Impact of QCD and SUSY-QCD Corrections on the Neutralino Dark Matter Relic Density.

Julia Harz, DESY Hamburg

in collaboration with B. Herrmann, M. Klasen, K. Kovarik and Q. Le Boulc'h

TR33 - Summer Institute: Particles and the Universe, Corfu

21.09.2012

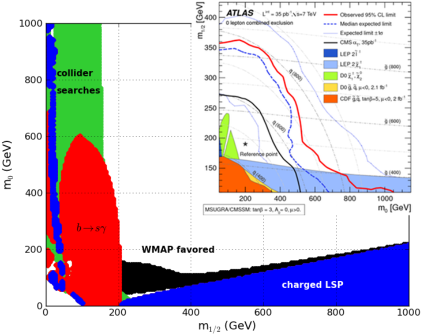
LANDESEXZELLENZINITIATIVE HAMBURG

Overview

Overview

Constraining the SUSY parameter space

Neutralino - LSP and cold dark matter candidate



Interplay between LHC and PLANCK data will be even more interesting

Particle physics bounds

- Collider searches
  e.g.
  $m_{\tilde{\chi}_1^0} > 46\ GeV,\ m_{\tilde{t}} > 95.7\ GeV$
  PDG (2012)
- Precision measurements
  e.g.
  $\mathrm{Br}(b \to s\gamma) = (3.55 \pm 0.26) \cdot 10^{-4}$
  HFAG collaboration (2010)

Cosmology bounds

- 7 year data of WMAP
  $\Rightarrow \Omega h^2 = 0.1123 \pm 0.035$
  WMAP collaboration (2011)

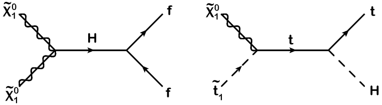
Overview

Calculating the relic density

Today's number density can be calculated via Boltzmann equation.

$$\dot{n} + 3Hn = -\langle \sigma v \rangle \left(n^2 - n_{eq}^2 \right)$$

σ cross section of annihilation and coannihilation



$$\langle \sigma v \rangle = \sum_{ij} \frac{2}{g_j} \left\langle \sigma_{ij} v_{ij} \frac{n_i^{eq}}{n^{eq}} \frac{n_j^{eq}}{n^{eq}} \right\rangle \quad \text{with} \quad \frac{n_i^{eq}}{n^{eq}} \propto \exp\left[\frac{-(m_i - m_\chi)}{T} \right]$$

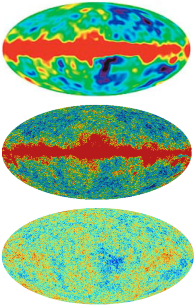
Coannihilation...
gets important, when masses of LSP and NLSP almost degenerate

K. Griest, D. Seckel. Phys. Rev. D **43** (1991) 10, 3191-3203

Calculating the relic density

On the basis of the number density one can calculate the relic density.

$$\Omega_{CDM}\, h^2 = \frac{m_\chi n_0}{\rho_C} \propto \frac{1}{\langle \sigma v \rangle}$$



Public computational programs (e.g.):

DarkSUSY

Gondolo, Edsjö, Ullio, Bergström, Bringmann et al. [astro-ph/0406204]

MicrOMEGAs

Bélanger, Boudjema, Pukhov et al. [hep-ph/1004.1092]

SuperIso Relic

Arbey, Mahmoudi [hep-ph/0906.0369]

Theoretical uncertainties in the relic density prediction

In cosmology

- Choice of cosmological model

  Hamann, Hannestad, et.al. (2006) [hep-ph/0611582]

- Variation in Hubble expansion rate

  Arbey, Mahmoudi (2008) [hep-ph/0803.0741]

In particle physics

- Precision of masses

  Allanach, Kraml, Porod (2003) [hep-ph/0302102]

- Uncertainties of spectrum calculators

  Bélanger, Kraml, Pukhov (2005) [hep-ph/0502079]

