Study of $h, H, A \rightarrow \tau \mu$ decays in the context of the MSSM within the Mass Insertion Approximation

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Outline

- Motivation
- Experimental Bounds
- MSSM + general slepton mixing
- Mass Insertion Approximation (MIA)
- Lepton Flavor Violation Higgs Decays (LFVHD) processes
- Results
- Phenomenology
- Conclusions
Work based on:


In continuation to:

Motivation

- LFV is a window to BSM physics: No LFV within SM.
- SUSY not seen yet at LHC (scale $m_{\text{SUSY}}$ at TeV range?)
- Higgs mediated processes are sensitive to SUSY via loops.

**Main here:**
the MIA allows us to derive simple analytical expressions for decay rates. Useful for Pheno!
Experimental Bounds

Some searched processes:

<table>
<thead>
<tr>
<th>LFV process</th>
<th>Present Upper Bound (90%CL)</th>
<th>Future Sensitivity (?)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{BR}(\mu \to e\gamma) )</td>
<td>( 5.7 \times 10^{-13} ) (MEG 2013)</td>
<td>( 5 \times 10^{-14} ) (MEGup)</td>
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<td>( \text{BR}(\tau \to e\gamma) )</td>
<td>( 3.3 \times 10^{-8} ) (BaBar 2010)</td>
<td>( 3 \times 10^{-9} ) (SuperB)</td>
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<td>( 2.4 \times 10^{-8} ) (SuperB)</td>
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<td>( \text{BR}(\mu \to eee) )</td>
<td>( 1 \times 10^{-12} ) (SINDRUM 1988)</td>
<td>( 1 \times 10^{-16} ) (Mu3E-PSI)</td>
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<td>( \text{BR}(\tau \to \mu\mu\mu) )</td>
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<td>( \text{CR}(\mu - e, \text{Au}) )</td>
<td>( 7 \times 10^{-13} ) (SINDRUM2 2006)</td>
<td>( 3.1 \times 10^{-15} ) (COMET-I, J-PARC)</td>
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<td>( \text{CR}(\mu - e, \text{Al}) )</td>
<td>( 4.3 \times 10^{-12} ) (SINDRUM2 2004)</td>
<td>( 2.6 \times 10^{-17} ) (COMET-II, J-PARC)</td>
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<tr>
<td>( \text{CR}(\mu - e, \text{Ti}) )</td>
<td>( 4.3 \times 10^{-12} ) (SINDRUM2 2004)</td>
<td>( 2.5 \times 10^{-17} ) (Mu2E-FermiLab)</td>
</tr>
</tbody>
</table>

New input from LHC: LFV Higgs Decays

\[
\text{BR}(H \to \tau\mu) < 1.51 \times 10^{-2} \text{ (95\%C.L.) [CMS 2015]} \ (2.4\sigma \text{ excess?})
\]

\[
\text{BR}(H \to \tau\mu) < 1.85 \times 10^{-2} \text{ (95\%C.L.) [ATLAS 2015]}
\]
The MSSM with general slepton mixing

Low energy parametrization for general slepton mixing (model independent).

\[ \mathcal{L}_{\text{soft}}^{\text{LFV}} = -\tilde{L}^\dagger m_L^2 \tilde{L} - \tilde{R}^* m_R^2 \tilde{R} + (\tilde{L}^\dagger A^l \tilde{R}^* H_1 + h.c.) \]

\[
m_L^2 = \begin{pmatrix}
m_{\tilde{L}1}^2 & \delta_{12} m_{\tilde{L}1} m_{\tilde{L}2} & \delta_{13} m_{\tilde{L}1} m_{\tilde{L}3} \\
\delta_{21} m_{\tilde{L}2} m_{\tilde{L}1} & m_{\tilde{L}2}^2 & \delta_{23} m_{\tilde{L}2} m_{\tilde{L}3} \\
\delta_{31} m_{\tilde{L}3} m_{\tilde{L}1} & \delta_{32} m_{\tilde{L}3} m_{\tilde{L}2} & m_{\tilde{L}3}^2
\end{pmatrix}
\]

