SUPERSYMMETRY AND (SUPER) HADRON-HADRON COLLIDERS

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ABSTRACT

We review the different ways to search for supersymmetric particles at present and future high energy $p\bar{p}$ colliders.

Introduction

The great success of the CERN pp collider since it started to work in June 1981 [1] together with the large activity in Supersymmetric theories these last years, has lead to the conviction that hadron-hadron colliders can be a very fundamental tool also for the search of Supersymmetric (SUSY) particles [2].

The situation in this theoretical field is still somewhat opened, so we will work most of the time along a theoretical scheme as briefly defined in (I). We then review the different processes that can give SUSY-particles in $p\bar{p}$ collisions, discuss the signatures and the background (II). We show in (III) how Supersymmetry is related to supercolliders and supertechniques. We end by discussing the supersymmetric prospects for $p\bar{p}$ colliders in (IV)*)

I - Scenario

As well known, Supersymmetry 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. So a completely new spectroscopy is predicted (see Table 1). Depending the supersymmetric framework, the mass of the SUSY particles can vary from a few GeV to a few TeV. The main consequences that this has for the experimentalist are summarized in both Table 1 and Fig.1. So, in particular, we shall assume that the photino ($\tilde{\gamma}$) would be the highest particle. The gluino ($\tilde{g}$) would predominantly decay in $q\bar{q}\tilde{\gamma}$, the scalar quark ($\tilde{q}$) would decay into $q\tilde{g}$ or $q\tilde{\gamma}$ and the charged scalar lepton ($\hat{\ell}$) into $\ell\tilde{\gamma}$. This is the most popular pattern nowadays although alternative schemes have been discussed in the litterature [3].

In addition, a set of hadron-hadron colliders as sketched in Fig.2 available now or in the future will allow to cover a large mass range, in particular for the gluino or the scalar quarks we have presented in Fig.3a,b the different masses (as computed by Isajet [4]) that each collider will be able to reach.

*). For a complete review showing how e^+e^-, hadron-hadron and ep machines can each contribute one interesting piece of information on the search for SUSY-particles, the reader is referred to [2].

Table 1
SUSY-spectroscopy

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

II - Different ways to search for SUSY-particles in hadron-hadron colliders

All kind of SUSY-particles can be produced in $p\bar{p}$ interaction via Drell-Yan mechanism or through W or Z^0 decay. We summarize in Table 2 most of these processes as well as their corresponding signatures; in addition, we give in Table 3 a comparison between SUSY and non-SUSY competing processes in $p\bar{p}$ collisions.

From these two tables, we can make the following remarks.

1 - The cross-sections for most of these processes have been already estimated [5]. Of course, they strongly depend on the mass of the SUSY-particles involved, but anyhow, in certain cases these cross-sections are relatively large (for instance the gluino pair production : Fig.4), or of the order of the W-production cross-section (for instance, for most of the W-decays into SUSY-particles : Fig.5), whenever the corresponding thresholds may be reached.

Table 2
Overview of possible SUSY signature in $p\bar{p}$ collisions

SUSY process	Signature
$p\bar{p} \to \tilde{g}\tilde{g}$	$(q\bar{q}\tilde{\gamma})$ on each side; so very small p_T imbalance and (1 broad jet or 2 jets) on each side
$p\bar{p} \to \tilde{g}\tilde{\gamma}$	Large missing energy and (1 broad jet or 2 jets: $\tilde{g} \to q\bar{q}\tilde{\gamma}$) on the other side
$p\bar{p} \to \tilde{q}\tilde{q}$	($q\tilde{g} = qq_1\bar{q}_2\tilde{\gamma}$, or $q\tilde{\gamma}$) on each side so: a small p_T imbalance and (1 "broad" jet ≡ 3 jets, or 1 jet) on each side
$p\bar{p} \to \tilde{q}\tilde{\gamma}$	($q\tilde{g}\tilde{\gamma} = qq_1\bar{q}_2\tilde{\gamma}\tilde{\gamma}$ or $q\tilde{\gamma}\tilde{\gamma}$) so (some p_T imbalance and a jet) or a good p_T imbalance and a "broad" jet ~ 3 jets
$p\bar{p} \to W^{\pm} \to \tilde{e}\tilde{\nu}$	= $(e\tilde{\gamma}, \nu\tilde{\gamma})$ 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
$p\bar{p} \to W^{\pm} \to \tilde{W}^{\pm}\tilde{\gamma}$ $\hookrightarrow \tilde{q}\bar{q}$	$(q_1q_2\bar{q}_3\tilde{\gamma}\bar{q}, \tilde{\gamma})$ or $(q\tilde{\gamma}\bar{q}, \tilde{\gamma})$, so large missing energy and a very broad jet ≡ 4 quark jets on the other side or some missing p_T and a broad jet ≡ 2 quark jets
$p\bar{p} \to W^{\pm} \to \tilde{W}^{\pm}\tilde{\gamma}$ $\hookrightarrow \ell\nu\tilde{\gamma}$ or $q'\bar{q}\tilde{\gamma}$	Missing energy + 1 lepton Missing energy + (1 "broad" jet ≡ 2 quark jets) on the other side
$p\bar{p} \to W^{\pm} \to \tilde{\ell}\tilde{\nu}$	= $\ell\tilde{\gamma}\tilde{\nu}$: missing energy + 1 lepton (or completely different picture if $\tilde{\nu}$ decays in charged mode)

2 - The signatures of most of the processes in terms of missing energy, jet and lepton recognition, are not completely UNAMBIGUOUS (as summarized in Table 3).

