Hunting long-lived particles at the LHC in the μνSSM

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The $\mu\nu SSM$

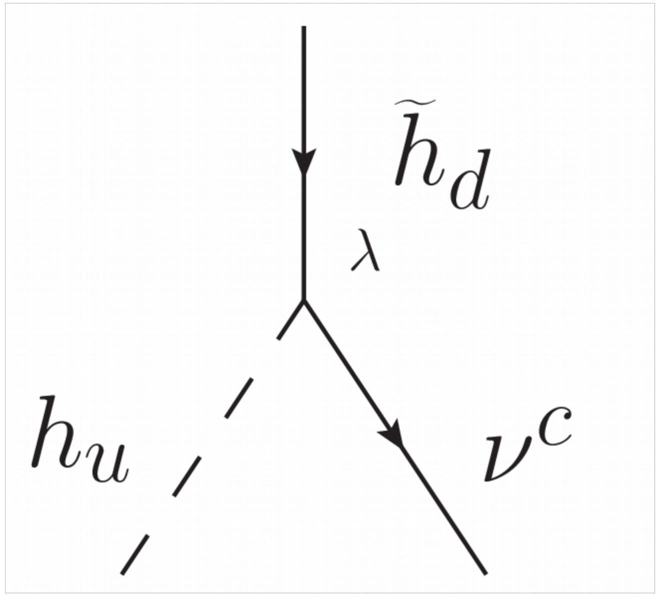
$$W = W_{MSSM_{\mu=0}} \underbrace{+Y_\nu^{ij}\hat{H}_u^b\hat{L}_i^a\hat{\nu}_j^c - \epsilon_{ab}\lambda_i\hat{\nu}_i^c\hat{H}_d^a\hat{H}_u^b + \frac{1}{3}\kappa^{ijk}\hat{\nu}_i^c\hat{\nu}_j^c\hat{\nu}_k^c.}_{\mu\nu SSM}$$

The $\mu\nu SSM$ extends the MSSM particle content with right handed neutrino superfields:
López-Fogliani, Muñoz.Phys. Rev. Lett. (2006)

- Coupling to Higgs superfields ⇒ Solve the μ problem of the MSSM.
- Coupling to Left handed lepton superfields ⇒ Give mass to neutrino sector.

The presence of both coupling breaks R-parity explicitly.

The LSP is no longer stable ⇒ Can’t be interpreted as dark matter.



However, the gravitino could be a viable DM candidate.
Ki-Young Choi et al JCAP (2010)
A. Albert et al JCAP (2014)

Electroweak baryogenesis can be realized.
D. J. H. Chung et al Phys. Rev. (2010)

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

After EWSB v_d , v_u , v_{iR} and v_{iL} acquire vevs:

- Effective μ-term for the higgs sector $\Rightarrow \mu_{eff} = \lambda_i v_{iR}$
- Dirac mass for neutrinos:

$$\left(m_D^{eff}\right)_{ij} = \frac{1}{\sqrt{2}} Y_{\nu ij} v_u$$

- Majorana mass for right handed neutrinos: $\left(M_M^{eff}\right)_{ij} = \sqrt{2}\kappa_{ijk} v_{kR}$

Generates electroweak scale Type-I see-saw. Correct values for $Y_\nu \sim 10^{-6}$

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

In the limit $Y_{\nu ij} \to 0$, R-parity is restored.

Dark Mater in the $\mu\nu SSM$

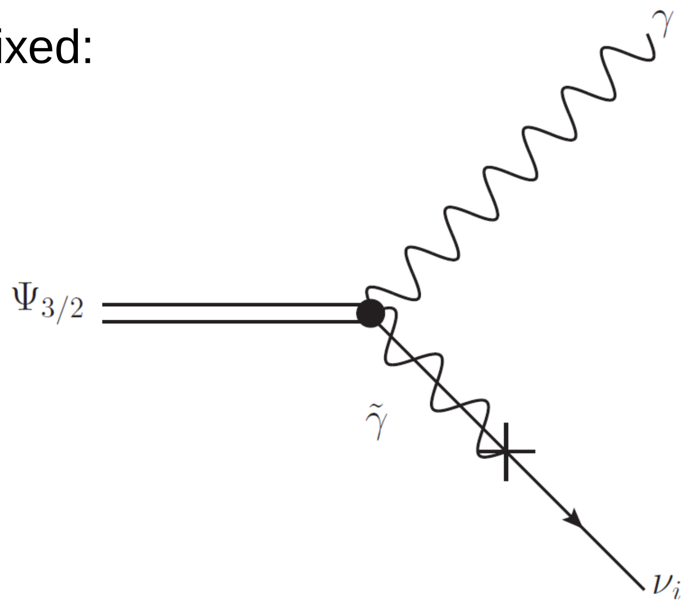
From supergravity ⇒ Interaction term gravitino-photon field strength and photino

