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LHC and dark matter signals motivated by the $\mu\nu$SSM

MultiDark
Multimessenger Approach for Dark Matter Detection

June 2018, Annesy, France

Supersymmetry: still the most compelling theory for physics beyond the standard model

- The lower bounds on SUSY particles ($\lesssim$ TeV) are still reasonable

- Experimentalists use simplified models that don't cover full SUSY phase space (BR variations for example)

- Run 2 is still going on,   low luminosity

- Most SUSY searches assume R parity conservation (RPC), thus the LSP is stable, requiring missing energy in the final state for its detection

- If R parity is violated (RPV), SUSY particles can decay to standard model particles, and the bounds become significantly weaker

MSSM: The Minimal Supersymmetric Standard Model

$$W = Y_u^{ij}\,\hat{H}_2^b\,\hat{Q}_i^a\,\hat{u}_j^c + Y_d^{ij}\,\hat{H}_1^a\,\hat{Q}_i^b\,\hat{d}_j^c + Y_e^{ij}\,\hat{H}_1^a\,\hat{L}_i^b\,\hat{e}_j^c \quad + \mu\,\hat{H}_1\,\hat{H}_2$$

- **From theoretical viewpoint has a crucial problem, the so-called μ-problem**

Kim, Nilles, PLB 138 (1984) 150

What is the origin of μ, and why is of order EW

- **From experimental viewpoint, another problem, since in the MSSM neutrino masses are zero**

- SUSY particles appear in pairs:
  - The LSP is a good dark matter candidate

  - Easy the check at colliders (missing energy searches)

R-parity conservation

The μ from ν Supersymmetric Standard Model : The μνSSM

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

- Only dimensionless parameters in the superpotential

No **μ**-problem

- R-parity is not a symmetry of the model

LSP not stable

The μ from ν Supersymmetric Standard Model : The μνSSM

Soft Terms

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

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

THE ONLY SCALE

The μ from ν Supersymmetric Standard Model : The 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:

$$\langle H_d^0 \rangle = \frac{v_d}{\sqrt{2}} \,, \quad \langle H_u^0 \rangle = \frac{v_u}{\sqrt{2}} \,, \quad \langle \widetilde{\nu}_{iR} \rangle = \frac{v_{iR}}{\sqrt{2}} \,, \quad \langle \widetilde{\nu}_{iL} \rangle = \frac{v_{iL}}{\sqrt{2}} \,.$$

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

The μ from ν Supersymmetric Standard Model : The μνSSM

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

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

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

$$\langle H_d^0\rangle = \frac{v_d}{\sqrt{2}}\,,\quad \langle H_u^0\rangle = \frac{v_u}{\sqrt{2}}\,,\quad \langle\widetilde{\nu}_{iR}\rangle = \frac{v_{iR}}{\sqrt{2}}\,,\quad \langle\widetilde{\nu}_{iL}\rangle = \frac{v_{iL}}{\sqrt{2}}\,.$$

The μ-from-ν supersymmetric Standard Model

- **Minimal NATURAL SUSY spectrum containing the SM and explaining Neutrino Physics:**

$$\hat{L}_i = \begin{pmatrix} \nu_i \\ e_i \end{pmatrix}, \quad \begin{matrix} e_i^c \\ \nu_i^c \end{matrix}, \quad Q_i = \begin{pmatrix} u_i \\ d_i \end{pmatrix}, \quad \begin{matrix} d_i^c \\ u_i^c \end{matrix} .$$

$$H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix}, \quad H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}$$

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

$$\begin{aligned} W &= Y_{ij}^e \, H_d \, L_i \, e_j^c + Y_{ij}^d \, H_d \, Q_i \, d_j^c - Y_{ij}^u \, H_u \, Q_i \, u_j^c - Y_{ij}^\nu \, H_u \, L_i \, \nu_j^c \\ &+ \underbrace{\lambda_{ijk} \, L_i \, L_j \, e_k^c + \lambda'_{ijk} \, L_i \, Q_j \, d_k^c}_{} + \frac{1}{3} \kappa_{ijk} \, \nu_i^c \, \nu_j^c \, \nu_k^c + \lambda_i \, H_u \, H_d \, \nu_i^c . \end{aligned}$$

For simplicity we can set it to zero still reproducing all the known phenomenology

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$$H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix}, \; H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}$$

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

$$\begin{aligned} W \;=\; & Y_{ij}^e\, H_d\, L_i\, e_j^c + Y_{ij}^d\, H_d\, Q_i\, d_j^c - Y_{ij}^u\, H_u\, Q_i\, u_j^c - Y_{ij}^\nu\, H_u\, L_i\, \nu_j^c \\ + \; & \lambda_{ijk}\, L_i\, L_j\, e_k^c + \lambda'_{ijk}\, L_i\, Q_j\, d_k^c + \frac{1}{3}\kappa_{ijk}\, \nu_i^c\, \nu_j^c\, \nu_k^c + \lambda_i\, H_u\, H_d\, \nu_i^c \, . \end{aligned}$$

For simplicity we can set it to zero still reproducing all the known phenomenology

- This spectrum, Allows very nice interpretations see arXiv:1701.02652; with interesting consequences arXiv:1705.02526; and others......

$$W = Y_{IJk}^e\, L_I\, L_J\, e_k^c + Y_{Ijk}^d\, L_I\, Q_j\, d_k^c - Y_{4jk}^u\, L_4^c\, Q_j\, u_k^c - Y_{4Jk}^\nu\, L_4^c\, L_J\, \nu_k^c + \frac{1}{3}\kappa_{ijk}\, \nu_i^c\, \nu_j^c\, \nu_k^c \, ;$$

The μ-from-ν supersymmetric Standard Model

- **Minimal NATURAL SUSY spectrum containing the SM and explaining Neutrino Physics:**

$$\hat{L}_i = \begin{pmatrix} \nu_i \\ e_i \end{pmatrix}, \quad \begin{matrix} e^c_i \\ \nu^c_i \end{matrix}, \quad Q_i = \begin{pmatrix} u_i \\ d_i \end{pmatrix}, \quad \begin{matrix} d^c_i \\ u^c_i \end{matrix} \; .$$

$$L_4 = \begin{pmatrix} \nu_4 \\ e_4 \end{pmatrix}, \; L^c_4 = \begin{pmatrix} e^c_4 \\ \nu^c_4 \end{pmatrix} .$$

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

$$\begin{aligned} W \;&=\; Y^e_{ij}\, H_d\, L_i\, e^c_j \;+ Y^d_{ij}\, H_d\, Q_i\, d^c_j \;- Y^u_{ij}\, H_u\, Q_i\, u^c_j \;- Y^\nu_{ij}\, H_u\, L_i\, \nu^c_j \\ &+\; \underbrace{\lambda_{ijk}\, L_i\, L_j\, e^c_k + \lambda'_{ijk}\, L_i\, Q_j\, d^c_k}_{} + \frac{1}{3}\kappa_{ijk}\, \nu^c_i\, \nu^c_j\, \nu^c_k + \lambda_i\, H_u\, H_d\, \nu^c_i \,. \end{aligned}$$

For simplicity we can set it to zero still reproducing all the known phenomenology

- **This spectrum, Allows very nice interpretations see arXiv:1701.02652; with interesting consequences arXiv:1705.02526; and others......**

$$W = Y^e_{IJk}\, L_I\, L_J\, e^c_k + Y^d_{Ijk}\, L_I\, Q_j\, d^c_k - Y^u_{4jk}\, L^c_4\, Q_j\, u^c_k - Y^\nu_{4Jk}\, L^c_4\, L_J\, \nu^c_k + \frac{1}{3}\kappa_{ijk}\, \nu^c_i\, \nu^c_j\, \nu^c_k \,;$$

The μ-from-ν supersymmetric Standard Model

- **Minimal NATURAL SUSY spectrum containing the SM and explaining Neutrino Physics:**

$$H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix}, \; H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}$$

