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SUPERSYMMETRY IN UNDERGROUND LABS AND ν-TELESCOPES

F. Anselmo[a]), L. Cifarelli[a,b,c]), D.V. Nanopoulos[a,d,e]),
A. Peterman[a,f]), and A. Zichichi[a])

[a]) CERN, Geneva, Switzerland
[b]) Department of Physics, University of Pisa, Pisa, Italy
[c]) INFN-Bologna, Bologna, Italy
[d]) Center for Theoretical Physics, Department of Physics,
Texas A&M University, USA
[e]) Astroparticle Physics Group, Houston Advanced Research Center (HARC),
The Woodlands, Texas, USA
[f]) CNRS-Luminy, Marseilles, France

ABSTRACT

The most recent results of two Supergravity models [SU(5) and SU(5)×U(1)] concerning the search for Supersymmetry effects in underground labs are reported. The two models are presented in the general framework of ongoing studies concerning the problem of establishing what effects are most suitable to be looked for and what are the conceptual bases of them.

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1 Introduction: One-Parameter Theory Needed

As all of you know, the Standard Model (SM) needs many parameters:

14 masses,
6 angles,
3 couplings,

and many free choices (often neglected). Let me recall that in the SM the negative Higgs mass needed for electroweak symmetry breaking is put "ad hoc". On the other hand also the so-called MSSM needs many additional parameters, even though it is called Minimal Supersymmetric extension of the Standard Model. The basic ingredients of the MSSM are shown in Table 1.

Table 1. The main ingredients of the Minimal Supersymmetric Extension of the Standard Model (MSSM).

			SPIN
Gauge forces	⇒	Gauge Bosons	1
SUSY	⇒	Gauginos	$1/2$
3 generations	⇒	quarks & leptons	$1/2$
SUSY	⇒	squarks & sleptons	0
2 doublets H_1, H_2	⇒	Higgs Bosons	0
SUSY	⇒	Higgsinos	$1/2$

Multiplicative exact R-parity

$$R = (-1)^{2s+L+3B}$$

s ≡ spin
L ≡ leptonic number
B ≡ baryonic number

Two complex Higgs doublets are needed to cancel the ABJ (triangle) anomaly. In fact, higgsinos, being fermions, contribute to the ABJ anomaly.

$$H_1 = (H_1^0, H_1^-)$$
$$H_2 = (H_2^+, H_2^0)$$

The list of additional parameters in the MSSM is given in Table 2, together with the corresponding list relative to Supergravity (SUGRA) models and in particular to SU(5) or SU(5)×U(1).

The two minimization conditions of the electroweak (EW) scalar potential impose two additional constraints which can be used to determine B and $|\mu|$, and thus reduce the parameter count in SUGRA down to 4, plus the sign of μ, plus the top-quark mass (versus 26, in the MSSM). Our problem is to choose a theoretical way able to reduce the number of parameters to only one. And this is possible with SU(5)×U(1), as we will see in section 2. Notice that by the time these proceedings were published, evidence for top quark with mass ~170 GeV was reported at Fermi-Lab [1]: this would imply for the "strict-no-scale" case in SU(5)×U(1) Supergravity the knowledge of the sign of μ, i.e. $\mu < 0$. For the definition of the various parameters in Table 2 we refer the reader to [2].

Table 2. List of additional parameters needed in the MSSM and in Supergravity (SUGRA) models.

MSSM		**SUGRA**	
M_1, M_2, M_3	3	1	$m_{1/2}$
$(\tilde{Q}, \tilde{U}^c, \tilde{D}^c, \tilde{L}, \tilde{E}^c)_i$	15	1	m_0
$\tilde{H}_1, \tilde{H}_2$	2	0	(m_0)
A_t, A_b, A_τ	3	1	A
B	1	1	B
μ	1	1	μ
$\lambda_{b,t,\tau}$, $\tan\beta$	2	2	λ_Y, $\tan\beta$
Total	$26+m_t$	$6+m_t$	
		$\Downarrow$	
		$4+m_t$	with EW radiative breaking

For completeness let us also recall, in Table 3, which are the expected supersymmetric particles.

A note of clarification is needed in order to understand the origin of the mixed states, charginos ($\chi^{\pm}_{1,2}$) and neutralinos ($\chi^{0}_{1,2,3,4}$). These states are the result of mixing between the charged and neutral superpartners of the electroweak gauge bosons (electroweak gauginos) and of the Higgs. The gauginos of $SU(2)_L$ are charged $\tilde{W}^{\pm}$ and neutral $\tilde{W}^{3}$, while the gaugino of $U(1)_Y$ is obviously neutral $\tilde{B}$ (also called bino).