- In R-parity conserving SUSY:

$$\Psi_{3/2} \to \gamma\chi^0 \text{ if } m_{\Psi_{3/2}} > m_{\chi^0} \text{ or } \chi^0 \to \gamma\Psi_{3/2} \text{ if } m_{\Psi_{3/2}} < m_{\chi^0}$$

- In the μνSSM photino and the left-handed neutrinos are mixed:

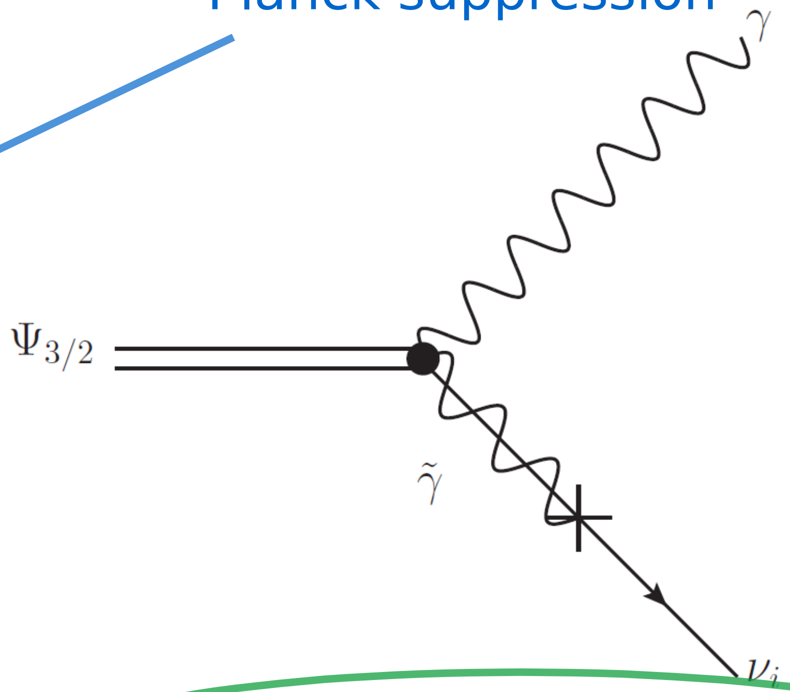
$$\Gamma\left(\Psi_{3/2} \to \sum_i \gamma\nu\right) \sim \frac{1}{32\pi}|U_{\tilde{\gamma}\nu}|^2 \frac{m_{3/2}^3}{M_P^2}$$



Dark Mater in the $\mu\nu SSM$

Planck suppression

$$\Gamma\left(\Psi_{3/2} \to \sum_i \gamma\nu\right) \sim \frac{1}{32\pi}|U_{\tilde{\gamma}\nu}|^2 \frac{m_{3/2}^3}{M_P^2}$$



