Higgs at 125 GeV and the NMSSM

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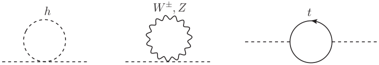
based on arXiv:1201.0982, with J.F. Gunion, S. Kraml

Outline

1. Preliminary Backgrounds: why the NMSSM?

Hierarchy Problem with the Standard Model

The Higgs mass is essentially a **free** parameter, but the Higgs boson hasn't been discovered yet ...⟶ Quantum correction to the Higgs mass



$$\underbrace{m_H^2}_{\sim\lambda v^2} = m^2_{\text{bare}} + \underbrace{\frac{1}{16\pi^2}\lambda\Lambda^2 + \frac{1}{16\pi^2}g^2\Lambda^2 - \frac{3}{8\pi^2}y_t^2\Lambda^2}_{\text{quadratically-divergent radiative correction}}$$

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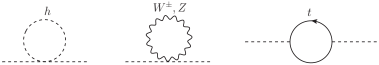

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- However, the SM is assumed to be an EFT with very heavy particles, so $\Lambda \gg v$ (i.e., $\Lambda \sim M_{\text{GUT}}, M_{\text{Pl}}$).

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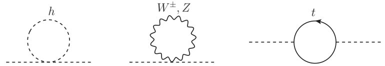

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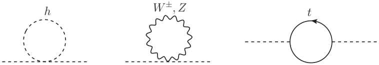

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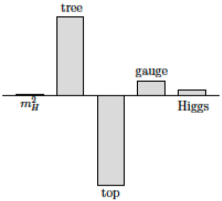
Fine-tuning

- The fine-tuning is needed for example, $\Lambda = 10$ TeV ⟶
- The fine-tuning required is much greater as Λ increases
- The fine-tuning completely disappeared at $\Lambda = 1$ TeV.



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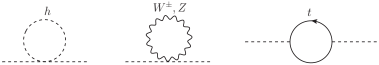

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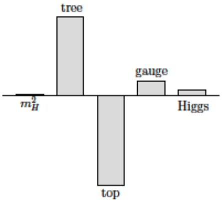

Supersymmetry and MSSM

Supersymmetry is a generalization of the space-time symmetries of quantum field theory that transforms fermions into bosons and vice versa.

- allows the unification of gauge couplings.
- solves the hierarchy problem by introducing superpartners

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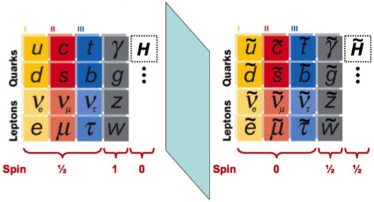
In a theory with unbroken supersymmetry, for every type of fermion there exists a corresponding type of boson with the same mass and internal quantum numbers, and vice-versa.

MSSM=SM+SM-Superpartners

fermion ⟷ sfermion

gauge boson ⟷ gaugino

Higgs ⟷ Higgsino



MSSM Higgs

- Higgs Family

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

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

$$m_A^2 = m_{H_u}^2 + m_{H_d}^2 = \frac{b}{s_\beta c_\beta}$$

$$m_{H^\pm}^2 = m_A^2 + m_W^2$$

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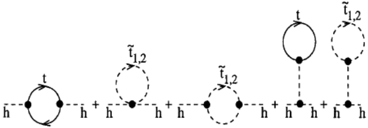
- Tree level upper bound: $m_h < |\cos 2\beta| M_Z$
  $\longrightarrow$ radiative corrections (at one-loop level)



$$m_h^2 < M_Z^2 + \underbrace{\frac{3g^2 m_t^4}{8\pi^2 M_W^2}\left[\overbrace{\ln\left(\frac{M_S^2}{m_t^2}\right)}^{\text{no squark mixing}} + \overbrace{\frac{A_t{}^2}{M_S^2}\left(1 - \frac{A_t{}^2}{12M_S^2}\right)}^{\text{with squark mixing}}\right]}_{\text{finite contributions of the order of the SUSY breaking scale}} < 130\text{ GeV}$$

where $M_S = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$

μ Problem of the MSSM

The MSSM superpotential contains the bilinear coupling $\mu H_u H_d$ of the two Higgs MSSM doublet superfields and. The b parameter arises from the soft SUSY breaking term $b H_u H_d$.

Higgs VEV Minimization 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 $\mu \sim \mathcal{O}(M_Z)$, $\surd$
- However, if SUSY derives from an underlying string theory, then

$$\mu \sim M_{\rm Pl}, M_{\rm string} \gg M_{\rm SUSY}, \quad \boxed{\text{FINE-TUNING}}$$

$\Longrightarrow$ large $m_{H_u}^2, m_{H_d}^2 \Longrightarrow$ large cancellation

$$\boxed{\mu\ \text{PROBLEM}}$$

The Scale-invariant NMSSM

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

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

The interactions are generated by the superpotential

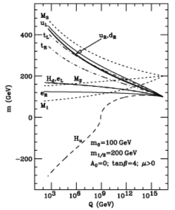
$$W_{NMSSM} = \bar{u}\mathbf{Y_u} Q H_u - \bar{d}\mathbf{Y_d} Q H_d - \bar{e}\mathbf{Y_e} L H_d + \lambda S H_u H_d + \frac{\kappa}{3} S^3$$

and the soft SUSY breaking terms are

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

$\mathbb{Z}_3$-symmetry: a multiplication of all components of chiral superfields by a phase $e^{2\pi i/3}$.

NMSSM Parameters



- GUT scale parameters (assume unification)
  1. Gaugino masses: $m_{1/2} \longrightarrow M_1, M_2, M_3$
  2. Squark masses: $m_0 \longrightarrow \mathbf{m}^2_{\tilde{Q}}, \mathbf{m}^2_{\tilde{L}}, \mathbf{m}^2_{\tilde{u}}, \mathbf{m}^2_{\tilde{d}}, \mathbf{m}^2_{\tilde{e}}$
  3. Trilinear couplings: $A_0 \longrightarrow \mathbf{A}_\mathbf{u}, \mathbf{A}_\mathbf{d}, \mathbf{A}_\mathbf{e}$

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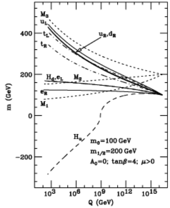

- SUSY scale parameters

$$\boxed{\begin{array}{c} \lambda, A_\lambda, A_\kappa, \kappa, m^2_S, m^2_{H_u}, m^2_{H_d} \\ v_u, v_d, s \end{array}}$$

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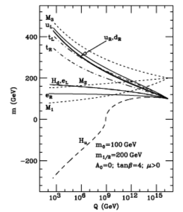

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v_u, v_d, s

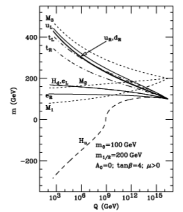
$$v_u\left(m_{H_u}^2+\mu_{\rm eff}^2+\lambda^2 v_d^2+\frac{g_1^2+g_2^2}{4}(v_u^2-v_d^2)\right)-v_d\mu_{\rm eff}(A_\lambda+\kappa s)=0$$

$$v_d\left(m_{H_d}^2+\mu_{\rm eff}^2+\lambda^2 v_u^2-\frac{g_1^2+g_2^2}{4}(v_u^2-v_d^2)\right)-v_u\mu_{\rm eff}(A_\lambda+\kappa s)=0$$

Higgs VEV Minimizations

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

NMSSM Parameters



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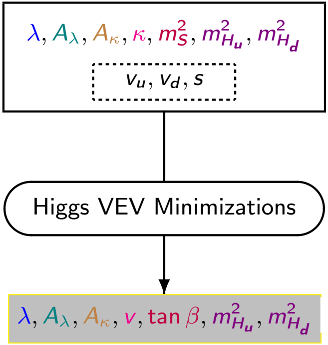

$\lambda, A_\lambda, A_\kappa, \kappa, m_S^2, m_{H_u}^2, m_{H_d}^2$

v_u, v_d, s

Higgs VEV Minimizations

$\lambda, A_\lambda, A_\kappa, v, \tan\beta, m_{H_u}^2, m_{H_d}^2$

Various choices for different scenarios

NMSSM Higgs

- $\mu_{\text{eff}} = \lambda \langle S \rangle \longrightarrow M_{\text{SUSY}}$ $\surd$
- Higgs Family

NMSSM Higgs Sector
3 CP-even neutral scalars: h_1, h_2, h_3
2 CP-odd neutral pseudoscalar: a_1, a_2
2 charged scalars: $H^{\pm}$

- The lightest CP-even Higgs mass

$$m_{h_1}^2 \simeq \overbrace{M_Z^2 \cos^2 2\beta}^{\text{tree level}} + \lambda^2 v^2 \sin^2 2\beta$$

where $m_S^2 \sim m_{Q_3}^2$

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$$\underline{m_{h_1}^2 \approx \overbrace{M_Z^2 \cos^2 2\beta}^{\text{tree level}} + \lambda^2 v^2 \sin^2 2\beta} - \frac{\lambda^2}{\kappa^2} v^2 (\lambda - \kappa \sin 2\beta)^2 + \frac{3m_t^4}{4\pi^2 v^2}\left[\ln\left(\frac{m_S^2}{m_t^2}\right) + \frac{A_t^2}{m_S^2}\left(1 - \frac{A_t^2}{12m_S^2}\right)\right]$$

