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Displaced vertices probing the μ-from-ν supersymmetric standard model (munuSSM)

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Introduction

MSSM: The Minimal Supersymmetric Standard Model

R-parity conserving model

MSSM: The Minimal Supersymmetric Standard Model

R-parity conserving model

R-parity
is a Z^2
symmetry

SUSY particles appear in even numbers. As a result the lightest SUSY particle, LSP, can not decay

MSSM: The Minimal Supersymmetric Standard Model

R-parity conserving model ⇨

The LSP is a good dark matter candidate. In particular:

Neutralino: Direct detection is possible

Gravitino: Really this candidate does not need an exact symmetry (to make it stable) to be a good candidate (interacts only gravitationally: can naturally be long life enough)

Also such symmetry complicates it viability (gravitino problem)

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Problems: μ-problem: It is necessary to include a SUSY conserving mass, but can not be at the natural scales, GUT (or Planck), in order to properly break EW symmetry spontaneously

Massless Neutrinos: To solve this GUT scale see-saw can be used

Regarding the superpotential:

$$W_0 = \epsilon_{ab} \left(Y_u^{ij} \, \hat{H}_2^b \, \hat{Q}_i^a \, \hat{u}_j^c + Y_d^{ij} \, \hat{H}_1^a \, \hat{Q}_i^b \, \hat{d}_j^c + Y_e^{ij} \, \hat{H}_1^a \, \hat{L}_i^b \, \hat{e}_j^c \right)$$

MSSM

$W_0 + \mu H_1 H_2$

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MSSM

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NMSSM solves the μ-problem adding a new superfield

$$W_0 + \lambda S H_1 H_2 + k S S S$$

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$$+ Y_\nu H_2 L \nu^c + M_M \nu^c \nu^c$$

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This are R-parity conserving models ….. But …..

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MSSM $\qquad W_0 + \mu \, H_1 \, H_2$

NMSSM solves the μ-problem adding a new superfield $\qquad W_0 + \lambda \, S \, H_1 \, H_2 + k \, S \, S \, S$

GUT scale see-saw can be used to give mass to the neutrinos $\qquad + \, Y_\nu \, H_2 \, L \, \nu^c + M_M \, \nu^c \nu^c$

This are R-parity conserving models ….. But …..

We do not need to add a new extra singlet superfield as in the NMSSM to solve the μ-problem • • •

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

SUSY model with minimal natural content of matter

Right-handed neutrino superfield(s) giving mass to the neutrinos

and solving the μ-problem of the MSSM

As a consequence: R-parity is explicitly broken

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

SUGRA (local SUSY)

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

(graviton, gravitino)

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

(Non Renormalizable)

Tree level amplitudes

Dark Matter candidate

SUSY

$\mu\nu$SSM

$M_{SUSY} \sim 1$ TeV

(Renormalizable)

Similar as in a Fermi theory where

$G_F \sim 1/M_W^2$

The Model

SUSY renormalizable model: μνSSM

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

All known particles + SUSY partners (including neutrinos physics)

SUSY renormalizable model: μνSSM

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

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

Only dimensionless parameters in the superpotential

Possible interpretation: particles are in principle massless but the spontaneous breaking of supersymmetry in the SUGRA theory generates the soft terms (breaking explicitly global SUSY)

SUSY renormalizable model: μνSSM

Soft Terms

Are given by SUGRA

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

The SUSY breaking scale, only source of spontaneous gauge breaking.

THE ONLY SCALE

SUSY renormalizable model: μνSSM

$$W = \epsilon_{ab}\left(Y_u^{ij}\,\hat{H}_2^b\,\hat{Q}_i^a\,\hat{u}_j^c + Y_d^{ij}\,\hat{H}_1^a\,\hat{Q}_i^b\,\hat{d}_j^c + Y_e^{ij}\,\hat{H}_1^a\,\hat{L}_i^b\,\hat{e}_j^c + Y_\nu^{ij}\,\hat{H}_2^b\,\hat{L}_i^a\,\hat{\nu}_j^c\right)$$
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R-parity is not a symmetry of the model

SUSY renormalizable model: μνSSM

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

Y_ν^{ij} = 0 => R-parity is conserved

Possible interpretation:

R-parity is not a exact symmetry giving the LSP as DM, is an approximative symmetry protecting neutrino masses to be small

SUSY renormalizable model: μνSSM

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

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

Once the electroweak symmetry is spontaneously broken, the neutral scalars develop in general the following VEVs:

$$\langle H_1^0 \rangle = v_1 \,, \quad \langle H_2^0 \rangle = v_2 \,, \quad \langle \tilde{\nu}_i^c \rangle = \nu_i^c \qquad \langle \tilde{\nu}_i \rangle = \nu_i$$

Goes to zero when $Y_\nu^{ij} \longrightarrow 0$

SUSY renormalizable model: μνSSM

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

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

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SUSY renormalizable model: μνSSM

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$$W = \epsilon_{ab}\left(Y_u^{ij}\,\hat H_2^b\,\hat Q_i^a\,\hat u_j^c + Y_d^{ij}\,\hat H_1^a\,\hat Q_i^b\,\hat d_j^c + Y_e^{ij}\,\hat H_1^a\,\hat L_i^b\,\hat e_j^c + \underbrace{Y_\nu^{ij}\,\hat H_2^b\,\hat L_i^a\,\hat \nu_j^c}_{\text{Effective Bilinear term}}\right)$$

$$- \epsilon_{ab}\underbrace{\lambda^i\,\hat\nu_i^c}_{\text{Effective }\mu\text{-term}}\,\hat H_1^a \hat H_2^b + \frac{1}{3}\underbrace{\kappa^{ijk}\hat\nu_i^c}_{\text{Effective Majorana Mass}}\hat\nu_j^c\hat\nu_k^c\,,$$

Effective bilinear term => One right-handed neutrino is enough to reproduce neutrino physics (through loops) but three is natural

SUSY renormalizable model: μνSSM

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Effective Bilinear term

Effective μ-term

Effective Majorana Mass

Effective bilinear term => One right-handed neutrino is enough to reproduce neutrino physics (through loops) but three is natural

MSSM + bilinear R-parity breaking term ($\varepsilon \, H_2 \, L$) is a very well known model (the μ-problem is augmented respect to the MSSM)

Hall, Suzuki, 1984; Lee, 1984; Dawson, 1985; **...**

Phenomenology of the $\mu\nu$SSM

R-parity conserving models (MSSM, NMSSM, etc.):

Lightest Supersymmetric particle (LSP) : Dark Matter candidate

(neutralino, sneutrino, gravitino, ...)

