Relic density of dark matter in the NMSSM

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LAPTH

based on

G. B., Boudjema, Hugonie, Pukhov, Semenov
hep-ph/0505142

Motivation

- Strong evidence for dark matter
- CMB (WMAP) gives precise information on the amount of dark matter
- Most attractive explanation for dark matter: new weakly interacting particle, for example those present in R-parity conserving SUSY model
- Need for a precise and accurate computation of the relic density of dark matter in different models
- So far most elaborate tools available for MSSM
  - DarkSUSY, micrOMEGAs, IsaTools
- Some analyses of relic density in NMSSM
  - Stephan, hep-ph/9704232; Menon, Morrissey, Wagner hep-ph/0404184; Gunion, Hooper, McElrath, hep-ph/0509024

NMSSM

- Provides solution to μ problem or why SUSY conserving Higgs mass term is order of weak scale
- Add singlet superfield, μ is related to vev of this singlet

$$\lambda \widehat{S} \widehat{H_u} \widehat{H_d} \qquad \mu = \lambda s$$

- Simplest extension of MSSM yet different phenomenology
  - Upper bound on Higgs mass increases by O(10GeV)
  - Very light Higgs not excluded
  - Light neutralino (singlino) allowed

NMSSM- the model

- MSSM with additional singlet superfield

  $W = -\lambda S H_u H_d + 1/3\, \kappa S^3$

$$-\mathcal{L}_{\rm soft} = m^2_{\rm H_u}|H_u|^2 + m^2_{\rm H_d}|H_d|^2 + m^2_{\rm S}|S|^2 + (\lambda A_\lambda H_u H_d S + \frac{1}{3}\kappa A_\kappa S^3 + {\rm h.c.}) - \frac{1}{2}(M_2\lambda_2\lambda_2 + M_1\lambda_1\lambda_1 + {\rm h.c.})\ .$$

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

$$\mu = \lambda s$$

- Parameters

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

Purely Higgs sector (A_λ, A_κ)

NMSSM- neutralino sector

- One additional neutralino

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

$$\nu = \kappa s$$

- Nature of LSP

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

- In limit $\lambda \to 0$ singlino is quasi pure state mass $2\kappa s$
- LSP coupling to Higgses

Singlet component of scalar

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

Singlino component

Implementation into micrOMEGAs

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

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

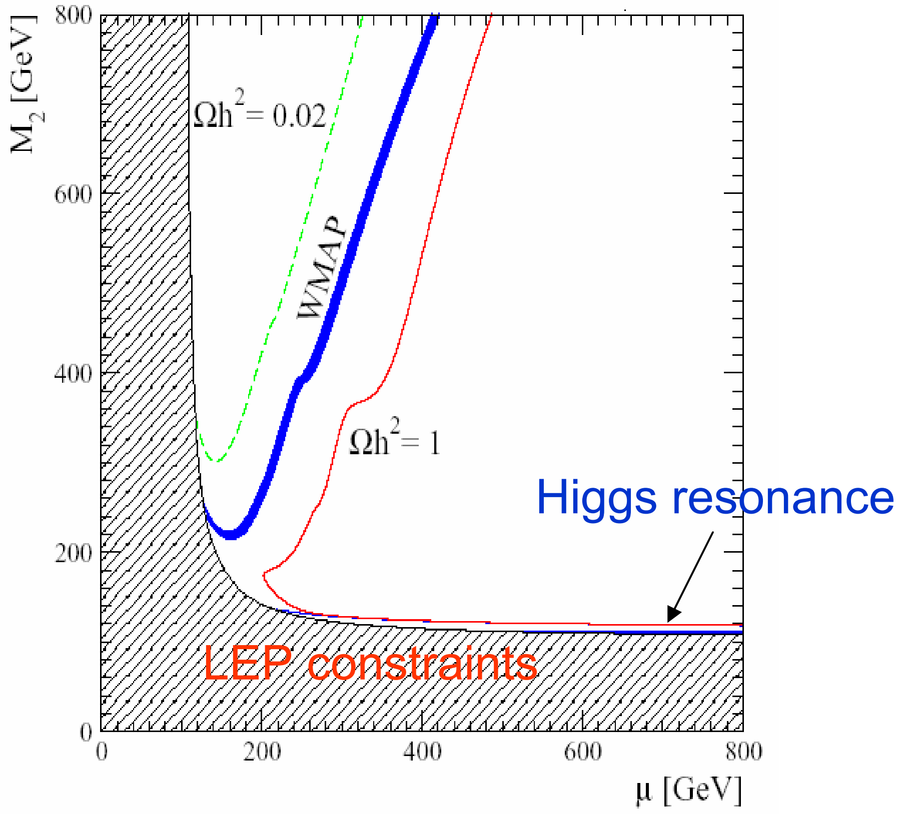
- New couplings must be calculated by an external program
  - We use NMHDECAY to calculate Higgs masses and mixings, U. Ellwanger, J. Gunion, C. Hugonie, JHEP02(2005)066
  - From this extract λ's and calculate Higgs self-couplings