\[
m_R^2 = \begin{pmatrix}
m_{\tilde{R}1}^2 & \delta_{12} m_{\tilde{R}1} m_{\tilde{R}2} & \delta_{13} m_{\tilde{R}1} m_{\tilde{R}3} \\
\delta_{21} m_{\tilde{R}2} m_{\tilde{R}1} & m_{\tilde{R}2}^2 & \delta_{23} m_{\tilde{R}2} m_{\tilde{R}3} \\
\delta_{31} m_{\tilde{R}3} m_{\tilde{R}1} & \delta_{32} m_{\tilde{R}3} m_{\tilde{R}2} & m_{\tilde{R}3}^2
\end{pmatrix}
\]

\[
\Delta_{mk}^{LL} \equiv (m_L^2)_{mk} = \delta_{mk}^L m_{\tilde{L}m} m_{\tilde{L}k}
\]

\[
\Delta_{mk}^{RR} \equiv (m_R^2)_{mk} = \delta_{mk}^R m_{\tilde{R}m} m_{\tilde{R}k}
\]

\[
v_1 A^l = \begin{pmatrix}
m_e A_e & \delta_{12}^L m_{\tilde{L}1} m_{\tilde{R}2} & \delta_{13}^L m_{\tilde{L}1} m_{\tilde{R}3} \\
\delta_{21}^L m_{\tilde{L}2} m_{\tilde{R}1} & m_\mu A_\mu & \delta_{23}^L m_{\tilde{L}2} m_{\tilde{R}3} \\
\delta_{31}^L m_{\tilde{L}3} m_{\tilde{R}1} & \delta_{32}^L m_{\tilde{L}3} m_{\tilde{R}2} & m_\tau A_\tau
\end{pmatrix}
\]

\[
\Delta_{mk}^{LR} \equiv (v_1 A^l)_{mk} = \tilde{\delta}_{mk}^{LR} v_1 \sqrt{m_{\tilde{L}m} m_{\tilde{R}k}} \implies \delta_{mk}^{LR} = \tilde{\delta}_{mk}^{LR} \frac{v_1}{\sqrt{m_{\tilde{L}m} m_{\tilde{R}k}}}
\]

\[
\Delta_{mk}^{RL} \equiv (v_1 A^l)_{km} = \tilde{\delta}_{mk}^{RL} v_1 \sqrt{m_{\tilde{R}m} m_{\tilde{L}k}} \implies \delta_{mk}^{RL} = \tilde{\delta}_{mk}^{RL} \frac{v_1}{\sqrt{m_{\tilde{R}m} m_{\tilde{L}k}}}
\]

\[
v_1(2) = \langle H_{1(2)} \rangle \quad \text{and} \quad \tan \beta = t_\beta = v_2/v_1
\]

\[ \Rightarrow \text{LFV is originated from the off-diagonal real } \delta_{mk}^{AB} \text{'s via SUSY loops.} \]
Full and MIA approach

Full Calculation

- Work with the mass basis $\rightarrow$ full diagonalization of mass matrix.
- Physical states: 6 sleptons $\tilde{l}_\alpha$ and 3 sneutrinos $\tilde{\nu}_\alpha$.
- Dependence on $\delta_{mk}^{AB}$ hidden in physical masses and rotation matrices.
- Numerical results for decay rates.

MIA Calculation

- Work with the EW interaction basis. Gauge states: $\tilde{l}_i^L$, $\tilde{l}_i^R$ and $\tilde{\nu}_i$ where $i$ denotes flavor $e, \mu, \tau$.
- Non-diagonal elements of the mass matrix are considered as two-field interactions. For example, explicit dependence on $\Delta_{mk}^{AB}$ appears in the lepton flavor violation insertions:

\[
\begin{align*}
- \tilde{l}_m^A \times \tilde{l}_k^B & \quad -i\Delta_{mk}^{AB} \\
\tilde{\nu}_m \times \tilde{\nu}_k & \quad -i\Delta_{mk}^{LL}
\end{align*}
\]

- Analytical expressions for decay rates as perturbative expansion of $\delta_{mk}^{AB}$ and other mass ratios.
LFVHD processes $h, H, A \rightarrow l_k \bar{l}_m$ with $m \neq k$

In this context, LFV Higgs Decays occur at one-loop order:

![Diagram](image)

**Our aim:**

to get the form factors $F$ as an expansion valid for heavy SUSY

$(m_{\text{SUSY}} \gg m_h, H, A, m_{\text{lep}}, m_W)$

$$
\Delta_{mk}^{AB} F(m_{H_x}, m_{\text{lep}}, m_W, m_{\text{SUSY}}) \sim \Delta_{mk}^{AB} \left( F|_{m_{\text{ext}}=0} + \mathcal{O}(M_{H_x}^2 / m_{\text{SUSY}}^2) + \mathcal{O}(M_W^2 / m_{\text{SUSY}}^2) \right)
$$

$F|_{m_{\text{ext}}=0} \sim \mathcal{O}(M_{H_x}^0 / m_{\text{SUSY}}^0)$ \rightarrow Non-Decoupling ND contributions (dominant terms).