Collider signature $\longrightarrow$ missing energy (Collider detectors are of order meter, a particle with lifetime bigger than 10^{-8} s can scape the detector, dark matter experiments are necessary)

$\mu\nu$SSM (minimal natural content of matter) :

R-parity breaking model:

Gravitino is a possible **dark matter** candidate: Indirect detection possible (more DM candidates, as for instance axion and axino, are possible)

Neutrino physics: very easy to reproduce neutrino physics

Sneutrinos are part of the **Higgs sector: Rich Higgs sector**

Collider signature: Multileptons, multijets, displaced vertices
(R-parity breaking related with neutrino physics. We have a long life particle. missing energy if decays outside the collider or in the form of neutrinos)

- **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

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

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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 \\
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-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 & \boxed{2\kappa_{11j}\nu_j^c} & 2\kappa_{12j}\nu_j^c & 2\kappa_{13j}\nu_j^c \\
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\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 $10^{-2}\,\mathrm{eV} = 10^{-11}\,\mathrm{GeV} \Rightarrow$

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

Effective Neutrino mass matrix

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

Using Diagonal Yukawas for Neutrinos

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

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

$$\frac{1}{M} = \frac{g_1^2}{M_1} + \frac{g_2^2}{M_2}$$

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

Some Important limits

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

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

Some Important limits

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

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

Gaugino see-saw

$\nu^c \to \infty$

$$\left(m_{eff|real}\right)_{ij} \simeq -\frac{1}{2M} \left[\nu_i \nu_j + \frac{v_d \left(Y_{\nu_i}\nu_j + Y_{\nu_j}\nu_i\right)}{3\lambda} + \frac{Y_{\nu_i} Y_{\nu_j} v_d^2}{9\lambda^2}\right]$$

and $\nu_i >> \frac{Y_{\nu_i} v_d}{3\lambda}$

$$\left(m_{eff|real}\right)_{ij} \simeq -\frac{\nu_i \nu_j}{2M}.$$

Some Important limits

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

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

Gaugino see-saw

$\nu^c \to \infty$

$$\left(m_{eff|real}\right)_{ij} \simeq -\frac{1}{2M} \left[\nu_i \nu_j + \frac{v_d \left(Y_{\nu_i}\nu_j + Y_{\nu_j}\nu_i\right)}{3\lambda} + \frac{Y_{\nu_i} Y_{\nu_j} v_d^2}{9\lambda^2}\right]$$

and $v_d \to 0$

$$\left(m_{eff|real}\right)_{ij} \simeq -\frac{\nu_i \nu_j}{2M}.$$

Some Important limits

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

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

ν_R-Higgsino See-Saw

$M \rightarrow \infty$

Some Important limits

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

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

ν_R-Higgsino See-Saw

$M \rightarrow \infty$;

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

Some Important limits

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

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

A very simple limit

$$v_d \rightarrow 0$$

or $\nu_i >> \frac{Y_{\nu_j} v_d}{3\lambda}$

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

$$M_{\rm eff} = M\left(1 - \frac{v^4}{12\kappa M \nu^{c^3}}\right)$$

Some Important limits

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

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

$$\frac{1}{M} = \frac{g_1^2}{M_1} + \frac{g_2^2}{M_2}$$

$$v_d \longrightarrow 0$$
$$M_{\text{eff}} \approx M$$

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

Gaugino see saw

Some Important limits

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

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

$v_d \longrightarrow 0$

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

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

ν_R-Higgsino see saw

Effective Neutrino mass matrix

(Diagonal Yukawas for Neutrinos)

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

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

$$v_d \rightarrow 0$$

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

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

ν_R-Higgsino see saw

Gaugino see saw

Also with diagonal Yukawas for neutrinos the mixtures could be generated

The ν_μ-ν_τ degenerate case. $Y_{\nu_2} = Y_{\nu_3}$ and $\nu_2 = \nu_3$

$$m_{eff} = \begin{pmatrix} d & c & c \\ c & A & B \\ c & B & A \end{pmatrix}$$

Also with diagonal Yukawas for neutrinos the mixtures could be genereted

The ν_μ-ν_τ degenerate case. $Y_{\nu_2} = Y_{\nu_3}$ and $\nu_2 = \nu_3$

$$m_{eff} = \begin{pmatrix} d & c & c \\ c & A & B \\ c & B & A \end{pmatrix}$$

$$\frac{1}{2}\left(A+B-\sqrt{8c^2+(A+B-d)^2}+d\right), \frac{1}{2}\left(A+B+\sqrt{8c^2+(A+B-d)^2}+d\right), A-B\,,$$

$$\left(-\tfrac{A+B+\sqrt{8c^2+(A+B-d)^2}-d}{2}, c, c\right), \quad \left(\tfrac{-A-B+\sqrt{8c^2+(A+B-d)^2}+d}{2c}, 1, 1\right), \qquad (0,-1,1)$$

Also with diagonal Yukawas for neutrinos the mixtures could be genereted

The ν_μ-ν_τ degenerate case. $Y_{\nu_2} = Y_{\nu_3}$ and $\nu_2 = \nu_3$

We have ordered the eigenvalues in such a way that it is clear how to obtain the normal hierarchy case

$$m_{eff} = \begin{pmatrix} d & c & c \\ c & A & B \\ c & B & A \end{pmatrix}$$

$$\frac{1}{2}\left(A+B-\sqrt{8c^2+(A+B-d)^2}+d\right), \frac{1}{2}\left(A+B+\sqrt{8c^2+(A+B-d)^2}+d\right), A-B\,,$$

$$\left(-\frac{A+B+\sqrt{8c^2+(A+B-d)^2}-d}{2}, c, c\right), \quad \left(\frac{-A-B+\sqrt{8c^2+(A+B-d)^2}+d}{2c}, 1, 1\right), \qquad (0,-1,1)$$

