Dark matter in the CNMSSM

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LAPTH

based on

Hugonie, GB, Pukhov arXiv:0707.0628

Motivation

- Strong evidence for dark matter and CMB (WMAP) gives precise information on the amount of dark matter
- Most attractive explanation for DM: new weakly interacting particle, for example those present in R-parity conserving SUSY model or XDim models or Little Higgs models …
- Neutralino in CMSSM has been studied extensively, including collider phenomenology + direct or indirect detection,
- Important to consider other DM models – here take simplest extension of MSSM – NMSSM and impose GUT scale boundary conditions.
- Precise prediction of spectrum + relic density
  - NMSSMTools + micrOMEGAs
- Some analyses of relic density in singlet extensions of NMSSM
  - Stephan, hep-ph/9704232; Menon, Morrissey, Wagner hep-ph/0404184; Gunion, Hooper, McElrath, hep-ph/0509024, Barger et al, hep-ph/0702063

NMSSM

- Provides solution to μ problem or why SUSY conserving Higgs mass term is order of weak scale
- Fine-tuning from non-observation of Higgs at LEP is less severe than in MSSM
- Add singlet superfield, μ is related to vev of this singlet

$$W = \lambda S H_u H_d + \frac{\kappa}{3} S^3 \qquad\qquad \mu = \lambda s$$

- Domain wall problem can be avoided by introducing non-renorm operators
  - Abel, hep-ph/9609323, Panagiotakopoulos, Tamvakis, hep-ph/9809475
- Simple extension of MSSM, in the limit λ->0, μ ≠0 recover MSSM + decoupled singlet sector
- Phenomenology can be different than in MSSM
  - Upper bound on Higgs mass increases by O(10GeV)
  - Very light Higgs not excluded
  - Light neutralino (singlino) allowed

NMSSM- neutralino sector

- One additional neutralino

$$\begin{pmatrix} M_1 & 0 & M_Z \sin\theta_W \sin\beta & -M_Z \sin\theta_W \cos\beta & 0 \\ 0 & M_2 & -M_Z \cos\theta_W \sin\beta & M_Z \cos\theta_W \cos\beta & 0 \\ M_Z \sin\theta_W \sin\beta & -M_Z \cos\theta_W \sin\beta & 0 & -\mu & -\lambda v \cos\beta \\ -M_Z \sin\theta_W \cos\beta & M_Z \cos\theta_W \cos\beta & -\mu & 0 & -\lambda v \sin\beta \\ 0 & 0 & -\lambda v \cos\beta & -\lambda v \sin\beta & 2\nu \end{pmatrix}$$

- Nature of LSP

$$\nu = \kappa s$$

$$\tilde{\chi}_1^0 = N_{11}\widetilde{B} + N_{12}\widetilde{W} + N_{13}\widetilde{H}_u + N_{14}\widetilde{H}_d + N_{15}\widetilde{S}$$

- In limit λ ->0 singlino is quasi pure state mass 2ν
- LSP coupling to Higgses

$$g_{\tilde{\chi}_1^0\tilde{\chi}_1^0 h_i} = g(N_{12} - N_{11}\tan\theta_W)(S_{i1}N_{13} - S_{i2}N_{14}) + \sqrt{2}\lambda N_{15}(S_{i1}N_{14} + S_{i2}N_{13}) + \sqrt{2}S_{i3}(\lambda N_{13}N_{14} - \kappa N_{15}^2) .$$

Singlet component of scalar (→ S_{i3})

Singlino component (→ N_{15})