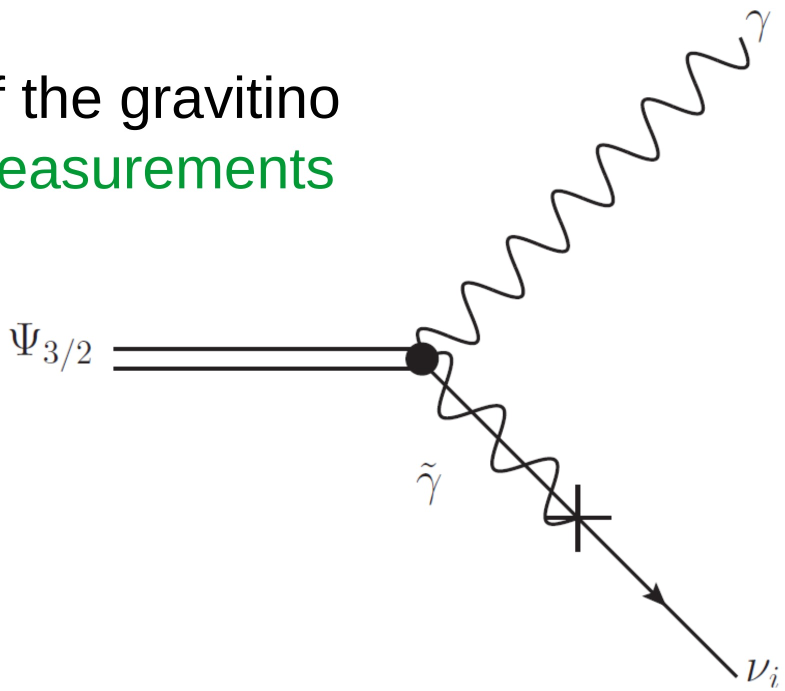
R-parity suppression

$$\tau_{3/2} \sim 3.0 \times 10^{27} s \left(\frac{|U_{\tilde{\gamma}\nu}|^2}{10^{-16}}\right)^{-1} \left(\frac{m_{3/2}}{10\text{GeV}}\right)^{-3} \gg 10^{17}\text{s} \sim \text{ age of the universe}$$

Correct neutrino physics forces $|U_{\tilde{\gamma}\nu}|^2 \sim 10^{-10} - 10^{-12}$

Dark Mater in the $\mu\nu SSM$

Monochromatic photons produced in the decay of the gravitino
⇒ Indirect detection of DM through gamma-ray measurements



Constraints from *Fermi*-LAT:

$$m_{3/2} < 17 \text{ GeV}$$

$$\tau_{3/2} > 4 \times 10^{25} \text{ s}$$

Gómez-Vargas, López-Fogliani, Muñoz, Perez, Ruiz de Austri JCAP (2017)

Collider phenomenology of the $\mu\nu SSM$

The violation of R-parity in the $\mu\nu SSM$ has also consequences for collider phenomenology:

- The LSP in not stable $\Rightarrow$ could be any particle.
- The characteristic signal of SUSY is no longer missing transverse energy.

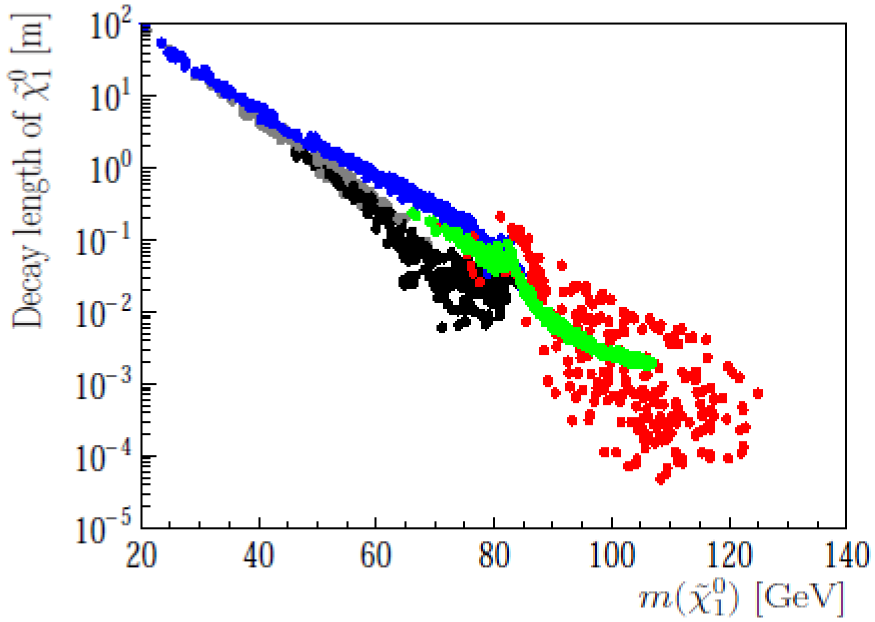
The small value of Y_ν required by neutrino seesaw imply small R-parity violation:

- Particles more massive than the LSP will produce the LSP in the decay.
- Suppression of the decay amplitude of the LSP $\Rightarrow$ long lived particle

Neutralino LSP

$Y_\nu \sim 10^{-6}$ and $m_\chi \sim 20\text{-}120$ GeV ⇒ proper decay length ~ m-mm

Bartl, Hirsch, Vicente, Liebler, Porod, JHEP 2009



Decay of neutralino produces leptons and bottom quarks at secondary vertex.