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$$\begin{aligned} W \;\; = \;\; & Y_{ij}^e \, H_d \, L_i \, e_j^c \; + Y_{ij}^d \, H_d \, Q_i \, d_j^c \; - Y_{ij}^u \, H_u \, Q_i \, u_j^c \; - Y_{ij}^\nu \, H_u \, L_i \, \nu_j^c \\ + \;\; & \lambda_{ijk} \, L_i \, L_j \, e_k^c + \lambda'_{ijk} \, L_i \, Q_j \, d_k^c + \frac{1}{3}\kappa_{ijk} \, \nu_i^c \, \nu_j^c \, \nu_k^c + \lambda_i \, H_u \, H_d \, \nu_i^c \; . \end{aligned}$$

For simplicity we can set it to zero still reproducing all the known phenomenology

- **All known phenomenology can be reproduced**

- **New Signals at LHC are expected**

The Neutrino mass matrix is:

$$
m_\nu = \begin{pmatrix}
0_{3\times3} & -\frac{1}{\sqrt{2}}g'\langle\widetilde{\nu}_{iL}\rangle^* & \frac{1}{\sqrt{2}}g\langle\widetilde{\nu}_{iL}\rangle^* & 0_{3\times1} & Y^\nu_{ik}\langle\widetilde{\nu}_{kR}\rangle^* & \langle H_u^0\rangle Y^\nu_{ij} \\
-\frac{1}{\sqrt{2}}g'\langle\widetilde{\nu}_{jL}\rangle^* & M_1 & 0 & -\frac{1}{\sqrt{2}}g'\langle H_d^0\rangle^* & \frac{1}{\sqrt{2}}g'\langle H_u^0\rangle^* & 0_{1\times3} \\
\frac{1}{\sqrt{2}}g\langle\widetilde{\nu}_{jL}\rangle^* & 0 & M_2 & \frac{1}{\sqrt{2}}g\langle H_d^0\rangle^* & -\frac{1}{\sqrt{2}}g\langle H_u^0\rangle^* & 0_{1\times3} \\
0_{1\times3} & -\frac{1}{\sqrt{2}}g'\langle H_d^0\rangle^* & \frac{1}{\sqrt{2}}g\langle H_d^0\rangle^* & 0 & -\lambda_k\langle\widetilde{\nu}_{kR}\rangle^* & -\lambda_j\langle H_u^0\rangle \\
Y^\nu_{jk}\langle\widetilde{\nu}_{kR}\rangle^* & \frac{1}{\sqrt{2}}g'\langle H_u^0\rangle^* & -\frac{1}{\sqrt{2}}g\langle H_u^0\rangle^* & -\lambda_k\langle\widetilde{\nu}_{kR}\rangle^* & 0 & -\lambda_j\langle H_d^0\rangle + Y^\nu_{kj}\langle\widetilde{\nu}_{kL}\rangle \\
\langle H_u^0\rangle (Y^\nu_{ij})^T & 0_{3\times1} & 0_{3\times1} & -\lambda_i\langle H_u^0\rangle & -\lambda_i\langle H_d^0\rangle + Y^\nu_{ki}\langle\widetilde{\nu}_{kL}\rangle & \boxed{2\kappa_{ijk}\langle\widetilde{\nu}_{kR}\rangle^*}
\end{pmatrix}. \tag{B.65}
$$

The Neutrino mass matrix is:

$$m_\nu = \begin{pmatrix} 0_{3\times3} & -\frac{1}{\sqrt{2}}g'\langle\tilde{\nu}_{iL}\rangle^* & \frac{1}{\sqrt{2}}g\langle\tilde{\nu}_{iL}\rangle^* & 0_{3\times1} & Y^\nu_{ik}\langle\tilde{\nu}_{kR}\rangle^* & \langle H_u^0\rangle Y^\nu_{ij} \\ -\frac{1}{\sqrt{2}}g'\langle\tilde{\nu}_{jL}\rangle^* & M_1 & 0 & -\frac{1}{\sqrt{2}}g'\langle H_d^0\rangle^* & \frac{1}{\sqrt{2}}g'\langle H_u^0\rangle^* & 0_{1\times3} \\ \frac{1}{\sqrt{2}}g\langle\tilde{\nu}_{jL}\rangle^* & 0 & M_2 & \frac{1}{\sqrt{2}}g\langle H_d^0\rangle^* & -\frac{1}{\sqrt{2}}g\langle H_u^0\rangle^* & 0_{1\times3} \\ 0_{1\times3} & -\frac{1}{\sqrt{2}}g'\langle H_d^0\rangle^* & \frac{1}{\sqrt{2}}g\langle H_d^0\rangle^* & 0 & -\lambda_k\langle\tilde{\nu}_{kR}\rangle^* & -\lambda_j\langle H_u^0\rangle \\ Y^\nu_{jk}\langle\tilde{\nu}_{kR}\rangle^* & \frac{1}{\sqrt{2}}g'\langle H_u^0\rangle^* & -\frac{1}{\sqrt{2}}g\langle H_u^0\rangle^* & -\lambda_k\langle\tilde{\nu}_{kR}\rangle^* & 0 & -\lambda_j\langle H_d^0\rangle + Y^\nu_{kj}\langle\tilde{\nu}_{kL}\rangle \\ \langle H_u^0\rangle(Y^\nu_{ij})^T & 0_{3\times1} & 0_{3\times1} & -\lambda_i\langle H_u^0\rangle & -\lambda_i\langle H_d^0\rangle + Y^\nu_{ki}\langle\tilde{\nu}_{kL}\rangle & 2\kappa_{ijk}\langle\tilde{\nu}_{kR}\rangle^* \end{pmatrix}. \tag{B.65}$$

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

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

Effective Neutrino mass matrix

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

Using Diagonal Yukawas for Neutrinos

$$(m_\nu^{\text{eff}})_{ij} \simeq \frac{Y_i^\nu Y_j^\nu v_u^2}{6\sqrt{2}\kappa v_R}(1 - 3\delta_{ij}) - \frac{v_{iL} v_{jL}}{4M^{\text{eff}}} - \frac{1}{4M^{\text{eff}}}\left[\frac{v_d\left(Y_i^\nu v_{jL} + Y_j^\nu v_{iL}\right)}{3\lambda} + \frac{Y_i^\nu Y_j^\nu v_d^2}{9\lambda^2}\right]$$

$$M^{\text{eff}} \equiv M - \frac{v^2}{2\sqrt{2}\left(\kappa v_R^2 + \lambda v_u v_d\right)\ 3\lambda v_R}\left(2\kappa v_R^2 \frac{v_u v_d}{v^2} + \frac{\lambda v^2}{2}\right) \qquad \frac{1}{M} = \frac{g_1^2}{M_1} + \frac{g_2^2}{M_2}$$

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

Simplify Formula:

$$(m_\nu^{\mathrm{eff}})_{ij} \simeq \frac{Y_i^\nu Y_j^\nu v_u^2}{6\sqrt{2}\kappa v_R}(1 - 3\delta_{ij}) - \frac{v_{iL} v_{jL}}{4M}$$

$$M \equiv \frac{M_1 M_2}{g_1^2 M_2 + g_2^2 M_1}.$$

"Neutral fermions"
(neutralinos+neutrinos)

$$\chi^{0T} = (\underbrace{\tilde{B}^0, \tilde{W}^0, \tilde{H}_d, \tilde{H}_u, \nu_{R_i}}_{\tilde{\chi}^0_{4,5,6,7,8,9,10}}, \underbrace{\nu_{L_i}}_{\tilde{\chi}^0_{1,2,3}}),$$

"Charge fermions"
(charginos+charged leptons)

$$\Psi^{+T} = (\underbrace{-i\tilde{\lambda}^+, \tilde{H}_u^+}_{\tilde{\chi}^+_{1,2}}, e_R^+, \mu_R^+, \tau_R^+)$$

