# *R*-Parity Violating $0\nu\beta\beta$ Decay with Light Neutralinos

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# MSSM and $R$-Parity Violation

- Minimal Supersymmetric Standard Model (MSSM):
  - Sleptons and squarks ($\tilde{\nu}_L$, $\tilde{e}_L$, $\tilde{u}_L$, $\tilde{d}_L$, $\tilde{e}_R$, $\tilde{u}_R$, $\tilde{d}_R$)
  - Neutralinos ($\tilde{\chi}_i^0$)

$$\tilde{\chi}_i^0 = N_{i1}\tilde{B} + N_{i2}\tilde{W}^0 + N_{i3}\tilde{H}_d^0 + N_{i4}\tilde{H}_u^0$$

  - Gluinos ($\tilde{g}$)
  - Gravitino ($\tilde{G}$)

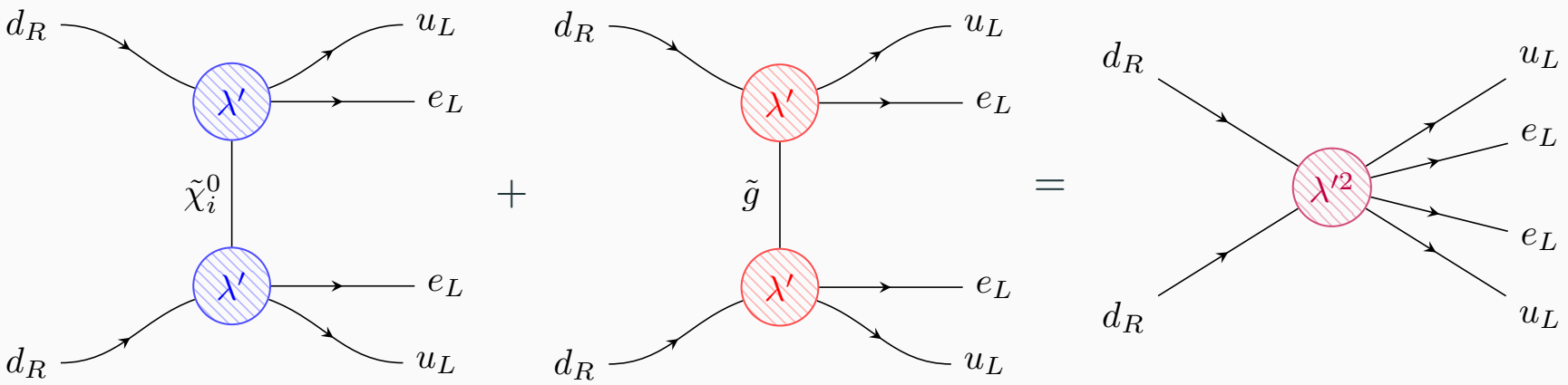
- In general one can write $R$-parity violating (RPV) terms:

$$W_{\not{R}_p} = \underbrace{\lambda\, LLE^c}_{\Delta L=1} + \underbrace{\lambda'\, LQD^c}_{\Delta L=1} + \underbrace{\lambda''\, U^c D^c D^c}_{\Delta B=1}$$

$R_p = (-1)^{3B+L+2S}$
SM: $R_p = +1$
SUSY: $R_p = -1$

- $\lambda'$: $0\nu\beta\beta$ decay; $(A, Z) \to (A, Z+2) + 2e^-$
- $\lambda''$: Proton decay; $p \to e^+\pi^0$

