2 Cascade Decays of Gluinos and Squarks

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For the actual detection of gluinos and squarks it is crucial to consider all their possible decay modes. If squarks are heavier than gluinos then the gluinos decay into

$$\tilde{g} \rightarrow q + \bar{q} + \tilde{\chi}_i^0 , \qquad (2.1)$$
$$\tilde{g} \rightarrow q + \bar{q}' + \tilde{\chi}_i^\pm , \qquad (2.2)$$
$$\tilde{g} \rightarrow g + \tilde{\chi}_i^0 . \qquad (2.3)$$

The charginos and neutralinos in turn decay according to ($\mathrm{H}_1^0 \equiv \mathrm{H}$, $\mathrm{H}_2^0 \equiv \mathrm{h}$, $\mathrm{H}_3^0 \equiv \mathrm{A}$)

$$\tilde{\chi}_i^0 \rightarrow Z^0 + \tilde{\chi}_k^0,\ W^\pm + \tilde{\chi}_k^\mp,\ H_l^0 + \tilde{\chi}_k^0,\ H^\pm + \tilde{\chi}_k^\mp , \qquad (2.4)$$

$$\tilde{\chi}_i^\pm \rightarrow Z^0 + \tilde{\chi}_k^\pm,\ H_l^0 + \tilde{\chi}_k^\pm,\ W^\pm + \tilde{\chi}_k^0,\ H^\pm + \tilde{\chi}_k^0 , \qquad (2.5)$$

if kinematically allowed. If the mass differences are too small, such that the two-body decays are forbidden, the decays $\tilde{\chi}_i^\pm \rightarrow l^\pm + \overset{(-)}{\nu} + \tilde{\chi}_k^0$, $q + \bar{q}' + \tilde{\chi}_k^0$, $\tilde{\chi}_i^0 \rightarrow l^+ + l^- + \tilde{\chi}_k^0$, etc. may become important. This will, in general, lead to cascade decays of squarks and gluinos. They end when the lightest supersymmetric particle $\tilde{\chi}_1^0$ is reached. If gluinos are heavier than squarks, then the squarks, have the following decay modes

$$\tilde{q}_{L,R} \rightarrow q + \tilde{\chi}_i^0 \qquad (2.6)$$
$$\tilde{u}_{L,R} \rightarrow d + \tilde{\chi}_i^+ \qquad (2.7)$$
$$\tilde{d}_L \rightarrow u + \tilde{\chi}_i^- . \qquad (2.8)$$

The neutralinos and charginos again decay as described above. Also here a variety of cascade decays is possible until the lightest neutralino is produced.

In the following we shall present a systematic study of all possible gluino- and squark-decay modes. We shall investigate the whole supersymmetry parameter space relevant for the LHC. We have extended the results of previous studies [2.1] in various ways. In our calculation of the decay widths for $\tilde{g} \rightarrow t + \bar{t} + \tilde{\chi}_i^0, \tilde{g} \rightarrow t + \bar{b} + \tilde{\chi}_i^-, \tilde{g} \rightarrow b + \bar{t} + \tilde{\chi}_i^+$ we have fully taken into account the top Yukawa coupling as well as all top mass terms. In comparison with Ref. [2.2] we have found that they are important. Furthermore, we have included the loop decay $\tilde{g} \rightarrow g + \tilde{\chi}_i^0$, Eq. (2.3). In discussing squark decays it is also important to include the top Yukawa coupling in the decays $\tilde{t}_{L,R} \rightarrow t + \tilde{\chi}_i^0, \tilde{t}_R \rightarrow b + \tilde{\chi}_i^+, \tilde{b}_L \rightarrow t + \tilde{\chi}_i^-$. A more comprehensive discussion of gluino and squark decays into heavy top quarks is given in Ref. [2.3].

As will be shown here, despite the complexity of the decay patterns of gluinos and squarks it is possible to find suitable signatures for detecting these particles.

