The gravitino, the muon g-2 and LLP searches at the LHC

Iñaki Lara Pérez

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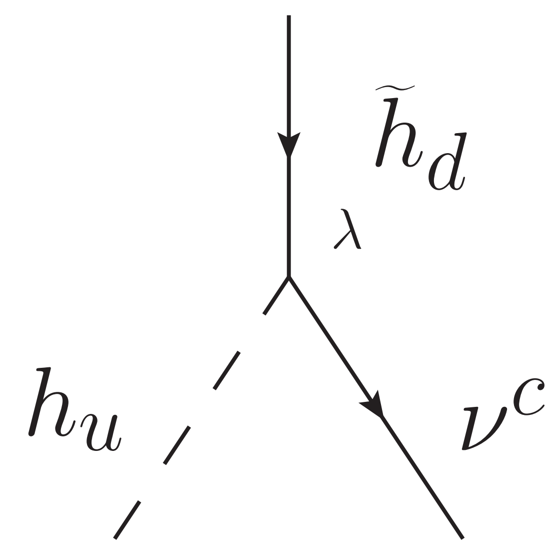
The $\mu\nu$SSM

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

D.López-Fogliani, C.Muñoz.Phys. Rev. Lett. 97 (2006) 041801 $\mu\nu$SSM extends the MSSM particle content with **right haded neutrino superfields:**

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

The presence of both couplings at the same time breaks R-parity explicitly.



The LSP is no longer stable ⇒ Can't be interpreted as DM

However, the gravitino could be a viable DM candidate.

Ki-Young Choi et al JCAP 03 (2010) 028
A. Albert et al JCAP 10 (2014) 023

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

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

- After EWSB, all neutral scalars can develop VEVs.

$$\langle H_d \rangle = \frac{v_d}{\sqrt{2}}, \langle H_u \rangle = \frac{v_u}{\sqrt{2}}, \langle \tilde{\nu}_{iR} \rangle = \frac{v_{iR}}{\sqrt{2}}, \langle \tilde{\nu}_{iL} \rangle = \frac{v_{iL}}{\sqrt{2}}$$

- The value of v_{iR} are naturally around M_{SUSY}. While $Y_\nu^{ij} \to 0$ implies $v_{iL} \to 0$, and can be estimated as $v_{iL} \sim Y_\nu^{ii} v_u$.

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

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

After EWSB the $<\phi>$ generates several effective terms in the Lagrangian:

- μ-term for the Higgs sector ⇒ $\mu^{eff} = \lambda_i v_{iR}$
- Majorana mass for rigth handed neutrinos ⇒ $(M_M^{eff})_{ij} = \sqrt{2}\kappa_{ijk} v_{kR}$
- Dirac mass for neutrinos ⇒ $(m_D^{eff})_{ij} = \frac{1}{\sqrt{2}} Y_{\nu_{ij}} v_u$

If the value of $Y_{\nu ij} \sim 10^{-6}$ ⇒ Electroweak scale Type-I seesaw.

The μνSSM mix all the states with the same spin, CP and charge properties. Phenomenology different from RPC models.

The $\mu\nu$SSM seesaw . $\chi^0 = \left(\widetilde{B}^0, \widetilde{W}^0, \widetilde{H}_d^0, \widetilde{H}_u^0, (\nu_{jR})^c, \nu_{iL}\right)$

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

A. Bartl, M. Hirsch, S. Liebler, W. Porod, A. Vicente JHEP 05 (2009) 120
J.Fidalgo, D.López-Fogliani, C.Muñoz, R.R.de Austri JHEP 08 (2009) 105

At first approximation $m_{eff} = -m^T \cdot M^{-1} \cdot m$. With 3 generations of right-handed neutrinos:

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

I.L., D. E. López-Fogliani, C. Muñoz, N. Nagata, H. Otono, and R. Ruiz De Austri Phys. Rev. D98 no. 7, (2018) 075004

With a single generation of right-handed neutrinos:

$$m_\nu = \frac{1}{4\,M_{\text{eff}}} \sum_i \left[v_i^2 + v_d\left(\frac{2v_i Y_{\nu_i}}{\lambda} + \frac{v_d Y_{\nu_i}^2}{\lambda^2}\right)\right], with \frac{1}{M} \approx \frac{g'^2}{M_1} + \frac{g^2}{M_2}.$$

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

- In R-parity conserving SUSY

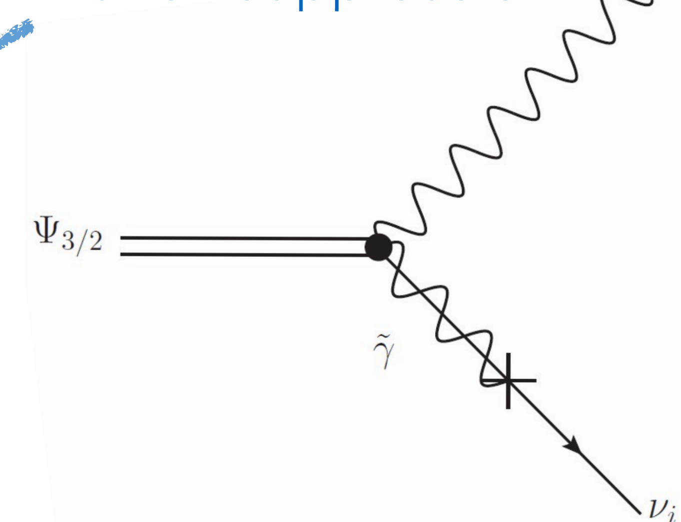
$$\psi_{3/2} \to \gamma\, \chi^0 \text{ if } m_{\psi_{3/2}} > m_{\chi^0} \text{ or } \chi^0 \to \gamma\, \psi_{3/2} \text{ if } m_{\psi_{3/2}} < m_{\chi^0}$$

- In the $\mu\nu$SSM, photino and left-handed neutrino are mixed:

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

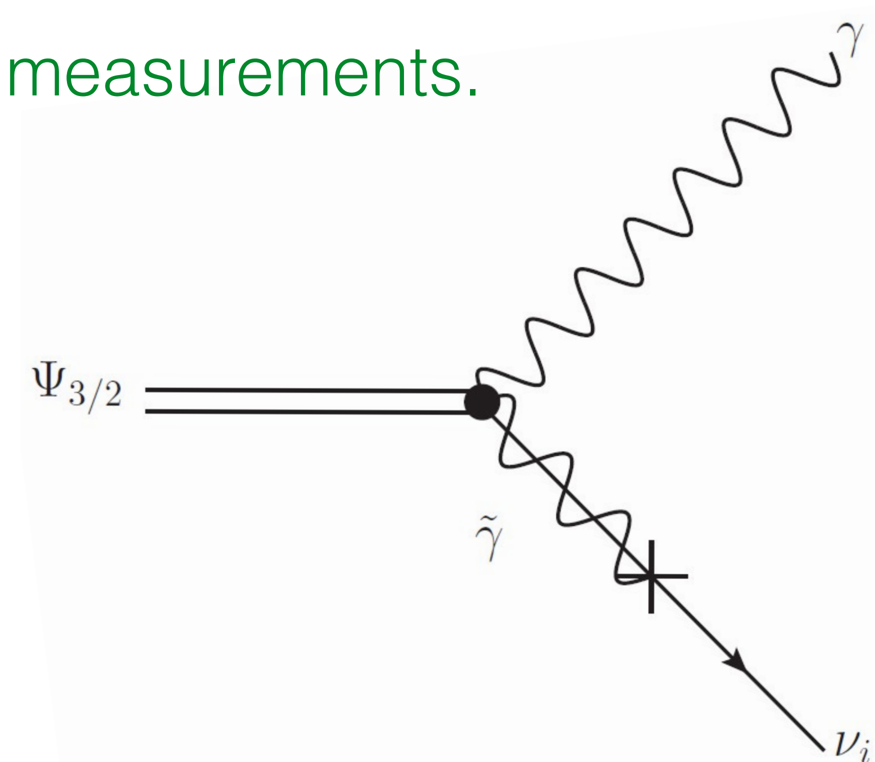


$$\tau_{3/2} \sim 3.0\times 10^{27}\, s \left(\frac{U_{\tilde{\gamma}\nu}^2}{10^{-16}}\right)^{-1} \left(\frac{m_{3/2}}{10GeV}\right)^{-3} \gg 10^{17}\, s \sim \text{age of the universe.}$$

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:

$$\mathrm{m}_{3/2} < 17\ \mathrm{GeV}$$

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

Germán A. Gómez-Vargas, Daniel E. López-Fogliani, Carlos Muñoz, Andres D. Perez, Roberto Ruiz de Austri JCAP 1703 (2017) no.03, 047

