Long-lived higgsinos as probes of gravitino dark matter at the LHC

In collaboration with S. Bobrovskyi & J. Hajer, to appear soon!

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The CERN Large Hadron Collider

- Only discovery so far.

- If no new strongly interacting physics is found, how can we further test for new electroweak physics at the LHC? How could the new physics be hiding from current searches?
If it is a Higgs, then what?

- Low Higgs mass in the SM is not natural - motivation for supersymmetry.

- **Naturalness in the MSSM** if light higgsinos & stops and not so heavy gluinos.

- But ~126 GeV is a high Higgs mass in the MSSM- need stops to be heavy. No gluinos observed either.

- Can also have natural MSSM with only higgsinos light (**higgsino world**). Kane (1996)

- **Observability?** Higgsinos can easily evade LHC searches.

- **Connection to dark matter?** WIMP not good candidate in higgsino world.
LHC is starting to probe EW SUSY production

- Model dependent!
Higgsino world

- The superpotential $W$ and soft SUSY-breaking terms of the MSSM:

$$W = \mu H_u H_d + \lambda_{i,j}^u q_i u^c_j H_u + \lambda_{i,j}^d d_i^c q_j H_d + \lambda_{i,j}^e l_i e^c_j H_d,$$

$$-\mathcal{L}_{\text{soft}} = m_u^2 H_u^\dagger H_u + m_d^2 H_d^\dagger H_d + (B H_u H_d + \text{h.c.})$$

$$+ \tilde{m}_{l_i}^2 \tilde{l}_i^\dagger \tilde{l}_i + \tilde{m}_{e_i}^2 \tilde{e}^c_i \tilde{e}^c_i + \tilde{m}_{q_i}^2 \tilde{q}_i^\dagger \tilde{q}_i + \tilde{m}_{u_i}^2 \tilde{u}_i^\dagger \tilde{u}_i + \tilde{m}_{d_i}^2 \tilde{d}_i^\dagger \tilde{d}_i$$

$$+ \frac{1}{2} \left( M_1 \tilde{B} \tilde{B} + M_2 \tilde{W} \tilde{W} + M_3 \tilde{g} \tilde{g} + \text{h.c.} \right) + \text{trilinear } A \text{ terms}$$

- In general no connection between the higgsino mass parameter $\mu$ and the soft SUSY breaking mass parameters...
Higgsino world

- **Gravity mediated SUSY breaking** generates nonzero $\mu$ (solves “$\mu$ problem”)

- **Gauge mediated SUSY breaking** soft masses from gauge coupled messengers (flavour universality, predictive)

- **Hybrid gauge-gravity mediation** from extra dimensional GUTs leads to a scenario with $\mu \sim 100$ GeV and the rest of the MSSM spectrum > TeV.
  \[ \text{Brümmer & Buchmüller (2011)} \]

- Difficult to detect at LHC due to small mass differences and mono-jet searches not being sensitive yet.
  \[ \text{Baer, Barger & Huang (2011)} \]

- Light higgsinos could be created@LHC all the time but evade detection!

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\[
\begin{array}{c}
q \\
\bar{q} \\
j \\
Z \\
\chi_1^0 \\
\chi_2^0
\end{array}
\]
Dark matter?

• The higgsinos are nearly mass degenerate, which leads to very low WIMP relic densities due to coannihilation.

• Possible solutions: moduli decays to WIMPs Gelmini et al (2006), axions Baer et al (2011) - or decaying gravitino dark matter:

  • Local SUSY leads to the prediction of the gravitino.

  • The thermal production of gravitinos depends on the reheating temperature, which should be high for leptogenesis to work. **Problem:** their decay can alter the successful BBN prediction.

  • **Solution:** the gravitino is the LSP and stable. The NLSP is meta-stable but ok with BBN if we have small R-parity violation. Allows for decaying dark matter!

