SFitter and the NMSSM

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Outline

1. Results for mSUGRA
   Latest Paper: Constraining Supersymmetry using the relic density and the Higgs boson [4]
   Phys. Rev. D 89, 055017 (2014), Sophie Henrot-Versillé et al.

2. SFitter - Software Update

3. First results for the constrained NMSSM starting from mSUGRA best fit points

SFitter

- We can constrain SUSY models via SM measurements (Higgs, B-Physics, . . .), Dark Matter, . . .

→ SFitter: Tool to determine the fundamental supersymmetric parameters from experimental measurements

- Monte Carlo Markov Chains
- Creates likelihood maps reducible to lower-dimensional profile likelihoods or Bayesian probability maps

Tools for MSSM

- SuSpect2, mass spectrum calculation
- Susy-Hit, SUspect-SdecaY-Hdecay-InTerface
- Higgsprod, Higgs couplings
- SusyPope, EW precision data
- MicrOMEGAs, relic density

- SuSpect2 $\rightarrow$ SuSpect3 c++ interface

Constraints from Data

- $m_h = (126.0 \pm 0.4\ _{st} \pm 0.4\ _{sy} \pm 3.0\ _{th})\,\mathrm{GeV}$ *(ATLAS/CMS)*
- $\Omega h^2 = 0.1187 \pm 0.0017\ _{st} \pm 0.0120\ _{th}$ *(Planck)*
- $a_\mu = (287 \pm 63\ _{st} \pm 49\ _{sy} \pm 20\ _{th}) \cdot 10^{-11}$
- B Physics:
  - $BR(B \to X_s\gamma) = (3.55 \pm 0.24\ _{st} \pm 0.09\ _{sy}) \cdot 10^{-4}$
  - $BR(B_s^0 \to \mu^+\mu^-) = (3.2 \pm 1.4\ _{st} \pm 0.5\ _{sy} \pm 0.2\ _{th}) \cdot 10^{-9}$
  - $BR(B \to \tau\nu) = (1.41 \pm 0.43\ _{st}) \cdot 10^{-4}$
  - $\Delta m_{B^0} = (0.510 \pm 0.004\ _{st} \pm 0.003\ _{sy} \pm 0.400\ _{th}) \cdot 10^{12}\ \hbar\mathrm{s}^{-1}$
  - $\Delta m_{B_s^0} = (17.69 \pm 0.08\ _{st} \pm 7.00\ _{th}) \cdot 10^{12}\ \hbar\mathrm{s}^{-1}$
- EW:
  - $\Gamma_{Z\to Inv} = (1.9 \pm 1.5\ _{st} \pm 0.2\ _{th})\,\mathrm{MeV}$
  - $\Gamma_{Z\to Higgs} = (6.5 \pm 2.3\ _{st} \pm 1.0\ _{th})\,\mathrm{MeV}$
- Higgs couplings

