EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-EP/83-132

9 September 1983

EXPERIMENTAL TESTS OF SUPERSYMMETRY

A. Savoy-Navarro^{*)}
CEA-Saclay, Gif-sur-Yvette, France

ABSTRACT

The main realistic possibilities of checking supersymmetry are reviewed here, taking into account the most recent developments in this theoretical field as well as the different machines (e^+e^- colliders, hadron-hadron colliders, ep machines) available presently or in the next 10 years and also the sky. A strong emphasis is put especially on how to test supersymmetry in the hadron-hadron colliders which are already now (SPS $p\bar{p}$ collider at CERN) or will be in the very near future (FNAL $p\bar{p}$ collider) very useful tools for such a purpose. The requirements of supersymmetry in terms of detector performances are studied with the present apparatuses and with the different prototypes which are being developed for the experiments at the next generation accelerators.

To be part of a Physics Report on:
Supersymmetry confronting experiment

^{*)} Present address: CERN, Geneva, Switzerland.

INTRODUCTION

After explaining **WHY**, as experimentalists, we have to worry about supersymmetry (SUSY), we will introduce the subject by explaining **FROM WHERE WE START**. So we will review the main aspects of SUSY as viewed by an experimentalist for experimentalists, giving also a brief status report on the few experimental results now existing on the subject, and also mentioning those accelerators which are already built, or which will be built or planned in the next 10 to 15 years.

We then describe which *realistic* experimental tests of SUSY can be performed in these different types of machines. By “realistic” we mean a process that gives a detectable signature, a reasonable rate, and an understandable background. So, following these criteria, we explain:

- 1) Why the e^+e^- colliders are “ideal SUSY-machines” (especially in connection with the search for scalar leptons, scalar quarks, and other SUSY particles expected as products of the Z^0 decay, and also why they constitute a unique way of searching for photinos).
- 2) How the hadron-hadron colliders can compete: because they arrive first in time; because all together they will cover an impressive energy range; because there it would be possible to find gluinos, scalar quarks, and different kinds of gauginos which should be produced in the W-decay.
- 3) Why the ep machines can also contribute a useful piece of information even if they are not clearly the “typical” SUSY-machine; namely, when studying the usual neutral-current (NC) and charged-current (CC) reactions, one might find effects due to the production of the scalar quark and scalar lepton as well as effects due to associated production of SUSY particles.
- 4) How baryon decay experiments can perhaps sometimes give an answer.

Finally, we discuss the ideal SUSY detector: so we explain the main requirements of SUSY concerning a *good jet recognition*, a *recognition of leptons near or inside a jet*, a *good missing p_T measurement*. For this discussion we will profit from present experience, obtained essentially at PETRA and at the SPS $p\bar{p}$ collider. We will finish by comparing the possible performances of different devices in this hunt for SUSY particles.

1. WHY?

Faced with the fundamental aim of supersymmetry theories, with the work done in this field by the theorists since almost ten years (with an exponential increase during these last 2 years), and with the nice collection of new particles proposed by SUSY, the experimentalists cannot remain completely ignorant or unconcerned about testing such ideas. For these reasons, a Workshop¹⁾ was organized at CERN last year to trigger interest among experimentalists, encouraging them to look for ways of testing SUSY. It showed, in fact, that a lot can be done with both the present program and that already envisaged for the next 10 years. So the “slogan” at that stage was “test SUSY in any possible way!”. Now, on the one hand, with the phenomenological and theoretical work and the progress in this field and, on the other hand, with the success of the SPS $p\bar{p}$ collider at CERN as well as the experience gained at the PETRA collider, we reach another level; essentially we try to see the real experimental possibilities for testing the prediction of such theory and not an exhaustive list full of fancy but unrealistic proposals.

Let us first explain the present scenario.

2. FROM WHERE DO WE START?

2.1 SUSY as viewed by an experimentalist^{*)}

Supersymmetry is an attempt to relate the fundamental interactions (electromagnetic, weak, strong) to gravity. Whilst doing so, it predicts a completely NEW SPECTROSCOPY in the range going from a few GeV to a few TeV (depending on the models; see Table 1); most of them favour a region around the W mass for most of the SUSY particles. It is a symmetry which links fermions and bosons in such a way that to each “standard” boson (resp. fermion) there corresponds a SUSY fermion (resp. boson) partner, as described in Table 1.

Up to last year, gravitational effects were supposed to be small, so SUSY was expressed as a global invariance³⁾ (at least to a good approximation). Important progress has since been made: the coupling of gauge theories to SUSY in the presence of super-Higgs effects has been achieved so that local SUSY or supergravity models have been proposed⁴⁾. Let me first briefly explain why and in which way this matters to us experimentalists (for a review of this subject, see references 1 and 5). The fact that gravitational effects are either neglected (global SUSY) or taken into account (local SUSY) gives us two different types of SUSY phenomenology. This appears, for instance, when looking at the predictions of the different types of local and global models with respect to the SUSY spectroscopy (see Table 1). As recent theoretical developments are more local-SUSY oriented, I will essentially insist on the phenomenological consequences of supergravity-type models (mentioning anyhow the main features of the global approach).

*) I will let my theoretician friends²⁾ do their job, i.e. explain to you all about SUSY. However, my purpose, in this section, is just to summarize a few ideas which can be of some use for the experimentalists, whilst remaining as least biased as possible (this is clearly much more difficult for the expert!).

In any case, $m_{3/2}$ (the gravitino mass) is related to the symmetry breaking by the relation: $m_{3/2} \sim M_S^2/M_P$ (where M_P is the Planck mass and M_S the SUSY-breaking scale). In the case of global SUSY, the gravitino mass is much smaller than the typical mass splitting between bosons and fermions which is larger than or equal to 20 GeV because the (eaten) goldstino couples through a dimensionless coupling constant $[O(e)?]$, or some power of this, if the coupling is radiative (so $M_S \ll \sqrt{M_W M_P}$)*). In the local case, $m_{3/2} \gtrsim 20 \text{ GeV} \sim O(M_W)$, and its coupling is gravitational (thus of order $1/M_P$); in this case $M_S = O(\sqrt{M_W M_P})$.

The more interesting consequences for the experimentalists concern the properties of the particle spectrum in supergravity models, $m_{3/2} \sim M_W$. The typical mass scale of SUSY partners of light particles such as gluinos, scalar quarks and scalar leptons, and winos would be of the order of the characteristic parameter of this theory, i.e. the gravitino mass, with an order of magnitude variation in both directions depending on the models.

The gravitino couplings to gluon-gluino, quark-scalar quark, etc. would be gravitational, so such couplings can be ignored in supergravity models — contrary to global models, where gravitino interactions are important.

For concreteness we shall assume that:

The photino ($\tilde{\gamma}$) would be the lightest particle. The range $(1/100) m_{3/2} \leq m_{\tilde{\gamma}} \leq m_{3/2}$ seems to be a reasonable one. It would then be a stable particle (a ν -like particle, i.e. MISSING ENERGY), contrary to global models where it might decay into γG (goldstino).

The gluino mass range would be $(1/10) m_{3/2} \leq m_{\tilde{g}} \leq \text{a few } m_{3/2}$, and its dominant decay mode $\tilde{g} \rightarrow q\bar{q}\tilde{\gamma}$ (whereas in global models one may also have $\tilde{g} \rightarrow gG$). A present experimental limit already exists from the beam dump experiments as a function of the spin-0 quark masses (see next section).

The scalar quark would decay into $q\tilde{g}$ (if $m_{3/2} > m_{\tilde{g}}$) or $q\tilde{\gamma}$ (if $m_{3/2} < m_{\tilde{g}}$). The charged scalar lepton would decay into $\ell\tilde{\gamma}$ (present experimental limits already exist from the PETRA experiments, giving $m_{\tilde{\ell}} \geq 17 \text{ GeV}$ and $m_{\tilde{q}} < 2 \text{ GeV}$ or $m_{\tilde{q}} > 16 \text{ GeV}$; see next section).

In Table 1**) we summarize the SUSY-spectroscopy, product of this theory (or theories), that the experimentalists have to explore.

*) However, if an extra $U(1)$ coupling constant is introduced which is very small, the gravitino is already heavy in this global invariance approach³⁾. [I thank P. Fayet for this remark, and refer the reader to the discussion concerning this point, given in his section.]

**) For Table 1 we have purposely chosen to present an overview of possibilities given by different models. For the global model we have chosen the D-type breaking one as proposed by Fayet³⁾, and the F-type breaking one as proposed by Ellis and Ross³⁾. For local SUSY we propose the view of authors quoted in Ref. (4).

2.2 Present experimental results

They come essentially from PETRA experiments, and from beam dump and proton decay experiments.