Also with diagonal Yukawas for neutrinos the mixtures could be genereted

The ν_μ-ν_τ degenerate case. $Y_{\nu_2} = Y_{\nu_3}$ and $\nu_2 = \nu_3$

Bimaximal case

$$m_{eff} = \begin{pmatrix} d & c & c \\ c & A & B \\ c & B & A \end{pmatrix}$$

$$\sin^2\theta_{23} = \frac{1}{2};$$

$$\sin^2\theta_{13} = 0$$

$$\frac{1}{2}\left(A+B-\sqrt{8c^2+(A+B-d)^2}+d\right), \frac{1}{2}\left(A+B+\sqrt{8c^2+(A+B-d)^2}+d\right), A-B\,,$$

$$\left(-\frac{A+B+\sqrt{8c^2+(A+B-d)^2}-d}{2}, c, c\right), \quad \left(\frac{-A-B+\sqrt{8c^2+(A+B-d)^2}+d}{2c}, 1, 1\right), \quad (0,-1,1)$$

Also with diagonal Yukawas for neutrinos the mixtures could be genereted

The ν_μ-ν_τ degenerate case. $Y_{\nu_2} = Y_{\nu_3}$ and $\nu_2 = \nu_3$

Tri-Bimaximal case $m_{eff} = \begin{pmatrix} d & c & c \\ c & A & B \\ c & B & A \end{pmatrix}$

$$\sin^2\theta_{23} = \frac{1}{2}$$

$$\sin^2\theta_{13} = 0$$

$$c = A + B - d \longrightarrow \sin^2\theta_{12} = 1/3$$

Also with diagonal Yukawas for neutrinos the mixtures could be genereted

The ν_μ-ν_τ degenerate case. $Y_{\nu_2} = Y_{\nu_3}$ and $\nu_2 = \nu_3$

Tri-Bimaximal case $m_{eff} = \begin{pmatrix} d & c & c \\ c & A & B \\ c & B & A \end{pmatrix}$

$$\sin^2\theta_{23} = \frac{1}{2};$$

$$\sin^2\theta_{13} = 0$$

$$c = A + B - d \longrightarrow \sin^2\theta_{12} = 1/3$$

Then close to the ν_μ-ν_τ degenerate case. **and** $c \approx A + B - d$

$\sin^2\theta_{23} \approx \frac{1}{2};$ $\sin^2\theta_{13} \approx 0$ $\sin^2\theta_{12} \approx 1/3$

Then is easy to satisfy the latest experimental results !!!

$$7.12 < \Delta m^2_{sol}/10^{-5}\ \mathrm{eV}^2 < 8.20\ ,\ \ 2.31 < \Delta m^2_{atm}/10^{-3}\ \mathrm{eV}^2 < 2.74$$

$$0.27 < \sin^2\theta_{12} < 0.37\ ,\ \ 0.017 < \sin^2\theta_{13} < 0.033\ ,\ \ 0.36 < \sin^2\theta_{23} < 0.68.$$

G. L. Fogli *et al.*, *Phys. Rev. D* **78** (2008) 033010 [arXiv:0805.2517 [hep-ph]]; T. Schwetz, M. Tortola and J. W. F. Valle, New J. Phys. **13** (2011) 063004 [arXiv:1103.0734 [hep-ph]].

With diagonal Yukawas for neutrinos (and diagonal effective Majorana mass) we can reproduce the experimental mixing angles.

In a sense we have an explanation of :
Why mixtures in Neutrino and quark sectors are so different?

Some papers on neutrino physics in this model:

J. Fidalgo, D. E. L-F, C.Muñoz and R. Ruiz de Austri, JHEP **08** (2009) 105

P. Ghosh, P. Dey, B. Mukhopadhyaya and S. Roy, JHEP **05** (2010) 087

Electroweak baryogenesis is possible in this model:

Daniel J. H. Chung and Andrew J. Long, Phys. Rev. **D81 (**2010)

R-parity is broken: LSP is not stable

Neutralino is not a Dark Matter candidate

Also sneutrino (with right-handed component) it is not

But .....

Neutralino has an important role in the SUSY see-saw (without imposing R parity)

Also sneutrinos Right handed as part of the Higgs has an important role

Lightest doublet-like Higgs

Tree level bound
On the Lightest Higgs

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

MSSM

$$\lambda^2 = \lambda_i\lambda_i$$

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

for $\tan\beta = 2(4)$ $\Longrightarrow$ $m_h \lesssim 111(98)$ GeV Tree Level

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

Easier than in the MSSM to have the lightest doublet-like Higgs with mass around 125 GeV

- If the lightest Higgses are dominated by right-handed sneutrinos the mixing helps to increase the mass of the lightest doublet-like Higgs

- 1 loop contributions increase the lightest doublet-like Higgs mass
- Possible to relax the Landau pole constraint (lower scale). We are not going to use this here.

N. Escudero, D.E. L-F, C. Muñoz and R. Ruiz de Austri, *JHEP* **12** (2008) 099

Gravitino: Good dark matter candidate

Direct detection: Not possible ☹

Indirect detection: In principle possible !!! ☺

Through the decay $\Psi_{3/2} \to \sum_i \gamma \nu_i$

K-Y.Choi, D.E.L-F, C. Muñoz and R. Ruiz de Austri, JCAP **03** (2010) 028

Possible signals at LHC

Displaced vertices:

Multi-leptons plus missing energy

P. Ghosh, D. E. L-F, V. Mitsou, C. Muñoz, R. Ruiz de Austri arXiv: 1211.3177

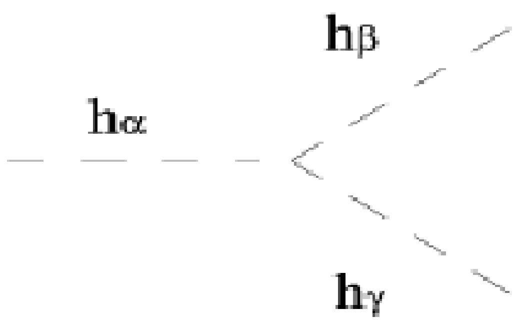
Some More papers on colliders signatures in this model:

A. Bartl, M. Hirsch, A. Vicente, S. Liebler and W. Porod, JHEP **05** (2009) 120

J. Fidalgo, D. E. L-F, C. Muñoz, R. Ruiz de Austri JHEP **10** (2011) 020

P. Bandyopadhyay, P. Ghosh and S. Roy, *Phys. Rev* D **84** (2011)

$h \to 2$ Standard Model fermions : $h \to \tau^+\tau^-$, $h \to \mu^+\mu^-$, $h \to b\bar{b}$, Etc.



$$h_\alpha \to h_\beta h_\gamma \ ,$$

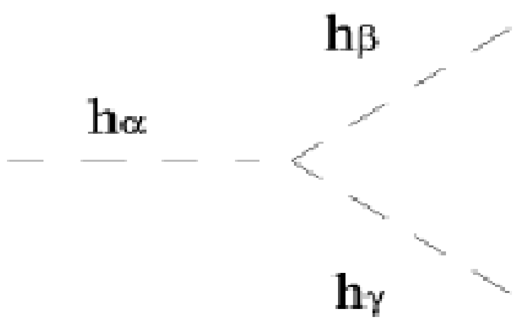
where $\alpha,\ \beta,\ \gamma = 1, \ldots, 8$ and $\alpha',\ \beta',\ \gamma' = 1, \ldots, 7$.

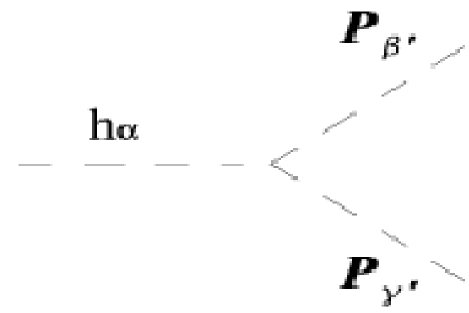
For example we have

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

$h \to 2$ Standard Model fermions : $h \to \tau^+\tau^-$, $h \to \mu^+\mu^-$, $h \to b\bar{b}$, Etc.

P $\to 2$ Standard Model fermions : P $\to \tau^+\tau^-$, P $\to \mu^+\mu^-$, P $\to b\bar{b}$, Etc.





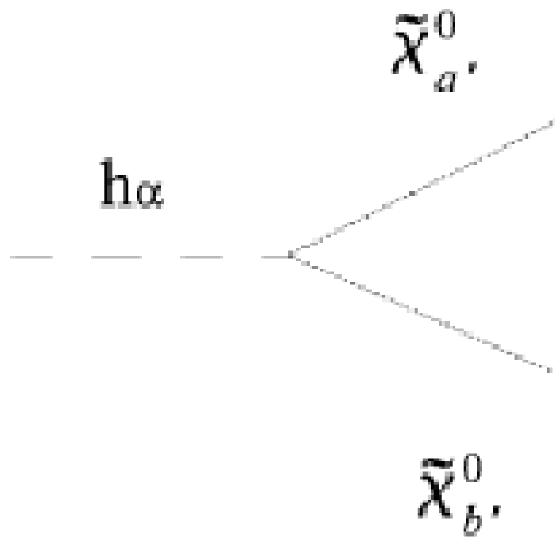
$$h_\alpha \to h_\beta h_\gamma \, , \qquad h_\alpha \to P_{\beta'} P_{\gamma'} \, , \qquad P_{\alpha'} \to P_{\beta'} h_\gamma \, ,$$

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

For example we have

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

Multileptons and multijets signals

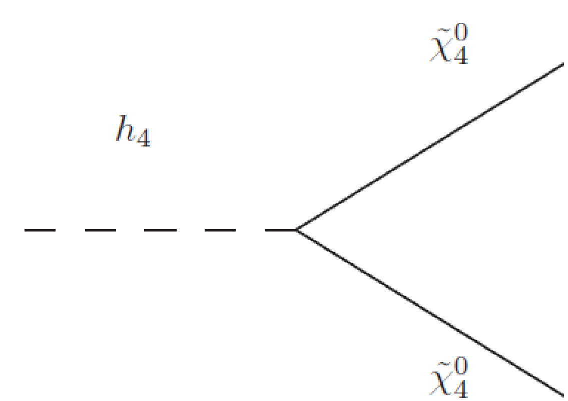


$$h_4 \to \tilde{\chi}^0 \tilde{\chi}^0 \to 2P2\nu \to 2b2\bar{b}2\nu$$

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

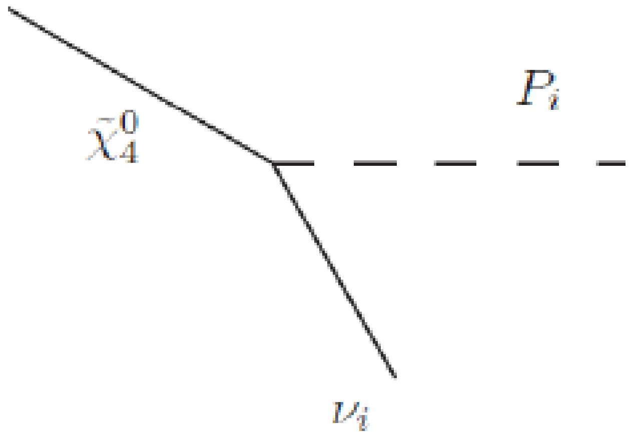
We took three light singlet-like Higgses, the fourth one is doublet-like

$$m_{h_4} \approx 125\,\mathrm{GeV}$$



Displaced vertices signals (or missing energy if $\tilde{\chi}^0_4$ decays outside the detector)

