Minimal SUSY Inverse Seesaw

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arXiv:0910.2435 [hep-ph]

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Outline

- Motivation
  - Hierarchy problem
  - Dark matter
  - Neutrino data
- SUSY inverse seesaw
- Minimal SUSY inverse seesaw
- LFV phenomenology
- Conclusions

Hierarchy problem

- Higgs mechanism:
  - gauge symmetry breaking
  - mass generation
- Gauge hierarchy problem
- Technical solution: Supersymmetry

Dark matter

- Experimental data
  - WMAP
  - Large scale structure formation

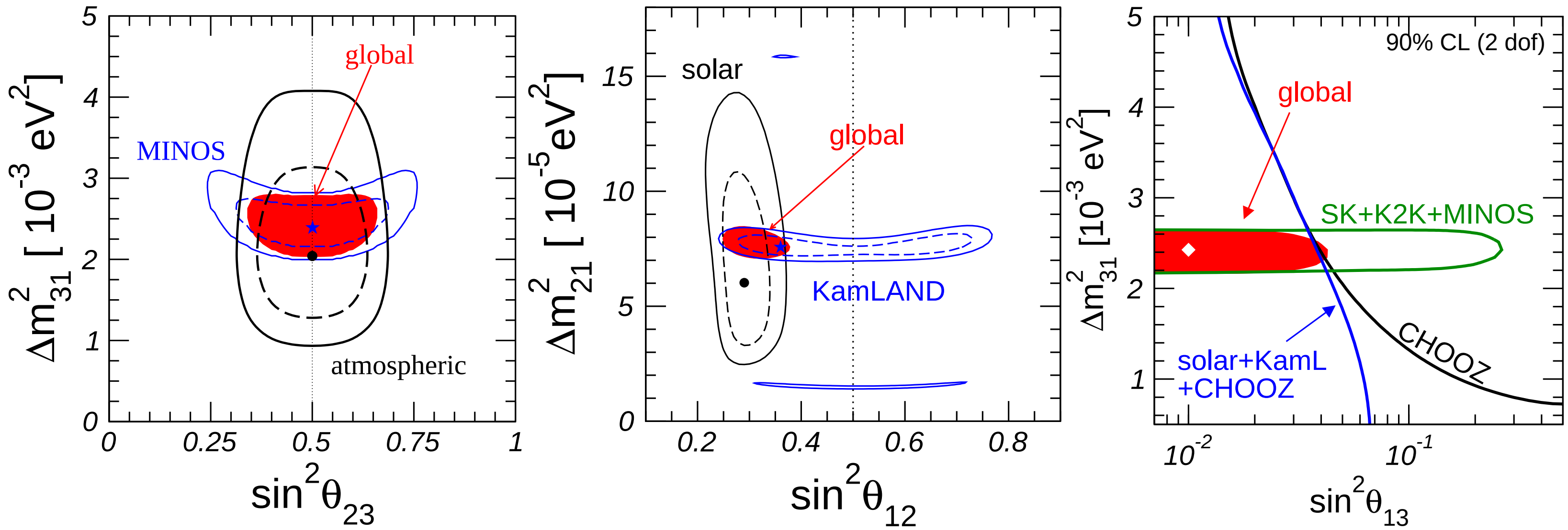
$\Rightarrow$ Evidence of non-baryonic dark matter

- Candidate?

Standard Model neutrinos

- SM neutrinos are massless since:
  - Right-handed neutrinos do not exist
  - Higgs triplets do not exist
  - Fermion triplets do not exist
  - Lepton number is "accidentally" conserved

