Supersymmetry Breaking and Dark Matter

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Outline

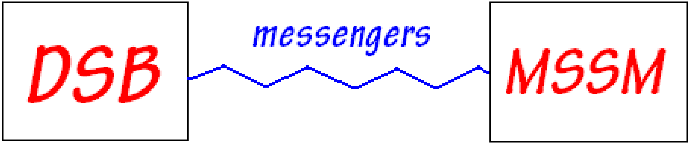
Attractive Features of Supersymmetry

- Resolution of the gauge hierarchy problem: the superpartners cancel the quadratic divergences in the theory.
- Unification of gauge couplings.
- Dark matter candidates.
- Seems to be required for the consistency of string theory.

Supersymmetry Breaking

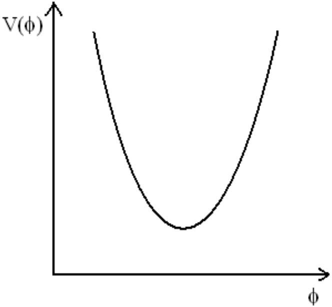
- Supersymmetry breaking cannot be done directly in MSSM (unlike a tree level Higgs mechanism for Electroweak symmetry breaking). There is a no go theorem : sum rules are violated.
- Dynamical supersymmetry breaking (DSB): involves an asymptotically free gauge force (in a hidden sector of the theory, *i.e.* outside the Standard Model) which becomes strong at low energies, and then non-perturbative effects trigger spontaneous supersymmetry breakdown.

Supersymmetry Breaking



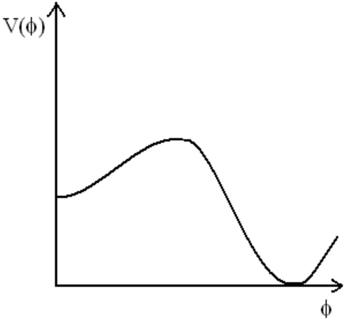
Metastable Supersymmetry Breaking

- It was presumed that DSB requires that the non-supersymmetric vacuum state of the hidden sector is the true vacuum, *i.e.* the global minimum of the effective potential.



Metastable Supersymmetry Breaking

- Intrilligator, Seiberg and Shih (ISS) proposed a simple DSB model in which the non-supersymmetric vacuum state is metastable with a very low tunneling rate to the true supersymmetric vacuum.



Direct Gauge Mediation

- The ISS model has a large unbroken flavor symmetry, which can be weakly gauged without spoiling the DSB mechanism.
- This makes it a convenient framework for a direct gauge mediation of supersymmetry breaking to the Standard Model.
- Some of the susy breaking sector particles are also charged under the Standard Model $SU(3) \times SU(2) \times U(1)$ gauge group, hence potentially visible.
- All the superpartners of Standard Model particles become massive via 1–loop and 2–loop diagrams, and their masses are calculable in terms of the susy breaking sector parameters.

Direct Gauge Mediation

In order to build a model of direct gauge mediation, one needs to overcome two features of the ISS model which are problematic for phenomenology :

- The presence of an accidental R-symmetry, that forbids the generation of gaugino masses.
- The spontaneous breaking of the flavor symmetry group, that introduces Goldstone bosons charged under the Standard Model gauge group.
- We will resolve both issues by breaking explicitly the R-symmetry and the flavor symmetry by mass terms that deform the ISS model.

Direct Gauge Mediation

We will present a construction with the following properties:

- The model is weakly coupled and calculable.
- The LSP gravitino is light ($m_{\frac{3}{2}} < 16\,\mathrm{eV}$), as required by the cosmological bounds (Viel et.al.).
- The MSSM spectrum is natural with a light Higgs.
- There is no tension between a long lifetime of the metastable vacuum and a large gaugino/scalar mass ratio, which typically leads to split supersymmetry.
- The supersymmetry breaking sector, which is usually hidden, is observable ($m \sim 1$ TeV). We discuss in detail its features, its production cross section at LHC and some of its decay channels.
- A UV completion in a quiver gauge theory.

Direct Gauge Mediation

We will present candidates for dark matter in models of gauge mediation based on metastable supersymmetry breaking.

- Such models typically contain classically flat directions, that receive one-loop masses of a few TeV. These pseudo-flat directions provide a new mechanism to account for the cold dark matter relic abundance (see also Shih).
- We also verify the possibility of heavy gravitino dark matter in such models (Pokorski).

The ISS Model

Consider the magnetic dual description of $\mathcal{N} = 1$ $SU(N_c)$ SQCD with N_f flavors, $N_c + 1 \leq N_f < \frac{3}{2} N_c$.