Table 3. The expected supersymmetric particles.

i)	***Squarks*** (spin = 0 (complex) bosons)	12
	$\tilde{\mathbf{q}}_{\mathbf{i}} = \begin{pmatrix}\tilde{u}_{iL}\\ \tilde{d}_{iL}\end{pmatrix}$; $\tilde{u}_{iR}$, $\tilde{d}_{iR}$; i =1, 2, 3 generation index	
ii)	***Sleptons*** (spin = 0 (complex) bosons)	9
	$\tilde{\boldsymbol{\ell}}_{\mathbf{i}} = \begin{pmatrix}\tilde{\nu}_{iL}\\ \tilde{e}_{iL}\end{pmatrix}$; $\tilde{e}_{iR}$; i =1, 2, 3 generation index	
iii)	***Gluinos*** (spin = $^1/_2$ (Majorana) fermions)	1
	$\lambda^{\mathbf{a}}$; a = 1,...,8 = $SU(3)_C$ colour index	
iv)	***Charginos*** (spin = $^1/_2$ fermions)	2
	$\chi_{\mathbf{i}}^{\pm}$; i = 1, 2 ; $m_i < m_j$ for i < j	
v)	***Neutralinos*** (spin = $^1/_2$ (Majorana) fermions)	4
	$\chi_{\mathbf{i}}^{0}$; i = 1,...,4 ; $m_i < m_j$ for i < j	
vi)	***Higgs*** (spin = 0 bosons)	
	$\mathbf{h^0, H^0}$; real CP even	2
	$\mathbf{A^0}$; real CP odd	1
	$\mathbf{H^{\pm}}$; complex	1
		32

The superpartners of the Higgs (Higgsino) are charged $\tilde{H}^{\pm}$ and neutral $\tilde{H}^0_{1,2}$. The mixing among the charged states

$$\begin{pmatrix}\tilde{W}^{+}\\ \tilde{H}^{+}\end{pmatrix} \text{ and } \begin{pmatrix}\tilde{W}^{-}\\ \tilde{H}^{-}\end{pmatrix}$$

will produce the above quoted charginos ($\chi^{\pm}_{1,2}$), while the mixing among the neutral states

$$\begin{pmatrix}\tilde{B}\\ \tilde{W}^{3}\\ \tilde{H}^0_1\\ \tilde{H}^0_2\end{pmatrix}$$

will produce the four neutralinos $\chi^0_{1,2,3,4}$. The gaugino-higgsino term in the Lagrangian is:

$$L = -\frac{1}{2} M_3 \bar{\lambda}_a \lambda_a - \frac{1}{2} \bar{\chi}_M M^{(0)} \chi_M - (\bar{\chi}_D M^{(c)} \chi_D + \mathrm{h.c.})$$

where λ_a (a = 1,..., 8) are (Majorana) gluino fields, χ_M are (Majorana) neutralino fields and χ_D are (Dirac) chargino fields.

The neutralinos $\chi^0_{1,2,3,4}$ and charginos $\chi^\pm_{1,2}$ masses depend on $\tan\beta$, $m_{\tilde{g}}$, and μ. Note that the magnitude of μ is calculable from the radiative EW breaking constraints, but its sign remains undetermined. This is why, when we will deal with the detailed calculations, all predictions will be given for $\mu > 0$ and $\mu < 0$ (the result of Fermi-Lab on $m_t \approx 170$ GeV favours $\mu < 0$, as already pointed out).

Let us now see how to search for Physics beyond the SM. This Physics is certainly there because we know that many problems are in front of us and cannot be answered by the SM. The synthesis of these problems is in Table 4.

Table 4. Problems beyond the Standard Model.

In contrast with Table 4 we have the fact that the present high-precision LEP data are in excellent agreement with the Standard Model. How to overcome this apparent big paradox?

Answer: the search for Physics beyond the SM cannot be implemented using qualitative arguments based on theoretical models with 26 parameters which can be arbitrarily varied at everybody's will. What we need is a rigorous theoretical model able to allow detailed calculations to be confronted with experimental data (see scheme in Fig. 1).