3 - Two ways exist to overcome this problem:
Statistics can help to distinguih between different competing processes by allowing to plot certain typical kinematical quantities.
Some processes, if true, would have a good signature. Among the few already proposed, we review here two of them :

Table 3
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	$p\bar{p} \to q\bar{q} \to$	q or g on each side
	gg	
	$\to Q\bar{Q} \to$	$(q_1 q_2 \bar{q}_3)$ or $(q_1 \ell^\pm \nu)$ on each side
	$\to L^+ L^{-*} \to$	$(q_1 \bar{q}_2 \nu_L)$ on each side
	$\to \tilde{g}\tilde{g}^* \to$	$(q_1 \bar{q}_2 \tilde{\gamma})$ on each side
	$\to \tilde{q}\tilde{\bar{q}} \to$	$(q_1 q_2 \bar{q}_3 \tilde{\gamma})$ or $(q_1 \tilde{\gamma})$ on each side
Missing p_T +	$p\bar{p} \to W^\pm g \to \nu$ + slow $\ell^\pm$ + g $\to$	Missing + g + $(\ell^\pm)$
1 "jet" on the other side	$p\bar{p} \to W^\pm \to L\nu^* \to$	Missing + $(q_1 \bar{q}_2 \nu_L)$
	$p\bar{p} \to \tilde{g}\tilde{\gamma}^* \to$	Missing + $(q_1 q_2 \tilde{\gamma})$
	$p\bar{p} \to \tilde{q}\tilde{\gamma} \to$	Missing + [$(q_1 q_2 \bar{q}_3 \tilde{\gamma})$ or $q\tilde{\gamma}$)]
	$p\bar{p} \to \tilde{W}^\pm \tilde{\gamma}$	Missing + ($q q_1 \bar{q}_2 \tilde{\gamma} \bar{q}$
	↳ $\tilde{q}\bar{q}^*$	or $q\tilde{\gamma}\bar{q}$
	↳ $W^\pm \gamma^* \to$	Missing + $(q_1 \bar{q} \bar{q}_2 \tilde{\gamma})$
Missing on 1 side	$p\bar{p} \to W^\pm \to L^\pm \nu^* \to$	Missing + 1 lepton
+	↳ $\ell^\pm \nu \bar{\nu}$	
1 lepton on the other side		
	$p\bar{p} \to W^\pm \to \tilde{e}^\pm \tilde{\bar{\nu}}_e \to$	Missing + $(e^\pm \tilde{\gamma})$ (if $\tilde{\bar{\nu}}$ does not
	$p\bar{p} \to W^\pm \to \tilde{W}^\pm \tilde{\gamma}^*$	decay in charged mode)
	↳ "$W^\pm$"$\tilde{\gamma}$	Missing + $(\ell^\pm \nu \tilde{\gamma})$
	↳ $\ell^\pm \nu$	

*) 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.

i - Drell-Yan production of $\tilde{q}$ as proposed in [6].

For light gluinos ($m_{\tilde{g}} \leq 20$ GeV) and scalar quarks having masses from 60 to 160 GeV. The latter would be produced through the interaction : $\tilde{g} + q \longrightarrow \tilde{q}$, involving a gluino-parton from the hadron and would occur (depending the parametrization of the structure function and the masses of the SUSY-particles) with the following rate :

$$\frac{\sigma(\tilde{q}) \equiv \sigma(p\bar{p} \rightarrow \tilde{q} + \text{all})}{\sigma(W) \equiv \sigma(p\bar{p} \rightarrow W + \text{all})} \sim 1 \text{ to } 14$$

The decay of the scalar quark into quark + photino would produce as typical signature a hard monojet + large missing energy. In addition we would get a resonant system with the well-known Jacobian peak in the p_t distribution of the monojet (may be less clear than the one of $W \rightarrow e\nu$ process, due to the width of $\tilde{q}$).

ii - W decay into $\tilde{\ell}\tilde{\nu}$

It has been proposed to look for such a process [7,8]. In particular, if $\tilde{\nu}_e$ would decay predominantly into a neutral mode ($\tilde{\nu} \rightarrow \nu\tilde{\gamma}$), an interesting signature has been proposed [7]: the e produced from the $\tilde{e}$ decay is symmetric, whereas the one from standard leptonic W decay is asymetric. But present results 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 possible through cascade decay, and the signature of $W \rightarrow \tilde{e}\tilde{\nu}_e$ is then completely different. The ratio of ($\tilde{\nu} \rightarrow$ neutral)/($\tilde{\nu} \rightarrow$ charged) has been computed [8] but at the moment it is hard to make any definitive quantitative statement because this ratio depends on parameters which still have unknown values.

