Direct detection of neutralino dark matter with DM@NLO

Michael Klasen[*][†]

Institut für Theoretische Physik, Westfälische Wilhelms-Universität Münster,
Wilhelm-Klemm-Straße 9, D-48149 Münster, Germany
E-mail: michael.klasen@uni-muenster.de

Karol Kovařík

Institut für Theoretische Physik, Westfälische Wilhelms-Universität Münster,
Wilhelm-Klemm-Straße 9, D-48149 Münster, Germany
E-mail: karol.kovarik@uni-muenster.de

Saskia Schmiemann[‡]

Institut für Theoretische Physik, Westfälische Wilhelms-Universität Münster,
Wilhelm-Klemm-Straße 9, D-48149 Münster, Germany
E-mail: saskia.schmiemann@uni-muenster.de

We calculate spin-independent and spin-dependent direct detection cross sections of neutralino dark matter at next-to-leading order of QCD. The numerical effects are comparable in size to the uncertainties in the nuclear matrix elements. Our results are applicable to bino, wino or higgsino dark matter and allow for consistent correlations with the relic density in DM@NLO.

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1. Direct detection of neutralino dark matter

The identification of dark matter (DM) is one of the most urgent questions in astroparticle physics. For many decades, evidence for its sizeable presence in the Universe and its important role in structure formation has been accumulating, and the overall relic density Ωh^2 (h being the present Hubble expansion rate in units of 100 km s^{-1} Mpc^{-1}) has been precisely measured [1]. The lightest neutral supersymmetric (SUSY) partner of electroweak gauge and Higgs bosons (neutralino $\tilde{\chi}_1^0$) continues to be a prime candidate for WIMP (weakly interacting massive particle) DM, and theoretical calculations of the DM relic density at next-to-leading order (NLO) of QCD with DM@NLO, which include all coannihilation channels (with the exception of $\tilde{t}_1\tilde{t}_1 \rightarrow q\bar{q}, gg$) now match the experimental precision [2]. For an unambiguous identification of DM, it must, however, be detected on Earth, e.g. with large kryogenic detectors like XENON1T [3]. Comparisons with theoretical cross section calculations and correlations with the relic density or other observables (e.g. from indirect detection or the LHC) should then allow for a precise extraction of the DM mass and couplings. For neutralinos, this is now possible thanks to the calculation of NLO SUSY-QCD corrections to the neutralino-nucleon cross section and the inclusion of this second DM observable in DM@NLO [4].

2. Neutralino-nucleon cross section

The differential rate for direct DM detection (in counts/kg/day/keV)

$$\frac{\mathrm{d}R}{\mathrm{d}E} = \sum_i c_i \frac{\sigma_i}{2m_{\tilde{\chi}_1^0}\mu_i^2}\rho_0\eta_i \tag{2.1}$$

is usually expressed in terms of the nuclear mass fractions c_i, reduced masses μ_i, local DM density $\rho_0 = 0.3$ GeV/cm^3, and velocity integrals $\eta_i = \int_{v_{\min,i}}^{v_{\mathrm{esc}}} \mathrm{d}^3 v\, f(\vec{v})/v$ with $v_{\min,i} = \sqrt{m_i E/(2\mu_i^2)}$.

Since the spin-*independent* cross sections for each isotope in the target

$$\sigma_i^{\mathrm{SI}} = \frac{\mu_i^2}{\pi}\left|Z_i g_p^{\mathrm{SI}} + (A_i - Z_i)g_n^{\mathrm{SI}}\right|^2 |F_i^{\mathrm{SI}}(Q_i)|^2 \tag{2.2}$$

depend on the nuclear charges Z_i, masses A_i and structure functions F_i^{SI}, they are often replaced by the one for a single nucleon (assuming $g_p = g_n$) to enable a direct comparison of different experiments. We use, however, the exact expressions

$$g_N^{\mathrm{SI}} = \sum_q \langle N|\bar{q}q|N\rangle \alpha_q^{\mathrm{SI}} \tag{2.3}$$

for the spin-independent four-fermion couplings. The Wilson coefficients α_q^{SI} contain the wanted information on the electroweak interaction of DM and quarks, while the nuclear matrix elements $\langle N|m_q\bar{q}q|N\rangle = f_{Tq}^N m_N$ are known to be subject to considerable uncertainties from the non-perturbative regime of QCD [5, 6, 7]. Beyond the tree-level, the Wilson coefficients α_q^{SI} are, however, also affected by (perturbative) QCD uncertainties and become related to the nuclear matrix elements through renormalisation group equations.[1]

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[1]The role of effective gluon interactions has been discussed in Ref. [8].