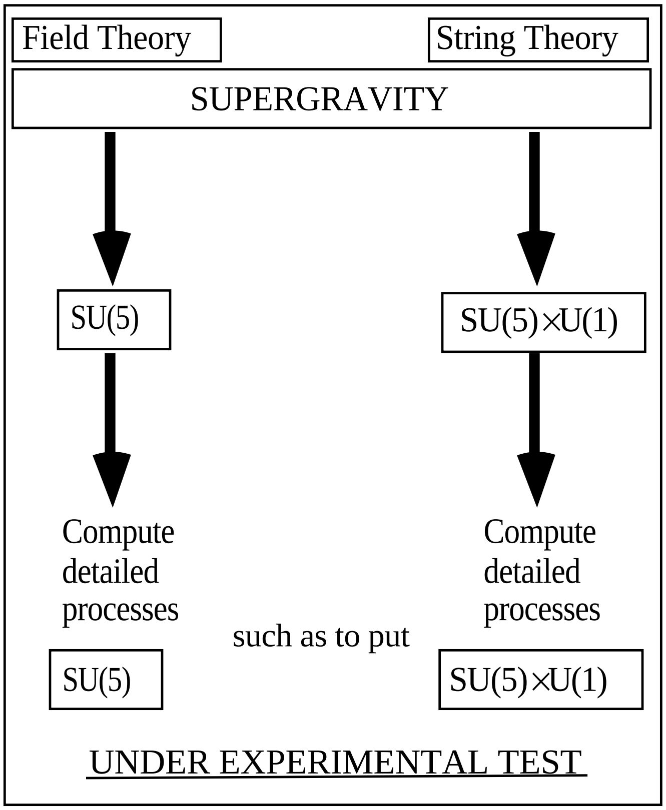


Figure 1. Guideline to the search for new Physics beyond the Standard Model.

The starting point is therefore the choice of a model described by the least number of parameters and based on well motivated theoretical assumptions.

Our choice is SU(5)×U(1) Supergravity for the following reasons:

a) it is derivable from String Theory;
b) it is the simplest unified gauge extension of the SM;
c) it allows special cases where only ONE parameter is needed: all SUSY Physics in one parameter !

d) it recalls the electroweak case where Nature has not chosen the simplest way out, i.e. SU(2), but SU(2)×U(1).

We will compare this model with SU(5) Supergravity because this is the only plausible minimal extension of the Standard Model. In fact the MSSM has 26 arbitrary parameters while SU(5) Supergravity can be expressed in terms of four parameters plus the sign of μ. Furthermore, SU(5) Supergravity can be taken as the representative of a non-string inspired approach to the Physics beyond the Standard Model: in fact so far no one has succeeded in deriving SU(5) from String. On the other hand SU(5)×U(1) is derivable from String and can therefore be considered as the best candidate for a string-inspired approach to the Physics beyond the Standard Model.

To compare these two Supergravity models on the basis of detailed calculations has been the main task of our group during the last years of work.

2 From Qualitative SUSY to Detailed Calculations

The result of the most complete analysis done [3-10] in the framework of a "qualitative" approach to SUSY Physics is shown in Fig. 2. This approach had as a fundamental quantity to describe low-energy Supersymmetry a unique parameter, M_{SUSY}. Let us quote few results of this "qualitative" approach to SUSY Physics: we have shown that the two-loop RGEs (Renormalization Group Equations) allow M_{SUSY} to be of the order of M_Z [4]; studying the heavy threshold effect [5] we have shown that high-precision LEP data do not exclude SUSY particle masses of the order of M_Z. A detailed study of the light threshold [7] allowed the knowledge of the spread of the SUSY particle spectrum without introducing any extra condition such as "naturalness". Let us note in passing that "naturalness" is an arbitrary choice of a parameter (theoretical "prejudice") in order to impose an upper bound on the SUSY spectrum.

Figure 2. This is the best proof that the convergence of the gauge couplings can be obtained with M_{SUSY} at an energy level as low as M_Z. Notice: the effects of "light" and "heavy" thresholds have been accounted for, as well as the Evolution of Gaugino Masses. E_{SU} is the string unification scale.

Figure 3. The correlation between all measured quantities, $\alpha_3(M_Z)$, $\sin^2\theta_W(M_Z)$, τ_p, the limits on the lightest detectable supersymmetric particle (here represented by M_{SUSY}) and the unification scale E_{GUT}.

Figure 3 shows the correlation among all basic quantities needed in this "qualitative" approach. In this figure the influence of the experimental lower bounds on the SUSY breaking scale and of the proton lifetime on the GUT scale are shown. Notice that the lower bound on M_{SUSY} causes an upper bound on E_{GUT} while the lower bound on τ_p produces a lower bound on E_{GUT}.

The basic trends -useful for mnemonic guide in the complex mathematical formalism needed to describe SUSY Physics- are summarized in Table 5. These studies are the most exhaustive and coherent before the new phase of SUSY.