# RPV Neutrinoless Double Beta Decay



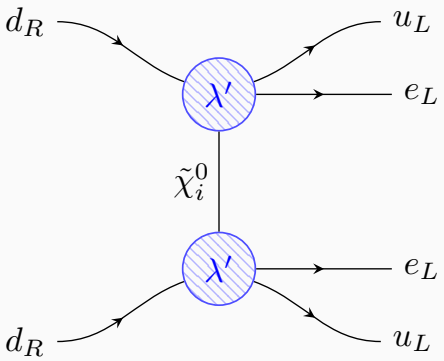

$m_{\tilde{\chi}_1^0}, m_{\tilde{g}} \gg p_F \sim 100$ MeV

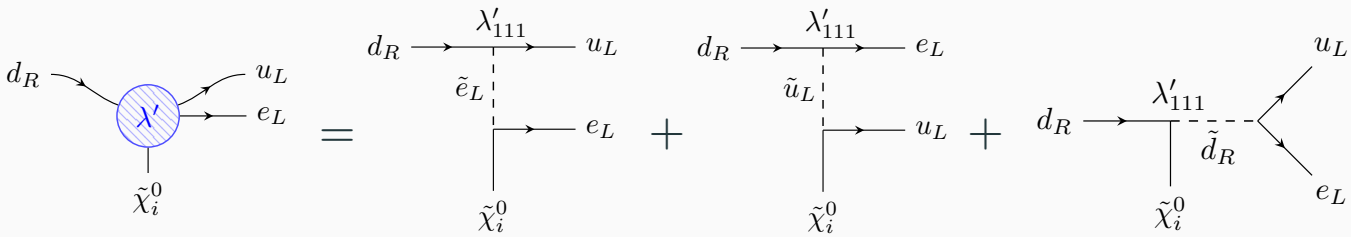
**'Short-range'**

$$(T_{1/2}^{0\nu})^{-1} = G_{0\nu} \left| \epsilon_1^{RRL} \mathcal{M}_1^{RR} + \epsilon_2^{RRL} \mathcal{M}_2^{RR} \right|^2$$

- $G_{0\nu}$: Phase Space Factor
- $\epsilon_1^{RRL}$, $\epsilon_2^{RRL}$: Scalar and tensor coefficients
- $\mathcal{M}_1^{RR}$, $\mathcal{M}_2^{RR}$: Short-range Nuclear Matrix Elements

