Hunting for SUSY and decaying gravitino DM with the μνSSM

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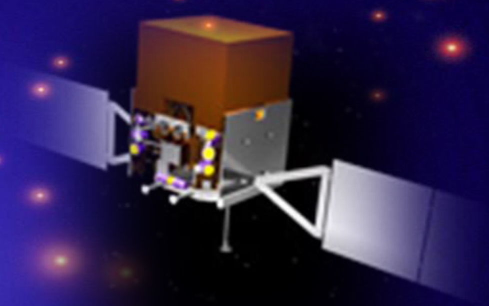


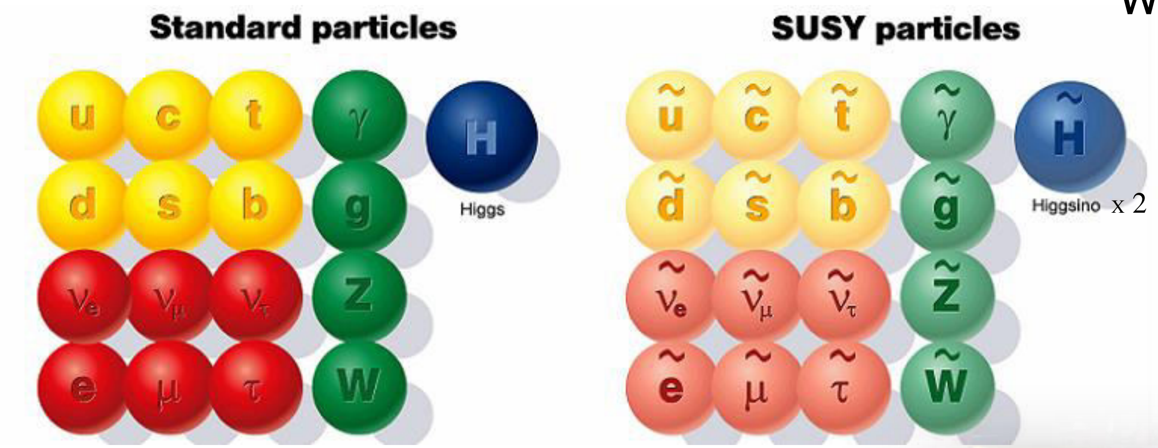
MultiDark
Multimessenger Approach for Dark Matter Detection

DSU 2016, Bergen, July 25-29

SUSY is still the most compelling theory for physics beyond the standard model

In **SUSY**, the spectrum of elementary particles is doubled

with masses ≈ 1 TeV



Thus even the simplest SUSY model,

The Minimal Supersymmetric Standard Model

MSSM ,

predicts a rich phenomenology

But… is SUSY still alive?

- 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, for the moment with low luminosity of about 20 fb^{-1}
- 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

- **Nevertheless, from theoretical viewpoint, SUSY has a crucial problem, the so-called μ problem**

Kim, Nilles, PLB 138 (1984) 150

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

The term $\mu\, H_1 H_2$ is necessary e.g. to generate Higgsino masses
Present experimental bounds imply: $\mu \geq 100$ GeV

What is the origin of μ, and why is so small << M_{Planck}

The **MSSM** does not solve the **μ** problem

one takes for granted that the **μ term is there and ~ M_w, and that's it**

in this sense the **MSSM** is a kind of effective theory

- **From experimental viewpoint, another problem of SUSY is to be able to reproduce neutrino data: masses and mixing angles**

The $\mu\nu$**SSM**, including right-handed neutrinos solves the μ problem of the MSSM while simultaneously explaining the origin of neutrino masses

Lopez-Fogliani, C. M., PRL 97 (2006) 041801

$\mu\nu$SSM In addition to the MSSM Yukawas for quarks and charged leptons, the $\mu\nu$SSM superpotential contains Yukawas for neutrinos, and two additional type of terms

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

Dirac neutrino masses

effective μ term generated by the VEVs of the **3** righ-handed sneutrinos

effective Majorana masses $M_M = \kappa_{ijk}\langle\tilde{\nu}_k^c\rangle$

with $\boxed{\mu \equiv \lambda^i\langle\tilde{\nu}_i^c\rangle}$.

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

No ad-hoc scales

$m_\nu \sim m_D^2/M_M = (\mathbf{Y}_\nu\, v_2)^2/(k\, v_{\nu c}) \sim (10^{-6}\,10^2)^2/10^3 = 10^{-11}$ GeV $= 10^{-2}$ eV

Like the electron Yukawa

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

because we have more couplings with respect to the MSSM

$$\langle H_d^0 \rangle = v_d \,, \quad \langle H_u^0 \rangle = v_u \,, \quad \langle \tilde{\nu}_i \rangle = \nu_i \,, \quad \langle \tilde{\nu}_i^c \rangle = \nu_i^c \,. \tag{2.7}$$