2.1 Discussion of gluino decays

At the LHC gluinos in a mass range up to ~ 1 TeV can be explored. In this section we shall assume that the gluinos are lighter than the squarks. In the numerical examples given below we shall take $m_{\tilde{q}_L} = m_{\tilde{q}_R} = 2\,m_{\tilde{g}}$, $\tan\beta = 2$, $M'/M = 5/3\,\tan^2\theta_W$, $M/m_{\tilde{g}} = \alpha_2/\alpha_s$, $m_{\tilde{g}} \simeq 0.3\,m_{\tilde{g}}$, $\alpha_s = 0.1$, $\sin^2\theta_W = 0.23$, and $m_t = 150$ GeV. Considering first gluino decays into light quarks, $\tilde{g} \to q + \bar{q} + \tilde{\chi}_i^{0,\pm}$, then for $|\mu| \leq m_{\tilde{g}}/3$ mainly the heavy chargino and the heaviest neutralino would be produced, whereas for $|\mu| \geq m_{\tilde{g}}/3$ the decays into the light chargino and the second lightest neutralino would dominate. This decay pattern is changed if the transitions $\tilde{g} \to g + \tilde{\chi}_i^0$ are also included, and in the decays $\tilde{g} \to t + \bar{t} + \tilde{\chi}_i^0$, $t + \bar{b} + \tilde{\chi}_i^-$, $b + \bar{t} + \tilde{\chi}_i^+$ the top mass is fully taken into account. In Fig. 2.1a we show the branching ratios for these decays into top quarks as a function of μ for a gluino mass $m_{\tilde{g}} = 1000$ GeV. Contrary to the light-quark case, in the parameter domain $|\mu| \leq m_{\tilde{g}}/3$ the dominant transition is that into the light chargino.

As to the loop decays $\tilde{g} \to g + \tilde{\chi}_i^0$, their branching ratios can go up to about 20%. The branching ratios for $\tilde{g} \to \tilde{\chi}_i^0 + q + \bar{q}$ (or g) and $\tilde{g} \to \tilde{\chi}_i^{\pm} + q + \bar{q}'$, summed over all quark flavours, are shown in Fig. 2.1b. Owing to the Yukawa coupling of the top quark there are appreciable transition rates into the light chargino and the light neutralinos for $|\mu| < m_{\tilde{g}}/3$. For $|\mu| > m_{\tilde{g}}/3$ the decays into the light chargino and the second lightest neutralino are the most important ones. Notice that the branching ratio for the decay into the lightest neutralino which leads to the classical signature for supersymmetry (large missing energy plus jets) is about 15 percent. It is smaller than that of the decay into $\tilde{\chi}_2^0$. The decay into $\tilde{\chi}_3^0$ occurs owing to $\tilde{g} \to g + \tilde{\chi}_3^0$.

We shall now discuss the interesting signatures for gluino production $p + p \to \tilde{g} + \tilde{g} + X$. As a result of the chargino and neutralino decays [2.4], Eqs. (2.4) and (2.5), the final state in general contains Z^0, $W^{\pm}$, Higgs particles, jets, leptons, neutrinos, and $\tilde{\chi}_1^0$'s. Of particular interest is the case where the gluino decays directly into $\tilde{\chi}_1^0$. Figure 2.2a shows the probability that only one of the gluinos decays directly into $\tilde{\chi}_1^0$ or both, for $m_{\tilde{g}} = 500$ GeV. The probability for one direct $\tilde{\chi}_1^0$ is about 30 %, for two direct $\tilde{\chi}_1^0$ a few per cent, only weakly dependent on μ. We also indicate the region in μ which will be covered by searching for charginos and neutralinos in the full energy range of LEP. For heavier gluinos we have found smaller values of these branching ratios (within a factor of 3) and a stronger dependence on μ.