$\mathcal{O}(M_{H_x}^2 / m_{\text{SUSY}}^2), \mathcal{O}(M_W^2 / m_{\text{SUSY}}^2)$ \rightarrow Decoupling D contributions (leading and subleading corrections).
Results for LFVHD in the MIA

In the next slides,

- SUSY scenarios: all heavy masses are proportional to one scale $m_{\text{SUSY}}$.
- All relevant one-loop diagrams for the full and MIA computation.
- Decay rate in terms of the form factors and $\Delta_{mk}^{AB}$.
- Study of the cases $\Delta_{mk}^{LL}$ and $\Delta_{mk}^{RR}$: Non-Decoupling behavior.
- Study of the cases $\Delta_{mk}^{LR}$ and $\Delta_{mk}^{RL}$: Decoupling behavior.
- Perturbativity on $\delta_{mk}^{AB}$’s.
- Comparison between MIA/Full calculation and with Effective approach.
- Pheno implications: numerical study of maximum rates allowed by experimental bounds from $\tau \rightarrow \mu \gamma$ and searches of neutral MSSM Higgs bosons.
SUSY scenarios

- **Equal masses** scenario: all the relevant parameters involved set to be equal

\[ M_1 = M_2 = \mu = m_{\tilde{L}} = m_{\tilde{R}} = A_\mu = A_\tau = m_{\text{SUSY}} \]

- **GUT approximation** scenario: set an approximate GUT relation for the gaugino masses

\[ M_2 = 2M_1 \quad \text{(GUT relation)} \]

We also relate the soft parameters and the \( \mu \) parameter to a common scale by choosing:

\[ m_{\tilde{L}} = m_{\tilde{R}} = M_2 = A_\mu = A_\tau = \mu/a = m_{\text{SUSY}} \quad \text{with} \quad a = \frac{3}{4}, \frac{4}{3} \]

- **Generic** scenario: we set different values for all the mass parameters involved

\[
\begin{align*}
M_1 &= 2.2 m_{\text{SUSY}}, M_2 = 2.4 m_{\text{SUSY}}, \mu = 2.1 m_{\text{SUSY}} \\
m_{\tilde{L}_1} &= 2 m_{\text{SUSY}}, m_{\tilde{L}_2} = 1.8 m_{\text{SUSY}}, m_{\tilde{L}_3} = 1.6 m_{\text{SUSY}} \\
m_{\tilde{R}_1} &= 1.4 m_{\text{SUSY}}, m_{\tilde{R}_2} = 1.2 m_{\text{SUSY}}, m_{\tilde{R}_3} = m_{\text{SUSY}} \\
A_\mu &= 0.6 m_{\text{SUSY}}, A_\tau = 0.8 m_{\text{SUSY}} 
\end{align*}
\]
One-loop diagrams for the Full results

Use mass basis for the internal SUSY particles: sleptons, sneutrinos, charginos and neutralinos.

[Arganda, Curiel, Herrero, Temes; 2005]
Relevant one-loop diagrams for $\Delta^{LL}_{mk}$

Use gauge basis for the internal SUSY particles: flavor sleptons, flavor sneutrinos, Bino, Winos, Higgsinos.
Relevant one-loop diagrams for $\Delta_{\text{LL}}^{mk}$

Other diagrams suppressed by extra factors of $(M_{\text{EW}}/m_{\text{SUSY}})^n$ and/or $(m_{\text{lep}}/m_{\text{SUSY}})^m$. 

