

Higher-order calculations in the $\mu\nu$ SSM

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in collaboration with Sven Heinemeyer and Carlos Muñoz
[hep-ph/1712.07475]

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Instituto de
Física
Teórica
UAM-CSIC



Why higher-order corrections?

- Accurate predictions ($\Delta^{\text{theo.}} < \Delta^{\text{exp.}}$) for precisely measured observables need to take into account **quantum corrections**
- Every model has to incorporate a **SM-like Higgs boson** with the properties measured at LHC

$$M_H^{\text{exp.}} = 125.09 \pm 0.21 \text{ (stat.)} \pm 0.11 \text{ (syst.)} \text{ GeV}$$

Atlas and CMS [hep-ex/1503.07589]

Already a precision observable at the per-mille level!

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- While in the SM M_H is a free parameter, SUSY models predict the Higgs boson mass dependent on the parameters of the model
- Higher-order corrections to scalar masses give substantial contributions, in some cases of the order of the tree-level mass
 \Rightarrow Large theoretical uncertainties: ~ 3 GeV (MSSM)

Degrassi, Heinemeyer, Hollik, Slavich, Weiglein [hep-ph/0212020]

Maybe now ~ 2 GeV?

Allanach, Voigt [hep-ph/1804.09410]
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Any model beyond the MSSM potentially has even larger uncertainty

\Rightarrow We present full one-loop + partial MSSM-like two-loop corrections to scalar masses in the $\mu\nu$ SSM.

Why go beyond MSSM?

- No new physics at LHC (so far)
- Big loop-corrections to Higgs mass needed (fine-tuning)
- μ -problem (MSSM superpotential has a scale)
- ν -problem: Neutrino masses
Why are they so light?

Three Generations of Matter (Fermions) spin $\frac{1}{2}$			Bosons (Force) spin 1		
I	II	III	B	G	H
mass - charge - name -	2.8 MeV 2/3 u up	1.27 GeV 2/3 c charm	171.2 GeV 2/3 t top	0 0 g gluon	1424 GeV 0 0 H Higgs
Quarks	d -1/3 down	s -1/3 strange	b -1/3 bottom	γ photon	Z Z boson
Leptons	e -1 electron	ν_e 0 electron neutrino	μ -1 muon	ν_μ 0 muon neutrino	τ -1 tau lepton
	0.511 MeV	105.7 MeV	1777 GeV	80.4 GeV	80.4 GeV

from 2013 J. Phys.: Conf. Ser. 408 012015

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name	u up	c charm	t top
mass - charge	2.1 MeV	1.27 GeV	171.2 GeV
name	d down	s strange	b bottom
mass - charge	-4.8 MeV	-1.9 MeV	-4.7 GeV
Leptons	e electron	ν_e electron neutrino	ν_τ tau neutrino
mass - charge	0.511 MeV	105.7 MeV	1777 GeV
name	μ muon	ν_μ muon neutrino	τ tau
mass - charge	0.105 GeV	0.0	0.0
Bosons (Force)	W weak force	Z weak force	H Higgs boson
mass - charge	80.4 GeV	0.0	122.0 GeV
spin	1	0	0

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$\mu\nu$ SSM: Simplest extension of the MSSM solving the μ - and the ν -problem at the same time.

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I	II	III	g	γ	H
mass - charge name	2.8 meV u up	1.27 meV c charm	171.2 GeV t top	0 g gluon	1424 GeV H Higgs
Quarks	d down -1/3	s strange -1/3	b bottom -1/3	γ photon 0	Z Z boson 0
Leptons	e^- electron -1	ν_e electron neutrino 0	μ^- muon -1	ν_μ muon neutrino 0	τ^- tau -1
	0.531 MeV	103.9 MeV	1777 GeV	80.4 GeV	126.5 GeV

from 2013 J. Phys.: Conf. Ser. 408 012015

$\mu\nu$ SSM: Simplest extension of the MSSM solving the μ - and the ν -problem at the same time.

Particle content: MSSM + 3 (1) gauge singlets $\hat{\nu}_j^c$

Couplings: $Y_{ij}^\nu \hat{H}_u \hat{L}_i \hat{\nu}_j^c \Rightarrow$ gauge singlet = right-handed neutrino

\rightarrow EWSB \Rightarrow Dirac masses for neutrinos ($Y_{ii}^\nu \approx Y_{11}^e$)

$\lambda_i \hat{\nu}_i^c \hat{H}_d \hat{H}_d$, $\frac{1}{3} \kappa_{ijk} \hat{\nu}_i^c \hat{\nu}_j^c \hat{\nu}_k^c$ (NMSSM-like)

\rightarrow EWSB \Rightarrow Effective μ -term generated at EW scale

\rightarrow EWSB \Rightarrow Majorana masses for R-handed neutrinos

Lagrangian and Symmetries

$$W = \epsilon_{ab} \left(Y_{ij}^e \hat{H}_d^a \hat{L}_i^b \hat{e}_j^c + Y_{ij}^d \hat{H}_d^a \hat{Q}_i^b \hat{d}_j^c + Y_{ij}^u \hat{H}_u^b \hat{Q}_i^a \hat{u}_j^c \right) \\ + \epsilon_{ab} \left(Y_{ij}^\nu \hat{H}_u^b \hat{L}_i^a \hat{\nu}_j^c - \lambda_i \hat{\nu}_i^c \hat{H}_u^b \hat{H}_d^a \right) + \frac{1}{3} \kappa_{ijk} \hat{\nu}_i^c \hat{\nu}_j^c \hat{\nu}_k^c$$

- Z_3 symmetry forbids μ -term and Majorana masses \rightarrow no scale in superpotential
- R -parity explicitly broken (via \not{L}) \rightarrow more complicated particle mixing
- Additional sources of LFV after EWSB
- Baryon Triality B_3 to forbid baryon number violation \rightarrow no proton decay

Lagrangian and Symmetries

$$W = \epsilon_{ab} \left(Y_{ij}^e \hat{H}_d^a \hat{L}_i^b \hat{e}_j^c + Y_{ij}^d \hat{H}_d^a \hat{Q}_i^b \hat{d}_j^c + Y_{ij}^u \hat{H}_u^b \hat{Q}_i^a \hat{u}_j^c \right) \\ + \epsilon_{ab} \left(Y_{ij}^\nu \hat{H}_u^b \hat{L}_i^a \hat{\nu}_j^c - \lambda_i \hat{\nu}_i^c \hat{H}_u^b \hat{H}_d^a \right) + \frac{1}{3} \kappa_{ijk} \hat{\nu}_i^c \hat{\nu}_j^c \hat{\nu}_k^c$$

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$$-\mathcal{L}_{\text{soft}} = \epsilon_{ab} \left(T_{ij}^e H_d^a \tilde{L}_{iL}^b \tilde{e}_{jR}^* + T_{ij}^d H_d^a \tilde{Q}_{iL}^b \tilde{d}_{jR}^* + T_{ij}^u H_u^b \tilde{Q}_{iL}^a \tilde{u}_{jR}^* + \text{h.c.} \right) \\ + \epsilon_{ab} \left(T_{ij}^\nu H_u^b \tilde{L}_{iL}^a \tilde{\nu}_{jR}^* - T_i^\lambda \tilde{\nu}_{iR}^* H_d^a H_u^b + \frac{1}{3} T_{ijk}^\kappa \tilde{\nu}_{iR}^* \tilde{\nu}_{jR}^* \tilde{\nu}_{kR}^* + \text{h.c.} \right) \\ + \left(m_{\tilde{Q}_L}^2 \right)_{ij} \tilde{Q}_{iL}^{a*} \tilde{Q}_{jL}^a + \left(m_{\tilde{u}_R}^2 \right)_{ij} \tilde{u}_{iR}^{*} \tilde{u}_{jR} + \left(m_{\tilde{d}_R}^2 \right)_{ij} \tilde{d}_{iR}^{*} \tilde{d}_{jR} + \left(m_{\tilde{L}_L}^2 \right)_{ij} \tilde{L}_{iL}^{a*} \tilde{L}_{jL}^a \\ + \left(m_{H_d \tilde{L}_L}^2 \right)_i H_d^{a*} \tilde{L}_{iL}^a + \left(m_{\tilde{\nu}_R}^2 \right)_{ij} \tilde{\nu}_{iR}^* \tilde{\nu}_{jR} + \left(m_{\tilde{e}_R}^2 \right)_{ij} \tilde{e}_{iR}^* \tilde{e}_{jR} + m_{H_d}^2 H_d^{a*} H_d^a + m_{H_u}^2 H_u^{a*} H_u^a \\ + \frac{1}{2} \left(M_3 \tilde{g} \tilde{g} + M_2 \tilde{W} \tilde{W} + M_1 \tilde{B}^0 \tilde{B}^0 + \text{h.c.} \right)$$

