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

Thomas Biekötter
in collaboration with Sven Heinemeyer and Carlos Muñoz

[hep-ph/1712.07475]

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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

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

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?

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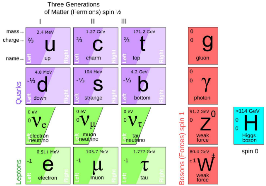
Any model beyond the MSSM potentially has even larger uncertainty
$\Rightarrow$ We present full one-loop + partial MSSM-like two-loop corrections to scalar masses in the $\mu\nu$SSM.

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?



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

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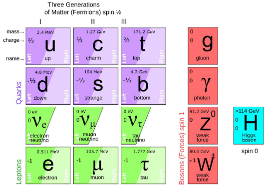

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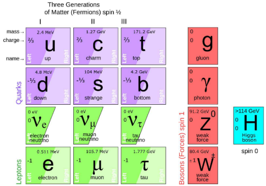

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$\mu\nu$SSM: Simplest extension of the MSSM solving the μ- and the ν-problem at the same time.

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

Couplings: $Y^\nu_{ij} \hat{H}_u \hat{L}_i \hat{\nu}^c_j \Rightarrow$ gauge singlet = right-handed neutrino

$\rightarrow$ EWSB $\Rightarrow$ Dirac masses for neutrinos ($Y^\nu_{ii} \approx Y^e_{11}$)

$\lambda_i \hat{\nu}^c_i \hat{H}_u \hat{H}_d$, $\frac{1}{3}\kappa_{ijk} \hat{\nu}^c_i \hat{\nu}^c_j \hat{\nu}^c_k$ (NMSSM-like)

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

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

Lopez-Fogliani, Munoz [hep-ph/0508297]
Escudero, Lopez-Fogliani, Munoz, Ruiz de Austri [hep-ph/0810.1507]

Lagrangian and Symmetries

$$W = \epsilon_{ab}\left(Y^e_{ij}\,\hat{H}^a_d\,\hat{L}^b_i\,\hat{e}^c_j + Y^d_{ij}\,\hat{H}^a_d\,\hat{Q}^b_i\,\hat{d}^c_j + Y^u_{ij}\,\hat{H}^b_u\,\hat{Q}^a_i\,\hat{u}^c_j\right) + \epsilon_{ab}\left(Y^\nu_{ij}\,\hat{H}^b_u\,\hat{L}^a_i\,\hat{\nu}^c_j - \lambda_i\,\hat{\nu}^c_i\,\hat{H}^b_u\hat{H}^a_d\right) + \frac{1}{3}\kappa_{ijk}\hat{\nu}^c_i\hat{\nu}^c_j\hat{\nu}^c_k$$

- 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
- Additinal sources of LFV after EWSB
- Baryon Triality B_3 to forbid baryon number violation $\rightarrow$ no proton decay

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$$\begin{aligned}
-\mathcal{L}_{\text{soft}} = \;& \epsilon_{ab}\left(T^e_{ij}\,H^a_d\,\widetilde{L}^b_{iL}\,\widetilde{e}^*_{jR} + T^d_{ij}\,H^a_d\,\widetilde{Q}^b_{iL}\,\widetilde{d}^*_{jR} + T^u_{ij}\,H^b_u\,\widetilde{Q}^a_{iL}\,\widetilde{u}^*_{jR} + \text{h.c.}\right) \\
+ \;& \epsilon_{ab}\left(T^\nu_{ij}\,H^b_u\,\widetilde{L}^a_{iL}\widetilde{\nu}^*_{jR} - T^\lambda_i\,\widetilde{\nu}^*_{iR}\,H^a_dH^b_u + \frac{1}{3}T^\kappa_{ijk}\,\widetilde{\nu}^*_{iR}\widetilde{\nu}^*_{jR}\widetilde{\nu}^*_{kR} + \text{h.c.}\right) \\
+ \;& \left(m^2_{\widetilde{Q}_L}\right)_{ij}\widetilde{Q}^{a*}_{iL}\,\widetilde{Q}^a_{jL} + \left(m^2_{\widetilde{u}_R}\right)_{ij}\widetilde{u}^*_{iR}\,\widetilde{u}_{jR} + \left(m^2_{\widetilde{d}_R}\right)_{ij}\widetilde{d}^*_{iR}\widetilde{d}_{jR} + \left(m^2_{\widetilde{L}_L}\right)_{ij}\widetilde{L}^{a*}_{iL}\widetilde{L}^a_{jL} \\
+ \;& \left(m^2_{H_d\widetilde{L}_L}\right)_i H^{a*}_d\,\widetilde{L}^a_{iL} + \left(m^2_{\widetilde{\nu}_R}\right)_{ij}\widetilde{\nu}^*_{iR}\widetilde{\nu}_{jR} + \left(m^2_{\widetilde{e}_R}\right)_{ij}\widetilde{e}^*_{iR}\widetilde{e}_{jR} + m^2_{H_d}H^{a*}_d\,H^a_d + m^2_{H_u}H^{a*}_u\,H^a_u \\
+ \;& \frac{1}{2}\left(M_3\,\widetilde{g}\,\widetilde{g} + M_2\,\widetilde{W}\,\widetilde{W} + M_1\,\widetilde{B}^0\,\widetilde{B}^0 + \text{h.c.}\right)
\end{aligned}$$

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: $\varphi^T = (H_d^{\mathcal{R}}, H_u^{\mathcal{R}}, \widetilde{\nu}_{iR}^{\mathcal{R}}, \widetilde{\nu}_{jL}^{\mathcal{R}})$

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: $\sigma^T = (H_d^{\mathcal{I}}, H_u^{\mathcal{I}}, \widetilde{\nu}_{iR}^{\mathcal{I}}, \widetilde{\nu}_{jL}^{\mathcal{I}})$

Includes the neutral Goldstone boson

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

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

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 LSP[1] can be charged or colored

$\rightarrow$ Opens distinct regions of parameter space
$\rightarrow$ 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, $\gamma\gamma$ + leptons/$\not{E}_T$

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Ghosh, Lopez-Fogliani, Mitsou, Munoz, Ruiz de Austri [hep-ph/1211.3177]
Ghosh, Lopez-Fogliani, Munoz, Ruiz de Austri [hep-ph/1107.4614]

