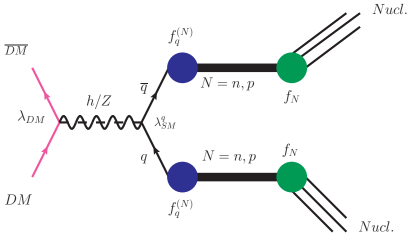
Direct Searches of High-Scale SUSY Dark Matter through NLO Corrections to the Direct Detection Cross-Sections

Subhadip Bisal

Institute of Physics, Bhubaneswar, India

January 25, 2025



- 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

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

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

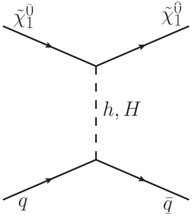
G. Jungman et. al.: Phys.Rept. 267 (1996) 195-373
M. Drees et. al.: Phys. Rev. D 48 (1993) 3483–3501, Phys. Rev. D 48 (1993) 3483–3501
J. Hisano et. al.: Phys. Rev. D 71 (2005) 015007, Phys. Lett. B 646 (2007) 34–38

MSSM:

- A minimal supersymmetric extension of the SM.
- Predicts sparticles (superpartners) for all SM particles.
- Extends Higgs sector $\Longrightarrow h, H, A, H^{\pm}$

Neutralino: Key Candidate for Dark Matter

- A mixture of superpartners of neutral gauge bosons and Higgs bosons:
  - Bino ($\tilde{B}$): Superpartner of the $U(1)_Y$ gauge boson.
  - Wino ($\tilde{W}$): Superpartner of the $SU(2)_L$ neutral gauge boson.
  - Higgsinos ($\tilde{H}_u^0, \tilde{H}_d^0$): Superpartners of the neutral Higgs bosons.
- MSSM predicts four neutralinos: $\tilde{\chi}_i^0$ $(i = 1, \ldots, 4)$, ordered by increasing mass.
- The composition of the lightest neutralino depends on MSSM parameters M_1, M_2, and μ.
  - $M_1 < M_2, \mu \Longrightarrow$ **Bino-dominated.**
  - $M_2 < M_1, \mu \Longrightarrow$ **Wino-dominated.**
  - $\mu < M_1, M_2 \Longrightarrow$ **Higgsino-dominated.**



- DM-nucleon scattering arises from Higgs boson or $\underbrace{\text{Squark exchange}}_{\textbf{Suppressed due to heavier masses}}$ at tree-level.

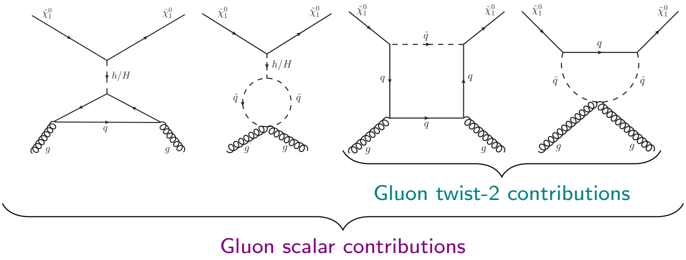
- The amplitude for Higgs exchange:

$$f_q[h,H] = (\text{Pre-factors}) \left[\frac{C_{h\tilde{\chi}_1^0\tilde{\chi}_1^0} C_{hqq}}{m_h^2} + \frac{C_{H\tilde{\chi}_1^0\tilde{\chi}_1^0} C_{Hqq}}{m_H^2} \right]$$

- SI direct detection cross-section: $\boxed{\sigma_{\rm SI} \propto \left| f_q[h,H] \right|^2}$

Theoretical calculations using MicrOMEGAs

- MicrOMEGAs calculates the DM DD via tree-level DM neucleon interactions and a few one-loop corrections.
- MicroMEGAs include the following loop diagrams:



- The squark-mediated diagrams are **suppressed** due to their heavier masses.
- No DM-Higgs vertex corrections are included in MicroMEGAs.

G. Belanger et. al.: Comput.Phys.Commun.180:747-767,2009
G. Belanger et. al.: Comput.Phys.Commun. 176 (2007) 367-382

The Wino-like DM

- For $M_2 < \mu, M_1 \implies$ Wino-like LSP with Higgsino and Bino admixture.
- Satisfy relic density at $\sim 2-3$ TeV.
- A Wino-like LSP scenario accomodates *New Physics* at high scale.
- For heavy Winos, the mixing with Higgsinos is small.
- The Wino-like $\tilde{\chi}_1^0$ is highly degenerate with $\tilde{\chi}_1^\pm$ for heavy Winos $\implies \delta m(\tilde{\chi}_1^0, \tilde{\chi}_1^\pm)$ is calculated from *Radiative Correction* ($\simeq 160$ MeV).
- The spin-independent direct detection for a Wino-like DM is very small at the leading order.
- We study the LSP-nucleon elastic scattering at the Next-to-Leading Order in the light of DM direct detection.

