# Searching for left-handed sneutrinos at the LHC

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V Postgraduate Meeting in Theoretical Phisics

I. Introduction

II. The $\mu\nu SSM$

III. The left handed sneutrino as the LSP

IV. Detection at the LHC

# Introduction

Supersymetric models has been an active area of phenomenological research since the 80's.

- ⋆ Solves the big hierarchy problem. Electro weak scale does not have quadratic sensitivity to high scales ⇒ Superpartners at the TeV scale.
- ⋆ Unification of gauge couplings.
- ⋆ Many models provide a viable dark matter candidate.

Simplest realizations of SUSY suffer from tension with experimental searches.

⇒ More complicated realizations of SUSY.

⇒ More elaborated experimental analysis to cover this scenarios.

# SUSY with broken $R$-parity

R-parity is proposed to protect proton from fast decay. $\Rightarrow$ Implies stable LSP and Missing transverse momentun signal at LHC.

$\star$ There are dimension-five operators permited by $R$-parity wich lead to proton decay:

$$\mathcal{O}_5 = \frac{\bar{u}\bar{u}\bar{d}e}{M}$$
$$\mathcal{O}_5 = \frac{QQQL}{M}$$

$\star$ There are alternatives to $R$-parity to prevent the proton to decay, such as *Proton Hexality* (equivalent at tree level to $R$-parity) or *Barion Triality* (Allows only for $\not{L}$). L.E. Ibáñez and G. Ross, Nucl. Phys. B 368, 3 (1992).H.K. Dreiner, C. Luhn and M. Thormeier, Phys. Rev. D 73, 075007 (2006)

*R-parity* violation is motivated in models explaining neutrino physics such as BRpV or $\mu\nu SSM$. Signatures at colliders are completely different.

# The $\mu\nu$SSM

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# The $\mu\nu SSM$

$\mu\nu SSM$ extends the MSSM particle content with three singlet chiral superfields. They couple to:

- ⋆ Higgs superfields ⇒ Solve the $\mu$ problem of the MSSM, as in the NMSSM. D.López-Fogliani, C.Muñoz.Phys. Rev. Lett. 97 (2006) 041801
- ⋆ Lepton superfields ⇒ Give mass to neutrino sector. J.Fidalgo, D. López-Fogliani, C.Muñoz, R.R. de Austri.JHEP 08 (2009) 105

The presence of both coupling breaks *R*-parity explicitly. But only generates lepton number violating interactions.

Neutralinos are no longer stable ⇒ Can't be interpreted as dark matter. However, the gravitino could be a viable DM candidate, producing monophoton signals in the decay. A. Albert et al JCAP 10 (2014) 023

# The $\mu\nu SSM$ Lagrangian

$$W = W_{MSSM_{\mu=0}} \underbrace{+ Y_\nu^{ij} \hat{H}_u^b \hat{L}_i^a \hat{\nu}_j^c - \epsilon_{ab} \lambda_i \hat{\nu}_i^c \hat{H}_d^a \hat{H}_u^b + \frac{1}{3} \kappa^{ijk} \hat{\nu}_i^c \hat{\nu}_j^c \hat{\nu}_k^c .}_{\mu\nu MSSM}$$

⋆ In the limit $Y_\nu^{ij} \to 0$, $R$-parity is restored.
⋆ We assume a soft-breaking sector with a structure inspired by SUGRA models with diagonal Kähler metric:

$$T_{\lambda_i} = A_{\lambda_i} \lambda_i ; T_{\kappa_{ijk}} = A_{\kappa_{ijk}} \kappa_{ijk} ; T_\nu^{ij} = A_\nu Y_\nu^{ij}$$
$$T_u^{ij} = A_u Y_u^{ij}; \;\; T_d^{ij} = A_d Y_d^{ij}; \;\; T_e^{ij} = A_e Y_e^{ij}$$

We also assume no intergenerational mixing in the trilinear terms, neither in the squared sfermion mass matrices.

# Scalar potential

The scalar potential recives contributions from F-terms, D-Terms and soft terms, mixing all neutral scalar states:

$$V^{(0)} = V_{soft} + V_D + V_F$$

With the choice of CP conservation, one can define the neutral scalars as:

$$H_1^0 = \frac{1}{\sqrt{2}}(\phi_1 + v_1 + i\sigma_1)$$

$$H_2^0 = \frac{1}{\sqrt{2}}(\phi_2 + v_2 + i\sigma_2)$$

$$\widetilde{\nu}_{iR} = \frac{1}{\sqrt{2}}(\phi_{iR} + v_{IR} + i\sigma_{iR})$$

$$\widetilde{\nu}_{iL} = \frac{1}{\sqrt{2}}(\phi_{iL} + v_{IL} + i\sigma_{iL})$$

After EWSB,all of them can develop real VEVs

$$\langle H_1 \rangle = \frac{v_1}{\sqrt{2}}, \langle H_2 \rangle = \frac{v_2}{\sqrt{2}}, \langle \widetilde{\nu}_{iR} \rangle = \frac{v_{iR}}{\sqrt{2}}, \langle \widetilde{\nu}_{iL} \rangle = \frac{v_{iL}}{\sqrt{2}}$$

However spontaneus CP violation is possible with all parameters real.

J.Fidalgo, D.López-Fogliani, C.Muñoz, R.R.de Austri JHEP 08 (2009) 105

# Minimization equations

$$m_{H_d}^2 = -\frac{1}{4} G^2 \left( v_{iL} v_{iL} + v_d^2 - v_u^2 \right) - \lambda_i \lambda_j v_{iR} v_{jR} - \lambda_i \lambda_i v_u^2$$
$$+ v_{iR} \tan\beta \left( T_{\lambda_i} + \lambda_j \kappa_{ijk} v_{kR} \right) + Y_{\nu_{ij}} \frac{v_{iL}}{v_d} \left( \lambda_k v_{kR} v_{jR} + \lambda_j v_u^2 \right) - \frac{1}{v_d} V_{v_d}^{(n)} , \quad (1)$$

$$m_{H_u}^2 = \frac{1}{4} G^2 \left( v_{iL} v_{iL} + v_d^2 - v_u^2 \right) - \lambda_i \lambda_j v_{iR} v_{jR} - \lambda_j \lambda_j v_d^2$$
$$+ 2\lambda_j Y_{\nu_{ij}} v_{iL} v_d - Y_{\nu_{ij}} Y_{\nu_{ik}} v_{kR} v_{jR} - Y_{\nu_{ij}} Y_{\nu_{kj}} v_{iL} v_{kL}$$
$$+ v_{iR} \frac{1}{\tan\beta} \left( T_{\lambda_i} + \lambda_j \kappa_{ijk} v_{kR} \right) - \frac{v_{iL}}{v_u} \left( T_{\nu_{ij}} v_{jR} + Y_{\nu_{ij}} \kappa_{ljk} v_{lR} v_{kR} \right) - \frac{1}{v_u} V_{v_u}^{(n)} , \quad (2)$$

$$m_{\widetilde{\nu}_{ij}^c}^2 v_{jR} = -T_{\nu_{ji}} v_{jL} v_u + T_{\lambda_i} v_u v_d - T_{\kappa_{ijk}} v_{jR} v_{kR} - \lambda_i \lambda_j \left( v_u^2 + v_d^2 \right) v_{jR} + 2\lambda_j \kappa_{ijk} v_d v_u v_{kR}$$
$$- 2\kappa_{lim} \kappa_{ljk} v_{mR} v_{jR} v_{kR} + Y_{\nu_{ji}} \lambda_k v_{jL} v_{kR} v_d + Y_{\nu_{kj}} \lambda_i v_d v_{kL} v_{jR} - 2 Y_{\nu_{jk}} \kappa_{ikl} v_u v_{jL} v_{lR}$$
$$- Y_{\nu_{ji}} Y_{\nu_{lk}} v_{jL} v_{\nu_l} v_{kR} - Y_{\nu_{ki}} Y_{\nu_{kj}} v_u^2 v_{jR} - V_{v_{iR}}^{(n)} , \quad (3)$$

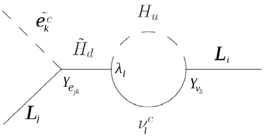
$$m_{\widetilde{L}_{ij}}^2 v_{jL} = -\frac{1}{4} G^2 \left( v_{jL} v_{jL} + v_d^2 - v_u^2 \right) v_{iL} - T_{\nu_{ij}} v_u v_{jR} + Y_{\nu_{ij}} \lambda_k v_d v_{jR} v_{kR} + Y_{\nu_{ij}} \lambda_j v_u^2 v_d$$
$$- criptsize Y_{\nu_{il}} \kappa_{ljk} v_u v_{jR} v_{kR} - Y_{\nu_{ij}} Y_{\nu_{lk}} v_{\nu_l} v_{jR} v_{kR} - Y_{\nu_{ik}} Y_{\nu_{jk}} v_u^2 v_{jR} - V_{v_{iL}}^{(n)} . \quad (4)$$

One can see that the vevs $v_{iR}$ are naturally above the EWSB scale. While from Eq.4, when $Y_\nu^{ij} \to 0$ then $v_{iL} \to 0$. And we can estimate $v_{iL} \sim Y_\nu^{ii} v_2$.

