Higgs boson decays into charginos and neutralinos including full one-loop corrections

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Paris, April 2004

Calculations are done in the MSSM with real parameters.

- tree-level properties:
  - charginos, neutralinos, and Higgs bosons
  - tree-level widths
- one-loop corrections
- numerics
- conclusions

Chargino sector in the MSSM

The tree-level chargino mass matrix

$$X = \begin{pmatrix} M & \sqrt{2} m_W \sin\beta \\ \sqrt{2} m_W \cos\beta & \mu \end{pmatrix}$$

is diagonalized by two matrices U and V leading to

$$m_{\tilde{\chi}^{\pm}_{1,2}} = \frac{1}{\sqrt{2}} \left(M^2 + \mu^2 + 2m_W^2 \mp \left((M^2 - \mu^2)^2 + 4m_W^2 \cos^2 2\beta + 4m_W^2 (M^2 + \mu^2 + 2M\mu \sin 2\beta) \right)^{1/2} \right)^{1/2}$$

When μ or M is large,
one chargino eigenstate is a pure gaugino and the other one a pure higgsino state

$$\begin{array}{lcll} |\mu| \gg & \rightarrow & m_{\tilde{\chi}^{\pm}_1} \sim M \,, & m_{\tilde{\chi}^{\pm}_2} \sim |\mu| \\ |M| \gg & \rightarrow & m_{\tilde{\chi}^{\pm}_1} \sim |\mu| & m_{\tilde{\chi}^{\pm}_2} \sim M \end{array}$$

Neutralino sector in the MSSM

The tree-level neutralino mass matrix

$$Y = \begin{pmatrix} M' & 0 & -m_Z s_W c_\beta & m_Z s_W s_\beta \\ 0 & M & m_Z c_W c_\beta & -m_Z c_W s_\beta \\ -m_Z s_W c_\beta & m_Z c_W c_\beta & 0 & -\mu \\ m_Z s_W s_\beta & -m_Z c_W s_\beta & -\mu & 0 \end{pmatrix}$$

is diagonalized by the unitary matrix Z,

$$Z^* Y Z^{-1} = Y_D = \mathrm{diag}(m_{\chi_1^0}, m_{\chi_2^0}, m_{\chi_3^0}, m_{\chi_4^0})$$

Gauge unification leads to $M' = \frac{5}{3}\tan^2\theta_W M$, valid for the $\overline{\mathrm{DR}}$ parameters.

If μ or M is large,
one neutralino eigenstate is a pure bino, one a pure W^3-ino and the other the other two ones pure higgsino states.

$$\begin{array}{lll} |\mu| \gg & \longrightarrow & m_{\tilde{\chi}_1^0} \sim M', \quad m_{\tilde{\chi}_2^0} \sim M\,, \qquad m_{\tilde{\chi}_3^0} \sim m_{\tilde{\chi}_4^0} \sim |\mu| \\ |M| \gg & \longrightarrow & m_{\tilde{\chi}_1^0} \sim m_{\tilde{\chi}_2^0} \sim |\mu| \qquad m_{\tilde{\chi}_3^0} \sim M', \quad m_{\tilde{\chi}_4^0} \sim M \end{array}$$

Higgs sector in the MSSM

$$H_1 = \begin{pmatrix} H_1^0 \\ H_1^- \end{pmatrix} \qquad H_2 = \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix}$$

electroweak SSB

$\Downarrow$

$h^0\,,\quad H^0$ $\qquad A^0\,(G^0)$ $\qquad H^\pm\,(G^\pm)$

mixing angle α $\qquad \longrightarrow m_{Z^0}$ $\qquad \longrightarrow m_{W^\pm}$

tree-level: 2 free parameters, m_{A^0}, $\tan\beta = \frac{v_2}{v_1}$ chosen

$$m_{h^0}^{\text{tree}} \le m_{Z^0}\,|\cos 2\beta|$$

one–loop corr. important for m_{h^0}, m_{H^0}, and α, leading terms $\sim \frac{m_t^4}{m_W^2}$

$$m_{h^0}^{\text{corr.}} \lesssim 135\,\text{GeV}$$

Mass matrix

$$M^2(H^0,h^0) = \begin{pmatrix} \sin^2\beta m_{A^0}^2 + \cos^2\beta m_{Z^0}^2 & -\sin\beta\cos\beta(m_{A^0}^2+m_{Z^0}^2) \\ -\sin\beta\cos\beta(m_{A^0}^2+m_{Z^0}^2) & \cos^2\beta m_{A^0}^2 + \sin^2\beta m_{Z^0}^2 \end{pmatrix} = (R^{h^0})^T . \begin{pmatrix} m_{H^0}^2 & 0 \\ 0 & m_{h^0}^2 \end{pmatrix} . R^{h^0}$$

$$\text{with} \quad R^{h^0} := \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} .$$

Special cases (at tree level):

Limes $m_{A^0} \gg m_{Z^0}$:

$$M^2(H^0,h^0) \sim \begin{pmatrix} \sin^2\beta & -\sin\beta\cos\beta \\ -\sin\beta\cos\beta & \cos^2\beta \end{pmatrix} m_{A^0}^2 \Rightarrow \begin{matrix} \cos\alpha \longrightarrow \sin\beta \\ \sin\alpha \longrightarrow -\cos\beta \end{matrix}$$

Limes large $\tan\beta$: ($m_{A^0} \sim m_{Z^0}$ – "intense coupling regime")

$$m_{Z^0} < m_{A^0} : \; M^2(H^0,h^0) \sim \begin{pmatrix} m_{A^0}^2 & 0 \\ 0 & m_{Z^0}^2 \end{pmatrix} \qquad m_{A^0} < m_{Z^0} : \; M^2(H^0,h^0) \sim \begin{pmatrix} m_{Z^0}^2 & 0 \\ 0 & m_{A^0}^2 \end{pmatrix}$$

$$\alpha \longrightarrow 0 \qquad\qquad \alpha \longrightarrow \pi/2$$

$\sin(\alpha) \longrightarrow 0/1$, $\cos(\alpha) \longrightarrow 1/0$,

tree-level decay widths

(see e. g. A. Djoudi et al., Phys. Lett. B 376 (1996) 220)

The decay width of $H_k = \{h^0, H^0, A^0, H^+\}$ is given by

$$\Gamma^{\rm tree}(H_k \to \tilde{\chi}_i\,\tilde{\chi}_j) = \frac{g^2}{16\pi m_{H_k}^3}\frac{\kappa}{1+\delta_{ij}}\Big((m_{H_k}^2 - m_{\tilde{\chi}_i}^2 - m_{\tilde{\chi}_j}^2)(F_{ijk}^2 + F_{jik}^2) - 4\eta_k F_{ijk}F_{jik}\Big)$$

with $\kappa = (m_{H_k}^2 - m_{\tilde{\chi}_i}^2 - m_{\tilde{\chi}_j}^2)^2 - 4m_{\tilde{\chi}_i}^2 m_{\tilde{\chi}_j}^2$ and $\eta_{1,2} = 1$ for the CP even states h^0 and H^0, and H^+, and $\eta_3 = -1$ for the CP odd state A^0.