- Precision in the calculation of (co)annihilation cross section

  Baro, Boudjema, Semenov (2007) [hep-ph/0710.1821]

Current status in calculating the relic density:

- Calculation in public programs only on effective tree level
- Current theoretical uncertainties bigger than future precision of PLANCK
- Significant impact of NLO-corrections on the relic density

Current packages at next-to-leading order

SLOOPS - electroweak corrections

- Huge number of processes and NLO-diagrams
- Automatized calculation
- Interface to micrOMEGAs

http://code.sloops.free.fr

Karlsruhe Institute of Technology

LAPTh Annecy-le-Vieux

RWTH AACHEN UNIVERSITY

DM@NLO - strong corrections

- SUSY-QCD corrections to (co)annihilation processes
- Efficient infrared treatment (dipole subtraction method)
- Interface to micrOMEGAs (and DarkSUSY in the future)

http://dmnlo.hepforge.org

DESY

LPSC Grenoble
Laboratoire de Physique Subatomique et de Cosmologie

Karlsruhe Institute of Technology

LAPTh Annecy-le-Vieux

Westfälische Wilhelms-Universität Münster

DESY

Overview

DM@NLO - relic density including QCD corrections

SPheno
calculation of sparticle masses, mixings & precision observables
W. Porod.

Input
setting parameters for cMSSM, pMSSM,...

MicrOMEGAs
integration of Boltzmann equation, etc.
G. Bélanger, F. Boudjema, A. Pukhov, A. Semenov.

relevant CalcHEP cross sections are replaced by DM@NLO calculated NLO cross sections

CalcHEP
calculation of (co)annihilation processes at tree level
A. Pukhov, A. Belyaev, N. Christensen.

DM@NLO
calculation of cross sections @ NLO level for relevant processes
J.Harz, B. Herrmann, M. Klasen, K. Kovarik, Q. Le Boulc'h.

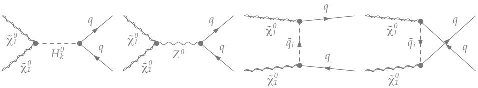
Output
neutralino relic density

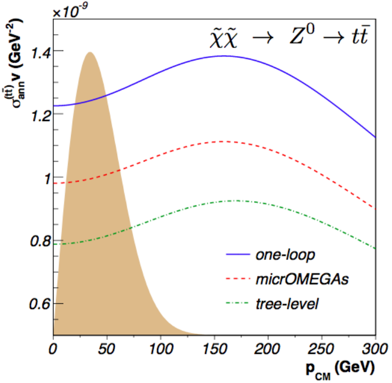
http://projects.hepforge.org/dmnlo

Impact of SUSY-QCD-corrections to annihilation

Example: Dominant Z-exchange

- Enhancement of annihilation cross section into quarks by 50 % through QCD-corrections
- Reduction of the predicted relic density
- Significant shift of the WMAP favoured region





$\tan\beta = 10$, $A_0 = 0$, $m_0 = 1500$, $M_2 = 600$, $\mu > 0$
Herrmann, Klasen, Kovarik (2009), arXiv:0907.0030 [hep-ph].

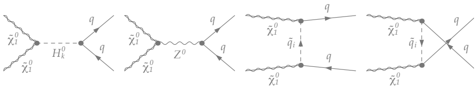
$\Rightarrow$ Effect of corrections to the relic density lager than current experimental uncertainties!

