The Higgs sector of the $\mu\nu$SSM

Outline

Theoretical and phenomenological motivations

Outline

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The $\mu\nu$SSM: Phenomenology

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Theoretical and phenomenological motivations

The $\mu\nu$SSM: Phenomenology

Summary

The MSSM

$$W = \epsilon_{ij} \left(Y_u \, H_2^j Q^i \, u + Y_d \, H_1^i Q^j \, d + Y_e \, H_1^i L^j \, e - \mu \, H_1^i H_2^j \right)$$

Natural value for $\mu \sim M_{\mathrm{Planck}}$

$$\begin{aligned} -\mathcal{L}_{\mathrm{soft}} &= m_{H_1}^2 \, H_1^* \, H_1 + m_{H_2}^2 \, H_2^* H_2 + \ldots - \epsilon_{ij} (B\mu \, H_1^i H_2^j + H.C.) \\ &- \frac{1}{2} \, (M_3 \, \lambda_3 \, \lambda_3 + M_2 \, \lambda_2 \, \lambda_2 + M_1 \, \lambda_1 \, \lambda_1 + \mathrm{H.c.}) \end{aligned}$$

$M_{\mathrm{soft}} \sim 1$ TeV

For Correct EW and without Hierarchy problem

Correct EW symmetry breaking $V_{\mathrm{Higgs}} \Rightarrow \mu \lesssim 1$ TeV $\Rightarrow$ μ-problem

Respect to LHC

The MSSM is an R-parity conserving model

the LSP is stable

missing energy is expected at LHC.

Goods of the MSSM:

Dark matter candidate:

Neutralino (or gravitino)

Solution to the hierarchy problem

Problems:

μ-problem

Massless Neutrinos

This motivate to postulate a New Supersymmetric Model, with the minimal natural content of fields and without μ-problem

The μ from ν Supersymmetric Standard Model ($\mu\nu$SSM)

We use the right-handed neutrinos superfields in order the give mass to the neutrinos without μ-problem

As a consequence R-parity is explicitly broken

L-F and Carlos Muñoz, *Phys. Rev. Lett. B* **97** (2006) 041801 [arXiv:hep-ph/0508297]

SUSY renormalizable theory: μνSSM

$$W = \epsilon_{ab}\left(Y_u^{ij}\,\hat{H}_2^b\,\hat{Q}_i^a\,\hat{u}_j^c + Y_d^{ij}\,\hat{H}_1^a\,\hat{Q}_i^b\,\hat{d}_j^c + Y_e^{ij}\,\hat{H}_1^a\,\hat{L}_i^b\,\hat{e}_j^c + Y_\nu^{ij}\,\hat{H}_2^b\,\hat{L}_i^a\,\hat{\nu}_j^c\right)$$
$$-\epsilon_{ab}\lambda^i\,\hat{\nu}_i^c\,\hat{H}_1^a\hat{H}_2^b + \frac{1}{3}\kappa^{ijk}\hat{\nu}_i^c\hat{\nu}_j^c\hat{\nu}_k^c\,,$$

+ SOFT TERMS

$M_{SUSY} \sim 1$ TeV

R-parity it is not symmetry of the model

SUSY renormalizable theory: μνSSM

$$W = \epsilon_{ab}\left(Y_u^{ij}\,\hat{H}_2^b\,\hat{Q}_i^a\,\hat{u}_j^c + Y_d^{ij}\,\hat{H}_1^a\,\hat{Q}_i^b\,\hat{d}_j^c + Y_e^{ij}\,\hat{H}_1^a\,\hat{L}_i^b\,\hat{e}_j^c + Y_\nu^{ij}\,\hat{H}_2^b\,\hat{L}_i^a\,\hat{\nu}_j^c\right)$$

$$-\,\epsilon_{ab}\lambda^i\,\hat{\nu}_i^c\,\hat{H}_1^a\hat{H}_2^b + \frac{1}{3}\kappa^{ijk}\hat{\nu}_i^c\hat{\nu}_j^c\hat{\nu}_k^c\,,$$

\+ SOFT TERMS

$M_{SUSY} \sim$ **1 TeV**

All known particles + SUSY partners (including neutrinos physics)

SUSY renormalizable theory: μνSSM

$$W = \epsilon_{ab}\left(Y_u^{ij}\,\hat{H}_2^b\,\hat{Q}_i^a\,\hat{u}_j^c + Y_d^{ij}\,\hat{H}_1^a\,\hat{Q}_i^b\,\hat{d}_j^c + Y_e^{ij}\,\hat{H}_1^a\,\hat{L}_i^b\,\hat{e}_j^c + Y_\nu^{ij}\,\hat{H}_2^b\,\hat{L}_i^a\,\hat{\nu}_j^c\right)$$

$$- \epsilon_{ab}\underbrace{\lambda^i\,\hat{\nu}_i^c}_{\text{Effective }\mu\text{-term}}\,\hat{H}_1^a\hat{H}_2^b + \frac{1}{3}\underbrace{\kappa^{ijk}\hat{\nu}_i^c}_{\text{Effective Majorana Mass}}\hat{\nu}_j^c\hat{\nu}_k^c\,,$$

\+ SOFT TERMS

$M_{SUSY} \sim 1$ TeV

All known particles + SUSY partners (including neutrinos physics)

SUSY renormalizable theory: μνSSM

$$W = \epsilon_{ab}\left(Y_u^{ij}\,\hat{H}_2^b\,\hat{Q}_i^a\,\hat{u}_j^c + Y_d^{ij}\,\hat{H}_1^a\,\hat{Q}_i^b\,\hat{d}_j^c + Y_e^{ij}\,\hat{H}_1^a\,\hat{L}_i^b\,\hat{e}_j^c + Y_\nu^{ij}\,\hat{H}_2^b\,\hat{L}_i^a\,\hat{\nu}_j^c\right)$$
$$- \epsilon_{ab}\lambda^i\,\hat{\nu}_i^c\,\hat{H}_1^a\hat{H}_2^b + \frac{1}{3}\kappa^{ijk}\hat{\nu}_i^c\hat{\nu}_j^c\hat{\nu}_k^c\,,$$

\+ SOFT TERMS

$M_{SUSY} \sim$ 1 TeV

Only one scale: The SUSY breaking scale, only source of gauge breaking

SUSY renormalizable theory: μνSSM

$$W = \epsilon_{ab}\left(Y_u^{ij}\,\hat{H}_2^b\,\hat{Q}_i^a\,\hat{u}_j^c + Y_d^{ij}\,\hat{H}_1^a\,\hat{Q}_i^b\,\hat{d}_j^c + Y_e^{ij}\,\hat{H}_1^a\,\hat{L}_i^b\,\hat{e}_j^c + Y_\nu^{ij}\,\hat{H}_2^b\,\hat{L}_i^a\,\hat{\nu}_j^c\right)$$

$$- \epsilon_{ab}\lambda^i\,\hat{\nu}_i^c\,\hat{H}_1^a\hat{H}_2^b + \frac{1}{3}\kappa^{ijk}\hat{\nu}_i^c\hat{\nu}_j^c\hat{\nu}_k^c\,,$$

\+ SOFT TERMS

$M_{SUSY} \sim$ 1 TeV

The model "behaves properly" up to Planck scale.

