Higgs at 125 GeV and the NMSSM

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UCD HEFTI LHC Lunch
02/22/2012

based on arXiv:1201.0982, with J.F. Gunion, S. Kraml

Outline

1. Preliminary Backgrounds: why NMSSM?

The successes of the standard model (SM)

1. The SM has 19 independent parameters
   - Gauge and fermion sectors: 4 real parameters (3 gauge couplings g, g' and g_S and the QCD vacuum angle θ_{QCD})
   - Higgs sector: 2 real parameters (μ^2 and λ or conventionally the vacuum expectation value v and the physical Higgs mass m_h)
   - Yukawa sector: 12 real parameters (6 quarks + 3 leptons + 3 CKM parameters) and 1 imaginary parameter (CKM matrix phase)
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3. The Higgs mass is essentially a free parameter, but the Higgs boson hasn't been discovered yet ...

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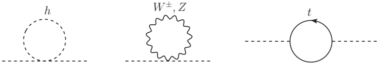
Problems with the SM

Quantum correction to the Higgs mass



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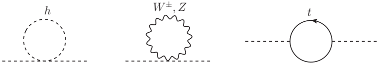

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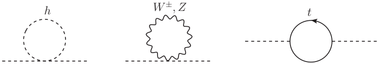

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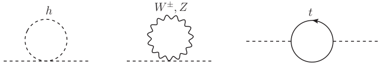

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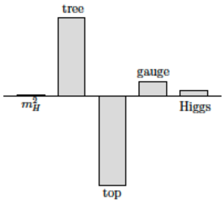

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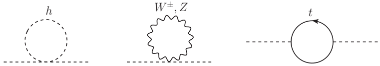

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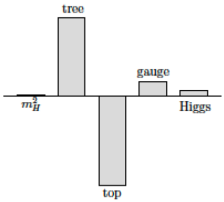

The candidate solutions beyond the SM

New physics at $\Lambda \sim 1$ TeV is:

Weakly Coupled

- Scalar DM (SM+a light singlet)
- **SUSY (MSSM, NMSSM, ...)**
- Little Higgs, Twin Higgs
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- Technicolor, Walking Techinicolor
- Top Color, Top See Saw
- Composite Higgs
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The Simplest SUSY Model: MSSM

1. MSSM possesses 124 independent parameters
   - 19-2 (Higgs sector) from the SM
   - 105+2 genuinely new parameters

$$\begin{cases} \text{Gaugino: } 5 \text{ (complex } M_1, M_2 \text{ and real } M_3) \\ \text{Higgs: } 5 \text{ (real } b, m^2_{H_u}, m^2_{H_d} \text{ and complex } \mu) \\ \qquad\qquad \text{or } (v, \tan\beta, m_A \text{ and complex } \mu) \\ \text{Sfermion \& trilinear: } 57 \text{ (12 squarks, 9 sleptons + 36 mixing angles)} \\ \qquad\qquad\qquad\qquad\quad 40 \text{ imaginary (new CP-violating phases)} \end{cases}$$

2. Higgs Family

MSSM Higgs Sector
2 CP-even neutral scalars: h, H
1 CP-odd neutral pseudoscalar: A
2 charged scalars: $H^\pm$

$$m_h^2 = \frac{1}{2}\left[m_A^2 + M_Z^2 - \sqrt{(m_A^2 + M_Z^2)^2 - 4M_Z^2 m_A^2 \cos^2 2\beta}\right]$$

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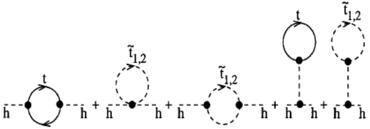
Problems of the MSSM

Tree level upper bound: $m_h < |\cos 2\beta| M_Z$

$\longrightarrow$ radiative corrections (at one-loop level)



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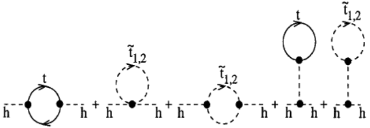

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VEV Minimum conditions
$$\begin{cases} |\mu|^2 + m_{H_u}^2 = b\cot\beta + (M_Z^2/2)\cos 2\beta \\ |\mu|^2 + m_{H_d}^2 = b\tan\beta - (M_Z^2/2)\cos 2\beta \end{cases}$$

- If $\mu \sim \mathcal{O}(M_Z)$, natural
- However, if the SUSY derives from an underlying string theory, so

$$\mu \sim M_{Pl}, M_{string} \gg M_{SUSY},$$ unnatural **μ PROBLEM**

$\Longrightarrow$ large $m_{H_u}^2, m_{H_d}^2$ $\Longrightarrow$ large cancellation needed **FINE-TUNING**

$\mathbb{Z}_3$-invariant NMSSM

NMSSM solves μ-problem by adding one singlet S, at the cost of adding 3 more particles

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$$\mathcal{L}_{\rm NMSSM} = \mathcal{L}_{\rm kinetic} + \mathcal{L}_{\rm int} + \mathcal{L}^{\rm NMSSM}_{\rm soft}$$

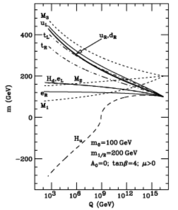
The interactions are generated by the superpotential

$$W_{NMSSM} = \bar{u}\mathbf{Y_u}QH_u - \bar{d}\mathbf{Y_d}QH_d - \bar{e}\mathbf{Y_e}LH_u + \lambda SH_uH_d + \frac{\kappa}{3}S^3$$

and the soft-SUSY breaking terms are

$$\mathcal{L}_{\rm soft}\begin{cases}\mathcal{L}_{\rm gaugino} = -\frac{1}{2}\left(M_3\tilde{G}^a\tilde{G}_a + M_2\tilde{W}^\alpha\tilde{W}_\alpha + M_1\tilde{B}\tilde{B}\right) + {\rm h.c.}\\ \mathcal{L}_{\rm sfermions} = -\tilde{Q}_L^*\mathbf{m}^2_{\tilde{\mathbf{Q}}}\tilde{Q}_L - \tilde{L}_L^*\mathbf{m}^2_{\tilde{\mathbf{L}}}\tilde{L}_L - \tilde{u}_R^*\mathbf{m}^2_{\tilde{\mathbf{u}}}\tilde{u}_R - \tilde{d}_R^*\mathbf{m}^2_{\tilde{\mathbf{d}}}\tilde{d}_R - \tilde{e}_R^*\mathbf{m}^2_{\tilde{\mathbf{e}}}\tilde{e}_R\\ \mathcal{L}_{\rm Higgs} = -m^2_{H_u}H_u^*H_u - m^2_{H_d}H_d^*H_d - m_S^2S^*S\\ \mathcal{L}_{\rm trilinear} = -\left(\tilde{u}_R\mathbf{A_u}\tilde{Q}_LH_u - \tilde{d}_R\mathbf{A_d}\tilde{Q}_LH_d - \tilde{e}_R\mathbf{A_e}\tilde{L}_LH_d + \lambda A_\lambda H_uH_dS + \frac{1}{3}\kappa A_\kappa S^3\right)\\ \qquad +{\rm h.c.}\end{cases}$$