Anyhow this could give peculiar type of events even if much rarer. For instance [8,10] the $\tilde{\nu}$ could decay in the following way : $\tilde{\nu} \rightarrow \nu_\ell \ell^+ e^- \tilde{\gamma}$ giving 3 leptons events final state in case of W decay or 2 lepton-final state for Z° but the 2 leptons would be in the same hemisphere.

III - Supersymmetry - Supercolliders - Supertechniques

We want to show in this section why Supersymmetry requires Supercolliders and Supertechniques.

It is clear from what we discuss in the two previous paragraphs that Supersymmetry, requires that accelerators go <u>higher and higher</u> in energy (to scan higher and higher mass range), have higher luminosity to get large statistics and to look for rarer but interesting processes :

Supersymmetry requires that detectors :

-have a <u>good jet recognition</u>; i.e. to distinguish neighbouring jets, measure their width and hopefully are able to look at the elementary jet structure of a "broad" jet. This implies a good tracking, an accurate charge and momentum measurement, good calorimetry (energy resolution of the order of few percent).

- measure accurately the missing energy; i.e. to measure a small p_t imbalance (less than of the order of 15 %) and even measure missing energy along the beam axis. This requires a 4π high resolution fine grained calorimeter.

- have a refined lepton recognition; i.e. to measure several μ, e of even low energy.

So SUSY is very DEMANDING, but 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° physics, heavy quarks, heavy leptons, Higgs, anything new ...)

In addition, the last results of UA1 experiment at the CERN $p\bar{p}$ collider for the 1983 run are quite promising. They show how such a device behave beyond the search for $W^{\pm} \rightarrow \ell^{\pm}\nu$ and $Z^{o} \rightarrow \ell^{+}\ell^{-}$. The results obtained in the search for dimuon events [11] show in particular that the central detector performs as well or even better than a bubble chamber; it allows to distinguish secondary vertex, to see very clearly Λ^{o}'s and K^{o}'s etc... (Fig. 6). For the first time also hard monojet balanced by large missing energy events have been identified [9] Fig. 7 . The search for events with one lepton (e or μ) and one or two jets is underway. From the analysis of the 1983 data we also finally learn what are the limitations of such device to do these types of physics and also how to improve it.

Already the next UA1 runs will be done with an improved apparatus, (microvertex detector, equipped muon-wall, more dedicated triggers, processus with refined on-line filtering) and higher luminosity.

A lot of development work is undertaken, motivated by the upgrading of UA experiments but also the building of new accelerators (LEP, SLC, etc...) Among the solutions proposed or studied at the moment, we quote the liquid Argon or TMS and Uranium plates (for highly granulated devices), the scintillating fibers, high density drift calorimeters, BGO, coupling of a BaF_2 scintillator to TMAE photocathode with a low-pressure wire chamber.

Thanks to all this activity on the technical and engineering side, some solutions to fulfill the SUSY requirements can be found such as :

-combining as much as possible the calorimetric and tracking functions in a well matched performance device (Argon or TMS + Uranium highly granulated plates devices ?) could give an homogeneous 4π accurate detector easy to calibrate and also to analyze data.

- high density device would be able to define accurately the jet structure of an event (single out the "quark-jet" i.e. the "elementary" jet and count them in a "broad" jet).

- identifying leptons inside a jet

- handling systematics effects really at the 1 % level.

IV - Supersymmetric prospects for the hadron-hadron colliders

We try first to sketch for the near future, i.e. the period going from 1984 to the end of 1986, the SUSY-scenario one can hope to get.

This scenario is defined in terms of accessible mass range and very rough estimates of the number of SUSY-particles possibly produced at the $p\bar{p}$-collider by the end of 1986.

Until end of 1986, two $p\bar{p}$ colliders will be operational : the CERN $p\bar{p}$ collider already working since 1981, the FNAL $p\bar{p}$ collider hopefully working by 1986. From Fig.3a,b we derive that the mass range accessible with these two colliders will be of the order of 100 GeV for the gluino and 200 GeV for the scalar quarks. We can also make a rough estimate of how many W and Z° will be produced by the end of 1986; the hypotheses or the rough guesses which enter in this computation as well as the results are summarized in Table 4. We finally try to guess the number of $\tilde{g}$ or $\tilde{q}$ which could be produced in $p\bar{p}$ collisions (by $\tilde{g}$ or $\tilde{q}$ pair production, $\tilde{g}\tilde{q}$ production or $\tilde{q}$ Drell-Yan production) from a computation using ISAJET Monte-Carlo. The results are quoted in Table 5. The numbers listed in this table give essentially a FEELING of how many gluinos and scalar quarks can be already produced at these 2 colliders provided their masses are low enough. So, by the end of 1986 if the $\tilde{g}$ and $\tilde{q}$ are in a mass range accessible to CERN or FNAL $p\bar{p}$ colliders we should have a fair amount of $\tilde{g}$ or $\tilde{q}$ produced (or a rather high upper limit on the masses of theses particles !)