The search for scalar objects performed at PETRA is summarized in Table 2 and Fig. 1. It shows just how good the e^+e^- colliders are for doing such a job⁶⁾, and give very good hope for the next generation of e^+e^- colliders (LEP and SLC). Their only limitation is the beam energy. The beam dump experiments performed both at the CERN Super Proton Synchrotron (SPS)⁷⁾ and at Fermilab⁸⁾ have tried to measure the gluino mass. The principle of this measurement is sketched in Fig. 2. Depending on their degree of conservatism and their theoretical prejudices, they arrive at a lower limit for the R-hadron (a colourless bound state of SUSY-particles, quarks and gluons) mass as a function of the mass of the spin-0 quark ($m_{\tilde{q}}$) (Fig. 2). By subtracting roughly 1 GeV/c² of the R-hadron mass, one gets an estimate of the gluino mass ($m_{\tilde{g}}$). The lower limit obtained on $m_{\tilde{g}}$ is of the order of 1 to 4 GeV/c² if the mass of the scalar quark $m_{\tilde{q}}$ is smaller than 40 or 100 GeV/c². These experiments already clearly show that it is quite hard for them to provide any definite answer. So personally I would not insist on going to higher energies (say a 10 TeV fixed target) and repeating such a measurement. The fixed target calorimeter experiment is also able to measure gluino pair production⁹⁾ (Fig. 2). It is certainly an interesting possibility to pursue, taking into account different sets of machines already or very soon available (SPS at CERN, FNAL Tevatron) and keeping in mind the interest for a fixed target Desertron (10 TeV). Of course a very highly performing calorimeter is required for such measurement (see Discussion in Section 4). Proton decay experiments do not give any definite answer either. We can summarize the present status by reporting the main conclusions as obtained by the Irvine-Michigan-Brookhaven (IMB) Collaboration¹⁰⁾.

- i) No possible candidate has been found for the decay $p \rightarrow e^+\pi^0$, so this set a limit of 6.5×10^{31} years for the lifetime branching ratio in this mode, with 90% CL. The maximum expected value for this number as calculated from the minimal SU(5) would have given seven such events, whereas none are seen.
- ii) Based on one possible candidate which could also be due to background, a lower limit for $p \rightarrow \mu^+K^0 = 1.3 \times 10^{31}$ years (with 90% CL) is set. This is a factor of 5 better than similar limits which can be set by other experiments, and casts some doubt on the μ^+K^0 interpretation of a candidate seen in the Mont Blanc experiment.

Before discussing how we can pursue this experimental work, we have to review the already planned program for building colliders for the next 10 to 15 years.

2.3 Set of machines available until the end of the century

We have summarized this in Fig. 3. Looking at this figure, we can make the following remarks:

- i) Already now (with the SPS $p\bar{p}$ collider) and until the end of the 80's, we will get a complete set of $p\bar{p}$, pp , ep , and e^+e^- colliders working typically in the range of the W mass. Most of them have been built (SPS $p\bar{p}$ collider at CERN), or are starting to be built (LEP, SLC, Tevatron), or are definitely approved (HERA).
- ii) Another step in the energy range appears after 1990; there is a marked enthusiasm for a Desertron machine in the United States and a super $p\bar{p}$ collider at CERN.

- iii) These super-machines seem most likely to be pp or $p\bar{p}$ colliders going above the 10 TeV energy range.
- vi) There also seems to be some interest in going to a very high Q^2 region in very high ep energy machines.

3. REVIEW OF REALISTIC EXPERIMENTAL TESTS OF SUPERSYMMETRY

Since last year an increasing number of papers¹¹⁾ have been produced which review all the possible and imaginable ways of testing SUSY experimentally. This is certainly a good starting point, because it could show the experimentalists that not only is SUSY a nice theoretical idea but also that it could perhaps be real; so it has to become part of the "normal" life of the high-energy physicist. We are now reaching the second level where we are able to better evaluate the essential tests to be done; this is the main purpose of this paper. People now tend to believe that most of the SUSY particles, if they exist, are heavy particles, and that essentially the next-generation machines will be more capable of looking for their possible existence. So in this section we are going to review the realistic experimental tests of SUSY that can be foreseen in the e^+e^- , pp, $p\bar{p}$, and ep colliders as well as in the baryon decay experiments.

By realistic, we mean a test which involves a production process, which has a high enough rate to be measurable, a signature which is distinguishable, and a background which is understandable and so can be vetoed.

3.1 Realistic experimental tests of SUSY in e^+e^- colliders

The e^+e^- colliders which are starting to be built and should be ready by the end of the 80's are the LEP at CERN and the SLC at SLAC; in addition, there is the TRISTAN project in Japan. They will reach a beam energy varying from 80 to 120 GeV (TRISTAN is ≈ 60 GeV).

Up to now this type of collider is the only place, together with the beam dump experiments, where some information about SUSY has been found (see the previous section). It has been demonstrated that they are able to do very clean work in the search for scalar quarks and scalar leptons and that their essential limitation is the beam energy (in fact this could be their main handicap!). We refer to Table 2 for this part of the discussion. As the projected e^+e^- colliders will be Z^0 factories they will also be the ideal place to look for all types of SUSY particles that could possibly be produced in the Z^0 decay (in particular, the Z^0 width will certainly be very accurately measured). These types of decays are similar to the W decays into SUSY particles and are extensively discussed in the $p\bar{p}$ part of this talk (subsection 3.3). These colliders are also the ideal place to look for scalar neutrinos (looking for the decay of Z^0 in $\tilde{\nu}\tilde{\nu} = \text{neutrino counting reaction}$) and almost a unique way of looking for photinos, according to the reaction in Fig. 4*).

Unfortunately we have to wait end of the 80's before these machines are running.

*) This point is well discussed in Fayet's talk and the reader is referred to the corresponding section.

3.2 Realistic experimental tests of SUSY in $p\bar{p}$ colliders

What we will try to show here is how well $p\bar{p}$ can compete with “the” SUSY machine, i.e. e^+e^- colliders. This is mainly due to the following different points: these machines will be the first to be built; all together they will cover a wide energy range; and they can look for gluinos, scalar quarks and other SUSY particles produced in W or Z^0 decay, such as winos, zinos, higgsinos, and scalar leptons. We now discuss these different points in more detail. Table 3, which summarizes the main characteristics of the pp and $p\bar{p}$ machines, clearly illustrates the first part of our statement.

Some of these machines are already fully operational or will very soon be working and will cover an energy range from 45 to 2000 GeV (and perhaps 20 TeV).

Owing to the increasing interest in testing SUSY experimentally, and to the very nice results obtained at the SPS $p\bar{p}$ collider at CERN, a lot of phenomenological work is being done, which already tends to show that pp and $p\bar{p}$ colliders are very good places to look especially for gluinos and scalar quarks, and for gaugino and higgsino production. Let us review the different possibilities.

3.2.1 Search for gluinos in $p\bar{p}$ colliders

The hadron-hadron collider seems to be a good place to search for gluinos. We can foresee different ways of looking for them, among which:

- *Gluino pair production* through the elementary mechanism shown in Fig. 5.

The attractive point in this case is that the cross-section of such a process is very high¹²⁾ (Fig. 6). An estimate for all possible sets of machines, going from 0.06 to 40 GeV in c.m.s. energy as a function of the gluino mass gives, for instance, a $\sigma_{g\bar{g}} = 1$ nb at 540 GeV for $m_{\tilde{g}} = 40$ GeV. As a gluino is expected to decay in $q\bar{q}\tilde{\gamma}$, assuming a heavy gluino, the signature of the event is characterized by two high- p_T states $(q\bar{q}\tilde{\gamma})_{1,2}$, no prompt lepton, and a generally small p_T imbalance. The background is very important since it is given by the usual light-quark production and then by heavy-quark production. The signature requires an accurate missing energy measurement and recognition of possible prompt leptons inside or near a jet. But we must note that this is just not enough, and we must look for a more sophisticated signature. A way has been proposed^{12,13)} to handle this problem. It is based on an estimate made with the Isajet¹⁴⁾ Monte Carlo program. Assuming a gluino mass of the order of 30 to 75 GeV and emphasizing the missing energy and the not back-to-back topology of the two high- p_T jets, two parameters have been proposed which account for this property:

$$x_E = -\vec{p}'_T \cdot \vec{p}_T / |\vec{p}_T|^2 \text{ and } p_{out} = \sqrt{|\vec{p}'_T|^2 - x_E^2 |\vec{p}_T|^2},$$

(where $\vec{p}'_T$ and $\vec{p}_T$ are the impulsion of each jet). By applying proper cuts on them, $x_E < 0.5$ and $p_{out} > 5$ GeV, one considerably reduces the main background due to the light quark jets (Fig. 7). These requirements could be applied on-line by means of a second-level trigger processor. In addition, a veto on prompt leptons would help to reduce the background. By applying these cuts, the sample of good candidates is also drastically diminished, and we will discuss later in this section what is the remaining background and how we can deal with it.

As, in any case, relatively high rate processes have to be strongly truncated already on-line, we may look to lower-rate processes, but ones which have a cleaner signature.

– $\tilde{g}\tilde{\gamma}$ production which occurs in $p\bar{p}$ through the elementary reaction $q\bar{q} \rightarrow (\tilde{q} \text{ exchange}) \rightarrow \tilde{g}\tilde{\gamma}$. Contrary to the previous reaction, this one has a much lower cross-section (roughly a factor $[a_{em}/a_s(p_T^2)] \times \text{colour factors}$). But the final state has a much larger p_T imbalance than in the case of the $\tilde{g}$ pair-production. It appears essentially as a broad jet (it is certainly difficult to separate q and $\bar{q}$ jets, unless $q\bar{q}$ are produced with a wide angle, which can happen when the p_T of $\tilde{g}$ is small) in one hemisphere and a lot of missing energy in the other hemisphere. So now, the main “backgrounds” are essentially due to $q\bar{q} \rightarrow Wg$, where the W decays in an energetic ν and a slow lepton (which can escape detection) or $q\bar{q} \rightarrow W$, where W decays into a heavy lepton and a neutrino. This implies the need to veto against the electron and to measure the missing p_T . We must note, in addition, that the width of the jet is also a useful signature because, for instance in the case of $W \rightarrow \tau\nu$, where τ decays into $q\bar{q}\nu$, we will get a pencil-like jet distinguishable from the one obtained in the decay $\tilde{g} \rightarrow q\bar{q}\tilde{\gamma}$.

