An effective scanning method of the NMSSM parameter space

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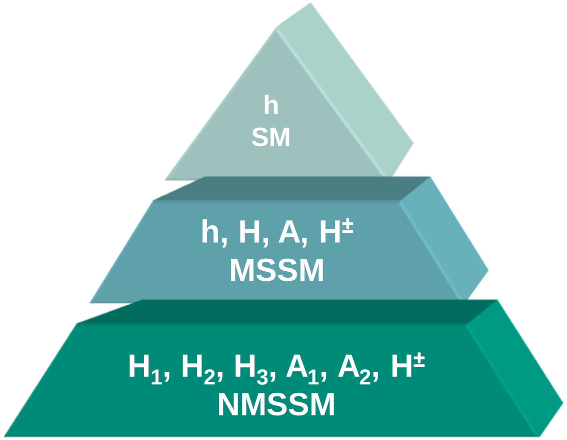
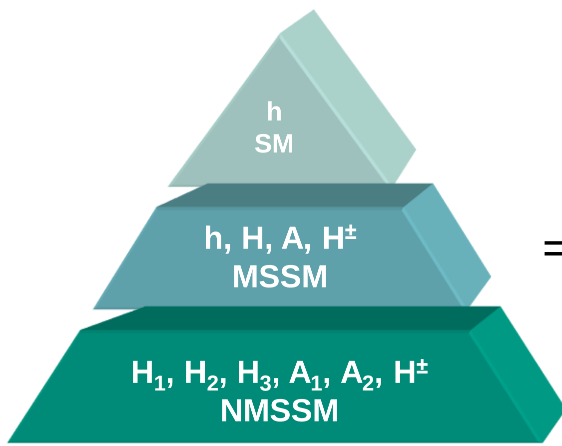


Parameters MSSM vs. NMSSM

- **NMSSM has one additional Higgs singlet**

  → additional terms in superpotential lead to more free parameters and lead to modifications in the Higgs and neutralino sector

SM Higgs
h = 125 GeV
H_1 or H_2 = 125 GeV



$$\Rightarrow \quad H_i = S_{i1}H_d + S_{i2}H_u$$

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

CMSSM

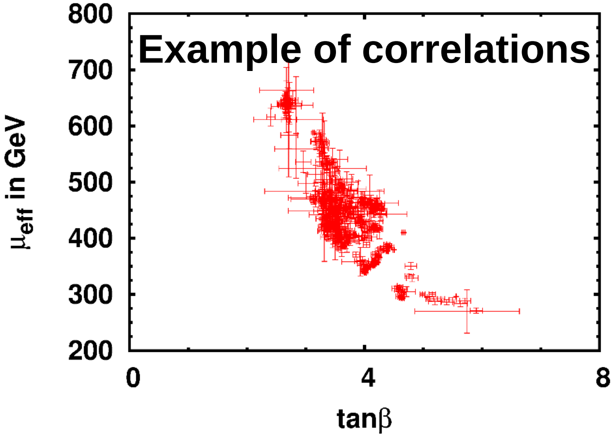
$$\boldsymbol{m_0, m_{1/2}, \tan\beta, A_0, \mathrm{sgn}(\mu)}$$

Semi CNMSSM

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

Problem with scanning NMSSM parameter space

- **large parameter space (7D in semi-constrained NMSSM)**
- **parameters are highly correlated, so random scan of parameter space very inefficient without correlation matrix, which tells how to step through the parameter space in a correlated way**
- **we do not know the 7x7 correlation matrix**



How to solve?

Idea: if there is a one-to-one relationship between Higgs masses and parameters, could we scan less correlated Higgs masses, which additionally have well known constraints from 125 GeV Higgs boson with SM-like couplings?

Analyzing the NMSSM parameter space using novel scanning technique

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

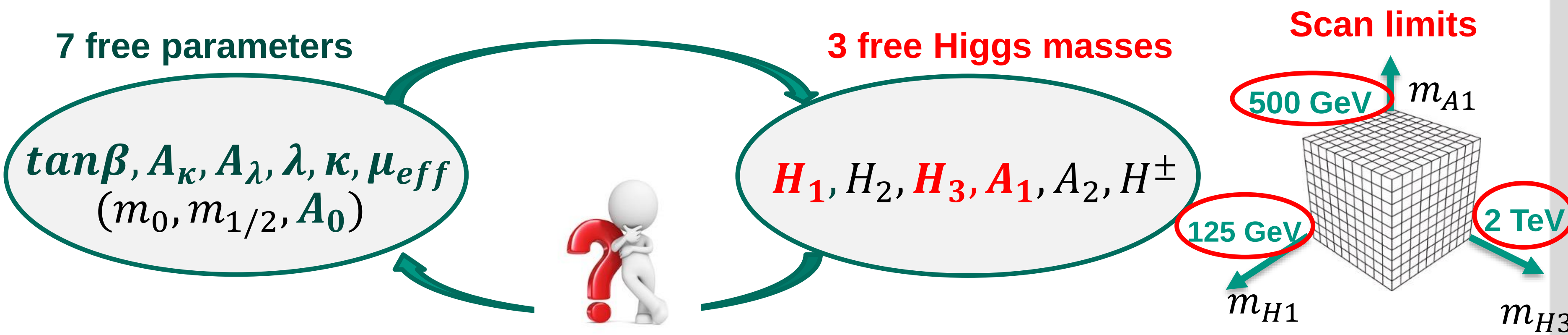
7 parameters spanning the 7D parameter space:
$\tan\beta$, λ, κ, A_0,
$A_\lambda, A_\kappa, \mu_{eff}$

Scanning strategy for accepted points:

- select 4 Higgs masses (left box)
- fit these masses with the 7 free NMSSM parameters (right box) using the constraints above (middle box)
- apply LHC and LEP Higgs mass limits
- Repeat the fit in a grid of all Higgs mass combinations of M_{A1}, M_{H1}, M_{H3} to obtain a scan over all accepted NMSSM parameters in the 7D parameter space.

