Decays of Higgs bosons into SM final states in the NMSSM – Gauge-dependence aspects

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Next-to-Minimal Supersymmetric Standard Model - Model and Motivations

Softly-broken SUSY extensions of the SM

- **Hierarchy Problem**: SUSY protects the Higgs mass from sensitivity to high-scale new-physics;
- **Higgs Physics**: $m_H \sim 125$ GeV lies in the SUSY-expected range;
- **One-step Unification**: SUSY matter-content ensures convergence of gauge couplings;
- **Dark matter**: WIMP candidate in the presence of R-parity;
- **Top-down approach**: Supergravity, Superstrings, etc.

SUSY obviously absent at low-energies: soft-breaking at the ~TeV scale!

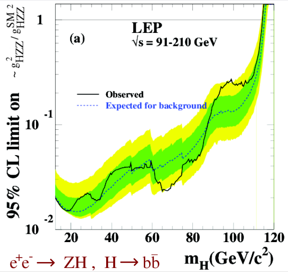
The μ-problem

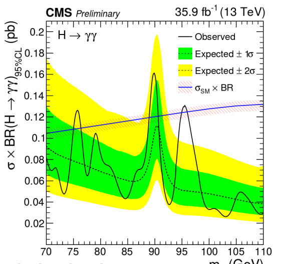
$$W_{MSSM} \ni \mu\, \hat{H}_u \cdot \hat{H}_d \quad \rightarrow \quad W_{NMSSM} \ni \lambda\, \hat{S}\, \hat{H}_u \cdot \hat{H}_d + \kappa \hat{S}^3$$

- μ : SUSY parameter → Natural Scale: $O(M_{\text{Planck,GUT,etc.}})\ldots$ or Zero!
- LEP Constraints on Chargino masses: $\mu \gtrsim 100\,\text{GeV}$
- Electroweak Symmetry Breaking needs: $\mu \lesssim O(TeV)$
- Additional Gauge-Singlet superfield $\hat{S}$ *[Fayet (1975)]*

  v.e.v. $\langle S \rangle = s \quad \Rightarrow \quad \mu_{eff} = \lambda s$
- $\mathbb{Z}_3$-symmetry: scale-invariant superpotential ⇒ *No naturalness problem!*

NMSSM – Phenomenological motivations





CMS-PAS-HIG-17-013

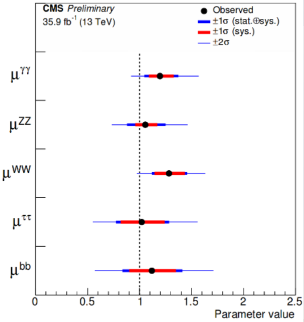
Higgs phenomenology

- $m_{H_{SM}} \sim 125$ GeV high (?) for the MSSM→ **2 NMSSM mechanisms:**
  - **Tree-level** contribution: $m^2_{H_{\sim SM}} \simeq M_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta$;
  - **Uplift** via singlet-doublet mixing ⇒ light singlet.
- A light (CP-even) Higgs singlet?
  - **suppressed production cross-section** (due to singlet couplings).
    ⇒ Limited impact of direct collider searches (LEP/LHC).
    + $H \to b\bar{b}$ LEP 2.3σ / $H \to \gamma\gamma$ CMS 2.9σ excesses at ∼ 100 GeV!
  - **Multiple-state mixing** ⇒ Possible deviations (at the % level) from strict SM couplings for h_{125} even with decoupling doublets.
  - **Search the singlet**? → Directly ($\gamma\gamma$, $\tau\bar{\tau}$, $b\bar{b}$), in Higgs pair production, in BSM decays, etc.
- A very light (CP-odd) Higgs singlet?
  - **Pseudo-Goldstone boson**? of $U(1)_{\rm PQ}$ or $U(1)_{\rm R}$.
  - **Mediator of light DM annihilation**? ⇒ Ensure singlino/bino relic abundance through resonance annihilation.