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Relevant one-loop diagrams for $\Delta^{LR}_{mk}$ and $\Delta^{RL}_{mk}$

- Case $\Delta^{LR}_{mk}$

- Case $\Delta^{RL}_{mk}$
Relevant one-loop diagrams for $\Delta_{m \bar{k}}^{R R}$
Analytical results in the MIA

The amplitude of $H_x(p_1) \rightarrow l_k(-p_2)l_m(p_3)$ for $H_x = h, H, A$ is

$$i\mathcal{M} = -ig\bar{u}_l(-p_2)(F_L^{(x)} P_L + F_R^{(x)} P_R)v_l m(p_3)$$

The decay rate reads as follows:

$$\Gamma(H_x \rightarrow l_k l_m) = \frac{g^2}{16\pi m_{H_x}} \sqrt{\left(1 - \left(\frac{m_{l_k} + m_{l_m}}{m_{H_x}}\right)^2\right)} \sqrt{1 - \left(\frac{m_{l_k} - m_{l_m}}{m_{H_x}}\right)^2}\times \left((m_{H_x}^2 - m_{l_k}^2 - m_{l_m}^2)(|F_L^{(x)}|^2 + |F_R^{(x)}|^2) - 4m_{l_k} m_{l_m} Re(F_L^{(x)} F_R^{(x)*})\right)$$

where the form factors are linear in $\Delta^{AB}_{m,k}$

$$F^{(x)}_{L,R} = \Delta^{LL}_{m,k} F^{(x)LL}_{L,R} + \Delta^{LR}_{m,k} F^{(x)LR}_{L,R} + \Delta^{RL}_{m,k} F^{(x)RL}_{L,R} + \Delta^{RR}_{m,k} F^{(x)RR}_{L,R}$$

- All of them are UV convergent: they are expressed in terms of the loop functions $C_0, C_2, D_0, \tilde{D}_0$ of three and four points because there are 2 scalar and 1 fermionic propagators at least.
- We perform a systematic expansion in powers of $p_{ext}$ and keep: the leading contributions $\mathcal{O}(p_{ext}^0)$ and the next-to-leading $\mathcal{O}(p_{ext}^2)$. 
Non-decoupling contributions for $\Delta_{m_k}^{LL}$ and $\Delta_{m_k}^{RR}$

\[
\left( \Delta_{23}^{LL} F_{LL}^{(x)LL} \right)_{\text{ND}} = \left( \frac{g^2}{16\pi^2} \frac{m_\tau}{2M_W} \right) \left[ \frac{\sigma_2(x) + \sigma_1(x)^*}{t_\beta} \right] \left( \delta_{23}^{LL} m_{\tilde{L}_2} m_{\tilde{L}_3} \right) \\
\times \left[ \frac{3}{2} \mu M_2 D_0(0, 0, 0, m_{\tilde{L}_2}, m_{\tilde{L}_3}, \mu, M_2) \right] \\
\times \left\{ O(M_{H_x}^0/m_0^{\text{SUSY}}) \right\}
\]

\[
\left( \Delta_{23}^{RR} F_{RR}^{(x)RR} \right)_{\text{ND}} = \left( \frac{g^2 t_W^2}{16\pi^2} \frac{m_\tau}{2M_W} \right) \left[ \frac{\sigma_2(x)^* + \sigma_1(x) t_\beta}{c_\beta} \right] \left( \delta_{23}^{RR} m_{\tilde{R}_2} m_{\tilde{R}_3} \right) \\
\times \left[ \mu M_1 D_0(0, 0, 0, m_{\tilde{R}_2}, m_{\tilde{R}_3}, \mu, M_1) \right] \\
\times \left\{ O(M_{H_x}^0/m_0^{\text{SUSY}}) \right\}
\]

where

\[ H_x = (h, H, A), \sigma_1^{(x)} = (s_\alpha, -c_\alpha, is_\beta), \sigma_2^{(x)} = (c_\alpha, s_\alpha, -ic_\beta) \]

⇒ Simple analytical expressions: we factorized the contributions of the loops and the rest of MSSM parameters ($t_\beta$ and $m_A$).
Non-decoupling contributions for $\Delta_{mk}^{LL}$ and $\Delta_{mk}^{RR}$

