Light Sectors in the NMSSM with Non-Universal Higgs Masses

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Based on arXiv 2006.03527, 2003.01662, 2002.05554, 1911.08319
On behalf of my students Kun WANG and Shiquan MA

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Outline

1. Introduction
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   - Supersymmetry (SUSY)
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2. The light sectors in the NMSSM-NUHM
   - Light Higgs (pseudo)scalars
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3. Summary and Outlook

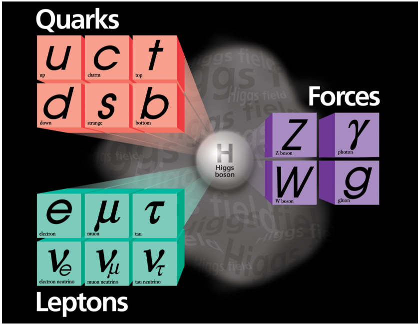
1 Introduction

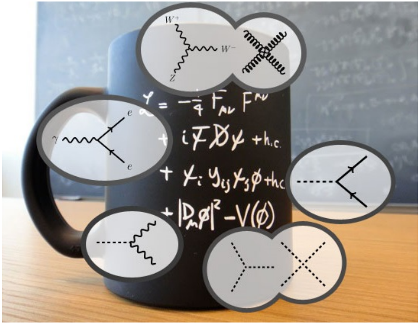
- The Standard Model (SM)
- Supersymmetry (SUSY)
- The constrained MSSM (CMSSM/mSUGRA)
- The NMSSM with Non-Universal Higgs Masses (NUHM)

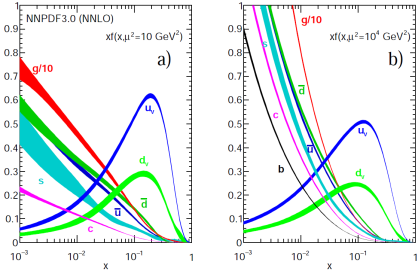
2 The light sectors in the NMSSM-NUHM

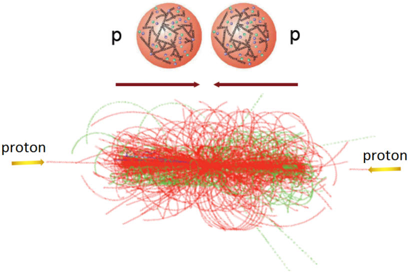
3 Summary and Outlook

The Standard Model (SM)

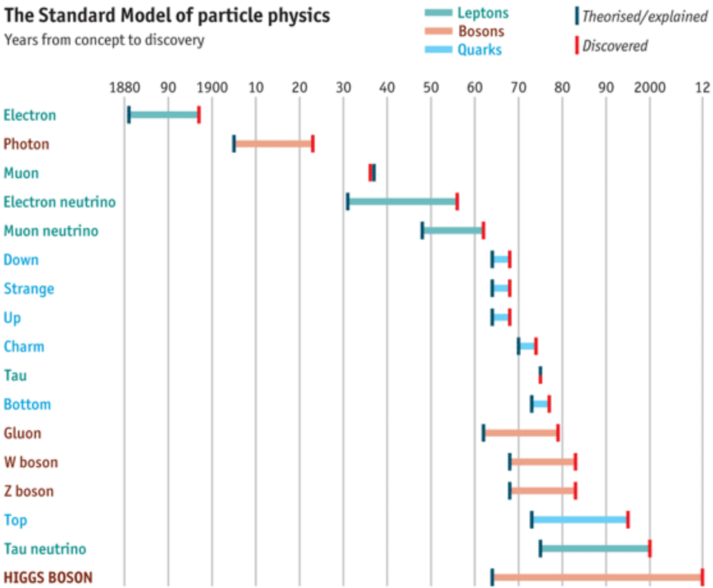








Discovery of the SM



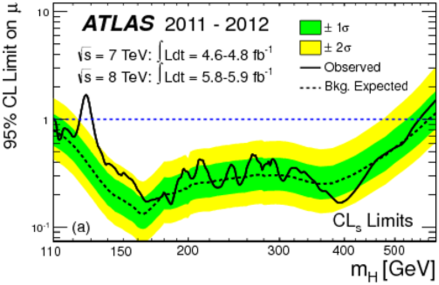
Higgs discovery: July 4th , 2012

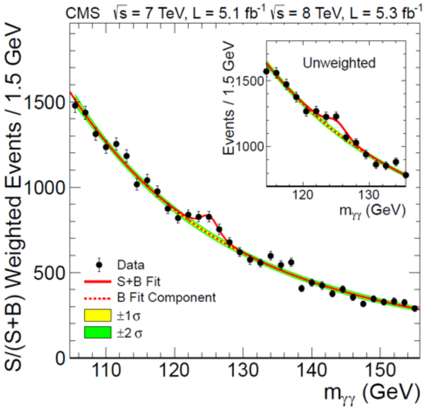
Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC #1
ATLAS Collaboration • Georges Aad (Freiburg U.) et al. (Jul 31, 2012)
Published in: Phys.Lett.B 716 (2012) 1-29 • e-Print: 1207.7214 [hep-ex]
pdf links DOI cite 11,414 citations

Observation of a New Boson at a Mass of 125 GeV with the CMS Experiment at the LHC #2
CMS Collaboration • Serguei Chatrchyan (Yerevan Phys. Inst.) et al. (Jul 31, 2012)
Published in: Phys.Lett.B 716 (2012) 30-61 • e-Print: 1207.7235 [hep-ex]
pdf links DOI cite 11,128 citations

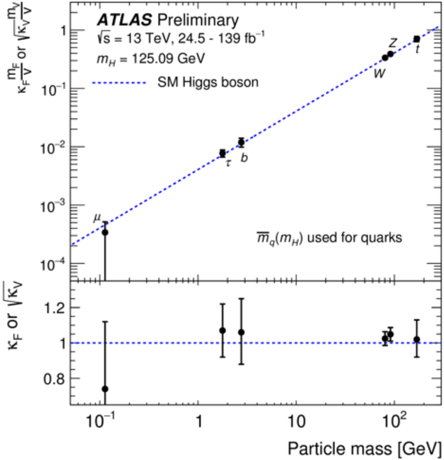
signal significance $\approx 5\sigma$

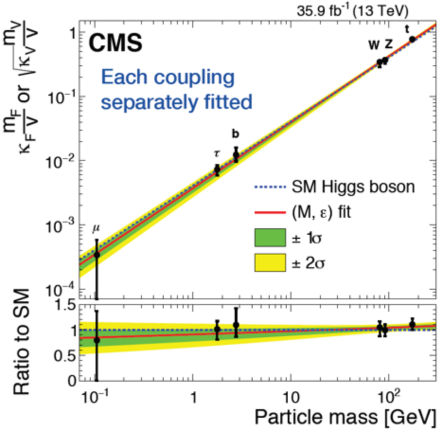
mass $m_h = 125.5 \pm 0.54\,\mathrm{GeV}$