# Effective terms

After EWSB, several effective terms are generated:

- ⋆ Trilinear terms $\Rightarrow \lambda_{ijk} \sim Y_{\nu_{ii}} \kappa \frac{m_{l_{jk}}}{v} \frac{(1-\delta_{ij})\delta_{jk}}{\sqrt{1+\tan^2\beta}}$ $\lambda'_{ijk} \sim Y_{\nu_{ii}} \kappa \frac{m_{d_{jk}}}{v} \frac{\delta_{jk}}{\sqrt{1+\tan^2\beta}}$




- ⋆ Bilinear $\Rightarrow \epsilon_i^{eff} \sim Y_{\nu_{ij}} v_{jR}$
- ⋆ $\mu$-term for the higgs sector$\Rightarrow \mu^{eff} = \lambda_i v_{iR}$
- ⋆ Majorana mass for right handed neutrinos $\Rightarrow \left(M_M^{eff}\right)_{ij} = \sqrt{2}\kappa_{ijk} v_{jR}$
- ⋆ Dirac mass for neutrinos $\Rightarrow \left(m_D^{eff}\right)_{ij} = \frac{1}{\sqrt{2}} Y_{\nu_{ij}} v_2$

An electroweak scale Type-I seesaw with $Y_{\nu_{ij}} \sim 10^{-6}$ appears naturally.

# The $\mu\nu SSM$ seesaw .

$$\mathcal{M}_n = \begin{pmatrix} M & m \\ m^T & 0_{3\times 3} \end{pmatrix}, \qquad \begin{array}{l} M \to M_1, M_2, \lambda_i v_{iR}, \sqrt{2}\kappa_{ijk} v_{jR} \sim \mathcal{O}(M_{SUSY}) \\ m \sim Y_\nu^{ii} v_u \end{array}$$

At first aproximation $m_{eff} = -m^T \cdot M^{-1} \cdot m$ and one can diagonalize as $U^T_{MNS} m_{eff} U_{MNS} = diag(m_1, m_2, m_3)$. Approximately:

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

In the limit of heavy gauginos $M \to \infty$:

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

In the limit of heavy singlinos $v_{iR} \to \infty$ and large $\tan\beta$:

$$(m_{eff\,|\,real})_{ij} \simeq -\frac{v_{iL} v_{jL}}{2M}.$$

⋆ Is possible to reproduce neutrino physics with diagonal Yukawa couplings.

# Scalar sector

The couplings and generated vevs on the $\mu\nu SSM$ mix all the states with the same spin, CP and charge properties. Thus the scalar sector is composed by

- ⋆ 8 Neutral scalars.
- ⋆ 7 Neutral pseudoscalars.
- ⋆ 7 charged scalars.
- ⋆ 12 squarks.

The squark sector is analoge to the MSSM. But the neutral and charged scalar sector is clearly different, The admixing of sneutrino states with higgses could have big implications in collider signatures.

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# Parameters for the analysis

⋆ For this first analysis focused on the detection of sneutrino LSP at the LHC, is simpler to work with only one family of RH neurinos. ⇒ Results concerning LHC phisics remain essentialy the same.
Free parameters in the neutral scalar sector at the low scale are:

$$\lambda_i \equiv \lambda, \kappa_{ijk} \equiv \kappa, Y_\nu^{ij} \equiv Y_\nu, \tan\beta, v_{iL}$$
$$v_{iR} \equiv v_R, A_i^\lambda \equiv A_\lambda, A_{ijk}^\kappa \equiv A_\kappa, A_i^\nu \equiv A_\nu$$

⋆ Scalar soft masses are eliminated in favor of vevs through the minimization equations.

The rest of the parameters take generic values choosen to keep the rest of the spectrum decoupled.

# Mass matrix

$$m^2_{H_d^{\mathcal{I}} H_d^{\mathcal{I}}} = v_{iR} \tan\beta \left(T_{\lambda_i} + \lambda_j \kappa_{ijk} v_{kR}\right) + \ldots \qquad m^2_{H_u^{\mathcal{I}} H_u^{\mathcal{I}}} = v_{iR} \frac{1}{\tan\beta} \left(T_{\lambda_i} + \lambda_j \kappa_{ijk} v_{kR}\right) + \ldots$$

$$m^2_{H_d^{\mathcal{I}} H_u^{\mathcal{I}}} = T_{\lambda_i} v_{iR} + \lambda_k \kappa_{ijk} v_{iR} v_{jR} + \ldots \quad m^2_{H_d^{\mathcal{I}} \widetilde{\nu}_{iR}^{\mathcal{I}}} = T_{\lambda_i} v_u + \ldots \quad m^2_{H_u^{\mathcal{I}} \widetilde{\nu}_{iR}^{\mathcal{I}}} = T_{\lambda_i} v_d + \ldots$$

$$m^2_{\widetilde{\nu}_{iR}^{\mathcal{I}} \widetilde{\nu}_{jR}^{\mathcal{I}}} = -2 \left( T_{\kappa_{ijk}} v_{kR} - \lambda_k \kappa_{ijk} v_d v_u + \kappa_{ijk} \kappa_{lmk} v_{lR} v_{mR} \right) + \ldots$$

$$m^2_{\widetilde{\nu}_{iL}^{\mathcal{I}} \widetilde{\nu}_{jL}^{\mathcal{I}}} = +\frac{\delta_{ij}}{v_{jL}} \left[ -T_{\nu_{ik}} v_u v_{kR} + Y_{\nu_{ik}} \left( \lambda_l v_d v_{kR} v_{lR} + \lambda_k v_d v_u^2 - \kappa_{klm} v_u v_{lR} v_{mR} - Y_{\nu_{mk}} v_{mL} v_u^2 - Y_{\nu_{ml}} v_{mL} v_{lR} v_{kR} \right) \right] + Y_{\nu_{ik}} Y_{\nu_{jk}} v_u^2 + Y_{\nu_{ik}} Y_{\nu_{jl}} v_{kR} v_{lR} + V^{(n)}_{v_{iL} v_{jL}} - \frac{\delta_{ij}}{v_{iL}} V^{(n)}_{v_{iL}} ,$$

Mixing of left handed sneutrinos with the rest of the scalar sector is supressed:

$$m^2_{H_d^{\mathcal{I}} \widetilde{\nu}_{iL}^{\mathcal{I}}} = -Y_{\nu_{ij}} \lambda_j v_u^2 - Y_{\nu_{ij}} \lambda_k v_{kR} v_{jR} + V^{(n)}_{v_d v_{iL}} , \qquad m^2_{H_u^{\mathcal{I}} \widetilde{\nu}_{iL}^{\mathcal{I}}} = -T_{\nu_{ij}} v_{\nu_j^c} - Y_{\nu_{ik}} \kappa_{ljk} v_{lR} v_{jR} + V^{(n)}_{v_u v_{iL}} ,$$

$$m^2_{\widetilde{\nu}_{iL}^{\mathcal{I}} \widetilde{\nu}_{jR}^{\mathcal{I}}} = -T_{\nu_{ij}} v_u + Y_{\nu_{ij}} \lambda_k v_d v_{kR} - Y_{\nu_{ik}} \lambda_j v_d v_{kR} + 2 Y_{\nu_{il}} \kappa_{jlk} v_u v_{kR} - Y_{\nu_{ij}} Y_{\nu_{lk}} v_{lL} v_{kR} + Y_{\nu_{ik}} Y_{\nu_{lj}} v_{lL} v_{kR} + V^{(n)}_{v_{iL} v_{jR}} ,$$

# Left handed Sneutrino mass

⋆The mass matrices for CP-odd/even scalar differ only by the D-terms: $= \frac{G^2}{2} v_{iL} v_{jL}$. Which are negligible. ⇒ CP-odd/even sneutrino states are degenerate in mass.

⋆ Left handed sleptons are always heavier than sneutrinos due to the contribution of the possitive D-term: $= \frac{g_2^2}{2}(v_u^2 - v_d^2)$. This contribution is small⇒ sleptons would be normaly the NLSP.

Neglecting small terms, the mass of sleptons is approximately:

$$m^2_{\widetilde{\nu}_i^{\mathcal{I}}\widetilde{\nu}_i^{\mathcal{I}}} \approx \frac{Y_\nu v_u}{v_{iL}} v_R \left(-A_\nu - \kappa v_R + \frac{\lambda v_R}{\tan\beta}\right) + \frac{\partial^2 V^{(n)}}{\partial v_{iL} \partial v_{iL}} - \frac{1}{v_{iL}} \frac{\partial V^{(n)}}{\partial v_{iL}} \,, \quad (5)$$

Since $v_{iL} \sim Y_\nu v_u$. One could have light sneutrinos with low values for $A_\nu, \kappa, v_R$ and $\lambda v_R$ (of the order of 50GeV) or/and with some cancelations between terms. ⇒The higher the value of $v_R$, the bigger need of tuning for a light left handed sneutrino.