Long life

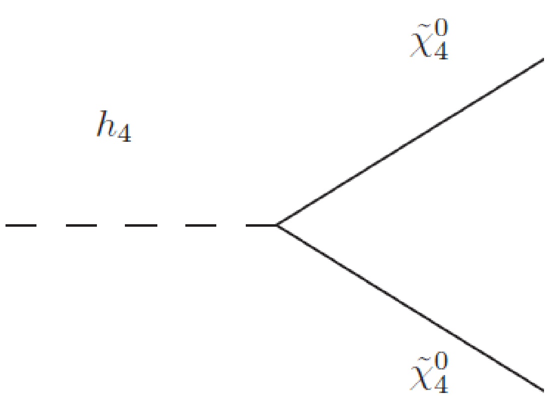


$$h_4 \to \tilde{\chi}^0\tilde{\chi}^0 \to 2P2\nu \to 2b2\bar{b}2\nu$$

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

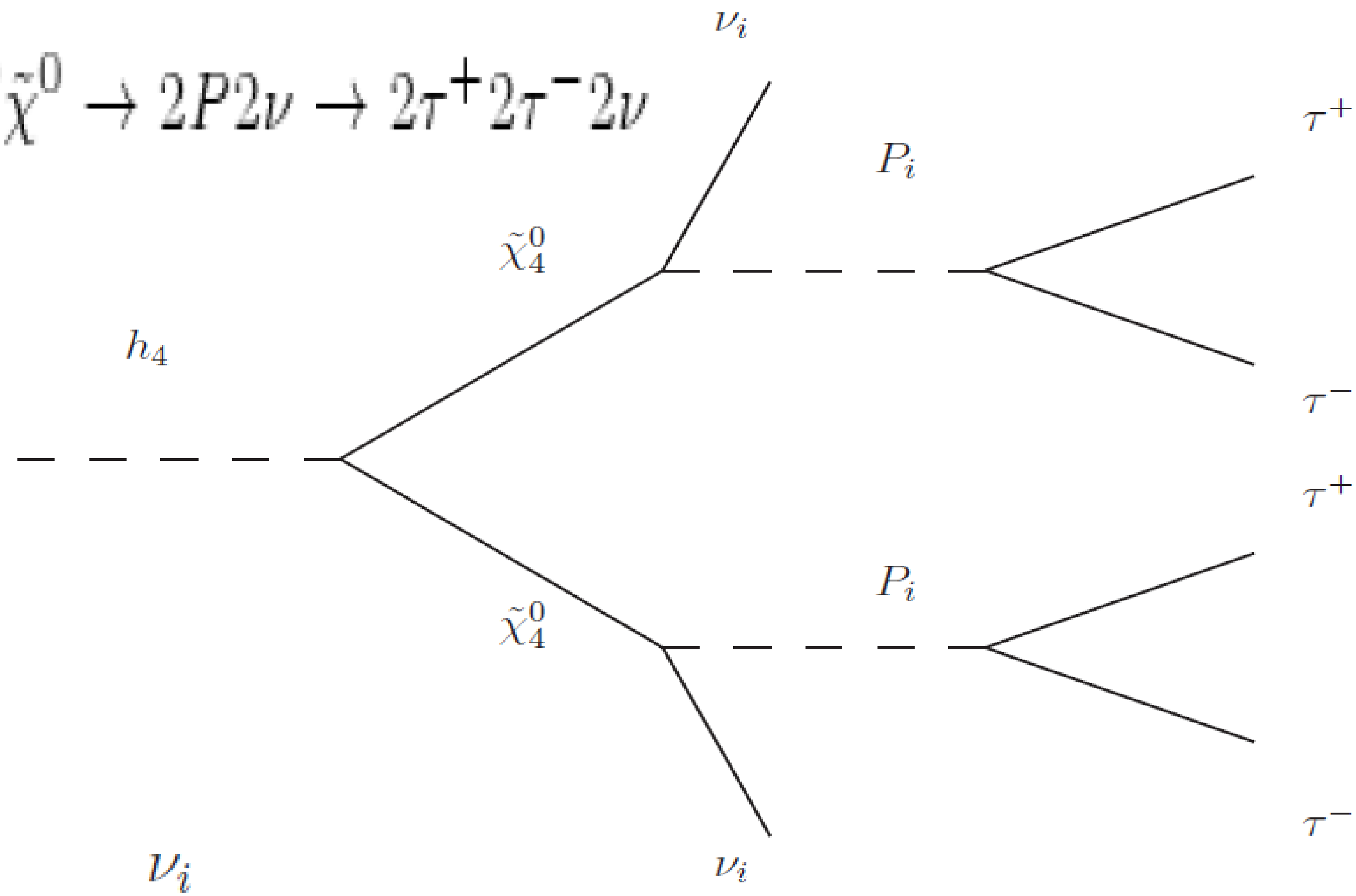
We took three light singlet-like Higgses, the fourth one is doublet-like

$$m_{h_4} \approx 125\,\mathrm{GeV}$$



Displaced vertices signals (or missing energy if $\tilde{\chi}_4^0$ decays outside the detector)