3.2.2 Search for scalar quarks

The discussion in this case is almost the same as in the previous one; but certainly this search is even harder.

– *Scalar quark pair production* through the reaction $q\bar{q} \rightarrow g \rightarrow \tilde{q}\tilde{q}$. This process is similar to the one of gluino pair production but most probably with a lower cross-section. The signature can be $q\tilde{\gamma}\bar{q}\tilde{\gamma}$ (so essentially it is the same discussion as before) or most probably $q\tilde{g}\bar{q}\tilde{g}$ ($\tilde{g}$ going into $q\bar{q}\tilde{\gamma}$); so it is even worse!

Another possibility is to look at

– $\tilde{q}\tilde{g}$ (or $\tilde{q}\tilde{\gamma}$) production, through the reaction $gq \rightarrow \tilde{q}\tilde{g}$ (or $\tilde{q}\tilde{\gamma}$). The cross-section has been calculated in the case of the CBA project¹²⁾ (pp collider at $\sqrt{s} = 800$ GeV), and is rather similar to that of the SPS $p\bar{p}$ collider at CERN, up to some rescaling (Fig. 8a,b,c).

The discussion concerning the background is almost the same as in the case of $\tilde{g}\tilde{\gamma}$ production, and Isajet calculations¹²⁾ based on similar types of cuts (missing p_T and lepton cuts) are reported in Fig. 8d).

3.2.3 Search for SUSY particles possibly produced in W decay or Z^0 decay

Another interesting field which can be prospected in pp and $p\bar{p}$ colliders is that of looking for $W^\pm$ or Z^0 decay in gauginos or scalar leptons. Most of these studies can be done in e^+e^- high-energy colliders, but the advantage of the high-energy hadron colliders is that they already exist!

There are essentially two proposed ways; W or Z^0 could decay, producing gauginos^{15,18)} or scalar leptons^{19,20)}.

$W \rightarrow \text{gauginos } (\tilde{W}^\pm)$

In SUSY models the gauginos (winos, zinos) and the higgsinos, or any mixture of these states (which we are now going to call for simplicity $\tilde{W}$), could be lighter than their respective partners ($W^\pm$, Z^0 , and Higgs). Several ways of producing them in the $W^\pm$ or Z^0 decays have been proposed, by means of:

$$W^\pm \rightarrow \tilde{W}^\pm + \begin{cases} \tilde{Z} \\ \tilde{h}^0 \\ \tilde{\gamma} \end{cases} \quad (1)$$

$$Z^0 \rightarrow \tilde{W}^\pm \tilde{W}^\mp \quad (2)$$

These new fermions can be produced with the following rates^{*)}:

$$W^\pm \rightarrow \tilde{W}^\pm + \tilde{\gamma} / W^\pm \rightarrow e^\pm + \nu \quad \lesssim 0.8 \quad (15)$$

$$W^\pm \rightarrow \tilde{W}^\pm + \tilde{Z} / W^\pm \rightarrow e^\pm + \nu \quad \lesssim 3 \quad (16)$$

$$W^\pm \rightarrow \tilde{W}^\pm + \tilde{h} / W^\pm \rightarrow e^\pm + \nu \quad \leq 1 \quad (16)$$

$$Z \rightarrow \tilde{W}^+ \tilde{W}^- / Z \rightarrow e^+ e^- \quad \lesssim 9 \quad (16)$$

$\tilde{W}^\pm$ is the lightest charged-mass eigenstate¹⁷⁾. The masses and mixing angles are model-dependent, but the coupling is not. It might be mainly Higgs-like, or a comparable mixture of fermions, Higgs, and winos. It can decay according to:

$$\tilde{W}^\pm \rightarrow \tilde{q} \tilde{q} \text{ [where } \tilde{q} \rightarrow q \tilde{g} \text{ or } q \tilde{\gamma}] ,$$

$$\tilde{W}^\pm \rightarrow (\tilde{Z}, \tilde{h}^0, \tilde{\gamma}) + \text{a virtual } W^\pm (\rightarrow \ell^\pm \nu \text{ or } q' \bar{q}) ,$$

$$\tilde{W}^\pm \rightarrow \nu + \tilde{\ell} [\tilde{\ell} \text{ decays into } \ell \tilde{\gamma}] .$$

So in the case of the W decay (considering only the $\tilde{\gamma}$ and assuming, as we have done throughout this paper, that it is the lightest particle), the final possible states for reaction (1) are $q \tilde{q} \tilde{\gamma}$ or $\ell \nu \tilde{\gamma}$ in one hemisphere and a $\tilde{\gamma}$, i.e. missing energy, in the other hemisphere. Thus the signature of such an

^{*)} The quoted results depend on the value of the mixing angles.

event is a missing p_T in one hemisphere “balancing” a jet ($q\bar{q}$) and a small missing p_T , OR a prompt lepton and a fair amount of missing energy: $\nu\tilde{\gamma}$ in the other hemisphere; in the latest case the total amount of missing energy can be very small. If we take the case where $\tilde{h}^0$ or $\tilde{Z}$ are produced, we would have to consider, in addition, $\tilde{h}^0 \rightarrow \tilde{\gamma}q\bar{q}$ and $\tilde{Z} \rightarrow \tilde{h}^0q\bar{q}(\tilde{h}^0 \rightarrow \gamma q\bar{q})$; the final picture would be much more complicated. For an obvious purpose of simplicity we will restrict ourselves to the case of light $\tilde{\gamma}$ produced.

The different “backgrounds” are the W decaying into heavy leptons and neutrinos; Wg produced directly, where the W decays into an energetic ν and a very slow lepton; and $\tilde{g}\tilde{\gamma}$ or $\tilde{q}\tilde{\gamma}$ production.

So obviously a good missing energy and lepton recognition are needed as well as a good jet recognition (especially to recognize between broad, less broad, or pencil-like jets). This is in order to ensure at least the signature of interesting physics. But how to distinguish between different processes will be discussed at the end of this section.

$$W \rightarrow \tilde{e} + \tilde{\nu}_e$$

It has been proposed to look for such a process^{19,20}. In particular, if $\tilde{\nu}_e$ would decay predominantly into a neutral mode ($\tilde{\nu} \rightarrow \nu\tilde{\gamma}$), an interesting signature has been proposed¹⁹: the e produced from the $\tilde{e}$ decay is symmetric, whereas the one from standard leptonic W decay is asymmetric. But present results²¹ are consistent with the asymmetry as predicted by the standard model.

In the case where the $\tilde{\nu}$ decays into charged particles, several decay modes are possible²⁰:

$$e^-u\bar{d}\tilde{g} + e^-c\bar{s}\tilde{g}$$

$$\sum_i \nu\bar{q}_i q_i \tilde{g}$$

$$e^-u\bar{d}\tilde{\gamma} + e^-c\bar{s}\tilde{\gamma}$$

$$\tilde{\nu} \rightarrow \nu\ell^+\ell^-\tilde{\gamma}, \text{ where } \ell^\pm \text{ can be } e, \mu, \tau,$$

$$\tilde{\nu} \rightarrow \sum_i \nu\bar{q}_i q_i \tilde{\gamma}$$

through cascade decay, and the signature of $W = \tilde{e}\tilde{\nu}_e$ is then completely different. The ratio of ($\tilde{\nu} \rightarrow$ neutral)/($\tilde{\nu} \rightarrow$ charged) has been computed²⁰, but at the moment it is hard to make any definite quantitative statement because this ratio depends on parameters which still have unknown values.

3.2.4 Typical SUSY signature in $p\bar{p}$;

What are the possibilities?

After reviewing the signatures of the different kinds of SUSY processes that can be foreseen at the moment in the $p\bar{p}$ colliders, we observe that this type of search requires a careful analysis of the event. Most of the SUSY processes, even after a first-level filter (done by applying the missing p_T

cut, jet-topology of the event, as well as lepton recognition), have still to compete with the remaining “backgrounds”. We are now going to discuss and summarize this situation in Tables 4–6, as well as try to see if there are some ways of distinguishing between different possible processes.

Table 4 gives a list of main SUSY $p\bar{p}$ processes and corresponding signatures; Table 5 gives a list of competitive non-SUSY processes. Table 6 compare both results.

After looking at these three tables, we can make the following concluding remarks:

- 1) EVEN if we may recognize leptons in the neighbourhood or inside a jet,
- 2) EVEN if we may measure missing p_T very accurately,
- 3) EVEN if we may well recognize the jet structure of an event (in terms of how many jets) as well as measure their width,

there are still some processes that have the same signature. So in order to distinguish between the different possible competing processes, we must then be able to find additional properties which allow them to be selected properly (for instance, the case of $W \rightarrow e\bar{\nu}$, with the property of the electron produced in the SUSY decay to be symmetric, whereas the standard ones are asymmetric).

Anyway, what we can conclude at this stage is that the sample of data obtained after the filtering criteria (1), (2), and (3) have been fulfilled, is already **INTERESTING PHYSICS**. Nevertheless on the one hand more work has to be done on the phenomenological side, especially to specify the most characteristic signatures of proposed processes. A plethora of proposals should be avoided (if not really needed!). On the other hand, sophisticated and highly-performing detectors as well as very careful analysis are clearly required (see Section 4).