"Neutral scalars"
(Higgses+sneutrinos)

$$\mathbf{S}'_\alpha = (\underbrace{h_d, h_u, (\widetilde{\nu}_i^c)^R}_{h_{4,5} \equiv h,\, H\ ,\ h_{1,2,3}}, \underbrace{(\widetilde{\nu}_i)^R}_{h_{6,7,8}}) \qquad \mathbf{P}'_\alpha = (\underbrace{P_d, P_u, (\widetilde{\nu}_i^c)^I}_{P_4 \equiv A\ ,\ P_{1,2,3}}, \underbrace{(\widetilde{\nu}_i)^I}_{P_{5,6,7}})$$

"Charged scalars"
(charged Higgses+sleptons)

$$\mathbf{S}'^+_\alpha = (\underbrace{H_d^+, H_u^+}_{H^+}, \tilde{e}_L^+, \widetilde{\mu}_L^+, \widetilde{\tau}_L^+, \tilde{e}_R^+, \mu_R^+, \tau_R^+),$$

We are going to concentrate our attention in the sneutrinos as a long life particle, giving interesting signals at LHC

Discerning the left sneutrino LSP with displaced-vertex searches

arXiv:1804.00067

in Collaboration with:

Iñaki Lara

Carlos Muñoz

Natsumi Nagata

Hidetoshi Otono

Roberto Ruiz de Austri

Discerning the left sneutrino LSP with displaced-vertex searches

- For simplicity we consider only one family of right-handed neutrinos -

The neutrino tree-level mass is given by:

$$m_\nu = \frac{1}{4M_{\text{eff}}} \sum_i \left[v_i^2 + v_d \left(\frac{2v_i Y_{\nu_i}}{\lambda} + \frac{v_d Y_{\nu_i}^2}{\lambda^2} \right) \right], \quad M_{\text{eff}} \equiv M \left[1 - \frac{v^2}{\sqrt{2} M (\kappa\, v_R^2 + \lambda v_d v_u)\, \lambda v_R} \left(\kappa\, v_R^2 \frac{v_d v_u}{v^2} + \frac{1}{4} \lambda v^2 \right) \right],$$

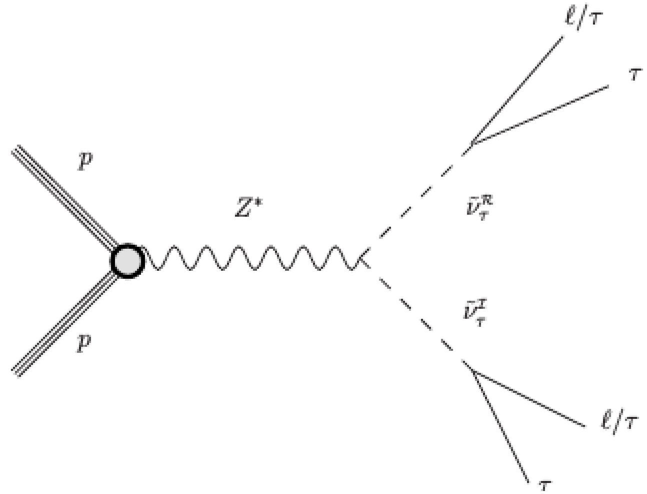
The sneutrino tree-level mass is given by:

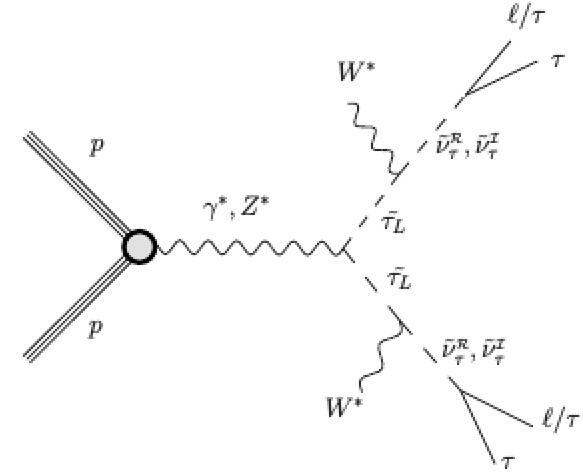
$$m_{\widetilde{\nu}_i^{\mathcal{R}}} \approx m_{\widetilde{\nu}_i^{\mathcal{I}}} \equiv m_{\widetilde{\nu}_i}. \qquad m_{\widetilde{\nu}_i}^2 \approx \frac{Y_{\nu_i} v_u}{2 v_i} v_R \left(-\sqrt{2} A_{\nu_i} - \kappa v_R + \frac{\lambda v_R}{\tan\beta} \right),$$

We consider $m^2_{\widetilde{\nu}_i} \lesssim 100 \text{ GeV}$ in order to obtain a long life particle

Left sneutrino LSP phenomenology in the µνSSM

- Mixing between left sneutrinos and Higgses, makes possible the decay of the sneutrinos
- The mixing is controlled by neutrino physics

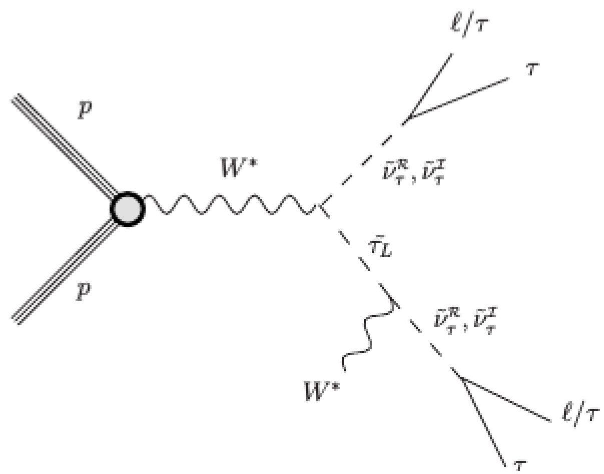




Stau LSP:

(a) Z channel

(b) γ, Z channels



(c) W channel

Figure 1: Decay channels into two $\tau\,\ell/\tau$, from a pair production at the LHC of scalar and pseudoscalar tau left sneutrinos co-LSPs. Decay channels into one $\tau\,\ell/\tau$ plus neutrinos are the same but substituting in (a), (b) and (c) one of the two vertices by a two-neutrino vertex.

Approximative formulas for decay widths:

$$\Gamma\left(\tilde{\nu}_\tau \to \tau\tau\right) \approx \frac{m_{\tilde{\nu}_\tau}}{16\pi}\left(Y_\tau Z^{H/A}_{\tilde{\nu}_\tau H_d} - Y_{\nu_\tau}\frac{Y_\tau}{\lambda}\right)^2,$$

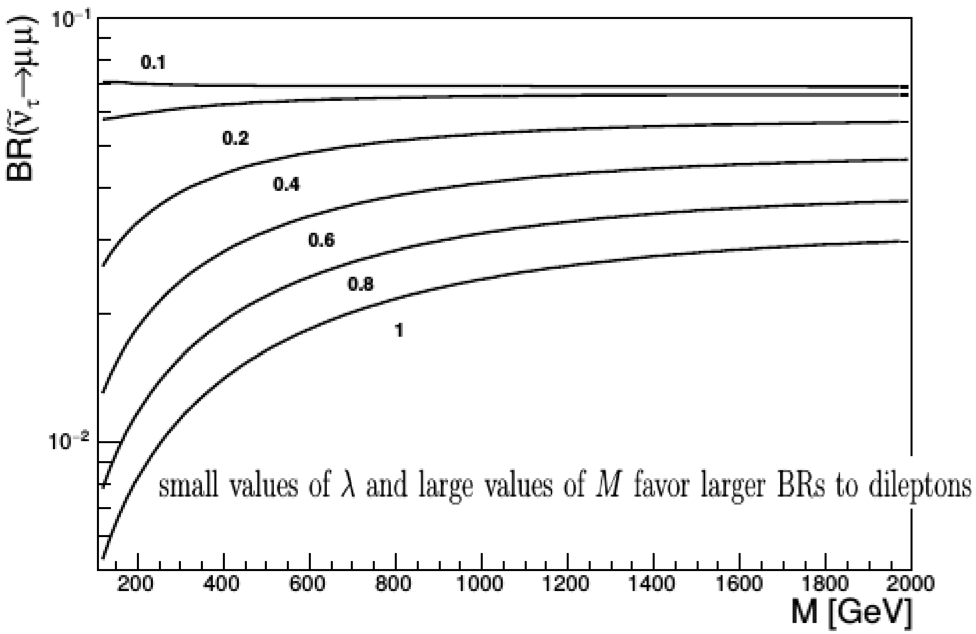
$$\Gamma\left(\tilde{\nu}_\tau \to \tau\ell\right) \approx \frac{m_{\tilde{\nu}_\tau}}{16\pi}\left(Y_{\nu_\ell}\frac{Y_\tau}{\lambda}\right)^2.$$

$$\sum_i \Gamma\left(\tilde{\nu}_\tau \to \nu_\tau\nu_i\right) \approx \frac{m_{\tilde{\nu}_\tau}}{16\pi}\frac{1}{2M^2}\sum_i v_i^2,$$

