Effect of radiative corrections to neutralino annihilation on the dark matter relic density

Björn Herrmann
LPSC Grenoble

in collaboration with Michael Klasen

[to be submitted to Phys. Lett. B]

SUSY 07
Karlsruhe, 27 July 2007

Outline

Relic density calculation

- WMAP mission has given precise range for dark matter relic density [Hamann *et al.* (2007)]

$$0.094 \leq \Omega_{CDM} h^2 \leq 0.136 \qquad \text{(at } 2\sigma)$$

- New physics provides interesting candidates for cold dark matter
  → in supersymmetry: lightest neutralino
- Relic density calculation allows to constrain supersymmetric models

$$\frac{dn}{dt} = -3Hn - \langle \sigma_{eff} v \rangle \left(n^2 - n_{eq}^2 \right)$$

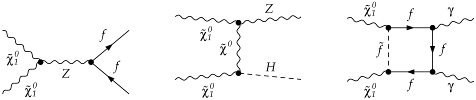
  → relic abundance involves neutralino mass and annihilation cross sections

$$\Omega_{CDM} h^2 \propto \frac{m_\chi}{\langle \sigma_{eff} v \rangle}$$

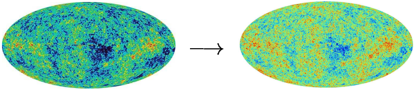
  → identify favoured regions in parameter space
- Public codes for supersymmetric dark matter calculation
  → `DarkSUSY` [Gondolo *et al.* (2004)]
  → `micrOMEGAs` [Bélanger *et al.* (2006)]

Why higher order corrections...?

- Most (co)annihilation processes implemented only at leading order



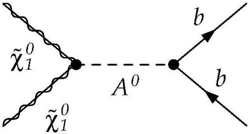
- Higher order corrections to annihilation cross section can be important
  $\rightarrow$ specific regions of parameter space
- New experimental cosmological data in near future
  $\rightarrow$ Planck will provide CMB anisotropy map with higher precision than WMAP
  $\rightarrow$ higher precision in theoretical results needed



- Higher precision in annihilation cross sections required
  $\rightarrow$ obtain better precision in relic density
  $\rightarrow$ higher order radiative corrections important within this context

Why $\tilde{\chi}_1^0\tilde{\chi}_1^0 \to A^0 \to b\bar{b}$...?

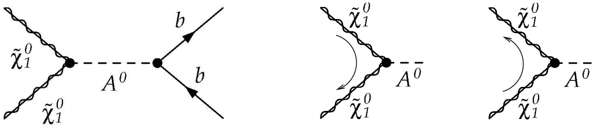
- Neutralino annihilation channel into fermion/antifermion pairs is always open
- Neutralino pair behaves like a pseudoscalar particle [Logan *et al.* (2005)]



- Dominant process in mSUGRA *A-funnel* region
  $\to$ large $\tan\beta$ (favoured by theory)
- Process possibly compatible with observed gamma-ray excess [de Boer *et al.* (2004)]
  $\to$ problem with corresponding positron flux [Salati *et al.* (2006)]
  $\to$ see also talks W. de Boer, C. Sander, M. Weber, I. Gebauer...

Born cross section

- Anti-symmetrization of Majorana neutralinos [Denner *et al.* (1992)]



- Process important at large $\tan\beta$

$$\sigma_{LO} \propto 2\alpha_{ew} N_C \tan^2\beta \, \frac{\sqrt{s-4m_b^2}\sqrt{s-4m_\chi^2}}{|s-m_A^2+im_A\Gamma_A|^2}$$

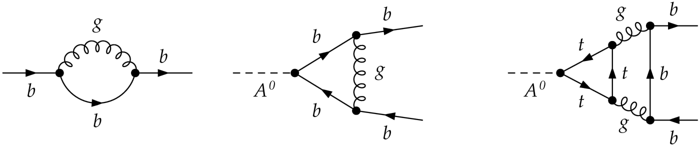
$\rightarrow$ dominant around A^0-resonance

- Non-relativistic expansion of cross section in agreement with previous results [Jungman *et al.* (1996)]