3.3 Lepton–proton interactions

The study of lepton–proton interactions can be carried out with fixed-target experiments using ν and μ beams or with ep colliders.

Let us first describe what is the situation from the point of view of available machines or projects.

So far we have the ν and μ beams at the CERN SPS. We will perhaps have μ and ν beams at the Tevatron at FNAL, and in a possible 20 TeV machine somewhere. The high-energy ep colliders are also just projects. In Fig. 9 we plot the kinematical range which would be covered by all these different possibilities (both ep colliders and μ and ν beams). In Table 7 are listed the main characteristics of the ep projects.

Reviewing essentially the computation of Refs. 23, 24, we will see that the main real hope for observing some manifestation of SUSY particles in the study of charged-current (CC) and neutral-current (NC) reactions, seems essentially due to:

- production of a scalar lepton and a scalar quark;
- production of associated SUSY particles (through a mechanism of photoproduction or photon–gluon fusion).

3.3.1 Direct production of a scalar lepton and a scalar quark in ep CC and NC reactions

This occurs in the reactions sketched in Fig. 10.

Estimates of the cross-section of these processes have been made, inserting different parametrizations of the parton distributions. What we notice is that the rates of such processes are quite high (Fig. 11) and depend strongly on the masses of the SUSY particles involved in the game (see Table 8).

If we consider the case of HERA ($s \simeq 10^5 \text{ GeV}^2$) and “realistic?” masses for $\tilde{\nu}$, $\tilde{q}$, and $\tilde{W}$, we get a cross-section for the SUSY process of the order of 10^{-36} cm^2 for left-handed e^- (so a rate of one event per day for a luminosity of $10^{31} \text{ cm}^{-2} \text{ s}^{-1}$, the expected luminosity at HERA being 10^{32}). If the $\tilde{\nu}$ decays in the neutral mode, $\tilde{\nu} \rightarrow \nu \tilde{\chi}$, the main background is the usual CC process $ep \rightarrow \nu X$, which in the same conditions is $1.2 \times 10^{-34} \text{ cm}^2$ (so perhaps of the order of 100 times the foreseen SUSY process).

Performing a standard CC analysis, using the x and y scaling, one may, however, hope to identify the SUSY process from this background, by applying the following trick as proposed in Ref. 23:

If E_H is the current jet energy and θ_H the angle of this jet with the beam axis, we can rewrite x and y as follows:

$$x = E_H(1 + \cos \theta_H)/\sqrt{s} - E_H(1 - \cos \theta_H) \quad \text{and} \quad y = E_H/\sqrt{s}(1 - \cos \theta_H).$$

By considering then the $(e^-, \text{fragmented parton})$ c.m., θ being the angle of q with the beam direction and E_q its energy, we have:

$$y = \lambda/2(1 - \cos \theta) \quad \text{and} \quad x/x_{\text{true}} = \lambda(1 + \cos \theta)/2 - \lambda(1 - \cos \theta), \quad (\text{if } \lambda = E_q\sqrt{s}/2).$$

We now remark that for the reaction $eq \rightarrow \nu X$, $\lambda = 1$ and the $\cos \theta$ and y distributions are uniform with $\langle y \rangle \simeq 1/2$, whereas in the corresponding SUSY process, where $\tilde{q} \rightarrow q \tilde{\chi}$, λ will be typically $1/2$ and $\langle y \rangle \simeq 1/4$. So already applying a cut at $y < 1/2$, the SUSY signal is significantly enhanced.

In the case where $\tilde{\nu}$ decays into charged particles (see subsection 3.2.3) the signature is essentially either two jets (it is certainly difficult to distinguish between the different $q\bar{q}$ jets) and some missing p_T (a small amount) or one jet, i.e. the current jet plus two charged leptons e or μ and also a small amount of missing p_T . If the rate of the charged decay of the $\tilde{\nu}$ is not small compared to the neutral decay, these special types of events would perhaps be more interesting to look at because of their more peculiar topology (especially compared with the standard CC process). The possible “backgrounds” would be reactions such as those shown in Fig. 12 and also the SUSY reactions sketched in subsection 3.3.2. In the reactions sketched in Fig. 12, the L^0 would decay into $e^-\mu^+\nu_\mu$ or $\nu_e\mu^+\mu^-$ or $L^-\mu^+\nu_\mu$ and the $L^\pm$ would decay into $e^\pm\nu_e\nu_L$ or $q_1\bar{q}_2\nu_L$. So most of the time, at least one usual lepton (e, μ) is produced directly or through the decay of a heavy lepton; good lepton recognition would then certainly help, as well as good jet recognition (in particular, study of the width of the jet). This is clearly a possibility which has to be looked into in more detail.

With regard to the neutral process, the SUSY contribution is of the order of 10^{-36} cm² to 10^{-37} cm² (Fig. 11) depending essentially on the mass of the SUSY particles involved in this reaction²³⁾. Provided the scalar $\tilde{e}$ decays in $e\tilde{\gamma}$, the main background is the standard NC reaction $ep \rightarrow eX$. The signature for the SUSY process is characterized by the missing energy due to the $\tilde{\gamma}$ in the e arm and the fact that the correlation between the e^- and the current jet ($\tilde{q} \rightarrow q\tilde{\gamma}$) will be very different.

From the analysis of the evolution of the structure functions versus Q^2 , we could also look at the supersymmetric content of the nucleon, in the same way that people look at the standard parton content of the nucleon²⁵⁾. Several phenomenological studies have been carried out in this direction, adding gluino and scalar constituents to the “usual” ones. These studies are purely academic exercises, because as experimentalists it is hard to believe that predicted effects are detectable unless going to very high Q^2 *) [$O(10^6 \text{ GeV}^2)$].

But we can hope to detect some manifestation of SUSY particles at HERA energies in $ep \rightarrow \tilde{e}\tilde{q}X$ and $\tilde{\nu}qX$ for masses up to 40 GeV for the $\tilde{q}$ and the $\tilde{\ell}$ and 80 GeV for the gauginos ($\tilde{W}$ and $\tilde{Z}$).

3.3.2 Associated production of SUSY particles

One can have $\tilde{q}\tilde{g}$ production by photoproduction mechanism or of $\tilde{q}\tilde{q}$ by photon-gluon fusion (Fig. 14). An estimate of the rates of such processes has been made^{23,24)} and is reported in Figs. 15 and 16.

Looking for the effect of such SUSY processes in the structure function of the CC reactions as proposed in Ref. 23 is clearly hopeless. However, we can try to search directly for SUSY particles produced by such a mechanism. The most important background is the one due to small Q^2 electroproduction of jets [the inclusive cross-section for such a process where jets have $p_T > 20 \text{ GeV}$ is of the order of 10^{-34} to 10^{-33} cm² at HERA] and of heavy quarks decaying semileptonically.

Provided the detector has sufficiently accurate missing p_T measurement and a good lepton and jet recognition, we can hope to isolate directly a sample of such events. Trying to distinguish between the two SUSY mechanisms as well as some of the possible ones sketched in Fig. 12 seems very hard, if not almost hopeless. In any case, the statement at the end of Section 2 still applies here: certainly we will get a sample of interesting physics; and clearly more work, from both experimental and phenomenological points of view, is still required.

3.4 Baryon decay experiment (or a good lesson for the experimentalist!)

I now refer back to the contribution of D.V. Nanopoulos to this report. The only point that is going to be raised is essentially in the form of a warning.

*) The predicted effects²⁶⁾ for the Q^2 range of the present ν and μ beams at the CERN SPS, even assuming a relatively very small gluino mass of 1 GeV, are really too small to be detected. By going to the HERA range [Q^2 up to $10^5 (\text{GeV})^2$] the effects²³⁾ are still too small (Fig. 13). Extrapolating these results to a Q^2 range up to 10^6 or $10^7 (\text{GeV})^2$ gives 5% to 10% momentum carried by $\tilde{g}$ and about 15% carried by $\tilde{q}$ (compared with $\sim 35\%$ carried by the gluon and 45% carried by the $\tilde{q}$); we could therefore think of measuring such effects in an ep Desertron!

On the theoretical side, the whole story has started with the prediction of SU(5) giving $p \rightarrow e^+ \pi^0$. When SUSY was introduced into the game, a set of possibilities followed: $p \rightarrow \nu_\tau K^+$, then $p \rightarrow \mu^+ K^0$, then again $p \rightarrow e^+ \pi^0$, then ...???

On the experimental side, a tremendous and ingenious effort has been made all over the world (see Table 9)²⁷⁾. The result of all this effort in relation to this search is summarized in Section 2.1. This clearly is a good example, showing that the experimentalist, when he builds a piece of apparatus and performs an experiment, must be essentially very open-minded!

4. THE IDEAL SUSY DETECTOR AND THE IDEAL SUSY MACHINE

From what we have studied so far, it is now really possible to review the main requirements of SUSY in terms of detector and apparatus. We can then summarize the performance of an apparatus such as that of UA1 and try to see what are the possible alternatives or improvements that can be foreseen for the next-generation experiments.