For the decay into the chargino pair $\chi_1^+\chi_1^-$, or neutralino pair $\chi_1^0\chi_1^0$ the decay width takes a simpler form

$$\Gamma^{\rm tree}(H_k^0 \to \tilde{\chi}_1\,\tilde{\chi}_1) = \frac{g^2}{16\pi} m_{H_k^0}\left(1 - \frac{4m_{\tilde{\chi}_1}}{m_{H_k}^2}\right)^p F_{11k}^2$$

with $p = 3$ for h^0, H^0 and $p = 1$ for A^0, corresponding to P- and S-wave final states.

The neutral Higgs bosons couple to mixtures of gaugino and higgsino components!

Large $\tan\beta$:

(e. g. $\tan\beta = 10 \leftrightarrow \beta = 84^\circ$, $\sin\beta = 0.995$, $\cos\beta = 0.099$),

$\alpha \to 0: \quad F_{112}^2 \sim F_{113}^2 \to$ Decoupling limes (SM limes)

$\alpha \to \pi/2: \quad F_{111}^2 \sim F_{113}^2 \to$ Limes intense coupling regime

one-loop corrections

The renormalization is done in the on-shell ren. scheme with the SUSY conserving $\overline{\mathrm{DR}}$ regularisation of the loop integrals.

The fermion-sfermion loop corrections are calculated fully analytically. These formulas are put in a Fortran code.

There exist a work by Zhang Ren-You et al., Phys. Rev. D65 (2002) 075018, where the leading Yukawa coupling corr. $\propto m_{t,b}^n\,(n = 1, 2, 3)$ are calculated. Comparing our (s)top-(s)bottom correction with them numerically, we agree by about 10% within the one-loop correction.

The full one-loop corrections are calculated using the package FeynArts with FormCalc and LoopTools by T. Hahn. et al. We included the necessary counter terms there.

We compared our own Fortran code on fermion-sfermion loop corrections with that of the automatically generated code from the Hahn-Package. We agree very well!

Renormalization

Work is done in the $\xi = 1$ 't Hooft gauge.

The renormalization of the $H_k \chi_i^+ \chi_i^-$ coupling can be expressed by the UV finite one-loop part ΔF_{ijk}.

The correction consists of three parts

$$\Delta F_{ijk} = \delta F_{ijk}^{(v)} + \delta F_{ijk}^{(w)} + \delta F_{ijk}^{(c)}$$

where the superscrits are: (v) = vertex, (w) = wave, and (c) = coupling corrections.

- The vertex contributions are all 1PI Feynman graphs
- The wave function contribution consists of parts with Higgs- and chargino/neutralino wave function constants δZ^H and $\delta Z^{\tilde{\chi}}$.
- By using symmetrized wave-functions for the charginos/neutralinos, the counter term to the rot. matrices is absorbed.
- For the system (h^0, H^0) we use α_{eff} which is defined to cancel the zero-momentum part of their selfenergies. After having included $\delta\alpha$ this leads to

$$\delta Z_{ab}^{H^0} \to \frac{2}{m_{H_a^0}^2 - m_{H_b^0}^2} \mathrm{Re}\left[\Pi_{ab}^{H^0}(m_{H_b^0}^2) - \Pi_{ab}^{H^0}(0)\right], \qquad a, b = (1,2),\ a \neq b \tag{1}$$

- $\tan\beta$ is fixed by the condition, that the renormalized transition $A^0 \to Z^0$ vanishes for $p^2 = m_{A^0}^2$.
  We also investigated the ren. condition with the $\overline{\mathrm{DR}}$ runnning $\tan\beta$ as input, difference is numerically very small in our case.

- $\delta g/g = \delta e/e - \delta \sin\theta_W / \sin\theta_W$ with $\delta \sin\theta_W / \sin\theta_W$ fixed by $\cos^2\theta_W = m_W^2/m_Z^2$, and $\delta e/e$ is fixed by the $\overline{\mathrm{MS}}$ $\alpha(m_Z)$, see e.g. our work [Eberl et al., hep-ph/0111303]

  or

  $\delta e/e$ is fixed by the effective four-fermion coupling G_{Fermi}.

- IR divergence treated by including the soft and hard photons. Total result is independent of the photon energy cut ΔE and the regularisation photon mass λ.