If W and Z° decays in winos ($\tilde{W}$) according the following predicted rates [10] :

$$\frac{W^{\pm} \to \tilde{W}^{\pm}\tilde{\gamma}}{W^{\pm} \to e^{\pm}\nu} \simeq 0.4$$

$$\frac{Z^{\circ} \to \tilde{W}^{+}\tilde{W}^{-}}{Z^{\circ} \to e^{+}e^{-}} \simeq 1$$

Table 4
Rough estimate of how many W and Z° will be produced by end of 1986 all over the world, in $p\bar{p}$ colliders (an estimate!)

Main historical fact	Year	UA1 # W	UA1 # Z°	UA2 # W	UA2 # Z°	CDF # W	CDF # Z°
$\int \mathcal{L}^{Sp\bar{p}S} dt = 150\ nb^{-1}$	83 e μ τ	50 14 10	4 5	35	4?		
$\int \mathcal{L}^{Sp\bar{p}S} dt = 4 * \int \mathcal{L}^{SppS}_{83}$	84 e μ τ	240 100 100	15 7 4	140	12		
new AA ? $\Rightarrow \int \mathcal{L}^{Sp\bar{p}S} dt \simeq 3 * \int \mathcal{L}_{84}$	85 e μ τ	700 300 300	50 20 15	420	35		
CERN ?? + Start of FNAL	86 e μ τ					} 1000	90

Table 5
Rough guess of how many gluinos and scalar quarks could be produced by end of 1986 in $p\bar{p}$ colliders (just a guess !)

Year	Expt	PROCESS $\tilde{g}\tilde{g}$ ($m_{\tilde{g}}$ = 25 GeV)	$\tilde{g}\tilde{g}$ ($m_{\tilde{g}}$ = 50 GeV)	$\tilde{q}\tilde{g}$ ($m_{\tilde{q}}$ = 700 GeV)
83	UA1	4800	100	150
84	UA1	20000	400	600
85	UA1	60000	1200	1800
86	CDF		15000	15000

we could get about 400 W decays in $\tilde{W}$ and 50 to 100 Z° decays in $\tilde{W}^+\tilde{W}^-$ as well as also $W^\pm \rightarrow \tilde{e}\tilde{\nu}_e$, $Z° \rightarrow \tilde{e}^+\tilde{e}^-$ etc...

So by the time SLC starts with MARK II (1987) we should have got clear ideas about possible :

W decays in SUSY-particles
$\tilde{g}$ up to masses of 100 GeV
$\tilde{q}$ up to masses of 200 GeV

Once SLC starts to run (10^4 Z°'s per day ! ?) it will allow to carefully scan the possible SUSY decays of Z° (Z° $\rightarrow \tilde{\nu}\tilde{\nu}$, $\tilde{W}^+\tilde{W}^-$, $\tilde{q}\tilde{\bar{q}}$, $\tilde{\gamma}\tilde{\gamma}$ ...) as well as to look for direct production of $\tilde{q}$ and $\tilde{\ell}$. The main limitation will be the beam energy.

It is quite clear that e^+e^- machines all TOGETHER with $p\bar{p}$ colliders will provide in the next years essential information for the test of Supersymmetry. Al least we hope so !