We put soft masses mixing different fields to zero at tree-level, explained by diagonal Kähler metric

in certain Sugra models

Brignole, Ibanez, Munoz [hep-ph/9707209]
Ghosh, Lara, Lopez-Fogliani, Munoz, Ruiz de Austri [hep-ph/1707.02471]

Particle Spectrum and Phenomenology

8 (6) CP-even neutral scalars: $\varphi^T = (H_d^{\mathcal{R}}, H_u^{\mathcal{R}}, \tilde{\nu}_{iR}^{\mathcal{R}}, \tilde{\nu}_{jL}^{\mathcal{R}})$

Left and right sneutrinos can be lighter than 125GeV

Mixing of left sneutrinos to H suppressed by Y^ν and v_L

8 (6) CP-odd neutral scalars: $\sigma^T = (H_d^{\mathcal{T}}, H_u^{\mathcal{T}}, \tilde{\nu}_{iR}^{\mathcal{T}}, \tilde{\nu}_{jL}^{\mathcal{T}})$

Includes the neutral Goldstone boson

Mixing of left sneutrinos to H suppressed by Y^ν and v_L

8 charged sleptons: $C^T = (H_d^{-*}, H_u^{+}, \tilde{e}_{iL}^{*}, \tilde{e}_{jR}^{*})$

Includes the charged Goldstone boson

Mixing of sleptons to H suppressed by Y^ν and v_L

5 charginos: $(\chi^-)^T = ((e_{iL})^c)^*, (\widetilde{W}^-, \widetilde{H}_d^-), (\chi^+)^T = ((e_{jR})^c, \widetilde{W}^+, \widetilde{H}_u^+)$

Three light states corresponding to e , μ and τ

Mixing of leptons to gauginos suppressed by Y^ν and v_L

10 (8) Majorana fermions: $(\chi^0)^T = ((\nu_{iL})^c)^*, (\widetilde{B}^0, \widetilde{W}^0, \widetilde{H}_d^0, \widetilde{H}_u^0, \nu_{jR}^*)$

Type-I seesaw at EW scale

Mass matrix of rank 10 (6) \Rightarrow 0 (2) massless states at tree-level

3 (1) neutrino masses of $\mathcal{O}(< \text{eV})$ at tree-level

3 (1) heavy right-handed neutrinos of $\mathcal{O}(< \text{TeV})$

Particle Spectrum and Phenomenology

Collider: MSSM-bounds from Atlas/CMS usually do not hold in the $\mu\nu$ SSM

The LSP¹ can be charged or colored

- Opens distinct regions of parameter space
- Different decay channels

Displaced vertices: Sneutrino: $\leq \mathcal{O}(mm)$, Singlino: $\leq \mathcal{O}(m)$

Ghosh, Lara, Lopez-Fogliani, Munoz, Ruiz de Austri [hep-ph/1707.02471]
Lara, Lopez-Fogliani, Munoz, Nagata, Otono, Ruiz de Austri [hep-ph/1804.00067]

Novel signals: FS with multi-/leptons/jets, $\gamma\gamma + \text{leptons}/\cancel{E}_T$

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Ghosh, Lopez-Fogliani, Munoz, Ruiz de Austri [hep-ph/1107.4614]

¹Forgetting about the gravitino because it is not relevant for colliders

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Dark Matter: Gravitino (one possibility) with lifetime longer than age of universe

Searches: γ -ray lines in Fermi-LAT or smooth γ background

Choi, Lopez-Fogliani, Munoz, Ruiz de Austri [hep-ph/0906.3681]
 Gomez-Vargas, Fornasa, Zandanel, Cuesta, Munoz, Prada, Yepes [hep-ph/1110.3305]
 Albert, Gomez-Vargas, Grefe, Munoz, Weniger, Bloom, Charles, Mazzotta, Morselli [hep-ph/1406.3430]
 Gomez-Vargas, Lopez-Fogliani, Munoz, Perez, Ruiz de Austri [hep-ph/1608.08640]

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Neutrinos: δm_{12}^2 , Δm_{13}^2 and s_{12}^2 , s_{13}^2 , s_{23}^2 can be reproduced (NO and IO)

Electroweak seesaw with $Y_{ii}^\nu \sim Y^e \sim 10^{-6} \Rightarrow v_{iL} \sim 10^{-4}$

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Neutrino physics

At tree-level in basis $(v_{iL}, \tilde{B}^0, \tilde{W}^0, \tilde{H}_d^0, \tilde{H}_u^0, v_{jR})$:

$$m_\nu = \begin{pmatrix} 0 & 0 & 0 & -\frac{g_1 v_{1L}}{\sqrt{2}} & \frac{g_2 v_{1L}}{\sqrt{2}} & 0 & \frac{v_{iR} Y_{1i}^\nu}{\sqrt{2}} & \frac{v_u Y_{11}^\nu}{\sqrt{2}} & \frac{v_u Y_{12}^\nu}{\sqrt{2}} & \frac{v_u Y_{13}^\nu}{\sqrt{2}} \\ 0 & 0 & 0 & -\frac{g_1 v_{2L}}{\sqrt{2}} & \frac{g_2 v_{2L}}{\sqrt{2}} & 0 & \frac{v_{iR} Y_{2i}^\nu}{\sqrt{2}} & \frac{v_u Y_{21}^\nu}{\sqrt{2}} & \frac{v_u Y_{22}^\nu}{\sqrt{2}} & \frac{v_u Y_{23}^\nu}{\sqrt{2}} \\ 0 & 0 & 0 & -\frac{g_1 v_{3L}}{\sqrt{2}} & \frac{g_2 v_{3L}}{\sqrt{2}} & 0 & \frac{v_{iR} Y_{3i}^\nu}{\sqrt{2}} & \frac{v_u Y_{31}^\nu}{\sqrt{2}} & \frac{v_u Y_{32}^\nu}{\sqrt{2}} & \frac{v_u Y_{33}^\nu}{\sqrt{2}} \\ -\frac{g_1 v_{1L}}{2} & \frac{g_1 v_{2L}}{2} & \frac{g_1 v_{3L}}{2} & M_1 & 0 & -\frac{g_1 v_d}{2} & \frac{g_1 v_u}{2} & 0 & 0 & 0 \\ \frac{g_2 v_{1L}^2}{2} & \frac{g_2 v_{2L}^2}{2} & \frac{g_2 v_{3L}^2}{2} & 0 & M_2 & \frac{g_2 v_d^2}{2} & -\frac{g_2 v_u}{2} & 0 & 0 & 0 \\ 0 & 0 & 0 & -\frac{g_1 v_d}{2} & \frac{g_2 v_d}{2} & 0 & -\frac{\lambda_i v_{iR}}{\sqrt{2}} & -\frac{\lambda_1 v_u}{\sqrt{2}} & -\frac{\lambda_2 v_u}{\sqrt{2}} & -\frac{\lambda_3 v_u}{\sqrt{2}} \\ \frac{v_{iR} Y_{1i}^\nu}{\sqrt{2}} & \frac{v_{iR} Y_{2i}^\nu}{\sqrt{2}} & \frac{v_{iR} Y_{3i}^\nu}{\sqrt{2}} & \frac{g_1 v_u}{2} & -\frac{g_2 v_u}{2} & -\frac{\lambda_i v_{iR}}{\sqrt{2}} & 0 & -\frac{v_d \lambda_1 + v_{iL} Y_{1i}^\nu}{\sqrt{2}} & -\frac{v_d \lambda_2 + v_{iL} Y_{2i}^\nu}{\sqrt{2}} & -\frac{v_d \lambda_3 + v_{iL} Y_{3i}^\nu}{\sqrt{2}} \\ \frac{v_u Y_{11}^\nu}{\sqrt{2}} & \frac{v_u Y_{21}^\nu}{\sqrt{2}} & \frac{v_u Y_{31}^\nu}{\sqrt{2}} & 0 & 0 & -\frac{v_u \lambda_1}{\sqrt{2}} & -\frac{v_d \lambda_1 + v_{iL} Y_{1i}^\nu}{\sqrt{2}} & \sqrt{2} \kappa_{11i} v_R & \sqrt{2} \kappa_{12i} v_R & \sqrt{2} \kappa_{13i} v_R \\ \frac{v_u Y_{12}^\nu}{\sqrt{2}} & \frac{v_u Y_{22}^\nu}{\sqrt{2}} & \frac{v_u Y_{32}^\nu}{\sqrt{2}} & 0 & 0 & -\frac{v_u \lambda_2}{\sqrt{2}} & -\frac{v_d \lambda_2 + v_{iL} Y_{2i}^\nu}{\sqrt{2}} & \sqrt{2} \kappa_{12i} v_R & \sqrt{2} \kappa_{22i} v_R & \sqrt{2} \kappa_{23i} v_R \\ \frac{v_u Y_{13}^\nu}{\sqrt{2}} & \frac{v_u Y_{23}^\nu}{\sqrt{2}} & \frac{v_u Y_{33}^\nu}{\sqrt{2}} & 0 & 0 & -\frac{v_u \lambda_3}{\sqrt{2}} & -\frac{v_d \lambda_3 + v_{iL} Y_{3i}^\nu}{\sqrt{2}} & \sqrt{2} \kappa_{13i} v_R & \sqrt{2} \kappa_{23i} v_R & \sqrt{2} \kappa_{33i} v_R \end{pmatrix}$$