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

Neutrino physics related with DM life-time

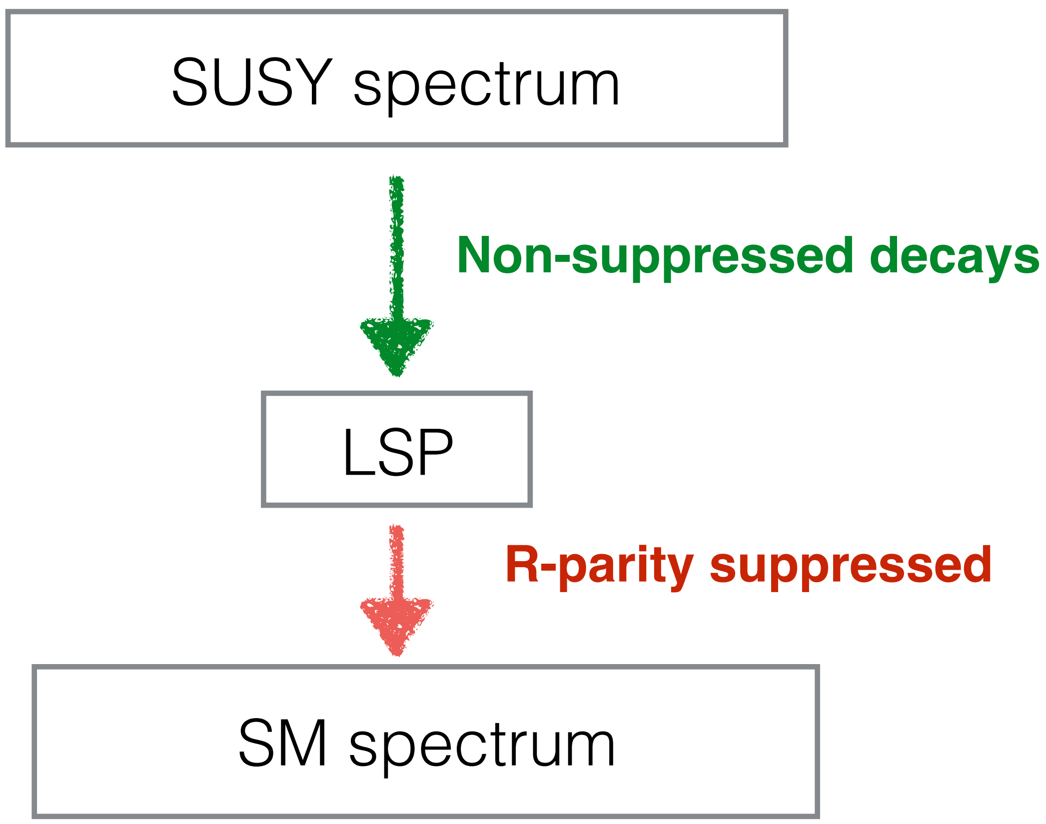
Collider phenomenology of the $\mu\nu$SSM

The violation of R-parity in the $\mu\nu$SSM produces a particular phenomenology:

- The **LSP** is not stable ⇒ any particle could be at the bottom of the SUSY spectrum.
- 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 ⇒ **long lived particle.**



Back to the neutrino seesaw

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

Three representative solutions with **diagonal Yukawas:**

- *M*<0, with $Y_{\nu 1} < Y_{\nu 2}$, $Y_{\nu 3}$, and $v_1 > v_2$, v_3. Needs a mild tuning between 1st and 2nd terms of the seesaw.⇒ $m_{\tilde{\nu}_1}$ **is the smallest sneutrino mass**.
- *M*>0, with $Y_{\nu 3} < Y_{\nu 1} < Y_{\nu 2}$, and $v_1 < v_2 \sim v_3$. Dominated by gaugino seesaw and $Y_{\nu 3}$ can be small⇒ $m_{\tilde{\nu}_3}$ **is the smallest**
- *M*>0, with $Y_{\nu 2} < Y_{\nu 1} < Y_{\nu 3}$, and $v_1 < v_2 \sim v_3$. Similar to previous solution but exchange on 2⟷3. ⇒ $m_{\tilde{\nu}_2}$ **is the smallest**

Neutrino physics makes the left sneutrino a natural LSP

Using non-diagonal Yukawas changes completely the story

Sneutrino a Natural LSP candidate

- CP-odd/even sneutrino states are (almost) degenerated in mass.
- Sleptons would normally be slightly more massive than sneutrinos: $-m_W^2 \cos 2\beta$
- Neglecting small terms, the mass of sneutrinos is approximately:

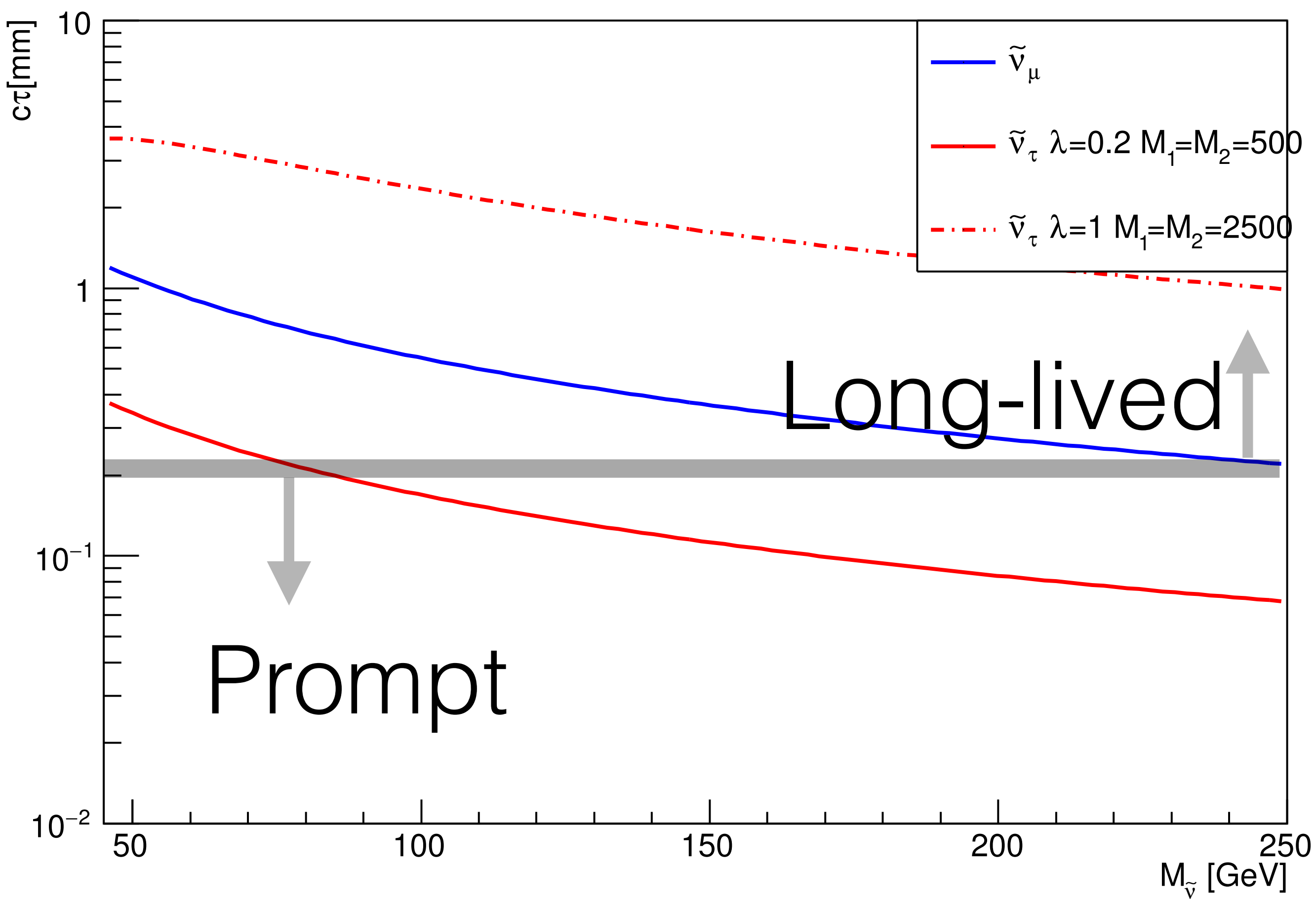
$$m^2_{\tilde{\nu}_i^{\mathcal{I}} \tilde{\nu}_i^{\mathcal{I}}} \approx \frac{Y_\nu v_u}{v_{iL}} v_R \left(-A_\nu - \kappa v_R + \frac{\lambda v_R}{\tan\beta} \right).$$

If M_{SUSY} lies at ~TeV scale with soft terms consistently at this scale and μ_{eff} at the same scale → Left sneutrino is naturally the LSP.

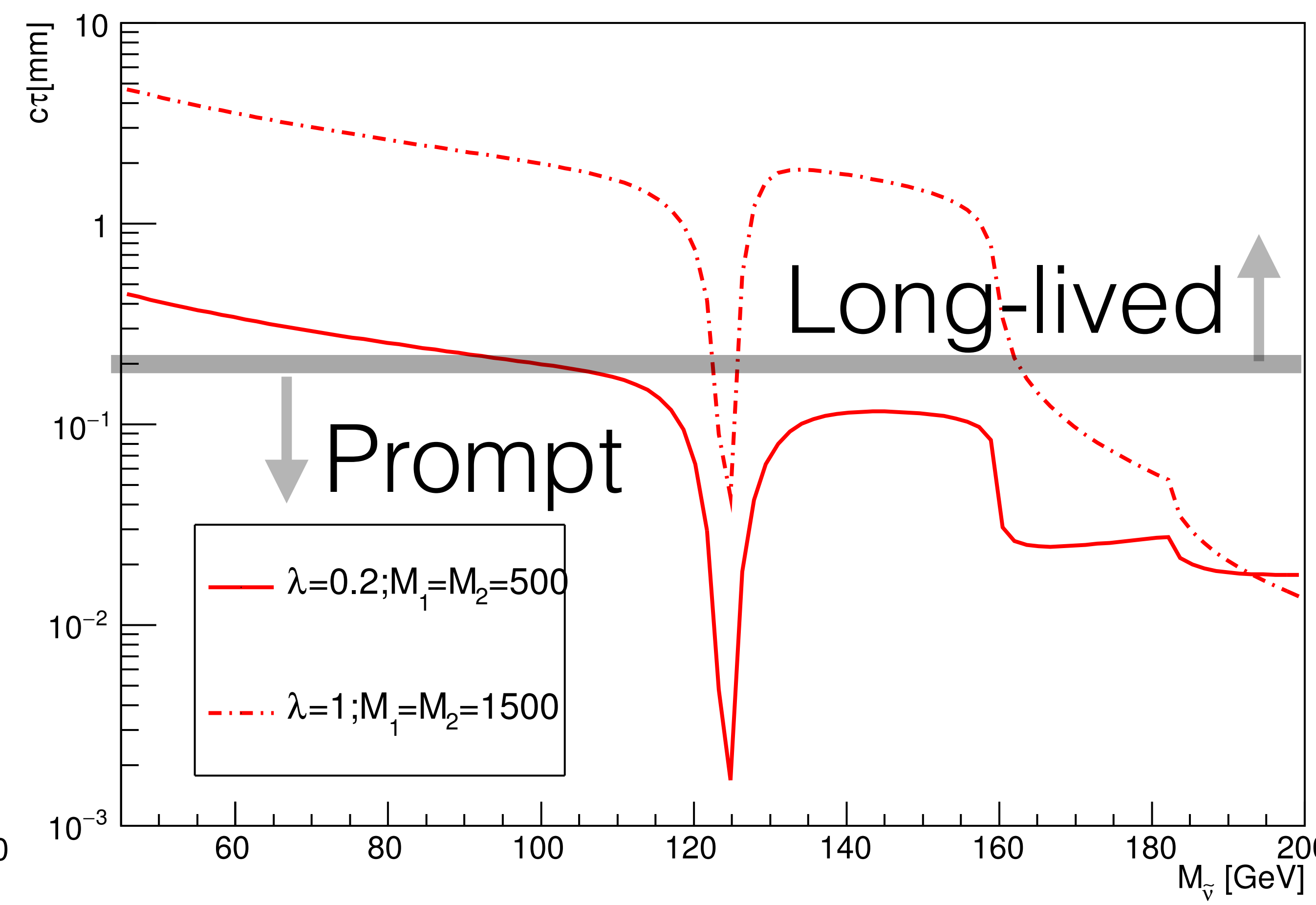
If v_R~1 TeV, $\frac{Y_\nu v_u}{v_{iL}}$ ~1 and A_ν ~ -100 GeV, then **the mass of the left sneutrino is ~ 100 GeV.**

