SLAC – PUB – 3550
January 1985
(T/E)

IMPLICATIONS FOR SUPERSYMMETRY OF THE CERN MONOJETS*

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Results of a comprehensive study of supersymmetric processes which could give monojet events similar to those observed at the CERN $Sp\bar{p}S$ are presented. If supersymmetry is to be the explanation of the monojets, strict bounds are obtained on possible supersymmetric masses.

In this talk, I will present work which was done in collaboration with R. Michael Barnett and Gordon Kane.[1] I have also added here a number of new results which we have obtained since the Santa Fe Meeting.

Because of recent interest in supersymmetric theories of particle physics, there has been considerable work to determine the likely signatures of supersymmetric particles.[2] A key feature of most of these models is that there exists a lightest stable supersymmetric particle which is electrically neutral and interacts weakly with ordinary matter (i.e. it behaves very much like a neutrino). For simplicity, we shall assume that this particle is the photino, $\tilde{\gamma}$ (although our results are more general than this assumption). This implies that an experimental signature for this new physics would be events with unbalanced energy and momentum.

In this article, I shall focus on events of this type which have been seen at the CERN collider by the UA1[3] collaboration. They are characterized by one or more large transverse momentum hadronic jets and substantial missing transverse energy. The most striking of the UA1 events are those where there is exactly one large p_T jet and substantial missing energy – these are called monojet events. These events are isolated by imposing a series of cuts and jet selection criteria. The relevant variables include E_T, the total scalar transverse energy, which is found by summing transverse energy over all calorimeter cells, and E_T^{miss}, the missing transverse energy in the event. E_T^{jet} denotes the transverse energy of the hadronic jet. The most important cuts are: (a) $E_T^{miss} > 4\sigma$ with $\sigma = 0.7 \times \sqrt{E_T}$. This cut attempts to eliminate events with missing energy which result from nonuniform calorimetry and other mismeasurements. (b) $E_T^{miss} \geq 15$ GeV, although we will impose a more severe constraint below. (c) Jets are defined according to the UA1 jet algorithm.[4] In addition, it is required that the most energetic jet have energy $E_T^{jet} \gtrsim 25$ GeV. All additional jets are counted as jets only if $E_T^{jet} \geq 12$ GeV. For example, monojets have one jet with $E_T^{jet} \geq 25$ GeV and <u>no</u> additional jets with $E_T^{jet'} \geq 12$ GeV.

The UA1 collaboration quotes the following number of events which passed the cuts during their 1983 run[3] (corresponding to 113 nb^{-1} of data): 17 monojets, 5 dijets and 3 three- (or more)-jet events. The UA1 collaboration then notices that a large fraction of events lie close to the 4σ cut on missing energy. To minimize the question of background, we have imposed one further cut in our analysis: we demand that $E_T^{miss} \geq 32$ GeV. We would then be left with 6 monojets, no dijets and one three-jet event. These events are well isolated and are more likely to live in a background free region.

We study the possibility that the monojets arise from the production of scalar-quarks and gluinos; the missing energy is attributed to one or more photinos which eventually result from supersymmetric particle decay. Previous analyses of the monojets in the context of supersymmetry can be found in Refs. 5-9. The couplings of scalar-quarks and gluinos are precisely known, being related by the supersymmetry to known gauge couplings. The supersymmetric masses are unknown and taken to be free parameters. For simplicitly, we have assumed that five flavors of scalar-quarks are mass degenerate and we take $M_{\tilde{\gamma}} = 0$.

We have attempted to calculate <u>every</u> supersymmetric process which could lead to monojet events of the type

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* Work supported in part by the Department of Energy, contracts DE-AC03-76SF00515 and DE-AM03-76SF00010.

Invited talk presented at the 1984 Annual Meeting of the Division of Particles and Fields of the American Physical Society, Santa Fe, New Mexico, October 31 - November 3, 1984