NMSSM - the Higgs sector

- MSSM with additional singlet superfield
- Higgs sector: 3 scalars, 2 pseudoscalars
  - μ parameter related to vev of singlet
  - Important radiative corrections to Higgs masses and mixings (calculated in NMHDECAY)
- Parameters

$$V_{\rm soft} = \left(\lambda A_\lambda H_u H_d S + \frac{1}{3}\kappa A_\kappa S^3 + {\rm hc}\right).$$

$$+\ m^2_{\rm H_u}|H_u|^2 + m^2_{\rm H_d}|H_d|^2 + m^2_{\rm S}|S|^2$$

$$\mu = \lambda s$$

Purely Higgs sector

$$\lambda,\ \kappa,\ \tan\beta,\ \mu,\ A_\lambda,\ A_\kappa\ .$$

CNMSSM – the model

- NMSSM with GUT scale boundary conditions
- 3 minimization conditions: h_u, h_d, s. First solve for μ and B, then soft singlet mass

$$
\begin{aligned}
\mu^2 &= \frac{m_{H_d}^2 - m_{H_u}^2 \tan\beta^2}{\tan\beta^2 - 1} - \frac{1}{2} M_Z^2 \,, \\
B &= \frac{\sin 2\beta}{2\mu} \left(m_{H_u}^2 + m_{H_d}^2 + 2\mu^2 + \lambda^2 (h_u^2 + h_d^2) \right) \,, \\
m_S^2 &= \lambda^2 \frac{h_u h_d}{\mu} (A_\lambda + 2\nu) - \nu (A_\kappa + 2\nu) - \lambda^2 (h_u^2 + h_d^2) \,.
\end{aligned}
$$

CNMSSM - parameters

- $M_{1/2}$, m_0, A_0: universal soft terms at GUT scale:
  - Note m_S^2 (output) – difficult to have solution with $m_s \sim m_0$
  - A_κ : non-universality in scalar sector, $A_0 = A_\kappa$ leads often to negative Higgs mass squared
  - λ at SUSY scale
- $\tan\beta$, sign (μ)

Check theoretical and experimental constraints in NMSSM_Tools (Ellwanger, Hugonie, hep-ph/0612134) includes NMHDECAY (Ellwanger, Gunion, Hugonie JHEP02(2005) 066) + NMSPEC.

Experimental constraints

For each point in the parameter space, NMHDecay checks:

- $\tilde{\chi}_1^0$ is the LSP
- LEP limits on $\tilde{\chi}^{\pm}$'s and $\tilde{\chi}^0$'s (direct search + $\Gamma_{\rm inv}(Z)$)
- Limits from Tevatron on squarks/gluino
- LEP limits on $\tilde{t} \to bl\tilde{\nu}$, $\tilde{t} \to c\tilde{\chi}^0$ and $\tilde{b} \to b\tilde{\chi}^0$
- LHWG limit on the charged Higgs mass $m_{h^\pm} > 78.6$ GeV
- LHWG constraints from neutral Higgs searches:
  - $e^+e^- \to hZ$ with $h \to b\bar{b},\ \tau^+\tau^-, jj,\ \gamma\gamma$, invisible, "any"
  - $e^+e^- \to hZ$ with $h \to aa \to 4b$
  - $e^+e^- \to ha \to 4b,\ 4\tau$
  - $e^+e^- \to ha$ with $h \to aa,\ h/a \to b\bar{b},\ \tau^+\tau^-$

Theoretical constraints

- No unphysical global minimum for the scalar potential (with one or more 0 vevs for the Higgs fields)
- No Landau pole below $M_{\rm GUT}$ for $\lambda, \kappa, h_t, h_b, h_\tau$:

  $\Rightarrow$ Integrate the two loop RGEs for $\lambda, \kappa, h_t, h_b, h_\tau$ including all the SUSY/Higgs thresholds up to $M_{\rm GUT}$ / $g_1(M_{\rm GUT}) = g_2(M_{\rm GUT})$
- Additional information:
  - Integration of the two loop RGEs for all the soft terms (including all the SUSY/Higgs thresholds) up to $M_{\rm GUT}$
  - Integration of the two loop RGEs down to $M_{\rm weak}$ for arbitrary (universal) soft parameters at $M_{\rm GUT}$