Decay of the sneutrino LSP mediated by RPV interactions **Suppressed**

CP-odd left sneutrino cτ vs mass



CP-even left sneutrino cτ vs mass



Below ~100 GeV the left sneutrino is **long lived**

If prompt, several visible signals:

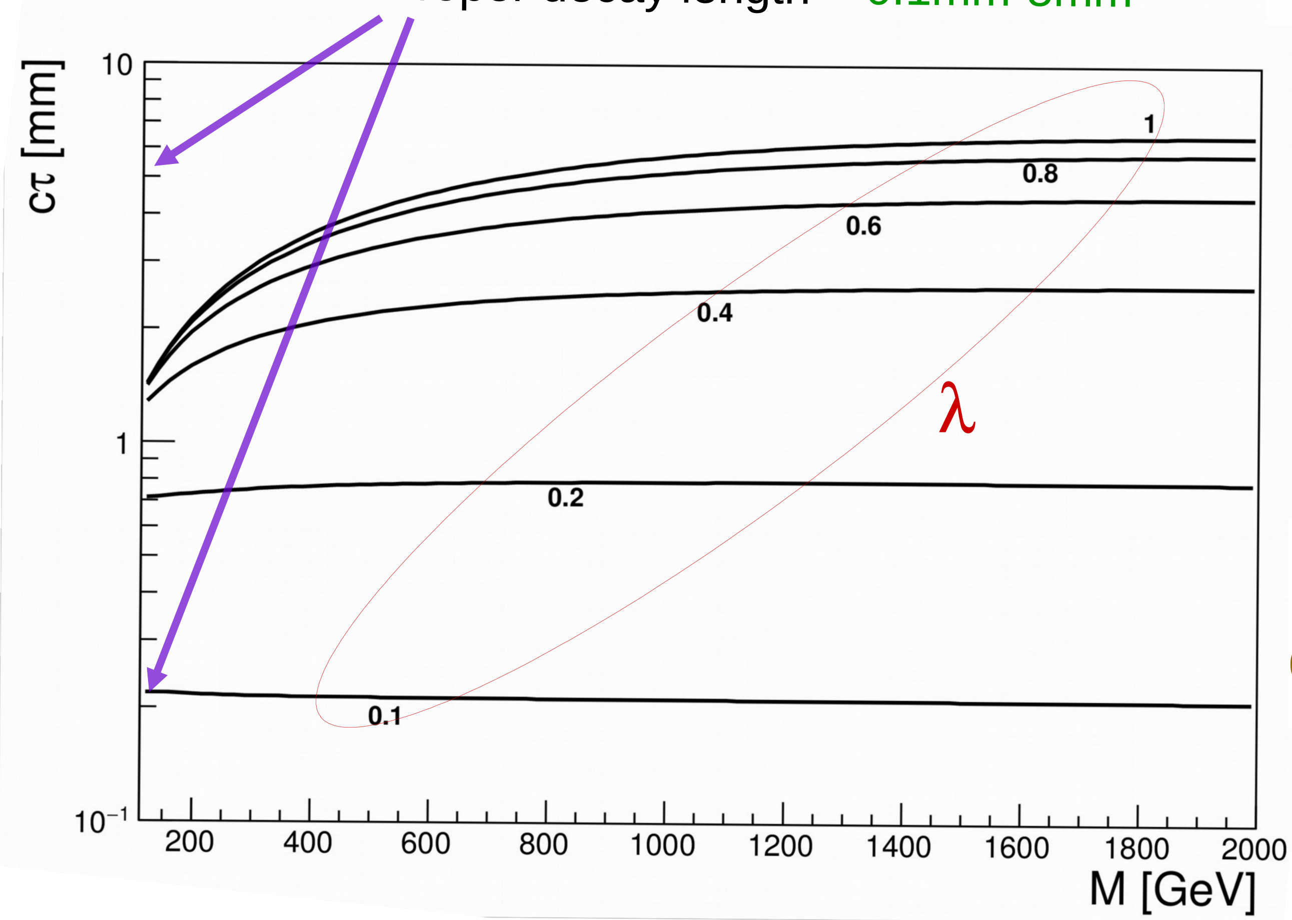
- Diphoton plus missing transverse momentum. For $\tilde{\nu}_{\mu,e}$
- Diphoton plus $\tau\ell$. For $\tilde{\nu}_{\tau}$
- Multilepton signal. For $\tilde{\nu}_{\tau}$

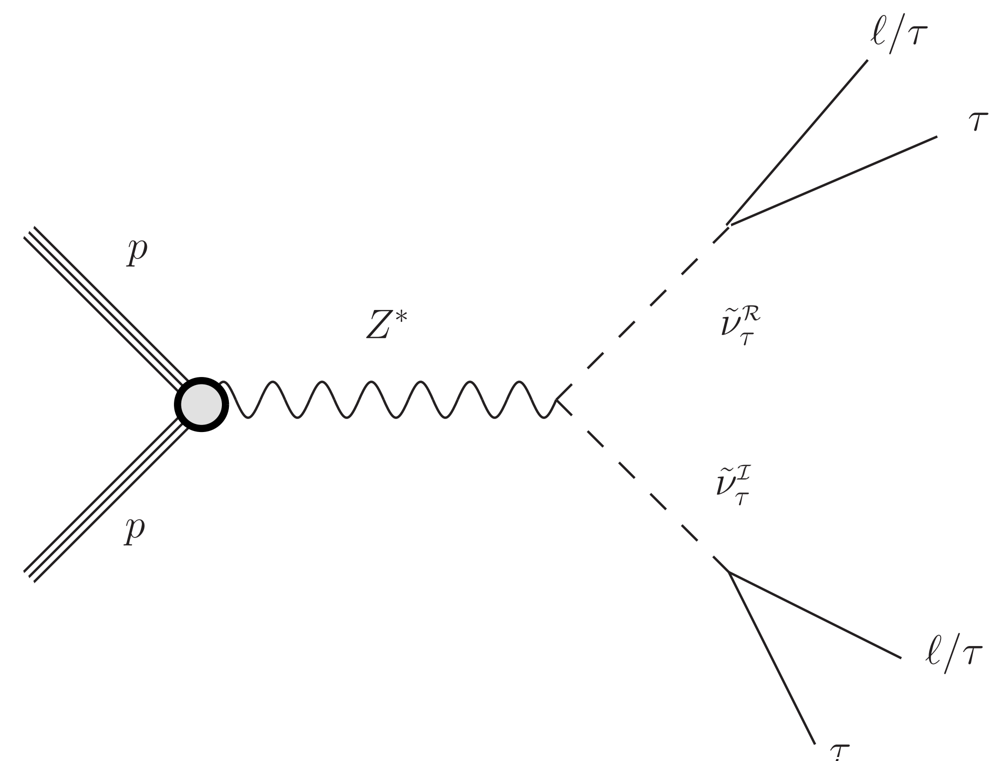
P. Ghosh, I. L, D. E. López-Fogliani, C. Muñoz, and R. Ruiz de Austri. Int. J. Mod. Phys. A33 (2018) 1850110 pp. 1-62

If displaced, dilepton signal:

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

Proper decay length ~ 0.1mm-5mm





I.L., Daniel E. López-Fogliani, Carlos Muñoz, Natsumi Nagata, Hidetoshi Otono, Roberto Ruiz de Austri Phys.Rev. D98 (2018) no.7, 075004

ATLAS search for long-lived particles using displaced lepton pairs

$20{,}3\ fb^{-1}$ @ 8TeV	μ^-	e^-
Trigger*	$p_T > 50$ GeV, $\|\eta\| < 1{,}07$	$p_{T_1} > 120$ or $p_{T_{1,2}} > 40$ GeV
Lepton tracks	$p_T > 10$ GeV , $0.02 \leq \|\eta\| \leq 2{,}5$	
	$d_0 > 2$ mm	$d_0 > 2{,}5$ mm
Vertex selection	$m_{DV} > 10$ GeV, $r_{DV} < 300$ mm, $\|Z_{DV}\| < 300$ mm	
	$\sqrt{(x_{DV} - x_{PV})^2 + (y_{DV} - y_{PV})^2} \geq 4$ mm	

*Both electron and muon triggers don't make use of tracking information. Large Pt cut imposed to reject background.