observed by UA1. The signature of a given process depends on whether $M_{\tilde{q}} > M_{\tilde{g}}$ or $M_{\tilde{g}} > M_{\tilde{q}}$. For $M_{\tilde{q}} > M_{\tilde{g}}$, $\tilde{g} \rightarrow q\bar{q}\tilde{\gamma}$ and $\tilde{q} \rightarrow q\tilde{g}$ or $q\tilde{\gamma}$ with a relative branching ratio of $(4/3)\alpha_s/\alpha e_q^2$. In this case, we studied the production of $\tilde{g}\tilde{g}$, $\tilde{g}\tilde{q}$ and $\tilde{\gamma}\tilde{g}$ final states. The relevant cross-sections for the elementary subprocesses can be found in Ref. 10. In addition, if the gluino is light enough, it would be perturbatively generated as a component of the proton.[9,11] We calculated the gluino structure function for various gluino masses, so that we could investigate $\tilde{g}+q \rightarrow \tilde{q}$ with $\tilde{q} \rightarrow q\tilde{g}$ or $q\tilde{\gamma}$. On the other hand, for $M_{\tilde{g}} > M_{\tilde{q}}$ the gluino and scalar-quark decay via: $\tilde{g} \rightarrow q\tilde{q}$ and $\tilde{q} \rightarrow q\tilde{\gamma}$. For this case, we have studied the production of $\tilde{q}\tilde{q}$, $\tilde{g}\tilde{g}$, $\tilde{\gamma}\tilde{q}$ and $\tilde{g}\tilde{q}$ final states. We employ the formalism of the QCD-improved parton model (with no additional K-factor) and have used the distribution functions of Ref. 12. Events are generated using a Monte Carlo integration technique and all final-state supersymmetric particles are allowed to decay. We interpret all final-state quarks as "hadronic jets," and the UA1 cuts and jet criteria are then implemented.

One subtlety worth mentioning is that the parton model methods described above cannot correctly predict the total scalar transverse energy, E_T. This is true because E_T arises in part[13] from the hadronization of quarks and gluons which come from both jets and spectators left behind. However, E_T is needed on an event-by-event basis, as it plays a role in the missing energy cut. To circumvent this problem we make direct use of the UA1 data. If one removes the leading jet from the monojets, the remaining events have an E_T that averages around 50 GeV (with large variation). This is not surprising since ordinary two-jet events have the property[14] that when the two jets are removed, the remaining E_T is roughly 40-50 GeV (i.e. twice that of minimum-bias events[15]). Thus, when we obtain events from our Monte Carlo, we have chosen to identify E_T as $E_T = \sum_i E_{Ti} + E_s$, where E_{Ti} consist of <u>all</u> final-state quarks whether or not they end up in jets which pass the UA1 cuts.[13] E_s is chosen based on a transverse energy distribution which corresponds to what is observed in minimum-bias events[15] scaled up so as to give an average which we have taken to be 40 GeV. (The jets which do not pass the cuts account for the remaining 10 GeV.)

We have computed cross-sections and distributions for monojets, dijets, etc. originating from the supersymmetric processes which successfully pass the UA1 cuts. Note that these events, which in reality contain many final state partons at large transverse energy, actually appear most often as monojets (or perhaps dijets) due to the nature of the UA1 cuts and selection criteria. We present our results in two stages. First, we investigate the question of how many monojets and dijets successfully pass the UA1 cuts (without regard to distributions). This allows us to make an initial determination of supersymmetric masses which can be consistent with the observed event rates. Second, we examine distributions of various quantities (E_T^{miss}, E_T^{jet} and the transverse mass, m_T, of the monojets) in order to further restrict the allowed region of supersymmetric parameters.

In Figs. 1-3, we present a number of predicted cross sections for the production of monojets <u>after</u> imposing the UA1 cuts and the additional restriction that $E_T^{miss} \geq 32$ GeV. These figures are computed only for a given mechanism as indicated. Note that the predictions in Figs. 1-2 differ (sometimes significantly) from the results of Refs. 5-8. We believe that these differences are due primarily to our more stringent cut on E_T^{miss} and to our improved handling of the UA1 cuts as described above. In particular, we expect fewer monojets events as compared to Refs. 5-8 for small $M_{\tilde{g}}$ or $M_{\tilde{q}}$; as a result, we do <u>not</u> rule out gluino masses below 40 GeV. We have in addition surveyed <u>all</u> the processes described earlier for a large variety of masses and have obtained results analogous to those of Figs. 1-3. For a given

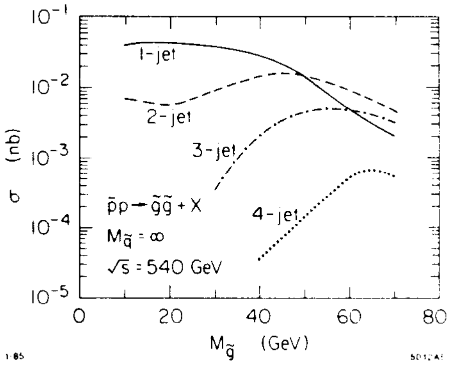

Fig. 1. Predicted cross-sections (after cuts) for $\bar{p}p \rightarrow n$-jets + missing transverse energy (where $n = 1, \ldots, 4$), resulting from the production of $\tilde{g}\tilde{g}$.

