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

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① Introduction

In general, one can write down renormalisable terms in the supersymmetric (SUSY) superpotential that violate either lepton number (L) or baryon number (B), or so-called R-parity ($R_p = (-1)^{3B+L+2S}$, where S is the particle spin),

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

where L, E^c, Q, U^c and D^c are chiral superfields containing the SM fermions and their scalar SUSY partners.

It has long been known that the $\Delta L = 1$ λ' term contributes to neutrinoless double beta ($0\nu\beta\beta$) decay with the exchange of either a **neutralino** ($\tilde\chi_i^0$) or **gluino** ($\tilde g$) [1]. In the Minimal SUSY Standard Model (MSSM), the neutralinos are admixtures of the neutral fermionic SUSY partners of the $\mathrm{U}(1)_Y$ and $\mathrm{SU}(2)_L$ gauge bosons and Higgs doublets. The gluinos are the color-charged fermionic SUSY partners of the $\mathrm{SU}(3)_c$ gluons.

It is usually assumed that the lightest neutralino is lighter than the average momentum exchange of $0\nu\beta\beta$ decay, i.e. $m_{\tilde\chi_1^0} \gg p_F \sim 100$ MeV. However, indirect collider bounds on the lightest neutralino can be evaded so that it can be very light or even massless [2]. The $0\nu\beta\beta$ decay process can therefore display **short-range** ($m_{\tilde\chi_1^0} \gg p_F$) or **long-range** ($m_{\tilde\chi_1^0} \ll p_F$) behaviour.

② RPV Contribution to $0\nu\beta\beta$ Decay

- For a heavy neutralino, the presence of the R-parity violating (RPV) coupling λ'_{111} results in the **dimension-9** Lagrangian

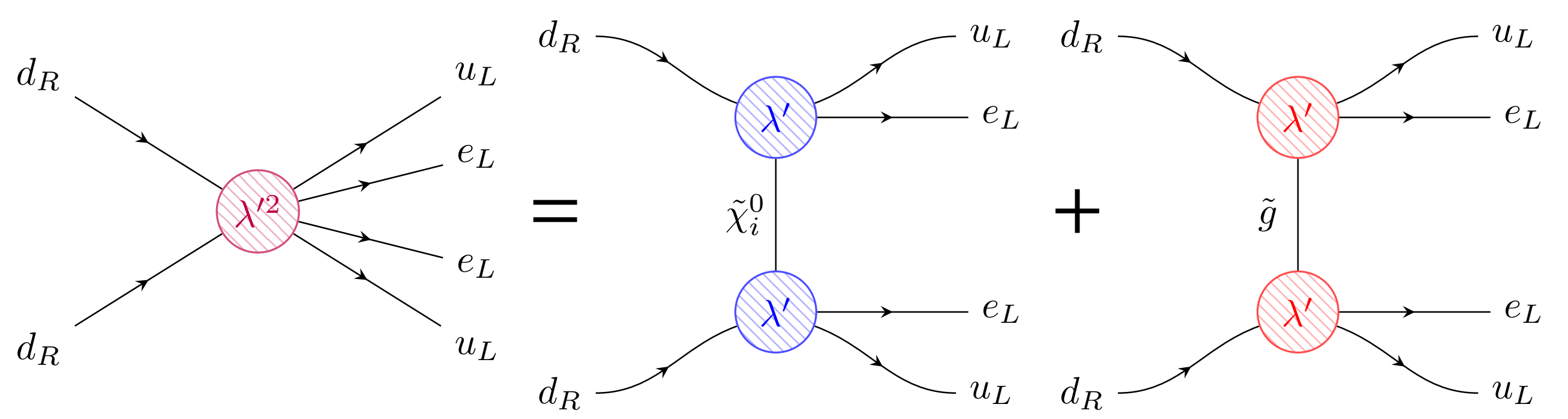
$$\mathcal{L}_9 = \frac{G_F^2 \cos^2\theta_C}{2m_p}\left(\epsilon_1^{RRL} J_R J_R + \epsilon_2^{RRL} J_R^{\mu\nu} J_{R\mu\nu}\right) j_L + \text{h.c.}\,,$$

where $j_L = \bar e\,(1+\gamma_5)\,e^c$, $J_R = \bar u\,(1+\gamma_5)\,d$ and $J_R^{\mu\nu} = \bar u \sigma^{\mu\nu}(1+\gamma_5)\,d$ for $\sigma_{\mu\nu} = \frac{i}{2}[\gamma_\mu,\gamma_\nu]$, i.e. **scalar** and **tensor** quark currents [1].

- The scalar and tensor coefficients can be decomposed as

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

where the $(\eta_{\tilde\chi}, \eta_{\tilde\chi\tilde e}, \eta_{\tilde\chi\tilde f})$ and $(\eta_{\tilde g}, \eta'_{\tilde g})$ factors encode the contributions from neutralino and gluino exchange diagrams respectively, i.e.