Soft Terms

$$\begin{aligned}
-\mathcal{L}_{\rm soft} &= m_{H_1}^2\, H_1^{a\,*}\, H_1^a + m_{H_2}^2\, H_2^{a\,*} H_2^a + (m_{\tilde{\nu}^c}^2)^{ij}\, \tilde{\nu}_i^{c\,*} \tilde{\nu}_j^c + \ldots \\
&+ \left[\epsilon_{ab} (A_\nu Y_\nu)^{ij}\, H_2^b\, \tilde{L}_i^a\, \tilde{\nu}_j^c + \ldots + \frac{1}{3} (A_\kappa \kappa)^{ijk} \tilde{\nu}_i^c \tilde{\nu}_j^c \tilde{\nu}_k^c \; + \text{H.c.}\right] \\
&- \frac{1}{2} \left(M_3\, \tilde{\lambda}_3\, \tilde{\lambda}_3 + M_2\, \tilde{\lambda}_2\, \tilde{\lambda}_2 + M_1\, \tilde{\lambda}_1\, \tilde{\lambda}_1 + \text{H.c.}\right) .
\end{aligned}$$

Are given by SUGRA

SUGRA (local SUSY)

Gravitino Dark matter candidate

$(G_{\mu\nu}, \Psi_\mu)$

(graviton, gravitino)

$M_{Planck} \sim 10^{16}$ TeV

(Non Renormalizable)

Tree level amplitudes

SUSY

$\mu\nu$SSM

$M_{SUSY} \sim 1$ TeV

(Renormalizable)

Similar as in a Fermi theory where

$G_F \sim 1/M_W^2$

Phenomenology of the $\mu\nu$SSM

Since R-parity it is not symmetry of the model the phenomenology is very different to the one of the MSSM

- **Neutrinos mix with neutralino (10 X 10)**
  3 light neutrinos (mainly neutrinos left-handed)
  + 7 mainly neutralinos (including neutrinos right-handed)

- **Neutral Higgs mix with sneutrinos (8 X 8)**
  8 CP even Higgses (5 + 3 mainly sneutrinos left-handed)

  7 CP odd Higgses (4 + 3 mainly sneutrinos left-handed)

The Neutralino-Neutrino mass matrix is:

$$\mathcal{M}_n = \begin{pmatrix} M & m \\ m^T & 0_{3\times 3} \end{pmatrix},$$

$$M = \begin{pmatrix} M_1 & 0 & -Av_d & Av_u & 0 & 0 & 0 \\ 0 & M_2 & Bv_d & -Bv_u & 0 & 0 & 0 \\ -Av_d & Bv_d & 0 & -\lambda_i \nu_i^c & -\lambda_1 v_u & -\lambda_2 v_u & -\lambda_3 v_u \\ Av_u & -Bv_u & -\lambda_i \nu_i^c & 0 & -\lambda_1 v_d + Y_{\nu_{i1}} \nu_i & -\lambda_2 v_d + Y_{\nu_{i2}} \nu_i & -\lambda_3 v_d + Y_{\nu_{i3}} \nu_i \\ 0 & 0 & -\lambda_1 v_u & -\lambda_1 v_d + Y_{\nu_{i1}} \nu_i & 2\kappa_{11j} \nu_j^c & 2\kappa_{12j} \nu_j^c & 2\kappa_{13j} \nu_j^c \\ 0 & 0 & -\lambda_2 v_u & -\lambda_2 v_d + Y_{\nu_{i2}} \nu_i & 2\kappa_{21j} \nu_j^c & 2\kappa_{22j} \nu_j^c & 2\kappa_{23j} \nu_j^c \\ 0 & 0 & -\lambda_3 v_u & -\lambda_3 v_d + Y_{\nu_{i3}} \nu_i & 2\kappa_{31j} \nu_j^c & 2\kappa_{32j} \nu_j^c & 2\kappa_{33j} \nu_j^c \end{pmatrix},$$

where $A = \frac{G}{\sqrt{2}} \sin\theta_W$, $B = \frac{G}{\sqrt{2}} \cos\theta_W$, and

$$m^T = \begin{pmatrix} -\frac{g_1}{\sqrt{2}}\nu_1 & \frac{g_2}{\sqrt{2}}\nu_1 & 0 & Y_{\nu_{1i}}\nu_i^c & Y_{\nu_{11}} v_u & Y_{\nu_{12}} v_u & Y_{\nu_{13}} v_u \\ -\frac{g_1}{\sqrt{2}}\nu_2 & \frac{g_2}{\sqrt{2}}\nu_2 & 0 & Y_{\nu_{2i}}\nu_i^c & Y_{\nu_{21}} v_u & Y_{\nu_{22}} v_u & Y_{\nu_{23}} v_u \\ -\frac{g_1}{\sqrt{2}}\nu_3 & \frac{g_2}{\sqrt{2}}\nu_3 & 0 & Y_{\nu_{3i}}\nu_i^c & Y_{\nu_{31}} v_u & Y_{\nu_{32}} v_u & Y_{\nu_{33}} v_u \end{pmatrix}$$

EW see-saw mechanism

In first approximation the light neutrinos mass matrix is:

$$M_\nu = m^T M^{-1} m$$

With neutrino masses of order $10^{-2}\,\mathrm{eV} = 10^{-11}\,\mathrm{GeV} \Rightarrow$

$$10^{-11}\mathrm{GeV} = \frac{\mathrm{Y}_\nu^2(10^2\mathrm{GeV})^2}{10^3\mathrm{GeV}} \rightarrow Y_\nu \sim 10^{-6}$$

The Neutralino-Neutrino mass matrix is:

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where $A = \frac{G}{\sqrt{2}} \sin\theta_W$, $B = \frac{G}{\sqrt{2}} \cos\theta_W$, and

