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Benchmark points for the NMSSM

CB et al. arXiv: 1402.4650

CB et al. arXiv: 1308.1333

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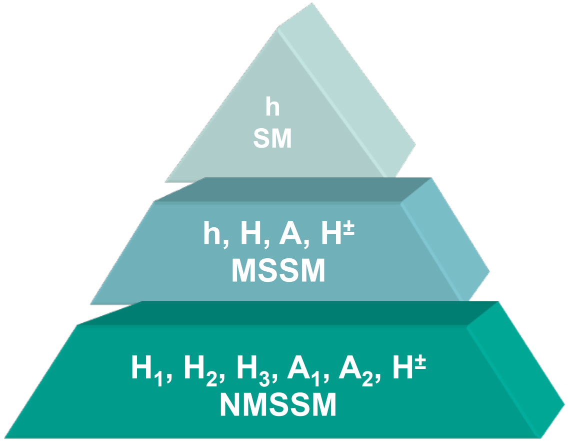

Status of NMSSM

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NMSSM solves μ-problem and predicts naturally M_h>M_Z, so no need for radiative corrections from multi-TeV stop masses. Many papers since discovery of 125 GeV Higgs, see e.g.

arXiv:1408.1120, arXiv:1407:4134, arXiv:1407.0955, arXiv:1406.7221, arXiv:1406.6372, arXiv:1405.6647, arXiv:1405.5330, arXiv:1405.3321, arXiv:1405.1152, arXiv:1404.1053, arXiv:1403.1561, arXiv:1402.3522, arXiv:1401.1878, arXiv:1312.4788, arXiv:1311.7260, arXiv:1310.8129, arXiv:1310.4518, arXiv:1309.4939, arXiv:1309.1665, arXiv:1405.5330, arXiv:1308.4447, arXiv:1308.4447, arXiv:1308.1333, arXiv:1307.7601, arXiv:1307.0851, arXiv:1306.5541, arXiv:1306.3926, arXiv:1306.3646, arXiv:1306.0279, arXiv:1305.3214, arXiv:1305.0591, arXiv:1305.0166, arXiv:1304.5437, arXiv:1304.3670, arXiv:1304.3182, arXiv:1303.6465, arXiv:1303.2113, arXiv:1303.1900, arXiv:1301.7584, arXiv:1301.6437, arXiv:1301.1325, arXiv:1301.0453, arXiv:1212.5243, arXiv:1211.5074, arXiv:1211.1693, arXiv:1211.0875, arXiv:1209.5984, arXiv:1209.2115, arXiv:1208.2555, arXiv:1207.1545, arXiv:1206.6806, arXiv:1206.1470, arXiv:1205.2486, arXiv:1205.1683, arXiv:1203.5048, arXiv:1203.3446, arXiv:1202.5821, arXiv:1201.2671, arXiv:1201.0982, arXiv:1112.3548, arXiv:1111.4952, arXiv:1109.1735, arXiv:1108.0595, arXiv:1106.1599, arXiv:1105.4191, arXiv:1104.1754, arXiv:1101.1137, arXiv:1012.4490

NMSSMTools and Micromegas

All calculations done with NMSSMTools, for details see:

U. Ellwanger and C. Hugonie, Comput. Phys. Commun.175 (2006) 290;
U. Ellwanger, J. F. Gunion, and C. Hugonie, JHEP 02 (2005) 066.
U. Ellwanger, C. Hugonie, and A. M. Teixeira, “The Next-to-Minimal Supersymmetric Standard Model”, Phys.Rept. 496 (2010) 1–77, arXiv:0910.1785

NMSSM has 3 scalar Higgs bosons

Consequences:

coupling λ between singlet and 2 doublets:

coupling κ between 3 singlets

trilinear couplings A_λ and A_κ

5 neutralinos: LSP is partner of scalar singlet (singlino)

Difference to MSSM:

Heaviest Higgs can decay into

1) 2 lighter Higgs (double Higgs production) H3 → H2+H1

2) gauginos

$$W_{\mathrm{NMSSM}} = W_F + \lambda \hat{H}_u \cdot \hat{H}_d \hat{S} + \frac{1}{3}\kappa \hat{S}^3,$$

$$V_{\mathrm{soft}}^{\mathrm{NMSSM}} = \tilde{m}_u^2 |H_u|^2 + \tilde{m}_d^2 |H_d|^2 + \tilde{m}_S^2 |S|^2 + (A_\lambda \lambda S H_u \cdot H_d + \frac{A_\kappa}{3}\kappa S^3)$$

$$\Longrightarrow \quad \tilde{\chi}_1^0 = \tilde{B} + \tilde{W} + \tilde{H}_1 + \tilde{H}_2 + \tilde{S}$$

How to proceed?