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

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Dark Matter: Gravitino (one possiblity) 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, Mazziotta, Morselli [hep-ph/1406.3430]
Gomez-Vargas, Lopez-Fogliani, Munoz, Perez, Ruiz de Austri [hep-ph/1608.08640]

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Neutrinos: δm^2_{12}, Δm^2_{13} and and s^2_{12}, s^2_{13}, s^2_{23} can be reproduced (NO and IO)

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

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

Neutrino physics

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

$$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^\nu_{1i}}{\sqrt{2}} & \frac{v_u Y^\nu_{11}}{\sqrt{2}} & \frac{v_u Y^\nu_{12}}{\sqrt{2}} & \frac{v_u Y^\nu_{13}}{\sqrt{2}} \\
0 & 0 & 0 & -\frac{g_1 v_{2L}}{\sqrt{2}} & \frac{g_2 v_{2L}}{\sqrt{2}} & 0 & \frac{v_{iR} Y^\nu_{2i}}{\sqrt{2}} & \frac{v_u Y^\nu_{21}}{\sqrt{2}} & \frac{v_u Y^\nu_{22}}{\sqrt{2}} & \frac{v_u Y^\nu_{23}}{\sqrt{2}} \\
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-\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^\nu_{1i}}{\sqrt{2}} & \frac{v_{iR} Y^\nu_{2i}}{\sqrt{2}} & \frac{v_{iR} Y^\nu_{3i}}{\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^\nu_{i1}}{\sqrt{2}} & \frac{-v_d \lambda_2 + v_{iL} Y^\nu_{i2}}{\sqrt{2}} & \frac{-v_d \lambda_3 + v_{iL} Y^\nu_{i3}}{\sqrt{2}} \\
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0 & 0 & 0 & -\frac{g_1 v_{3L}}{\sqrt{2}} & \frac{g_2 v_{3L}}{\sqrt{2}} & 0 & \frac{v_{iR} Y^\nu_{3i}}{\sqrt{2}} & \frac{v_u Y^\nu_{31}}{\sqrt{2}} & \frac{v_u Y^\nu_{32}}{\sqrt{2}} & \frac{v_u Y^\nu_{33}}{\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^\nu_{1i}}{\sqrt{2}} & \frac{v_{iR} Y^\nu_{2i}}{\sqrt{2}} & \frac{v_{iR} Y^\nu_{3i}}{\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^\nu_{i1}}{\sqrt{2}} & \frac{-v_d \lambda_2 + v_{iL} Y^\nu_{i2}}{\sqrt{2}} & \frac{-v_d \lambda_3 + v_{iL} Y^\nu_{i3}}{\sqrt{2}} \\
\frac{v_u Y^\nu_{11}}{\sqrt{2}} & \frac{v_u Y^\nu_{21}}{\sqrt{2}} & \frac{v_u Y^\nu_{31}}{\sqrt{2}} & 0 & 0 & -\frac{v_u \lambda_1}{\sqrt{2}} & \frac{-v_d \lambda_1 + v_{iL} Y^\nu_{i1}}{\sqrt{2}} & \sqrt{2}\kappa_{11i} v_R & \sqrt{2}\kappa_{12i} v_R & \sqrt{2}\kappa_{13i} v_R \\
\frac{v_u Y^\nu_{12}}{\sqrt{2}} & \frac{v_u Y^\nu_{22}}{\sqrt{2}} & \frac{v_u Y^\nu_{32}}{\sqrt{2}} & 0 & 0 & -\frac{v_u \lambda_2}{\sqrt{2}} & \frac{-v_d \lambda_2 + v_{iL} Y^\nu_{i2}}{\sqrt{2}} & \sqrt{2}\kappa_{12i} v_R & \sqrt{2}\kappa_{22i} v_R & \sqrt{2}\kappa_{23i} v_R \\
\frac{v_u Y^\nu_{13}}{\sqrt{2}} & \frac{v_u Y^\nu_{23}}{\sqrt{2}} & \frac{v_u Y^\nu_{33}}{\sqrt{2}} & 0 & 0 & -\frac{v_u \lambda_3}{\sqrt{2}} & \frac{-v_d \lambda_3 + v_{iL} Y^\nu_{i3}}{\sqrt{2}} & \sqrt{2}\kappa_{13i} v_R & \sqrt{2}\kappa_{23i} v_R & \sqrt{2}\kappa_{33i} v_R
\end{pmatrix}$$

Neutrino physics

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

$$
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^\nu_{1i}}{\sqrt{2}} & \frac{v_u Y^\nu_{11}}{\sqrt{2}} & \frac{v_u Y^\nu_{12}}{\sqrt{2}} & \frac{v_u Y^\nu_{13}}{\sqrt{2}} \\
0 & 0 & 0 & -\frac{g_1 v_{2L}}{\sqrt{2}} & -\frac{g_2 v_{2L}}{\sqrt{2}} & 0 & \frac{v_{iR} Y^\nu_{2i}}{\sqrt{2}} & \frac{v_u Y^\nu_{21}}{\sqrt{2}} & \frac{v_u Y^\nu_{22}}{\sqrt{2}} & \frac{v_u Y^\nu_{23}}{\sqrt{2}} \\
0 & 0 & 0 & -\frac{g_1 v_{3L}}{\sqrt{2}} & -\frac{g_2 v_{3L}}{\sqrt{2}} & 0 & \frac{v_{iR} Y^\nu_{3i}}{\sqrt{2}} & \frac{v_u Y^\nu_{31}}{\sqrt{2}} & \frac{v_u Y^\nu_{32}}{\sqrt{2}} & \frac{v_u Y^\nu_{33}}{\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^\nu_{1i}}{\sqrt{2}} & \frac{v_{iR} Y^\nu_{2i}}{\sqrt{2}} & \frac{v_{iR} Y^\nu_{3i}}{\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^\nu_{i1}}{\sqrt{2}} & \frac{-v_d \lambda_2 + v_{iL} Y^\nu_{i2}}{\sqrt{2}} & \frac{-v_d \lambda_3 + v_{iL} Y^\nu_{i3}}{\sqrt{2}} \\
\frac{v_u Y^\nu_{11}}{\sqrt{2}} & \frac{v_u Y^\nu_{21}}{\sqrt{2}} & \frac{v_u Y^\nu_{31}}{\sqrt{2}} & 0 & 0 & -\frac{v_u \lambda_1}{\sqrt{2}} & \frac{-v_d \lambda_1 + v_{iL} Y^\nu_{i1}}{\sqrt{2}} & \sqrt{2}\kappa_{11i} v_R & \sqrt{2}\kappa_{12i} v_R & \sqrt{2}\kappa_{13i} v_R \\
\frac{v_u Y^\nu_{12}}{\sqrt{2}} & \frac{v_u Y^\nu_{22}}{\sqrt{2}} & \frac{v_u Y^\nu_{32}}{\sqrt{2}} & 0 & 0 & -\frac{v_u \lambda_2}{\sqrt{2}} & \frac{-v_d \lambda_2 + v_{iL} Y^\nu_{i2}}{\sqrt{2}} & \sqrt{2}\kappa_{12i} v_R & \sqrt{2}\kappa_{22i} v_R & \sqrt{2}\kappa_{23i} v_R \\
\frac{v_u Y^\nu_{13}}{\sqrt{2}} & \frac{v_u Y^\nu_{23}}{\sqrt{2}} & \frac{v_u Y^\nu_{33}}{\sqrt{2}} & 0 & 0 & -\frac{v_u \lambda_3}{\sqrt{2}} & \frac{-v_d \lambda_3 + v_{iL} Y^\nu_{i3}}{\sqrt{2}} & \sqrt{2}\kappa_{13i} v_R & \sqrt{2}\kappa_{23i} v_R & \sqrt{2}\kappa_{33i} v_R
\end{pmatrix}
$$