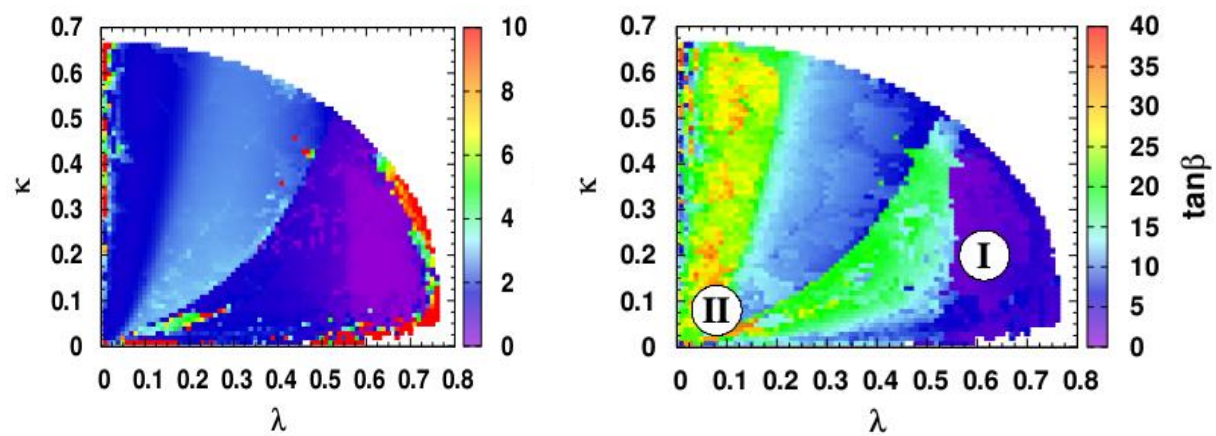
* We allow also the possibility $M_{H1} = 125$ GeV and SM-like

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



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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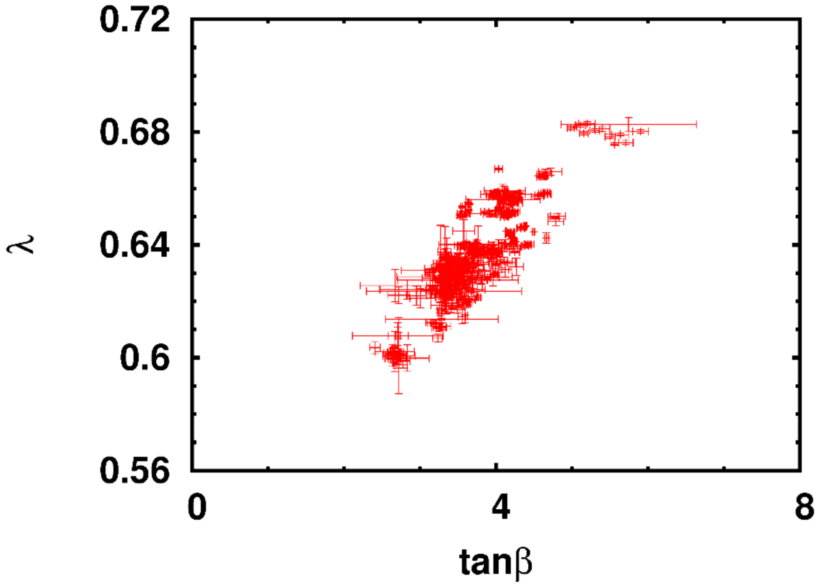
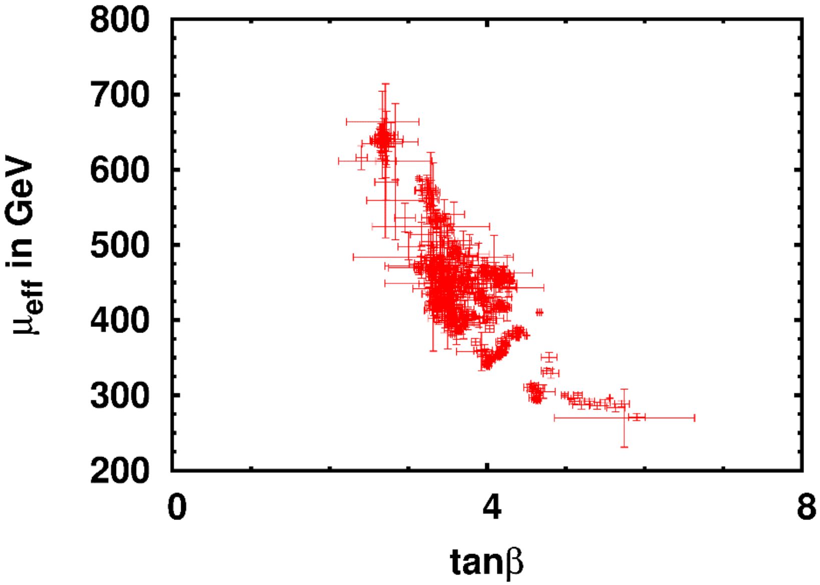
- $\chi^2_{H_S} = \frac{\left(m_{H_1} - m_{grid,H_1}\right)^2}{\sigma^2_{H_1}}$
  - m_{grid,H_1} : Chosen point in the 3D mass space
  - m_{H_1}: singlet-like Higgs boson, σ_{H_1} set to 1‰ m_{H_1} GeV
- $\chi^2_{H_{SM}} = \frac{\left(m_{H_2} - m_{obs}\right)^2}{\sigma^2_{SM}}$
  - 125.2 GeV Higgs boson with σ_{SM} set to 1‰ m_{H_2} GeV
- $\chi^2_{H_3/A_1} = \frac{\left(m_{H_3/A_1} - m_{grid,H_3/A_1}\right)^2}{\sigma^2_{H_3/A_1}}$ 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
- $\chi^2_{H_{SM}} = \sum_i \left(\mu^i_{H_2} - \mu_{obs}\right)^2 / \sigma^2_\mu$
  - 125.2 GeV with SM couplings, $\mu^i_{H_2}$: reduced cross section of H_2 to particle $i = \tau, b, W/Z, \gamma$ for ggf/ttH and VBF/VH production. μ_{obs} equals 1 with σ_μ set to 5‰