Table 5. The trends emerging from the studies [4-10]. When the theoretical accuracy A increases, high values of $\alpha_3(M_Z)$ are preferred. When $\alpha_3(M_Z)$ increases, E_{GUT} increases and M_{SUSY} decreases. EC means Evolution of Couplings. EGM stands for Evolution of Gaugino Masses.

BASIC TRENDS

$A\ (EC)\quad (\uparrow) \Rightarrow \alpha_3\ (M_Z)\quad (\uparrow)$

$\alpha_3(M_Z)\quad (\uparrow) \Rightarrow E_{GUT}\quad (\uparrow)$

$\alpha_3(M_Z)\quad (\uparrow) \Rightarrow M_{SUSY}\quad (\downarrow)$

$E_{GUT}\quad (\downarrow) \Rightarrow M_{SUSY}\quad (\uparrow)$

$A(EGM)\quad (\uparrow) \Rightarrow M_{SUSY}\quad (\uparrow)$

$\alpha_3(M_Z)\quad (\uparrow) \Rightarrow \sin^2\theta_W(M_Z)\quad (\downarrow)$

The new phase consists in a series of detailed calculations for Supersymmetry searches at the existing facilities: Gran Sasso, SuperKamiokande, LEP-I & II, Fermi-Lab, HERA, in the framework of two Supergravity models: SU(5) and SU(5)×U(1) [11-24]. These two models add only four parameters (plus the top-quark mass) to those of the SM in order to account for the masses of the 32 SUSY particles. But SU(5)×U(1) has the advantage that it can be reduced to only one parameter. The SU(5) features are listed in Table 6, the SU(5)×U(1) ones in Table 7. There are two possible ways for SUSY breaking in SU(5)×U(1): via MODULI or DILATON fields. They are common in String construction and have therefore received most attention. In the DILATON scenario $<F_S> \neq 0$, whereas in the MODULI one $<F_T> \neq 0$ ($<F_S>$ and $<F_T>$ actually characterize the scalar and tensor fields). Usually a quantity $\tan\theta = <F_S>/<F_T>$ is defined. A crucial point is that the scalar masses are given by:

$$\tilde{m}_i^2 = m_{3/2}^2 \,(1 + n_i \cos\theta)$$

where $m_{3/2}$ is the gravitino mass and n_i are the modular weights of matter fields.

Table 6. Major features of the SU(5) Supergravity model and its spectrum.

SU(5)
• Not easily string-derivable, no known examples
• Symmetry breaking to Standard Model: due to vevs of 24, independent of Supersymmetry breaking
• No simple doublet-triplet splitting mechanism
• Proton decay: d = 5 large operators, strong constraints needed
• Baryon asymmetry ?
Spectrum
• 4 parameters: $\tan\beta$, $m_{1/2}$, m_0, A; plus m_t
• Universal soft-supersymmetric breaking automatic
• $m_0/m_{1/2} > 3$, $\tan\beta \lesssim 3.5$
• Dark matter: $\Omega_\chi h_0^2 \gg 1$, 1/6 of points excluded
• $m_{\tilde{g}} < 400$ GeV, $m_{\tilde{q}} > m_{\tilde{\ell}} > 2m_{\tilde{g}} \gtrsim 500$ GeV
• $m_{\tilde{t}_1} > 45$ GeV
• 60 GeV $< m_h <$ 100 GeV
• $2m_{\chi_1^0} \approx m_{\chi_2^0} \approx m_{\chi_1^\pm} \approx 0.28 m_{\tilde{g}} \lesssim 100$ GeV
• $m_{\chi_3^0} \approx m_{\chi_4^0} \approx m_{\chi_2^\pm} \approx \|\mu\|$
• Chargino and Higgs easily accessible soon

Table 7. Major features of the no-scale SU(5)×U(1) Supergravity model and comparison of the two Supersymmetry breaking scenaria considered.