Neutrino experimental data



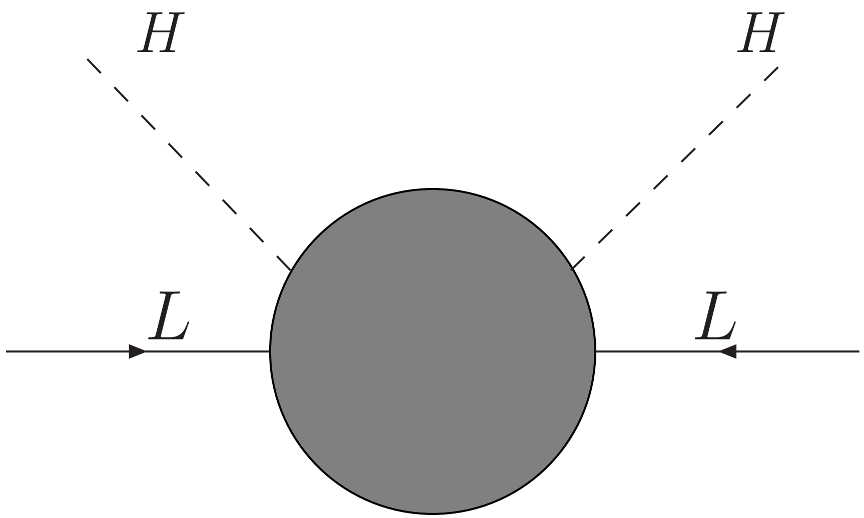
parameter	best fit	3σ
Δm^2_{21} $[10^{-5}\text{eV}^2]$	$7.65^{+0.23}_{-0.20}$	7.05–8.34
$\|\Delta m^2_{31}\|$ $[10^{-3}\text{eV}^2]$	$2.40^{+0.12}_{-0.11}$	2.07–2.75
$\sin^2\theta_{12}$	$0.304^{+0.022}_{-0.016}$	0.25–0.37
$\sin^2\theta_{23}$	$0.50^{+0.07}_{-0.06}$	0.36–0.67
$\sin^2\theta_{13}$	$0.01^{+0.016}_{-0.011}$	≤ 0.056

[T. Schwetz, M. A. Tortola and J. W. F. Valle, New J. Phys. **10**, 113011 (2008) [arXiv:0808.2016 [hep-ph]]]

Neutrino mass models

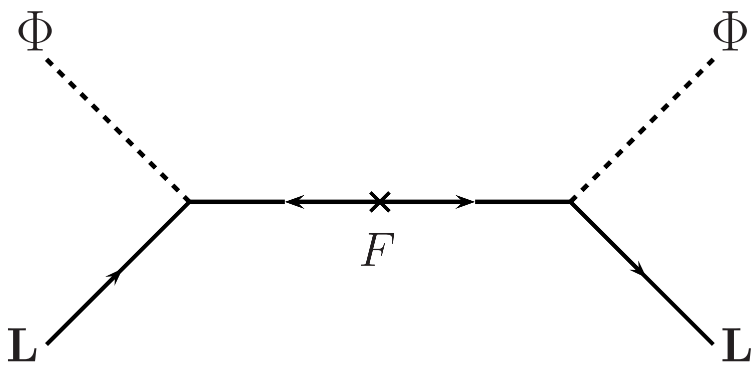
- What is the mechanism of ν mass generation?
- Effective field theory:

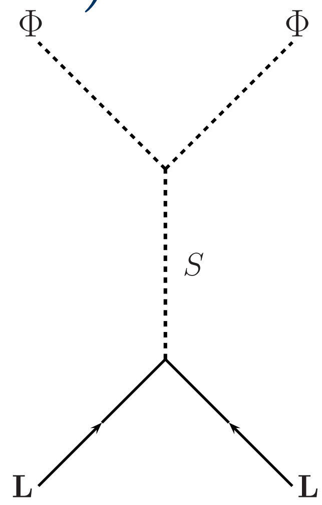
$$\mathcal{L}_{\text{dim}=5} = \frac{f}{\Lambda}(LH)(LH)$$



Standard seesaw mechanisms

- Why ν masses are so tiny?
  Large Λ in $\mathcal{L}_{\text{dim}=5} = \frac{f}{\Lambda}(LH)(LH)$





- ♦ Type-I: Singlet fermion
- ♦ Type-II: Triplet scalar
- ♦ Type-III: Triplet fermion

Non-standard seesaw mechanisms

- Combinations of types-I, II and/or III
- Different gauge groups
- Different multiplet contents
- Gauged or ungauged $B - L$
- Explicitly or spontaneously broken $B - L$
- Breaking at hight or low energy
- With or without SUSY
- ...