Dark matter : NMSSM_tools + micrOMEGAs

- LanHEP: from the Lagrangian writes all masses and couplings in CalcHEP notation
- Higgs sector: write effective potential

$$
\begin{aligned}
V_{\rm rad} &= \lambda_1 (H_u H_u^*)^2/2 + \lambda_2 (H_d H_d^*)^2/2 + \lambda_3 (H_u H_u^*)(H_d H_d^*) \\
&+ \lambda_4 (\epsilon H_u H_d)(\epsilon H_u^* H_d^*) + \lambda_5 ((\epsilon H_u H_d)^2 + (\epsilon H_u^* H_d^*)^2)/2 \\
&+ \lambda_1^s (H_u H_u^*) S S^* + \lambda_2^s (H_d H_d^*) S S^* + \lambda_s^s (S S^*)^2/2 \\
&+ \lambda_5^s ((\epsilon H_u H_d) S^2 + (\epsilon H_u^* H_d^*) S^{*2})/2 + \lambda_p^s (S^4 + S^{*4})\,.
\end{aligned}
$$

- We use NMSSMTools to calculate Higgs masses and mixings,
- From this extract λ's and calculate Higgs self-couplings

Dark matter

- CalcHEP calculates automatically all necessary cross-sections
- Computation of relic density within micrOMEGAs:
  - Input parameters : SLHA_nmssm
  - Masses/mixings of Higgses: from NMHDECAY
  - Other SUSY masses: calculated at tree-level from the soft terms
  - As in MSSM: solve evolution equation, include all coannihilation channels, improved width for Higgs (e.g. Hff), careful treatment of poles
  - Also calculates all 2->2 cross-sections and 1->2 decays (tree-level)
  - LEP constraints and other theoretical constraints given by NMSSMTools
  - Other routines such as b-sγ not implemented yet (will do through NMHDECAY)
- Available on NMSSMTools web page :
  - http://www.th.u-psud.fr/NMHDECAY/nmssmtools.htm
- And on http://wwwlapp.in2p3.fr/lapth/micromegas
  - GB, Boudjema, Hugonie, Pukhov, Semenov, hep-ph/0505142

Dark matter - properties

- CMSSM scenarios
  - Bino LSP with light sfermion exchange
  - Annihilation near resonance (light or heavy)
  - Annihilation of bino/Higgsino LSP (focus)
  - Coannihilation with sfermions (stau,stop)

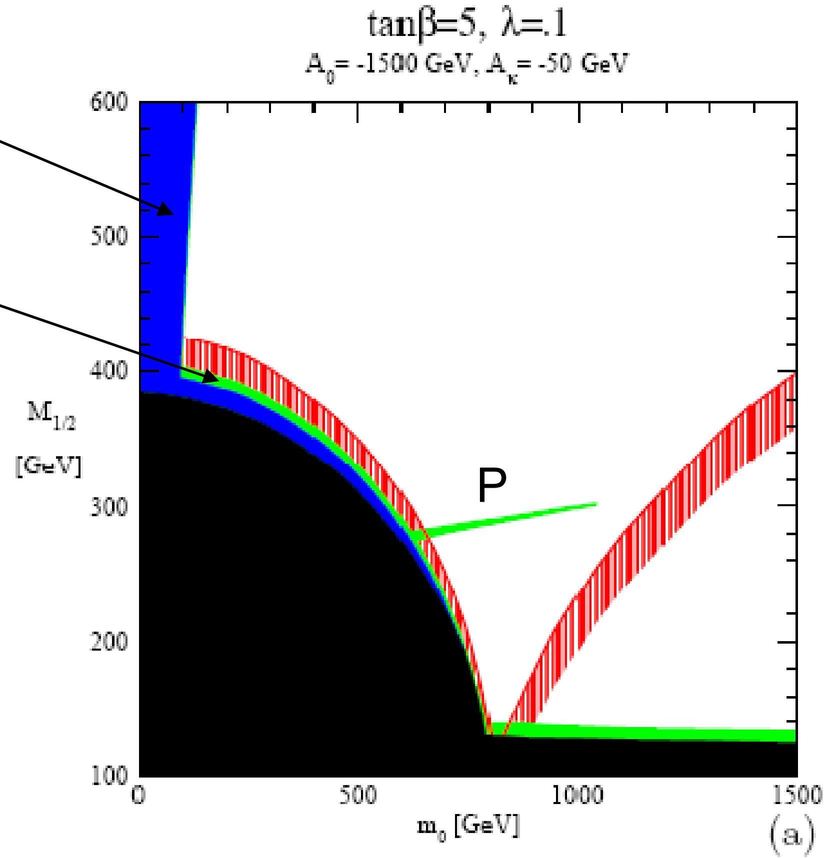
- Additional CNMSSM scenarios
  - Annihilation near a pseudoscalar singlet resonance (needs $\lambda > 0.1$)
  - Coannihilation of singlino with sfermions
  - Coannihilation of singlino and Higgsino
  - Coannihilation of singlino with bino