4.1 What does SUSY require?

From the point of view of detectors, SUSY's requirements are as follows:

- i) *A good jet recognition.* This means that the recognition of two high- p_T back-to-back jets is not enough; the apparatus must be able to distinguish neighbouring jets, and to measure the width of the jets that is in fact an essential signature. This implies a good central tracking, accurate charge and momentum measurement, highly energetic particle identification, and good calorimetry (giving an energy resolution of the order of percent).
- ii) *An accurate missing total transverse momentum evaluation.* The aim here is not only to distinguish events with a large p_T imbalance but also to be able to measure small p_T imbalance (i.e. less than or of the order of 15%). This means a very high resolution calorimeter, complete coverage, and even able to measure the missing energy along the longitudinal component (= beam direction). This last requirement implies, of course, a very good fine-grained forward calorimetry.
- iii) *A very refined lepton recognition.* The apparatus must not only recognize isolated energetic leptons but also leptons (in particular e^-) in the neighbourhood of a jet or in a jet, and also slow leptons (momentum of, say, $\lesssim 5$ GeV). This implies a good fine-grained calorimeter together with a good lepton-to-hadron discrimination and a high power of particle separation.

From the point of view of accelerators, SUSY essentially requires the following:

- i) *Higher and higher energy*, so that one can look for heavier and heavier objects. It is also important to note that in the case of heavier energies, jets are expected to be more pencil-like.
- ii) *Higher intensity or luminosity*, which of course will provide higher rates of "rare" decay modes.

So SUSY is very **demanding**, but it is already important to make two remarks. The first remark is that the goals of SUSY are in fact the goals of most of the physics one has to pursue with the new-generation machines (W and Z^0 physics, heavy quarks, heavy leptons, Higgs, anything new ...). The second remark is that, with the running of the UA experiments at the CERN $p\bar{p}$ collider, one has great hopes for the future; UA1 and UA2 have shown that high-energy hadron colliders produce events with nice jet-like structure (no longer the privilege of the e^+e^- collider). UA1 has shown how well such a device can measure missing energy, and how well it can recognize leptons (both e and μ). The UA experiments also give IDEAS of how to do possibly better.

Let us now emphasize the main properties of an apparatus such as the UA1 detector and of other possible alternatives.

4.2 Review of UA1 detector performances; possible alternatives

The UA1 detector can “ormai” be considered as a “classical” 4π multi-purpose detector. It has been described in different papers²⁸⁾ to which the reader can refer. We want to emphasize here those of its characteristics that are of interest for our subject. The description as well as the performances of its calorimetric part are summarized in Tables 10 and 11. Table 12 lists the main parameters of the central tracking device. This detector has demonstrated to be able to nicely detect, among the possible event zoology: jetty structured events (Fig. 17a), famous e and μ pairs (Fig. 17b, 17c), now classical e with missing energy (Fig. 17c) and also $e + \text{jet}$ and $\mu + \text{jet(s)}$ events.

After two years of successful operation at the CERN SPS $p\bar{p}$ collider, we note that some limitations of this detector appear essentially at a very acrobatic level of requirements (unfortunately sometimes needed in our case); for instance, recognition of slow leptons (μ can be identified above 3 GeV/c, and presumably also the e^- except if the event is jetty; this is due to lack of good enough calorimetric granularity); good measurement of jets characteristics in some regions of poor acceptance of the central tracking device or of the calorimeters; accurate evaluation of missing energy in the beam direction or of a small amount of total transverse energy (typically the error on missing E_T is $\simeq 4$ GeV for minimum-bias events).

For LEP and other projects, other solutions are foreseen or tested, or even already built (at least at the prototype level). Some of these alternatives have COMBINED the so-called calorimetric and tracking functions in one global or matched performance device. These new-generation detectors, thanks in particular to refined granularity, present the advantage of homogeneity, and thus of better modularity; they are also simpler to calibrate and the data obtained with them are easier to analyze. It seems to me that they are the real solution to our problems and may be so, in fact, for most of the physics which is going to be studied in the next years.

Among the detectors which are either available now or will be in a near future, we quote:

- The liquid-argon detector with uranium plates²⁹⁾,
- the scintillating fibres,
- the high-density drift calorimeters³⁰⁾,
- the BGO detector,
- the coupling of a BaF_2 scintillator to a tetrakis(dimethylamine)ethylene (TMAE) photocathode with a low-pressure wire chamber³¹⁾ (science fiction or a solution for after tomorrow?).

Our purpose here is not to go into a detailed study of these different devices³²⁾; we will just point out some aspects which can allow to choose between these different possibilities:

- i) *Density of the detector*: to be able to define, in an accurate way, the jet structure of an event. What is in fact required is to single out the “quark jets” (that we will call “elementary jets”) contained in a so-called “broad jet”, and to count them. The opening angle between such elementary jets may be small; therefore an accuracy comparable to that required to recognize particles inside an elementary jet could be necessary. So clearly gas detectors would be disfavoured compared to higher density devices.

- ii) *Identification of leptons inside a jet:* at the present stage, it is hard to have the “universal” device able to equally well (meaning to the very demanding limits required by SUSY) sign an e^- and a μ^- inside a jet and to measure both perfectly. A possibility is to make a definite choice between one of these two leptons, i.e. to measure perfectly one of them and to be able to only recognize the other one. Two LEP proposals have looked into this problem: the ELECTRA proposal concentrated on the detection of the e^- , whereas the L3 experiment will detect the μ^- using a BGO detector. The high-density drift calorimeter also is very good for μ^- identification.
- iii) *Handling of systematic effects at the true 1% level:* (Let us remark that we stand by now at the 3–4% level, so we have essentially already jumped from 10% to a few percent.) The choice of the calorimetric device will mainly depend on this; for instance the argon/uranium plates detector offer at the moment the best control of systematic effects. The choice of the calorimeter readout depends also on possibilities to control these effects.

Other factors enter in the game too. It is clear that the decision is also a function of the “goût du risque et goût du jour”, or of the degree of conservatism, of cost, etc. No magic solution exists so far, but a lot of development work has been undertaken on both the mechanical and electronical sides, and we can hope to have highly performing apparatus by the end of the eighties. Until then, with the detectors available by now, we can hope to do a pioneering work and at least to clear the road.

5. CONCLUDING REMARKS

After the discovery of the intermediate bosons, the check of SUSY is clearly the next main goal. But it is much harder!

If the masses of the SUSY particles are around the W-mass, there is a good chance that we may find them in $p\bar{p}$, e^+e^- , and ep colliders (perhaps we can also get some news from the sky) with the set of machines operational by now or by the end of the eighties (SPS $p\bar{p}$, Tevatron $p\bar{p}$, LEP, SLC, HERA, etc.). If the masses are higher, we have to wait for the next generation of machines, e.g. the so-called Desertron.

But maybe this theory is completely wrong (!?), and as experimentalists we must always keep our eyes wide open. In any case, being prepared for SUSY is also a good pretext for being prepared to discover anything that is completely unforeseen at the moment!

Acknowledgements

I am specially indebted to C.A. Savoy and P. Fayet for their critical reading of the manuscript.

I wish to thank C.W. Fabjan and F. Sauli for useful discussions.

I would also like to thank C. Rubbia: this work has certainly profited from the stimulating and exciting atmosphere he maintained in the UA1 Collaboration since the beginning.

REFERENCES

- 1) CERN Supersymmetry versus Experiment Workshop, Report CERN TH 3311/EP 82-63 (1982), eds. D.V. Nanopoulos, A. Savoy-Navarro, C. Tao.
- 2) Contributions of J. Ellis, P. Fayet, S. Ferrara, C. Llewellyn Smith and D.V. Nanopoulos in this Physics Report.
- 3) P. Fayet, Phys. Lett. 86B (1979) 272 (D-breaking).
J. Ellis and G.G. Ross, Phys. Lett. 117B (1982) 397 (F-breaking).
- 4) R. Barbieri, S. Ferrara and C.A. Savoy, Phys. Lett. 119B (1982) 343.
E. Cremmer, P. Fayet and L. Girardello, Phys. Lett. 112B (1983) 346.
S. Ferrara, D.V. Nanopoulos and C.A. Savoy, Phys. Lett. 123B (1983) 214.
L. Alvarez-Gaumé, J. Polchinski and M.B. Wise, Harvard preprint HUTP-82/AO63 (1983).
J. Ellis, J.S. Hagelin, D.V. Nanopoulos and K. Tamvakis, Stanford preprint SLAC-PUB-3029 (1983).
- 5) C.A. Savoy, Saclay preprint SPhT/83/73: invited talks at the XVIIIth Rencontres de Moriond, La Plagne, March 1983 (to be published).
- 6) H.J. Behrend et al., Phys. Lett. 114B (1982) 287;
W. Bartel et al., Phys. Lett. 114B (1982) 211;
D. Cords, Proc. XXth Int. Conf. on High Energy Physics, Madison, 1980 (Amer. Inst. Phys., New York, 1981), p. 590.
D.P. Barber et al., Phys. Rev. Lett. 45 (1980) 1904;
B. Adeva et al., Phys. Lett. 115B (1982) 345;
C.A. Blocker et al., Phys. Rev. Lett. 49 (1982) 517;
H. Spitzer, Proc. XVth Rencontres de Moriond, Les Arcs, 1980 (Ed. Frontières, Dreux, 1980), vol. 2, p. 157;
TASSO Collaboration, Phys. Lett. 117B (1982) 365;
G. Barbiellini et al., preprint DESY 79/67 (1979).
- 7) CHARM Collaboration, Phys. Lett. 121B (1983) 429.
- 8) R.C. Ball et al., contribution to the XXIst Int. Conf. on High Energy Physics, Paris (1982).
- 9) G.R. Farrar and P. Fayet, Phys. Lett. 76B (1978) 575; 79B (1978) 442.
J.P. Dishaw et al., Phys. Lett. 85B (1979) 142.
- 10) R.M. Bionta et al. (IMB Collaboration), Phys. Rev. Lett. 51 (1983) 27.
J. Van der Velde, private communication.
- 11) Proc. American Physical Society Summer Study on Elementary Particle Physics and Future Facilities, Snowmass, 1982 (Amer. Inst. Phys., New York, 1983).
A. Savoy-Navarro, contribution to the XXIst Int. Conf. on High Energy Physics, Paris (1982).
A. Savoy-Navarro, 1st Symposium on Frontiers in Physics, Capri (17-20 May 1983), to be published in the Proceedings.
- 12) I. Hinchliffe and L. Littenberg, Berkeley preprint LBL-15022 (1982)..
- 13) C. Fabjan, in the report quoted in Ref. 1, p. 85.
- 14) F.E. Paige and S.D. Protopopescu, ISAJET program, BNL 29777 (1981).
- 15) S. Weinberg, Phys. Rev. Lett. 50 (1983) 387.
- 16) P. Fayet, Phys. Lett., Vol. 125B (1983) 178;
P. Fayet, private communication, to be published in the Proceedings of the Gif-sur-Yvette Summer School, 1982.