micromegas_nmssm

- 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 NMHDECAY
  - Other routines such as b-sγ not implemented yet (will do through NMHDECAY)
- Available on NMHDECAY web page :
  - http://www.th.u-psud.fr/NMHDECAY/
- Soon on http://wwwlapp.in2p3.fr/lapth/micromegas
  - GB, Boudjema, Hugonie, Pukhov, Semenov, hep-ph/0505142

Some results

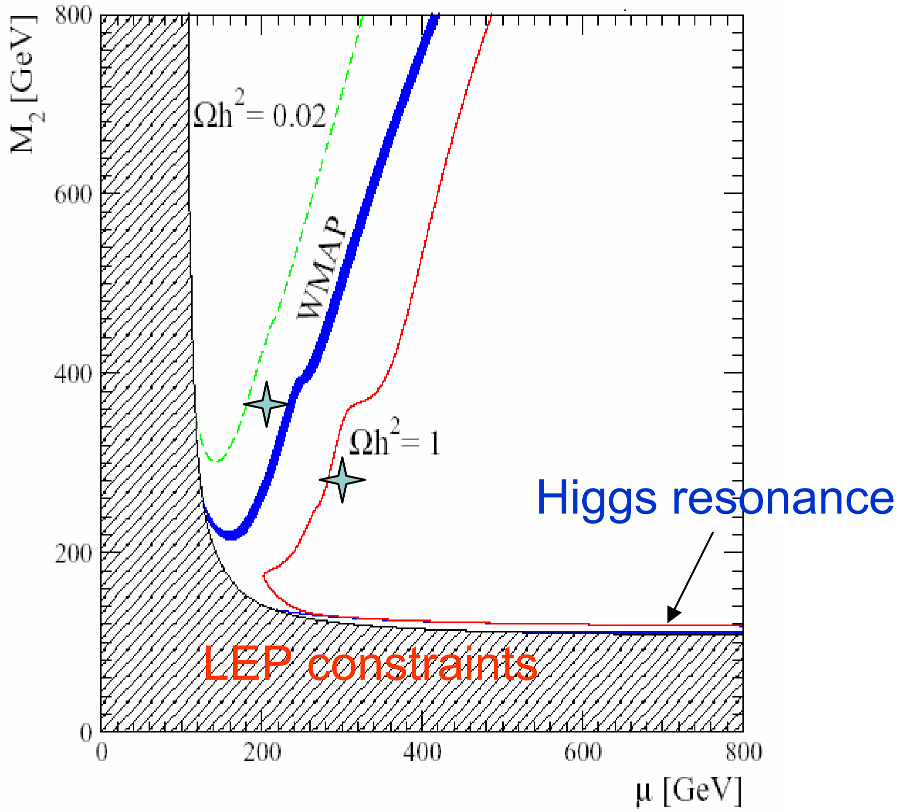
- Assume universality of gaugino mass at GUT scale, $M_1 \sim .5 M_2$ at weak scale
- Assume heavy sfermions ~1TeV
- As in the MSSM, WMAP favours models with LSP mixed bino/Higgsino (~25% Higgsino)
  - Main annihilation $\chi\chi \to WW$, through Higgs exchange and t-channel chargino
  - Also annihilation $\chi\chi \to tt$
- For almost pure bino LSP, annihilation near Higgs resonance give relic compatible with WMAP
- For different parameters can have other WMAP regions because annihilation through Higgs resonances



$\lambda = \kappa = 0.1$, $\tan\beta = 5$, $A_\lambda = 500$, $A_\kappa = 0$

What's different?