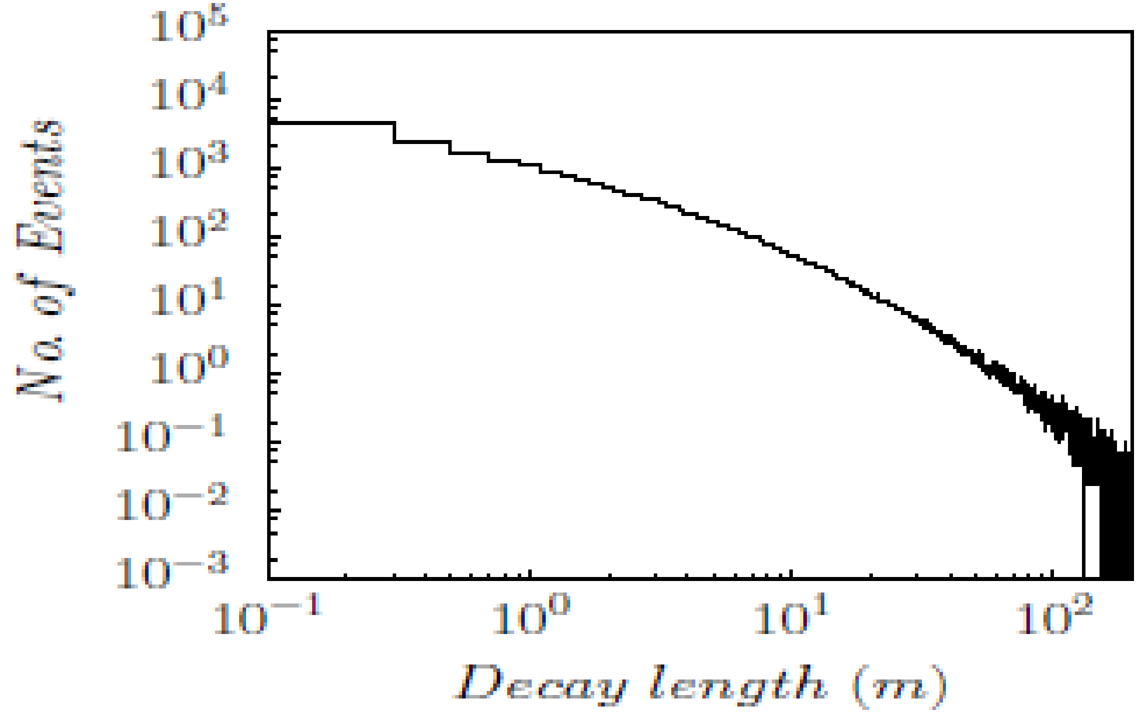
$$h_4 \to \tilde{\chi}^0 \tilde{\chi}^0 \to 2P2\nu \to 2\tau^+ 2\tau^- 2\nu$$



$$Br(\tilde{\chi}_4^0 \to \sum_{i=1}^{3} \tilde{\chi}_i^0 \tau^+ \tau^-) \approx 99\% \qquad Br(h_4 \to \tilde{\chi}_4^0 \tilde{\chi}_4^0) \approx 6\%$$

$$m_{\tilde{\chi}_4^0} \approx 9.6\,\mathrm{GeV} \qquad m_{P_1} \approx 3.6\,\mathrm{GeV},\ m_{P_2} \approx 3.8\,\mathrm{GeV} \quad m_{P_3} \approx 5.5\,\mathrm{GeV}$$

Lightest Neutralino proper lifetime: $\tau_{\tilde{\chi}_4^0} \approx 10^{-9}$ s



$\sqrt{s} = 8$ TeV with $\mathcal{L} = 20$ fb^{-1}

$h_4 \to \tilde{\chi}^0 \tilde{\chi}^0 \to 2P2\nu \to 2\tau^+ 2\tau^- 2\nu$ $\sqrt{s} = 8$ TeV with $\mathcal{L} = 20$ fb^{-1}