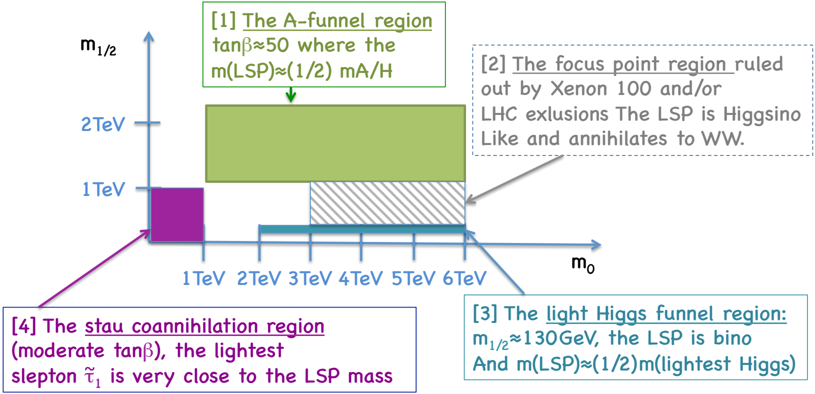
mSUGRA

minimal SUper GRAvity
Unification of masses and couplings at GUT scale

Input parameters set at mGUT

$m_0 < 5\,\mathrm{TeV}$	common scalar mass parameter
$m_{1/2} < 5\,\mathrm{TeV}$	common gaugino mass parameter
$\lvert A_0\rvert < 4\,\mathrm{TeV}$	common trilinear coupling
$\tan\beta \leq 60$	ratio of the vacuum expectation values of the two Higgs doublets
$\mathrm{sgn}(\mu) = +1$	sign of Higgsino mass parameter
(m_t)	

Annihilation channels: Illustration with mSUGRA

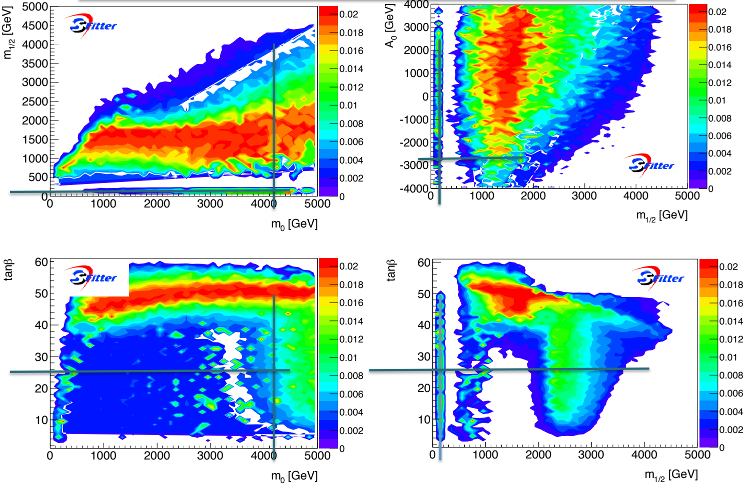


mSUGRA

h funnel

- ⇒ the LSP is mostly bino
- ⇒ Mtop(fitted value)=174.2GeV
- ⇒ $M(\tilde{\chi}_1^0)$=59GeV, $M(\tilde{g})$=476GeV

Excluded by ATLAS/CMS Inclusive squark and gluinos searches



Sophie Henrot-Versillé et al., *Constraining Supersymmetry using the relic density and the Higgs boson*, Phys. Rev. D 89, 055017 (2014)

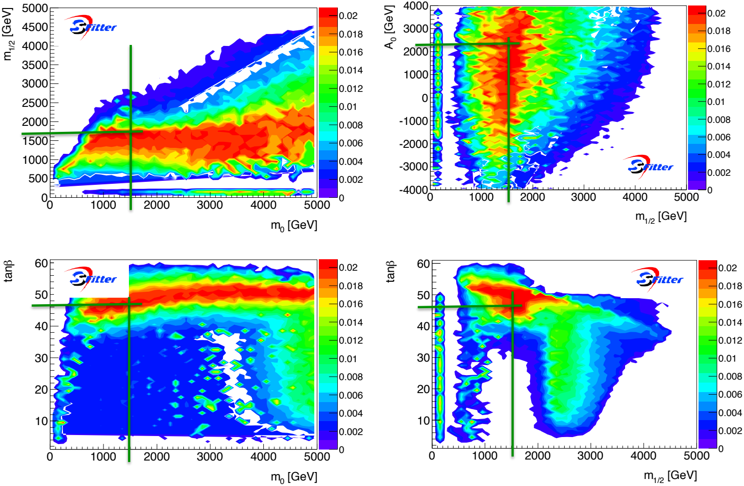
mSUGRA

A funnel

⇒ the LSP is mostly bino

⇒ Mtop(fitted value)=173.9GeV

⇒ $M(\tilde{\chi}_1^0)$=745GeV, $M(\tilde{q})\approx$3.4TeV, $M(\tilde{g})\approx$3.6TeV