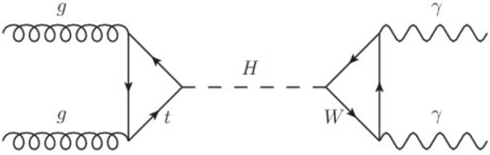


Higgs data: couplings



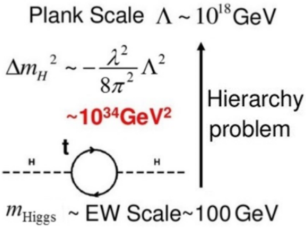


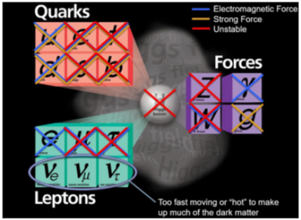
Assuming no BSM particles in the loops

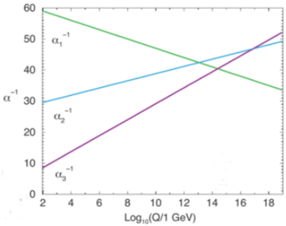


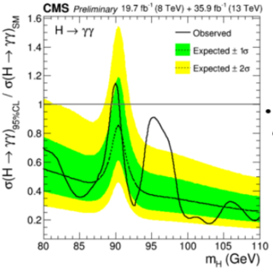
The SM: not a final theory

- hierarchy problem
- gauge couplings can not unify
- lack dark matter candidates
- possible anomaly at the LHC??? $150 \mapsto 3000\ \text{fb}^{-1}$
- … …



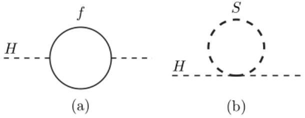






…… ???

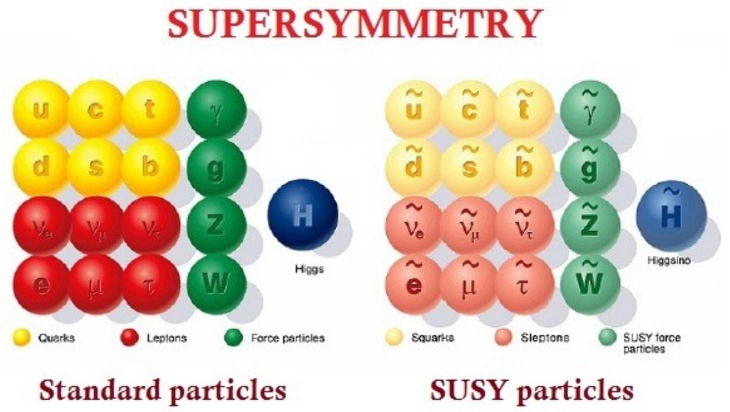
Supersymmetry (SUSY)



Martin, arXiv:9709356

$$\Delta m^2_{H(a)} = -\frac{|\lambda_f|^2}{8\pi^2}\Lambda^2_{\rm UV} + \ldots$$

$$\Delta m^2_{H(b)} = \frac{\lambda_S}{16\pi^2}\left[\Lambda^2_{\rm UV} - 2m_S^2 \ln(\Lambda_{\rm UV}/m_S) + \ldots\right]$$



$$W \supseteq \mu H_u \cdot H_d$$
$$V_{\rm soft} \supseteq B_\mu (H_u \cdot H_d + h.c.)$$
$$V = V_F + V_D + V_{\rm soft}$$

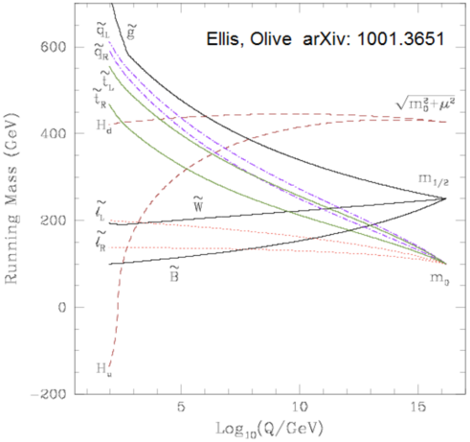
$$\frac{\partial V}{\partial \phi_u} = 0, \quad \frac{\partial V}{\partial \phi_d} = 0$$
$$\mu, B_\mu \Rightarrow v_u, v_d$$
$$\tan\beta \equiv \frac{v_u}{v_d}, \sqrt{v_u^2 + v_d^2} = 173\,\mathrm{GeV}$$

At $M_{\rm GUT}$ scale:

$$M_{\tilde{q},\tilde{\ell}} = M_0, \quad M^2_{H_u,H_d} = M_0^2 + \mu^2$$
$$A_{q,\ell} = A_0, \quad M_{1,2,3} = M_{1/2}$$

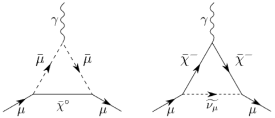
The free parameters

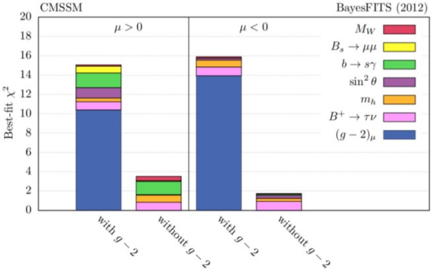
$\tan\beta,\ M_{1/2},\ M_0,\ A_0,\ \mathrm{Sign}(\mu)$



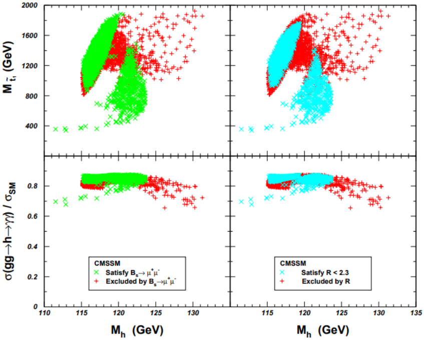
The CMSSM vs experiments

- 125 GeV SM-like Higgs mass
- High mass bound of the gluino
  $m_{\tilde{g}} \approx 2M_{1/2} \gtrsim 2$ TeV
- Dark matter relic density and direct detection
  $m_{\chi_1^0} \approx 0.4M_{1/2} \gtrsim 400$ GeV
- Muon g-2

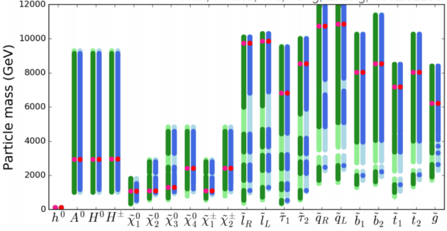




Cao, Heng, Li, Yang, 1112.4391



Han, Hikasa, Wu, Yang, Zhang, 1612.02296



The Higgs potential in the NMSSM

$$
\begin{aligned}
W &\supseteq \lambda \hat{S}\hat{H}_u \cdot \hat{H}_d + \frac{1}{3}\kappa \hat{S}^3 \\
V_{\rm F} &\supseteq |\lambda S|^2(|H_u|^2 + |H_d|^2) + |\lambda H_u \cdot H_d + \kappa S^2|^2 \\
V_{\rm D} &= \frac{1}{8}\left(g_1^2 + g_2^2\right)\left(|H_d|^2 - |H_u|^2\right)^2 + \frac{1}{2}g_2^2\left|H_u^\dagger H_d\right|^2 \\
V_{\rm soft} &\supseteq M_{H_u}^2|H_u|^2 + M_{H_d}^2|H_d|^2 + M_S^2|S|^2 \\
&\quad + \left(\lambda A_\lambda S H_u \cdot H_d + \frac{1}{3}\kappa A_\kappa S^3 + h.c.\right) \\
V &= V_{\rm F} + V_{\rm D} + V_{\rm soft}
\end{aligned}
$$