Signal analyzed in the decay of SM-higgs → $h_{SM} \to \chi^0 \chi^0 \to 2\tau^+ 2\tau^- 2\nu$

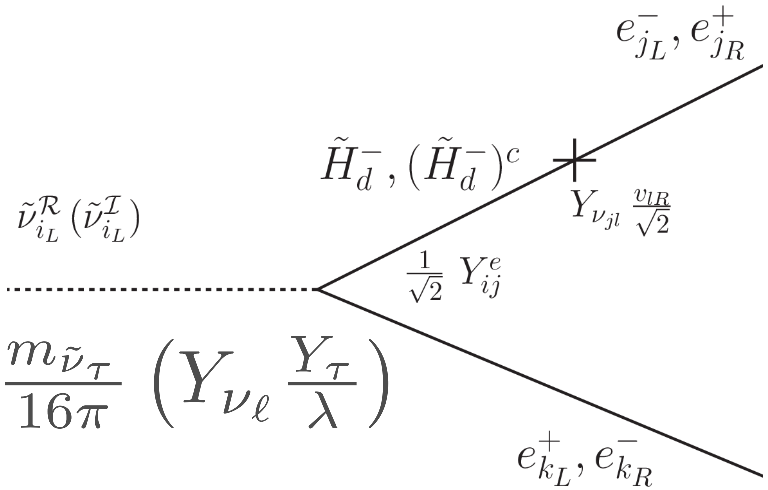
Ghosh, Lopez-Fogliani, Mitsou, C.M., Ruiz de Austri, PRD 2013

Displaced dileptons

Left sneutrino LSP

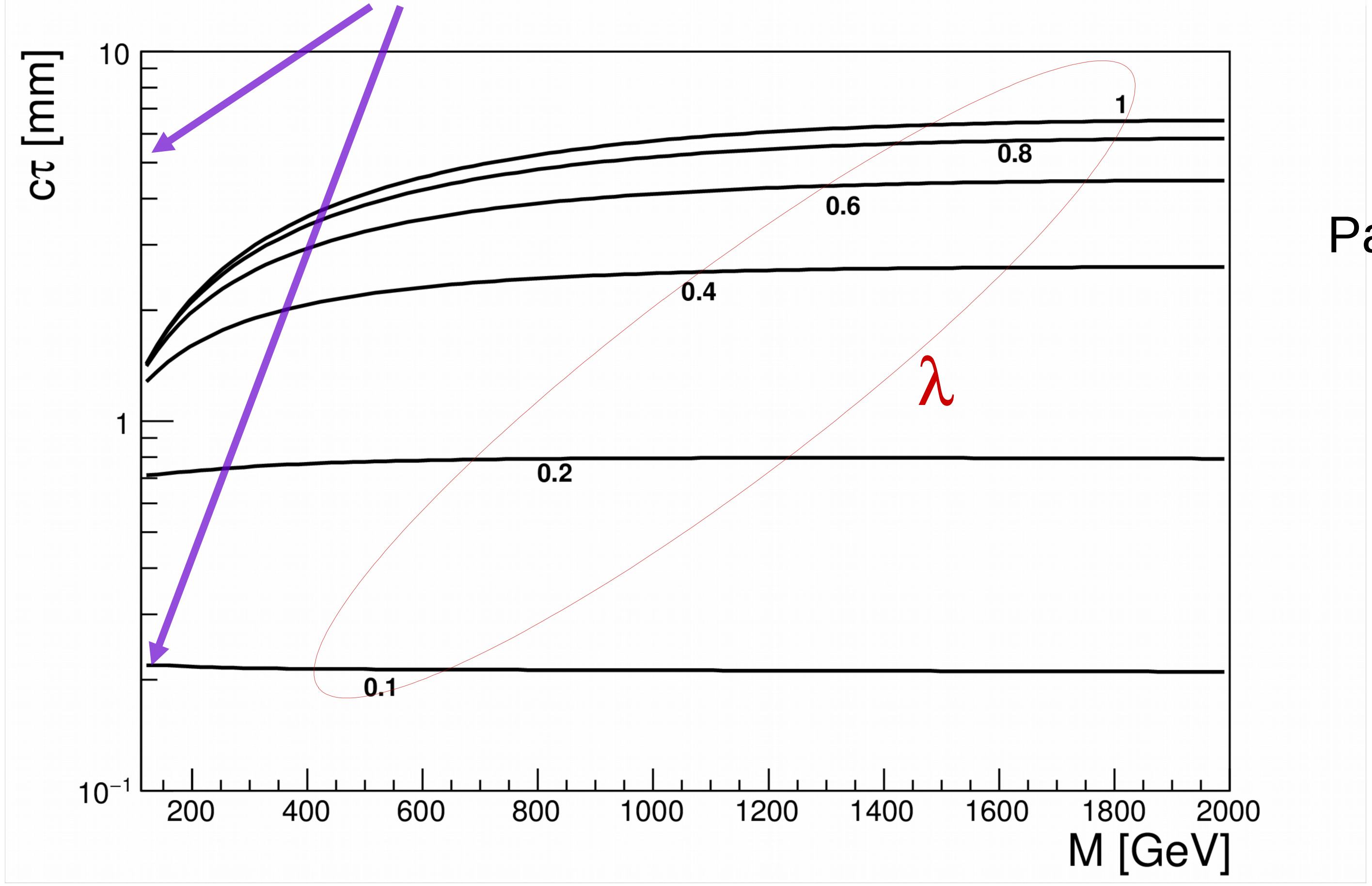
I.L., López-Fogliani,Muñoz,Nagata, Otono, Ruiz de Austri Phys.Rev. (2018)
Ghosh, I.L., López-Fogliani,Muñoz., Ruiz de Austri Int.J.Mod.Phys. (2018)

