Higgs Sector of NMSSM

Based on :

NMSSM Higgs production at the LHC Run II, Monoranjan Guchait, Jacky Kumar

Calculations for Modern and Future Colliders, JINR Dubna

Jacky Kumar
Tata Institute of fundamental research, Mumbai INDIA

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Content:

- Higgs Discovery and Supersymmetry
- Introduction to NMSSM
- Higgs sector and Higgs couplings
- Scanning NMSSM parameters and Constraints
- Non-standard Higgs branching ratios
- NMSSM production at the LHC Run II

Motivation: Higgs Discovery and NMSSM

Higgs Discovery: LHC has found a Higgs like particle.

$$Mass : 125.02 GeV$$

$$CMS : \mu = 1.00 \pm 0.13$$

$\Longrightarrow$ Consistent with Standard model but some discrepancy is still allowed.

But SM suffers from Naturalness problem, need some mechanism to cancel the quadratic divergences, and possibility of the found Higgs as non-standard Higgs is not ruled out .

Possible solution is Supersymmetry: So one possibility is this can be MSSM Higgs.

But it is difficult to get 125.02 GeV value in MSSM because:

In decoupling limit, upper bound on m_h:

$$m_h^2 = m_Z^2 \cos^2 2\beta + \delta_t^2$$

δ_t^2 comes from top squarks/ top quark loops

To achieve this value we need ....

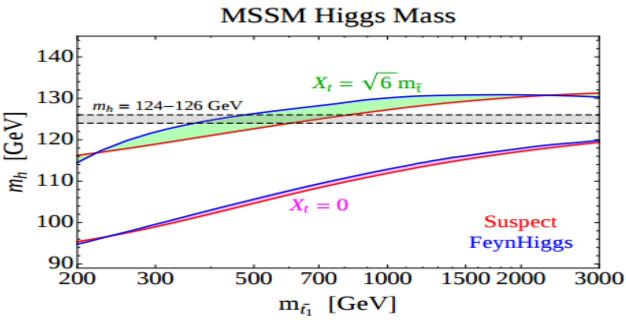
Motivation: Higgs Discovery and NMSSM

Heavy top squarks or large mixing in stop mass matrix:

But heavy stops give large contributions to quadratic term of Higgs potential

$$\delta m_{H_u}^2 = -\frac{3y_t^2}{8\pi^2}\left(m_{Q_3}^2 + m_{u_3}^2 + |A_t^2|\right)\ln\frac{\Lambda}{m_{\tilde{t}}}$$

If $m_{H_u}^2$ becomes too large parameters of the theory has to be tuned to get correct scale of EWSB .



[L.Hall et al. 1112. 2703]

Introduction to NMSSM

This motivates us to study non-minimal models.
One such model is Next-to-Minimal-supersymmetric-Standard-model abbreviated as NMSSM:

It was originally introduced to solve μ problem of MSSM.

But it has importance in the context of Higgs discovery, because it comfortably offers 125.02 GeV Higgs mass..

$$m_h^2 = m_z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta$$

MSSM: two Higgs doublets

$$H_1 = \begin{bmatrix} H_1^o \\ H_1^- \end{bmatrix}, H_2 = \begin{bmatrix} H_2^+ \\ H_2^0 \end{bmatrix}$$

NMSSM: two Higgs doublets + one singlet

$$H_1 = \begin{bmatrix} H_1^o \\ H_1^- \end{bmatrix}, H_2 = \begin{bmatrix} H_2^+ \\ H_2^0 \end{bmatrix}, \; S$$

μ problem : Superpotential MSSM and NMSSM :

MSSM:

$$W_{MSSM} = \mu.H_u.H_d - h_d H_d.Q\ \bar{D} - h_u Q.H_u\ \bar{U} - h_e H_d.L\ \bar{E}$$

Correct phenomenology demand, $\mu \sim$ EW sacle : The question how it assumes the value if this order is known as μ problem:

NMSSM:

$$W_{NMSSM} = W_{MSSM} + \lambda H_u.H_d\ S + \frac{1}{2}\kappa S^3$$

when S gets v.e.v μ is dynamically generated of the desired order.