1) Consider „natural“ NMSSM

„vevs“ of all Higgs fields of the same order so $v_1 \approx v_2 \approx v_s$, so $\mu = \lambda v_s \approx$ 100-200 GeV.
Then ALL Higgses in twice this range ($mH_3 \simeq mA \approx mH^{\pm} \simeq 2\mu/\sin 2\beta \approx 2.5\mu$)

2) Consider „unnatural“ NMSSM with $\mu = \lambda v_s \approx$ 1 TeV

It is just a question of taste to decide what is natural, but clearly natural NMSSM of much more interest for next LHC run

Example for natural NMSSM

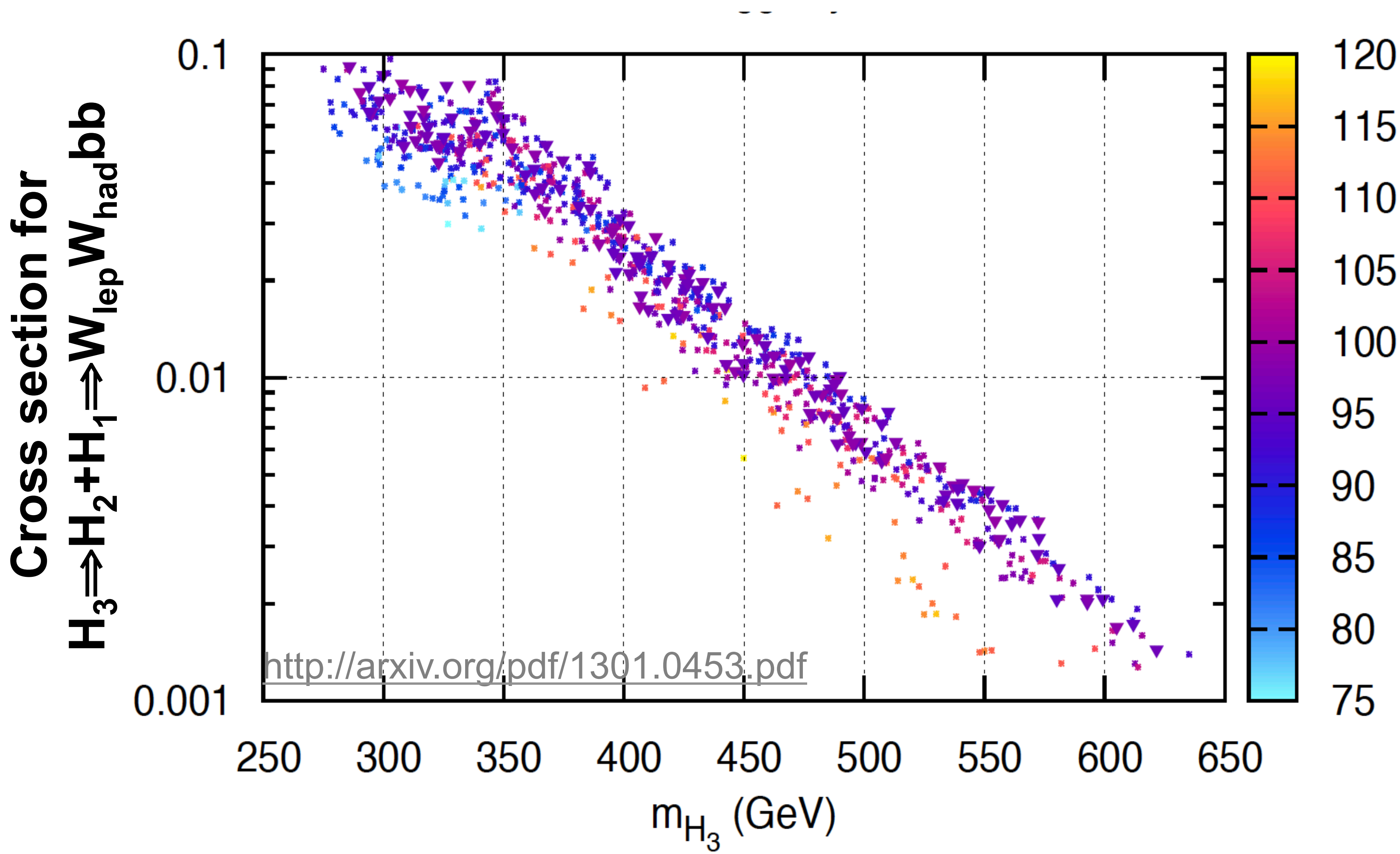
Probing the CP-even Higgs Sector via $\mathbf{H_3} \rightarrow \mathbf{H_2 H_1}$ in the Natural NMSSM,Kang, Li, Li, Liu and Shu, arXiv 1301.0453.

Light Higgs Bosons in the Pushing-Upward Scenario: The SM-like Higgs boson can be accommodated without recurring severe fine-tuning, and we can show that the whole Higgs sector is light. Restricted to the **Z3−**NMSSM, naturalness conditions point to a predictive parameter space

$\boldsymbol{\lambda}$: 0.6 − 0.7, tan $\boldsymbol{\beta}$: 1.3 − 3.0,
$\boldsymbol{\mu} = \boldsymbol{\lambda v_s}$: 100 GeV − 200 GeV

$\mathbf{mH_3 \simeq mA \approx mH^{\pm} \simeq 2\mu/ \sin 2\beta \approx 2.5\mu}$

Mass dependence of cross section at 14 TeV



Significance in WWbb channel after 500/fb at 14 TeV

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	m_{H_1} (GeV)	m_{H_3} (GeV)	σ (fb)	$\frac{S}{\sqrt{S+B}}$
B1	100	300	70	0.81
B2	65	300	50	3.84
B3	98	400	25	4.73
B4	65	400	20	7.68
B5	100	600	2	2.79
B6	65	600	2	4.99

Note: background and production x-section strong function of m_{H3}
For WWbb mainly ttbar, so difficult if MH1 and MH2 both heavy.
For light MH3 in addition trigger problem: decay into 4 objects gives small pt.