With τ decaying to e, μ, or hadronically

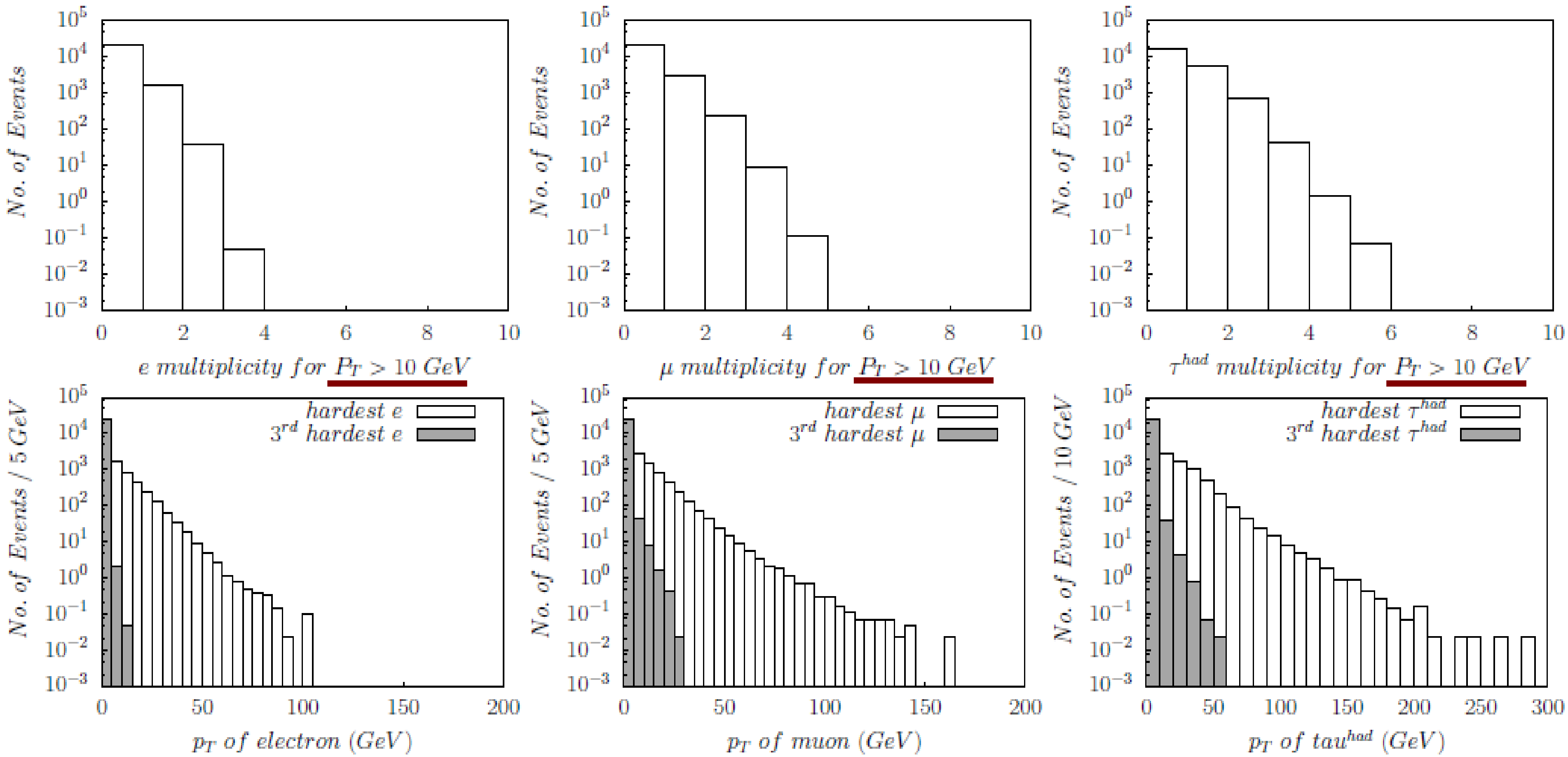
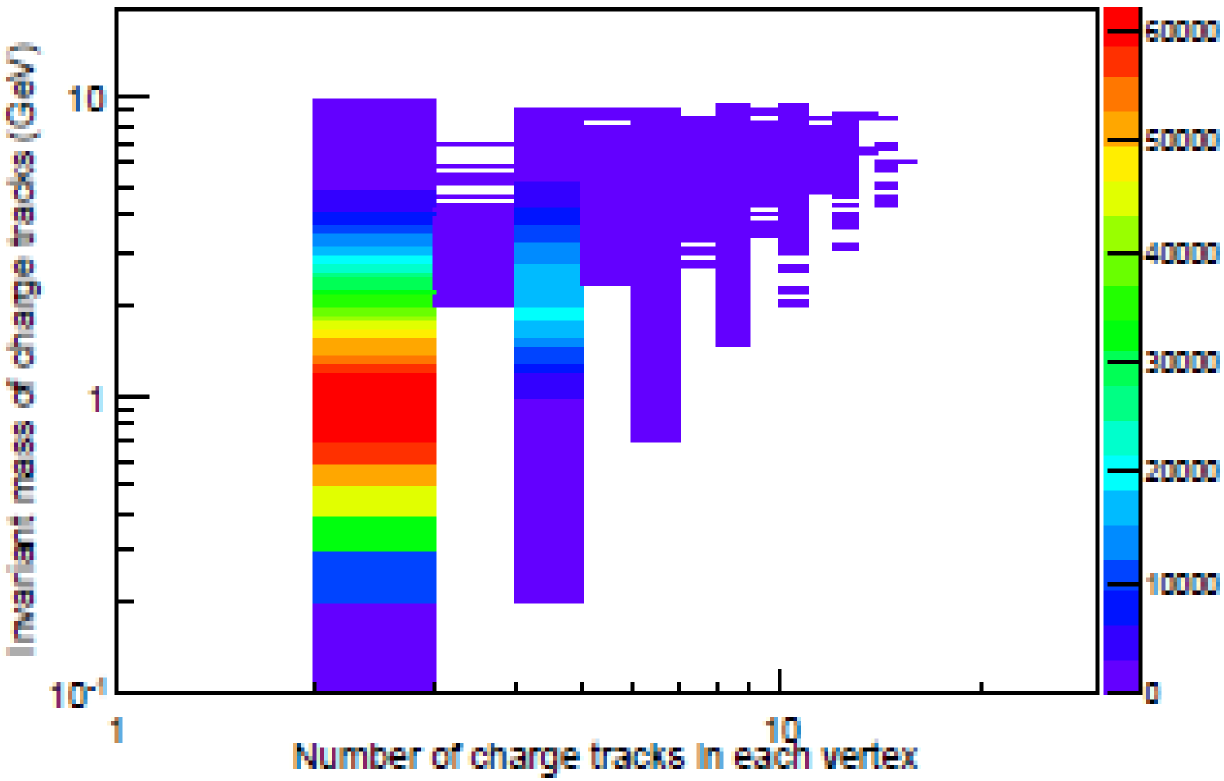
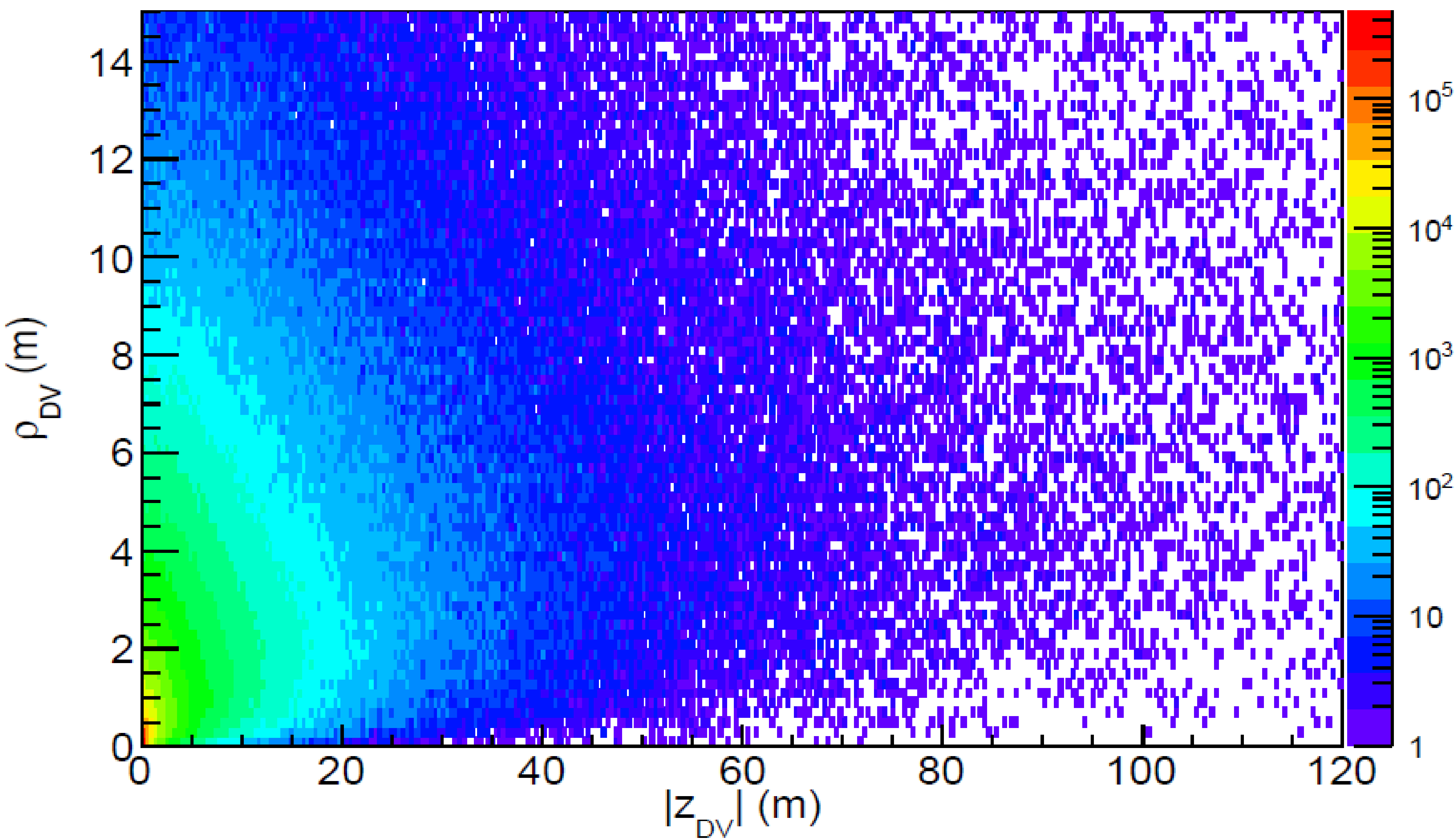