$$\mu_{eff} = \lambda v_s$$

NMSSM: $\rightarrow$ solves μ problem

$\rightarrow$ easy to accommodate 125.02 GeV Higgs boson found at LHC

S $\rightarrow$ addition of CP even scalar

$\rightarrow$ addition of CP odd scalar

$\rightarrow$ addition of neutralino

NMSSM scalar potential and Parameters :

$$V = V_F + V_D + V_{soft},$$

$$V_F = |\lambda S|^2(|H_u|^2 + |H_d|^2) + |\lambda H_u H_d + \kappa S^2|^2$$
$$V_D = \frac{1}{8}\bar{g}^2(|H_d|^2 - |H_u|^2)^2 + \frac{1}{2}g^2|H_u^\dagger H_d|^2$$
$$V_{soft} = m_{H_u}^2|H_u|^2 + m_{H_d}^2|H_d|^2 + m_S^2|S|^2 + \left[\lambda A_\lambda S H_u H_d + \frac{1}{3}\kappa A_\kappa S^3 + h.c\right]$$

Parameters in Higgs sector :

Couplings: λ, κ

Soft parameters: A_λ, A_κ

Related to v.e.v: $\tan\beta, \mu_{eff}$

Radiative Corrections: $m_Q^2, m_U^2, m_D^2, A_U, A_D$

NMSSM spectra :

3 scalars: H_1, H_2, H_3

2 pseudo scalars A_1, A_2

2 charged $H^\pm$

The Higgs Sector of NMSSM : CP-even

Re[H_d^0, H_u^0, S] gives 3×3 CP even Higgs mass matrix $M_S^2 =$

$$S \begin{pmatrix} g^2 v_d^2 + \mu_{eff} B_{eff} \tan\beta & (2\lambda^2 - g^2) v_u v_d - \mu_{eff} B_{eff} & \lambda(2\mu_{eff} v_d - (B_{eff} + \kappa s) v_u) \\ & g^2 v_u^2 + \mu_{eff} B_{eff} / \tan\beta & \lambda(2\mu_{eff} v_u - (B_{eff} + \kappa s) v_d) \\ & & \lambda A_\lambda \frac{v_u v_d}{s} + \kappa s (A_{\kappa + 4\kappa s}) \end{pmatrix}.$$

$$H_1 = S_{11} H_d^0 + S_{12} H_u^0 + S_{13} S$$

$$H_2 = S_{21} H_d^0 + S_{22} H_u^0 + S_{23} S$$

$$H_3 = S_{31} H_d^0 + S_{32} H_u^0 + S_{23} S$$

Singlet -Doublet mixing $\propto \quad \lambda$

In limit M_A high,

$$m_{H_1}^2 \leq m_Z^2 \cos^2 2\beta + \lambda^2 \sin^2 2\beta$$

The extra term is Highly welcomed in the context of 125 GeV Higgs Discovery.

The Higgs Sector of NMSSM: CP-odd

Imm[H_d^0, H_u^0, S] gives 3×3 CP even Higgs mass matrix $M_P^2 =$

$$R(\beta)^T \begin{pmatrix} \mu_{eff} B_{eff} \tan\beta & \mu_{eff} B_{eff} & \lambda v_u (A_\lambda - 2\kappa s) \\ & \mu_{eff} B_{eff} / \tan\beta & \lambda v_d (A_\lambda - 2\kappa s) \\ & & \lambda (B_{eff} + 3\kappa s) \frac{v_u . v_d}{s} - 3\kappa A_\kappa s \end{pmatrix} R(\beta)$$

$A = \sin\beta H_d^0 + \cos\beta H_u^0$
$G = -\cos\beta H_d^0 + \sin\beta H_u^0 \rightarrow \mathrm{GoldstonMode}$
$S = S$
In basis (A,S)

$$M^2 = P^T \begin{pmatrix} M_A^2 & \lambda(A_\lambda - 3\kappa s) \\ & \lambda (B_{eff} + 3\kappa s) \frac{v_u . v_d}{s} - 3\kappa A_\kappa s \end{pmatrix} P$$

$A_1 = P_{11} A + P_{12} S$
$A_1 = P_{21} A + P_{22} S$

The Higgs Sector of NMSSM: Charged

$$M_{\pm}^2 = \left(\mu_{eff} B_{eff} + v_u v_d \left(\frac{g_2^2}{2} - \lambda^2 \right) \right) \begin{bmatrix} \cot\beta & 1 \\ 1 & \tan\beta \end{bmatrix}$$

