Lighting up the LHC with Dark Matter

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Based on 2303.01523 in collaboration with
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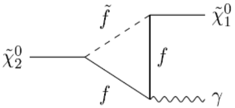
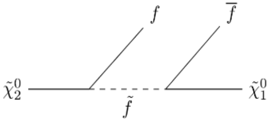
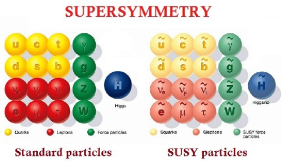


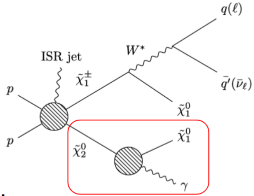


Dark matter, $(g_\mu - 2)$, and LHC searches in MSSM

We evaluate the region of parameter space where the electroweak sector of Minimal Supersymmetric Standard Model (MSSM) explains the origin of dark matter, and the $(g_\mu - 2)$ anomaly simultaneously. An interesting, previously unexplored photon signal is found to be prominent in this region, while the conventionally searched multi-lepton final state is suppressed.

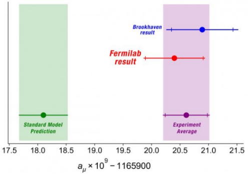


In the LHC



Dark Matter

Muon's anomalous magnetic moment



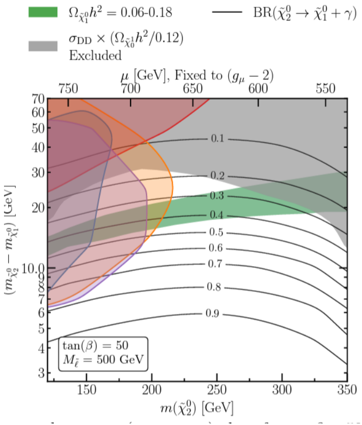
Lightest neutralino as dark matter candidate

The observed dark matter relic density is $\Omega h^2 \simeq 0.12$, which sets an upper bound for every dark matter candidate.

- In the parameter space that explains dark matter and $(g_\mu - 2)$ and satisfies all the experimental constraints, the lightest neutralino is $\tilde{\chi}_1^0 \approx \widetilde{B}$ [superpartner of the SM $U(1)$ gauge boson].
- In this case, the annihilations among the $\tilde{\chi}_1^0$ itself are known to be insufficient to produce the right dark matter relic density.
- Therefore, we resort to the co-annihilations involving the second lightest neutralino or the lightest chargino:

$$\tilde{\chi}_1^0 \leftrightarrow \tilde{\chi}_2^0 \tilde{\chi}_2^0 \to f\bar{f} \text{ (or } \tilde{\chi}_1^{\pm} \tilde{\chi}_1^{\mp} \to f\bar{f}\text{)}$$

For the conversion in the first step to happen, the masses of $\tilde{\chi}_1^0$ and $\tilde{\chi}_2^0(\tilde{\chi}_1^{\pm})$ should be close, which is the so-called "compressed region".



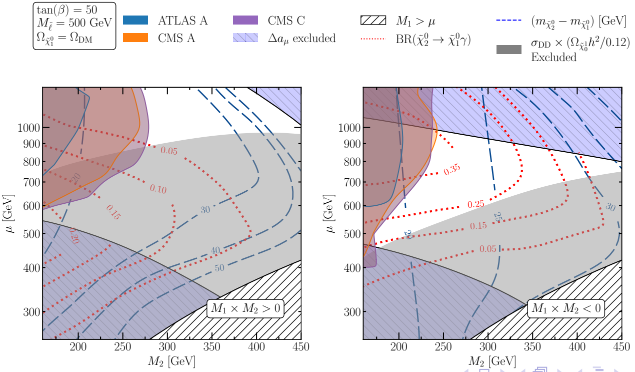
This plot is for $(M_1 \times M_2) < 0$. Color shaded regions on the left are excluded by LHC multi-lepton searches.

Constraints from DM direct detection

The direct detection cross section for $\tilde{\chi}_1^0$ relies on the signs of the SUSY breaking parameters M_1 (mass parameter for $\tilde{\chi}_1^0$) and μ (mass parameter for Higgsino $\widetilde{H}$):

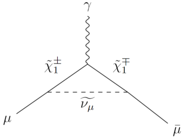
$$\mathcal{M}_p^{\mathrm{SI}} \propto \frac{v}{\mu^2}\left[2\frac{(M_1+\mu\sin 2\beta)}{m_h^2} - \frac{\mu\cos 2\beta\tan\beta}{m_H^2}\right] \approx \frac{v}{\mu^2}\left[2\frac{(M_1+2\mu/\tan\beta)}{m_h^2} + \frac{\mu\tan\beta}{m_H^2}\right]$$

The second approximation applies to large $\tan\beta$ needed to explain $(g_\mu - 2)$. There would be a cancellation between the two terms in the square bracket if $(M_1 \times \mu) < 0$, strongly suppressing the DD cross section.