Similarly, the spin-*dependent* cross section

$$\sigma_i^{\rm SD} = \frac{4\mu_i^2}{2J+1}\left(|g_p^{\rm SD}|^2 S_{{\rm pp},i}(Q_i) + |g_n^{\rm SD}|^2 S_{{\rm nn},i}(Q_i) + |g_p^{\rm SD} g_n^{\rm SD}| S_{{\rm pn},i}(Q_i)\right) \tag{2.4}$$

depends on the spin structure functions $S_{NN,i}$ and spin-dependent four-fermion couplings

$$g_N^{\rm SD} = \sum_{q=u,d,s} (\Delta q)_N \alpha_q^{\rm SD}. \tag{2.5}$$

Here, the nuclear spin J is supposed to be carried mostly by the three light quark flavours and to be isospin symmetric.[2]

The tree-level diagrams for neutralino-quark scattering are shown in Fig. 1. After the calcula-
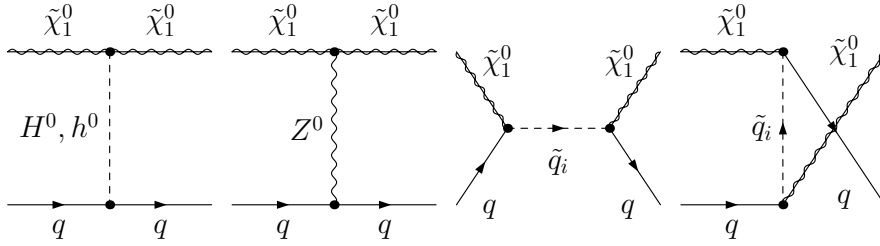
Figure 1: Full tree-level Feynman diagrams for neutralino-quark scattering.

tion of all self-energy, vertex and box corrections, we renormalise the ultraviolet (UV) divergences in a mixed on-shell and $\overline{\rm DR}$ scheme [4]. It has the advantages of being perturbatively stable, in particular in the top sector, and of allowing for meaningful correlations with our relic density calculations [2] and tree-level comparisons with micrOMEGAs [6], where the same on-shell squark masses are used that are provided by the SUSY spectrum generator SPheno [11].
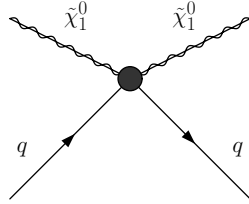
Figure 2: Effective tree-level diagram for neutralino-quark scattering.

In the non-relativistic regime, our full calculation is then matched to the spin-independent and spin-dependent operators $Q_{1,2}$ in the effective Lagrangian

$$\mathcal{L}_{\rm eff} = c_1 Q_1 + c_2 Q_2 = c_1 \bar{\chi}\chi\bar{q}q + c_2 \bar{\chi}\gamma_\mu\gamma_5\chi\bar{q}\gamma^\mu\gamma_5 q \tag{2.6}$$

as shown symbolically in Fig. 2. As expected, the tree-level coefficients, obtained after a Fierz transformation for the squark processes, agree with those in DarkSUSY [5]. After the one-loop

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[2]This need not be the case as discussed in Refs. [9, 10].

corrections in the effective theory have also been computed, the matching condition

$$\mathscr{M}_{\text{full}}^{\text{tree}} + \mathscr{M}_{\text{full}}^{\text{1loop}} \overset{!}{=} (c_1^{\text{tree}} + c_1^{\text{1loop}})(Q_1^{\text{tree}} + Q_1^{\text{1loop}}) + (c_2^{\text{tree}} + c_2^{\text{1loop}})(Q_2^{\text{tree}} + Q_2^{\text{1loop}}) \quad (2.7)$$

leads to a refactorisation and UV-finite, but scale-dependent redefinitions of Wilson coefficients and operators. In the spin-idependent case, the quark masses $m_q(\mu)$ are factorised in c_1 and run from the high SUSY-breaking scale 1 TeV to the low scale 5 GeV, where the nuclear matrix elements are defined. In the spin-dependent case, the running of c_2 is given by

$$\frac{c_2(\mu_{\text{low}})}{c_2(\mu_{\text{high}})} = \exp\left(\frac{2n_f(\alpha_s(\mu_{\text{high}}) - \alpha_s(\mu_{\text{low}}))}{\beta_0 \pi}\right). \quad (2.8)$$