# Left handed Sneutrino mass II

⋆ We want to analize a left handed sneutrino LPS in the range $95 \to 145$GeV. Detectable zone on the direct production at the LHC. This means that if $v_R \sim 1$TeV and $\frac{Y_\nu v_u}{v_{iL}} \sim 1$, then $A_\nu \sim 100$GeV and a 1 % tuning is necessary.

⋆ Is also possible to suppress the mass of sneutrinos with a higger value of sneutrino vevs, $v_{iL} >> Y_\nu v_u$. But this make difficult to reproduce experimental constraints in neutrino phisics.

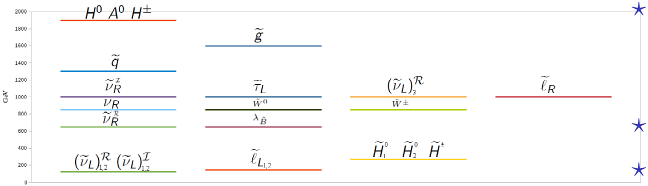
⋆ Universal values for $v_{iL}$, $Y_\nu$ and $A_\nu$, produce degenerate masses, broken only by small loop efects. A hierarchy could be introduced with nonuniversal values of any of this parameters. Possibly given by neutrino phisics.

# Benchmark points used

We consider the scenario of only $\widetilde{\nu}_{1,2}$ light or $\widetilde{\nu}_3$ light. And the rest of the spectrum decoupled.

$A_\nu = 386$ GeV
$M_1 = 600$ GeV
$M_2 = 900$ GeV
$M_3 = 1600$ GeV
$|A_{Q,u,d,e,\lambda,\kappa}| = 1$TeV
$v_R \approx 1.9$ TeV

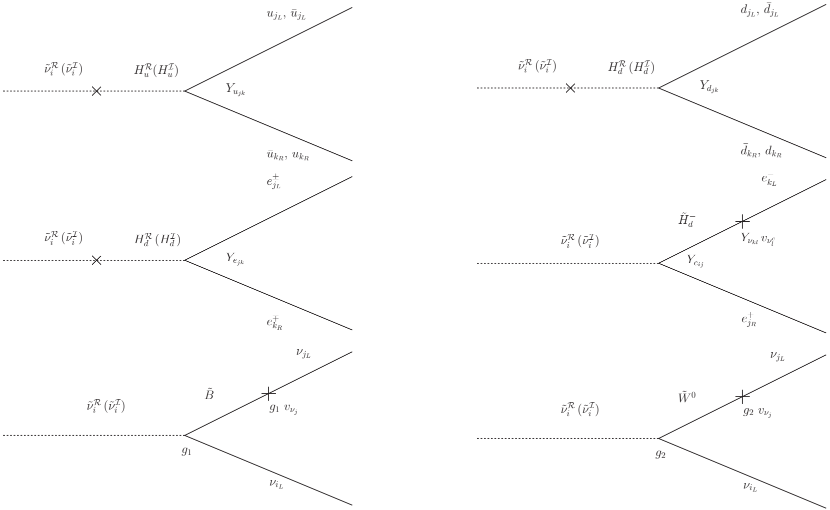
$A_u \approx 3$ TeV
$m_{Q,u,d} = 1.3$TeV
$m_{e^c} = 1$ TeV
$\tan\beta = 10$ ; $Y_\nu = 5 \times 10^{-7}$
$\lambda = 0.2$ ; $\kappa = 0.3$




- ⋆ Squarks and gauginos have a mass of the order of $M_{SUSY}$.
- ⋆ $\widetilde{H} \sim \lambda v_R$.
- ⋆ $\nu_R \sim 2\kappa v_R$.
- ⋆ $\widetilde{\nu}_R \sim \kappa^2 v_R^2$.

# Decays modes of the LSP

⋆ Decays of the LSP are always supressed by some power of $Y_\nu$ or $v_\nu$ in the admixing of mass eigenstates. In the mass insertion approximation:



# Decay modes of the CP-odd state I

⋆ Through $H_d$:

$$\Gamma_{\widetilde{\nu}^I \to dd} \sim \frac{Y_d Y_\nu \lambda v_R}{\lambda(A_\lambda + \kappa v_R)\tan\beta}$$

$$\Gamma_{\widetilde{\nu}^I \to \ell\ell} \sim \frac{Y_\ell Y_\nu \lambda v_R}{\lambda(A_\lambda + \kappa v_R)\tan\beta}$$

Dominant in the b channel, and subdominant in the $\tau$ channel.

⋆ Through $H_u$:

The state with dominant $H_u$ composition will be the Goldstone boson. Since $G^0$ does not have pure composition, we can represent the decay of the sneutrino through $H_u$ couplings as if it happend through the state with second dominant $H_u$ composition. As a result, this decay would be more supressed than naively expected.

# Decay modes of the CP-odd state II

⋆ Through $\widetilde{H_d}$:

$$\Gamma_{\widetilde{\nu}_i{}^I \to e_i e_j} \sim \frac{Y_{\ell_{ii}} Y_{\nu_j}}{\lambda}$$

This channel is only visible if $i = 3$. And if $i \neq j$ could produce LFV decays. The strength of each of the possible channels depend on the hierarchy in $Y_{\nu_j}$.

⋆ Through $\widetilde{B}^0 / \widetilde{W}^0$:

$$\Gamma_{\widetilde{\nu}_i{}^I \to \nu\nu} \sim g_1^2 \frac{v_{iL}}{M_1}$$

$$\Gamma_{\widetilde{\nu}_i{}^I \to \nu\nu} \sim g_2^2 \frac{v_{iL}}{M_2}$$

If $i = 1, 2$ then this would be the dominant decay channel. For $i = 3$ this channel is in competition with the decay to $\tau e / \tau \mu$.

# Decay modes of the CP-even state I

For the CP-even states, the decay through the state with dominant $H_u$ composition (SM higgs) is open. The dominant decay channels through $H_u$ are:

- Decay to up-type quarks:

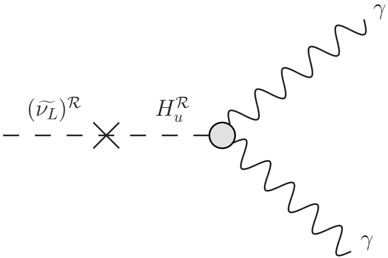
$$\Gamma_{\widetilde{\nu}^I \to cc} \sim \frac{Y_c Y_\nu (A_\lambda + \kappa v_R) \tan\beta}{\lambda (A_\lambda + \kappa v_R)}$$

- The decay to gauge bosons $VV^*$.

The lightest scalar has a small but significant composition of $H_d$ therefore the decay of to down-type quarks and leptons is bigger than expected from mass insertion aproximation. Moreover, the presence of two eigenstates with similar masses in the mass matrix enhance the mixing of them and the mass insertion aproximation is no longer valid$\Rightarrow$ The decay pattern of the left handed sneutrino mimic the one of the SM-like higgs.

# Decay modes of the CP-even state II

Of special interest is the diphon decay of the higgs through $W^{\pm}$ and top loops.




The BR is small, but big enough to produce a clean signal easy to disentangle from backgrounds.

# Experimental constraints

- ⋆ Stable $\widetilde{\nu}_L$ excluded from DM searches. $\Rightarrow$ Not of aplication in the $\mu\nu SSM$.
- ⋆ Single $\widetilde{\nu}_L$ production through trilinear couplings excluded from ATLAS and CMS searches in $e\mu$, $e\tau$,$\mu\tau$ final states assuming large values of some $\lambda_{ijk}, \lambda'_{ijk}$ couplings. $\Rightarrow$ The smallness of the effective trilinear couplings make this searches inefective.
- ⋆ Contraints form flavour phisics on products of trilinear terms $|\lambda_{ijk}\lambda_{lkm}|$,$|\lambda_{ijk}\lambda'_{lkm}| \ldots \Rightarrow$ The trilinear effective terms are far below the limits.

