Effect of SUSY-QCD corrections on the dark matter relic density.

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Overview

Overview

Neutralino dark matter

- Minimal Supersymmetric extension of Standard Model (MSSM) with R-parity conservation

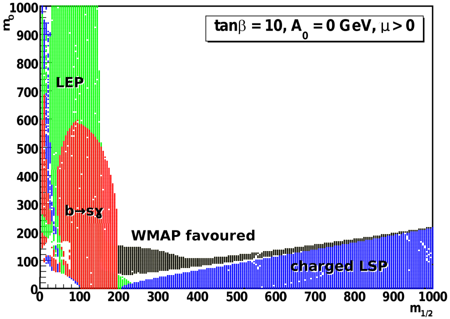
$$P_R = (-1)^{3(B-L)+2s} = \begin{cases} +1 & \text{SM} \\ -1 & \text{SUSY} \end{cases}$$

- Neutralino as lightest supersymmetric particle
- perfect cold dark matter candidate
- parameter studies in cMSSM with 5 universal parameters at GUT-scale

$$m_{1/2} \quad m_0 \quad A_0 \quad \tan\beta = \frac{v_u}{v_d} \quad \text{sign}\mu$$

Constraining the SUSY parameter space

Interplay of particle and astro particle physics



With LHC and PLANCK data it will be even more interesting

particle physics bounds

- direct searches
  e.g.
  $m_{\tilde{\chi}_0^1} > 46\ GeV$, $m_{\tilde{t}} > 95.7\ GeV$,
  $m_{\tilde{\tau}} > 81.9\ GeV$, $m_{\tilde{g}} > 107\ GeV$
- precision measurements
  e.g.
  $\mathrm{Br}(b \to s\gamma) = (3.55 \pm 0.26) \cdot 10^{-4}$

cosmology bounds

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

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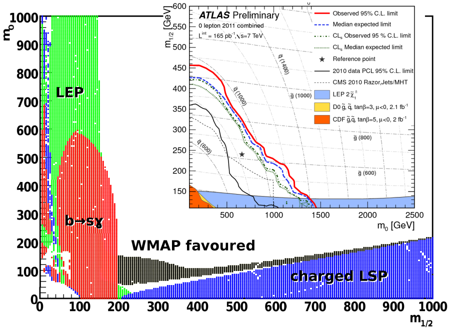

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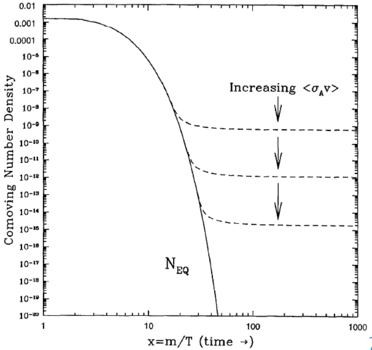
Overview

Relic density and freeze out

Relic density is the number density of dark matter particles.

- **early universe:**
  thermal equilibrium $\tilde{\chi}_1^0 \leftrightarrow \mathrm{SM}$
- **freeze out:**
  out of therm. equilibrium,
  dark matter non-relativistic
- **up to today:**
  comoving number density constant, relic density measurable
  ($\rightarrow$ WMAP, PLANCK)

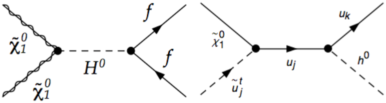


$$\Omega \propto \frac{1}{<\sigma v>}$$

Boltzmann equation

Relic density can be described by Boltzmann equation.

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



$\langle \sigma v \rangle$ cross section of annihilation and coannihilation

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

$\Rightarrow$ Coannihilation gets important, when masses of LSP and NLSP almost degenerate

Public computational tools (e.g.):

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

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

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

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

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

Current status in calculating relic density

- Calculation in MicrOMEGAs and DarkSUSY only on extended tree level
- current theoretical uncertainties bigger than future precision of PLANCK
- significant impact of NLO-corrections on the relic density expected

$\Rightarrow$ Package DM@NLO for linking SUSY-QCD corrections to public programs

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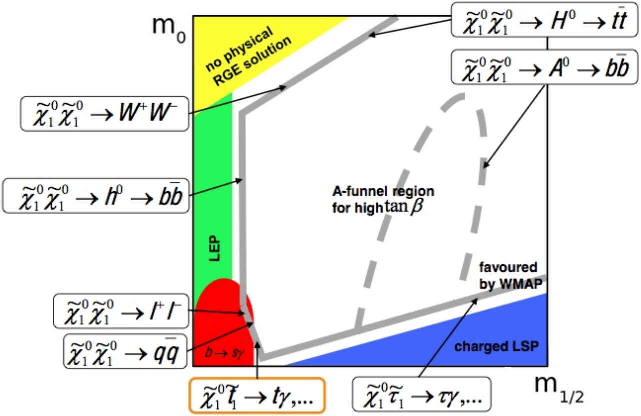
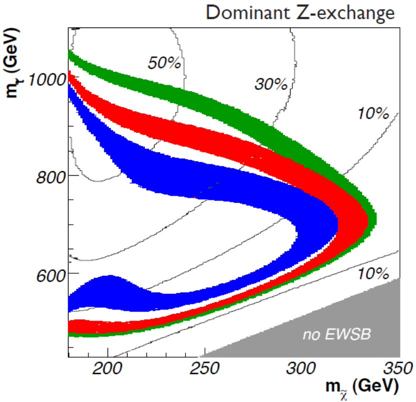
Dominant processes in relic density calculation