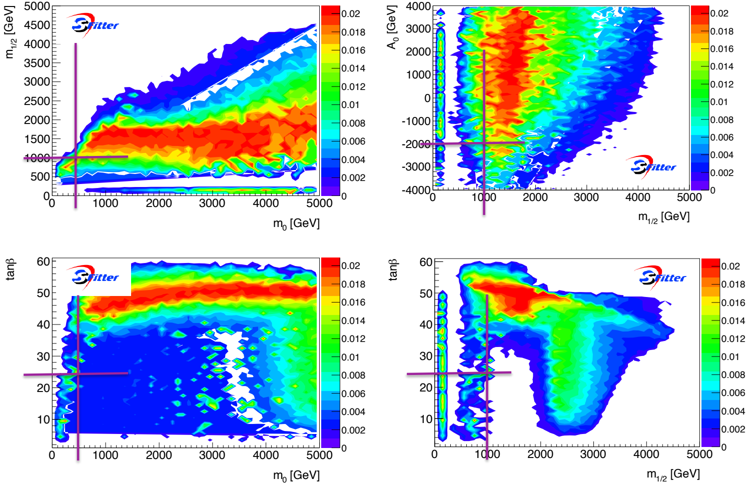
Sophie Henrot-Versillé et al., *Constraining Supersymmetry using the relic density and the Higgs boson*, Phys. Rev. D 89, 055017 (2014)

mSUGRA

Coannihilation

$\Rightarrow$ Mtop(fitted value)=174. GeV

$\Rightarrow$ $M(\tilde{\chi}_1^0)$=429GeV, $M(\tilde{q})\approx$2TeV, $M(\tilde{g})\approx$2TeV



Sophie Henrot-Versillé et al., *Constraining Supersymmetry using the relic density and the Higgs boson*, Phys. Rev. D 89, 055017 (2014)

We found three allowed regions:

h-funnel

- $m_{LSP} = 1/2 m_h \rightarrow m_{1/2} \approx 130\,\mathrm{GeV}$

A-funnel

- $m_{LSP} = 1/2 m_A \rightarrow m_{1/2} \approx 1.7\,\mathrm{TeV}$

co-annihilation

- $m_{LSP} \approx m_{\tilde{\tau}}$
- $m_{1/2} < 1\,\mathrm{TeV}$, $m_0 < 500\,\mathrm{GeV}$

Expand to NMSSM, using these regions as starting points.
What is the influence of additional parameters?

$\rightarrow$ new SFitter code

Software Update

- Include NMSSMTools (U. Ellwanger, C. Hugonie):
  - NMSPEC computes mass spectrum [3]
    - + g_μ
    - + B Physics observables $(\Delta m_{B^0}, \Delta m_{B_s^0}, BR(B \to X_s\gamma), \ldots)$
  - NMHDECAY computes Higgs masses, coupling and decay widths [1], [2]
- Update interfaces for other tools:
  - HiggsProd $\to$ free to specify which Higgs (h_1, h_2, h_3) is the Standard Model like
  - Micromegas $\to$ switch to dynamic libraries
- NMSSMTools provides a wide range of models.
- SFitter needs specific model
- First model: semi constrained NMSSM

Model

- From MSSM to NMSSM:

$$W_{NMSSM} = W_{MSSM} + \lambda S H_u H_d + \frac{1}{3}\kappa S^3$$

  $\rightarrow$ additional singlet S
- Semi constrained version of the NMSSM, comparable to MSUGRA
- Unification of squark, slepton and gaugino masses, gauge couplings
- Additional soft SUSY breaking parameters appear:

$$-\mathcal{L}_{soft} \supset \lambda A_\lambda H_u H_d S + \frac{1}{3}\kappa A_\kappa S^3$$