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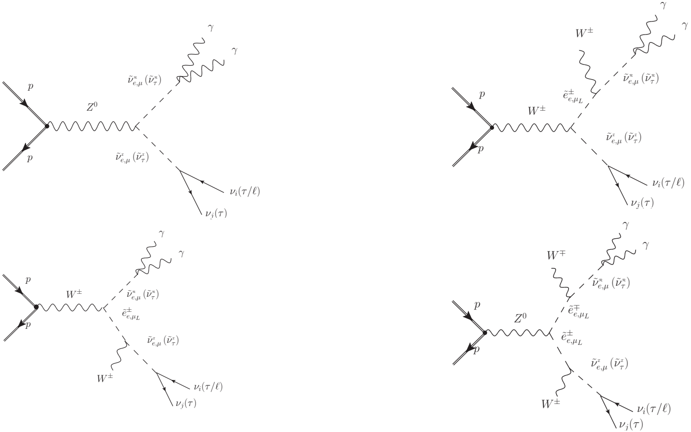
# Detection at the LHC

⋆ If the mass of the sneutrino is around EW scale.CP-even state decays "SM-Higgs-like". And the CP-odd state decays mainly to neutrinos.⇒ Clean diphoton signal plus missing transverse momentum.
⋆ If the mass of the sneutrinos is above $2M_W$ the diboson channel saturates de decays of the CP-even $\widetilde{\nu}_i$, and $Z + h_{SM}$ saturates de decay of the CP-odd $\widetilde{\nu}_i$. Also direct production crossection drasticaly reduced.
⋆ We focuss in the signals:

- → Diphoton plus missing transverse momentum. For $\widetilde{\nu}_{1,2}$
- → Diphoton plus $\tau\ell$. For $\widetilde{\nu}_3$

# Production

⋆ We are interested in the signal from directly pair produced sneutrinos:




⋆ Since the sleptons are directly produced → not very boosted. And $M_{\widetilde{e}_L} - M_{\widetilde{\nu}} < M_W$. The decay $\widetilde{e}_L \rightarrow W\widetilde{\nu}$ produce very soft products of an offshell W decay plus $\widetilde{\nu}$ ⇒Sneutrino production enhanced by slepton production.

# Production

$\star$ BR($\rightarrow \gamma\gamma$)$\sim 10^{-3}$ supress the signal strength. We need enough crossection to compensate. And BR($\rightarrow \gamma\gamma$) drop fast as we go far from $M_{\tilde{\nu}} \sim 125$ GeV. $\Rightarrow$ Above 145 GeV no signal expected

$\star$ Energetic photons plus large missing transverse momentum needed to discriminate from backgrounds.$\Rightarrow$ A small mass would make the selection cuts to reject all the signal, even if the crossection is bigger.

# Signals I

⋆ UFO files generated with `SARAH-4.8.1` + Spectrum generated with `SPHENO-3.3.6`→ Montecarlo simulation at LO with `MadGraph5_aMC@NLO-2.3.2.2`.
⋆ Output interfased with `PITHYIA-6.428` for decay and hadronization.
⋆ Fast detector simulation with `PGS` + ATLAS card.

⋆ Two signal regions designed for analysis:

$\gamma\gamma + E_T^{miss}$

→ Selection cuts:
$E_T^{miss} > 200$ GeV, $P_T^{\gamma} > 100{,}50$ GeV, $\Delta R_{\gamma\gamma}$ <1.5, $M_{\gamma\gamma}$

→ backgrounds: QCD-diphoton, ggF, Z+H, Z+ISR, W+FSR.

$\gamma\gamma + \tau + \tau/\ell$

→ Selection cuts:
$N_\ell > 1$ & $N_{\tau^h} = 1$
$P_T^{\gamma} > 100{,}50$ GeV, $\Delta R_{\gamma\gamma}$ <1.5, $M_{\gamma\gamma}$

→ backgrounds: Z+H, Z+ISR, W+FSR.

# Signals II

## @13TeV $\mathcal{L} = 300 fb^{-1}$

$\gamma\gamma + E_T^{miss}$

| $M_{\tilde{\nu}}$(GeV) | Signal | Background |
|---|---|---|
| $\sim 95$ | 15 ev | 3 ev |
| $\sim 125$ | 27 ev | 3 ev |
| $\sim 145$ | 12 ev | 2 ev |

$\gamma\gamma + \tau + \tau/\ell$

| $M_{\tilde{\nu}}$(GeV) | Signal | Background |
|---|---|---|
| $\sim 95$ | 1 ev | «1 ev |
| $\sim 125$ | 4 ev | $<$1 ev |
| $\sim 145$ | 1 ev | «1 ev |

$\star$ Leptonic signal is very sensitive to the value of $Y_\nu$.The relative value of the BR corresponding to each $\ell$ depends on the hierarchy in $Y_\nu$. Also, if the masses of $M_1$ and $M_2$ are smaller, the signal is reduced.

# Decay length and Displaced vertices

⋆ Decay width of the LSP always mediated by $\not{R}$ interactions $\Rightarrow$ Always suppresed by $Y_\nu$.

⋆ When $M_{\tilde{\nu}}$ ∼125 GeV width enhanced by bigger admixing. In other cases mean life close to observable values.

⋆ Calculations in 1-generation model predict decay length below mm scale. Also boost factor $\beta\gamma$ small due to direct production of sneutrinos.

⋆ Backgrounds for displaced vertex producing jets, photons or leptons are extremely low. $\Rightarrow$ Even small crossection could give a significant signal.

⋆ Detailed analysis of possible displaced decays needs full 3-generation analysis. Which is beyond the scope of present work.

⋆ No available public code to simulate detector response to long lived particles.

# Conclusions.

⋆ The $\mu\nu SSM$ is the minimal extension of the MSSM which the $\mu$ problem and reproduces neutrino physics.
⋆ Since $R$-parity is broken, a sneutrino LSP is not ruled out.
⋆ Light sneutrinos require small and tuned $A_\lambda$ coupling.
⋆ If 95 $\mathrm{GeV} \lesssim M_{\tilde{\nu}} \lesssim$ 145 $\mathrm{GeV}$ the signals $\gamma\gamma + E_T^{miss}$ and $\gamma\gamma + \tau/\ell$ would be detectable at the end of RUN II.
⋆ Supressed decay width of the sneutrino could lead to displaced vertices. Reliable results require further dedicated analysis.

In the Future:
⋆ Extend analysis to three generations of right handed neutrinos.
⋆ Analyze possible production of displaced vertex.
⋆ Study long decay chains of squarks and gluinos with a sneutrino LSP.
⋆ Include possbility of spontaneous CP violation.

Thank you for your time!

# Pseudoscalar mass Matrix I

$$
\begin{aligned}
m^2_{H_d^{\mathcal{I}} H_d^{\mathcal{I}}} &= v_{iR}\tan\beta\left(T_{\lambda_i}+\lambda_j\kappa_{ijk}v_{kR}\right)+Y_{\nu_{ij}}\frac{v_{iL}}{v_d}\left(\lambda_k v_{jR}v_{kR}+\lambda_j v_u^2\right)+V^{(n)}_{v_d v_d}-\frac{1}{v_d}V^{(n)}_{v_d}\ ,\\
m^2_{H_u^{\mathcal{I}} H_u^{\mathcal{I}}} &= v_{iR}\frac{1}{\tan\beta}\left(T_{\lambda_i}+\lambda_j\kappa_{ijk}v_{kR}\right)-\frac{v_{iL}}{v_u}\left(T_{\nu_{ij}}v_{jR}+Y_{\nu_{ij}}\kappa_{ljk}v_{lR}v_{kR}\right)+V^{(n)}_{v_u v_u}-\frac{1}{v_u}V^{(n)}_{v_u}\ ,\\
m^2_{H_d^{\mathcal{I}} H_u^{\mathcal{I}}} &= T_{\lambda_i}v_{iR}+\lambda_k\kappa_{ijk}v_{iR}v_{jR}+V^{(n)}_{v_d v_u}\ ,\\
m^2_{H_d^{\mathcal{I}} \widetilde{\nu}_{iR}^{\mathcal{I}}} &= T_{\lambda_i}v_u-2\lambda_k\kappa_{ijk}v_u v_{jR}-Y_{\nu_{ji}}\lambda_k v_{jL}v_{kR}+Y_{\nu_{jk}}\lambda_i v_{jL}v_{kR}+V^{(n)}_{v_d v_{iR}}\ ,\\
m^2_{H_u^{\mathcal{I}} \widetilde{\nu}_{iR}^{\mathcal{I}}} &= T_{\lambda_i}v_d-T_{\nu_{ji}}v_{jR}-2\lambda_k\kappa_{ilk}v_d v_{lR}+2Y_{\nu_{jk}}\kappa_{ilk}v_{jL}v_{lR}+V^{(n)}_{v_u v_{iR}}\ ,\\
m^2_{\widetilde{\nu}_{iR}^{\mathcal{I}} \widetilde{\nu}_{jR}^{\mathcal{I}}} &= -2\left(T_{\kappa_{ijk}}v_{kR}-\lambda_k\kappa_{ijk}v_d v_u+\kappa_{ijk}\kappa_{lmk}v_{lR}v_{mR}\right)+4\kappa_{ilk}\kappa_{jmk}v_{lR}v_{mR}+\lambda_i\lambda_j(v_d^2+v_u^2)\\
&\quad -2Y_{\nu_{lk}}\kappa_{ijk}v_u v_{lL}-\left(Y_{\nu_{kj}}\lambda_i+Y_{\nu_{ki}}\lambda_j\right)v_d v_{kL}+Y_{\nu_{ki}}Y_{\nu_{kj}}v_u^2+Y_{\nu_{li}}Y_{\nu_{kj}}v_{kL}v_{lL}\\
&\quad +\frac{\delta_{ij}}{v_{jR}}\left[-T_{\nu_{ki}}v_{kL}v_u+T_{\lambda_i}v_u v_d-T_{\kappa_{ilk}}v_{lR}v_{kR}+2\lambda_l\kappa_{ilk}v_d v_u v_{kR}-2\kappa_{lim}\kappa_{lnk}v_{mR}v_{\nu_n^c}v_{kR}\right.\\
&\quad -\lambda_i\lambda_l(v_d^2+v_u^2)v_{lR}-2Y_{\nu_{lk}}\kappa_{ikm}v_u v_{lL}v_{mR}+\left(Y_{\nu_{kl}}\lambda_i+Y_{\nu_{ki}}\lambda_l\right)v_d v_{kL}v_{lR}\\
&\quad \left.-Y_{\nu_{ki}}Y_{\nu_{kl}}v_u^2 v_{lR}-Y_{\nu_{ki}}Y_{\nu_{lm}}v_{kL}v_{lL}v_{mR}\right]+V^{(n)}_{v_{iR}v_{jR}}-\frac{\delta_{ij}}{v_{iR}}V^{(n)}_{v_{iR}}\ ,
\end{aligned}
$$