SUSY phenomenology

- Singlino Dark Matter.
- ‘Stealth’ scenarios in collider searches.

Precision physics in the Higgs sector



Towards a precise determination of the Higgs properties

- Higgs mass: $125.09 \pm 0.21 \pm 0.11$ (LHC Run 1);
- couplings to EW gauge: $\sim 20\%$ (LHC Run 1 & 2);
- couplings to τ, b, t: $\sim 30\%$ (LHC Run 1 & 2);
- couplings to μ, c, $Z\gamma$: on-going searches;
- Higgs self-coupling: constrained by a factor 10.
- Prospects of an ILC:
  - → uncertainty $< 1\%$ on couplings to SM fermions and gauge bosons;
  - → Higgs self-couplings at $10 - 30\%$.

Status in SUSY models

- Higgs masses: known at (leading) 2-loop order
  - → for h^0_{SM}, uncertainty $\gtrsim O(\mathrm{GeV})$; larger for heavier states.
- Higgs decays: at best 1-loop (often less), large uncertainties.

→ Improved accuracy on the theory side is needed to exploit precision tests.

Many tools designed for the NMSSM (NMSSMCalc, NMSSMTools, Sloops, SoftSUSY, Spheno, etc.) with slightly different approaches / schemes.

Higgs decays into SM final states

Setting up the calculation

- We consider the **1-loop** order (+ some higher-order effects).
- Feynman diagrams computed with FeynArts and FormCalc.
- **Renormalization scheme**:
  → SM fermion and gauge boson masses and fields *on shell*.
  → Charged Higgs mass *on shell*.
  → Other parameters ($\tan\beta$, μ_{eff}, λ, κ, Higgs fields, etc.) $\overline{DR}$.
- **Decay amplitude** defined by the LSZ reduction formula.
  → wave-function diagrams on Higgs leg absorbed in a mixing formalism.
  → Higgs mixing with Goldstone/weak gauge boson processed separately.
  → no wave-function diagrams for the SM final states (on shell scheme).
  → QED/QCD vertex corrections factorized out (add soft+hard radiation).
  → other vertex contrib. include EW + Higgs + SM ferm. + SUSY loops.
- Higgs leg → kinematical mass set to the loop-corrected value.
- Feynman-'t Hooft gauge (unless otherwise indicated).

Issue 1: $h_i \to \gamma\gamma$ and the Ward identity

Decay amplitude

$$\mathcal{A}[h_i(p) \to \gamma(k_1)\gamma(k_2)] = A_i\, \varepsilon^*_\gamma(k_1)\cdot\varepsilon^*_\gamma(k_2) + B_i\,[p\cdot\varepsilon^*_\gamma(k_1)][p\cdot\varepsilon^*_\gamma(k_2)] + C_i\,\varepsilon_{\mu\nu\rho\sigma} k_1^\mu \varepsilon_\gamma^{\nu *}(k_1) k_2^\rho \varepsilon_\gamma^{\sigma *}(k_2)$$

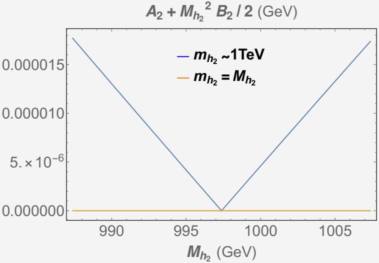
The decay appears at the loop level. A_i, B_i, C_i are form factors.

Ward identity

Replacement $\varepsilon^*_\gamma(k_1) \to k_1$ in $\mathcal{A}[h_i(p) \to \gamma(k_1)\gamma(k_2)]$ generates the identity:

$$A_i + M^2_{h_i} B_i/2 = 0$$

(M_{h_i} kinematical Higgs mass vs. m_{h_i} tree-level mass)



Testing the Ward identity

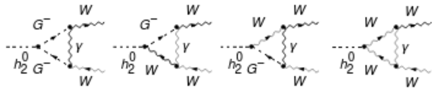
→ At the numerical level, only $M_{h_i} = m_{h_i}$ satisfies the identity.