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Effective Neutrino mass matrix

$$M_\nu = m^T M^{-1} m$$

Using Diagonal Yukawas for Neutrinos

$$(m_{eff|real})_{ij} \simeq \frac{v_u^2}{6\kappa\nu^c} Y_{\nu_i} Y_{\nu_j} \left(1 - 3\,\delta_{ij}\right) - \frac{1}{2M_{eff}} \left[\nu_i \nu_j + \frac{v_d\left(Y_{\nu_i}\nu_j + Y_{\nu_j}\nu_i\right)}{3\lambda} + \frac{Y_{\nu_i} Y_{\nu_j} v_d^2}{9\lambda^2}\right]$$

$$M_{eff} \equiv M\left[1 - \frac{v^2}{2M\left(\kappa\nu^{c^2} + \lambda v_u v_d\right)\, 3\lambda\nu^c}\left(2\kappa\nu^{c^2}\frac{v_u v_d}{v^2} + \frac{\lambda v^2}{2}\right)\right] \qquad \frac{1}{M} = \frac{g_1^2}{M_1} + \frac{g_2^2}{M_2}$$

We have neglected all the terms of order $Y_\nu^2\nu^2$, $Y_\nu^3\nu$ and $Y_\nu\nu^3$

Effective Neutrino mass matrix

(Diagonal Yukawas for Neutrinos)

$$\left(m_{eff|real}\right)_{ij} \simeq \frac{v_u^2}{6\kappa\nu^c} Y_{\nu_i} Y_{\nu_j} \left(1 - 3\,\delta_{ij}\right) - \frac{1}{2M_{eff}} \left[\nu_i \nu_j + \frac{v_d \left(Y_{\nu_i}\nu_j + Y_{\nu_j}\nu_i\right)}{3\lambda} + \frac{Y_{\nu_i} Y_{\nu_j} v_d^2}{9\lambda^2}\right]$$

$$M_{eff} \equiv M \left[1 - \frac{v^2}{2M\left(\kappa\nu^{c^2} + \lambda v_u v_d\right)\, 3\lambda\nu^c}\left(2\kappa\nu^{c^2}\frac{v_u v_d}{v^2} + \frac{\lambda v^2}{2}\right)\right] \qquad \frac{1}{M} = \frac{g_1^2}{M_1} + \frac{g_2^2}{M_2}$$

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(Diagonal Yukawas for Neutrinos)

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$$v_d \longrightarrow 0$$

$$M_{\text{eff}} \approx M$$

$$\left(m_{eff|real}\right)_{ij} \simeq \frac{v_u^2}{6\kappa\nu^c} Y_{\nu_i} Y_{\nu_j} \left(1 - 3\delta_{ij}\right) - \frac{1}{2M} \nu_i \nu_j$$

Effective Neutrino mass matrix

(Diagonal Yukawas for Neutrinos)

$$\left(m_{eff|real}\right)_{ij} \simeq \frac{v_u^2}{6\kappa\nu^c} Y_{\nu_i} Y_{\nu_j} \left(1 - 3\,\delta_{ij}\right) - \frac{1}{2M_{eff}} \left[\nu_i \nu_j + \frac{v_d\left(Y_{\nu_i}\nu_j + Y_{\nu_j}\nu_i\right)}{3\lambda} + \frac{Y_{\nu_i} Y_{\nu_j} v_d^2}{9\lambda^2}\right]$$

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$$v_d \to 0$$
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$$\left(m_{eff|real}\right)_{ij} \simeq \frac{v_u^2}{6\kappa\nu^c} Y_{\nu_i} Y_{\nu_j} \left(1 - 3\delta_{ij}\right) - \frac{1}{2M} \nu_i \nu_j$$

Gaugino see saw

Effective Neutrino mass matrix

(Diagonal Yukawas for Neutrinos)

$$(m_{eff|real})_{ij} \simeq \frac{v_u^2}{6\kappa\nu^c} Y_{\nu_i} Y_{\nu_j} \left(1 - 3\,\delta_{ij}\right) - \frac{1}{2M_{eff}} \left[\nu_i \nu_j + \frac{v_d \left(Y_{\nu_i}\nu_j + Y_{\nu_j}\nu_i\right)}{3\lambda} + \frac{Y_{\nu_i} Y_{\nu_j} v_d^2}{9\lambda^2} \right]$$

$$M_{eff} \equiv M \left[1 - \frac{v^2}{2M\left(\kappa\nu^{c^2} + \lambda v_u v_d\right)\,3\lambda\nu^c} \left(2\kappa\nu^{c^2} \frac{v_u v_d}{v^2} + \frac{\lambda v^2}{2} \right) \right] \qquad \frac{1}{M} = \frac{g_1^2}{M_1} + \frac{g_2^2}{M_2}$$

$v_d \longrightarrow 0$

$M_{\text{eff}} \approx M$

$$(m_{eff|real})_{ij} \simeq \frac{v_u^2}{6\kappa\nu^c} Y_{\nu_i} Y_{\nu_j} (1 - 3\delta_{ij}) - \frac{1}{2M} \nu_i \nu_j$$

ν_R-Higgsino see saw

With diagonal Yukawas for neutrinos we could reproduce the experimental mixing angles.

In a sense we have an explanation of :

Why mixtures in Neutrino and quark sectors are so different?

LHC: Higgs signals

$$W = \epsilon_{ab}\left(Y_u^{ij}\,\hat{H}_2^b\,\hat{Q}_i^a\,\hat{u}_j^c + Y_d^{ij}\,\hat{H}_1^a\,\hat{Q}_i^b\,\hat{d}_j^c + Y_e^{ij}\,\hat{H}_1^a\,\hat{L}_i^b\,\hat{e}_j^c + Y_\nu^{ij}\,\hat{H}_2^b\,\hat{L}_i^a\,\hat{\nu}_j^c\right)$$

$$-\epsilon_{ab}\lambda^i\,\hat{\nu}_i^c\,\hat{H}_1^a\hat{H}_2^b + \frac{1}{3}\kappa^{ijk}\hat{\nu}_i^c\hat{\nu}_j^c\hat{\nu}_k^c\,,$$

$$\begin{aligned} -\mathcal{L}_{\rm soft} &= m_{H_1}^2\,H_1^*\,H_1 + m_{H_2}^2\,H_2^*H_2 + \ldots - \epsilon_{ij}(B\mu\,H_1^iH_2^j + H.C.) \\ &- \frac{1}{2}\,(M_3\,\lambda_3\,\lambda_3 + M_2\,\lambda_2\,\lambda_2 + M_1\,\lambda_1\,\lambda_1 + \mathrm{H.c.}) \end{aligned}$$

$$\lambda_i = \lambda,\ \tan\beta,\ \kappa_{iii},\ \nu_i^c = \nu^c,\ \nu_1,\ \nu_2 = \nu_3,\ Y_{\nu_1},\ Y_{\nu_2} = Y_{\nu_3},\ A_\lambda,\ A_\kappa,\ M_2,$$