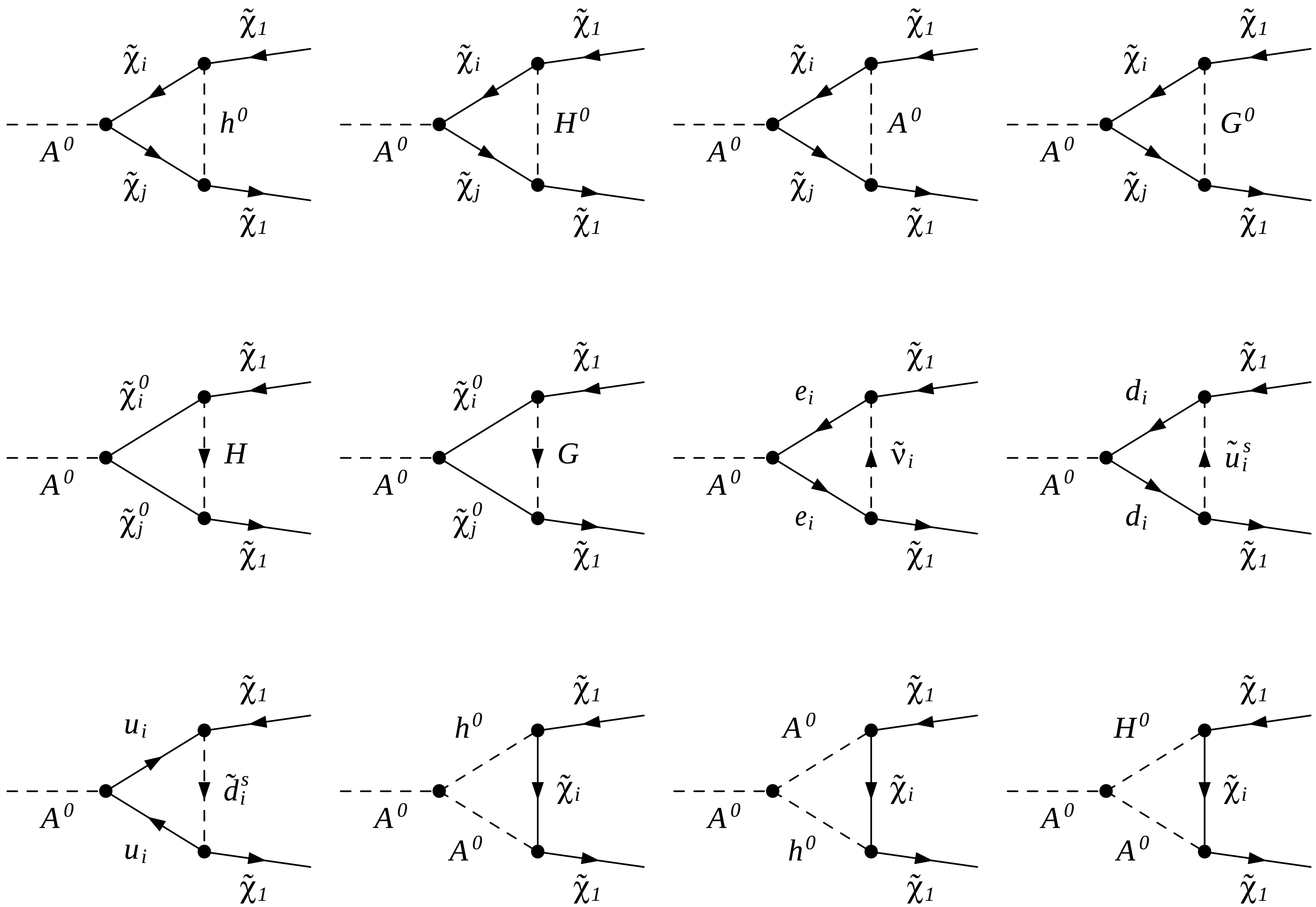
- The QED part cannot be separated!

- Full one-loop chargino/neutralino mass matrix corrections are included using the technique by [Eberl, Kincel, Majerotto; Öller et al.]. We checked numerically that this is equivalent at one-loop level with the technique used by [Fritsche and Hollik]. (by taking into account the different meaning of μ and M)

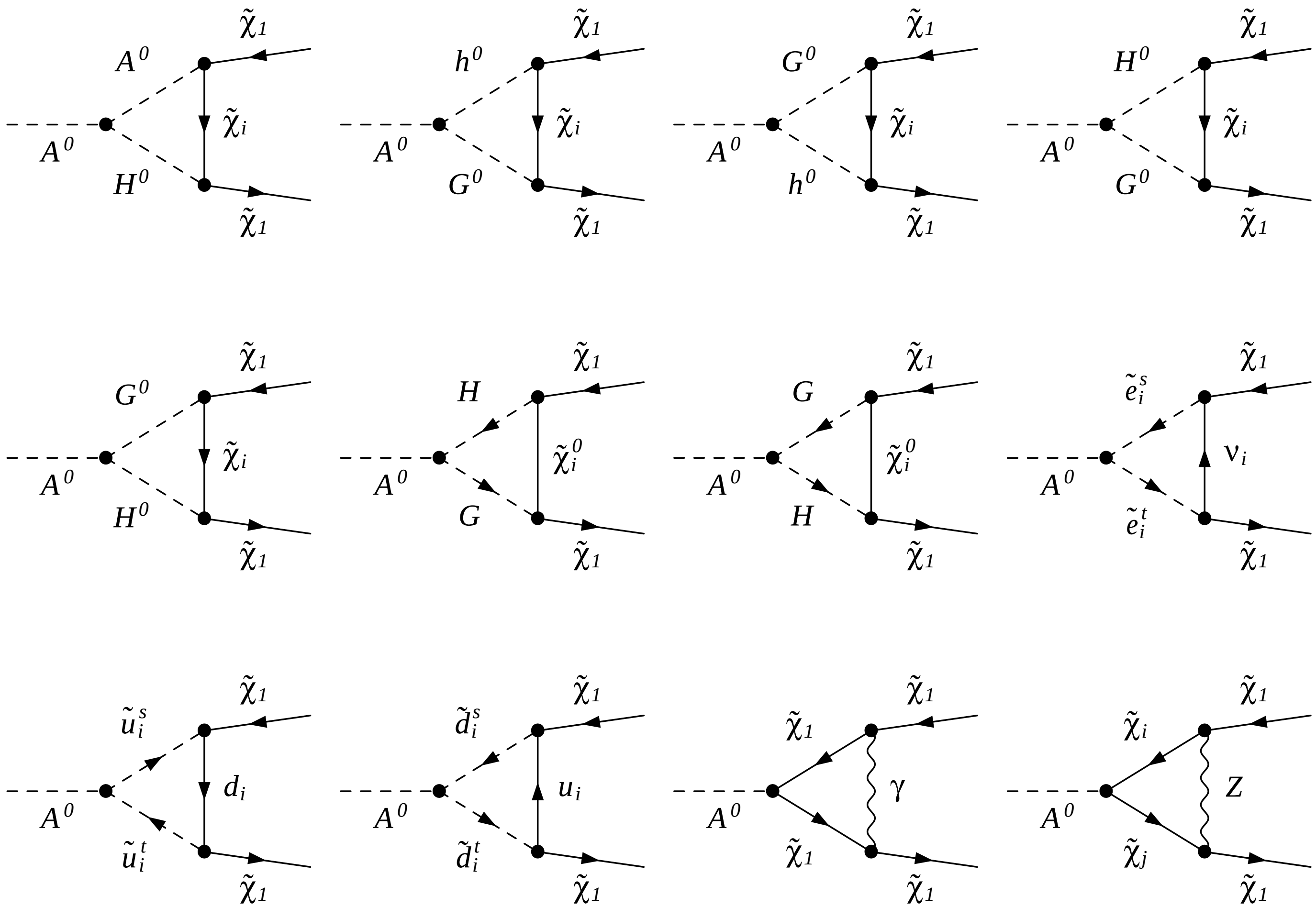
- The $\overline{\mathrm{DR}}$ running values A_t, and A_b at the scale of the decaying particle are input.

- $m_b(m_b)|_{\overline{\mathrm{MS}}}$ and $m_t|_{\mathrm{pole}}$ are input, internally $\overline{\mathrm{DR}}$ running values are used.