SU(5)×U(1): NO-SCALE SUPERGRAVITY	
• Easily string-derivable, several known examples • Symmetry breaking to Standard Model: due to vevs of 10, $\overline{10}$, tied to onset of Supersymmetry breaking • Natural doublet-triplet splitting mechanism • Proton decay: Dimension 5 operators very small • Baryon asymmetry through lepton number asymmetry (induced by the decay of heavy neutrinos) as processed by non-perturbative electroweak interactions	
SUPERSYMMETRY BREAKING MECHANISM	
MODULI	DILATON
• 2 parameters: $\tan\beta$, $m_{1/2}$; plus m_t	• 2 parameters: $\tan\beta$, $m_{1/2}$; plus m_t
• Universal soft-supersymmetric breaking automatic	• Universal soft-supersymmetric breaking automatic
• $m_0 = 0$, $A = 0$	• $m_0 = {}^1\!/\!\sqrt{3}\, m_{1/2}$, $A = -m_{1/2}$
• Dark matter: $\Omega_\chi h_0^2 < 0.25$	• Dark matter: $\Omega_\chi h_0^2 < 0.90$
• $m_{1/2} < 475$ GeV, $\tan\beta < 32$	• $m_{1/2} < 465$ GeV, $\tan\beta < 46$
• $m_{\tilde g} > 245$ GeV, $m_{\tilde q} > 240$ GeV	• $m_{\tilde g} > 195$ GeV, $m_{\tilde q} > 195$ GeV
• $m_{\tilde q} \approx 0.97\, m_{\tilde g}$	• $m_{\tilde q} \approx 1.01\, m_{\tilde g}$
• $m_{\tilde t_1} > 155$ GeV	• $m_{\tilde t_1} > 90$ GeV
• $m_{\tilde e_R} \approx 0.18\, m_{\tilde g}$, $m_{\tilde e_L} \approx 0.30\, m_{\tilde g}$, $m_{\tilde e_R}/m_{\tilde e_L} \approx 0.61$	• $m_{\tilde e_R} \approx 0.33\, m_{\tilde g}$, $m_{\tilde e_L} \approx 0.41\, m_{\tilde g}$, $m_{\tilde e_R}/m_{\tilde e_L} \approx 0.81$
• 60 GeV $< m_h <$ 125 GeV	• 60 GeV $< m_h <$ 125 GeV
• $2m_{\chi_1^0} \approx m_{\chi_2^0} \approx m_{\chi_1^\pm} \approx$ $\approx 0.28 m_{\tilde g} \lesssim 290$ GeV	• $2m_{\chi_1^0} \approx m_{\chi_2^0} \approx m_{\chi_1^\pm} \approx$ $\approx 0.28 m_{\tilde g} \lesssim 285$ GeV
• $m_{\chi_3^0} \approx m_{\chi_4^0} \approx m_{\chi_2^\pm} \approx \lvert\mu\rvert$	• $m_{\chi_3^0} \approx m_{\chi_4^0} \approx m_{\chi_2^\pm} \approx \lvert\mu\rvert$
• Spectrum easily accessible soon	• Spectrum accessible soon

Table 7 (continued).

SU(5)×U(1)	
STRICT NO-SCALE	
MODULI	DILATON
• B(M_U) = 0 • $\tan\beta = \tan\beta(m_t, m_{\tilde{g}})$ • $m_t \lesssim 135$ GeV ⇒ $\mu > 0$ and • $m_h \lesssim 100$ GeV • $m_t \gtrsim 140$ GeV ⇒ $\mu < 0$ and • $m_h \gtrsim 100$ GeV m_t determines the sign of μ	• B(M_U) = $2m_0$ • $\tan\beta = \tan\beta(m_t, m_{\tilde{g}})$ • $\tan\beta \approx 1.4$-1.6, $m_t < 155$ GeV • $m_h \approx 61$-91 GeV • $m_{\tilde{t}_1} > 67$ GeV only $\mu < 0$ is allowed
Note: the quoted values for m_t correspond to the "running" top quark mass. The experimentally observable mass is the "pole" mass and the relation between the two masses is $m_t^{pole} \approx 1.07\, m_t$.	

DILATON and MODULI fields are two ways to get universal masses as needed to avoid large FCNC (Flavour Changing Neutral Currents):

i) with DILATON: $\theta = \pi/2$; i.e. $\langle F_S \rangle \gg \langle F_T \rangle$;

ii) with MODULI : $\theta = 0$; i.e. $\langle F_T \rangle \gg \langle F_S \rangle$;

This implies:

i) with DILATON: $m_0 = {}^{1}/\sqrt{3}\; m_{1/2}$; $A = -m_{1/2}$.

ii) with MODULI : $m_0 = A = 0$; $m_{1/2} \neq 0$.

There are two "strict no-scale" possibilities, where a relation is required for B at M_U.

For the Special DILATON case, B(M_U) = 2 m_0 and solutions exist only for $\mu < 0$.

For the Special MODULI case, B(M_U) = 0 and solutions exist only for $m_t \lesssim 135$ GeV if $\mu > 0$ and for $m_t \gtrsim 140$ GeV if $\mu < 0$. Notice that for $\mu < 0$, $\tan\beta$ is uniquely determined as function of m_t and $m_{\tilde{g}}$, whereas for $\mu > 0$, $\tan\beta$ can be double valued. As mentioned in the introduction, the Fermi-Lab result on $m_t \approx 170$ GeV would imply that the sign of μ is negative.

