EXPERIMENTAL CONSTRAINTS ON GLUINO MASSES AND SUPERSYMMETRIC THEORIES

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We extend the analyses of Fayet, and Fayet and Farrar, of experimental searches for gluinos, the supersymmetric partners of gluons Because of their large production cross sections, present data appears to exclude gluino masses below 3 5–6 GeV/c^2 and may be more restrictive Lifetime considerations give an upper limit on scalar quark masses and on the scale of supersymmetry breaking, and experiments sensitive to missing energy will provide interesting limits on the latter Since gluinos remain very light in many models, they will either be detected soon or many supersymmetric theories will be excluded

1 Introduction Supersymmetric (SS) theories have been of considerable interest for some time, and have recently been studied intensively [1] because they incorporate scalars naturally into the theory and may allow progress toward solving the gauge hierarchy problem

In SS theories conventional particles have associated particles differing by 1/2 unit of spin For each quark and lepton there should exist a spinless partner, with the same mass Since these are not seen, SS must be broken If SS is to be of value for solving the gauge hierarchy problem, the scale of SS breaking (Λ_{SS}) may [1] have to be of order 1 TeV When SS is broken, the light scalars will get masses from radiative corrections The masses are expected to be of order m_Z, so it is not surprising that the scalar partners of quarks and leptons have not yet been observed Broken global supersymmetries must [2] have a Goldstone fermion, the goldstino (G) which couples to the gluon (g) and its supersymmetric partner, the gluino ($\tilde{g}$)

The gluinos have spin 1/2 and we assume they carry the same quantum members of the gluons, i e they are color octets Apparently it is hard to give much mass to gluinos, so it *is* rather surprising that they have not yet been seen Fayet, and Fayet and Farrar, have already discussed this question [1,3] In this paper we extend their analyses, with several new results We argue that existing data probably implies that gluino masses are larger than about 3 5–6 GeV, depending on Λ_{SS} We suspect that existing data gives even stronger constraints, but normally data is not published in the form we need and will have to be reanalyzed by the experimenters involved Achieving a gluino mass [1] that large represents a serious challenge to SS theories that have a $\Lambda_{SS} < 1$ TeV

It may be useful to point out where we go beyond the analysis of Fayet, and Fayet and Farrar (1) For gluino masses beyond about 1 GeV we can calculate production cross sections perturbatively Since gluinos are color octets these cross sections are quite large, up to twenty times those for quark pairs of similar mass, and give stringent limits It should be emphasized that our limits are conservative, since for heavy quarks the perturbative calculations are known to underestimate the cross sections (2) We consider larger gluino masses, and scales of SS breaking $\Lambda \lesssim 1$ TeV, where the $\tilde{g}gG$ vertex (i) dominates the gluino decay, (ii) leads to

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[1] Given the couplings of a gluino, its constituent mass then fixes its production cross section Since gluinos are colored they will be shielded by strong color forces, most probably forming gluinoballs with gluons or quark–antiquark pairs These hadrons will have of order 1 GeV of constituent mass even in the limit of massless gluinos Thus the limits on masses that go in the lagrangian should be reduced somewhat (by <1 GeV) from the numbers we give Since it is not completely clear how to do that, we will always quote the mass that comes directly from analysis of experimental data and let the reader make the adjustment

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larger missing energy, and (iii) leads to larger goldstino interaction cross sections All these effects lead to better signatures hence easier detectability (3) We consider new production processes which give *upper* limits on gluino masses (or lower limits on Λ_{SS}) in broken global SS theories (4) Since lifetimes of gluinos cannot be too long upper limits on Λ_{SS} or scalar quark masses can be obtained (5) We emphasize the kinds of experiments needed to detect gluinos this is timely because present experiments could find them For example, in pp collisions at the ISR with $\mathcal{L} = 10^{32}/(\mathrm{cm}^2\ \mathrm{s})$ and running time of 10^6 s, if the gluino mass were 2 5 GeV then $3\ 5 \times 10^9$ gluino pairs were produced, all with detectable signatures in principle

