$	$\tan\beta = 4.0$
$\mu = -40$ GeV/c^2	$m_{\tilde{q}} = 110$ GeV/c^2 $m_{\tilde{g}} = 140$ GeV/c^2	$m_{\tilde{q}} =$ (NL) $m_{\tilde{g}} = 113$ GeV/c^2
$\mu = -60$ GeV/c^2	$m_{\tilde{q}} =$ (NL) $m_{\tilde{g}} = 105$ GeV/c^2	$m_{\tilde{q}} =$ (NL) $m_{\tilde{g}} = 97$ GeV/c^2
$\mu = -80$ GeV/c^2	$m_{\tilde{q}} =$ (NL) $m_{\tilde{g}} =$ (NL)	$m_{\tilde{q}} =$ (NL) $m_{\tilde{g}} = 78$ GeV/c2

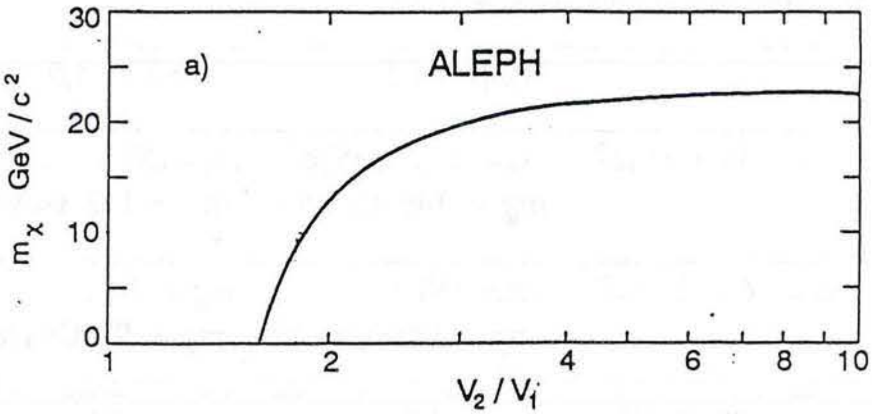


Fig. 1(a)

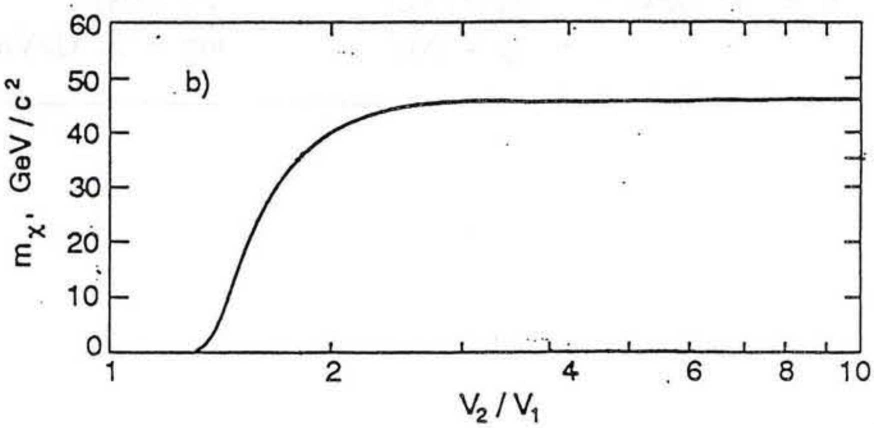


Fig. 1(b)