$$
H_u = \begin{pmatrix} H_u^+ \\ v_u + \frac{\phi_1 + i\varphi_1}{\sqrt{2}} \end{pmatrix}, \quad H_d = \begin{pmatrix} v_d + \frac{\phi_2 + i\varphi_2}{\sqrt{2}} \\ H_d^- \end{pmatrix},
$$

$$
S = v_s + \frac{\phi_3 + i\varphi_3}{\sqrt{2}}.
$$

The parameters in the NMSSM-NUHM

$$\frac{\partial V}{\partial \phi_d} = \frac{v_s v_u \lambda}{2}(-\sqrt{2}A_\lambda - \kappa v_s) - \frac{(g_1^2+g_2^2)}{8} v_d(v_u^2 - v_d^2) + m_{H_d}^2 v_d + \frac{\lambda^2}{2}(v_s^2 + v_u^2)v_d,$$
$$\frac{\partial V}{\partial \phi_u} = \frac{v_s v_d \lambda}{2}(-\sqrt{2}A_\lambda - \kappa v_s) + \frac{(g_1^2+g_2^2)}{8} v_u(v_u^2 - v_d^2) + m_{H_u}^2 v_u + \frac{\lambda^2}{2}(v_s^2 + v_d^2)v_u,$$
$$\frac{\partial V}{\partial \phi_s} = \frac{v_s}{2}(\sqrt{2}A_\kappa \kappa v_s + 2m_S^2 + \lambda^2(v_d^2+v_u^2) - 2\kappa\lambda v_u v_d + 2\kappa^2 v_s^2) - \frac{A_\lambda \lambda}{\sqrt{2}} v_u v_d.$$

$$M_{H_u}^2 \neq M_0^2 + \mu^2$$
$$M_{H_d}^2 \neq M_0^2 + \mu^2$$
$$M_S^2 \neq M_0^2 + \mu^2$$
$$A_\lambda \neq A_0$$
$$A_\kappa \neq A_0$$

$$\frac{\partial V}{\partial \phi_d} = 0, \quad \frac{\partial V}{\partial \phi_u} = 0, \quad \frac{\partial V}{\partial \phi_s} = 0$$

$$M_{H_u}^2,\ M_{H_d}^2,\ M_S^2$$
$$\Leftrightarrow \lambda,\ \kappa,\ \mu_{\rm eff} \equiv \lambda v_s$$

$$\text{CNMSSM/CMSSM}: \quad \tan\beta,\ A_0,\ M_0,\ M_{1/2} \Rightarrow$$
$$\text{NMSSM}-\text{NUHM}: \quad \lambda,\ \kappa,\ \mu_{\rm eff},\ A_\lambda,\ A_\kappa,\ \tan\beta,\ A_0,\ M_0,\ M_{1/2}$$

The electroweakino sector in NMSSM-NUHM

In the NMSSM, there are five neutralinos $\tilde{\chi}_i^0$ ($i=$ 1,2,3,4,5), which are the mixture of $\tilde{B}$ (bino), $\tilde{W}^3$ (wino), $\tilde{H}_d^0$, $\tilde{H}_u^0$ (higgsinos) and $\tilde{S}$ (singlino). In the gauge-eigenstate basis $\psi^0=(\tilde{B},\tilde{W}^3,\tilde{H}_d^0,\tilde{H}_u^0,\tilde{S})$, the neutralino mass matrix takes the form [19]

$$M_{\tilde{\chi}^0}=\begin{pmatrix} M_1 & 0 & -c_\beta s_W m_Z & s_\beta s_W m_Z & 0 \\ 0 & M_2 & c_\beta c_w m_z & -s_\beta c_W m_Z & 0 \\ -c_\beta s_W m_Z & c_\beta c_w m_z & 0 & -\mu & -\lambda v_d \\ s_\beta s_W m_Z & -s_\beta c_W m_Z & -\mu & 0 & -\lambda v_u \\ 0 & 0 & -\lambda v_d & -\lambda v_u & 2\kappa v_s \end{pmatrix}$$

where $s_\beta=\sin\beta, c_\beta=\cos\beta, s_W=\sin\theta_W, c_W=\cos\theta_W$. To get the mass eigenstates, one can diagonalize the neutralino mass matrix $M_{\tilde{\chi}^0}$

2β.

$$N^* M_{\tilde{\chi}^0} N^{-1}=M^D_{\tilde{\chi}^0}=\mathrm{Diag}(m_{\tilde{\chi}_1^0},m_{\tilde{\chi}_2^0},m_{\tilde{\chi}_3^0},m_{\tilde{\chi}_4^0},m_{\tilde{\chi}_5^0})$$

In the scNMSSM, bino and wino were constrained to be very heavy, because of the high mass bounds of gluino and the universal gaugino mass at the GUT scale, thus they can be decoupled from the light sector. Then the following relations for the N_{ij} can be found [21]:

$$N_{i3}:N_{i4}:N_{i5}=\left[\frac{m_{\tilde{\chi}_i^0}}{\mu}s_\beta-c_\beta\right]:\left[\frac{m_{\tilde{\chi}_i^0}}{\mu}c_\beta-s_\beta\right]:\frac{\mu-m_{\tilde{\chi}_i^0}}{\lambda v}$$

The chargino sector in the NMSSM is similar to neutralino sector. The charged higgsino $\tilde{H}_u^+$, $\tilde{H}_d^-$ (with mass scale μ) and the charged gaugino $\tilde{W}^\pm$ (with mass scale M_2) can also mix respectively, forming two couples of physical chargino $\chi_1^\pm,\chi_2^\pm$. In the gauge-eigenstate basis $(\tilde{W}^+,\tilde{H}_u^+,\tilde{W}^-,\tilde{H}_d^-)$, the chargino mass matrix is given by [19]

$$M_{\tilde{C}}=\begin{pmatrix} 0 & X^T \\ X & 0 \end{pmatrix}, \quad \text{where } X=\begin{pmatrix} M_2 & \sqrt{2}s_\beta m_W \\ \sqrt{2}c_\beta m_W & \mu \end{pmatrix} \qquad (30)$$

To obtain the chargino mass eigenstates, one can use two unitary matrix to diagonalize the chargino mass matrix by

$$U^* X V^{-1}=M^D_{\tilde{\chi}^\pm}=\mathrm{Diag}(m_{\tilde{\chi}_1^\pm},m_{\tilde{\chi}_2^\pm}) \qquad (31)$$

where $M^D_{\tilde{\chi}^\pm}$ means the diagonal mass matrix, and the order of eigenvalues is $m_{\tilde{\chi}_1^\pm}<m_{\tilde{\chi}_2^\pm}$. Meanwhile, we can get the mass eigenstates

$$\begin{pmatrix} \tilde{\chi}_1^+ \\ \tilde{\chi}_2^+ \end{pmatrix}=V_{ij}\begin{pmatrix} \tilde{W}^+ \\ \tilde{H}_u^+ \end{pmatrix}, \quad \begin{pmatrix} \tilde{\chi}_1^- \\ \tilde{\chi}_2^- \end{pmatrix}=U_{ij}\begin{pmatrix} \tilde{W}^- \\ \tilde{H}_d^- \end{pmatrix}. \qquad (32)$$