ATLAS collaboration found no displaced dilepton events:

Channel	No. of background vertices ($\times 10^{-3}$)
e^+e^-	$1{,}0 \pm 0{,}2\ ^{+0{,}3}_{-0{,}6}$
$e^\pm\mu^\mp$	$2{,}4 \pm 0{,}9\ ^{+0{,}8}_{-1{,}5}$
$\mu^+\mu^-$	$2{,}0 \pm 0{,}5\ ^{+0{,}3}_{-1{,}4}$

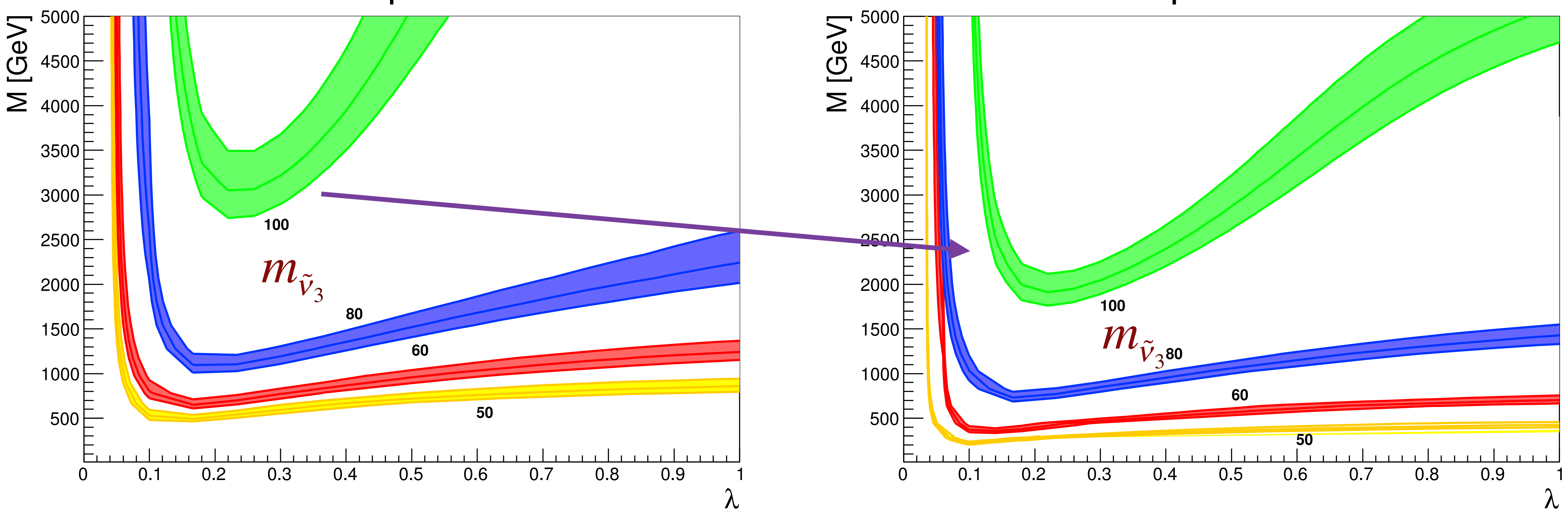
Exclusion power highly limited by harsh trigger requirements

Optimization

Using inner detector information we can change the trigger to mu24i(G.Aad et al. Eur. Phys. J. C75 (2015) 120). Looser Pt and η requirements on tracks.⇒More signal

Background still under control increase of order ~10 still compatible with zero

Non-optimized Optimized



20.3fb^{-1} @ 8TeV

Analysis of the 3-generations $\mu\nu$SSM parameter space

E. Kpatcha ,I.L., Daniel E. López-Fogliani, Carlos Muñoz, Natsumi Nagata, Hidetoshi Otono, Roberto Ruiz de Austri. To be published

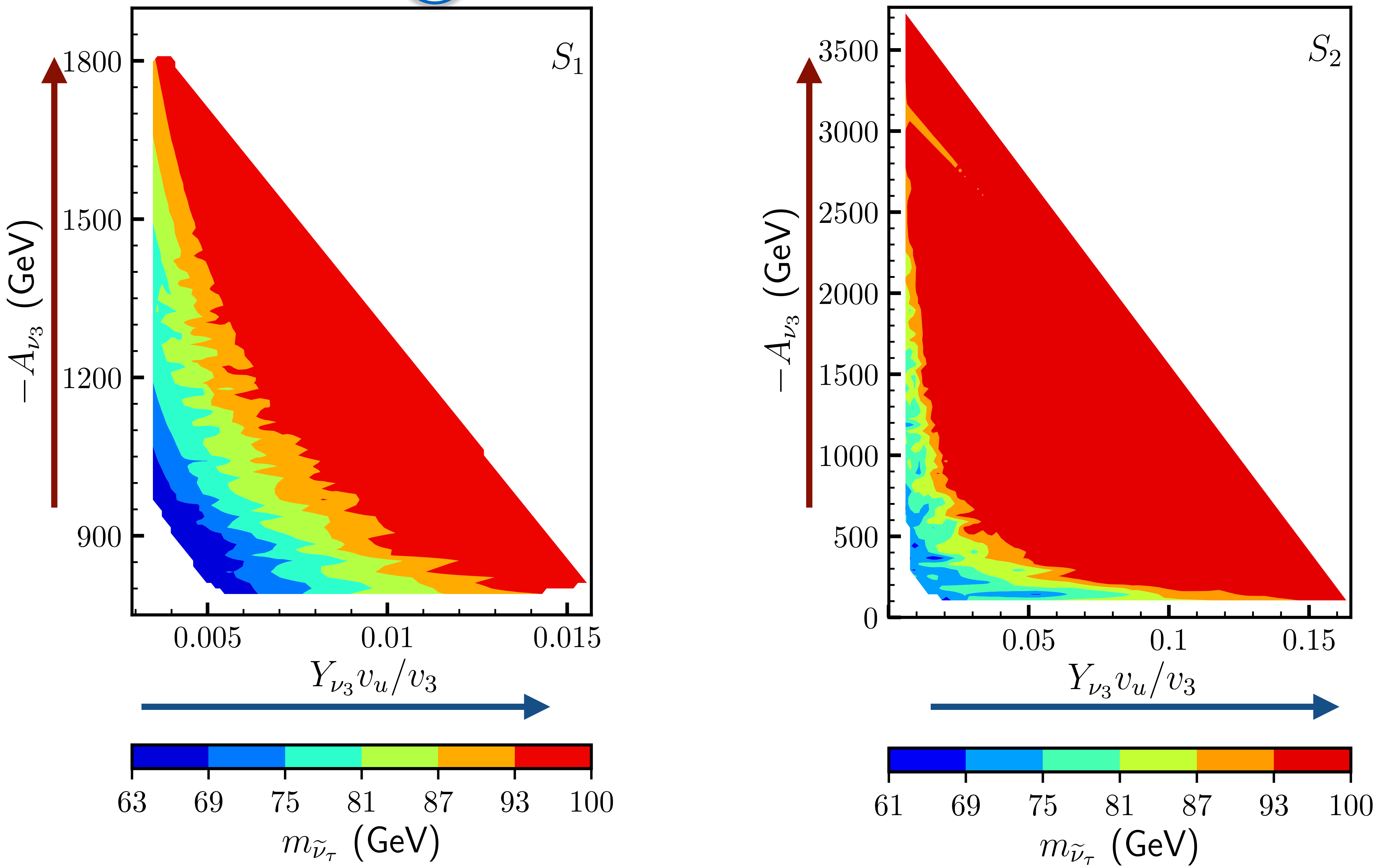
Scan 1 (S_1)	**Scan 2** (S_2)
$\tan\beta \in (10, 16)$	$\tan\beta \in (1, 4)$
$Y_{\nu_i} \in (10^{-8}, 10^{-6})$ $v_i \in (10^{-6}, 10^{-3})$ $-T_{\nu_3} \in (10^{-6}, 10^{-4})$ $M_2 \in (150, 2000)$	