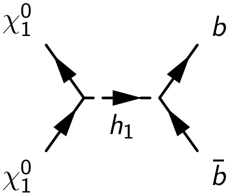
Complete set of input parameters

$m_0, m_{1/2}, A_0, tan\beta, \mu_{eff}(, m_t)$
$\lambda, \kappa, A_\lambda, A_\kappa$

h-funnel in mSUGRA

Best fit input parameters:

m_0	4232 GeV
$m_{1/2}$	135 GeV
$\tan\beta$	26.6
A_0	-2925 GeV
$\mathrm{sgn}(\mu)$	$+1$
m_t	174.2 GeV
μ_{eff}	484.44 GeV



Predictions:

Ωh^2	0.1105
m_h	123.84 GeV
m_H	3626 GeV
m_A	3626 GeV
m_{H^+}	3627 GeV
$m_{\chi_1^0}$	59.48 GeV
$m_{\chi_2^0}$	119 GeV
$m_{\tilde{q}_L}$	4175 GeV
$m_{\tilde{t}_1}$	2376 GeV
m_g	477 GeV

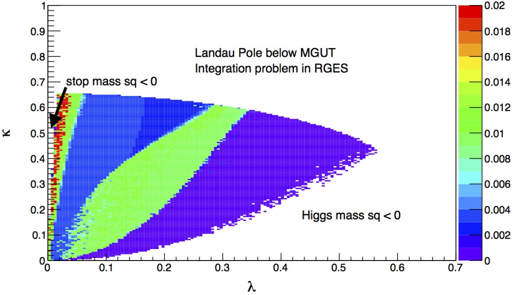
mSUGRA as starting point for the NMSSM

- mSUGRA input:
  $m_0 = 4232\,\mathrm{GeV}, m_{1/2} = 135\,\mathrm{GeV}, \tan\beta = 26.6, A_0 = -2925\,\mathrm{GeV}$
- $\lambda \ll 1$, κ and μ_{eff} calculated by unification of $m^2_{H_u}$ and $m^2_{H_d}$

Model	mSUGRA	CNMSSM	
λ		1E-16	1E-16
m_t [GeV]	174.2	174.2	175.4
κ		1.408E-15	5.775E-16
μ_{eff} [GeV]	484.4	259.4	482.5
m_{h1} [GeV]	123.84	121.9	122.2
m_{h2} [GeV]	3626	3613	3633
$m_{\chi^0_1}$ [GeV]	59.48	57.86	59.68
$m_{\tilde{t}_1}$ [GeV]	2376	2429	2406
Ωh^2	0.1105	0.0209	0.0804

- μ_{eff} depends through M^2_{Hu} strongly on the Yukawa coupling h^2_t, results of extrapolation differ $\rightarrow$ adjust the mass of top quark (Many thanks to U. Ellwanger!)

Likelihood Fit over $\lambda, \kappa, A_\lambda$ and A_κ



Profile likelihood fit for the best fit parameter of the MSUGRA h-funnel region.
$-4\,\mathrm{TeV} < A_\lambda < 4\,\mathrm{TeV}$,
$-8\,\mathrm{TeV} < A_\kappa < 0\,\mathrm{TeV}$.

$\lambda < 0.6, \kappa < 0.7$

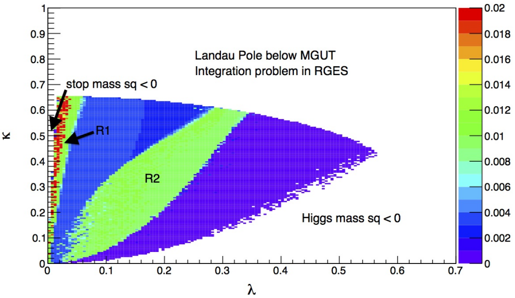
Input parameters are given @SUSY scale
$\rightarrow$ RGEs:

$$16\pi^2 \frac{d\lambda^2}{d\ln Q^2} = 4\lambda^4 + 2\lambda^2\kappa^2 + \ldots$$

$$16\pi^2 \frac{d\kappa^2}{d\ln Q^2} = 6\kappa^4 + 6\kappa^2\lambda^2 + \ldots$$

λ, κ increase with $Q \rightarrow$ upper limit on λ, κ to keep $\lambda, \kappa < 1$ up to GUT scale.