Constraints

- Theoretical constraints of vacuum stability, and no Landau pole below $M_{\rm GUT}$
- The lower mass bounds of charginos and sleptons from the LEP
- Constraints from B physics, such as $B_s \to \mu^+\mu^-$, $B_d \to \mu^+\mu^-$, $b \to s\gamma$, etc.
- A SM-like Higgs with mass 123∼127 GeV and signal rates fitting data globally

- The DM relic density Ωh^2 from WMAP/Planck, with upper bound $\Omega h^2 \leq 0.131$, considering there may be other sources of DM; where the dark matter observables are calculated by micrOMEGAs 5.0 inside NMSSMTools.
- The spin-independent DM-nucleon cross section is constrained by XENON1T, where we rescale the original values by Ω/Ω_0 with $\Omega_0 h^2 = 0.1187$;
- The muon g-2 at 2σ level including all errors. $\delta a_\mu \equiv a_\mu^{\rm ex} - a_\mu^{\rm SM} = (27.4 \pm 9.3) \times 10^{-10}$, where $a_\mu^{\rm SM}$ contains no Higgs contribution. The central value of SUSY (including Higgses) contribution to muon g-2, can be $5.8 \sim 49.0 \times 10^{-10}$, left out the theoretical error of SUSY contribution about 1.5×10^{-10}.

- The upper limit of Higgs invisible decay, 19% by CMS
- The lower mass bound of $\tilde{g}$, $\tilde{q}_{1,2}$, $\geqslant 2$ TeV
- The CMS constraints on charginos and neutralinos inside NMSSMTools-5.5.2
- The SUSY search results implemented inside SModelS v1.2.2
- The Higgs search results at the LEP, Tevatron and LHC, with HiggsBounds-5.5.0
- The sparticle search results, with CheckMATE-2.0.26 (arXiv 1911.08319)

Mixings in the Higgs sector

$$\begin{bmatrix} h_{SM} \\ H_{new} \\ s \end{bmatrix} \approx \begin{bmatrix} 1 & \eta_{ud} & \eta_{us} \\ -\eta_{ud} & 1 & \eta_{ds} \\ -\eta_{us} & -\eta_{ds} & 1 \end{bmatrix} \begin{bmatrix} \phi_u \\ \phi_d \\ \phi_s \end{bmatrix}, \qquad \begin{bmatrix} a_2 \\ Z \\ a_1 \end{bmatrix} \approx \begin{bmatrix} 1 & \eta'_{ud} & \eta'_{us} \\ -\eta'_{ud} & 1 & \eta'_{ds} \\ -\eta'_{us} & -\eta'_{ds} & 1 \end{bmatrix} \begin{bmatrix} \varphi_u \\ \varphi_d \\ \varphi_s \end{bmatrix}$$

$$\eta_{us} \approx \frac{2\lambda v \mu_{\rm eff}[1 - (\frac{M_A}{2\mu/\sin 2\beta})^2 - \frac{\kappa}{2\lambda}\sin 2\beta]}{m_h^2 - m_s^2}, \qquad \eta'_{ds} \approx \frac{\lambda v \frac{M_A^2}{2\mu_{\rm eff}/\sin 2\beta} - 3\kappa v \mu_{\rm eff}}{m_{a_2}^2 - m_{a_1}^2} \approx \frac{\lambda v}{\mu_{\rm eff}\tan\beta},$$

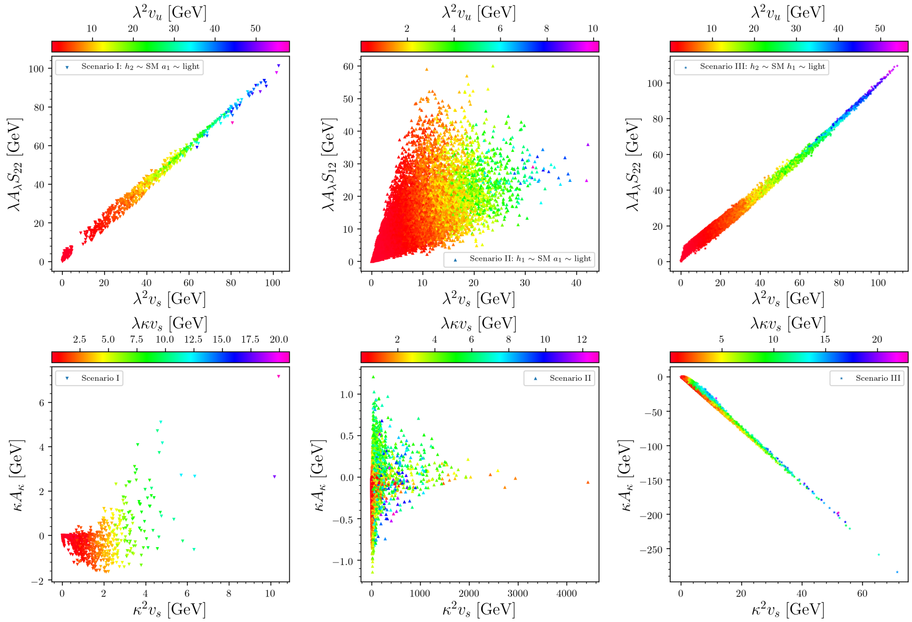
$$\eta_{ud} \approx \frac{1}{\tan\beta}, \qquad \eta'_{ud} \approx \frac{1}{\tan\beta},$$

$$\eta_{ds} \approx -\frac{\eta_{us}}{\tan\beta}, \qquad \eta'_{us} \approx -\frac{\eta'_{ds}}{\tan\beta},$$

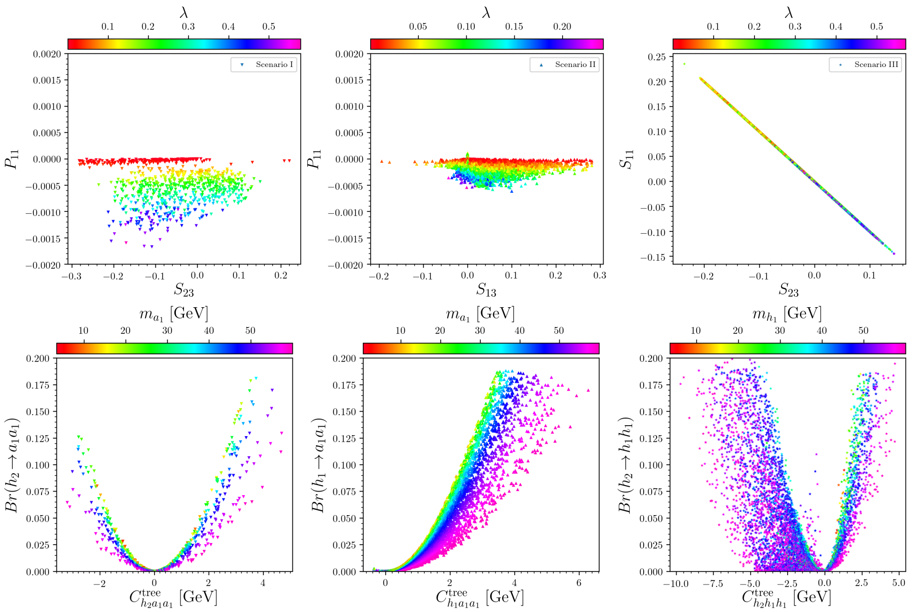
$$|\eta_{ds}| \ll |\eta_{us}|, |\eta_{ud}| \ll 1 \qquad |\eta'_{us}| \ll |\eta'_{ds}|, |\eta'_{ud}| \ll 1$$