Parameter space

- 7 free parameters:
  - m_0, $M_{1/2}$, sgn(μ) tanβ, A_0, A_k, λ
- When do we expect pseudoscalar resonance
  - When λ small, small singlet-doublet mixing
  - $A_k < 0$ $$m_P^2 = -3\nu A_\kappa \, .$$
- When do we expect singlino LSP?
  - Need $\lambda \ll 1$: singlino decouples $m_{\tilde{S}} = 2\nu.$
  - $A_k<0$ and A_0 small, small values of m_0, $M_{1/2}$
  - $A_k>0$ - large m_0, $M_{1/2}$

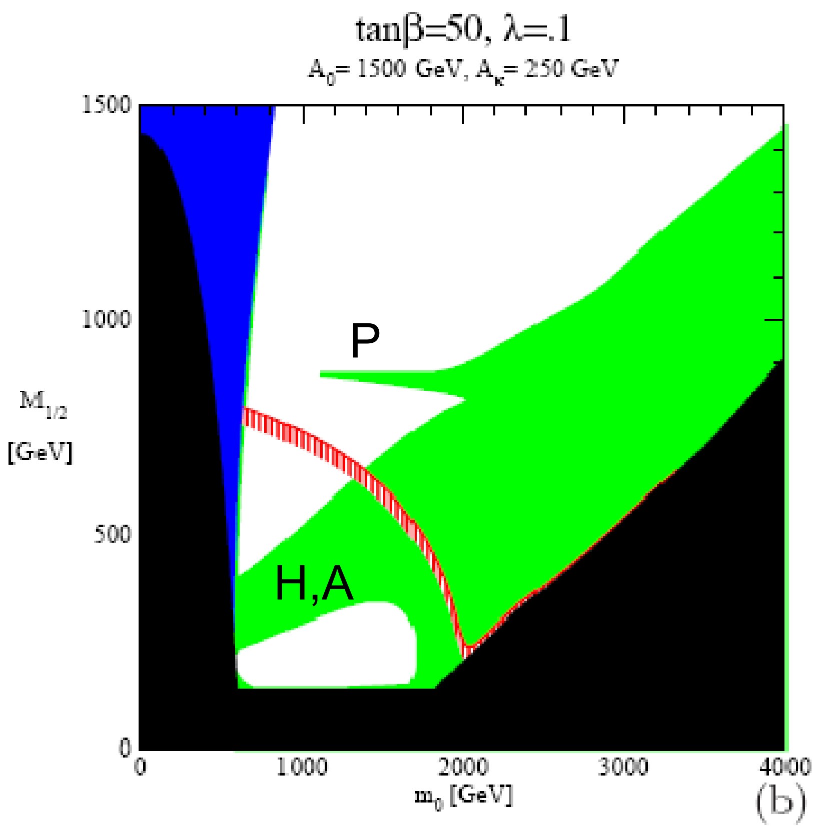
Some results

- Stau coannihilation
- Stop coannihilation
- Light Higgs resonance
- Pseudoscalar resonance
  - Even tanβ=2, λ=0.5 is allowed