2 *Gluino couplings* Since gluinos are the partners of gluons they will have the interactions shown in fig 1a The coupling at each vertex is the standard QCD coupling g [‡2] In addition, for a broken SS a coupling to the goldstino is introduced as in fig 1b Gauge invariance requires a magnetic type coupling, $h\bar{\mathrm{u}}_{\mathrm{G}}\sigma^{\mu\nu} \times \mathrm{u}^{a}_{\tilde{\mathrm{g}}} F^{a}_{\mu\nu}$ where u_{G} and $\mathrm{u}^{a}_{\tilde{\mathrm{g}}}$ are spinors for a goldstino and gluino of color a, respectively, and $F^{a}_{\mu\nu}$ the gluon field strength The coupling strength h is fixed by supercurrent algebra [‡3] Indeed taking the matrix element of the supercurrent S_μ between a gluino and a gluon, including the goldstino pole term and requiring zero divergence, yields $h = \tilde{m}/2\Lambda^2_{SS}$ where $\tilde{m}$ is the gluino current algebra mass and Λ_{SS} sets the scale of SS breaking, defined by $\langle 0|S_\mu|\mathrm{G}\rangle = \Lambda^2_{SS}\gamma_\mu \mathrm{u}_{\mathrm{G}}$

Some of our results only require the interactions of fig 1a, for production of gluinos via gluons They hold in any theory where the gluinos are color octets In local SS the goldstino may become the helicity 1/2 part of a spin 3/2 state so our results involving goldstinos may not directly hold However, since the gluinos will have to decay (see below), essentially equivalent results will be valid

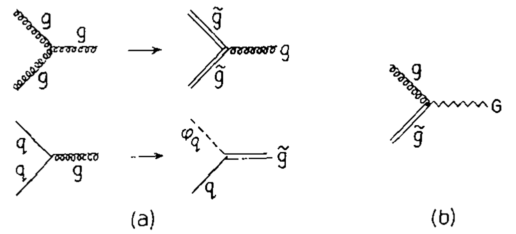

Fig 1 Gluino couplings in supersymmetric theories We represent gluons by g, gluinos by g̃, goldstinos by G, quarks by q, scalar partners of quarks by ϕq, and the photino by $\tilde{\gamma}$ The vertices of (a) will be present in every supersymmetric theory when gluinos carry color The vertex of (b) is present in global supersymmetric theories

3 *Gluino lifetimes and interactions* In a spontaneously broken global SS, the decay of the gluino proceeds dominantly via the vertex in fig 1b We obtain the lifetime

$$\tilde{\tau}_{\mathrm{G}} = (0\ 33 \times 10^{-15}/h^2\Lambda^4_{SS})\,(\Lambda_{SS}/M_{\mathrm{Z}})^4(1\ \mathrm{GeV}/\tilde{m})^3\ \mathrm{s} \tag{1}$$

Since current algebra arguments yield $h \simeq \tilde{m}/2\Lambda^2_{SS}$, this becomes

$$\tilde{\tau}_{\mathrm{G}} \approx 1\ 1 \times 10^{-15}(\Lambda_{SS}/M_{\mathrm{Z}})^4(1\ \mathrm{GeV}/\tilde{m})^5\ \mathrm{s} \tag{2}$$

If observations imply $\tilde{m} > 3$ GeV, and $\Lambda_{SS} < 1$ TeV for the cases of interest, then $\tilde{\tau} < 0\ 7 \times 10^{-13}$ s If g̃ is produced with $\gamma = 20$, it will travel typically 0 4 mm On the other hand, if $\tilde{m} \simeq 1$ GeV, and $\Lambda_{SS} = 1$ TeV, it goes 3^6 times further, typically 0 30 m with, of course, some going over a meter Note that eq (2) provides an interesting upper limit on Λ_{SS} for a given $\tilde{m}$ (see fig 2) If data excludes production of a gluino which travels more than about 10 cm (see below), then any theory must satisfy $\Lambda_{SS}/\tilde{m}^{1\ 5} \lesssim 1000$, with Λ_{SS} and $\tilde{m}$ in GeV units

If the g̃gG vertex is suppressed or absent as perhaps could occur in a local SS, the gluino will decay via a virtual scalar quark to a quark–antiquark pair and a photino ($\tilde{\gamma}$) (provided that the gluino is heavier than the photino)

For the mode $\tilde{\mathrm{g}} \to \mathrm{q}\bar{\mathrm{q}}\tilde{\gamma}$, the lifetime is

$$\tilde{\tau}_{\tilde{\gamma}} = 0\ 8 \times 10\ \ ^{6}(m_\mu/\tilde{m})^5(M_\phi/M_{\mathrm{W}})^4\ \mathrm{s}$$

M_ϕ is the lightest scalar quark mass associated with quark s lighter than the gluino By comparison, the $\tilde{\gamma}$ mode dominates if $M_\phi < 0\ 09\ \Lambda_{SS}$, if $M_\phi = M_{\mathrm{W}}/2$, the photino mode dominates for $\Lambda_{SS} \gtrsim 400$ GeV (see fig 2)