NMSSM Parameters



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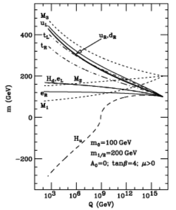

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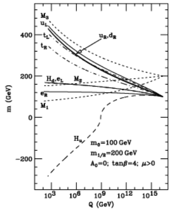

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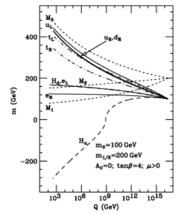
Higgs VEV Minimizations

$$s\left(m^2_S + \kappa A_\kappa s + 2\kappa^2 s^2 + \lambda^2(v_u^2 + v_d^2) - 2\lambda\kappa v_u v_d\right) - \lambda v_u v_d A_\lambda = 0$$

NMSSM Parameters



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↓

Higgs VEV Minimizations

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$\lambda, A_\lambda, A_\kappa, v, \tan\beta, m^2_{H_u}, m^2_{H_d}$ Various choices for different scenarios

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Maximal Higgs Mass Overviews

A. Arbey, M. Battaglia, A. Djouadi, F. Mahmoudi, J. Quevillon, Phys.Lett. B708(2012)162

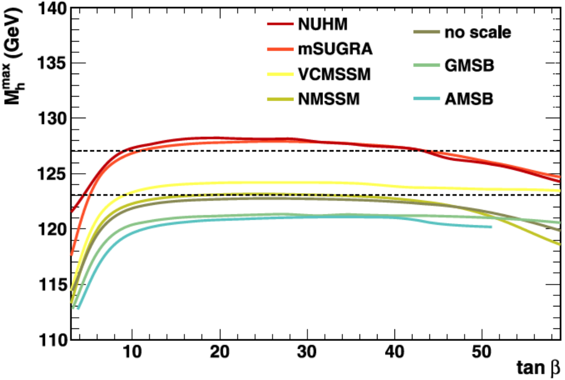
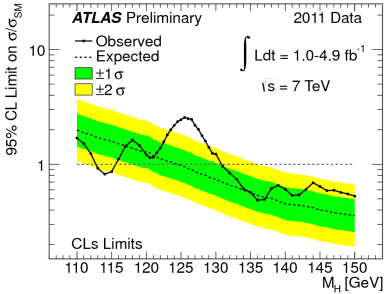


Fig. 2. The maximal value of the h mass defined as the value for which 99% of the scan points have a mass smaller than it, shown as a function of $\tan\beta$ for the various constrained MSSM models.

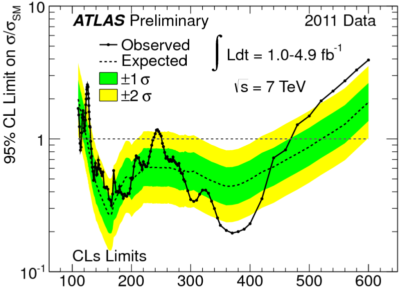
Here the NMSSM refers to the constrained NMSSM.

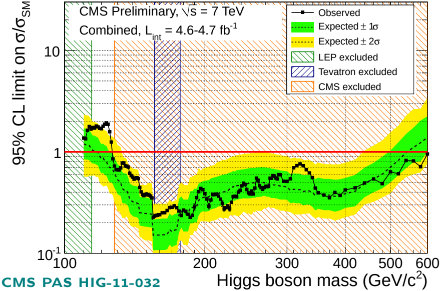
Outline

ATLAS and CMS excess around 125 GeV Higgs



ATLAS-CONF-2011-163

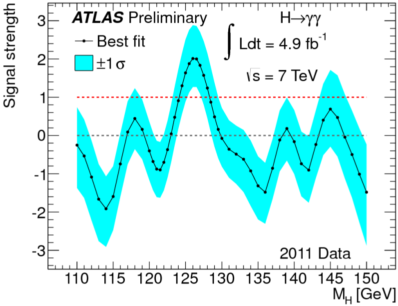




CMS PAS HIG-11-032

- Excess around 125 GeV seen by both ATLAS and CMS.
- ATLAS exclusion: 112.7-115.5;131-237;251-468 GeV (95% C.L.)
- CMS exclusion: 127-600 GeV (95% C.L.)

Best-fit for a near 125 GeV Higgs



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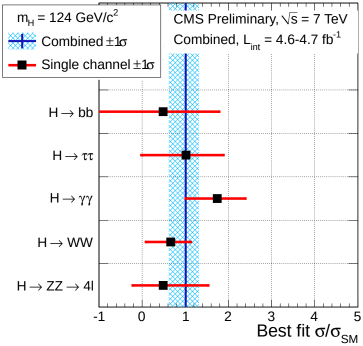

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1.3 σ excess w.r.t. the SM

1 σ excess w.r.t. the SM

Motivations

Find the most constrained version of the NMSSM consistent with a fairly SM-like Higgs at 125 GeV and implications thereof.

- The MSSM has been explored in numerous papers with a general conclusion that the MSSM—especially a constrained version such as the CMSSM—is hard pressed to yield a fairly SM-like light Higgs boson at 125 GeV when satisfying all the constraints including a_μ and Ωh^2.
  arXiv:1112.3017; 1112.3021; 1112.3026; 1112.3032; 1112.3068; 1112.3123; 1112.3142; 1112.3336; 1112.3564; 1112.3645; 1112.3647; 1112.4391; 1112.4835; 1112.5666; PLB 708(2012)162
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Outline

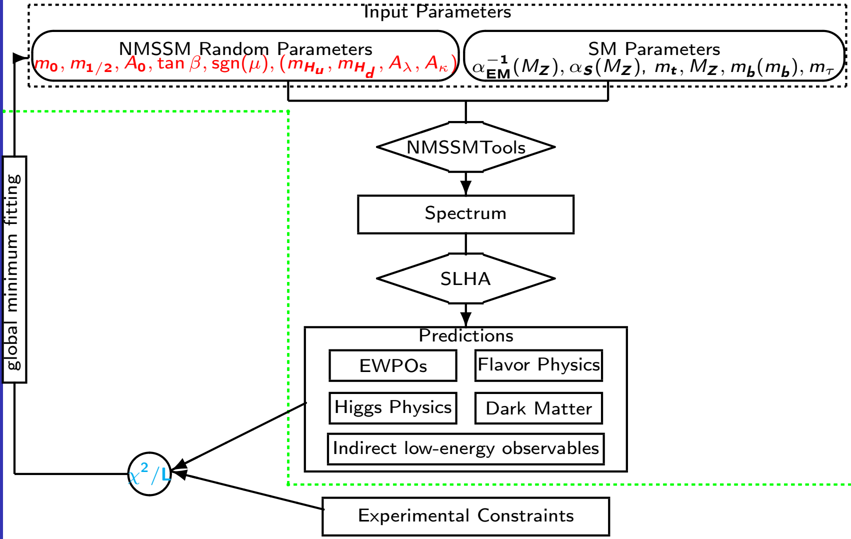
The Constrained NMSSM Models

We have examined the following models:

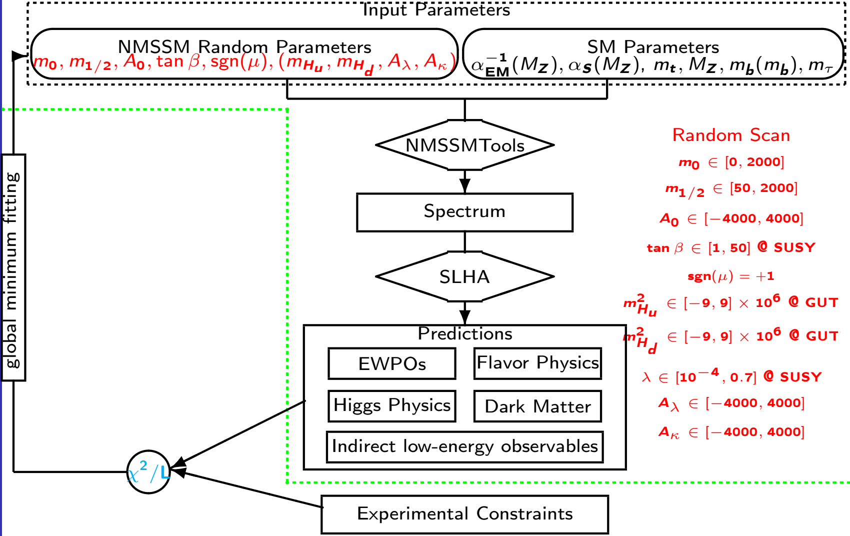
- Model I: $U(1)_R$ imposed, constrained NMSSM (cNMSSM)
  $\tan\beta,\ \lambda,\ m_0,\ m_{1/2},\ A_0 = A_{t,b,\tau},\ A_\lambda = A_\kappa = 0$
- Model II: $U(1)_R$ imposed, NUHM
  $\tan\beta,\ \lambda,\ m_0,\ m_{1/2},\ m_{H_u},\ m_{H_d},\ A_0 = A_{t,b,\tau},\ A_\lambda = A_\kappa = 0$
- Model III: NUHM, with general A_λ and A_κ
  $\tan\beta,\ \lambda,\ m_0,\ m_{1/2},\ m_{H_u},\ m_{H_d},\ A_0 = A_{t,b,\tau},\ A_\lambda,\ A_\kappa$

The constraints are imposed at the GUT scale and then low-scale parameters are obtained by RGE evolution.

Flow Chart


Input Parameters
NMSSM Random Parameters
$m_0, m_{1/2}, A_0, \tan\beta, \mathrm{sgn}(\mu), (m_{H_u}, m_{H_d}, A_\lambda, A_\kappa)$
SM Parameters
$\alpha_{EM}^{-1}(M_Z), \alpha_s(M_Z), m_t, M_Z, m_b(m_b), m_\tau$
NMSSMTools
Spectrum
SLHA
Predictions
EWPOs
Flavor Physics
Higgs Physics
Dark Matter
Indirect low-energy observables
χ^2/L
Experimental Constraints
global minimum fitting

Flow Chart



Random Scan

$m_0 \in [0, 2000]$

$m_{1/2} \in [50, 2000]$

$A_0 \in [-4000, 4000]$

$\tan\beta \in [1, 50]$ @ SUSY

$\mathrm{sgn}(\mu) = +1$

$m_{H_u}^2 \in [-9, 9] \times 10^6$ @ GUT

$m_{H_d}^2 \in [-9, 9] \times 10^6$ @ GUT

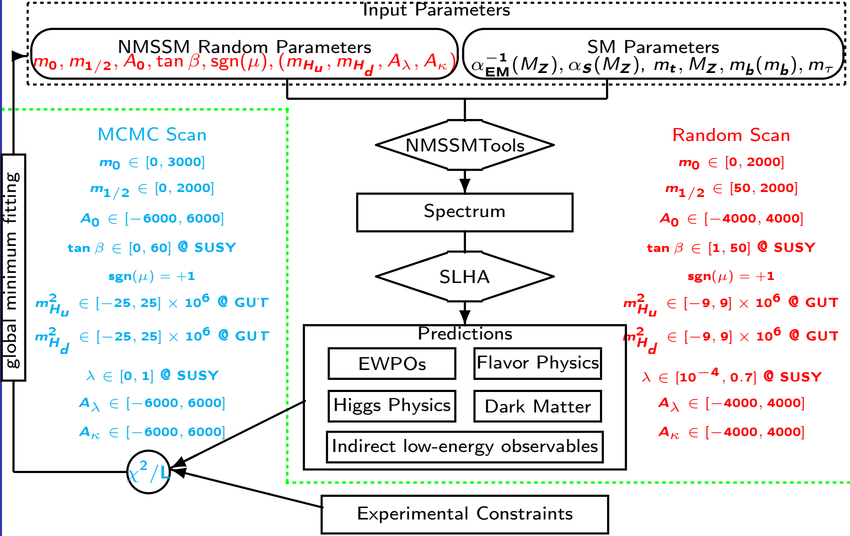
$\lambda \in [10^{-4}, 0.7]$ @ SUSY

$A_\lambda \in [-4000, 4000]$

$A_\kappa \in [-4000, 4000]$

Random Scan: most points, 5×10^5 points for each scan

Flow Chart



Random Scan: most points, 5×10^5 points for each scan

Markov Chain Monte Carlo (MCMC): (almost) good points around 125 GeV

χ^2/Likelihood Definition

- Type I: with a central value $\xi_i^{(\mathrm{I})\mathrm{exp}}$

$$\chi^2(\xi^{(\mathrm{I})}) = \sum_i \frac{\left(\xi_i^{(\mathrm{I})} - \xi_i^{(\mathrm{I})\mathrm{exp}}\right)^2}{\sigma^2(\xi_i^{(\mathrm{I})}) + \tau^2(\xi_i^{(\mathrm{I})})}$$

Examples: $BR(B_s \to X_s\gamma)$, ΔM_s, ΔM_d, $BR(B^+ \to \tau^+\nu_\tau)$, $BR(B \to X_s\mu^+\mu^-)$, $m_{\mathrm{h}}^{\mathrm{light}}$ and ATLAS signal strength best-fit.