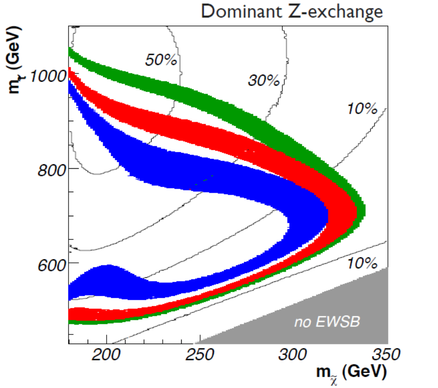
B. Herrmann, M. Klasen, K. Kovarik

Impact of SUSY-QCD-corrections to annihilation

Example: Dominant Z-exchange

- Enhancement of annihilation cross section into quarks by 50 % through QCD-corrections
- Reduction of the predicted relic density
- Significant shift of the WMAP favoured region





$\tan\beta = 10$, $A_0 = 0$, $m_0 = 1500$, $M_2 = 600$, $\mu > 0$
Herrmann, Klasen, Kovarik (2009), arXiv:0907.0030 [hep-ph].

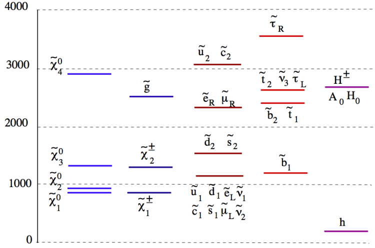
$\Rightarrow$ Effect of corrections to the relic density lager than current experimental uncertainties!

B. Herrmann, M. Klasen, K. Kovarik

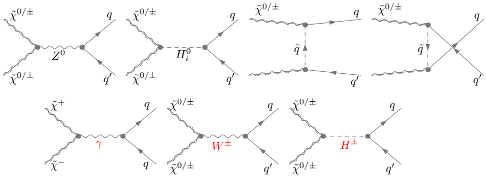
Impact of SUSY-QCD-corrections to annihilation

Extension: annihilation of other gauginos

- Especially relevant for wino- or higgsino-like neutralinos
- Realisation e.g. in pMSSM
- Generalisation of neutralino annihilation code
- Addition of few new contributions concerning charginos



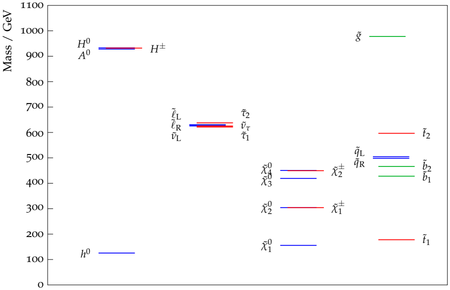
AbdusSalam, Allanach and Quevedo, Phys. Rev. **D** 81 (2012).

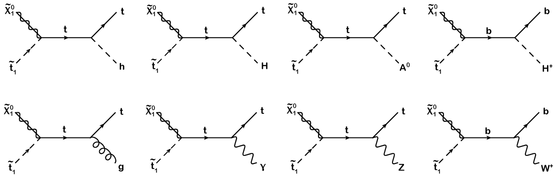


B. Herrmann, M. Klasen, K. Kovarik, M. Meinecke (in progress).

Coannihilation with Squarks

- Contribution if squarks and neutralino almost degenerate
- Dominant in different regions of parameter space
- Extendable to coannihilation of gauginos with sleptons in general



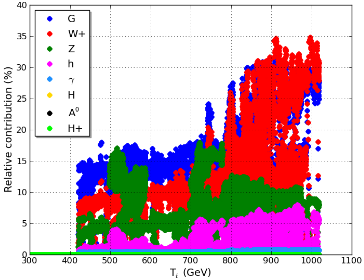


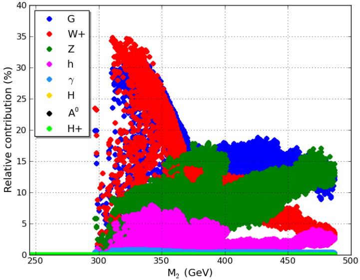
J.H., B. Herrmann, M. Klasen, K. Kovarik, Q. Le Boulc'h (in progress)