- The $0\nu\beta\beta$ decay half-life is then given by

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

where $G_{0\nu}$ is a phase space factor and $\mathcal{M}_1^{RR}$, $\mathcal{M}_2^{RR}$ are nuclear matrix elements.

- **QCD corrections** induce an RGE running and mixing of the coefficients ϵ_1^{RRL} and ϵ_2^{RRL} from the scale of new physics $\Lambda_{\text{NP}} \sim 1$ TeV to the QCD scale $\Lambda_{\text{QCD}} \sim 1$ GeV [3].

③ Collider Constraints and a Light Neutralino

- The factors $\eta_{\tilde\chi}, \eta_{\tilde\chi\tilde e}, \eta_{\tilde\chi\tilde f}, \eta_{\tilde g}$ and $\eta'_{\tilde g}$ depend on the selectron ($\tilde e_L$), up squark ($\tilde u_L$), down squark ($\tilde d_R$), neutralino and gluino masses.
- Collider experiments **ATLAS** and **CMS** have excluded portions of the SUSY partner mass parameter space via searches for e.g., $\tilde e_L \to e\tilde\chi_1^0$, $\tilde q \to q\tilde\chi_1^0$ and $\tilde g \to q\bar q\tilde\chi_1^0$ (missing E_T). Direct constraints on λ'_{111} can be made from measurements of $\boldsymbol{V_{ud}}$ and $\boldsymbol{R_\pi}$.

- To descibe the **long-range** behaviour of a light neutralino, we replace

$$\boxed{\eta_{\tilde\chi}, \eta_{\tilde\chi\tilde e}, \eta_{\tilde\chi\tilde f} \propto \frac{\lambda'^2_{111}}{m_{\tilde\chi_1^0}} \to \frac{\lambda'^2_{111} m_{\tilde\chi_1^0}}{\langle \mathbf{p}^2\rangle + m^2_{\tilde\chi_1^0}}}$$

where $\langle \mathbf{p}^2\rangle = 150$ MeV. A similar **interpolating** function can be used for a sterile neutrino N with mass m_N above or below p_F.

④ Bounds on SUSY Parameter Space from $0\nu\beta\beta$ Decay and Other Experiments

- Lower limit on the $0\nu\beta\beta$ half-life $(T_{1/2}^{0\nu})_{\text{exp}}$ can be related to the RPV prediction. The resulting inequality can be rearranged for λ'_{111},

$$(T_{1/2}^{0\nu})_{\text{exp}} < T_{1/2}^{0\nu} \quad\Rightarrow\quad \lambda'_{111} < F\left(m_{\tilde\chi_1^0}, m_{\tilde e_L}, m_{\tilde u_L}, m_{\tilde d_R}, m_{\tilde g}, (T_{1/2}^{0\nu})_{\text{exp}}\right)$$

i.e. an upper limit on λ'_{111} as a function of $(T_{1/2}^{0\nu})_{\text{exp}}$ and the SUSY masses.