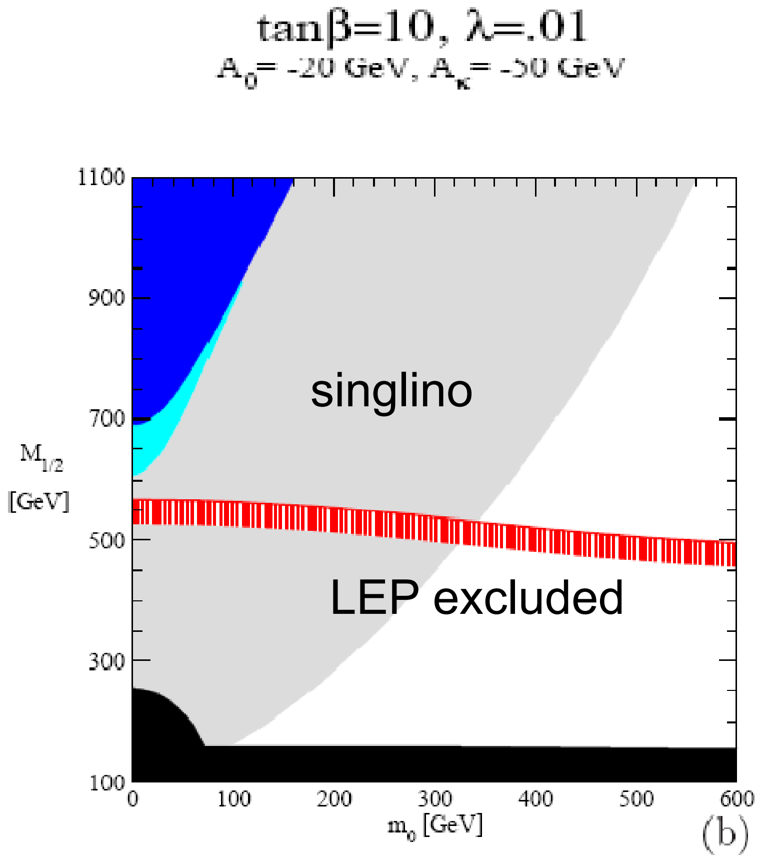
Some results

- Large tanβ : more resonances
  - Light/heavy doublet
  - Pseudoscalar
- Large M_0 : μ small, mixed bino/Higgsino
- Note: unphysical region where $M^2 < 0$ for lightest pseudoscalar can happen before LSP becomes Higgsino (especially at intermediate tan β)
- Annihilation channels : bb, τ τ when annihilation through Higgs