$$M_{\pm}^2 = M_A^2 + v^2 \left(\frac{g_2^2}{2} - \lambda^2 \right)$$

Higgs couplings in SM and NMSSM

	SM	NMSSM
$H_i t_L t_R^c$	$\frac{m_t}{v}$	$\frac{m_t}{\sqrt{2} v \sin\beta} S_{i2}$
$H_i b_L b_R^c$	$\frac{m_b}{v}$	$\frac{m_b}{\sqrt{2} v \cos\beta} S_{i1}$
$H_i Z_\mu Z_\nu$	$g_{\mu\nu} \frac{2m_Z^2}{v}$	$g_{\mu\nu} \frac{\sqrt{2} M_Z^2}{v} (\cos\beta S_{i1} + \sin\beta S_{i2})$
$H_i W_\mu^+ W_\nu^-$	$g_{\mu\nu} \frac{2m_W^2}{v}$	$g_{\mu\nu} \frac{\sqrt{2} M_W^2}{v} (\cos\beta S_{i1} + \sin\beta S_{i2})$
$A_i t_L t_R^c$		$\frac{m_t}{\sqrt{2} v \sin\beta} P_{i1}$
$A_i b_L b_R^c$		$\frac{m_b}{\sqrt{2} v \cos\beta} P_{i1}$

Note : NMSSM Higgs couplings are related to parameters $(\lambda, \kappa, \tan\beta, \mu, A_\lambda, A_\kappa)$ etc, in very complicated way through **S** and **P**.

This will lead to very different NMSSM phenomenology (see next slides).

NMSSM scan

With goal of having either H_1/H_2 to be SM like and interpreting this as the Higgs found at the LHC.

Preformed a through scan of NMSSM parameters using NMSSMTools.

Studied the phenomenology of other Higgs Bosons in NMSSM.

Used up to date constraints from LHC.
Flavour physics
Dark matter
g-2 ...

Specific to Higgs sector

$\lambda \sim 0.1 - 0.8$

$\kappa \sim 0.1 - 0.8$

$\tan\beta \sim 1.5 - 30$

$\mu(GeV) \sim 100 - 2000$

$A_\lambda(GeV) \sim 0 - 1000$

$A_\kappa(GeV) \sim -600, 100$

Gaugino mass parameters (GeV)

$M_1 \sim 50 - 500$

$M_2 \sim 50 - 500$

Third generation (GeV)

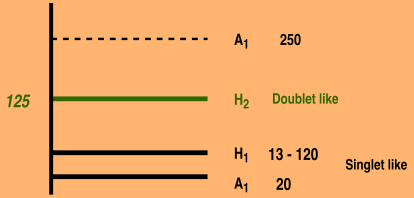
$A_t \sim$-4000 ,4000

$M_{Q_3} \sim$ 500 -3000

$m_{U_3} \sim$ 500- 3000

NMSSM Higgs Spectra

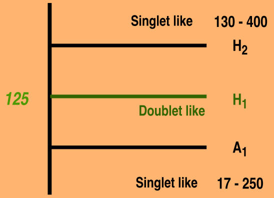
Case A



Non-Standard Decay Modes: $H_1 H_1$

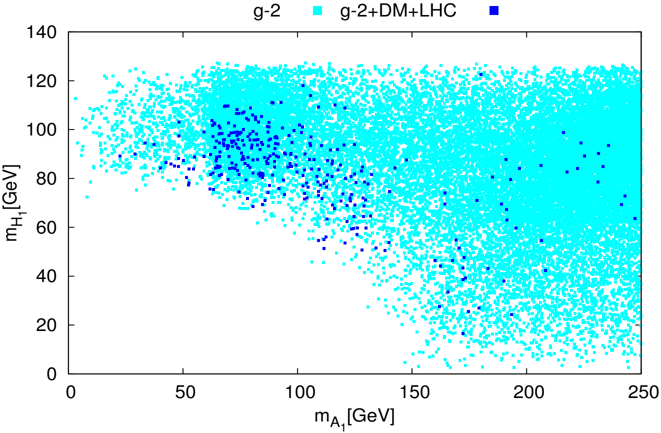
$A_1 A_1$

Case B



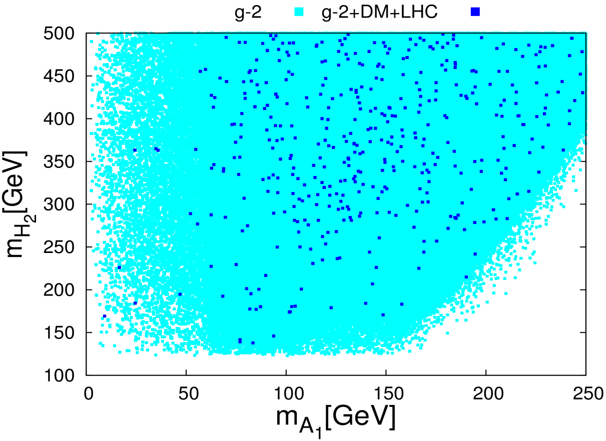
Non-Standard Decay modes: $A_1 A_1$

Mass range $H_1, A_1,\ m_{H_2} = 125$



So there can be two light Higgs Bosons below 125 GeV.

