Possible NMSSM deviations from the SM-like signal strengths of the 125 GeV Higgs boson

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Input

4 Higgs masses spanning the 4D parameter space: M_{H1}, M_{H2}, M_{A1}, $M_{H3} \approx M_{A2} \approx M_{H^\pm}$

+

Fit Constraints

For a given point M'_{H1}, M'_{H3}, M'_{A1} in 3D the following constraints are used: $M_{H2} = 125$ GeV and SM-like*, $M_{H1} = M'_{H1}$, $M_{A1} = M'_{A1}$, $M_{H3} = M'_{H3}$,

Minuit

Connection between Input and Output from NMSSMTools

Output

7 parameters spanning the 7D parameter space: $\tan\beta$, λ, κ, A_0, $A_\lambda, A_\kappa, \mu_{eff}$

How to cover the 7D NMSSM parameter space by scanning the 3D Higgs parameter space?

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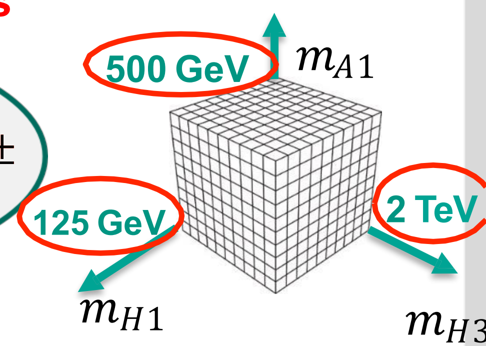
7 free parameters

$\tan\beta, A_\kappa, A_\lambda, \lambda, \kappa, \mu_{eff}$
$(m_0, m_{1/2}, A_0)$

3 free Higgs masses

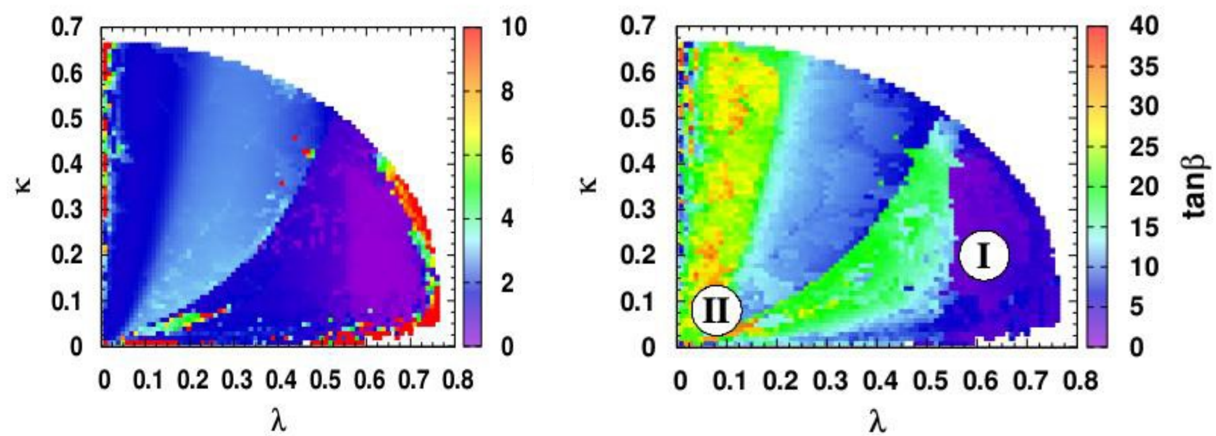
$H_1, H_2, H_3, A_1, A_2, H^\pm$

Scan limits



7 free NMSSM parameters can be determined from fitting the selected Higgs masses on the 3D grid with constraints (same problem as extracting parameters from a completely and perfectly measured set of Higgs masses determining uniquely the corresponding parameters) → no random scan

***λ,κ*-plane as an example for output from deterministic scan of 3D mass space:**



χ^2 function $\chi^2_{tot} = \chi^2_{H_S} + \chi^2_{H_{SM}} + \chi^2_{\mu_{SM}} + \chi^2_{H_3} + \chi^2_{A_1} + \chi^2_{LEP} + \chi^2_{LHC}$