FIG. 1: Multiplicity (top row) for e (top left), μ (top middle) and hadronically decaying τ (top right) with $p_T >$ 10 GeV. p_T distributions (bottom row) for the leading (white) and the 3rd leading (light grey) e (bottom left), μ (bottom middle) and hadronically decaying τ (bottom right). These plots correspond to $\sqrt{s} = 8$ TeV with $\mathcal{L} = 20$ fb^{-1}.

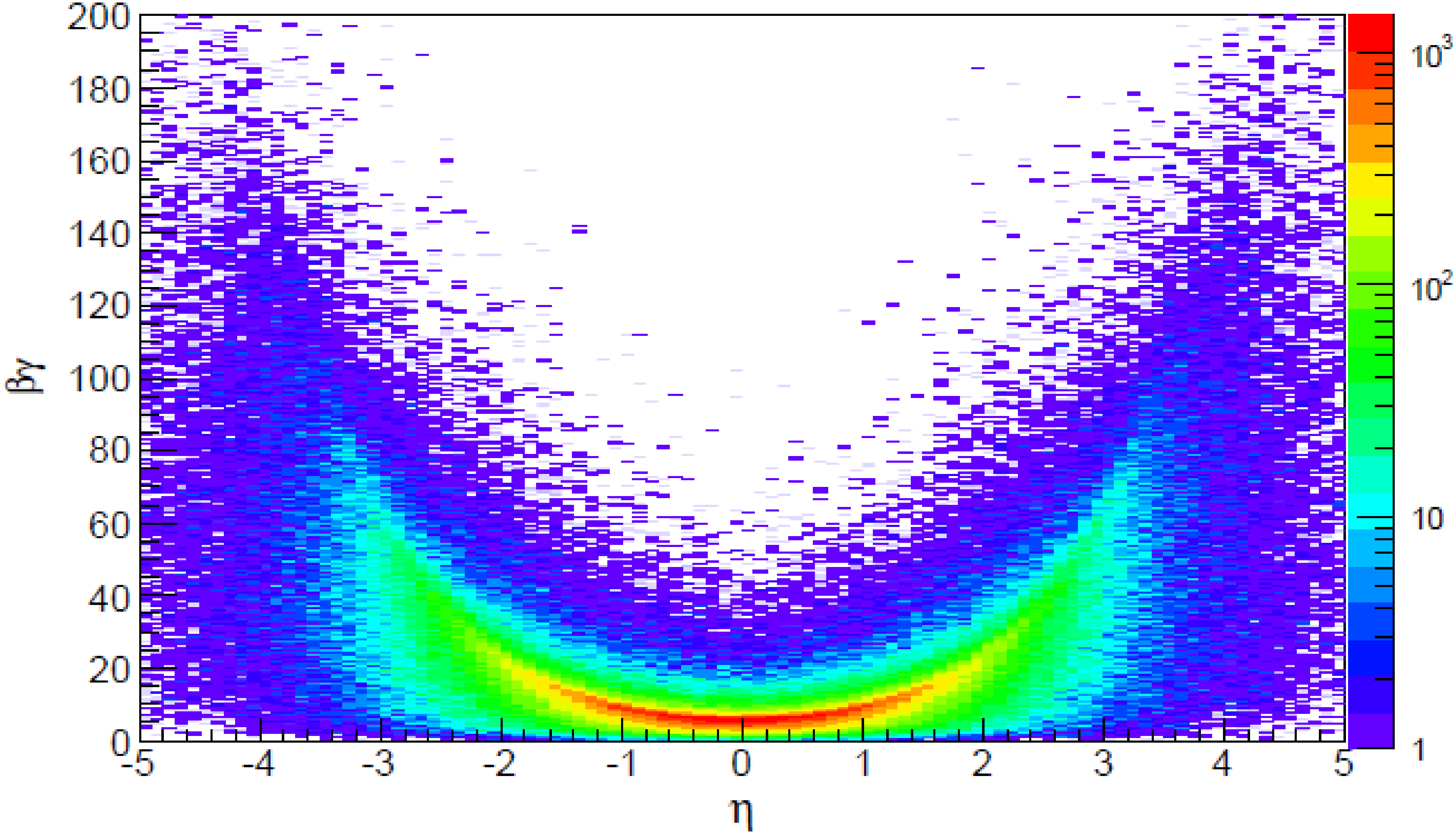
$$\sqrt{s} = 8 \text{ TeV with } \mathcal{L} = 20 \text{ fb}^{-1}$$



charged-track mass versus the number of charge particles



ρ_{DV} versus $|z_{\mathrm{DV}}|$



$\beta\gamma$ versus η (left)

Summary

The discovery of a Higgs candidate opens the door to discover new physics

Different possibilities of physics beyond the SM, for instance the **μνSSM can be tested**