# Pseudoscalar mass Matrix II

$$
\begin{aligned}
m^2_{H_d^{\mathcal{I}}\widetilde{\nu}_{iL}^{\mathcal{I}}} &= -Y_{\nu_{ij}}\lambda_j v_u^2 - Y_{\nu_{ij}}\lambda_k v_{kR} v_{jR} + V^{(n)}_{v_d v_{iL}} \ , \\
m^2_{H_u^{\mathcal{I}}\widetilde{\nu}_{iL}^{\mathcal{I}}} &= -T_{\nu_{ij}} v_{\nu_j^c} - Y_{\nu_{ik}}\kappa_{ljk} v_{lR} v_{jR} + V^{(n)}_{v_u v_{iL}} \ , \\
m^2_{\widetilde{\nu}_{iL}^{\mathcal{I}}\widetilde{\nu}_{jR}^{\mathcal{I}}} &= -T_{\nu_{ij}} v_u + Y_{\nu_{ij}}\lambda_k v_d v_{kR} - Y_{\nu_{ik}}\lambda_j v_d v_{kR} + 2Y_{\nu_{il}}\kappa_{jlk} v_u v_{kR} \\
& \quad -Y_{\nu_{ij}} Y_{\nu_{lk}} v_{lL} v_{kR} + Y_{\nu_{ik}} Y_{\nu_{lj}} v_{lL} v_{kR} + V^{(n)}_{v_{iL} v_{jR}} \ , \\
m^2_{\widetilde{\nu}_{iL}^{\mathcal{I}}\widetilde{\nu}_{jL}^{\mathcal{I}}} &= Y_{\nu_{ik}} Y_{\nu_{jk}} v_u^2 + Y_{\nu_{ik}} Y_{\nu_{jl}} v_{kR} v_{lR} \\
& \quad + \frac{\delta_{ij}}{v_{jL}} \left[ -T_{\nu_{ik}} v_u v_{kR} + Y_{\nu_{ik}} \left( \lambda_l v_d v_{kR} v_{lR} + \lambda_k v_d v_u^2 - \kappa_{klm} v_u v_{lR} v_{mR} - Y_{\nu_{mk}} v_{mL} v_u^2 \right.\right. \\
& \quad \left.\left. -Y_{\nu_{ml}} v_{mL} v_{lR} v_{kR} \right) \right] + V^{(n)}_{v_{iL} v_{jL}} - \frac{\delta_{ij}}{v_{iL}} V^{(n)}_{v_{iL}} \ ,
\end{aligned}
$$

# Scalar mass Matrix I

$$
\begin{aligned}
m^2_{H_d^{\mathcal{R}} H_d^{\mathcal{R}}} &= m^2_{H_d^{\mathcal{I}} H_d^{\mathcal{I}}} + \frac{G^2}{2} v_d^2 \ , \\
m^2_{H_u^{\mathcal{R}} H_u^{\mathcal{R}}} &= m^2_{H_u^{\mathcal{I}} H_u^{\mathcal{I}}} + \frac{G^2}{2} v_u^2 \ , \\
m^2_{H_d^{\mathcal{R}} H_u^{\mathcal{R}}} &= -\frac{G^2}{2} v_d v_u - T_{\lambda_i} v_{iR} - \lambda_k \kappa_{ijk} v_{iR} v_{jR} + 2 v_d v_u \lambda_i \lambda_i - 2 Y_{\nu_{ij}} \lambda_j v_u v_{iL} + V^{(n)}_{v_d v_u} \ , \\
m^2_{H_d^{\mathcal{R}} \widetilde{\nu}_i^{c\mathcal{R}}} &= -T_{\lambda_i} v_u - 2\lambda_k \kappa_{ijk} v_u v_{jR} + 2\lambda_i \lambda_j v_d v_{jR} - Y_{\nu_{ji}} \lambda_k v_{jL} v_{kR} - Y_{\nu_{jk}} \lambda_i v_{jL} v_{kR} + V^{(n)}_{v_d v_{iR}} \ , \\
m^2_{H_u^{\mathcal{R}} \widetilde{\nu}_i^{c\mathcal{R}}} &= -T_{\lambda_i} v_d + T_{\nu_{ji}} v_{jL} - 2\lambda_k \kappa_{ilk} v_d v_{lR} + 2\lambda_i \lambda_j v_u v_{jR} + 2 Y_{\nu_{jk}} \kappa_{ilk} v_{jL} v_{lR} \\
&\quad + 2 Y_{\nu_{jk}} Y_{\nu_{ji}} v_u v_{kR} + V^{(n)}_{v_u v_{iR}} ,
\end{aligned}
$$

# Scalar mass Matrix II

$$
\begin{aligned}
m^2_{\widetilde{\nu}^{\mathcal{R}}_{iR}\widetilde{\nu}^{\mathcal{R}}_{jR}} &= m^2_{\widetilde{\nu}^{\mathcal{I}}_{iR}\widetilde{\nu}^{\mathcal{I}}_{jR}} + 4\left(T_{\kappa_{ijk}} v_{kR} - \lambda_k \kappa_{ijk} v_d v_u + \kappa_{ijk}\kappa_{lmk} v_{lR} v_{mR}\right) \ , \\
m^2_{H^{\mathcal{R}}_d \widetilde{\nu}^{\mathcal{R}}_i} &= \frac{G^2}{2} v_d v_{iL} - Y_{\nu_{ij}} \lambda_j v_u^2 - Y_{\nu_{ij}} \lambda_k v_{kR} v_{jR} + V^{(n)}_{v_d v_{iL}} \ , \\
m^2_{H^{\mathcal{R}}_u \widetilde{\nu}^{\mathcal{R}}_i} &= -\frac{G^2}{2} v_u v_{iL} + T_{\nu_{ij}} v_{jR} + Y_{\nu_{ik}} \kappa_{ljk} v_{lR} v_{jR} - 2 Y_{\nu_{ij}} \lambda_j v_d v_u + 2 Y_{\nu_{ij}} Y_{\nu_{kj}} v_u v_{kL} + V^{(n)}_{v_u v_{iL}} \ , \\
m^2_{\widetilde{\nu}^{\mathcal{R}}_{iL}\widetilde{\nu}^{c\mathcal{R}}_{j}} &= T_{\nu_{ij}} v_u - Y_{\nu_{ij}} \lambda_k v_d v_{kR} - Y_{\nu_{ik}} \lambda_j v_d v_{kR} + 2 Y_{\nu_{ik}} \kappa_{jlk} v_u v_{lR} + Y_{\nu_{ij}} Y_{\nu_{kl}} v_{kL} v_{lR} \\
&\quad + Y_{\nu_{il}} Y_{\nu_{kj}} v_{kL} v_{lR} + V^{(n)}_{v_{iL} v_{jR}} \ , \\
m^2_{\widetilde{\nu}^{\mathcal{R}}_{iL}\widetilde{\nu}^{\mathcal{R}}_{jL}} &= m^2_{\widetilde{\nu}^{\mathcal{I}}_{iL}\widetilde{\nu}^{\mathcal{I}}_{jL}} + \frac{G^2}{2} v_{iL} v_{jL} \ ,
\end{aligned}
$$