Mixing higgsino-lepton makes possible the decay:
sneutrino → 2leptons

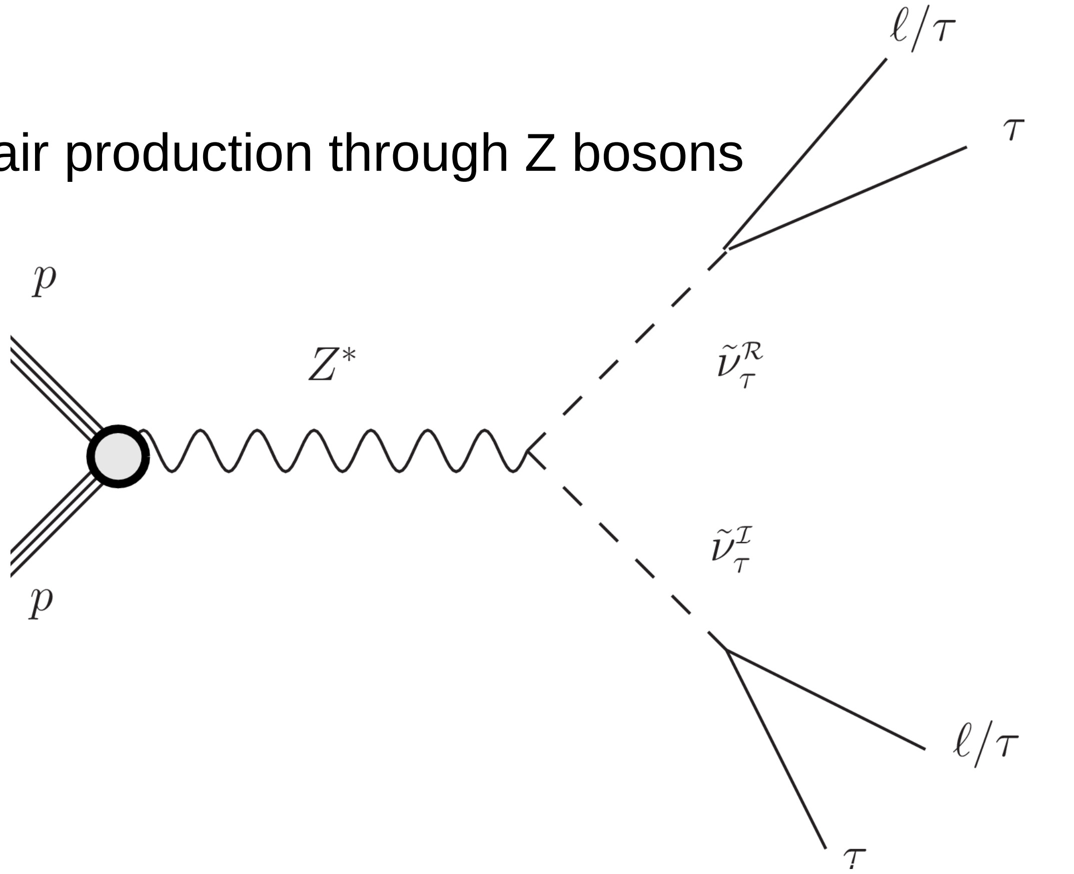


$$\Gamma(\tilde{\nu} \to \tau\ell) \sim \frac{m_{\tilde{\nu}_\tau}}{16\pi}\left(Y_{\nu_\ell}\frac{Y_\tau}{\lambda}\right)$$