Questions

1) Are these 6 bench mark points representative?
2) Are these bench mark points compatible with other constraints (EWSB, DM, SM-like)?
3) What are other decay modes?
4) What happens in „unnatural“ scenarios?

Other Experimental Constraints

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Dark Matter

Relic density Ωh^2

Direct Dark Matter Searches

Precision Measurements

B-physics ($B_S \rightarrow \mu^+ \mu^-$, …)

Myon g-2

Multi-Step Fitting Approach of a combined χ^2 function

(semi-constr. NMSSM)

Direct Measurements

LHC: $\sigma\left(pp \rightarrow \tilde{g}, \tilde{q}\right)$

$m_{\tilde{q},\tilde{g}} > 1\,TeV$

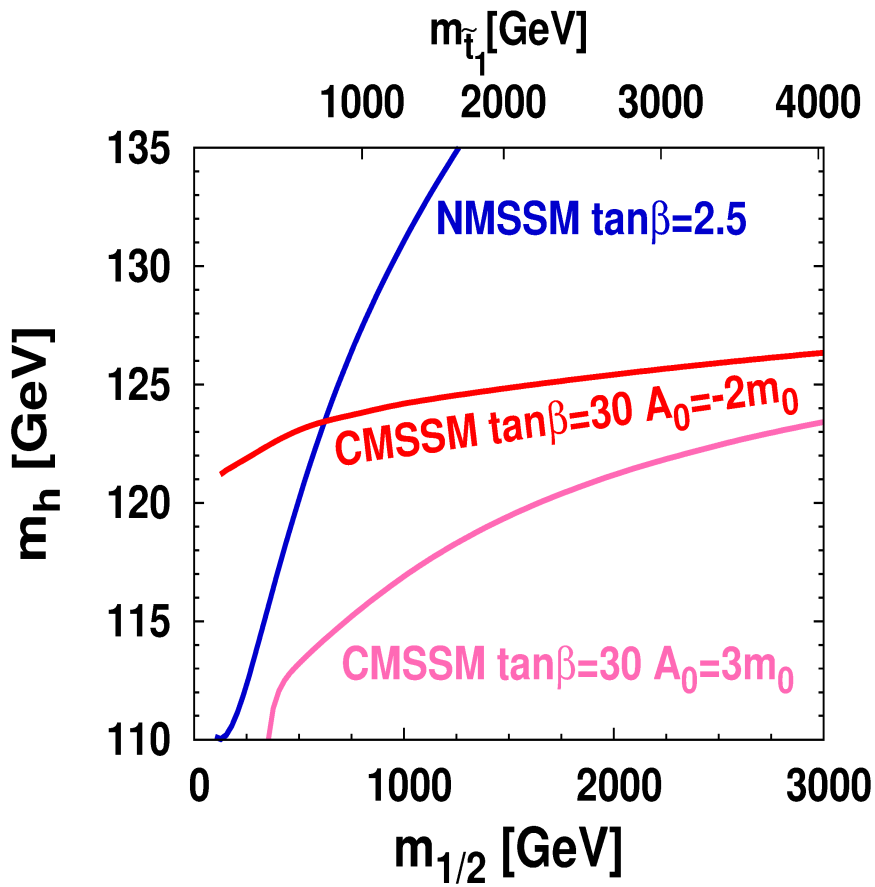
Higgs Boson

Mass and couplings

NMSSM: tree level SM-like Higgs > M_Z

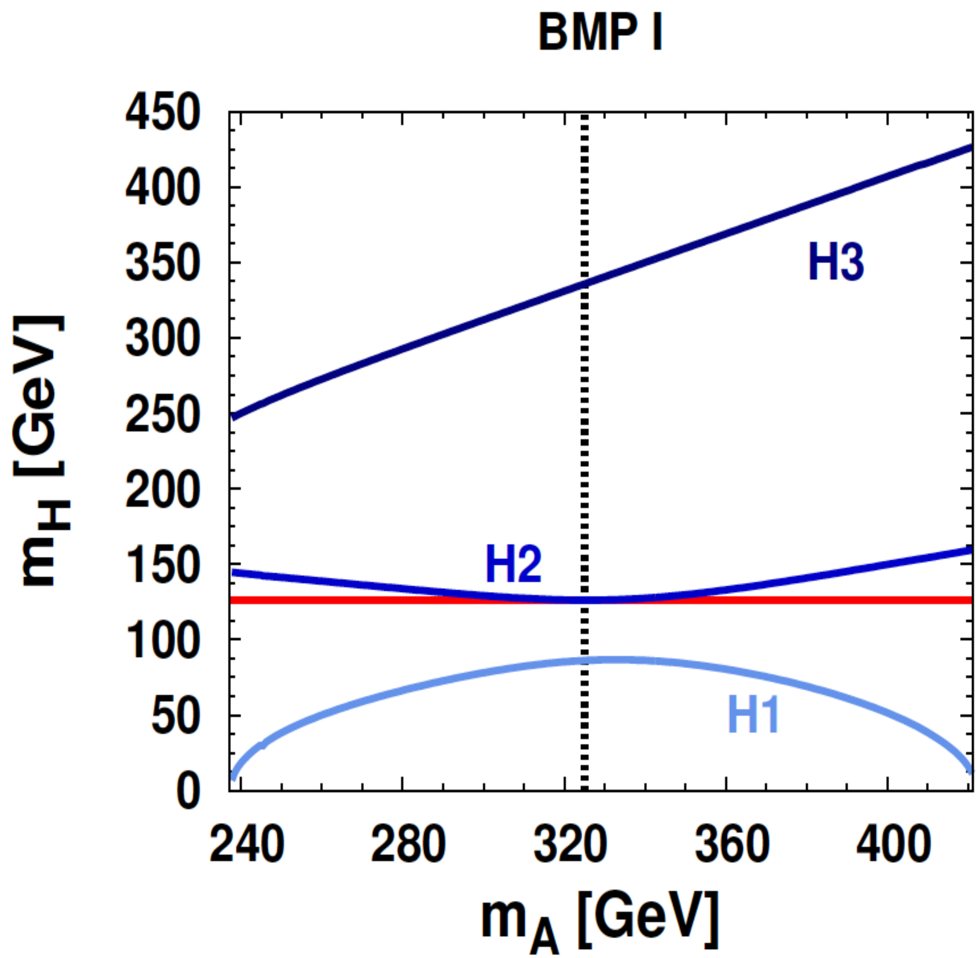
$$M_{11}^2 = M_A^2 + (m_Z^2 - \lambda^2 v^2)\sin^2 2\beta,$$
$$M_{12}^2 = -\frac{1}{2}(m_Z^2 - \lambda^2 v^2)\sin 4\beta,$$
$$M_{13}^2 = -\frac{1}{2}(M_A^2 \sin 2\beta + \frac{2\kappa\mu^2}{\lambda})\frac{\lambda v}{\mu}\cos 2\beta,$$
$$M_{22}^2 = m_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta,$$
$$M_{23}^2 = 2\lambda\mu v\left[1 - (\frac{M_A \sin 2\beta}{2\mu})^2 - \frac{\kappa}{2\lambda}\sin 2\beta\right],$$
$$M_{33}^2 = \frac{1}{4}\lambda^2 v^2 (\frac{M_A \sin 2\beta}{\mu})^2 + \frac{\kappa\mu}{\lambda}(A_\kappa + \frac{4\kappa\mu}{\lambda}) - \frac{1}{2}\lambda\kappa v^2 \sin 2\beta$$