- Scenario I : $h_2 \to a_1 a_1$, $S_{23} = \eta_{us}$, $S_{22} = \eta_{ud}$, $P_{11} = \eta'_{us}$, $P_{12} = \eta'_{ds}$;
- Scenario II : $h_1 \to a_1 a_1$, $S_{13} = \eta_{us}$, $S_{12} = \eta_{ud}$, $P_{11} = \eta'_{us}$, $P_{12} = \eta'_{ds}$;
- Scenario III: $h_2 \to h_1 h_1$, $S_{23} = \eta_{us}$, $S_{22} = \eta_{ud}$, $S_{11} = -\eta_{us}$, $S_{12} = \eta_{ds}$.

Light Higgs scalars



Light Higgs scalars



Higgs decay to light scalars

$$C^{\rm tree}_{h_2h_1h_1} = \frac{\lambda^2}{\sqrt{2}}[v_u(\Pi^{122}_{211}+\Pi^{133}_{211}) + v_d(\Pi^{211}_{211}+\Pi^{233}_{211}) + v_s(\Pi^{311}_{211}+\Pi^{322}_{211})] - \frac{\lambda\kappa}{\sqrt{2}}(v_u\Pi^{323}_{211} + v_d\Pi^{313}_{211} + 2v_s\Pi^{123}_{211}) + \sqrt{2}\kappa^2 v_s\Pi^{333}_{211} - \frac{\lambda A_\lambda}{\sqrt{2}}\Pi^{123}_{211} + \frac{\kappa A_\kappa}{3\sqrt{2}}\Pi^{333}_{211} + \frac{g^2}{2\sqrt{2}}\left[v_u(\Pi^{111}_{211}-\Pi^{122}_{211}) - v_d(\Pi^{211}_{211}-\Pi^{222}_{211})\right],$$

where

$$\Pi^{ijk}_{211} = 2S_{2i}S_{1j}S_{1k} + 2S_{1i}S_{2j}S_{1k} + 2S_{1i}S_{1j}S_{2k};$$

$$C^{\rm tree}_{h_aa_1a_1} = \frac{\lambda^2}{\sqrt{2}}[v_u(\Pi^{122}_{a11}+\Pi^{133}_{a11}) + v_d(\Pi^{211}_{a11}+\Pi^{233}_{a11}) + v_s(\Pi^{311}_{a11}+\Pi^{322}_{a11})] + \frac{\lambda\kappa}{\sqrt{2}}[v_u(\Pi^{233}_{a11}-2\Pi^{323}_{a11}) + v_d(\Pi^{133}_{a11}-2\Pi^{313}_{a11}) + 2v_s(\Pi^{312}_{a11}-\Pi^{123}_{a11}-\Pi^{213}_{a11})] + \sqrt{2}\kappa^2 v_s\Pi^{333}_{a11} + \frac{\lambda A_\lambda}{\sqrt{2}}(\Pi^{123}_{a11}+\Pi^{213}_{a11}+\Pi^{312}_{a11}) - \frac{\kappa A_\kappa}{3\sqrt{2}}\Pi^{333}_{a11} + \frac{g^2}{2\sqrt{2}}\left[v_u(\Pi^{111}_{a11}-\Pi^{122}_{a11}) - v_d(\Pi^{211}_{a11}-\Pi^{222}_{a11})\right],$$

where $\Pi^{ijk}_{a11} = 2S_{ai}P_{1j}P_{1k}$ and $a = 1, 2$.

$$C^{\rm tree}_{h_2a_1a_1} \simeq \sqrt{2}\lambda^2 v_u + \sqrt{2}\lambda A_\lambda P_{11}\tan\beta,$$

$$C^{\rm tree}_{h_1a_1a_1} \simeq \sqrt{2}\lambda^2 v_u + \sqrt{2}\lambda A_\lambda P_{11}\tan\beta + 2\sqrt{2}\kappa^2 v_s S_{13},$$

$$C^{\rm tree}_{h_2h_1h_1} \simeq \sqrt{2}\lambda^2 v_u - \sqrt{2}\lambda A_\lambda S_{12} + \sqrt{2}\lambda^2 v_s S_{11} + 2\sqrt{2}\kappa^2 v_s S_{23} + \frac{3g^2}{\sqrt{2}}v_u S_{11}S_{11} - 2\sqrt{2}\lambda\kappa v_s S_{12}.$$

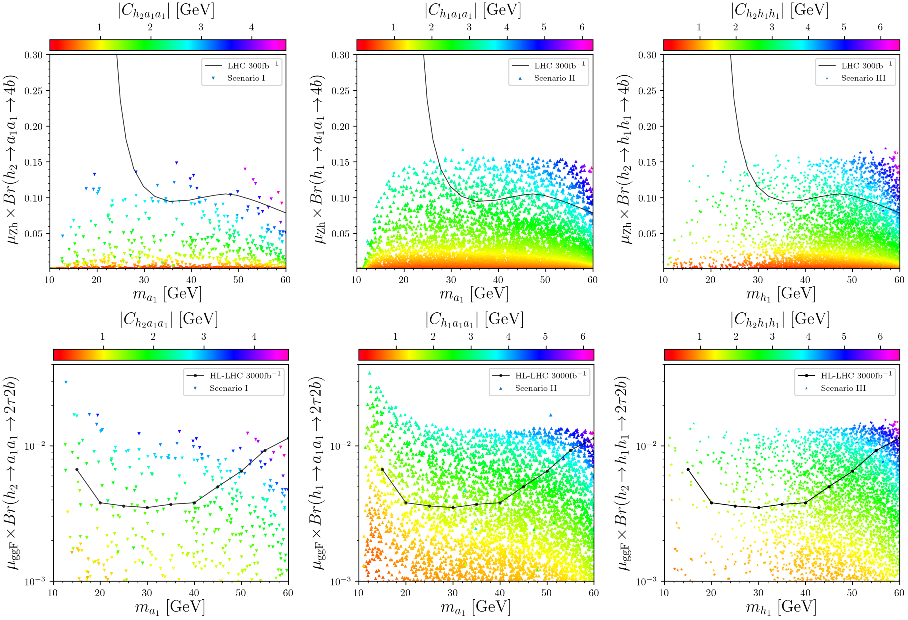
$$\Delta C_{h_2h_1h_1} \simeq S_{21}S_{11}^2\frac{3\sqrt{2}m_t^4}{16\pi^2 v_u^3}\ln\left(\frac{m_{\tilde{t}_1}m_{\tilde{t}_2}}{m_t^2}\right),$$

$$\Delta C_{h_2a_1a_1} \simeq S_{21}P_{11}^2\frac{3\sqrt{2}m_t^4}{16\pi^2 v_u^3}\ln\left(\frac{m_{\tilde{t}_1}m_{\tilde{t}_2}}{m_t^2}\right),$$

