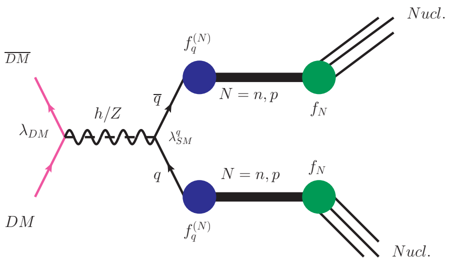
Prospects for Direct Searches of Neutralino Dark Matter through Next-to-Leading Order Corrections to the Direct Detection Cross-Sections

Subhadip Bisal

Institute of Physics, Bhubaneswar, India

July 10, 2024



- Several **simple** extensions of SM (e.g. Z-portal, H-portal, Z'-portal etc.) have been proposed to explain the **DM** phenomenology.
- The **Higgs portal** models $\Rightarrow$ most relevant in SI DD for many favoured **BSM** scenarios (e.g. **SUSY**).

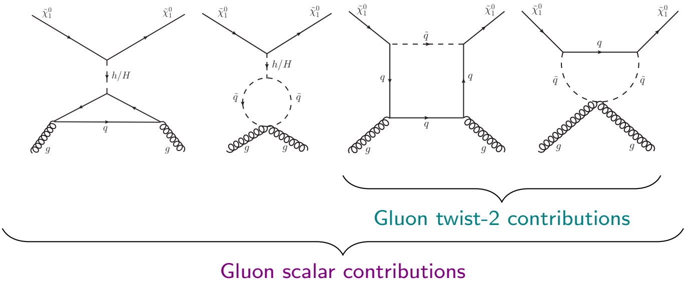
The generic Lagrangian for DM DD

$$\mathcal{L}^{\rm eff}_q = \underbrace{\boxed{\lambda_q m_q \bar{\tilde\chi}^0_1 \tilde\chi^0_1 \bar q q}}_{\text{Scalar quark (SI)}} + \underbrace{\eta_q \bar{\tilde\chi}^0_1 \gamma^\mu \gamma_5 \tilde\chi^0_1 \bar q \gamma_\mu \gamma_5 q}_{\text{Axial vector term (SD)}} + \underbrace{\frac{g_q^{(1)}}{m_{\tilde\chi^0_1}} \bar{\tilde\chi}^0_1 i\partial^\mu \gamma^\nu \tilde\chi^0_1 \mathcal{O}^q_{\mu\nu} + \frac{g_q^{(2)}}{m^2_{\tilde\chi^0_1}} \bar{\tilde\chi}^0_1 (i\partial^\mu)(i\partial^\nu) \tilde\chi^0_1 \mathcal{O}^q_{\mu\nu}}_{\text{Quark twist-2 (SI, SD)}}$$

$$\mathcal{L}^{\rm eff}_g = \underbrace{\boxed{\lambda_G \bar{\tilde\chi}^0_1 \tilde\chi^0_1 G^a_{\mu\nu} G^{a\,\mu\nu}}}_{\text{Scalar gluon (SI)}} + \underbrace{\frac{g_G^{(1)}}{m_{\tilde\chi^0_1}} \bar{\tilde\chi}^0_1 i\partial^\mu \gamma^\nu \tilde\chi^0_1 \mathcal{O}^g_{\mu\nu} + \frac{g_G^{(2)}}{m^2_{\tilde\chi^0_1}} \bar{\tilde\chi}^0_1 (i\partial^\mu)(i\partial^\nu) \tilde\chi^0_1 \mathcal{O}^g_{\mu\nu}}_{\text{Gluon twist-2 (SI)}}$$

$$\mathcal{O}^q_{\mu\nu} = (i/2)\bar q \left[\partial_\mu \gamma_\nu + \partial_\nu \gamma_\mu + (1/2) g_{\mu\nu} \not\partial\right] q$$

- MicrOMEGAs calculates the DM DD via LO DM-neucleon interactions
- MicroMEGAs include the following loop diagrams:



- No DM-Higgs vertex corrections are included in MicroMEGAs.
- There may be significant radiative corrections from DM-Higgs vertex for a doublet/triplet/mixed doublet-triplet DM.

Upshots

- The LO neutralino-Higgs interactions
- The relevant Feynman diagrams for NLO calculations
- Renormalization of the neutralino-Higgs vertex at NLO
- Flow chart for the calculations
- Bino-, Wino-, and Higgsino-like DM

- *"Naturalness"* requires $\Longrightarrow \mu \lesssim 1$ TeV, $m_{\tilde{t}} \lesssim 1$ TeV and $m_{\tilde{q},\tilde{g}} \lesssim 2-3$ TeV. Taking M_1, M_2 in the multi-TeV scale, this scenario leads to the Higgsino-like LSP $\Longrightarrow$ We constrain the μ-parameter from DM DD searches.