LHC: Higgs signals

$$W = \epsilon_{ab} \left(Y_u^{ij} \, \hat{H}_2^b \, \hat{Q}_i^a \, \hat{u}_j^c + Y_d^{ij} \, \hat{H}_1^a \, \hat{Q}_i^b \, \hat{d}_j^c + Y_e^{ij} \, \hat{H}_1^a \, \hat{L}_i^b \, \hat{e}_j^c + Y_\nu^{ij} \, \hat{H}_2^b \, \hat{L}_i^a \, \hat{\nu}_j^c \right)$$

$$- \epsilon_{ab} \lambda^i \, \hat{\nu}_i^c \, \hat{H}_1^a \hat{H}_2^b + \frac{1}{3} \kappa^{ijk} \hat{\nu}_i^c \hat{\nu}_j^c \hat{\nu}_k^c \,,$$

$$\begin{aligned} -\mathcal{L}_{\text{soft}} &= m_{H_1}^2 \, H_1^* \, H_1 + m_{H_2}^2 \, H_2^* H_2 + \ldots - \epsilon_{ij} (B\mu \, H_1^i H_2^j + H.C.) \\ &- \frac{1}{2} \, (M_3 \, \lambda_3 \, \lambda_3 + M_2 \, \lambda_2 \, \lambda_2 + M_1 \, \lambda_1 \, \lambda_1 + \text{H.c.}) \end{aligned}$$

$$\lambda_i = \lambda, \;\; \tan\beta, \;\; \kappa_{iii}, \;\; \nu_i^c = \nu^c, \;\; \nu_1, \;\; \nu_2 = \nu_3, \;\; Y_{\nu_1}, \;\; Y_{\nu_2} = Y_{\nu_3}, \;\; A_\lambda, \;\; A_\kappa, \;\; M_2,$$

Gauge unification $M_1 = \frac{\alpha_1^2}{\alpha_2^2} M_2, M_3 = \frac{\alpha_3^2}{\alpha_2^2} M_2$ $\quad M_1 \approx 0.5 M_2, \; M_3 = 2.7 \, M_2 \, .$

Lightest Higgs (tree level bound)

$$m_h^2 \leq M_Z^2 \left(\cos^2 2\beta + \frac{2\boldsymbol{\lambda}^2 \cos^2\theta_W}{g_2^2} \sin^2 2\beta \right) \approx M_Z^2 \left(\cos^2 2\beta + 3.62\, \boldsymbol{\lambda}^2 \sin^2 2\beta \right)$$

$$\boldsymbol{\lambda}^2 = \lambda_i \lambda_i$$

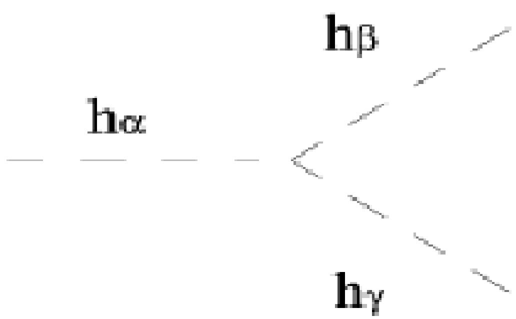
Landau pole condition (GUT) $\Longrightarrow$ $\boldsymbol{\lambda}^2 \lesssim (0.7)^2$ $\quad \lambda \equiv \lambda_i \lesssim 0.7/\sqrt{3} \approx 0.4$

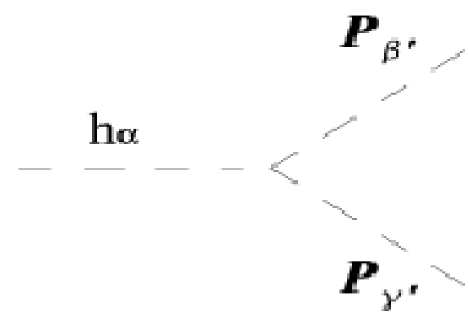
$$\text{for } \tan\beta = 2(4) \quad \Longrightarrow \quad m_h \lesssim 111(98) \text{ GeV}$$

Pure doublet $\longrightarrow$ $\lambda_i \to 0$ or $A_{\lambda_i} = \frac{2\mu}{\sin 2\beta} - \frac{2}{\lambda_i} \sum_{j,k} \kappa_{ijk} \lambda_j \nu_k^c$

1 loop $\longrightarrow$ $m_h \lesssim 140$ GeV

$h_1 \to 2$ Standard Model fermions



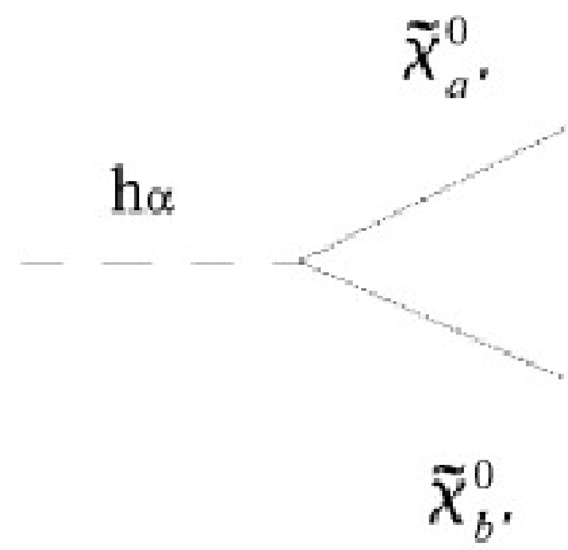


$$h_\alpha \to h_\beta h_\gamma \ , \qquad h_\alpha \to P_{\beta'} P_{\gamma'} \ , \qquad P_{\alpha'} \to P_{\beta'} h_\gamma \ ,$$

where $\alpha,\ \beta,\ \gamma = 1, \ldots, 8$ and $\alpha',\ \beta',\ \gamma' = 1, \ldots, 7$.

For example we have

$$h_3 \to 2h_2 \to 4h_1 \to 8 \text{ Standard Model fermions}$$

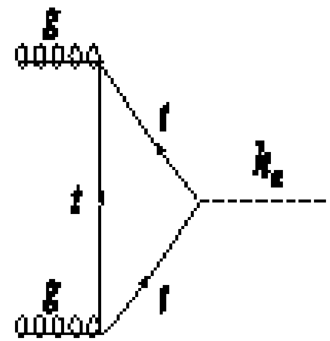


: $h_4 \to \tilde{\chi}^0\tilde{\chi}^0 \to 2P2\nu \to 2\tau^+2\tau^-2\nu$.

$h_4 \to \tilde{\chi}^0\tilde{\chi}^0 \to 2P2\nu \to 2b2\bar{b}2\nu$.