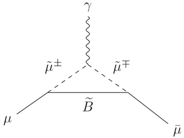
MSSM contribution to the muon's anomalous magnetic moment

The two leading MSSM contributions are the chargino-sneutrino loop ($a_\mu^{\tilde{\chi}^\pm}$) and the Bino-slepton loop ($a_\mu^{\tilde{\chi}^0}$). They are given approximately by



$$a_\mu^{\tilde{\chi}^\pm} \approx \frac{\alpha m_\mu^2 \mu M_2 \tan\beta}{4\pi \sin^2\theta_W m_{\tilde{\nu}_\mu}^2} \left[\frac{f_{\tilde{\chi}^\pm}(M_2^2/m_{\tilde{\nu}_\mu}^2) - f_{\tilde{\chi}^\pm}(\mu^2/m_{\tilde{\nu}_\mu}^2)}{M_2^2 - \mu^2} \right],$$

$$a_\mu^{\tilde{\chi}^0} \approx \frac{\alpha m_\mu^2 M_1 (\mu \tan\beta - A_\mu)}{4\pi \cos^2\theta_W \left(m_{\tilde{l}_R}^2 - m_{\tilde{l}_L}^2 \right)} \left[\frac{f_{\tilde{\chi}^0}(M_1^2/m_{\tilde{l}_R})}{m_{\tilde{l}_R}^2} - \frac{f_{\tilde{\chi}^0}(M_1^2/m_{\tilde{l}_L})}{m_{\tilde{l}_L}^2} \right],$$



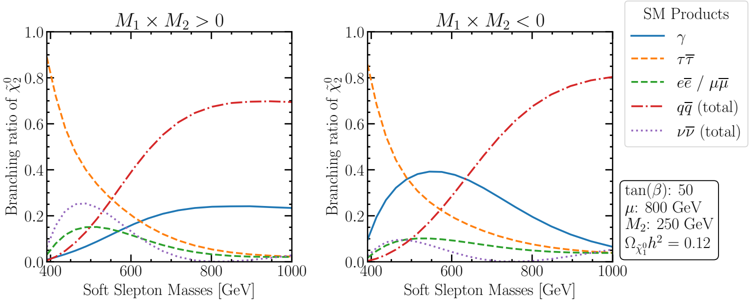
$a_\mu^{\tilde{\chi}^\pm}$ provides the dominant contribution. Hence to match $\Delta a_\mu = a_\mu^{\rm exp} - a_\mu^{\rm SM} \simeq 25.1 \times 10^{-10}$, μ and M_2 must have the same sign.

Summary: The explanations for dark matter and Δa_μ work optimally when

- $m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} \sim \mathcal{O}(10)$ GeV
- $M_1 \times M_2 < 0$

Decay patterns of the second neutralino

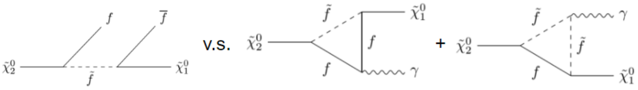
Numerical results for the decay branching ratios of the second neutralino $\tilde{\chi}_2^0$ to the lightest neutralino $\tilde{\chi}_1^0$ and other particles:



Observations:

- For light sleptons, $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \tau\bar{\tau}$ is the dominant channel ($\tilde{\tau}$ is the lightest slepton).
- For intermediate sleptons, $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \gamma$ becomes prominent for $M_1 \times M_2 < 0$, but not for $M_1 \times M_2 > 0$.
- For heavy sleptons, $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 q\bar{q}$ becomes dominant.

Understanding the enhancement of the radiative decay



Focusing on the compressed region, define the mass splitting parameter ε as

$$\varepsilon \equiv \frac{m_{\tilde{\chi}_2^0}}{m_{\tilde{\chi}_1^0}} - 1.$$

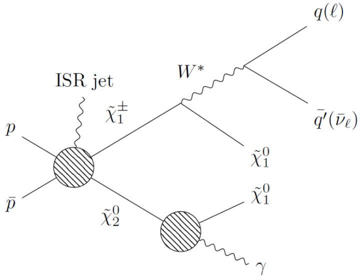
- Kinematic suppression: As the mass difference shrinks, the tree-level decay ($\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \ell\bar{\ell}$) is suppressed as $\sim \varepsilon^5$, while the loop-level radiative decay ($\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \gamma$) is suppressed as $\sim \varepsilon^3$. Therefore the loop-level decay becomes prominent in the compressed region.
- The dominant channel for radiative decay is mediated by $f - \tilde{f}$ loop, the effective coupling for which is

