Status of supersymmetric Dark Matter

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Introduction: Supersymmetry after LHC run 1

Neutralino DM:
- Bino and the coannihilation corner(s)
- Higgsino Dark Matter
- Wino Dark Matter and Indirect Detection

Gravitino Dark Matter:
- Gravitino production & the Gluino mass
- High scale SUSY for baryogenesis

Outlook
Introduction
Very strong constraints on the SUSY mass spectrum, but...

**ATLAS SUSY Searches** - 95% CL Lower Limits

<table>
<thead>
<tr>
<th>Model</th>
<th>(e, \mu, \tau, \gamma) Jets</th>
<th>(E_{T}^{miss}) ([\text{GeV}^{\text{jet}}])</th>
<th>Mass limit</th>
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<tbody>
<tr>
<td><strong>Inclusive Searches</strong></td>
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<tr>
<td>MSUGG/SMSSM</td>
<td>0-3, 0/1-2/1</td>
<td>850/700</td>
<td>1.33/1.26</td>
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<tr>
<td>(\tilde{q}, \tilde{g}/\tilde{q}^0)</td>
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<tr>
<td>(\tilde{q}, \tilde{g}/\tilde{q}^0) (compressed)</td>
<td>1-3 jets</td>
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<td>1/2 z + 0/1 f</td>
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<td>GGM (higgsino NLS)</td>
<td>2 \gamma</td>
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<td><strong>Direct searches</strong></td>
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<td>Direct (\tilde{t} \rightarrow qb) prod., long-lived (\tilde{t})</td>
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<td><strong>Scalar charm, (\tilde{c} \rightarrow q\tilde{t})</strong></td>
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<td>760/650</td>
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<td><strong>Other</strong></td>
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**Reference**

- 1507.0525
- 1405.7875
- 1507.0525
- 1505.03220
- 1405.7875
- 1507.0525
- 1505.03220
- 1407.0603
- 1507.05493
- 1507.05493
- 1503.03290
- 1503.05158
- 1407.0600
- 1308.1841
- 1407.0600
- 1407.0600
- 1407.0600
- 1308.2331
- 1404.2500
- 1209.2102, 1407.0583
- 1508.08816
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- 1403.5222
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- 1501.07110
- 1405.5086
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- 1404.2500
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- 1503.04430
- 1404.2500
- 1405.5086
- 1405.5086
- 1502.0668
- 1502.0668
- 1404.2500
- ATLAS-CONF-2015-026
- ATLAS-CONF-2015-015

*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1\(\sigma\) theoretical signal cross section uncertainty.*
In the generic pMSSM limits on the gluino mass are less strong than in constrained/simplified models!

[Arbey et al. 1505.04595]
# SUSY at LHC Run 2

## ATLAS SUSY Searches* - 95% CL Lower Limits

**Status:** March 2017

### Model

<table>
<thead>
<tr>
<th>Model</th>
<th>( \xi, \mu, \tau, \gamma )</th>
<th>( L_{\kappa_{\text{min}}} )</th>
<th>( L_{\kappa} )</th>
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<tr>
<td>MSUGRA/CMSSM</td>
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<td>0</td>
<td>2-6 jets</td>
<td>20.3</td>
<td>1.86 TeV</td>
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<td>GGM (bino NLSP)</td>
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<td>-</td>
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<td>3.2</td>
<td>1.92 TeV</td>
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<td>2</td>
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### Inclusive Searches

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### ATLAS Preliminary

\( \sqrt{s} = 7, 8, 13 \) TeV

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*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on