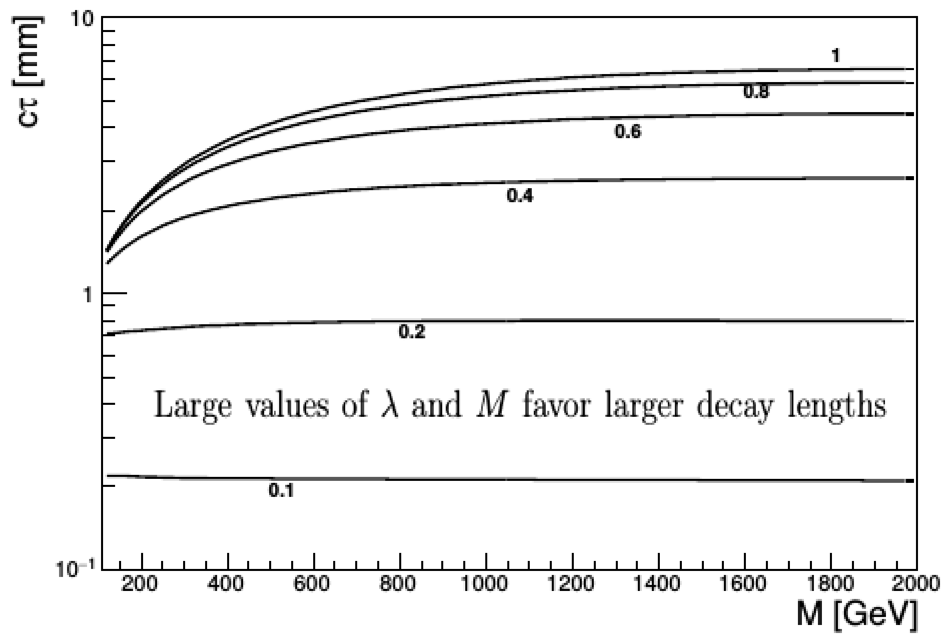
$$\mathrm{BR}\left(\tilde{\nu}_\tau \to \mu\mu\right) \approx 0.068 \times \left(1 + \frac{r}{3}\right)^{-1},$$

$$r \approx \left(\frac{\lambda}{Y_\tau}\right)^2 \frac{2m_\nu}{Y_\nu^2 M},$$

$$c\tau \gtrsim 100\ \mu\mathrm{m}$$



(a) Branching ratio



(b) Decay length

(a) BR versus M for the decay of a $\widetilde{\nu}_\tau$ with $m_{\widetilde{\nu}_\tau} = 60$ GeV into $\mu\mu$; (b) Proper decay distance $c\tau$ of the $\widetilde{\nu}_\tau$ versus M. In both plots (a) and (b), the neutrino Yukawas are set to $Y_\nu = 5 \times 10^{-7}$, and several values of the coupling λ are used such as $\lambda = 0.1$, 0.2, 0.4, 0.6, 0.8, 1.

$\sum_i v_i^2$ with the heavier neutrino mass fixed by the experimental $m_\nu \sim [0.05,\ 0.23]$ eV

$$c\tau \approx 0.22 \times \left(\frac{Y_\nu}{5\times 10^{-7}}\right)^{-2} \left(\frac{\lambda}{Y_\tau}\right)^{2} \left(1+\frac{r}{3}\right)^{-1} \left(\frac{m_{\widetilde{\nu}_\tau}}{60\ \mathrm{GeV}}\right)^{-1}\ \mathrm{mm},$$

Long-lived particle searches at the LHC

- Since sneutrinos are electrically neutral, we are unable to use disappearing track searches or metastable charged particle searches to probe them

- We may detect the longevity of the sneutrinos by reconstructing their decay vertices, using the charged tracks associated with the daughter particles. This type of search strategies is dubbed as the displaced-vertex searches.

significant distance from the production point (1 mm)

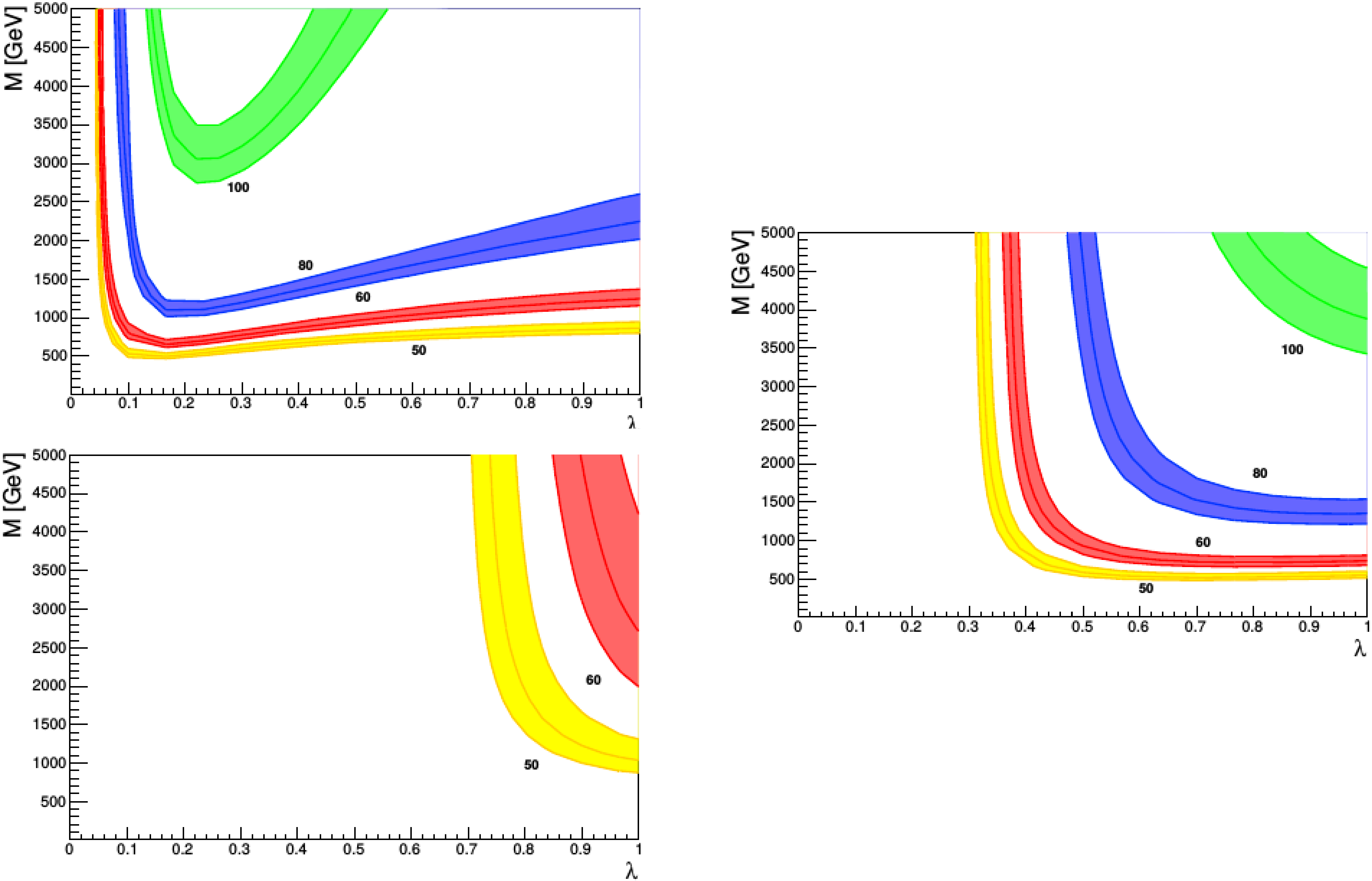
The ATLAS 8-TeV analysis is general enough as to be sensitive to the decay of the $\tilde{\nu}_\tau$

The ATLAS displaced-vertex search

ATLAS collaboration, G. Aad et al., *Search for massive, long-lived particles using multitrack displaced vertices or displaced lepton pairs in pp collisions at $\sqrt{s}$ = 8 TeV with the ATLAS detector*, Phys. Rev. **D92** (2015) 072004, [1504.05162].