  Buchmüller, Covi, Hamaguchi, Ibarra, Yanagida (2007)
R-parity violation

• **R-parity conservation** is not required from a theoretical point of view, but imposing it in the MSSM leads to:

  • **stability of proton** (can be achieved by either B or L conservation)
  
  • **stability of the LSP** (natural WIMP dark matter candidate and missing energy at colliders)

• Allowing for RPV terms in the MSSM in general introduces many new parameters:

\[
\Delta W = \mu_i H_u l_i + \frac{1}{2} \lambda_{ijk} l_i e_j^c l_k + \lambda'_{ijk} d_i^c q_j l_k + \lambda''_{ijk} u_i^c d_j^c d_k^c ,
\]

\[-\Delta \mathcal{L} = B_i H_u \tilde{l}_i + \left( m_{id}^2 \tilde{l}_i^\dagger H_d + \text{h.c.} \right) + \text{trilinear terms} .\]
Bilinear R-parity violation

- Extend the MSSM only with bilinear RPV terms:

\[ \Delta W = \mu_i H_u l_i, \quad -\Delta \mathcal{L} = B_i H_u \tilde{l}_i + (m_{id}^2 \tilde{l}_i H_d + \text{h.c.}) \]

- Small number of new parameters + B number conserved!

- The fields can be rotated to get a description in terms of L-violating trilinear terms proportional to the yukawa couplings.

- The new phenomenology depends mostly on the parameter \( \zeta_i \):

\[ \zeta_i = \frac{\epsilon_i' v_d + \epsilon_i'' v_u}{v}, \quad \zeta^2 = \sum_i \zeta_i^2 \]

where the \( \epsilon \)'s are functions of both MSSM and RPV parameters.

Bobrovskyi, Buchmüller, Hajer & Schmidt (2010)
Cosmological constraints on $\zeta$

\[
\zeta = 4 \times 2^{3/4} \sqrt{\frac{G_F}{\alpha}} \sqrt{\frac{M_P}{m_{3/2}^3}} \frac{M_1M_2}{M_2 - M_1}
\]

- All neutralinos decay before BBN if $\zeta \gtrsim 10^{-12}$

- Can we get the right relic abundance of gravitinos?
  
  - SQCD processes in early universe $gg \rightarrow \tilde{g}\Psi_\mu$, $\Omega_{3/2} \propto \frac{T_R m_{\tilde{g}}^2}{m_{3/2}}$
  
  - We want to allow for multi-TeV gluino masses.

- Scenario with spontaneous breaking of B-L in the early universe allows for lower reheating temperature than in thermal leptogenesis.

- 2 TeV gluino gives a minimum gravitino mass of 40 GeV. Allows for higgsino masses from 100 GeV.

Buchmüller, Domcke, Schmitz (2012)
Cosmological constraints on $\zeta$

- Fermi-LAT bound on the lifetime of decaying dark matter leads to $\zeta \lesssim 10^{-8}$

- Gravitino lifetime many orders of magnitude larger than the age of the universe

$$\tau_{3/2}(\gamma\nu) = 1 \times 10^{27} \text{ s } \left( \frac{\zeta}{10^{-8}} \right)^{-2} \left( \frac{m_{\chi_0}}{1 \text{ TeV}} \right)^2 \left( \frac{m_{3/2}}{10 \text{ GeV}} \right)^{-3}$$
LHC signature

- Macroscopic decay lengths for the higgsino NLSP:

\[ c\tau_{\chi^0_1} \geq 40 \text{ cm} \left( \frac{m_{\chi^0_1}}{100 \text{ GeV}} \right)^{-1} \left( \frac{m_{3/2}}{10 \text{ GeV}} \right)^3 \left( \frac{\tau_{3/2}(\gamma\nu)}{10^{28} \text{ s}} \right) f_W(m_{\chi^0_1})^{-1} \]

- Displaced muons at the LHC
LHC signature

- Two isolated muons with opposite sign without an inner track and with an impact parameter larger than 10 cm.

- Analysis: Madgraph/Madevent+Pythia+Delphes detector simulation, taking into account radial information.
Benchmark points

- LEP bound on chargino mass for degenerate spectra $\mu > 95$ GeV.

- We take $m_A = 800$ GeV, $m_0 = m_{1/2} = M_1 = M_2 = M_3 = 3$ TeV.

  and $50 = \tan \beta \sim \frac{m_{H_u}^2 + m_{H_d}^2 + 2|\mu|^2}{2B_\mu}$ (large in higgsino world).

- We get a Higgs mass of $\sim 125$ GeV in all models.