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- $\chi^2_{H_S} = \frac{(m_{H_1} - m_{grid,H_1})^2}{\sigma^2_{H_1}}$
  - m_{grid,H_1} : chosen point in the 3D mass space
  - m_{H_1}: singlet-like Higgs boson, σ_{H_1} set to 1‰ m_{H_1} GeV
- $\chi^2_{H_{SM}} = \frac{(m_{H_2} - m_{obs})^2}{\sigma^2_{SM}}$
  - 125.2 GeV Higgs boson with σ_{SM} set to 1‰ m_{H_2} GeV
- $\chi^2_{H_3/A_1} = \frac{(m_{H_3/A_1} - m_{grid,H_3/A_1})^2}{\sigma^2_{H_3/A_1}}$ as $\chi^2_{H_S}$
- χ^2_{LEP}: includes the LEP constraints on the couplings of a light Higgs boson below 115 GeV and the limit on the chargino mass
- χ^2_{LHC}: includes the LHC constraints as implemented in NMSSMTools
- $\chi^2_{H_{SM}} = \sigma_i (\mu^i_{H_2} - \mu_{obs})^2 / \sigma^2_\mu$
  - 125.2 GeV with SM couplings, so 8 reduced signal strengths of H_2 to particle $i = \tau, b, W/Z, \gamma$ for ggf/ttH and VBF/VH production μ_{obs} required to be 1

NMSSM scalar Higgs sector

- Scalar Higgs bosons H_i are mixtures of the CP-even weak eigenstates H_u, H_d and S

$$H_i = S_{i1}H_d + S_{i2}H_u + S_{i3}S$$

- Higgs couplings dependent on $\tan\beta$, the Higgs mixing elements S_{ij} and the corresponding Yukawa couplings

$$H_i t_L t_R^c : -\frac{h_t}{\sqrt{2}} S_{i2} \qquad h_t = \frac{m_t}{v\sin\beta}$$

$$H_i b_L b_R^c : -\frac{h_b}{\sqrt{2}} S_{i1} \qquad h_b = \frac{m_b}{v\cos\beta}$$

$$H_i \tau_L \tau_R^c : -\frac{h_\tau}{\sqrt{2}} S_{i1} \qquad h_\tau = \frac{m_\tau}{v\cos\beta}$$

$$H_i Z_\mu Z_\nu : g_{\mu\nu}\frac{g_1^2 + g_2^2}{\sqrt{2}}(v_d S_{i1} + v_u S_{i2})$$

$$H_i W_\mu^+ W_\nu^- : g_{\mu\nu}\frac{g_2^2}{\sqrt{2}}(v_d S_{i1} + v_u S_{i2})$$

- Effective couplings to gluons and photons encoded in NMSSMTools*
- In decoupling limit $m_{H3/A2} \gg m_Z$ and small mixing between singlet and doublets, NMSSM prefers SM-like couplings for one of the light Higgses

* D. Das, U. Ellwanger, and A. M. Teixeira, arXiv:1106.5633

Reduced couplings (without loops)

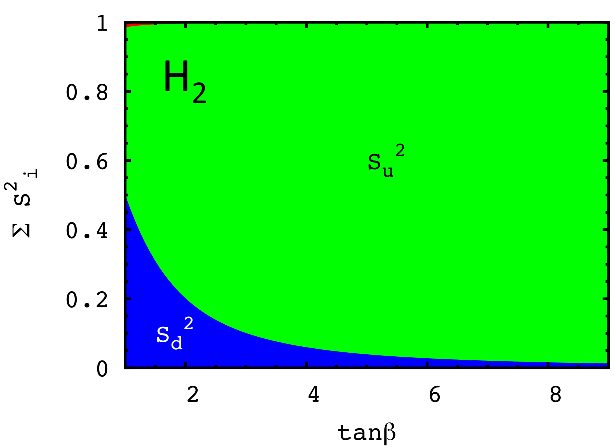
- **Reduced couplings**, i.e. Higgs couplings divided by SM prediction, to fermions and bosons depend on tanβ and Higgs mixing matrix elements S_{ij}

$$c_u = \frac{S_{i2}}{\sin\beta} \qquad c_d = \frac{S_{i1}}{\cos\beta} \qquad c_{W/Z} = \cos\beta \cdot S_{i1} + \sin\beta \cdot S_{i2}$$

H_2 SM-like if

$$S_{22} \approx \sin\beta \qquad S_{21} \approx \cos\beta \qquad \approx (\cos\beta)^2 + (\sin\beta)^2 = 1$$