We took three light singlet-like Higgses, the four is doublet-like

Gluon Fusion dominate the Higgs production at LHC



$$\sigma(gg \to h_4) = \sigma(gg \to H_{\rm SM})\frac{\Gamma(h_4 \to gg)}{\Gamma(H_{\rm SM} \to gg)} \simeq \sigma(gg \to H_{\rm SM})$$

$$0.75\ \sigma(gg \to H_{\rm SM}) \lesssim \sigma(gg \to h_4) \lesssim \sigma(gg \to H_{\rm SM})$$

$\sigma(gg \to H_{\rm SM})$ is about $17 - 19.5$ pb For center of mass energy of 7 TeV

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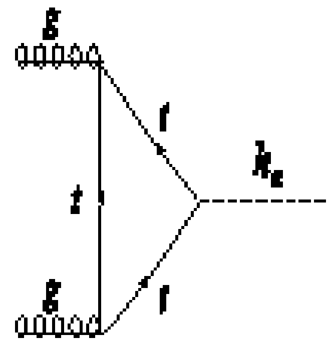

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$\sigma(gg \to H_{\rm SM})$ is about $17 - 19.5$ pb For center of mass energy of 7 TeV

Many Colliders constraints

- $h \to$ invisible [36, 37]. Here we are assuming as invisible the light neutrinos. A more elaborated analysis requires a re-analysis of LEP data, taking into account for instance that neutralinos could partially contribute to the missing energy when the decay distance is comparable to the size of the detector. We have checked that in the points where the decay length of the lightest neutralino is considerably greater than $\mathcal{O}(1\text{ m})$, considering also the LSP as invisible, the constraint is satisfied.
- $h \to \gamma\gamma$, from LEP Higgs working group results [19].
- $h \to b\bar{b}$, from the LEP Higgs working group [21].
- h to two jets, from OPAL and the LEP Higgs working group, both at LEP2 [38, 39].
- $h \to \tau^+\tau^-$, from the LEP Higgs working group [21].
- $h \to PP$ with PP decaying to 4 jets, 2 jets + cc, 2 jets + $\tau^+\tau^-$, 4 $\tau' s$, cccc, $\tau\tau + cc$, from OPAL results [26].

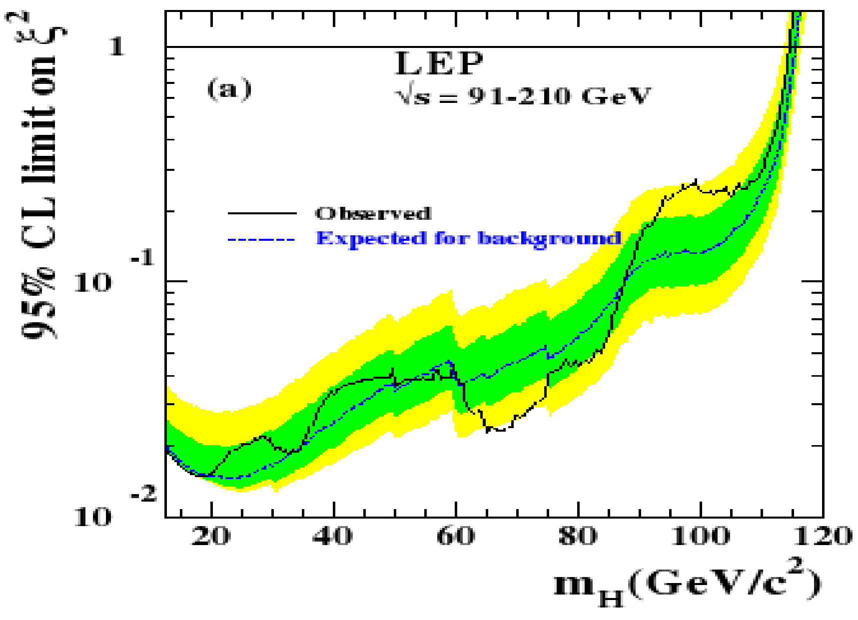
2) For $e^+e^- \to hP$ with hP decaying into $4\,b$, $4\,\tau$, and $PPP \to 6b$ studied by DELPHI [23].

3) For $e^+e^- \to hZ \to PPZ \to 4b + 2jets$ the DELPHI constraints [23].

4) For $e^+e^- \to hZ$ independent of h decay mode, combining the results of ALEPH and OPAL collaborations [36, 21].

……

One of the most important LEP constraints



G. Abbiendi *et al.*, LEP Working Group for Higgs Boson Searches, *Phys. Lett.* **B565** (2003) 61 [arXiv:hep-ex/0306033].