### Mass scale [TeV]

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**SUSY at LHC Run 2**

### ATLAS SUSY Searches* - 95% CL Lower Limits

| Model                  | $\epsilon, \mu, \tau, \gamma$ Jets $k_{\text{miss}}^T$ | $L$ or $t$ h $|E_t|$ | Mass limit | $\sqrt{s} = 7, 8 \text{ TeV}$ | $\sqrt{s} = 13 \text{ TeV}$ | Reference |
|------------------------|-------------------------------------------------------|------------------------|------------|-------------------------------|-------------------------------|-----------|
| MSUGRA/CMSSM           | 0-3, $\nu/1-2 \tau$ 2-10 jets/3 h                   | Yes                     | 20.3       | 1.86 TeV                      | 208 GeV                       | 1507.05025 |
| GGM (bino NLSP)        | 2, mono-jet                                           | Yes                     | 36.1       | 1.92 TeV                      | 600 GeV                       | 1507.05025 |
| GGM (higgsino-bino NLSP)| γ 1, 16                                              | Yes                     | 20.3       | 1.37 TeV                      | 1.8 TeV                       | 1507.05025 |
| GGM (higgsino NLSP)    | γ 2, 2 jets                                          | Yes                     | 13.3       | 2.0 TeV                       | 1.65 TeV                      | 1507.05025 |
| Gravitino LSP          | 0, mono-jet                                           | Yes                     | 900 GeV    | 900 GeV                       | 1.8 TeV                       | 1507.05025 |

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on publications from ATLAS and CMS collaborations.*
Take neutralino DM or gravitino DM with neutralino NLSP within the RPC pMSSM with 19+1 parameters, i.e. no unification assumption, flavour & CP conserving SUSY breaking. Impose all constraints from low energy, flavour observables, LHC SUSY searches and monojets, as well as DM density and BBN limits on neutralino NLSP...
Well-tempered neutralino

Relic density strongly dependent on neutralino nature !!!

[Arkani-Hamed, Delgado & Giudice 0601041]
The neutralino compositions in the two scenarios is very different and so also the LHC reach in the next run: only half the neutralino DM points will be excluded, while 75% of the gravitino DM points...

[Arbey et al. 1505.04595]
Neutralino
Dark Matter
Bino coannihilation

To have the correct relic density for a Bino LSP, need to suppress the density, e.g. by coannihilation... also in CMSSM:

[Olive 1510.06412]
**Bino coannihilation**

To have the correct relic density for a Bino LSP, need to suppress the density, e.g. by coannihilation... also in CMSSM:

[Olive 1510.06412]
**Bino-gluino coannihilation**

For non-universal gaugino masses also the gluino plays a role and extends the mass to the multiTeVs!

[Ellis, Evans, Luo & Olive 1510.03498]

[Nagata, Otono & Shirai 1701.07664]
MSSM-7 Dark Matter

With more parameters, more mechanisms are possible, i.e. in the MSSM with 7 parameters: both Bino & Higgsino DM!

[For Higgsino coannihilation with charginos is always present!]

For Higgsino coannihilation with charginos is always present!
Higgsino Dark Matter

The Higgsino DM region mostly covered by Direct Detection:

Nevertheless for other compositions low cross-section is possible.

[GAMBIT coll. 1705.07917]
Wino Dark Matter

In the case of the Wino also the Sommerfeld enhancement of the cross-section plays an important role! In this case then indirect detection can exclude pure Wino and also most of the Wino-Higgsino parameter space...

[Beneke et al.1611.00804]
Gravitino
Dark Matter
Gravitinos can interact very weakly with other particles and therefore cause trouble in cosmology, either because they decay too late, if they are not LSP, or, if they are the LSP, because the NLSP decays too late...

If gravitinos are in thermal equilibrium in the Early Universe, they decouple when relativistic with number density given by

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

Warm DM! [Pagels & Primack 82]

If the gravitinos are NOT in thermal equilibrium instead

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

[Bolz, Brandenburg & Buchmuller 01], [Pradler & Steffen 06, Rychkov & Strumia 07]
The gravitino, the spin 3/2 superpartner of the graviton, interacts only “gravitationally” and therefore decays (or “is decayed into”) very late on cosmological scales.

\[ \tau_{3/2} = 6 \times 10^7 \text{s} \left( \frac{m_{3/2}}{100 \text{GeV}} \right)^{-3} \]

BBN is safe only if the gravitino mass is larger than 40 TeV, i.e. the lifetime is shorter than \( \sim 1 \) s, or if the reheating temperature is small! Indeed due to non-renormalizable coupling

\[ \Omega_{3/2} \propto T_R \frac{M_i^2}{m_{3/2}} \]
BBN bounds on pMSSM

Many points for various NLSPs excluded by BBN: only the sneutrino survives to large gravitino masses. Heavy NLSP is actually preferred!
Gravitino DM in pMSSM

Interplay between gravitino production and gaugino masses very strong: high $T_{RH}$ region corresponds to light gauginos and it is more easily tested as well as SuperWIMP region!