Some more examples of correlation of NMSSM parameters

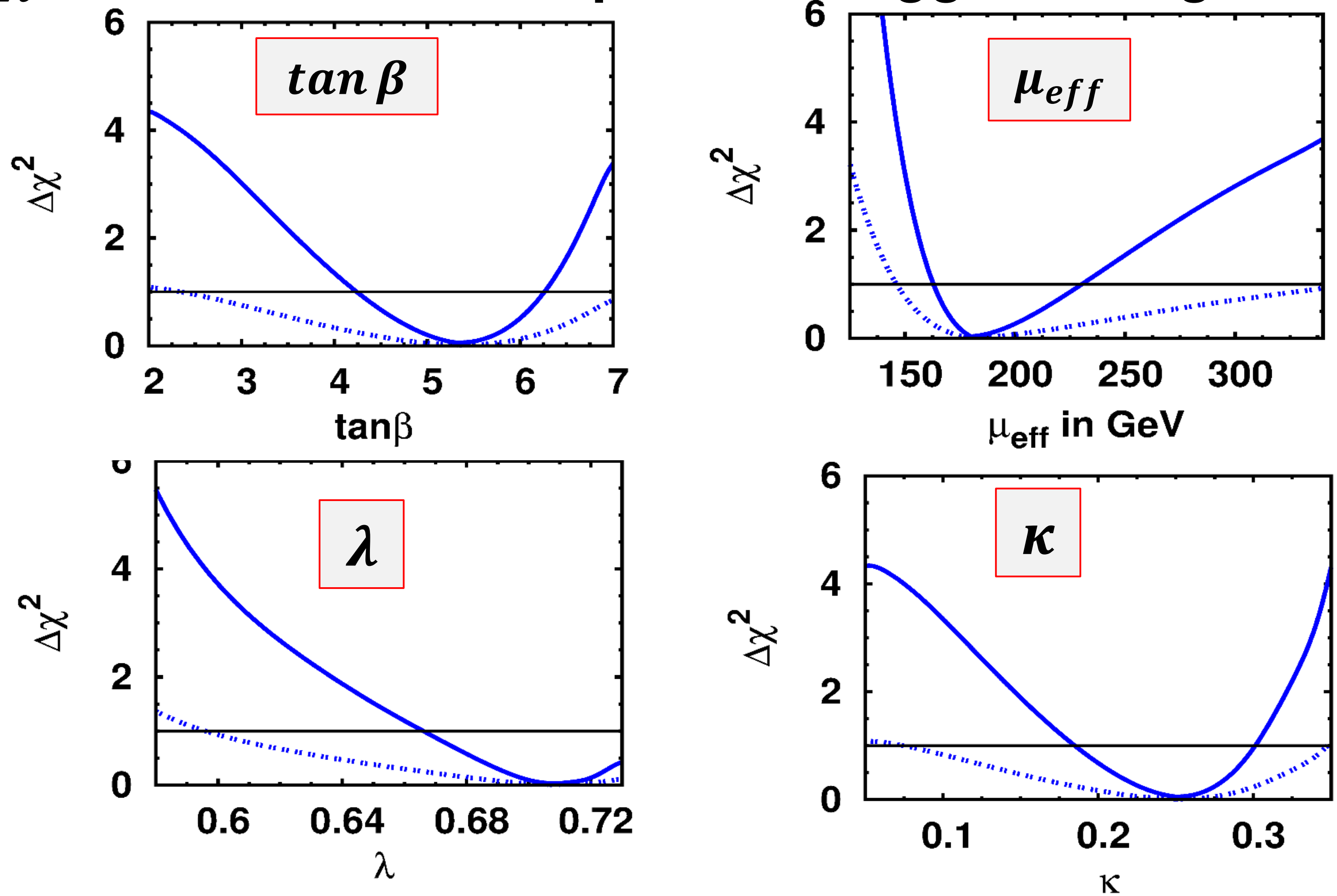
- Correlation for selected NMSSM parameters tan β, λ and μ_{eff}
- The error bars correspond to the error determined by the Minuit fit for each mass combination





Only best points after a χ^2 cut plotted.
Distribution depends on cut value
(or equally: assumed error values for chosen Higgs masses)

χ^2 distributions for a point on Higgs mass grid

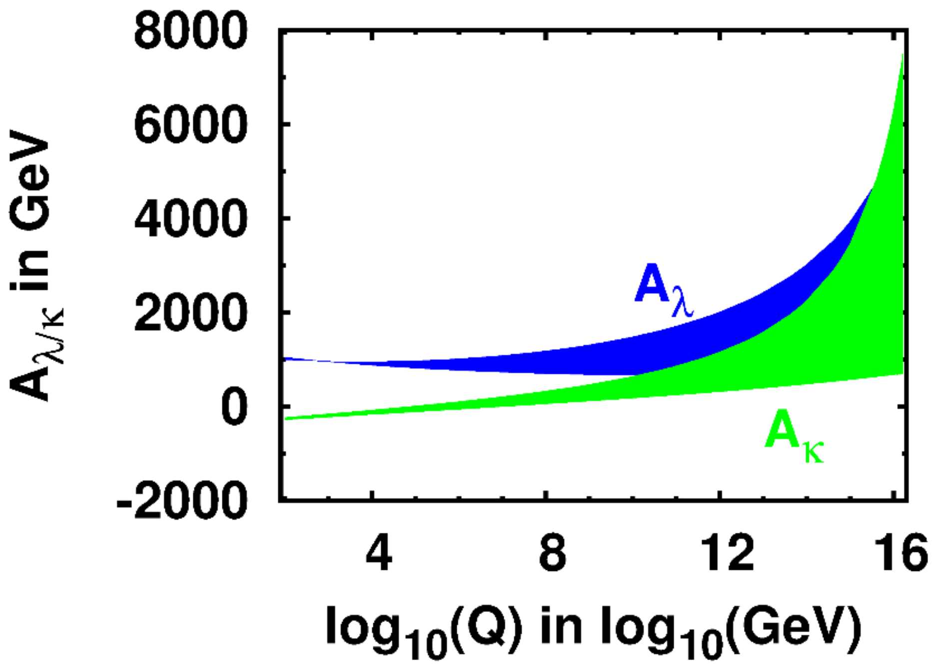


1(5)‰ error

1% error

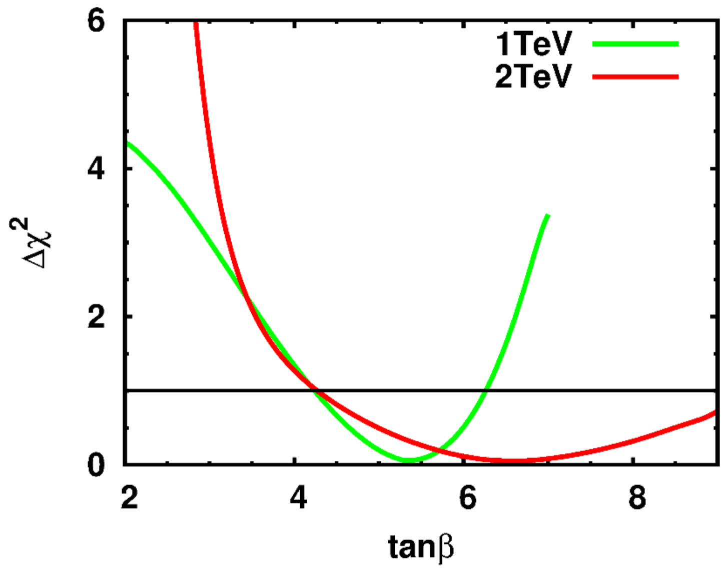
1D χ^2 distribution examples of $\tan\beta$, μ_{eff}, λ and κ. For larger allowed errors the minimum around the best fit points gets flatter (dotted lines).

