M_h in the MSSM-seesaw with ILC precision

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S.H., M. J. Herrero, S.P., A.M. Rodriguez-Sanchez, arXiv:1007.5512v2 [hep-ph], JHEP05 (2011) 063

1. Motivations
2. MSSM-seesaw framework and Neutrino physics
   - MSSM-Seesaw model
   - Seesaw model for one generation neutrinos/sneutrinos
   - Sneutrino and Higgs boson sectors
   - Renormalization prescription
3. One Loop $\nu/\tilde{\nu}$ corrections to m_h : Results
   - $\Delta m_h^{\mathrm{m}\overline{\mathrm{DR}}} = M_h^{\nu/\tilde{\nu}} - M_h$
4. Conclusions

Motivations: Hunting the Higgs

- The mechanism of EWSB is still unknown
- The Higgs mass will be a precision observable
- Prospects in precision meaurements on the SM-like Higgs boson mass

  LHC: $\Delta m_h \approx 0.2$ GeV

  ILC: $\Delta m_h \approx 0.05$ GeV
- Global fit to all SM data:
  - The combinations from the LEPEWWG are used to perform stringent tests the Standard Model of particle physics by comparing the precise results with theory predictions.
  - The constraint on the mass of the Higgs boson is of particular interest

Motivations: Higgs mass corrections

- SUSY: Contrary to the SM: m_h is not a free parameter
- MSSM tree-level bound:
  $m_h < M_Z$, excluded by LEP Higgs searches
- Large radiative corrections:
  - Dominant one-loop corrections (Yukawa sector): $\sim G_F m_t^4 \ln\left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}\right)$
  - Higgs boson mass have been computed with very good precision at one, two loop level...
  - 2-loop corrections: $m_h < 135$ GeV
- Measurement of m_h, Higgs couplings $\Rightarrow$ test of the theory

Present work:

MSSM-seesaw scenario: MSSM + massive right handed neutrinos and their supersymmetric partners

How can the massive neutrinos affect m_h?

MSSM-Seesaw model

- Neutrino mass and mixing and Neutrino Oscillations requires new physics beyond the standard model
- Seesaw solution: Add right handed neutrinos to SM with Majorana mass
- MSSM-Seesaw model: MSSM + massive right handed neutrinos and their SUSY partners
- A seesaw mechanism of type I is implemented to generate the neutrino masses and mixing angle
- SUSY version of type I seesaw model:
  - Smallness of neutrino masses
  - Stabilizing EW scale without fine-tuning
  - Providing a natural candidate for a dark matter
  - Grand unification of SU(3)xSU(2)xU(1)
- Present work:

  For simplicity we restrict to the one generation neutrinos/sneutrinos case (three generations for a future work)

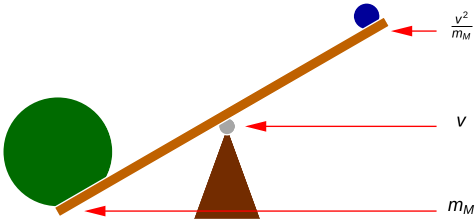
Seesaw model for one generation neutrinos

$$-\mathcal{L}_\nu = \frac{1}{2} \begin{pmatrix} \overline{\nu_L} & \overline{\nu_R^c} \end{pmatrix} \begin{pmatrix} 0 & m_D \\ m_D & m_M \end{pmatrix} \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix} . \qquad m_D = Y_\nu v_2$$

$$\nu = \nu^c = \cos\theta(\nu_L + (\nu_L)^c) - \sin\theta(\nu_R + (\nu_R)^c) ,$$

$$N = N^c = \sin\theta(\nu_L + (\nu_L)^c) + \cos\theta(\nu_R + (\nu_R)^c)$$

$$m_{\nu,N} = \frac{1}{2}\left(m_M \mp \sqrt{m_M^2 + 4m_D^2}\right) \xrightarrow[m_D < m_M]{} \begin{cases} m_\nu \sim -\frac{m_D^2}{m_M} \text{ (light)} \\ m_N \sim m_M \text{ (heavy)} \end{cases}$$