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$$m_\nu = \begin{pmatrix} 0 & 0 & 0 & -\frac{g_1 v_{1L}}{\sqrt{2}} & \frac{g_2 v_{1L}}{\sqrt{2}} & 0 & \frac{v_{iR} Y_{1i}^\nu}{\sqrt{2}} & \frac{v_u Y_{11}^\nu}{\sqrt{2}} & \frac{v_u Y_{12}^\nu}{\sqrt{2}} & \frac{v_u Y_{13}^\nu}{\sqrt{2}} \\ 0 & 0 & 0 & -\frac{g_1 v_{2L}}{\sqrt{2}} & \frac{g_2 v_{2L}}{\sqrt{2}} & 0 & \frac{v_{iR} Y_{2i}^\nu}{\sqrt{2}} & \frac{v_u Y_{21}^\nu}{\sqrt{2}} & \frac{v_u Y_{22}^\nu}{\sqrt{2}} & \frac{v_u Y_{23}^\nu}{\sqrt{2}} \\ 0 & 0 & 0 & -\frac{g_1 v_{3L}}{\sqrt{2}} & \frac{g_2 v_{3L}}{\sqrt{2}} & 0 & \frac{v_{iR} Y_{3i}^\nu}{\sqrt{2}} & \frac{v_u Y_{31}^\nu}{\sqrt{2}} & \frac{v_u Y_{32}^\nu}{\sqrt{2}} & \frac{v_u Y_{33}^\nu}{\sqrt{2}} \\ -\frac{g_1 v_{1L}}{2} & \frac{g_1 v_{2L}}{2} & \frac{g_1 v_{3L}}{2} & M_1 & 0 & -\frac{g_1 v_d}{2} & \frac{g_1 v_u}{2} & 0 & 0 & 0 \\ \frac{g_2 v_{1L}}{2} & \frac{g_2 v_{2L}}{2} & \frac{g_2 v_{3L}}{2} & 0 & M_2 & \frac{g_2 v_d}{2} & \frac{g_2 v_u}{2} & 0 & 0 & 0 \\ 0 & 0 & 0 & -\frac{g_1 v_d}{2} & \frac{g_2 v_d}{2} & 0 & -\frac{\lambda_i v_{iR}}{\sqrt{2}} & -\frac{\lambda_1 v_u}{\sqrt{2}} & -\frac{\lambda_2 v_u}{\sqrt{2}} & -\frac{\lambda_3 v_u}{\sqrt{2}} \\ \frac{v_{iR} Y_{1i}^\nu}{\sqrt{2}} & \frac{v_{iR} Y_{2i}^\nu}{\sqrt{2}} & \frac{v_{iR} Y_{3i}^\nu}{\sqrt{2}} & \frac{g_1 v_u}{2} & -\frac{g_2 v_u}{2} & -\frac{\lambda_i v_{iR}}{\sqrt{2}} & 0 & -\frac{v_d \lambda_1 + v_{iL} Y_{1i}^\nu}{\sqrt{2}} & -\frac{v_d \lambda_2 + v_{iL} Y_{2i}^\nu}{\sqrt{2}} & -\frac{v_d \lambda_3 + v_{iL} Y_{3i}^\nu}{\sqrt{2}} \\ \frac{v_u Y_{11}^\nu}{\sqrt{2}} & \frac{v_u Y_{21}^\nu}{\sqrt{2}} & \frac{v_u Y_{31}^\nu}{\sqrt{2}} & 0 & 0 & -\frac{v_u \lambda_1}{\sqrt{2}} & -\frac{v_d \lambda_1 + v_{iL} Y_{1i}^\nu}{\sqrt{2}} & \sqrt{2} \kappa_{11i} v_R & \sqrt{2} \kappa_{12i} v_R & \sqrt{2} \kappa_{13i} v_R \\ \frac{v_u Y_{12}^\nu}{\sqrt{2}} & \frac{v_u Y_{22}^\nu}{\sqrt{2}} & \frac{v_u Y_{32}^\nu}{\sqrt{2}} & 0 & 0 & -\frac{v_u \lambda_2}{\sqrt{2}} & -\frac{v_d \lambda_2 + v_{iL} Y_{2i}^\nu}{\sqrt{2}} & \sqrt{2} \kappa_{12i} v_R & \sqrt{2} \kappa_{22i} v_R & \sqrt{2} \kappa_{23i} v_R \\ \frac{v_u Y_{13}^\nu}{\sqrt{2}} & \frac{v_u Y_{23}^\nu}{\sqrt{2}} & \frac{v_u Y_{33}^\nu}{\sqrt{2}} & 0 & 0 & -\frac{v_u \lambda_3}{\sqrt{2}} & -\frac{v_d \lambda_3 + v_{iL} Y_{3i}^\nu}{\sqrt{2}} & \sqrt{2} \kappa_{13i} v_R & \sqrt{2} \kappa_{23i} v_R & \sqrt{2} \kappa_{33i} v_R \end{pmatrix}$$

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Simplified formula for the effective neutrino mixing matrix: (Y^ν diagonal)

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

Fidalgo, Lopez-Fogliani, Munoz, Ruiz de Austri [hep-ph/0904.3112]

with

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

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Parts of \mathcal{L} contributing:

Higgs potential

$$W^{\text{Higgs}} = \epsilon_{ab} \left(Y_{ij}^\nu \hat{H}_u^b \hat{L}_i^a \hat{\nu}_j^c - \lambda_i \hat{\nu}_i^c \hat{H}_u^b \hat{H}_d^a \right) + \frac{1}{3} \kappa_{ijk} \hat{\nu}_i^c \hat{\nu}_j^c \hat{\nu}_k^c$$

$$\mathcal{L}_{\text{soft}}^{\text{Higgs}} = \epsilon_{ab} \left(T_{ij}^\nu H_u^b \tilde{L}_{il}^a \tilde{\nu}_{jR}^* - T_i^\lambda \tilde{\nu}_{iR}^* H_d^a H_u^b + \frac{1}{3} T_{ijk}^\kappa \tilde{\nu}_{iR}^* \tilde{\nu}_{jR}^* \tilde{\nu}_{kR}^* + \text{h.c.} \right)$$

$$+ \left(m_{\tilde{L}_L}^2 \right)_{ij} \tilde{L}_{il}^{a*} \tilde{L}_{jl}^a + \left(m_{H_d \tilde{L}_L}^2 \right)_i H_d^{a*} \tilde{L}_{il}^a + \left(m_{\tilde{\nu}_R}^2 \right)_{ij} \tilde{\nu}_R^* \tilde{\nu}_R + m_{H_d}^2 H_d^{a*} H_d^a + m_{H_u}^2 H_u^{a*} H_u^a$$