- WEAKER constraints from the Electroweakino searches at the LHC.

- In other scenarios: $M_1 < \mu, M_2 \lesssim \mathcal{O}(\mathrm{TeV}) \Longrightarrow$ Bino-like LSP with Higgsino and Wino admixture $\Longrightarrow$ We constrain the Bino-Higgsino mixing.

- In Bino-like LSP scenario, light Electroweakino states help to satisfy $(g-2)_\mu$.

- A Wino-like LSP scenario (M_2 is lighter) accomodates *New Physics* at high scale.

- The LHC constraints are much more STRONGER in the mixed Bino-like LSP than the Higgsino-like or Wino-like case.

P. Nath et al, U. Chattopadhyay et al
R. Barbieri et al, G.F. Giudice et al
H. Baer et al, N. Arkani-Hamed et al.

- For a Bino-like LSP,

$$C^{\rm LO}_{L,R}(h) = -\frac{g_2}{2}\, t_W \,\frac{M_Z s_W}{\mu^2 - M_1^2}\,(\mu s_\alpha - M_1 c_\alpha)$$

- For a Wino-like LSP,

$$C^{\rm LO}_{L,R}(h) = -\frac{g_2}{2}\,\frac{M_W}{M_2^2 - \mu^2}\,(M_2 + \mu s_{2\beta})$$

- For a Higgsino-like LSP,

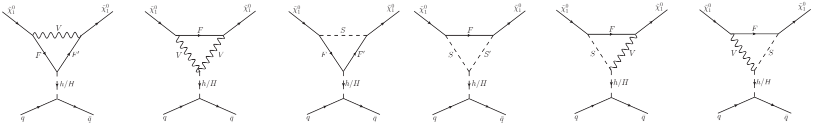
$$C^{\rm LO}_{L,R}(h) = \mp\frac{t_W^2}{2}\,\frac{M_W}{M_1 - |\mu|}\,(1 \pm \sin 2\beta) \mp \frac{1}{2}\,\frac{M_W}{M_2 - |\mu|}\,(1 \pm \sin 2\beta)$$

- For a PURE (i.e., NO MIXING) Bino/Wino/Higgsino LSP, $\boxed{C^{\rm LO}_{L,R} = 0}$ $\Longrightarrow$ No SI DD cross-sections at the tree-level.

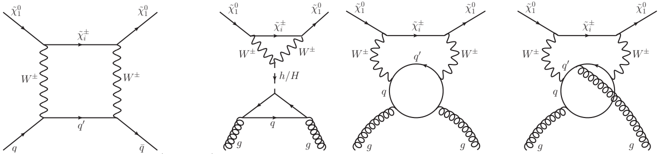
- The neutralino-Higgs couplings may be generated through *Radiative Corrections* $\Longrightarrow$ non-zero SI DD cross-sections.

- Non-zero mixing $\Longrightarrow$ tree-level $\tilde{\chi}_1^0\tilde{\chi}_1^0 h_i$ coupling $\Longrightarrow$ renormalization of $\tilde{\chi}_1^0\tilde{\chi}_1^0 h_i$ at one-loop becomes necessary.

Relevant Topologies



Quark scalar contributions



Quark twist-2 contributions

Gluon twist-2 and scalar contributions

- Total vertex corrections $\Longrightarrow$ $\boxed{\Gamma_{\tilde{\chi}_1^0\tilde{\chi}_1^0 h_i} = C_L^{1\mathrm{L}} \mathrm{P_L} + C_R^{1\mathrm{L}} \mathrm{P_R}}$

J. Hisano et al, J. Ellis et al
M. Drees et al, M. Cirelli et al,
S. Bisal et al.

- OS scheme: The masses of $\tilde{\chi}^{\pm}_{1,2}$ and one of the $\tilde{\chi}^0_n$ $(n \in \{1, \ldots, 4\})$ are defined as the pole of the propagator $\Longrightarrow$ CCN[n] scheme (according to FormCalc notation)

- Bino-like LSP: $M_1 < \mu < M_2$ or $M_1 < M_2 < \mu$ $\Longrightarrow$ CCN[1] scheme

- Wino-like LSP: $M_2 < \mu < M_1$ or $M_2 < M_1 < \mu$ $\Longrightarrow$ CCN[2] scheme

- Higgsino-like LSP: $\mu < M_2 < M_1$ or $\mu < M_1 < M_2$ $\Longrightarrow$ CCN[4] scheme