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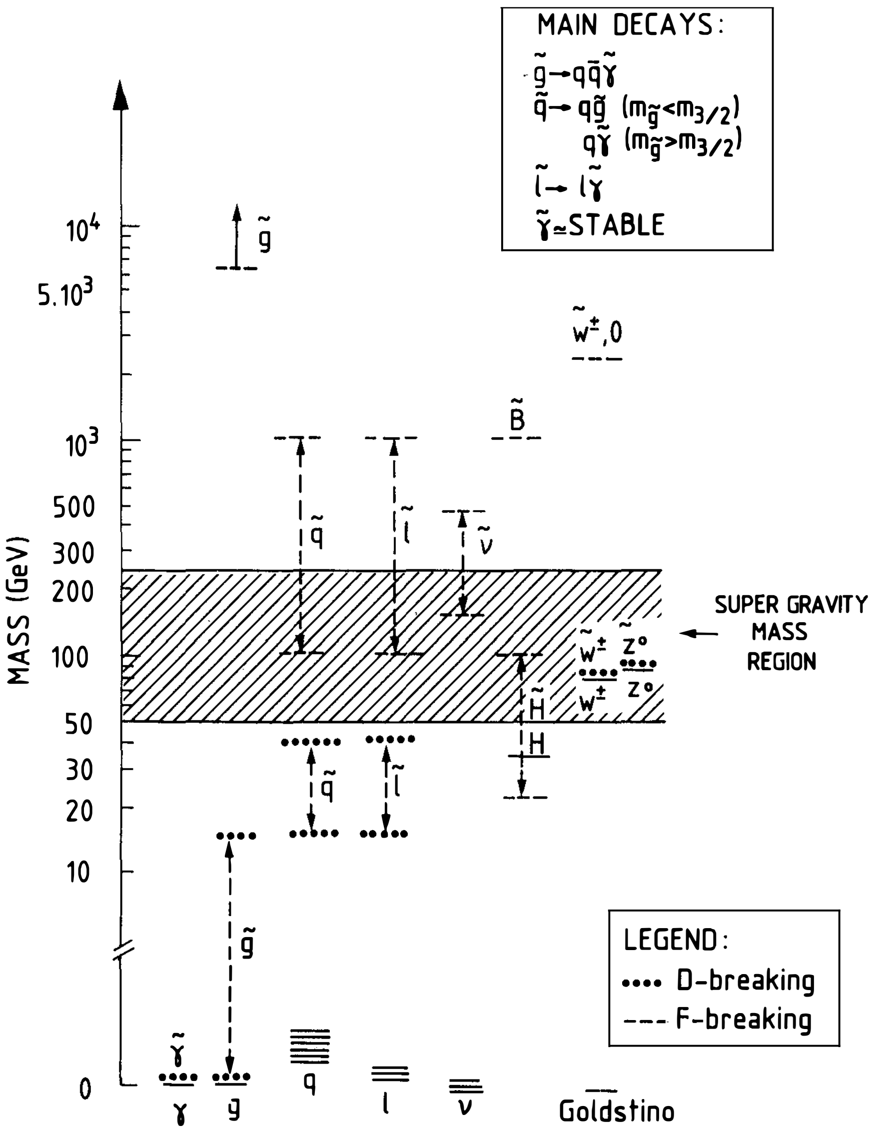