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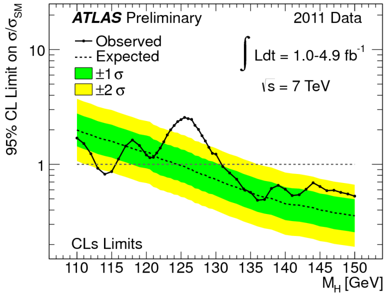
ATLAS and CMS excess around 125 GeV Higgs



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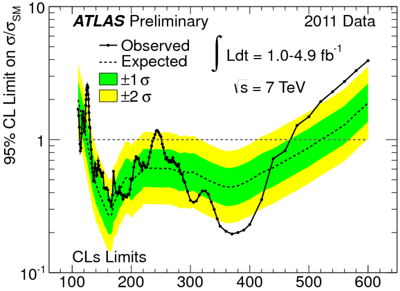
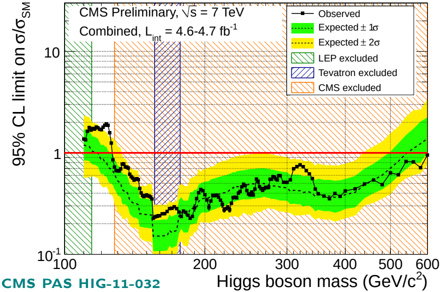
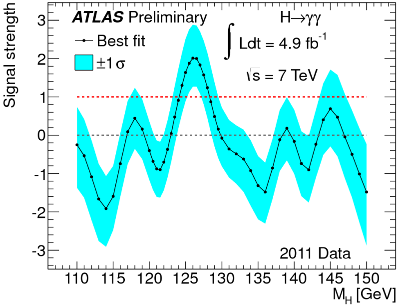




CMS PAS HIG-11-032

- 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 ($H \to \gamma\gamma$)



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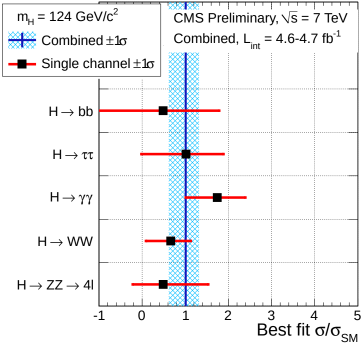


CMS PAS HIG-11-032

1.3 σ excess w.r.t. the SM

1 σ excess w.r.t. the SM

Outline

1. Preliminary Background: why the NMSSM?
2. Motivation
3. Methodology

The Constrained NMSSM Models

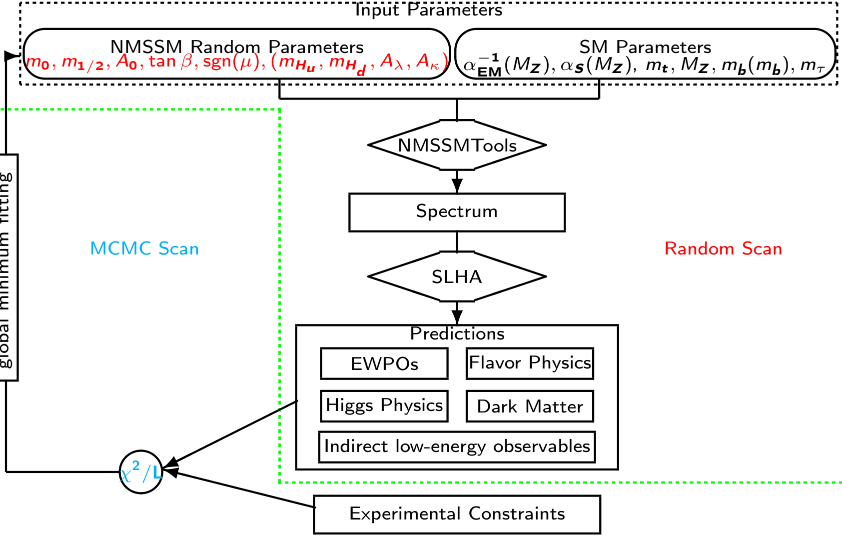
Find the most constrained version of the NMSSM consistent with a fairly SM-like Higgs at 125 GeV and implications thereof.

We have examined the following models:

1. Model I: $U(1)_R$ imposed, constrained NMSSM (cNMSSM)
   $\tan\beta,\ \lambda,\ m_0,\ m_{1/2},\ A_0 = A_{t,b,\tau},\ A_\lambda = A_\kappa = 0$
2. Model II: $U(1)_R$ imposed, NUHM
   $\tan\beta,\ \lambda,\ m_0,\ m_{1/2},\ m_{H_u},\ m_{H_d},\ A_0 = A_{t,b,\tau},\ A_\lambda = A_\kappa = 0$
3. 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.
- $U(1)_R$ symmetry is only imposed on the Higgs sector of the scale-invariant NMSSM. The R charge for the superfields H_u, H_d and S is $2/3$.

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
$\alpha^{-1}_{EM}(M_Z), \alpha_S(M_Z), m_t, M_Z, m_b(m_b), m_\tau$

NMSSMTools

Spectrum

SLHA

Predictions

EWPOs

Flavor Physics

Higgs Physics

Dark Matter

Indirect low-energy observables

Experimental Constraints

χ^2/L

global minimum fitting

MCMC Scan

Random Scan

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

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

Constraint Categories

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

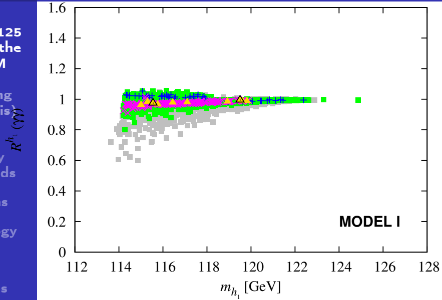
Observables	Constraints
ΔM_d	0.507 ± 0.008 (2σ)
ΔM_s	17.77 ± 0.24 (2σ)
$\mathrm{BR}(B \to X_s \gamma)$	3.55 ± 0.51 (2σ)
$\mathrm{BR}(B^+ \to \tau^+ \nu)$	$(1.67 \pm 0.78) \times 10^{-4}$ (2σ)
$\mathrm{BR}(B_s \to \mu^+ \mu^-)$	$< 1.1 \times 10^{-8}$ (95% C.L.)

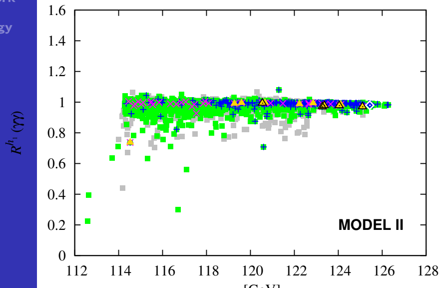
Outline

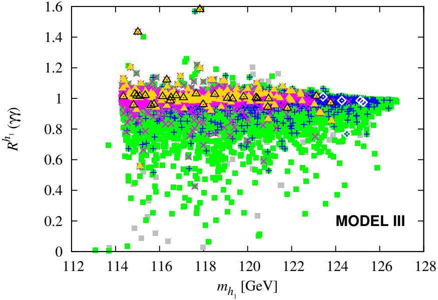
1. Preliminary Backgrounds: why the NMSSM?
2. Motivations
3. Methodology
4. Result Analysis

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

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







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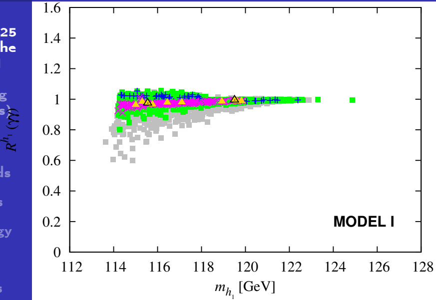
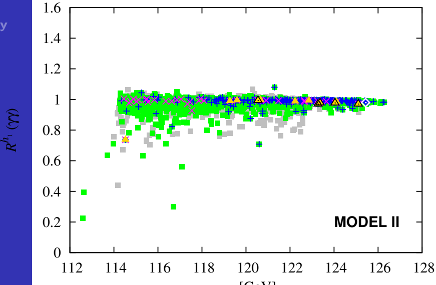
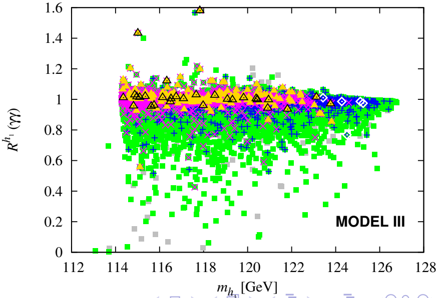


For $m_{h_1} \sim 124 - 125$ GeV,

Model I: NO perfect points





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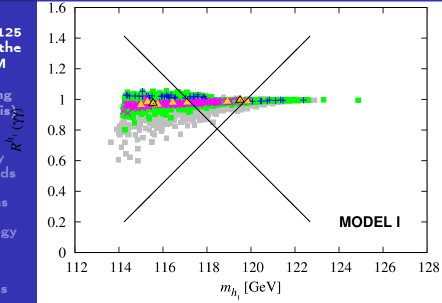
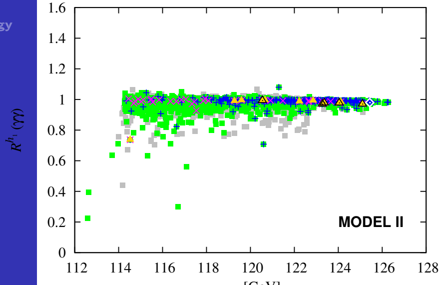
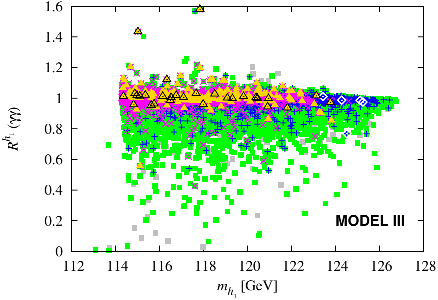