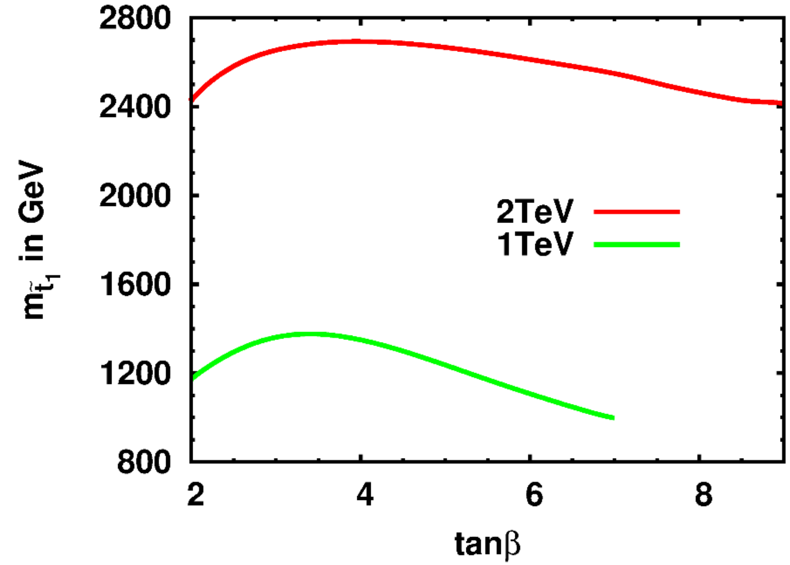
Fix-point solutions for the trilinear couplings



For different Higgs mass combination, the low scale values vary, but the running from a large allowed range at the GUT scale towards a fix-point solution (meaning independent of GUT scale value) at the SUSY scale remains.

Impact of the common SUSY masses



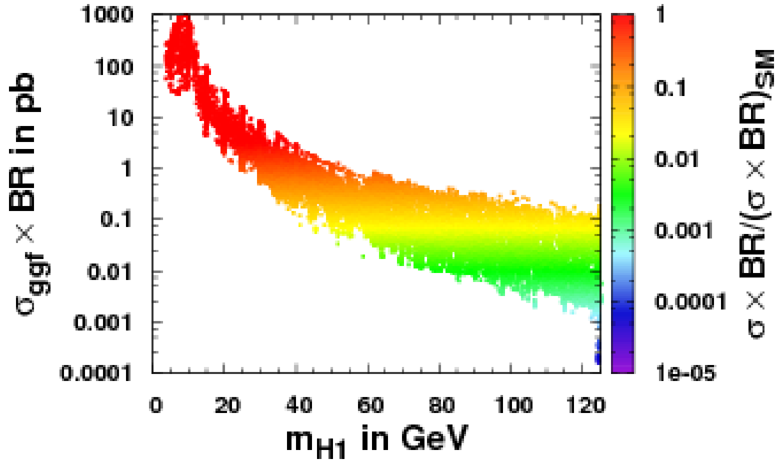


m_0 and $m_{1/2}$ enter only in the stop corrections $\Delta\tilde{t}$, so different stop masses lead to small shifts in the Higgs masses which can be compensated by small shifts in the optimal values of the NMSSM parameters

The dominant contribution to the total $\Delta\chi^2$ function is coming from the signal strength constraint. This contribution is less sensitive if the masses of the SUSY particles are getting heavier.

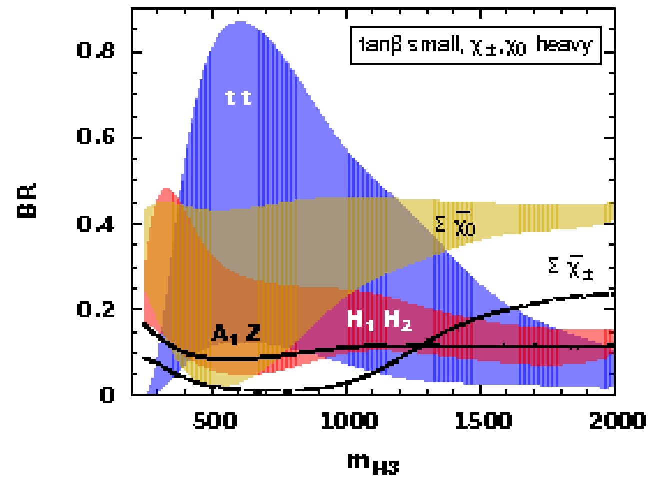
Present results from novel scanning technique

Light Higgs BR x XSs
PLB782 (2018) 69-76
arXiv:1712.02531



For light singlet-like Higgs bosons the values for XSxBR are compatible to the SM Higgs boson but studies of efficiencies and backgrounds needed.

Heavy Higgs BRs
PLB759 (2016) 141-148
arXiv:1602.08707



Additional promising channels in the NMSSM for heavy Higgs H3 boson like A1Z and H1H2 in contrast to MSSM

Outlook:
Many more detailed studies possible, e.g. possible signal strength deviations from SM predictions (see next talk)

Summary

- **Novel scanning technique** avoiding random scan of strongly correlated 7 NMSSM parameters
- **Instead:** scanning 7 Higgs mass space, which becomes only 3D in decoupling limit in which all heavy masses are identical and the known 125 GeV Higgs mass.
- **3D Higgs mass space** can be scanned by probing all mass combinations on a grid, so **no random scan**. This guarantees complete coverage.
- **Using the novel scanning** technique we determined the allowed range of the **BR x XSs for light and heavy Higgs bosons** and provided benchmark points and discovery channels which allow a detailed simulation and studies of the background and efficiencies

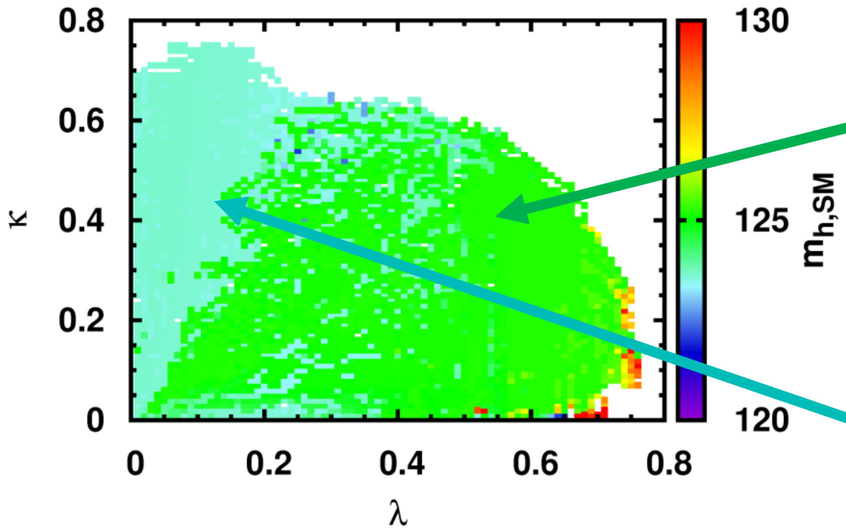
Backup

Is there a unique solution for the SM Higgs mass?