Fig.1 - SUSY spectroscopy and main decay of decay of SUSY particles

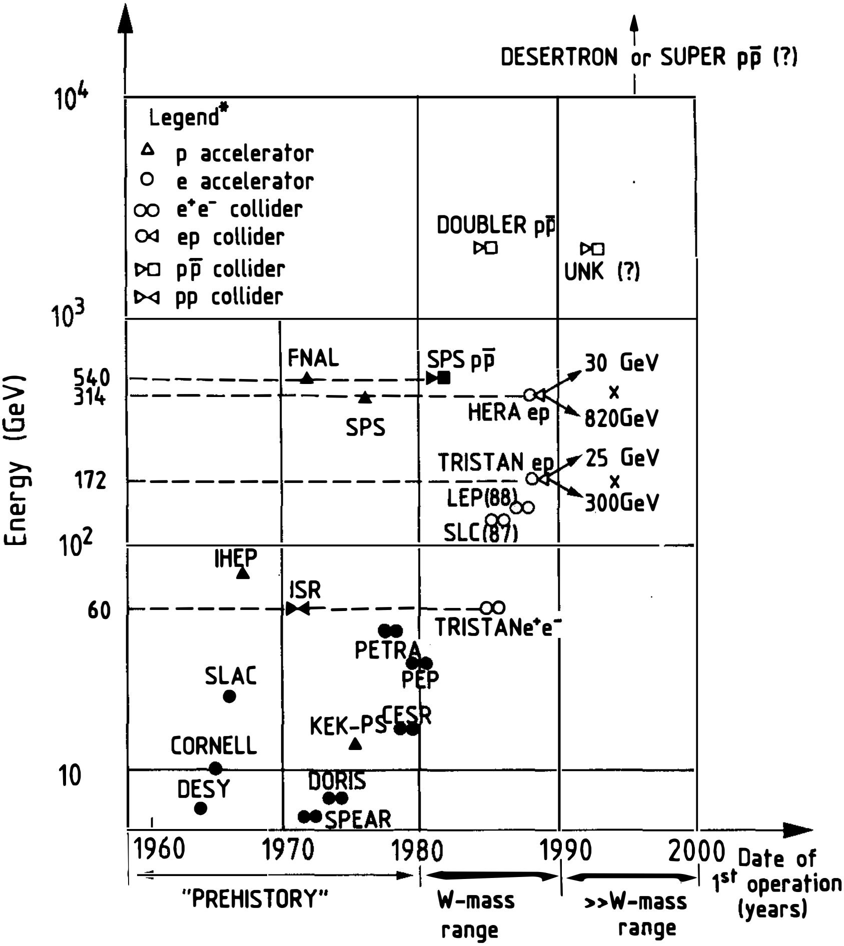

Fig.2 - Set of hadron-hadron colliders available now or planified until 1995

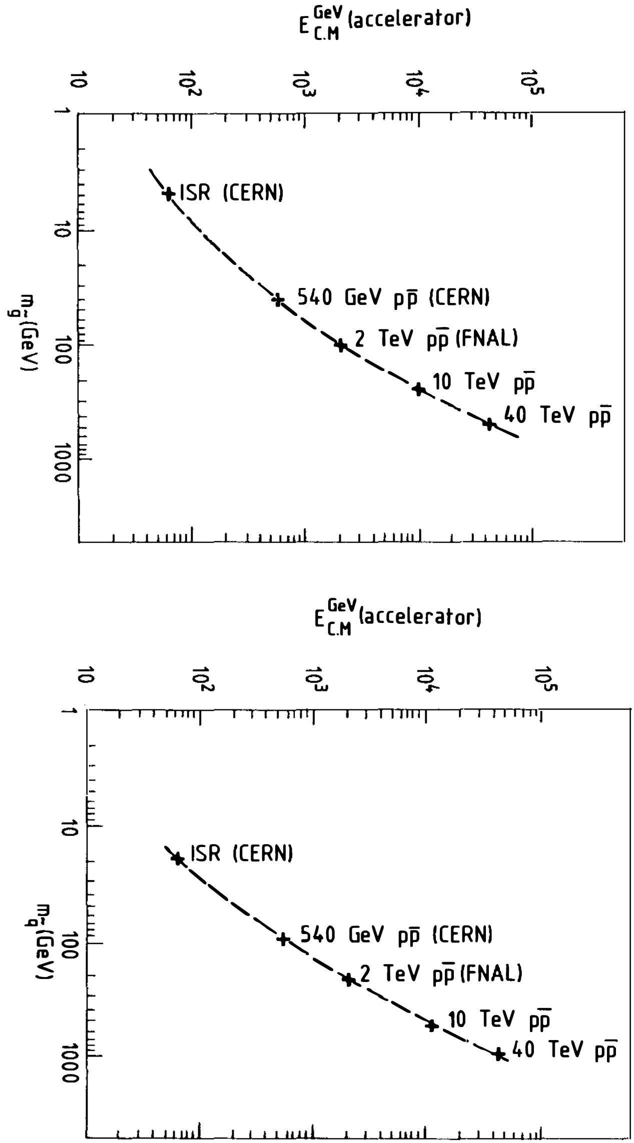

Fig.3 - a) Mass range for the gluino available with the different pp or $p\bar{p}$ colliders already built or planified until 1995 as computed in [4]

b) Mass range of the scalar quark, available with the different pp or $p\bar{p}$ colliders already built or planified until 1995

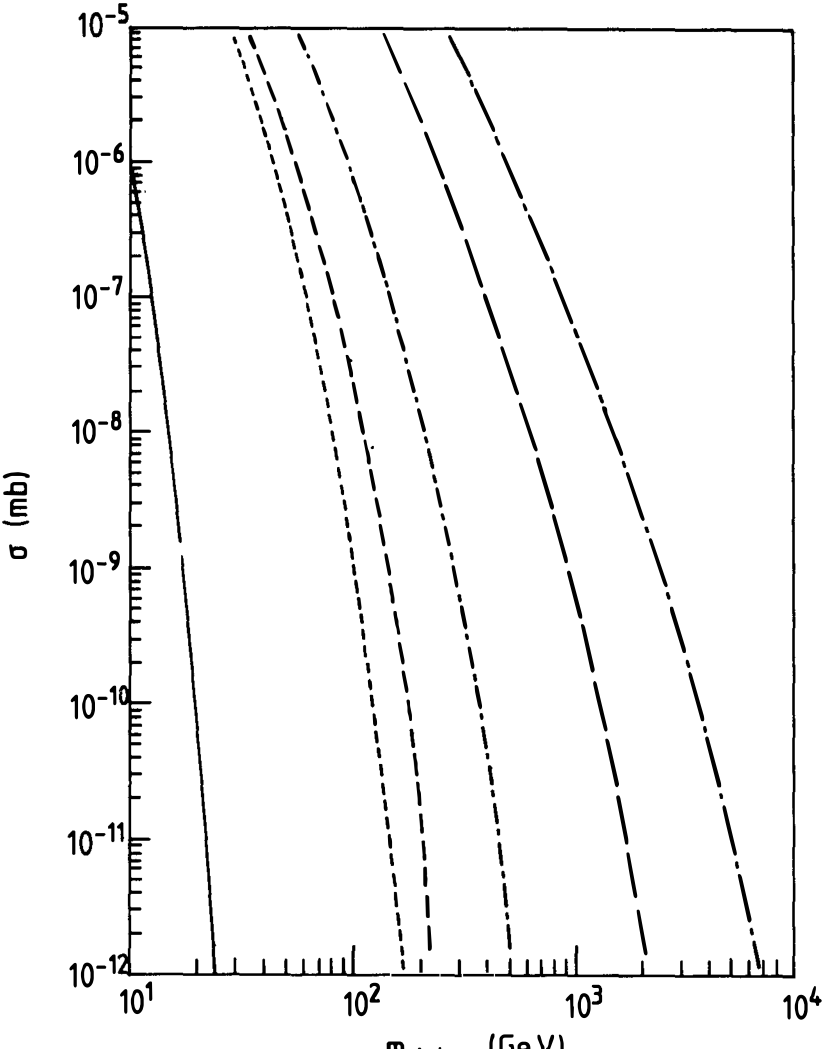

Fig.4 - Gluino pair production cross section for different beam energies according the ISAJET computation of [4]