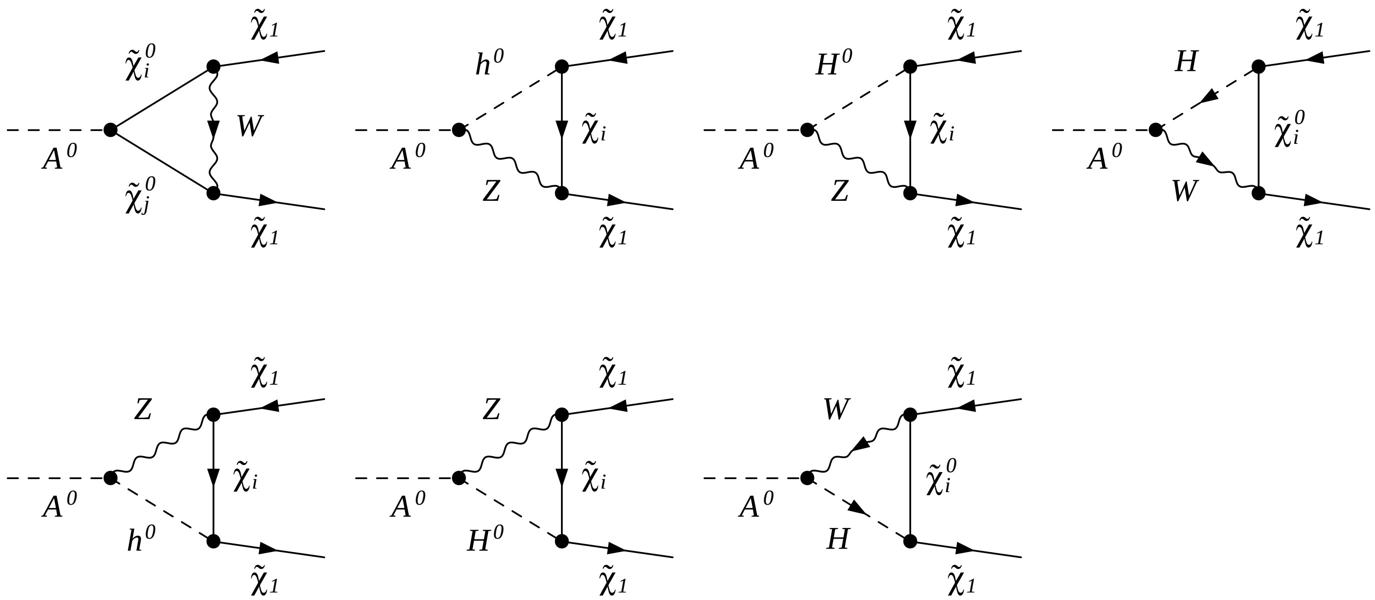
A^0 decay, all one-loop vertex graphs, page 1:



A^0 decay, all one-loop vertex graphs, page 2:



A^0 decay, all one-loop vertex graphs, page 3:



Numerics

SM parameters:

$\alpha(m_Z) = 1/127.922$, $G_F = 1.1663910^{-5}\,\text{GeV}^{-2}$,

$m_Z = 91.1876$ GeV, $m_W = 80.423$ GeV, $m_t = 174.3$ GeV, $m_b = 4.2$ GeV

SUSY parameters, SPS1a scenario used:

$\tan\beta = 10.2$, $M = 197.6$ GeV, $\mu = 353.1$ GeV

$m_{h^0} = 112.3$ GeV, $m_{H^0} = 394.1$ GeV, $m_{A^0} = 393.6$ GeV, $m_{H^+} = 401.7$ GeV

$m_{\tilde{\chi}^+} = \{181.0, 378.7\}$ GeV,
$m_{\tilde{\chi}^0} = \{94.8, 181.5, 360.4, 377.3\}$ GeV,
$m_{\tilde{t}} = \{400.1, 588.5\}$ GeV, $m_{\tilde{b}} = \{510.5, 542.0\}$ GeV

In plots only one parameter varied, other ones fixed by SPS1a input.

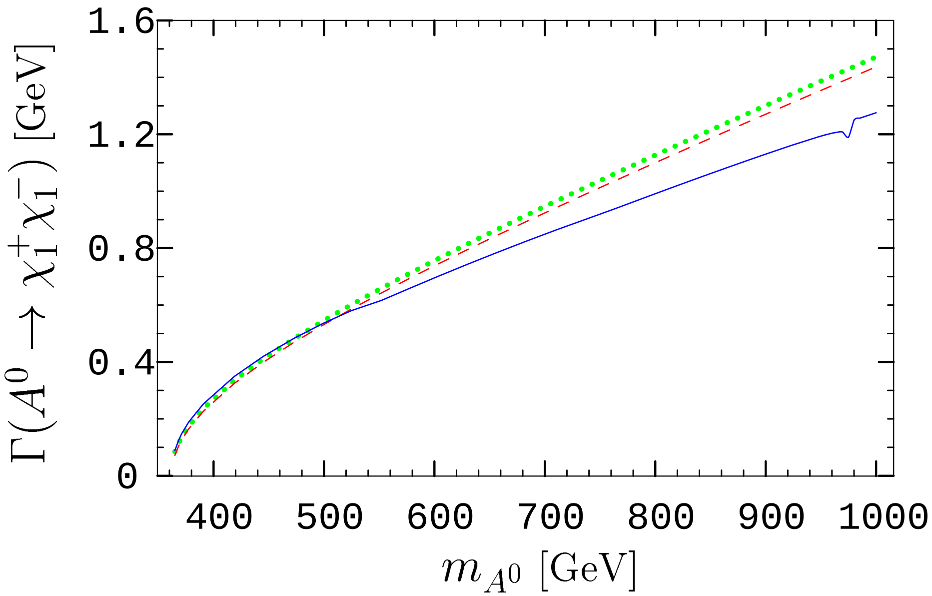
Abbreviations used:

- naive tree $\equiv \Gamma^{\text{naive tree}} \equiv$ tree level width
- tree $\equiv \Gamma^{\text{tree}} \equiv$ tree level width including chargino/neutralino mass corr. effect
- full $\equiv \Gamma^{\text{corr.}} \equiv$ 1loop contr. with all particles inclusive soft and hard photons