Proper decay length ~ 0.1mm-5mm

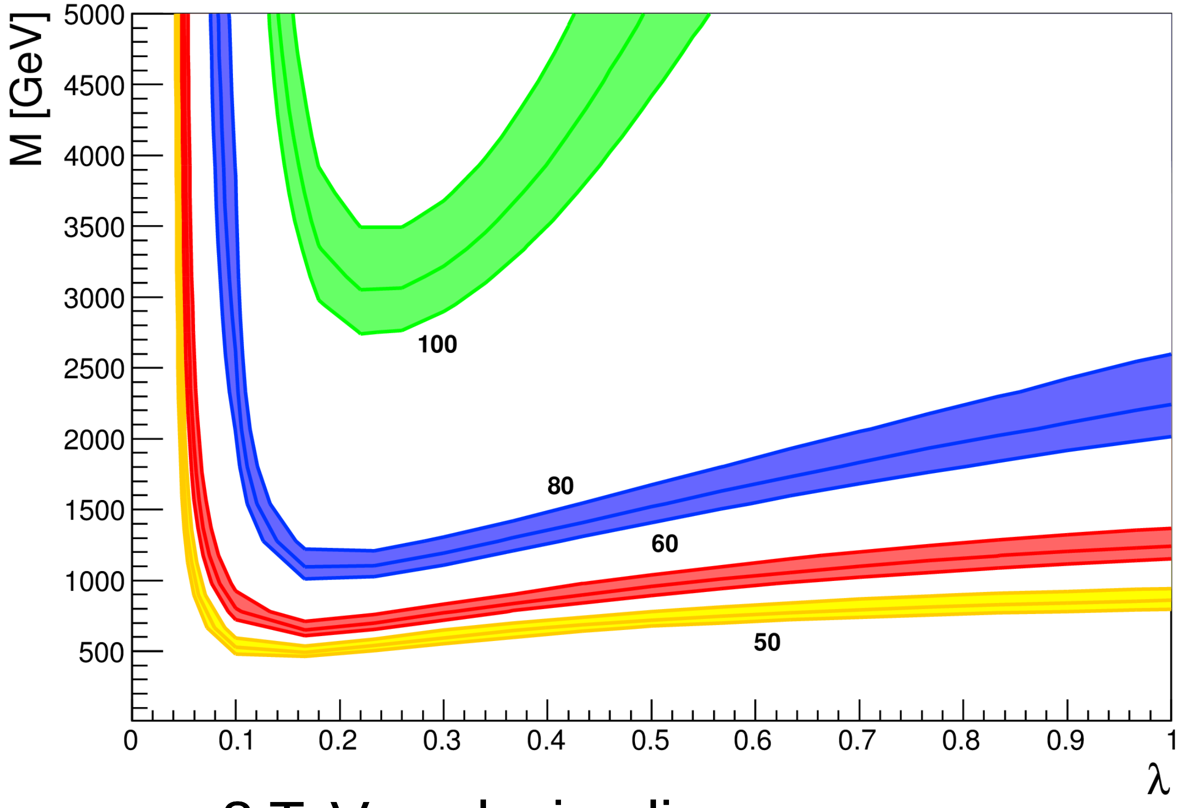


Pair production through Z bosons

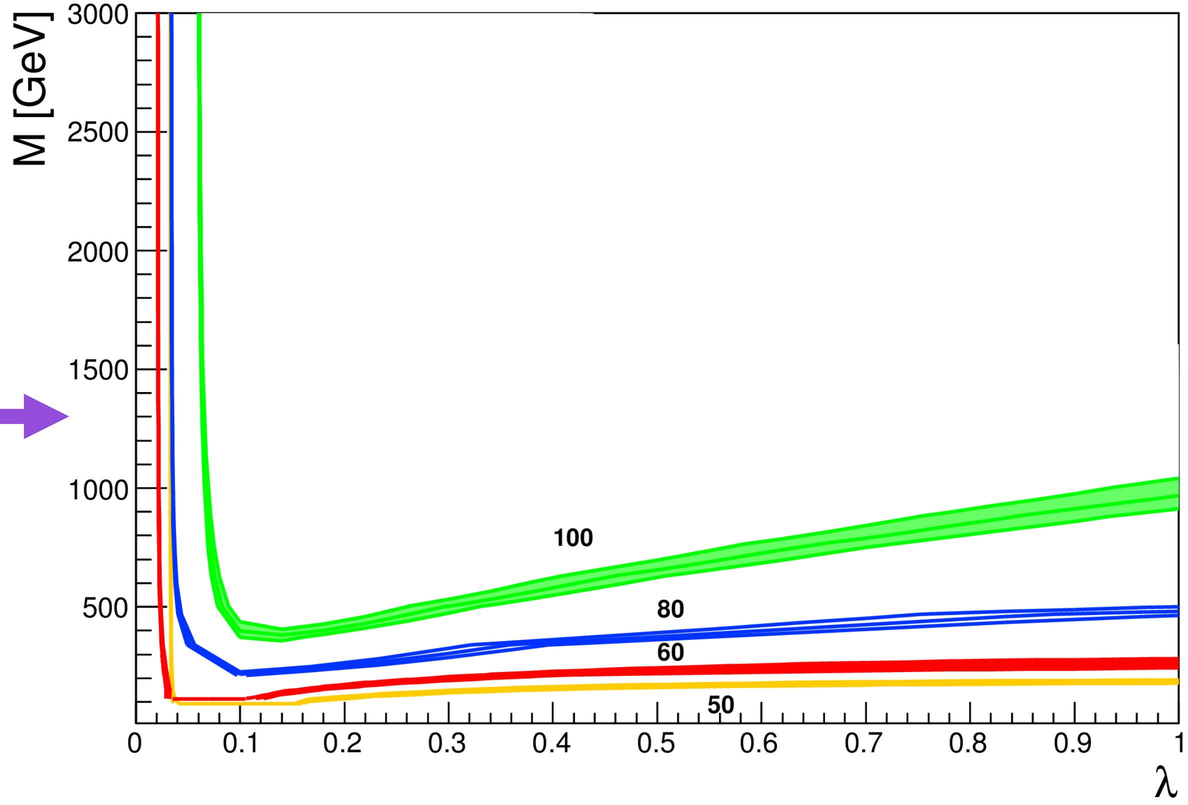


Left sneutrino LSP

Reinterpretation of *ATLAS collaboration, Phys. Rev. (2015)* , [Search for massive, long-lived particles using multitrack displaced vertices or **displaced lepton pairs** ...]