Inverse seesaw

- Why ν masses are so tiny?
  Small f instead of large Λ

$$\mathcal{L}_{\mathrm{dim}=5} = \frac{f}{\Lambda}(LH)(LH)$$

  - Loop-induced $\Rightarrow$ Radiative schemes
  - Symmetry limit $\Rightarrow$ Inverse seesaw

SUSY inverse seesaw

- This model addresses:
  - Hierarchy problem
  - Dark matter
  - Neutrino data

$\Rightarrow$ Relations between:
  - LFV neutrino sector
  - Collider LFV
  - Low-energy LFV

Type-I vs. inverse seesaw

- SUSY type-I seesaw:

$$\begin{array}{ccc} \text{MSSM} & + & 3\,\hat{\nu}_i^c \\ L = & & -1 \end{array}$$

- SUSY inverse seesaw:

$$\begin{array}{ccccc} \text{MSSM} & + & 3\,\hat{\nu}_i^c & + & 3\,\hat{S}_i \\ L = & & -1 & & +1 \end{array}$$

Type-I vs. inverse seesaw

- SUSY type-I seesaw:

$$W = W_{\text{MSSM}} + Y_\nu^{ji} \hat{L}_i \hat{\nu}_j^c \hat{H}_u + \frac{1}{2} M_R^{ij} \hat{\nu}_i^c \hat{\nu}_j^c$$

$$M_R : \quad \Delta L = 2$$

- SUSY inverse seesaw:

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$$M_R : \quad \Delta L = 0 \qquad \mu_S : \quad \Delta L = 2$$

Type-I vs. inverse seesaw

- SUSY type-I seesaw:

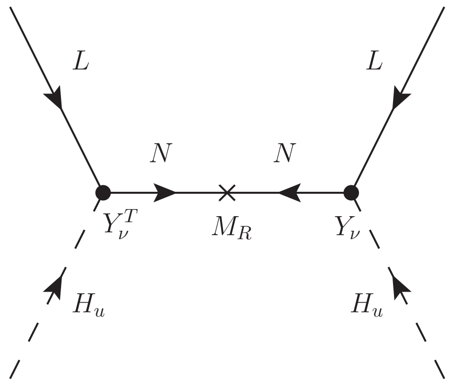
$$M = \begin{array}{cc} \begin{pmatrix} 0 & m_D^T \\ m_D & M_R \end{pmatrix} & \begin{array}{c} \nu \\ \nu^c \end{array} \end{array}$$

- SUSY inverse seesaw:

$$M = \begin{array}{cc} \begin{pmatrix} 0 & m_D^T & 0 \\ m_D & 0 & M_R^T \\ 0 & M_R & \mu_S \end{pmatrix} & \begin{array}{c} \nu \\ \nu^c \\ S \end{array} \end{array}$$

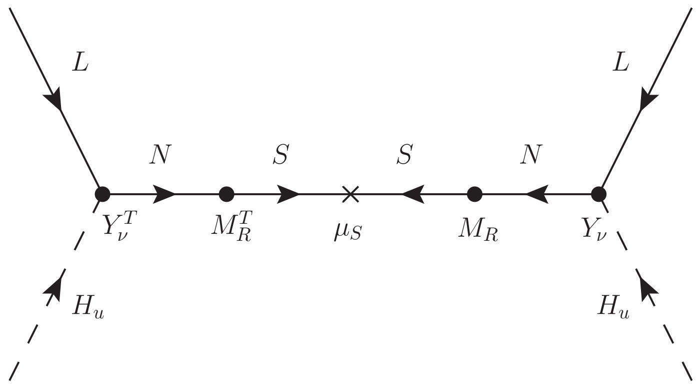
Type-I vs. inverse seesaw

- SUSY type-I seesaw:



$$m_\nu \simeq m_D^T \cdot M_R^{-1} \cdot m_D$$

- SUSY inverse seesaw:



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Type-I vs. inverse seesaw

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- SUSY inverse seesaw:

$$m_\nu \simeq m_D^T \cdot M_R^{T-1} \cdot \mu_S \cdot M_R^{-1} \cdot m_D$$

  - $\propto M_R^{-2}$ instead of $\propto M_R^{-1}$
  - $m_\nu \longrightarrow 0$ if $\mu_S \longrightarrow 0$
  - Singlet sneutrino $\Rightarrow$ DM candidate

    [C. Arina, F. Bazzocchi, N. Fornengo, J. C. Romao and J. W. F. Valle, Phys. Rev. Lett. **101**, 161802 (2008) [arXiv:0806.3225 [hep-ph]]]

Naturalness

$$W = W_{\mathrm{MSSM}} + Y_\nu^{ji} \hat{L}_i \hat{\nu}_j^c \hat{H}_u + M_R^{ij} \hat{S}_i \hat{\nu}_j^c + \frac{1}{2} \mu_S^{ij} \hat{S}_i \hat{S}_j$$