[‡2] The gluinos are colored fermions and contribute to the β-function like quarks The numerical increase in $\alpha_s(Q^2)$ is small, however, and we may safely neglect it

[‡3] This is an extension to the colored states of the same argument given for photinos in ref [4] See also ref [5] and Dine et al , ref [1]

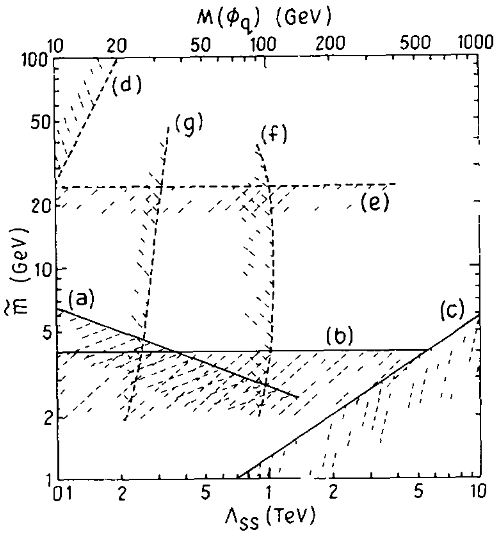

Fig 2 Excluded region in the $\tilde{m}-\Lambda_{SS}$ plane Solid curves are from present data Dashed curves are attainable limits from future experiments (a) Valid if $\tilde{g}gG$ vertex is present (b) From $\tilde{g} \to q\bar{q}\tilde{\gamma}$ with subsequent $\tilde{\gamma}$ interaction in a beam dump detector This curve is always present We have assumed $M_{\phi_q} = M_W/2$ (c) Gives upper limit on Λ_{SS} (lower scale) or M_{ϕ_q} (upper scale) from the requirement that $\tilde{g}$ lifetime not be too long (d) Upper limit on $\tilde{m}$ from double goldstino production at Isabelle (e) The region below this line would be excluded by a failure to detect gluino production by an SPS detector with $\mathcal{L} = 10^{29}/\mathrm{cm}^2$ (f) The region to the left is excluded if 100 events of G + $\tilde{g}$ production are not detected at Isabelle (g) Same as (f) for FNAL collider

Thus we expect that experiments sensitive to neutral hadrons that can travel centimeters or meters will give a lower limit on the gluino mass When a gluino is produced it will be shielded to make a color singlet hadron Most probably the gluino will bind with a gluon, because of the octet binding forces, though sometimes the gluino could attach to a color octet $q\bar{q}$ pair The electrically neutral, color singlet, hadron will interact like a normal hadron, with a total interaction probability like that of a kaon or a D^0, with $\sigma_{tot} \sim$ few mb As observed [1,3] by Fayet and Farrar, and as we will reaffirm below, any objects produced with several μb cross sections, and having such lifetimes and interactions, would probably have been observed

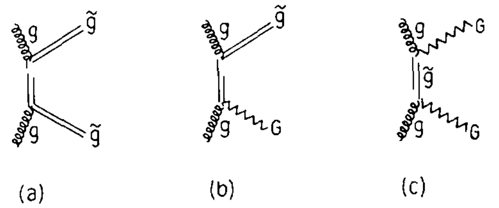

Fig 3 Production mechanism for gluinos and goldstinos (a) is present in any theory where gluinos carry color It gives the cross sections of fig 4 for color octet gluinos (b) and (c) are present in globally supersymmetric theories and give upper limits of fig 2

4 Gluino and goldstino production Once the small mass range $\tilde{m} < 1$ GeV is excluded by the absence of long-lived, electrically neutral, strongly interacting hadrons, we can reliably use perturbative QCD to calculate (lower limits on) the production cross sections, and these are very large for color octet gluinos Further, in any theory where there is a $\tilde{g}gG$ coupling, the double or single direct goldstino production cross (figs 3b, 3c) sections increase with $\tilde{m}$ and the absence of experimental detection of such events will give an upper limit on $\tilde{m}$

We show the gluino pair-production mechanisms for pp and p$\bar{\text{p}}$ collisions in fig 3 Fig 4 shows the production cross section versus the gluino mass $\tilde{m}$ for a number of beam energies Since the curves fall rapidly, a small error in estimating the cross section

