Direct detection of neutralino DM with DM@NLO

Michael Klasen

Institute for Theoretical Physics, University of Münster

6 July 2017

Work done in collaboration with K. Kovarik and P. Steppeler

DFG

Graduiertenkolleg 2149
Research Training Group

GEFÖRDERT VOM
Bundesministerium
für Bildung
und Forschung

References

Current state of the art:

- J. Harz, B. Herrmann, M. Klasen, K. Kovarik, P. Steppeler
  Theoretical uncertainty of the supersymmetric dark matter relic density from scheme and scale variations
  Phys. Rev. D 93 (2016) 114023 [arXiv:1602.08103]
- M. Klasen, K. Kovarik, P. Steppeler
  SUSY-QCD corrections for direct detection of neutralino dark matter and correlations with relic density
  Phys. Rev. D 97 (2016) 095002 [arXiv:1607.06396]

Direct detection rate (1)

Differential rate [counts/kg/day/keV]:

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

Nuclear mass fractions c_i, local DM density $\rho_0 = 0.3$ GeV/cm^3.

Velocity integral $\eta_i = \int_{v_{\mathrm{min},i}}^{v_{\mathrm{esc}}} \mathrm{d}^3v\, f(\vec{v})/v$, $v_{\mathrm{min},i} = \sqrt{m_i E/(2\mu_i^2)}$.

Spin-independent cross section:

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

Often replaced by σ_i^{SI} for a single nucleon, assuming $g_p = g_n$.

Spin-independent four-fermion couplings:

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

Quark matrix elements

Relation to scalar coefficients: $\langle N|m_q\bar{q}q|N\rangle = f^N_{Tq} m_N$

Scalar coefficient	DM@NLO	DarkSUSY	micrOMEGAs
f^p_{Tu}	0.0208	0.023	0.0153
f^n_{Tu}	0.0189	0.019	0.0110
f^p_{Td}	0.0411	0.034	0.0191
f^n_{Td}	0.0451	0.041	0.0273
$f^p_{Ts} = f^n_{Ts}$	0.043	0.14	0.0447
$f^p_{Tc} = f^p_{Tb} = f^p_{Tt}$	0.0663	0.0595	0.0682
$f^n_{Tc} = f^n_{Tb} = f^n_{Tt}$	0.0661	0.0592	0.0679

- DarkSUSY: P. Gondolo et al., JCAP 0407 (2004) 008
- micrOMEGAs: G. Bélanger et al., CPC 177 (2007) 894
- DM@NLO: A. Crivellin et al., PRD 89 (2014) 054021

Direct detection rate (2)

Spin-dependent cross section:

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

Spin-dependent four-fermion couplings:

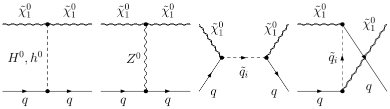
$$g_N^{\mathrm{SD}} = \sum_{q=u,d,s} (\Delta q)_N \alpha_q^{\mathrm{SD}}$$

Polarised quark densities (isospin symmetry, micrOMEGAs):

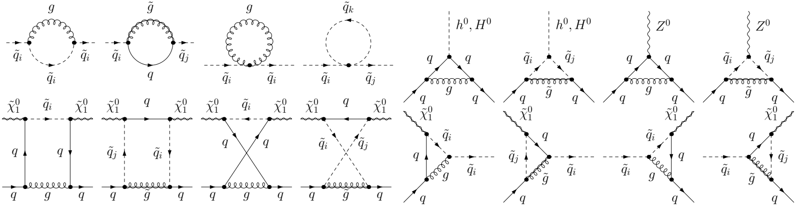
$$\begin{aligned} (\Delta u)_p = (\Delta d)_n &= 0.842, \\ (\Delta d)_p = (\Delta u)_n &= -0.427, \\ (\Delta s)_p = (\Delta s)_n &= -0.085. \end{aligned}$$