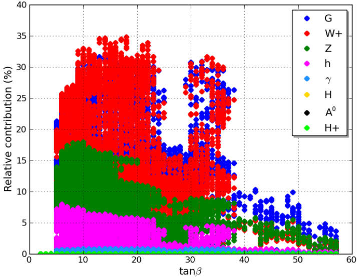
Coannihilation with Squarks

Interesting scenario: pMSSM8

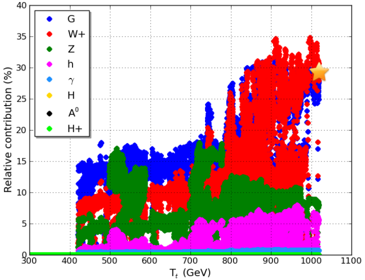
- 8 free parameters:
  μ, $\tan\beta$, A_t, M_2, m_A, $M_{\tilde{q}_{1,2}}$, $M_{\tilde{q}_3}$, $M_{\tilde{l}}$
  $A_b = A_\tau = 0$
  $M_2 = 2M_1 = M_3/3$





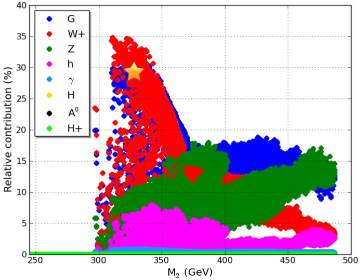


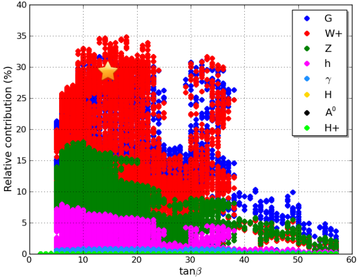
Coannihilation with Squarks



Interesting scenario: pMSSM8

- 8 free parameters:
  μ, $\tan\beta$, A_t, M_2, m_A, $M_{\tilde{q}_{1,2}}$, $M_{\tilde{q}_3}$, $M_{\tilde{l}}$
  $A_b = A_\tau = 0$
  $M_2 = 2M_1 = M_3/3$





Coannihilation with Squarks

One example point in pMSSM8

- μ = 421, tanβ = 14, T_t = 1017,
  m_A = 928, $M_{\tilde{q}_{1,2}}$ = 434, $M_{\tilde{q}_3}$ = 388,
  $M_{\tilde{l}}$ = 627,
  $A_b = A_\tau = 0$,
  $M_2 = 2M_1 = M_3/3$=325
- fully dominated by coannihilation processes:

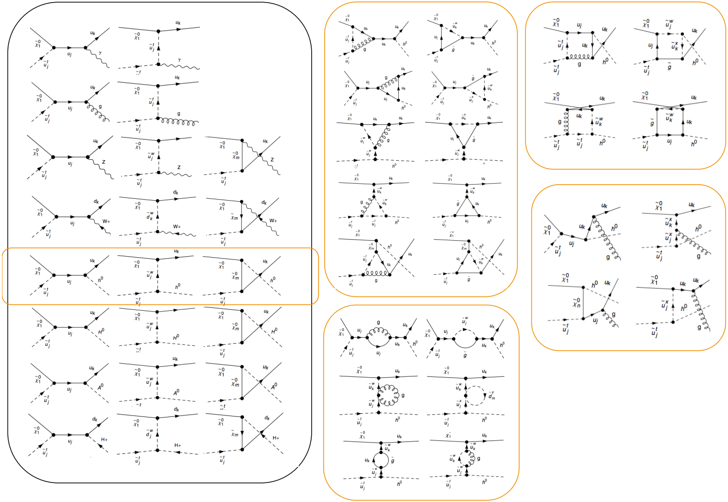
$$\begin{array}{lll} \tilde{\chi}_1^0 \tilde{t}_1 \rightarrow \mathrm{bW}^+ & 29\ \% \\ \tilde{\chi}_1^0 \tilde{t}_1 \rightarrow \mathrm{tg} & 26\ \% \\ \tilde{t}_1 \tilde{t}_1 \rightarrow \mathrm{gg} & 15\ \% \\ \tilde{\chi}_1^0 \tilde{t}_1 \rightarrow \mathrm{tZ} & 8\ \% \\ \tilde{\chi}_1^0 \tilde{t}_1 \rightarrow \mathrm{th} & 6\ \% \end{array}$$