Scan over significant parameters for sneutrino phenomenology

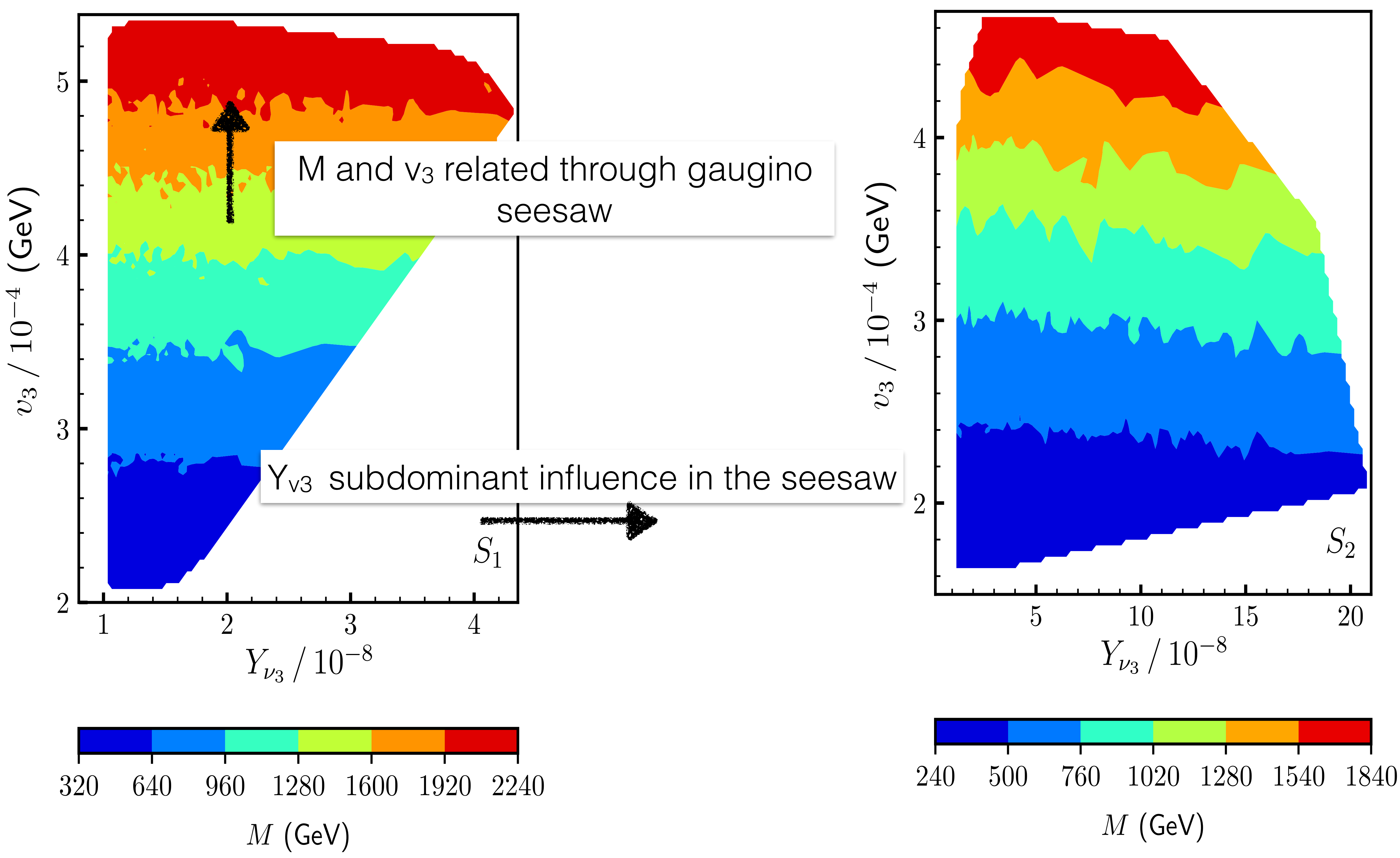
Impose constraints form:

- Neutrino mass differences and mixing angles (NO)
- Higgs physics (`HiggsBounds+HiggsSignals`)
- Flavour observables
- Chargino mass bound
- Stability of EWSB vacua (Vevacious)

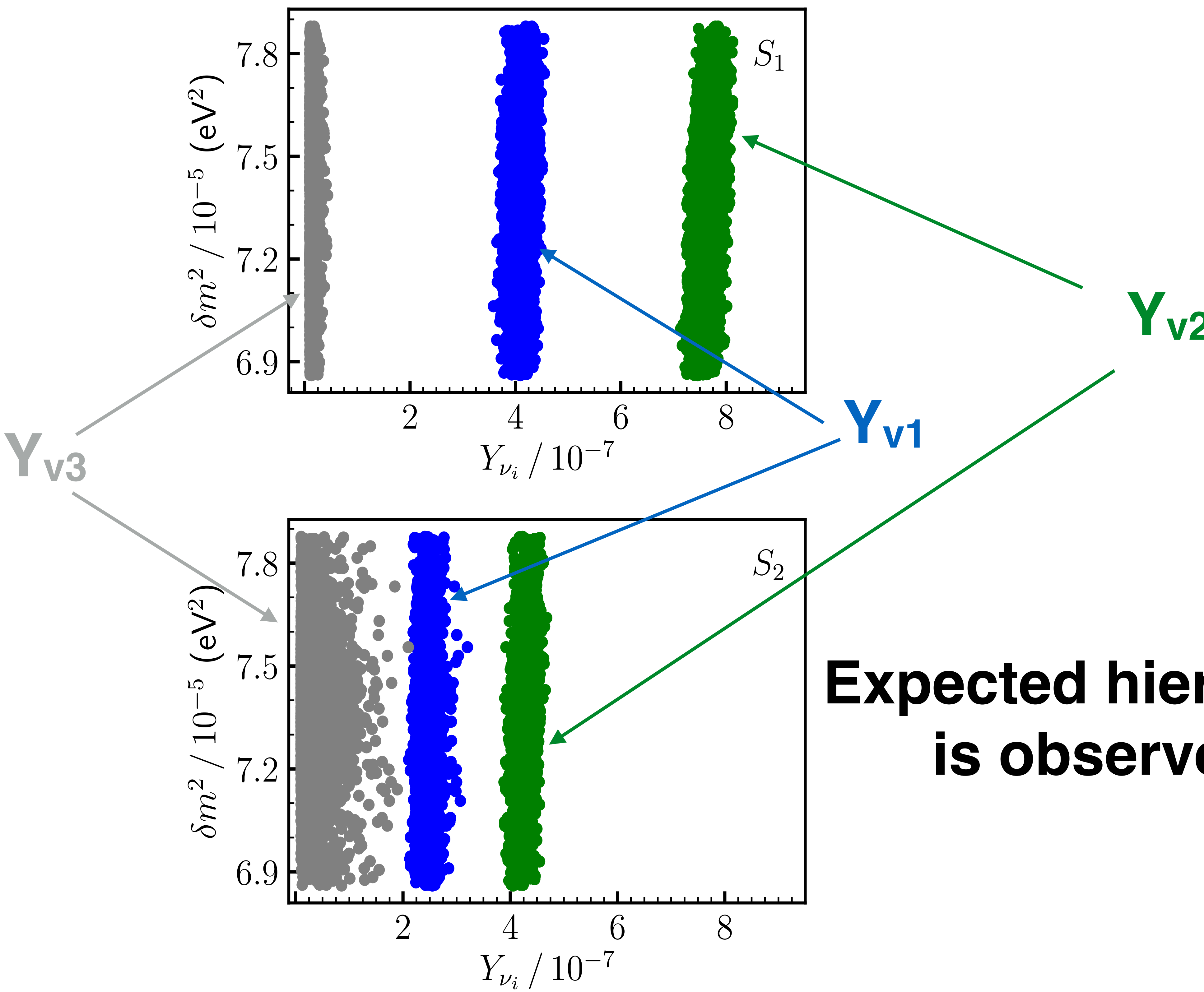
$$m^2_{\tilde{\nu}_i^{\mathcal{I}}\tilde{\nu}_i^{\mathcal{I}}} \approx \frac{Y_\nu v_u}{v_{iL}} v_R \left(-A_\nu - \kappa v_R + \frac{\lambda v_R}{\tan\beta}\right).$$



2nd solution to neutrino seesaw



2nd solution to neutrino seesaw



Expected hierarchy is observed

$$\Gamma\left(\tilde{\nu}_\tau \to \tau\ell\right) \approx \frac{m_{\tilde{\nu}_\tau}}{16\pi}\left(Y_{\nu_{\tau,j}} \frac{Y_\tau v_{Rj}}{\sum_{l=1}^{3} \lambda_l v_{Rl}} \right)^2$$

Seesaw imposes decay to $\mu\tau$ as the main **visible** channel

$$\sum_i \Gamma(\tilde{\nu}_\tau \to \nu_\tau \nu_i) \approx \frac{m_{\tilde{\nu}_\tau}}{16\pi} \sum_i \left| \frac{g'}{2} U^V_{i4} - \frac{g}{2} U^V_{i5} \right|^2,$$

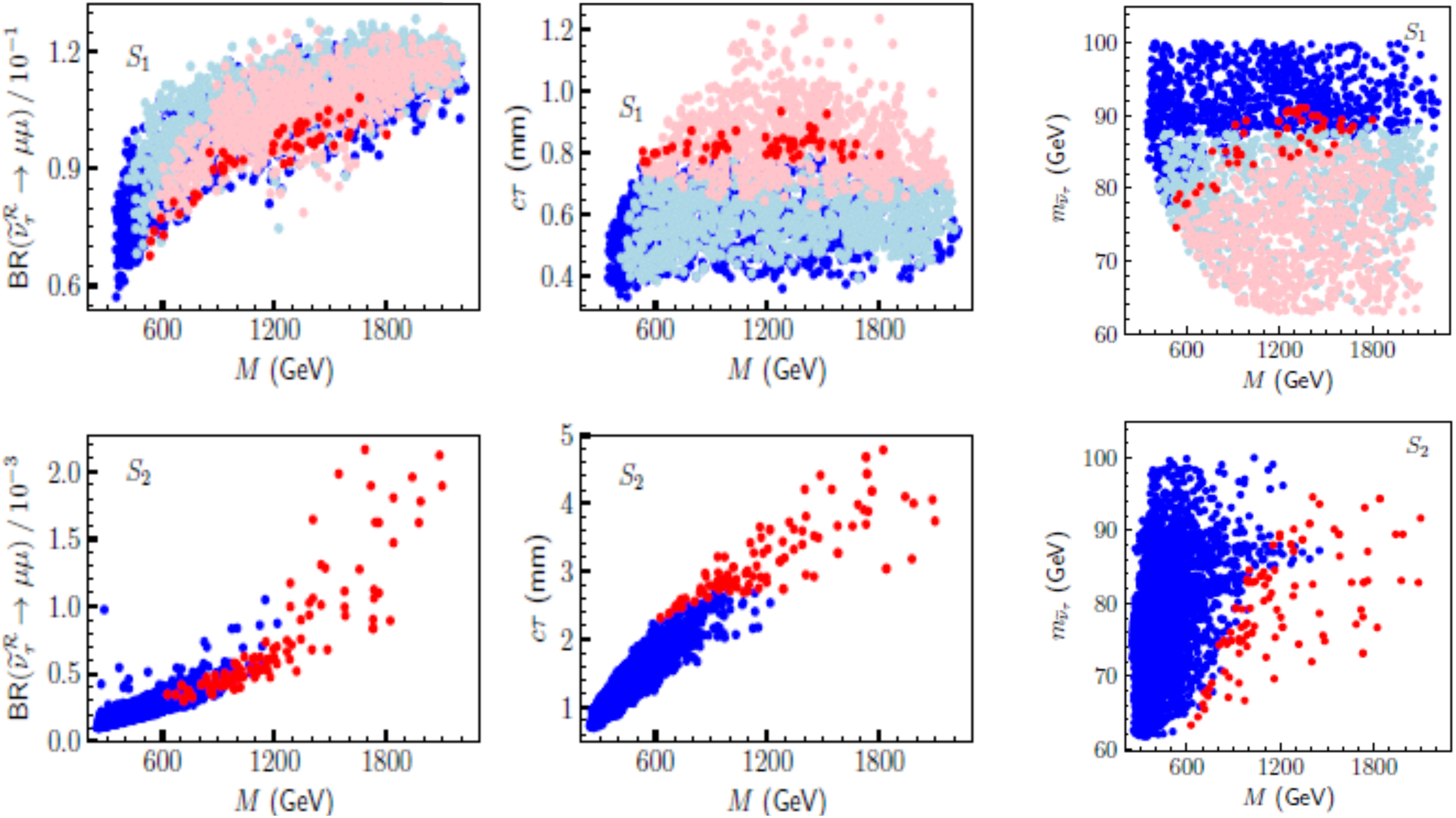
$$U^V_{i4} \approx \frac{-g'}{\sqrt{2} M_1} \sum_l v_l U^{PMNS}_{il},$$