Neutralino-quark scattering

Tree-level diagrams:



One-loop corrections:



Renormalisation scheme

Quark sector:

- On-shell m_t
- SM $\overline{\mathrm{MS}}$ $m_b(m_b \to \mu_R) \to$ SM $\overline{\mathrm{DR}} \to$ MSSM $\overline{\mathrm{DR}}$
- SM $\overline{\mathrm{MS}}$ $\alpha_s^{n_f=5\to 6}(m_Z \to \mu_R) \to$ SM $\overline{\mathrm{DR}} \to$ MSSM $\overline{\mathrm{DR}}$

Squark sector:

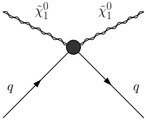
- On-shell $m_{\tilde{q}}$; $m_{\tilde{t}_1}$, $m_{\tilde{b}_1}$, $m_{\tilde{b}_2}$
- MSSM $\overline{\mathrm{DR}}$ A_t, $A_b = 0$
- Dependent $\theta_{\tilde{t}}$, $\theta_{\tilde{b}}$, $m_{\tilde{t}_2}$

Advantages:

- Identical schemes for relic density and direct detection
- Perturbatively stable, in particular in the top sector
- Easy comparison with micrOMEGAs (identical squark masses)

Effective field theory (1)

Tree-level diagram:



Effective Lagrangian:

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

Tree-level coefficients:

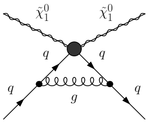
$$c_1^{\rm tree} = \alpha_q^{\rm SI} = \sum_{\phi=h^0,H^0} \frac{g^R_{\tilde{\chi}\tilde{\chi}\phi} g^L_{qq\phi}}{m^2_\phi} - \frac{1}{4}\sum_{i=1}^{2} \frac{g^L_{\tilde{\chi}\tilde{q}_i q} g^{R*}_{\tilde{\chi}\tilde{q}_i q}}{m^2_{\tilde{q}_i} - s} - \frac{1}{4}\sum_{i=1}^{2} \frac{g^L_{\tilde{\chi}\tilde{q}_i q} g^{R*}_{\tilde{\chi}\tilde{q}_i q}}{m^2_{\tilde{q}_i} - u},$$

$$c_2^{\rm tree} = \alpha_q^{\rm SD} = \frac{1}{2}\frac{g^R_{\tilde{\chi}\tilde{\chi}Z^0}(g^L_{qqZ^0} - g^R_{qqZ^0})}{m^2_{Z^0}} + \frac{1}{8}\sum_{i=1}^{2} \frac{|g^L_{\tilde{\chi}\tilde{q}_i q}|^2 + |g^R_{\tilde{\chi}\tilde{q}_i q}|^2}{m^2_{\tilde{q}_i} - s} + \frac{1}{8}\sum_{i=1}^{2} \frac{|g^L_{\tilde{\chi}\tilde{q}_i q}|^2 + |g^R_{\tilde{\chi}\tilde{q}_i q}|^2}{m^2_{\tilde{q}_i} - u}.$$

Fierz transformation for squark processes! Agrees with DarkSUSY.

Effective field theory (2)

One-loop correction:



Matching condition:

$$\mathcal{M}_{\rm full}^{\rm tree} + \mathcal{M}_{\rm full}^{\rm 1loop} \stackrel{!}{=} (c_1^{\rm tree} + c_1^{\rm 1loop})(Q_1^{\rm tree} + Q_1^{\rm 1loop}) + (c_2^{\rm tree} + c_2^{\rm 1loop})(Q_2^{\rm tree} + Q_2^{\rm 1loop})$$

Effective operators:

$$\begin{aligned} Q_i^{\rm 1loop} &= (\mathcal{K}_{\rm EFTV,i} + \mathcal{K}_{\rm EFTVC,i}) Q_i^{\rm tree}, \\ \mathcal{K}_{\rm EFTV,1} &= \frac{\alpha_s C_F}{4\pi}\Big[4B_0 - 2 + 4p_b p_2 (C_0 + C_1 + C_2)\Big], \\ \mathcal{K}_{\rm EFTV,2} &= \frac{\alpha_s C_F}{4\pi}\Big[2B_0 + 4p_b p_2 (C_0 + C_1 + C_2) - 4C_{00} - 1\Big]. \end{aligned}$$

Fierz transformation for gluon boxes, vanishing Gram determinants!