If $m_M \sim 10^{14}$ GeV one can get $m_\nu \sim 0.1$ eV with $Y_\nu \sim \mathcal{O}(1)$

Sneutrino sector/masses

$$W_{MSSM+\nu\tilde{\nu}} = \epsilon_{ij}\left[\mu H_1^i H_2^j + Y_\nu \hat{H}_2^i \hat{L}^j \hat{N}\right] + \frac{1}{2}\hat{N}\, m_M\, \hat{N}\,;\hat{N} = (\tilde{\nu}_R^*, (\nu_R)^c)$$

$$V_{\rm soft}^{\tilde{\nu}} = m_{\tilde{L}}^2 \tilde{\nu}_L^* \tilde{\nu}_L + m_{\tilde{R}}^2 \tilde{\nu}_R^* \tilde{\nu}_R + (Y_\nu A_\nu H_2^2 \tilde{\nu}_L \tilde{\nu}_R^* + m_M B_\nu \tilde{\nu}_R \tilde{\nu}_R + {\rm h.c.})\,.$$

$$\mathcal{L}_{\tilde{\nu} H} = \begin{cases} -\frac{g m_D m_M}{2 M_W \sin\beta}\left[(\tilde{\nu}_L \tilde{\nu}_R + \tilde{\nu}_L^* \tilde{\nu}_R^*)(H \sin\alpha + h\cos\alpha)\right] \\ -i\,\frac{g m_D m_M}{2 M_W \sin\beta}\left[(\tilde{\nu}_L \tilde{\nu}_R - \tilde{\nu}_L^* \tilde{\nu}_R^*) A\cos\beta\right] \\ +\text{usual int. terms } \tilde{f}\tilde{f}h_i,\ \tilde{f}\tilde{f}h_i h_i \end{cases}$$

$$\text{4 mass eigenstates} \begin{cases} \tilde{\nu}_+, \tilde{N}_+ \rightarrow \text{CP even} \\ \tilde{\nu}_-, \tilde{N}_- \rightarrow \text{CP odd} \end{cases}$$

$$m^2_{\tilde{\nu}_+,\tilde{\nu}_-} = m^2_{\tilde{L}} + \frac{1}{2} M_Z^2 \cos 2\beta \mp 2 m_D^2 (A_\nu - \mu\cot\beta - B_\nu)/m_M\,,$$

$$m^2_{\tilde{N}_+,\tilde{N}_-} = m_M^2 \pm 2 B_\nu m_M + m^2_{\tilde{R}} + 2 m_D^2\,.$$

seesaw limit: $m_M >> $ all the other scales involved

- The Higgs sector content in the MSSM-seesaw is as in the MSSM

$$\begin{aligned} \text{3 neutral bosons} &: h, H\ (\mathcal{CP}=+1), A\ (\mathcal{CP}=-1) \\ \text{2 charged bosons} &: H^+, H^- \end{aligned}$$

two ind. parameters $\rightarrow \tan\beta = v_2/v_1$ and $M_A{}^2 = -m_{12}^2(\tan\beta + \cot\beta)$

$$m^2_{H,h\ \mathrm{tree}} = \frac{1}{2}\left[M_A^2 + M_Z^2 \pm \sqrt{(M_A^2+M_Z^2)^2 - 4M_Z^2M_A^2\cos^2 2\beta}\right]$$

$$m^2_{h\ \mathrm{tree}} \leq M_Z|\cos 2\beta| \leq M_Z \qquad m^2_{h_{\mathrm{SM}}} = \frac{1}{2}\lambda v^2$$