[Arbey et al. 1505.04595]
Gluino mass is an important parameter in gravitino thermal production: the next LHC run will probe the parameter space compatible with classical (no-flavour) thermal leptogenesis.

Minimal gravitino mass such that $\Omega_{\tilde{G}} h^2 < 0.12$ is given by $m_{\tilde{G}} \propto m_{\tilde{g}}^2$
Gravitino DM & T_RH

The LHC run 2 already constrains the heavy T_RH scenario for gravitino DM with bilinear RPV:

[Ibe, Suzuki & Yanagida 1609.06834]
STOP NLSP & BBN

Sommerfeld enhancement does not make a difference...
The BBN constraints allow only for $T_R$ about few $10^7$ GeV
Bounds are avoided with a small amount of RPV!
STOP NLSPs AT LHC

[LC & F. Dradi 1403.4923]

We have for the lightest stop always relatively long lifetimes, both for R-parity conservation or violation...

**RPC:** \( \tilde{t}_1 \to t \tilde{G} \to b W^+ \tilde{G} \to b \ell^+ \nu \tilde{G} \)

\[
\tau_{\tilde{t}_1} \sim 19 \text{ s} \left( \frac{m_{\tilde{t}_1}}{500 \text{ GeV}} \right)^{-5} \left( \frac{m_{3/2}}{1 \text{ GeV}} \right)^2
\]

**RPV:** \( \tilde{t}_1 \to b \ell^+ \)

\[
\tau_{\tilde{t}_1} \sim 10^{-4} \text{ s} \left( \frac{m_{\tilde{t}_1}}{500 \text{ GeV}} \right)^{-1} \left( \frac{\epsilon \sin \theta_{\tilde{t}}}{10^{-9}} \right)^{-2}
\]

The usual searches looking for prompt decay do not apply!
LHC: long-lived stop

Best strategy: combine searches for metastable particles (out) and displaced decay vertices in tracker or pixel CMS detector. Draw the lines for 10 events of any type to be conservative:

\[ n_{Tr} < 10 \]
\[ n_{Pi} < 10 \]
\[ n_{Out} < 10 \]

MP Excluded Today

\[ L = 25 \, fb^{-1} \]
\[ L = 3000 \, fb^{-1} \]

Band is the +/- 1 sigma fluctuation for a Poisson distribution.
LHC: stop in RPC/RPV

From the previous plot, we can get the LHC reach in the parameter space both for RPC and RPV decay...

\[ n_{\Pi} < 10 \]
\[ n_{\text{Tr}} < 10 \]
\[ n_{\text{Out}} < 10 \]

\[ T_R = 10^7 \text{ GeV, } \frac{M_i}{m_t} = 1.1 \]

\[ \text{BBN excluded} \]

\[ \text{CDM excluded} \]

\[ \text{MP Excluded Today} \]

\[ \epsilon = \frac{100}{m_{\ell}} \]

\[ \text{ID excluded} \]

\[ n_{\text{Out}} < 10 \]

\[ n_{\text{Tr}} < 10 \]

\[ n_{\Pi} < 10 \]

\[ L = 3000 \text{ fb}^{-1} \]
High scale SUSY for baryogenesis
**Baryogenesis in RPV SUSY**

[Sundrum & Cui 12, Cui 13, Rompineve 13, ...]

Realization of good old baryogenesis via out-of-equilibrium decay of a superpartner, possibly WIMP-like, e.g. in the model by Cui with Bino decay via RPV B-violating coupling.