Renormalisation in EFT

Counterterms:

$$
\begin{aligned}
\mathcal{K}_{\mathrm{EFTVC,i}} &= \frac{\delta c_i^L / c_i^{\mathrm{tree},L} + \delta c_i^R / c_i^{\mathrm{tree},R}}{2}, \\
\delta c_1^L &= c_1^{\mathrm{tree},L} \left(\frac{\delta Z_m}{m_q} + \frac{1}{2}\delta Z_q^L + \frac{1}{2}\delta Z_q^{R*} \right), \\
\delta c_2^L &= c_2^{\mathrm{tree},L} \left(\frac{1}{2}\delta Z_q^{\mathrm{SM},L} + \frac{1}{2}\delta Z_q^{\mathrm{SM},L*} + \frac{\alpha_s C_F}{\pi} \right),
\end{aligned}
$$

and similarly for $L \leftrightarrow R$. Conventional term for axial current div.

Wilson coefficients:

$$
\begin{aligned}
c_1^{\mathrm{1loop}} &= \alpha_{q,\mathrm{P}}^{\mathrm{SI}} + \alpha_{q,\mathrm{PC}}^{\mathrm{SI}} + \alpha_{q,\mathrm{V}}^{\mathrm{SI}} + \alpha_{q,\mathrm{VC}}^{\mathrm{SI}} + \alpha_{q,\mathrm{B}}^{\mathrm{SI}} - c_1^{\mathrm{tree}}(\mathcal{K}_{\mathrm{EFTV1}} + \mathcal{K}_{\mathrm{EFTVC1}}), \\
c_2^{\mathrm{1loop}} &= \alpha_{q,\mathrm{P}}^{\mathrm{SD}} + \alpha_{q,\mathrm{PC}}^{\mathrm{SD}} + \alpha_{q,\mathrm{V}}^{\mathrm{SD}} + \alpha_{q,\mathrm{VC}}^{\mathrm{SD}} + \alpha_{q,\mathrm{B}}^{\mathrm{SD}} - c_2^{\mathrm{tree}}(\mathcal{K}_{\mathrm{EFTV2}} + \mathcal{K}_{\mathrm{EFTVC2}}).
\end{aligned}
$$

Propagator, vertex, box, operator corrections separately UV-finite.

Scale matching

Spin-independent case:

- $m_q \bar{q} q$ is scale-independent
- Factorize $m_q(\mu)$ in c_1, run from 1 TeV to 5 GeV
- Replace $\langle N | m_q \bar{q} q | N \rangle = f_{Tq}^N m_N$

Spin-dependent case:

- Renormalisation constant:

$$Z_A^{\mathrm{Singlet}} = 1 + \frac{\alpha_s C_F}{\pi} - \frac{1}{\epsilon_{UV}} \left(\frac{\alpha_s}{4\pi} \right)^2 \left(\frac{20}{9} n_f + \frac{88}{3} \right) + \mathcal{O}(\alpha_s^3)$$

- Anomalous dimension:

$$\gamma_A^{\mathrm{Singlet}} = (Z_A^{\mathrm{Singlet}})^{-1} \frac{\mathrm{d}}{\mathrm{d} \log \mu} Z_A^{\mathrm{Singlet}} = \left(\frac{\alpha_s}{4\pi} \right)^2 16 n_f + \mathcal{O}(\alpha_s^3)$$