# Light Neutralino



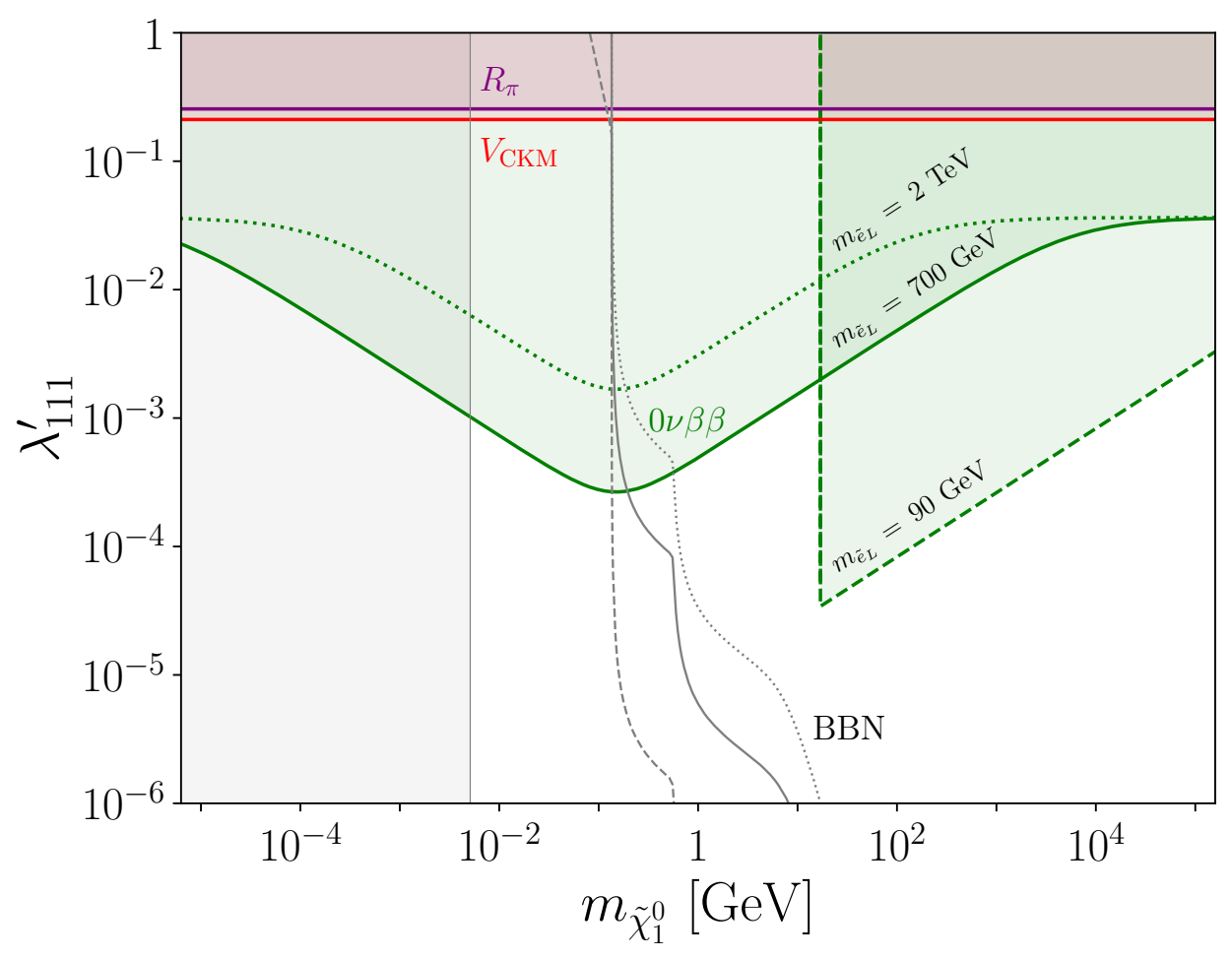

$$\epsilon_1^{RRL} = \eta_{\tilde{\chi}} + \eta_{\tilde{\chi}\tilde{e}} + \eta_{\tilde{\chi}\tilde{f}} + \eta_{\tilde{g}} + \eta'_{\tilde{g}}$$
$$\epsilon_2^{RRL} = -\frac{1}{4}\left(\eta_{\tilde{\chi}} + \eta_{\tilde{g}}\right)$$

- Coefficients depend on $m_{\tilde{e}_L}$, $m_{\tilde{u}_L}$ and $m_{\tilde{d}_R}$ $\Rightarrow$ collider constraints (ATLAS, CMS, ALEPH, OPAL)
- Collider lower bound on $m_{\tilde{\chi}_1^0}$ can be evaded
  - Lightest neutralino *very light* or *massless*
  - For $m_{\tilde{\chi}_1^0} \ll p_F$, '**long-range**' $0\nu\beta\beta$ decay

$$\eta_{\tilde{\chi}}, \eta_{\tilde{\chi}\tilde{e}}, \eta_{\tilde{\chi}\tilde{f}} \propto \underbrace{\frac{\lambda'^2_{111}}{m_{\tilde{\chi}_1^0}}}_{\text{Short-range}} \rightarrow \underbrace{\frac{\lambda'^2_{111} m_{\tilde{\chi}_1^0}}{\langle \mathbf{p}^2 \rangle + m^2_{\tilde{\chi}_1^0}}}_{\text{Interpolating}}$$

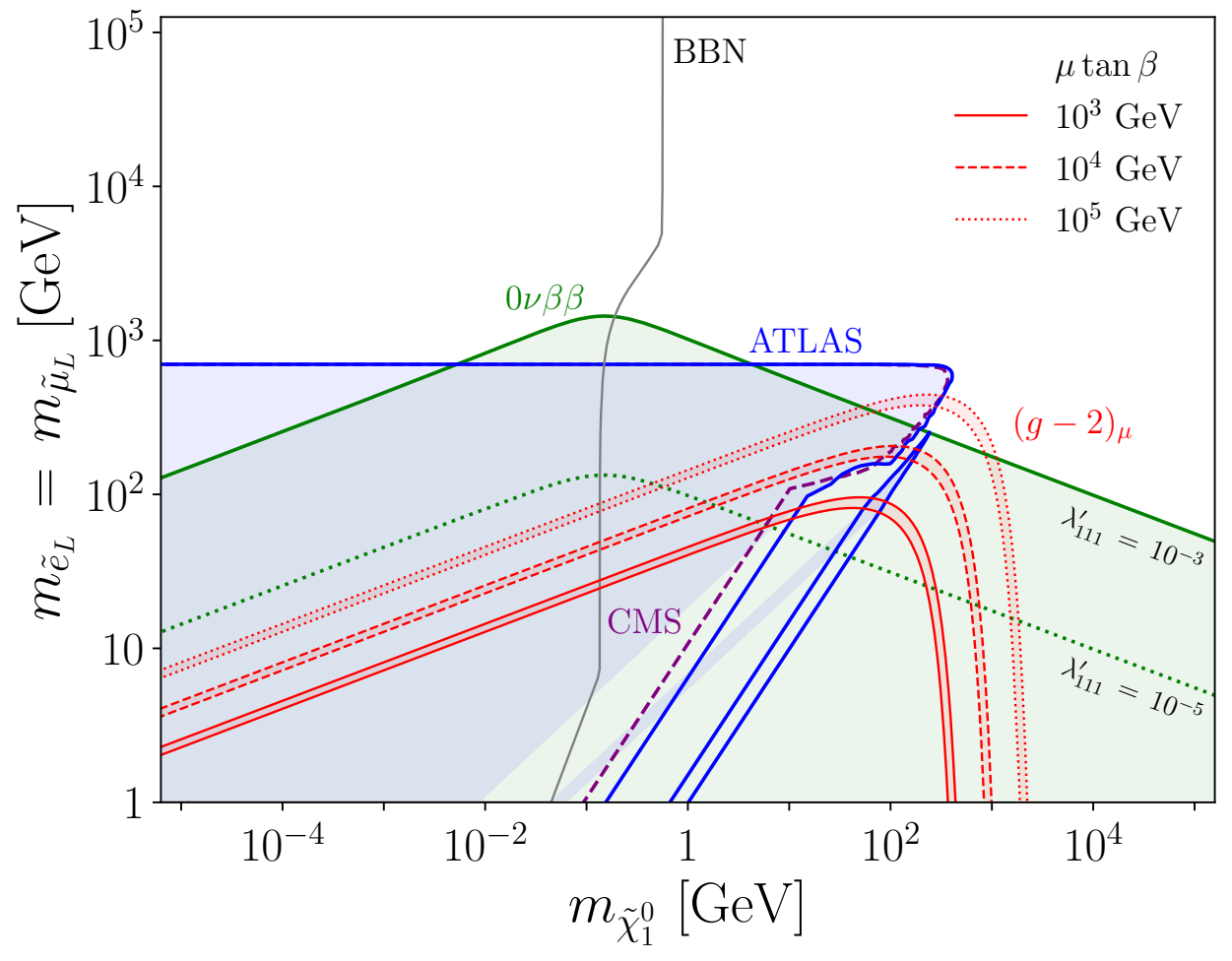
# Updated Constraints from $0\nu\beta\beta$ Decay