$\sim$ EW $\quad \sim$ EW $\quad \sim$ EW

and one can define as usual:

$$H_u^0 = h_u + iP_u + v_u \,, \quad H_d^0 = h_d + iP_d + v_d \,,$$
$$\tilde{\nu}_i^c = (\tilde{\nu}_i^c)^R + i(\tilde{\nu}_i^c)^I + \nu_i^c \,, \quad \tilde{\nu}_i = (\tilde{\nu}_i)^R + i(\tilde{\nu}_i)^I + \nu_i \,.$$

$$0 = \frac{1}{4}G^2\left(\nu_i\nu_i + v_d^2 - v_u^2\right)v_d + m_{H_d}^2 v_d - a_{\lambda_i} v_u \nu_i^c + \lambda_i \lambda_j v_d \nu_i^c \nu_j^c$$
$$+ \lambda_i \lambda_i v_d v_u^2 - \lambda_j \kappa_{ijk} v_u \nu_i^c \nu_k^c - Y_{\nu_{ij}} \lambda_k \nu_i \nu_k^c \nu_j^c - Y_{\nu_{ij}} \lambda_j v_u^2 \nu_i \,,$$

$$0 = -\frac{1}{4}G^2\left(\nu_i\nu_i + v_d^2 - v_u^2\right)v_u + m_{H_u}^2 v_u + a_{\nu_{ij}} \nu_i \nu_j^c - a_{\lambda_i} \nu_i^c v_d$$
$$+ \lambda_i \lambda_j v_u \nu_i^c \nu_j^c + \lambda_j \lambda_j v_d^2 v_u - \lambda_j \kappa_{ijk} v_d \nu_i^c \nu_k^c + Y_{\nu_{ij}} \kappa_{ljk} \nu_i \nu_l^c \nu_k^c$$
$$- 2\lambda_j Y_{\nu_{ij}} v_d v_u \nu_i + Y_{\nu_{ij}} Y_{\nu_{ik}} v_u \nu_k^c \nu_j^c + Y_{\nu_{ij}} Y_{\nu_{kj}} v_u \nu_i \nu_k \,,$$

similar to MSSM

2 + (1+2) + 3 minimization eqs.

similar to NMSSM

$$0 = m_{\tilde{\nu}_{ij}^c}^2 \nu_j^c + a_{\nu_{ji}} \nu_j v_u - a_{\lambda_i} v_u v_d + a_{\kappa_{ijk}} \nu_j^c \nu_k^c + \lambda_i \lambda_j v_u^2 \nu_j^c + \lambda_i \lambda_j v_d^2 \nu_j^c$$
$$- 2\lambda_j \kappa_{ijk} v_d v_u \nu_k^c + 2\kappa_{lim} \kappa_{ljk} \nu_m^c \nu_j^c \nu_k^c - Y_{\nu_{ji}} \lambda_k \nu_j \nu_k^c v_d - Y_{\nu_{kj}} \lambda_i v_d \nu_k \nu_j^c$$
$$+ 2Y_{\nu_{jk}} \kappa_{ikl} v_u \nu_j \nu_l^c + Y_{\nu_{ji}} Y_{\nu_{lk}} \nu_j \nu_l \nu_k^c + Y_{\nu_{ki}} Y_{\nu_{kj}} v_u^2 \nu_j^c \,,$$

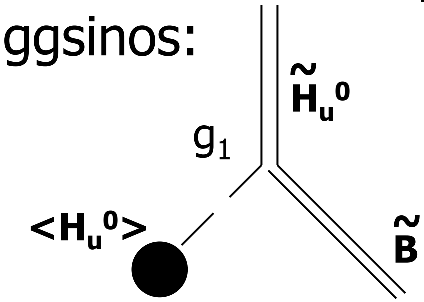
Only one scale in the model: the soft SUSY-breaking scale $\sim$ TeV

$$0 = \frac{1}{4}G^2(\nu_j\nu_j + v_d^2 - v_u^2)\nu_i + m_{\tilde{L}_{ij}}^2 \nu_j + a_{\nu_{ij}} v_u \nu_j^c - Y_{\nu_{ij}} \lambda_k v_d \nu_j^c \nu_k^c$$
$$- Y_{\nu_{ij}} \lambda_j v_u^2 v_d + Y_{\nu_{il}} \kappa_{ljk} v_u \nu_j^c \nu_k^c + Y_{\nu_{ij}} Y_{\nu_{lk}} \nu_l \nu_j^c \nu_k^c + Y_{\nu_{ik}} Y_{\nu_{jk}} v_u^2 \nu_j \,.$$

Notice that in the last equation $\nu \to 0$ as $Y_\nu \to 0$, and since the coupling Y_ν **$Y_\nu \leq 10^{-6}$**, ν has to be very small. Using this rough argument we can also get an estimate of the value, $\nu \lesssim m_D$. $\sim 10^{-4}$ GeV

In the MSSM $W = \epsilon_{ab}\left(Y_u^{ij}\,\hat H_2^b\,\hat Q_i^a\,\hat u_j^c + Y_d^{ij}\,\hat H_1^a\,\hat Q_i^b\,\hat d_j^c + Y_e^{ij}\,\hat H_1^a\,\hat L_i^b\,\hat e_j^c\right) + \mu\,\hat H_1\,\hat H_2$

because of the couplings and VEVs, there is a mixing of neutral gauginos and Higgsinos:



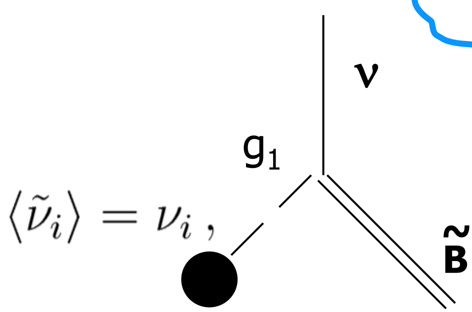
$$(\tilde B^0, \tilde W^0, \tilde H_1^0, \tilde H_2^0) \longrightarrow \mathcal{M} = \begin{pmatrix} M_1 & 0 & -\frac{g'\nu_1}{\sqrt2} & \frac{g'\nu_2}{\sqrt2} \\ 0 & M_2 & \frac{g\nu_1}{\sqrt2} & -\frac{g\nu_2}{\sqrt2} \\ -\frac{g'\nu_1}{\sqrt2} & \frac{g\nu_1}{\sqrt2} & 0 & -\mu \\ \frac{g'\nu_2}{\sqrt2} & -\frac{g\nu_2}{\sqrt2} & -\mu & 0 \end{pmatrix}$$

e.g. the lightest mass eigenstate (lightest neutralino)

$$\tilde\chi_1^0 = N_{11}\tilde B^0 + N_{12}\tilde W^0 + N_{13}\tilde H_1^0 + N_{14}\tilde H_2^0$$