- in agreement with experimental bounds

$$\mathrm{m}_h = 125.4\,GeV$$
$$\Omega h^2 = 0.1159$$

$\Rightarrow$ precise relic density prediction needs next-to-leading order corrections for coannihilation

Full NLO calculation for coannihilation with Squarks



J.H., B. Herrmann, M. Klasen, K. Kovarik, Q. Le Boulc'h (in progress)

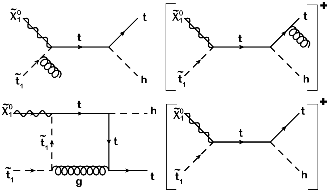
Some technicalities

Handling of IR-divergencies - I

- Phase-space-slicing

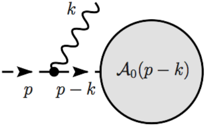
$$\sigma^{NLO} = \int_{2\to3} \mathrm{d}\sigma^{R} + \int_{2\to2} \mathrm{d}\sigma^{V}$$

$$\sigma_{2\to3}^{brems}(\lambda) = \sigma^{soft}(\Delta E, \lambda) + \sigma^{hard}(\Delta E)$$



$$\mathcal{M} = \frac{i(2p-k)^{\mu}\varepsilon_{\mu}(k)}{(p-k)^2 - m^2}\left(-ig_s T^a\right)\mathcal{A}_0(p-k)$$

$$\mathcal{M} = -\left(g_s T^a\right)\frac{\varepsilon.p}{p.k}\mathcal{M}_0 \qquad \text{with} \quad k^{\mu} \ll p^{\mu}$$



$$\left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right)_{soft} = -\left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right)_0 \times \frac{g_s^2 C_F}{(2\pi)^3}\int_{|\vec{k}|\leq\Delta E}\frac{\mathrm{d}^3k}{2\omega}\frac{-2k_1.p_2}{(p_2.k)(k_1.k)}$$

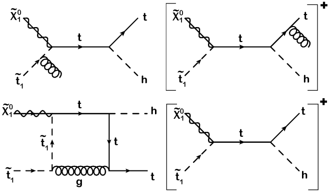
Some technicalities

Handling of IR-divergencies - I

- Phase-space-slicing

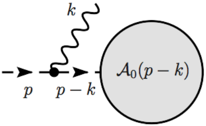
$$\sigma^{NLO} = \int_{2\to3} d\sigma^R + \int_{2\to2} d\sigma^V$$

$$\sigma^{brems}_{2\to3}(\lambda) = \sigma^{soft}(\Delta E, \lambda) + \sigma^{hard}(\Delta E)$$



$$\mathcal{M} = \frac{i(2p-k)^\mu \varepsilon_\mu(k)}{(p-k)^2 - m^2} \left(-ig_s T^a\right) \mathcal{A}_0(p-k)$$

$$\mathcal{M} = -\left(g_s T^a\right) \frac{\varepsilon.p}{p.k} \mathcal{M}_0 \qquad \text{with} \quad k^\mu \ll p^\mu$$



$$\left(\frac{d\sigma}{d\Omega}\right)_{soft} = -\left(\frac{d\sigma}{d\Omega}\right)_0 \times \frac{g_s^2 C_F}{(2\pi)^3} \int_{|\vec{k}|\leq\Delta E} \frac{d^3k}{2\omega} \frac{-2k_1.p_2}{(p_2.k)(k_1.k)}$$