Mass range of $A_1, H_2, m_{H_1} = 125$



In this case there can be one light Higgs below 125 GeV.

Next question would be how to find them at the LHC? For that we need to study their couplings and branching ratios and production cross-section etc.

Couplings of H_1, $H_2 = 125 GeV$

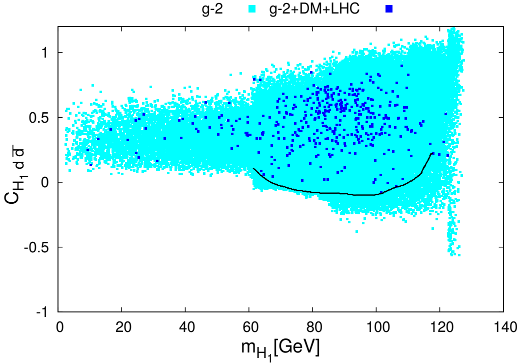
Recall that Higgs couplings are complicated functions parameters through S and P mixing matrices.

$$\mathbf{g_d} = \frac{\mathbf{m_b}}{\sqrt{2}\mathbf{v}\cos\beta}\mathbf{S_{11}}, \quad \mathbf{\tan\beta} \quad \mathbf{enhanced}$$

but if

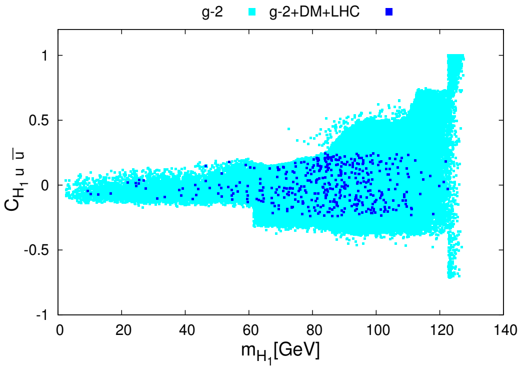
$$S_{11} \to 0 \implies c_d \to 0 \ (NMSSM\ effect)$$

This has important consequences



$$\Gamma(b\bar{b}) \propto G_F\ m_H\ \frac{m_b}{\cos\beta}^2\ S_{11}^2$$

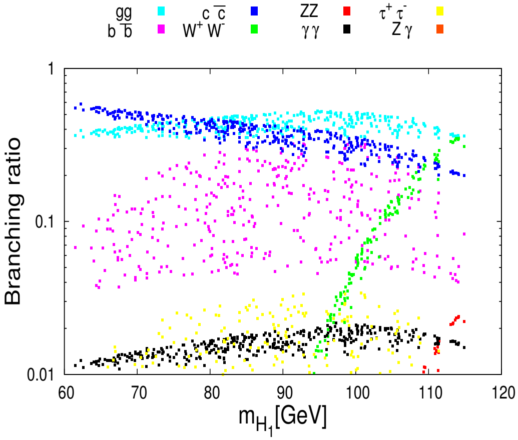
$$g_u = \frac{m_t}{\sqrt{2} v \sin\beta} S_{21}$$



c_u enters in BR(gg) and BR(cc) : in this region these will be the dominant decay modes.

$$\Gamma(gg) \propto g^2_{H_1 gg}(S_{11}, S_{12})$$

$$\Gamma(c\bar{c}) \propto G_F\left(\frac{m_c}{\sin\beta}\right)^2 m_H.\ S^2_{11}$$