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- Absent in tree-level Lagrangian because it spoils the EW seesaw mechanism

$$\Rightarrow v_{iL} \rightarrow 0 \text{ when } Y_{ij}^\nu \rightarrow 0$$

- Justified if one assumes diagonal Kähler metric in certain supergravity models

Brignole, Ibanez, Munoz [hep-ph/9707209]

Ghosh, Lara, Lopez-Fogliani, Munoz, Ruiz de Austri [hep-ph/1707.02471]

- Included here because needed for renormalization already at one-loop

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$$\tilde{\nu}_{iR} = \frac{1}{\sqrt{2}} \left(\tilde{\nu}_{iR}^{\mathcal{R}} + v_{iR} + i \tilde{\nu}_{iR}^{\mathcal{I}} \right), \quad \tilde{\nu}_{iL} = \frac{1}{\sqrt{2}} \left(\tilde{\nu}_{iL}^{\mathcal{R}} + v_{iL} + i \tilde{\nu}_{iL}^{\mathcal{I}} \right) \ll v_{u,d,R}$$

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$$\tilde{\nu}_{iR} = \frac{1}{\sqrt{2}} \left(\tilde{\nu}_{iR}^{\mathcal{R}} + v_{iR} + i \tilde{\nu}_{iR}^{\mathcal{I}} \right), \quad \tilde{\nu}_{iL} = \frac{1}{\sqrt{2}} \left(\tilde{\nu}_{iL}^{\mathcal{R}} + v_{iL} + i \tilde{\nu}_{iL}^{\mathcal{I}} \right) \ll v_{u,d,R}$$

Parameter counting:

Total: 69 needed for renormalization

In practice: 26 needed for phenomenology (avoiding large flavour-mixing)

Higgs potential

Replacements:

- $m_{H_d}^2, m_{H_u}^2, (m_{\tilde{L}_L}^2)_{ii}, (m_{\tilde{\nu}_R}^2)_{ii} \xrightarrow{\text{Tadpole eq.}} T_{H_d^R}, T_{H_u^R}, T_{\tilde{\nu}_{iL}^R}, T_{\tilde{\nu}_{iR}^R}$
- $v_d, v_u \rightarrow \tan \beta, v$ with $\tan \beta = \frac{v_u}{v_d}, v^2 = v_u^2 + v_d^2 + v_{iL} v_{iL}$
- $g_1, g_2 \rightarrow M_W^2, M_Z^2$ with $M_W^2 = \frac{1}{4} g_2^2 v^2, M_Z^2 = \frac{1}{4} (g_1^2 + g_2^2) v^2$

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The effective μ -term gets three contributions:

$$\mu = \frac{\lambda_i v_{iR}}{\sqrt{2}}$$

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-

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$$\mu = \frac{\lambda_i v_{iR}}{\sqrt{2}}$$

Tree-level upper bound on the lightest Higgs mass:

$$m_h^2 \leq M_Z^2 \left(\cos^2 2\beta + \frac{2\lambda_i \lambda_i \cos^2 \Theta_W}{g_2^2} \sin^2 2\beta \right) \stackrel{\text{GUT}}{\sim} M_Z^2 \left(\cos^2 2\beta + 1.77 \sin^2 2\beta \right)$$

Renormalization scheme

Calculations in $\overline{\text{DR}}$ schemes have the disadvantage that parameters cannot directly be related to physical observables.

⇒ Mixed On-Shell/ $\overline{\text{DR}}$ scheme

(N)MSSM-pieces treated as in (N)MSSM (FeynHiggs)

Renormalization scheme

Calculations in $\overline{\text{DR}}$ schemes have the disadvantage that parameters cannot directly be related to physical observables.

\Rightarrow Mixed On-Shell/ $\overline{\text{DR}}$ scheme

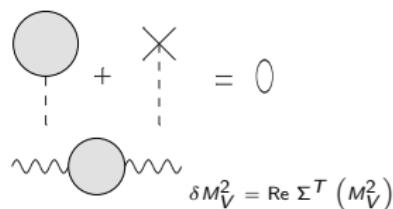
(N)MSSM-pieces treated as in (N)MSSM (FeynHiggs)

On-shell parameters:

$$T_{H_d^R} \rightarrow T_{H_d^R} + \delta T_{H_d^R}, \quad T_{\tilde{\nu}_{iL}^R} \rightarrow T_{\tilde{\nu}_{iL}^R} + \delta T_{\tilde{\nu}_{iL}^R},$$

$$T_{H_u^R} \rightarrow T_{H_u^R} + \delta T_{H_u^R}, \quad M_W^2 \rightarrow M_W^2 + \delta M_W^2,$$

$$T_{\tilde{\nu}_{iR}^R} \rightarrow T_{\tilde{\nu}_{iR}^R} + \delta T_{\tilde{\nu}_{iR}^R}, \quad M_Z^2 \rightarrow M_Z^2 + \delta M_Z^2.$$



Renormalization scheme

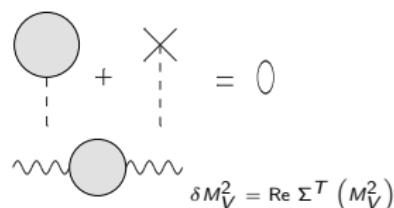
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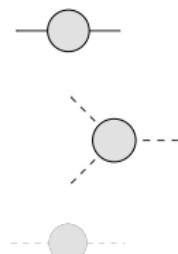
On-shell parameters:

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$\overline{\text{DR}}$ parameters:

$$\begin{aligned} m_{L_{i \neq j}}^2 &\rightarrow m_{L_{i \neq j}}^2 + \delta m_{L_{i \neq j}}^2, & v^2 &\rightarrow v^2 + \delta v^2, & Y_{ij}^\nu &\rightarrow Y_{ij}^\nu + \delta Y_{ij}^\nu, \\ m_{H_d \tilde{L}_i}^2 &\rightarrow m_{H_d \tilde{L}_i}^2 + \delta m_{H_d \tilde{L}_i}^2, & v_{iR}^2 &\rightarrow v_{iR}^2 + \delta v_{iR}^2, & T_i^\lambda &\rightarrow T_i^\lambda + \delta T_i^\lambda, \\ m_{\tilde{\nu}_{R i \neq j}}^2 &\rightarrow m_{\tilde{\nu}_{R i \neq j}}^2 + \delta m_{\tilde{\nu}_{R i \neq j}}^2, & v_{iL}^2 &\rightarrow v_{iL}^2 + \delta v_{iL}^2, & T_{ijk}^\kappa &\rightarrow T_{ijk}^\kappa + \delta T_{ijk}^\kappa, \\ \tan \beta &\rightarrow \tan \beta + \delta \tan \beta, & \lambda_i &\rightarrow \lambda_i + \delta \lambda_i, & T_{ij}^\nu &\rightarrow T_{ij}^\nu + \delta T_{ij}^\nu. \\ && \kappa_{ijk} &\rightarrow \kappa_{ijk} + \delta \kappa_{ijk}, & & \end{aligned}$$

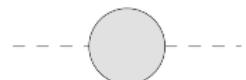


Details in: TB, Heinemeyer, Munoz [hep-ph/1712.07475]

Loop-correction to scalar masses

$$\hat{\Gamma}_h = i \left[p^2 \mathbb{1} - \left(m_h^2 - \hat{\Sigma}_h(p^2) \right) \right] , \quad \hat{\Sigma}_h: \text{Renormalized self-energies}$$

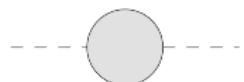
$$\det \left(\hat{\Gamma}_h(p^2) \right) \Big|_{p^2=p_i^2} = 0 \quad \text{then} \quad m_{h_i}^2 = \text{Re}(p_i^2)$$



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Fixed-order Feynman-diagrammatic calculation:

Advantages: All contribution of the order included

Full control of scalar self-energies (momentum-dependence)

Many scales included

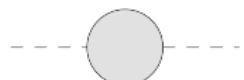
Disadvantages: Large logs of higher orders missing

Cannot be extended to very large scales

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Fixed-order Feynman-diagrammatic calculation:

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⇒ Full one-loop corrections supplemented by partial (MSSM-like) two-loop corrections and resummed large logs

$$\hat{\Sigma}_h(p^2) = \hat{\Sigma}_h^{(1)}(p^2) + \hat{\Sigma}_h^{(2')} + \hat{\Sigma}_h^{\text{resum}}$$

$\hat{\Sigma}_h^{(1)}$: Full $\mu\nu$ SSM one-loop

$\hat{\Sigma}_h^{(2')}$: Partial two-loop $\mathcal{O}(\alpha_s \alpha_t, \alpha_s \alpha_b, \alpha_t^2, \alpha_t \alpha_b)$ from FeynHiggs v. 2.13

$\hat{\Sigma}_h^{\text{resum}}$: Resummation of large logs from FeynHiggs v. 2.13

$\mu\nu$ SSM with 1 right-handed sneutrino

$$\nu_{iL}/\sqrt{2} = 10^{-4} \text{ GeV}$$

$$Y_i^\nu = 10^{-6}$$

$$A_i^\nu = -1000 \text{ GeV}$$

$$\tan \beta = 8$$

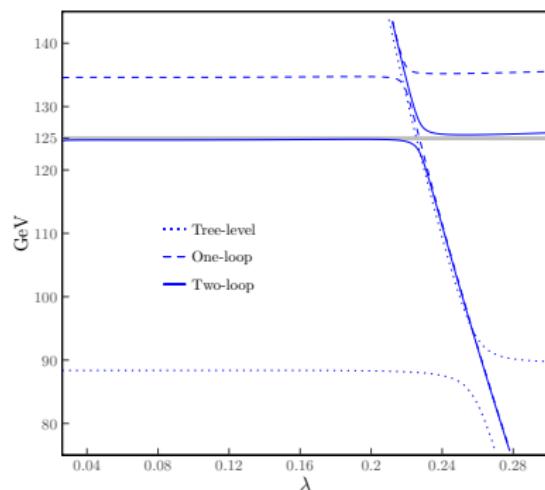
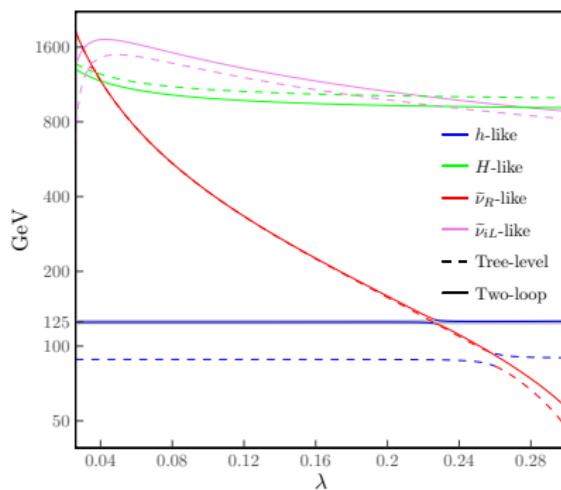
$$\mu = 125 \text{ GeV}$$

$$\kappa = 0.2$$

$$A^{\kappa} = -300 \text{ GeV}$$

$$A^t = -2000 \text{ GeV}$$

$$A^b = -1500 \text{ GeV}$$

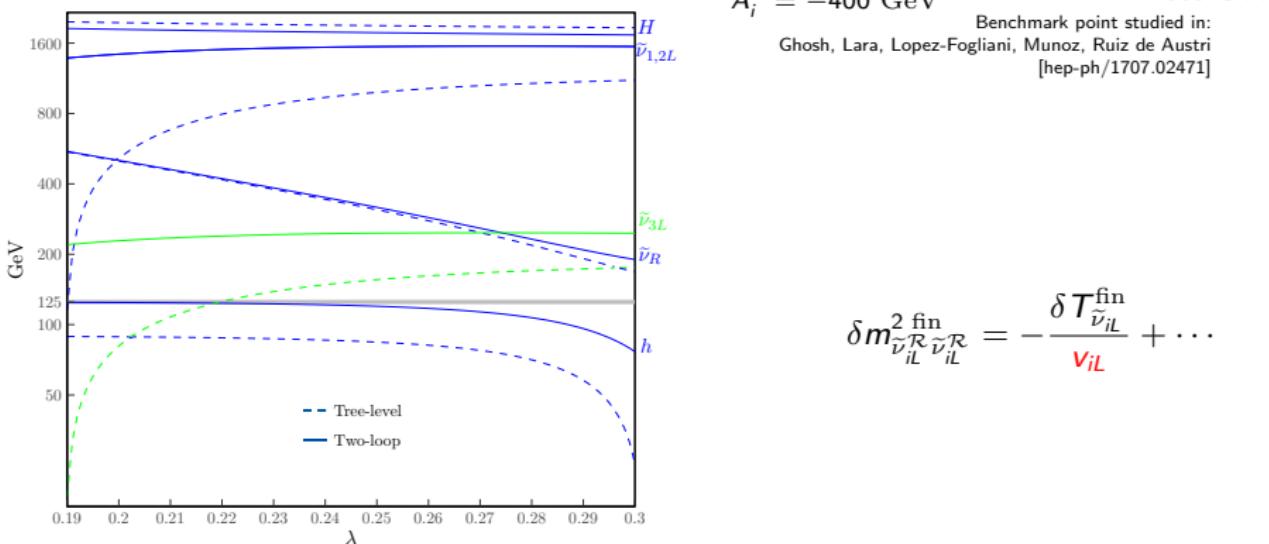


⇒ MSSM-like 2-loop corrections are crucial for reproducing the correct value of the SM-like Higgs boson mass

$\mu\nu$ SSM with 1 right-handed sneutrino

$$m_{\tilde{\nu}_{iL}^R \tilde{\nu}_{iL}^R}^2 \approx \frac{Y_i^\nu v_R v_u}{2 v_{iL}} \left(-\sqrt{2} A_i^\nu - \kappa v_R + \frac{\sqrt{2} \mu}{\tan \beta} \right) \Rightarrow \begin{aligned} v_{1,2L}/\sqrt{2} &= 10^{-5} \text{ GeV} \\ v_{3L}/\sqrt{2} &= 4 \cdot 10^{-4} \text{ GeV} \end{aligned}$$

$$\begin{aligned} Y_i^\nu &= 5 \cdot 10^{-7} & \kappa &= 0.3 \\ A_i^\nu &= -400 \text{ GeV} & A^\kappa &= -1000 \text{ GeV} \end{aligned}$$

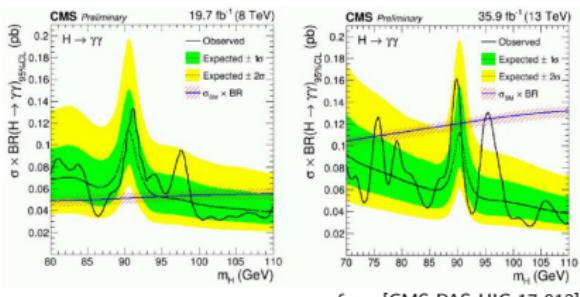


$$\delta m_{\tilde{\nu}_{iL}^R \tilde{\nu}_{iL}^R}^2 = -\frac{\delta T_{\tilde{\nu}_{iL}}^{\text{fin}}}{v_{iL}} + \dots$$

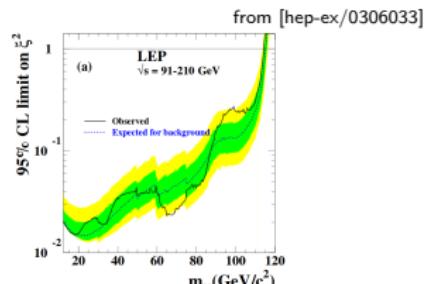
⇒ Light left-handed sneutrinos get huge loop corrections

$\mu\nu$ SSM with 1 right-handed sneutrino

Can we explain an excess at ~ 96 GeV of LEP and CMS?