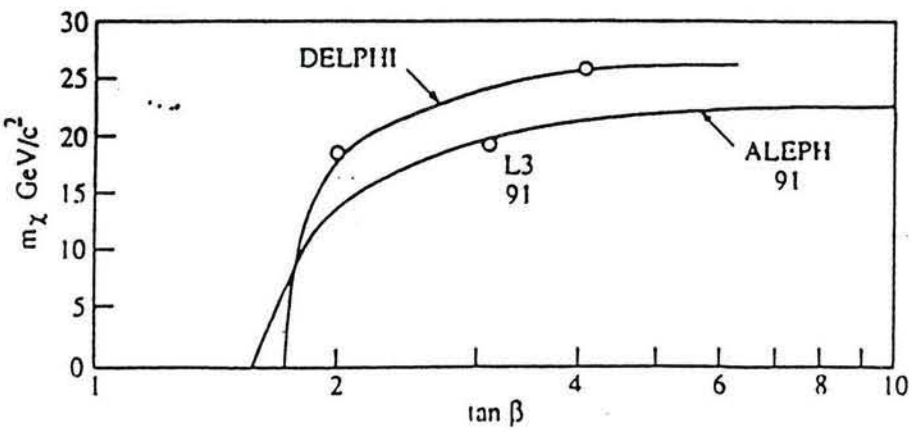
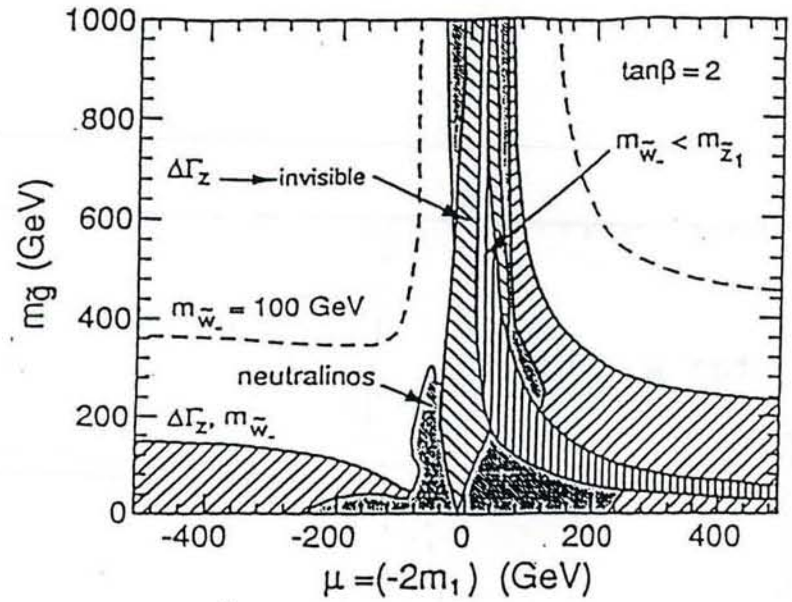
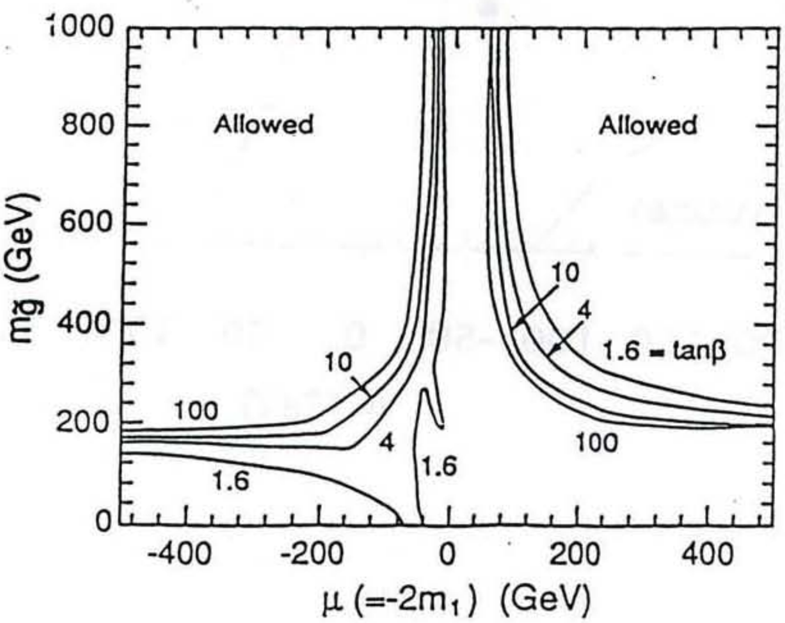


Fig. 1(c)