For $m_{h_1} \sim 124 - 125$ GeV,

Models II, III: have perfect points

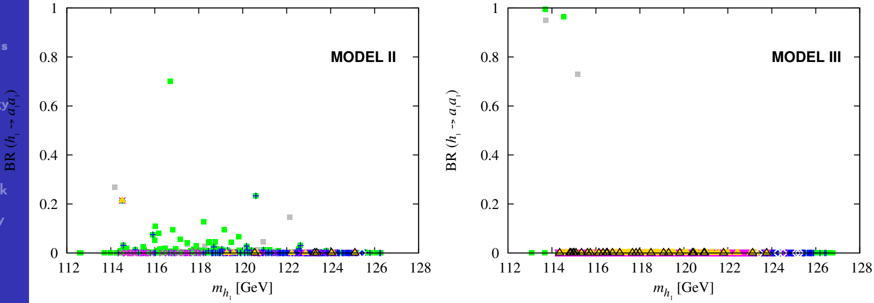
- Typically, $R^{h_1}(\gamma\gamma)$ of order 0.98.
- Almost perfect points (small δa_μ relaxation) emerge more easily.
- NO (almost) perfect points with $R^{h_1}(\gamma\gamma) > 1$ for $m_{h_1} = 123 - 128$ GeV.





$BR(h_1 \to a_1 a_1)$ Figures

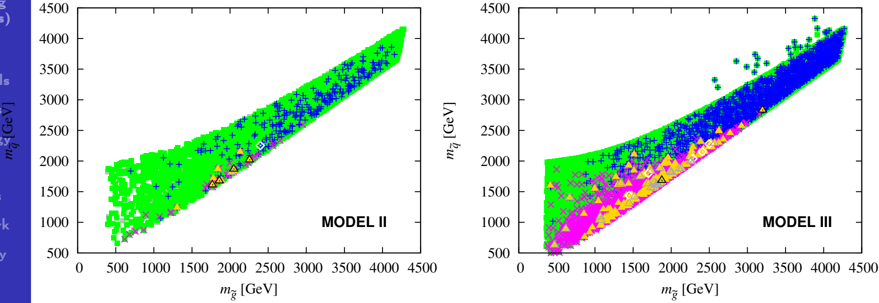
Are there any perfect or almost perfect points with measurable $h_1 \to a_1 a_1$ decays? NO! (not surprising given $R^{h_1}(\gamma\gamma) \sim 1$.)



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.

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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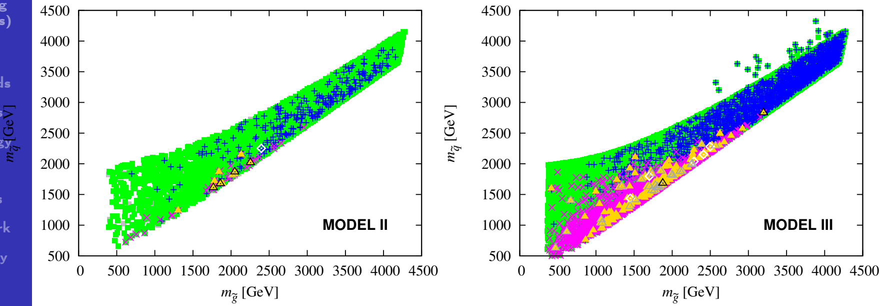

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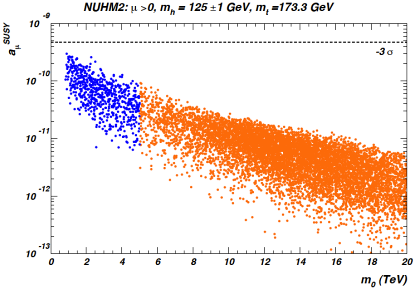
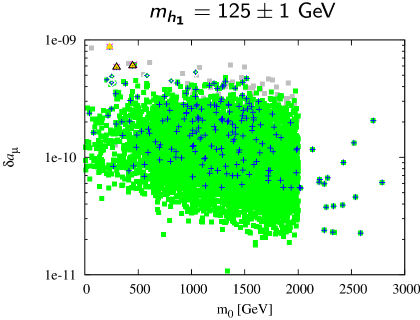
More Analysis (δa_μ vs m_0)



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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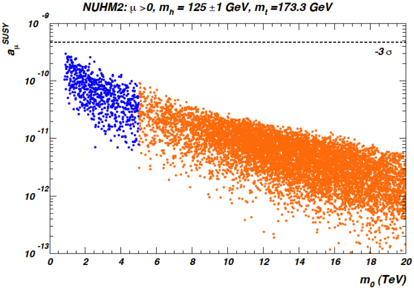

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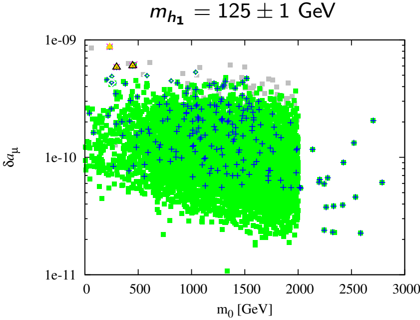

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Spectrum

	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
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$m_{\tilde{\chi}_1^\pm}$	398	446	472	364	408	471	478
$m_{\tilde{\chi}_1^0}$	363	410	438	328	307	440	452
$\delta a_\mu(\times 10^{-10})$	6.01	5.85	4.48	6.87	5.31	4.89	4.96
Ωh^2	0.094	0.099	0.114	0.097	0.135	0.128	0.101
σ_{SI} $[\times 10^{-8}\text{pb}]$	4.3	3.8	3.7	4.5	5.8	4.0	4.0

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- μ_{eff} is small for all points, $\Rightarrow$ EW fine-tuning problem may not be severe.
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- $U(1)_R$ imposed NUHM allows quite perfect points with a SM-like Higgs near 125 GeV satisfying all constraints.
- 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

Future Work

- 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.
- 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.

Thank you for your attention!

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

Terminology

The Standard Model

Type	Notation		Generation			$(SU(3)_C, SU(2)_W)_{U(1)_Y}$
Fermion*	Q_L^i	=	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}$,	$\begin{pmatrix} c_L \\ s_L \end{pmatrix}$,	$\begin{pmatrix} t_L \\ b_L \end{pmatrix}$	$(3, 2)_{\frac{1}{6}}$
	u_R^i	=	u_R,	c_R,	t_R	$(3, 1)_{\frac{2}{3}}$
	d_R^i	=	d_R,	s_R,	b_R	$(3, 1)_{-\frac{1}{3}}$
	L_L^i	=	$\begin{pmatrix} \nu_{eL} \\ e_L \end{pmatrix}$,	$\begin{pmatrix} \nu_{\mu L} \\ \mu_L \end{pmatrix}$,	$\begin{pmatrix} \nu_{\tau L} \\ \tau_L \end{pmatrix}$	$(1, 2)_{-\frac{1}{2}}$
	e_R^i	=	e_R,	ν_R,	τ_R	$(1, 1)_{-1}$
Scalar	H	=	$\begin{pmatrix} H^+ \\ H^0 \end{pmatrix}$,			$(1, 2)_{\frac{1}{2}}$
Gauge Boson	G_μ^A		$A = 1, 2, \ldots, 8$			$(8, 1)_0$
	W_μ^a		$a = 1, 2, 3$			$(1, 3)_0$
	B_μ					$(1, 1)_0$

The hypercharge Y is defined $Y = Q - T_L^3$, where T_L^3 is the third component $SU(2)$ generator. For the charge conjugate spinors, $Y = -\frac{2}{3}$ for u_R^c, $Y = \frac{1}{3}$ for d_R^c and $Y = 1$ for e_R^c.
*Moreover, all fermion spinors are 2-component Weyl spinors.

$$L_{\text{SM}} = L_{\text{gauge}} + L_{\text{fermion}} + L_{\text{Higgs}} + L_{\text{Yukawa}}$$

$$L_{\text{gauge}} = -\frac{1}{4} G_{\mu\nu}^A G^{A\mu\nu} - \frac{1}{4} W_{\mu\nu}^a W^{a\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} - \frac{g_S^2 \Theta_S}{64\pi^2} \epsilon_{\epsilon} \mu\nu\lambda\rho G^{A\mu\nu} G^{A\lambda\rho}$$

$$L_{\text{fermion}} = \bar{Q}_{L\alpha i} i\not{D} Q_L^{\alpha i} + \bar{L}_{L\alpha i} i\not{D} L_L^{\alpha i} + \bar{u}_{Ri} i\not{D} u_R^i + \bar{d}_{Ri} i\not{D} d_R^i + \bar{e}_{Ri} i\not{D} e_R^i$$

$$L_{\text{Higgs}} = (D^\mu H)^\dagger D_\mu H - V(H)$$

$$L_{\text{Yukawa}} = -(\mathrm{y_u})_i^j \bar{Q}_{La\alpha i} H_\beta^c \epsilon^{\alpha\beta} u_R^{aj} - (\mathrm{y_d})_i^j \bar{Q}_{La\alpha i} H^\alpha d_R^{aj} - (\mathrm{y_e})_i^j \bar{L}_{L\alpha i} H^\alpha e_R^j + \text{h.c.}$$

Naturalness

t'Hooft (1979)

At any energy scale μ, a physical parameter or set of parameters $\alpha_i(\mu)$ is allowed to be very small only if the replacement $\alpha_i(\mu) = 0$ would increase the symmetry of the system.