- Higher-order corrections to m_h

$M_h, M_H \rightarrow$ poles of the propagator matrix $\rightarrow$ solution of the eq:

$$\left[p^2 - m^2_{h\ \mathrm{tree}} + \hat{\Sigma}_{hh}(p^2)\right]\left[p^2 - m^2_{H\ \mathrm{tree}} + \hat{\Sigma}_{HH}(p^2)\right] - \left[\hat{\Sigma}_{hH}(p^2)\right]^2 = 0$$

$$\hat{\Sigma}_{hh}(p^2) = \Sigma_{hh}(p^2) + \delta Z_{hh}(p^2 - m^2_{h,\mathrm{tree}}) - \delta m_h^2$$

$$\delta m_h^2 = f(\delta M_A^2, \delta M_Z^2, \delta T_H, \delta T_h, \delta\tan\beta)$$

Renormalization conditions

Different Renormalization schemes adopted

- OS

$$\hat{\Sigma}'_{hh}(m^2_{h,\text{tree}}) = 0 \;\Rightarrow \delta Z^{\text{OS}}_{\mathcal{H}_2} = -\,\text{Re}\,\Sigma'_{hh}\,_{|\alpha=0}$$

$$\hat{\Sigma}'_{HH}(m^2_{H,\text{tree}}) = 0 \;\Rightarrow \delta Z^{\text{OS}}_{\mathcal{H}_1} = -\,\text{Re}\,\Sigma'_{HH}\,_{|\alpha=0}$$

$$\delta\tan\beta^{\,\text{OS}} = \frac{1}{2}\left(\delta Z^{\text{OS}}_{\mathcal{H}_2} - \delta Z^{\text{OS}}_{\mathcal{H}_1}\right) \;.$$

too large corrections in the MSSM $\Rightarrow$ big higher order corrections

JHEP 0702(2007)047, Heinemeyer, Frank, Hollik, Weiglein

gauge dependent corrections at the one-loop level (Phys.Rev.D 66, Freitas,Stockinger)

- $\overline{\text{DR}}$

$$\delta Z^{\overline{\text{DR}}}_{\mathcal{H}_1} = \left[\delta Z^{\text{OS}}_{\mathcal{H}_1}\right]^{\text{div}},\, \delta Z^{\overline{\text{DR}}}_{\mathcal{H}_2} = \left[\delta Z^{\text{OS}}_{\mathcal{H}_2}\right]^{\text{div}}$$

$$\delta\tan\beta^{\,\overline{\text{DR}}} = \frac{1}{2}\left(\delta Z^{\overline{\text{DR}}}_{\mathcal{H}_2} - \delta Z^{\overline{\text{DR}}}_{\mathcal{H}_1}\right) \;.$$

$$[\;]^{\text{div}}\text{terms} \propto \Delta \equiv 2/\varepsilon - \gamma_{\text{E}} + \log(4\pi)$$

The renormalization scale, $\mu_{\overline{\text{DR}}}$ has to be set

- m$\overline{\text{DR}}$ $[\;]^{\text{div}}$ terms $\propto \Delta_m \equiv \Delta - \log(m_M^2/\mu^2_{\overline{\text{DR}}}) \to \mu_{\overline{\text{DR}}} = m_M$

Present work: One Loop Calculation to m_h

S.H., M. J. Herrero, S.P., A.M. Rodriguez-Sanchez, arXiv:1007.5512v2 [hep-ph]

- One-loop $\nu/\tilde{\nu}$ corrections to $\hat{\Sigma}^{\nu/\tilde{\nu}}_{hh}$, $\hat{\Sigma}^{\nu/\tilde{\nu}}_{HH}$ and $\hat{\Sigma}^{\nu/\tilde{\nu}}_{hH}$ with Feynarts and FormCalc

  http://www.feynarts.de/ by Thomas Hahn

- New Feynman rules neu/sneu sector in an available model file
- One point functions and two point functions involved
- Cancellation of divergences in OS,$\overline{\mathrm{DR}}$,m$\overline{\mathrm{DR}}$
- Yukawa and gauge contributions