- Note that if $\mu_S \to 0 \Rightarrow L$ is conserved

Naturalness

NATURALNESS, CHIRAL SYMMETRY, AND SPONTANEOUS CHIRAL SYMMETRY BREAKING

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Institute for Theoretical Physics
Utrecht, The Netherlands

ABSTRACT

A properly called "naturalness" is imposed on gauge theories. It is an order-of-magnitude restriction that must hold at all energy scales μ. To construct models with complete naturalness for elementary particles one needs more types of confining gauge theories besides quantum chromodynamics. We propose a search program for models with improved naturalness and concentrate on the possibility that presently elementary fermions can be considered as composite. Chiral symmetry must then be responsible for the masslessness of these fermions. Thus we search for QCD-like models where chiral symmetry is not or only partly broken spontaneously. They are restricted by index relations that often cannot be satisfied by other than unphysical fractional indices. This difficulty made the author's own search unsuccessful so far. As a by-product we find yet another reason why in ordinary QCD chiral symmetry must be broken spontaneously.

III.1. INTRODUCTION

The concept of causality requires that macroscopic phenomena follow from microscopic equations. Thus the properties of liquids and solids follow from the microscopic properties of molecules and atoms. One may either consider these microscopic properties to have been chosen at random by Nature, or attempt to deduce these from even more fundamental equations at still smaller length and time scales. In either case, it is unlikely that the microscopic equations contain various free parameters that are carefully adjusted by Nature to give cancelling effects such that the macroscopic systems have some special properties. This is a

Naturalness

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– at any energy scale μ, a physical parameter or set of physical parameters $\alpha_i(\mu)$ is allowed to be very small only if the replacement $\alpha_i(\mu) = 0$ would increase the symmetry of the system. –

It is an order-of-magnitude restriction that must hold at all energy scales μ. To construct models with complete naturalness for elementary particles one needs more types of confining gauge theories besides quantum chromodynamics. We propose a search program for models with improved naturalness and concentrate on the possibility that presently elementary fermions can be considered as composite. Chiral symmetry must then be responsible for the masslessness of these fermions. Thus we search for QCD-like models where chiral symmetry is not or only partly broken spontaneously. They are restricted by index relations that often cannot be satisfied by other than unphysical fractional indices. This difficulty made the author's own search unsuccessful so far. As a by-product we find yet another reason why in ordinary QCD chiral symmetry must be broken spontaneously.

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$$Y_\nu^{ji} \to Y_\nu^i \qquad M_R^{ij} \to M_R \qquad \mu_S^{ij} \to \mu_S$$

Minimal SUSY inverse seesaw

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$$\begin{aligned} -\mathcal{L}_{\text{soft}} &= -\mathcal{L}_{\text{soft}}^{\text{MSSM}} + m_{\nu^c}^2 \widetilde{\nu}^{c\dagger} \widetilde{\nu}^c + m_S^2 \widetilde{S}^\dagger \widetilde{S} \\ &+ \left(\varepsilon_{ab} A_{h_\nu}^i \widetilde{L}_i^a \widetilde{\nu}^c H_u^b + B_{M_R} \widetilde{\nu}^c \widetilde{S} + \frac{1}{2} B_{\mu_S} \widetilde{S} \widetilde{S} + \text{h.c.} \right) \end{aligned}$$

Neutrino physics

- Neutrino masses
  - At tree level: μ_S

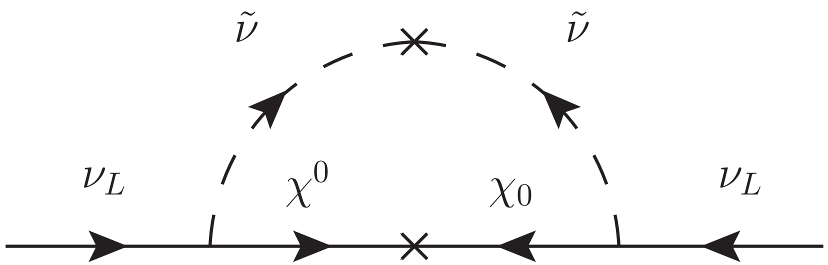
$$(M_\nu^{\rm tree})_{ij} = \frac{\mu_S}{M_R^2} m_{D_i} m_{D_j}$$

