Gravitino Dark Matter confronts LHC

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Abstract. We review the scenario of gravitino LSP and Dark Matter and its cosmological constraints both in the case of R-parity conservation and R-parity violation. We discuss the possible signals and compare with the recent LHC results.

1. Introduction
Dark Matter is surely one of the stronger indications for physics beyond the Standard Model and its identification within the particle zoo is still an open question for both cosmology and particle physics. Indeed from astrophysical and cosmological observations, we have a very clear idea of the Dark Matter density (the most recent WMAP determination is $\Omega_{CDM} h^2 = 0.1126 \pm 0.0036$ [1]) and what it is not: not baryonic, not made of Massive Compact Halo Objects or Hot Dark Matter (and therefore the only neutral massive SM particles, the neutrinos are unfortunately excluded...), not collisional, possibly only interacting gravitationally, but maybe also participating in the weak interaction [2].

Since most Dark Matter candidates "looks" the same from the cosmological point of view (all sufficiently non-relativistic particles are just matter for a cosmologist !), one way to select a Dark Matter particles is theoretical prejudice based on the well-trodden path of an enhanced symmetry. In that respect the leading candidate for enlarging the Standard Model symmetries is supersymmetry, the maximal extension of the Poincaré symmetry. Supersymmetry, especially in its low-energy version, has also other important theoretical advantages since it stabilized the electroweak scale, it can give rise even to radiative symmetry breaking and allows for the possibility of Grand Unification. Still, even within "minimal" Supersymmetry many different Dark Matter candidates are present, i.e. all the superpartners of neutral SM particles like the sneutrino, the neutralino and also the gravitino. The gravitino is often not considered in the supersymmetric phenomenology since gravity is usually neglected: indeed the gravitino is the superpartner of the graviton and appears inevitably in any supersymmetrization of gravity (for an introduction to supersymmetry and supergravity see [3] ). It has both Lorentz and spinor indices, corresponding to a spin 3/2 particle, and is in some sense the gauge field of local supersymmetry and it becomes massive as soon as supersymmetry is broken by absorbing the Goldstino field. Observing the gravitino would therefore be for supergravity the equivalent of the observation of the $W^\pm$ boson for the electroweak symmetry. Due to such particular nature, the interactions of the gravitino are completely fixed by supersymmetry and since it belong to the gravity sector all couplings are suppressed by the Planck scale.

Gravitinos are often a nuisance in cosmology, since if they are not the LSP and therefore unstable towards a decay into a lighter superparticle, their lifetime is naturally long on
cosmological scales, due to the Planck scale suppression. If the gravitinos are not sufficiently heavy, i.e. well beyond 30 TeV, they decay during or after Big Bang Nucleosynthesis (BBN) giving rise to the famous "gravitino problem" \cite{4; 5}. In that case, in order to reduce the damage, the gravitino density has to be small enough at the cost of an upper bound on the reheat temperature of the Universe (see e.g. \cite{6}). On the other hand, if gravitinos are the LSP, they can be very good Dark Matter candidates, either as stable particles or as metastable particles with lifetime much longer than the age of the Universe. Then gravitino Dark Matter can be in some cases compatible with thermal leptogenesis (for a review see \cite{7}), a mechanism for baryogenesis that in the simplest realization requires reheat temperatures above $10^{9}$ GeV \cite{7; 8}. We will discuss in the following different scenarios for gravitino Dark Matter with and without R-parity breaking and their phenomenology at the LHC.

2. Gravitinos as Dark Matter
Gravitinos were the first supersymmetric Dark Matter candidates ever proposed: they were discussed in a paper by Pagels & Primack \cite{9} as relativistic thermal relics whose energy density is given by \cite{1}

$$\Omega_{3/2}h^2 \sim 0.1 \left( \frac{m_{3/2}}{0.1\text{keV}} \right) \left( \frac{g_*}{106.75} \right)^{-1}$$

where $m_{3/2}$ is the gravitino mass and $g_*$ is the effective number of degrees of freedom thermalized at the time of gravitino decoupling. We see that in this case to have the right energy density gravitinos have to be light and therefore they are Warm/Hot Dark Matter and excluded by structure formation.

To be a Cold Dark Matter (CDM) candidate, the gravitinos must be heavier and then their number density smaller than the equilibrium density. Scattering processes in the primordial plasma can produce a sufficiently large gravitino population for gravitino CDM. Such scatterings are mediated by non-renormalizable interactions, in particular dimension 5 operators involving the gauge interactions.

Then the gravitino energy density can be computed by integrating a Boltzmann equation without back-reaction and it turns out to be proportional to the reheat temperature due to the non-renormalization nature of the interaction. Different groups \cite{10–12} have computed the production rate for gravitinos including one-loop HTML resummation and thermal corrections. Assuming that the Goldstino component dominates the production, i.e. when the gravitino is sufficiently lighter than the other superpartners, the energy density of gravitinos is given by

$$\Omega_{3/2}h^2 \sim 0.3 \left( \frac{m_{3/2}}{1\text{GeV}} \right)^{-1} \left( \frac{T_{RH}}{10^{10}\text{GeV}} \right) \sum_i c_i \left( \frac{M_i}{100\text{GeV}} \right)^2$$

where $c_i$ are coefficients of order 1 and $M_i$ denote the three gaugino masses at EW temperature (RGE effects to $T_{RH}$ can be included in the coefficients $c_i$).