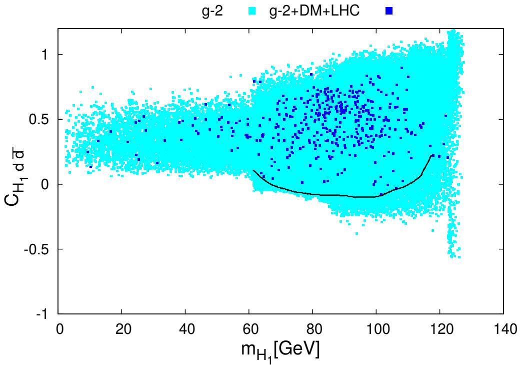
BR(gg) up to 55 %
BR(cc) up to 60 %

Coupings of H_1, $H_2 = 125 GeV$

$$\mathbf{g_d} = \frac{\mathbf{m_b}}{\sqrt{2}\mathbf{v}\cos\beta}\mathbf{S_{11}}, \quad \mathbf{tan}\beta \quad \textbf{enhanced}$$

but if

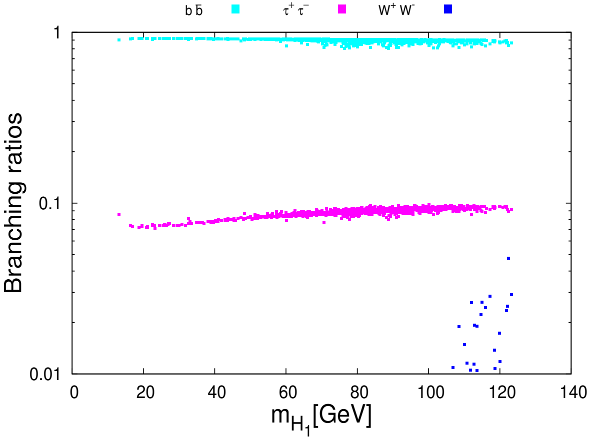
$$S_{i2} : significant \implies c_d \to large \; (as \; in \; MSSM)$$



$$\Gamma(b\bar{b}) \propto G_F \; m_H \; \frac{m_b}{\cos\beta}^2 \; S_{11}^2$$

Natural width of H_1 will be very large.

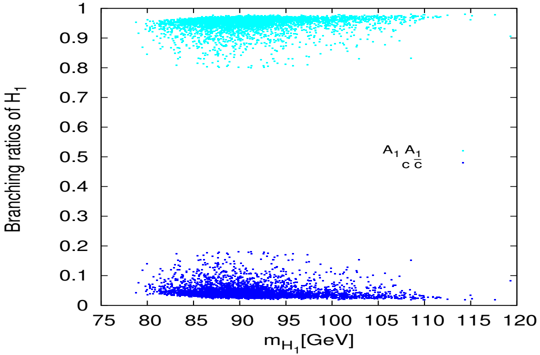
Branching ratios of H_1 : :H_2 SM like



In this region bb and $\tau\tau$ would be dominant modes.

Branching ratios of H_1, H_2 =125

On the other hand whenever $M_{A_1} \leq 0.5 M_{H_1}$



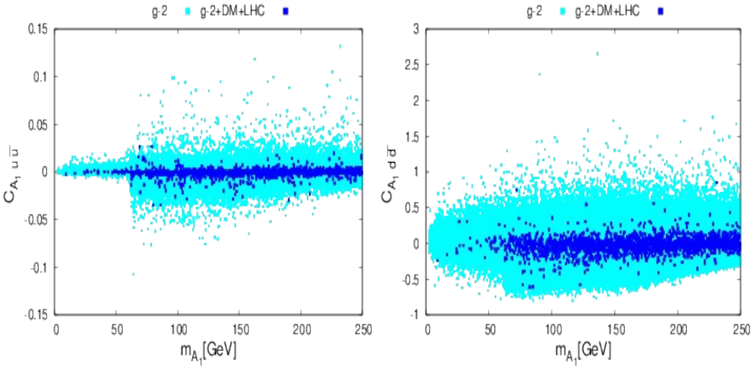
A_1 A_1 mode will take over. (width propotional to tripple Higgs couplings κv_s)

$$\Gamma_{H_1 A_1 A_1} \propto \frac{2\kappa^2 (\frac{\kappa\mu}{\lambda} - \frac{A_\kappa}{2})^2}{m_H}$$

$\Longrightarrow$ whenever kinematically allowed, $H_1 \to A_1 A_1$ will dominate.

A_1 reduced couplings H_1 =125 GeV

$$g_u = \frac{m_t}{\sqrt{2} v \sin\beta} P_{11}$$
$$g_d = \frac{m_b}{\sqrt{2} v \cos\beta} P_{11}$$

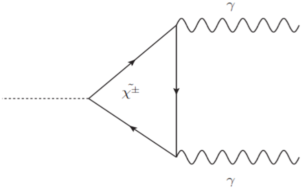


A_1 is singlet like and has decopled from SM particles. But it can interact through loop.