$$M_A^2 \equiv \frac{2\mu(A_\lambda + \kappa s)}{\sin 2\beta}$$



NMSSM: m_h=125 GeV for TeV instead of multi-TeV stops

Eigenvalues after diagonalizing Higgs mass matrix



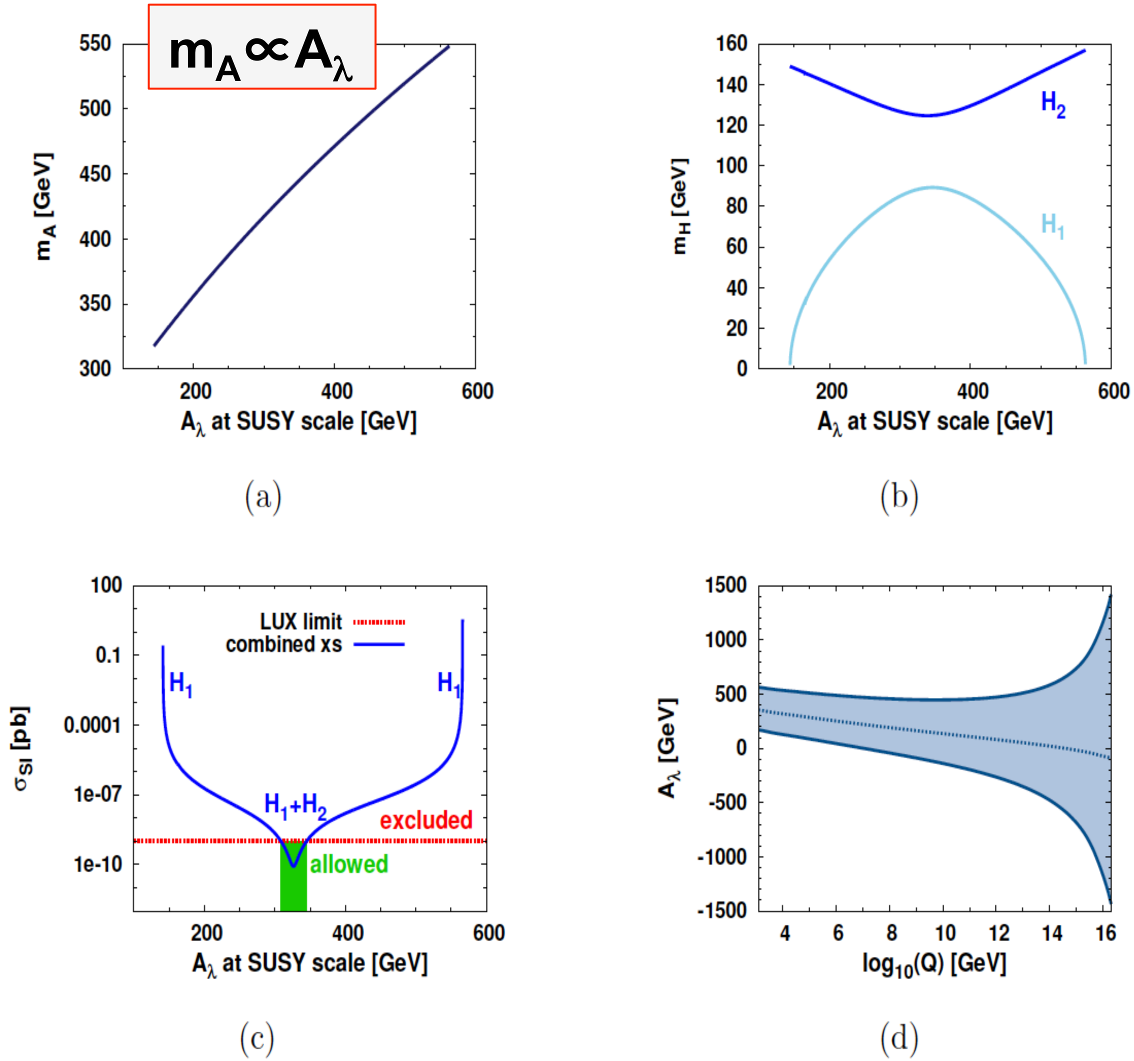
For larger or smaller m_A H2 „pushed up“, H1 pushed down