- More resonances, even at low tanβ
- Annihilation into light Higgses (scalar or pseudoscalar)
- Singlino LSP: can be compatible with WMAP



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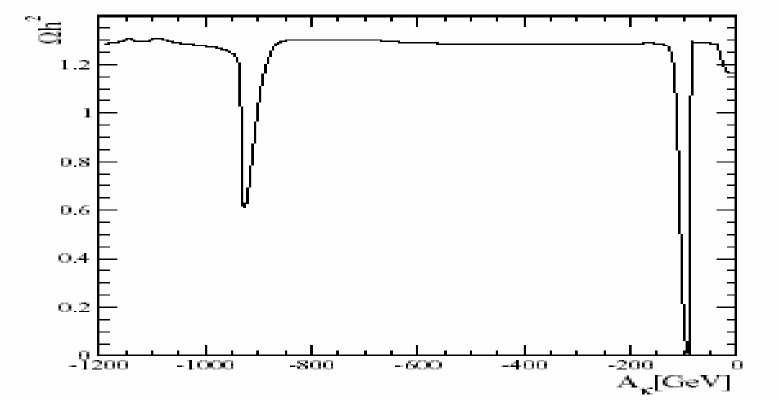
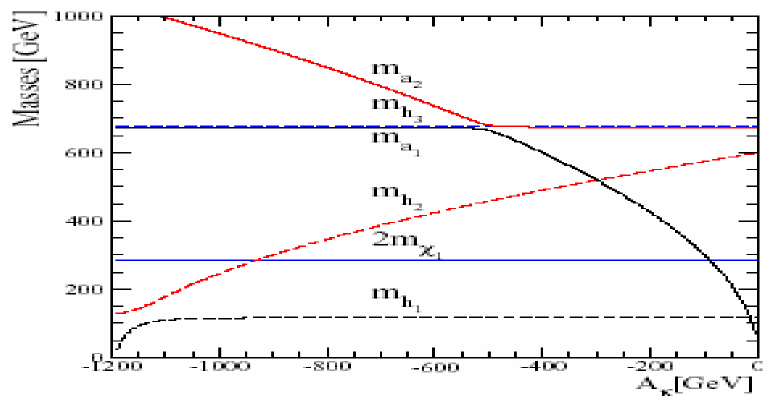
Case 1: Higgs annihilation

- More resonances
  - Even at low tanβ
  - Mass of scalars and pseudoscalars depend on A_λ A_κ
  - Can be h2,a1 …