$A_1 \to \gamma\gamma$

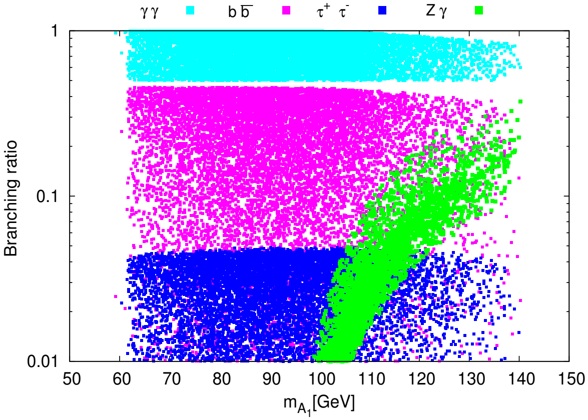
It can still couple to charginos through $\lambda \hat{H}_u \hat{H}_d \hat{S}$ in the superpotential (NMSSM effect)

$$g_{A_a \chi_i^+ \chi_j^-} = \frac{i}{\sqrt{2}} \left(\lambda P_{a3} U_{i2} V_{j2} - g_2 (P_{a2} U_{i1} V_{j2} + P_{a1} U_{i2} V_{j1}) \right)$$



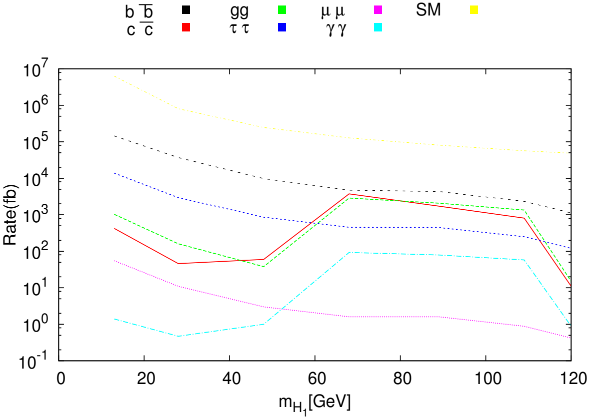
While singlet like A_1 has mostly decoupled from SM particles it can still couple to photons through Chargino loop.

$A_1 \to \gamma\gamma$



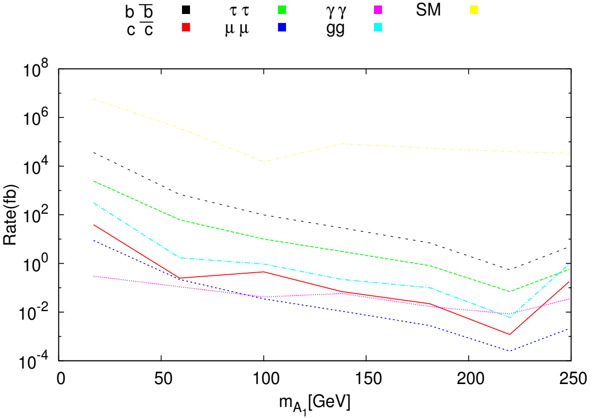
This high branching ratio is not possible in SM or MSSM, it can be used to distinguish NMSSM from MSSM.

Production rate of H_1 at LHC Run II



[Obtained using SusHi and NMSSMTools]

Production rate of A_1 at LHC Run II

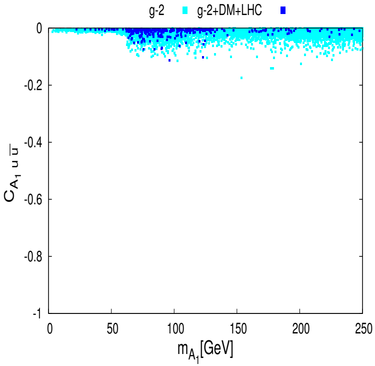


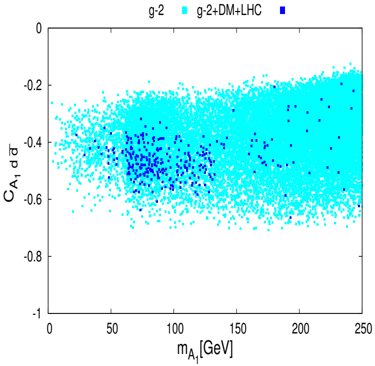
[Obtained using SusHi and NMSSMTools]

Thanks for your attention.