Impact of SUSY-QCD-corrections to annihilation

Example: Dominant Z-exchange

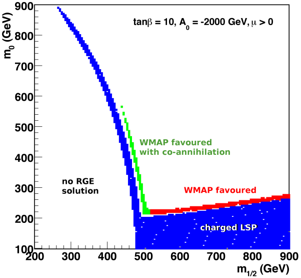
- enhancement of annihilation cross section into quarks by 50 % through QCD-corrections
- reduction of the predicted relic density
- significant shift of the WMAP favoured region

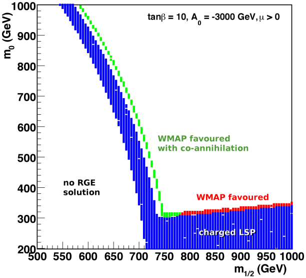


$\tan\beta = 10$, $A_0 = 0$, $m_0 = 1500$, $M_2 = 600$, $\mu > 0$
Herrmann, Klasen, Kovarik (2009), arXiv:0907.0030 [hep-ph].

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

Interesting $\tilde{\chi}_1^0 \tilde{t}_1$-co-annihilation regions





$\tilde{\chi}_1^0 \tilde{t}_1 \to \mathrm{th}$	26.8 %	$\tilde{\chi}_1^0 \tilde{t}_1 \to \mathrm{th}$	34.3 %
$\tilde{\chi}_1^0 \tilde{t}_1 \to \mathrm{tg}$	7.0 %	$\tilde{\chi}_1^0 \tilde{t}_1 \to \mathrm{tg}$	16.1 %
$\tilde{\chi}_1^0 \tilde{t}_1 \to \mathrm{bW}^+$	1.8 %	$\tilde{\chi}_1^0 \tilde{t}_1 \to \mathrm{bW}^+$	3.4 %
$\tilde{\chi}_1^0 \tilde{t}_1 \to \mathrm{tZ}$	0.6 %	$\tilde{\chi}_1^0 \tilde{t}_1 \to \mathrm{tZ}$	1.4 %
$\tilde{\chi}_1^0 \tilde{t}_1 \to \mathrm{t}\gamma$	0.2 %	$\tilde{\chi}_1^0 \tilde{t}_1 \to \mathrm{t}\gamma$	0.4 %

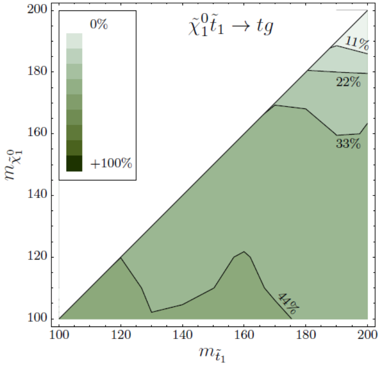
$\Rightarrow$ Co-annihilation especially dominant for high values of A_0

Impact of SUSY-QCD corrections to co-annihilation

Rough estimation for $\tilde{\chi}_1^0\tilde{t}_1$-co-annihilation

Freitas (2007)

- only $\tilde{\chi}_1^0\tilde{t}_1 \to \mathrm{tg}$ and $\tilde{\chi}_1^0\tilde{t}_1 \to \mathrm{bW}^+$ processes were taken into account
- co-annihilation contribution to the cross section of up to 85% expected
- significant effects through NLO-corrections expected (up to 50%)



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

$\Rightarrow$ SUSY-QCD-corrections to co-annihilation cross section promising!

Overview

DM@NLO - current status

(DESY, Münster, Karlsruhe, Grenoble and Annecy)

Package DM@NLO enables linking of SUSY-QCD-corrections to (co-)annhilation at full next to leading order to MicrOMEGAs and DarkSUSY.