→ $\mathcal{L} \ni -\frac{m^2_{h_i}}{\sqrt{2}v}(\cos\beta\, X^R_{id} + \sin\beta\, X^R_{iu})\, h_i G^+ G^-$

→ To force the identity at $M_{h_i} \neq m_{h_i}$, one can promote $m_{h_i} \to M_{h_i}$ in amplitude.

$\Rightarrow$ 1L order shift in a 1L amplitude $= O(2L)$.

Issue 2: $h_i \to WW(\gamma)$ and IR-divergences



QED corrections to $h_i \to WW$

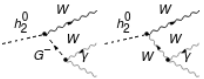
$$\Gamma^{\mathrm{QED}}[h_i \to WW] = \Gamma^{\mathrm{tree}}[h_i \to WW](1 + \delta_{\mathrm{virt}})$$

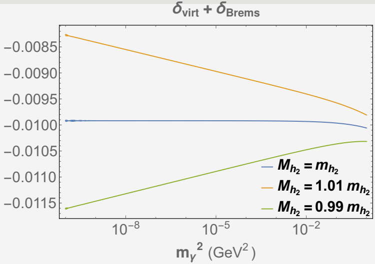
$$\delta_{\mathrm{virt}} = \frac{\alpha}{\pi}\left\{ \ln \frac{m_\gamma^2}{M_W^2} F[M_{h_i}^2, m_{h_i}^2, M_W^2] + \cdots \right\}$$ $\to$ Dependence on $m_{h_i}^2$ from $h_i G^+ G^-$.

Photon radiation

$$\Gamma^{\mathrm{tree}}[h_i \to WW\gamma] = \Gamma^{\mathrm{tree}}[h_i \to WW]\delta_{\mathrm{Brems}}$$

$$\delta_{\mathrm{Brems}} = \frac{\alpha}{\pi}\left\{ -\ln \frac{m_\gamma^2}{M_W^2} F[M_{h_i}^2, M_{h_i}^2, M_W^2] + \cdots \right\}$$





Cancellation of IR divergences

$\to$ Only achieved for $M_{h_i} = m_{h_i}$.

$\to$ Upgrade $m_{h_i} \to M_{h_i}$ in $h_i G^+ G^-$ again extends the cancellation.

$\hookrightarrow$ Once more: shift $= O(2\mathrm{L})$.

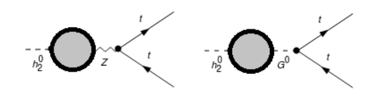
Issue 3: Slavnov-Taylor identity in Higgs-G^0/Z mixing

Slavnov-Taylor identity

$$M_Z\,\Sigma_{h_iG^0}(p^2)+\imath\,p^2\,\Sigma_{h_iZ}(p^2)+M_Z(p^2-m^2_{h_i})f(p^2)+\text{tadpoles}=0$$

$\rightarrow f(p^2)$ is a gauge-dependent term $\propto \xi_Z$.

The identity is indeed satisfied at the numerical level...



$h_i - G^0/Z$ contribution to fermionic decays

Injecting the relation between $\Sigma_{h_iG^0}$ and Σ_{h_iZ} in the amplitude:

$$\mathcal{A}^{h_i-G^0/Z}[h_i(p)\rightarrow f\bar{f}]=\frac{g_2 m_f I_3^f}{v\,p^2}\left\{\hat{\Sigma}_{h_iG^0}(p^2)-(p^2-m^2_{h_i})\frac{\xi_Z M_Z^2 f(p^2)}{p^2-\xi_Z M_Z^2}\right\}$$

$\Rightarrow$ The ξ_Z-dependent part disappears only if $m_{h_i}\rightarrow M_{h_i}$ in h_i-G^0 couplings