$\sigma(\xi_i)$: experimental (statistical and systematical) uncertainty
$\tau(\xi_i)$: estimate of theoretical uncertainty

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- Type II: only having an upper/lower bound limit $\bar{\xi}_i^{(\mathrm{II})}$

$$\mathrm{Likelihood}(\xi^{(\mathrm{II})}) = \prod_i \left(1 + e^{\pm\frac{\xi_i^{(\mathrm{II})} - \bar{\xi}_i^{(\mathrm{II})}}{\sigma}}\right)^{-1}$$

in the exponent + for upper limit/- for lower limit
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$$\text{Total Likelihood}=\mathrm{Likelihood}(\xi^{(\mathrm{II})})e^{-\frac{\chi^2(\xi^{(\mathrm{I})})}{2}}$$

Constraint Categories

	LEP/Teva	B-physics	$\Omega h^2 > 0$	$\delta a_\mu (\times 10^{10})$	m_{h_1}	Remark
■	√	×	×	×	×	
■ (green)	√	√	×	×	×	
+	√	√	<0.136	×	×	
×	√	√	×	5.77-49.1	×	
▲	√	√	<0.136	5.77-49.1	×	
△ (grey)	√	√	0.094-0.136	5.77-49.1	<123	
△	√	√	0.094-0.136	5.77-49.1	⩾123	perfect
◊	√	√	0.094-0.136	4.27-5.77	⩾123	almost perfect

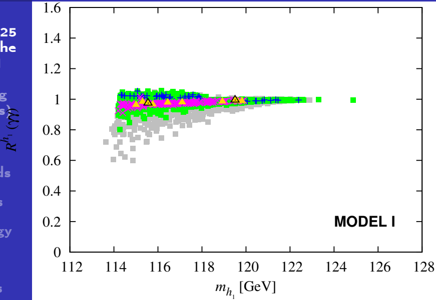
- All points give a proper RGE solution, have no Landau pole, have a neutralino LSP.
- Higgs mass limits are from LEP, TEVATRON, and early LHC data; SUSY mass limits are essentially from LEP.
- B-physics constraints

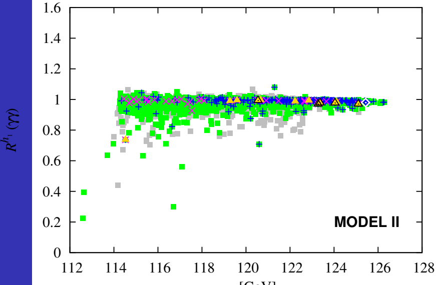
Observables	Constraints
ΔM_d	0.507 ± 0.008 (2σ)
ΔM_s	17.77 ± 0.24 (2σ)
$BR(B \to X_s \gamma)$	3.55 ± 0.51 (2σ)
$BR(B^+ \to \tau^+ \nu)$	$(1.67 \pm 0.78) \times 10^{-4}$ (2σ)
$BR(B_s \to \mu^+ \mu^-)$	$< 1.1 \times 10^{-8}$ (95% C.L.)

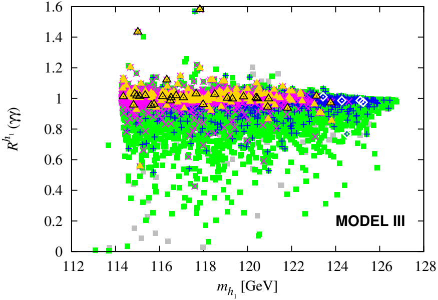
Outline

$R^{h_1}(\gamma\gamma)$ Figures

$$R^{h_i}(X) \equiv \frac{\Gamma(gg\to h_i)\ BR(h_i\to X)}{\Gamma(gg\to h_{SM})\ BR(h_{SM}\to X)}$$







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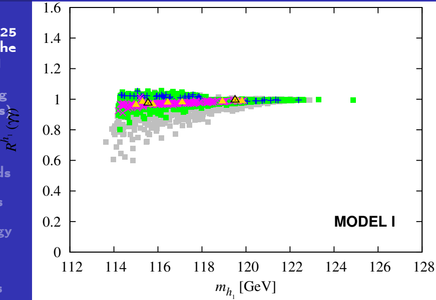
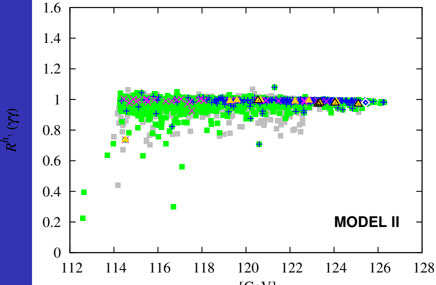
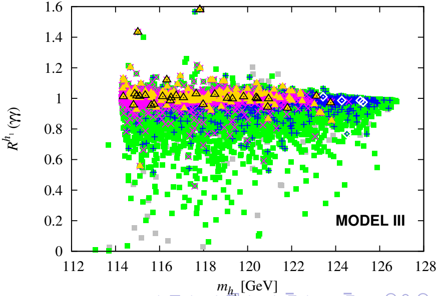
For $m_{h_1} \sim 124 - 125$ GeV,

Model I: NO perfect points







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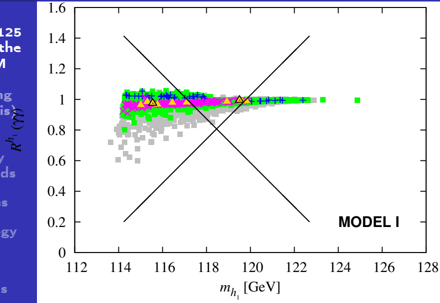
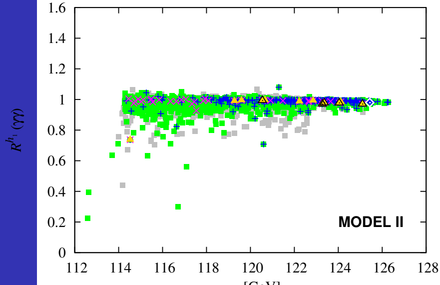
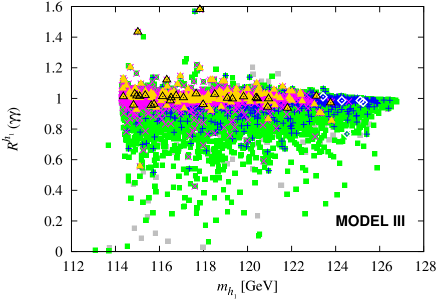


For $m_{h_1} \sim 124 - 125$ GeV,

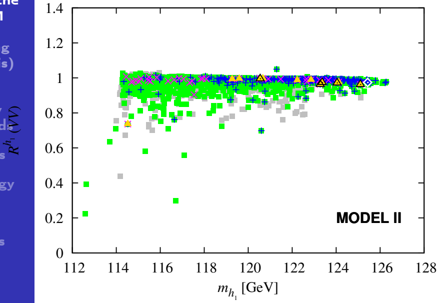
Models II, III: have perfect points

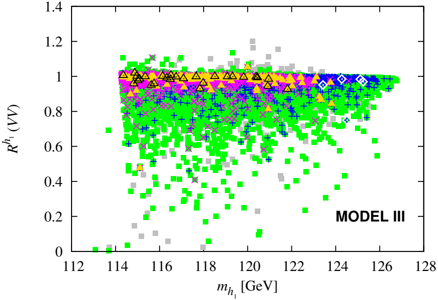
- Typically, $R^{h_1}(\gamma\gamma)$ of order 0.98.
- Almost perfect points (small δa_μ relaxation) emerge more easily.
- NO (almost) perfect points with $R^{h_1}(\gamma\gamma) > 1$ for $m_{h_1} = 123 - 128$ GeV.