Is based on the 8-TeV data with an integrated luminosity of 20.3 / fb. The dilepton displaced-vertex selection channel, where each displaced vertex is formed from at least two oppositely-charged leptons, may be used for the long-lived.

- One muon with $p_T > 50$ GeV and $|\eta| < 1.07$, one electron with $p_T > 120$ GeV or two electrons with $p_T > 40$ GeV.
- One pair e^+e^-, $\mu^+\mu^-$ or $e^\pm\mu^\mp$ with $p_T > 10$ GeV and $0.02 < |\eta| < 2.5$ for each one.



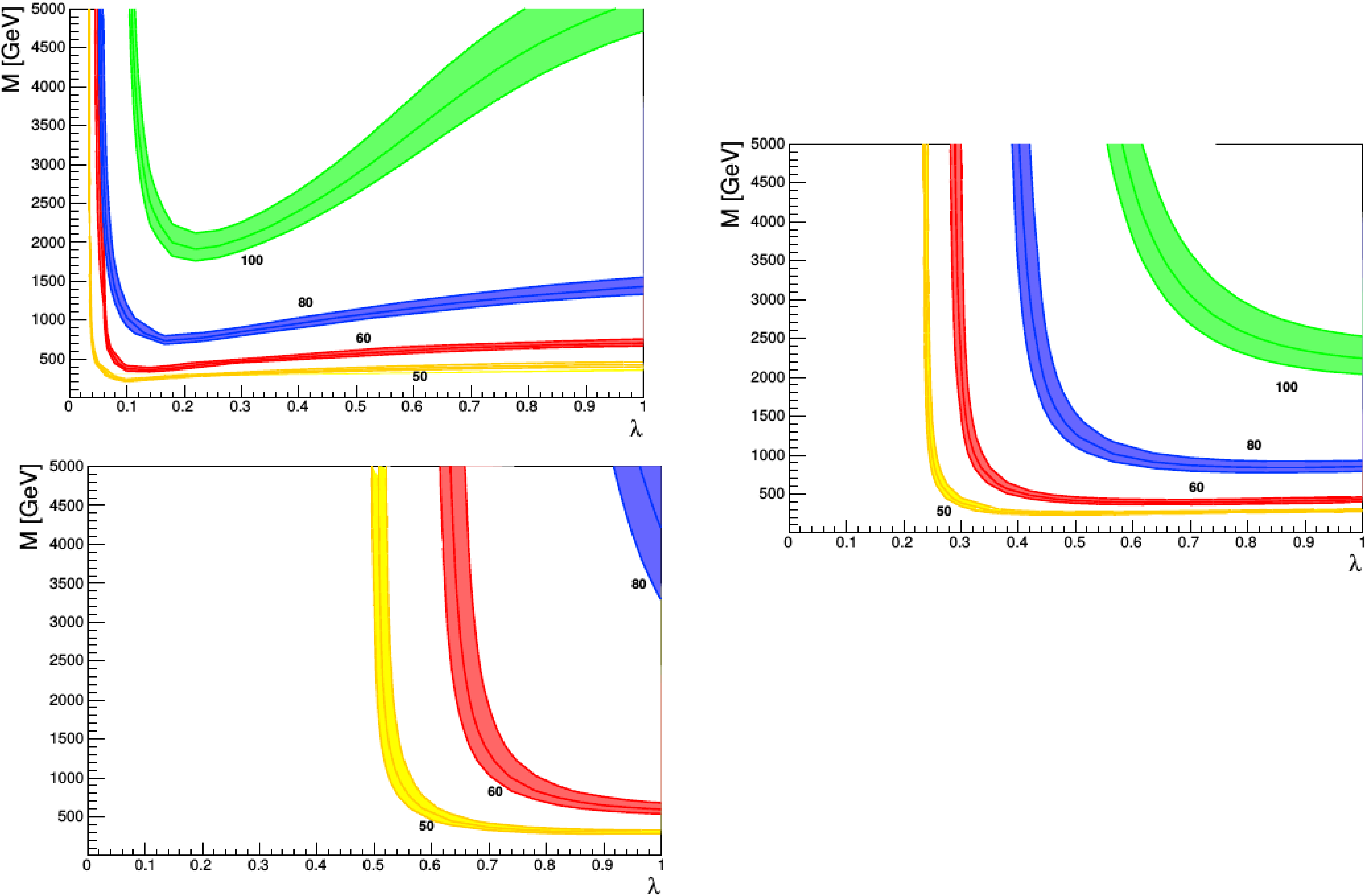
Limits on the $\mu\nu$SSM parameter space from the ATLAS 8-TeV displaced-vertex search with an integrated luminosity of 20.3 fb^{-1}, combining the $\mu\mu$ and $e\mu$ channels. The region inside each colored line is excluded. The neutrino mass scale is fixed to be $m_\nu \sim 0.05$ eV, and the neutrino Yukawa couplings are set to $Y_\nu = 10^{-7}$, 5×10^{-7}, and 10^{-6} in the top, middle, and bottom panels, respectively. The yellow, red, blue, and green lines correspond to the sneutrino mass of 50, 60, 80 and 100 GeV, respectively.

The mu24i trigger, which is an isolated single muon trigger at the event-filter, also uses the information from the inner detector and requires the transverse momentum threshold of $p_{\mathrm{T}} > 24$ GeV

ATLAS collaboration, G. Aad et al., *Performance of the ATLAS muon trigger in pp collisions at $\sqrt{s} = 8$ TeV*, *Eur. Phys. J.* **C75** (2015) 120, [1408.3179].

We use the following criteria for the optimized 8-TeV analysis:

- At least one muon with $p_{\mathrm{T}} > 24$ GeV.
- One pair $\mu^+\mu^-$ or $e^{\pm}\mu^{\mp}$ with $p_{\mathrm{T}} > 10$ GeV and $0.02 < |\eta| < 2.5$ for each one.