# Charged scalar mass matrix I.

$$
\begin{aligned}
m^2_{H_d^- H_d^{-*}} &= m^2_{H_d^{\mathcal{I}} H_d^{\mathcal{I}}} + \frac{g_2^2}{2}(v_u^2 - v_{iL}v_{iL}) - \lambda_i\lambda_j v_u^2 + Y_{e_{ik}} Y_{e_{jk}} v_{iL} v_{jL} \ , \\
m^2_{H_u^{+*} H_u^+} &= m^2_{H_u^{\mathcal{I}} H_u^{\mathcal{I}}} + \frac{g_2^2}{2}(v_d^2 + v_{iL}v_{iL}) - \lambda_i\lambda_i v_d^2 + 2Y_{\nu_{ij}}\lambda_j v_d v_{iL} - Y_{\nu_{ik}} Y_{\nu_{jk}} v_{iL} v_{jL} \ , \\
m^2_{H_d^- H_u^+} &= \frac{g_2^2}{2} v_d v_u + T_{\lambda_i} v_{iR} + \lambda_k \kappa_{ijk} v_{iR} v_{jR} - \lambda_i\lambda_i v_d v_u + Y_{\nu_{ij}}\lambda_j v_u v_{iL} + V^{(n)}_{v_d v_u} \ , \\
m^2_{\tilde{e}_i H_d^{-*}} &= \frac{g_2^2}{2} v_d v_{iL} - Y_{\nu_{ij}}\lambda_k v_{kR} v_{jR} - Y_{e_{ij}} Y_{e_{kj}} v_d v_{kL} + V^{(n)}_{v_{iL} v_d} \ , \\
m^2_{\tilde{e}_i H_u^+} &= \frac{g_2^2}{2} v_u v_{iL} - T_{\nu_{ij}} v_{jR} - Y_{\nu_{ij}} \kappa_{ljk} v_{lR} v_{kR} + Y_{\nu_{ij}}\lambda_j v_d v_u - Y_{\nu_{ik}} Y_{\nu_{kj}} v_u v_{jL} + V^{(n)}_{v_{iL} v_u} \ , \\
m^2_{\tilde{e}_i^c H_d^{-*}} &= -T_{e_{ji}} v_{iL} - Y_{e_{ki}} Y_{\nu_{kj}} v_u v_{jR} + V^{(n)}_{\tilde{e}_i^{c*} v_d} \ , \\
m^2_{\tilde{e}_i^c H_u^+} &= -Y_{e_{ki}}(\lambda_j v_{kL} v_{jR} + Y_{\nu_{kj}} v_d v_{jR}) + V^{(n)}_{\tilde{e}_i^{c*} v_u} \ ,
\end{aligned}
$$

# Charged scalar mass matrix II.

$$
\begin{aligned}
m^2_{\widetilde{e}_i \widetilde{e}^{c*}_j} &= T_{e_{ij}} v_d - Y_{e_{ij}} \lambda_k v_u v_{kR} + V^{(n)}_{v_{\nu_i} \widetilde{e}^{c*}_j} \ , \\
m^2_{\widetilde{e}^c_j \widetilde{e}^*_i} &= m^2_{\widetilde{e}_i \widetilde{e}^{c*}_j} + V^{(n)}_{\widetilde{e}^{c*}_i v_{\nu_j}} \ , \\
m^2_{\widetilde{e}^c_i \widetilde{e}^{c*}_j} &= m^2_{\widetilde{e}^c_{ij}} + \frac{g_1^2}{2}(v_u^2 - v_d^2 - v_{kL} v_{kL})\delta_{ij} + Y_{e_{ki}} Y_{e_{kj}} v_d^2 + Y_{e_{li}} Y_{e_{kj}} v_{kL} v_{lL} + V^{(n)}_{\widetilde{e}^{c*}_i \widetilde{e}^{c*}_j} \ . \\
m^2_{\widetilde{e}_i \widetilde{e}^*_j} &= m^2_{\widetilde{\nu}^{\mathcal{I}}_{iL} \widetilde{\nu}^{\mathcal{I}}_{jL}} + \frac{g_2^2}{2}(v_u^2 - v_d^2 - v_{kL} v_{kL})\delta_{ij} + \frac{g_2^2}{2} v_{iL} v_{jL} - Y_{\nu_{ik}} Y_{\nu_{jk}} v_u^2 + Y_{e_{il}} Y_{e_{jl}} v_d^2 \ ,
\end{aligned}
$$

# Couplings I.

⋆ CP even neutral scalar–up quarks–up quarks

$$-i\frac{1}{\sqrt{2}}\delta_{\alpha\beta}\sum_{b=1}^{3}U^{u,*}_{L,jb}\sum_{a=1}^{3}U^{u,*}_{R,ia}Y_{u,ab}Z^{H}_{k2}P_L - i\frac{1}{\sqrt{2}}\delta_{\alpha\beta}\sum_{a,b=1}^{3}Y^{*}_{u,ab}U^{u}_{R,ja}U^{u}_{L,ib}Z^{H}_{k2}P_R \ .$$

⋆ CP odd neutral scalar–up quarks–up quarks

$$\frac{1}{\sqrt{2}}\delta_{\alpha\beta}\sum_{b=1}^{3}U^{u,*}_{L,jb}\sum_{a=1}^{3}U^{u,*}_{R,ia}Y_{u,ab}Z^{A}_{k2}P_L - \frac{1}{\sqrt{2}}\delta_{\alpha\beta}\sum_{a,b=1}^{3}Y^{*}_{u,ab}U^{u}_{R,ja}U^{u}_{L,ib}Z^{A}_{k2}P_R \ .$$

⋆ CP even neutral scalar–down quarks–down quarks

$$-i\frac{1}{\sqrt{2}}\delta_{\alpha\beta}\sum_{b=1}^{3}U^{d,*}_{L,jb}\sum_{a=1}^{3}U^{d,*}_{R,ia}Y_{d,ab}Z^{H}_{k1}P_L - i\frac{1}{\sqrt{2}}\delta_{\alpha\beta}\sum_{a,b=1}^{3}Y^{*}_{d,ab}U^{d}_{R,ja}U^{d}_{L,ib}Z^{H}_{k1}P_R \ .$$

⋆ CP odd neutral scalar–down quarks–down quarks

$$\frac{1}{\sqrt{2}}\delta_{\alpha\beta}\sum_{b=1}^{3}U^{d,*}_{L,jb}\sum_{a=1}^{3}U^{d,*}_{R,ia}Y_{d,ab}Z^{A}_{k1}P_L - \frac{1}{\sqrt{2}}\delta_{\alpha\beta}\sum_{a,b=1}^{3}Y^{*}_{d,ab}U^{d}_{R,ja}U^{d}_{L,ib}Z^{A}_{k1}P_R \ .$$

⋆ CP even neutral scalar–charged fermion–charged fermion

$$-i\frac{1}{\sqrt{2}}\Big\{\sum_{a,b=1}^{3}U^{e,*}_{R,jb}U^{e,*}_{L,ia}Y_{e,ab}Z^{H}_{k1}+g_2U^{e,*}_{L,i4}\Big(U^{e,*}_{R,j5}Z^{H}_{k1}+\sum_{a=1}^{3}U^{e,*}_{R,ja}Z^{H}_{k3+a}\Big)+g_2U^{e,*}_{R,j4}U^{e,*}_{L,i5}Z^{H}_{k2}$$

$$-U^{e,*}_{L,i5}\sum_{a=1}^{3}U^{e,*}_{R,ja}Y_{\nu,a}Z^{H}_{k3}+U^{e,*}_{R,j5}\Big(\lambda U^{e,*}_{L,i5}Z^{H}_{k3}-\sum_{a,b=1}^{3}U^{e,*}_{L,ia}Y_{e,ab}Z^{H}_{k3+b}\Big)\Big\}P_L$$

$$+i\frac{1}{\sqrt{2}}\Big\{\sum_{a,b=1}^{3}Y^{*}_{e,ab}U^{e}_{L,ja}Z^{H}_{k3+b}U^{e}_{R,i5}-g_2\sum_{a=1}^{3}U^{e}_{R,ia}Z^{H}_{k3+a}U^{e}_{L,j4}-\sum_{a,b=1}^{3}Y^{*}_{e,ab}U^{e}_{L,ja}U^{e}_{R,ib}Z^{H}_{k1}$$

$$-g_2U^{e}_{R,i5}U^{e}_{L,j4}Z^{H}_{k1}-g_2U^{e}_{R,i4}U^{e}_{L,j5}Z^{H}_{k2}+\sum_{a=1}^{3}Y^{*}_{\nu,a}U^{e}_{R,ia}U^{e}_{L,j5}Z^{H}_{k3}-\lambda^{*}U^{e}_{R,i5}U^{e}_{L,j5}Z^{H}_{k3}\Big\}P_R\ .$$