H2 SM-like, if close to minimum

Range of m_A limited by requiring $m_{H1}>0$

$m_{H3} \approx m_A$

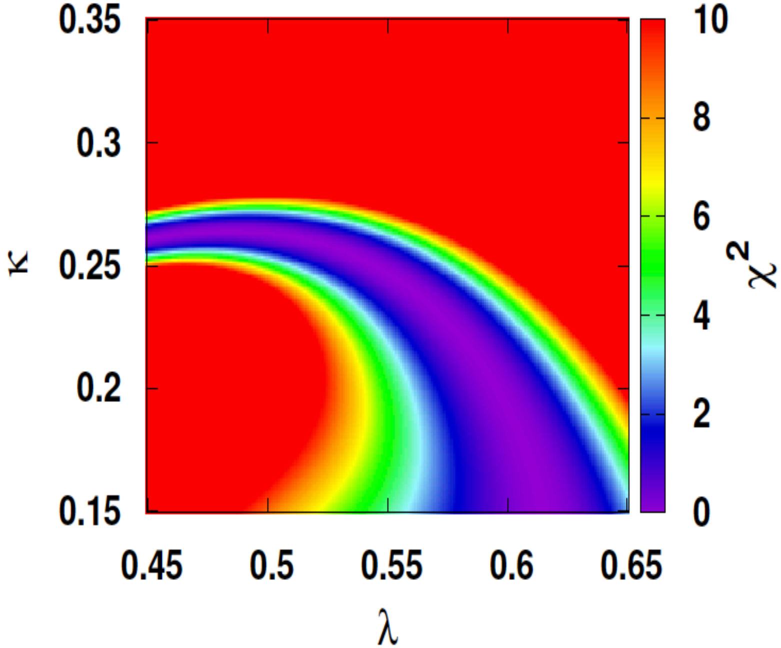
LSP-nucleon scattering x-section limits



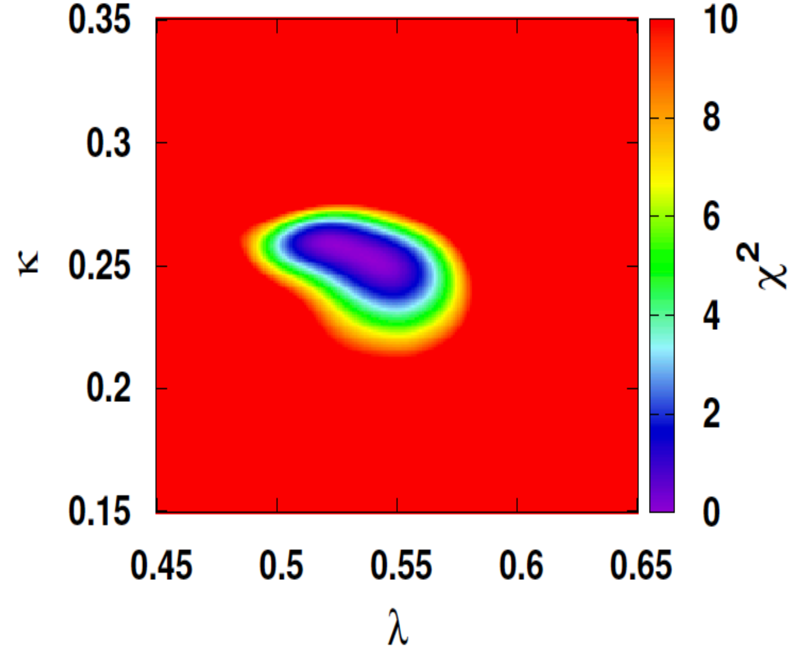
A_λ fixed point in range where mH1≈mH2, so neg. interference strong to get low x-sect. If MH1<<MH2 huge spin-indep. LSP-nucleon scattering x-section. Requires mH1 to be roughly >60 GeV

A_λ running to quasi-fixed point

Constraints on κ and λ
(Other parameters fixed)

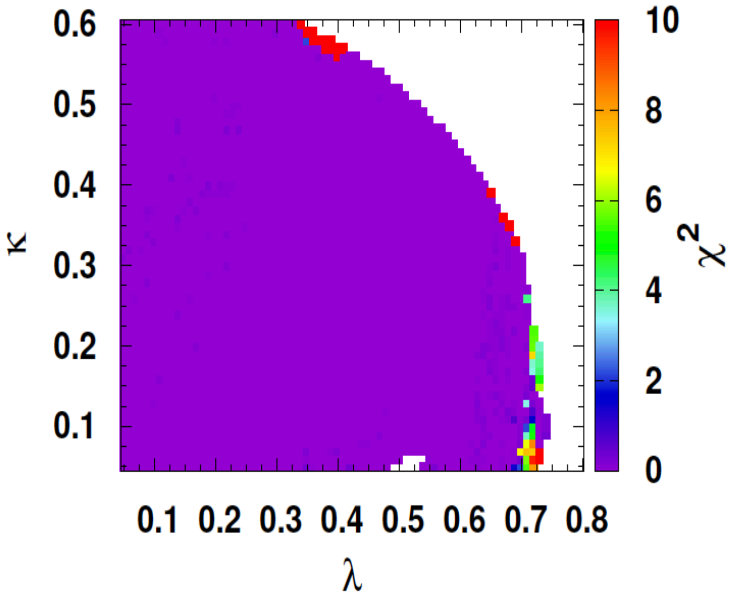


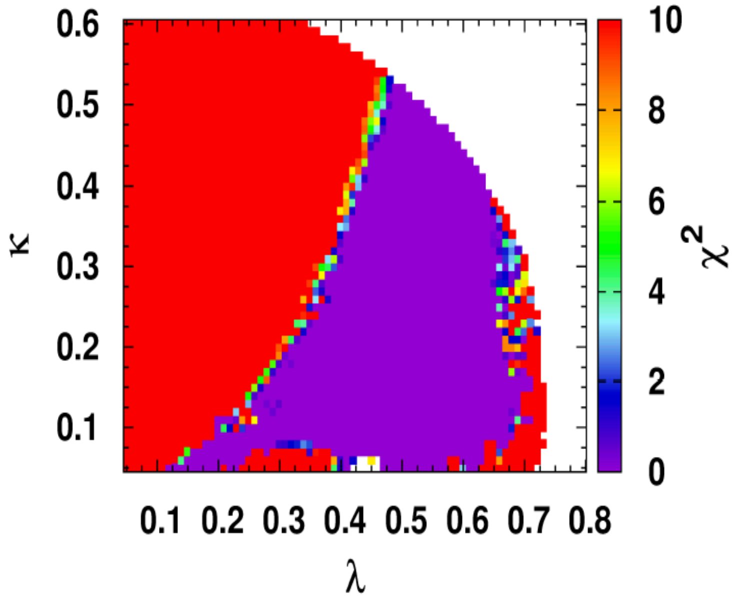
MH2=125 GeV



MH2=125 GeV +
Planck relic density

Larger freedom in κ and λ
(if other parameters free)





MH2=125 GeV

MH2=125 GeV +