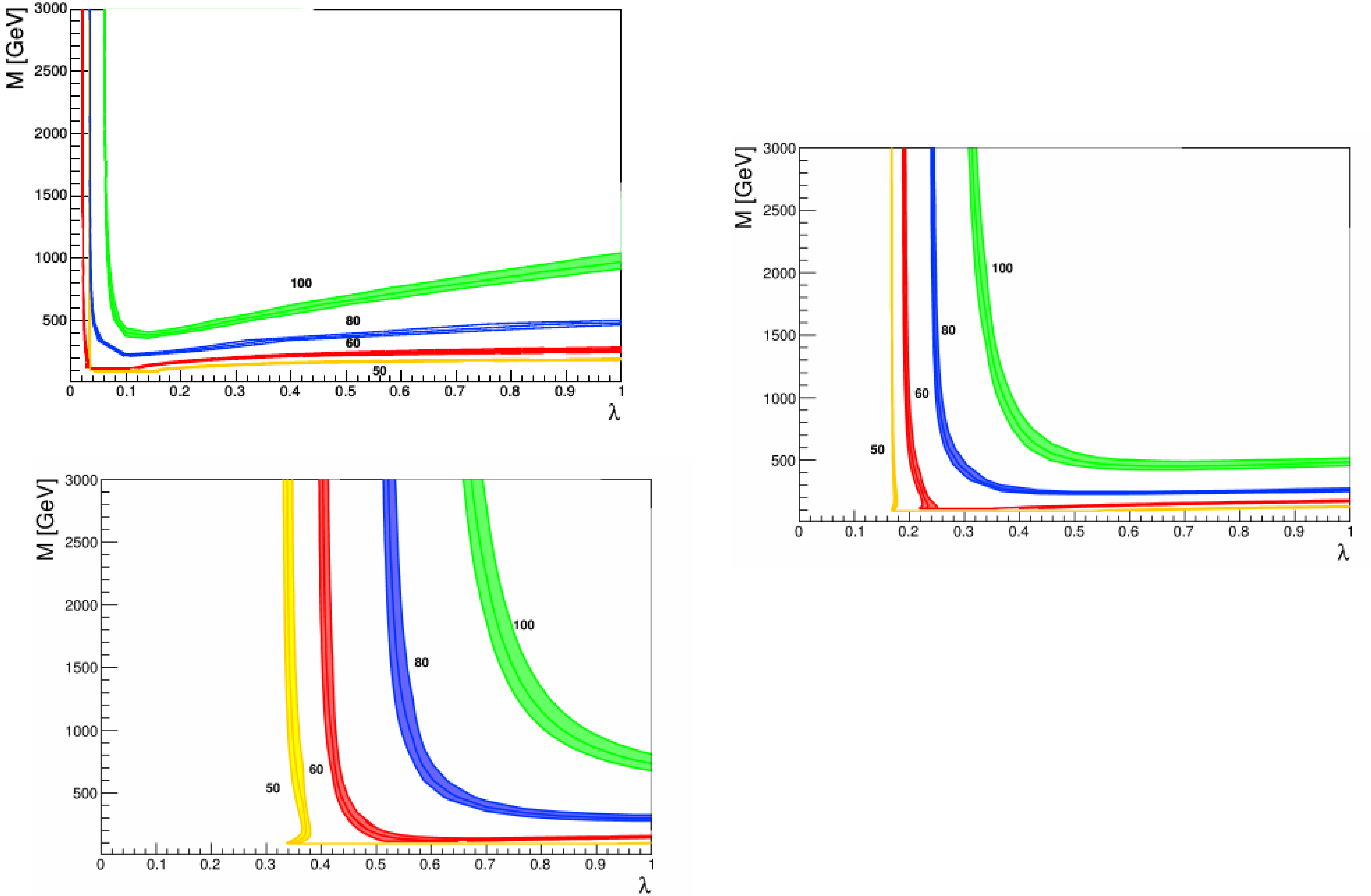


$m_\nu \sim 0.05$ eV, but considering the optimization of the trigger requirements discussed in the text.

For the 13-TeV LHC run

- At least one electron or muon with $p_{\mathrm{T}} > 26$ GeV.
- One pair $\mu^+\mu^-$, e^+e^-, or $e^\pm\mu^\mp$ with $p_{\mathrm{T}} > 10$ GeV and $0.02 < |\eta| < 2.5$ for each one.

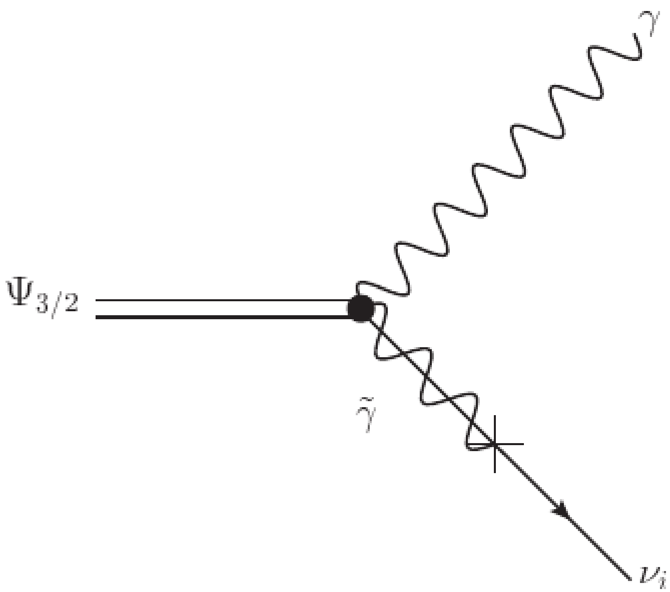
$$\begin{aligned}\#\mathrm{Dimuons} = &\left[\sigma(pp \to Z \to \widetilde{\nu}_\tau\widetilde{\nu}_\tau)\epsilon_{\mathrm{sel}}^{Z} + \sigma(pp \to W \to \widetilde{\nu}_\tau\widetilde{\tau})\epsilon_{\mathrm{sel}}^{W} + \sigma(pp \to \gamma, Z \to \widetilde{\tau}\widetilde{\tau})\epsilon_{\mathrm{sel}}^{\gamma,Z}\right] \\ &\times \mathcal{L} \times \left[\mathrm{BR}(\widetilde{\nu}_\tau^{\mathcal{R}} \to \mu\mu)\ \epsilon_{\mathrm{vert}}^{\mu\mu}(c\tau^{\mathcal{R}}) + \mathrm{BR}(\widetilde{\nu}_\tau^{\mathcal{I}} \to \mu\mu)\ \epsilon_{\mathrm{vert}}^{\mu\mu}(c\tau^{\mathcal{I}})\right], \qquad (3.1)\end{aligned}$$



$m_\nu \sim 0.05$ eV, but analyzing the prospects for the 13-TeV search with an integrated luminosity of 300 fb^{-1}, combining the $\mu\mu$, $e\mu$ and ee channels, and considering also the optimization of the trigger requirements discussed in the text.

Gravitino Dark Matter in the ***μνSSM***

If the gravitino is the LSP can be the Dark Matter



$$\Gamma(\Psi_{3/2} \to \sum_i \gamma \nu_i) \simeq \frac{m_{3/2}^3}{64\pi M_P^2} |U_{\tilde{\gamma}\nu}|^2$$

$$M_P \simeq 2.4 \times 10^{18}\,\mathrm{GeV}$$

$$|U_{\tilde{\gamma}\nu}|^2 = \sum_{i=1}^{3} |N_{i1}\,\cos\theta_W + N_{i2}\,\sin\theta_W|^2$$

The same result for the decay width holds for the conjugated processes $\Psi_{3/2} \to \gamma \bar{\nu}_i$

Previous works analysing the two body decays and the detectability at FERMI-LaT

Choi, L-F, Muñoz, Ruiz de Austri, JCAP 1003 (2010) 028 [arXiv:0906.368]

Work including *Fermi*-LAT collaboration

Search for 100 MeV to 10 GeV γ-ray lines in the *Fermi*-LAT data and implications for gravitino dark matter in the μνSSM

arXiv:1406.3430 [astro-ph.HE], *JCAP 10 (2014) 023*

Category II paper:
-*Fermi*-LAT Collaboration: Albert, Bloom, Charles, Gómez-Vargas, Mazziotta, Morselli
External authors: C. M., Grefe, Weniger