$$U^V_{i5} \approx \frac{g}{\sqrt{2} M_2} \sum_l v_l U^{PMNS}_{il}.$$

Dominant decay is to neutrinos⇒ Consequence of **gaugino-seesaw** dominance

Light red and light

blue points are excluded by LEP

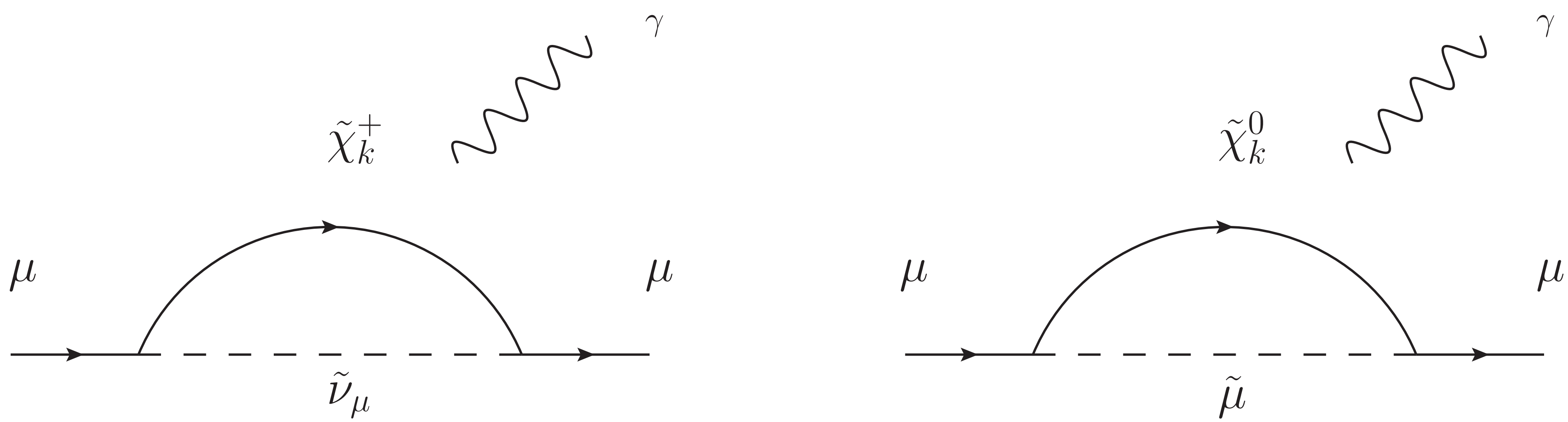


Dark red points can be tested with 13-TeV optimized proposal

Exchange second and third generations on seesaw solution:

Muon sneutrino is the LSP

Light sleptons-sneutrinos have an impact on the anomalous magnetic moment of the leptons.



$$a_\mu^{\tilde{\chi}^0} = \frac{g_1^2 - g_2^2}{192\pi^2}\frac{m_\mu^2}{M_{SUSY}^2}\tan\beta\,\mathrm{sign}(\mu_{eff}M_2)[1+\mathcal{O}(\frac{1}{\tan\beta},\frac{M_W}{M_{SUSY}})]$$

$$a_\mu^{\tilde{\chi}^\pm} = \frac{g_2^2}{32\pi^2}\frac{m_\mu^2}{M_{SUSY}^2}\tan\beta\,\mathrm{sign}(\mu_{eff}M_2)[1+\mathcal{O}(\frac{1}{\tan\beta},\frac{M_W}{M_{SUSY}})]$$

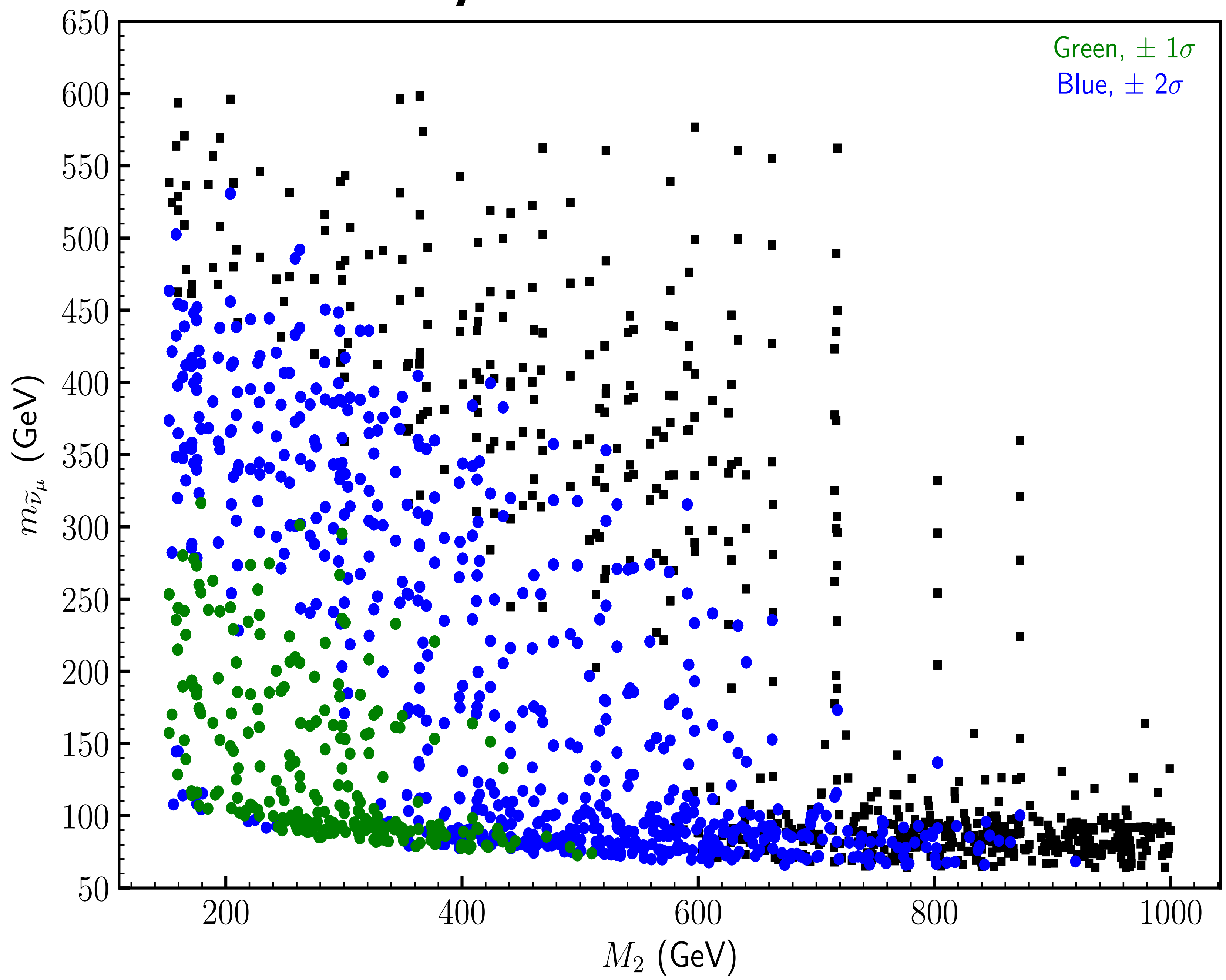
T.Moroi. Phys. Rev. D 53 (1996) 6565, hep-ph/9512396