- The magnetic gauge group is $SU(N)$ ($N = N_f - N_c$) and we have N_f flavors of (magnetic) quarks and antiquarks $\tilde{q}^f$ and $q_{\tilde{f}}$, coupled to N_f^2 singlet chiral superfields $\Phi_f^{\tilde{f}}$, via the superpotential

$$W = h \mathrm{Tr}\, \tilde{q} \Phi q - h \mu^2 \mathrm{Tr}\, \Phi \qquad (1)$$

- The second term corresponds to the mass term of the electric quarks.
- This theory has a global $SU(N_f) \times U(1)_B \times U(1)_R$ symmetry, which is spontaneously broken to $SU(N)_{\mathrm{diag}} \times SU(N_f - N) \times U(1)_R$ in the ISS vacuum by the expectation value $\tilde{q} q = \mu^2 \mathbf{1_N}$.

Deformation of the ISS Model

- In order to avoid the Goldstone bosons, we explicitly break the global symmetry by splitting the fields as (Kitano, Ooguri and Ookouchi)

$$\Phi = \begin{pmatrix} Y_{IJ} & Z_{Ia} \\ \tilde{Z}_{aI} & \hat{\Phi}_{ab} \end{pmatrix}$$

$$q = \begin{pmatrix} \chi_{IJ} & \rho_{Ia} \end{pmatrix} \, , \quad \tilde{q}^t = \begin{pmatrix} \tilde{\chi}_{IJ} & \tilde{\rho}_{aI} \end{pmatrix} \tag{2}$$

$I, J = 1, \ldots, N_f - N_c \equiv N$, $a, b = 1, \ldots, N_f - N = N_c$.

- We split the linear term

$$-h\mu^2 \mathrm{Tr}\, \Phi \rightarrow -hm^2 \mathrm{Tr}\ Y - h\mu^2 \mathrm{Tr}\ \hat{\Phi}\ . \tag{3}$$

Metastability

- We will need to work in the regime of parameters $\mu < m$. This corresponds in the electric theory to having N_c light flavours $(\tilde{Q}_a, Q_a)$ and $N_f - N_c$ heavier ones $(\tilde{Q}_I, Q_I)$.
- It has been shown by Giveon et.al. that $SU(N_c)$ SQCD with a number of light flavors less than N_c does not have an ISS metastable vacuum, due to a two loop effect that destabilizes it. In our case the number of light flavors in the electric description is N_c and this two loop effect is absent.

R-Symmetry Breaking

- We break the R-symmetry explicitly by adding a mass term to the off diagonal components of the singlet $h^2 m_z \mathrm{Tr}\ \tilde{Z}Z$. This corresponds to a quartic coupling of the electric quarks $Tr(Q_a Q_l \tilde{Q}_a \tilde{Q}_l)$.
- The final superpotential reads

$$\begin{aligned} W = h\mathrm{Tr}\ &\left(\tilde{\chi} Y \chi + \tilde{\rho} Z \chi + \tilde{\chi} \tilde{Z} \rho + \tilde{\rho} \hat{\Phi} \rho\right) \\ &- hm^2 \mathrm{Tr}\ Y - h\mu^2 \mathrm{Tr}\ \hat{\Phi} + h^2 m_z \mathrm{Tr}\ \tilde{Z} Z \end{aligned} \tag{4}$$

- We will use this model for a direct mediation of supersymmetry breaking and analyze its phenomenological features.

The Model Parameters

- The relevant parameters are the dimensionless coupling h, the dimension one mass parameters (μ, m, m_z) and the dimension one magnetic scale Λ_m.
- At energies $E < \Lambda_m$ we have the weakly coupled magnetic description with a canonical Kahler potential and at $E > \Lambda_m$ we have an electric description. At certain higher energies we need UV completion.
- We will constrain the parameters by consistency and experimental requirements.

Non-Genericity

- The mass term $h^2 m_z \mathrm{Tr}\, \tilde{Z} Z$ breaks R-symmetry, thus allowing gaugino masses. Nelson and Seiberg: Generically, such a breaking creates new supersymmetric vacua and the longevity of the metastable vacuum requires small gaugino masses compared to the scalar masses (split supersymmetry).
- The superpotential (4) is not generic, i.e. a generic one would include also quadratic and cubic terms in $\hat{\Phi}$, and it does not introduce new supersymmetric vacua.

Gaugino Masses

- Even when R-symmetry is explicitly broken, the gaugino masses remain generically anomalously small (vanish at leading order in susy breaking) relative to the soft scalar masses.
- In order to avoid this one needs a SUSY-breaking metastable vacuum, which is part of an approximate pseudo-moduli space, along which some messengers are unstable at some other point (Komargodski and Shih).

Longevity and Split Supersymmetry

- The dimensionless parameter $\frac{m_z}{m}$ controls the split between the gaugino and squarks masses.
- The longevity of the metastable vacuum is controlled by $\frac{\mu}{m}$.
- Having two parameters will allow us to avoid split susperymmetry, while maintaining longevity.