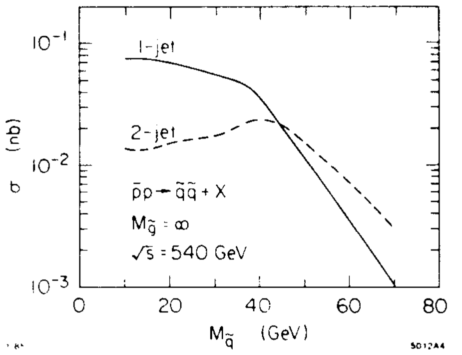

Fig. 2. Predicted cross-sections (after cuts) for $\bar{p}p \rightarrow n$-jets + missing transverse energy (where $n = 1$ or 2), resulting from the production of $\tilde{q}\tilde{q}$.

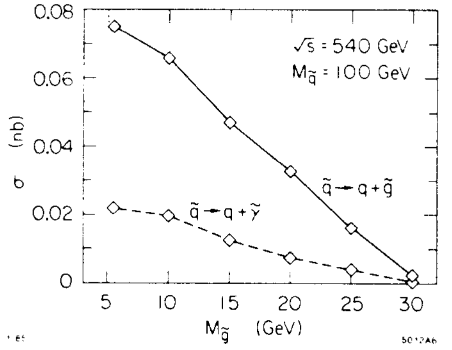

Fig. 3. Predicted cross-sections (after cuts) for $\bar{p}p \rightarrow$ monojets due to the subprocess $q + \tilde{g} \rightarrow \tilde{q}$. We have generated the gluino distribution function for $M_{\tilde{g}} = 10$, 15, 20 and 25 GeV. For comparison, we have used the EHLQ distribution functions[12] for the b and t quarks, multiplied by 6 (the appropriate color factor) for $M_{\tilde{g}} = 5$ and 30 GeV respectively. Results for the two $\tilde{q}$ decay modes are shown separately.

$M_{\tilde{q}}$ and $M_{\tilde{g}}$, we can then add up all contributions and determine the number of monojets and dijets which would survive the cuts. The outcome of this procedure is shown in Figs. 4-5. We expect these results to be fairly reliable except for $M_{\tilde{q}}$ or $M_{\tilde{g}} \lesssim 5$ GeV. In this regime, there are two problems: First, although cross-sections rapidly increase for decreasing $M_{\tilde{q}}$ or $M_{\tilde{g}}$, virtually nothing passes the cuts; as a result one needs to generate an extremely large number of Monte Carlo events in order to get decent statistics. Second, when the probability for passing the cuts becomes small, fragmentation and hadronization effects become important and can totally alter the results (e.g. by changing the missing energy spectrum such that far fewer events pass the E_T^{miss} cut). At this stage, constraints on supersymmetric masses can be read-off directly from Figs. 4-5. As an example, current data would lead us to expect the allowed regions to be roughly 2-10 events per 100 nb^{-1} in Fig. 4 and more monojets than dijets in Fig. 5.

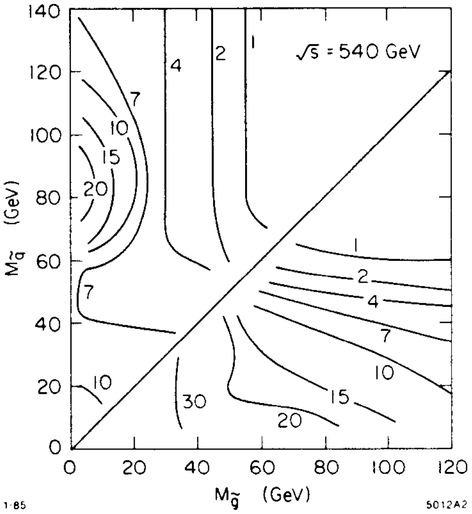

Fig. 4. The number of monojets per 100 nb^{-1} from all supersymmetric sources passing the UA1 cuts and $E_T^{miss} \geq 32$ GeV are shown as a contour plot as a function of $M_{\tilde{g}}$ and $M_{\tilde{q}}$.