Electroweak sparticles shouldn't be far above the EW scale

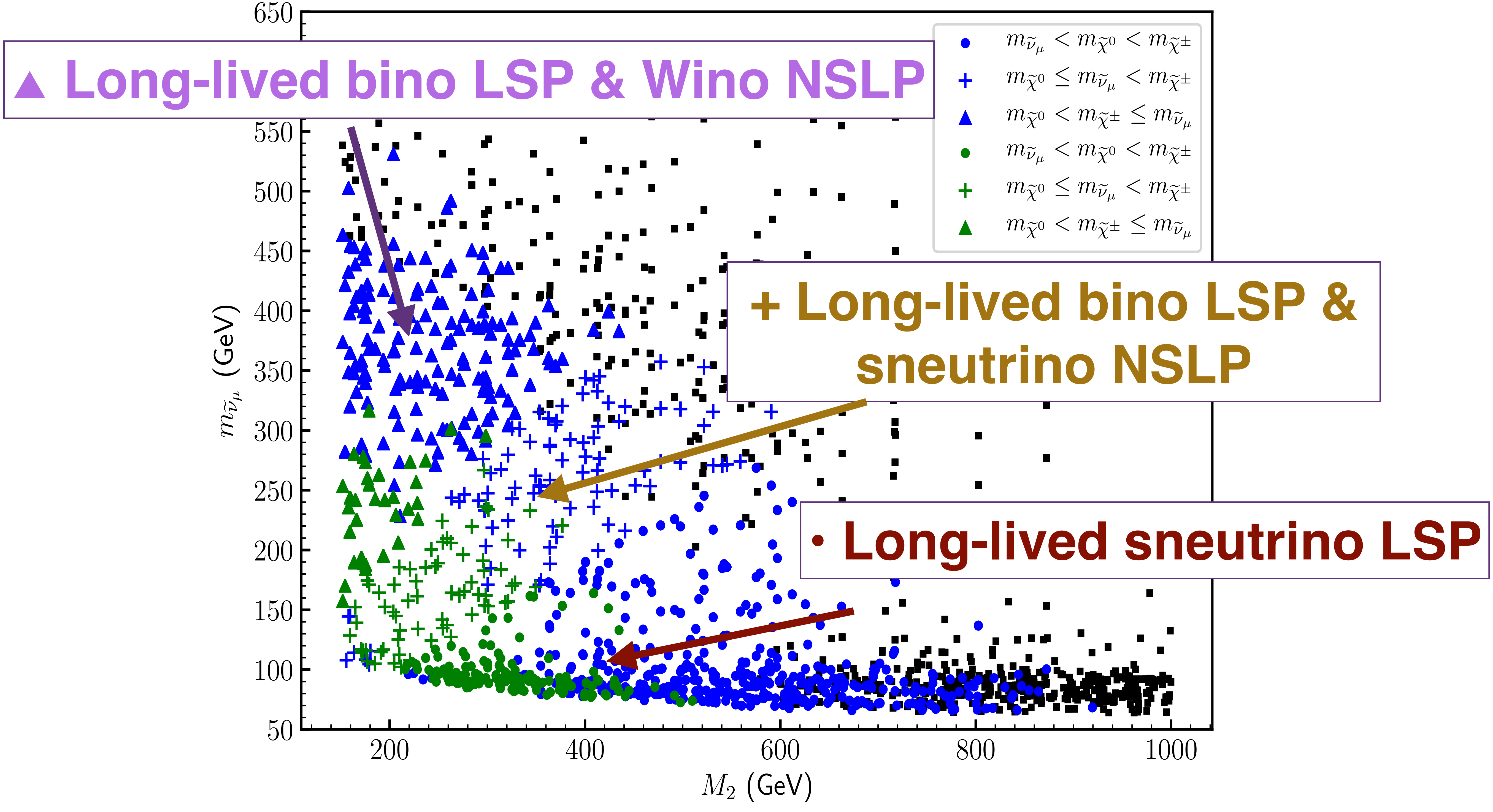
$$a_\mu^{SUSY,1L} \approx 13 \times 10^{-10} \left(\frac{100\ \text{GeV}}{M_{SUSY}}\right)^2 \tan\beta$$