S_{ij} as function of $\tan\beta$



S_{ij} (%)	d	u	s	c_u	c_d	$c_{W/Z}$
H_1	11.41	-2.54	99.31	-0.026	0.622	-0.004
H_2	18.42	98.29	0.40	1.000	1.004	1.000
H_3	97.62	-18.24	-11.69	-0.186	5.322	<-0.001

S_{ij} and reduced couplings for $\tan\beta = 5.36$, $m_{H1} = 90$ GeV, for $m_{H3} = 1000$ GeV and for $m_{A1} = 200$ GeV

Reduced signal strengths

production mode

$$\mu_j^i = \frac{\sigma_i \times BR_j}{(\sigma_i \times BR_j)_{SM}} = c_i^2 \cdot \frac{BR_j}{(BR_j)_{SM}}$$

decay mode

- **Reduced signal strength**: cross section times branching ratio divided by the SM prediction
- In the ratio the dominant error of scale dependence compensated (?)
- **4 reduced couplings** c_i : the effective reduced gluon coupling c_{gluon} for gluon fusion (ggf), $c_{W/Z}$ for vector boson fusion (VBF) and Higgs strahlung (VH) and c_u for top fusion (tth)

8 observed signal strengths:

4 fermion signal strengths $\mu_{1/2}$: $\mu_{\tau\tau}^{VBF/VH}, \mu_{\tau\tau}^{ggf}, \mu_{bb}^{VBF/VH}, \mu_{bb}^{ttH}$

4 boson signal strengths μ_1: $\mu_{Z/W}^{VBF/VH}, \mu_{Z/W}^{ggf}, \mu_{\gamma\gamma}^{VBF/VH}, \mu_{\gamma\gamma}^{ggf}$

Example of reduced signal strengths

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- for $\tan\beta = 5.36$, $m_{H1} = 90$ GeV, for $m_{H3} = 1000$ GeV and for $m_{A1} = 200$ GeV

	H1	H2	H3
$\mu_{\tau\tau}^{ggf}$	0.0173	1.0026	24.7435
μ_{bb}^{ttH}	0.0007	1.0021	18.0317
$\mu_{Z/W}^{VBF/VH}$	0.0000	0.9946	< 0.0001
$\mu_{Z/W}^{ggf}$	0.0000	0.9946	< 0.0001
$\mu_{\gamma\gamma}^{VBF/VH}$	< 0.0001	1.0057	< 0.0001
$\mu_{\gamma\gamma}^{ggf}$	0.0009	1.0057	0.1080
$\mu_{\tau\tau}^{VBF/VH}$	< 0.0001	1.0026	< 0.0001
$\mu_{bb}^{VBF/VH}$	< 0.0001	1.0024	< 0.0001

tan β enhanced

No coupling to gauge bosons

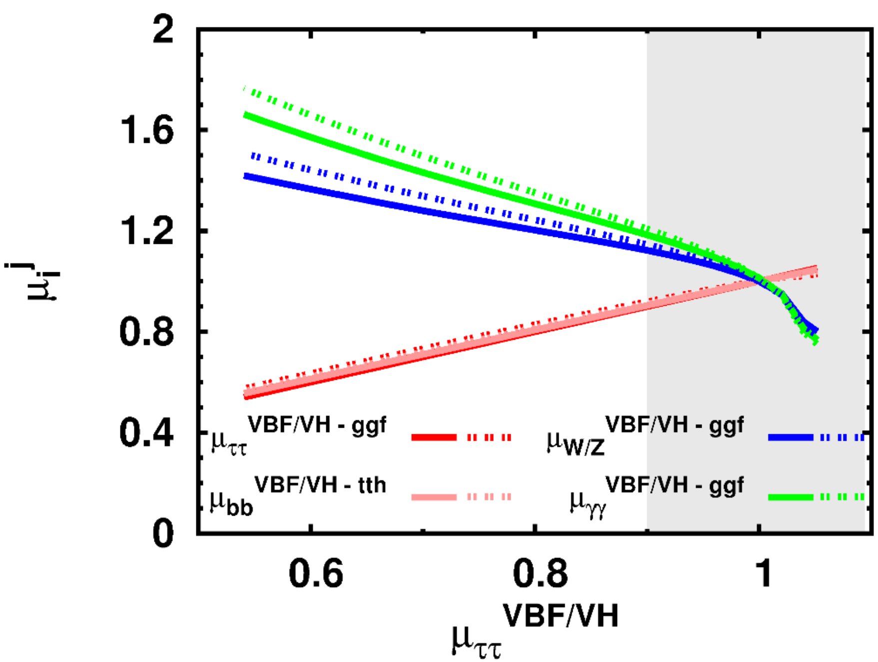
Singlet

SM-like

Are larger deviations from SM allowed?