3. Numerical results

Phenomenological minimal SUSY Standard Model (pMSSM) scenarios with eleven free parameters and bino-wino, bino-higgsino, or higgsino-bino DM, that satisfy all current experimental constraints, have been presented in Ref. [2]. Scenario B, e.g., contains a bino-higgsino DM candidate of about 267 GeV mass and up- and down-type squarks of mass 550 and 556 GeV, respectively. Fig. 3 shows a scan in the bino mass parameter M_1 around this point, indicated there by full verti-
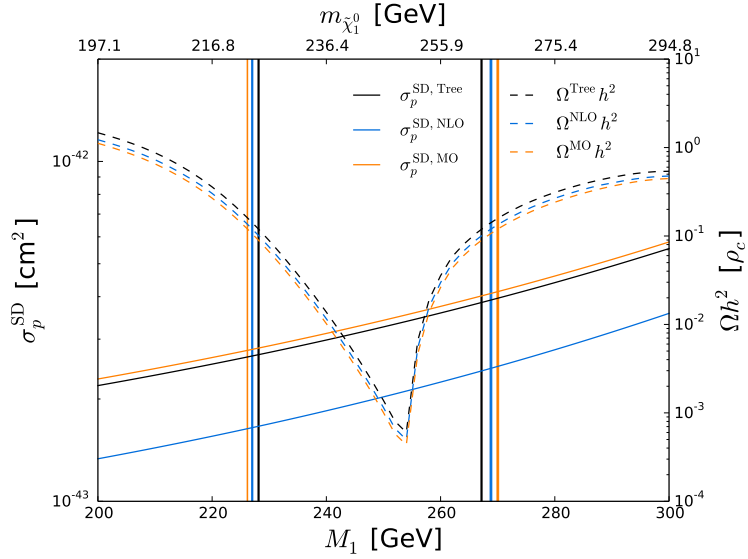
Figure 3: Combined relic density and direct detection calculation in scnenario B.

cal lines at tree-level (black), with micrOMEGAs (orange), and in NLO (blue). In the shown mass region, a second viable scenario with a lower DM mass of about 228 GeV is found, indicated by a second set of vertical lines. One observes good agreement at leading order, but a significant shift at NLO in the spin-dependent direct detection cross section (left ordinate and full curves). The corresponding numbers are listed in Tab. 1. When correlated with the relic density calculations at the same order (dashed curves), this leads to shifts in the extracted bino mass parameter M_1 of several GeV. In other SUSY scenarios, these effects can even be considerably larger.

Table 1: Resulting M_1 and spin-dependent neutralino-proton cross section when combining direct detection and relic density routines in scenario B.

	M_1 [GeV]	σ_p^{SD} [10^{-43}cm^2]	Shift of σ_p^{SD}
micrOMEGAs	226	2.78	$+3\%$
Tree level	228	2.70	
Full NLO	227	1.65	-39%
micrOMEGAs	270	4.14	$+8\%$
Tree level	267	3.84	
Full NLO	269	2.47	-36%

4. Conclusion

In conclusion, we have summarised our recent analytical calculation of NLO SUSY-QCD corrections to spin-independent and spin-dependent neutralino-nucleon cross sections, emphasising our choice of renormalisation scheme, the matching of the full diagrammatic calculation to the effective scalar and axial-vector operators, and the renormalisation group running of the Wilson coefficients. More technical issues like our specific tensor reduction method, that avoids vanishing Gram determinants at non-relativistic velocities, were omitted from our discussion, but can be found in Ref. [4].

Numerical results for the direct detection of SUSY DM can now be obtained with DM@NLO for any neutralino decomposition (bino, wino, or higgsino). For a specific bino-higgsino benchmark scenario we found sizeable NLO corrections, which are in fact comparable to the nuclear uncertainties, and we demonstrated that correlations of the relic density and direct detection rates at NLO lead to more precise determinations of the underlying SUSY model parameters.

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