- Non-Decoupling behavior of $\text{BR}(H_x \rightarrow \tau \mu) \sim m_{\text{SUSY}}^0$ in contrast with the decoupling behavior of $\text{BR}(\tau \rightarrow \mu \gamma) \sim m_{\text{SUSY}}^{-4}$.
- First order MIA approximates the full calculation very well.
- Largest rates for $LL$ and large $t_\beta$: $\text{BR}(H_x \rightarrow \tau \mu) \sim t_\beta^2$.
- Similar results in other scenarios.
Decoupling contributions for $\Delta_{LR}^{mk}$ and $\Delta_{RL}^{mk}$

$$
\left( \Delta_{23}^{LR} F_{L}^{(x)LR} \right)_D = \left( \frac{g^2 t_W^2}{16\pi^2} \frac{M_1}{2M_W} \right) \left[ \sigma_1^{(x)} \right] \left( \delta_{23}^{LR} \sqrt{m_{\tilde{L}_2} m_{\tilde{R}_3}} \right)
\times \left\{ O\left( \frac{M_{Hx}^2}{m_{SUSY}^2} \right) \right\}
\Rightarrow \text{Simple analytical expressions: we factorized the contributions of the loops and the rest of MSSM parameters (} t_\beta \text{ and } m_A \text{).}
$$

- Exact cancellations between Non-Decoupling terms.
- Decoupling behavior of $\text{BR}(H_x \rightarrow \tau \mu) \sim m_{SUSY}^{-4}$ like $\text{BR}(\tau \rightarrow \mu \gamma)$.
- First order MIA for $H$ and $A$ approximates the full calculation better than the $h$.
- Very small rates for $LR$ and $RL$.
- Similar results in other scenarios.
Limitations of the MIA results

Perturbativity works reasonably well within $|\delta_{23}^{AB}| \leq \mathcal{O}(1)$. 

$m_A = 800 \text{ GeV}, \tan \beta = 40, m_{\text{SUSY}} = 5 \text{ TeV}$

GUT approx. $\mu = 4/3 m_{\text{SUSY}}$
Equal masses scenario: form factors

Dominant contributions for each $\delta$:

$$F^{(x)}_{L,R} = \delta_{23}^{LL} \hat{F}^{(x)}_{L,R}^{LL} + \delta_{23}^{LR} \hat{F}^{(x)}_{L,R}^{LR} + \delta_{23}^{RL} \hat{F}^{(x)}_{L,R}^{RL} + \delta_{23}^{RR} \hat{F}^{(x)}_{L,R}^{RR}$$

As in the generic scenario, for $\delta_{23}^{LL}$ we get

$$\hat{F}^{(x)}_{L}^{LL} = \frac{g^2}{16\pi^2} \frac{m_\tau}{2M_W} \left[ \frac{\sigma_{2}^{(x)} + \sigma_{1}^{(x)*} t_\beta}{c_\beta} \right] \frac{1 - t_W^2}{4} \} \text{ ND}$$

For $\delta_{23}^{LR}, \delta_{23}^{RL}, \delta_{23}^{RR}$, strong cancellations produce

$$\hat{F}^{(x)}_{L}^{LR} = \frac{gt_W^2}{16\pi^2} \frac{1}{24\sqrt{2}} \left[ \sigma_{1}^{(x)*} \right] \frac{m_{H_x}^2}{m_S^2}$$

$$\hat{F}^{(x)}_{R}^{RL} = \frac{gt_W^2}{16\pi^2} \frac{1}{24\sqrt{2}} \left[ \sigma_{1}^{(x)} \right] \frac{m_{H_x}^2}{m_S^2}$$

$$\hat{F}^{(x)}_{R}^{RR} = - \frac{g^2 t_W^2}{16\pi^2} \frac{m_\tau}{2M_W} \left[ \frac{2\sigma_{2}^{(x)*} + \sigma_{1}^{(x)}}{120c_\beta} \right] \frac{m_{H_x}^2}{m_S^2} \} \text{ D}$$
Equal masses scenario: simplest effective vertices

The most relevant mixing for phenomenology is $\delta_{23}^{LL}$. For this case, we can write the dominant effective vertex $-igV_{H_x \tau \mu}^{\text{eff}} \hat{P}_L$

$$V_{H_x \tau \mu}^{\text{eff}} = \frac{g^2}{16\pi^2} \frac{m_\tau}{2M_W} \left[ \frac{\sigma_2^{(x)} + \sigma_1^{(x)} t_\beta}{c_\beta} \right] \left( \frac{1 - t_\beta^2}{4} \right) \delta_{23}^{LL}$$