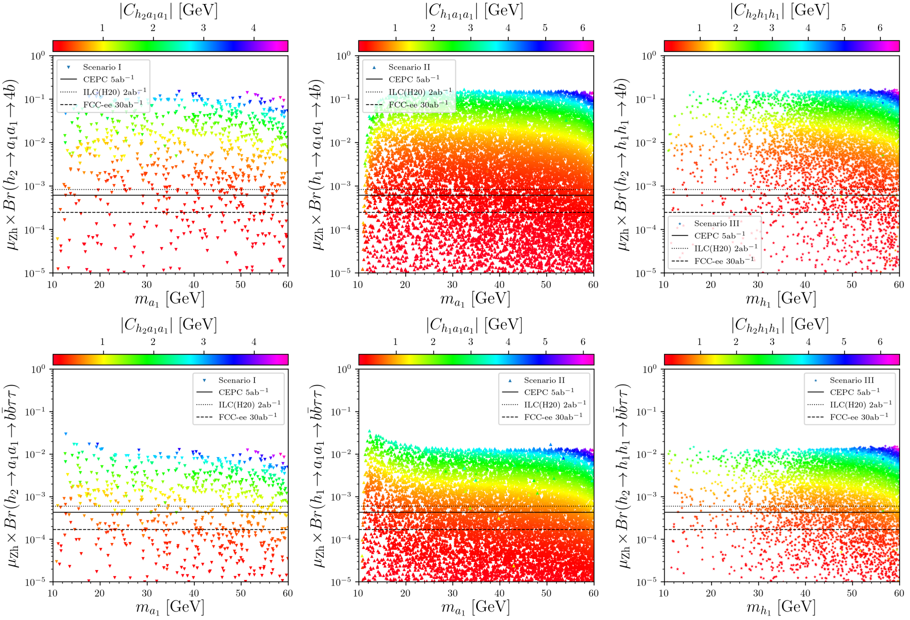
$$\Delta C_{h_1a_1a_1} \simeq S_{11}P_{11}^2\frac{3\sqrt{2}m_t^4}{16\pi^2 v_u^3}\ln\left(\frac{m_{\tilde{t}_1}m_{\tilde{t}_2}}{m_t^2}\right).$$

$P_{11} \ll S_{11}$ or $\eta'_{us} \ll \eta_{us}$

Higgs decay to light scalars



Higgs decay to light scalars



Higgs decay to light scalars

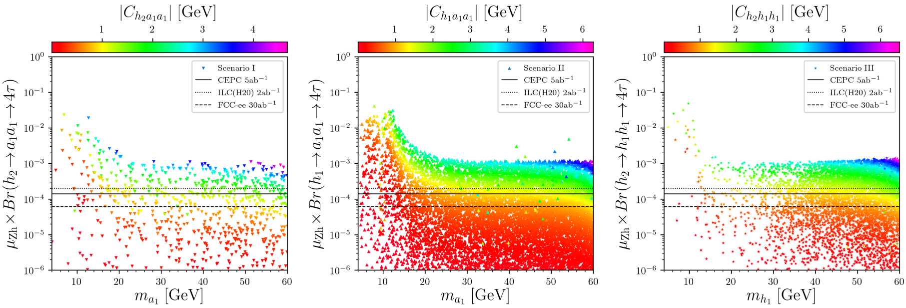
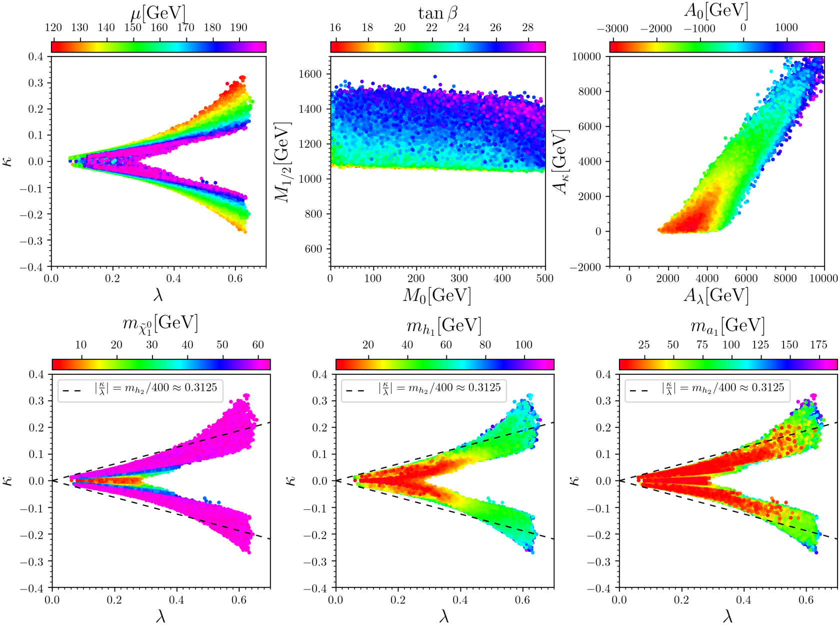


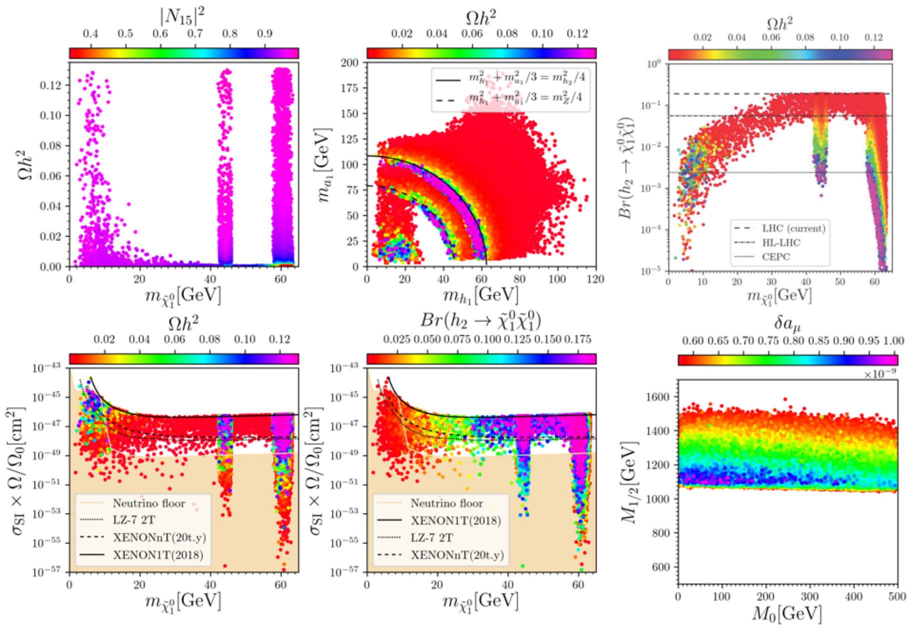
TABLE II. The minimum integrated luminosity for discovering the exotic Higgs decay at the future colliders, where the "@I, II, III" means the three different scenarios.