8 TeV exclusion lines



Prospect for 13TeV proposed search

Work in preparation relating neutrino physics with collider signature of long-lived sneutrino decay:

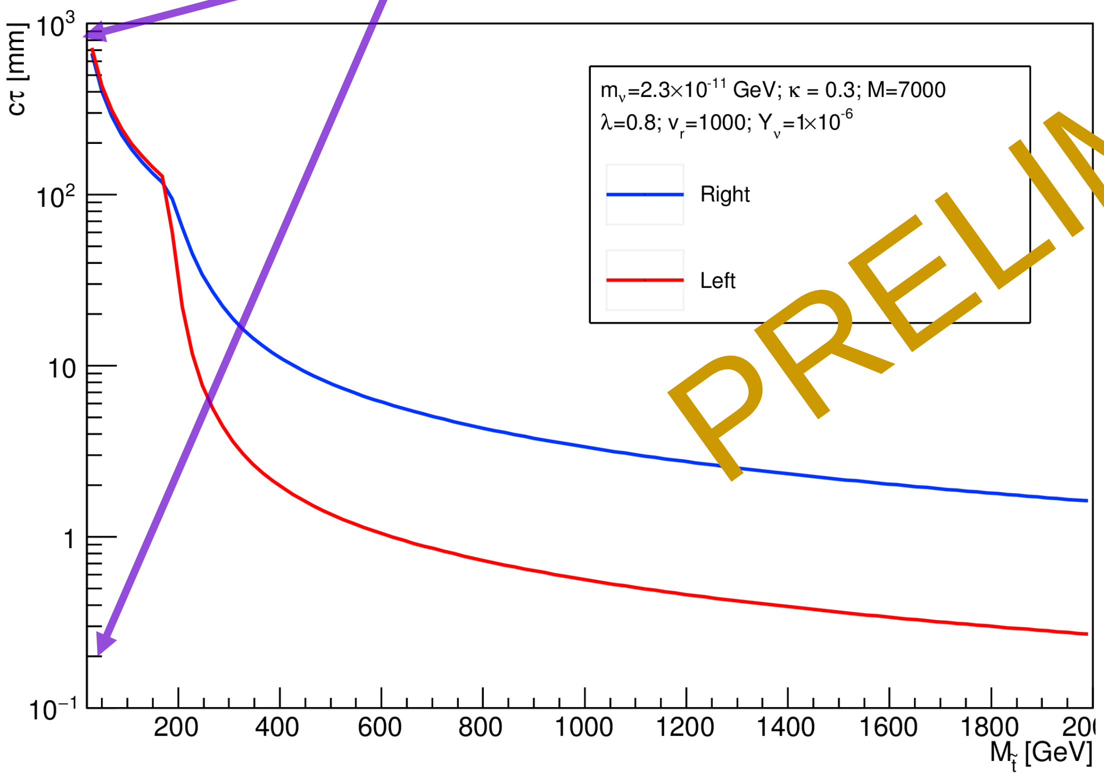
Kaptcha, I.L., López-Fogliani, Muñoz,Nagata,Otono, Ruiz de Austri