Neutrino physics

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

$$
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^\nu_{1i}}{\sqrt{2}} & \frac{v_u Y^\nu_{11}}{\sqrt{2}} & \frac{v_u Y^\nu_{12}}{\sqrt{2}} & \frac{v_u Y^\nu_{13}}{\sqrt{2}} \\
0 & 0 & 0 & -\frac{g_1 v_{2L}}{\sqrt{2}} & -\frac{g_2 v_{2L}}{\sqrt{2}} & 0 & \frac{v_{iR} Y^\nu_{2i}}{\sqrt{2}} & \frac{v_u Y^\nu_{21}}{\sqrt{2}} & \frac{v_u Y^\nu_{22}}{\sqrt{2}} & \frac{v_u Y^\nu_{23}}{\sqrt{2}} \\
0 & 0 & 0 & -\frac{g_1 v_{3L}}{\sqrt{2}} & -\frac{g_2 v_{3L}}{\sqrt{2}} & 0 & \frac{v_{iR} Y^\nu_{3i}}{\sqrt{2}} & \frac{v_u Y^\nu_{31}}{\sqrt{2}} & \frac{v_u Y^\nu_{32}}{\sqrt{2}} & \frac{v_u Y^\nu_{33}}{\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^\nu_{1i}}{\sqrt{2}} & \frac{v_{iR} Y^\nu_{2i}}{\sqrt{2}} & \frac{v_{iR} Y^\nu_{3i}}{\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^\nu_{i1}}{\sqrt{2}} & \frac{-v_d \lambda_2 + v_{iL} Y^\nu_{i2}}{\sqrt{2}} & \frac{-v_d \lambda_3 + v_{iL} Y^\nu_{i3}}{\sqrt{2}} \\
\frac{v_u Y^\nu_{11}}{\sqrt{2}} & \frac{v_u Y^\nu_{21}}{\sqrt{2}} & \frac{v_u Y^\nu_{31}}{\sqrt{2}} & 0 & 0 & -\frac{v_u \lambda_1}{\sqrt{2}} & \frac{-v_d \lambda_1 + v_{iL} Y^\nu_{i1}}{\sqrt{2}} & \sqrt{2}\kappa_{11i} v_R & \sqrt{2}\kappa_{12i} v_R & \sqrt{2}\kappa_{13i} v_R \\
\frac{v_u Y^\nu_{12}}{\sqrt{2}} & \frac{v_u Y^\nu_{22}}{\sqrt{2}} & \frac{v_u Y^\nu_{32}}{\sqrt{2}} & 0 & 0 & -\frac{v_u \lambda_2}{\sqrt{2}} & \frac{-v_d \lambda_2 + v_{iL} Y^\nu_{i2}}{\sqrt{2}} & \sqrt{2}\kappa_{12i} v_R & \sqrt{2}\kappa_{22i} v_R & \sqrt{2}\kappa_{23i} v_R \\
\frac{v_u Y^\nu_{13}}{\sqrt{2}} & \frac{v_u Y^\nu_{23}}{\sqrt{2}} & \frac{v_u Y^\nu_{33}}{\sqrt{2}} & 0 & 0 & -\frac{v_u \lambda_3}{\sqrt{2}} & \frac{-v_d \lambda_3 + v_{iL} Y^\nu_{i3}}{\sqrt{2}} & \sqrt{2}\kappa_{13i} v_R & \sqrt{2}\kappa_{23i} v_R & \sqrt{2}\kappa_{33i} v_R
\end{pmatrix}
$$

