Karlsruhe Institute of Technology

Constraining Supersymmetry using the relic density and the Higgs boson

in collaboration with S. Henrot-Versillé, R. Lafaye, T. Plehn, D. Zerwas, S. Plaszczynski, B. Rouillé d'Orfeuil and M. Spinelli,
Phys. Rev. D **89** (2014) 055017 [arXiv:1309.6958 [hep-ph]]

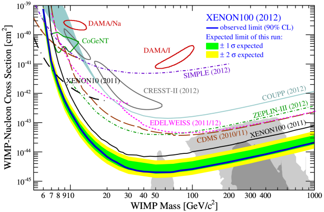
Michael Rauch | SUSY 2014, Jul 2014

INSTITUTE FOR THEORETICAL PHYSICS

Motivation

Experimental status:

- light Higgs found ⇒ hierarchy problem now real
- dark matter search experiments cutting into parameter space of weakly interacting dark matter
- direct searches:
  - Pessimist's view: no sign of additional SUSY particles
  - Optimist's view: first half already found,
    but no indication of second half yet



⇒ available parameter space from indirect constraints

Models studied:

- mSUGRA/CMSSM
  test case for models where Higgs sector, weak dark matter sector and strongly interacting sector linked at high scale
- 13-parameter TeV-scale pMSSM
  bottom-up approach: no unification scheme imposed a priori
  → ultimately determine high-scale unification from data

Input and Tools

Input measurements

measurement	value and error
m_h	$(126 \pm 0.4 \pm 0.4 \pm 3)$ GeV
$\Omega_{\text{cdm}} h^2$ Planck	$0.1187 \pm 0.0017 \pm 0.012$
$\Omega_{\text{cdm}} h^2$ WMAP-9year	$0.1157 \pm 0.0023 \pm 0.012$
$\text{BR}(B_s \to \mu^+\mu^-)$	$(3.2^{+1.5}_{-1.2} \pm 0.2) \times 10^{-9}$
$\text{BR}(b \to X_s\gamma)$	$(3.55 \pm 0.24 \pm 0.09) \times 10^{-4}$
Δa_μ	$(287 \pm 63 \pm 49 \pm 20) \times 10^{-11}$
m_t	$(173.5 \pm 0.6 \pm 0.8)$ GeV

+ Xenon100 + Higgs couplings + EW precision
(in total 95 individual measurements)

Tools

- SUSY spectrum: SuSpect 2 [Djouadi, Kneur, Moultaka]
- Higgs BR: SUSY-Hit [Djouadi, Mühlleitner, Spira]
- Dark matter: micrOMEGAs [Bélanger, Boudjema, Pukhov, Semenov]
- Electroweak precision data: SUSYPope [Weber et al.]
- B decay & $(g-2)_\mu$: SuSpect 2 + micrOMEGAs

Context

Latest results by other groups:

- Fittino: LHC data + WMAP-7year on CMSSM and NUHM
- MasterCode: also including Xenon100 and Planck, CMSSM and NUHM
  more general models work in progress
- C. Boehm et al.: Light neutralino DM with Planck + Higgs + Xenon100
  in TeV-scale MSSM
- BayesFITS: Planck, Higgs, DM, … in CMSSM and 9-parameter MSSM
- Mühlleitner, Walz et al.: global NMSSM fit in progress
- …(many papers looking at more specific aspects)

⇒ Only one other group going beyond high-scale unification models so far

⇒ Our analysis:
- wider explored SUSY parameter space
- updated measurements

SFitter

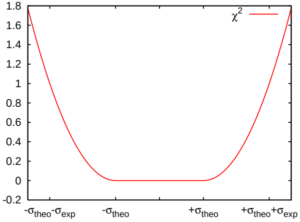
Algorithms:

- Weighted Markov chain
- Cooling Markov chain ($\sim$ simulated annealing)
- Modified gradient fit (Minuit)
- Grid scan
- Nested Sampling [Skilling; Feroz, Hobson]