LHC: CMS

CMS PAS HIG-11-022

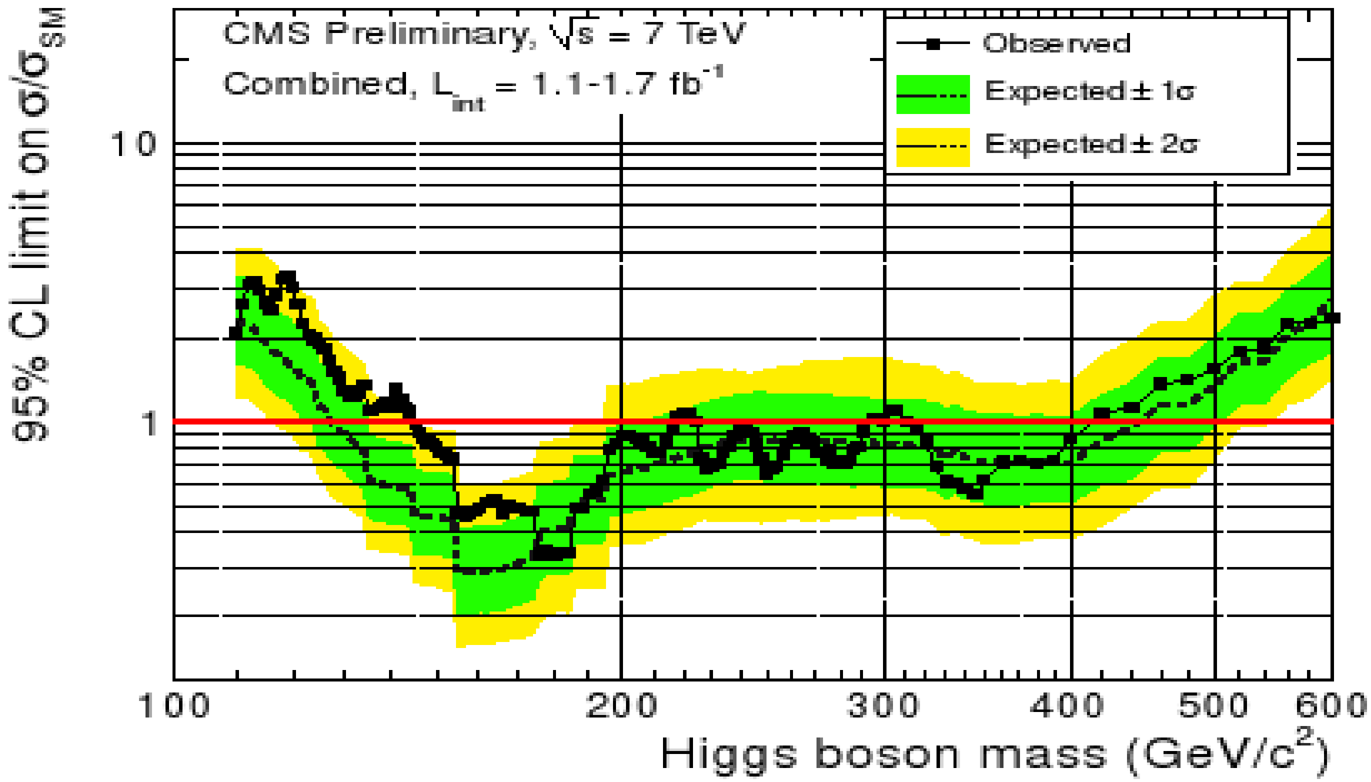


Figure 21: The combined 95% C.L. upper limits on the signal strength modifier $\mu = \sigma/\sigma_{SM}$, as a function of the SM Higgs boson mass in the range 110-600 GeV/c^2. The observed limits are shown by the solid symbols and the black line. The dashed line indicates the median expected limit on μ for the background-only hypothesis, while the green/yellow bands indicate the ranges that are expected to contain 68%/95% of all observed limit excursions from the median.

CMS PAS HIG-11-032

LHC: CMS

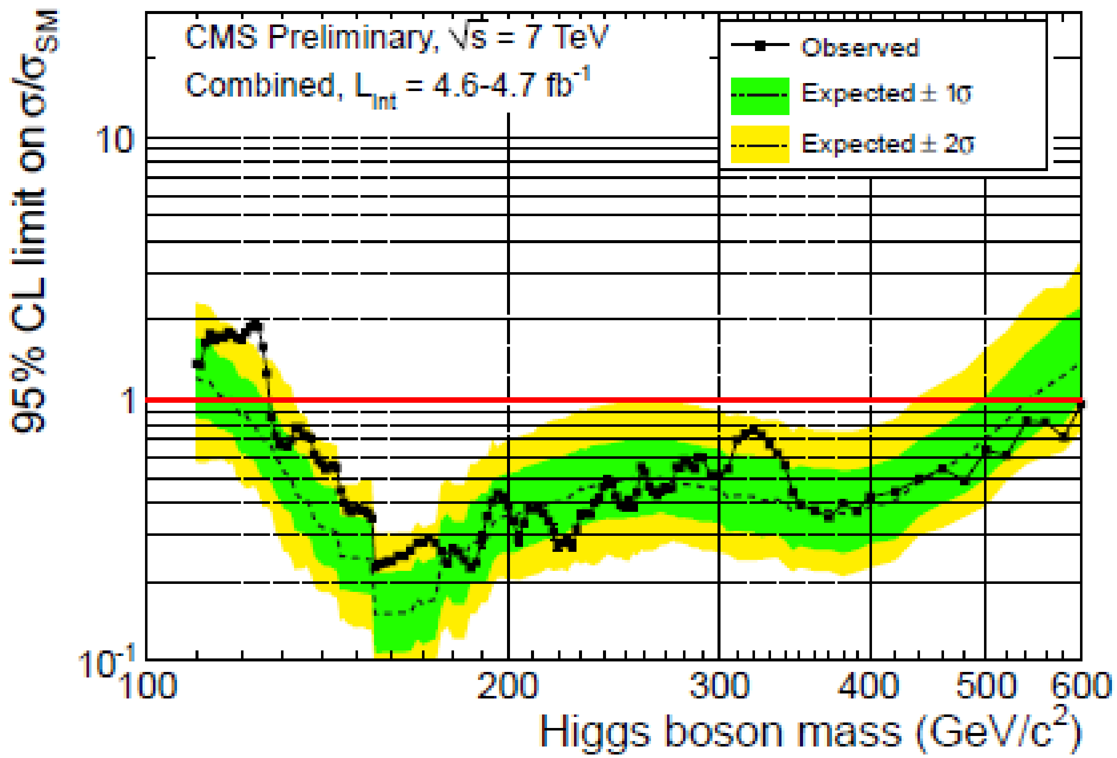
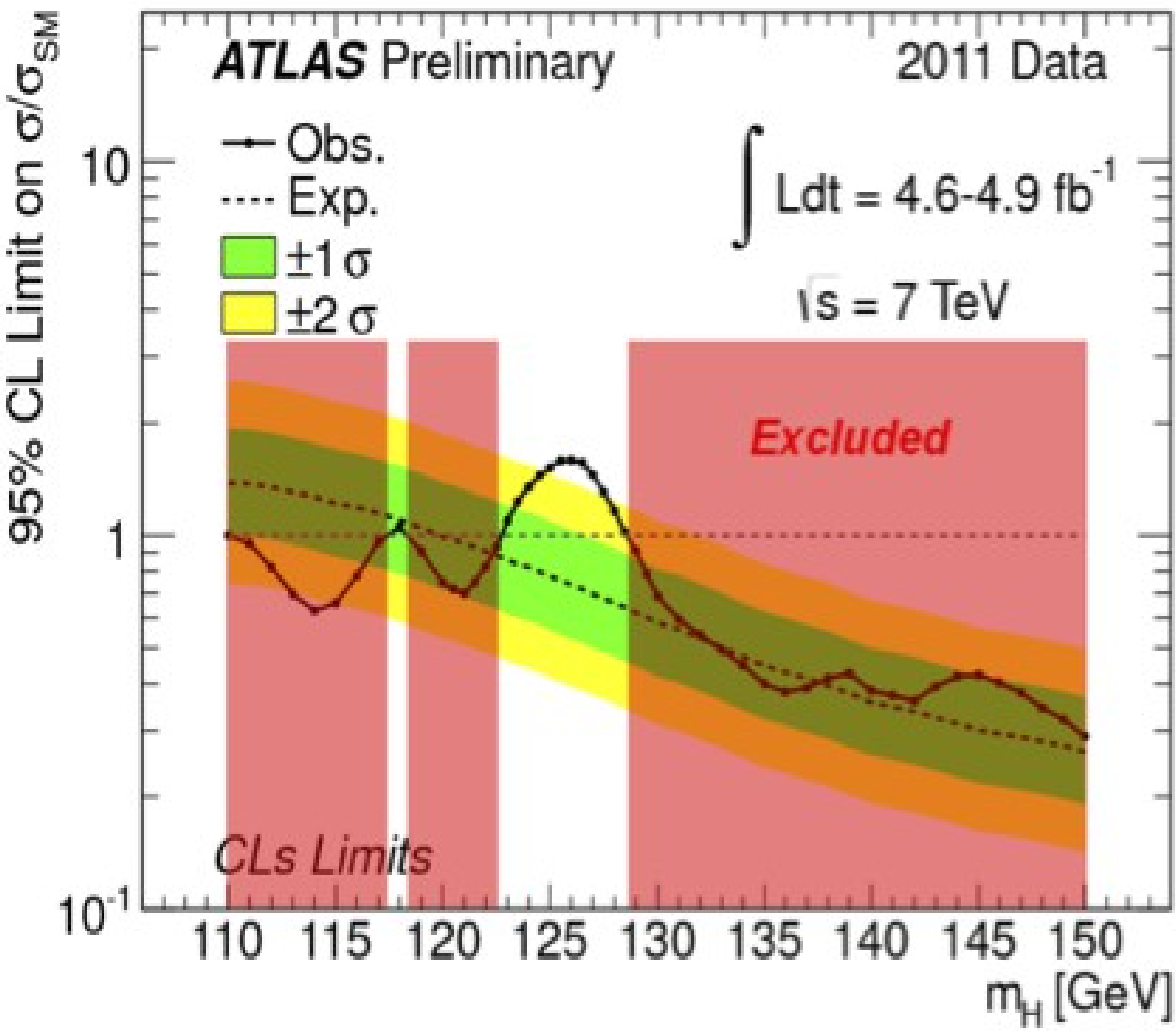