Classical vacua

- The model does not have classical supersymmetric vacua, but only supersymmetry breaking ones.
- The ISS vacuum :

$$\chi_{IJ} = m\,\delta_{IJ}\,, \quad \tilde{\chi}_{IJ} = m\,\delta_{IJ} \tag{5}$$

  and all other fields in (4) have zero vev. $\hat{\Phi}$ is a pseudomodulus. This is the vacuum on which we will base the analysis.
- The classical vacuum energy is

$$V = V_{ISS} = (N_f - N)|h\mu^2|^2 \tag{6}$$

- At one loop, a potential for the pseudomodulus is generated that gives a mass and an expectation value to $\hat{\Phi}$.

Classical vacua

- N additional supersymmetry breaking vacua

$$\begin{aligned} \rho = \tilde{\rho}^t = & \quad \mu \mathbb{1}_n \,, \\ Z^t = \tilde{Z} = & \quad -\frac{\mu m}{h m_z} \mathbb{1}_n \,, \\ Y = \frac{\mu^2}{h m_z} \mathbb{1}_N \,, & \quad \hat{\Phi} = \frac{m^2}{h m_z} \mathbb{1}_n \,, \end{aligned} \tag{7}$$

  with classical vacuum energy

$$V_n = (N_f - N - n)|h\mu^2|^2, \quad n = 1, \ldots, N \tag{8}$$

- Nonperturbatively, a dynamical superpotential is generated, which introduces supersymmetric vacua related to gaugino condensation in the $SU(N)$ gauge group. These extra vacua are very far in the $\hat{\Phi}$ field direction.

Direct mediation of supersymmetry breaking

- In order to build a model for direct mediation of supersymmetry breaking, we embed the Standard Model gauge group in the global symmetry group $SU(N) \times SU(N_f - N)$, i.e. we get the Standard Model gauge group by gauging a subgroup of the flavor symmetry group.
- We embed the MSSM gauge group in the unbroken flavor symmetry group $SU(N_f - N)$ and require $N_f - N \geq 5$. In the analysis we will take $N_f = 6, N = 1$, and we will use the metastable vacuum (5).

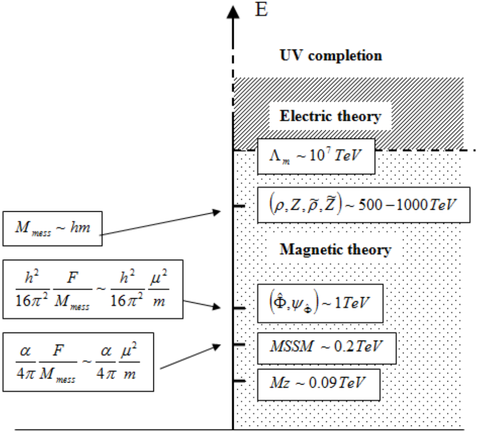
Direct mediation of supersymmetry breaking

- The superpotential around this vacuum takes the form

$$W = h\mathrm{Tr}\left(\tilde{\rho}Z\chi + \tilde{\chi}\tilde{Z}\rho + \tilde{\rho}\hat{\Phi}\rho + m\tilde{\rho}Z + m\tilde{Z}\rho - \mu^2\hat{\Phi} + hm_z\tilde{Z}Z\right)$$

  where we shifted $\chi \to m + \chi$ and $\tilde{\chi} \to m + \tilde{\chi}$ and we omitted the terms involving Y, which are not relevant for the rest of the discussion.
- The messenger fields are $\{\rho, \tilde{\rho}, Z, \tilde{Z}\}$, and they couple through the superpotential to $\hat{\Phi}$ whose F-term $F_{\hat{\Phi}}$ breaks supersymmetry.
- $\{\rho, \tilde{\rho}, Z, \tilde{Z}\}$ and $\hat{\Phi}$ are charged under the MSSM gauge group and couple to the MSSM fields through gauge interactions.

The various scales



E

UV completion

Electric theory

$\Lambda_m \sim 10^7\, TeV$

$\left(\rho, Z, \tilde{\rho}, \tilde{Z}\right) \sim 500 - 1000\, TeV$

Magnetic theory

$\left(\hat{\Phi}, \psi_{\hat{\Phi}}\right) \sim 1\, TeV$

$MSSM \sim 0.2\, TeV$

$Mz \sim 0.09\, TeV$

$M_{mess} \sim hm$

$\frac{h^2}{16\pi^2}\frac{F}{M_{mess}} \sim \frac{h^2}{16\pi^2}\frac{\mu^2}{m}$

$\frac{\alpha}{4\pi}\frac{F}{M_{mess}} \sim \frac{\alpha}{4\pi}\frac{\mu^2}{m}$

Constraints on the parameter space

- $\frac{h}{4\pi}$ is used for a perturbative expansion, therefore we require that h is at most $\sim O(1)$. From the LEP bound on the Higgs mass we find that $h > 1$.
- The gravitino has to be light in order to be consistent with cosmological bounds

$$m_{\frac{3}{2}} = \frac{F}{\sqrt{3}M_{Pl}} < 16eV \tag{10}$$

This can be translated into a constraint on h and μ:

$$h\mu^2 = \frac{F}{N_f - N} < (150\mathrm{TeV})^2 \tag{11}$$

Constraints on the parameter space

- The ratio $\frac{\mu}{m}$ controls the longevity of the metastable vacuum and we get an upper bound $\frac{\mu}{m} < \frac{1}{5}$.
- The ratio $\frac{\mu^2}{m}$ determines the soft supersymmetry breaking terms (m controls the messenger masses while μ controls the supersymmetry breaking scale) and is therefore constrained from below by bounds from the MSSM spectrum.
- m_z controls the R-symmetry breaking, allowing gaugino masses.
- The dimensionless parameter $\frac{m_z}{m}$ controls the split between the gaugino and squarks masses, i.e. for $\frac{m_z}{m} \sim 1$ we avoid split supersymmetry.

Constraints on the parameter space

- In order to avoid tachyonic messengers we require

$$|m^2 \pm h m_z \hat{\Phi}_0|^2 > \mu^2(m^2 + h^2 m_z^2) \qquad (12)$$

  This can be translated to constraints on m_z.
- The scale Λ_m is the scale at which the weakly coupled magnetic description (4) breaks down: at energies $E > \Lambda_m$ we have an electric description.
- Nonpertubative effects restore supersymmetry at large values of $\hat{\Phi}$. To suppress the decay to this true vacuum it is sufficient that $\Lambda_m/m > 5$.
- Requiring that the full messenger spectrum lies below the cutoff scale, we need approximately $\Lambda_m/m > 10$.

Constraints on the parameter space

We are thus lead to a relatively small range in parameter space. Compiling all the above considerations leads to a representative set of values for the input parameters:

$$h \sim 2, \quad \mu \sim 100\,\mathrm{TeV}, \quad m \sim 500\,\mathrm{TeV}, \quad \Lambda_m > 5000\,\mathrm{TeV}, \\ m_z < 220\,\mathrm{TeV} \quad \mathrm{or} \quad 330\,\mathrm{TeV} < m_z < 650\,\mathrm{TeV} \tag{13}$$

Other values of h in its allowed range will also lead to reasonable phenomenology with similar features.

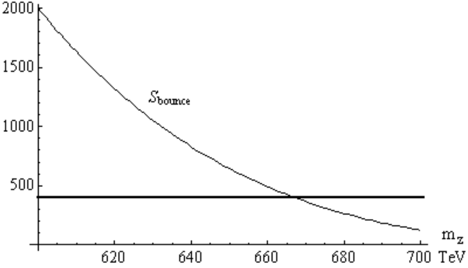
Longevity

- The ISS vacuum can decay either to the closest metastable vacua (7) or to the supersymmetric vacuum.
- In order to have a long lifetime we require that the euclidean bounce action S_{bounce} for the decay from the ISS into another vacuum is

$$S_{bounce} > 400 \tag{14}$$

The bounce action

- Numerical evaluation of the bounce action for the decay to the closest vacuum as a function of m_Z.



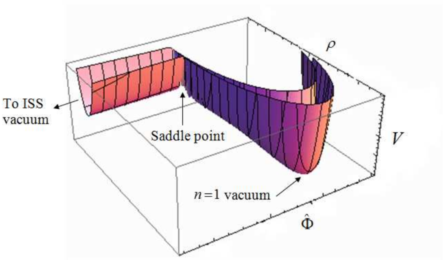
Longevity

- For the decay to the supersymmetric vacuum we have

$$S_{bounce} \sim \left(\frac{m}{\mu}\right)^4 \left(\frac{\Lambda_m}{m}\right)^{\frac{4(N_f-3N)}{N_f-N}} \tag{15}$$

The effective potential

- The effective potential for a real slice of the potential $V_{eff}(\hat{\Phi})$ for the $\hat{\Phi}$ bounce trajectory. The plot is evaluated at $m_Z = 150\,\mathrm{TeV}$.



Gaugino and squarks masses

- The gaugino masses are

$$\begin{aligned} m_r &= \tfrac{\alpha_r}{4\pi} F_{\hat{\Phi}} \partial_{\hat{\Phi}} \det \log \mathcal{M} \\ &= \tfrac{\alpha_r}{4\pi} F_{\hat{\Phi}} \sum_{\pm} \frac{\partial_{\hat{\Phi}} \mathcal{M}_{\pm}}{\mathcal{M}_{\pm}} \end{aligned} \tag{16}$$

- $\mathcal{M}$ is the superpotential mass matrix

$$\mathcal{M} = \begin{pmatrix} h\hat{\Phi}_0 & hm \\ hm & h^2 m_z \end{pmatrix}$$

and $\mathcal{M}_{\pm}$ its eigenvalues

$$\mathcal{M}_{\pm} = \left| \frac{1}{2} h \left(hm_z + \hat{\Phi}_0 \pm \sqrt{4m^2 + (-hm_z + \hat{\Phi}_0)^2} \right) \right| \tag{17}$$