Another way to search for gluinos could be to look for Z^0's in the final state. We have calculated the branching ratio for $\tilde{g} + \tilde{g} \to 2\,Z^0 +$ anything. It is shown in Fig. 2.2b for $m_{\tilde{g}} = 1000$ GeV (taking a charged Higgs mass $m_{H^\pm} = 500$ GeV). The branching ratio is a few per cent. In the case of $m_{\tilde{g}} = 500$ GeV the $2\,Z^0$ branching ratio becomes very small for $|\mu| > 300$ GeV because of phase space.

For detecting gluinos the rate of events with isolated leptons will be important In Fig. 2.2b we show the branching ratios $\tilde{g} + \tilde{g} \to 4\,\mu$, $5\,\mu$, and $6\,\mu$. Here we have summed over all events with μ's coming from Z^0, $W^{\pm}$, and three-body decays of charginos and neutralinos, and from t-quark decays into $b\,W$. For $m_{\tilde{g}} = 1000$ GeV the $4\,\mu$ rate is about 10^{-4} and the $5\,\mu$ rate between 10^{-5} and 10^{-6}. In the case where $m_{\tilde{g}} = 500$ GeV these branching ratios depend more strongly on $\tan\beta$. For $\tan\beta = 10$ the $4\,\mu$ branching ratio is about 10^{-4} and the $5\,\mu$ branching ratio between 10^{-5} and 10^{-7}, whereas for $\tan\beta = 2$ the corresponding values are much smaller.

2.2 Discussion of squark decays

In this section we consider the case where the squarks are lighter than the gluinos. At the LHC a squark mass range up to ~ 1 TeV can be explored. In the following we shall always assume $m_{\tilde{g}} = 1.5\,m_{\tilde{q}}$, $m_{\tilde{q}_L} = m_{\tilde{q}_R}$.

If the quarks in the final state of Eqs. (2.6)–(2.8) are light, right squarks decay only into neutralinos, for $|\mu| > m_{\tilde{g}}/3$ to practically 100 percent into $\tilde{\chi}_1^0$, and for $|\mu| < m_{\tilde{g}}/3$ to more than 90 percent into $\tilde{\chi}_3^0$. Left squarks decay dominantly into charginos as can be seen in Fig. 2.3a, where we plot the branching ratios of $\tilde{u}_L \to d + \tilde{\chi}_i^+$, $u + \tilde{\chi}_i^0$ for $m_{\tilde{q}} = 500$ GeV. For $|\mu| > m_{\tilde{g}}/3$ ($|\mu| < m_{\tilde{g}}/3$) the transition into the lighter (heavier) chargino has the largest branching ratio. The decays into $\tilde{\chi}_2^0$ ($\tilde{\chi}_4^0$) have appreciable rates for $|\mu| > m_{\tilde{g}}/3$ ($|\mu| < m_{\tilde{g}}/3$). A qualitatively similar pattern holds for $\tilde{d}_L$ decays.

Taking into account the top-quark mass again changes the picture just described. The $\tilde{t}_R$ now dominantly decays into charginos. For $|\mu| \leq m_{\tilde{g}}/3$ the transition into the lighter chargino accounts for approximately 50% of all $\tilde{t}_R$ decays. In the decays of the $\tilde{t}_L$ the essential changes due to the top mass occur in the region $|\mu| \leq m_{\tilde{g}}/3$ (see Fig. 2.3b). Now the decays into $\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$, $\tilde{\chi}_3^0$ become important, as can be seen by comparing Figs. 2.3a and 2.3b. Also the decays of $\tilde{b}_L$ are substantially influenced by the top-quark mass terms [2.3].