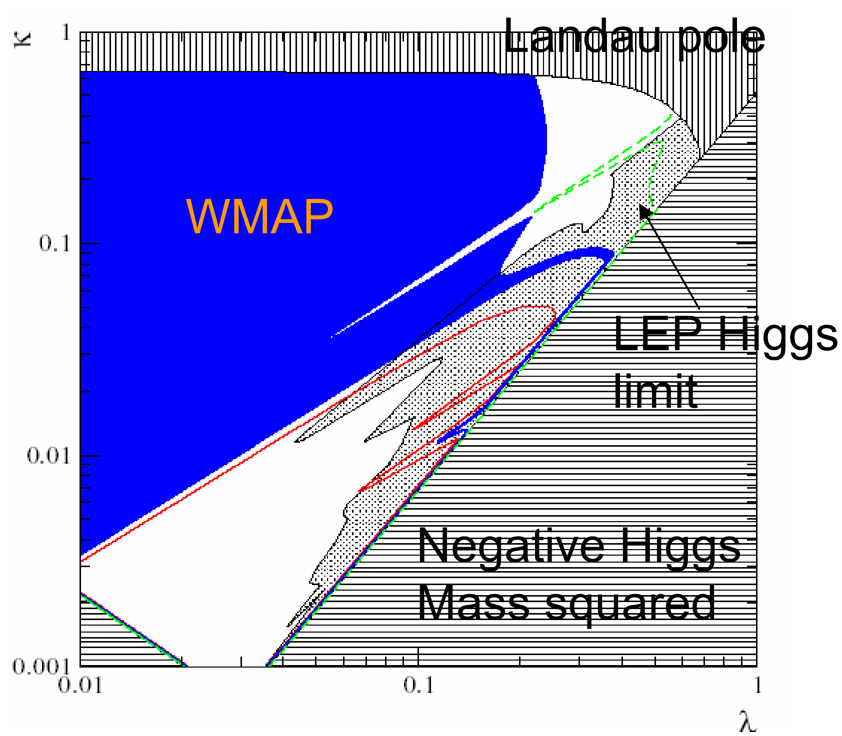


μ=300,M_2=300, λ=0.1, κ=0.1 tb=5

Case 2: mixed bino-Higgsino LSP

- Large parameter space in λ-κ plane allowed
- Annihilation near resonance
- Annihilation into light Higgses (scalar or pseudoscalar)
- Singlino LSP: can be compatible with WMAP (here excluded by LEP)

μ=220, M_2=320, tanβ=5, A_λ =500, A_κ=0

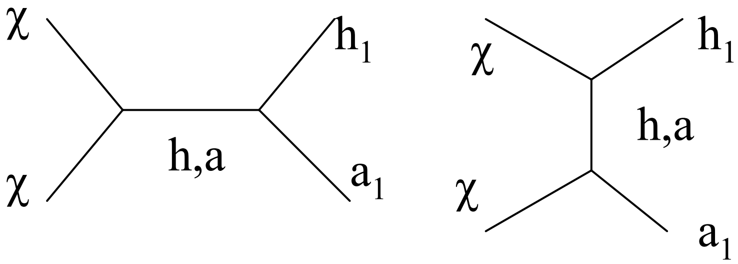


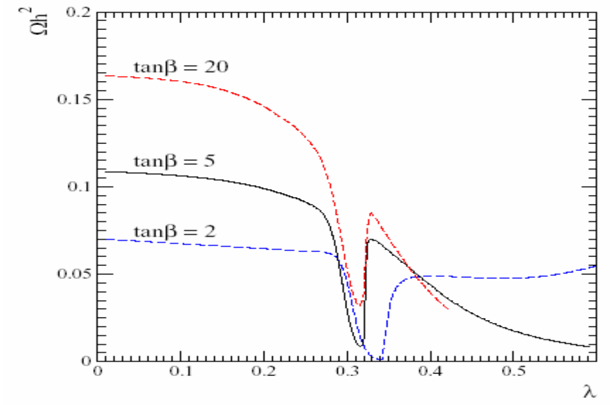
G.B. et al, hep-ph/0505142

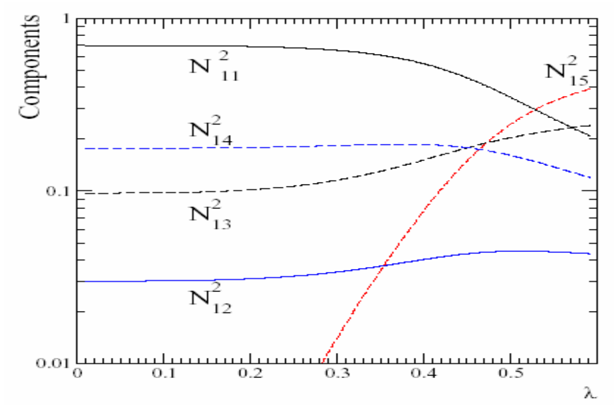
Case 2

- Neutralino annihilation into light Higgses: large cross-section (small Ωh^2) even though LSP has significant singlino component
- Recall neutralino coupling to Higgs has term proportional to N_{15}

$$+\sqrt{2}\lambda N_{15}(S_{i1}N_{14} + S_{i2}N_{13}) + \sqrt{2}S_{i3}(\lambda N_{13}N_{14} - \kappa N_{15}^2)$$