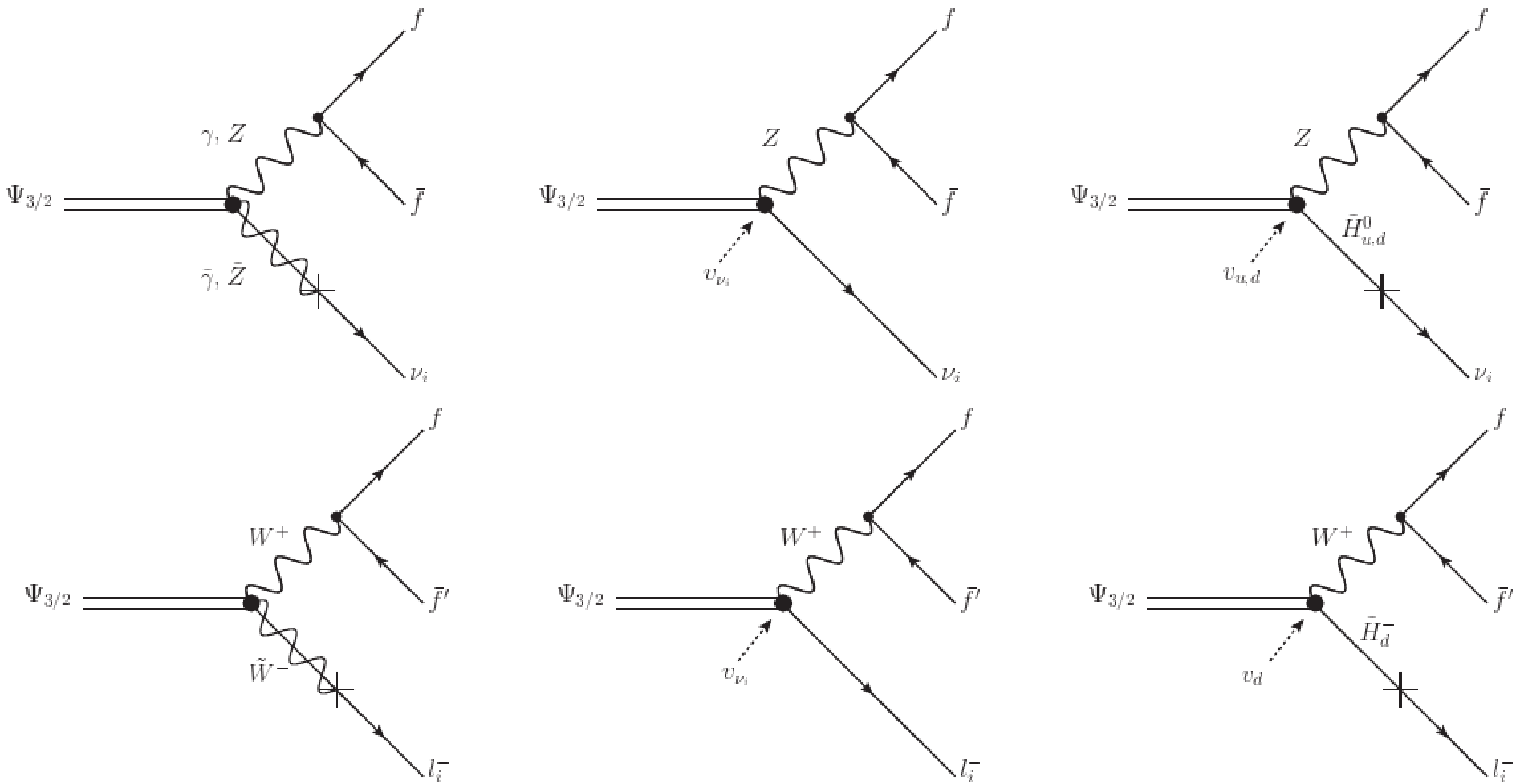
And more works related .....

$$\tau_{3/2}(\Psi_{3/2} \to \sum_i \gamma\nu_i) = \frac{1}{2\Gamma\left(\Psi_{3/2} \to \sum_i \gamma\nu_i\right)} \simeq 3.8 \times 10^{27}\, s \left(\frac{10^{-16}}{|U_{\tilde{\gamma}\nu}|^2}\right)\left(\frac{10\,\mathrm{GeV}}{m_{3/2}}\right)^3$$

Using $10^{-16} \lesssim |U_{\tilde{\gamma}\nu}|^2 \lesssim 10^{-14}$ Obtained the bound: $m_{3/2} \lesssim 5$ GeV.

New analysis: arxiv:1608.08640 Gomez-Vargas, L-F, Muñoz, Perez, Ruiz de Austri

Deep exploration of the parameter space, **we include three body decays**



Thus we obtain the following result:

Using *Fermi*-LAT 95% CL upper limits on the total diffuse extragalactic γ-ray background using 50 months of data, together with the upper limits on line emission from an updated analysis using 69.9 months of data.

$$10^{-20} \lesssim |U_{\tilde{\gamma}\nu}|^2 \lesssim 10^{-14}$$

$$m_{3/2} \lesssim 17 \text{ GeV and } \tau_{3/2} \gtrsim 4 \times 10^{25} \text{ s.}$$

We have found that in standard scenarios such as those with the low-energy GUT relation $M_2 = 2\,M_1$, the line limits are crucial and only allow gravitinos with masses $\lesssim 4$ GeV (and lifetimes $\gtrsim 10^{28}$ s), even for values of $|M_1|$ as large as 10 TeV. In the case $M_2 \to M_1$, although the line size is suppressed restricting less the gravitino mass ($\lesssim 17$ GeV), still the line limits are more important than the diffuse extragalactic γ-ray background

ArXiv: 1608.08640, In collaboration with:G. Gomez-Vargas, C. Muñoz, A. Perez, R. Ruiz de Austri

Work in preparation

Decaying Dark Matter: *NLSP → LSP + axion*

gravitino NLSP → axino LSP + axion: $\Gamma(\psi_\mu \to \tilde{a} + a) = \frac{m_{3/2}^3}{192\pi M_P^2}(1 - r_{\tilde{a}})^2(1 - r_{\tilde{a}}^2)^3$

gravitino thermal relic density: $\Omega_{3/2}h^2 \simeq 0.02\left(\frac{T_R}{10^5\ \mathrm{GeV}}\right)\left(\frac{1\ \mathrm{GeV}}{m_{3/2}}\right)\left(\frac{M_3(T_R)}{3\ \mathrm{TeV}}\right)^2\left(\frac{\gamma/(T_R^6/M_P^2)}{0.4}\right)$

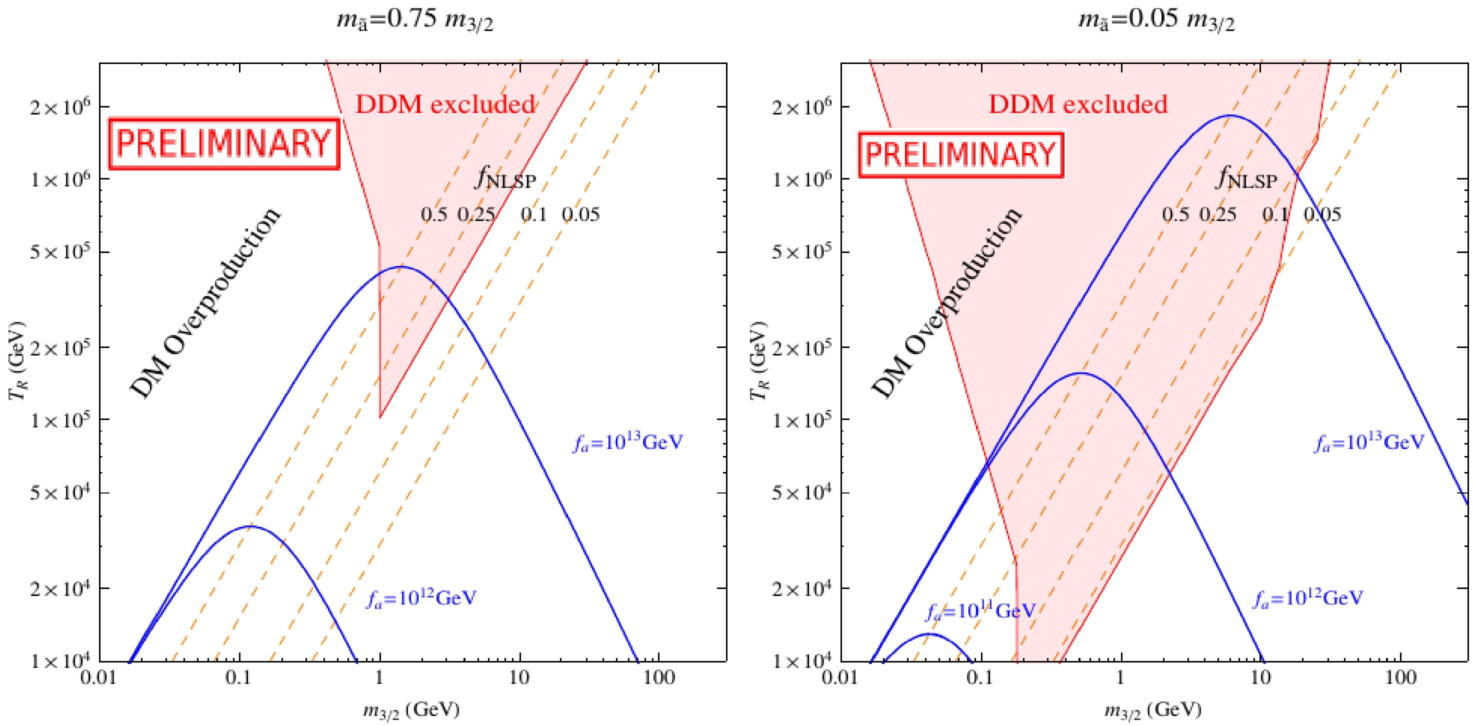
axino NLSP → gravitino LSP + axion: $\Gamma(\tilde{a} \to \psi_\mu + a) = \frac{m_{\tilde{a}}^5}{96\pi m_{3/2}^2 M_P^2}(1 - r_{\tilde{a}}^{-1})^2(1 - r_{\tilde{a}}^{-2})^3$