3 Predictions for ν-telescopes from SU(5) and SU(5)×U(1)

Galactic halo neutralinos χ_1^0 (i.e. the lightest mixture of photino, Zino, and neutral Higgsino) captured by the Sun or the Earth produce high-energy neutrinos as end-products of various annihilation modes. These neutrinos can travel from the Sun or Earth cores to the neighbourhood of underground detectors, "Neutrino Telescopes" (NT), where they can interact and produce upwardly-moving muons. We have computed [20] these muon fluxes in the context of two Supergravity models: SU(5) and SU(5)×U(1) (with the two special cases of DILATON and MODULI scenarios).

We have also determined the regions of parameter space that would be accessible with the improvements expected at Gran Sasso (GS) and SuperKamiokande (SKK) and other facilities (DUMAND, AMANDA, NESTOR) currently under construction (see Figs. 5-14, as will be discussed later).

The coherent neutralino-nucleon scattering cross-section goes like:

$$\sigma(\chi_1^0, N) \approx m_h^{-4}\,(1 + \tan^2\beta).$$

The capture rate (C_{Sun} or C_{Earth}) goes like m_h^{-4}. Note that m_h is proportional to $m_{\chi_1^0}$ with a positive constant of proportionality; i.e. when one increases (decreases) the other increases (decreases) too.

The detection rate (Γ_{Sun} or Γ_{Earth}) is proportional to the capture rate and therefore decreases as $m_{\chi_1^0}$ increases.

But in SU(5)×U(1) new annihilation channels open up, such as WW, ZZ, hH. These channels could have compensating effects on the detection rate:

a) the presence of new channels to produce high-energy neutrinos leads to an enhancement of the detection rate;

b) the decrease of the branching ratio for fermion-pair channels makes the neutrino yield from $\tau^+\tau^-$, $c\bar{c}$, $b\bar{b}$ smaller and hence reduces the detection rate.

Therefore these new annihilation channels could increase or decrease the detection rate: it depends who wins between a) and b) above.

It has also been found that for small $\tan\beta$ and $\mu < 0$ the WW channel can become dominant, if open, basically because $\chi_1^0 \approx \tilde{W}^3$, i.e. the neutralino is mostly Wino. This explains the distortion of the detection rate curves in the cases where $\mu < 0$ (see Figs. 7 and 8).

Let us explain the origin of the anomalous lines in Γ_{Sun} and Γ_{Earth} (for instance in Fig. 8):

- for large values of tanβ, the CP-odd Higgs boson A can be light and the presence of the A-pole when $m_{\chi_1^0} \approx {}^1/_2\, m_A$ makes the relic density very small;
- $\Omega_\chi h_0^2$ as a function of m_χ is first lower than 0.05, then it increases with $m_{\chi_1^0}$ and eventually reaches values above 0.05 when $m_{\chi_1^0}$ moves away from the A-pole.

Thus the detection rates (Γ_{Sun} and Γ_{Earth}) show this behaviour, i.e. the anomalous lines in Fig. 8.

4 Can Underground Labs Compete with Supercolliders ?

Table 8 summarizes the strategies to look for signals predicted at existing facilities by the two Supergravity models SU(5) and SU(5)×U(1).

Table 8. Basic experimental strategies at various existing facilities to look for SUSY particles.

		Tested SUGRA Model	
LAB	SIGNAL	SU(5)	SU(5)×U(1)
FERMI-LAB	• trileptons	YES	YES
LEP-I & II	• m_h	YES	YES
	• acoplanar multi-leptons	YES	YES
	• mixed events (jet + lepton)	YES	YES
HERA	• $\tilde{e}_R$ with $p_t \gtrsim 20$ GeV	NO	YES
	• LPS with $1-x_L = 0.2$	NO	YES
Gran Sasso	$\tau(p \to \bar{\nu} K^+)$	YES	NO
SuperKamiokande	ν telescopes	YES	YES
DUMAND	ν oscillations	YES	YES
AMANDA			

At Fermi-Lab (FNAL) maybe the top quark has been found with $m_t \approx 170$ GeV and maybe one could even see trilepton signals from Supersymmetry. At LEP-I & II maybe the Higgs will escape the detection ($m_h \gtrsim 80$ GeV) but jets-leptons and multi-leptons signatures could be seen. At HERA right-handed selectrons with $p_t \gtrsim 20$ GeV could be within reach, but indirect information on SUSY particles could come from the Leading Proton Spectrometer (LPS) of ZEUS. At Gran Sasso (GS) and SuperKamiokande (SKK), according to SU(5) Supergravity, the proton decay channel $p \rightarrow \bar{\nu} K^+$ is observable for most of the allowed parameter space (a lifetime of the order of 10^{32} yr is possible).