$$M_H^2 \approx M_Z^2 \cos^2 2\beta + \Delta_{\tilde{t}} + \lambda^2 v^2 \sin^2 2\beta - \frac{\lambda^2}{\kappa^2}(\lambda - \kappa \sin 2\beta)^2$$

CMSSM-like (small λ, κ , large tanβ)
Region II

NMSSM specific (large λ, κ , small tanβ)
Region I



Almost in the whole $\lambda - \kappa$ plane 125 GeV Higgs mass fulfilled (green region)

Higgs mass (H_1) too light. Stop mass corrections not enough to reach 125 GeV similar to MSSM. Can be compensated by larger value of $m_0/m_{1/2}$

Is the 125 GeV SM-like?
→ couplings/signal strengths

Couplings and reduced XSs/signal strengths

- Reduced XS proportional to Higgs couplings which include the Higgs mixing elements S_{ij} and the Yukawa couplings

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

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

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

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

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

χ^2 includes 8 signal strengths $\mu = \frac{\sigma \times BR}{\sigma_{SM} \times BR_{SM}}$

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

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

Are deviations of reduced couplings from SM really 0?

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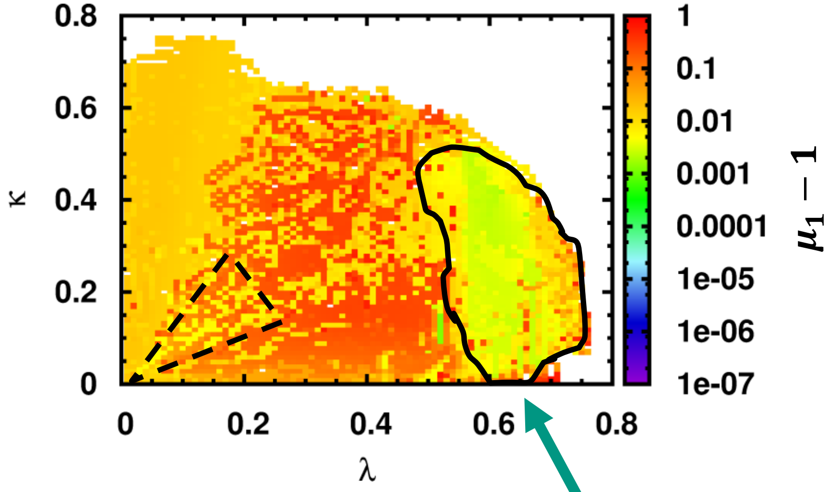
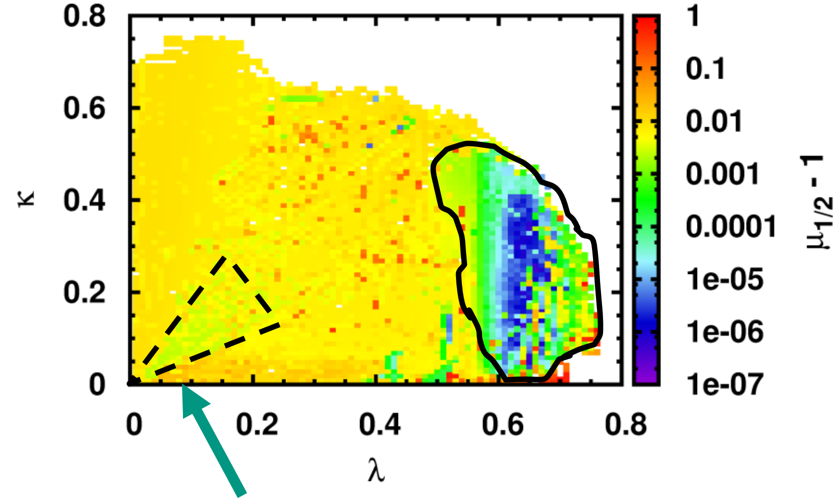
Bosonic signal strength



Fermionic signal strength



Region I (large λ, κ , small tanβ)

Region II (small λ, κ , large tanβ)

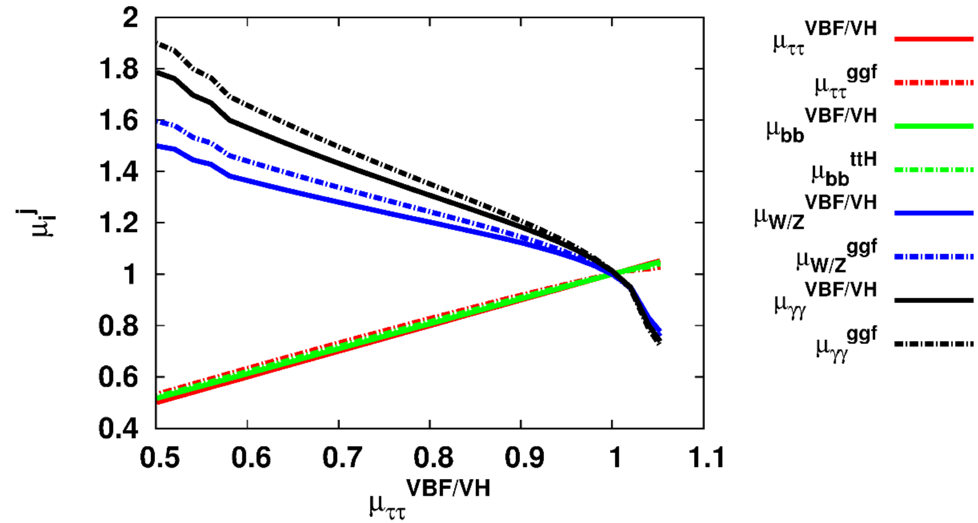
Signal strengths of observed Higgs equal SM in Region I.
In Region II small deviations preferred.
In intermediate regions larger deviations, only allowed if errors are enlarged.