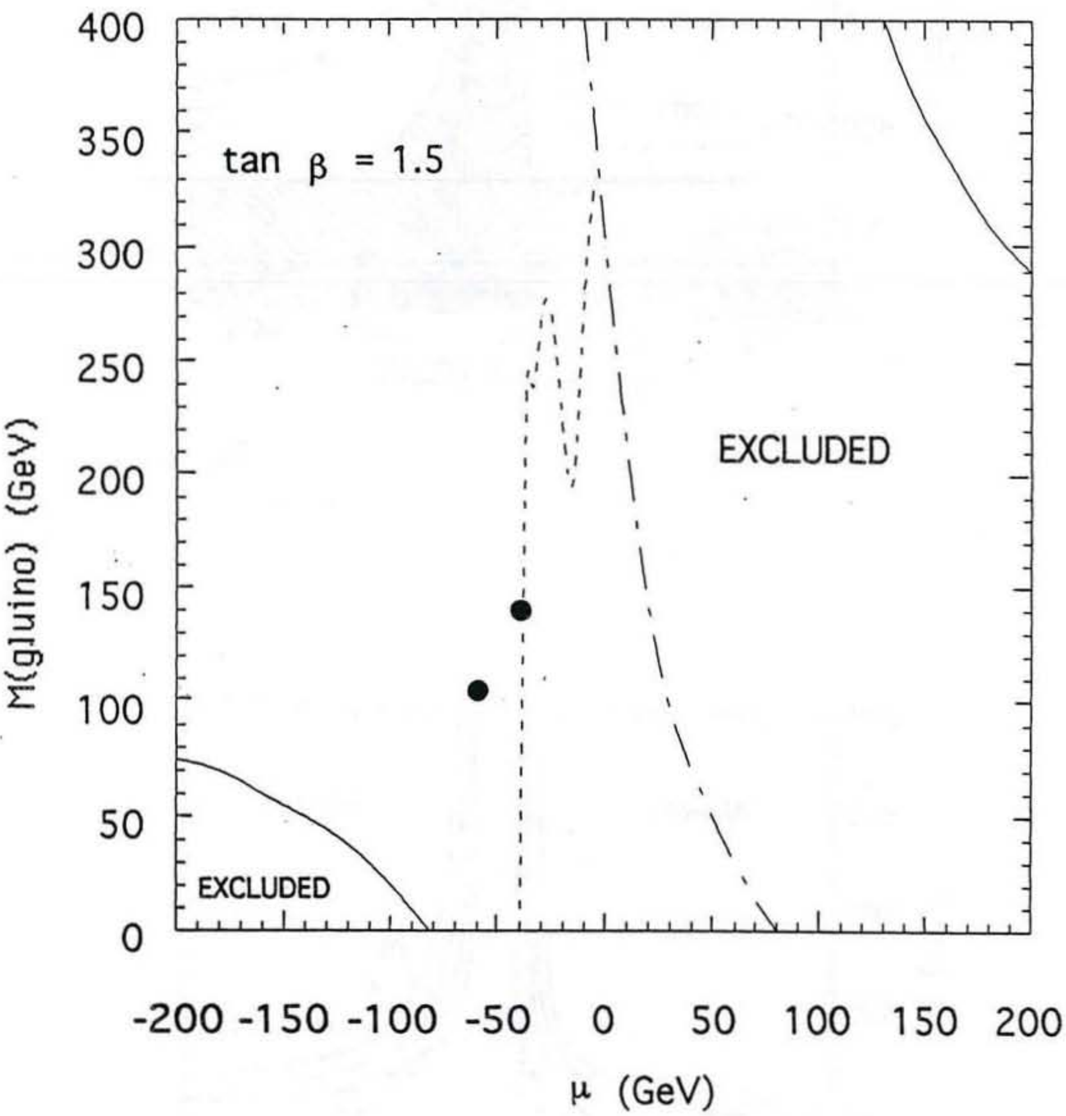
tanβ = 2
ΔΓz → invisible
m_W̃- < m_Z̃1
m_W̃- = 100 GeV
neutralinos
ΔΓz, m_W̃-
mg̃ (GeV)
μ =(-2m1) (GeV)

Fig. 2



Allowed
Allowed
10
4
1.6 = tanβ
10
100
4
1.6
1.6
100
mg̃ (GeV)
μ (=-2m1) (GeV)

Fig.3



400
350
300
250
200
150
100
50
0
tan β = 1.5
EXCLUDED
EXCLUDED
M(gluino) (GeV)
-200 -150 -100 -50 0 50 100 150 200
μ (GeV)

Fig. 4