- Wilson coefficient:

$$\frac{\mathrm{d}}{\mathrm{d} \log \mu} c_2(\mu) = \gamma_A^{\mathrm{Singlet}} c_2(\mu) \quad \rightarrow \quad \frac{c_2(\mu_{\mathrm{low}})}{c_2(\mu_{\mathrm{high}})} = \exp \left(\frac{2 n_f (\alpha_s(\mu_{\mathrm{high}}) - \alpha_s(\mu_{\mathrm{low}}))}{\beta_0 \pi} \right)$$

Theoretical setup

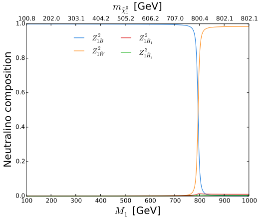
pMSSM-11 scenarios:

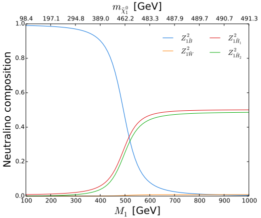
	$\tan\beta$	μ	m_A	M_1	M_2	M_3	$M_{\tilde{q}_{1,2}}$	$M_{\tilde{q}_3}$	$M_{\tilde{u}_3}$	$M_{\tilde{\ell}}$	A_t
A	13.4	1286.3	1592.9	731.0	766.0	1906.3	3252.6	1634.3	1054.4	3589.6	-2792.3
B	13.7	493.0	500.8	270.0	1123.4	1020.3	479.9	1535.5	836.7	3469.4	-2070.9
C	7.0	815.0	1452.8	675.3	1423.4	1020.3	809.9	1835.5	1436.7	3469.4	-2670.9

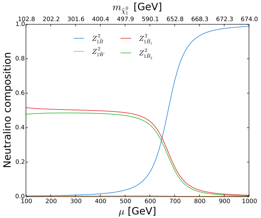
Physical masses and dark matter relic density:

	$m_{\tilde{\chi}_1^0}$	$m_{\tilde{\chi}_2^0}$	$m_{\tilde{\chi}_1^\pm}$	$m_{\tilde{\chi}_2^\pm}$	$m_{\tilde{u}_1}$	$m_{\tilde{d}_1}$	$m_{\tilde{t}_1}$	$m_{\tilde{b}_1}$	$m_{\tilde{g}}$	m_{h^0}	$\Omega_{\tilde{\chi}_1^0} h^2$
A	738.1	802.4	802.3	1295.1	3270.9	3271.6	993.9	1622.9	2049.9	126.3	0.1244
B	265.7	498.4	495.7	1135.3	549.5	555.7	802.9	1531.0	1061.2	124.8	0.1199
C	669.2	826.6	819.6	1438.9	865.0	868.4	1389.1	1832.3	1090.7	125.2	0.1179

Neutralino decomposition:







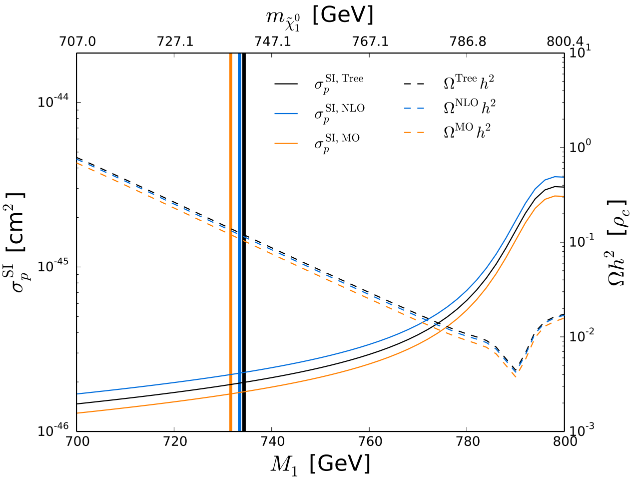
Most important (co-)annihilation channels