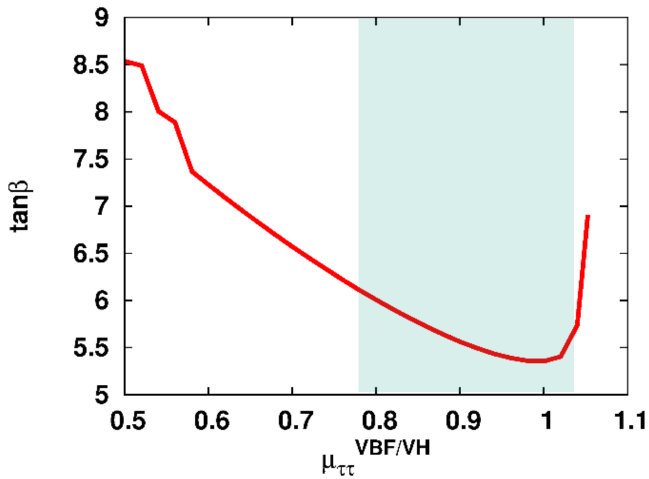
Allowed range of signal strengths/couplings allows determination of BRs and BR x XSs for all Higgs bosons.

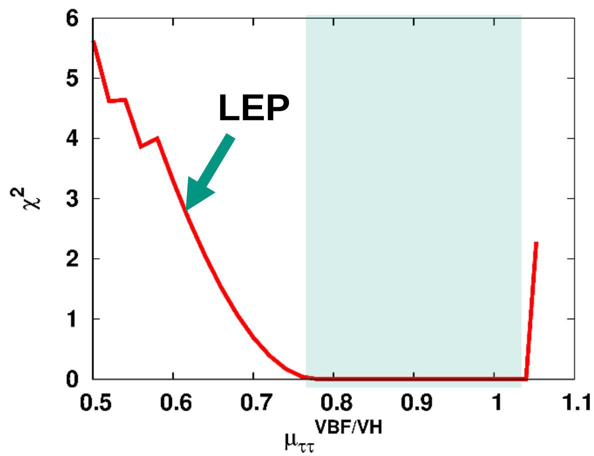
Are larger deviations from SM allowed?

- Only possible if $\mu_{1/2} \neq \mu_1$
- Low $\mu_{1/2}$ can be compensated by large μ_1
- Signal strength distribution sensitive to tanβ, see p.10

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







Precise measurements of signal strengths restricts tanβ

Couplings of singlet like Higgs to fermions and allowed range for Higgs mixing elements

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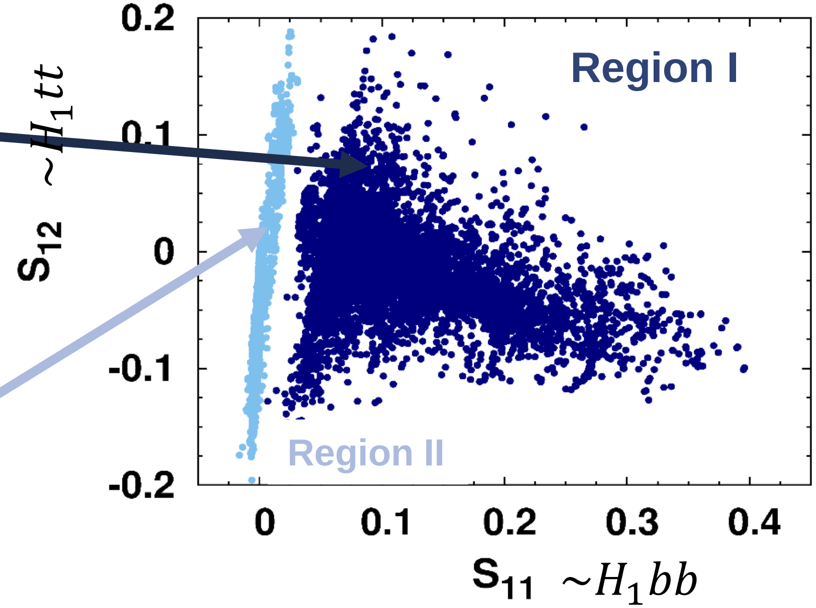
S_{11} $(\sim H_1 bb)$ large and positive in Region I

S_{11} $(\sim H_1 bb)$ almost zero due to zero crossing in Region II $\rightarrow$ $tan\beta$ enhancement small compared to small S_{11} values



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

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

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

SM Higgs mixing elements and heavy Higgs boson fixed by SM Higgs couplings constraint $\rightarrow$ allowed range of singlet Higgs mixing matrix elements

Couplings of singlet like Higgs to fermions and allowed range for Higgs mixing elements