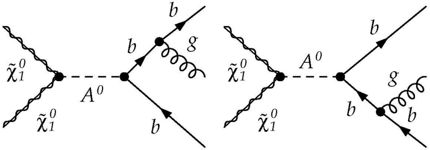
$$\sigma_{LO} v_{rel} = a + b v_{rel}^2 + \mathcal{O}(v_{rel}^4)$$

QCD corrections: diagrams

- Virtual QCD corrections



- Real gluon emission correction



- On-shell renormalization for virtual part

$$\sigma_V = \sigma_{LO}\left[\Delta_V + \delta Z_m + \delta Z_\psi\right]$$

$\rightarrow$ cancel UV-singularities

QCD corrections: dipole subtraction and resummation

- Dipole subtraction method to combine virtual and real part [Catani *et al.* (2002)]

$$\sigma_{\rm QCD} = \left[\sigma_{\rm V} + \int d\sigma_{\rm aux}\right]_{\epsilon=0} + \int \left[d\sigma_{\rm R} - d\sigma_{\rm aux}\right]_{\epsilon=0} = \sigma_{\rm LO}\left[1 + \tilde{\Delta}_{\rm QCD}\right]$$

  → cancel remaining IR-singularities

- Logarithmic singularity at high energies
  → resummation of leading logarithmic terms
  → use running quark mass

$$m_b \to \bar{m}_b(Q^2)$$

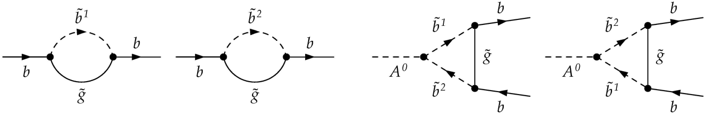
- Matching of low and high energy part

$$\Delta_{QCD} = \frac{4m_b^2}{s}\Delta_{QCD}^{(LE)} + \left(1 - \frac{4m_b^2}{s}\right)\Delta_{QCD}^{(HE)}$$

- Include known higher order correction terms
  → QCD correction up to $\mathcal{O}(\alpha_s^3)$ [Chetyrkin *et al.* (1997)]
  → top-induced correction at $\mathcal{O}(\alpha_s^2)$ [Chetyrkin *et al.* (1996)]

SUSY-QCD corrections: diagrams

- Virtual SUSY-QCD corrections



- Renormalized correction term

$$\Delta_{\rm SUSY} \sim \frac{1}{m_b^2}\sum_{i=1,2}\Big[A_0(m^2_{\tilde{b}_i}) - A_0(m^2_{\tilde{g}}) - (m^2_{\tilde{b}_i} - m^2_{\tilde{g}})B_0(m^2_b, m^2_{\tilde{g}}, m^2_{\tilde{b}_i})$$
$$+(m^2_b + m^2_{\tilde{g}} - m^2_{\tilde{b}_i})B_0'(m^2_b, m^2_{\tilde{g}}, m^2_{\tilde{b}_i})\Big]$$
$$+\frac{m_{\tilde{g}}(\mu + A_b\tan\beta)}{\tan\beta} C_0(m^2_b, s, m^2_b; m^2_{\tilde{b}_1}, m^2_{\tilde{b}_2}, m^2_{\tilde{g}})$$

- Low energy limit of SUSY-QCD correction

$$\Delta^{(LE)}_{SUSY} \sim C_0(0,0,0; m^2_{\tilde{b}_1}, m^2_{\tilde{b}_1}, m^2_{\tilde{g}})$$

SUSY-QCD corrections: mass and coupling resummation

- Radiative corrections to bottom mass

$$\frac{\Delta m_b}{m_b} = -\frac{\alpha_s C_F}{2\pi} m_{\tilde{g}} (A_b - \mu \tan\beta)\, C_0(0,0,0; m^2_{\tilde{b}_1}, m^2_{\tilde{b}_2}, m^2_{\tilde{g}}) = \Delta_1 + \Delta_2$$

$\rightarrow$ low energy part of SUSY correction can be absorbed into bottom mass