Branching ratios at SPS1a

Based on output from SPheno we get:

$$\begin{aligned}
\mathrm{Br}(A^0 \to \tilde{\chi}_1^+ \tilde{\chi}_1^-) &= 0.207 \\
\mathrm{Br}(H^0 \to \tilde{\chi}_1^+ \tilde{\chi}_1^-) &= 0.054 \\
\mathrm{Br}(\tilde{\chi}_2^+ \to \tilde{\chi}_1^+ h^0) &= 0.190 \\
\mathrm{Br}(H^0 \to \tilde{\chi}_1^0 \tilde{\chi}_2^0) &= 0.065 \\
\mathrm{Br}(\tilde{\chi}_3^0 \to \tilde{\chi}_1^0 h^0) &= 0.022 \\
\mathrm{Br}(H^+ \to \tilde{\chi}_1^+ \tilde{\chi}_1^0) &= 0.219
\end{aligned}$$



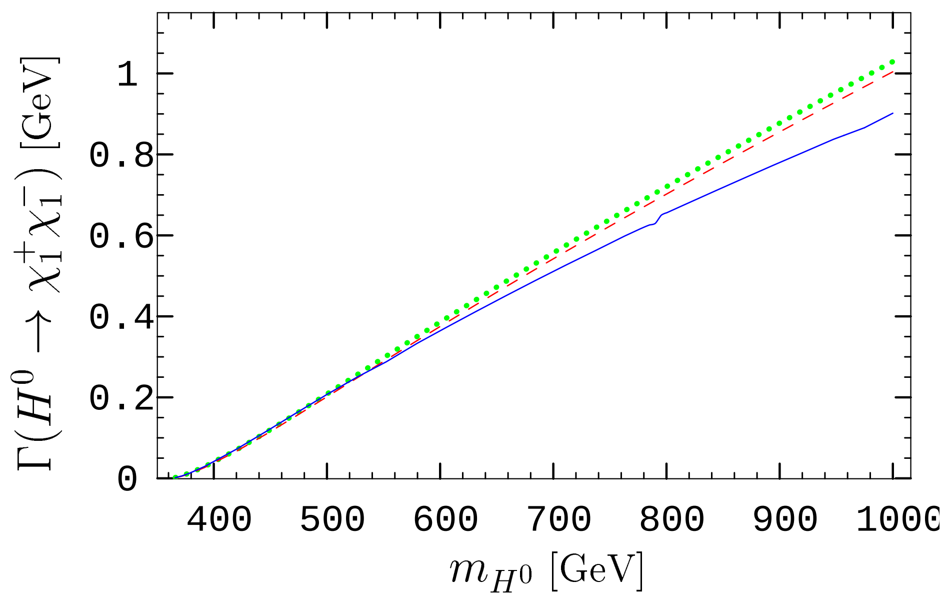


FIGURE : **Naive tree-level (dotted), tree-level (dashed) and one-loop corrected (solid) widths in the $\alpha(m_Z)$ schemes for the renormalization of the SU(2) gauge coupling g.**

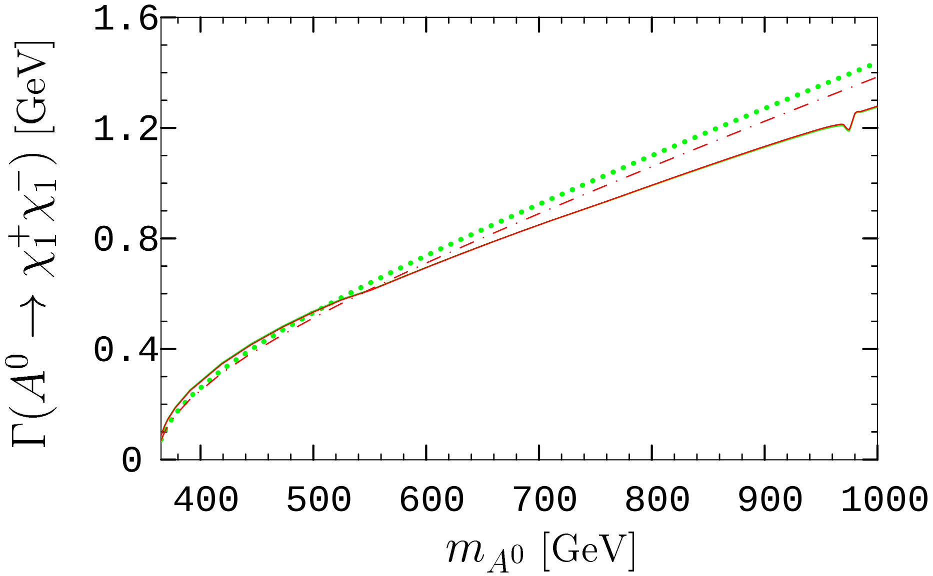


FIGURE : **Comparison of the results using the $\alpha(m_Z)$ scheme or the G_F scheme. The dotted and the solid (dash-dotted and dashed) lines denote the tree-level and one-loop corrected width in the $\alpha(m_Z)$ (G_F) scheme.**

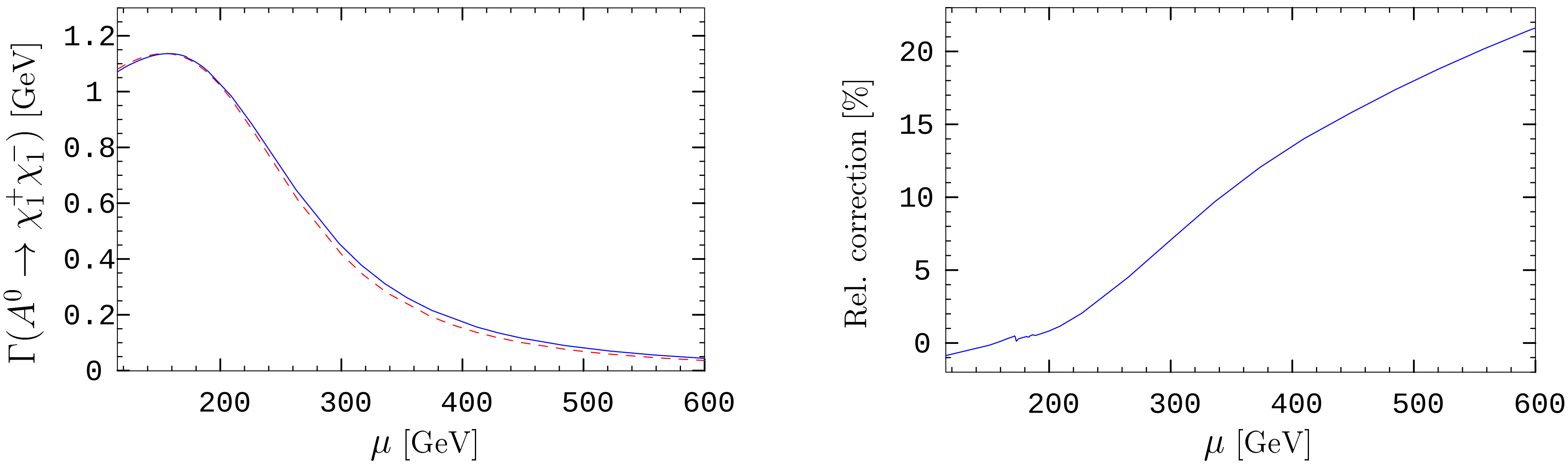


FIGURE : **Left the tree-level (dotted) and one-loop corrected (solid) widths and right the correction of this process relative to the tree-level width**