- Perform fit requiring a ***single selected*** signal strength μ_{sel} out of the total 8 signal strengths to be fitted to a specific value μ_{theo}, which can be done by replacing the 8 mu constraints by a single χ^2 a term:

$$\chi^2 = (\mu_{sel} - \mu_{theo})^2/\sigma^2$$



- μ_{sel} can be chosen to be $\mu_{\tau\tau}$ and μ_{theo} is fitted in the range of 0.5 to 1.5

  Low $\mu_{1/2}$ can be compensated by large μ_1
- Deviations constrained by experimental error (grey band)

For $m_{H1} = 90$ GeV, for $m_{H3} = 1000$ GeV and for $m_{A1} = 200$ GeV

Deviations from SM from varying $\tan\beta \rightarrow$ varying BR to down type fermions $\rightarrow$ anticorrelation with W/Z and γ, if no other channels possible

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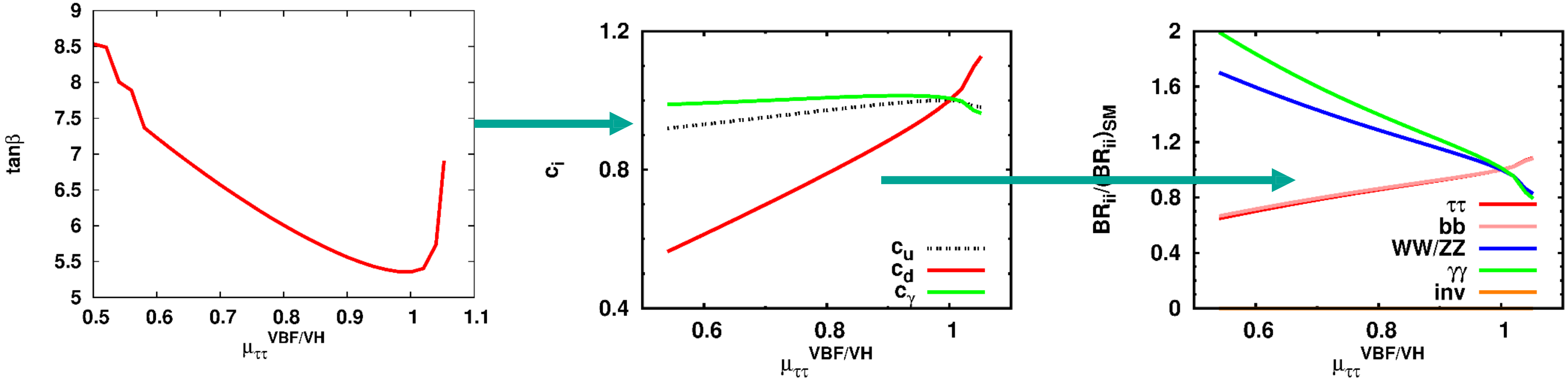


$$\mu_{\tau\tau}^{VBF/VH} = c_{W/Z}^2 \cdot \frac{BR(H \rightarrow \tau\tau)}{BR(H \rightarrow \tau\tau)_{SM}}$$

- Varying μ_{theo} changes fitted tanb and hence, all BR to down-type fermions

- Since the total width stays rather constant, changing a partial width leads to an anticorrelation with the others, here between fermions and bosons