- 17) J.M. Frère and G.L. Kane, Univ. Michigan preprint UM-TH 83-2 (1983).
- 18) J. Ellis, J.S. Hagelin, D.V. Nanopoulos and M. Srednicki, Phys. Lett. 125B (1983) 385.
- 19) R. Barbieri, N. Cabibbo, L. Maiani and S. Petrarca, Supersymmetric decay modes of the W and single e^- production in $p\bar{p}$ collisions, INFN Rome preprint (1983).
- 20) R.M. Barnett, K. Lackner and H.E. Haber, Stanford preprint SLAC-PUB-3066 (1983).
- 21) G. Arnison et al., Further evidence for charged Intermediate Vector Bosons at the SPS Collider, to appear in Phys. Letters.
- 22) UA2 Collaboration, Results from 1983 data presented at the EPS High Energy Physics Conf., Brighton, 1983.
- 23) S.K. Jones and C.H. Llewellyn Smith, Oxford preprint OUTP 82-73 (1982).
- 24) J. Lévellé, private communication.
- 25) H. Abramowicz et al., CDHS Collaboration, Z. Phys. C 12 (1982) 289.
- 26) I. Antoniadis, C. Kounnas and R. Lacaze, Nucl. Phys. B 211 (1983) 216.
- 27) SOUDAN 2, a 1000 ton tracking calorimeter for nucleon decay, Argonne preprint ANL-HEP-PR 81-12 (1981).
- 28) UA1 proposal: a 4π solid-angle detector for the SPS used as a proton-antiproton collider at a centre-of-mass energy of 540 GeV, CERN/SPSC 78-06 (1978);
M. Barranco Luque et al., Nucl. Instrum. Methods 176 (1980) 175;
M. Calvetti et al., Nucl. Instrum. Methods 176 (1980) 255;
K. Eggert et al., Nucl. Instrum. Methods 176 (1980) 217 and 233;
A. Astbury, Phys. Scripta 23 (1981) 397;
J. Timmer, The UA1 detector, presented at the XVIIIth Rencontre de Moriond, La Plagne, March 1983 (to be published).
- 29) C.W. Fabjan et al., Nucl. Instrum. Methods 141 (1977) 61;
J.H. Cobb et al., Nucl. Instrum. Methods 158 (1979) 93.
- 30) H.G. Fischer and O. Ullaland, IEEE Trans. Nucl. Sci. NS-27 (1980) 38.
- 31) D.F. Anderson, R. Bouclier, G. Charpak and S. Majewski, Coupling of a BaF_2 scintillator to a TMAE photocathode and a low-pressure wire chambre, preprint CERN-EP/83-34, presented at Wire Chamber Conference, Vienna, 1983.
- 32) C.W. Fabjan and T. Ludlam, Annu. Rev. Nucl. Part. Sci. 32 (1982) 335.
C.W. Fabjan and H.G. Fischer, Rep. Prog. Phys. 43 (1980) 1003.
U. Amaldi, Fluctuations in calorimetry measurements, preprint CERN-EP/80-212 (1980).

Table 1
SUSY-spectroscopy

Standard particles	SUSY partners	Predicted masses in various SUSY-models		
		Global SUSY		Local SUSY ⁴⁾
		D-type breaking ³⁾	F-type breaking ³⁾	
	Gravitino ----- Goldstino	} very light $\ll 1$ GeV		} $m_{3/2} > 20$ GeV
Gluon (g)	Gluino ($\tilde{g}$)	0 + radiative corrections $\rightarrow O(\text{few GeV})$	$\leq O(1 \text{ TeV})$	$O(m_{3/2})$ or at least $\gtrsim \alpha_s(m_{\tilde{g}}) m_{3/2} \gtrsim 4 \text{ GeV}$
Photon (γ)	Photino ($\tilde{\gamma}$)	0 + radiative corrections $\rightarrow O(\text{few GeV})$	No photino, but a W^3 ino and a Bino $\leq O(1 \text{ TeV})$	$m_{\tilde{g}} \times O(2 \alpha_{em}/\alpha_s) \rightarrow \sim 1/8 m_{\tilde{g}}$
$W^\pm$	Winos ($\tilde{W}^\pm$)	} 2 winos ($\tilde{W}_{1,2}^\pm$) $m_{\tilde{W}_{1,2}} \sim m_W$	1 state mostly “gaugino”	} $\simeq m_W \pm O(m_{3/2})$
Higgs $\nearrow H^\pm$ $\searrow H^0$	Higgsinos $\nearrow \tilde{h}^\pm$ $\searrow \tilde{h}^0$		1 state mostly “higgsino”	
Z^0	Zinos ($\tilde{Z}$)	} 2 zinos ($\tilde{Z}_{1,2}$) $m_{\tilde{Z}_{1,2}} \sim m_Z$	1 state mostly “higgsino”	} $\simeq m_Z \pm O(m_{3/2})$
			1 state mostly “gaugino”	
Quarks	Scalar quarks ($\tilde{q}$)	$\lesssim 40 \text{ GeV}$	few 100 GeV $\rightarrow 1 \text{ TeV}$	$\simeq [m_{3/2}^2 + O(m_{\tilde{g}}^2)]^{1/2} \pm O(m_q)$
Leptons	Scalar leptons ($\tilde{\ell}$)	$\lesssim 40 \text{ GeV}$	few 100 GeV $\rightarrow 1 \text{ TeV}$	$\simeq m_{3/2} \pm O(m_\ell) $

Table 2

SUSY object	Production mode(s)	Signature	Background(s)	Comments
SCALAR LEPTONS	$e^+e^- \rightarrow \tilde{\mu}^+\tilde{\mu}^-$	$E_\mu \gtrsim 20\% E_{\text{beam}}$ Acoplanarity $\gtrsim 20^\circ$ $E_{\text{em/had}} \leq 20\% E_{\text{beam}}$	$e^+e^- \rightarrow e^+e^-\mu^+\mu^-$ $\mu^+\mu^-\gamma$ $\tau^+\tau^-\gamma$	CLEAN Experiment Signatures are clear + well-defined background + simple analysis
	$e^+e^- \rightarrow \tilde{e}^+\tilde{e}^-$	$E_e \gtrsim 15\% E_{\text{beam}}$ Acoplanarity $\gtrsim 30^\circ$ No photon	$e^+e^- \rightarrow e^+e^-e^+e^-$ $e^+e^-\gamma$ $\tau^+\tau^-\gamma$	↓
	$e^+e^- \rightarrow \tilde{\tau}^+\tilde{\tau}^-$	1 μ + hadronic shower 1) If low-mass range: background in $e^+e^- \rightarrow \tau^+\tau^-$ 2) If higher mass range: Acoplanar μ -hadrons; missing energy	$e^+e^- \rightarrow \tau^+\tau^-$ $\tau^+\tau^-\gamma$ $e^+e^-\tau^+\tau^-$ $q\bar{q}\gamma$ $\tilde{W}^+\tilde{W}^-$ $\pi^+\pi^-$	Test or no test of scalar leptons existence (may not be so clean at LEP because much higher effect of rad. corrections) Only experimental limitation = E_{beam} (cf. present PETRA results) ⁶⁾ LEP + SLC will allow $m \rightarrow 60 \text{ GeV}$
SCALAR QUARKS	$e^+e^- \rightarrow \tilde{q}\tilde{q}^*$	2 JETS 1) Low-mass range: background to R 2) Higher mass range: 2 acoplanar jets; missing energy; no photon.	$e^+e^- \rightarrow e^+e^-q\bar{q}$ $q\bar{q}\gamma$ $\tau^+\tau^-\gamma$ $e^+e^-\tau^+\tau^-$	Main limitations: Beam energy + which model? (the acceptance depends a lot on the model) PETRA $\rightarrow$ 2/3 quarks: $m \leq 4 \text{ GeV}$ or $m \geq 16 \text{ GeV}$ — 1/3 quarks: $m \leq 2.5 \text{ GeV}$ or $m \gtrsim 15 \text{ GeV}$ $\rightarrow$ Wait for LEP + SLC

Table 3
Main characteristics of the $p\bar{p}$ machines

Machines	$\sqrt{s}$ (GeV)	L ($\text{cm}^{-2} \cdot \text{s}^{-1}$)	Date
ISR (pp): CERN	40 → 64	10^{32}	1972 → 1984
SPS ($p\bar{p}$): CERN	540	10^{29} ($10^{30}?$)	1981 → ?
$p\bar{p}$ TEVATRON: FNAL	2000	10^{31}	1986 → ?
Super $p\bar{p}$: CERN	?	?	?
Desertron: US	?	?	?