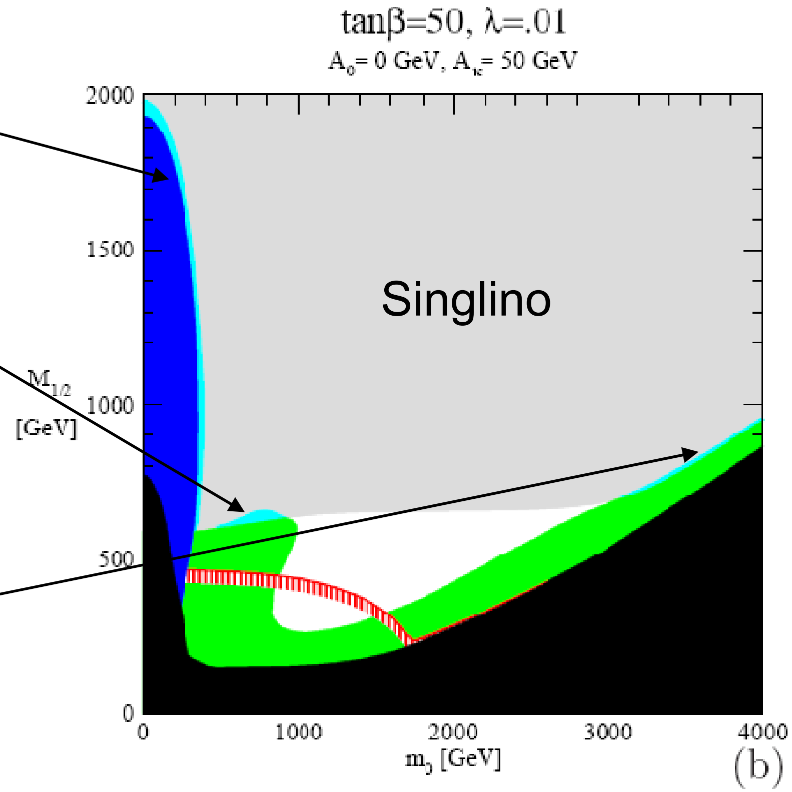
Singlino LSP

- Λ<<1
- $m_{\tilde{S}} = 2(\bar{B} - A_\lambda)$. $< m_B$
- Small to intermediate tanβ: only annihilation mechanism: stau coannihilation



Singlino LSP – large tanβ

- Stau coannihilation
- Rapid annihilation of bino LSP
- Coannihilation with bino/Higgsino NLSP
  - possibly NLSP annihilates near heavy Higgs resonance



Singlino LSP

- In CNMSSM we have found only a subset of possible scenarios for singlino LSP in the NMSSM
- Annihilation of singlino near Z or light scalar/pseudoscalar resonance does not occur, nor does annihilation of singlino/Higgsino into Higgs and W pairs
- For this require $\lambda > 0.1$, μ small, $\kappa s < \mu$
  - Set of conditions not fulfilled in CNMSSM
  - No scenario where LSP~<50GeV as in the CMSSM

CNMSSM - LHC

- Scenarios for DM are in general similar to CMSSM ones BUT additional scenarios with either singlino LSP or pseudoscalar resonance.
- Impact for LHC
  - Modification of sfermions decay chain
    - decay of stau-NLSP-> singlino
    - Kraml, Porod, hep-ph/0507055
  - In general hard to find 5 neutralinos
  - Important to search for P (or 3rd scalar) – will allow to establish that the model is not MSSM.
    - P-mass range in WMAP compatible scenarios: 100-300 GeV but suppressed couplings to fermions as compared to doublet Higgs - in some favourable cases (large tanβ) preliminary results show that it might be possible

Outlook - Reconstructing Ωh^2 at LHC

- Few case studies in CMSSM and MSSM: $\Delta\Omega \sim 10\%$ in favourable cases
  - Nojiri, Tovey Polesello, JHEP 0603:063 (2006)

- In (C)NMSSM looks harder
  - Pure NMSSM scenario : P annihilation
  - Can we tell if CNMSSM rather than CMSSM – need to discover P
  - Relevant parameter for relic density: mass difference LSP- P if near resonance - difficult to get precision needed
  - LHC will discover sparticles and a fit to CMSSM, if P is invisible will give $\Omega h^2 > 1$

- Also small DD rate in P scenario since no resonance enhancement
  - Only at large tanβ, rates larger ($\sigma \sim 10^{-9}$pb) since contribution also from Higgs doublet

Conclusion

- We have performed a precise calculation of relic density of dark matter in the CNMSSM with micrOMEGAs +NMSSMTools

- As compared to the CMSSM, in the CNMSSM there are new possibilities for neutralino annihilation that leads to relic density in agreement with WMAP: pseudoscalar resonances, possibility of singlino LSP.

- *These new scenarios are a challenge for colliders and DM detection experiments.*