# Couplings III.

⋆ CP even neutral scalar–neutral fermion–neutral fermion

$$\frac{i}{2}\Big\{g_1 U^{V,*}_{i4}\sum_{a=1}^{3}U^{V,*}_{ja}Z^H_{k3+a} - g_2 U^{V,*}_{i5}\sum_{a=1}^{3}U^{V,*}_{ja}Z^H_{k3+a} - \sqrt{2}(U^{V,*}_{i8}U^{V,*}_{j7} + U^{V,*}_{i7}U^{V,*}_{j8})\sum_{a=1}^{3}Y_{\nu,a}Z^H_{k3+a}$$
$$+g_1 U^{V,*}_{i4}U^{V,*}_{j6}Z^H_{k1} - g_2 U^{V,*}_{i5}U^{V,*}_{j6}Z^H_{k1} + \sqrt{2}\lambda(U^{V,*}_{i8}U^{V,*}_{j7}Z^H_{k1} + U^{V,*}_{i7}U^{V,*}_{j8}Z^H_{k1} + U^{V,*}_{i8}U^{V,*}_{j6}Z^H_{k2})$$
$$-g_1 U^{V,*}_{i4}U^{V,*}_{j7}Z^H_{k2} + g_2 U^{V,*}_{i5}U^{V,*}_{j7}Z^H_{k2} + \sqrt{2}\lambda U^{V,*}_{i6}U^{V,*}_{j8}Z^H_{k2} - \sqrt{2}U^{V,*}_{j8}\sum_{a=1}^{3}U^{V,*}_{ia}Y_{\nu,a}Z^H_{k2}$$
$$-\sqrt{2}U^{V,*}_{i8}\sum_{a=1}^{3}U^{V,*}_{ja}Y_{\nu,a}Z^H_{k2} + g_1 U^{V,*}_{j4}\Big(U^{V,*}_{i6}Z^H_{k1} - U^{V,*}_{i7}Z^H_{k2} + \sum_{a=1}^{3}U^{V,*}_{ia}Z^H_{k3+a}\Big) - 2\sqrt{2}\kappa U^{V,*}_{i8}U^{V,*}_{j8}Z^H_{k3}$$
$$-g_2 U^{V,*}_{j5}\Big(U^{V,*}_{i6}Z^H_{k1} - U^{V,*}_{i7}Z^H_{k2} + \sum_{a=1}^{3}U^{V,*}_{ia}Z^H_{k3+a}\Big) + \sqrt{2}\lambda(U^{V,*}_{i7}U^{V,*}_{j6}Z^H_{k3} + U^{V,*}_{i6}U^{V,*}_{j7}Z^H_{k3})$$
$$-\sqrt{2}U^{V,*}_{j7}\sum_{a=1}^{3}U^{V,*}_{ia}Y_{\nu,a}Z^H_{k3} - \sqrt{2}U^{V,*}_{i7}\sum_{a=1}^{3}U^{V,*}_{ja}Y_{\nu,a}Z^H_{k3}\Big\}P_L + \frac{i}{2}\Big\{\sum_{a=1}^{3}Z^H_{k3+a}U^V_{ja}\Big(g_1 U^V_{i4} - g_2 U^V_{i5}\Big)$$
$$-\sqrt{2}\sum_{a=1}^{3}Y^*_{\nu,a}U^V_{ja}\Big(Z^H_{k2}U^V_{i8} + Z^H_{k3}U^V_{i7}\Big) + g_1\sum_{a=1}^{3}Z^H_{k3+a}U^V_{ia}U^V_{j4} + g_1 Z^H_{k1}U^V_{i6}U^V_{j4} - g_1 Z^H_{k2}U^V_{i7}U^V_{j4}$$

# Couplings IV.

$$-g_2 \sum_{a=1}^{3} Z^H_{k3+a} U^V_{ia} U^V_{j5} - g_2 Z^H_{k1} U^V_{i6} U^V_{j5} + g_2 Z^H_{k2} U^V_{i7} U^V_{j5} + g_1 Z^H_{k1} U^V_{i4} U^V_{j6} - g_2 Z^H_{k1} U^V_{i5} U^V_{j6} + \sqrt{2}\lambda^* Z^H_{k3} U^V_{i7} U^V_{j6}$$

$$+\sqrt{2}\lambda^* Z^H_{k2} U^V_{i8} U^V_{j6} - \sqrt{2} \sum_{a=1}^{3} Y^*_{\nu,a} U^V_{ia} Z^H_{k3} U^V_{j7} - g_1 Z^H_{k2} U^V_{i4} U^V_{j7} + g_2 Z^H_{k2} U^V_{i5} U^V_{j7} + \sqrt{2}\lambda^* Z^H_{k3} U^V_{i6} U^V_{j7}$$

$$-\sqrt{2} \sum_{a=1}^{3} Y^*_{\nu,a} Z^H_{k3+a} U^V_{i8} U^V_{j7} + \sqrt{2}\lambda^* Z^H_{k1} U^V_{i8} U^V_{j7} - \sqrt{2} \sum_{a=1}^{3} Y^*_{\nu,a} U^V_{ia} Z^H_{k2} U^V_{j8} + \sqrt{2}\lambda^* Z^H_{k2} U^V_{i6} U^V_{j8}$$

$$-\sqrt{2} \sum_{a=1}^{3} Y^*_{\nu,a} Z^H_{k3+a} U^V_{i7} U^V_{j8} + \sqrt{2}\lambda^* Z^H_{k1} U^V_{i7} U^V_{j8} - 2\sqrt{2}\kappa^* Z^H_{k3} U^V_{i8} U^V_{j8} \Big\} P_R \; .$$

# Couplings V.

⋆ CP odd neutral scalar–charged fermion–charged fermion

$$-\frac{1}{\sqrt{2}}\Big\{-\sum_{a,b=1}^{3}U^{e,*}_{R,jb}U^{e,*}_{L,ia}Y_{e,ab}Z^{A}_{k1}+g_2U^{e,*}_{L,i4}\Big(U^{e,*}_{R,j5}Z^{A}_{k1}+\sum_{a=1}^{3}U^{e,*}_{R,ja}Z^{A}_{k3+a}\Big)+g_2U^{e,*}_{R,j4}U^{e,*}_{L,i5}Z^{A}_{k2}$$

$$-U^{e,*}_{L,i5}\sum_{a=1}^{3}U^{e,*}_{R,ja}Y_{\nu,a}Z^{A}_{k3}+U^{e,*}_{R,j5}\Big(\lambda U^{e,*}_{L,i5}Z^{A}_{k3}+\sum_{a,b=1}^{3}U^{e,*}_{L,ia}Y_{e,ab}Z^{A}_{k3+b}\Big)\Big\}P_L$$

$$+\frac{1}{\sqrt{2}}\Big\{\sum_{a,b=1}^{3}Y^{*}_{e,ab}U^{e}_{L,ja}Z^{A}_{k3+b}U^{e}_{R,i5}+g_2\sum_{a=1}^{3}U^{e}_{R,ia}Z^{A}_{k3+a}U^{e}_{L,j4}-\sum_{a,b=1}^{3}Y^{*}_{e,ab}U^{e}_{L,ja}U^{e}_{R,ib}Z^{A}_{k1}$$

$$+g_2U^{e}_{R,i5}U^{e}_{L,j4}Z^{A}_{k1}+g_2U^{e}_{R,i4}U^{e}_{L,j5}Z^{A}_{k2}-\sum_{a=1}^{3}Y^{*}_{\nu,a}U^{e}_{R,ia}U^{e}_{L,j5}Z^{A}_{k3}+\lambda^{*}U^{e}_{R,i5}U^{e}_{L,j5}Z^{A}_{k3}\Big\}P_R\,.$$

# Couplings VI.

⋆ CP odd neutral scalar–charged fermion–charged fermion

$$
\begin{aligned}
&\frac{1}{2}\Big\{g_1 U^{V,*}_{i4}\sum_{a=1}^{3} U^{V,*}_{ja} Z^{A}_{k3+a} - g_2 U^{V,*}_{i5}\sum_{a=1}^{3} U^{V,*}_{ja} Z^{A}_{k3+a} + \sqrt{2}(U^{V,*}_{i8} U^{V,*}_{j7} + U^{V,*}_{i7} U^{V,*}_{j8})\sum_{a=1}^{3} Y_{\nu,a} Z^{A}_{k3+a} \\
&+g_1 U^{V,*}_{i4} U^{V,*}_{j6} Z^{A}_{k1} - g_2 U^{V,*}_{i5} U^{V,*}_{j6} Z^{A}_{k1} - \sqrt{2}\lambda(U^{V,*}_{i8} U^{V,*}_{j7} Z^{A}_{k1} - U^{V,*}_{i7} U^{V,*}_{j8} Z^{A}_{k1} - U^{V,*}_{i8} U^{V,*}_{j6} Z^{A}_{k2}) \\
&-g_1 U^{V,*}_{i4} U^{V,*}_{j7} Z^{A}_{k2} + g_2 U^{V,*}_{i5} U^{V,*}_{j7} Z^{A}_{k2} - \sqrt{2}\lambda U^{V,*}_{i6} U^{V,*}_{j8} Z^{A}_{k2} + \sqrt{2} U^{V,*}_{j8}\sum_{a=1}^{3} U^{V,*}_{ia} Y_{\nu,a} Z^{A}_{k2} \\
&+\sqrt{2} U^{V,*}_{i8}\sum_{a=1}^{3} U^{V,*}_{ja} Y_{\nu,a} Z^{A}_{k2} + g_1 U^{V,*}_{j4}\Big(U^{V,*}_{i6} Z^{A}_{k1} - U^{V,*}_{i7} Z^{A}_{k2} + \sum_{a=1}^{3} U^{V,*}_{ia} Z^{A}_{k3+a}\Big) - 2\sqrt{2}\kappa U^{V,*}_{i8} U^{V,*}_{j8} Z^{A}_{k3} \\
&-g_2 U^{V,*}_{j5}\Big(U^{V,*}_{i6} Z^{A}_{k1} - U^{V,*}_{i7} Z^{A}_{k2} + \sum_{a=1}^{3} U^{V,*}_{ia} Z^{A}_{k3+a}\Big) + \sqrt{2}\lambda U^{V,*}_{i7} U^{V,*}_{j6} Z^{A}_{k3} + \sqrt{2}\lambda U^{V,*}_{i6} U^{V,*}_{j7} Z^{A}_{k3} \\
&-\sqrt{2} U^{V,*}_{j7}\sum_{a=1}^{3} U^{V,*}_{ia} Y_{\nu,a} Z^{A}_{k3} - \sqrt{2} U^{V,*}_{i7}\sum_{a=1}^{3} U^{V,*}_{ja} Y_{\nu,a} Z^{A}_{k3}\Big\} P_L + \frac{1}{2}\Big\{\sum_{a=1}^{3} Z^{A}_{k3+a} U^{V}_{ja}\Big(-g_1 U^{V}_{i4} + g_2 U^{V}_{i5}\Big) \\
&+\sqrt{2}\sum_{a=1}^{3} Y^{*}_{\nu,a} U^{V}_{ja}\Big(-Z^{A}_{k2} U^{V}_{i8} + Z^{A}_{k3} U^{V}_{i7}\Big) - g_1\sum_{a=1}^{3} Z^{A}_{k3+a} U^{V}_{ia} U^{V}_{j4} - g_1 Z^{A}_{k1} U^{V}_{i6} U^{V}_{j4} + g_1 Z^{A}_{k2} U^{V}_{i7} U^{V}_{j4}
\end{aligned}
\tag{6}
$$