Table 4
Overview of possible SUSY signature in $p\bar{p}$ collisions

SUSY process	Signature
$p\bar{p} \rightarrow \tilde{g}\tilde{g}$	$(q\bar{q}\tilde{\gamma})$ on each side; so very small p_T imbalance and (1 broad jet or 2 jets) on each side
$p\bar{p} \rightarrow \tilde{g}\tilde{\gamma}$	Large missing energy and (1 broad jet or 2 jets: $\tilde{g} \rightarrow q\bar{q}\tilde{\gamma}$) on the other side
$p\bar{p} \rightarrow \tilde{q}\tilde{q}$	$(q\tilde{g} = qq_1\bar{q}_2\tilde{\gamma}, \text{ or } q\tilde{\gamma})$ on each side so: a small p_T imbalance and (1 “broad” jet $\equiv$ 3 jets, or 1 jet) on each side
$p\bar{p} \rightarrow \tilde{q}\tilde{\gamma}$	$(q\tilde{g}\tilde{\gamma} = qq_1\bar{q}_2\tilde{\gamma}\tilde{\gamma} \text{ or } q\tilde{\gamma}\tilde{\gamma})$ so (some p_T imbalance and a jet) or a good p_T imbalance and a “broad” jet $\sim$ 3 jets
$p\bar{p} \rightarrow W^\pm \rightarrow \tilde{e}\tilde{\nu}$	$= (e\tilde{\gamma}, \nu\tilde{\gamma})$ or $(e\tilde{\gamma}, \nu\ell^+\ell^-\tilde{\gamma})$ or $(e\tilde{\gamma}, q\bar{q}\tilde{\gamma})$, so a large missing energy on one side and an energetic lepton on the other side ($e^\pm$ produced would be SYMMETRIC) or an e on one side and 2 leptons + some missing energy on the other side or an e on one side and a broad jet on the other side and some amount of missing p_T
$p\bar{p} \rightarrow W^\pm \rightarrow \tilde{W}^\pm\tilde{\gamma}$ $\quad \hookrightarrow \tilde{q}\bar{q}$	$(q_1q_2\bar{q}_3\tilde{\gamma}\bar{q}, \tilde{\gamma})$ or $(q\tilde{\gamma}\bar{q}, \tilde{\gamma})$, so large missing energy and a very broad jet $\equiv$ 4 quark jets on the other side or some missing p_T and a broad jet $\equiv$ 2 quark jets
$p\bar{p} \rightarrow W^\pm \rightarrow \tilde{W}^\pm\tilde{\gamma}$ $\quad \hookrightarrow \ell\nu\tilde{\gamma}$ $\quad \text{or } q'\bar{q}\tilde{\gamma}$	Missing energy + 1 lepton Missing energy + (1 “broad” jet $\equiv$ 2 quark jets) on the other side
$p\bar{p} \rightarrow W^\pm \rightarrow \tilde{\ell}\tilde{\nu}$	$= \ell\tilde{\gamma}\tilde{\nu}$: missing energy + 1 lepton (or completely different picture if $\tilde{\nu}$ decays in charged mode)

Table 5
Non-SUSY competing processes in $p\bar{p}$ collisions

Process	Signature
$p\bar{p} \rightarrow q\bar{q}$ gg	1 jet on each side
$p\bar{p} \rightarrow Q\bar{Q}$ $\hookrightarrow q_1 q_2 \bar{q}_3$ $\hookrightarrow q\ell^\pm \nu$	(1 “broad” jet or 3 quark jets) or (1 quark jet + 1 lepton + small missing energy) } on each side
$p\bar{p} \rightarrow L^+ L^-$ $\hookrightarrow \ell \nu \nu_L$ $\hookrightarrow q_1 \bar{q}_2 \nu_L$	(Missing + 1 lepton) or (Missing + 1 “broad” jet = 2 quark jets) } on each side
$p\bar{p} \rightarrow W^\pm (g \text{ or } q)$ $\hookrightarrow \text{energetic } \nu + \text{slow lepton}$	1 jet on one side + [missing energy and maybe (if detected) a lepton] on the other side
$p\bar{p} \rightarrow W^\pm$ $\hookrightarrow \ell^\pm \nu$	Missing p_T + lepton
$p\bar{p} \rightarrow W^\pm$ $\hookrightarrow L\nu$ $\hookrightarrow \ell \nu \bar{\nu}$ $\hookrightarrow q\bar{q}\nu$	Small missing p_T + one energetic lepton or Missing p_T + 1 “broad” jet or 2 quark jets

Table 6*)

Comparison between SUSY and non-SUSY competing processes in $p\bar{p}$ collisions

Kind of signature	Processes having the same signature	
	Process	Final state
1 jet on each side	$p\bar{p} \rightarrow q\bar{q} \rightarrow$ gg $\rightarrow Q\bar{Q} \rightarrow$ $\rightarrow L^+L^-^* \rightarrow$ $\rightarrow \tilde{g}\tilde{g}^* \rightarrow$ $\rightarrow \tilde{q}\tilde{q} \rightarrow$	q or g on each side $(q_1q_2\bar{q}_3)$ or $(q_1\ell^\pm\nu)$ on each side $(q_1\bar{q}_2\nu_L)$ on each side $(q_1\bar{q}_2\tilde{\gamma})$ on each side $(q_1q_2\bar{q}_3\tilde{\gamma})$ or $(q_1\tilde{\gamma})$ on each side
Missing p_T + 1 "jet" on the other side	$p\bar{p} \rightarrow W^\pm g \rightarrow \nu + \text{slow } \ell^\pm + g \rightarrow$ $p\bar{p} \rightarrow W^\pm \rightarrow L\nu^* \rightarrow$ $p\bar{p} \rightarrow \tilde{g}\tilde{\gamma}^* \rightarrow$ $p\bar{p} \rightarrow \tilde{q}\tilde{\gamma} \rightarrow$ $p\bar{p} \rightarrow \tilde{W}^\pm \tilde{\gamma}$ $\hookrightarrow \tilde{q}\bar{q}^*$ $\hookrightarrow W^\pm \gamma^* \rightarrow$	Missing + g + $(\ell^\pm)$ Missing + $(q_1\bar{q}_2\nu_L)$ Missing + $(q_1q_2\tilde{\gamma})$ Missing + $[(q_1q_2\bar{q}_3\tilde{\gamma}) \text{ or } q\tilde{\gamma}]$ Missing + $(q_1q_2\bar{q}_3\tilde{\gamma})$ or $q\tilde{\gamma}\bar{q}$ Missing + $(q_1\bar{q}_2\tilde{\gamma})$
Missing on 1 side + 1 lepton on the other side	$p\bar{p} \rightarrow W^\pm \rightarrow L^\pm \nu^* \rightarrow$ $\hookrightarrow \ell^\pm \nu \bar{\nu}$ $p\bar{p} \rightarrow W^\pm \rightarrow \tilde{e}^\pm \tilde{\nu}_e \rightarrow$ $p\bar{p} \rightarrow W^\pm \rightarrow \tilde{W}^\pm \tilde{\gamma}^*$ $\hookrightarrow "W^\pm" \tilde{\gamma}$ $\hookrightarrow \ell^\pm \nu$	Missing + 1 lepton Missing + $(e^\pm \tilde{\gamma})$ (if $\tilde{\nu}$ does not decay in charged mode) Missing + $(\ell^\pm \nu \tilde{\gamma})$

*) We denote with an asterisk the processes which have just an identical signature in terms of missing p_T , jetty structure and lepton content and by " $W^\pm$ " a virtual W.

Table 7
ep machines and their main parameters

Machine	E_e (GeV)	E_p (GeV)	$\sqrt{s}$ (GeV)	Luminosity L ($\text{cm}^{-2} \text{s}^{-1}$)	Q^2 (GeV) ²
TRISTAN (JAPAN:?)	25	300	173	10^{31}	5×10^4
HERA ^{a)} (RFA: 1989)	30	820	314	10^{32}	10^5
FLAB (USA:?)					
“ep.DESERTRON” (?.?)	140	20000	3350	10^{31}	10^7
UNK (USSR:?)	?	?	?	?	?

a) Approved.

Table 8^{a)}
Cross-section for production of SUSY particles in ep NC processes

$\tilde{\nu}$ mass (GeV)	$\tilde{q}$ mass (GeV)	$\tilde{W}$ mass (GeV)	$\sigma(e_L^- \rightarrow \tilde{\nu})$ (cm^2)	$\sigma(e_R^- \rightarrow \tilde{\nu})$ (cm^2)
40	40	80	2.0×10^{-35}	0.5×10^{-35}
20	20	80	$(9 \pm 1) \times 10^{-35}$	$(4.4 \pm 1.2) \times 10^{-35}$
40	100	200	1.3×10^{-36}	$(0.06 \pm 0.02) \times 10^{-36}$

a) Quoted numbers are extracted from Ref. (23).