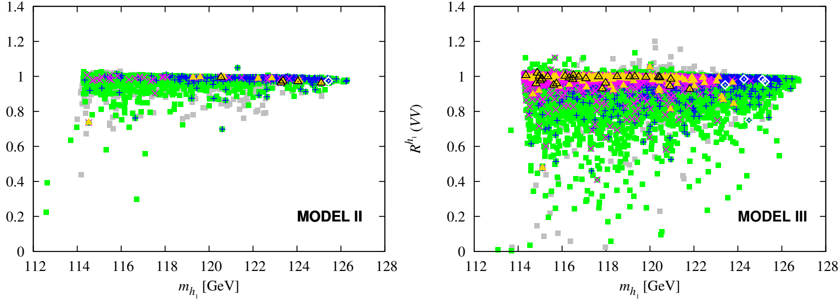
$R^{h_1}(VV = WW, ZZ)$ Figures





- As for the $\gamma\gamma$ final state, for $m_{h_1} \gtrsim 123$ GeV the predicted rates in the VV channels are very nearly SM-like for perfect or almost perfect points.
- We did not find perfect or almost perfect points with mass above 126 GeV.

$R^{h_1}(VV = WW, ZZ)$ Figures



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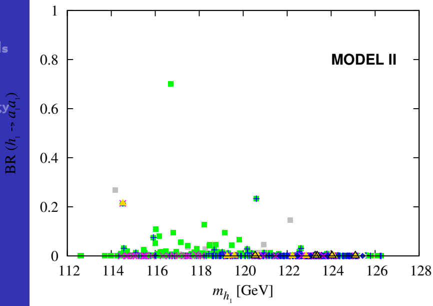
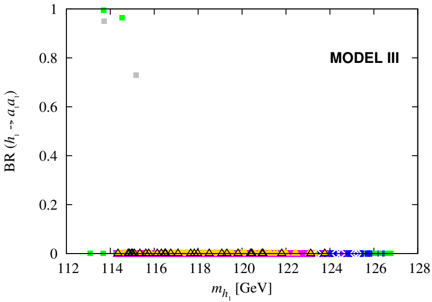
$BR(h_1 \to a_1 a_1)$ Figures

Are there any perfect or almost perfect points with measurable $h_1 \to a_1 a_1$ decays? NO! (not surprising given $R^{h_1}(\gamma\gamma) \sim 1$.)

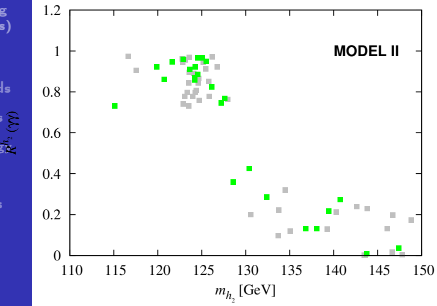


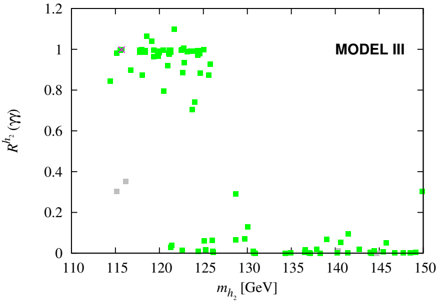


Large BR is possible while satisfying basic and B-physics constraints. However, $BR \lesssim 0.2$ once additional constraints are imposed. Thus, a light Higgs has nowhere to hide in these models.

$R^{h_2}(\gamma\gamma)$ Figures

How about the next lightest Higgs, h_2?





- In the $m_{h_2} \in [110 - 150]$ GeV region, points only pass the basic constraints and the B-physics constraints and not the others.
- Thus, it appears that within these constrained models with GUT unification conditions it is the h_1 that must be identified with the Higgs observed at the LHC.

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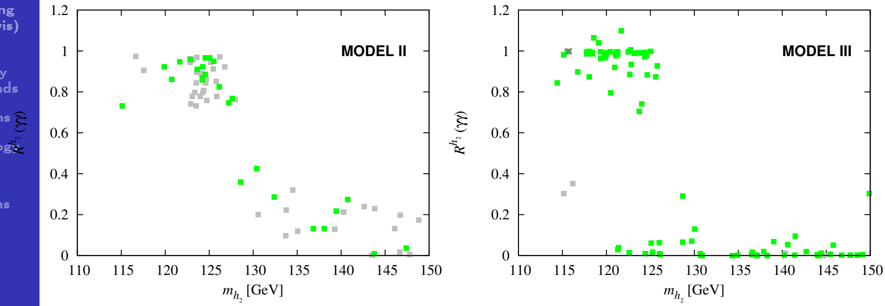

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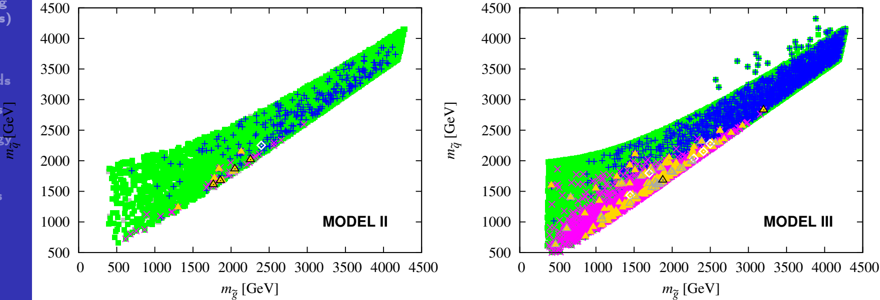
SUSY Searches

Are such points consistent with current LHC limits on SUSY particles, in particular squarks and gluinos?



- All the (almost) perfect points with $m_{h_1} \gtrsim 123$ GeV have squark and gluino masses above 1.5 TeV and thus have not yet been probed by current LHC data sets.
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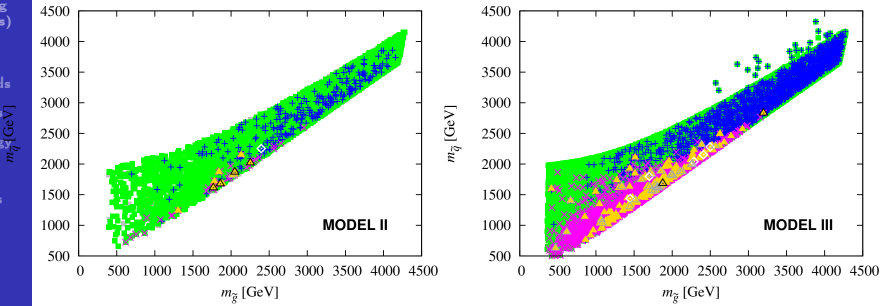

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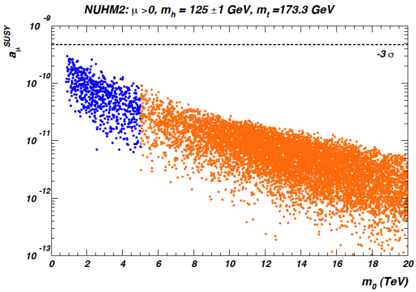
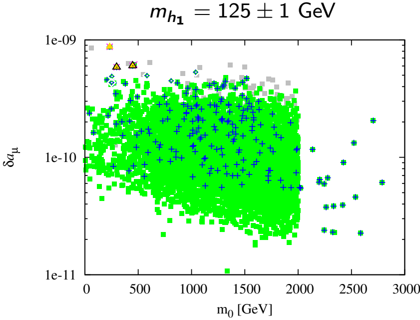
More Analysis (δa_μ vs m_0)



CMSSM, Baer 1112.3017



NUHM-NMSSM

- Slightly relaxing the δa_μ requirement to almost perfect makes it much easier to find viable points with $m_{h_1} \sim 125$ GeV. Thus there is a mild tension between good δa_μ and large m_{h_1}.
- The tension between δa_μ and $m_{h_1} = 125$ GeV is less in the NMSSM with NUHM relaxation than in the MSSM with NUHM relaxation.