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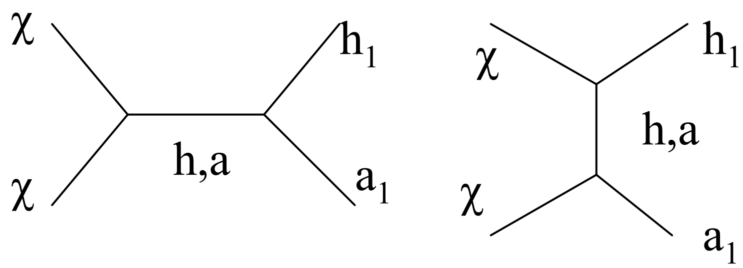

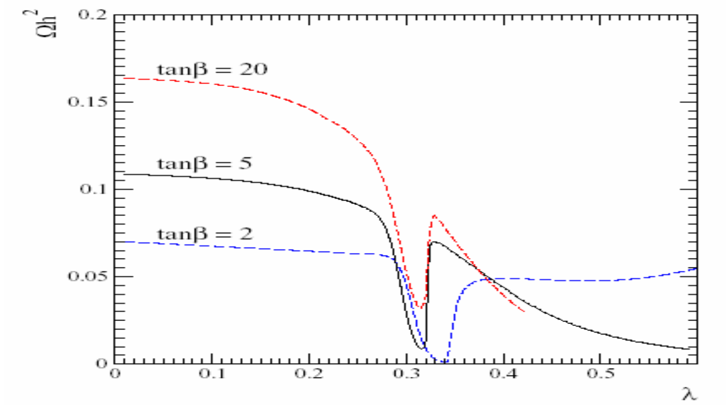

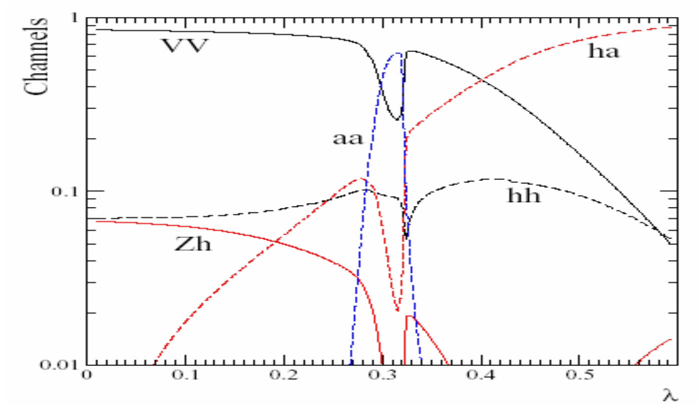

Case 3: singlino LSP

- Require predominantly singlino LSP and search parameter space to find scenarios compatible with WMAP
- 3 possible scenarios:
  - Mixed bino/singlino/Higgsino annihilation ha or WW (1,2)
  - Similar to case 2 already discussed
  - Almost pure singlino with resonance annihilation (3,4,5)
    - Light (few GeV) LSP possible
    - See also Gunion,Hooper,McElrath
  - Singlino with dominant coannihilation channels (6)
    - NLSP has large higgsino component

Point	1	2
λ	0.6	0.24
κ	0.12	0.096
$\tan\beta$	2	5
μ [GeV]	265	200
A_λ [GeV]	550	690
A_κ [GeV]	-40	-10
M_2 [GeV]	1000	690
$m_{\tilde{\chi}_1^0}$ [GeV]	122	148
$N_{13}^2 + N_{14}^2$	0.12	0.29
N_{15}^2	0.88	0.69
$m_{\tilde{\chi}_2^0}$ [GeV]	259	199
$m_{\tilde{\chi}_1^\pm}$ [GeV]	258	193
m_{h_1} [GeV]	117	116
S_{13}^2	0.88	0.04
m_{h_2} [GeV]	128	158
S_{23}^2	0.11	0.96
m_{a_1} [GeV]	114	59
$P_{12}^{\prime 2}$	0.99	1.00
Ωh^2	0.1092	0.1179
Channels	ha (73%) VV (13%) Zh (8%) hh (3%) qq (2%) ll (1%)	VV (75%) ha (17%) hh (5%) Zh (2%)