- **Lower limit** e.g. $T^{0\nu}_{1/2} > 1.8 \times 10^{26}$ y from GERDA-II experiment ($^{76}$Ge) $\Rightarrow$ **Upper limit** on $\lambda'_{111}$
  - Most stringent limits for minimum $m_{\tilde{e}_L}$ allowed by colliders
- Also constraints from $V_{ud}$, $R_\pi$ and BBN ($\tau_{\tilde{\chi}^0_1} < 1$ s)



# Muon g-2

- The muon $(g-2)_\mu$ anomaly: Generated by loop diagram with $\tilde{\chi}_1^0$ and $\tilde{\mu}_L, \tilde{\mu}_R$
  - Assume $m_{\tilde{\mu}_L} = m_{\tilde{\mu}_R} = m_{\tilde{e}_L}$
  - Compare $(g-2)_\mu$ favoured region with collider and $0\nu\beta\beta$ decay constraints



# Conclusions

- We have studied:
  - Contribution of the RPV coupling $\lambda'_{111}$ to $0\nu\beta\beta$ decay
  - Arbitrary mass lightest neutralino $\tilde{\chi}_1^0$
  - Interpolating function: Change from **short-range** ($m_{\tilde{\chi}_1^0} \gg p_F$) to **long-range** ($m_{\tilde{\chi}_1^0} \ll p_F$) behaviour
  - Region of parameter space excluded by $0\nu\beta\beta$ decay but compatible with collider constraints
  - Compared $(g-2)_\mu$ favoured region to collider and $0\nu\beta\beta$ excluded regions

# References


M. Hirsch, H. V. Klapdor-Kleingrothaus and S. G. Kovalenko

**Supersymmetry and neutrinoless double beta decay**

Phys. Rev. D, 53:1329-1348 (1996).

H. K. Dreiner, S. Heinemeyer, O. Kittel, U. Langenfeld, A. M. Weber and G. Weiglein

**Mass Bounds on a Very Light Neutralino**

Eur. Phys. J. C, 62:547-572 (2009).

M. González, M. Hirsch and S. Kovalenko

**QCD running in neutrinoless double beta decay: Short-range mechanisms**

Phys. Rev. D, 93(1):013017 (2016).

G. Aad et al.

**Search for electroweak production of charginos and sleptons decaying into final states with two leptons and missing transverse momentum in $\sqrt{s} = 13$ TeV pp collisions using the ATLAS detector**

Eur. Phys. J. C, 80(2):123 (2020)

T. Moroi

**The Muon anomalous magnetic dipole moment in the minimal supersymmetric standard model**

Phys. Rev. D 56, 4424 (1997).