We see then that the Dark Matter density is set by the model parameters (i.e. the sparticle masses) and the reheat temperature of the universe $T_{RH}$. It is therefore possible to arrange for the right density by setting such temperature, e.g. from a particular inflationary model and reheating dynamics. A large reheat temperature around $10^{10}$ GeV is possible only for gravitino masses above approximately 1-10 GeV and in general an upper bound on $T_{RH}$ is obtained to avoid overclosure.

\textsuperscript{1} We give energy densities as a function of the critical energy density $\rho_c$, i.e. as $\Omega h^2 = \rho h^2 / \rho_c$. $\Omega h^2$ corresponds to a density in units of $1.05 \times 10^{-5}$ GeV cm$^{-3}$. 
Note that another population of gravitinos is generated by the decay of the NLSP out of equilibrium in the SuperWIMP mechanism [13; 14], as

$$\Omega_{\tilde{3}/2} h^2 = \frac{m_{\tilde{3}/2}}{m_{WIMP}} \Omega_{WIMP} h^2$$

where we are assuming the NLSP to be a WIMP particle [15]. But if such decay happens during or after BBN, the energy density of the NLSP is very strongly constrained by BBN [16]. Then it has often to be smaller than the present DM density and therefore this gravitino population is effectively negligible.

3. Stable gravitino CDM

In the case of R-parity conservation, the gravitino LSP is stable, and the NLSP decays into gravitinos and Standard Model particles with a very long lifetime. For the case of a Bino NLSP one has simply

$$\tau_{\tilde{B}} = \frac{5.7 \times 10^6}{m_{\tilde{B}}/100 GeV} \left( \frac{m_{\tilde{3}/2}}{10 GeV} \right)^2 s$$

This means that the decay takes place after BBN has already started, apart if the Bino is sufficiently heavy: $\tau_{\tilde{B}} < 0.1$ s requires

$$m_{\tilde{B}} \geq 3.6 \text{ TeV} \left( \frac{m_{\tilde{3}/2}}{10 GeV} \right)^{2/5}$$

well beyond the reach of the LHC if the gravitino is not much lighter than 10 GeV. For longer lifetimes, one has to take into account the different BBN constraints [16], depending on the branching ratios of the neutralino and the energy released in electromagnetic or hadronic showers. We will discuss here only the case of a general neutralino NLSP and comment on the case of a colored NLSP like the stop or the gluino.

The neutralino NLSP number density at freeze-out in the CMSSM is quite large and therefore most parameter space is excluded, as it has been found by different groups [17; 18]. We recently considered the bounds for a general neutralino NLSP in [19], computing the neutralino branching ratio into hadrons and comparing with the bounds for neutral relics in [20]. We found that even if it possible to suppress the hadronic branching ratio tuning the neutralino composition, this does not allow to relax the bounds very much and so only very special cases are still allowed. For example for a neutralino with substantial Higgsino component the energy density can be sufficiently reduced by resonant annihilation or in the case of a very light Wino, the hadronic branching ratio is small enough due to phase-space suppression.

Another mechanism that helps bypassing the bounds and allows also to keep the reheat temperature as small as possible, is to consider the case of quasi-degenerate gauginos [21]. Then in fact the efficient coannihilation between neutralino and gluino reduces the neutralino density by more than three orders of magnitude. Including as well the Sommerfeld enhancement gains approximately four orders of magnitude suppression at the cost of a mass degeneracy of the order of few percent. These scenarios with very compressed spectrum are a challenge for the LHC, since very soft particles are produced in the chain decays.

Since the lower the NLSP number density the weaker the constraints, it may seem a good idea to select a colored NLSP instead of the neutralino. Unfortunately the BBN bounds on colored relics are much stronger than those for charged or neutral particles due to bound state effects that modify strongly the rates of the nuclear processes during BBN. Such constraints have been computed by [22] and they approximately exclude NLSP lifetimes longer than $\sim 100$ s. Even increasing the colored state annihilation cross-section including the Sommerfeld effect does not relax those bounds substantially since the curves are very steep in the number density.
The only other way to relax the bound is to consider a sufficiently heavy NLSP so that the decay happens early enough. For the stop NLSP, considering as dominant decay channel the one to top and gravitino, we obtain

\[ m_{\tilde{t}} \geq 1 \text{ TeV} \left( \frac{m_{3/2}}{10 \text{ GeV}} \right)^{2/5}. \]  

A slightly weaker bound can be obtained for the gluino NLSP, which annihilates a bit more efficiently.

### 4. Unstable gravitino CDM

Another simple way to satisfy the BBN constraints is to break R-parity and allow the NLSP to decay only to SM particles (long) before BBN [23]. Note that the gravitino is a good Dark Matter candidate also for broken R-parity, as long as the breaking is sufficiently small. In fact the gravitino decay rate is suppressed both by the Planck mass and by the small R-parity breaking coupling and so can be naturally many orders of magnitude longer than the age of the Universe.