axino thermal relic density: $\Omega_{\tilde{a}}h^2 \simeq 0.30 * g_3(T_R)^4\left(\frac{F(g_3(T_R))}{23}\right)\left(\frac{m_{\tilde{a}}}{1\ \mathrm{GeV}}\right)\left(\frac{T_R}{10^4\ \mathrm{GeV}}\right)\left(\frac{10^{12}\ \mathrm{GeV}}{f_a}\right)^2$

- In a multicomponent scenario, the *dark matter relic density* come from thermal and from non-thermal production (NLSP decay) → $\Omega_{LSP}h^2 = \Omega_{LSP}^{TP}h^2 + \Omega_{LSP}^{NTP}h^2 = \Omega_{LSP}^{TP}h^2 + \frac{m_{LSP}}{m_{NSLP}}\Omega_{NLSP}h^2$

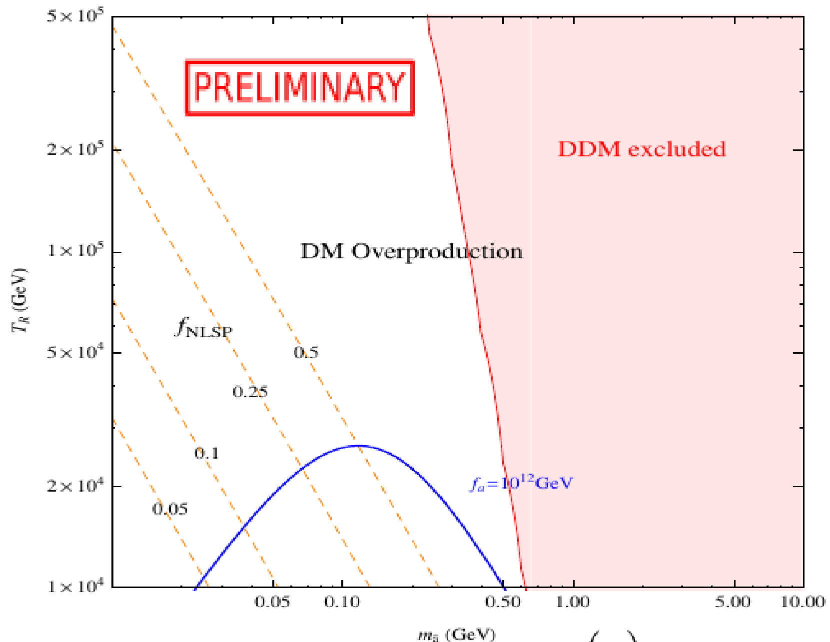
Work in collaboration with: Gomez-Vargas, A Perez, C Muñoz

Axino LSP plus Gravitino NLSP dark matter

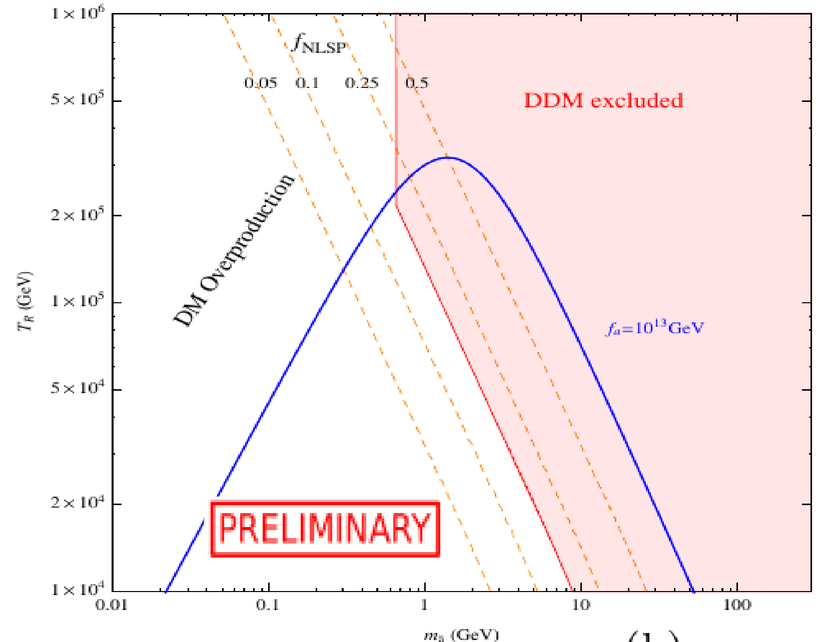


Reheating temperature, T_R, versus the gravitino mass, $m_{3/2}$, for the contours $\Omega_{3/2}h^2 + \Omega_{\tilde{a}}h^2 \simeq 0.12$ shown in blue corresponding to the axino LSP plus gravitino NLSP scenario, for different PQ scales. The regions above the blue curves are excluded by overproduction of CDM. The red region is excluded by cosmological observations for DDM models [7–10]. The orange dashed curves correspond to NLSP fraction, $f_{NLSP} = \frac{\Omega_{3/2}h^2}{\Omega_{cdm}^{Planck}h^2} = 0.5, 0.25, 0.1$ and 0.05.

Gravitino LSP plus Axino NLSP dark matter



(a)



(b)

Reheating temperature, T_R, versus the axino mass, m_a, for the contours $\Omega_{3/2}h^2 + \Omega_{\tilde{a}}h^2 \simeq 0.12$ shown in blue corresponding to the gravitino LSP plus axino NLSP scenario, for different PQ scales. The regions above the blue curves are excluded by overproduction of CDM. The red region is excluded by cosmological observations for DDM models [7–10]. The orange dashed curves correspond to the NLSP fraction, $f_{NLSP} = \frac{\Omega_{\tilde{a}}h^2}{\Omega_{cdm}^{Planck}h^2} = 0.5, 0.25, 0.1$ and 0.05.

Summary

The **μνSSM can be tested**

Interesting signals of displaced vertices at LHC

The displaced dilepton search channel is most sensitive to the sneutrino LSP, where at least one of the pair-produced left sneutrinos is required to decay into $\tau\tau$ or $\tau\ell$
With the final-state tau leptons decaying leptonically.

$m^2_{\widetilde{\nu}_i}$ ~ $45–100$ GeV

DV $\gtrsim 1$ mm

Dark matter signals at indirect detection experiments

Thank you

END