Planck relic density

Comparison Higgs BR in CMSSM and natural NMSSM

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Branching Ratios [%]								
	CMSSM			NMSSM (BMP I)				
Mass [GeV]	h 126	H 2256	A 2256	H_1 86	H_2 126	H_3 336	A_1 214	A_2 325
$b\bar{b}$	67.6	85.2	85.2	90.6	63.6	3.0	0.2	1.9
W^+W^-	17.7	1.7e-5	-	6.5e-7	19.6	0.2	-	-
$\tau\tau$	5.0	14.6	14.6	8.8	6.5	0.4	0.02	0.2
hh	-	8.9e-5	-	-	-	-	-	-
H_1H_2	-	-	-	-	-	41.9	-	-
A_1H_1	-	-	-	-	-	-	-	4.0
Zh	-	-	1.7e-5	-	-	-	-	-
ZH_1	-	-	-	-	-	-	0.3	26.8
$\chi_1^0\chi_1^0$	-	4.7e-5	5.3e-4	-	-	5.7	99.5	38.1
$\chi_1^0\chi_3^0$	-	-	-	-	-	20.8	-	4.2
$\chi_1^+\chi_1^-$	-	-	-	-	-	20.7	-	18.4
σ_{prod} [pb]	19.3	1.3e-5	1.3e-5	2.57	19.1	0.57	1.6e-2	0.41