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

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

Neutrino physics

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

$$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^\nu_{1i}}{\sqrt{2}} & \frac{v_u Y^\nu_{11}}{\sqrt{2}} & \frac{v_u Y^\nu_{12}}{\sqrt{2}} & \frac{v_u Y^\nu_{13}}{\sqrt{2}} \\
0 & 0 & 0 & -\frac{g_1 v_{2L}}{\sqrt{2}} & -\frac{g_2 v_{2L}}{\sqrt{2}} & 0 & \frac{v_{iR} Y^\nu_{2i}}{\sqrt{2}} & \frac{v_u Y^\nu_{21}}{\sqrt{2}} & \frac{v_u Y^\nu_{22}}{\sqrt{2}} & \frac{v_u Y^\nu_{23}}{\sqrt{2}} \\
0 & 0 & 0 & -\frac{g_1 v_{3L}}{\sqrt{2}} & -\frac{g_2 v_{3L}}{\sqrt{2}} & 0 & \frac{v_{iR} Y^\nu_{3i}}{\sqrt{2}} & \frac{v_u Y^\nu_{31}}{\sqrt{2}} & \frac{v_u Y^\nu_{32}}{\sqrt{2}} & \frac{v_u Y^\nu_{33}}{\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^\nu_{1i}}{\sqrt{2}} & \frac{v_{iR} Y^\nu_{2i}}{\sqrt{2}} & \frac{v_{iR} Y^\nu_{3i}}{\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^\nu_{i1}}{\sqrt{2}} & \frac{-v_d\lambda_2 + v_{iL} Y^\nu_{i2}}{\sqrt{2}} & \frac{-v_d\lambda_3 + v_{iL} Y^\nu_{i3}}{\sqrt{2}} \\
\frac{v_u Y^\nu_{11}}{\sqrt{2}} & \frac{v_u Y^\nu_{21}}{\sqrt{2}} & \frac{v_u Y^\nu_{31}}{\sqrt{2}} & 0 & 0 & -\frac{v_u\lambda_1}{\sqrt{2}} & \frac{-v_d\lambda_1 + v_{iL} Y^\nu_{i1}}{\sqrt{2}} & \sqrt{2}\kappa_{11i} v_R & \sqrt{2}\kappa_{12i} v_R & \sqrt{2}\kappa_{13i} v_R \\
\frac{v_u Y^\nu_{12}}{\sqrt{2}} & \frac{v_u Y^\nu_{22}}{\sqrt{2}} & \frac{v_u Y^\nu_{32}}{\sqrt{2}} & 0 & 0 & -\frac{v_u\lambda_2}{\sqrt{2}} & \frac{-v_d\lambda_2 + v_{iL} Y^\nu_{i2}}{\sqrt{2}} & \sqrt{2}\kappa_{12i} v_R & \sqrt{2}\kappa_{22i} v_R & \sqrt{2}\kappa_{23i} v_R \\
\frac{v_u Y^\nu_{13}}{\sqrt{2}} & \frac{v_u Y^\nu_{23}}{\sqrt{2}} & \frac{v_u Y^\nu_{33}}{\sqrt{2}} & 0 & 0 & -\frac{v_u\lambda_3}{\sqrt{2}} & \frac{-v_d\lambda_3 + v_{iL} Y^\nu_{i3}}{\sqrt{2}} & \sqrt{2}\kappa_{13i} v_R & \sqrt{2}\kappa_{23i} v_R & \sqrt{2}\kappa_{33i} v_R
\end{pmatrix}$$

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

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

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

with

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

Higgs potential

Parts of $\mathcal{L}$ contributing:

$$W^{\text{Higgs}} = \epsilon_{ab}\left(Y^{\nu}_{ij}\,\hat{H}^b_u\,\hat{L}^a_i\,\hat{\nu}^c_j - \lambda_i\,\hat{\nu}^c_i\,\hat{H}^b_u\hat{H}^a_d\right) + \frac{1}{3}\kappa_{ijk}\hat{\nu}^c_i\hat{\nu}^c_j\hat{\nu}^c_k$$

$$\mathcal{L}^{\text{Higgs}}_{\text{soft}} = \epsilon_{ab}\left(T^{\nu}_{ij}\,H^b_u\,\widetilde{L}^a_{iL}\widetilde{\nu}^*_{jR} - T^{\lambda}_i\,\widetilde{\nu}^*_{iR}\,H^a_d H^b_u + \frac{1}{3}\,T^{\kappa}_{ijk}\,\widetilde{\nu}^*_{iR}\widetilde{\nu}^*_{jR}\widetilde{\nu}^*_{kR}\ + \text{h.c.}\right)$$
$$+\left(m^2_{\widetilde{L}_L}\right)_{ij}\widetilde{L}^{a*}_{iL}\widetilde{L}^a_{jL} + \left(m^2_{H_d\widetilde{L}_L}\right)_i H^{a*}_d\widetilde{L}^a_{iL} + \left(m^2_{\widetilde{\nu}_R}\right)_{ij}\widetilde{\nu}^*_R\widetilde{\nu}_R + m^2_{H_d}H^{a\,*}_d H^a_d + m^2_{H_u}H^{a\,*}_u H^a_u$$

Higgs potential

Parts of $\mathcal{L}$ contributing:

$$W^{\text{Higgs}} = \epsilon_{ab}\left(Y^{\nu}_{ij}\,\hat{H}^b_u\,\hat{L}^a_i\,\hat{\nu}^c_j - \lambda_i\,\hat{\nu}^c_i\,\hat{H}^b_u\hat{H}^a_d\right) + \frac{1}{3}\kappa_{ijk}\hat{\nu}^c_i\hat{\nu}^c_j\hat{\nu}^c_k$$

$$\mathcal{L}^{\text{Higgs}}_{\text{soft}} = \epsilon_{ab}\left(T^{\nu}_{ij}\,H^b_u\,\widetilde{L}^a_{iL}\widetilde{\nu}^*_{jR} - T^{\lambda}_i\,\widetilde{\nu}^*_{iR}\,H^a_dH^b_u + \frac{1}{3}T^{\kappa}_{ijk}\,\widetilde{\nu}^*_{iR}\widetilde{\nu}^*_{jR}\widetilde{\nu}^*_{kR} + \text{h.c.}\right)$$
$$+ \left(m^2_{\widetilde{L}_L}\right)_{ij}\widetilde{L}^{a*}_{iL}\widetilde{L}^a_{jL} + \left(m^2_{H_d\widetilde{L}_L}\right)_i H^{a*}_d\widetilde{L}^a_{iL} + \left(m^2_{\widetilde{\nu}_R}\right)_{ij}\widetilde{\nu}^*_R\widetilde{\nu}_R + m^2_{H_d}H^{a*}_dH^a_d + m^2_{H_u}H^{a*}_uH^a_u$$

$$\downarrow$$

- Absent in tree-level Lagrangian because it spoils the EW seesaw mechanism
  $\Rightarrow v_{iL} \to 0$ when $Y^{\nu}_{ij} \to 0$
- 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