We would like to add a short note on minimal SU(5) Supergravity.

- The proton lifetime predicted by SU(5) Supergravity was four times higher than the value obtained using the Evolution of Gaugino Masses (EGM) at two loops.
- Now with EGM calculations at two loops, the proton lifetime is more accessible to experimental detection. The points in the parameter space shown in Fig. 4 are illustrative examples.

Figure 4. The calculated values of the proton lifetime into $p \rightarrow \bar{\nu} K^+$ versus the lightest chargino (or second-to-lightest neutralino) mass for both signs of μ. Note that we have taken $\alpha_3(M_Z)^{WA}+1\sigma$ in order to maximize τ_p. Note also that future proton decay experiments should be sensitive up to $\tau_p \approx 20 \times 10^{32}$ yr.

We now show in detail the observable effects in underground labs of the two Supergravity models, in terms of predictions for the Neutrino Telescopes (NT).

If neutralinos (χ_1^0) are present in the halo, then neutrino telescopes (NT) can be used to explore more than one half of the allowed parameter space of these specific models, and more generally of a large class of Supergravity models, in many ways going beyond the reach of traditional collider experiments provided the present NT sensitivity is increased by a factor of 12. Notice that NESTOR would allow to explore the range $m_\chi > 10^2$ GeV as from now. The detailed calculations are illustrated in the set of Figs. 5-14.

The direct comparison between underground facilities and supercolliders is reported in Table 8.

Figure 5. The neutralino capture rate for the Sun and Earth as a function of the neutralino mass in the no-scale (MODULI scenario) $SU(5)\times U(1)$ Supergravity model. The representative value of $m_t = 150$ GeV has been used. Note the depletion of neutralinos in the halo near the Z-resonance, and the enhancement in the Earth capture rate near the iron nucleus mass (52.0 GeV).

Figure 6. Same as Fig. 5 but for the DILATON scenario.

Figure 7. The upwardly-moving flux in underground detectors originating from neutralino annihilation in the Sun and Earth, as a function of the neutralino mass in the no-scale (MODULI scenario) SU(5)×U(1) Supergravity model. The representative value of m_t = 150 GeV has been used. Notice that this value represents the "running" top mass. The

observable mass is the "pole" mass: as mentioned in Table 7, $m_t^{pole} \approx 1.07\ m_t$. The dashed lines represent the present Kamiokande 90% C.L. experimental upper limits.

Figure 8. Same as Fig.7 but for the DILATON scenario.

Figure 9. The neutralino capture rate for the Sun and Earth as a function of the neutralino mass in the minimal SU(5) Supergravity model.

Figure 10. The upwardly-moving flux in underground detectors originating from neutralino annihilation in the Sun and Earth, as a function of the neutralino mass in the minimal SU(5) Supergravity model. The dashed lines represent the present Kamiokande 90% C.L. experimental upper limits.