[Lafaye, Plehn, MR,Zerwas]
[Eur.Phys.J.C54:617-644,2008, [arXiv:0709.3985 [hep-ph]]]
[JHEP08(2009)009 [arXiv:0904.3866 [hep-ph]]]

Errors:

- three types:
  - Gaussian – arbitrary correlations possible ($\rightarrow$ systematic errors)
  - Poisson
  - box-shaped (RFit) [CKMFitter]
- assignment as in exp. studies
- adaption to likelihood input easy



Output of SFitter:

- fully-dimensional log-likelihood map
- one- and two-dimensional distributions via
  - marginalization (Bayesian)
  - profile likelihood (Frequentist)
- list of best points

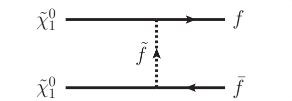
Neutralino as LSP

Assume lightest neutralino $\tilde{\chi}_1^0$ is the LSP

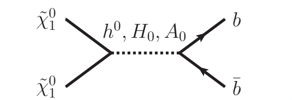
Neutralinos are linear combinations of gauge eigenstates $\left(\tilde{B}, \tilde{W}^3, \tilde{H}_1^1, \tilde{H}_2^2\right)$

Bulk relic density too high $\rightarrow$ need reduction mechanism

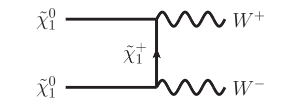
Bino LSP, light $\tilde{\chi}_1^0$



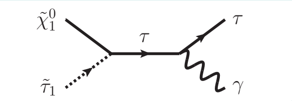
Higgs funnel, $m_{\tilde{\chi}_1^0} \simeq \frac{m_H}{2}$



Higgsino LSP



Coannihilation, $m_{\tilde{\chi}_1^0} \simeq m_{\tilde{\tau}_1}$



mSUGRA/CMSSM

CMSSM as test case

Free parameters:

- m_0 common scalar mass parameter: $m_0 \in [0; 5]$ TeV
- $m_{1/2}$ common gaugino mass parameter $m_{1/2} \in [0; 5]$ TeV
- A_0 common trilinear mass parameter $A_0 \in [-4; 4]$ TeV
- $\tan\beta$ ratio of vevs $\tan\beta \in [1; 61]$
- $\mathrm{sign}(\mu)$ sign of Higgsino mass parameter both cases (only $\mu > 0$ shown)
- m_t top mass

$\to$ small number of parameters

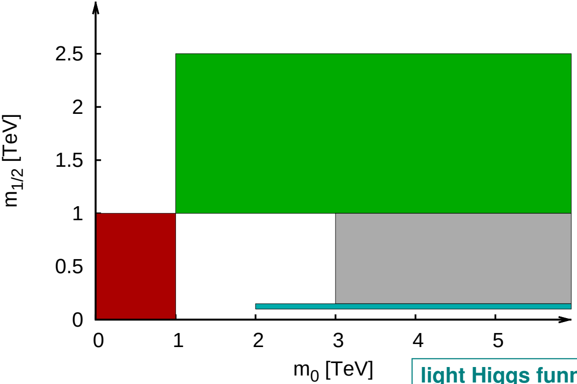
$\to$ highly correlated

e.g.

$$A_t = A_0 \left(1 - \frac{0.75}{\sin^2\beta}\right) - 3.5 m_{1/2} \left(1 - \frac{0.41}{\sin^2\beta}\right) \approx \begin{cases} 0.62 A_0 - 2.8 m_{1/2} & \text{for } \tan\beta = 1 \\ 0.25 A_0 - 2.1 m_{1/2} & \text{for } \tan\beta \gg 1 \end{cases}$$

$\leftrightarrow$ driven by $m_{1/2}$ for larger $\tan\beta$ ($\to$ Higgs mass)

Annihilation channels in CMSSM



A-funnel region
$\tan\beta \simeq 50$
$m_{\text{LSP}} \simeq \frac{1}{2} m_{A_0,H_0}$