Figure 2: The combined 95% C.L. upper limits on the signal strength modifier $\mu = \sigma/\sigma_{SM}$ as a function of the SM Higgs boson mass in the range 110–600 GeV$/c^2$. The observed limits are shown by the solid symbols and the black line. The dashed line indicates the median expected limit on μ for the background-only hypothesis, while the green (yellow) bands indicate the ranges that are expected to contain 68% (95%) of all observed limit excursions from the median.

From Sandra Kortner talk at
Recontres Moriond 2012



Fidalgo, L-F, Munoz, Ruiz de Austri, 2011

Benchmark point	Cascade	$\sigma(gg \to h_4) \times BR_{\text{cascade}}$ (fb)
1	$h_4 \to \tilde{\chi}_4^0 \tilde{\chi}_4^0 \to 2P2\nu \to 2b2\bar{b}2\nu$	270
	$h_4 \to \tilde{\chi}_4^0 \tilde{\chi}_4^0 \to 2h2\nu \to 4P2\nu \to 4b4\bar{b}2\nu$	44
2	$h_4 \to \tilde{\chi}_4^0 \tilde{\chi}_4^0 \to 2P2\nu \to 2\tau^+2\tau^-2\nu$	1620
3	$h_4 \to \tilde{\chi}_4^0 \tilde{\chi}_4^0 \to 2P2\nu \to 2b2\bar{b}2\nu$	70
4	$h_4 \to \tilde{\chi}_4^0 \tilde{\chi}_4^0 \to 2P2\nu \to 2b2\bar{b}2\nu$	5860
5	$h_4 \to \tilde{\chi}_4^0 \tilde{\chi}_4^0 \to 2P2\nu \to 2b2\bar{b}2\nu$	4870
6	$h_1 \to \tilde{\chi}_4^0 \tilde{\chi}_4^0 \to 2l2q2\bar{q}$	150
	$h_1 \to \tilde{\chi}_4^0 \tilde{\chi}_4^0 \to 2\nu 2l2\bar{l}$	80
	$h_1 \to \tilde{\chi}_4^0 \tilde{\chi}_4^0 \to 2\nu 2q2\bar{q}$	40
	$h_1 \to \tilde{\chi}_4^0 \tilde{\chi}_4^0 \to 6\nu$	15
7	$h_4 \to 2P \to 2b2\bar{b}$	5450
	$h_4 \to 2h_1 \to 4P \to 4b4\bar{b}$	460
8	$h_4 \to 2P_3 \to 2b2\bar{b}$	1660
	$h_4 \to h_1 h_1 \to 4P_{1,2} \to 4\tau^+4\tau^-$	460
	$h_4 \to \tilde{\chi}_4^0 \tilde{\chi}_4^0 \to 2P_{1,2}2\nu \to 2\tau^+2\tau^-2\nu$	80
	$h_4 \to \tilde{\chi}_4^0 \tilde{\chi}_4^0 \to 2h2\nu \to 4P_{1,2}2\nu \to 4\tau^+4\tau^-2\nu$	150
	$h_4 \to \tilde{\chi}_4^0 \tilde{\chi}_4^0 \to 2P_3 2\nu \to 2b2\bar{b}2\nu$	20

Table 9: Production cross section multiplied by branching ratios of the cascades, for the benchmark points discussed in the text.

Fidalgo, L-F, Munoz, Ruiz de Austri, 2011

Benchmark point	Cascade	$\sigma(gg \to h_4) \times BR_{\text{cascade}}$ (fb)
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	$h_4 \to \tilde{\chi}_4^0 \tilde{\chi}_4^0 \to 2h2\nu \to 4P2\nu \to 4b4\bar{b}2\nu$	44
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	$h_1 \to \tilde{\chi}_4^0 \tilde{\chi}_4^0 \to 2\nu 2l2\bar{l}$	80
	$h_1 \to \tilde{\chi}_4^0 \tilde{\chi}_4^0 \to 2\nu 2q2\bar{q}$	40
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	$h_4 \to \tilde{\chi}_4^0 \tilde{\chi}_4^0 \to 2P_{1,2}2\nu \to 2\tau^+2\tau^-2\nu$	80
	$h_4 \to \tilde{\chi}_4^0 \tilde{\chi}_4^0 \to 2h2\nu \to 4P_{1,2}2\nu \to 4\tau^+4\tau^-2\nu$	150
	$h_4 \to \tilde{\chi}_4^0 \tilde{\chi}_4^0 \to 2P_3 2\nu \to 2b2\bar{b}2\nu$	20

Table 9: Production cross section multiplied by branching ratios of the cascades, for the benchmark points discussed in the text.