We have calculated the probabilities that the squarks produced decay directly into exactly one or two $\tilde{\chi}_1^0$, i.e. $\tilde{q} + \bar{\tilde{q}} \to \tilde{\chi}_1^0 + X$ and $\tilde{q} + \bar{\tilde{q}} \to \tilde{\chi}_1^0 + \tilde{\chi}_1^0 + X$ (where X does not contain another $\tilde{\chi}_1^0$). We have averaged over left and right squarks and all flavours. The results are shown in Fig. 2.4a for $m_{\tilde{q}} = 500$ GeV. It is remarkable that over a large range of μ the branching ratio into $2\,\tilde{\chi}_1^0$ is almost an order of magnitude larger than that of producing only one $\tilde{\chi}_1^0$. This implies that about 40% of the events coming from squark production will have a large missing energy. The reason is that for $|\mu| \geq m_{\tilde{g}}/3$ the right squarks (except $\tilde{t}_R$) almost exclusively decay into $\tilde{\chi}_1^0$. This feature is also quite independent of $\tan\beta$.

On the other hand, the squarks may decay in cascades until the lightest supersymmetric particle is produced. We show in Fig. 2.4b the rate for $\tilde{q} + \bar{\tilde{q}} \to 2\,Z^0 +$ anything for $m_{\tilde{q}} =$ 750 GeV (taking a charged Higgs mass $m_{H^\pm} = 500$ GeV). Depending on μ this rate can go up to a few per cent. Figure 2.4b also shows the rate of multimuon events, i.e. $\tilde{q} + \bar{\tilde{q}} \to 4\mu$, 5μ, 6μ, including all μ's coming from Z^0, $W^\pm$, and three-body decays of neutralinos and charginos as well as from t-quark decay $t \to Wb$.

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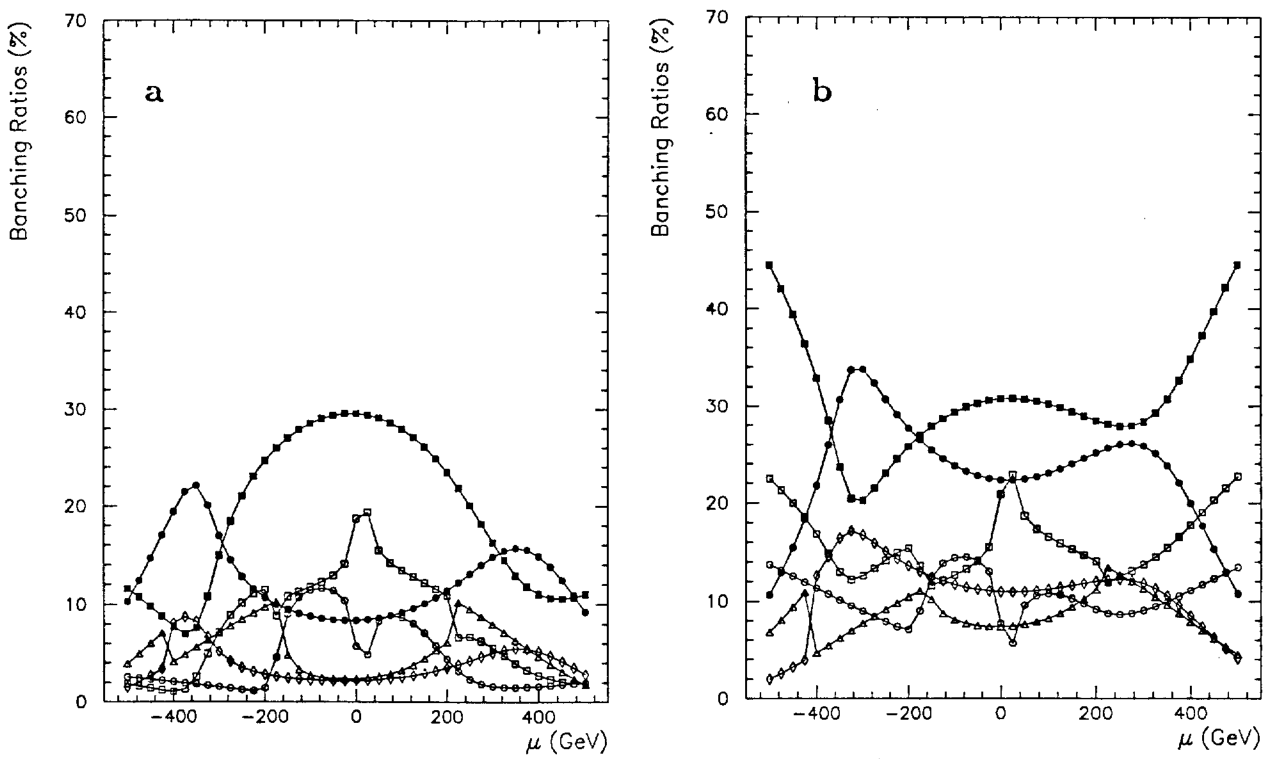