K.L. Chan, U.Chattopadhyay et. al.: Phys.Rev.D58:096004,1998
U.Chattopadhyay et. al. :Phys. Rev. D 75 (2007) 073014, JHEP 09 (2017) 064
R. BARBIERI, G.F. GIUDICE: Nuclear Physics B306 (1988) 63-76
H. Baer et. al.:Phys.Rev.Lett. 109 (2012) 161802
N. Arkani-Hamed et. al.: Nuclear Physics B 741 (2006) 108–130
H.Eberl et. al.: e, Phys. Rev. D 64 (2001) 115013

The LO Neutralino-Higgs Couplings

- 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,

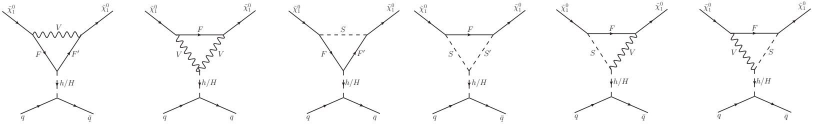
$$C^{\rm LO}_{L,R}(h) = \mp\frac{t_W^2}{2}\,\frac{M_W}{M_1 - |\mu|}\,(1 \pm \sin 2\beta) \mp \frac{1}{2}\,\frac{M_W}{M_2 - |\mu|}\,(1 \pm \sin 2\beta)$$

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

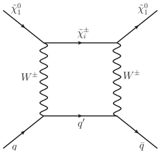
- The neutralino-Higgs couplings may be generated through *Radiative Corrections* $\Longrightarrow$ non-zero SI DD cross-sections.

- 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.

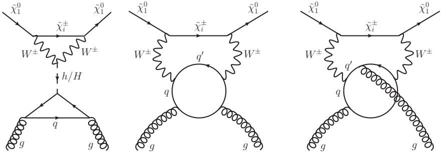
Relevant Topologies



Quark scalar contributions



Quark twist-2 contributions



Gluon twist-2 and scalar contributions

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

J. Hisano et al: Phys.Lett.B690:311-315,2010
J. Hisano et al: Phys.Rev. D87 (2013) 035020
J. Hisano et al: JHEP 07 (2011) 005
S. Bisal et al: Phys.Rev.D 110 (2024) 2, 023043
S. Bisal et al: Phys.Rev.D 110 (2024) 1, 015021

Renormalizations of neutralino-Higgs vertex at NLO

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

- Bino-like LSP: $\boxed{M_1 < \mu < M_2}$ or $\boxed{M_1 < M_2 < \mu}$ $\Longrightarrow$ $\boxed{\texttt{CCN[1]}}$

- Wino-like LSP: $\boxed{M_2 < M_1 < \mu}$ or $\boxed{M_2 < \mu < M_1}$ $\Longrightarrow$ $\boxed{\texttt{CCN[2] or CCN[4]}}$

- Higgsino-like LSP: $\boxed{\mu < M_1 < M_2}$ or $\boxed{\mu < M_2 < M_1}$ $\Longrightarrow$ $\boxed{\texttt{CCN[3] or CCN[4]}}$

- Suitable choice of the renormalization scheme is necessary to avoid large unphysical contributions.

- 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:

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

H. Eberl et al: Phys.Rev. D64 (2001) 115013, T. Fritzsche et al: Eur.Phys.J.C24:619-629,2002
M. Drees et al: JHEP02(2007)032, S. Heinemeyer et al: Eur.Phys.J. C72 (2012) 1892
A. Chatterjee et al: Phys.Rev.D 86 (2012) 105025, A. Bharucha et al: Phys.Rev. D86 (2012) 075023

