Searching for light neutralinos with a displaced vertex at the LHC

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Motivation

- No signs of TeV-scale SUSY.
- SUSY provides many scenarios with long-lived particles (LLPs)
  (e.g., long-lived gluinos, charginos, neutralinos,...)

  $\Rightarrow$ The lifetime frontier has become increasingly important.
- Current bounds on the lightest neutralino mass are much weaker than those on squark, slepton, and gluino masses.
- A bino-like lightest neutralino ($m_{\tilde{\chi}^0} \sim \mathcal{O}(\text{GeV})$) is consistent with current astrophysical and cosmological bounds, provided it decays (e.g., through RPV couplings).
- There are many studies of a light bino-like neutralino, where the neutralino is procuded from B-meson, D-meson, or Z-boson decays (constraining masses below ~ 45 GeV).
- We propose a DV search where $\tilde{\chi}_1^0$ is produced from a heavy slepton decay, allowing to probe masses up to 200 GeV.

RPV MSSM

In the RPV-MSSM, the MSSM is supplemented with the following RPV superpotential

$$W_{\mathsf{RPV}} = \sum_i \mu_i L_i H_u + \sum_{i,j,k} \left(\frac{1}{2} \lambda_{ijk} L_i L_j E_k^c + \lambda'_{ijk} L_i Q_j D_k^c + \frac{1}{2} \lambda''_{ijk} U_i^c D_j^c D_k^c \right), \quad (1)$$

where Q_i, D_i^c, U_i^c, and L_i, E_i^c are chiral superfields and $i, j, k = (1, 2, 3)$ are generation indices.

Our benchmark model: Only LQD^c turned on.

RPV MSSM

The Yukawa couplings generated by LQD^c are

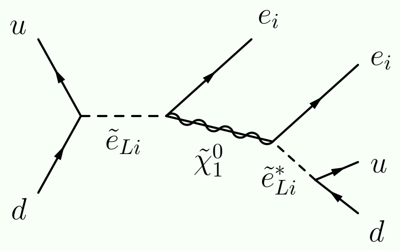
$$L_{\mathsf{RPV}} = \lambda'_{ijk} \Big(\tilde{\nu}_{iL} \bar{d}_{kR} d_{jL} + \tilde{d}_{jL} \bar{d}_{kR} \nu_{iL} + \tilde{d}^*_{kR} \bar{\nu}^c_{iR} d_{jL} - \tilde{e}_{iL} \bar{d}_{kR} u_{jL} - \tilde{u}_{jL} \bar{d}_{kR} e_{iL} - \tilde{d}^*_{kR} \bar{e}^c_{iR} u_{jL} \Big) + h.c. \qquad (2)$$

Allows for the neutralinos to be produced at the LHC

- We study neutralinos produced at the LHC through this RPV coupling (together with a prompt charged lepton).
- The same RPV coupling allows for the neutralino decay.

Neutralino Production and Decay

Neutralino ($\tilde{\chi}_1^0$) production and decay through the λ'_{i11} coupling at the LHC:



- We trigger on the prompt charged lepton (e_i) produced in the slepton ($\tilde{e}_{Li}$) decay.

Neutralino Lifetime

- We consider $\tilde{\chi}_1^0$ to be the lightest supersymmetric particle, so it can only decay through the RPV terms, with a total decay width proportional to the λ'_{ijk} couplings squared,

$$\Gamma_{\tilde{\chi}_1^0} \propto m_{\tilde{\chi}_1^0}^5 \left(\frac{\lambda'_{ijk}}{m_{\tilde{f}}^2} \right)^2 , \tag{3}$$

- Consequently, for small enough RPV couplings (and $m_{\tilde{\chi}_1^0}$) the neutralino will be long-lived.
- The decay products of this long-lived neutralino will be identified as displaced tracks from a common origin, i.e., a displaced vertex (DV).