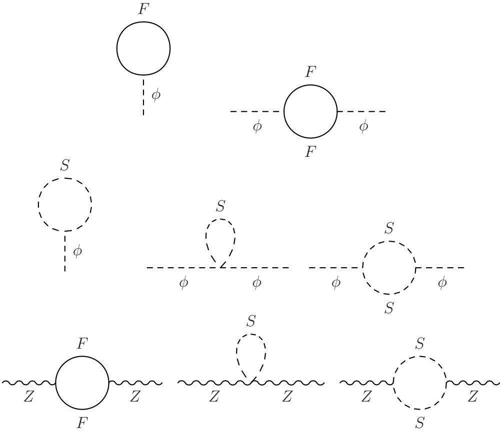
$$\hat{\Sigma}(p^2)|_{\mathrm{full}} = \hat{\Sigma}(p^2)|_{\mathrm{gauge}} + \hat{\Sigma}(p^2)|_{\mathrm{Yukawa}} \; ; \hat{\Sigma}(p^2)|_{\mathrm{gauge}} = \hat{\Sigma}(p^2)|_{\mathrm{MSSM}}$$

- Study seesaw limit $m_D << m_M$ and Dirac limit $m_M = 0$
- Calculation of the new Higgs corrections $\Delta m_h^{\mathrm{m}\overline{\mathrm{DR}}}$ coming from the $\nu/\tilde{\nu}$ sector:

$$\Delta m_h^{\mathrm{m}\overline{\mathrm{DR}}} = M_h^{\nu/\tilde{\nu}} - M_h$$

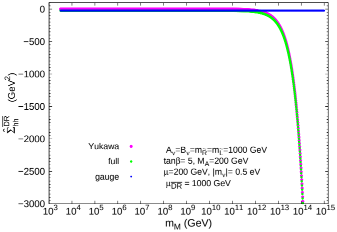
One Loop Calculation to m_h

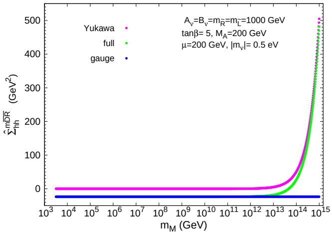
- Set of one-loop Feynman diagrams:

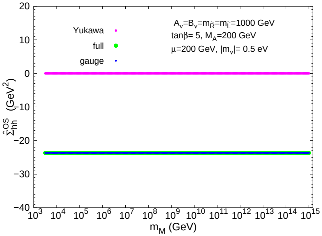


- Parameters of the MSSM-Seesaw: m_M, $\tan\beta$, M_A, $\mu, A_\nu, m_{\tilde{L}}$, $m_{\tilde{R}}$, m_ν, B_ν and p

Results: Dependence of $\hat{\Sigma}_{hh}$ on m_M







- For $10^3 < m_M < 10^{12}$ GeV $\rightarrow$ $\hat{\Sigma}_{hh}^{\overline{\rm DR}} = \hat{\Sigma}_{hh}^{\rm OS} = \hat{\Sigma}_{hh}^{m\overline{\rm DR}} \rightarrow$ gauge
- For $m_M > 10^{12}$ GeV very different behaviour :

- $\hat{\Sigma}_{hh}^{\rm OS} \sim \hat{\Sigma}_{hh}^{\rm OS}|_{\rm gauge}$, no dependence with m_M
- $\hat{\Sigma}_{hh}^{m\overline{\rm DR}}$ grow with m_M due to $Y_\nu \propto \sqrt{m_M}$
- $\hat{\Sigma}_{hh}^{\overline{\rm DR}}$ has huge growing with m_M due to $Y_\nu \propto \sqrt{m_M}$ and extra $\log(m_M/\mu_{\overline{\rm DR}})$