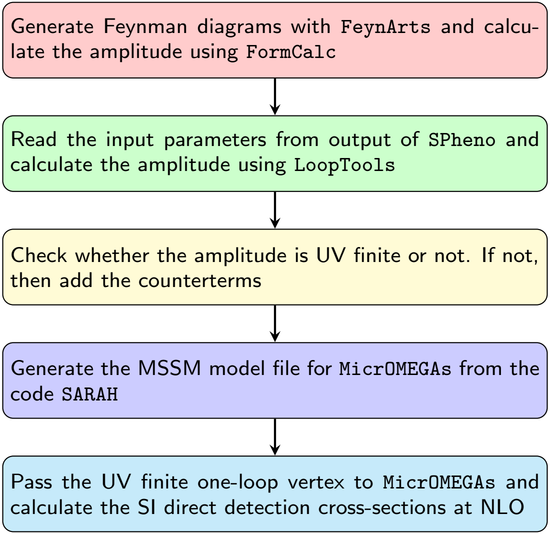
- The counterterms can be written as:

$$\delta\Gamma_{\tilde{\chi}^0_1\tilde{\chi}^0_1 h_i} = \mathrm{P_L}\,\delta C^{L}_{\tilde{\chi}^0_1\tilde{\chi}^0_1 h_i} + \mathrm{P_R}\,\delta C^{R}_{\tilde{\chi}^0_1\tilde{\chi}^0_1 h_i}$$

- Finally, the NLO vertex can be expressed as:

$$\Gamma^{\rm NLO} = \mathrm{P_L}\left(C_L^{\rm LO} + C_L^{\rm 1L} + \delta C_L\right) + \mathrm{P_R}\left(C_R^{\rm LO} + C_R^{\rm 1L} + \delta C_R\right)$$

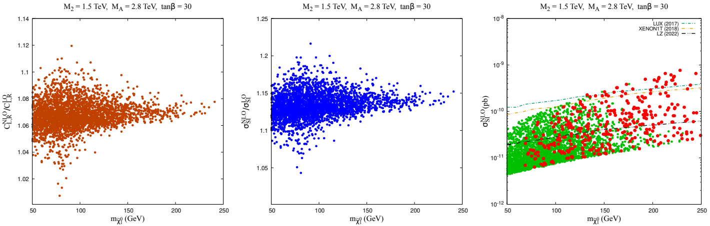
H. Eberl et al, T. Fritzsche et al
M. Drees et al, S. Heinemeyer et al
A. Chatterjee et al, A. Bharucha et al.


Generate Feynman diagrams with FeynArts and calculate the amplitude using FormCalc
Read the input parameters from output of SPheno and calculate the amplitude using LoopTools
Check whether the amplitude is UV finite or not. If not, then add the counterterms
Generate the MSSM model file for MicrOMEGAs from the code SARAH
Pass the UV finite one-loop vertex to MicrOMEGAs and calculate the SI direct detection cross-sections at NLO

Bino-like DM

- For Bino-Higgsino DM:

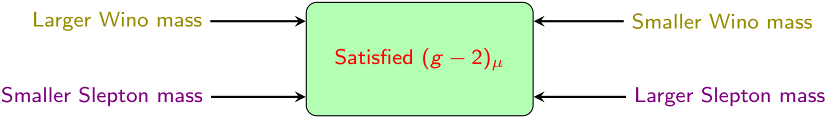
$$50 \le M_1 \le 300, \;\; 400 \le \mu \le 1000, \;\; 100 \le m_{\tilde{\mu}_L, \tilde{\mu}_R} \le 350, \;\; 100 \le m_{\tilde{e}_L, \tilde{e}_R} \le 350 \; .$$

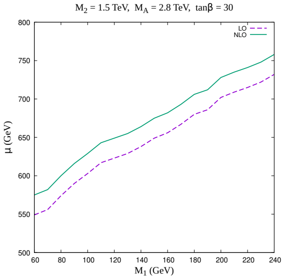


- The NLO cross-section: $\sigma_{\rm SI}^{\rm NLO} = \sigma_{\rm SI}^{\rm LO} \dfrac{(C_{L,R}^{\rm NLO})^2}{(C_{L,R}^{\rm LO})^2} \simeq \sigma_{\rm SI}^{\rm LO} \left[1 + \dfrac{2C_{L,R}^{\rm 1L}}{C_{L,R}^{\rm LO}} + \dfrac{2\delta C_{L,R}}{C_{L,R}^{\rm LO}} \right].$
- All the points satisfy the B-physics constraints, done using SPheno
- All the points satisfy $(g-2)_\mu$, done using SPheno
- Red points satisfy the present SUSY search constraints, done using SModelS
- Enhancement in the cross-section $\sim 20\%$