Gaugino and squarks masses

- The final expression reads

$$\begin{aligned} m_r &= \frac{\alpha_r}{4\pi}\Lambda_g \ , \\ \Lambda_g &= N\,\frac{h^2\mu^2 m_z}{m^2 - h\hat{\Phi}_0 m_z} \end{aligned} \qquad (18)$$

- The scalar masses are given by

$$\begin{aligned} m^2_{\tilde{f}} &= \sum_{r=1}^{3} 2C^r_{\tilde{f}}\left(\frac{\alpha_r}{4\pi}\right)^2 \Lambda^2_S \ , \\ \Lambda^2_S &= \frac{1}{2}N|F_{\hat{\Phi}}|^2 \frac{\partial^2}{\partial\hat{\Phi}\partial\hat{\Phi}^\dagger}\sum_{\pm}\left(\log|\mathcal{M}_\pm|^2\right)^2 \ , \\ &= N|F_{\hat{\Phi}}|^2\sum_{\pm}\left|\frac{\partial_{\hat{\Phi}}\mathcal{M}_\pm}{\mathcal{M}_\pm}\right|^2 \end{aligned} \qquad (19)$$

Gaugino and squarks masses

- The gaugino masses and the scalar masses share the same dependence on the small parameter μ/m, which is the one that controls the longevity of the vacua and the breaking of supersymmetry.
- The gaugino mass depends on the parameter m_z/m, which is unrelated to the longevity of the vacuum. Hence, in the vacuum (5), we can relax the tension between having a long lived metastable vacuum and large gaugino masses, thus avoiding a split supersymmetry spectrum.

Gaugino and squarks masses

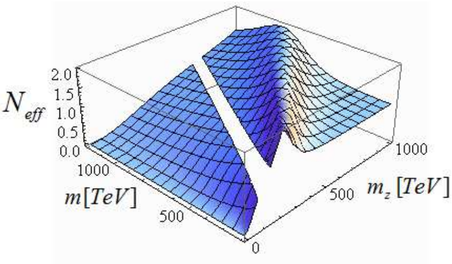
- In ordinary gauge mediation models the number of messengers is the ratio $N_{mess} = \Lambda_g^2/\Lambda_s^2$. This is not the case in our model, and we can define an effective messenger number

$$N_{eff}(m_z) = \Lambda_g^2/\Lambda_s^2 \tag{20}$$

- By varying continuously $\frac{m_z}{m}$, inside the region allowed by the phenomenological constraints, N_{eff} varies between zero and two (the number of messengers).

Gaugino and squarks masses

- The effective number of messengers as a function of $\frac{m_z}{m}$ varies between zero and two. The plot is disconnected in the regime where m_z is not allowed.



The Gravitino

- The LSP in the model is the gravitino. A decay of an NLSP $\tilde{\chi}$ to the LSP gravitino and a Standard Model particle, $\tilde{\chi} \to SM + \tilde{G}$ is characterized by a decay rate $\Gamma \sim \frac{m_{\tilde{\chi}}^5}{16\pi F^2}$, yielding a life time $\tau \sim 10^{-12} sec$ and is observable in LHC ("displaced" secondary vertex).

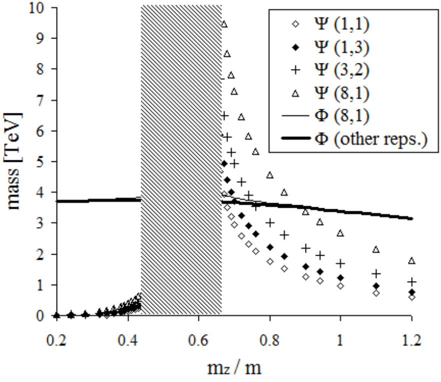
A visible supersymmetry breaking sector

- An important prediction of our model of direct mediation is the presence of light particles coming from the supersymmetry breaking sector. They carry MSSM quantum numbers.
- In our model it is the traceless part of the chiral superfield $\hat{\Phi}$, in the adjoint representation of $SU(5)$, which decomposes in the following way under $SU(3) \times SU(2)_L \times U(1)_Y$: $\mathbf{24} = (\mathbf{8}, \mathbf{1})_0 \oplus (\mathbf{1}, \mathbf{3})_0 \oplus (\mathbf{3}, \mathbf{2})_{-5/6} \oplus (\mathbf{3}, \mathbf{2})_{5/6} \oplus (\mathbf{1}, \mathbf{1})_0$
- $\hat{\Phi}$ decomposes as

$$\begin{aligned} \hat{\Phi} &= \quad \varphi_8 \oplus \varphi_3 \oplus \tilde{p} \oplus \tilde{p}' \oplus S \;, \\ \psi_{\hat{\Phi}} &= \Psi_8 \oplus \Psi_3 \oplus \Psi_{\tilde{p}} \oplus \Psi'_{\tilde{p}} \oplus \Psi_S \end{aligned} \tag{21}$$