Deacy Mode	Futrue colliders			
	HL-LHC	CEPC	FCC-*ee*	ILC
$(b\bar{b})(b\bar{b})$	650 fb^{-1}(@II)	0.42 fb^{-1}(@III)	0.41 fb^{-1}(@III)	0.31 fb^{-1}(@II)
$(jj)(jj)$	-	21 fb^{-1}(@II)	18 fb^{-1}(@II)	25 fb^{-1}(@II)
$(\tau^+\tau^-)(\tau^+\tau^-)$	-	0.26 fb^{-1}(@III)	0.22 fb^{-1}(@III)	0.31 fb^{-1}(@III)
$(b\bar{b})(\tau^+\tau^-)$	1500 fb^{-1}(@II)	4.6 fb^{-1}(@II)	3.6 fb^{-1}(@II)	4.4 fb^{-1}(@II)
$(\mu^+\mu^-)(\tau^+\tau^-)$	1000 fb^{-1}(@II)	-	-	-

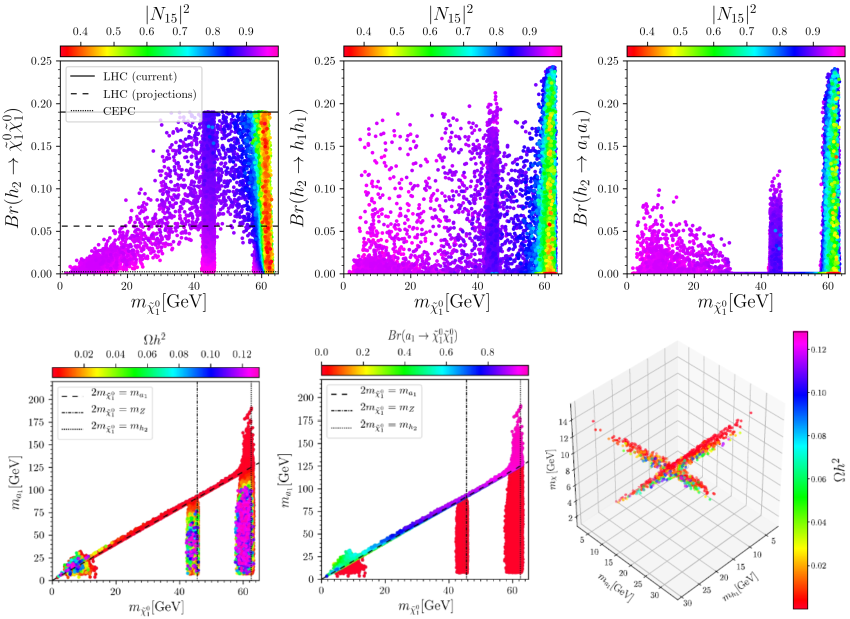
Light dark matter



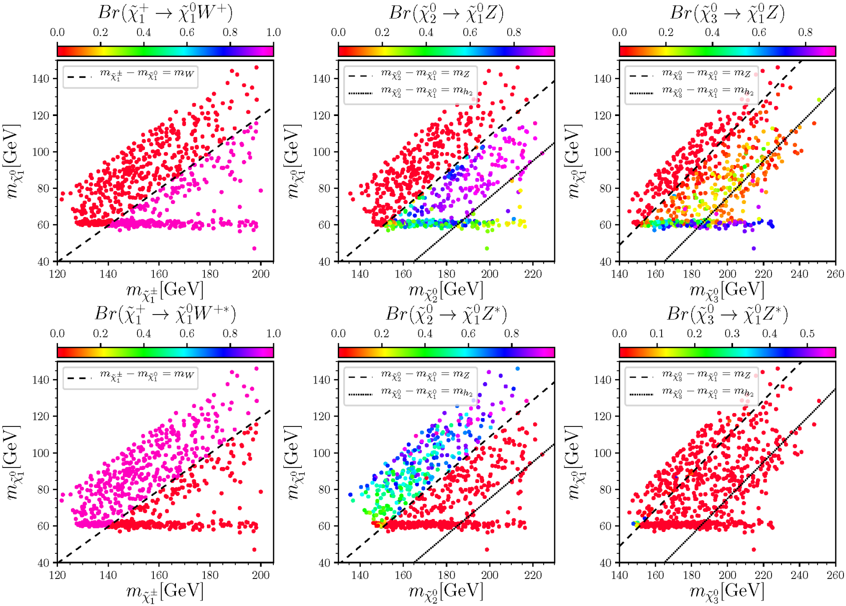
Light dark matter



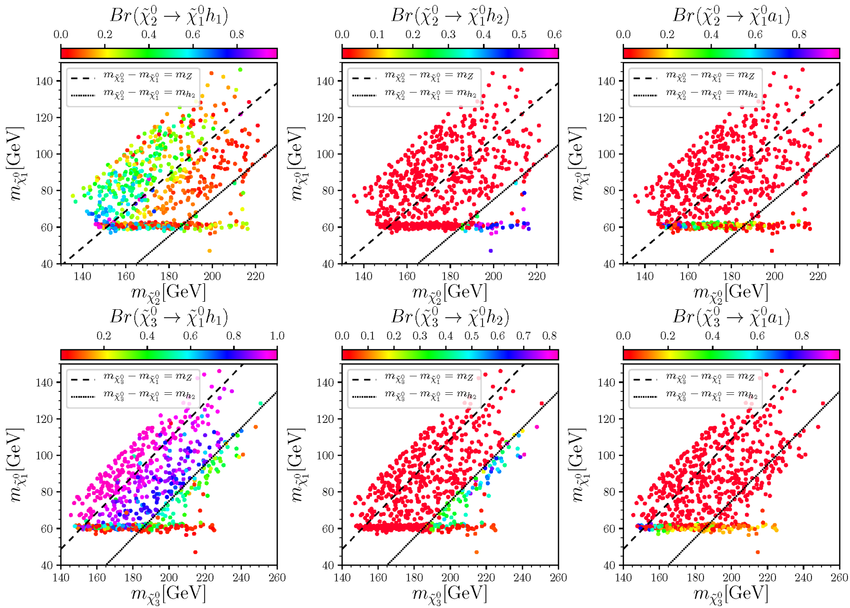
Funnel annihilations of light dark matter and the invisible Higgs decay