CP violation arises from diagrams with on-shell gluino lighter than the Bino. To obtain right baryon number the RPC decay has to be suppressed, i.e. due to heavy squarks, the RPV coupling large and the Bino density very large...
Baryogenesis & SW DM

[Arcadi, LC & Nardecchia 1312.5703]

In such scenario it is also possible to get gravitino DM via the SuperWIMP mechanism and the baryon and DM densities can be naturally of comparable order due to the suppression by the CP violation and Branching Ratio respectively...

$$\Omega_{\Delta B} = \frac{m_p}{m_\chi} \varepsilon_{CP} BR(\chi \rightarrow \bar{B}) \Omega_{\chi}^{\tau \rightarrow \infty}$$

$$\Omega_{DM} = \frac{m_{DM}}{m_\chi} BR(\chi \rightarrow DM + \text{anything}) \Omega_{\chi}^{\tau \rightarrow \infty}$$

$$\frac{\Omega_{\Delta B}}{\Omega_{DM}} = \frac{m_p}{m_{DM}} \frac{\varepsilon_{CP} BR(\chi \rightarrow \bar{B})}{BR(\chi \rightarrow DM + \text{anything})}$$

Small numbers

independent of Bino density

Gravitino DM: BR is naturally small and DM stable enough!
CP violation can be provided either by a phase difference between the Bino and Gluino masses or by flavour effects in the RPV couplings and CKM-mixing for squarks. The latter suffers unfortunately of GIM-like cancellations for degenerate squarks... Study of full flavour structure with general squark mass spectrum is on-going [G. Arcadi, LC & F. Kirk work in progress]
Unfortunately realistic models are more complicated than expected: wash-out effects play a very important role !!!

Asymmetry suppressed by the high scalars

Asymmetry suppressed by wash-out

Rather definite prediction for range of scalar masses

Heavy !!!

G. Arcadi - Invisibles ’15
Moreover the large scalar mass suppresses the branching ratio into gravitinos too much...

\[ BR(\tilde{B} \rightarrow \psi_{3/2} + \text{any}) \ll \epsilon_{CP} \]

Need a large gravitino mass to compensate & obtain \( \Omega_{DM} \sim 5 \Omega_B \), not so simple explanation after all..., but still possible with \( m_{3/2} < m_{\tilde{g}} \) .
Gravitino DM in RPV SUSY

Thanks to the large gravitino mass, the squark mass suppression is partially compensated and a visible gravitino decay is possible:

$$\Gamma(\psi_{3/2} \rightarrow u_k d_i d_j) = \frac{3\lambda^2}{124\pi^3} \frac{m_{3/2}^7}{m_0^4 M_P^2}$$

$$\tau_{3/2} = 0.26 \times 10^{28} s \left( \frac{\lambda}{0.4} \right)^{-2} \left( \frac{m_{3/2}}{1 \text{TeV}} \right)^{-7} \left( \frac{m_0}{1 \text{TeV}} \right)^4$$

Right ballpark for indirect DM detection, but strongly dependent on the gravitino mass...
Dominant decay into antiprotons, possibly observable !!!
The gluino is in this scenario the lightest SUSY particle and may be produced at colliders; but it should be not too much lighter than the Bino, i.e. $m_{\tilde{g}} \sim 0.1 - 0.4 \ m_{\tilde{B}} \sim 7 - 28$ TeV, possibly in the reach of a 100 TeV collider.

$$c\tau_{\tilde{g}} \sim 1.5 \ cm \left( \frac{\lambda''}{0.4} \right)^{-2} \left( \frac{m_0}{4 \times 10^7 \text{GeV}} \right)^4 \left( \frac{m_{\tilde{g}}}{7 \text{ TeV}} \right)^{-5}$$

The heavy squarks give displaced vertices for the gluino decay via RPV, even for RPV coupling of order 1. Gluino decay into gravitino DM is much too suppressed to be measured.
Outlook
Outlook

Supersymmetry is too rich a theory to be easily excluded... Very different DM candidates are possible with various signatures!

Nevertheless the simplest models of supersymmetric Dark Matter like Bino in the CMSSM are under siege and survive only in corners of the parameter space.

On the other side Wino Dark Matter is also challenged by indirect detection thanks to the Sommerfeld enhancement.

For gravitino Dark Matter a lot of parameter space is still viable, but the window for thermal leptogenesis may be closed soon by the LHC, if the gluino is not seen below ~2 TeV.

Cosmologically though there are advantages to heavy SUSY, like scenarios for baryogenesis in RPV with gravitino DM!