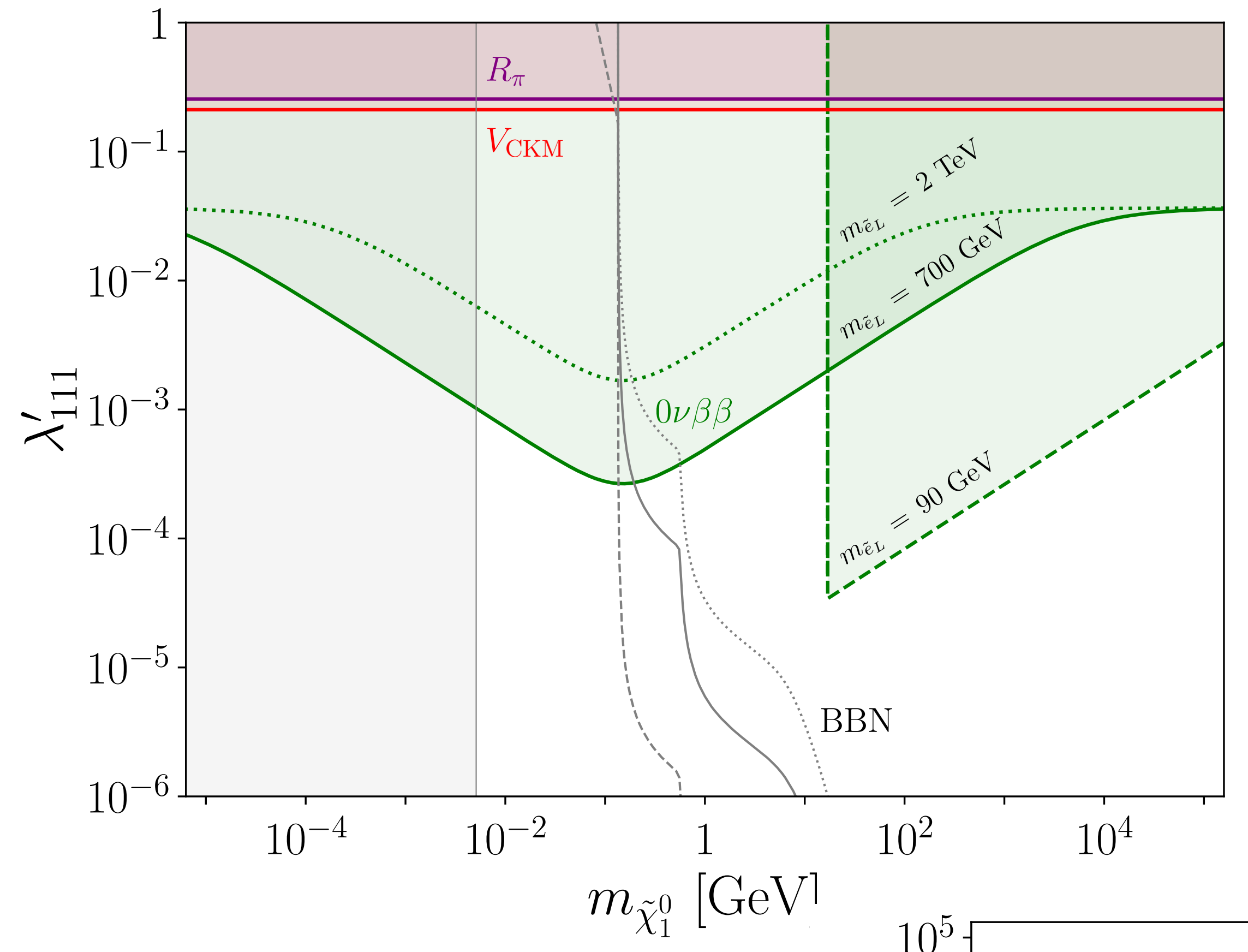
- **Parameter Scan**: Perform scan of SUSY masses allowed by collider experiments, with absolute lower limit from phenomenological MSSM analyses $\Rightarrow$ Find corresponding upper limit on λ'_{111}.
- Best $0\nu\beta\beta$ limits for $m_{\tilde e_L} = 700$ GeV (lower limit from ATLAS for $m_{\tilde\chi_1^0} = 0$ GeV) and $m_{\tilde e_L} = 90$ GeV (OPAL lower limit for $m_{\tilde\chi_1^0} > m_{\tilde e_L}$).

- Big Bang Nucleosynthesis (BBN): Naive limits by requiring the lifetime of the lightest neutralino be less than 1 second. Also depends on **gravitino** mass.

- $(g-2)_\mu$ anomaly has persisted at Fermilab g-2 experiment [6].
- For a neutralino and degenerate selectron and smuon, obtain