In the large $t_\beta$ limit:

$$V_{h \tau \mu}^{\text{eff}} |_{t_\beta \gg 1} = -\frac{g^2}{16\pi^2} \frac{m_\tau}{MW} \frac{M_Z^2}{m_A^2} t_\beta \left( \frac{1 - t_W^2}{4} \right) \delta_{23}^{LL}$$

$$V_{H \tau \mu}^{\text{eff}} |_{t_\beta \gg 1} = -iV_{A \tau \mu}^{\text{eff}} |_{t_\beta \gg 1} = -\frac{g^2}{16\pi^2} \frac{m_\tau}{2MW} t_\beta^2 \left( \frac{1 - t_W^2}{4} \right) \delta_{23}^{LL}$$

We deduce:

- For light Higgs: effective vertex suppressed by $M_Z^2/m_A^2$ ($m_A \to \infty$, $h$ is SM-like).
- For heavy Higgs: effective vertex enhanced by $t_\beta^2$ (in agreement with [Brignole, Rossi; 2003])
Phenomenology

- Shaded pink area: excluded by BR(τ → µγ) < 4.4 × 10⁻⁸.
- Shaded blue area: excluded by negative searches by ATLAS and CMS of neutral MSSM Higgs bosons decaying to tau pairs.

⇒ Maximum allowed rates are ∼ 5 × 10⁻⁵ for H and A (below LHC sensitivity).
• We can set $m_{\text{SUSY}} = 4$ TeV (ND terms) $\rightarrow$ no constraints by $\tau \rightarrow \mu \gamma$.
• Shaded blue area: excluded by negative searches by ATLAS and CMS of neutral MSSM Higgs bosons decaying to tau pairs.

⇒ Maximum allowed rates are $\sim 3.5 \times 10^{-4}$ for $H$ and $A$.
Taking in account both channels $\tau \bar{\mu}$ and $\bar{\tau} \mu$, $\text{BR} \sim 10^{-3}$ closer to LHC sensitivity!
$h, H, A \rightarrow \tau\mu$ at LHC

- Shaded gray area: excluded by $\tau \rightarrow \mu\gamma$.
- Shaded blue area: excluded by negative searches by ATLAS and CMS.

$\Rightarrow$ Most promising for $H$ and $A$: in the region $t_\beta \sim 40 - 60$, $m_A \sim 900 - 1000$ GeV and $m_{\text{SUSY}} > 4$ TeV, for $\sqrt{s} = 14$ TeV and $\mathcal{L} \sim 100$ fb$^{-1}$ we predict $\mathcal{O}(1-10)$ events.
Conclusions

• We performed a diagramatic computation of LFVHD within the MIA. We found simple analytical expressions for the form factors. They are very useful for phenomenology and comparison with data.

• We compared MIA vs Full results: good agreement in most cases, in particular for the Non-Decoupling terms (phenomenological important ones).

• Also, we compared with the effective vertices approach: in accordance with previous results in the literature.

• We understood the BR behavior with the MSSM parameters $t_\beta$ and $m_A$.

• We concluded that $H, A \rightarrow \tau\mu$ are promising channels at the LHC.
Back-up
Subleading corrections: $O(M_W^2/m_{\text{SUSY}}^2)$

\[ \tilde{F}_{R}(x)_{RR} = \frac{g^2 t_W^2}{16 \pi^2} \frac{m_\tau}{2 m_W c_\beta} \frac{M_W^2}{m_S^2} \frac{t_\beta^2}{1 + t_\beta^2} \left[ \frac{\sigma_1(x)}{60} \left( 3 t_W^2 + 13 - 4 t_W^2 t_\beta - 12 t_\beta \right) \right. \\
- \frac{\sigma_1(x)^*}{5} - \frac{4 \sigma_2(x)}{15} - \frac{2 \sigma_2(x)^*}{15} + \left. \frac{\sigma_3(x)}{12 t_\beta} \sqrt{1 + t_\beta^2} \left( 1 + t_W^2 \right) \right. \\
+ \left( \frac{1 + t_W^2}{60 t_\beta} \left( -8 \sigma_1(x) + 4 \sigma_1(x)^* + \sigma_2(x) + \sigma_2(x)^* \right) + \frac{\sigma_3(x)}{12 t_\beta^2} \left( 1 + 5 t_W^2 \right) \right) \\
+ \left( \frac{1 + t_W^2}{30 t_\beta^2} \left( -\sigma_1(x) + \sigma_1(x)^* + \sigma_2(x) - \sigma_2(x)^* \right) \right] \]