μνSSM has larger mass matrices than those of the MSSM or NMSSM, because of the new couplings and VEVs:

$\langle H_u^0\rangle = v_u \quad \langle H_d^0\rangle = v_d \qquad \langle\tilde\nu_i\rangle = \nu_i \qquad \langle\tilde\nu_i^c\rangle = \nu_i^c$



"Neutralinos"

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

Neutrino Physics in the $\mu\nu$SSM

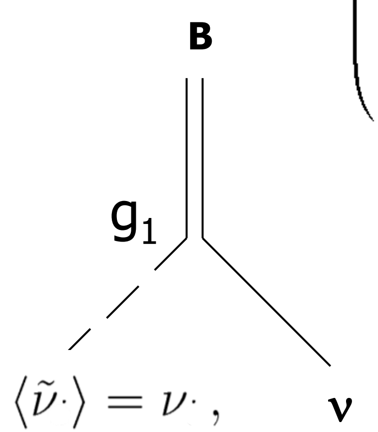
Escudero, Lopez-Fogliani, C. M., Ruiz de Austri, JHEP 12 (2008) 099
Ghosh, Roy, JHEP 04 (2009) 069
Fidalgo, Lopez-Fogliani, C.M., Ruiz de Austri, JHEP 08 (2009) 105
Ghosh, Dey, Mukhopadhyaya, Roy, JHEP 05 (2010) 087

"Neutralinos" $\chi^{0T} = (\tilde{B}^0, \tilde{W}^0, \tilde{H}_d, \tilde{H}_u, \nu_{R_i}, \nu_{L_i}),$

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

Because of the new couplings and VEVs, the model has a **generalized seesaw**, involving not only the right-handed neutrinos, but also the neutralinos

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



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

Neutralino mass eigenstates $\tilde{\chi}^0_{1,\ldots,10}$
- 7 eigenvalues from the mixing of neutralinos and ν_{Ri}
- 3 very small eigenvalues corresponding to the light neutrino masses

neutralinos RH neutrinos

LH neutrinos

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

This generalized seesaw

implies that neutrino masses and mixing angles can easily be fitted to experimental data

(even with flavour diagonal neutrino Yukawa couplings)

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

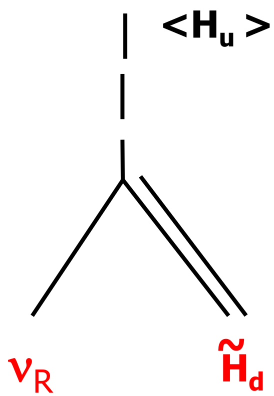
In a sense, this gives an answer to the question

why the mixing angles are so different in the quark vs. lepton sector

(because no generalized seesaw exists for the quarks)

μνSSM has larger mass matrices than those of the MSSM or NMSSM, because of the new couplings and VEVs:

$$\langle H_u^0\rangle = v_u \quad \langle H_d^0\rangle = v_d \qquad \langle\tilde\nu_i\rangle = \nu_i \qquad \langle\tilde\nu_i^c\rangle = \nu_i^c$$



"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)

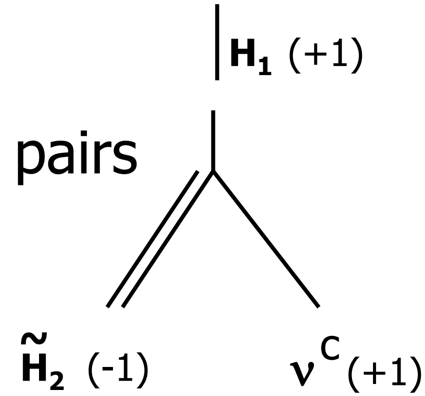
$$\mathbf{S}'_\alpha = (\underbrace{h_d, h_u, (\tilde\nu_i^c)^R}_{h_{4,5}\equiv h,\, H\ ,\ h_{1,2,3}}, \underbrace{(\tilde\nu_i)^R}_{h_{6,7,8}}) \qquad \mathbf{P}'_\alpha = (\underbrace{P_d, P_u, (\tilde\nu_i^c)^I}_{P_4\equiv A\ ,\ P_{1,2,3}}, \underbrace{(\tilde\nu_i)^I}_{P_{5,6,7}})$$

"Charged scalars"
(charged Higgses+sleptons)

$$\mathbf{S}'^+_\alpha = (\underbrace{H_d^+, H_u^+}_{H^+}, \tilde e_L^+, \tilde\mu_L^+, \tilde\tau_L^+, \tilde e_R^+, \mu_R^+, \tau_R^+),$$

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

In the new couplings SUSY particles do not appear in pairs



Thus we say that R-parity is broken, implying that the phenomenology of the μνSSM is very different from the one of the MSSM/NMSSM

Size of the breaking is small because the EW seesaw implies $\mathbf{Y}_\nu \sim 10^{-6}$

The <u>LSP is no longer stable</u> since it can decay to two SM particles

Thus all particles, not only the neutral ones, are potential LSP's
stau, squark, chargino,…, sneutrino