Using data from scan over $\mu\nu$SSM

Agreement between corrected a_μ and experiment

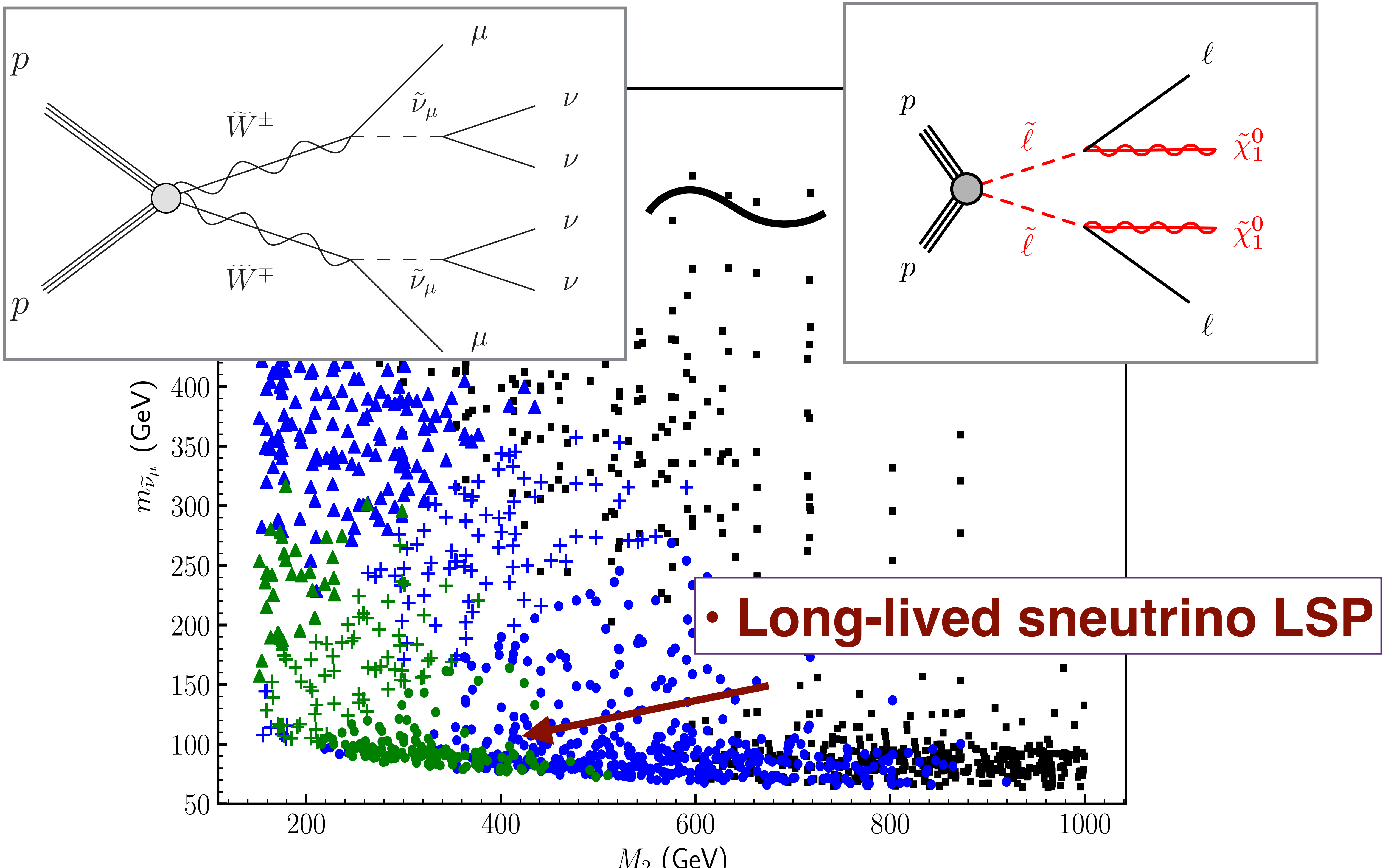


Experimental limits



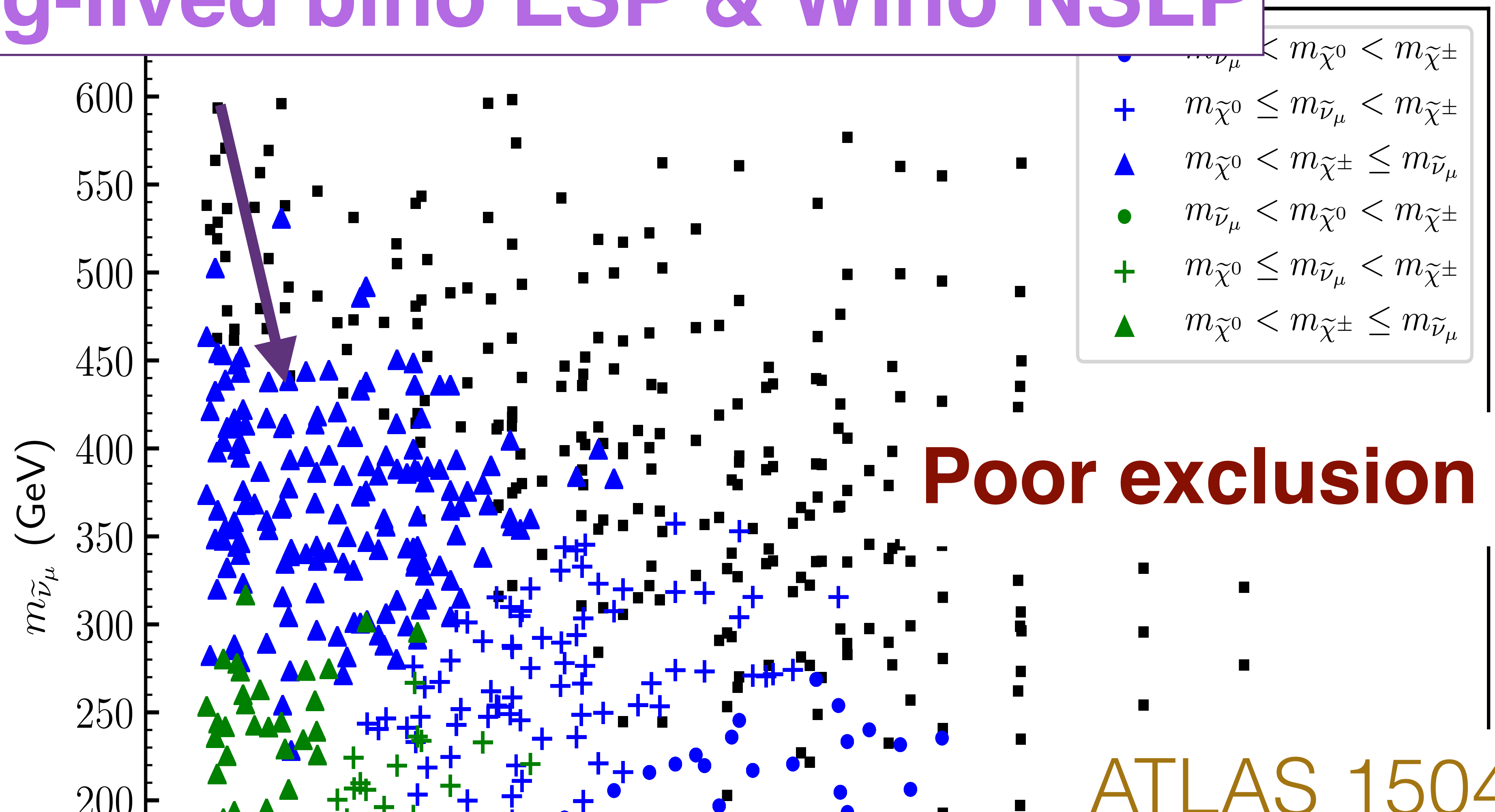
Long-lived sneutrinos decay invisibly

ATLAS 1908.08215



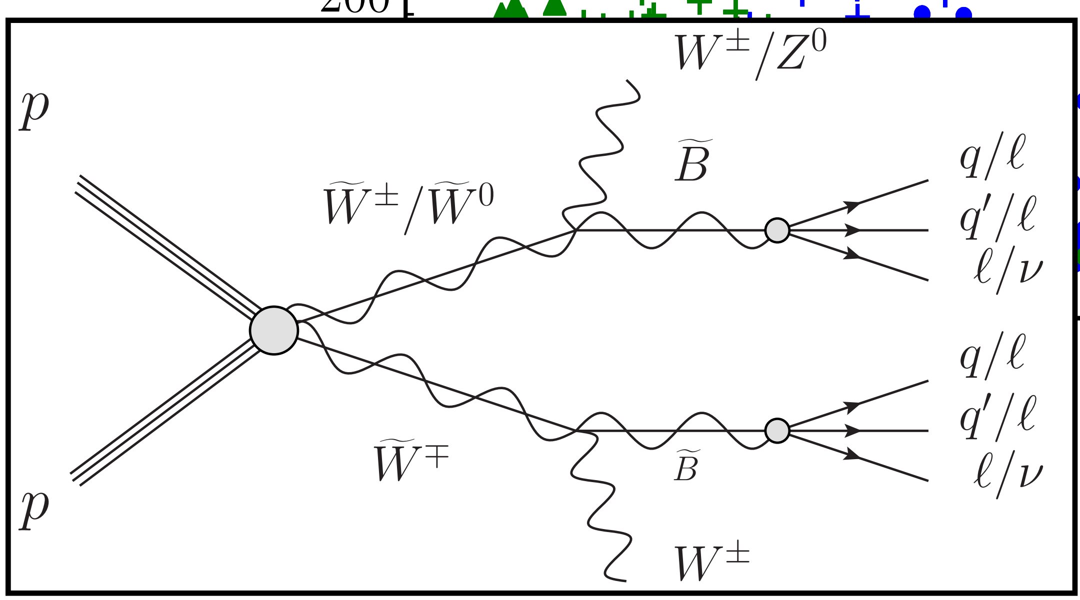
Exclusion is difficult if wino-sneutrino masses are close

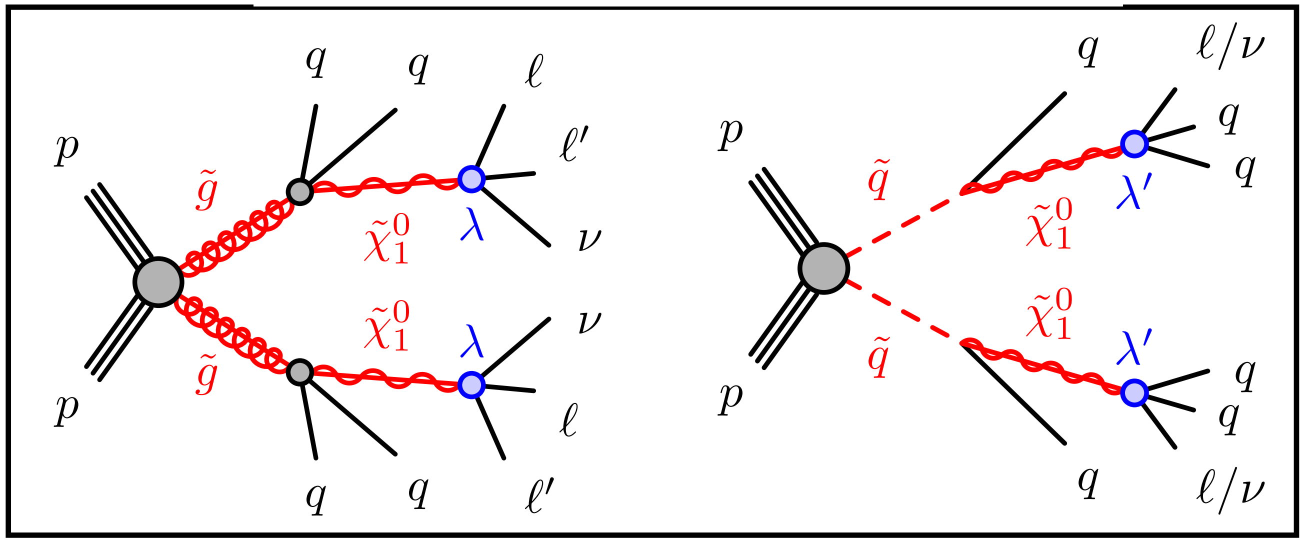
Long-lived bino LSP & Wino NSLP



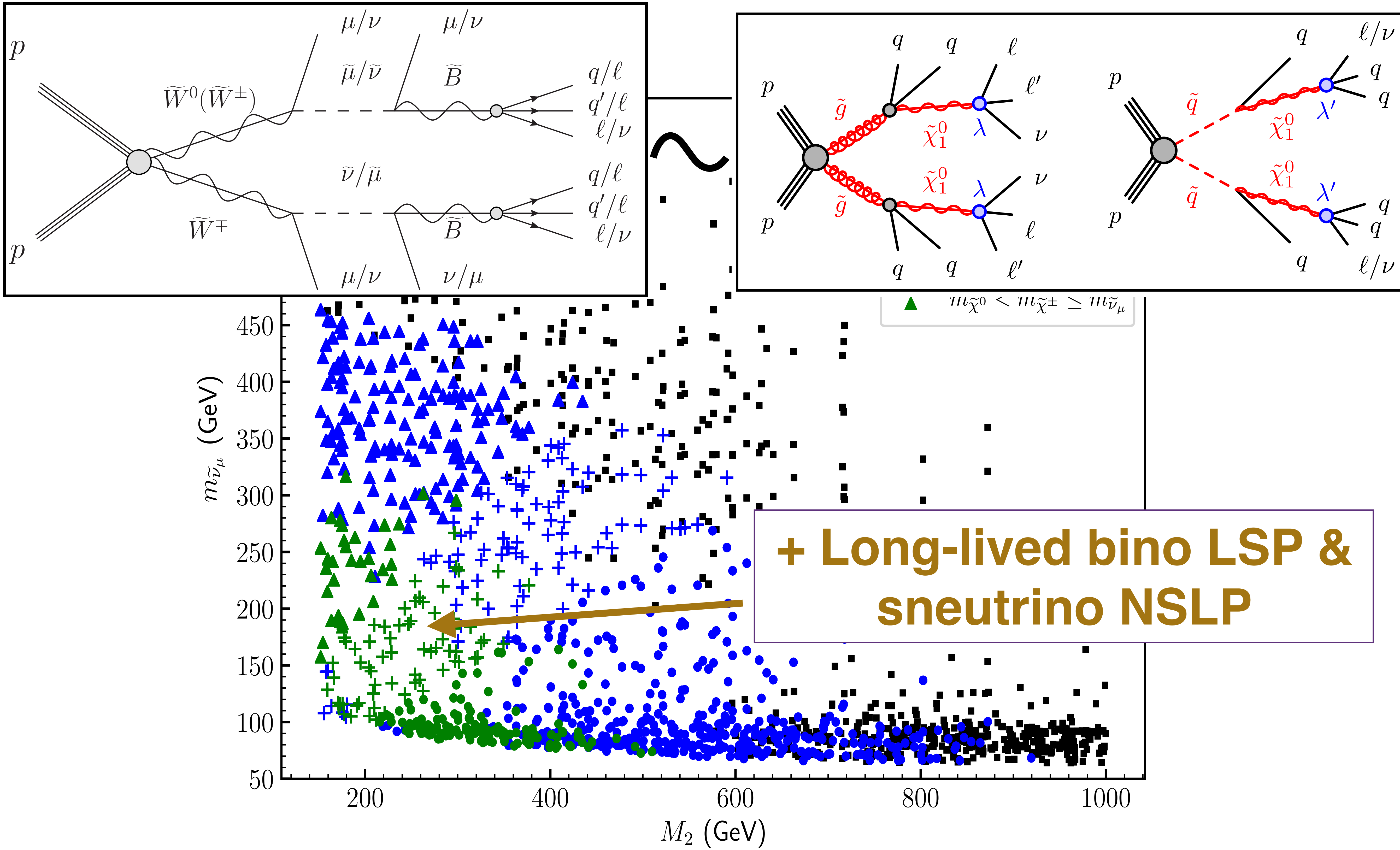
Poor exclusion if c$\tau \lesssim$ 1mm

ATLAS 1504.05162





ATLAS 1504.05162



More muons to trigger, but more compressed spectrum

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 natural solutions of the generalized seesaw (with diagonal yukawa couplings) motivates one of the sneutrinos to be light.
- LHC data @13 TeV could test a tau left sneutrino as the LSP.
- A light muon sneutrino could induce the necessary contribution to a_{μ} to close the gap between the theory and experiment,