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

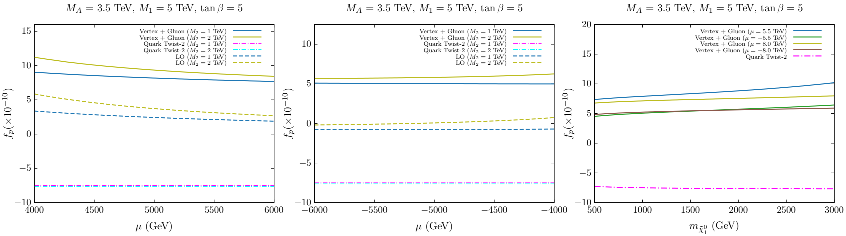
↓

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

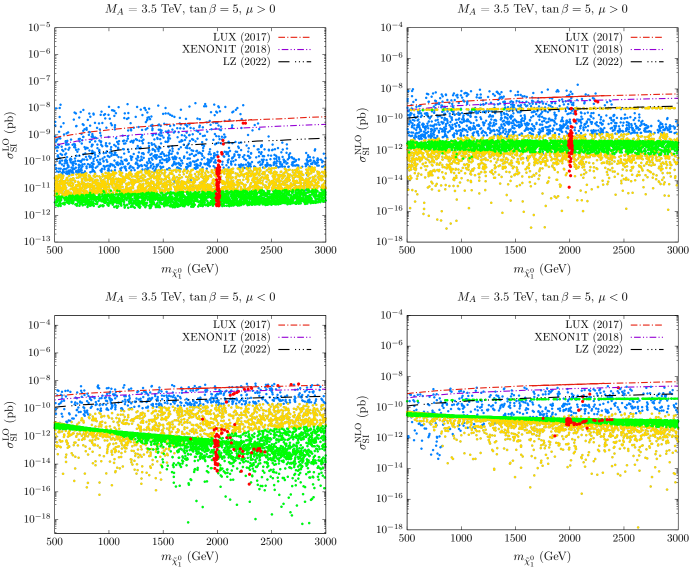
DM-nucleon amplitude



- Strong cancellation between Vertex+Gluon and Quark Twist-2 contributions.
- For $\mu > 0$, **maximum cancellations** occur at
  (i) $\mu = 5.5$ TeV, $m_{\tilde{\chi}_1^0} \simeq 500$ GeV, (ii) $\mu = 8.0$ TeV, $m_{\tilde{\chi}_1^0} \simeq 2.25$ TeV
  $\Longrightarrow$In both cases **Higgsino fraction** $\sim 0.02\%$
- Larger μ values $\Longrightarrow$ *Blind Spot* at larger $m_{\tilde{\chi}_1^0}$.
- For $\mu < 0$, LO amplitude reaches its minimum $\Longrightarrow$ $\boxed{M_2 + \mu \sin(2\beta) = 0}$
- LO *Blind Spot* occurs at
  (i) $M_2 = 1$ TeV, $\mu = -2.6$ TeV, (ii) $M_2 = 2.5$ TeV, $\mu = -6$ TeV
- The LO *Blind Spots* can be disappeared after NLO corrections.
- NEW *Blind Spots* appear at NLO.

SB, A. Chatterjee, D. Das, S.A. Pasha, Arxiv: 2410.18206

Wino-like DM



SB, A. Chatterjee, D. Das, S.A. Pasha, Arxiv: 2410.18206

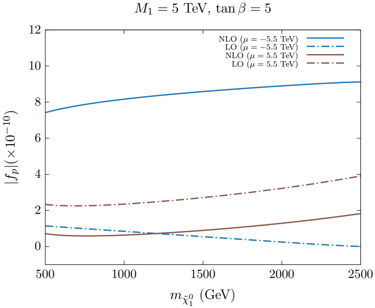
Summary

- We have assumed the Wino-like LSP to be the DM candidate and calculated the DD cross-sections at NLO.
- For a Wino-like DM, the NLO corrections can be ~ 7 times the LO cross-section for $\mu > 0$ and up to $\sim 10^4$ times for $\mu < 0$.
- For $\mu > 0$, there are no LO blind spots but appear at NLO.
- For $\mu < 0$, LO blind spots appear but disappear after NLO corrections. New blind spots appear at NLO.
- In some parameter space for $\mu < 0$, the SI cross-sections enhance significantly, making it potentially detectable in the next generation of DD experiments for DM searches.

THANK YOU

FOR YOUR ATTENTION

Smaller value of heavy Higgs mass



- m_H is varried in the range $m_H \in [450, 1200]$
- For $\mu < 0$, cancellation occurs between SM-like Higgs and heavy Higgs mediated LO amplitudes
- No such cancellation for $\mu > 0$.
- Minimum NLO amplitude occurs around $m_{\tilde{\chi}_1^0} \sim 700$ GeV i.e., **it shifts compared to larger m_H scenario**.

The 4×4 neutralino mass matrix in the basis $(\tilde{B}, \tilde{W}^0, \tilde{H}^0_d, \tilde{H}^0_u)$ can be written as

$$\overline{\mathbb{M}}_{\tilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -M_Z s_W c_\beta & M_Z s_W s_\beta \\ 0 & M_2 & M_Z c_W c_\beta & -M_Z c_W s_\beta \\ -M_Z s_W c_\beta & M_Z c_W c_\beta & 0 & -\mu \\ M_Z s_W s_\beta & -M_Z c_W s_\beta & -\mu & 0 \end{pmatrix},$$