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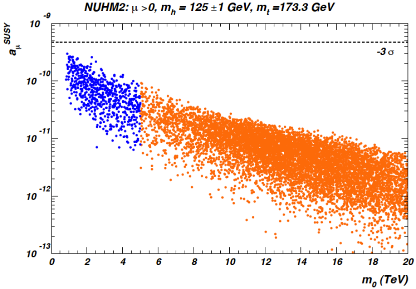

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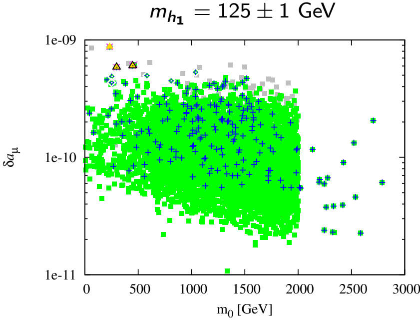

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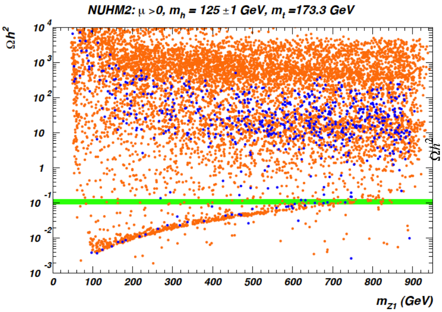

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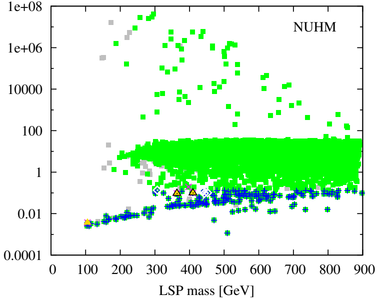

NUHM-NMSSM

- There is a lower bound on Ωh^2 for each LSP mass.
- The maximum LSP mass increases a bit if the δa_μ constraint is relaxed to the almost perfect level.
- No obvious difference with CMSSM.

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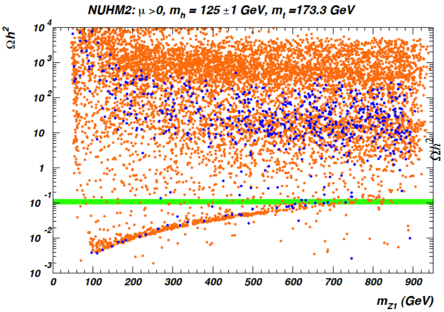

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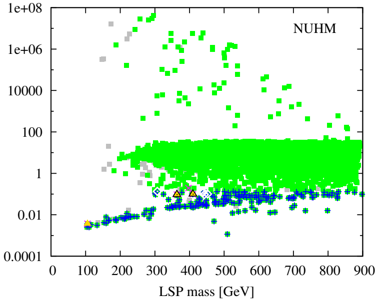

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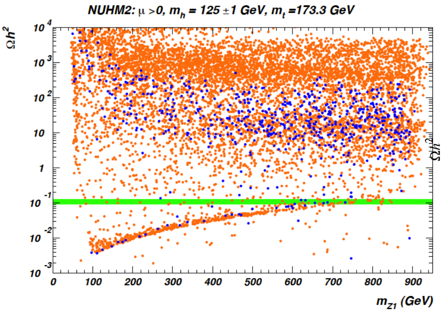

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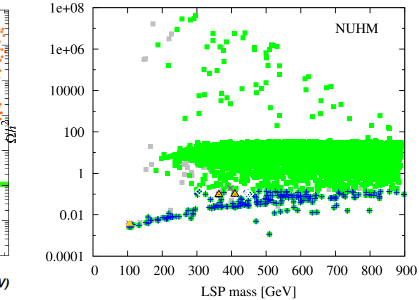

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GUT Scale Parameters

	Model II			Model III			
Pt. #	1	2	3	4	5	6	7*
$\tan\beta(m_Z)$	17.9	17.8	21.4	15.1	26.2	17.9	24.2
λ	0.078	0.0096	0.023	0.084	0.028	0.027	0.064
κ	0.079	0.011	0.037	0.158	-0.045	0.020	0.343
$m_{1/2}$	923	1026	1087	842	738	1104	1143
m_0	447	297	809	244	1038	252	582
A_0	-1948	-2236	-2399	-1755	-2447	-2403	-2306
A_λ	0	0	0	-251	-385	-86.8	-2910
A_κ	0	0	0	-920	883	-199	-5292
$m^2_{H_d}$	$(2942)^2$	$(3365)^2$	$(4361)^2$	$(2481)^2$	$(935)^2$	$(3202)^2$	$(3253)^2$
$m^2_{H_u}$	$(1774)^2$	$(1922)^2$	$(2089)^2$	$(1612)^2$	$(1998)^2$	$(2073)^2$	$(2127)^2$
m_{h_1}	124.0	125.1	125.4	123.8	124.5	125.2	125.1

- Modest A_λ and A_κ from MCMC scan due to our setting $|A_{\lambda,\kappa}| \leq 1$ TeV, while almost perfect point (#7) from completely random scan has quite large A_λ and A_κ values.
- However, the general random scan over A_λ and A_κ did not find any perfect points with $m_{h_1} \gtrsim 124$ GeV, whereas such points were fairly quickly found using the MCMC technique.
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GUT Scale Parameters

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Higgs Content

	Model II			Model III			
Pt. #	1	2	3	4	5	6	7*
m_{h_1}	124.0	125.1	125.4	123.8	124.5	125.2	125.1
m_{h_2}	797	1011	1514	1089	430	663	302
m_{a_1}	66.5	9.83	3.07	1317	430	352	302
C_u	0.999	0.999	0.999	0.999	0.999	0.999	0.999
C_d	1.002	1.002	1.001	1.003	1.139	1.002	1.002
C_V	0.999	0.999	0.999	0.999	0.999	0.999	0.999
$C_{\gamma\gamma}$	1.003	1.004	1.004	1.004	1.012	1.003	1.001
C_{gg}	0.987	0.982	0.988	0.984	0.950	0.986	0.994
$R^{h_1}(\gamma\gamma)$	0.977	0.970	0.980	0.980	0.971	0.768	0.975
$R^{h_1}(ZZ, WW)$	0.971	0.962	0.974	0.974	0.964	0.750	0.969
χ^2_{ATLAS}	0.59	1.27	1.47	0.72	1.57	1.34	1.20

- For the (almost) perfect points with $m_{h_1} \gtrsim 123$ GeV, the h_1 is very SM-like since all C's (and R's) are close to 1.