The seesaw limit

- expansion of $\hat{\Sigma}^{\overline{\rm DR}}_{hh}, \hat{\Sigma}^{\rm OS}_{hh}, \hat{\Sigma}^{m\overline{\rm DR}}_{hh}$ in powers of the seesaw parameter $\xi = \frac{m_D}{m_M}$

$$\hat{\Sigma}(p^2) = \underbrace{\left(\hat{\Sigma}(p^2)\right)_{m_D^0}}_{\text{gauge-MSSM}} + \underbrace{\left(\hat{\Sigma}(p^2)\right)_{m_D^2} + \left(\hat{\Sigma}(p^2)\right)_{m_D^4} + \ldots}_{\text{Yukawa}} .$$

- $A_\nu = \mu = B_\nu = 0$ and universal SOFT SUSY masses $m_{\tilde{L}} = m_{\tilde{R}} = m_{\rm SUSY}$
- expand in powers of $\frac{M_Z}{m_M}$, $\frac{M_A}{m_M}$, $\frac{p}{m_M}$ and $\frac{m_{\rm SUSY}}{m_M}$
- The main difference between the OS scheme and the $\overline{\rm DR}$/m$\overline{\rm DR}$ schemes appears in the Yukawa part, especially in the term of $\mathcal{O}(m_D^2)$

O(m_D^2) relevant term

$$\left(\hat{\Sigma}_{hh}^{\overline{\rm DR}}(p^2)\right)_{m_D^2} = \left(\frac{g^2 m_D^2}{64\pi^2 M_W^2 \sin^2\beta}\right)\left[1 - \log\left(\frac{m_M^2}{\mu_{\overline{\rm DR}}^2}\right)\right]\left[-2M_A^2\cos^2(\alpha-\beta)\cos^2\beta\right.$$
$$\left. + 2p^2\cos^2\alpha - M_Z^2 \sin\beta\sin(\alpha+\beta)\left(2\left(1+\cos^2\beta\right)\cos\alpha - \sin 2\beta\sin\alpha\right)\right]$$

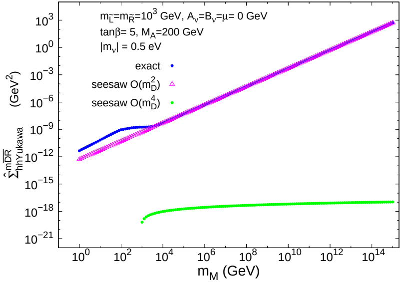
$$\left(\hat{\Sigma}_{hh}^{{\rm m}\overline{\rm DR}}(p^2)\right)_{m_D^2} = \left(\hat{\Sigma}_{hh}^{\overline{\rm DR}}(p^2)\right)_{m_D^2}\Big|_{\mu_{\overline{\rm DR}}=m_M}$$

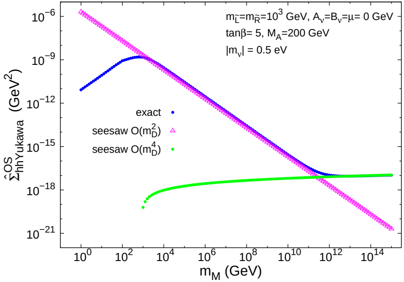
$$\left(\hat{\Sigma}_{hh}^{\rm OS}(p^2)\right)_{m_D^2} \propto \underbrace{\frac{g^2 m_D^2(M_{\rm EW}^2, m_{\rm SUSY}^2)}{m_M^2 M_Z^2}}$$