- Only 1 non-zero mass eigenvalue: $\mathrm{diag}(0,\,0,\,m_\nu^{\rm tree})$

$$m_\nu^{\rm tree} = \frac{\mu_S}{M_R^2} \sum_i m_{D_i}^2$$

Neutrino physics

- Neutrino masses
  - At tree level: μ_S
  - 1-loop: B_{μ_S}



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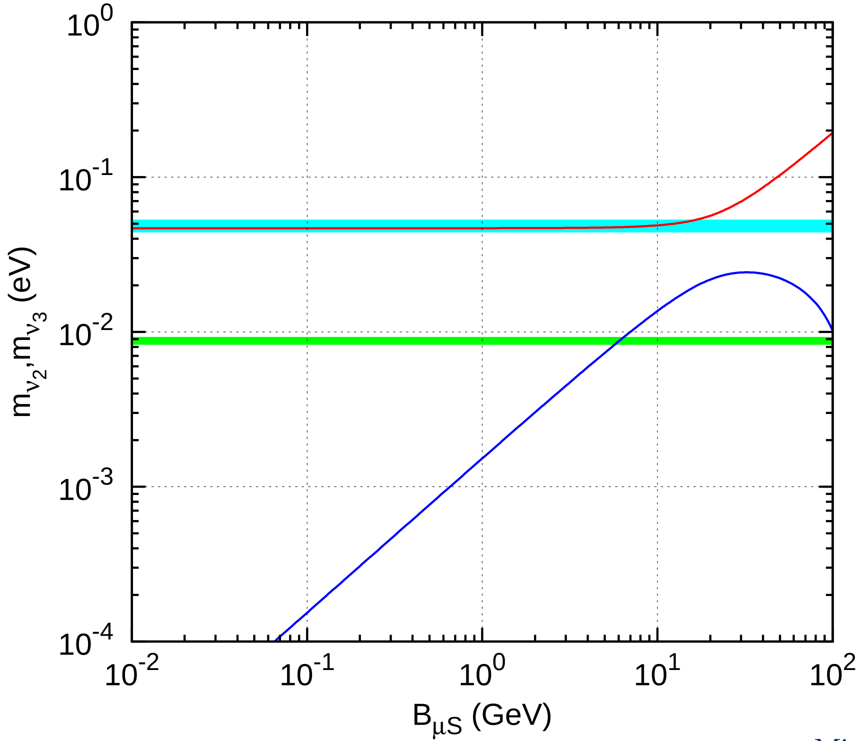

Neutrino physics

- Neutrino masses
  - At tree level: μ_S
  - 1-loop: B_{μ_S}
- Neutrino mixing angles
  - At tree level: m_{D_i}

$$\tan^2\theta_{23} = \frac{m_{D_2}^2}{m_{D_3}^2} \qquad \tan^2\theta_{13} = \frac{m_{D_1}^2}{m_{D_2}^2 + m_{D_3}^2}$$

Neutrino physics

- Neutrino masses
  - At tree level: μ_S
  - 1-loop: B_{μ_S}
- Neutrino mixing angles
  - At tree level: m_{D_i}
  - 1-loop: $\delta_i \equiv A^i_{h_\nu} v_u - \mu\, m_{D_i} \cot\beta$

$$\left(M_\nu^{1-\text{loop}}\right)_{ij} = a\, \varepsilon_i \varepsilon_j + b\, (\varepsilon_i \delta_j + \delta_i \varepsilon_j) + c\, \delta_i \delta_j$$

$$\varepsilon_i \equiv m_{D_i} M_R \qquad \delta_i \equiv A^i_{h_\nu} v_u - \mu\, m_{D_i} \cot\beta$$

Neutrino physics

- Neutrino masses
  - At tree level: μ_S
  - 1-loop: B_{μ_S}
- Neutrino mixing angles
  - At tree level: m_{D_i}
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LFV chargino decays

- LSP: singlet sneutrino $\Rightarrow$ DM

  $\Rightarrow$ End of SUSY decay chains

LFV chargino decays

- As $m_{\widetilde{N}_1} \approx m_{\widetilde{N}_2}$ and $m_{\widetilde{N}_3} \approx m_{\widetilde{N}_4}$,

$$\Gamma(\widetilde{\chi}_1^{\pm} \to \widetilde{N}_{1+2} + \ell_i^{\pm}) \equiv \Gamma(\widetilde{\chi}_1^{\pm} \to \widetilde{N}_1 + \ell_i^{\pm}) + \Gamma(\widetilde{\chi}_1^{\pm} \to \widetilde{N}_2 + \ell_i^{\pm})$$

$$\Gamma(\widetilde{\chi}_1^{\pm} \to \widetilde{N}_{3+4} + \ell_i^{\pm}) \equiv \Gamma(\widetilde{\chi}_1^{\pm} \to \widetilde{N}_3 + \ell_i^{\pm}) + \Gamma(\widetilde{\chi}_1^{\pm} \to \widetilde{N}_4 + \ell_i^{\pm})$$