S_{11} ($\sim H_1 bb$) large and positive in Region I

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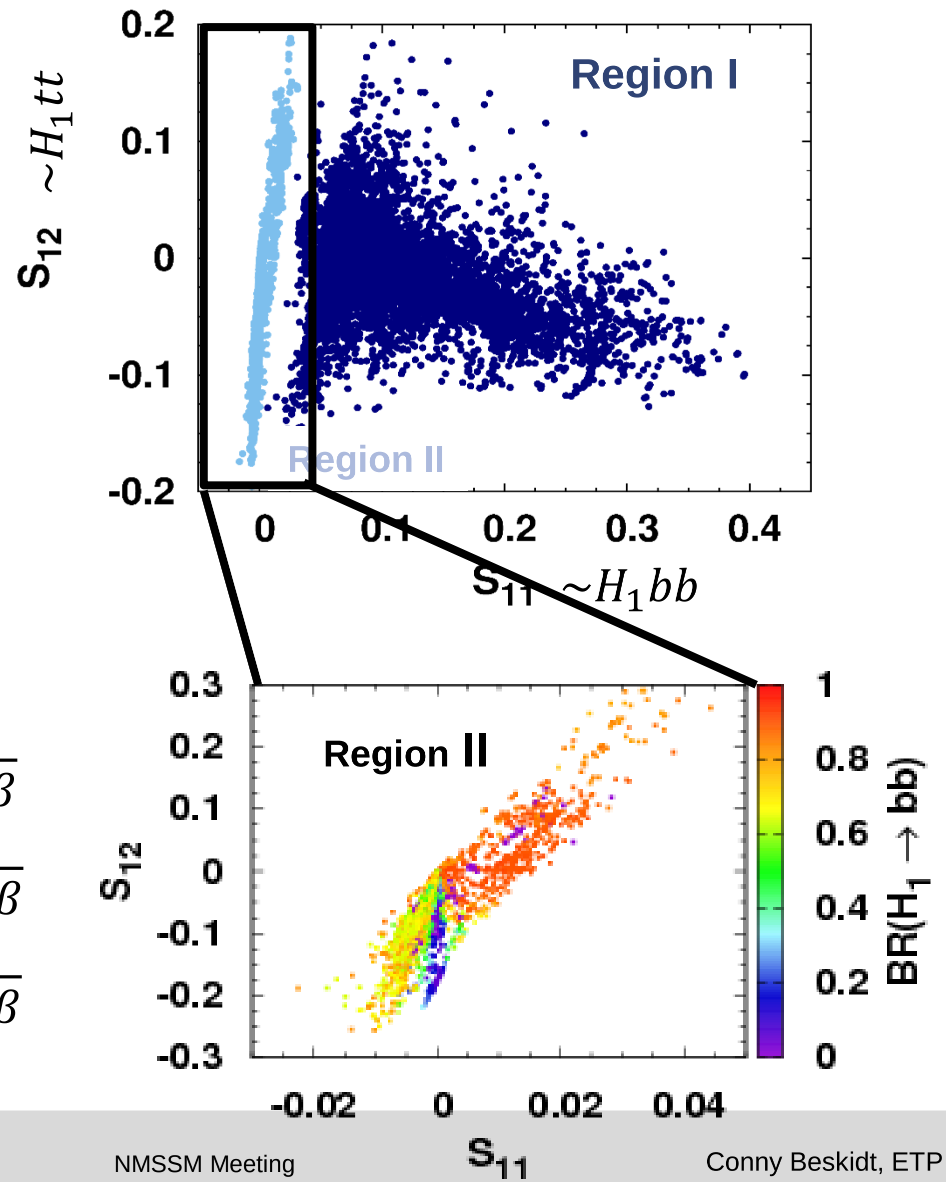
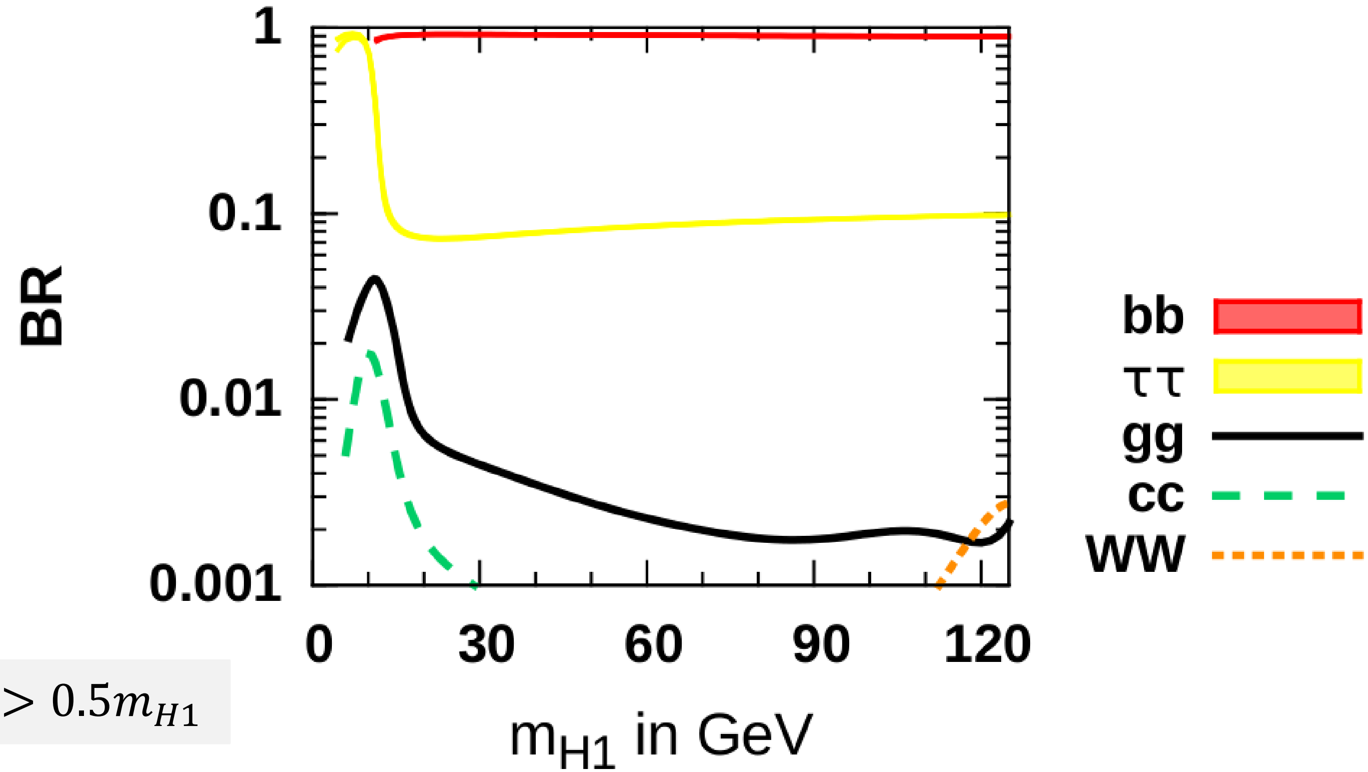