Difficulties with the naturalness occur only in theories with scalar fields, Higgs fields in the SM.

- If $\Lambda \sim v$, m_H^2 is not small (compared to the energy scale Λ).
- If $\Lambda \gg v$, m_H^2 is small so that we could set $m_H \rightarrow 0$. However. it does not increase the symmetry due to the presence of the quartic Higgs self-interaction $\lambda\phi^4$ and gauge interaction as well. This is what is called unnatural.

Superpotential

$$W = E^j\phi_j + \frac{1}{2}M^{jk}\phi_i\phi_k + \frac{1}{6}y^{jkn}\phi_j\phi_k\phi_n$$

- $W^j = \frac{\partial W}{\partial \phi_{\boldsymbol{j}}}$.
- $W^{jk} = \frac{\partial^2 W}{\partial \phi_{\boldsymbol{j}} \partial \phi_{\boldsymbol{k}}}$ is analytic (holomorphic) in the complex fields ϕ_n.
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MSSM Lagrangian

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

The interactions are generated by the superpotential

$$W_{MSSM} = \bar{u}\mathbf{Y_u}QH_u - \bar{d}\mathbf{Y_d}QH_d - \bar{e}\mathbf{Y_e}LH_d + \mu H_u H_d$$

and the soft-SUSY breaking terms are

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

Procedure for generating the full Lagrangian

1. Expanding the superfield $\Phi = \phi + \sqrt{2}\theta\psi + \theta^2\mathcal{F}$.
2. Applying $\int d^4x d^2\theta W(\Phi) + \text{h.c.} = \int d^4x \mathcal{L}_{\text{int}}$ to generate $\mathcal{L}_{\text{int}}$.
3. Adding $\mathcal{F}_i\mathcal{F}_i^*$ for each superfield to get full $\mathcal{F}$-part Lagrangian.
4. Eliminating $\mathcal{F}$ by virtue of the equation of motion.
5. Obtaining the Higgs mass term, cubic and quartic scalar interactions among squarks, sleptons and Higgs.

MSSM Higgs Sector

$$V_{\text{Higgs}} = (\mu^2 + m^2_{H_u})\left(|H_u^+|^2 + |H_u^0|^2\right) + (\mu^2 + m^2_{H_d})\left(|H_d^-|^2 + |H_d^0|^2\right) + \left[b\left(H_u^+ H_d^- - H_u^0 H_d^0\right) + h.c.\right]$$

$$+ \frac{g^2}{2}|H_u^+ H_d^{0*} + H_u^0 H_d^{-*}|^2 + \frac{g^2 + g'^2}{8}\left(|H_u^+|^2 + |H_u^0|^2 - |H_d^0|^2 - |H_d^-|^2\right)^2$$

Expanding the Higgs fields around the VEVs

$$H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix} \longrightarrow \begin{pmatrix} 0 \\ v_u/\sqrt{2} \end{pmatrix} + \begin{pmatrix} H_u^+ \\ \text{Re}H_u^0 + i\text{Im}H_u^0 \end{pmatrix}$$

$$H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix} \longrightarrow \begin{pmatrix} v_u/\sqrt{2} \\ 0 \end{pmatrix} + \begin{pmatrix} \text{Re}H_d^0 + i\text{Im}H_d^0 \\ H_d^- \end{pmatrix}$$

Higge mass eigenstates

$$\begin{pmatrix} \text{Re}H_u^0 \\ \text{Re}H_d^0 \end{pmatrix} \xrightarrow{\alpha} \begin{pmatrix} h \\ H \end{pmatrix}, \qquad \begin{pmatrix} \text{Im}H_u^0 \\ \text{Im}H_d^0 \end{pmatrix} \xrightarrow{\beta} \begin{pmatrix} \text{N.G.B} \\ A \end{pmatrix}, \qquad \begin{pmatrix} H_u^+ \\ H_d^{-*} = H_d^+ \end{pmatrix} \xrightarrow{\beta} \begin{pmatrix} \text{N.G.B} \\ H^+ \end{pmatrix}.$$

Upper Bound for m_h

Proof.

The function of m_h^2 increases monotonously with m_A^2.

$$\begin{aligned} m_h^2 &= \frac{1}{2}\left(m_A^2 + M_Z^2 - \sqrt{m_A^4 + 2m_A^2M_Z^2 + M_Z^4 - 4M_Z^2m_A^2\cos^2 2\beta}\right) \\ &= \frac{1}{2}\left(m_A^2 + M_Z^2 - m_A^2\sqrt{1 + \frac{2M_Z^2(1-2\cos^2 2\beta)}{m_A^2} + \left(\frac{M_Z}{m_A}\right)^4}\right) \\ &= \frac{1}{2}m_A^2\left(1 + \frac{M_Z^2}{m_A^2} - \sqrt{1 + \frac{2M_Z^2(1-2\cos^2 2\beta)}{m_A^2} + \left(\frac{M_Z}{m_A}\right)^4}\right) \end{aligned}$$

At the limit $m_A = \infty$, we use $(1+x)^{1/2} = 1 + \frac{1}{2}x + \mathcal{O}(x)$ to expand the square root

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

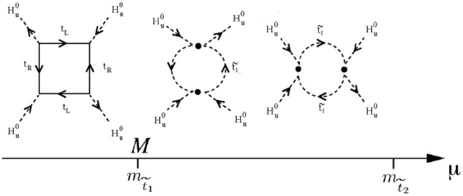
Dropping the second term, we obtain the upper bound on m_h

$$m_h \leq |\cos 2\beta| M_Z$$

$\square$

m_h Radiative Corrections

1. direct diagrammatic calculations
2. renormalization group methods



- in the absence of $\tilde{t}_L - \tilde{t}_R$ mixing, only the diagrams below the SUSY scale contributes to the β function for the quartic coupling: $(4\pi)^2\beta_\lambda = -4N_c|y_t|^4$. This leads to a shift in the physical Higgs mass squared of

$$\Delta h^2 = 2\delta\lambda v_u^2 = 2v_u^2 \int_{m_t}^{m_{\tilde{t}}} \beta_\lambda \, d\ln\mu$$

- in the presence of $\tilde{t}_L - \tilde{t}_R$ mixing, only the left diagram contributes to β_λ running from m_t to $m_{\tilde{t}_1}$ and all diagrams contributes to β_λ running from $m_{\tilde{t}_1}$ to $m_{\tilde{t}_2}$.

3. effective potential techniques

MSSM Higgs Minimization Conditions

$$V_{\text{Higgs}} = (\mu^2 + m^2_{H_u})\left(|H_u^+|^2 + |H_u^0|^2\right) + (\mu^2 + m^2_{H_d})\left(|H_d^-|^2 + |H_d^0|^2\right) + \left[b\left(H_u^+ H_d^- - H_u^0 H_d^0\right) + h.c.\right]$$
$$+ \frac{g^2}{2}|H_u^+ H_d^{0*} + H_u^0 H_d^{-*}|^2 + \frac{g^2 + g'^2}{8}\left(|H_u^+|^2 + |H_u^0|^2 - |H_d^0|^2 - |H_d^-|^2\right)^2$$

from D-term potential $V_D = \frac{1}{2}(D^a D^a + D' D')$ with

$$D^a|_{\text{Higgs}} = -g\left[(H_u^*)^{\alpha}(\tau^a)_{\alpha}^{\beta}(H_u)_{\beta} + (H_d^*)^{\alpha}(\tau^a)_{\alpha}^{\beta}(H_d)_{\beta}\right],$$
$$D'|_{\text{Higgs}} = -\frac{g'}{2}\left(|H_u^+|^2 + |H_u^0|^2 - |H_d^0|^2 - |H_d^-|^2\right)$$

- Only electrically neutral components of the Higgs acquire VEV. ($\langle H_u^+\rangle = 0 \Longrightarrow \langle H_d^-\rangle = 0$)
- For the purpose of finding the minimum potential, we can simply take b, H_u^0 and H_d^0 in the neutral potential to be real and simplify the b-term.

Proof.

Absorb the phase b into the phase of the fields, for example, taking $b = |b|e^{i\theta}$ and redefine the Higgs fields $H_u^0 \to H_u^{0'} = e^{i\alpha}H_u^0$, $H_d^0 \to H_d^{0'} = e^{i\beta}H_d^0$ with $\alpha + \beta = \theta$.