- Resummed bottom mass and coupling

$$\Delta m_b^{(\mathrm{QCD})} \rightarrow \frac{\Delta m_b^{(\mathrm{QCD})}}{1+\Delta_1} \equiv \Delta m_b \qquad g_{Ab} \rightarrow \frac{g_{Ab}}{1+\Delta_1}\left(1 - \frac{\Delta m_b}{\tan^2\beta}\right) = g_{Ab}\,(1+\Delta g_{Ab})$$

- Final SUSY-QCD cross section

$$\sigma_{\mathrm{SUSY}} = (1+\Delta g_{Ab}) \left[1 + \Delta g_{Ab} + \left(C_A\big|_{s\neq 0} - C_A\big|_{s=0}\right)\frac{\alpha_s}{\pi}\right] \sigma_{\mathrm{QCD}}(\bar{m}_b)$$

where

$$C_A = -m_{\tilde{g}}\ \mu\ \frac{1+\tan^2\beta}{\tan\beta}\ C_0(0,s,0; m^2_{\tilde{b}_1}, m^2_{\tilde{b}_2}, m^2_{\tilde{g}})$$

Supersymmetric model

- mSUGRA scenario: five parameters at high (GUT) scale

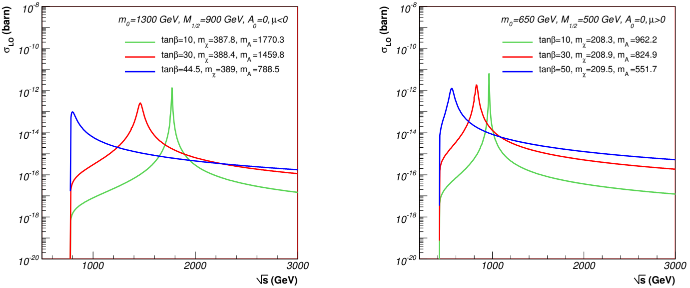
$$m_0, \quad m_{1/2}, \quad A_0, \quad \tan\beta, \quad \mathrm{sgn}(\mu)$$

- Assume R-parity conservation and dark matter is made of 100% neutralino
- Calculation of mass spectrum and relic density using `SPheno 2.2.3`, `FeynHiggs 2.5.1` and modified `DarkSUSY 4.1`
  [Porod (2006), Heinemeyer *et al.* (2000), Gondolo *et al.* (2004)]
- Cold dark matter range based on WMAP [Hamann *et al.* (2007)]

$$0.094 \leq \Omega_{CDM} h^2 \leq 0.136 \qquad \text{(at } 2\sigma\text{)}$$

$\rightarrow$ determine cross section and favoured parameter region including / not including correction terms

Born cross section

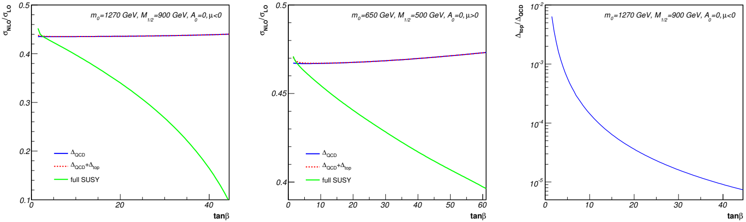


- Process important at large $\tan\beta$

$$\sigma_{LO} \propto 2\alpha_{ew} N_C \tan^2\beta \, \frac{\sqrt{s-4m_b^2}\sqrt{s-4m_\chi^2}}{|s-m_A^2+im_A\Gamma_A|^2}$$

$\rightarrow$ dominant around A^0-resonance

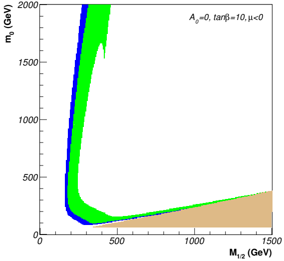
Cross section at NLO

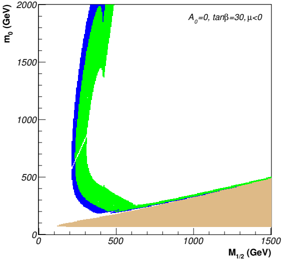


- QCD correction decreases cross section by about 50%
- SUSY-QCD correction can contribute to up to another 40%
  $\rightarrow$ importance depends on sgn(μ) and $\tan\beta$
- Top-quark induced correction negligable for large $\tan\beta$ (i.e. *A-funnel* region)