$$\Uparrow$$

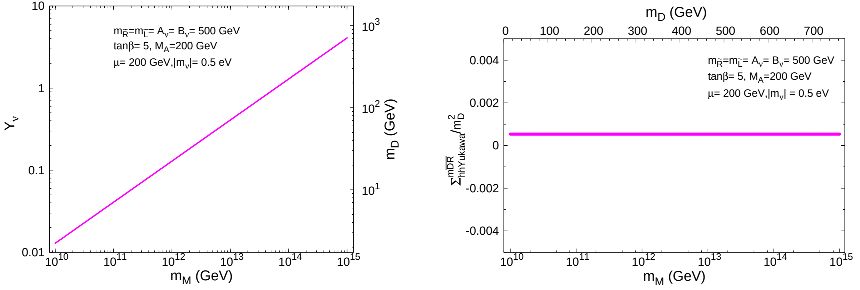
$\delta^{\rm OS} Z_{hh}|_{\rm finite}$ and $\delta^{\rm OS}\tan\beta|_{\rm finite}$ exactly cancel the leading $O(m_D^2)$ terms that appear in $\hat{\Sigma}_{hh}^{\overline{\rm DR}}(p^2)$

EXACT versus SEESAW LIMIT $m\overline{\mathrm{DR}}$ and OS



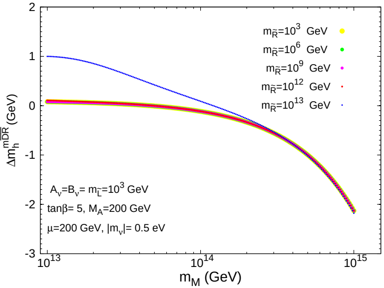


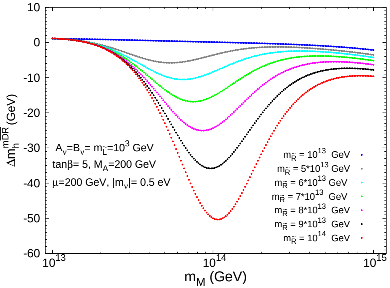
- seesaw limit approximates very well the exact results for $m_M > M_{\mathrm{EW}}, m_{\mathrm{SUSY}}$
- $O(m_D^2)$ dominates the $m\overline{\mathrm{DR}}$ Yukawa contribution $\rightarrow$ relevant size for $m_M \geq 10^{14}$ GeV
- negiglible OS Yukawa contribution $\rightarrow$ decreases with m_M up to $m_M \leq 10^{12}$ GeV
  For $m_M \geq 10^{12}$ the $O(m_D^4/m_M^2) \propto$ constant dominates



- growing of $\hat{\Sigma}^{m\overline{\rm DR}}_{hh}(p^2)$ with m_M ONLY due to Y_ν dependence on m_M $\rightarrow Y_\nu \propto \sqrt{m_M}$
- constant non-decoupling behaviour in the Majorana case
- perturbative regime for $m_M \lesssim 10^{15}$ GeV

$\Delta m_h^{\mathrm{m\overline{DR}}}$ dependence on m_M for different $m_{\tilde{R}}$

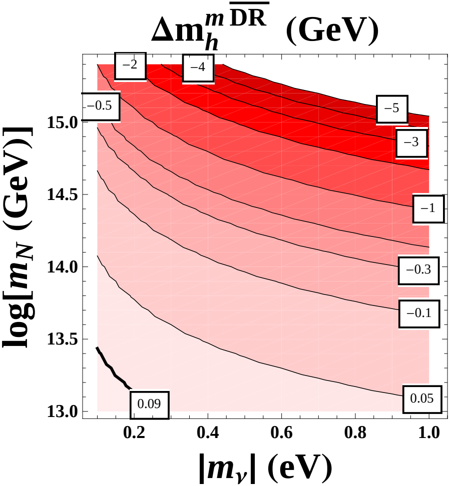




- For $m_M \leq 5 \times 10^{13}$ GeV tiny positive corrections, $\Delta m_h^{\mathrm{m\overline{DR}}} < 0.1$ GeV
- For $m_M \geq 5 \times 10^{13}$ GeV $\Rightarrow$ negative Higgs mass corrections, they increase with m_M up to a few GeV.
- The corrections are independent of $m_{\tilde{R}}$ when $m_{\tilde{R}} < 10^{13}$ GeV
- For $m_{\tilde{R}} \geq 10^{13}$ GeV $\Rightarrow$ $\Delta m_h^{\mathrm{m\overline{DR}}}$ can be very big reaching its maximum at $m_{\tilde{R}} = m_M$ ($\Delta m_h^{\mathrm{m\overline{DR}}} = -50$ GeV for $m_{\tilde{R}} = m_M = 10^{14}$ GeV)