- We vary the RPV parameter for each model from $\zeta = 10^{-8}$ and down...

| higgsino | $\mu$ |
|----------|------|
| $\chi_2^0$ | 106 209 311 413 |
| $\chi_1^\pm$ | 104 207 309 411 |
| $\chi_1^0$ | 102 205 307 408 |

higgsino masses in GeV
LHC signature

| cuts                      | $t\bar{t}$ | $Z \rightarrow \mu\mu$ | WW | WZ | ZZ | $1 \times 10^{-8}$ | $5 \times 10^{-9}$ | $1 \times 10^{-8}$ | $5 \times 10^{-9}$ |
|---------------------------|------------|--------------------------|----|----|----|---------------------|---------------------|---------------------|
| $N(\mu) \geq 2$           | 2160       | 385000                   | 352| 333| 283| 2.79                | 0.929               | 3.21                | 0.714               |
| Class 1                   | 1790       | 385000                   | 351| 296| 256| 0.219               | 0.109               | 0.394               | 0.0959              |
| $d(\text{Vertex}) > 10 \text{ cm}$ | 0.245     | 0                         | 0  | 0  | 0  | 0.164               | 0.109               | 0.352               | 0.0746              |
| $\Delta d(\text{Vertex})_{ij} < 1 \text{ mm}$ | 0.0460    | 0                         | 0  | 0  | 0  | 0.164               | 0.109               | 0.300               | 0.0640              |
| Class 2                   | 0          | 0                         | 0  | 0  | 0  | 2.57                | 0.820               | 2.29                | 0.586               |
| Total                     | 0.0460     | 0                         | 0  | 0  | 0  | 2.73                | 0.929               | 2.59                | 0.650               |

- Cut flow (cross sections $\sigma$ after cuts in fb, $N=\sigma L$)

- SM background to OS very efficiently removed by displaced vertex requirement.
Statistical measures for discovery prospects

• $S > 5 \sqrt{B}$ is not adequate when the background is very low.

• Assume Poisson distribution!

• Probability to observe $N$ events or less: 
  $$P(N; B) = \sum_{i=0}^{N} e^{-B} \frac{B^i}{i!}$$

• 5σ detection: 
  $$1 - P(N; B) < 2.9 \cdot 10^{-7}$$ (one-sided Gaussian)

• Probability to observe $N$ under signal hypothesis? 
  $$1 - P(N; S + B) \geq P_{\text{obs}}$$

• Expressed in terms of gamma functions useful in practice. See discussion of different measures in Gustafsson, SR, Lopez-Honorez, Lundström (2012)
Discovery reach @ LHC 8 TeV

- $5\sigma$ discovery with 50%, 90% and 99% probability to observe signal:

$$\zeta \mu 100 200 300 400 \times 10^{-8}.$$
Higgsino mass determination

- In case of signal, can we further test the hypothesis?

- Advantage of the signature: can reconstruct higgsino mass edge

\[
T(m_{\mu\mu}) = \frac{1}{\sqrt{2\pi}\sigma} \int_0^{m_{\text{cut}}} dy \ y \exp\left(-\frac{1}{2}\left(\frac{m_{\mu\mu} - y}{\sigma}\right)^2\right)
\]

(a) Large number of events (#).

(b) Small number of events (#).

(Figure 6)

Number of Events per bin

100

80

60

40

20

0

62.5

Invert mass of $\mu^+\mu^-$ [GeV]

1405 63.9

50 63.8

17 47.7

102 GeV

Figure 8

Amount of R-parity violation $\zeta$

$10^{-8}$

$10^{-9}$

$10^{1}$

$10^{2}$

$10^{3}$

Integrated Luminosity $\mathcal{L}$ [fb$^{-1}$]

(Figure 7)

Fermi-LAT Excluded

$\mu$

$100$

$200$

$300$

$400$

0

3

2

1

0

62.5

Invert mass of $\mu^+\mu^-$ [GeV]

100

80

60

40

20

0

62.5

Invert mass of $\mu^+\mu^-$ [GeV]

100

80

60

40

20

0

62.5

Invert mass of $\mu^+\mu^-$ [GeV]

100

80

60

40

20

0

62.5

Invert mass of $\mu^+\mu^-$ [GeV]
Summary & conclusion

- A higgsino-world scenario is well motivated both from theory and phenomenology.

- With small R-parity violation we can also have a consistent cosmology and gravitino dark matter.

- The bounds on decaying dark matter motivates a search for displaced higgsino decays at the LHC.

- In the 8 TeV run, LHC searches can extend the reach in the RPV parameter $\zeta$ as compared to current gamma-ray searches, and a signal can show up at integrated luminosities of 10-30/fb.

- In the case of a signal, the displaced dimuon signature allows for reconstruction of the higgsino mass.