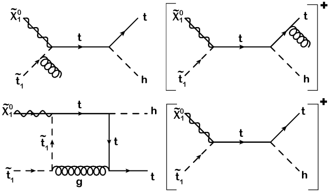
Some technicalities

Handling of IR-divergencies - I

- Phase-space-slicing

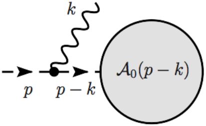
$$\sigma^{NLO} = \int_{2\to3} \mathrm{d}\sigma^{R} + \int_{2\to2} \mathrm{d}\sigma^{V}$$

$$\sigma^{brems}_{2\to3}(\lambda) = \sigma^{soft}(\Delta E, \lambda) + \sigma^{hard}(\Delta E)$$



$$\mathcal{M} = \frac{i(2p-k)^{\mu}\varepsilon_{\mu}(k)}{(p-k)^2 - m^2}\left(-ig_s T^a\right)\mathcal{A}_0(p-k)$$

$$\mathcal{M} = -\left(g_s T^a\right)\frac{\varepsilon.p}{p.k}\mathcal{M}_0 \qquad \text{with} \quad k^{\mu} \ll p^{\mu}$$

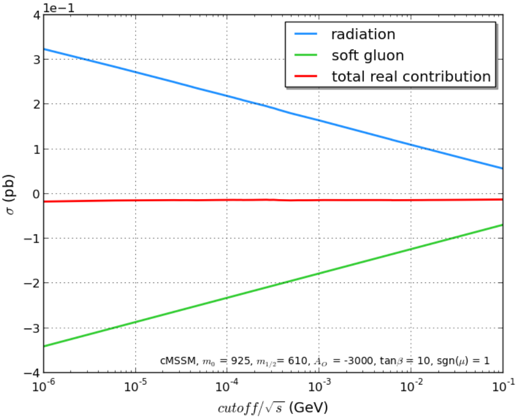


$$\left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right)_{soft} = -\left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right)_0 \times \frac{g_s^2 C_F}{(2\pi)^3}\int_{|\vec{k}|\leq\Delta E}\frac{\mathrm{d}^3k}{2\omega}\,\frac{-2k_1.p_2}{(p_2.k)(k_1.k)}$$

Some technicalities

Handling of IR-divergencies - I

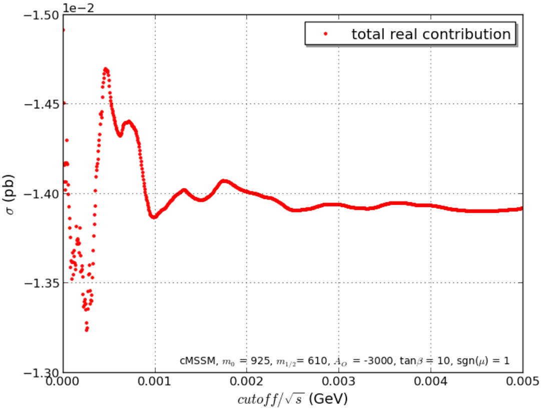
- Phase-space-slicing



Some technicalities

Handling of IR-divergencies - I

- Phase-space-slicing



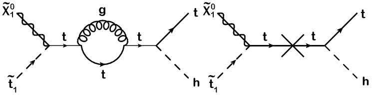
Some technicalities

Handling of IR-divergencies - II

- Dipole-Subtraction-formalism

$$\sigma^{NLO} = \int_{2\to 3} \left[\mathrm{d}\sigma^{R} - \mathrm{d}\sigma^{A} \right] |_{\varepsilon=0} + \int_{2\to 2} \left[\mathrm{d}\sigma^{V} + \int_{1} \mathrm{d}\sigma^{A} \right] |_{\varepsilon=0}$$