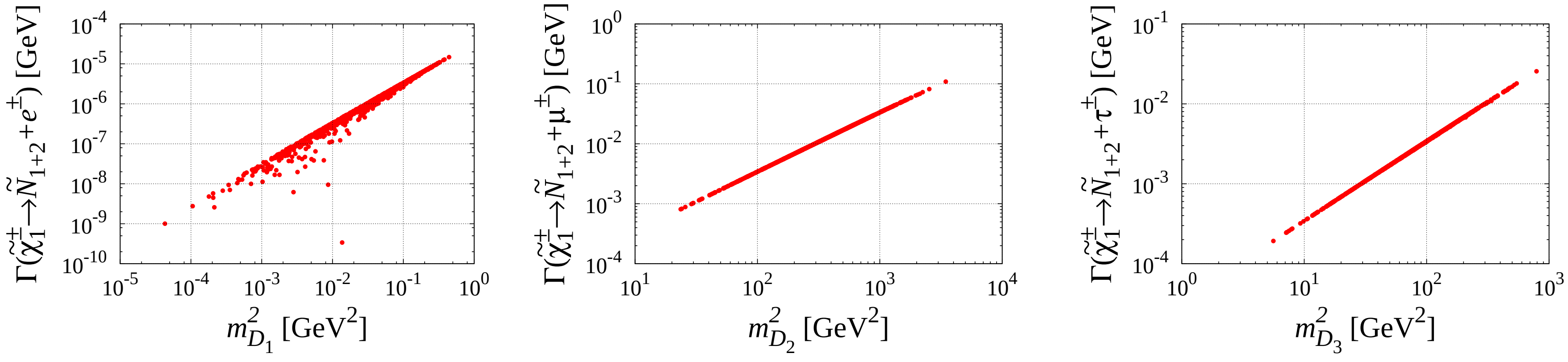
LFV chargino decays

- Numerical study
  - Random parameters:

$$\left(\sum_i m^2_{D_i}\right)^{1/2} \in 10^{[-4,2.6]}, \quad \left(\sum_i \delta_i^2\right)^{1/4} \in 10^{[-4,3]}$$

  - Calculated parameters:
    - $\mu_S \Rightarrow$ ATM scale at tree-level
    - $B_{\mu_S} \Rightarrow$ SOL scale at 1-loop
  - EXP constraints:
    - ν physics (3σ)
    - Low-energy LFV

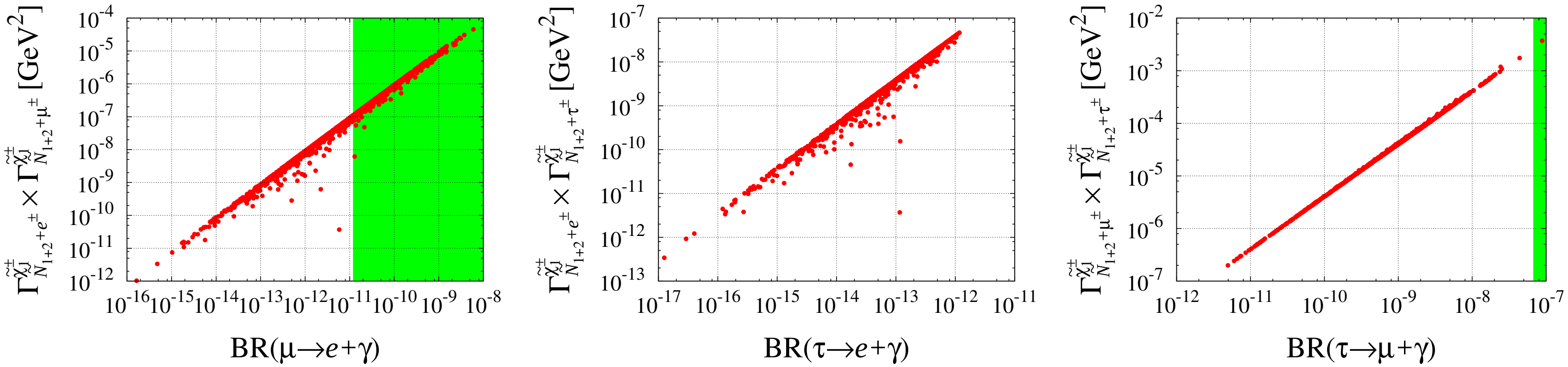
LFV chargino decays



- As $m_{D_1} \ll m_{D_2}, m_{D_3} \quad \Rightarrow \quad$ worse correlation
- Also for $\Gamma(\tilde{\chi}_1^\pm \to \tilde{N}_{3+4} + \ell_i^\pm)$