Table 9²⁷⁾

Summary of experiments currently under way to search for nucleon decay

Experimental group	Reference	Location	Depth (metres water equivalent)	Monitored material (metric tons)	Total mass (fiducial mass)	Detectors	Operational
Irvine-Michigan-Brookhaven	2	Morton Salt Mine, Ohio	1600	water	8000 (3000)	2400 photo-multiplier tubes	late 1981
Harvard-Purdue-Wisconsin	4	Silver King Mine, Utah	1600	water	800	800 photo-multiplier tubes	early 1982
Minnesota-Argonne	1	Soudan Iron Mine, Minnesota	1800	concrete & iron (4-cm spacing)	30-16)	3456 gas proportional tubes	operational
Minnesota-Argonne-Oxford	this proposal	Soudan Iron Mine, Minnesota	2000	iron (0.5-cm plates)	1000 (650)	10,000 drift chambers	proposed (late 1983)
University of Pennsylvania	5	Homestake Gold Mine, South Dakota	4400	water	300 (150)	144 photo-multiplier tubes in water	operational
Frascati-Milano-Torino	6	Mont Blanc Tunnel, France/Italy	5000	iron (1-cm plates)	150 (85)	47,168 limited-streamer tubes	late 1981
Orsay-Palaiseau-Paris-Saclay	7	Fréjus Tunnel, France	4200	iron (0.3-cm plates)	1500 (1000)	1600 flash chambers, 200 limited-streamer chambers	proposed (late 1983)
Tata-Osaka-Tokyo	8	Kolar Gold Fields, India	7600	iron (1.7-cm plates)	140 (100)	1700 gas proportional tubes	operational

Table 10
UA1 – Description of the calorimetry

Calorimeter		Angular coverage θ (°)	Thickness		Cell size		Sampling step	Segmenta- tion in depth
			No. rad. lengths	No. abs. lengths	$\Delta\theta$ (°)	$\Delta\phi$ (°)		
Barrel	e.m.: gondolas	25–155	$26/\sin\theta$	$1.1/\sin\theta$	5	180	1.2 mm Pb 1.5 mm scint.	$3.3/6.6/9.9/6.6 X_0$ $2.5/2.5\lambda$
	hadr.: c's		–	$5.0/\sin\theta$	15	18	50 mm Fe 10 mm scint.	
End-caps	e.m.: bouchons	5–25	$27/\cos\theta$	$1.1/\cos\theta$	20	11	4 mm Pb 5 mm scint.	$4/7/9/7 X_0$ $3.5/3.5\lambda$
	hadr.: I's	155–175	–	$7.1/\cos\theta$	5	10	50 mm Fe 10 mm scint.	
Calcom	e.m.	0.7–5	30	1.2	4	45	3 mm Pb 3 mm scint.	$4 \times 7.5 X_0$ $6 \times 1.7\lambda$
	hadr.	175–179.3	–	10.2	–	–	40 mm Fe 8 mm scint.	
Very forward	e.m.	0.2–0.7	24.5	1.0	0.5	90	3 mm Pb 6 mm scint.	$5.7/5.3/5.8/7.7 X_0$ $5 \times 1.25\lambda$
	hadr.	179.3–179.8	–	5.7	0.5	90	40 mm Fe 10 mm scint.	

Table 11
UA1 calorimetry performances

Calori- meter	Energy resolu- tion	Missing power	e ⁻ separation resolution	Spatial resolution	Calibration and monitoring
e.m. BARREL	$0.15/\sqrt{E}$		The ratio of the hadronic shower response to the e.m. shower response ≈ 0.9 , for energies > 20 GeV;	$\Delta X = 6 \text{ cm}/\sqrt{E}$ (X = beam direction) $\Delta\phi = 0.3$ rad/ $\sqrt{E}$ (ϕ azimuthal angle)	e ⁻ test beam + ⁶⁰ C → absolute energy scale calibration + attenuation map and monitor- ing of performances of the detector versus time.
e.m. END CAP	$0.12/\sqrt{E_T}$	$0.6/\sqrt{\Sigma E_T}$	0.84 at 5 GeV and decreases for energies < 5 GeV	$\Delta X \approx 8 \text{ mm}$ $\Delta Y \approx 8 \text{ mm}$ (Measured by position detec- tor)	Laser, test pulse, LEDs → calibration and monitoring of the electronic chain (PM gain, gain amplifier, electronic offset)
HADRO- NIC	$0.8/\sqrt{E}$		An e ⁻ of 40 GeV depo- sits less than 1% in the hadronic calorimeter		¹⁰⁶ Ru β-sources → absolute energy scale calibration Cosmic μ: used to check and adjust calibration LASER: monitors PM's gain

Table 12
UA1 tracking characteristics (central part)

Spatial measurement			Two track resolution	Particle identification	Momentum measurement	Critical parameters
X direction = along beam axis	Y direction	Z direction				
Given by wire position	Measured by drift time	Measured by charge division	Provided by pulsed shaping electronics (A pulse has to drop below a certain threshold before a new one is tagged → 2 track resolution $\simeq 2$ cm is improved by: 1) on-line decision via the read-out processor: → 5 mm 2) By dE/dx → almost a "perfect" 2 tracks recognition	Provided by sum of left and right pulse weights of each sense wire. Only useful for particles with: $0.5 < p < 1.0$ (GeV/c) $\sigma(dE/dx)/dE/dx = 11\%$	$\sigma(p)/p \simeq 1/p_T \simeq 1.5\%/(GeV/c)$ (is approximately constant for tracks > 50 cm) $\rightarrow \sigma(p)/p \simeq (0.5-1)p$ (GeV/c)% Minimum measurable momentum $\simeq 100$ MeV	Drift angle θ_D , Drift velocity v_D , time t_0 provide inclinations and displacements of the various track segments. Depend essentially on absolute chamber geometry and diffusion effects Are adjusted to $\Delta\theta_D \sim 0.1^\circ$ $\Delta v_D \approx 0.1\%$ $\Delta t_0 < 1$ nsec
$\sigma_x = 150 \mu m$ (A sense wire each 1 cm)	$\sigma_y \simeq 290 \mu m$	$\sigma_z \sim 2\%$ of the wire length (which varies from 0.8 → 2.2 m)				

Figure captions

- Fig. 1 Present limits on masses of scalar leptons as given by PETRA experiments.
- Fig. 2 Scheme of gluino production in beam dump and calorimeter fixed target experiments.
 (a) Results on beam dump CHARM experiment at CERN SPS
 (b) Results on beam dump experiment at FNAL
- Fig. 3 “Plan sur la comète” accelerators already built or in project all over the world.
- Fig. 4 Counting neutrino reaction diagram in e^+e^- collision.
- Fig. 5 Some diagrams of gluino pair production in $p\bar{p}$ collisions.
- Fig. 6 Production cross-sections for the reactions $pp \rightarrow \tilde{g}\tilde{g}x$ as a function of gluino masses as calculated in Ref. 12. For $\sqrt{s} = 0.06, 0.54, 0.8, 2, 10$ and 40 TeV (from left to right curves).
- Fig. 7 x_E and p_{out} cuts effects for gluino mass of 30 or 75 GeV and gluino pair production at $\sqrt{s} = 800$ GeV (Isajet Monte Carlo results).
- Fig. 8 Production cross-sections for the reaction $pp \rightarrow \tilde{g}\tilde{u}x$ as a function of $m_{\tilde{u}}$, for $\sqrt{s} = 0.06, 0.54, 0.8, 2, 10$ and 40 TeV (from left curves), assuming
 a) $m_{\tilde{g}} = m_{\tilde{u}}$
 b) $m_{\tilde{g}} = 0.1 m_{\tilde{u}}$
 c) $m_{\tilde{g}} = 10 m_{\tilde{u}}$
 d) Effect of cut in visible p_T distribution for $p+p \rightarrow \tilde{g}+\tilde{u}+X$ at $\sqrt{s} = 800$ GeV $m_{\tilde{g}} = 20$ GeV/ c^2 and $m_{\tilde{u}} = 200$ GeV/ c^2 (results from Ref. 12).
- Fig. 9 (Q^2, ν) kinematical region for the different ep projects as well as the νp and μp interactions.
- Fig. 10 Diagrams of SUSY particle production in ep CC and NC reactions.
- Fig. 11 Cross-sections of production of scalar quarks and scalar leptons in CC and NC ep reactions (results from Ref. 23).
- Fig. 12 Diagrams of some possible 2-jet events in ep collisions.
- Fig. 13 Fraction of momentum carried by each component including SUSY particle as calculated in Ref. 23.
- Fig. 14 Diagram of associated production of SUSY particles in ep collision via photoproduction mechanism or photon–gluon fusion.
- Fig. 15 Rates corresponding to such mechanisms according to the calculation of Ref. 24.
- Fig. 16 Cross-section corresponding to such mechanism according to the calculation of Ref. 23.
- Fig. 17 Events as measured by the UA1 detector.

Fig. 1

Fixed-target calorimeter

Beam-dump

- (a) CHARM collaboration result
- (b) FNAL beam dump result

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9

a)

or

b)

Fig. 10

Fig. 11

Fig. 12

Fig. 13

($V =$ off shell γ , Z , $W^\pm$ or real γ)

Fig. 14

Fig. 15

Fig. 16

Fig. 17

d)

Fig. 17 (cont.)