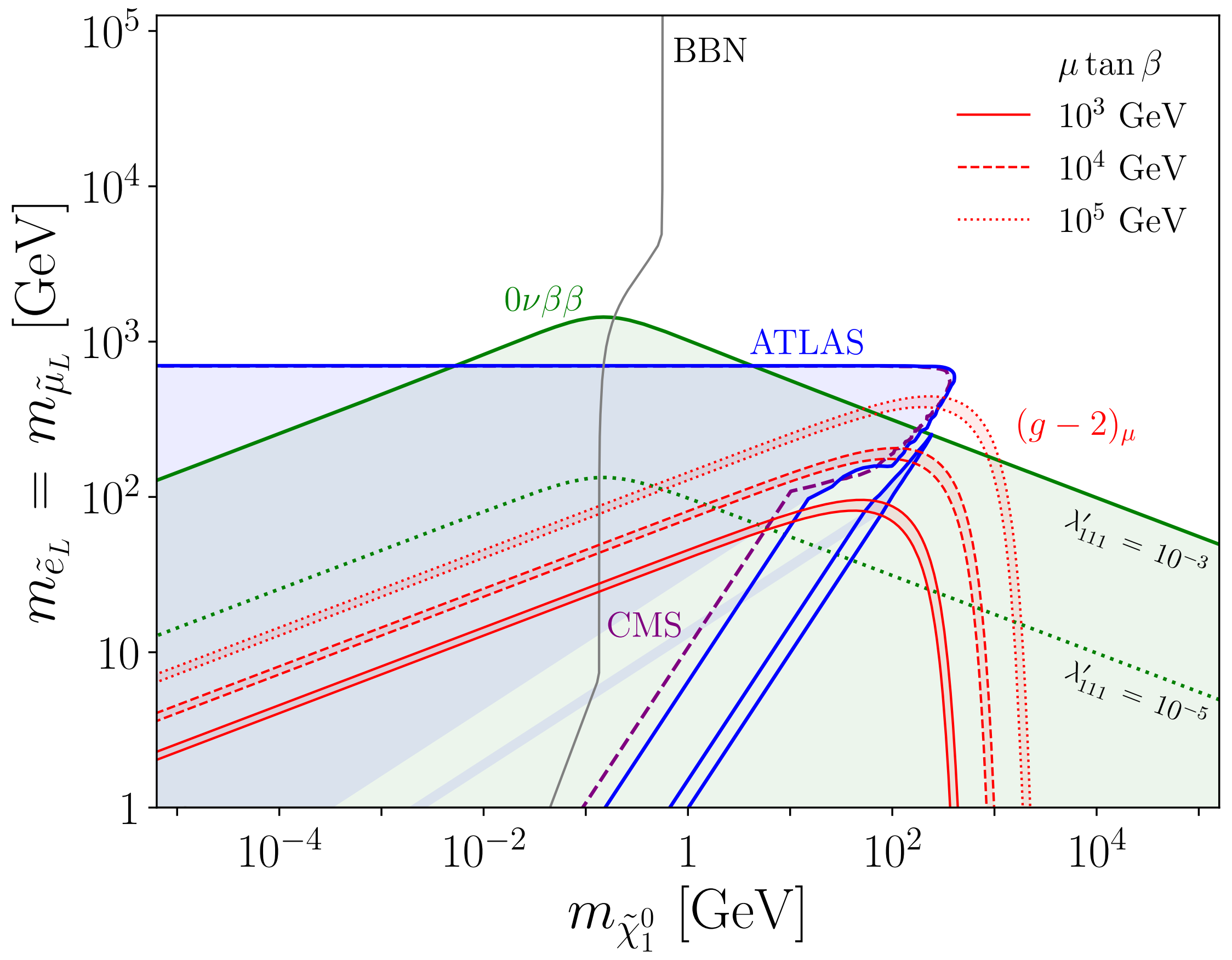
$$\Delta a_\mu^{\tilde\chi_1^0} \approx \frac{\alpha_Y}{6\pi}\frac{m_\mu^2\,\mu\tan\beta}{m^3_{\tilde\chi_1^0}}\, G\left(\frac{m^2_{\tilde e_L}}{m^2_{\tilde\chi_1^0}}\right),$$

where $G(x)$ is a loop function [5]. Defines a **favoured region** in $(m_{\tilde\chi_1^0}, m_{\tilde e_L})$ plane depending on MSSM parameters μ and $\tan\beta$.



Left: Exlcuded regions in $(m_{\tilde\chi_1^0}, \lambda'_{111})$ plane from BBN, $0\nu\beta\beta$ decay (shown for different selectron masses $m_{\tilde e_L}$), V_{ud} and R_π.

Right: Exlcuded regions in $(m_{\tilde\chi_1^0}, m_{\tilde e_L})$ plane from BBN, $0\nu\beta\beta$ decay (shown for different λ'_{111} values) and colliders compared to the $(g-2)_\mu$ favoured region.



⑤ Conclusions

To conclude, we have performed a detailed study of the **RPV** contribution to $0\nu\beta\beta$ decay with an arbitrary mass lightest **neutralino** $\tilde\chi_1^0$. Previous studies have only considered neutralinos more massive than the average momentum exchange of $0\nu\beta\beta$ decay, $p_F \sim 100$ MeV. We made use of an **interpolating** function to encapsulate the change from short-range ($m_{\tilde\chi_1^0} \gg p_F$) to long-range ($m_{\tilde\chi_1^0} \ll p_F$) behaviour depending on the $\tilde\chi_1^0$ mass.

In deriving constraints on the RPV coupling λ'_{111} as a function of $m_{\tilde\chi_1^0}$, we performed a scan over the relevant SUSY masses allowed by collider constraints. We compared the $0\nu\beta\beta$ decay constraints to naive limits from BBN and the region favoured by the $(g-2)_\mu$ anomaly.

References

[1] M. Hirsch, H. V. Klapdor-Kleingrothaus and S. G. Kovalenko, Phys. Rev. D, 53:1329-1348 (1996).
[2] H. K. Dreiner, S. Heinemeyer, O. Kittel, U. Langenfeld, A. M. Weber and G. Weiglein, Eur. Phys. J. C, 62:547-572 (2009).
[3] M. González, M. Hirsch and S. Kovalenko, Phys. Rev. D, 93(1):013017 (2016).
[4] G. Aad et al., Eur. Phys. J. C, 80(2):123 (2020).
[5] T. Moroi, Phys. Rev. D 56, 4424 (1997).
[6] B. Abi et. al., Phys. Rev. Lett., 126(14):141801 (2021).

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