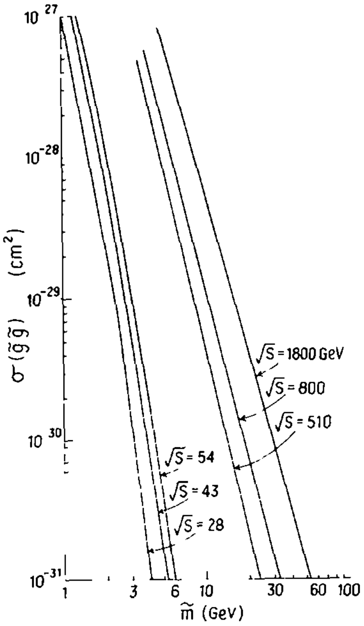

Fig 4 Gluino production cross sections computed from fig 4a, including scaling violations, as parametrized by Baier et al in ref [11] for several values of $\sqrt{s}$ (in GeV)

limit has little effect on the associated mass limit Once again these are expected to be conservative lower limits since production of $c\bar{c}$ and $b\bar{b}$ is larger than the perturbative prediction

It should be emphasized that the cross sections are quite large The actual calculation includes not only the diagram of fig 3a, but the crossed graph, the direct gluon pole term, and the production via quarks, $q\bar{q} \to g \to \tilde{g}\tilde{g}$ In the region of interest the subprocess shown is the largest one in the Feynman gauge, and to understand the size of the cross section we can compare it to $q\bar{q}$ production With generators F^a in the octet representation and $\lambda^a/2$ in the fundamental representation, we have for equal kinematics, and infinite energy,

$$\frac{\sigma(gg \to \tilde{g}\tilde{g})}{\sigma(gg \to q\bar{q})} \approx \frac{\mathrm{tr}\, F^aF^aF^bF^b}{\mathrm{tr}\, \lambda^a\lambda^a\lambda^b\lambda^b/16} = 13\ 5$$

For the actual calculation [‡4] the gluino pair cross section varies from 16–20 times the cross section for production of a pair of quarks of the same mass

5 Rectroactive analysis of data It is obviously difficult to analyze existing experiments to see what limits they put on gluino masses It has even been suggested that experimenters only find what they are looking for We will abstract from past data some estimates on what might have been seen, our results are summarized in fig 2 We want to emphasize that they are only estimates, and should not be taken as firm limits until experimenters have analyzed their own data with a full knowledge of backgrounds, cuts, etc *Experiments in progress can set significantly better limits than we obtain if they are analyzed with gluino (or goldstino) detection in mind, and experiments at SPS, ISABELLE or FNAL can go to very high masses*

(a) Small gluino masses and longer lifetimes As discussed above, if $\tilde{m}$ is of the order of 1 GeV the lifetime is fairly long Fayet and Farrar have already argued that this is not allowed by data, and we agree The case can be made very strong For small $\tilde{m}$, while perturbative calculations are not reliable, the production cross section will not be smaller than that of fig 4, so $\sigma \gtrsim 1$ mb Produced gluinos will be shielded by gluons or $q\bar{q}$ octet pairs, so an electrically neutral hadron will be produced, travel a distance from millimeters to meters, and decay into an even number of charged hadrons (often four or more hadrons) which do not point back to the production vertex *There is missing energy because of the goldstino (or photino) but no charged leptons* The shielded gluino will interact with a total cross section in the mb range The experiment [6] of Gustafson et al can put limits of order 10^{-32} cm^2 on any neutral object produced in appropriate regions of p_T and X_T which goes several meters and then interacts with a millibarn cross section Experiments in hyperon beams may [7] be able to put limits of order 10^{-3}–10^{-4} times the Λ cross section on objects which go a few meters and decay into an even number of charged prongs which do not point back to the production vertex In hydrogen bubble chambers there are strong restrictions [‡5] on events which would give a visible gap and an even number of prongs (neutrons give a recoil proton and an odd number of prongs) Altogether, we think it is convincing that objects with the properties of light gluinos are not produced with cross sections of even a few μb, so $\tilde{m} \gtrsim 2$–3 GeV If $\sigma < 1/2\ \mu$b, then $m \gtrsim 3\ 5$ GeV We assume fixed target pp collisions with $\sqrt{s} \simeq 28$ GeV for these numbers, they vary a little for other energies or beams