Low energy LFV

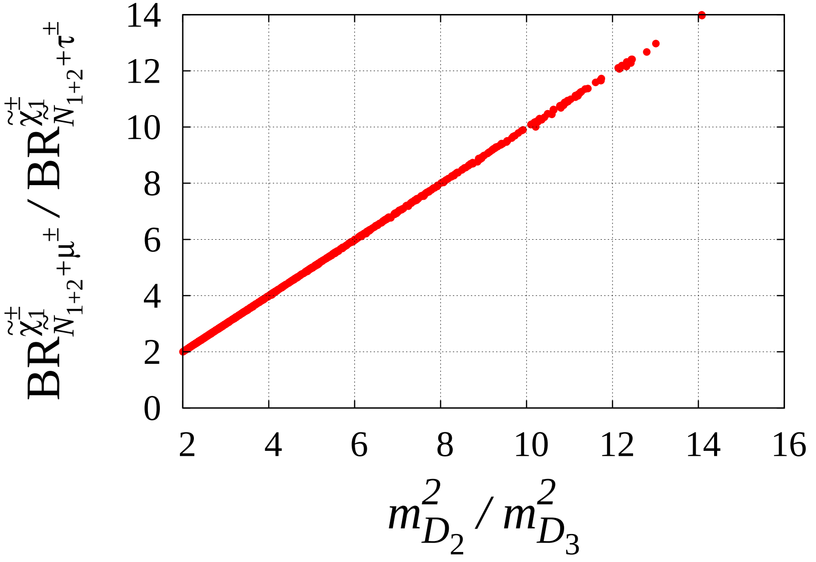
- $\Gamma(\widetilde{\chi}_1^{\pm} \longrightarrow \widetilde{N}_{1+2} + \ell_j{}^{\pm}) \times \Gamma(\widetilde{\chi}_1^{\pm} \longrightarrow \widetilde{N}_{1+2} + \ell_i{}^{\pm})$ is correlated with $\mathrm{BR}(\ell_j \longrightarrow \ell_i \gamma)$

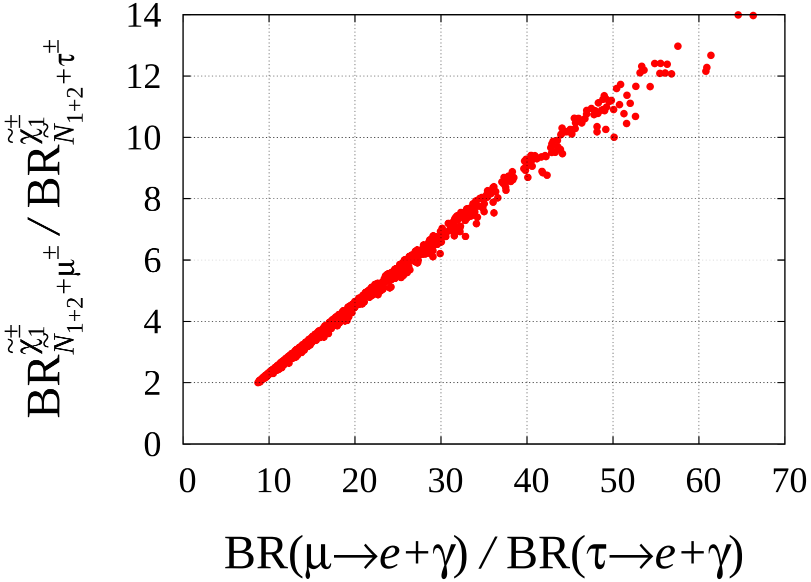


- Worse correlation for e
- Also for $\tilde{N}_{3+4}$

Low energy LFV

- However, at LHC: not Γ but BR





- Also for $\tilde{N}_{3+4}$

Relations with neutrino sector

- As

$$\frac{\Gamma(\widetilde{\chi}_1^{\pm} \to \widetilde{N}_{1+2} + \mu^{\pm})}{\Gamma(\widetilde{\chi}_1^{\pm} \to \widetilde{N}_{1+2} + \tau^{\pm})} \propto \frac{m_{D_2}^2}{m_{D_3}^2}$$

$$\frac{\mathrm{BR}(\mu \to e\gamma)}{\mathrm{BR}(\tau \to e\gamma)} \propto \frac{m_{D_2}^2}{m_{D_3}^2}$$