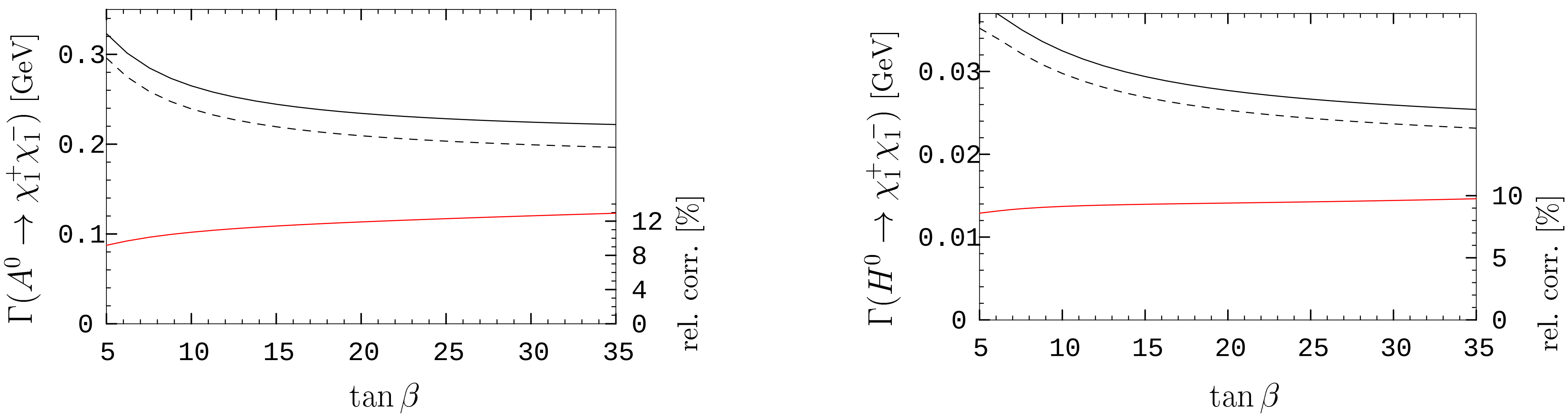


FIGURE : **Tree-level (dotted), one-loop corrected (solid) widths and the correction (red lines) relative to the the tree-level width.**

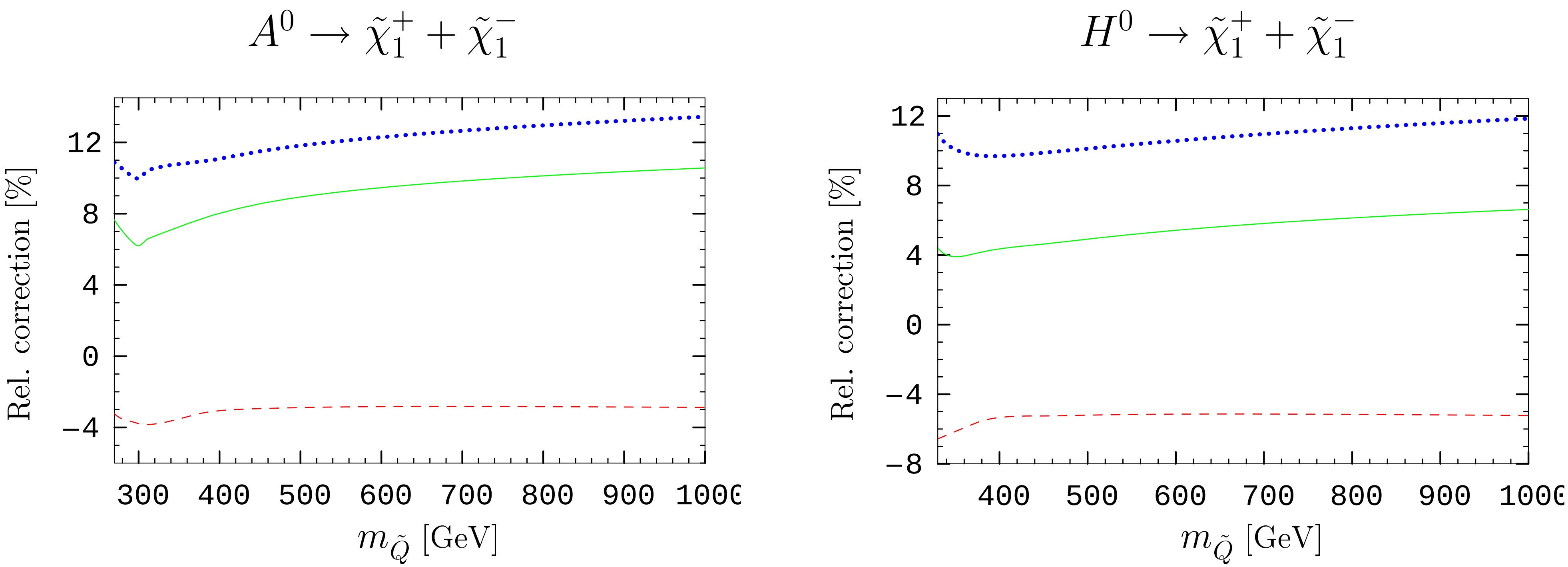


FIGURE : **The full one-loop corrected (solid), the tree-level (dashed), and the conventional one-loop corrected width (dotted) relative to the naive tree-level width. (Note that the tree-level already includes the correction due to the chargino mass matrix renormalization.)**