Issue 4: Gauge invariance in e.g. $h_i \to t\bar{t}$

ξ-dependence from the charged current

- In R_ξ gauge, considering only ξ-dependence from charged current:

$$\mathcal{A}^{\text{vert}}[h_i(p) \to t(p_t)\bar{t}(p_{\bar{t}})] \ni \frac{\imath g^3 m_t}{64\pi^2 M_W^3}\,\bar{u}(p_t)\Big\{(p^2 - m_{h_i}^2)\Big[(c_\beta X_{id}^R + s_\beta X_{iu}^R)\,I_1 + (-s_\beta X_{id}^* + c_\beta X_{iu})\,I_2 + (-s_\beta X_{id} + c_\beta X_{iu}^*)\,I_2'\Big] + B\text{-functions}\Big\}v(p_{\bar{t}})$$

$$I_1 \equiv \frac{\imath 16\pi^2}{m_t}\int\frac{d^Dk}{(2\pi)^D}\,\frac{\not{k}(m_t^2 P_R + m_b^2 P_L) - m_t m_b^2}{[k^2 - m_b^2][(k-p_t)^2 - \xi M_W^2][(k+p_{\bar{t}})^2 - \xi M_W^2]}$$

$$I_2 \equiv \frac{\imath 16\pi^2}{m_t}\int\frac{d^Dk}{(2\pi)^D}\,\frac{\not{k}(m_t^2 t_\beta^{-1} P_R - m_b^2 t_\beta P_L) + m_t m_b^2(t_\beta P_R - t_\beta^{-1} P_L)}{[k^2 - m_b^2][(k-p_t)^2 - m_{H^\pm}^2][(k+p_{\bar{t}})^2 - \xi M_W^2]} \qquad I_2' \equiv I_2(p_{\bar{t}} \leftrightarrow -p_t)$$

$\hookrightarrow$ Here, the dependence on $m_{h_i}^2$ comes both from $h_i G^+ G^-$ and $h_i H^\pm G^\mp$:

$$\mathcal{L} \ni \frac{m_{H^\pm}^2 - m_{h_i}^2}{\sqrt{2}v}(-s_\beta X_{id} + c_\beta X_{iu}^*)\,h_i H^+ G^- + \text{h.c.}$$

- The ξ-dependent B-functions are matched by corrections from Higgs wave-function and lead also to $\propto (p^2 - m_{h_i}^2)$.

$\Rightarrow$ To ensure gauge invariance, also $h_i H^\pm G^\mp$ need an 'upgrade'.

$\hookrightarrow$ Again a $O(2\text{L})$ effect at the level of the amplitude.

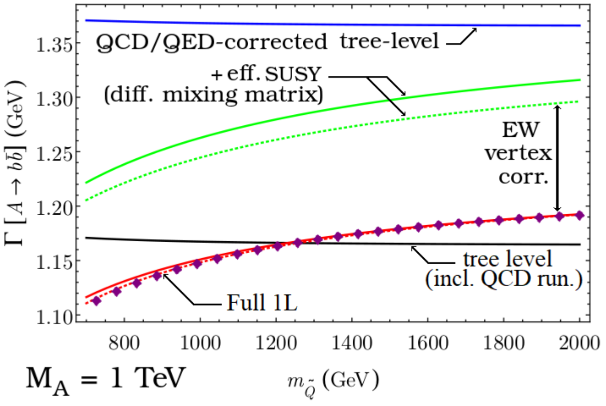
Case of the neutral current

Same conclusion as in the charged case with $h_i G^0 G^0$ and $h_i h_j G^0$ couplings.