Likelihood Fit over $\lambda, \kappa, A_\lambda$ and A_κ



Profile likelihood fit for the best fit parameter of the MSUGRA h-funnel region.
$-4\,\mathrm{TeV} < A_\lambda < 4\,\mathrm{TeV}$,
$-8\,\mathrm{TeV} < A_\kappa < 0\,\mathrm{TeV}$.

Two regions are observed:

R_1 : $10 \lesssim \kappa/\lambda \lesssim 30$: for $\kappa < 0.1$ and fixed values of A_λ and A_κ the relic density depends only on the ratio κ/λ

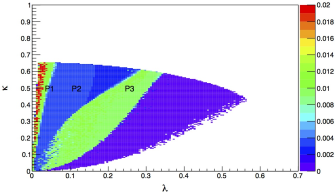
R_2 : $\lambda_{min} = 0.02$, $\kappa/\lambda \approx 2.2$

The regions are limited by Ωh^2.
DM annihilation by h-funnel ($87\% : \chi_1^0 + \chi_1^0 \to b + \bar{b}$)

Dependence of Ωh^2 on λ

Ωh^2 depends on m_{h_1} which depends through $m_{\tilde{t}_R}$ and A_λ on λ.

	P_1	P_2	P_3
λ	0.05	0.15	0.2
κ	0.5	0.5	0.5
m_{h_1} [GeV]	120.66	120.83	120.47
$m_{\chi_1^0}$ [GeV]	60.043	59.981	59.959
Ωh^2	0.1065	0.0854	0.1075



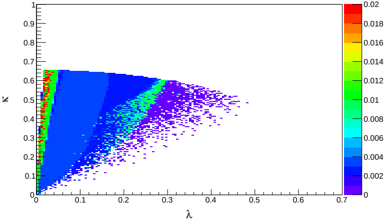
$P_1 \to P_2$ m_{h_1} increases, $m_{\chi_1^0}$ decreases $\to$ closer to onshell condition
$\to \sigma$ increases $\to \Omega h^2$ decreases

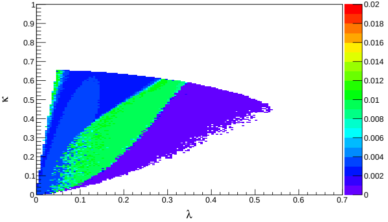
$P_2 \to P_3$ m_{h_1} decreases by $\approx 300\,\mathrm{MeV}$
$\to \Omega h^2$ increases

Investigate influence of mixing in Higgs sector:

1. Decouple the singlet part:
   require the heaviest Higgs Boson to be mainly singlet
   $\rightarrow$ Higgs mixing matrix $N_{HMIX,33} > 0.99$
2. Compare to a singlet like second Higgs Boson
   $N_{HMIX,23} > 0.99$

Singletlike Higgs ($h_2 \& h_3$)





- $N_{HMIX,33} > 99\%$
- R_1 restricted to $13 \lesssim \kappa/\lambda \lesssim 30$
- R_2 strongly reduced

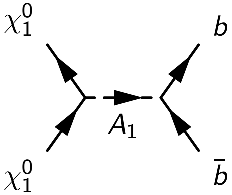
- $N_{HMIX,23} > 99\%$
- mainly congruent with unconstrained fit

$\rightarrow$ R_1 is reduced to $10 < \kappa/\lambda < 13$

A-funnel in MSUGRA

Best fit input parameters:

m_0	1500 GeV
$m_{1/2}$	1700 GeV
$\tan\beta$	46.5
A_0	2231 GeV
$\mathrm{sgn}(\mu)$	$+1$
m_t	173.9 GeV
μ_{eff}	1559.5 GeV