How well do the points above describe the ATLAS Higgs data?

- The smallest χ^2_{ATLAS}, of order 0.6 to 0.7, is obtained for $m_{h_1} \sim 124$ GeV because at this mass the ATLAS fits to $R^{h_1}(\gamma\gamma)$ and $R^{h_1}(4\ell)$ are very close to 1.
- For $m_{h_1} \sim 125$ GeV, the R^{h_1}'s for the ATLAS data are somewhat larger than 1 leading to a discrepancy with the NMSSM SM-like prediction. Roughly, χ^2_{ATLAS} is of order 1.3 to 1.6.

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Spectrum

	Model II			Model III			
Pt. #	1	2	3	4	5	6	7*
μ_{eff}	400	447	472	368	421	472	477
$m_{\tilde{g}}$	2048	2253	2397	1876	1699	2410	2497
$m_{\tilde{q}}$	1867	2020	2252	1685	1797	2151	2280
$m_{\tilde{b}_1}$	1462	1563	1715	1335	1217	1664	1754
$m_{\tilde{t}_1}$	727	691	775	658	498	784	1018
$m_{\tilde{e}_L}$	648	581	878	520	1716	653	856
$m_{\tilde{e}_R}$	771	785	1244	581	997	727	905
$m_{\tilde{\tau}_1}$	535	416	642	433	784	443	458
$m_{\tilde{\chi}_1^\pm}$	398	446	472	364	408	471	478
$m_{\tilde{\chi}_1^0}$	363	410	438	328	307	440	452
$f_{\tilde{B}}$	0.506	0.534	0.511	0.529	0.914	0.464	0.370
$f_{\tilde{W}}$	0.011	0.009	0.008	0.012	0.002	0.009	0.009
$f_{\tilde{H}}$	0.483	0.457	0.482	0.459	0.083	0.528	0.622
$f_{\tilde{S}}$	10^{-4}	10^{-6}	10^{-6}	10^{-4}	10^{-6}	10^{-4}	10^{-6}

- $m_{\tilde{g}}$ and $m_{\tilde{q}}$ above 1.5 TeV. even above 2 TeV. Although $\tilde{t}_1$ mass is distinctly below 1 TeV, detection of the $\tilde{t}_1$ as an entity separate from the other squarks and the gluino will be quite difficult at 500 GeV – 1 TeV. Thus discovering SUSY may require the 14 TeV LHC upgrade.
- $m_{\tilde{\chi}_1^0}$ is rather similar, $\approx 300 - 450$ GeV. And the $\tilde{\chi}_1^0$ has an approximately equal mixture of higgsino and bino except for Pt. #5.
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δa_μ and Dark Matter details

Pt. #	δa_μ	Ωh^2	Prim. Ann. Channels	σ_{SI} [pb]
1	6.01	0.094	$\widetilde{\chi}_1^0\widetilde{\chi}_1^0 \to W^+W^-(31.5\%), ZZ(21.1\%)$	4.3×10^{-8}
2	5.85	0.099	$\widetilde{\nu}_\tau\widetilde{\nu}_\tau \to \nu_\tau\nu_\tau(11.4\%), \widetilde{\nu}_\tau\overline{\widetilde{\nu}}_\tau \to W^+W^-(8.8\%)$	3.8×10^{-8}
3	4.48	0.114	$\widetilde{\chi}_1^0\widetilde{\chi}_1^0 \to W^+W^-(23.9\%), ZZ(17.1\%)$	3.7×10^{-8}
4	6.87	0.097	$\widetilde{\chi}_1^0\widetilde{\chi}_1^0 \to W^+W^-(36.9\%), ZZ(23.5\%)$	4.5×10^{-8}
5	5.31	0.135	$\widetilde{\chi}_1^0\widetilde{\chi}_1^0 \to b\bar{b}(39.5\%), h_1 a_1(20.3\%)$	5.8×10^{-8}
6	4.89	0.128	$\widetilde{\tau}_1\widetilde{\tau}_1 \to \tau\tau(17.4\%), \widetilde{\chi}_1^0\widetilde{\chi}_1^0 \to W^+W^-(14.8\%)$	4.0×10^{-8}
7*	4.96	0.101	$\widetilde{\chi}_1^0\widetilde{\chi}_1^0 \to W^+W^-(17.7\%), ZZ(12.9\%)$	4.0×10^{-8}

- There is some variation in the primary annihilation mechanism, with $\widetilde{\tau}_1\widetilde{\tau}_1$ and $\widetilde{\chi}_1^0\widetilde{\chi}_1^0$ annihilation being the dominant channels except for Pt. #2 for which $\widetilde{\nu}_\tau\widetilde{\nu}_\tau$ and $\widetilde{\nu}_\tau\overline{\widetilde{\nu}}_\tau$ annihilations are dominant.
- In the case of dominant $\widetilde{\tau}_1\widetilde{\tau}_1$ annihilation, the bulk of the $\widetilde{\chi}_1^0$'s come from those $\widetilde{\tau}$'s that have not annihilated against one another or co-annihilated with a $\widetilde{\chi}_1^0$.
- All the points yield a spin-independent direct detection cross section of order $(3.5-6) \times 10^{-8}$ pb, i.e. well within reach of next generation of direct detection experiments for indicated $\widetilde{\chi}_1^0$ masses.

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1	6.01	0.094	$\tilde\chi_1^0\tilde\chi_1^0 \to W^+W^-(31.5\%), ZZ(21.1\%)$	4.3×10^{-8}
2	5.85	0.099	$\tilde\nu_\tau\tilde\nu_\tau \to \nu_\tau\nu_\tau(11.4\%), \tilde\nu_\tau\bar{\tilde\nu}_\tau \to W^+W^-(8.8\%)$	3.8×10^{-8}
3	4.48	0.114	$\tilde\chi_1^0\tilde\chi_1^0 \to W^+W^-(23.9\%), ZZ(17.1\%)$	3.7×10^{-8}
4	6.87	0.097	$\tilde\chi_1^0\tilde\chi_1^0 \to W^+W^-(36.9\%), ZZ(23.5\%)$	4.5×10^{-8}
5	5.31	0.135	$\tilde\chi_1^0\tilde\chi_1^0 \to b\bar b(39.5\%), h_1 a_1(20.3\%)$	5.8×10^{-8}
6	4.89	0.128	$\tilde\tau_1\tilde\tau_1 \to \tau\tau(17.4\%), \tilde\chi_1^0\tilde\chi_1^0 \to W^+W^-(14.8\%)$	4.0×10^{-8}
7*	4.96	0.101	$\tilde\chi_1^0\tilde\chi_1^0 \to W^+W^-(17.7\%), ZZ(12.9\%)$	4.0×10^{-8}

- There is some variation in the primary annihilation mechanism, with $\tilde\tau_1\tilde\tau_1$ and $\tilde\chi_1^0\tilde\chi_1^0$ annihilation being the dominant channels except for Pt. #2 for which $\tilde\nu_\tau\tilde\nu_\tau$ and $\tilde\nu_\tau\bar{\tilde\nu}_\tau$ annihilations are dominant.
- In the case of dominant $\tilde\tau_1\tilde\tau_1$ annihilation, the bulk of the $\tilde\chi_1^0$'s come from those $\tilde\tau$'s that have not annihilated against one another or co-annihilated with a $\tilde\chi_1^0$.
- All the points yield a spin-independent direct detection cross section of order $(3.5-6)\times 10^{-8}$ pb, i.e. well within reach of next generation of direct detection experiments for indicated $\tilde\chi_1^0$ masses.