Couplings of A_1 : H_2 SM-like

$$g_u^{NMSSM} = c_u \ g_u^{SM}, \qquad g_d^{NMSSM} = c_d \ g_d^{SM}$$





Down-type coplings can be substantial because of presence of good fraction of H_d component.

Branching ratio profile of H_1: :H_2 SM like

$$\Gamma(b\bar{b}) \propto G_F(\frac{m_b}{\cos\beta})^2 m_H.\ S_{12}^2$$

$$\Gamma(c\bar{c}) \propto G_F(\frac{m_c}{\sin\beta})^2 m_H.\ S_{11}^2$$

$$\Gamma(A_1 A_1) \propto \frac{g^2_{H_1 A_1 A_1}}{m_H}$$

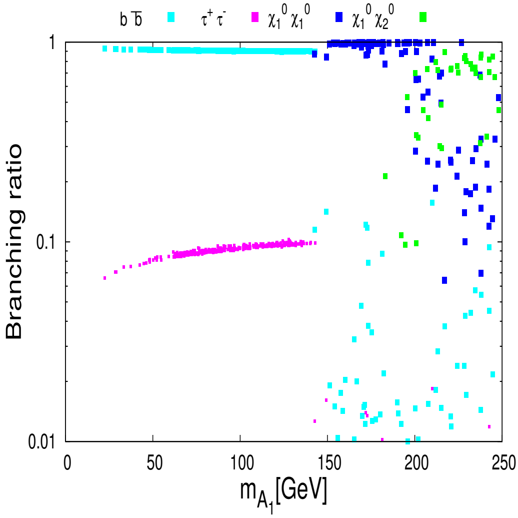
$g_{H_1 A_1 A_1} \sim \sqrt{2}\kappa(\frac{\kappa\mu}{\lambda} - \frac{A_\kappa}{2})$
We are considering mainly -ve values of $A_k \implies$

$$\Gamma_{H_1 A_1 A_1} \propto \frac{2\kappa^2(\frac{\kappa\mu}{\lambda} - \frac{A_\kappa}{2})^2}{m_H}$$

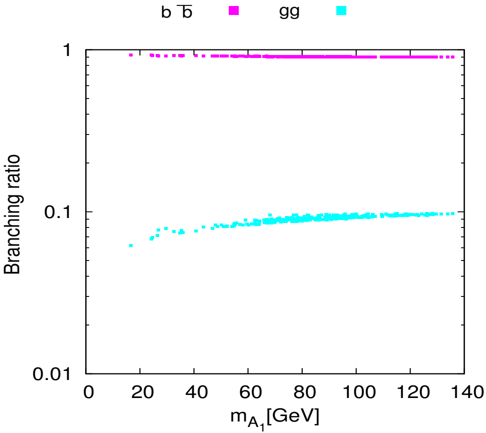
$\implies$ whenever kinematically allowed, $H_1 \to A_1 A_1$ will dominate over $b\bar{b}$. Naively we expect that otherwise $b\bar{b}$ should dominate. That is not the case actually.

$$\Gamma(gg) \propto g^2_{H_1 gg}(S_{11}, S_{12})$$
$$\Gamma(\gamma\gamma) \propto g^2_{H_1 \gamma\gamma}(S_{11}, S_{12})$$

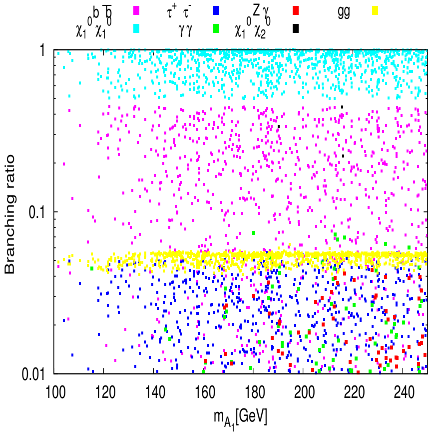
Branching Ratio A_1 : : H_2 SM like



Branching Ratio of A_1 : H_1 SM like



Branching Ratio of A_1 : H_1 SM like



Non-standard Higgs production and signal at LHC

We use approximate formulas to estimate the Higgs cross section:

$$\sigma_{ggF}(\phi \to XX) = \sigma^{\phi}_{ggF} \times Br(\phi \to XX)$$

Here

$$\sigma_{ggF}(\phi) \sim {C^{eff}_{gg\phi}}^{2} \times \sigma^{SM}_{ggF}$$

and

$$\phi = A_1, H_1, H_2$$

$C^{eff}_{gg\phi}$ is one loop coupling comprising Bosonic and Fermionic loops.σ^{SM}_{ggF} is calculated using SusHi [Robert V. Harlander et el].