(b) Beam dump experiments Once the mass is as large as established in (a) above, most gluinos decay within a few cm, and either beam dump or missing energy detectors will be most restrictive In beam dump experiments the goldstino will interact in the detector, giving no charged lepton and thus candidate neutral-current (NC) events Recent experiments looking for axions quote [8] an upper limit (2σ) $\sigma_{\mathrm{int}} \leqslant 2 \times 10^{-67}$ cm^4 where σ is the production cross section for the gluino in our case and σ_{int} the interaction cross section for the goldstino Assuming that the goldstino interaction is like a charged-current neutrino interaction, and an average energy of 60 GeV for the goldstino (a typical ν energy in such an experiment), we find again that $\sigma \lesssim 1/2\ \mu$b or equivalently $\tilde{m} \gtrsim 3\ 5$ GeV

[‡4] In all calculations we have assumed that the gluinos are Dirac fermions If they are Majorana fermions there is an extra factor of 1/2 in the phase space Since the cross sections are falling exponentially with the masses of the produced gluinos this does not affect our final conclusions substantially

[‡5] We thank B Roe and R Rau for discussions on this data

For some ranges of $\tilde{m}$ and Λ_{SS} this result can be considerably strengthened by further data analysis. First, in any theory with a $\tilde{g}gG$ vertex the goldstino interaction will be much larger than the ν charged cross section. Indeed the goldstino can interact with protons in the detector by fusing with a constituent gluon, which yields the rate

$$\sigma_G = (\pi/\Lambda_{SS}^2)(\tilde{m}/\Lambda_{SS})^2 xG(x, \tilde{m}^2) ,$$

where $x \equiv \tilde{m}^2/s$ and $xG(x, \tilde{m}^2)$ is the gluon distribution function evaluated at x and $Q^2 \approx \tilde{m}^2$. For the range of masses and energy considered we may safely use $xG \simeq 3(1-x)^5$ which yields

$$\sigma_G = (3.7/\Lambda_{SS}^4) sx (1-x)^5 \text{ mb}$$

with s and Λ_{SS} in GeV units. Using 60 GeV for a mean goldstino energy and Λ_{SS} = 300 GeV, we find that $\sigma_G > \sigma_\nu$ in the range 1 GeV $\lesssim \tilde{m} \lesssim$ 6 GeV and the goldstino interaction cross section is increased by a factor of 4–6 over the contributions considered previously. This strengthens the previous limits and pushes $\tilde{m}$ to about 4.5 GeV. Second [‡6], a ν NC event has large missing p_T for the hadrons, and a spectrum of visible hadron energy (E_{vis}) which peaks at low E_{vis} and does not have a long tail. A goldstino induced event, on the other hand, will have considerably larger E_{vis} (thus it could not account for any extra events at small E_{vis}) and much smaller $(p_\perp/p_L)_{had}$. Cuts on these variables could eliminate most ν NC candidates and allow a small goldstino signal to be found, or give a limit well below 1 μb.

The photino interaction cross section is dominated by the process $\gamma + q \to q + g$, with a scalar quark exchanged, as discussed by Fayet [3]. This gives a cross section

$$\sigma_{int} = 1.2 \times 10^{-38} E (M_W/M_\phi)^4 \times \sum_q \int_{\tilde{m}^2/s}^{1} xq(x)(1 - m^2/xs)^3 dx\, e_q^2 \, (\text{cm}^2)$$

with E in GeV. We assume that the lightest scalar quark has $M_\phi = M_W/2$. Then combining this with the beam dump limit gives curve (b) of fig. 2, drawn for fixed M_ϕ and Λ_{SS} (in a particular theory, M_ϕ may depend on Λ_{SS}). Even if the goldstino is not present the photino decay together with the beam dump data already provides a stringent lower limit on $\tilde{m}$.

(c) Missing energy and p_T experiments. The most powerful limits will come from experiments, at Tevatron and collider energies, which constrain missing energy and momentum as well as possible. Again, we emphasize SS theories with a $\tilde{g}gG$ vertex, but our remarks apply also to theories without such a vertex so far as a lower limit on $\tilde{m}$ is concerned. The upper limit on $\tilde{m}$ depends crucially on such a vertex.

Consider an experiment at the ISR pp collider with a typical integrated luminosity of $10^{37}/\text{cm}^2$. Then if $\sigma > 10^{-33}$ cm^2 it had 10^4 gluino pairs produced. This corresponds to $\tilde{m} \gtrsim 10$ GeV if gluinos were not found. Similarly, consider $\int \mathcal{L} dt = 10^{35}/\text{cm}^2$ at the SPS collider. Then 10^4 events correspond to $\sigma = 10^{-31}$ cm^2, or $m \gtrsim 24$ GeV!