Possible „natural“ NMSSM signatures

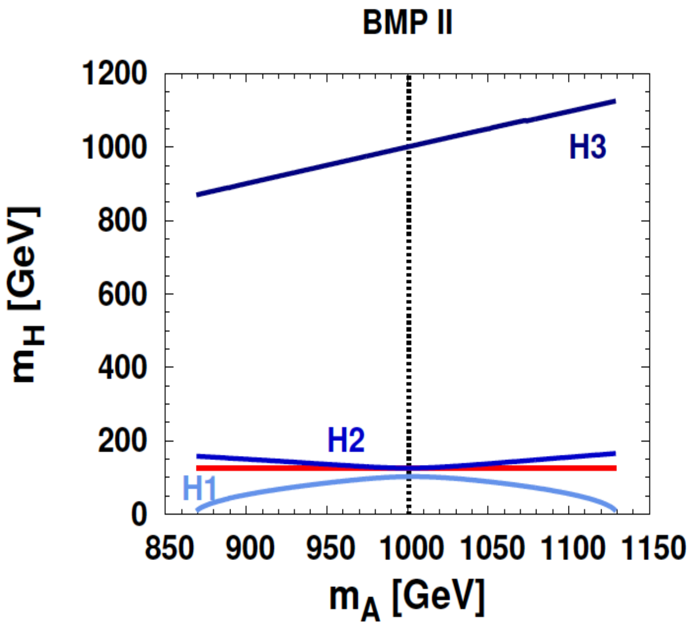
H3→H2+H1 with H2→WW,bb,ττ and H1→bb, ττ
Signatures: WWbb, bbbb, bbττ

H3→gauginos
Signatures:
invisible decays
Z+MET,
W+W- + MET,
Higgs +MET

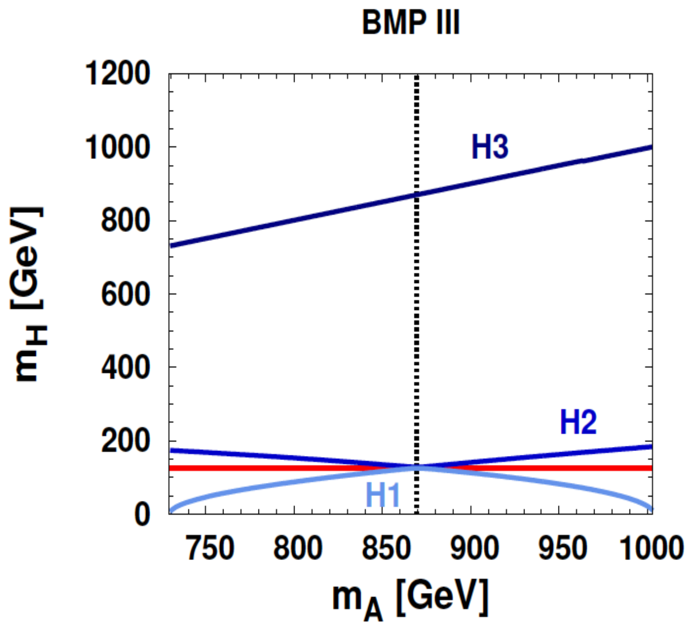
Given the small cross sections,
we should investigate all of them

Possible „unnatural" NMSSM signatures

Choose m_A in TeV range (e.g. larger μ)
What is minimum value of mA?
Chargino limit from LEP ➔limit on μ ➔m_A>280 GeV



mH2=125 GeV



mH1=125 GeV

Higgs mixing and couplings

		Higgs mixing [%]			Reduced couplings		
		H_d	H_u	S	κ_u	κ_d	$\kappa_{W,Z}$
BMP I $\sim$ BMP II	H_1	26.9	-11.4	95.6	-0.12	0.77	-0.01
	H_2	36.5	93.1	0.8	0.99	1.04	1.00
	H_3	89.1	-34.7	-29.3	-0.37	2.55	-0.01
	A_1	-14.6	-5.4	98.8	-0.06	-0.42	0.00
	A_2	92.6	34.4	15.6	0.37	2.66	0.00
BMP III	H_1	30.1	95.0	-8.2	0.99	0.98	0.99
	H_2	12.7	4.6	99.1	0.05	0.41	0.08
	H_3	94.5	-30.9	-10.7	-0.32	3.18	0.003
	A_1	-9.3	-3.0	99.5	-0.03	-0.30	0.00
	A_2	94.7	30.7	9.8	0.32	3.07	0.00