Summary on gauge-invariance considerations

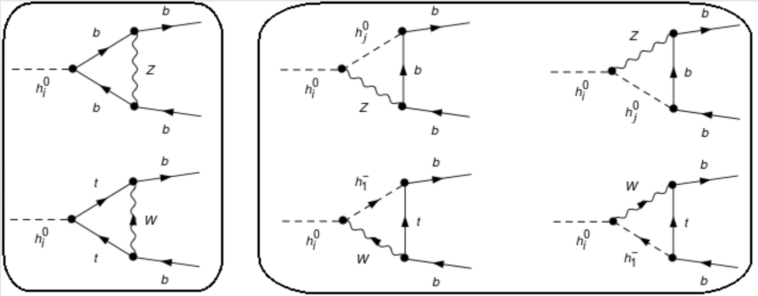
- Gauge invariance holds indeed at the order of the calculation (1L).
- But: gauge-violating pieces of 2L order are present unless
  1) the kinematical Higgs mass is set to the tree-level value;
  2) all the Higgs-Goldstone couplings are 'upgraded'.
- We choose 2), → amounting to a shift of the amplitude of 2L order;
  → 'saving' the kinematics;
  → easily interpreted in terms of EFT
  (Goldstone couplings related to mass).

Higgs decays into SM fermions – Numerical results



- QCD/QED corrections to inclusive widths known since the '80 / '90:
  $\hookrightarrow$ leading QCD logs can be resummed via running Yukawa couplings.
- Leading SUSY effects project onto dim. 4 Higgs-fermion operators.
- Electroweak corrections: reach $\sim 10\%$ for $M_A \sim 1$ TeV $\rightarrow$*Why?*

Electroweak corrections – Vertex



Sudakov double logarithms

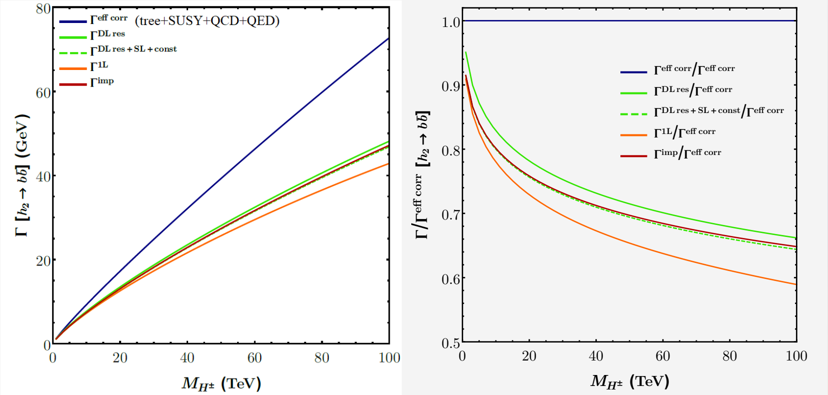
Topologies with: → internal EW gauge boson and light fermions;
→ EW gauge / fermion / Higgs with mass $\sim M_H$;

generate contributions $\propto \frac{g^2}{16\pi^2} \ln^2 \frac{M_V^2}{M_H^2}$.

Not '*standard*' Sud. DL because massive Higgs line is EW-charged.

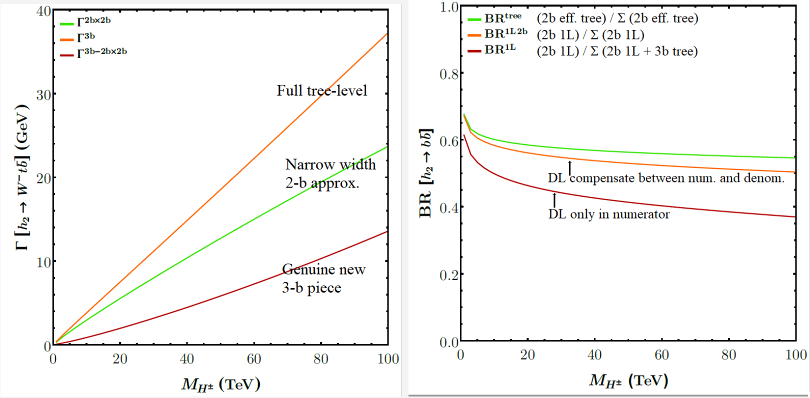
↪ Sud. DL can be resummed at all orders (determined by IR).