Focus point region
ruled out by Xenon100
and LHC $\tilde{g}$ exclusions
LSP mostly Higgsino-like ($\to WW$)

light Higgs funnel region
$m_{h^0} \simeq 2m_{\text{LSP}} \simeq 126$ GeV
LSP mostly Bino ($\sim$ 10% Higgsino admixture)
ruled out by LHC $\tilde{g}$ exclusion

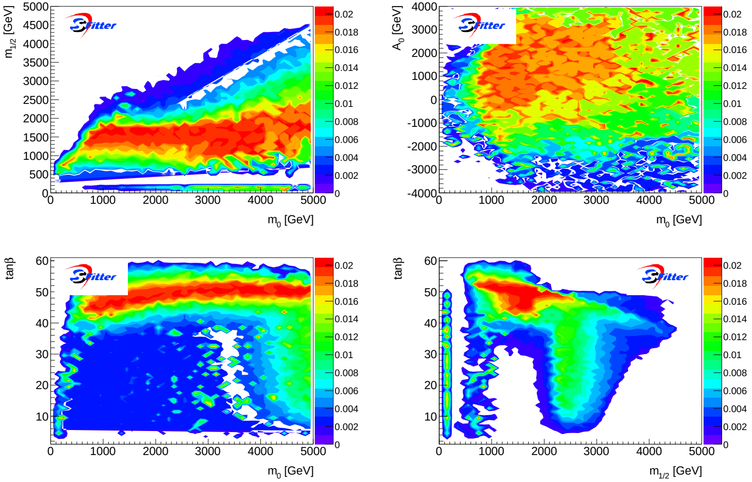
stau co-annihilation region
moderate $\tan\beta$
$m_{\text{LSP}} \simeq m_{\tilde{\tau}_1}$

not in CMSSM parameter space:

neutralino-chargino co-annihilation region
containing H^0 funnel contribution
LSP mainly Wino or Higgsino

CMSSM results

CMSSM results



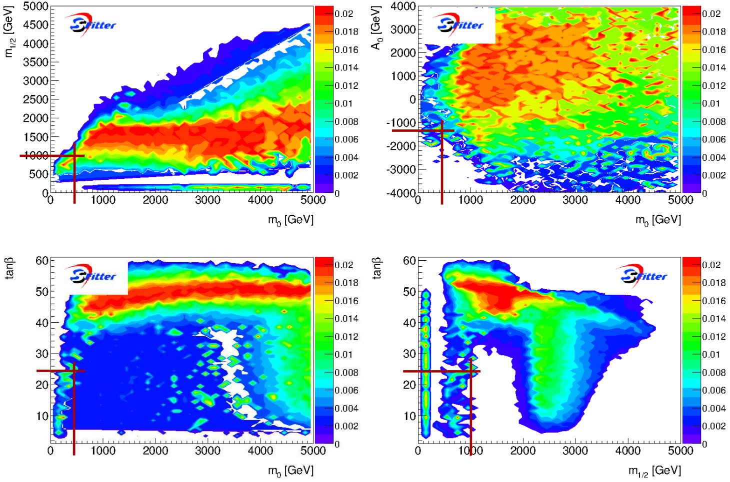
clearly structures visible → identify with annihilation channels

CMSSM results

Coannihilation region

Best-fit point:

m_0	$m_{1/2}$	$\tan\beta$	A_0	$-2\log L/\mathrm{dof}$
442 GeV	999 GeV	24.6	-1347 GeV	49.0/75

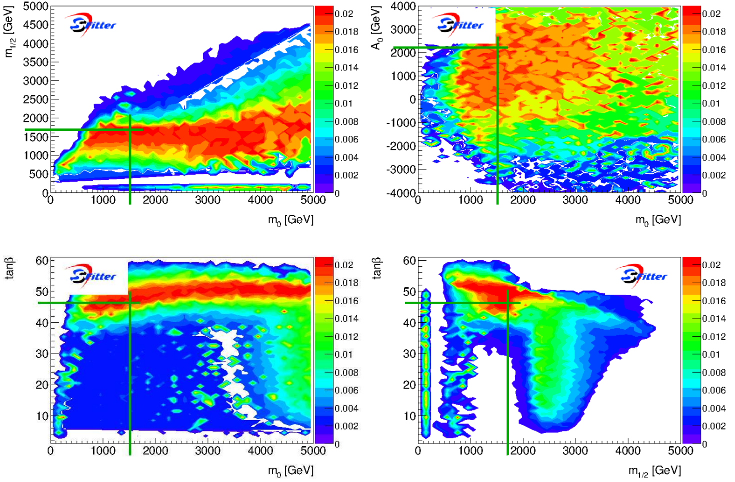


CMSSM results

A-funnel region

Best-fit point:

m_0	$m_{1/2}$	$\tan\beta$	A_0	$-2\log L$/dof
1500 GeV	1700 GeV	46.5	2231 GeV	49.2/75

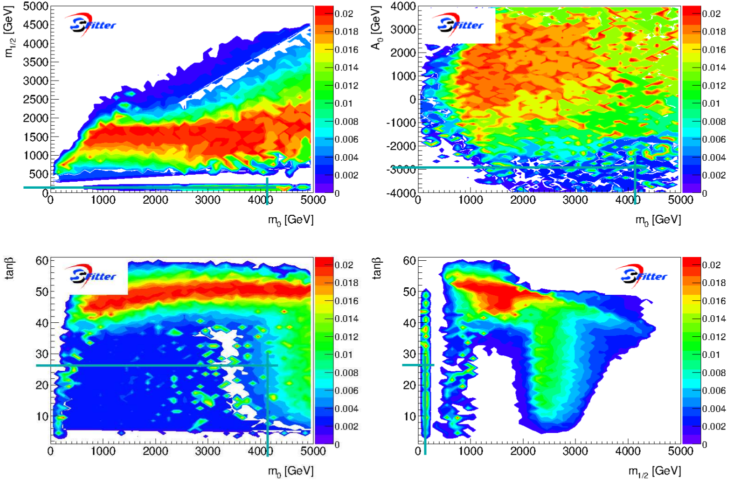


CMSSM results

h^0-funnel region $m_{\tilde{g}} = 476$ GeV $\rightarrow$ ruled out by LHC $\tilde{g}$ searches

Best-fit point:

m_0	$m_{1/2}$	$\tan\beta$	A_0	$-2\log L$/dof
4232 GeV	135 GeV	26.6	-2925 GeV	46.1/75



MSSM parameter space

Assumptions:

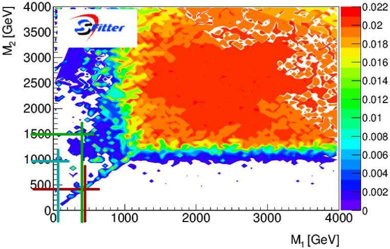
- all squark and gluino masses above LHC actual limits
  $\Rightarrow M_{\tilde{q}_{1,L}} = M_{\tilde{q}_{2,L}} = M_{\tilde{u}_R,\tilde{d}_R,\tilde{c}_R,\tilde{s}_R,\tilde{b}_R} = M_3 = 2\ \mathrm{TeV}$
- $A_b = 0$

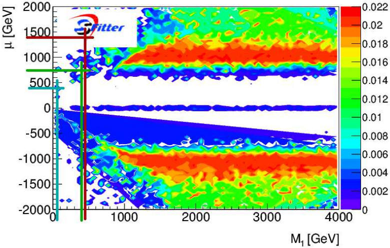
$\Rightarrow$ 13-parameter pMSSM:

- $\tan\beta \in [1; 61]$
- $M_1 \in [0; 4]\ \mathrm{TeV}$
- $M_2 \in [0; 4]\ \mathrm{TeV}$
- $\mu \in [-2; 2]\ \mathrm{TeV}$
- $m_A \in [0; 5]\ \mathrm{TeV}$
- $A_\tau \in [-4; 4]\ \mathrm{TeV}$
- $A_t \in [-4; 4]\ \mathrm{TeV}$
- $M_{\tilde{e}_L} = M_{\tilde{\mu}_L} \in [0; 5]\ \mathrm{TeV}$
- $M_{\tilde{e}_R} = M_{\tilde{\mu}_R} \in [0; 5]\ \mathrm{TeV}$
- $M_{\tilde{\tau}_L} \in [0; 5]\ \mathrm{TeV}$
- $M_{\tilde{\tau}_R} \in [0; 5]\ \mathrm{TeV}$
- $M_{\tilde{q}_{3,L}} \in [0; 5]\ \mathrm{TeV}$
- $M_{\tilde{t}_R} \in [0; 5]\ \mathrm{TeV}$
-
- m_t

$\rightarrow$ decouples strongly interacting MSSM sector from weak sector (Higgs and DM predictions)
$\leftrightarrow$ stop part retained due to large effect on Higgs sector

MSSM results

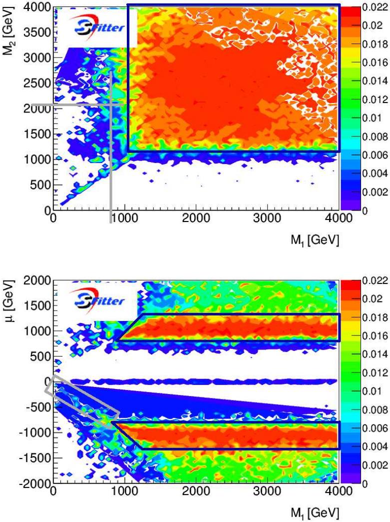




Recover regions of CMSSM scenario:

- stau co-annihilation
  diagonal strip at small M_1, M_2
  e.g. $m_{\tilde{\chi}_0^1} = 429$ GeV,
  $m_{\tilde{\tau}_1} = 429.7$ GeV
- h^0 funnel
  $M_1 \sim 63$ GeV
  almost independent of M_2
  gluino mass now independent parameter
  $\Rightarrow$ no longer constrained by direct searches
- A funnel
  e.g. $M_1 = 400$ GeV, $M_2 = 1500$ GeV,
  $\mu = 750$ GeV
  same behaviour as in CMSSM

MSSM results



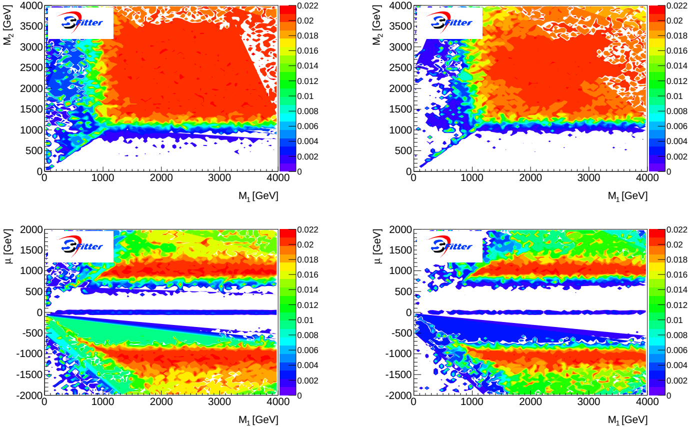
New allowed regions show up:

- bino-higgsino region
  strip in M_1-μ plane for $\mu < 0$,
  $M_1 \sim |\mu|$
  including chargino co-annihilation
  e.g. $M_1 = 800$ GeV, $\mu = -800$ GeV
- large higgsino region
  M_1, $M_2 > 1.2$ TeV with $|\mu| \sim 1.2$ TeV
  dominated by
  chargino co-annihilation

Impact of Planck

WMAP
$\Omega_{cdm} h^2 = 0.1157 \pm 0.0023 \pm 0.012$

Planck:
$\Omega_{cdm} h^2 = 0.1187 \pm 0.0017 \pm 0.012$



only small differences visible

- bino-higgsino region less constrained with WMAP data
- stricter constraints for larger μ in higgsino LSP scenario
- h^0 funnel more constrained