# Couplings VII.

$$+g_2 \sum_{a=1}^{3} Z^A_{k3+a} U^V_{ia} U^V_{j5} + g_2 Z^A_{k1} U^V_{i6} U^V_{j5} - g_2 Z^A_{k2} U^V_{i7} U^V_{j5} - g_1 Z^A_{k1} U^V_{i4} U^V_{j6} + g_2 Z^A_{k1} U^V_{i5} U^V_{j6}$$

$$-\sqrt{2}\lambda^* (Z^A_{k3} U^V_{i7} U^V_{j6} + Z^A_{k2} U^V_{i8} U^V_{j6}) + \sqrt{2} \sum_{a=1}^{3} Y^*_{\nu,a} U^V_{ia} Z^A_{k3} U^V_{j7} + g_1 Z^A_{k2} U^V_{i4} U^V_{j7} - g_2 Z^A_{k2} U^V_{i5} U^V_{j7}$$

$$-\sqrt{2}\lambda^* Z^A_{k3} U^V_{i6} U^V_{j7} - \sqrt{2} \sum_{a=1}^{3} Y^*_{\nu,a} Z^A_{k3+a} U^V_{i8} U^V_{j7} + \sqrt{2}\lambda^* Z^A_{k1} U^V_{i8} U^V_{j7} - \sqrt{2} \sum_{a=1}^{3} Y^*_{\nu,a} U^V_{ia} Z^A_{k2} U^V_{j8}$$

$$+\sqrt{2}\lambda^* Z^A_{k2} U^V_{i6} U^V_{j8} - \sqrt{2} \sum_{a=1}^{3} Y^*_{\nu,a} Z^A_{k3+a} U^V_{i7} U^V_{j8} + \sqrt{2}\lambda^* Z^A_{k1} U^V_{i7} U^V_{j8} + 2\sqrt{2}\kappa^* Z^A_{k3} U^V_{i8} U^V_{j8} \Big\} P_R \ .$$

# Constraints on trilinear+bilinear

## After EWSB effective terms are generated:

Trilinear terms

- $\lambda_{ijk} \sim Y_{\nu_{ii}} \kappa \frac{m_{l_{jk}}}{v} \frac{(1-\delta_{ij})\delta_{jk}}{\sqrt{1+\tan^2\beta}} \lesssim 2 \times 10^{-10}$ for $j = k = 3$
- $\lambda'_{ijk} \sim Y_{\nu_{ii}} \kappa \frac{m_{d_{jk}}}{v} \frac{\delta_{jk}}{\sqrt{1+\tan^2\beta}} \lesssim 2 \times 10^{-10}$ for $j = k = 3$

Bilinear

- $\epsilon_i^{eff} \sim Y_{\nu_{ij}} v_{jR} \lesssim 2 \times 10^{-3}$ GeV for $i = j = 3$

Experimental contraints form Cosmology, Colliders and Flavour physics are:

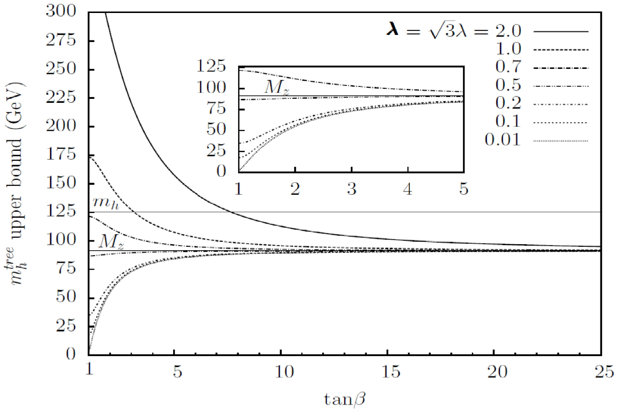
- *R-parity* $\lesssim \mathcal{O}(10^{-20}) \Rightarrow$ DM candidate.
- $\mathcal{O}(10^{-20}) \lesssim$ *R-parity* $\lesssim \mathcal{O}(10^{-12}) \Rightarrow$ Ruled out (Interference with Big-bang nucleosynthesis).
- $\mathcal{O}(10^{-12}) \lesssim$ *R-parity* $\lesssim \mathcal{O}(10^{-9}) \Rightarrow$ Decay outside detector ($E_T^{miss}$).

Stringest constraints (with $m_Soft \sim$ 1TeV) over:

- $|\lambda^*_{ij2}\lambda_{ij1}| \lesssim 8.2\times10^{-5}$ [$\mu \to e\gamma$].
- $|\lambda^*_{i12}\lambda_{i11}| \lesssim 6.6\times10^{-7}$ [$\mu \to 3e$].
- $|\lambda^*_{i12}\lambda'_{i12}| \lesssim 6\times10^{-9}$ [$K_L \to e\mu$].
- $|\lambda'^*_{i21}\lambda'_{i12}| \lesssim 4.5\times10^{-9}$ [$K\bar{K}$].
- $|\lambda'^*_{i31}\lambda'_{i13}| \lesssim 3.3\times10^{-8}$ [$B\bar{B}$].
- $|\lambda'^*_{ij1}\lambda'_{2j2}| \lesssim 3\times10^{-7}$ [$K_L \to e\mu$].

# Higgs mass in the $\mu\nu SSM$

⋆ Additional tree-level contributions from new $F$-terms and or $D$-terms.




⋆ In the $\mu\nu SSM$ is possible a tree-level mass around 125 GeV $\Rightarrow$ At higher tan $\beta$, stronger $\lambda$ coupling is needed.

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

# $Z_3$ Symmetric superpotential

⋆ If a discrete $Z_3$ symmetry is imposed to the superpotential, to avoid dimensionful parameters ⇒ Once spontaneously broken after EWSB Domain walls are generated which can dominate the energy density of the universe, producing large anisotropies on the CMB

⋆ If $Z_3$ is an accidental symmetry ⇒ Nonrenormalizable interactions lift the degeneracy between vacua

⋆ If the right handed neutrino superfields couple in the most general way to heavy fiels ⇒Radiative corrections can induce very large terms in the effective action linear in $\hat{\nu}_R$

⋆ Impose R-symmetries in the nonrenormalizable lagrangian allow only non-dangerous higher dimension terms

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# LFV

⋆ Same QFV contraints as to the NMSSM apply to the $\mu\nu SSM$.

⋆ The $\mu\nu SSM$ superpotential includes terms which break splicitly Lepton number conservation. ⇒ Small violation:

- $BR(\mu \to e\gamma)_{\mu\nu SSM} = 3.96\times10^{-26}$ « $BR(\mu \to e\gamma)_{exp} < 5.7\times10^{-13}$
- $BR(\tau \to e\gamma)_{\mu\nu SSM} = 2.23\times10^{-28}$ « $BR(\tau \to e\gamma)_{exp} < 3.3\times10^{-8}$
- $BR(\tau \to \mu\gamma)_{\mu\nu SSM} = 2.22\times10^{-28}$ « $BR(\tau \to \mu\gamma)_{exp} < 4.4\times10^{-8}$
- $BR(\mu \to eee)_{\mu\nu SSM} = 1.0\times10^{-26}$ « $BR(\mu \to eee)_{exp} < 1.0\times10^{-12}$
- $BR(\tau \to e\mu\mu)_{\mu\nu SSM} = 1.341\times10^{-28}$ « $BR(\tau \to e\mu\mu)_{exp} < 4.4\times10^{-8}$
- Limits on $\mu \to e$ conversion: $\mu\nu SSM \sim 10^{-26}$ « Exp Limits $\lesssim 10^{-11}$