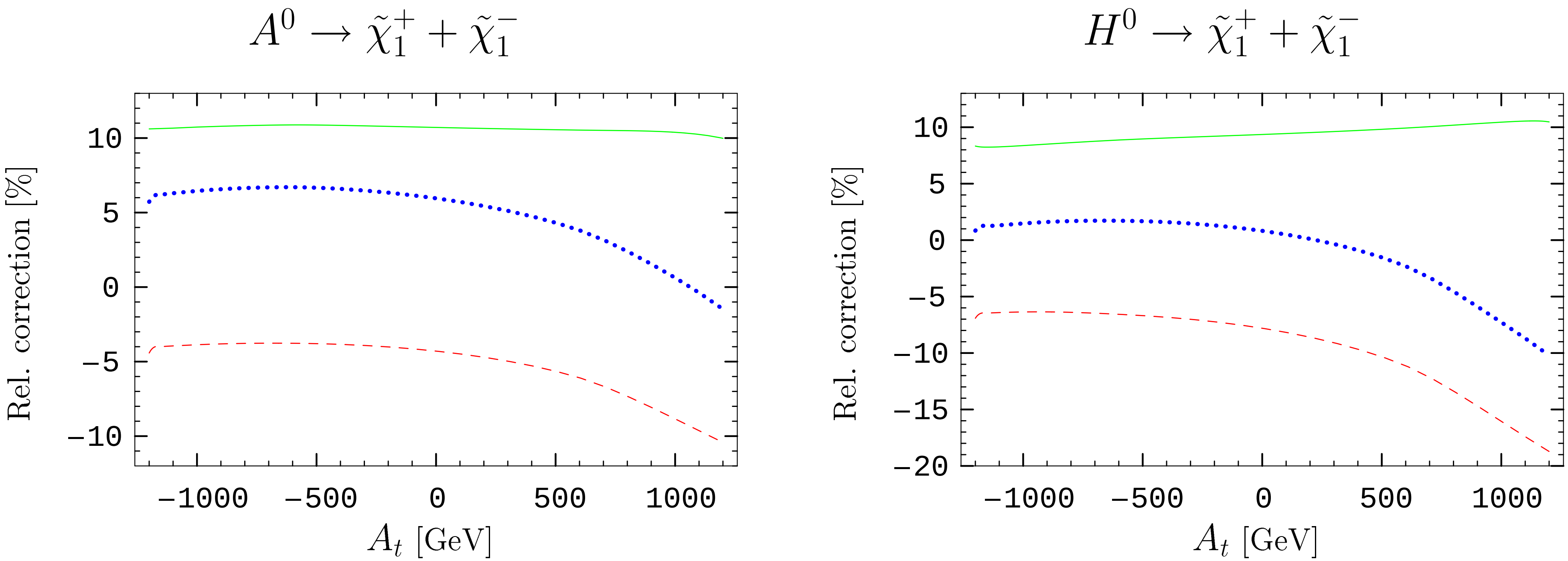


FIGURE : **The dashed lines denote $\Gamma^{\text{tree}}/\Gamma^{\text{naive tree}} - 1$, the solid lines denote $\Gamma^{\text{corr.}}/\Gamma^{\text{naive tree}} - 1$ and the dotted lines $\Gamma^{\text{corr.}}/\Gamma^{\text{tree}} - 1$**

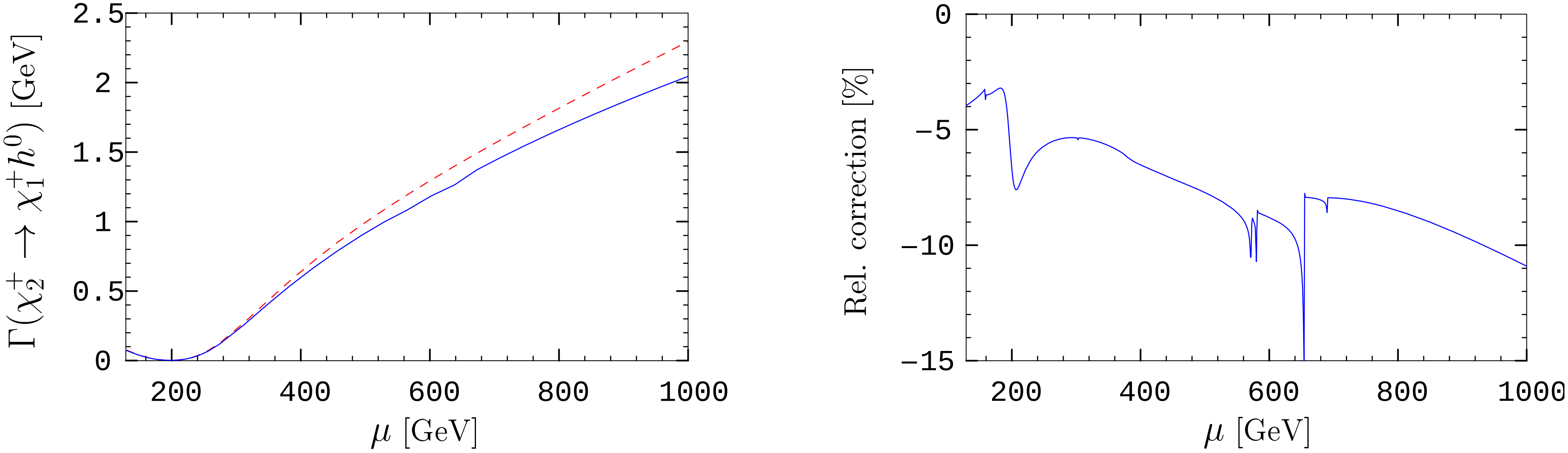


FIGURE : **Left: the dashed line and solid line correspond to the tree-level and loop-corrected widths, respectively. Right:** $\Gamma^{\text{corr.}}/\Gamma^{\text{tree}} - 1$