Fig. 2.1: Branching ratios for **a)** $\tilde{g} \to \tilde{\chi}_i^0 + \bar{t} + t$, $\tilde{\chi}_i^- + \bar{b} + t$, $\tilde{\chi}_i^+ + \bar{t} + b$; **b)** $\tilde{g} \to \tilde{\chi}_i^0 + q + \bar{q}$, $\tilde{\chi}_i^0 + g$, $\tilde{\chi}_j^\pm + q + \bar{q}'$ (summed over all flavours). Decays into $\tilde{\chi}_1^\pm$ (■) $\tilde{\chi}_2^\pm$ (•), $\tilde{\chi}_1^0$ (○), $\tilde{\chi}_2^0$ (□), $\tilde{\chi}_3^0$ (△), and $\tilde{\chi}_4^0$ (◇), for $m_{\tilde{g}} = 1000$ GeV, $\tan\beta = 2$.

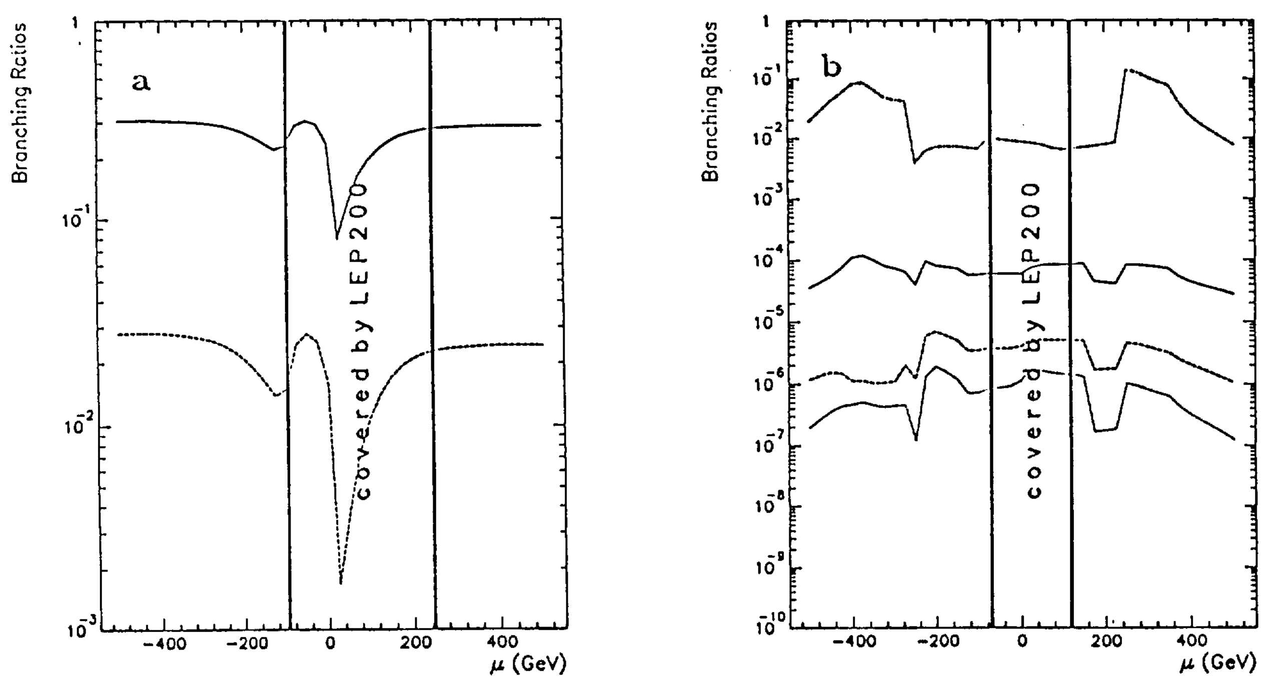