In order to occur a stable minimum of V at non-zero VEV of H_u^0 and H_d^0, we require

$$\left.\frac{\partial V}{\partial H_u^{0'}}\right|_{\text{VEV}} = \left[(|\mu|^2 + m^2_{H_u}) + \frac{1}{4}(g^2 + g'^2)(|\langle H_u^{0'}\rangle|^2 - |\langle H_d^{0'}\rangle|^2)\right]\langle H_u^{0'*}\rangle - |b|\langle H_d^{0'}\rangle = 0$$

Since the coefficients of VEV $\langle H_u^{0'*}\rangle$ and $\langle H_d^{0'}\rangle$ are real and do not have any phase, so the VEV $\langle H_u^{0'*}\rangle$ and $\langle H_d^{0'}\rangle$ have the same phase, or equivalently, the VEV $\langle H_u^{0'}\rangle$ and $\langle H_d^{0'}\rangle$ must have equal and opposite phase so that $H_u^{0'} H_d^{0'}$ in the b-term is real. Thus,

$$V(H_u^0, H_d^0) = (|\mu|^2 + m^2_{H_u})(H_u^0)^2 + (|\mu|^2 + m^2_{H_d})(H_d^0)^2 - 2bH_u^0 H_d^0 + \frac{1}{8}(g^2 + g'^2)[(H_u^0)^2 - (H_d^0)^2]^2 \quad \square$$

What is "Soft"?

- In general, the terminology “soft” in particle physics refers to “low energy” or “low frequency” while “hard” refers to “high energy” or “high frequency”.
- In SUSY theory “soft” means the modification of physics at high energies is so small.
- **Soft SUSY breaking** is type of supersymmetry breaking that does not cause ultraviolet divergences to appear in scalar masses such as the Higgs. However, it obviously allows - and does cause - finite loop corrections to the Higgs mass.

NMSSM Higgs sector

$$D^a|_{\text{Higgs}} = -g\left[(H_u^*)^\alpha(\tau^a)_\alpha^\beta(H_u)_\beta + (H_d^*)^\alpha(\tau^a)_\alpha^\beta(H_d)_\beta + |S|^2\right],$$

$$D'|_{\text{Higgs}} = -\frac{g'}{2}\left(|H_u^+|^2 + |H_u^0|^2 - |H_d^0|^2 - |H_d^-|^2\right)$$

$$\begin{aligned}V = {} & (|\mu+\lambda S|^2 + m_{H_u}^2)\left(|H_u^+|^2 + |H_u^0|^2\right) + (|\mu+\lambda S|^2 + m_{H_d}^2)\left(|H_d^-|^2 + |H_d^0|^2\right) \\ & + \frac{g^2}{2}|H_u^+ H_d^{0*} + H_u^0 H_d^{-*}|^2 + \frac{g^2+g'^2}{8}\left(|H_u^+|^2 + |H_u^0|^2 - |H_d^0|^2 - |H_d^-|^2\right)^2 \\ & + m_S^2|S|^2 + \left|\kappa S^2 + \lambda\left(H_u^+H_d^- - H_u^0H_d^0\right)\right|^2 + \left[(b+\lambda A_\lambda S)\left(H_u^+H_d^- - H_u^0H_d^0\right) + \frac{1}{3}\kappa A_\kappa S^3 + h.c.\right]\end{aligned}$$

Expanding the Higgs fields around the VEVs

$$H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix} \longrightarrow \begin{pmatrix} 0 \\ v_u/\sqrt{2} \end{pmatrix} + \begin{pmatrix} H_u^+ \\ \text{Re}H_u^0 + i\text{Im}H_u^0 \end{pmatrix}$$

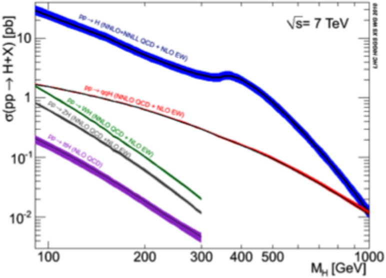
$$H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix} \longrightarrow \begin{pmatrix} v_u/\sqrt{2} \\ 0 \end{pmatrix} + \begin{pmatrix} \text{Re}H_d^0 + i\text{Im}H_d^0 \\ H_d^- \end{pmatrix}$$

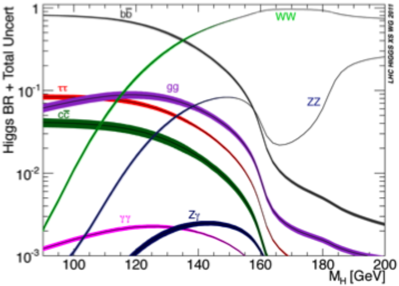
$$S \longrightarrow v_u/\sqrt{2} + \text{Re}S + i\text{Im}S$$

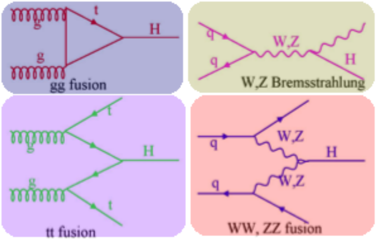
Higge mass eigenstates

$$\begin{pmatrix} \text{Re}H_d^0 \\ \text{Re}H_u^0 \\ \text{Re}S \end{pmatrix} \xrightarrow{\alpha} \begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix}, \qquad \begin{pmatrix} \text{Im}H_d^0 \\ \text{Im}H_u^0 \\ \text{Im}S \end{pmatrix} \xrightarrow{\beta} \begin{pmatrix} a_1 \\ \text{N.G.B} \\ a_2 \end{pmatrix}, \qquad \begin{pmatrix} H_u^+ \\ H_d^{-*} = H_d^+ \end{pmatrix} \xrightarrow{\beta} \begin{pmatrix} \text{N.G.B} \\ H^+ \end{pmatrix}.$$

Higgs Production and Decay Overview





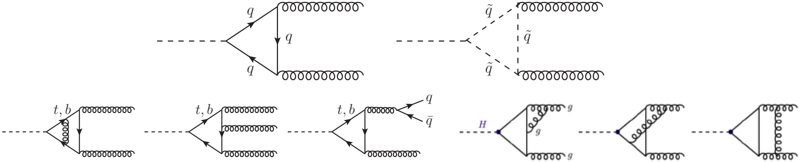


- gluon-gluon production mechanism is dominant at LHC.
- $\gamma\gamma$ channel is of our interest in this talk.

Loop-induced h_1 Decays

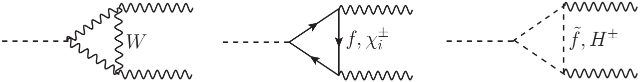
Djouadi, Phys.. Rep. 459(2008)1

☐ **Decays into two gluons** $\Gamma(H \to gg) = \frac{G_F \alpha_S^2 m_H^3}{36\sqrt{2}\pi^3}\left|\sum_q g_{h_1 qq} A_{1/2}^{h_1}(\tau_q) + \frac{3}{4}\mathcal{A}_{\mathrm{SUSY}}^{h_1}\right|$



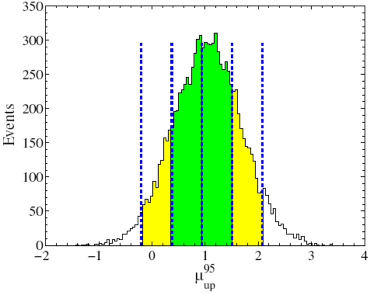
☐ **Decay into two photons**

$$\Gamma(H \to \gamma\gamma) = \frac{G_F \alpha^2 m_H^3}{128\sqrt{2}\pi^3}\left|\sum_f N_c Q_f^2 g_{h_1 ff} A_{1/2}^{h_1}(\tau_f) + g_{h_1 VV} A_{1/2}^{h_1}(\tau_W) + \frac{M_W^2 \lambda_{h_1 H^+ H^-}}{2 c_W^2 M_{H^\pm}^2} A_0^{h_1}(\tau_{H^\pm}) + \mathcal{A}_{\mathrm{SUSY}}^{h_1}\right|$$



How to Read Higgs Exclusion Plots

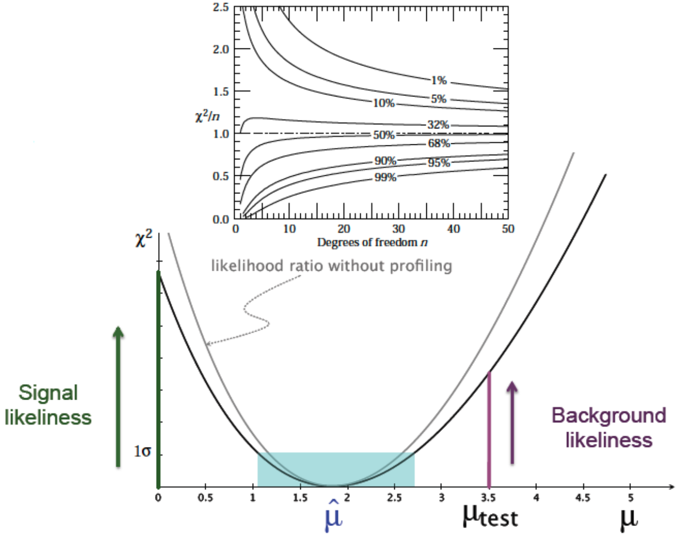
- $\pm 1\sigma$ (green) and $\pm 2\sigma$ (yellow) bands from Monte Carlo



- 95% CL upper limit

$$\alpha = e^{-s_{\text{up}}} \frac{\sum_{m=0}^{n} (s_{\text{up}} + b)^m / m!}{\sum_{m=0}^{n} b^m / m!} = 1 - 95\%$$

How to Construct the Best-fit Plot



RGE solution & Landau pole

- In theories that are not asymptotically free, the coupling grows when it is run up higher energies. The Landau pole is the momentum (or energy) scale at which the coupling becomes infinite.
- In general, any parameter with the mass dimension goes either up or down in scale. The running is governed by the renormalization group equation (RGE). Proper RGE solution means there is no divergence appearing along with the running integration.