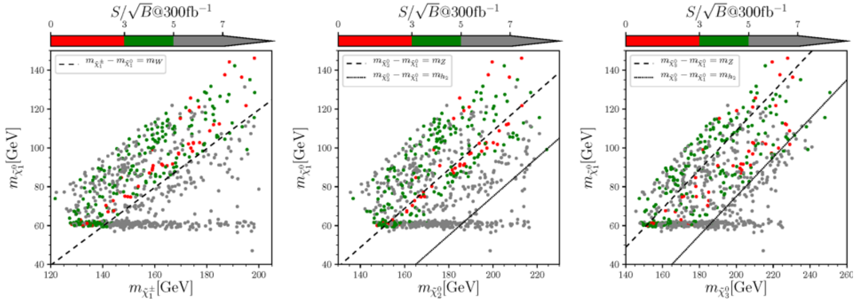
Light Higgsino NLSPs: decay mode

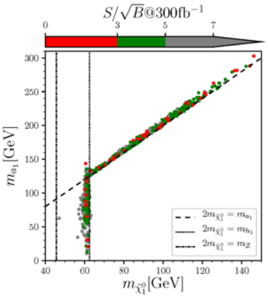


Light Higgsino NLSPs: decay mode

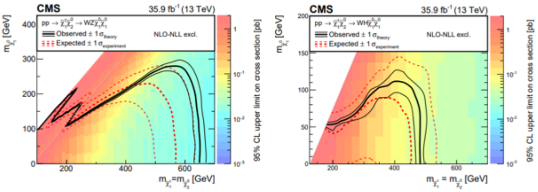


Light Higgsino NLSPs: detections





Wang, Zhu, 1911.08319



CMS, 1801.03957

Several light (s)particles: benchmark points

Point	P1	P2	P3	P4
λ	0.100	0.0693	0.161	0.148
$\kappa[10^{-2}]$	−2.05	1.18	0.182	0.297
$\tan\beta$	27.0	23.9	21.1	23.0
$\mu_{\rm eff}$ [GeV]	150	128	171	166
A_λ [TeV]	3.75	2.23	2.98	3.29
A_κ [GeV]	98.0	126	180	173
M_0 [GeV]	480	432	13.2	302
$M_{1/2}$ [TeV]	1.37	1.11	1.11	1.15
A_0 [TeV]	−1.48	−1.23	−1.58	−1.35
m_{h_2} [GeV]	125.2	124.3	125.1	124.6
m_{h_1} [GeV]	61.1	40.0	15.7	15.5
m_{a_1} [GeV]	19.5	31.0	9.30	7.82
m_χ [GeV]	62.4	44.4	4.00	6.78
$m_{\chi_2^0}$ [GeV]	149	125	170	165
$m_{\chi_3^0}$ [GeV]	160	136	182	176
$m_{\chi_1^\pm}$ [GeV]	153	130	173	169
$m_{\tilde{\tau}_1}$ [GeV]	279	485	128	133
$m_{\tilde{\nu}_\tau}$ [GeV]	270	578	104	109
Ωh^2	0.118	0.116	0.111	0.117
$\mathrm{Br}(h_2\to\chi\chi)[10^{-3}]$	0.03	3.94	2.19	3.52
$\mathrm{Br}(h_1\to\chi\chi)$	0.000	0.000	0.244	0.117
$\mathrm{Br}(a_1\to\chi\chi)$	0.000	0.000	0.194	0.000
$\mathrm{Br}(h_2\to a_1a_1)[10^{-3}]$	2.50	0.67	0.84	0.26
$\mathrm{Br}(h_2\to h_1h_1)[10^{-3}]$	0.13	0.52	2.08	0.45

Wang, Zhu, 2003.01662

$\mathrm{Br}(\chi_1^\pm\to W^\pm\chi)$	1.000	1.000	0.477	0.445
$\mathrm{Br}(\chi_1^\pm\to\tilde{\nu}_\tau\tau^\pm)$	0.000	0.000	0.518	0.552
$\mathrm{Br}(\chi_1^\pm\to\tilde{\tau}_1^\pm\nu_\tau)[10^{-3}]$	0.00	0.00	4.89	2.81
$\mathrm{Br}(\chi_2^0\to Z\chi)$	0.000	0.000	0.322	0.333
$\mathrm{Br}(\chi_2^0\to h_1\chi)$	0.028	0.710	0.021	0.019
$\mathrm{Br}(\chi_2^0\to a_1\chi)$	0.612	0.085	0.012	0.011
$\mathrm{Br}(\chi_2^0\to h_2\chi)$	0.000	0.000	0.141	0.144
$\mathrm{Br}(\chi_2^0\to\tilde{\tau}_1^\pm\tau_1^\mp)$	0.000	0.000	0.388	0.387
$\mathrm{Br}(\chi_2^0\to\tilde{\nu}_\tau\bar{\nu}_\tau)$	0.000	0.000	0.117	0.106
$\mathrm{Br}(\chi_2^0\to\chi f\bar{f})$	0.360	0.205	0.000	0.000
$\mathrm{Br}(\chi_3^0\to Z\chi)$	0.957	0.306	0.422	0.419
$\mathrm{Br}(\chi_3^0\to h_1\chi)$	0.030	0.142	0.013	0.010
$\mathrm{Br}(\chi_3^0\to a_1\chi)$	0.014	0.552	0.012	0.011
$\mathrm{Br}(\chi_3^0\to h_2\chi)[10^{-3}]$	0.000	0.000	0.096	0.080
$\mathrm{Br}(\chi_3^0\to\tilde{\tau}_1^\pm\tau_1^\mp)$	0.000	0.000	0.420	0.443
$\mathrm{Br}(\chi_3^0\to\tilde{\nu}_\tau\bar{\nu}_\tau)$	0.000	0.000	0.037	0.036
$\sigma(pp\to\chi_1^+\chi_2^0)$ [fb]	780	1410	496	548
$\sigma(pp\to\chi_1^-\chi_2^0)$ [fb]	445	833	275	306
$\sigma(pp\to\chi_1^+\chi_3^0)$ [fb]	683	1220	438	485
$\sigma(pp\to\chi_1^-\chi_3^0)$ [fb]	387	714	241	269
$\sigma(pp\to W^\pm Z\chi\chi)$ [fb]	1481	1067	255	267
$\sigma_{95\%}^{\rm lim}$ [fb]	2957	1908	645	625

Summary and Outlook

- New light (s)particles are possible in NMSSM-NUHM
  - Light Higgs (pseudo)scalars (10∼60 GeV)
    - ⋆ mixing between up-doublet, down-doublet, singlet fields
    - ⋆ tuning to get an appropriate exotic decay $h \to ss$
    - ⋆ loop effects in the exotic decay
    - ⋆ detection at HL-LHC and leptonic colliders
  - Light LSP dark matter (1∼60 GeV)
    - ⋆ machine learning to get right relic density (see Kun WANG's talk)
    - ⋆ four funnel-annihilation mechanisms for light LSP dark matter
    - ⋆ correlation between annihilation mechanism and Higgs invisible decay
  - Light Higgs partners (100∼200 GeV)
    - ⋆ simulation for signal at the LHC
    - ⋆ multi-lepton channel most effective to check light Higgsino
    - ⋆ can be checked in the near future with $m_{\text{NLSP}} - m_{\text{LSP}} > m_Z$
  - Light sleptons
    - ⋆ can coexist with light dark matter, Higgs scalar, Higgsino
- The decay mode of heavy (s)particles can be changed, thus new detecting methods are needed, or current experimental results need to be reinterpreted.
- The new (s)particles may play important roles in precision measurements.

Thank you!