Fig. 2.2: Branching ratios for $\tan\beta = 2$ for **a)** $\tilde{g} + \tilde{g} \to \tilde{\chi}_1^0 + X$ (solid line), $2\,\tilde{\chi}_1^0 + X$ (dash), for $m_{\tilde{g}} = 500$ GeV; **b)** $\tilde{g} + \tilde{g} \to 2Z^0 + X$ (dot dash), $4\mu + X$ (solid), $5\mu + X$ (dash), $6\mu + X$ (dot), for $m_{\tilde{g}} = 1000$ GeV.

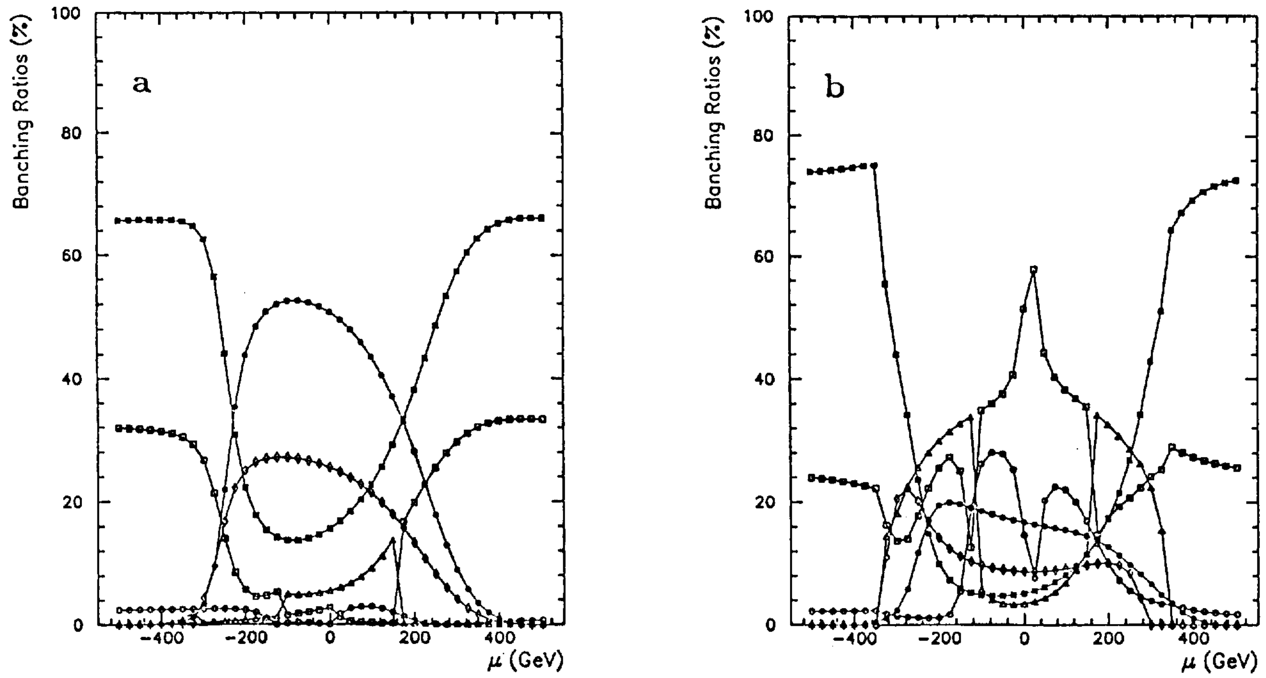

Fig. 2.3: Branching ratios for **a)** $\tilde{u}_L \to \tilde{\chi}_i^0 + u,\ \tilde{\chi}_i^+ + d$; **b)** $\tilde{t}_L \to \tilde{\chi}_i^0 + t,\ \tilde{\chi}_i^+ + b$, for $m_{\tilde{q}} = 500$ GeV and $\tan\beta = 2$. The symbols are as in Fig. 2.1.