NMSSM signal at the LHC

$$H_1 \to b\bar{b},\ c\bar{c},\ \tau\tau,\ gg,\ WW$$

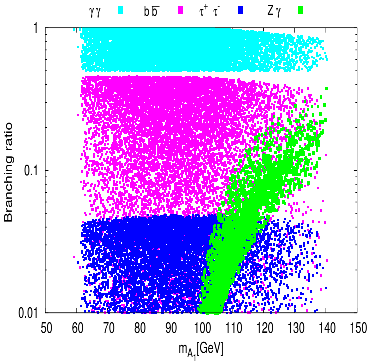
$$A_1 \to b\bar{b},\ c\bar{c},\ \tau\tau,\ gg,\ \chi\chi$$

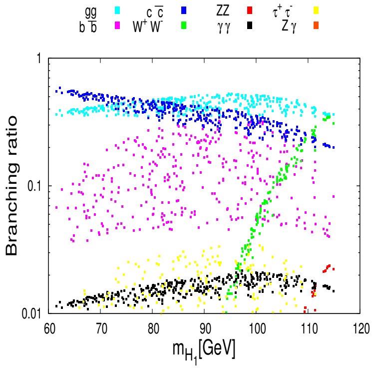
1: $\phi \to \tau\tau : \tau_l\tau_l + \mathbf{E_T},\ \tau_l\tau_h + \not{E}_T,\quad \mathbf{M_{A_1} \sim 100GeV, Events \sim 7000}$

2: $\phi \to \mathbf{b\bar{b}} : \phi + \mathbf{1\ jet\ , M_{A_1} \sim 100\ GeV, Events \sim 65000}$

3. $\phi \to$ Susy particles, $\chi_2\chi_1 \to$ 2 leptons
$+\not{E}_T \quad M_{A_1} \sim 180\ GeV, Events \sim 2$

Characteristic features of NMSSM signal

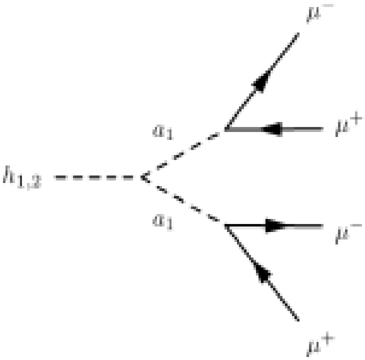




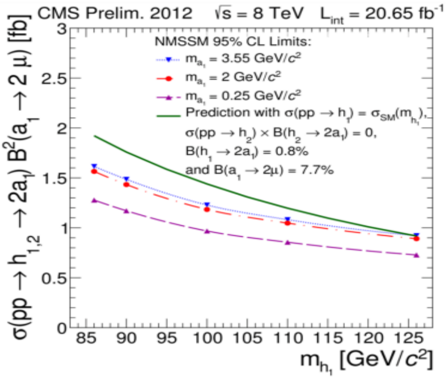
$\phi \to \gamma\gamma$: $\mathbf{M_{A_1} \sim 17\ GeV}$, **Events** $\sim$ **60**

$\phi \to$ **gg**, $\mathbf{c\bar{c}}$: $\phi + $ **1 jet** , $\mathbf{M_{H_1} \sim 50\ GeV}$, **Events** $\sim$ **3900 gg**

NMSSM Higgs search at LHC



NMSSM



Important References

Discovery Prospects for NMSSM Higgs Bosons at the High-Energy Large Hadron Collider, S.King et al.

A light NMSSM pseudoscalar Higgs boson at the LHC Run 2, Bomark et el.

125 GeV Higgs and enhanced diphoton signal of a light singlet-like scalar in NMSSM, M. Badziak et al.

A light Higgs scalar in the NMSSM confronted with the latest LHC Higgs data, J Cao et al.

Conclusion

In context of Higgs Discovery NMSSM is more natural model as compare to MSSM and solves the μ problem of MSSM.

NMSSM predicts very CP even as well as CP scalar, so has quite interesting phenomenology for LHC.

Prepration under progress soon to be published. Thanks for your attention.