Could such events have been seen already? Their signature is fairly dramatic. The gluinos are produced in the central region, and decay via $\tilde{g} \to gG$. The gluon gives a hadronic jet so there is a pair of acoplanar jets, plus a lot of missing transverse energy and momentum, and no prompt charged leptons. Typically, about 25% of the energy will go into the central collision, so 10–15% of the total energy and about half of the central energy will be missing. Certainly 10^4 such events could be found in ISR or SPS experiments specifically looking for them in the near future.

6. *Upper limits.* Since the cross sections for double goldstino production grow as $\tilde{m}$, they give upper limits on $\tilde{m}$ or lower limits on Λ_{SS} if a signal is not found. The signature for goldstino pair production is an event with an interaction and beam jets but essentially no central region energy. The goldstino–gluino production is easier to see as $\tilde{g} \to gG$ giving one jet (or $\tilde{g} \to q\bar{q}\tilde{\gamma}$), with no particles detected in the opposite direction. Neither type of event has prompt charged leptons. These give the future curves d, f, g of fig. 2.

7. *Gluino masses.* Fayet has discussed [3] gluino in some detail. In the unbroken theory $\tilde{m} = 0$ since they are degenerate with gluons. Gluinos will not get mass at tree level even if SS is broken since color symmetry is unbroken. Of course, an explicit ad hoc mass term could be written for gluinos, but that explains nothing. Fayet [9] suggests one mechanism to give gluinos a Dirac mass of order 1 GeV, but it requires

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[‡6] We thank J. Morfin for discussions on this analysis.

adding a color octet of "paragluinos" and may not be tolerable if grand unification is a goal [10] SS theories often have U(1) symmetries (called R-invariances [9]) which must be broken to allow a Majorana mass for $\tilde{g}$

So far, not much attention has been paid to gluino masses when constructing models Perhaps by focusing attention on models where $\widetilde{m}$ satisfies the constraints of fig 2, progress can be made towards finding a realistic theory

8 Conclusions Since gluinos tend to be lighter than other supersymmetric partners, and are produced with large cross sections, they should be considered as the prime hope in deciding experimentally whether nature is supersymmetric We think, conservatively, that gluinos would probably have been detected if their masses were in the excluded region of fig 2, basically, $\widetilde{m} \gtrsim 4$ GeV Analysis of existing data by experimenters, and experiments in progress, can strengthen these limits considerably if gluinos are not detected Since gluino properties depend on the scale of SS breaking and on scalar quark masses, interesting upper/lower limits on all of these are implied by upper limits on lifetimes of long-lived neutral hadrons and on production cross sections

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References

[1] Recent references related to the questions we discuss include P Fayet, Supersymmetry, particle physics, and gravitation, in Unification of the fundamental particle interactions, eds S Ferrara, J Ellis and P van Nieuwenhuizen (1980),
G R Farrar, Supersymmetry in nature, Lectures at the Intern School of Subnuclear Physics (Erice, 1978),
M Dine, W Fischler and M Srednicki, Nucl Phys B189 (1981) 575,
N Sakai, Tohuku Univ preprint #TU/81/225,
L E Ibanez and G G Ross Oxford Univ preprint (1981),
E Witten, Princeton preprint (1981),
S Dimopoulos and S Raby, Nucl Phys B192 (1981) 353,
S Dimopoulos and H Georgi, Nucl Phys B193 (1981) 150,
G Barbiellini et al, LEP Study, DESY 79/67 (1979)
[2] P Fayet and J Illiopoulos, Phys Lett 51B (1974) 461
[3] G R Farrar and P Fayet, Phys Lett 198 (1978) 442, 76B (1978) 575,
P Fayet, Phys Lett 78B (1978) 417
[4] N Cabibbo, G R Farrar and L Maiani Phys Lett 105B (1981) 155
[5] P Fayet, Phys Lett 70B (1977) 461
[6] H R Gustafson, C A Ayre, L W Jones, M J Longo and P V R Murthy, Phys Rev Lett 37 (1976) 474
[7] O Overseth, private communication
[8] See e g, Proc XXth Intern Conf on High energy physics, Madison, eds, L Durand and L G Pondrom (1980)
[9] P Fayet, Nucl Phys B90 (1975) 104,
A Salam and J Strathdee, Nucl Phys B87 (1975) 85
[10] S Dimopoulos, private communication
[11] R Baier et al, Z Phys C2 (1979) 265