Stop LSP

Kaptcha, I.L., López-Fogliani,Muñoz,Nagata,Otono, Ruiz de Austri

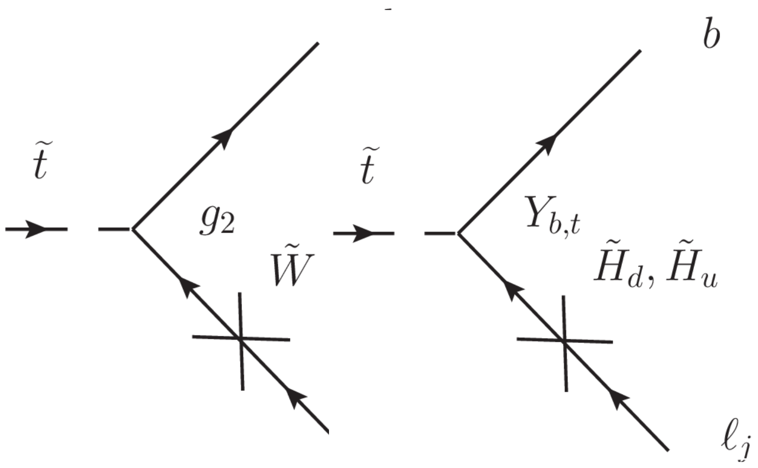
Signal of displaced leptons produced in the decay of the stop

Proper decay length 0.1 mm - m



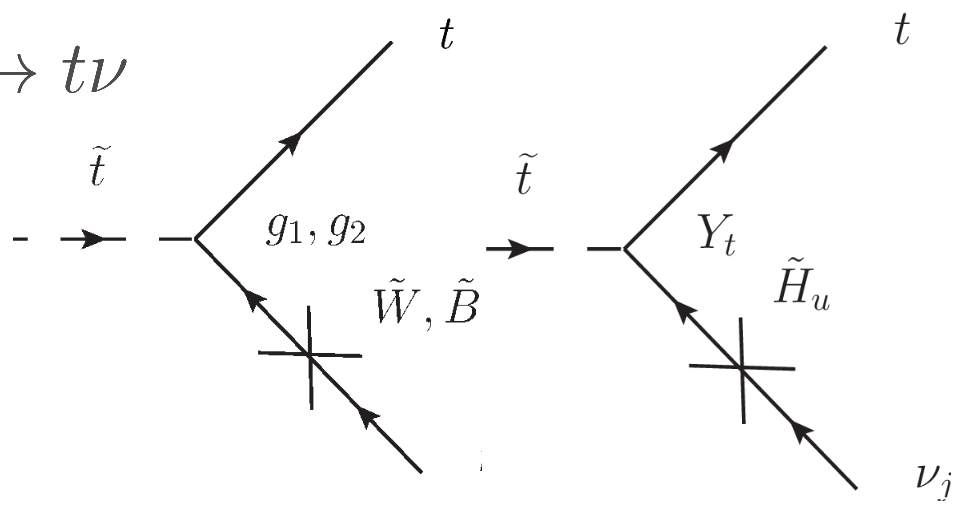
PRELIMINARY

Decay $\tilde{t} \to b\ell$



Apply also limits from prompt searches

Decay $\tilde{t} \to t\nu$



Conclusions.

- The μνSSM is a well-motivated model of SUSY which addresses the solution of the μ-problem and explains the origin of neutrino masses.
- In the μνSSM R-parity is broken ⇒ the LSP is unstable.
- Correct neutrino masses require small R-parity violation.
- The gravitino can be a viable DM candidate thanks to the Planck suppression and the R-parity suppression of its decays.
- The smallness of neutrino masses is directly related with the decay amplitude of the LSP. ⇒ The decay of the LSP usually produces displaced vertices.
- Neutralino, left sneutrino and stop decays can produce detectable displaced leptons at the LHC.
- The decay length of the LSP depends on the value of Y_ν which also sets the life-time of the DM.