Input parameters for discussed bench mark points

Input	m_0	$m_{1/2}$	A_0	$\tan\beta$	A_κ	A_λ	κ_{SUSY}	λ_{SUSY}	μ
CMSSM	2500	2375	-4999	48.11	-	-	-	-	3339
BMP I	2400	550	-976	2.69	-848	-509	0.38	0.65	120
BMP II	2450	550	-1840	4.18	2549	1774	0.12	0.68	229
BMP III	2400	600	-1902	3.08	1206	756	0.14	0.64	263

Table 1: List of GUT scale input parameters for several benchmark points in the CMSSM and NMSSM, respectively. The top and bottom masses are $m_t = 172.5$ GeV and $m_b = 4.25$ GeV; $sgn(\mu) = +1$ for both models. The input parameters have been chosen to yield a Higgs boson mass of 126 GeV and have SUSY masses just outside the excluded regions in Fig. 4. κ and λ are given at the SUSY scale as input. The GUT scale values for BMP I(II,III) are $\kappa_{GUT} = 3.04(0.35, 0.34)$ and $\lambda_{GUT} = 2.16(1.46, 1.22)$.

SUSY masses for discussed bench mark points

	χ_1^0	χ_2^0	χ_3^0	χ_4^0	χ_5^0	$\chi_1^\pm$	$\chi_2^\pm$	$\tilde{t}_1$	$\tilde{t}_2$	$\tilde{b}_1$	$\tilde{b}_2$
CMSSM	1075	1993	3332	3334	-	1993	3334	3263	3908	3902	4014
BMP I	76	160	197	248	477	109	477	992	1925	1918	2552
BMP II	80	212	266	271	484	217	484	983	1957	1947	2596
BMP III	119	232	293	297	527	249	526	960	1952	1942	2588

Table 2: The masses of neutralinos, charginos, stops and sbottoms in GeV for the CMSSM and the three NMSSM benchmark points (BMP I-III) in Table 1.

BR in „unnatural“ NMSSM

Branching Ratios [%]

	NMSSM (BMP II)					NMSSM (BMP III)				
	H_1	H_2	H_3	A_1	A_2	H_1	H_2	H_3	A_1	A_2
Mass [GeV]	103	126	1001	91	1001	126	129	870	118	869
$b\bar{b}$	90.5	61.9	0.9	90.9	0.9	61.7	88.6	0.7	90.4	0.6
$t\bar{t}$	0.0	0.0	9.6	0.0	10.4	0.0	0.0	22.1	0.0	23.5
$\tau\tau$	9.1	6.4	0.1	8.8	0.1	6.3	9.3	0.1	9.3	0.1
W^+W^-	1.2e-4	20.6	1.7e-4	-	-	20.6	1.7	7.9e-3	-	-
$\chi_1^0\chi_1^0$	-	-	10.7	-	11.8	-	-	9.0	-	9.6
$\chi_1^0\chi_3^0$	-	-	5.1	-	6.3	-	-	5.5	-	8.9
$\chi_1^+\chi_1^-$	-	-	3.2	-	5.9	-	-	2.4	-	6.3
H_1H_2	-	-	14.8	-	-	-	-	13.6	-	-
A_1H_2	-	-	-	-	13.5	-	-	-	-	0.2
ZA_1	-	-	12.3	-	-	-	-	10.6	-	-
ZH_1	-	-	-	-	13.6	-	-	-	-	0.04
A_1H_1	-	-	-	-	0.3	-	-	-	-	11.7
ZH_2	-	-	-	-	8.1e-4	-	-	-	-	11.9
σ_{prod} [pb]	0.33	19.3	1.6e-3	0.13	1.9e-3	19.5	3.9e-2	7.1e-3	1.7e-2	7.6e-3

Extended range of BMPs

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NMSSM: Higgs sector largely decoupled from SUSY particles
(in CMSSM: LSP=Bino and DM annihilation via M_A s-channel resonance: $M_A \approx 2x\ M_{LSP} \approx m_{1/2}$)

$$M_A^2 \equiv \frac{2\mu(A_\lambda + \kappa s)}{\sin 2\beta}$$

Range of M_A≈MH3: 280<MH3<600 GeV (natural)

100<μ<200 GeV (μ=λv_s „natural" vev, v_s=170 GeV)
200<A_λ<500 GeV (quasi fixed point solution of RGE))

Range of MH1: 60<MH1<125 GeV
(lower limit, else if MH1<<MH2=125 GeV, too large LSP-nucleon scattering x-section)

Propose to start with scan over MH1 and MH3 in these ranges
Similar BR for semi-constrained and „natural" models

Task of NMSSM Working Group

Theorists: look at previous non-NMSSM analysis (e.g.WWbb (Atlas, arXiv 1312.1956), bbbb (CMS-PAS-HIG-14-013) and see if they can be reinterpreted in NMSSM

Experimentalists: check if proposed scenarios by theorists are realistic (e.g. WWbb discovery after 500/fb for some Higgs mass combinations?)

Combined effort: see if one can get good efficiency and background suppression for all mass ranges (challenging)

I did not find anything you have been suggesting

Don‘t worry, I have many other good ideas