Handling of UV-divergencies



- input parameters:
  $m_b^{\overline{MS}}, m_t^{OS}, A_b^{\overline{DR}}, A_t^{\overline{DR}}, m_{\tilde{b}_1}^{OS}, m_{\tilde{b}_2}^{OS}, m_{\tilde{t}_1}^{OS}$

$$\begin{pmatrix} M_{\tilde{Q}}^2 + m_q^2 + M_Z^2 c_{2\beta}(T_q^3 - Q_q s_w^2) & m_q(A_q - \mu^* \kappa) \\ m_q(A_q - \mu\kappa) & M_{\tilde{q}}^2 + m_q^2 + M_Z^2 c_{2\beta} Q_q s_w^2 \end{pmatrix} = \mathcal{U}_{\tilde{q}} \begin{pmatrix} m_{\tilde{q}_1}^2 & 0 \\ 0 & m_{\tilde{q}_2}^2 \end{pmatrix} \mathcal{U}_{\tilde{q}}^{\dagger}$$

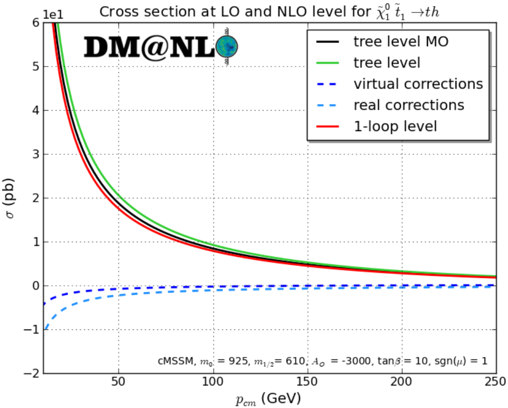
- consistent renormalization scheme for all (co-)annihilation processes

Impact of SUSY-QCD-corrections to coannihilation

Example scenario: cMSSM

$\tilde{\chi}_1^0 \tilde{t}_1 \rightarrow \mathrm{th}$	34.3 %
$\tilde{\chi}_1^0 \tilde{t}_1 \rightarrow \mathrm{tg}$	16.1 %
$\tilde{\chi}_1^0 \tilde{t}_1 \rightarrow \mathrm{bW}^+$	3.4 %
$\tilde{\chi}_1^0 \tilde{t}_1 \rightarrow \mathrm{tZ}$	1.4 %
$\tilde{\chi}_1^0 \tilde{t}_1 \rightarrow \mathrm{t}\gamma$	0.4 %

For $\tilde{\chi}_1^0 \tilde{t}_1 \rightarrow \mathrm{t\,h}$ @ p_{cm} = 50 GeV:
$\rightarrow$ relative correction: -14.8 %



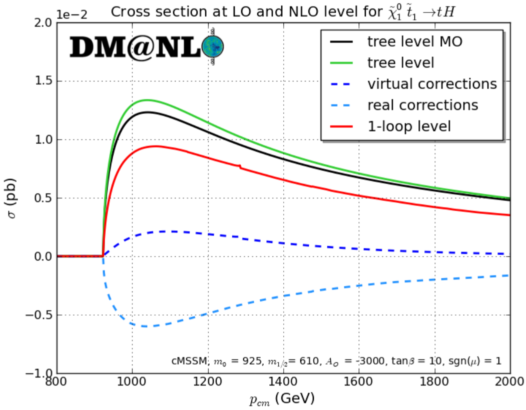
Impact of SUSY-QCD-corrections to coannihilation

Example scenario: cMSSM

$\tilde{\chi}_1^0 \tilde{t}_1 \to \mathrm{th}$	34.3 %
$\tilde{\chi}_1^0 \tilde{t}_1 \to \mathrm{tg}$	16.1 %
$\tilde{\chi}_1^0 \tilde{t}_1 \to \mathrm{bW}^+$	3.4 %
$\tilde{\chi}_1^0 \tilde{t}_1 \to \mathrm{tZ}$	1.4 %
$\tilde{\chi}_1^0 \tilde{t}_1 \to \mathrm{t}\gamma$	0.4 %