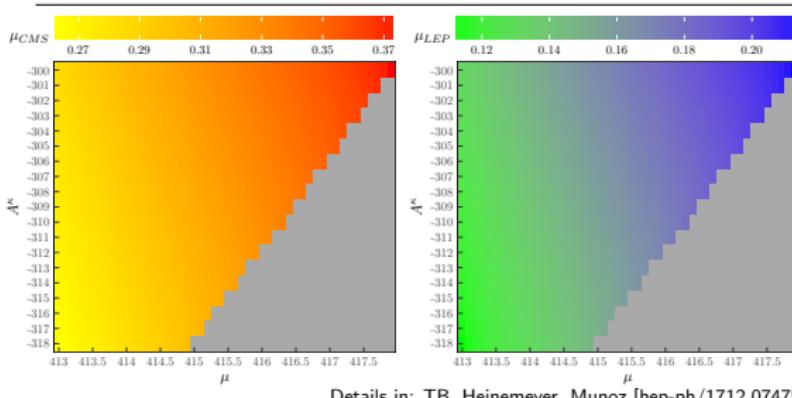


$$\mu_{CMS} (gg \rightarrow h \rightarrow \gamma\gamma) = 0.6 \pm 0.2$$



$$\mu_{LEP} (e^+ e^- \rightarrow Zh \rightarrow Zb\bar{b}) = 0.117 \pm 0.057$$

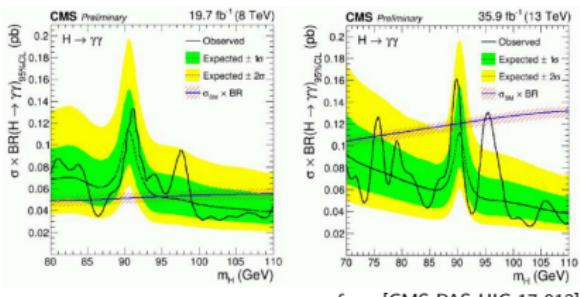
Value from [arXiv:1612.08522]



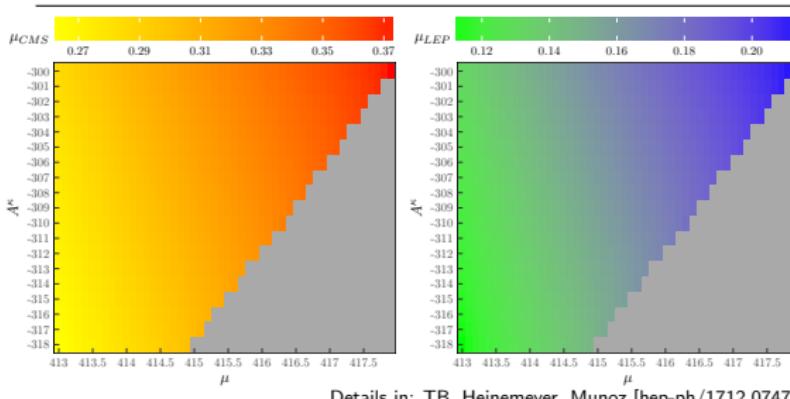
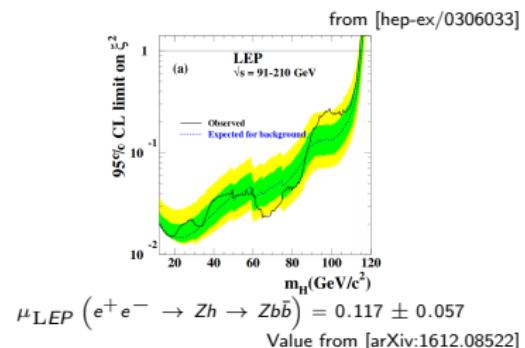
⇒ Simultaneously explained at 1σ by a right-handed sneutrino with $m_{\tilde{\nu}_R} \sim 96$ GeV

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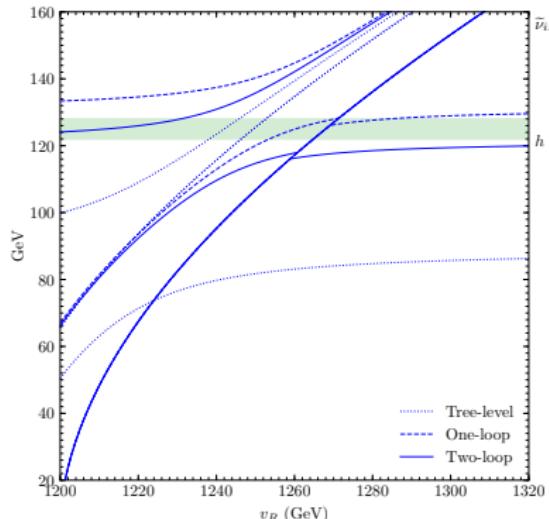
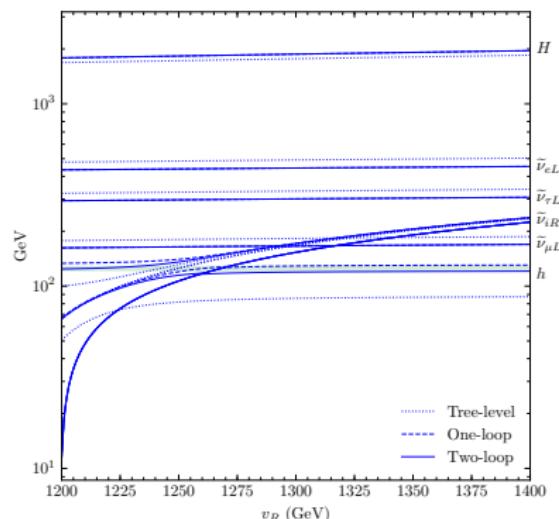
⇒ Simultaneously explained at 1σ by a right-handed sneutrino with $m_{\tilde{\nu}_R} \sim 96$ GeV

However: Atlas update from ICHEP ⇒ no excess in diphoton channel

Int. Conf. on HEP, 5. July 2018
[ATLAS-CONF-2018-025]

$\mu\nu$ SSM with 3 right-handed sneutrinos

Fitting the SM-like Higgs mass and the neutrino properties:



$$\tan \beta = 11$$

$$\nu_{iR} = \nu_R$$

$$A_i^\lambda = 1000 \text{ GeV}$$

$$\lambda_i = 0.08$$

$$A_{ii}^\nu = -1000 \text{ GeV}$$

$$\kappa_{iii} = 0.3$$

$$A_{iii}^\kappa = -1000 \text{ GeV}$$

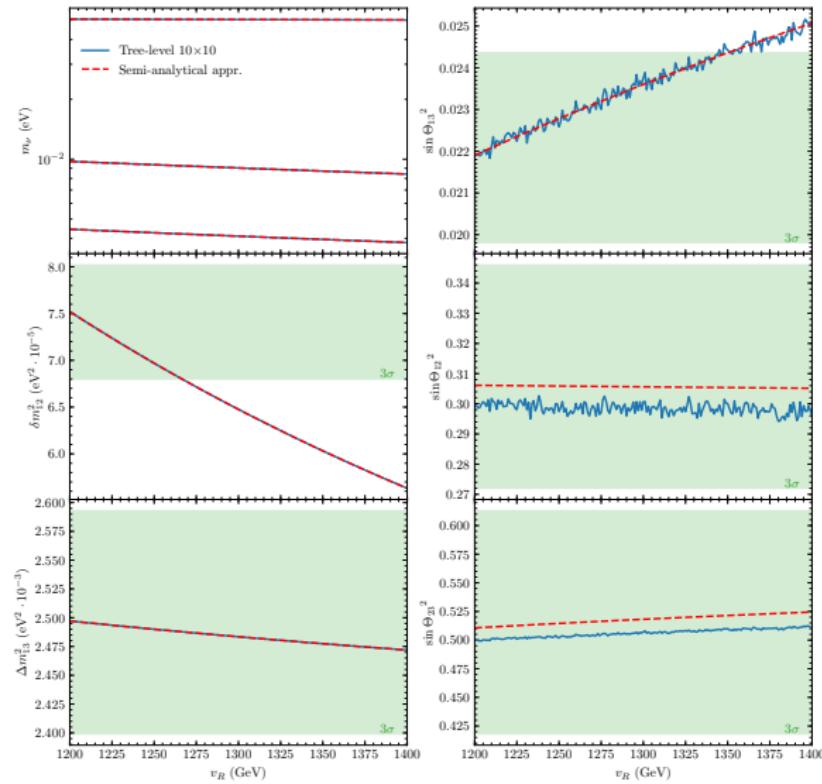
$$A^t = -2000 \text{ GeV}$$

$$A^b = -1500 \text{ GeV}$$

$$A^\tau = -1000 \text{ GeV}$$

$\mu\nu$ SSM with 3 right-handed sneutrinos

Fitting the SM-like Higgs mass and the neutrino properties:



$$\delta m_{12}^2 = (7.41 \pm 0.61) \cdot 10^{-5} \text{ eV}^2$$

$$\Delta m_{13}^2 = (2.4655 \pm 0.0965) \cdot 10^{-3} \text{ eV}^2$$

$$\sin^2 \Theta_{13} = 0.022085 \pm 0.002275$$

$$\sin^2 \Theta_{12} = 0.309 \pm 0.037$$

$$\sin^2 \Theta_{23} = 0.5155 \pm 0.0975$$

from NuFIT '18 results

$$v_{1L} = 2.45 \cdot 10^{-4} \text{ GeV}$$

$$v_{2L} = 9.73 \cdot 10^{-4} \text{ GeV}$$

$$v_{3L} = 7.71 \cdot 10^{-4} \text{ GeV}$$

$$Y_{11}^\nu = 3.52 \cdot 10^{-7}$$

$$Y_{22}^\nu = 1.93 \cdot 10^{-7}$$

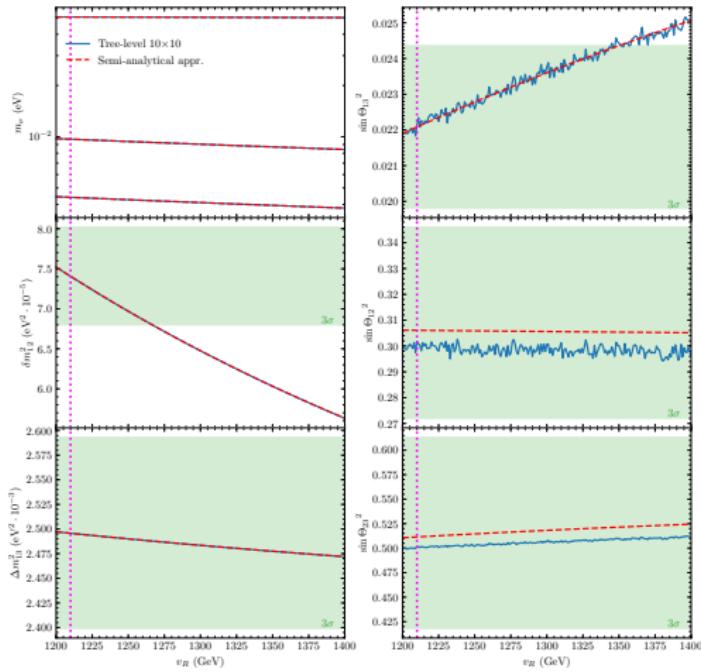
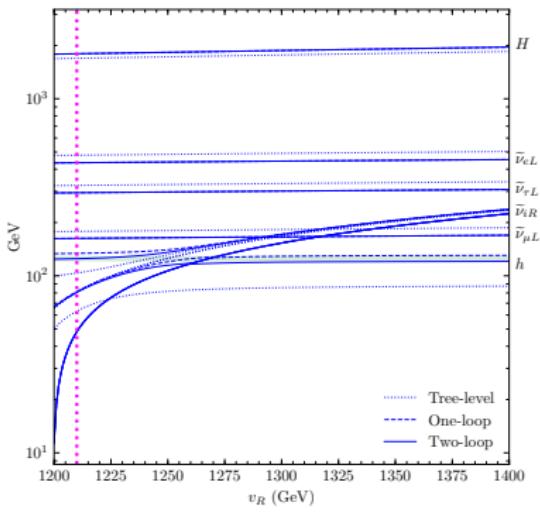
$$Y_{33}^\nu = 5.06 \cdot 10^{-7}$$

$$M_1 = 3011 \text{ GeV}$$

$$M_2 = 6000 \text{ GeV}$$

How restrictive are neutrino limits?

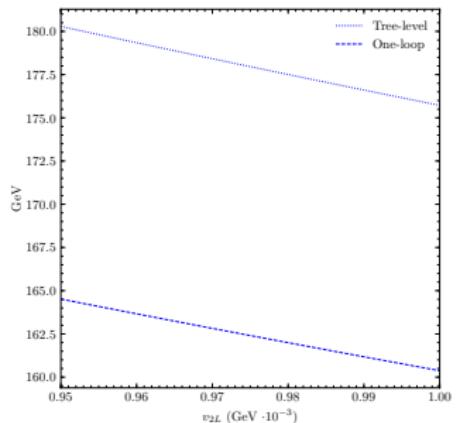
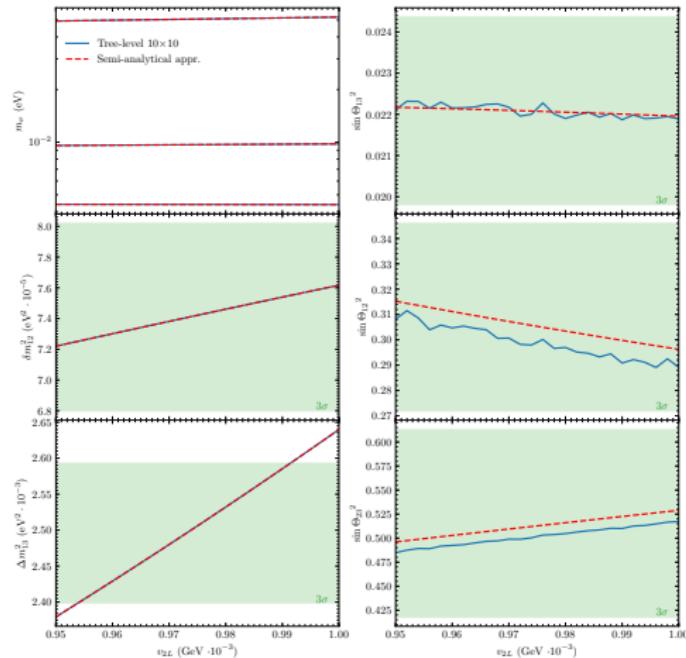
Best-fit point: $v_R \sim 1210$ GeV



How restrictive are neutrino limits?

Best-fit point: $v_R \sim 1210$ GeV

1. Vary $v_{2L} \Rightarrow$ How much does mass of $\tilde{\nu}_{\mu L}$ change?

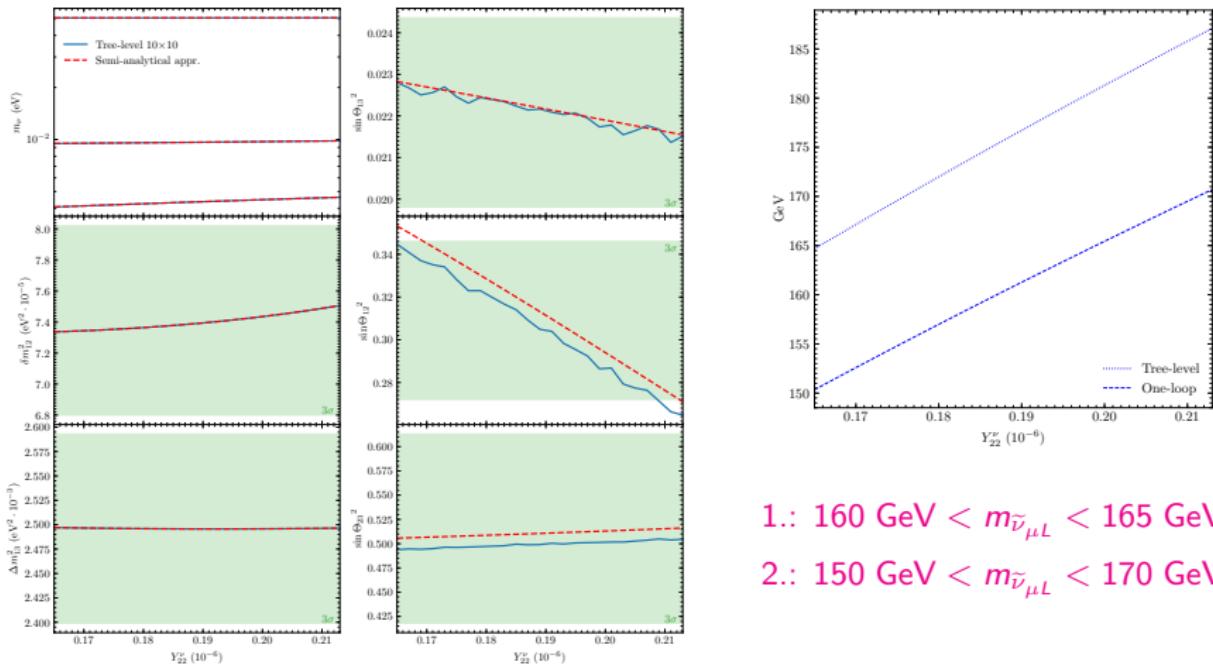


1.: $160 \text{ GeV} < m_{\tilde{\nu}_{\mu L}} < 165 \text{ GeV}$

How restrictive are neutrino limits?