- And

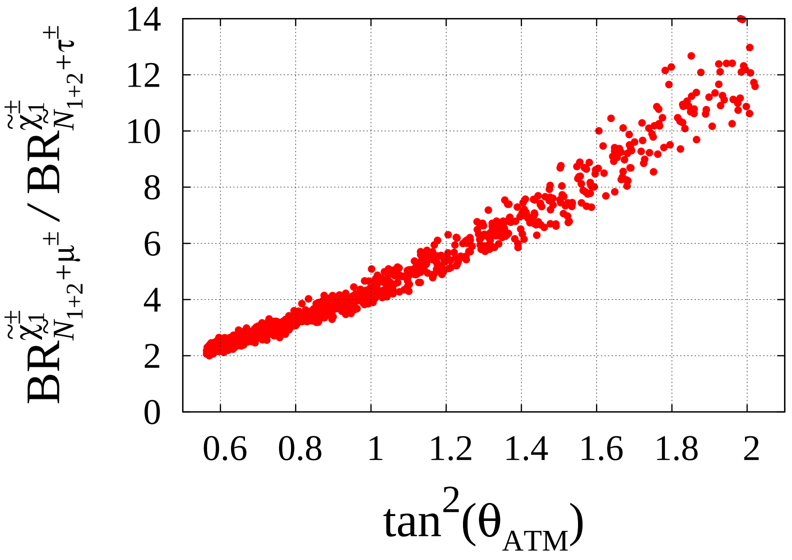
$$\tan^2 \theta_{\mathrm{ATM}} = \frac{m_{D_2}^2}{m_{D_3}^2}$$

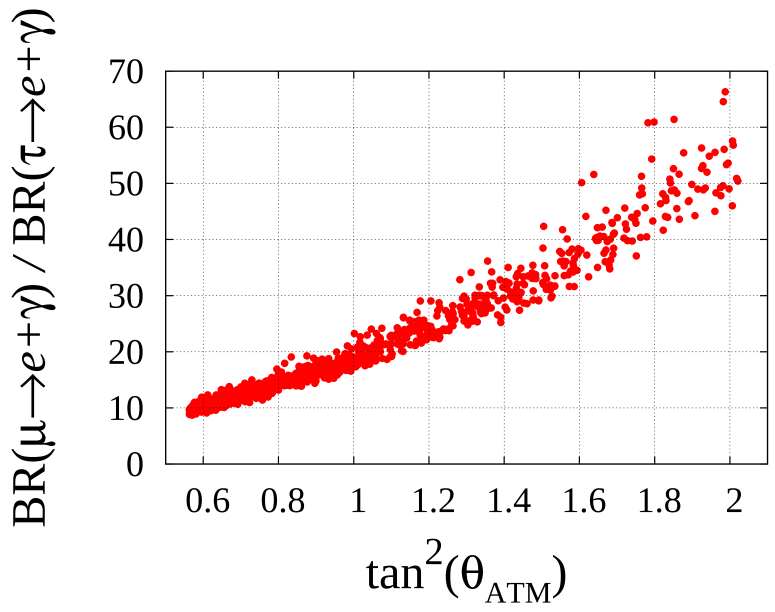
Relations with neutrino sector

- Neutrino sector $\Leftrightarrow$ Collider LFV observables
- Neutrino sector $\Leftrightarrow$ Low-energy LFV observ.

Relations with neutrino sector

- Neutrino sector ⇔ Collider LFV observables
- Neutrino sector ⇔ Low-energy LFV observ.





- Also for $\tilde{N}_{3+4}$

Conclusions

- Motivation
  - Hierarchy problem
  - Dark matter
  - Neutrino data
- Minimal SUSY inverse seesaw
  - Explains neutrino data
  - DM candidate: singlet sneutrino
  - Relates neutrino sector with:
    - Collider LFV: $\mathrm{BR}(\widetilde{\chi}_1^{\pm} \to \widetilde{N}_a + \ell_i^{\pm})$
    - Low-energy LFV: $\mathrm{BR}(\ell_j \to \ell_i \gamma)$