LSP and *R* Parity

- LSP means the lightest supersymmetric particle. It is electrically neutral and colorless. For most typical choices of model parameters, the lightest neutralino is the LSP.

- The supersymmetric particles must be produced in pairs and they are unstable and decay quickly into lighter states—LSP.

- LSP is absolutely stable if *R*-parity is conserved.

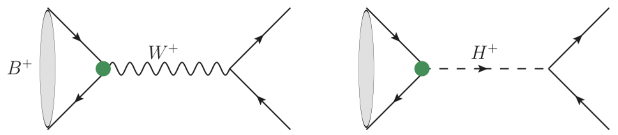
R parity

- $R = (-1)^{3(B-L)+2S}$ for a particle of spin S.
- All the ordinary Standard Model particles have even R parity and superpartners have odd R parity.
- If R parity was conserved, starting from an initial state involving ordinary particles, it follows that superpartners must be produced in pairs and the LSP is absolutely stable.

B-Meson Leptonic Decay

$B^+(u\bar{b}) \longrightarrow \tau^+\nu_\tau$

Phys. Rev. D 48(1993)2342; J. Phys. G 29(2003)2311

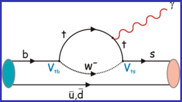


$$BR(B^+ \to \tau^+\nu_\tau) = \overbrace{\frac{G_F^2}{8\pi} f_B^2 |V_{ub}|^2 m_B m_\tau^2 \left(1 - \frac{m_\tau^2}{m_B^2}\right)^2}^{\Gamma_{SM}(B^+\to\tau^+\nu_\tau)} \left(1 - \tan^2\beta \frac{m_{B^+}^2}{m_{H^+}^2}\right)^2 \tau_B$$

for pion decay, see Griffith, Introduction to Elementary Particles, p322

- f_B: B meson decay constant
- V_{ub}: CKM mixing suppressed
- m_τ^2: helicity suppression
- $\frac{\tan^2\beta}{m_{H^+}^2}$: tree-level sensitivity to $H^\pm$, so provide important constraints on this ratio

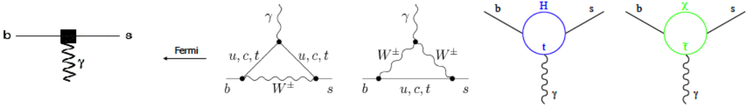
B-Meson Radiative Decay



$\bar{B}^0(d\bar{b}) \longrightarrow X_s\gamma$ Nucl. Phys. B 611(2001)338; hep-ph/0212360; Phys. Rev. Lett. 98(2007)022002

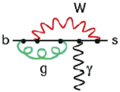
$b \to s\gamma$ decay proceed via flavor changing neutral current (FCNC) penguin diagrams

- forbidden in the SM at tree level.
- sensitive to the contributions of heavy particles in loop diagrams.



Technique: Operator product expansion

$$\mathcal{L}_{\text{eff}} \sim V_{td}^* V_{ts} \sum_{i=1}^{10} C_i \hat{\mathcal{O}}_i$$



C_i: Wilson coefficients — encode the hard-gluon exchange

$\hat{\mathcal{O}}_{1-6}$: 4-quark; $\hat{\mathcal{O}}_7$: EM dipole; $\hat{\mathcal{O}}_8$: gluonic dipole; $\hat{\mathcal{O}}_{10}$: axial-vector EW

$$\boxed{\Gamma(b \to s\gamma) = \frac{G_F^2 \alpha_{\text{em}}}{32\pi^4} m_b^5 |V_{td}^* V_{ts}|^2 \left(|C_7^{\text{eff}}|^2 + \frac{\alpha_s}{m_b}\text{corrections} + + \frac{1}{m_b^2}\text{corrections} \right)}$$

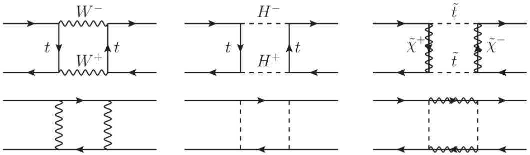
$B_i^0 - \bar{B}_i^0\,(i = s, d)$ Mixing

Langacker, The Standard Model and Beyond, p391
Griffith, Introduction to Elementary Particles, p146
Nucl. Phys. B 659(2003)3

- Strong interaction eigenstates $B_d^0(d\bar{b})$, $B_s^0(s\bar{b})$
  $CP|B^0_{d,s}\rangle = -|\bar{B}^0_{d,s}\rangle$, B's are neutral peudoscalars
- CP eigenstates
  $|B_{H_i}\rangle = p_i|B_i^0\rangle + q_i|\bar{B}_i^0\rangle$, $|B_{L_i}\rangle = p_i|B_i^0\rangle - q_i|\bar{B}_i^0\rangle$ with $\frac{q_i}{p_i} \neq 1$

$$\boxed{\Delta M_i \equiv m_{H_i} - m_{L_i} = 2|\mathcal{M}_{B_i\bar{B}_i}| = \frac{G_F^2 M_W^2}{6\pi^2}\eta_B m_{B_i^0}|V_{ti}^* V_{tb}|^2 \hat{B}_{B_i} f_{B_i}^2 F_{tt}^S}$$

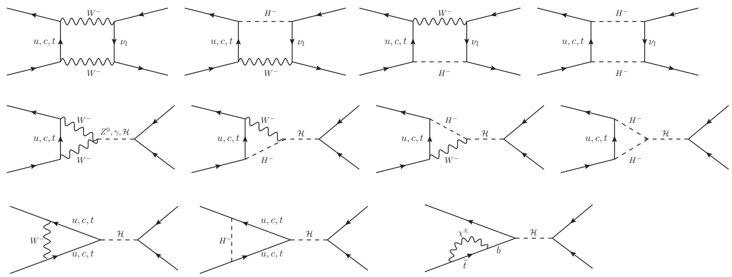
- $\eta_B = 0.55$: short distance QCD correction
- $V_{ti}^* V_{tb}$: top quark mixing dominant
- $\hat{B}_{B_i}$: scale-invariant departure from the vacuum saturation with $B_{B_i} = \dfrac{\langle B_i^0|\mathcal{L}_{\text{eff}}^{|\Delta B|=2}|\bar{B^0}_i\rangle}{\langle B_i^0|\mathcal{L}_{\text{eff}}^{|\Delta B|=2}|\bar{B^0}_i\rangle\text{vac}}$
- f_{B_i}: decay constant
- $F_{tt}^S = (S_0(m_t/M_W) +$ charged Higgs and chargino box-diagrams $+$ double penguin diagrams$)$



Rare B_s Decay

$B_s^0(s\bar{b}) \to \mu^+\mu^-$

Phys. Rev. D64(2001)074014



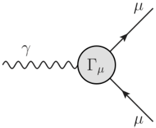
$$BR(B_s^0 \to \mu^+\mu^-) = \frac{G_F^2 \alpha^2 M_{B_s} f_{B_s}^2 \tau_{B_s}}{16\pi^3 \sin^4 \theta_W} |V_{tb} V_{ts}^*|^2 \sqrt{1 - \frac{4m_\mu^2}{M_{B_s}^2}} \left\{ \left(1 - \frac{4m_\mu^2}{M_{B_s}^2}\right) |F_S|^2 + |F_P + 2m_\mu F_A|^2 \right\}$$

where F_S, F_P and F_A are scalar, pseudoscalar and axial vector form factors associated with the Wilson coefficients.

Nucl. Phys. B630(2002)87

Muon Anomalous Magnetic Dipole Moment

Classical: the dipole moments can arise from either electrical charges or currents.
$\vec{\mu} = g \frac{\mu_B}{\hbar} \vec{S}$, $\mu_B = \frac{e\hbar}{2m_e}$ (circulating current)
$V = -\vec{\mu} \cdot \vec{B}$
QFT: our interest is the motion of a lepton in an external electromagnetic field under consideration of the full relativistic quantum behavior.



$$= -ie\bar{u}(p')\Gamma_\mu u(p) A^{cl}_\mu = i\mathcal{M}$$

Expanding the vertex Γ_μ in terms of the linear combination of γ_μ, $(p-p')_\mu$ and $(p+p')_\mu$, taking $A^\mu_{cl}(x) = (0, \vec{A}_{cl}(\vec{x}))$and using the Gordon identity,

$$i\mathcal{M} = ie\tilde{A}^i_{cl}(\vec{q})\bar{u}(p')\left[\gamma^i F_1(q^2) + \frac{i\sigma^{i\nu}q_\nu}{2m} F_2(q^2)\right] u(p)$$

In the classical limit ($q^2 \to 0$),

$$i\mathcal{M} = ie\xi'\left(-i\epsilon^{ijk} q^i \tilde{A}^j_{cl}(\vec{q})\sigma^k [F_1(0) + F_2(0)]\right)\xi = ie\xi' \tilde{B}^k(\vec{q})\sigma^k [F_1(0) + F_2(0)]\xi$$

with the identification $i\mathcal{M} = -i2m\tilde{V}(\vec{q})$, we obtain the Lande factor

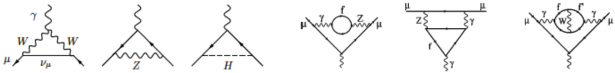
$$g = 2[F_1(0) + F_2(0)] = 2 + 2F_2(0) \text{ or } \boxed{a \equiv \frac{1}{2}(g-2) = F_2(0)}$$

where $F_1(0) = 1$ defining the electric charge and $F_2(0)$ is contributed from the loop calculations.