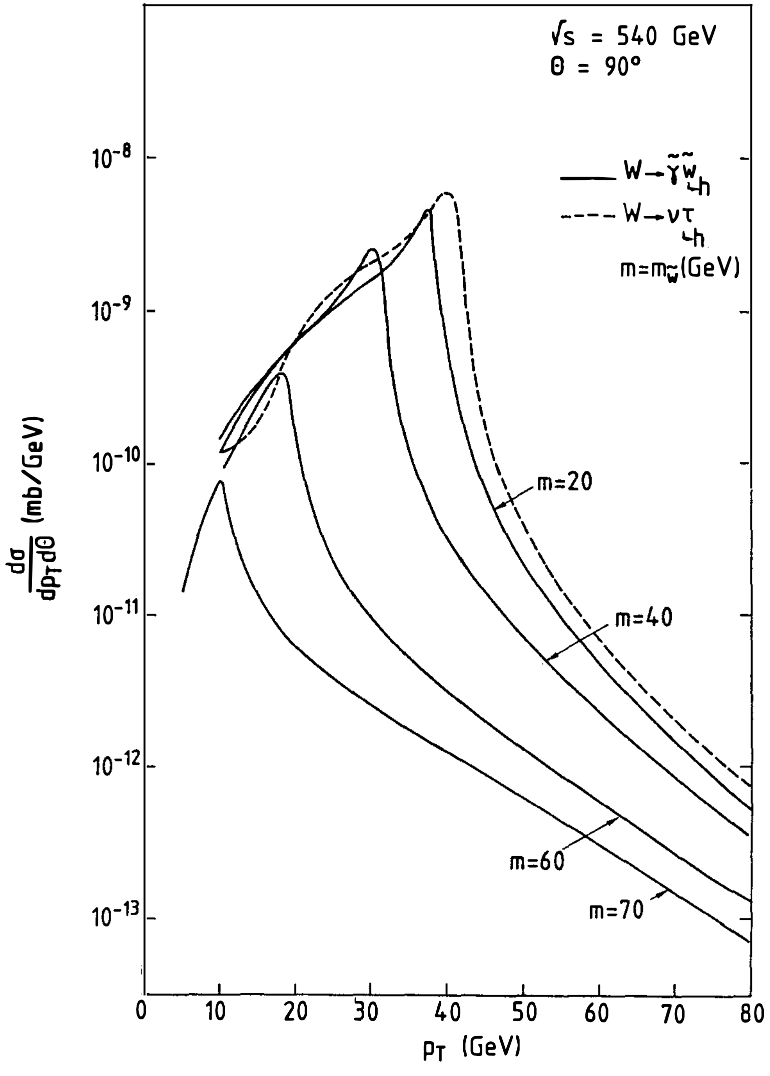

Fig.5 - $\frac{d\sigma}{dp_T d\theta}$ (mb/GeV) as a function of p_T for the decay of the W in $\tilde{W}\tilde{\gamma}$ as got from Altarelli et al. [5]