Electroweak corrections – Results



- EW effects range from ~ 10 to $\sim 50\%$ for $M_{H^\pm} \in [1, 100]$ TeV.
- Resummation begins to matter at $\gtrsim 10$ TeV.
- Double logarithms dominate the EW corrections.
- EW corrections dominated by double, then single logs + const.

Radiation of electroweak gauge bosons



- Order-counting: tree-level 3-body ~ 1L 2-body.
- Piece mediated by on-shell internal line subtracted (2-body).
- DL in gauge radiation match DL in virtual corrections.
- Significant impact on the branching ratio (via total width).

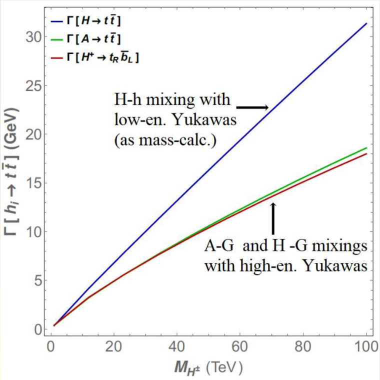
Exploiting $SU(2)_L$ in the decoupling limit

$M_{h_i,H^\pm} \gg M_Z$ $\Rightarrow SU(2)_L$ conserved up to $O\left(\frac{M_Z}{M_h}\right)$ corrections.

$\hookrightarrow$ 'Heavy doublet' states are $SU(2)_L$ partners:

$\Rightarrow$ almost degenerate $M_{H^\pm} \approx M_H \approx M_A$;

$\Rightarrow$ also their decay widths should be related.

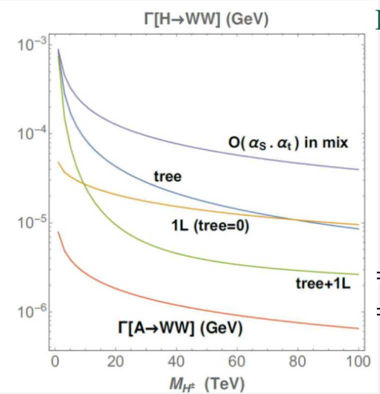


Example of the fermionic decays

- Explicit agreement of 1L $\ln M_Z/M_h$.
- Different treatment of Higgs mixing:
  - $\to h - H$ with 'low-energy' Yukawas
  - $\to G^0/Z - A$ and $G^+/W^+ - H^+$ with $Y_q(M_H^2)$ (as hinted by QCD).
- Large difference of 2L-order:
  - i) considered as uncertainty;
  - ii) harmonize mixing procedure;
  - iii) QCD-inclusive favors $Y_q(M_H^2)$.

$SU(2)_L$ and decays into weak gauge bosons

- $\Gamma^{\text{tree}}[A \to WW, ZZ]$ and $\Gamma^{\text{tree}}[H^+ \to W^+ Z]$ exactly vanish.
- $\Gamma^{\text{tree}}[H \to WW, ZZ]$ suppressed (decoupling limit).
  $\hookrightarrow$ No $SU(2)_L$-conserving operator with 1 doublet + gauge triplets.



Balance between mixing and vertex

- Large cancellations between mixing and vertex contributions.
- Inclusion of $O(\alpha_S \alpha_t)$ corrections in mixing produces an imbalance (not matched by corresponding order in vertices).

$\Rightarrow$ Mixing orders is misleading.

$\Rightarrow$ Higher orders in mixing (but not in vertex) *worsen* the prediction.

Conclusions

- Effects beyond 1L can be large, especially for heavy states.
  $\hookrightarrow$ Symmetries (gauge-invariance, global $SU(2)_L$) can be used to control them.
- Processing mixing and vertex at different orders is artificial and source of problematic effects.
- 3-body decays should be included together with 1L 2-body for a consistent evaluation of branching ratios at this order.
- These effects are not restricted to the NMSSM…