λ	κ_{111}	κ_{222}	κ_{333}	A_κ (GeV)	M_2 (GeV)
1.0×10^{-1}	7.7×10^{-3}	7.5×10^{-3}	7.3×10^{-3}	-1.0	-1.7×10^3
$\tan\beta$	A_λ (GeV)	ν_1 (GeV)	$\nu_{2,3}$(GeV)	Y_{ν_1}	$Y_{\nu_{2,3}}$
3.7	1.0×10^3	2.92×10^{-5}	1.46×10^{-4}	2.70×10^{-8}	1.51×10^{-7}
ν^c (GeV)	m_{h_1} (GeV)	m_{h_2} (GeV)	m_{h_3} (GeV)	m_{h_4} (GeV)	m_{P_1} (GeV)
8.0×10^2	13.6	13.9	17.0	116.2	8.4
m_{P_2} (GeV)	m_{P_3} (GeV)	$m_{\tilde{\chi}^0_4}$ (GeV)	$m_{\tilde{\chi}^0_5}$ (GeV)	$m_{\tilde{\chi}^0_8}$ (GeV)	—
9.5	9.6	11.8	12.2	14.0	—
$BR(h_4 \to \sum_{i,j=4}^{6} \tilde{\chi}^0_i \tilde{\chi}^0_j)$	$BR(\tilde{\chi}^0_4 \to \sum_{i=1}^{3} P_i \nu)$	$BR(P_1 \to \tau^+\tau^-)$	$BR(P_2 \to \tau^+\tau^-)$	$BR(P_3 \to \tau^+\tau^-)$	$l_{\tilde{\chi}^0_4 \to}$ (cm)
0.12	1.0	0.89	0.83	0.82	189

benchmark point 2

λ	κ_{111}	κ_{222}	κ_{333}	A_κ (GeV)	M_2 (GeV)
1.0×10^{-1}	1.66×10^{-2}	1.65×10^{-2}	1.64×10^{-2}	-5.0	-1.7×10^3
$\tan\beta$	A_λ (GeV)	ν_1 (GeV)	$\nu_{2,3}$(GeV)	Y_{ν_1}	$Y_{\nu_{2,3}}$
4.9	1.0×10^3	5.84×10^{-5}	2.25×10^{-4}	1.25×10^{-7}	2.26×10^{-7}
ν^c (GeV)	m_{h_1} (GeV)	m_{h_2} (GeV)	m_{h_3} (GeV)	m_{h_4} (GeV)	m_{P_1} (GeV)
8.0×10^2	19.8	21.6	21.8	120.2	8.8
m_{P_2} (GeV)	m_{P_3} (GeV)	$m_{\tilde{\chi}^0_4}$ (GeV)	$m_{\tilde{\chi}^0_5}$ (GeV)	$m_{\tilde{\chi}^0_8}$ (GeV)	—
8.9	16.9	26.3	26.5	27.8	—
$BR(h_4 \to h_1 h_1)$	$BR(h_4 \to P_3 P_3)$	$BR(h_4 \to \sum_{i,j=4}^{6} \tilde{\chi}^0_i \tilde{\chi}^0_j)$	$BR(h_4 \to b\bar{b})$	$BR(h_1 \to \sum_{i,j=1}^{2} P_i P_j)$	$BR(h_{2,3} \to \sum_{i,j=1}^{2} P_i P_j)$
0.05	0.12	0.06	0.55	0.98	1.0
$BR(P_{1,2} \to \tau^+\tau^-)$	$BR(P_3 \to b\bar{b})$	$BR(\tilde{\chi}^0_4 \to \sum_{i=1}^{3} h_i \nu)$	$BR(\tilde{\chi}^0_4 \to P_{1,2}\nu)$	$BR(\tilde{\chi}^0_4 \to P_3\nu)$	$l_{\tilde{\chi}^0_4}$ (cm)
0.88	0.93	0.51	0.33	0.16	15

benchmark point 8.

Possible signals at LHC

Displaced vertices

multi-jets plus missing energy

multi-leptons plus missing energy

SUMMARY

❶ The μνSSM includes right-handed neutrino superfields to solve the μ-problem of the MSSM generating also the masses for the neutrinos. The only source for EW breaking are the soft terms

❷ After EW symmetry breaking → see saw mechanism at EW scale (is possible to reproduce experiments with diagonal Yukawas for the leptonic sector)

❸ Gravitino can be the Dark Matter giving visible signals Fermi satellite

❹ LHC the Higgs phenomenology is very rich. Multileptons and/or multijets decays are possible

Higgs Prodution by: quark quark fusion

$$\sigma(b\bar{b} \to h_4) = \sigma(b\bar{b} \to H_{\rm SM}) \left(\frac{Y_{bbh_4}}{Y_{bbH_{\rm SM}}}\right)^2 = \sigma(b\bar{b} \to H_{\rm SM}) \frac{S^2(d,4)}{\cos^2\beta}$$

Neutrino Physics

$$7.14 < \Delta m^2_{sol}/10^{-5}\ \mathrm{eV}^2 < 8.19\ ,\ 2.06 < \Delta m^2_{atm}/10^{-3}\ \mathrm{eV}^2 < 2.81$$

$$0.263 < \sin^2\theta_{12} < 0.375\ ,\ \sin^2\theta_{13} < 0.046\ ,\ 0.331 < \sin^2\theta_{23} < 0.644$$

- Charginos mix with charged leptons

$$\Psi^{+T} = (-i\tilde{\lambda}^+, \tilde{H}_u^+, e_R^+, \mu_R^+, \tau_R^+) \qquad \Psi^{-T} = (-i\tilde{\lambda}^-, \tilde{H}_d^-, e_L^-, \mu_L^-, \tau_L^-)$$

$$-\frac{1}{2}(\psi^{+T}, \psi^{-T}) \begin{pmatrix} 0 & M_C^T \\ M_C & 0 \end{pmatrix} \begin{pmatrix} \psi^{+T} \\ \psi^{-T} \end{pmatrix}$$

$$M_C = \begin{pmatrix} M_2 & g_2 v_u & 0 & 0 & 0 \\ g_2 v_d & \lambda_i \nu_i^c & -Y_{e_{i1}} \nu_i & -Y_{e_{i2}} \nu_i & -Y_{e_{i3}} \nu_i \\ g_2 \nu_1 & -Y_{\nu_{1i}} \nu_i^c & Y_{e_{11}} v_d & Y_{e_{12}} v_d & Y_{e_{13}} v_d \\ g_2 \nu_2 & -Y_{\nu_{2i}} \nu_i^c & Y_{e_{21}} v_d & Y_{e_{22}} v_d & Y_{e_{23}} v_d \\ g_2 \nu_3 & -Y_{\nu_{3i}} \nu_i^c & Y_{e_{31}} v_d & Y_{e_{32}} v_d & Y_{e_{33}} v_d \end{pmatrix}$$

- Neutral Higgs mix with sneutrinos

- Charged Higgs mix with charged sleptons