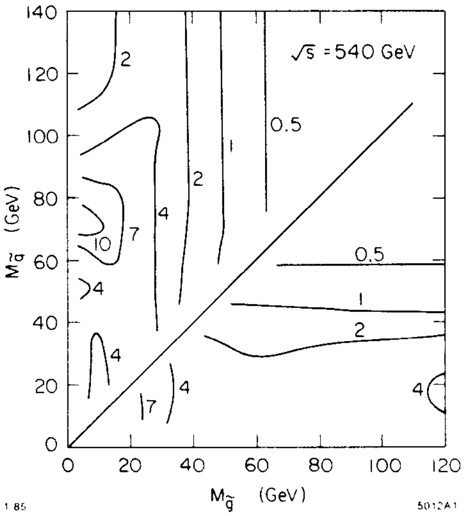

Fig. 5. The ratio of the number of monojets to the number of dijets passing the UA1 cuts and $E_T^{miss} \geq 32$ GeV are shown as a contour plot as a function of $M_{\tilde{g}}$ and $M_{\tilde{q}}$.

We now turn briefly to distributions. In Fig. 6, the m_T distribution for $M_{\tilde{g}} = 20$ GeV and $M_{\tilde{q}} = 100$ GeV is shown. The contributions of two subprocesses are shown separately;

the curves should be added to get the total result. By comparing with the actual data of Ref. 3, it is evident that the curve for $\tilde{g}\tilde{g}$ production (the dashed curve) peaks at significantly lower values of m_T than do the data; very similar results occur for E_T^{jet} and E_T^{miss}. We have found that the same is true for any process with two supersymmetric particles in the final state as long as the masses of these particles are less than about 60 GeV (at which point, the absolute rate becomes too small). An improved fit (see solid curve in Fig. 6) is found from the decay of the scalar-quark from $\tilde{g} + q \rightarrow \tilde{q}$ when the scalar-quark has a mass of about 100 GeV. However, the $\tilde{g}\tilde{g}$ process continues to contribute about 3 events no matter how large $M_{\tilde{q}}$ is, so that in this scenario we always expect events at lower m_T, E_T^{jet} and E_T^{miss}. One must either argue that the efficiency for finding such events is lower than the efficiency for events with larger E_T^{miss}, or argue that increased statistics will indicate the presence of such events.

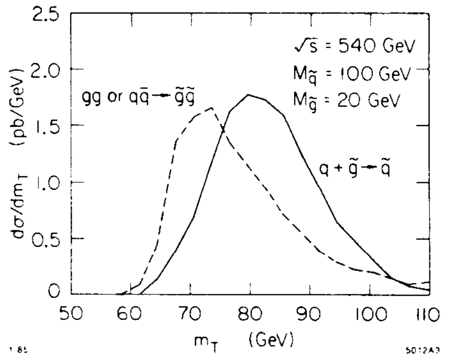

Fig. 6. The transverse mass distribution for monojet events passing the UA1 cuts and $E_T^{miss} > 32$ GeV. The solid curve shows events arising from $\tilde{g}+q \rightarrow \tilde{q}$ where $\tilde{q} \rightarrow q + \tilde{g}$ and $\tilde{q} \rightarrow q + \tilde{\gamma}$ have been summed. The dashed curve is from the associated production (and decay) of $\tilde{g}\tilde{g}$.

The conclusion we draw from the analysis of the distributions, is that in order to get enough events at large values of m_T of order 90-100 GeV, the $\tilde{g} + q \rightarrow \tilde{q}$ mechanism must be important. As a result, we find that the monojets can be consistent with supersymmetry if $M_{\tilde{q}} \approx 100 - 120$ GeV and $M_{\tilde{g}} \lesssim 20$ GeV. This would imply that when further data has been collected: (a) more events must found for m_T below 90 GeV as shown in Fig. 6 (and similarly, more events should be seen at lower E_T^{jet} and E_T^{miss}) which are attributable to supersymmetry, and (b) dijets should be found at a rate which is not too small as compared to monojets (see Fig. 2).

ACKNOWLEDGEMENTS

I am grateful to Burt Ovrut for the invitation to participate in his session on supersymmetry. In addition, I would like to thank Witold Kozanecki for many invaluable discussions concerning the UA1 experiment.

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