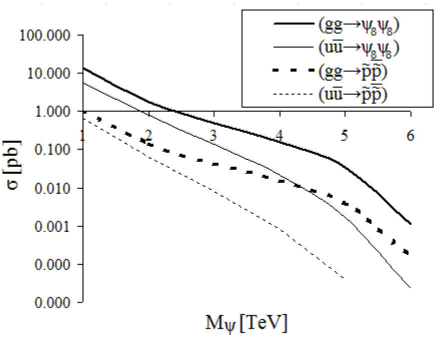
A visible supersymmetry breaking sector

- The masses of the visible fields from the supersymmetry breaking sector:



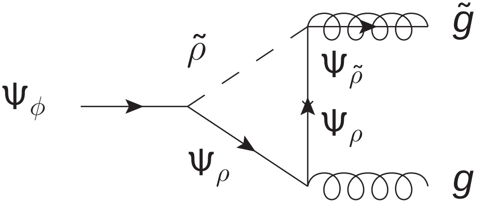
Production of the supersymmetry breaking sector

- The cross section for production of supersymmetry breaking sector colored particles in the LHC as a function of their mass:



Decay of the supersymmetry breaking sector

- The leading decay channel of such particle is $\Psi_8 \rightarrow \tilde{g}g$, namely it decays into a gluon and a gluino, through the effective vertex



Detailed MSSM spectrum

- The low energy spectrum of the theory is calculated using a modified version of SoftSUSY 2.0. The modifications allow introduction of multiple messenger scales, adjustment of the MSSM β functions to include the contribution of the light fields in the supersymmetry breaking sector ($\hat{\Phi}$), and they also enable running of the $\hat{\Phi}$ masses.
- The seemingly large parameter space of the model is restricted to a narrow window by theoretical and phenomenological constraints. We chose to focus on the following set of parameters:

$$h = 2\,, \quad \mu = 100\,\mathrm{TeV}\,, \quad m = 500\,\mathrm{TeV}\,, 0.2 < mz/m < 1.2 \qquad (22)$$

Detailed MSSM spectrum

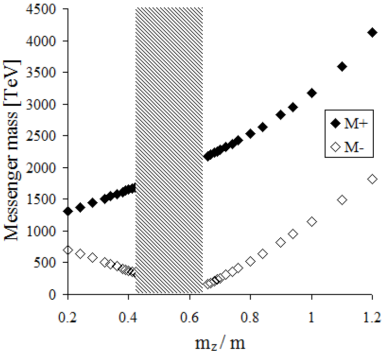
- The remaining parameter in the theory, Λ_m, does not affect the low energy spectrum.
- In addition to the parameters of the supersymmetry breaking sector, there are two more degrees of freedom introduced by the EWSB sector in the MSSM, for which we took the following values:

$$5 < \tan\beta < 35\ , \quad sgn(\mu) = \pm 1$$

$$\tan\beta \equiv \frac{\langle H_u^0\rangle >}{\langle H_d^0\rangle >} \qquad W_{MSSM} = \mu H_u H_d \tag{23}$$

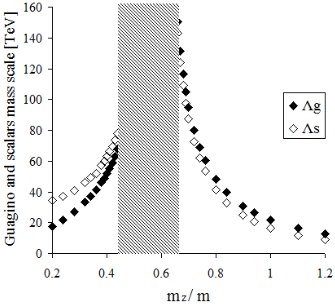
The messenger mass

- The messenger mass as a function of m_z/m. In marked area the light messenger is too light or tachyonic, hence we exclude it.



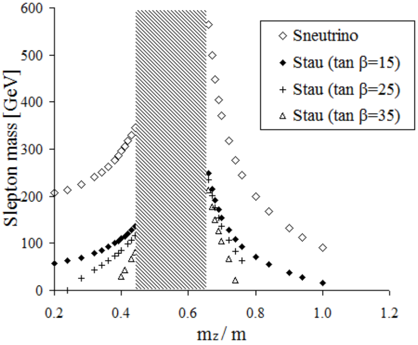
The soft supersymmetry breaking mass scales

- The soft supersymmetry breaking mass scales, Λ_s and Λ_g as a function of m_z/m. Largest values are obtained close to the light messenger region.



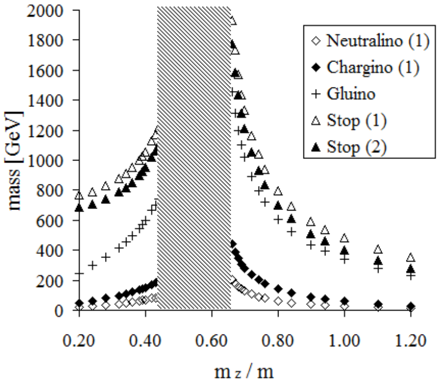
The sparticle masses

- The slepton masses as a function of m_z/m. The stau mass is very sensitive to $\tan\beta$. The sneutrino becomes tachyonic at $m_z/m > 1.2$.