Surprise:

after selecting another mass combination of input masses,

the **anticorrelation became a correlation**

Before: $m_{H1} = 90$ GeV, $m_{H3} = 1000$ GeV and $m_{A1} = 200$ GeV

New: $m_{H1} = 90$ GeV, $m_{H3} = 2000$ GeV and $m_{A1} = 200$ GeV

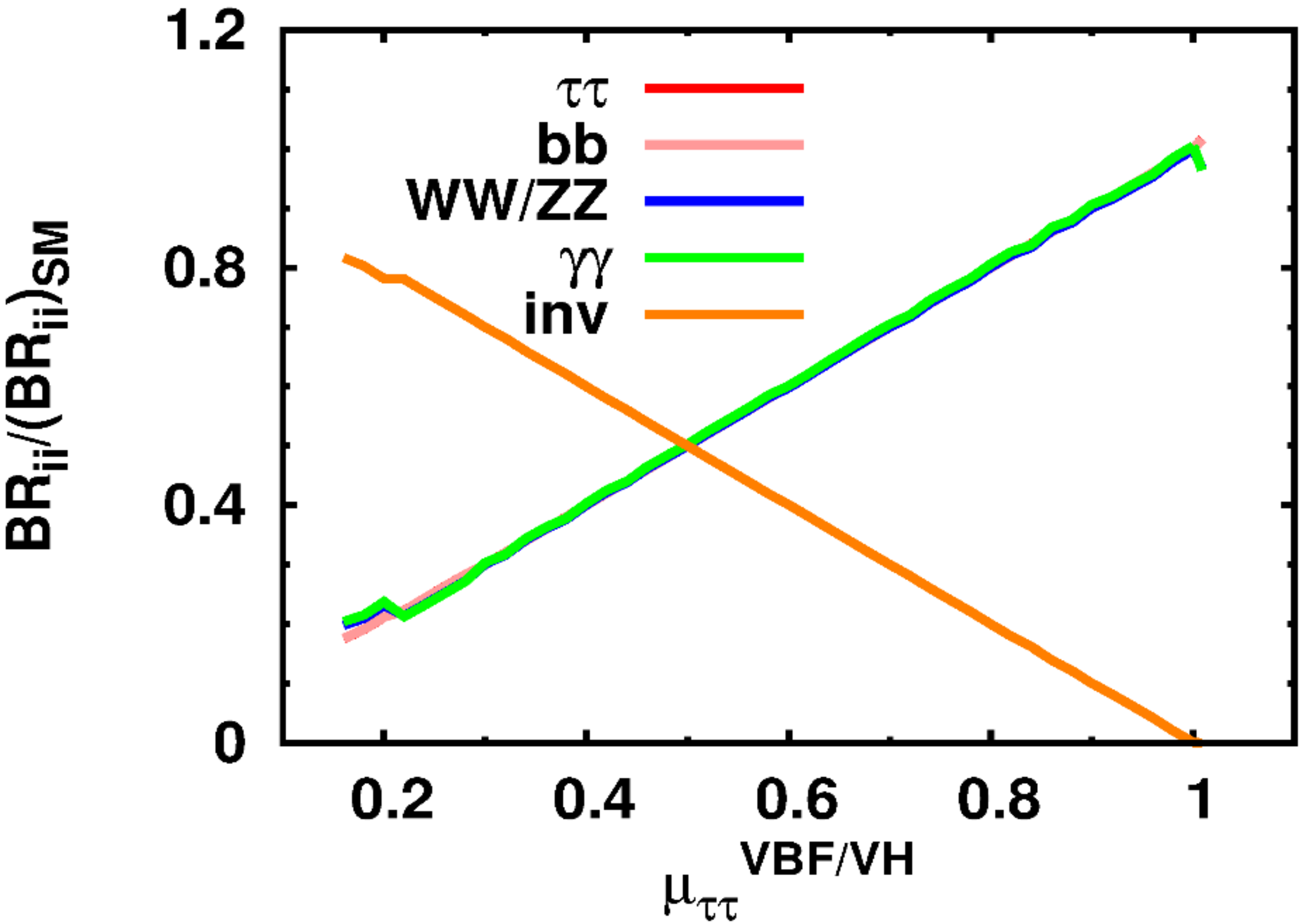
What happened? Invisible width suddenly popped up

All masses correlated: $m_{H1} < (2\kappa/\lambda) \cdot \mu_{eff}$ and $m\tilde{\chi}_1^0 \sim (2\kappa/\lambda) \cdot \mu_{eff}$, $m_{H3} = f(\mu_{eff})$

$\mu_{\tau\tau}^{VBF/VH}$	m_{H1} in GeV	m_{H3} in TeV	m_{A1} in GeV	m_{χ^0} in GeV
1	90	1	200	103.2
1	90	2	200	62.5
0.7	90	2	200	52.1