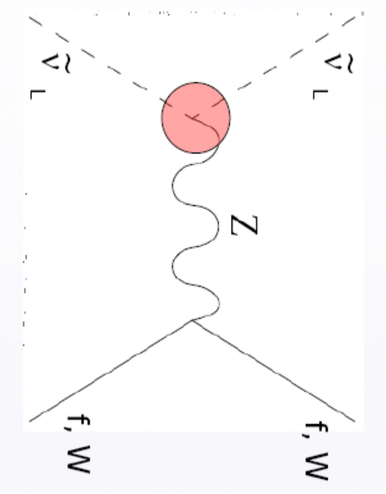
The problem of stable charged particles as DM is not present

An example of the different phenomenology: The left-handed sneutrino

If the LH sneutrino is the LSP in the MSSM, it is stable and therefore DM

(Ibáñez '84; Hagelin, Kane, Rabi '84)

Left-handed sneutrino couples with Z boson



Too large direct detection cross section
(disfavoured by experiments)

(Falk, Olive, Srednicki '94)

No problem in the μνSSM for a LH sneutrino LSP, since it is not stable

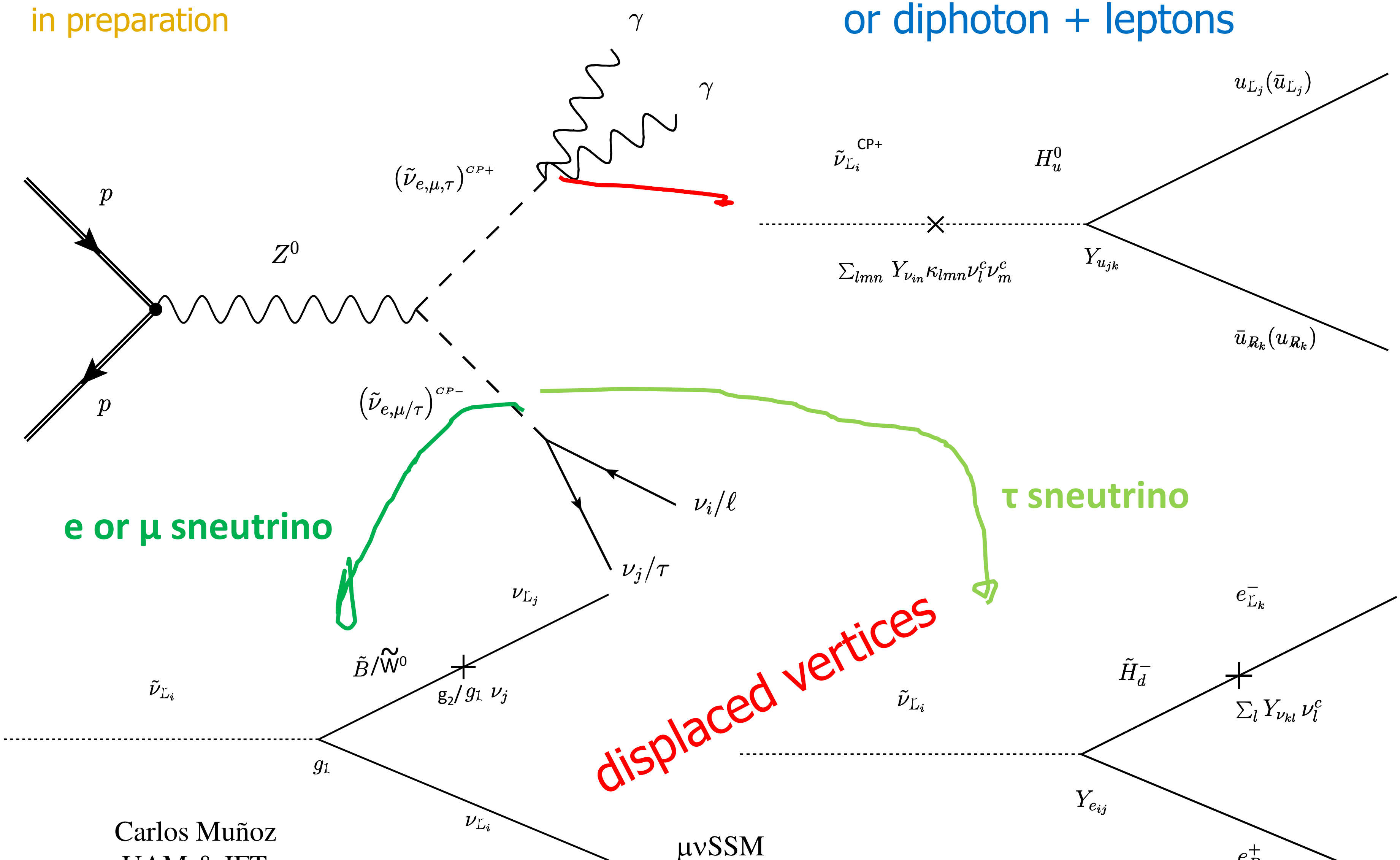
To be precise, the lightest mass eigenstate is a LH sneutrino-like neutral scalar

$$\mathbf{P'}_\alpha = \Big(\underbrace{P_d, P_u, (\widetilde{\nu}_i^c)^I}_{P_4 \equiv A\ ,\ P_{1,2,3}}, \underbrace{(\widetilde{\nu}_i)^I}_{P_{5,6,7}}\Big)$$

e.g. in the μνSSM a left-handed sneutrino LSP with a mass ~ 90-150 GeV will produce for $\mathcal{L}$=100-300 fb^{-1} a detectable number of events at LHC with