Benchmark Scenario

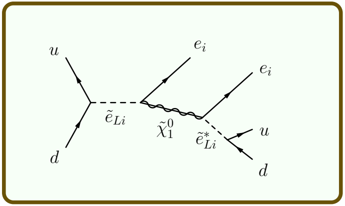
- RPV SUSY with $\tilde{\chi}_1^0$ the lightest supersymmetric particle.
- Only LQD^c RPV-interactions turned on.
- For concreteness, we analyze the sensitivity of the LHC to $\lambda'_{ijk} = \lambda'_{111}$, but the search strategy described here is expected to give similar constraints for λ'_{211}.
- For simplicity, all the superpartners different from $\tilde{\chi}_1^0$ and $\tilde{e}_L$ are taken to be heavy (10 TeV), so that they are effectively decoupled.
- In this scenario, the phenomenology at the LHC can be controlled by the following three parameters only:

$$\lambda'_{111}, m_{\tilde{e}_L}, m_{\tilde{\chi}_1^0}.$$

Existing Bounds

Neutrinoless double beta ($0\nu\beta\beta$) decay

- **We compare our results with $0\nu\beta\beta$-decay searches.** These limits were obtained by comparing the theoretical calculations from Ref. `arXiv:2112.12658` of the RPV SUSY contribution to $0\nu\beta\beta$ half-life, mediated by light neutralinos and selectrons with the experimental current limits on the $0\nu\beta\beta$ half-life $T_{1/2}^{exp} > 1.8 \times 10^{26}$yr for the isotope ^{76}Ge.



$$(T_{1/2}^{0\nu\beta\beta})^{-1} \propto \left| \frac{\lambda'^2_{111}}{m_{\tilde{\chi}_1^0} m^4_{\tilde{e}_L}} \right|^2$$

Monolepton Searches

- We also compare our results with monolepton searches.
- ATLAS has presented a search for a monolepton signal:

$$pp \to W' \to \ell\nu,$$

based on $\mathcal{L} = 36.1$ fb^{-1} of statistics taken at $\sqrt{s} = 13$ TeV [arXiv:1706.04786].

- We reinterpret this prompt search for a new W' decaying to $W' \to e\nu$, in the context of our RPV signal, $\tilde{e} \to e\tilde{\chi}_1^0$.
- We obtain the limits by extracting a contour on the significance at 36.1 fb^{-1}, i.e. $Z_{36} \equiv S/\sqrt{B} = 2$, with S the number of signal events after the monolopton cuts and B the number of background events taken from the ATLAS search.
- Finally, we project this limit for the same monolepton search for a luminosity of 3000 fb^{-1}. The contour is again obtained at $Z_{3000} = 2$ after re-scaling with $Z_{3000} \equiv \sqrt{3000/36.1} \cdot Z_{36}$.

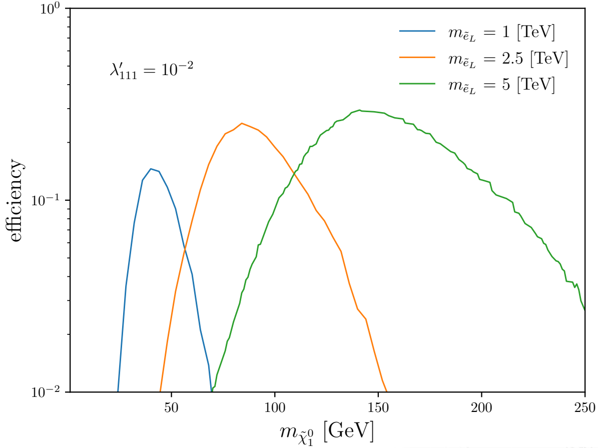
Simulation and Event Selection

- We simulate the process $pp \to \tilde{\chi}_1^0 e$ in MadGraph 5[1] at $\sqrt{s} = 13$ TeV ($p_T \geq 10$ GeV and $|\eta| < 2.5$ for the outgoing electron or positron).
- For showering and hadronization we use Pythia 8.
- We perform a custom detector simulation.
- We select events triggering on a prompt, isolated electron (with $p_T > 25$ GeV and with $|\eta| < 2.47$).
- DVs are selected from tracks with a high transverse impact parameter ($|d_0| > 2$ mm and $p_T > 1$ GeV).
- Vertices are required to be within the inner tracker acceptance (transverse decay positions r_{DV} between 4 and 300 mm, longitudinal distance $|z_{\text{DV}}| < 300$ mm).
- DVs must have at least 5 tracks and mass $m_{\text{DV}} \geq 10$ GeV.