For $\tilde{\chi}_1^0 \tilde{t}_1 \to \mathrm{t\,h}$ @ p_{cm} = 50 GeV:
$\to$ relative correction: -14.8 %

For $\tilde{\chi}_1^0 \tilde{t}_1 \to \mathrm{t\,H}$ @ p_{cm} = 1000 GeV:
$\to$ relative correction: -32.0 %



Impact of SUSY-QCD-corrections to coannihilation

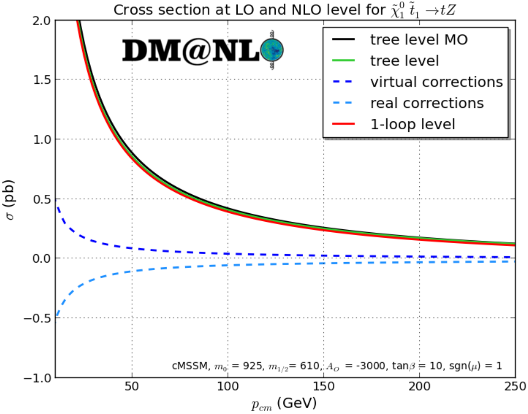
Example scenario: cMSSM

$\tilde{\chi}_1^0 \tilde{t}_1 \to \mathrm{th}$	34.3 %
$\tilde{\chi}_1^0 \tilde{t}_1 \to \mathrm{tg}$	16.1 %
$\tilde{\chi}_1^0 \tilde{t}_1 \to \mathrm{bW}^+$	3.4 %
$\tilde{\chi}_1^0 \tilde{t}_1 \to \mathrm{tZ}$	1.4 %
$\tilde{\chi}_1^0 \tilde{t}_1 \to \mathrm{t}\gamma$	0.4 %

For $\tilde{\chi}_1^0 \tilde{t}_1 \to \mathrm{t\ h}$ @ p_{cm} = 50 GeV:
$\to$ relative correction: -14.8 %

For $\tilde{\chi}_1^0 \tilde{t}_1 \to \mathrm{t\ H}$ @ p_{cm} = 1000 GeV:
$\to$ relative correction: -32.0 %

For $\tilde{\chi}_1^0 \tilde{t}_1 \to \mathrm{t\ Z}$ @ p_{cm} = 50 GeV:
$\to$ relative correction: -2.2 %



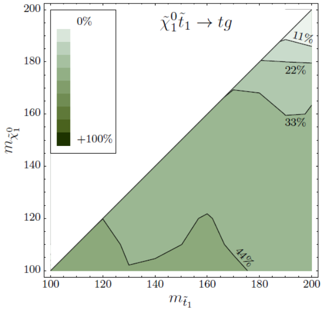
$\Rightarrow$ NLO-corrections to coannihilation have significant impact on cross section

Consequences on the relic density

- huge impact on relic density through

$$\Omega_{CDM}\, h^2 = \frac{m_\chi n_0}{\rho_C} \propto \frac{1}{\langle \sigma v \rangle}$$

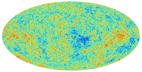
- vector boson and gluon final states will be soon finished
- similiar effects up to 50% through corrections expected

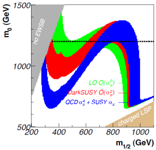


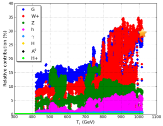
Freitas (2007), arXiv:0705.4027v2 [hep-ph].

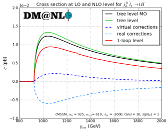
⇒ SUSY-QCD-corrections to coannihilation will have sizeable impact on relic density prediction!

Conclusion and Outlook









- Public codes do not take into account full NLO corrections
- DM@NLO will contain SUSY-QCD corrections to Gaugino annihilation and Neutralino-Squark coannihilation
- corrections up to 50 % expected and thus a huge impact on the relic density prediction
- Package DM@NLO allows to link SUSY-QCD corrections to the public codes

→ Code will be public available!

http://dmnlo.hepforge.org