Higgs potential

Parts of $\mathcal{L}$ contributing:

$$W^{\text{Higgs}} = \epsilon_{ab}\left(Y^{\nu}_{ij}\,\hat{H}^b_u\,\hat{L}^a_i\,\hat{\nu}^c_j - \lambda_i\,\hat{\nu}^c_i\,\hat{H}^b_u\hat{H}^a_d\right) + \frac{1}{3}\kappa_{ijk}\hat{\nu}^c_i\hat{\nu}^c_j\hat{\nu}^c_k$$

$$\mathcal{L}^{\text{Higgs}}_{\text{soft}} = \epsilon_{ab}\left(T^{\nu}_{ij}\,H^b_u\,\widetilde{L}^a_{iL}\widetilde{\nu}^*_{jR} - T^{\lambda}_i\,\widetilde{\nu}^*_{iR}\,H^a_dH^b_u + \frac{1}{3}T^{\kappa}_{ijk}\,\widetilde{\nu}^*_{iR}\widetilde{\nu}^*_{jR}\widetilde{\nu}^*_{kR}\;+\text{h.c.}\right)$$
$$+\left(m^2_{\widetilde{L}_L}\right)_{ij}\widetilde{L}^{a*}_{iL}\widetilde{L}^a_{jL} + \left(m^2_{H_d\widetilde{L}_L}\right)_i H^{a*}_d\widetilde{L}^a_{iL} + \left(m^2_{\widetilde{\nu}_R}\right)_{ij}\widetilde{\nu}^*_R\widetilde{\nu}_R + m^2_{H_d}H^{a*}_dH^a_d + m^2_{H_u}H^{a*}_uH^a_u$$

$\downarrow$

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

Assuming CP-conservation:

$$H^0_d = \frac{1}{\sqrt{2}}\left(H^{\mathcal{R}}_d + v_d + \text{i}\;H^{\mathcal{I}}_d\right)\;, \qquad H^0_u = \frac{1}{\sqrt{2}}\left(H^{\mathcal{R}}_u + v_u + \text{i}\;H^{\mathcal{I}}_u\right)$$

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

Higgs potential

Parts of $\mathcal{L}$ contributing:

$$W^{\text{Higgs}} = \epsilon_{ab} \left(Y^{\nu}_{ij} \, \hat{H}^b_u \, \hat{L}^a_i \, \hat{\nu}^c_j - \lambda_i \, \hat{\nu}^c_i \, \hat{H}^b_u \hat{H}^a_d \right) + \frac{1}{3} \kappa_{ijk} \hat{\nu}^c_i \hat{\nu}^c_j \hat{\nu}^c_k$$

$$\mathcal{L}^{\text{Higgs}}_{\text{soft}} = \epsilon_{ab} \left(T^{\nu}_{ij} \, H^b_u \, \widetilde{L}^a_{iL} \widetilde{\nu}^*_{jR} - T^{\lambda}_i \, \widetilde{\nu}^*_{iR} \, H^a_d H^b_u + \frac{1}{3} T^{\kappa}_{ijk} \, \widetilde{\nu}^*_{iR} \widetilde{\nu}^*_{jR} \widetilde{\nu}^*_{kR} \; + \text{h.c.} \right)$$
$$+ \left(m^2_{\widetilde{L}_L} \right)_{ij} \widetilde{L}^{a*}_{iL} \widetilde{L}^a_{jL} + \left(m^2_{H_d \widetilde{L}_L} \right)_i H^{a*}_d \widetilde{L}^a_{iL} + \left(m^2_{\widetilde{\nu}_R} \right)_{ij} \widetilde{\nu}^*_R \widetilde{\nu}_R + m^2_{H_d} H^{a*}_d H^a_d + m^2_{H_u} H^{a*}_u H^a_u$$

$$\downarrow$$

- Absent in tree-level Lagrangian because it spoils the EW seesaw mechanism
  $\Rightarrow v_{iL} \rightarrow 0$ when $Y^{\nu}_{ij} \rightarrow 0$
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Assuming CP-conservation:

$$H^0_d = \frac{1}{\sqrt{2}} \left(H^{\mathcal{R}}_d + v_d + \mathrm{i} \; H^{\mathcal{I}}_d \right) \; , \qquad H^0_u = \frac{1}{\sqrt{2}} \left(H^{\mathcal{R}}_u + v_u + \mathrm{i} \; H^{\mathcal{I}}_u \right)$$

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

Parameter counting:

Total: 69 needed for renormalization

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

Higgs potential

Replacements:

- $m_{H_d}^2,\ m_{H_u}^2,\ \left(m_{\widetilde{L}_L}^2\right)_{ii},\ \left(m_{\widetilde{\nu}_R}^2\right)_{ii} \xrightarrow{\text{Tadpole eq.}} T_{H_d^{\mathcal{R}}},\ T_{H_u^{\mathcal{R}}},\ T_{\widetilde{\nu}_{iL}^{\mathcal{R}}},\ T_{\widetilde{\nu}_{iR}^{\mathcal{R}}}$
- $v_d,\ v_u \to \tan\beta,\ v$ with $\tan\beta = \frac{v_u}{v_d},\ v^2 = v_u^2 + v_d^2 + v_{iL}v_{iL}$
- $g_1,\ g_2 \to M_W^2,\ M_Z^2$ 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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Tree-level upper bound on the lightest Higgs mass:

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

Renormalization scheme

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

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

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

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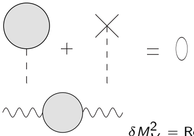

$$\delta M_V^2 = \mathrm{Re}\,\Sigma^T\left(M_V^2\right)$$

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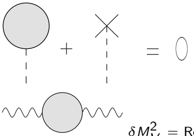

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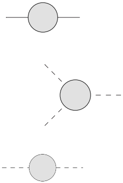
$\overline{\mathrm{DR}}$ parameters:

$$m^2_{\tilde{L}_{L\,i\neq j}} \to m^2_{\tilde{L}_{L\,i\neq j}} + \delta m^2_{\tilde{L}_{L\,i\neq j}} \,, \qquad v^2 \to v^2 + \delta v^2 \,, \qquad Y^\nu_{ij} \to Y^\nu_{ij} + \delta Y^\nu_{ij} \,,$$
$$m^2_{H_d \tilde{L}_{L\,i}} \to m^2_{H_d \tilde{L}_{L\,i}} + \delta m^2_{H_d \tilde{L}_{L\,i}} \,, \qquad v^2_{iR} \to v^2_{iR} + \delta v^2_{iR} \,, \qquad T^\lambda_i \to T^\lambda_i + \delta T^\lambda_i \,,$$
$$m^2_{\tilde{\nu}_{R\,i\neq j}} \to m^2_{\tilde{\nu}_{R\,i\neq j}} + \delta m^2_{\tilde{\nu}_{R\,i\neq j}} \,, \qquad v^2_{iL} \to v^2_{iL} + \delta v^2_{iL} \,, \qquad T^\kappa_{ijk} \to T^\kappa_{ijk} + \delta T^\kappa_{ijk} \,,$$
$$\tan\beta \to \tan\beta + \delta\tan\beta \,, \qquad \lambda_i \to \lambda_i + \delta\lambda_i \,, \qquad T^\nu_{ij} \to T^\nu_{ij} + \delta T^\nu_{ij} \,.$$
$$\kappa_{ijk} \to \kappa_{ijk} + \delta\kappa_{ijk} \,,$$