[1] We use the RPV-MSSM UFO model file implemented in https://github.com/ilmonteux/RPVMSSM_UFO

- The last two previous cuts define the region where the signal is expected to be found free of Standard Model and instrumental background events [`arXiv:1710.04901`].
- Additionally, in order to further characterize the detector response to DVs within the above mentioned regions, we make use of the parametrized vertex-level efficiencies provided by ATLAS in `arXiv:1710.04901`.
- The DV selection efficiency as a function of the neutralino mass, for three values of the slepton mass is:

Selection Efficiency



Where the boosted decay length of the neutralino is

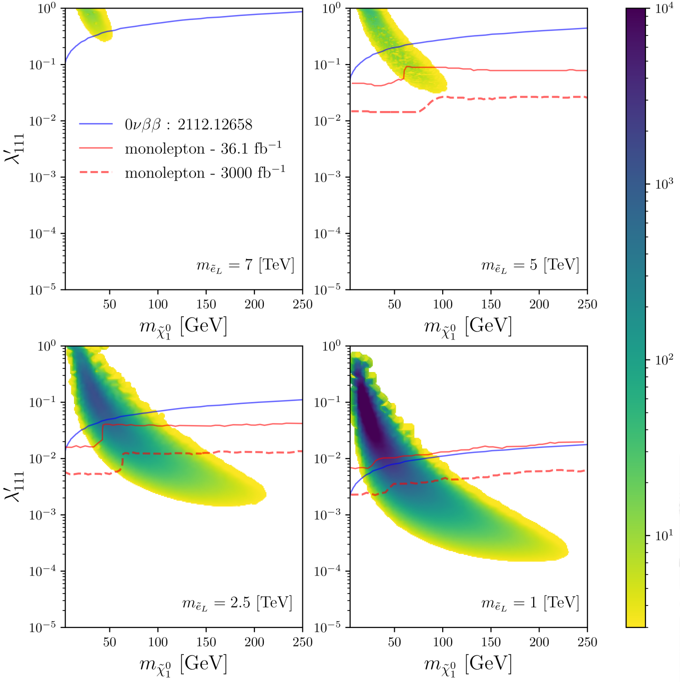
$$\beta\gamma c\tau = \frac{|\vec{p}_{\tilde{\chi}_1^0}|}{m_{\tilde{\chi}_1^0}} \frac{\hbar c}{\Gamma_{\tilde{\chi}_1^0}} \propto \frac{m_{\tilde{e}_L}^4}{m_{\tilde{\chi}_1^0}^6}. \quad (4)$$

Results

- With the above DV search strategy, we estimate exclusion limits (in the λ'_{111} vs. $m_{\tilde{\chi}_1^0}$ plane) under the assumption of zero background and requiring three signal events.

Results:

Sensitivity reach with the proposed DV search strategy with 3000 fb^{-1}. Red lines show the recasted monolepton limits. Constraints from $0\nu\beta\beta$ are shown in solid blue.



Summary and Conclusions

- In recent years, increasingly more searches for long-lived particles have been proposed and performed at the LHC and other experiments.
- In RPV-SUSY a bino-like lightest neutralino is allowed to be light ($m \sim \mathcal{O}(1-100)$GeV) as long as it decays via RPV couplings.
- If $m_{\tilde{\chi}_1^0}$ and λ' are small, $\tilde{\chi}_1^0$ is naturally long-lived.
- We proposed DV search strategy and performed Monte-Carlo simulations to estimate the sensitivities at the HL-LHC.
- We consider the process $pp \to \tilde{e}_L \to e\tilde{\chi}_1^0$, where $\tilde{\chi}_1^0$ travels a macroscopic distance before decaying into $\tilde{\chi}_1^0 \to ejj$.
- For a $m_{\tilde{e}} = 1$ TeV, the proposed search at HL-LHC can probe values of λ'_{111} up to two orders of magnitude smaller than current bounds from $0\nu\beta\beta$-decay, as well as up to 40 times smaller than our recast of an LHC monolepton search projected to 3000 fb^{-1}.
- While the focus was on the λ'_{111} coupling, simmilar results can be obtained for λ'_{211}.