diphoton + missing energy
or diphoton + leptons

Ghosh, Lara, Lopez-Fogliani, C. M., Ruiz de Austri, in preparation



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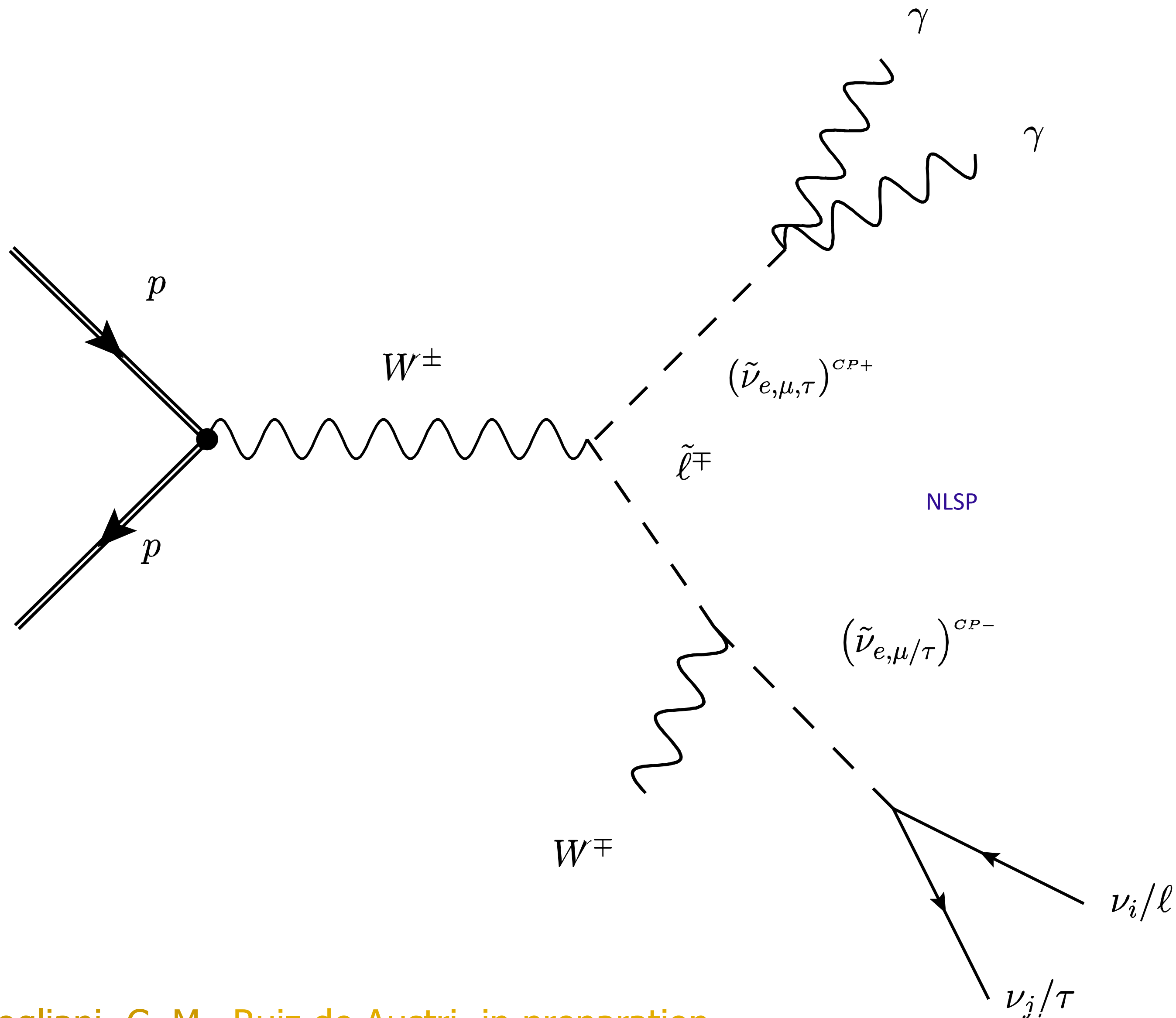
$\Gamma(h_2)$	1.1×10^{-10}	$\Gamma(A_2^0)$	8.4×10^{-14}
$\Gamma(h_3)$	8.0×10^{-11}	$\Gamma(A_3^0)$	8.2×10^{-14}

$BR(h_2\to bb)$	0.4628	$BR(h_3\to bb)$	0.4606
$BR(h_2\to WW^*)$	0.2636	$BR(h_3\to WW^*)$	0.2660
$BR(h_2\to gg)$	0.1221	$BR(h_3\to gg)$	0.1220
$BR(h_2\to\bar\tau\tau)$	0.0848	$BR(h_3\to\bar\tau\tau)$	0.0844
$BR(h_2\to\bar cc)$	0.0326	$BR(h_3\to\bar cc)$	0.0324
$BR(h_2\to ZZ^*)$	0.0296	$BR(h_3\to ZZ^*)$	0.0300
$BR(h_2\to\gamma\gamma)$	0.00308	$BR(h_3\to\gamma\gamma)$	0.00307
$BR(h_2\to\nu\nu)$	0.0007	$BR(h_3\to\nu\nu)$	0.0010
$BR(A_2^0\to\nu\nu)$	0.96	$BR(A_3^0\to\nu\nu)$	0.988
$BR(A_2^0\to\bar bb)$	0.002	$BR(A_3^0\to\bar bb)$	0.0021
$BR(A_2^0\to\bar\mu e)$	0.0085	–	–
$BR(A_2^0\to\bar\mu\mu)$	0.0081	–	–
$BR(A_2^0\to\bar\mu\tau)$	0.0081	–	–
$BR(A_2^0\to\bar\tau\tau)$	0.00037	$BR(A_3^0\to\bar\tau\tau)$	0.0004
$BR(A_2^0\to\bar cc)$	0.0009	$BR(A_3^0\to\bar cc)$	0.0009
–	–	$BR(A_3^0\to gg)$	0.0083