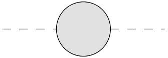


Details in: TB, Heinemeyer, Munoz [hep-ph/1712.07475]

Loop-correction to scalar masses

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

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



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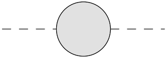

Fixed-order Feynman-diagrammatic calculation:

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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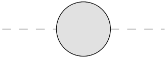

Fixed-order Feynman-diagrammatic calculation:

Advantages: All contribution of the order included
Full control of scalar self-energies (momentum-dependence)
Many scales included

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

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

$\hat{\Sigma}_h^{(1)}$: 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

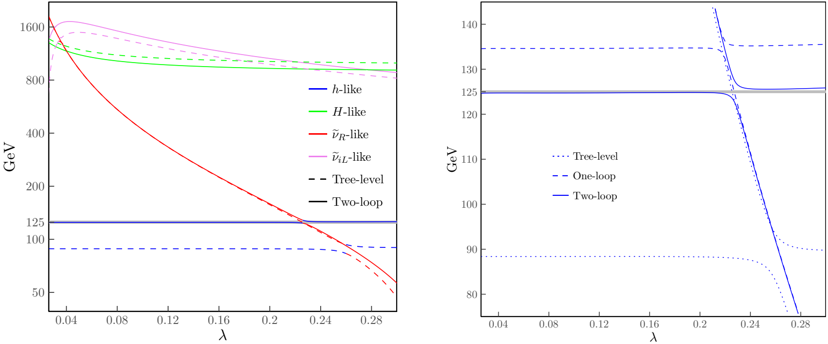
$\hat{\Sigma}_h^{\mathrm{resum}}$: Resummation of large logs from FeynHiggs v. 2.13

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

$$v_{iL}/\sqrt{2} = 10^{-4}\ \mathrm{GeV} \qquad \tan\beta = 8 \qquad A^{\kappa} = -300\ \mathrm{GeV}$$

$$Y_i^{\nu} = 10^{-6} \qquad \mu = 125\ \mathrm{GeV} \qquad A^{t} = -2000\ \mathrm{GeV}$$

$$A_i^{\nu} = -1000\ \mathrm{GeV} \qquad \kappa = 0.2 \qquad A^{b} = -1500\ \mathrm{GeV}$$



⇒ 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

$$m^2_{\widetilde{\nu}^{\mathcal{R}}_{iL}\widetilde{\nu}^{\mathcal{R}}_{iL}} \approx \frac{Y^\nu_i v_R v_u}{2 v_{iL}} \left(-\sqrt{2} A^\nu_i - \kappa v_R + \frac{\sqrt{2}\mu}{\tan\beta} \right) \Rightarrow$$

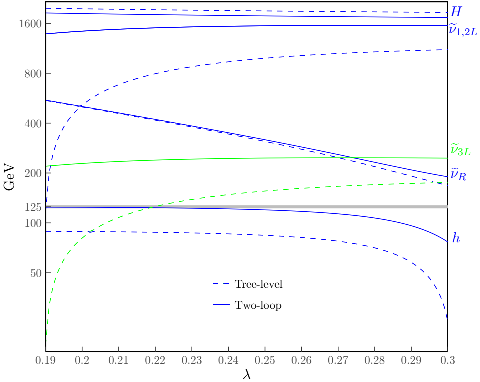
$$v_{1,2L}/\sqrt{2} = 10^{-5}\ \mathrm{GeV} \qquad \tan\beta = 10$$

$$v_{3L}/\sqrt{2} = 4 \cdot 10^{-4}\ \mathrm{GeV} \qquad \mu = 270\ \mathrm{GeV}$$

$$Y^\nu_i = 5 \cdot 10^{-7} \qquad \kappa = 0.3$$

$$A^\nu_i = -400\ \mathrm{GeV} \qquad A^\kappa = -1000\ \mathrm{GeV}$$

Benchmark point studied in:
Ghosh, Lara, Lopez-Fogliani, Munoz, Ruiz de Austri
[hep-ph/1707.02471]

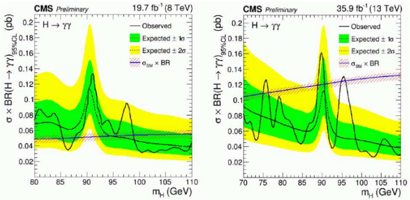


$$\delta m^{2\,\mathrm{fin}}_{\widetilde{\nu}^{\mathcal{R}}_{iL}\widetilde{\nu}^{\mathcal{R}}_{iL}} = -\frac{\delta T^{\mathrm{fin}}_{\widetilde{\nu}_{iL}}}{v_{iL}} + \cdots$$

$\Rightarrow$ Light left-handed sneutrinos get huge loop corrections

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

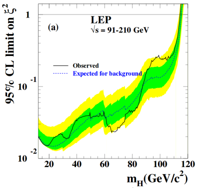
Can we explain an excess at ~ 96 GeV of LEP and CMS?



from [CMS PAS HIG-17-013]

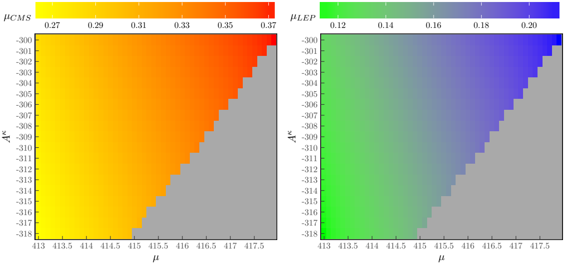
$\mu_{CMS}\,(gg \to h \to \gamma\gamma) = 0.6 \pm 0.2$

from [hep-ex/0306033]



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

Value from [arXiv:1612.08522]



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

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

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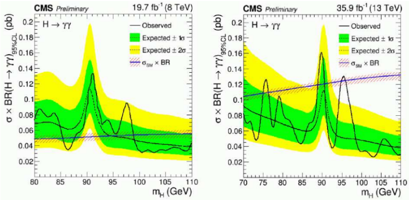