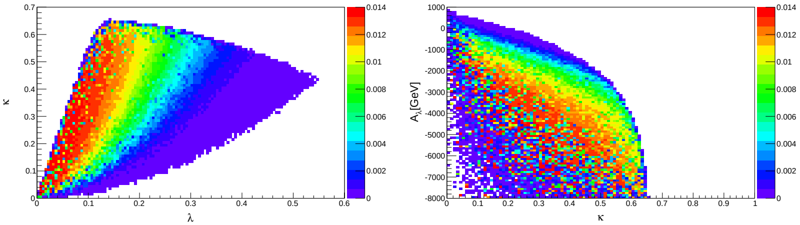


Predictions:

Ωh^2	0.1127
m_h	123.03 GeV
m_H	1498 GeV
m_A	1498 GeV
m_{H^+}	1500 GeV
$m_{\chi_1^0}$	745 GeV
$m_{\chi_2^0}$	1379 GeV
$m_{\tilde{q}_L}$	3527 GeV
$m_{\tilde{t}_1}$	2771 GeV
m_g	3595 GeV

Likelihood Fit over $\lambda, \kappa, A_\lambda$ and A_κ

First results:



- Linear correlation between λ and κ
- Correlation between κ and A_λ

Summary

- NMSSMTools interfaced to SFitter
- started investigation of the NMSSM starting from mSUGRA analysis

Many thanks to

- Dirk Zerwas, Sophie Henrot-Versillé, Laurent Duflot for discussions and advise at all stages of the project
- Ulrich Ellwanger and Cyril Hugonie for support with all NMSSM related issues
- the SFitter team (Rémi Lafaye, Michael Rauch, Tilman Plehn, Dirk Zerwas)

- Ulrich Ellwanger, John F. Gunion, and Cyril Hugonie, *NMHDECAY: A Fortran Code for the Higgs Masses, Couplings and Decay Widths in the NMSSM*, JHEP **0502** (2005), no. 066.
- Ulrich Ellwanger and Cyril Hugonie, *NMHDECAY 2.0: An updated program for Sparticle masses, Higgs masses, couplings and decay widths in the NMSSM*, Comput.Phys.Commun. **175** (2006), 209–303.
- ______, *NMSPEC: A Fortran code for the sparticle and Higgs masses in the NMSSM with GUT scale boundary conditions*, Comput.Phys.Commun. **177** (2007), 399:407.
- Sophie Henrot-Versillé, Rémi Lafaye, Tilman Plehn, Michael Rauch, Dirk Zerwas, Stéphane Plaszczynski, Benjamin Rouillé d'Orfeuil, and Marta Spinelli, *Constraining Supersymmetry using the relic density and the Higgs boson*, Phys. Rev. D **89** (2014), no. 055017.

Best fitting points for different mixing constraints in the Higgs sector

Model	MSUGRA	CNMSSM		
		without const.	$N_{H,33}$	$N_{H,23}$
λ		0.026	0.030	0.037
κ		0.589	0.554	0.505
A_λ [GeV]		2540	3085	3852
A_κ [GeV]		-1125	-7853	-6600
Ωh^2	0.1105	0.1198	0.1108	0.1067
m_{h1} [GeV]	123.84	125.3	124.9	120.4
m_{h2} [GeV]	3626	14015	13944	12702
m_{h3} [GeV]		22833	17794	12916
m_{H^+} [GeV]	3627	14015	13944	12916
$m_{\chi_1^0}$ [GeV]	59.48	60.08	60.08	59.92
$m_{\chi_2^0}$ [GeV]	119	120.8	120.81	120.63
$m_{\tilde{q}_L}$ [GeV]	4175	4380	4380	4347
$m_{\tilde{t}_1}$ [GeV]	2376	212.3	215	1095
$m_{\tilde{g}}$ [GeV]	477	462	462	471