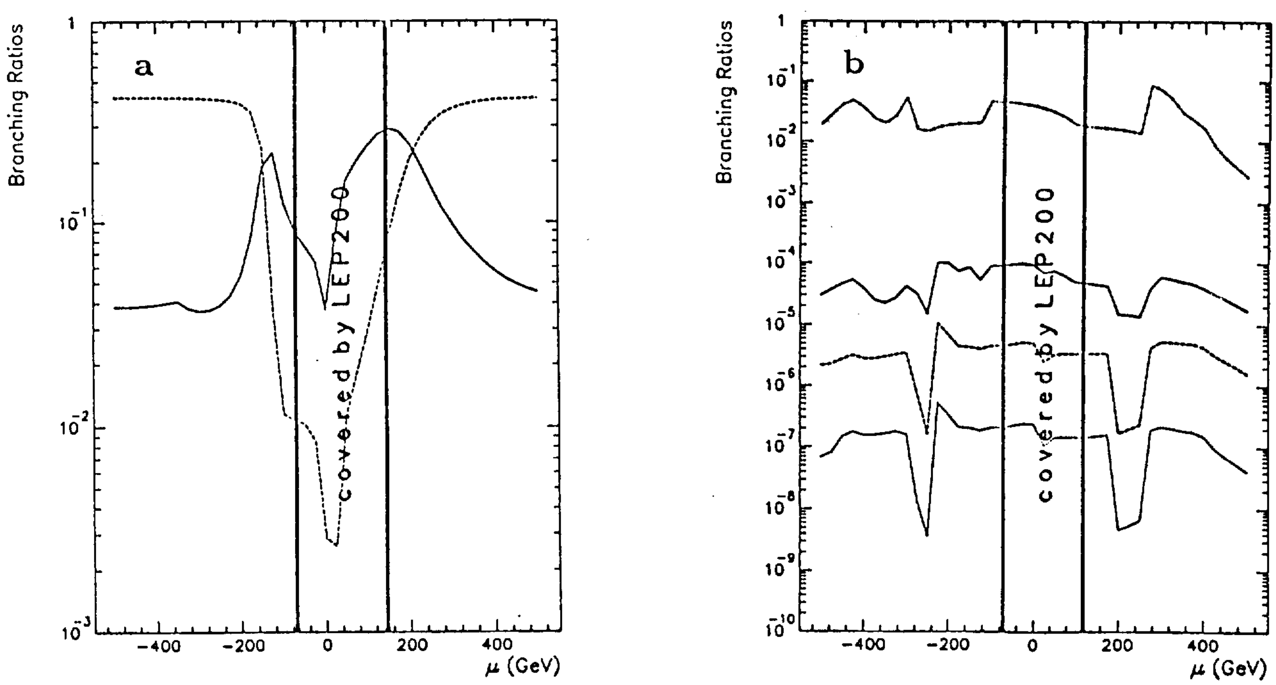

Fig. 2.4: Branching ratios for $\tan\beta = 2$ for **a)** $\tilde{q}+\bar{\tilde{q}} \to \tilde{\chi}_1^0 + X$ (solid), $\tilde{\chi}_1^0 + \tilde{\chi}_1^0 + X$ (dashed), for $m_{\tilde{q}} = 500$ GeV; **b)** $\tilde{q}+\bar{\tilde{q}} \to 2Z^0 + X$ (dash dotted), $4\mu + X$ (solid), $5\mu + X$ (dashed), $6\mu + X$ (dotted), for $m_{\tilde{q}} = 750$ GeV.