$$H^0 \longrightarrow \tilde{\chi}_1^0 + \tilde{\chi}_2^0$$

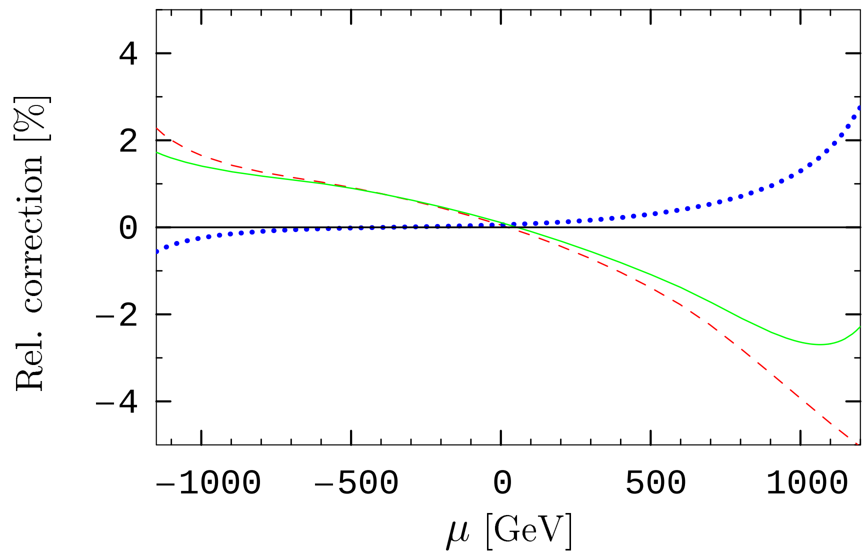
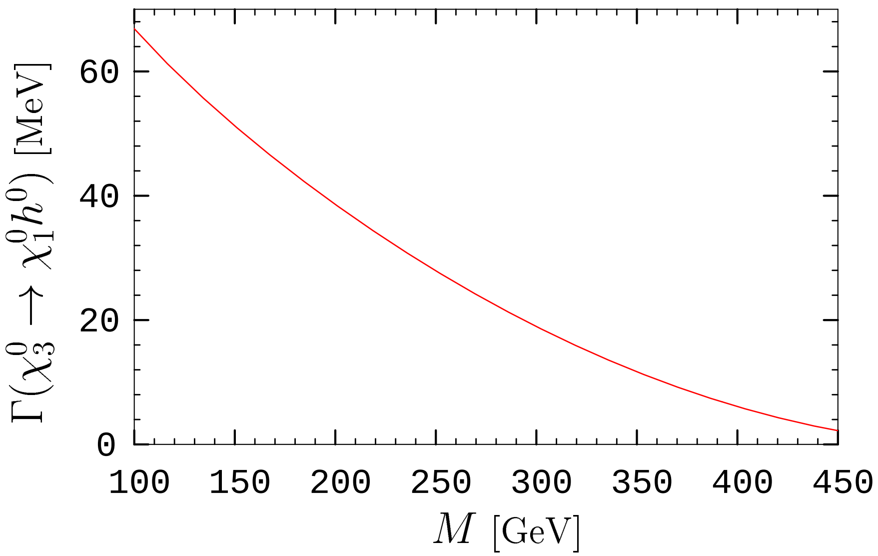


FIGURE : **The dashed lines denote** $\Gamma^{\text{tree}}/\Gamma^{\text{naive tree}} - 1$**, the solid lines** $(\Gamma^{\text{corr.}} - \Gamma^{\text{tree}})/\Gamma^{\text{naive tree}}$ **and the dotted lines** $\Gamma^{\text{corr.}}/\Gamma^{\text{naive tree}} - 1$



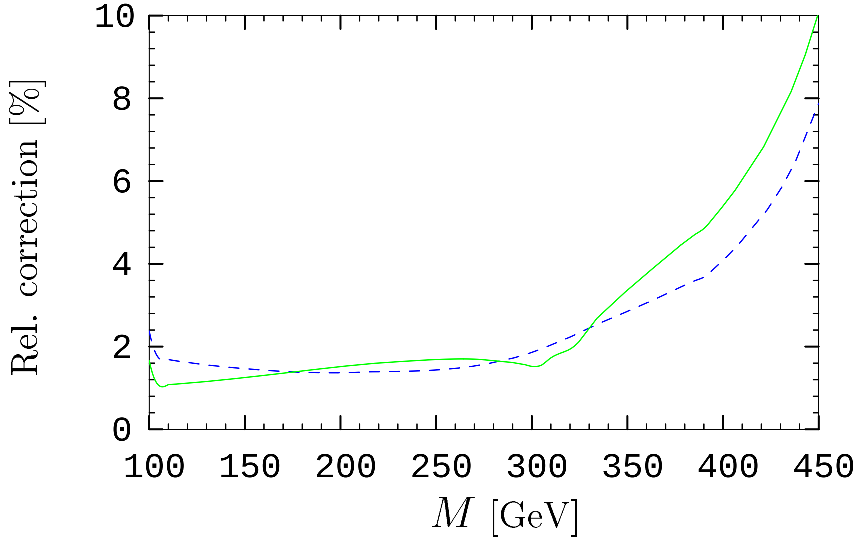


FIGURE : **Left:** $\Gamma^{\text{naive tree}}$**, right: the dashed line denotes** $\Gamma^{\text{tree}}/\Gamma^{\text{naive tree}} - 1$ **and the solid one** $\Gamma^{\text{corr.}}/\Gamma^{\text{naive tree}} - 1$

$$H^+ \longrightarrow \tilde{\chi}_1^+ + \tilde{\chi}_1^0$$

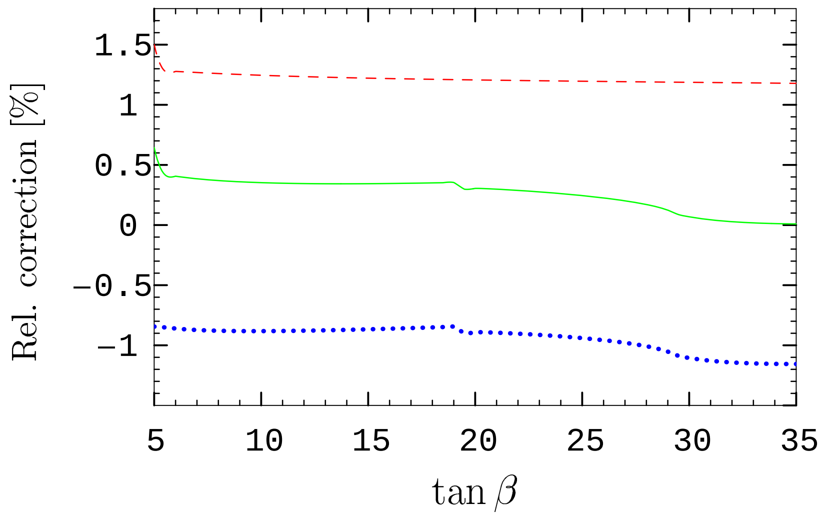


FIGURE : **The dashed line denote** $\Gamma^{\text{tree}}/\Gamma^{\text{naive tree}} - 1$**, the solid one denote** $\Gamma^{\text{corr.}}/\Gamma^{\text{naive tree}} - 1$ **and the dotted one** $\Gamma^{\text{corr.}}/\Gamma^{\text{tree}} - 1$**.**

Conclusions

- **we calculated the full one-loop corrections to the decay widths involving Higgs-chargino/neutralino couplings.**
- **work was done in the on-shell scheme with some improvements.**
- **comparison of $\alpha(m_Z)$ and G_{Fermi} scheme, difference less than 1%.**
- **QED cannot be separated**
- **(s)fermion loop correction are small at SPS1a, full correction can go up to $\sim$ 20%.**