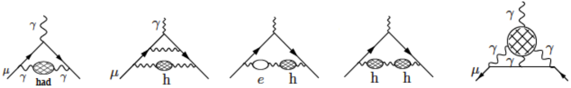
Muon Anomalous Magnetic Dipole Moment (Diagrams)

- **SM QED (up to 6-loop)** Acta Phys. Polo B 38(2007)3021; NPB 699(2004)103

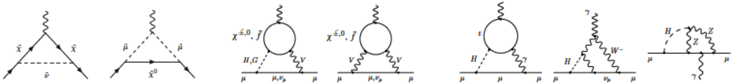
- **SM Electroweak (up to 3-loop)**
  Acta Phys. Polo B 38(2007)3021; PRD 67(2003)073006; PRD 58(1998)053007



- **SM Hadron (up to 2-loop)** Acta Phys. Polo B 38(2007)3021



- **SUSY contribution (up to 2-loop)**
  Acta Phys. Polo B 38(2007)3021; PRD 64(2001)111301, 64(2001)035003, 65(2002)075002; NPB 699(2004)103; J. Phys. G: Nucl. Part. Phys. 34(2007)R45



Relic Density

Binétruy, Supersymmetry: Theory, Experiment, and Cosmology

$$\Omega_\chi \equiv \frac{\rho_\chi}{\rho_c} = 40\sqrt{\frac{\pi}{5}}\frac{m_\chi}{H_0^2}\frac{s_0}{k^2 T_f}\frac{\hbar^3}{M_{\rm Pl}^3\langle\sigma_{\rm ann} v\rangle}\frac{g_*^{1/2}}{g_s}$$

$\rho_\chi = m_\chi n_\chi(T_0)$: present CDM energy density
$\rho_c = 3H_0^2 M_{\rm Pl}^2$: critical density
s_0: present entropy density of the Universe

The larger the annihilation cross-section, the smaller the relic density.

Proof.

Freezing temperature T_f at $\underbrace{H(T_f)}_{\text{expansion rate}} \sim \underbrace{n_\chi(T_f)\langle\sigma_{\rm ann} v\rangle}_{\text{annihilation rate}}$

- cold relic (nonrelativistic at T_f: $kT_f \ll m$): $n(T_f) = g\left(\frac{mkT_f}{2\pi\hbar^2}\right) exp[-m/(kT_f)]$
- radiation dominant: $H(T_f) = \frac{2\pi}{3\hbar}\sqrt{\frac{\pi}{5}}g_*^{1/2}\frac{(kT_f)^2}{M_{\rm Pl}}$

combining them to find T_f. On the other hand, for $T_0 < T_f$, $\frac{n_\chi(T_0)}{T_0^3} \sim \frac{n_\chi(T_f)}{T_f^3}$, so that

$$\rho_\chi(T_0) = m_\chi\left(\frac{kT_0}{kT_f}\right)^3\frac{H(T_f)}{\langle\sigma_{\rm ann} v\rangle}$$

The last step is to express $(kT_0)^3$ in terms of s_0 and g_s with

$$s_0 = \frac{2}{3}g_s\sigma T^3, \ \sigma \text{ is black body constant}$$

$$g_s = \sum_{\rm boson} g_i\left(\frac{T_i}{T_0}\right)^3 + \frac{7}{8}\sum_{\rm fermion} g_i\left(\frac{T_i}{T_0}\right)^3, \quad g_* = \sum_{\rm boson} g_i\left(\frac{T_i}{T_0}\right)^4 + \frac{7}{8}\sum_{\rm fermion} g_i\left(\frac{T_i}{T_0}\right)^4$$

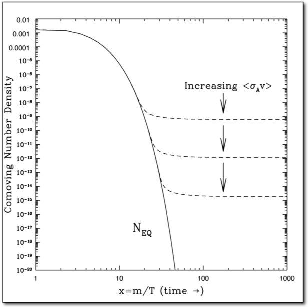
□

LSP Annihilation

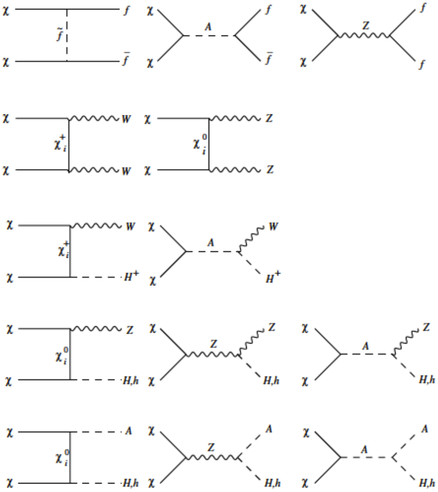
Binétruy, *Supersymmetry: Theory, Experiment, and Cosmology*

- Assumption: LSP is the lightest neutralino χ_1^0.
- χ_1^0 is not at rest at the time of freezing.

$$\langle \sigma_{\text{ann}} v\rangle = \underbrace{a}_{\chi\ \textbf{decay}} + \underbrace{b\langle v^2\rangle}_{\chi\chi\ \textbf{scattering}} + \cdots$$



Dodelson, *Modern Cosmology, p78*



Cosmological Data Measurement

Friedmann equation

$$\frac{k}{R_0^2} = H_0^2\,(\Omega_{\text{tot}} - 1)$$

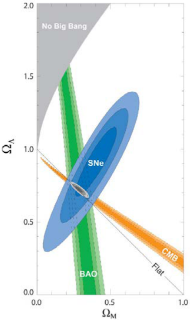
The subscript 0 indicates the present-day value. The total cosmological density Ω_{tot} has several contributions:

- $\Omega_{\mathbf{m}}$: **pressureless matter density of the Universe**
- $\Omega_{\mathbf{r}}$: **CMB radiation density of the Universe (very small $T = 2.73K$)**
- $\Omega_{\Lambda} = \Lambda/3H^2$: **cosmological constant term**

CMB: Cosmic Microwave Background
BAO: Baryonic Acoustic Oscillation
SNe: (Type Ia) Supernova

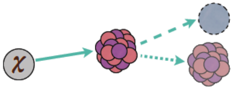
$\Omega_{\Lambda} = 0.74 \pm 0.03,\ \Omega_{\mathbf{m}} = 0.27 \pm 0.03$

$\Omega_{\text{tot}} = 1.006 \pm 0.006$ **slightly closed Universe**

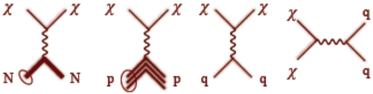


$$\Omega_{\mathbf{m}} \begin{cases} \Omega_{\mathbf{b}} & : \textbf{baryonic matter density, measured by Big Bang nucleosynthesis (BBN)} \\ \Omega_{\mathbf{CDM}} & : \textbf{cold dark matter density} \end{cases}$$

WIMP-nucleus Interaction



- Elastic scattering of the neutralino off a nucleus can occur via spin-dependent/independent channels.
- How does a weakly interacting massive particle (WIMP) interact with a nucleus?



Spin-independent Scattering

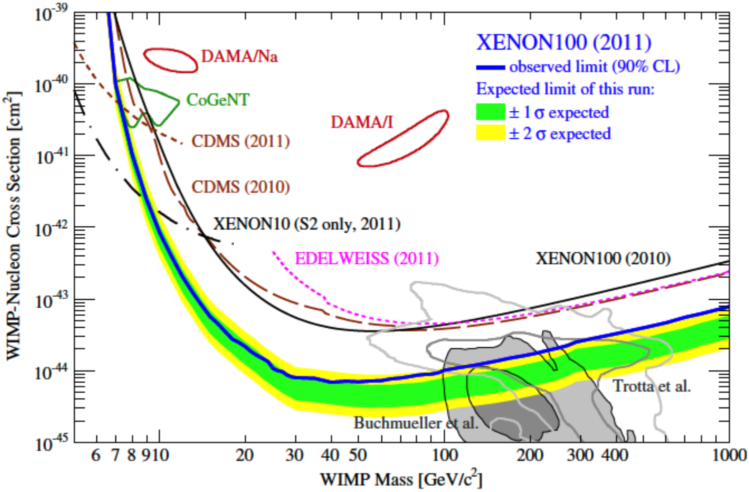
- The scattering amplitudes from individual nucleons interfere.
- For zero momentum transfer collisions (extremely soft bumps) they add coherently:

$$\sigma_{\mathrm{SI}} \simeq \frac{4m_r^2}{\pi} f A^2$$

where $m_r = \frac{m_\chi m_N}{m_\chi + m_N}$ is the reduced mass, f is coupling constant and A is the atomic mass.

DM Direct Detection

Phys. Rev. Lett 107(2011)131302



$$1\text{pb} = 10^{-36}\text{cm}^2$$

Back Up

Model Parameter Counting

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

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

Literature Survey

- 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.