Best-fit point: $v_R \sim 1210$ GeV

2. Vary $Y_{22}^\nu \Rightarrow$ How much does mass of $\tilde{\nu}_{\mu L}$ change?



1.: $160 \text{ GeV} < m_{\tilde{\nu}_{\mu L}} < 165 \text{ GeV}$

2.: $150 \text{ GeV} < m_{\tilde{\nu}_{\mu L}} < 170 \text{ GeV}$

Conclusions

- Neutral scalar potential is renormalized at 1-loop
- SM-like Higgs mass is reproduced when MSSM-like 2-loop corrections are taken into account (crucial)
- In the $\mu\nu$ SSM the 96 GeV LEP+CMS excess could be explained by a right-handed sneutrino
- Simultaneously, neutrino physics and SM-like Higgs can be reproduced
- Neutrino measurements can (in principle) be used to constrain mass range of sneutrinos
- Interesting collider signals when sneutrinos are light (when loop corrections are important)

THANKS

Tadpole equations

$$\begin{aligned}
T_{H_d^R} = & -m_{H_d}^2 v_d - \left(m_{H_d}^2 \tilde{L}_L \right)_i v_{iL} - \frac{1}{8} (g_1^2 + g_2^2) v_d (v_d^2 + v_{iL} v_{iL} - v_u^2) \\
& - \frac{1}{2} v_d v_u^2 \lambda_i \lambda_i + \frac{1}{\sqrt{2}} v_u v_{iR} T_i^\lambda + \frac{1}{2} v_u^2 Y_{ji}^\nu \lambda_i v_{jL} - \frac{1}{2} v_d v_{iR} \lambda_i v_{jR} \lambda_j \\
& + \frac{1}{2} v_u \kappa_{ikj} \lambda_i v_{jR} v_{kR} + \frac{1}{2} v_{iR} \lambda_i v_{jL} Y_{jk}^\nu v_{kR} ,
\end{aligned} \tag{1}$$

$$\begin{aligned}
T_{H_u^R} = & -m_{H_u}^2 v_u + \frac{1}{8} (g_1^2 + g_2^2) v_u (v_d^2 + v_{iL} v_{iL} - v_u^2) \\
& - \frac{1}{2} v_d^2 v_u \lambda_i \lambda_i + \frac{1}{\sqrt{2}} v_d v_{iR} T_i^\lambda + v_d v_u Y_{ji}^\nu \lambda_i v_{jL} - \frac{1}{\sqrt{2}} v_{iL} T_{ij}^\nu v_{jR} - \frac{1}{2} v_u v_{iR} \lambda_i v_{jR} \lambda_j \\
& - \frac{1}{2} v_u Y_{ji}^\nu Y_{ki}^\nu v_{jL} v_{kL} - \frac{1}{2} v_u Y_{ij}^\nu Y_{ik}^\nu v_{jR} v_{kR} + \frac{1}{2} v_d \kappa_{ijk} \lambda_i v_{jR} v_{kR} - \frac{1}{2} Y_{li}^\nu \kappa_{ikj} v_{jR} v_{kR} v_{iL} ,
\end{aligned} \tag{2}$$

$$\begin{aligned}
T_{\tilde{\nu}_{iR}^R} = & - \left(m_{\tilde{\nu}_R}^2 \right)_{ij} v_{jR} - \frac{1}{\sqrt{2}} v_u v_{jL} T_{ji}^\nu - \frac{1}{2} v_u^2 Y_{ji}^\nu Y_{jk}^\nu v_{kR} + v_d v_u \kappa_{ijk} \lambda_j v_{kR} - \frac{1}{\sqrt{2}} T_{ijk}^\kappa v_{jR} v_{kR} \\
& + \frac{1}{2} v_d v_{jL} Y_{ji}^\nu v_{kR} \lambda_k - v_u Y_{ij}^\nu \kappa_{ijk} v_{kR} v_{iL} - \frac{1}{2} v_{jL} Y_{ji}^\nu v_{kL} Y_{kl}^\nu v_{iR} - \kappa_{ijm} \kappa_{jlk} v_{kR} v_{iR} v_{mR} \\
& - \frac{1}{2} (v_d^2 + v_u^2) \lambda_i \lambda_j v_{jR} + \frac{1}{2} v_d v_{jL} Y_{jk}^\nu v_{kR} \lambda_i + \frac{1}{\sqrt{2}} v_d v_u T_i^\lambda ,
\end{aligned} \tag{3}$$

$$\begin{aligned}
T_{\tilde{\nu}_{iL}^R} = & - \left(m_{\tilde{\nu}_L}^2 \right)_{ij} v_{jL} - \left(m_{H_d}^2 \tilde{L}_L \right)_i v_d - \frac{1}{8} (g_1^2 + g_2^2) v_{iL} (v_d^2 + v_{jL} v_{jL} - v_u^2) \\
& + \frac{1}{2} v_d v_u^2 Y_{ij}^\nu \lambda_j - \frac{1}{\sqrt{2}} v_u v_{jR} T_{ij}^\nu - \frac{1}{2} v_u^2 Y_{ij}^\nu Y_{ji}^\nu k v_{kL} + \frac{1}{2} v_d v_{jR} Y_{ij}^\nu v_{kR} \lambda_k \\
& - \frac{1}{2} v_u Y_{ij}^\nu \kappa_{jkl} v_{kR} v_{iR} - \frac{1}{2} v_{jR} Y_{ij}^\nu v_{kL} Y_{kl}^\nu v_{iR} .
\end{aligned} \tag{4}$$

Renormalization scheme

$\overline{\text{DR}}$ field renormalization:

$$\begin{pmatrix} H_d \\ H_u \\ \tilde{\nu}_{iR} \\ \tilde{\nu}_{jL} \end{pmatrix} \rightarrow \sqrt{Z} \begin{pmatrix} H_d \\ H_u \\ \tilde{\nu}_{iR} \\ \tilde{\nu}_{jL} \end{pmatrix} = \left(\mathbb{1} + \frac{1}{2} \delta Z \right) \begin{pmatrix} H_d \\ H_u \\ \tilde{\nu}_{iR} \\ \tilde{\nu}_{jL} \end{pmatrix}$$

\sqrt{Z} : 8 (6) \times 8 (6) matrix, equal sign valid in 1L

$\overline{\text{DR}}$ conditions: $\delta Z_{ij} = - \left. \frac{d}{dp^2} \Sigma_{\varphi_i \varphi_j} \right|^{\text{div}}$

Not diagonal in gauge eigenstate
basis (\mathcal{L} , LFV)

$$\delta Z_{1,5+a} = \frac{\Delta}{16\pi^2} \lambda_i Y_{ai}^\nu$$

$$\delta Z_{2+a,2+b} = - \frac{\Delta}{16\pi^2} (\kappa_{a\bar{i}\bar{j}} \kappa_{b\bar{i}\bar{j}} + \lambda_a \lambda_b + Y_{ia}^\nu Y_{ib}^\nu)$$

$$\delta Z_{5+a,5+b} = - \frac{\Delta}{16\pi^2} (Y_{ia}^e Y_{ib}^e + Y_{ai}^\nu Y_{bi}^\nu)$$