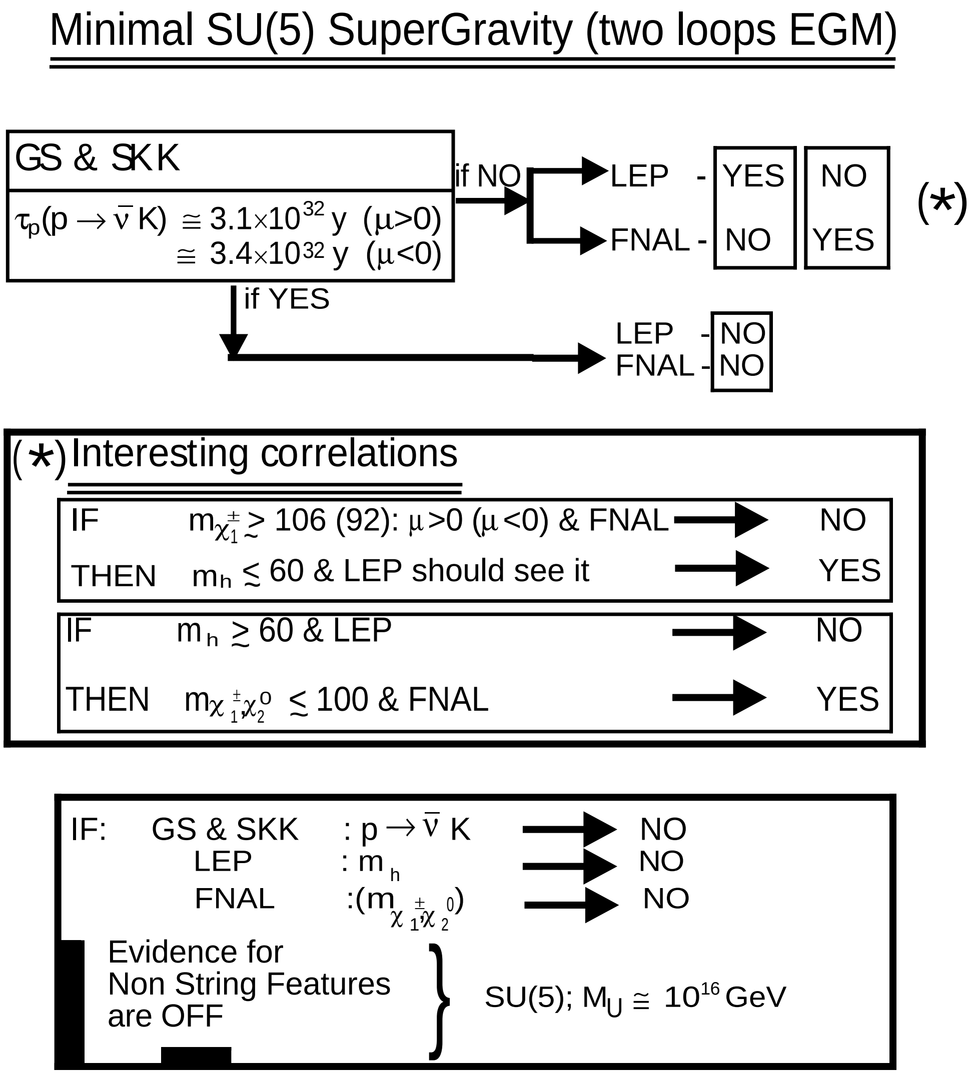
Figure 11. The allowed parameter space of the no-scale (MODULI scenario) SU(5)×U(1) Supergravity model (in the ($m_{\chi_1^\pm}$,tanβ) plane) after the present "neutrino telescopes" (NT) constraint has been applied. Two values of m_t (130, 150 GeV) have been chosen. The crosses denote those points which could be probed with an increase in sensitivity by a factor of 2.

Figure 12. Same as Fig.11 but for the DILATON scenario.

5 Conclusions

I- The two Supergravity models discussed have a great predictive power. For example SU(5) Supergravity (computed at the two loop level) can be put under precise definite experimental test, as reported in Table 9.

Table 9. Experimental checks for NON-STRING-FEATURES



II- Combining the results of underground and collider experiments it is possible to obtain significant tests of this class of models whose basic value is the very limited number of parameters needed. From four [m_0, $m_{1/2}$, A, (λ_Y,tanβ)] to one ($m_{1/2}$).

Examples of data from underground labs, once their sensitivity is increased as indicated (factor 12) are reported in Figs. 13-14 for negative μ, as the recent Fermi-Lab results would imply.

Figure 13. The allowed parameter space of the no-scale (MODULI scenario) SU(5)×U(1) Supergravity model for $\mu < 0$ and $m_t^{pole} = 160.5$ GeV, in the ($m_{\chi_1^\pm}$, tanβ) plane. The crosses denote those points which could be probed with an increase in NT sensitivity by a factor of 12.

Figure 14. Same as Fig. 13 but for the DILATON scenario.

III- Each single experiment by itself can limit the allowed parameter space; together they can test the validity of each model and disentangle SU(5) from SU(5)×U(1): thus allowing one day to distinguish between point-like and string-like physics.

Let me allow a remark from a very recent work of our group [24].

Figure 15. The number of allowed points in parameter space of no-scale SU(5)×U(1) Supergravity model in the MODULI and DILATON scenarios, as a function of m_t when the basic theoretical and experimental LEP constraints have been imposed ("theory+LEP"), and when all known direct and indirect experimental constraints have been additionally imposed ("All"). Note that $m_t \lesssim 180$ GeV is required.

On the basis of SU(5)×U(1) Supergravity, once all experimental data are taken into account, there are no points in the parameter space for $m_t > 180$ GeV as one can see in Fig. 15. The very recent Fermi-Lab results -if confirmed- are in excellent agreement with this "prediction" of SU(5)×U(1) Supergravity [24].

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