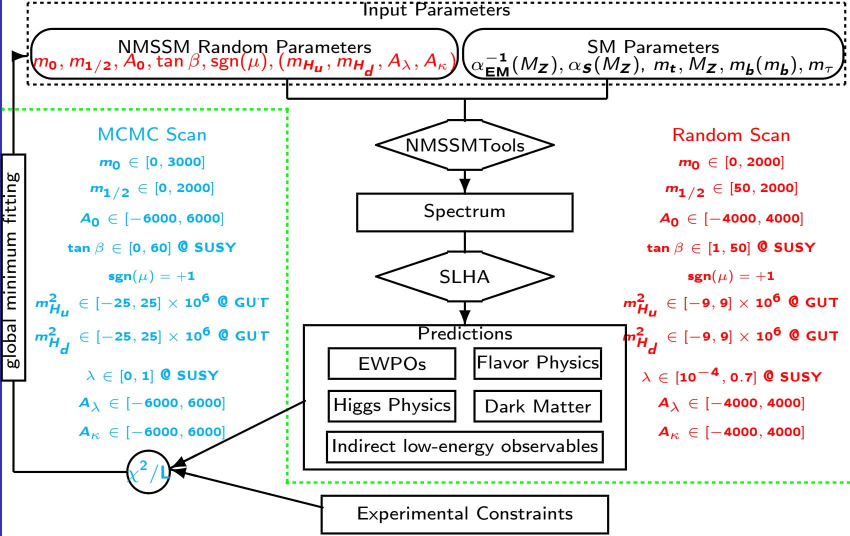
  arXiv:1112.3017; 1112.3021; 1112.3026; 1112.3032; 1112.3068; 1112.3123; 1112.3142; 1112.3336; 1112.3564; 1112.3645; 1112.3647; 1112.4391; 1112.4835; 1112.5666; PLB 708(2012)162

- The NMSSM has also been explored showing that for completely general parameters there is less tension between a light Higgs with mass $\sim$ 125 GeV and a lighter SUSY mass spectrum.

  arXiv:1112.2703; 1112.3548; 1201.2671; 1201.5305

- However, none of these studies were done for a constrained version of the NMSSM.

Scan Parameter List



Input Parameters

NMSSM Random Parameters
$m_0, m_{1/2}, A_0, \tan\beta, \text{sgn}(\mu), (m_{H_u}, m_{H_d}, A_\lambda, A_\kappa)$

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

Experimental Constraints

χ^2/L

global minimum fitting

MCMC Scan

$m_0 \in [0, 3000]$

$m_{1/2} \in [0, 2000]$

$A_0 \in [-6000, 6000]$

$\tan\beta \in [0, 60]$ @ SUSY

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

$m^2_{H_u} \in [-25, 25] \times 10^6$ @ GUT

$m^2_{H_d} \in [-25, 25] \times 10^6$ @ GUT

$\lambda \in [0, 1]$ @ SUSY

$A_\lambda \in [-6000, 6000]$

$A_\kappa \in [-6000, 6000]$

Random Scan

$m_0 \in [0, 2000]$

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

$A_0 \in [-4000, 4000]$

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

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

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

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

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.

- 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
Examples: $BR(B_s \to \mu^+\mu^-)$ and Ωh^2.

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

$$\boxed{\text{Total Likelihood}=\text{Likelihood}(\xi^{(\mathrm{II})})e^{-\frac{\chi^2(\xi^{(\mathrm{I})})}{2}}}$$

R definition

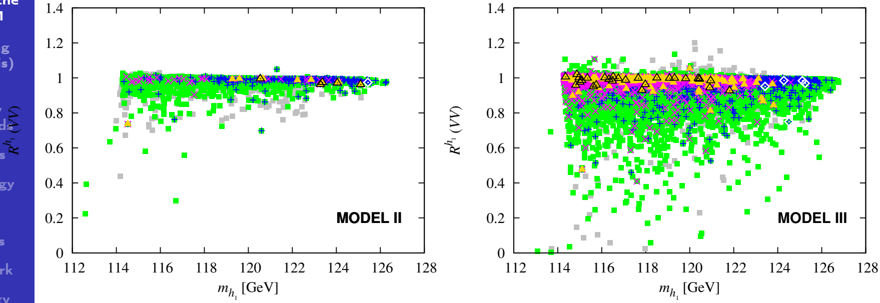
- Higgs production @ LHC: gluon-gluon to Higgs

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

- 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) $BR(h_{\rm SM} \to Y) = \Gamma^{h_{\rm SM}}(Y)/\Gamma^{h_{\rm SM}}_{\rm tot}$

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

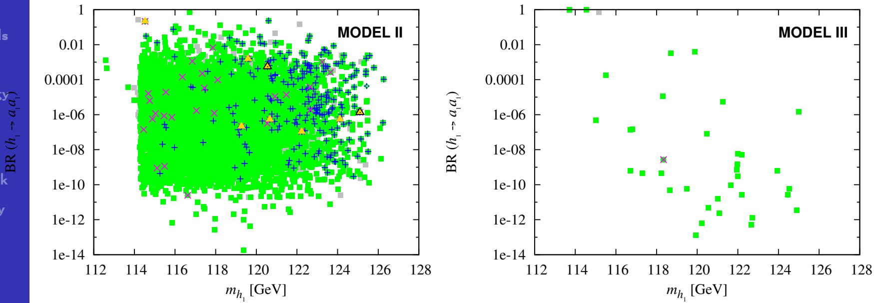
$R^{h_1}(VV = WW, ZZ)$ Figures



- 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.

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

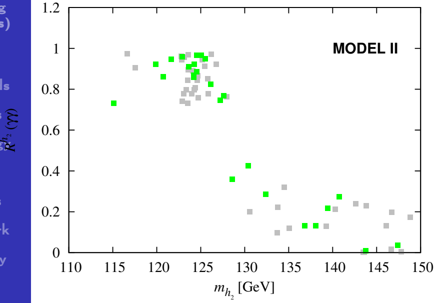
Are there any perfect or almost perfect points with measurable $h_1 \rightarrow a_1 a_1$ decays? NO! (not surprising given $R^{h_1}(\gamma\gamma) \sim 1$.)

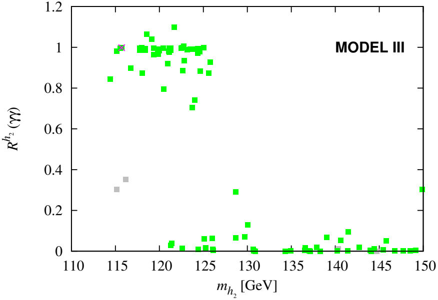


Large BR is possible while satisfying basic and B-physics constraints. However, $BR \lesssim 0.2$ once additional constraints are imposed. Thus, a light Higgs has nowhere to hide in these models.

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

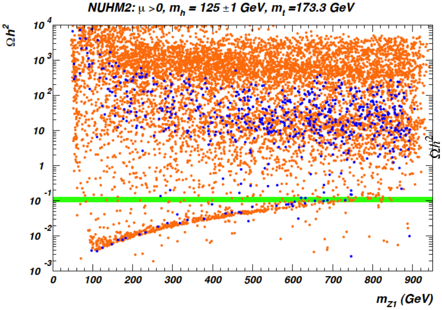
How about the next lightest Higgs, h_2?



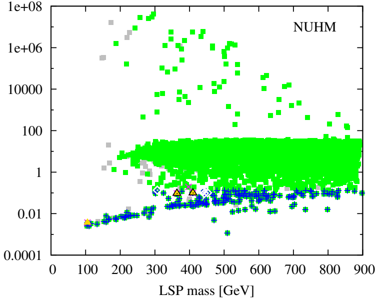


- In the $m_{h_2} \in [110 - 150]$ GeV region, points only pass the basic constraints and the B-physics constraints and not the others.
- Thus, it appears that within these constrained models with GUT unification conditions it is the h_1 that must be identified with the Higgs observed at the LHC.

More Analysis (Ωh^2 vs m_{LSP})



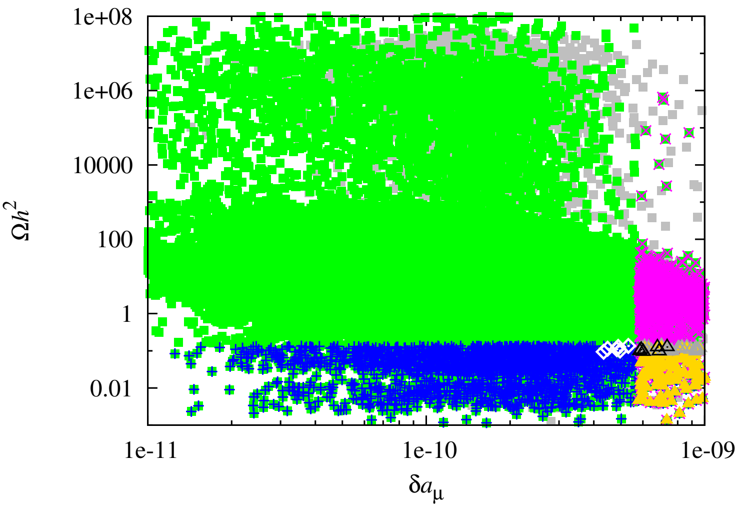
CMSSM, Baer 1112.3017



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.

More Analysis (Ωh^2 vs δa_μ)



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

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.
- This suggests that such points are quite fine-tuned in the general scan sense.

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
$\chi^2_{\mathbf{ATLAS}}$	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 $\chi^2_{\mathbf{ATLAS}}$, 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, $\chi^2_{\mathbf{ATLAS}}$ is of order 1.3 to 1.6.

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.
- μ_{eff} is small for all points, $\Rightarrow$ EW fine-tuning problem may not be severe.

δa_μ and Dark Matter details

Pt. #	δa_μ	Ωh^2	Prim. Ann. Channels	σ_{SI} [pb]
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.