Bino-like DM: Constraints on μ parameter

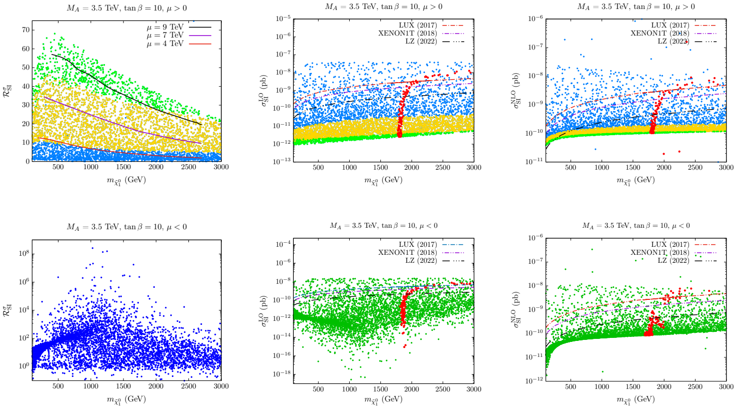
- For Bino-Wino-Higgsino DM:
  Wino is varried between Bino and Higgsino $\Longrightarrow$ $150 \leq M_2 \leq 600$
- Enhancement in the cross-section $\sim 20\%$
- In both cases, Bino-fraction $\geq 97\%$
- $(g-2)_\mu$ can be satisfied in two ways:





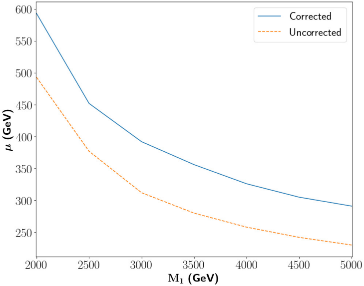
The value of μ shifts upwards by $\sim$ 25 GeV to satisfy the SI direct detection, relic density, B-physics constraints, and $(g-2)_\mu$

Wino-like DM



- $\boxed{\text{For } \mu > 0,\ \mathcal{R}^{\sigma}_{\rm SI} = \left.\frac{\sigma^{\rm NLO}_{\rm SI}}{\sigma^{\rm LO}_{\rm SI}}\right|_{Max.} = 70}$; $\boxed{\text{For } \mu > 0,\ \mathcal{R}^{\sigma}_{\rm SI} = \left.\frac{\sigma^{\rm NLO}_{\rm SI}}{\sigma^{\rm LO}_{\rm SI}}\right|_{Max.} = 10^7}$
- The LO coupling can be made 0 for $\mu < 0$, it maximizes the NLO corrections.
- For $\mu < 0$, the *Blind Spots* dissapears after NLO corrections.

(Appearing soon in arXiv)



The value of μ shifts upwards by $\sim 60 - 100$ GeV to satisfy the SI direct detection

- For $M_1 = 2$ TeV ($\tan\beta = 10$, $M_A \simeq 1.5$ TeV) $\Longrightarrow$ $\boxed{\mu \lesssim 493 \text{ GeV}}$ is EXCLUDED by LZ experiment when the LO $\tilde{\chi}_1^0\tilde{\chi}_1^0 h$ vertex is used to calculate the DD cross-section.
- When the NLO corrected $\tilde{\chi}_1^0\tilde{\chi}_1^0 h$ vertex is used $\Longrightarrow$ $\boxed{\mu \lesssim 593 \text{ GeV}}$.
- Similarly, for $M_1 = 5$ TeV, the μ bound shifts from 230 GeV to 291 GeV.

Conclusions

- We have assumed the neutralino LSP to be the DM candidate and calculated the DD cross-sections at NLO.

- A Bino-like DM can be as light as $\mathcal{O}(100)$ GeV while simultaneously satisfying the B-physics constraints, DD, LHC constraints, and $(g-2)_\mu$.

- The NLO corrections to the DD cross-sections is up to $\sim 20\%$ for a Bino-like DM and $\sim 50\%$ for a Higgsino-like DM. Also, the shift of μ parameter ~ 25 GeV and $\sim 60 - 100$ GeV can be observed for a Bino- and Higgsino-like DM, respectively.

- For a Wino-like DM, the NLO corrections can be ~ 70 times the LO cross-section for $\mu > 0$ and up to $\sim 10^7$ times for $\mu < 0$. For $\mu < 0$, the Blind Spots at LO cross-sections can be removed after including the NLO corrections.

THANK YOU

FOR YOUR ATTENTION