DM@NLO contains (almost) all (co-)annihilations in NLO QCD

(Co-)annihilation channels in scenarios A–C ($\geq 1\%$):

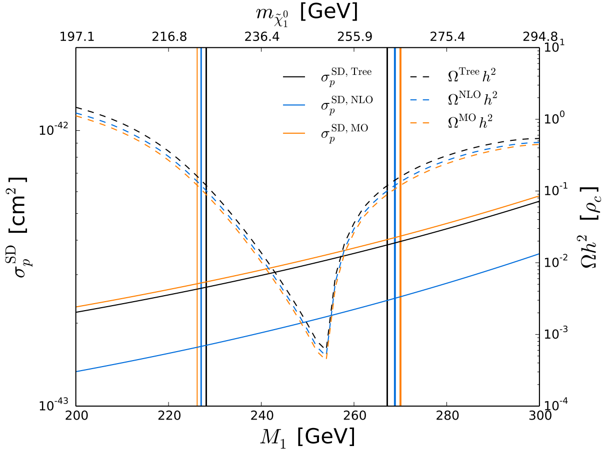
		A	B	C
$\tilde{\chi}_1^0\tilde{\chi}_1^0 \to$	$t\bar{t}$	1%	10%	52%
	$b\bar{b}$	9%	78%	40%
$\tilde{\chi}_1^0\tilde{\chi}_2^0 \to$	$t\bar{t}$	3%		
	$b\bar{b}$	23%		
$\tilde{\chi}_1^0\tilde{\chi}_1^\pm \to$	$t\bar{b}$	43%		
Total		79%	88%	92%

Scenario A: Bino-wino dark matter



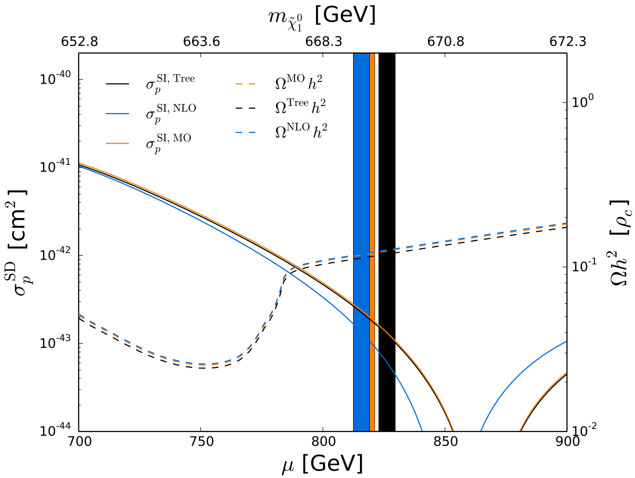
	M_1 [GeV]	σ_p^{SI} [10^{-46}cm^2]	Shift of σ_p^{SI}
micrOMEGAs	731	1.68	−15%
Tree level	734	1.98	
Full NLO	733	2.26	+14%

Scenario B: Bino-higgsino dark matter



	M_1 [GeV]	$\sigma_p^{\rm SD}$ [10^{-43}cm^2]	Shift of $\sigma_p^{\rm SD}$
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%

Scenario C: Higgsino-bino dark matter



	μ [GeV]	σ_p^{SD} [10^{-43}cm^2]	Shift of σ_p^{SD}
micrOMEGAs	815 - 821	1.80 - 2.43	+63%
Tree level	823 - 829	1.06 - 1.53	
Full NLO	813 - 819	1.08 - 1.62	+4%

Conclusion

Neutralino-nucleon cross section:

- Analytical computation of NLO SUSY-QCD corrections
- Tensor reduction for vanishing Gram determinants
- Matching to scalar and axial-vector operators
- Renormalisation group running of Wilson coefficients

Numerical results:

- Bino, wino, and higgsino dark matter
- Three viable benchmark scenarios
- Perturbative corrections comparable to nuclear uncertainties
- Correlation of relic density and direct detection rate at NLO