Small and intermediate tan β

- QCD and SUSY-QCD corrections decrease cross section by at least 50%





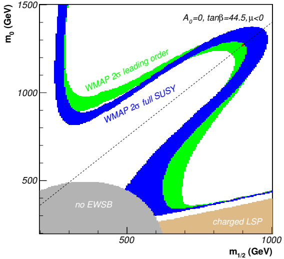
- No significant effect on WMAP favoured region

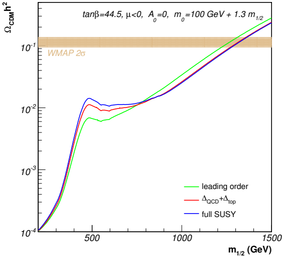
$$0.094 < \Omega_{CDM} h^2 < 0.136 \qquad (0.1 < \Omega_{CDM} h^2 < 0.3)$$

$\rightarrow$ annihilation through A^0 does not significantly contribute to $\langle \sigma_{eff} v \rangle$
$\rightarrow$ no dependence on sgn(μ)

A-funnel region for $\mu < 0$

- QCD and SUSY-QCD corrections decrease cross section by about 50% and 40%
  $\rightarrow$ SUSY-QCD contribution has same size as QCD part

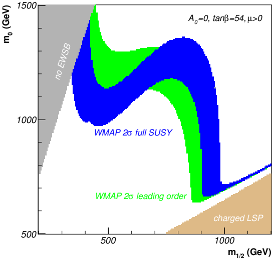




- Constriction of WMAP favoured region towards smaller SUSY masses
  $\rightarrow$ compensation of smaller cross section

A-funnel region for $\mu > 0$

- QCD and SUSY-QCD corrections decrease cross section by about 50% and 10%
  $\rightarrow$ main contribution comes from QCD part

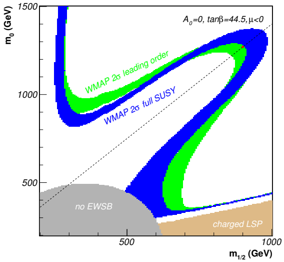


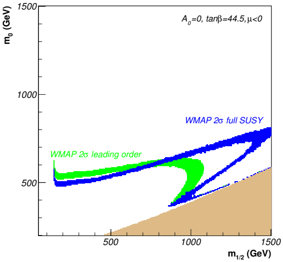
- Constriction of WMAP favoured region towards smaller SUSY masses
  $\rightarrow$ compensation of smaller cross section
  $\rightarrow$ effect slightly less important than for $\mu < 0$

Dependence on spectrum generator

- SPheno vs. IsaJET

  → *A-funnel*/WMAP 2σ contour depends on spectrum code





- Neutralino and Higgs masses especially sensible to spectrum code

  [Kraml *et al.* (2003, 2005)]

  → A^0 resonance of the process shifted

- Effect of (SUSY-)QCD corrections remains the same

Conclusion and perspectives

- Relic density calculation is interesting tool to constrain supersymmetry
  $\rightarrow$ in times of high precision cosmology radiative corrections become important
- Calculation of higher order QCD and SUSY-QCD corrections to $\chi\chi \rightarrow A \rightarrow b\bar{b}$
  $\rightarrow$ complete NLO correction
- Numerical evaluation of annihilation cross section
  $\rightarrow$ QCD diagrams reduce cross section by about 50%
  $\rightarrow$ SUSY-QCD diagrams reduce cross section by another up to 40%
- Numerical evaluation of dark matter relic density
  $\rightarrow$ WMAP favoured contour is shifted to smaller SUSY masses
- Perspectives
  $\rightarrow$ study further interesting annihilation processes
  $\rightarrow$ include electroweak corrections