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Point	3	4	5
λ	0.4	0.23	0.31
κ	0.028	0.0037	0.006
$\tan\beta$	3	3.1	2.7
μ [GeV]	180	215	210
A_λ [GeV]	580	725	600
A_κ [GeV]	-60	-24	-6
M_2 [GeV]	660	200	540
$m_{\tilde{\chi}_1^0}$ [GeV]	35	10	15
$N_{13}^2 + N_{14}^2$	0.12	0.03	0.06
N_{15}^2	0.87	0.95	0.94
$m_{\tilde{\chi}_2^0}$ [GeV]	169	87	182
$m_{\tilde{\chi}_1^\pm}$ [GeV]	171	139	196
m_{h_1} [GeV]	36	22	34
S_{13}^2	0.98	1.00	1.00
m_{h_2} [GeV]	117	114	113
S_{23}^2	0.01	0.00	0.00
m_{a_1} [GeV]	56	18	15
$P_{12}'^2$	0.99	1.00	0.99
Ωh^2	0.1155	0.1068	0.1124
Channels	qq (65%) ll (35%)	qq (93%) ll (7%)	aa (92%) qq (7%) ll (1%)

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- 3 possible scenarios:
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  - Almost pure singlino with resonance annihilation (3,4,5)
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    - See also Gunion,Hooper,McElrath
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Point	6
λ	0.0348
κ	0.0124
$\tan\beta$	5
μ [GeV]	285
A_λ [GeV]	50
A_κ [GeV]	-150
M_2 [GeV]	470
$m_{\tilde{\chi}_1^0}$ [GeV]	203
$N_{13}^2 + N_{14}^2$	0.02
N_{15}^2	0.96
$m_{\tilde{\chi}_2^0}$ [GeV]	214
$m_{\tilde{\chi}_1^\pm}$ [GeV]	266
m_{h_1} [GeV]	115
S_{13}^2	0.04
m_{h_2} [GeV]	163
S_{23}^2	0.96
m_{a_1} [GeV]	214
$P_{12}^{\prime 2}$	1.00
Ωh^2	0.1023
Channels	$\tilde{\chi}_2^0\tilde{\chi}_2^0 \to X$ (81%) $\tilde{\chi}_1^0\tilde{\chi}_2^0 \to X$ (15%) $\tilde{\chi}_1^0\tilde{\chi}_1^\pm \to X$ (2%) qq (2%)

Outlook

- Can we make precise prediction of value of relic density in NMSSM, assuming measurements of parameters at LHC and ILC in particular to match WMAP (or even PLANCK) accuracy?
- Such studies are being performed in context of MSSM and results are rather encouraging for ILC. In Snowmass:
  - F. Richard et al, J. Alexander et al. M. Peskin et al.

- In NMSSM looks harder in many cases.
- First question: can we tell if NMSSM rather than MSSM ?
  - G. Moortgat-Pick et al. hep-ph/0502036
- What are relevant parameters for relic density: mass difference if near resonance, parameters of neutralino sector and couplings to Higgses
- Consider one of the specific NMSSM scenarios (Case 2)

Case 2 – some remarks

- Annihilation channels are into WW (35%) pairs and Higgs pairs h_1h_1(17%) h_1a_1(40%)
- This point with mixed bino/Higgsino is somewhat similar, but not as favourable, as LCC2 (in this case precise determination of parameters for relic density ~5% possible, J. Alexander et al.)
- Can produce 4 neutralinos @500GeV (σ~20fb) and chargino pairs (σ~106fb)
  - Neutralino masses: 146, 209, 263, 276, 368GeV
  - Chargino masses: 215, 364GeV
  - Scalar Higgs masses: 106, 257, 894GeV
  - Pseudoscalar masses: 57, 893GeV
- Main problem: dependence on parameters of Higgs sector, in particular light pseudoscalar. Need to measure mass and couplings of a_1 but it is singlet, how to produce it?

$$\sigma(e^+e^- \to h_1\, a_1) \sim 10^{-7}\mathrm{fb}$$

Conclusion

- We have performed precise calculation of relic density of dark matter in the NMSSM with micrOMEGAs +NMHDECAY

- As compared to the MSSM, in the NMSSM there are new possibilities for neutralino annihilation that leads to relic density in agreement with WMAP: more resonances, annihilation into light Higgses, possibility of singlino LSP (even very light).

- *Remains to be seen whether a precise prediction of the relic density in the NMSSM is possible assuming discovery and measurements of some SUSY parameters.*