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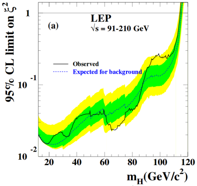

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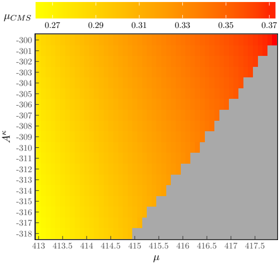

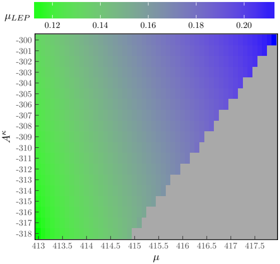

Details in: TB, Heinemeyer, Munoz [hep-ph/1712.07475]

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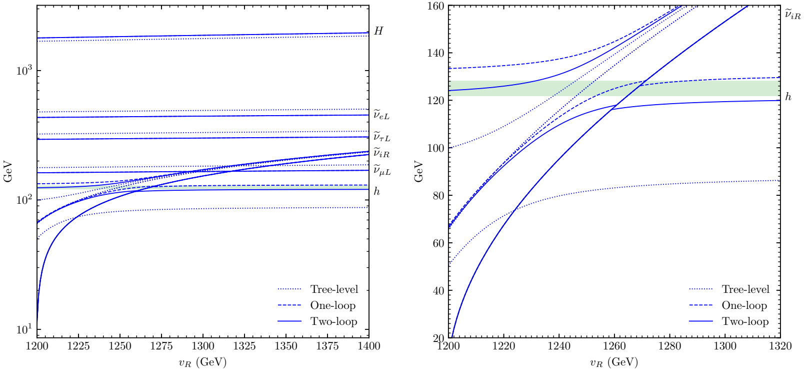
However: Atlas update from ICHEP $\Rightarrow$ no excess in diphoton channel

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:



$$v_{iR} = v_R \qquad \tan\beta = 11 \quad \lambda_i = 0.08 \quad \kappa_{iii} = 0.3$$

$$A_i^{\lambda} = 1000 \text{ GeV} \quad A_{ii}^{\nu} = -1000 \text{ GeV} \quad A_{iii}^{\kappa} = -1000 \text{ GeV}$$

$$A^t = -2000 \text{ GeV} \quad A^b = -1500 \text{ GeV} \quad A^{\tau} = -1000 \text{ GeV}$$

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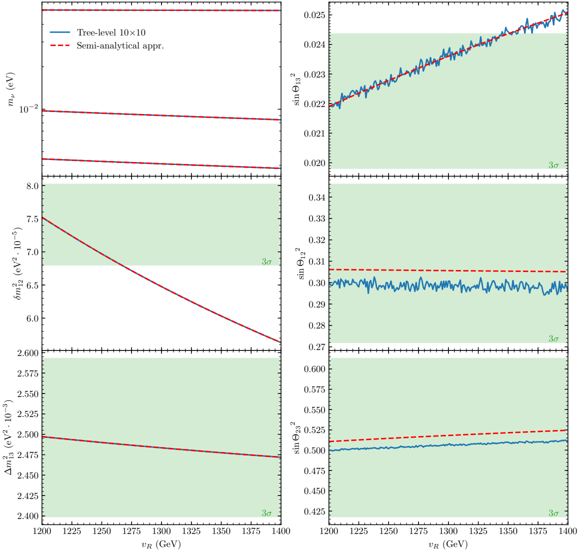


$$\delta m_{12}^2 = (7.41 \pm 0.61) \cdot 10^{-5}\ \text{eV}^2$$
$$\Delta m_{13}^2 = (2.4655 \pm 0.0965) \cdot 10^{-3}\ \text{eV}^2$$
$$\sin^2\Theta_{13} = 0.022085 \pm 0.002275$$
$$\sin^2\Theta_{12} = 0.309 \pm 0.037$$
$$\sin^2\Theta_{23} = 0.5155 \pm 0.0975$$

from NuFIT '18 results

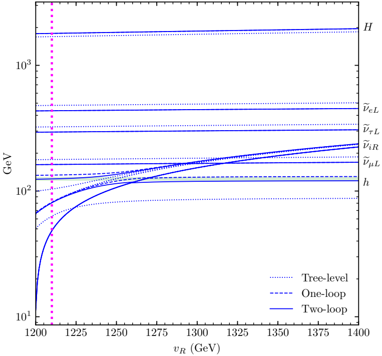
$$v_{1L} = 2.45 \cdot 10^{-4}\ \text{GeV}$$
$$v_{2L} = 9.73 \cdot 10^{-4}\ \text{GeV}$$
$$v_{3L} = 7.71 \cdot 10^{-4}\ \text{GeV}$$

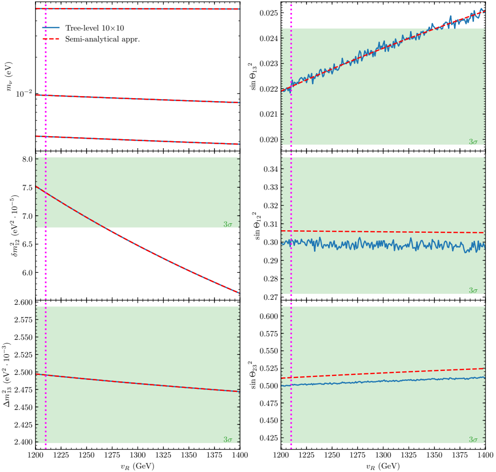
$$Y_{11}^\nu = 3.52 \cdot 10^{-7}$$
$$Y_{22}^\nu = 1.93 \cdot 10^{-7}$$
$$Y_{33}^\nu = 5.06 \cdot 10^{-7}$$

$$M_1 = 3011\ \text{GeV}$$
$$M_2 = 6000\ \text{GeV}$$

How restrictive are neutrino limits?