Contourplot of $\Delta m_h^{\mathrm{m}\overline{\mathrm{DR}}}$ as a function of m_N and $|m_\nu|$

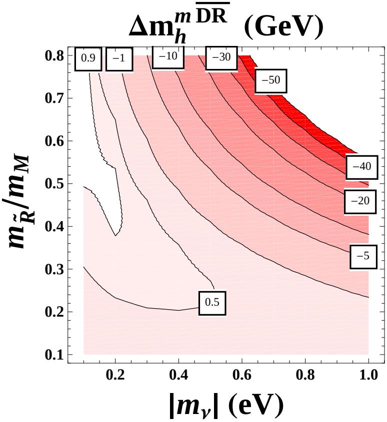
$A_\nu = B_\nu = m_{\tilde{L}} = m_{\tilde{R}} = 10^3$ GeV, $\tan\beta = 5, M_A = \mu = 200$ GeV



- $\Delta m_h^{\mathrm{m}\overline{\mathrm{DR}}} < 0.1$ GeV if 10^{13} GeV $< m_M < 10^{14}$ GeV (or, equivalently, 10^{13} GeV $< m_N < 10^{14}$ GeV) and 0.1 eV $< |m_\nu| < 1$ eV
- $\Delta m_h^{\mathrm{m}\overline{\mathrm{DR}}}$ change to negative sign and grow in size for larger m_M and/or $|m_\nu|$ values (up to ~ -5 GeV for $m_M = 10^{15}$ GeV and $|m_\nu| = 1$ eV)

Contourplot of $\Delta m_h^{\mathrm{m}\overline{\mathrm{DR}}}$ as a function of $m_{\tilde{R}}/m_M$ and $|m_\nu|$

$m_M = 10^{14}$ GeV,
$A_\nu = B_\nu = m_{\tilde{L}} = 10^3$ GeV, $\tan\beta = 5, M_A = \mu = 200$ GeV



- Very large negative corrections for large m_M and $m_{\tilde{R}}$, of $\mathcal{O}(10^{14})$ GeV, and $|m_\nu|$ of $\mathcal{O}(1)$ eV:
  $\Delta m_h^{\mathrm{m}\overline{\mathrm{DR}}} \sim -30$ GeV
  for $m_M = 10^{14}$ GeV,
  $m_{\tilde{R}}/m_M = 0.7$ and
  $|m_\nu| = 0.6$ eV

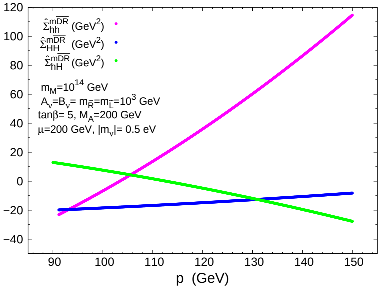
Conclusions

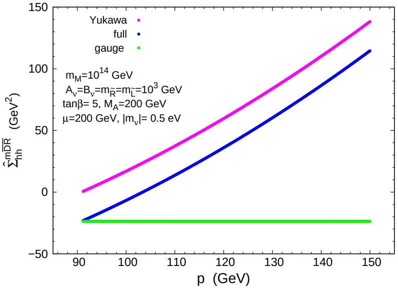
- The MSSM Higgs sector is sensitive to the heavy Majorana scale
- The radiative corrections to the higgs mass h_0 can be relevant when $m_M > 10^{13}$ GeV, bigger than the anticipated experimental precision (LHC-0.2 GeV, ILC-0.05 GeV) $\Rightarrow$ they should be taken into account
- The corresponding contribution of dirac neutrinos is negligible and completely indistinguisable of the MSSM with no masive neutrinos
- The generalization to the realistic 3-neutrino-sneutrino case is appealing and could give extra contributions due to the big mixing angles as it happens in some LFV observables. (work in progress)