The requirement for the NLSP to decay early enough and for the lepton- or baryon-violating processes connected to R-parity violation not to be in equilibrium at the same time as the sphaleron processes [24; 25], singles out a particular window in the range of couplings:

\[ 10^{-12} \leq \lambda \leq 10^{-7} \]  

where \( \lambda \) is a generic R-parity breaking coupling. Of course once R-parity is broken, the danger of too fast proton decay reappears in the MSSM, but it can be avoided if e.g. only the lepton flavour violating couplings are switched on.

The general R-parity breaking renormalizable MSSM superpotential is given by [26]

\[ W_{R} = \mu_i H_u L_i + \lambda_{ijk} L_i L_j E_k + \lambda'_{ijk} L_i Q_j D_k + \lambda''_{ijk} U_i D_j D_k. \]  

One particular class of models is that of bilinear R-parity violation, where the dominant R-parity breaking coupling is the first one in the expression above. In that case the main effect is to mix the neutrinos with the neutralinos and the charged leptons with the chargino and this opens up the decay of the gravitino into neutral gauge (\( \gamma, Z \)) or Higgs boson and neutrino or \( W^\pm \) and charged lepton [23; 27]. If instead the trilinear R-parity breaking couplings dominate, the gravitino decays at three level in the three-bodies, while the 2-body decay is realized only at one loop [28].

If the R-parity breaking couplings are large enough such a decay could be observable in different channels of indirect DM detection observations, [29–35]. At the moment the FERMI data set a lower bound on the DM lifetime in photons of the order of \( 5 \times 10^{28} \) s, already excluding part of the R-parity breaking parameter space [36; 37]. In the case of non-universal gaugino masses, the gravitino signal in the gamma-line can be suppressed [38], while allowing also R-parity breaking couplings sufficiently large to explain the neutrino masses.

### 5. Gravitinos and the LHC

The supersymmetric models with gravitino Dark Matter can give at the LHC quite different signals than the neutralino DM case: in fact, the different types of signatures depend strongly on the nature of the NLSP particle and its lifetime. In many of the cosmology inspired scenarios we discussed, either because the gravitino is sufficiently heavy or because the R-parity breaking coupling is small, the NLSP may even appear stable at colliders. Then, if the NLSP is charged, the very striking signature of a charged track passing through the whole detector would indicate immediately that such particle is not the Dark Matter and that a very weakly interacting particle
like the gravitino could play such role. The LHC collaborations have already performed searches for exotic metastable particles, setting strong constraints on the masses of the stop and gluino NLSP, reaching a lower limits of the order of about 800 and 1200 GeV respectively [39]. Weaker constraints apply on the other hand to the stau as well as the other particles of the electroweak spectrum.

On the other hand, also displaced vertices are possible, with the NLSP decaying inside the detector. In that case, of example in the R-parity violating models, the LHC can probe the case of neutralino NLSP also beyond the parameter space already excluded by FERMI [40].

If the gaugino spectrum is nearly-degenerate, as in many other compressed spectrum scenarios, the most promising channel is the monojet signature with a large missing $E_T$. In the case we discussed, the jet may be coming either from Initial State Radiation or from the associate production of gluino and squark. The monojet channel has been recently studied by the LHC collaborations giving bounds for the case of graviton production in extra-dimensional scenarios and for Dark Matter production at colliders [41; 42]. Those results have been also reinterpreted for the case of a degenerate gaugino spectrum and they give important constraints, excluding gluino masses up to 450-500 GeV [43]. Still these bounds are much weaker than the gluino mass bound for non-degenerate spectra, which exceeds now 1 TeV.

6. Conclusion

The gravitino is a very good Dark Matter particle, both in the case of conserved and broken R-parity. In the first case, BBN imposes some cosmological restrictions on the scenario, depending on the nature of the NLSP and its lifetime and number density. For neutralino NLSP, these constraints possibly point to particular supersymmetric parameter ranges, where the neutralino density is suppressed. One example is the case of quasi-degenerate gauginos. These mass spectra are more difficult to disentangle at colliders than the normal case of large mass differences, but are nevertheless starting to be explored at the LHC, until now without success. On the other hand, for heavy NLSP the BBN constraints are relaxed and the gravitino can be a viable DM candidate also if the superparticles spectrum is beyond the reach of the LHC. The price to pay in this case is a much lower reheat temperature than that required by thermal leptogenesis.

In the case of R-parity violation, the gravitino DM can decay and therefore indirect Dark Matter searches can offer a complementary channel of discovery. So far no signal of gravitino Dark Matter has been found and the present FERMI data already exclude part of the parameter space. Further constraints or even a discovery are still possible at the LHC, for example in channels with displaced vertices. The R-parity violating models have in fact only recently started to be studied systematically at the LHC.

The search for gravitino Dark Matter at LHC and in indirect DM detection is only at the beginning and, even if no evidence has been found so far, let us hope for a new signal soon!

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