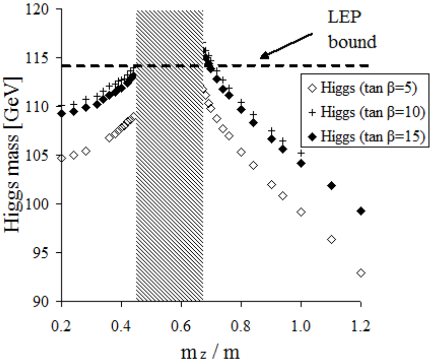
The sparticle masses

- Masses of several sparticles in the spectrum as a function of m_z/m.



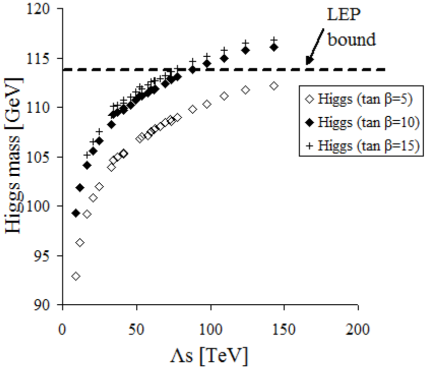
The Higgs mass

- The Higgs mass as a function of m_z/m: The LEP bound rules out a large region of parameter space.



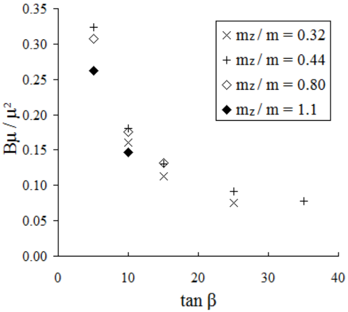
The Higgs mass

- The Higgs mass as a function of Λ_S.



The $B\mu/\mu$ problem

- The couplings of the Higgs mixing terms, μ and $B\mu$, are determined by the values of the Z boson mass and $\tan\beta$.
- $B\mu/\mu^2$ as a function of $\tan\beta$ for several values of $\frac{m_Z}{m}$:



Varying the Parameters

- Varying the parameters, for instance by taking a different Yukawa within the range $1 < h < 2$, leads to similar spectra.
- The main difference is the lower masses of the Ψ_Φ fermions. In the range where the Higgs mass satisfies the LEP bound, these masses remain above 1 TeV.
- By decreasing h, the constraints on the values of m_z change: the excluded window where the light messenger becomes tachyonic moves to larger values of m_z.

A brief summary

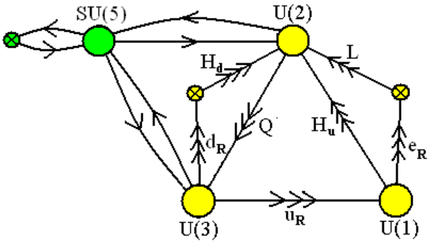
- The LSP is a light gravitino ($<$ 16 eV).
- The NLSP is usualy a Bino like neutralino (20–200 GeV). For large tan β the NLSP can be a stau.
- Visible supersymmetry breaking sector $m \sim 1 - 10 TeV$.
- Light Higgs mass: The Higgs mass is in the range $100 - 117$ GeV. The LEP bound rules out a large part of parameter space.
- Gaugino/scalar mass ratio $N_{eff} \sim 1$ is preferred by the Higgs mass constraint.

UV completion

- In models of direct mediation in which the supersymmetry breaking sector is a deformation of ISS there is a tension between a light gravitino with $m_{\frac{3}{2}} < 16$ eV and gauge coupling unification.
- To satisfy the first requirement, one needs a supersymmetry breaking scale below a hundred TeV.
- On the other hand, the supersymmetry breaking sector contains a large number of fields, charged under the MSSM gauge groups, which drive the running couplings towards a Landau pole before reaching unification.
- This happens in our model as well.

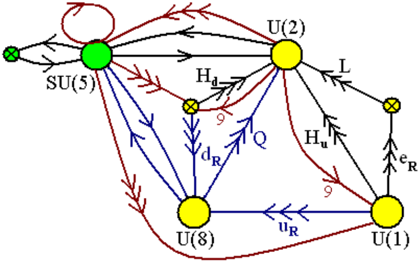
UV completion

- We will consider a UV completion in terms of a duality cascade.
- Embedding of the MSSM (yellow) coupled to the supersymmetry breaking sector (green) into a minimal quiver



UV completion

- The first step of the cascade, after dualizing the QCD node of the MSSM from $SU(3)$ to $SU(8)$ (in red). Dual mesons are red, dual quarks blue



Gravitino Dark Matter

- In theories of gauge mediated supersymmetry breaking the gravitino LSP is light (with mass in the eV to GeV range), due to the low scale of supersymmetry breaking. This leaves a narrow window to realize the gravitino dark matter (the so called sweet spot of $\mathcal{O}(1)$ GeV (Ibe and Kitano)).
- This can be accomodated consistently in our model: $h \sim 2, m \sim 10^{10} TeV, \mu \sim 10^{6} TeV, m_z \sim 10^{10} TeV$.
- Still, this poses a problem of identifying alternative possibilities for cold dark matter.