$\sigma(pp\to Z^*\to h_2A_2^0)$	88.18	$\sigma(pp\to Z^*\to h_3A_3^0)$	87.63
$\sigma(pp\to Z^*\to H_2^\pm H_2^\mp\to h_2A_2^0+W^\pm_{soft}W^\mp_{soft})$	3.72	$\sigma(pp\to Z^*\to H_3^\pm H_3^\mp\to h_3A_3^0+W^\pm_{soft}W^\mp_{soft})$	2.6
$\sigma(pp\to W^{\pm^*}\to H_2^\pm\ h_2/A_2^0\to h_2A_2^0+W^\pm_{soft})$	120.9	$\sigma(pp\to W^{\pm^*}\to H_3^\pm\ h_3/A_3^0\to h_3A_3^0+W^\pm_{soft})$	119.4

Dataset	N_{ev}	$\not E_T>200$	$P_{T1}>100$	$P_{T2}>50$	N_γ=2	$N_l=0$	$\Delta R<1.5$	$M_{\gamma\gamma}\in[115,135]$
Signal	371.73±0.02	85.2±0.6	70.7±0.6	37.7±0.5	37.7±0.5	34.9±0.5	34.6±0.5	31.4±0.4
$2j$+I/FSR	10^7	0	0	0	0	0	0	0
j+I/FSR	10^7	0	0	0	0	0	0	0
higgs	5424	0	0	0	0	0	0	0
Z+h	93.8±0.4	5.4±0.2	4.6±0.2	2.5±0.2	2.5±0.2	2.5±0.1	2.4±0.1	2.2±0.1
Z+ISR	8667±30	80±8	75±8	25±5	25±5	25±5	6±2	0.9±0.9
W+FSR	12552±45	35±5	33±5	8±2	8±2	3±2	0.8±0.8	0
$(\frac{S}{\sqrt{B}})$	—	7.77±0.5	6.7±0.5	6.4±0.7	6.4±0.7	6.3±0.7	11±2	18±3



Ghosh, Lara, Lopez-Fogliani, C. M., Ruiz de Austri, in preparation

Gravitino DM

- If the gravitino is the LSP, it can be a dark matter candidate

It decays to SM particles as any other LSP,
but its lifetime can be longer than the age of the Universe

Under this assumption of gravitino DM, in our previous analysis:

Thus all particles, not only the neutral ones, are potential ~~LSP's~~ → NLSP's

stau, squark, chargino,..., sneutrino

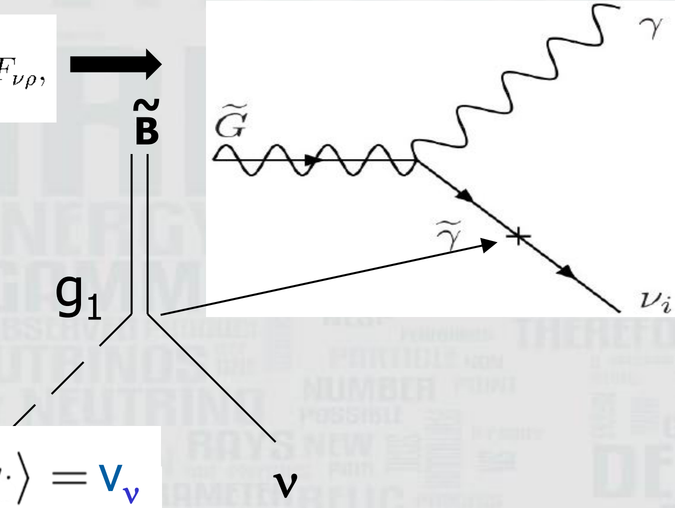
NLSP decays into ordinary particles, and our analysis is not modified.

The gravitino LSP in RPV decays due to the photino-neutrino mixing, opening the channel

Takayama, Yamaguchi, 2000

In supergravity

$$L_{int} = -\frac{i}{8M_{pl}}\bar{\psi}_\mu[\gamma^\nu, \gamma^\rho]\gamma^\mu \lambda F_{\nu\rho},$$



$\langle \tilde{\nu}_\cdot \rangle = v_\nu$

$$\Gamma(\psi_{3/2} \to \gamma\nu) = \frac{1}{32\pi}|U_{\tilde{\gamma}\nu}|^2 \frac{m_{3/2}^3}{M_P{}^2} .$$

The decay width is supressed both by the Planck mass and the R-parity breaking, which is expected to be very small:

$|U_{\tilde{\gamma}\nu}|^2 \sim |g_1 v_\nu / M_1|^2 \sim 10^{-14} - 10^{-15}$

Since $v_\nu \sim 10^{-4}$ GeV because its minimization equation contains the small Yukawa $Y_\nu \sim 10^{-6}$ in order to reproduce neutrino data

Thus the lifetime can be longer than the age of the Universe ($\sim 10^{17}$ s), and the gravitino can be a good DM candidate

$$\tau_{3/2} = \Gamma^{-1}(\tilde{G} \to \gamma\nu) \simeq 8.3 \times 10^{26}\,\text{sec} \times \left(\frac{m_{3/2}}{1\text{GeV}}\right)^{-3} \left(\frac{|U_{\gamma\nu}|^2}{7 \times 10^{-13}}\right)^{-1}$$