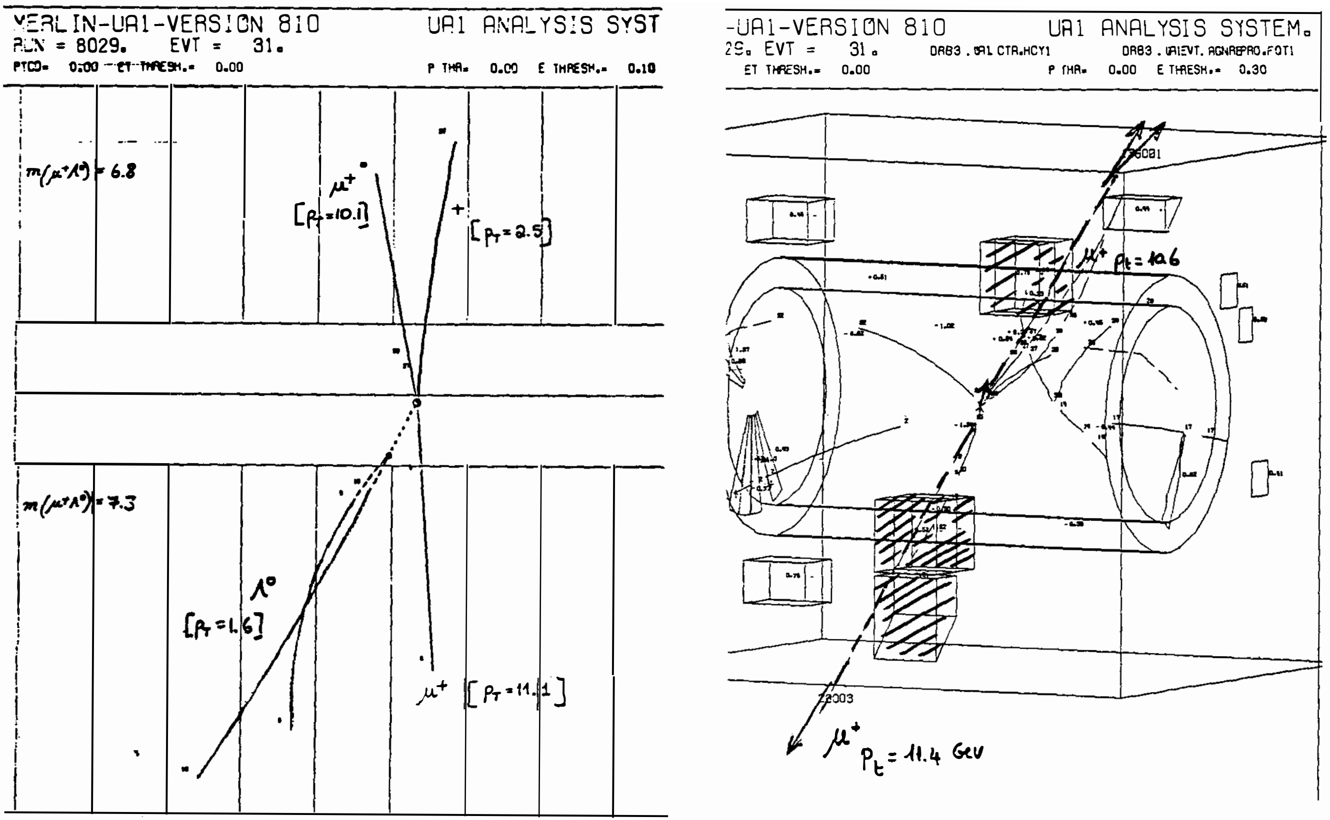

Fig.6 - Dimuon events as got from UA1 experiment in the 1983 data

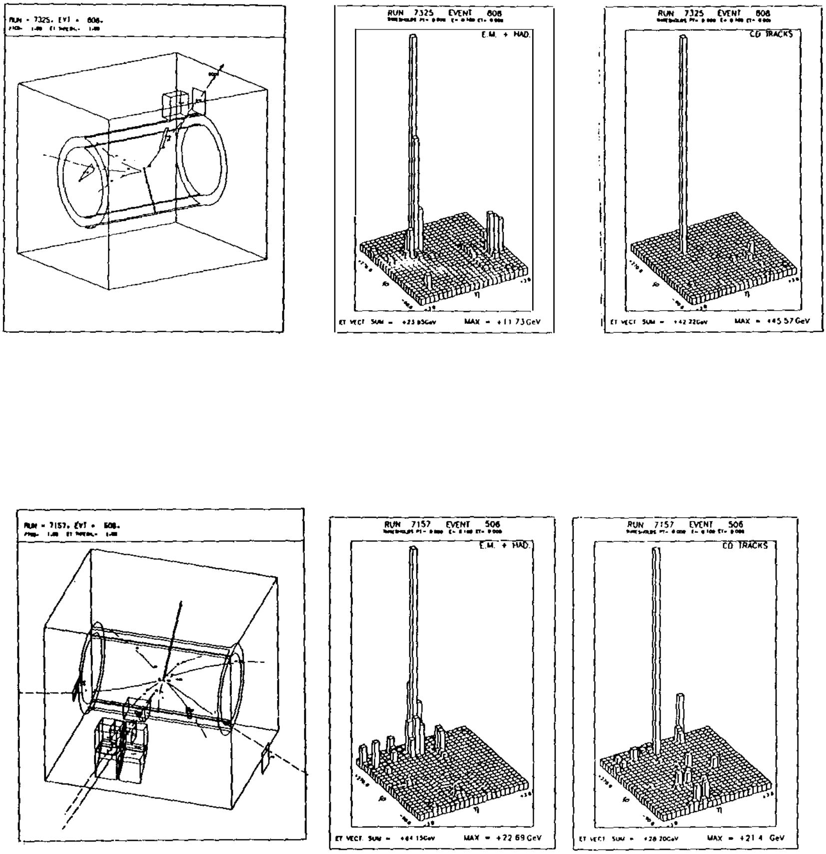

Fig.7 - Monojet + missing energy event as got from UA1 experiment in the 1983 data