Conclusions

Analysis of MSSM parameter space

- CMSSM and 13-parameter pMSSM
- bottom-up approach for latter
  $\rightarrow$ determine high-scale unification from data
- include constraints from
  - cosmological studies
  - direct dark matter searches
  - collider measurements (e.g. Higgs mass)
  - direct and indirect collider constraints

Classification by dark matter annihilation channel

- regions in both CMSSM and pMSSM13:
  stau co-annihilation, *A*-funnel
- new channels for pMSSM13 only:
  light-Higgs funnel, mixed bino-higgsino region, large higgsino region

$\rightarrow$ SUSY pushed towards high new-physics mass scale

$\rightarrow$ little tension from non-observation at 8 TeV run of LHC

CMSSM particle masses

Supersymmetric particles' masses (in GeV) for the three best–fit points:

	co-ann	A	h
$\tilde{e}_L$	792	1860	4210
$\tilde{e}_R$	575	1621	4223
$\tilde{\nu}_{eL}$	788	1858	4209
$\tilde{\mu}_L$	792	1860	4210
$\tilde{\mu}_R$	575	1621	4223
$\tilde{\nu}_{\mu L}$	788	1858	4209
$\tilde{\tau}_1^-$	430	1103	3920
$\tilde{\tau}_2^-$	756	1666	4062
$\tilde{\nu}_{\tau L}$	744	1661	4061

	co-ann	A	h
$\tilde{g}$	2178	3596	476
$\tilde{\chi}_1^0$	429	745	59
$\tilde{\chi}_2^0$	809	1379	118
$\tilde{\chi}_3^0$	-1407	-1588	-507
$\tilde{\chi}_4^0$	1412	1603	512
$\tilde{\chi}_1^+$	810	1379	119
$\tilde{\chi}_2^+$	1412	1603	514

	co-ann	A	h
$\tilde{q}_L$	2020	3527	4174
$\tilde{q}_R$	1939	3397	4192
$\tilde{b}_1$	1754	3046	3190
$\tilde{b}_2$	1849	3101	3877
$\tilde{t}_1$	1426	2771	2374
$\tilde{t}_2$	1791	3105	3212

	co-ann	A	h
h	123.0	123.0	124.8
H	1423	1498	3624
A	1423	1498	3624
H^+	1425	1500	3625

MSSM best-fit points and particle masses

	co-ann	A-funnel	h-funnel	bino–higgs	higgsino
$\tan\beta$	25	18	26.6	54	29
M_1	430	400	59	800	1543
M_2	788	1500	960	2174	2898
μ	1400	750	484	-800	1070
$M_{\tilde{\mu}_L}$	791	1586	4210	3994	2884
$M_{\tilde{\mu}_R}$	573	2789	4223	1002	2790
$M_{\tilde{\tau}_L}$	747	1067	4062	3744	3355
$M_{\tilde{\tau}_R}$	440	2789	3921	2040	2058
A_τ	-1690	-3038	-2570	2338	-3533
$M_{\tilde{q}_{3L}}$	1744	3938	3162	1683	2210
$M_{\tilde{t}_R}$	1441	3997	2319	2111	2984
A_t	-2142	-3158	-1230	-2162	-3026
m_A	1423	781	3626	1000	784
m_t	174.0	173.5	173.5	173.6	173.5
$-2\log L/\text{dof}$	47.9/65	44.2/65	46.5/65	42.5/65	37.8/65

	co-ann	A-funnel	h-funnel	bino–higgs	higgsino
$\tilde{\chi}_1^0$	429	398	58.5	768	1066
$\tilde{\chi}_2^0$	783	749	480	-801	-1071
$\tilde{\chi}_3^0$	-1402	-751	-488	829	1545
$\tilde{\chi}_4^0$	1406	1506	969	2178	2900
$\tilde{\chi}_1^+$	784	747	480	799	1069
$\tilde{\chi}_2^+$	1407	1506	969	2178	2900
h	123.2	125.3	122.1	123.2	124.5
H	1423	781	3626	1000	784
A	1423	781	3626	1000	784
H^+	1425	785	3627	1003	788