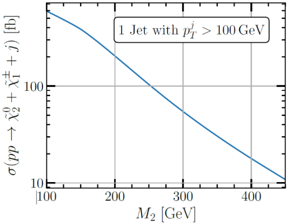
$$g_{\tilde{f}/f} \approx \frac{eg^2 m_{\tilde{\chi}_2^0}}{32\pi^2} \sum_f Q_f C_f \left(G_L F_R - G_R F_L\right) \left[(\xi_1 \times \xi_2) m_{\tilde{\chi}_2^0} \left(I_2 - K\right) - m_{\tilde{\chi}_1^0} K\right]$$

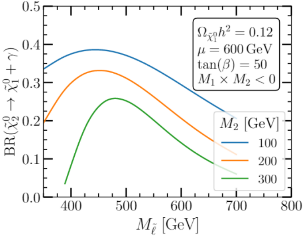
I_2 and K are the loop integrals, and $I_2 - K = K + \mathcal{O}(\varepsilon)$! Hence if the product of the signs of $m_{\tilde{\chi}_2^0}$ and $m_{\tilde{\chi}_1^0}$: $\xi_1 \times \xi_2 = -1$, the radiative decay gets enhanced.

LHC outlook

We therefore propose a new search channel:
A soft photon $[E \sim \mathcal{O}(m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0})]$ + missing E_T [boosted by a hard ISR jet]
to complement the existing SUSY searches for the multi-lepton final states.







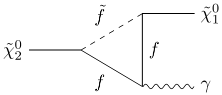
Conclusion

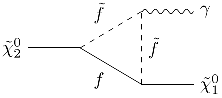
- We evaluate the paramater space where MSSM explains dark matter and the observed muon's magnetic moment simultaneously. We find that the explanation works optimally in the region where $(M_1 \times \mu) < 0$ and $(M_2 \times \mu) > 0$.
- In the region with $(M_1 \times M_2) < 0$, we find that the radiative decay of the second neutralino is significantly enhanced if the slepton mass is about 100-200 GeV heavier than the second neutralino. This observation is made in the numerical results, and explained by analytical analysis.
- Based on the observation above, we propose a new search channel for [a soft photon+missing transverse energy] to complement the existing SUSY searches for multi-lepton final states, which would enhance the reach of LHC in the region where MSSM explains both dark matter and $(g_\mu - 2)$.

Thanks!

Questions and comments are welcome :)

More on the radiative decay mediated by $f - \tilde{f}$ loop





Effective coupling:

$$g_{\tilde{f}/f} = \frac{eg^2 m_{\tilde{\chi}_2^0}}{32\pi^2} \sum_f Q_f C_f \left\{ (G_L F_R - G_R F_L) \left[(\xi_1 \times \xi_2) m_{\tilde{\chi}_2^0} (I_2 - K) - m_{\tilde{\chi}_1^0} K \right] \right.$$

$$\left. + \xi_1 m_f (G_L F_L - G_R F_R) I \right\} ,$$

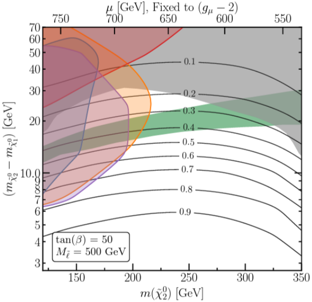
$$G_L F_R - G_R F_L = \mathbf{N}_1^- \mathbf{N}_2^- + 4 T_{3u} Q_u \tan\theta_W \left(\mathbf{N}_{11} \mathbf{N}_2^- + \mathbf{N}_{21} \mathbf{N}_1^- \right) ,$$

$$G_L F_L - G_R F_R = -\frac{2 m_u}{m_W \sin\beta} \left[\mathbf{N}_{14} \left(T_{3u} \mathbf{N}_2^- + Q_u \tan\theta_W \mathbf{N}_{21} \right) \right.$$

$$\left. - \mathbf{N}_{24} \left(T_{3u} \mathbf{N}_1^- + Q_u \tan\theta_W \mathbf{N}_{11} \right) - Q_u \tan\theta_W \left(\mathbf{N}_{24} \mathbf{N}_{11} - \mathbf{N}_{14} \mathbf{N}_{21} \right) \right] ,$$

$G_L F_L - G_R F_R$ is suppressed by the light fermion mass m_u (up-type fermion), and the small mixing between electroweakinos and Higgsinos. Hence $g_{\tilde{f}/f}$ is dominated by the first line.

Varying $\tan\beta$ and $M_{\tilde{l}}$



Observed DM relic density is obtained in the green band. Grey region is excluded by DM direct detection. Black contours are BRs of radiative decay. Color shaded regions on the left are excluded by LHC searches. The plots shown here are all for $(M_1 \times M_2) < 0$.