B. Abi et. al.

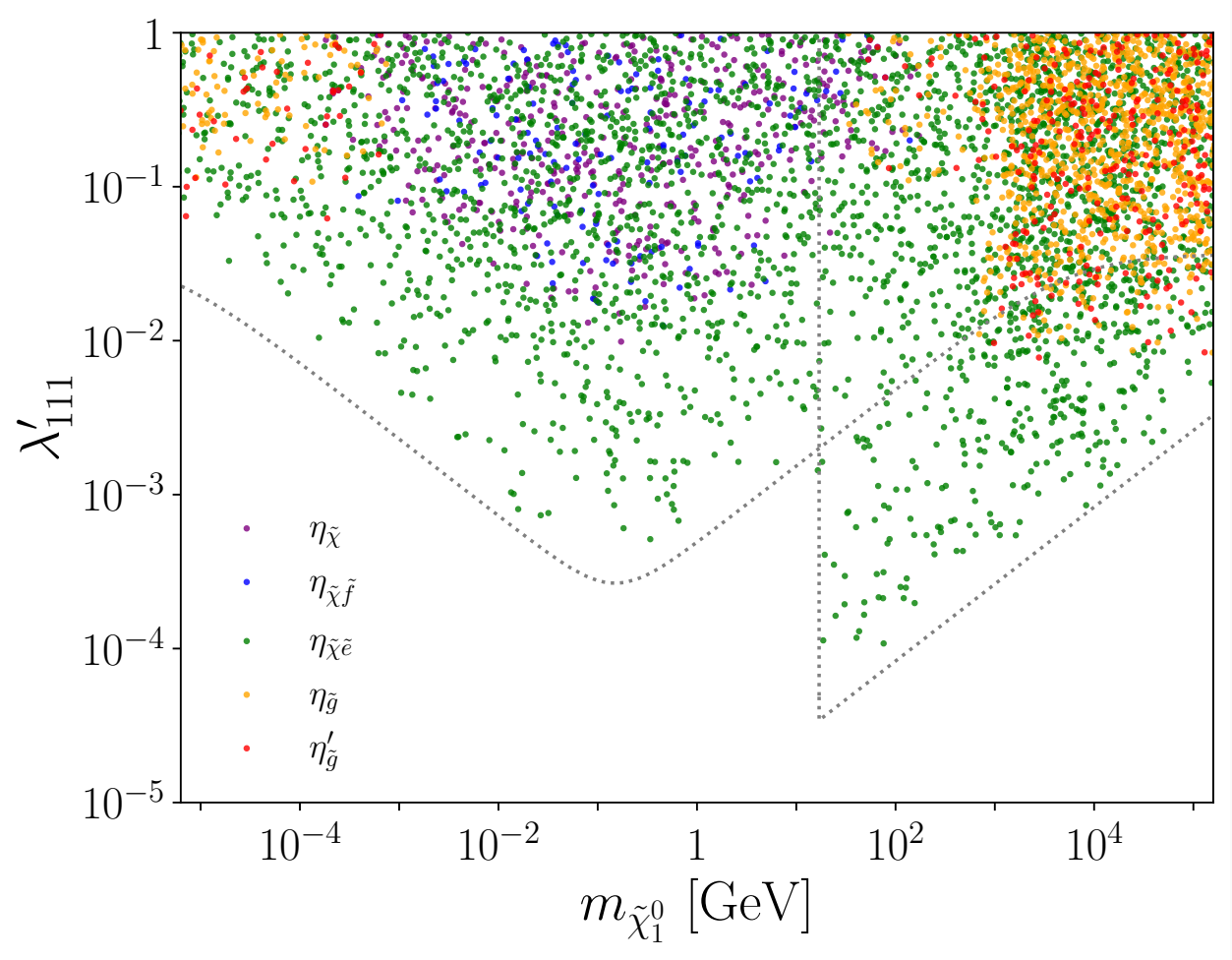
**Measurement of the Positive Muon Anomalous Magnetic Moment to 0.46 ppm**

Phys. Rev. Lett., 126(14):141801 (2021).

# Backup

# Parameter Scan

- Perform scan of the SUSY parameter space:
  - SUSY masses compatible with collider constraints (e.g. ATLAS, CMS)
  - $\lambda'_{111}$ values excluded by $0\nu\beta\beta$ decay
  - Determine $\eta$ factor which dominates. Selectron exchange most constraining



# Muon Anomalous Magnetic Moment

$$a_\mu^{\tilde{\chi}_1^0} \approx \frac{\alpha_Y}{6\pi} \frac{m_\mu^2 \, \mu \tan\beta}{m^3_{\tilde{\chi}_1^0}} \, G\left(\frac{m^2_{\tilde{e}_L}}{m^2_{\tilde{\chi}_1^0}}\right)$$