So by increasing $m_{H3} = f(\mu_{eff})$ LSP neutralino mass drops below $m_{H2}/2$, so invisible decay possible and deviations from SM BR expected. For large deviations, strong invisible widths

Invisible decays increase total width ($\Gamma_{tot} = \Gamma_{vis} + \Gamma_{inv}$), so all other branching ratios decrease ($BR = \Gamma / \Gamma_{tot}$)



In case of invisible channels, all other BR decrease in correlated way (no anticorrelation)

Second surprise: larger mixing between the two light Higgs bosons leads to correlated deviations from SM BRs

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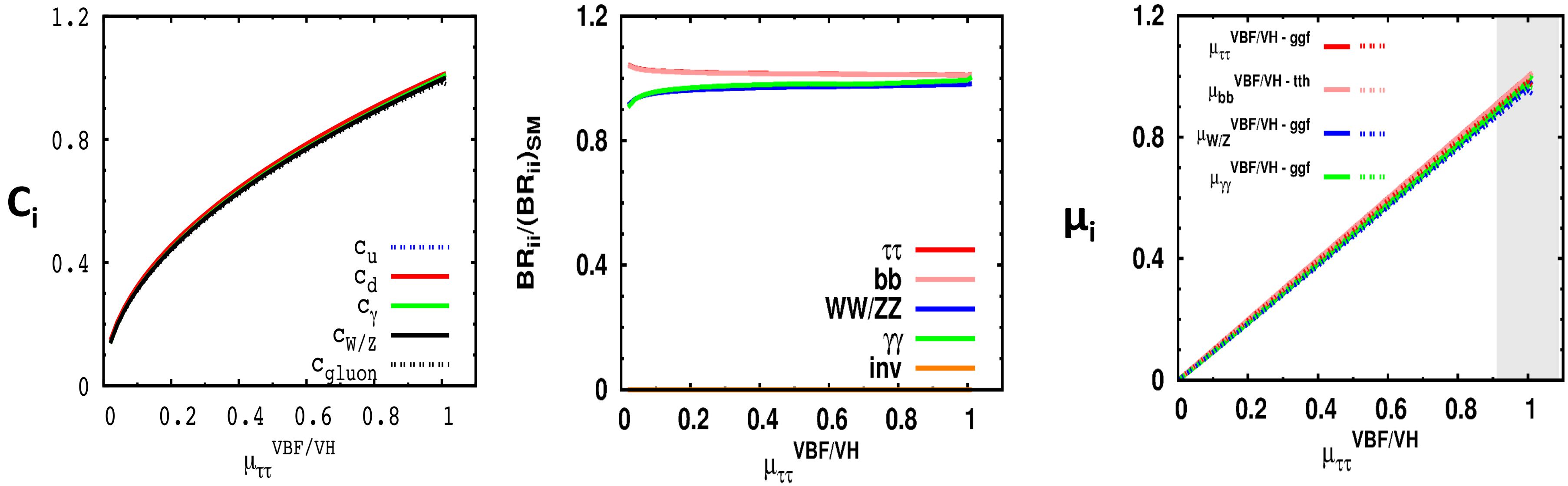
- Choose mass point with $m_{H2} - m_{H1} < 3$ GeV → stronger mixing between H_1 and H_2 → increase of singlet component S of SM-like boson → simultaneous decrease of all SM-like couplings to fulfill $S_u^2 + S_d^2 + S^2 = 1$ → smaller reduced strengths: $\mu_i = c_i^2 \times BR_i/BR_{SM}$

- Only deviations <1 possible and deviations for all channels correlated



- **For m_{H1} = 122.9 GeV, m_{H3} = 1300 GeV and m_{A1} = 200 GeV**

Summary

- By using the new scanning technique, we investigate the regions of parameter space where the signal strength of the observed 125 GeV Higgs boson can deviate from one and the correlation between the deviations for signal strengths to vector bosons and fermions is investigated

- Three different regions with signal strengths deviating from 1:

  i) the variation of the coupling to down-type fermions (via tanb)

  ii) the variation of the invisible Higgs decay (via neutralino mass)

  iii) the variation of the singlet component of the SM Higgs boson (via difference between H_1 and H_2 masses)

  The latter two cases lead to correlated changes of fermion and boson signal strengths, the first case to an anticorrelated change of the fermion and boson signal strengths

- Observed signal strengths compatible with SM constrain these three different regions