δa_μ and Dark Matter details

Pt. #	δa_μ	Ωh^2	Prim. Ann. Channels	σ_{SI} [pb]
1	6.01	0.094	$\widetilde{\chi}_1^0\widetilde{\chi}_1^0 \to W^+W^-(31.5\%), ZZ(21.1\%)$	4.3×10^{-8}
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- There is some variation in the primary annihilation mechanism, with $\widetilde{\tau}_1\widetilde{\tau}_1$ and $\widetilde{\chi}_1^0\widetilde{\chi}_1^0$ annihilation being the dominant channels except for Pt. #2 for which $\widetilde{\nu}_\tau\widetilde{\nu}_\tau$ and $\widetilde{\nu}_\tau\overline{\widetilde{\nu}}_\tau$ annihilations are dominant.
- In the case of dominant $\widetilde{\tau}_1\widetilde{\tau}_1$ annihilation, the bulk of the $\widetilde{\chi}_1^0$'s come from those $\widetilde{\tau}$'s that have not annihilated against one another or co-annihilated with a $\widetilde{\chi}_1^0$.
- All the points yield a spin-independent direct detection cross section of order $(3.5-6)\times 10^{-8}$ pb, i.e. well within reach of next generation of direct detection experiments for indicated $\widetilde{\chi}_1^0$ masses.

Outline

Conclusions

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Conclusions

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- $U(1)_R$ imposed NUHM allows quite perfect points with a SM-like Higgs near 125 GeV satisfying all constraints.
- Perfect and almost perfect points prefer to have relatively small A_λ, A_κ values.
- Direct detection of SUSY may have to await the 14 TeV upgrade of the LHC, but direct detection of the LSP will be possible with the next round of upgrades.

Outline

Work in Progress

- If future data confirms a $\gamma\gamma$ rate in excess of the SM prediction, then it will be necessary to go beyond the constrained versions of the NMSSM considered here.
- How to enhance the ratio R up to 1.4?
- The random scan of the full parameter space for the general NMSSM without any GUT unification is in progress.

Thank you for your attention!

Thanks to Profs. Gunion and Kraml for their patient guidance and help.

Back Up

R definition

- Higgs production @ LHC: gluon-gluon to Higgs

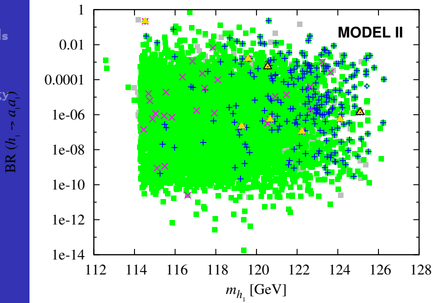
$$R^{h_i}(X) \equiv \frac{\Gamma(gg \to h_i)\ BR(h_i \to X)}{\Gamma(gg \to h_{\rm SM})\ BR(h_{\rm SM} \to X)},$$

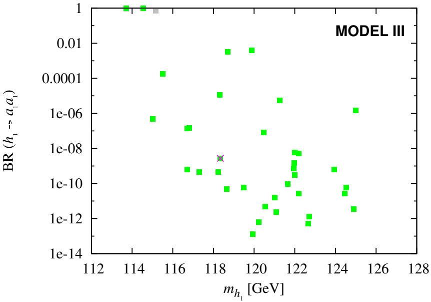
- SM denominator computation:
  1) NMHDECAY computes the reduced Higgs couplings $C_{h_i Y} \equiv g_{h_i Y}/g_{h_{\rm SM} Y}$, where $Y = gg, VV, b\bar{b}, \tau^+\tau^-, \gamma\gamma, \ldots$
  2) $\Gamma^{h_{\rm SM}}(Y) = \Gamma^{h_i}(Y)/[C_Y^{h_i}]^2 = \Gamma^{h_i}_{\rm tot} BR(h_i \to Y)/[C_Y^{h_i}]^2$
  3) $\Gamma^{h_{\rm SM}}_{\rm tot} = \sum_Y \Gamma^{h_{\rm SM}}(Y)$
  4) $BR(h_{\rm SM} \to Y) = \Gamma^{h_{\rm SM}}(Y)/\Gamma^{h_{\rm SM}}_{\rm tot}$

$$\boxed{R^{h_i}(X) = C^2_{h_1 gg} C^2_{h_1 X} \sum_Y \frac{BR(h_1 \to Y)}{C^2_{h_1 Y}}}$$

$BR(h_1 \to a_1 a_1)$ Figures (log scale)

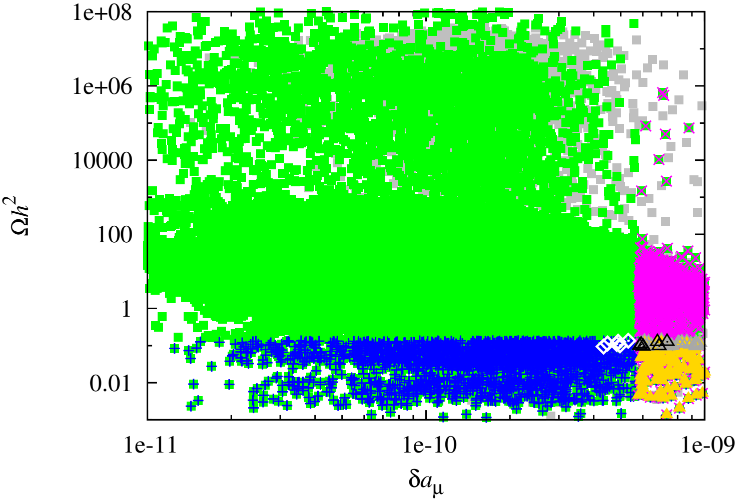
Are there any perfect or almost perfect points with measurable $h_1 \to a_1 a_1$ decays? NO! (not surprising given $R^{h_1}(\gamma\gamma) \sim 1$.)





Large BR is possible while satisfying basic and B-physics constraints. However, $BR \lesssim 0.2$ once additional constraints are imposed. Thus, a light Higgs has nowhere to hide in these models.

More Analysis (Ωh^2 vs δa_μ)



No tension between Ωh^2 and δa_μ in the NUHM-NMSSM.