Detection of gravitino DM

- Decays of **gravitinos** in the galactic halo, at a sufficiently high rate, would produce gamma rays that could be detectable in experiments

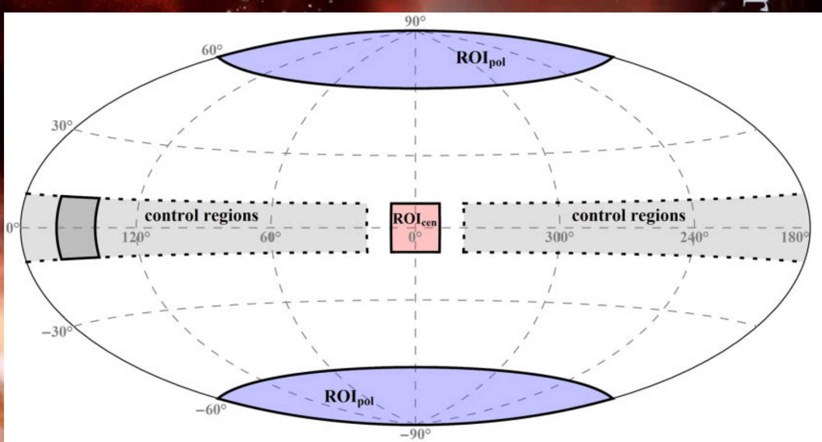
***Fermi* Large Area Telescope (LAT)**, might in principle detect this flux of gamma rays predicted in RPV models with gravitino DM

Buchmuller, Covi, Hamaguchi, Ibarra, Yanagida, 07; Bertone, Buchmuller, Covi, Ibarra, 07
Ibarra, Tran, 08 ; Ishiwata, Matsumoto, Moroi, 08
Choi, López-Fogliani, C.M., Ruiz de Austri, 09
Choi, Yaguna, 10; Choi, Restrepo, Yaguna, Zapata, 10 ; Diaz, García Saenz, Koch, 11
Restrepo, Taoso, Valle, Zapata, 11
Gómez-Vargas, Fornasa, Zandanel, Cuesta, C.M., Prada, Yepes, 11

$$\left[E^2\frac{dJ}{dE}\right]_{\rm halo} = \frac{2E^2}{m_{3/2}}\frac{dN_\gamma}{dE}\frac{1}{8\pi\tau_{3/2}}\int_{\rm los}\rho_{\rm halo}(\vec{l})d\vec{l}\,,$$

particle physics   astrophysics

Since a gravitino decays into a photon (and a neutrino), this produces a line at energies equal to $\mathbf{m_{3/2}/2}$



Together with Fermi-LAT collaborators we performed the following:

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

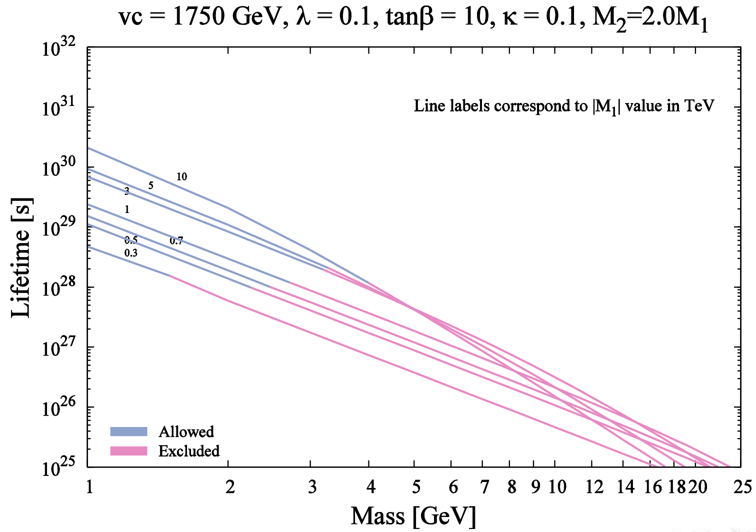
arXiv:1406.3430 [astro-ph.HE], *JCAP 10 (2014) 023*

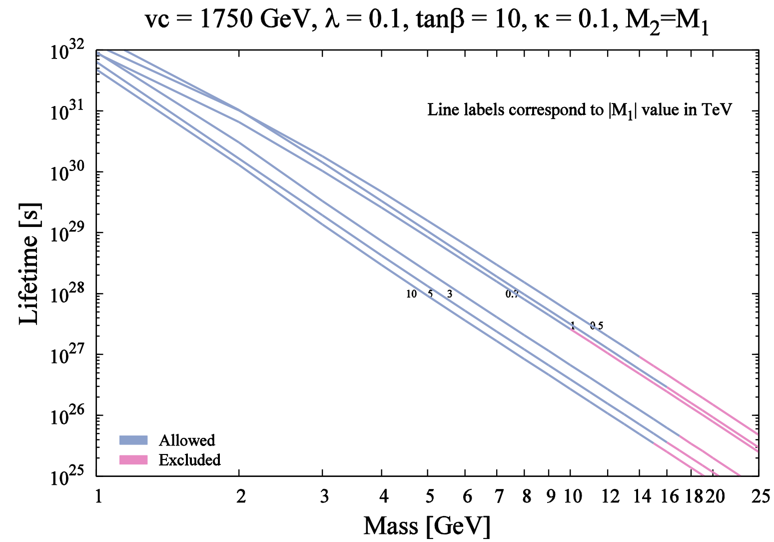
Category II paper:
-*Fermi*-LAT Collaboration: Albert, Bloom, Charles, Gómez-Vargas, Mazziotta, Morselli
External authors: C. M., Grefe, Weniger