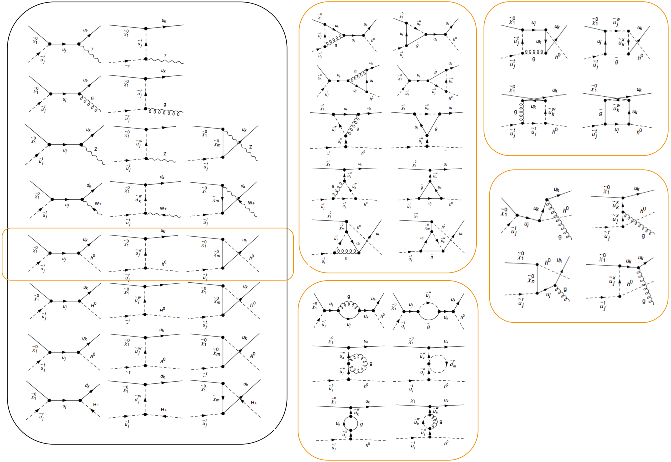
- work on corrections to annihilation already finished

  [B. Herrmann, M. Klasen, K Kovarik (2009)]

- $\tilde{\chi}^0_x \tilde{q}$-coannihilation work in progress

  [JH, Q. Le Boulc'h, B. Herrmann, M. Klasen, K. Kovarik]

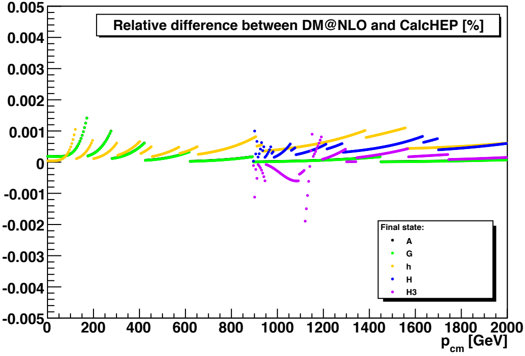
Status of the $\tilde{\chi}^0_x \tilde{q}$-co-annihilation project



$\Rightarrow$ Having to consider eight final states with self energies, vertex corrections, boxes and real emission.

Verifying the co-annihilation tree level results

- Tree level for $\tilde{\chi}^0_x \tilde{q}$-co-annihilation completely implemented
- Tree level results with CalcHEP sucessfully verified
- Virtual corrections analytically calculated
- Implementation of virtual corrections with their counter terms



$\Rightarrow$ Very good agreement with tree level results of CalcHEP!

Regularization and renormalization

- Dimensional reduction (DRED) for preserving SUSY d.o.f.
- On-shell renormalization for real external particles

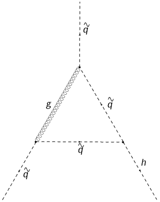
$$\sigma^{(v)} = \sigma_g^{(v)} + \sigma_{\tilde{g}}^{(v)} =$$

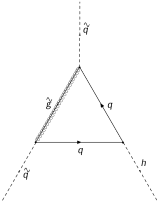
$$\frac{C_F}{16\pi^2} g_0 g_1 g_2 \left[\frac{1}{\epsilon}\right] + \mathrm{UV-finite}$$

$$+ \frac{2C_F}{16\pi^2}\Big((g_0^L g_2^R g_1^L + g_0^R g_2^L g_1^R) m_{f1} + (g_0^L g_2^L g_1^R + g_0^R g_2^R g_1^L) m_{f2}$$

$$+ (g_0^L g_2^R g_1^R + g_0^R g_2^L g_1^L) m_{\tilde{g}} \Big) \left[\frac{1}{\epsilon}\right] + \mathrm{UV-finite}$$

$$\sigma^{(ren)} = \sigma_g^{(v)} + \sigma_{\tilde{g}}^{(v)} + \sigma_g^{(w)} + \sigma_{\tilde{g}}^{(w)} + \sigma^{(c)}$$





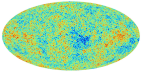
$\Rightarrow$ UV-cancellation allows first cross check during implementation

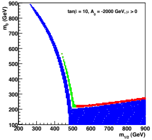
$\Rightarrow$ IR-cancellation through real emission

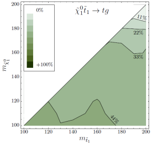
$\Rightarrow$ Cross check between Higgs and vector boson final states through Goldstone boson equivalence theorem

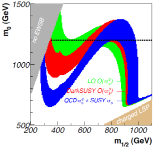
Conclusions

- PLANCK will give stricter bounds on relic density with errors less than current theoretical uncertainties
- public codes like MicrOMEGAS and DarkSUSY do not take into account full NLO corrections
- Importance of co-annihilation processes in case of small mass differences between LSP and NLSP
- Expectation of significant impact of these corrections on the relic density
- Package DM@NLO allows to link the SUSY-QCD corrections to the public codes
- Interesting parameter studies with more precise predicted constrains and experimental data will be possible





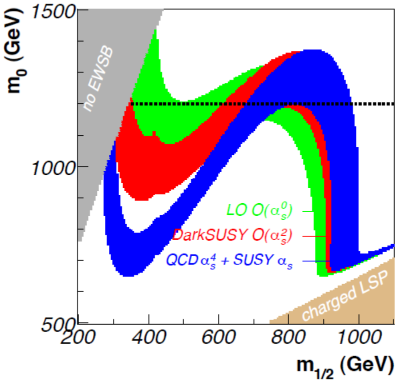




Impact of SUSY-QCD corrections to annihilation

Example: A-Funnel region

- annihilation cross section reduced through QCD corrections by more than a factor two
- WMAP favoured regions shifted to smaller masses
- reverse effect at resonance point through corrections to the Higgs width



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