Dependence of $\hat{\Sigma}_{hh}^{m\overline{\rm DR}}(p^2)$ on $\tan\beta$, M_A, μ, A_ν, $m_{\tilde{L}}$, B_ν

- Reference chosen values:
  $\tan\beta = 5, M_A = 200 GeV, A_\nu = 1000 GeV, \mu = 200$ GeV
- For $\tan\beta > 5$ and $M_A > 150$ GeV $\rightarrow \hat{\Sigma}_{hh}^{m\overline{\rm DR}}(p^2) \sim$ constant
- $\hat{\Sigma}_{hh}^{m\overline{\rm DR}}(p^2)$ independent of A_ν and of μ for $[-1000, 1000]$ GeV
- The gauge part increases logarithmically in modulus with the soft breaking mass $m_{\tilde{L}}$
- The behavior with B_ν is flat for most of the explored range, except at very large values, $B_\nu > 10^{12}$ GeV
- Dependence on $\boldsymbol{m_{\tilde{R}}}$ (not constrained by data):
  - The gauge part is completely independent of $\boldsymbol{m_{\tilde{R}}}$. The $\tilde{\nu}_R, \nu_R$ don't interact weakly with the Z boson.
  - The Yukawa part insensitive to $\boldsymbol{m_{\tilde{R}}}$ up to $\boldsymbol{m_{\tilde{R}}} \sim \mathbf{10^{13}}$ GeV

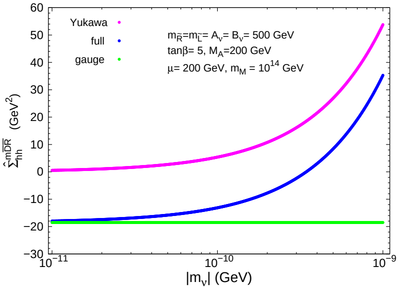
Dependence of $\hat{\Sigma}^{m\overline{\rm DR}}_{hh}(p^2)$ on p

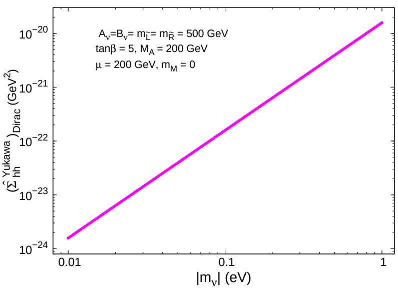




- Strong dependence of $\hat{\Sigma}_{hh}$ with the external momentum $\rightarrow$ usual $p = 0$ aprrox not valid
- The gauge part is quasi insensitive to p $\rightarrow$ $\hat{\Sigma}^{gauge}_{hh} \sim p^2 M_Z^2 / m^2_{\rm SUSY}$
- The yukawa part increases with p $\rightarrow$ $\left(\hat{\Sigma}^{\overline{\rm DR}}_{hh}(p^2)\right)_{m_D^2} \sim Y_\nu^2 p^2$

Dependence of $\hat{\Sigma}^{m\overline{\rm DR}}_{hh}(p^2)$ on m_ν → Majorana versus Dirac





- In both cases $\hat{\Sigma}_{hh}$ grow with the neutrino mass, due to the Y_ν dependence on m_ν
  - Dirac case → $Y_\nu = m_\nu/v_2$ → O(10^{-12})
  - Majorana case → $Y_\nu = m_D/v_2 \sim \sqrt{|m_\nu| m_M}/v_2$

$\Delta m_h^{\mathrm{m\overline{DR}}}$ dependence on m_M for different B_ν and on m_ν