Constraining $m_{3/2}$
and gravitino lifetime

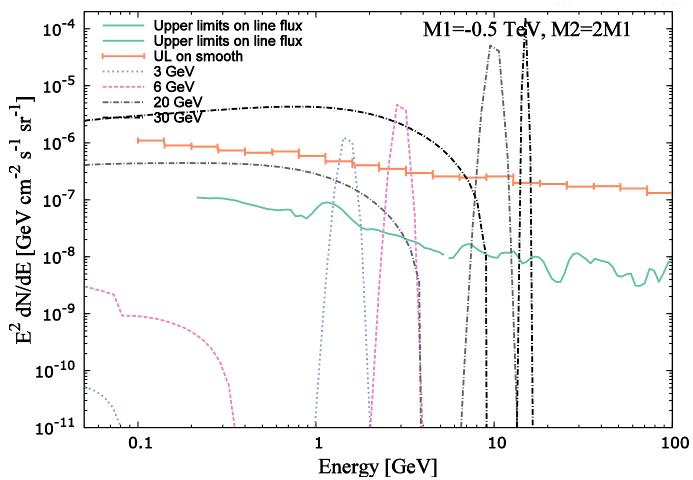
Results updated with 5.8 years of data from Fermi LAT

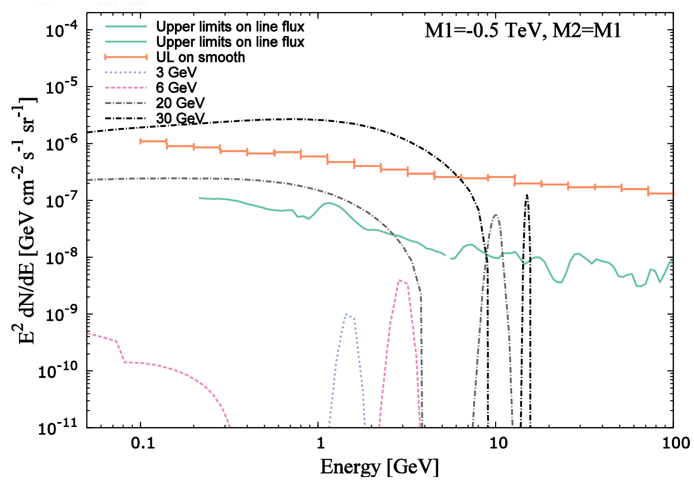
Gómez-Vargas, López-Fogliani, C.M., Perez, Ruiz de Austri, in preparation





$$|U_{\tilde{\gamma}\nu}| \approx \frac{M_Z(M_2 - M_1)s_W c_W}{(M_1 c_w^2 + M_2 s_w^2)(M_1 s_W^2 + M_2 c_W^2)},$$





If the gravitino is the DM: $m_{3/2} < 20$ GeV

Conclusions

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

Solves the μ problem with **neutrinos**: $\hat{\nu}^c_i \, \hat{H}_1 \, \hat{H}_2$

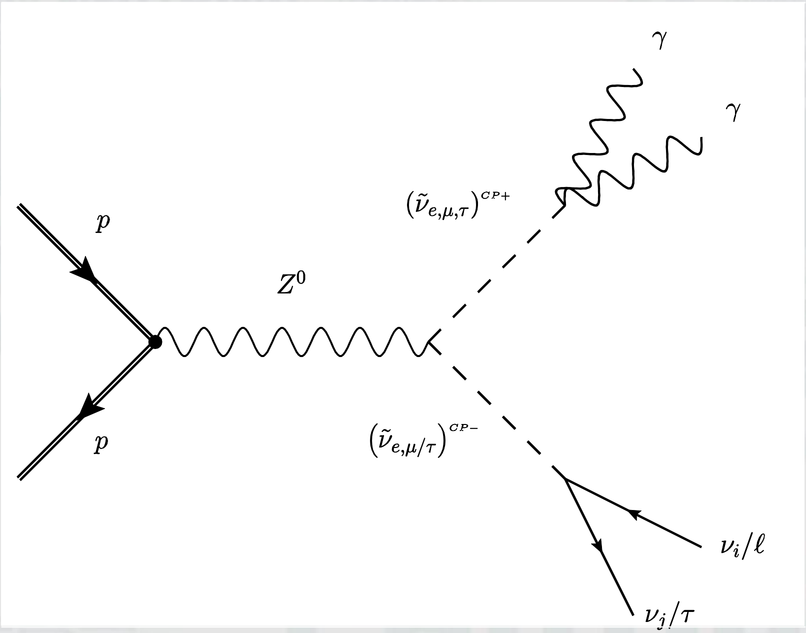
An electroweak seesaw is generated dynamically
(no Majorana masses have to be introduced by hand) $\hat{\nu}^c_i \hat{\nu}^c_j \hat{\nu}^c_k$

The phenomenology of the μνSSM is very rich, e.g.:

* The LSP/NLSP, which can be neutral or charged, can decay within the detectors but with a length large enough to show displaced vertices

* Lepton events can be produced in the decay chains

e.g.:



Gravitino is an interesting DM candidate in the μνSSM that can be observed in indirect detection experiments

Fermi LAT data allow to constrain the parameter space of the model:

e.g. μνSSM gravitino DM must have a mass no larger than 20 GeV

THE END