Thank you!

Backup Slides

$\sigma(pp \to \tilde{\chi}_1^0 e)/\lambda'^2_{111}$

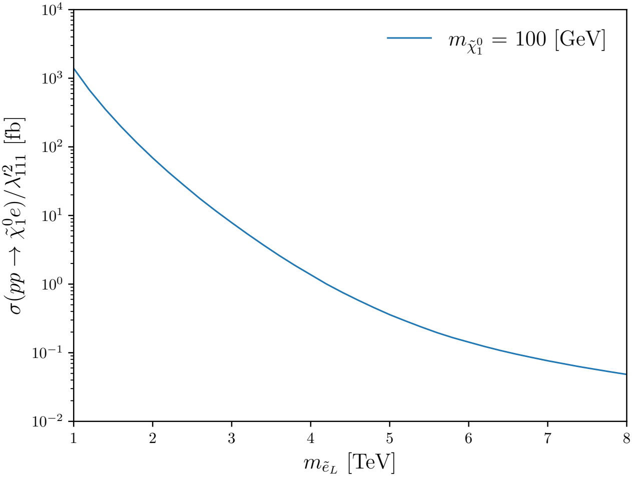


Figure: Production cross section of $pp \to \tilde{\chi}_1^0 e$ divided by λ'^2_{111} as a function of $m_{\tilde{e}_L}$ for $m_{\tilde{\chi}_1^0}$ =100 GeV.

Bounds from $0\nu\beta\beta$-decay

- The neutrinoless double beta decay limits were obtained by comparing the theoretical calculations from Ref. `arXiv:2112.12658` of the RPV SUSY contribution to $0\nu\beta\beta$ half-life, mediated by light neutralinos and selectrons with the experimental current limits on the $0\nu\beta\beta$ half-life $T_{1/2}^{exp} > 1.8 \times 10^{26}$yr for the isotope ^{76}Ge.
- Figure 3 in the previous reference shows the calculation of the contribution of light neutralinos and selectrons to the $0\nu\beta\beta$ half-life for $\lambda'_{111} = 10^{-3}$ and $m_{\tilde{e}_L}$ = 2 TeV (green dashed line).
- We have re-scaled these results for different values of λ'_{111} and $m_{\tilde{e}_L}$ using the proportionality relation $(T_{1/2}^{0\nu\beta\beta})^{-1} \propto |\lambda'^2_{111}/m^4_{\tilde{e}_L}|^2$. (See equation (4.5) in the same reference.)

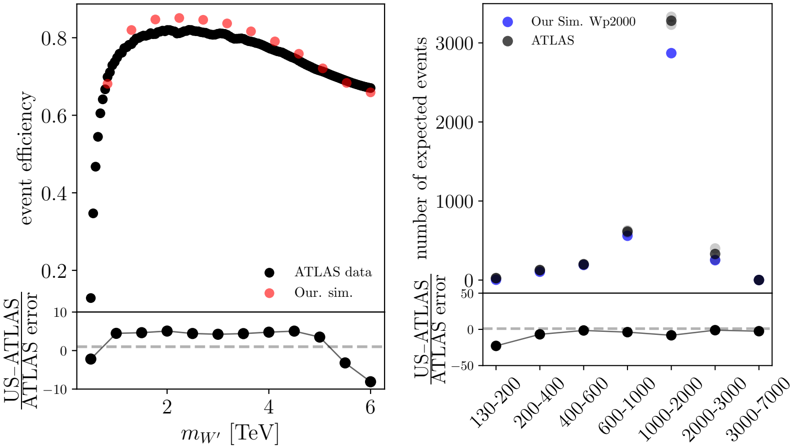


Figure: Validation plots per $m_{W'}$ mass point and per m_T ATLAS-defined bins. Comparison with the ATLAS expectation is provided in the bottom frames. (left) Event efficiency as a function of $m_{W'}$. (right) Number of expected events as a function of m_T bins.