Cold Dark Matter

- A successful strategy assumes that the supersymmetry breaking sector is strongly coupled and hidden sector baryons or mesons, of mass larger than the TeV scale, provide the cold dark matter (Dimopoulos, Giudice and Pomarol).
- In metastable supersymmetry breaking models there is no strong dynamics that can lead to a composite hidden sector hadron responsible for the cold dark matter; hence the necessity to look for alternative weakly coupled candidates for cold dark matter.

Pseudo-flat Cold Dark Matter

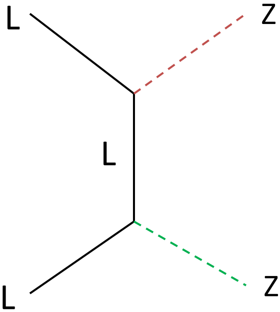
- The pseudo-flat directions are classically flat directions, that receive mass at one-loop upon supersymmetry breaking
$$m_L^2 \sim \frac{\alpha_h}{4\pi}\Lambda^2 \ ,$$
where $\alpha_h = h^2/4\pi$ is some small Yukawa interaction in the hidden sector and we denote by L such light fields.
- These fields may be stable or cosmologically long lived (lifetime $> 10^{26}$ sec), with masses typically in the range of a few TeV and they generate a relic density abundance roughly given by
$$\Omega h^2 \simeq \left(\frac{10^{-10} GeV^{-2}}{\langle\sigma|v|\rangle}\right) \ .$$

Pseudo-flat Cold Dark Matter

- They may provide therefore the correct dark matter relic abundance $\Omega h^2 \sim 0.1$, depending on their (velocity averaged) total annihilation cross section $\langle\sigma|v|\rangle$. The limit on the cross section for them to be not over-abundant is then
$$\langle\sigma|v|\rangle \gtrsim 10^{-9} - 10^{-10}\ \mathrm{GeV}^{-2}\ .$$
- Indeed in some cases they can be viable cold dark matter candidates.

Pseudo-flat Cold Dark Matter as WIMP

- If are charged under the SM gauge group, then the leading interaction with the MSSM is at tree-level



Example: Pseudo-flat Cold Dark Matter as WIMP

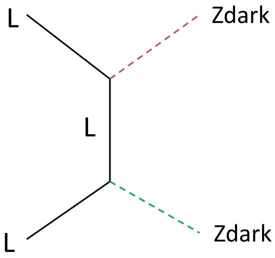
- The cross section is given by

$$\langle\sigma|v|\rangle \sim \frac{\pi\alpha_{SM}^2}{m_L^2} \sim 10^{-3}\cdot m_L^{-2} \tag{24}$$

- Therefore with a particle of mass $\sim$ 1 TeV satisfies we can get a viable dark matter candidate – a WIMP.
- Note that larger masses will lead to over-abundance.

Example: Hidden Gauge Bosons

- The hidden sector might contain Higgsed gauge bosons with mass m_D and strength $\alpha_D = g_D^2/4\pi$. If the light fields L are charged under this gauge symmetry, they can annihilate into gauge bosons via tree-level diagrams.



Pseudo-flat Cold Dark Matter

- The annihilation cross section will be

$$\langle \sigma |v| \rangle \sim \frac{\pi \alpha_D^2}{m_L^2} \ . \tag{25}$$

- The parameters can easily be set to satisfy the relic abundance condition, e.g.

$$\alpha_D \sim 1/100 \ , \qquad m_L \sim 1 - 10 \ \mathrm{TeV} \ . \tag{26}$$

- The dark gauge boson mass needs to be lower than the light field mass $m_D \lesssim m_L$ for this scenario to be realized.

Outlook

- We presented a detailed phenomenology of direct gauge mediation using a deformation of the ISS vacuum, with explicitly broken R-symmetry.
- One of the aims of this model has been to show that it is indeed possible to obtain a natural MSSM spectrum from a metastable vacuum.
- We found new interesting distinctive signatures of this model: an ultralight gravitino; a light susy breaking sector, which might be accessible at LHC energies.
- We proposed a UV completion in terms of a duality cascade that will eventually lead to a full string theory description presumably below the GUT scale.

Outlook

- We considered candidates for dark matter in models of gauge mediated supersymmetry breaking, in which the supersymmetry breaking sector is weakly coupled and calculable. Such models typically contain classically flat directions, that receive one-loop masses of a few TeV. These pseudo-flat directions provide a new mechanism to account for the cold dark matter relic abundance.
- We considered the possibility of heavy gravitino dark matter in such models.