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

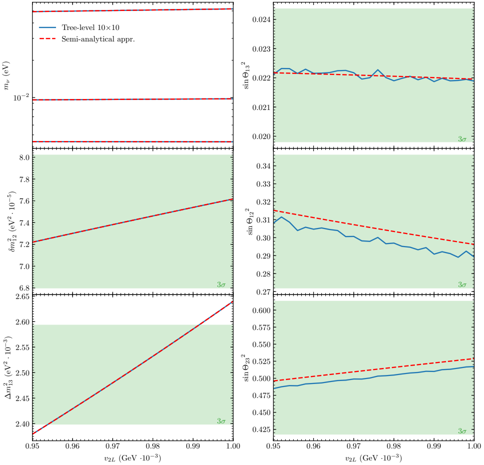


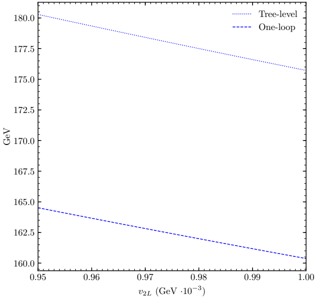


How restrictive are neutrino limits?

Best-fit point: $v_R \sim 1210\ \mathrm{GeV}$

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



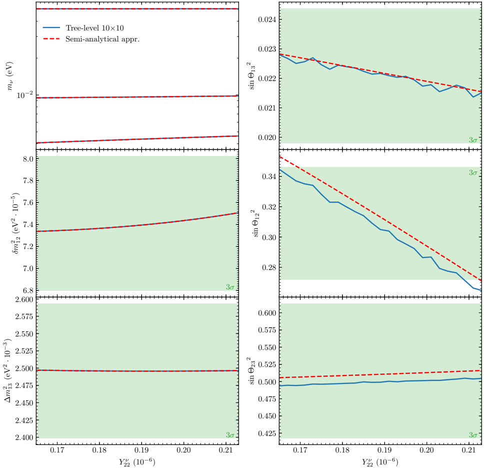


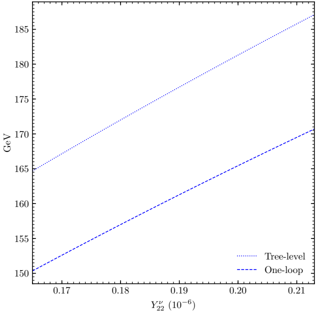
1.: 160 GeV $< m_{\widetilde{\nu}_{\mu L}} <$ 165 GeV

How restrictive are neutrino limits?

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

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





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

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

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

$$
\begin{aligned}
T_{H_u^{\mathcal{R}}} = &- m^2_{H_u} v_u + \frac{1}{8}\left(g_1^2 + g_2^2\right) v_u \left(v_d^2 + v_{iL} v_{iL} - v_u^2\right) \\
&- \frac{1}{2} v_d^2 v_u \lambda_i \lambda_i + \frac{1}{\sqrt{2}} v_d v_{iR} T_i^{\lambda} + v_d v_u Y^{\nu}_{ji} \lambda_i v_{jL} - \frac{1}{\sqrt{2}} v_{iL} T^{\nu}_{ij} v_{jR} - \frac{1}{2} v_u v_{iR} \lambda_i v_{jR} \lambda_j \\
&- \frac{1}{2} v_u Y^{\nu}_{ji} Y^{\nu}_{ki} v_{jL} v_{kL} - \frac{1}{2} v_u Y^{\nu}_{ij} Y^{\nu}_{ik} v_{jR} v_{kR} + \frac{1}{2} v_d \kappa_{ijk} \lambda_i v_{jR} v_{kR} - \frac{1}{2} Y^{\nu}_{li} \kappa_{ikj} v_{jR} v_{kR} v_{lL} \ , \qquad (2)
\end{aligned}
$$

$$
\begin{aligned}
T_{\widetilde{\nu}_{iR}^{\mathcal{R}}} = &- \left(m^2_{\widetilde{\nu}_R}\right)_{ij} v_{jR} - \frac{1}{\sqrt{2}} v_u v_{jL} T^{\nu}_{ji} - \frac{1}{2} v_u^2 Y^{\nu}_{ji} Y^{\nu}_{jk} v_{kR} + v_d v_u \kappa_{ijk} \lambda_j v_{kR} - \frac{1}{\sqrt{2}} T^{\kappa}_{ijk} v_{jR} v_{kR} \\
&+ \frac{1}{2} v_d v_{jL} Y^{\nu}_{ji} v_{kR} \lambda_k - v_u Y^{\nu}_{lj} \kappa_{ijk} v_{kR} v_{lL} - \frac{1}{2} v_{jL} Y^{\nu}_{ji} v_{kL} Y^{\nu}_{kl} v_{lR} - \kappa_{ijm} \kappa_{jlk} v_{kR} v_{lR} v_{mR} \\
&- \frac{1}{2}\left(v_d^2 + v_u^2\right) \lambda_i \lambda_j v_{jR} + \frac{1}{2} v_d v_{jL} Y^{\nu}_{jk} v_{kR} \lambda_i + \frac{1}{\sqrt{2}} v_d v_u T_i^{\lambda} \ , \qquad (3)
\end{aligned}
$$

$$
\begin{aligned}
T_{\widetilde{\nu}_{iL}^{\mathcal{R}}} = &- \left(m^2_{\widetilde{L}_L}\right)_{ij} v_{jL} - \left(m^2_{H_d \widetilde{L}_L}\right)_i v_d - \frac{1}{8}\left(g_1^2 + g_2^2\right) v_{iL} \left(v_d^2 + v_{jL} v_{jL} - v_u^2\right) \\
&+ \frac{1}{2} v_d v_u^2 Y^{\nu}_{ij} \lambda_j - \frac{1}{\sqrt{2}} v_u v_{jR} T^{\nu}_{ij} - \frac{1}{2} v_u^2 Y^{\nu}_{ij} Y^{\nu}{}_{kj} v_{kL} + \frac{1}{2} v_d v_{jR} Y^{\nu}_{ij} v_{kR} \lambda_k \\
&- \frac{1}{2} v_u Y^{\nu}_{ij} \kappa_{jkl} v_{kR} v_{lR} - \frac{1}{2} v_{jR} Y^{\nu}_{ij} v_{kL} Y^{\nu}_{kl} v_{lR} \ . \qquad (4)
\end{aligned}
$$

Renormalization scheme

$\overline{\mathrm{DR}}$ **field renormalization:**

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

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

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

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

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

$$\delta Z_{2+a,2+b} = -\frac{\Delta}{16\pi^2} \left(\kappa_{aij} \kappa_{bij} + \lambda_a \lambda_b + Y^{\nu}_{ia} Y^{\nu}_{ib} \right)$$

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