BRs for light (singlet-like) Higgs boson

Region I – NMSSM-like
large $\lambda, \kappa,$ small $tan\beta$

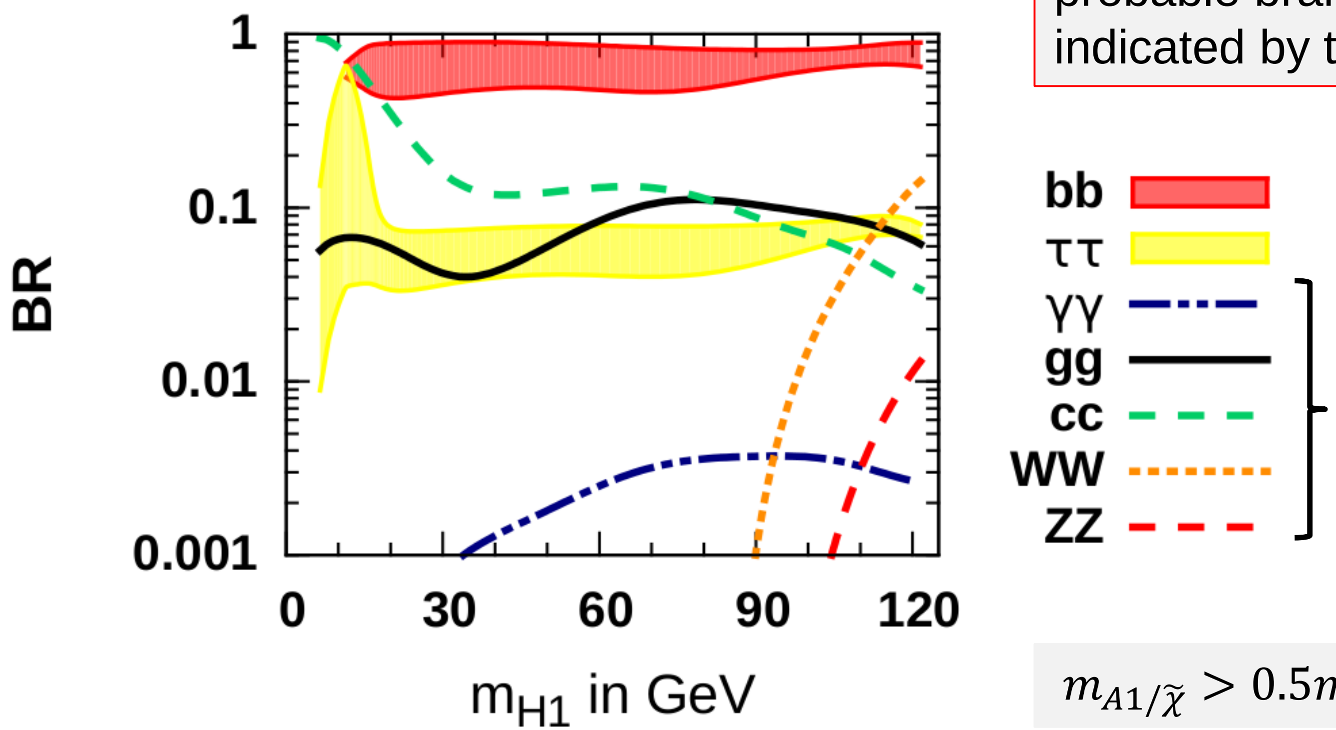


$m_{A1/\tilde{\chi}} > 0.5 m_{H1}$

Large coupling to down-type fermions → dominant decay into b quarks as in the SM.

BRs for light (singlet-like) Higgs boson

Region II – CMSSM-like
small $\lambda, \kappa,$ large $tan\beta$



Bands include 68% of the sampled points around the most probable branching ratio indicated by the lines.

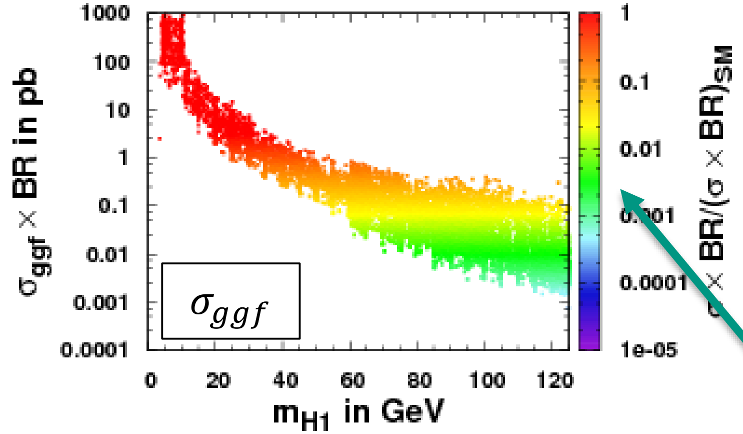
Lines plotted for better visibility. Channels have similar width for BR bands as bb and $\tau\tau$.

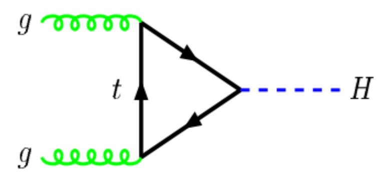
$m_{A1/\tilde{\chi}} > 0.5 m_{H1}$

CMSSM-like region BRs different from SM due to zero crossing of S_{11} leading to broad allowed bands for BRs for all channels.

Discovery potential for tau final states @14TeV

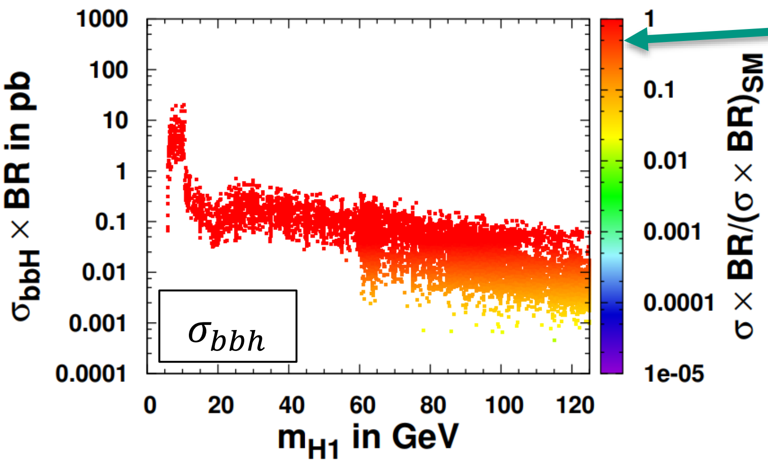
Region I – large $\lambda, \kappa,$ small $tan\beta$

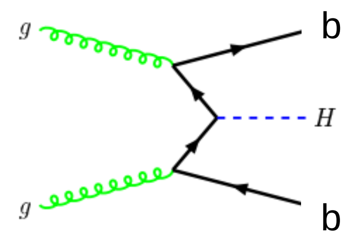




Color coding corresponds to the ratio $\frac{\sigma \times BR}{(\sigma \times BR)_{SM}}$

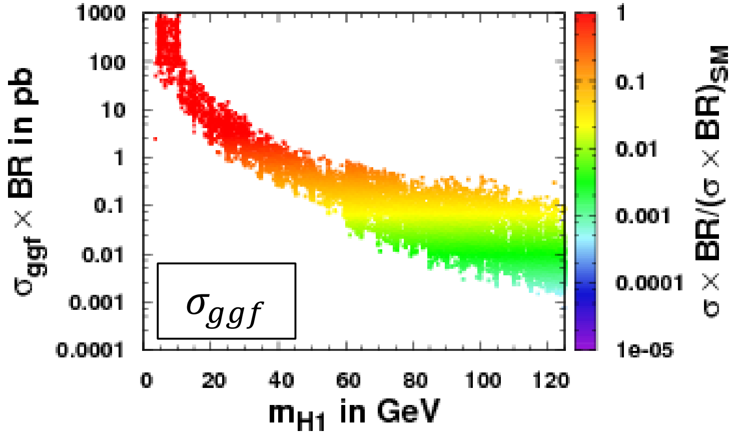
Red means 20-100%$(\sigma \times BR)_{SM}$ and **green** 1‰-1%$(\sigma \times BR)_{SM}$



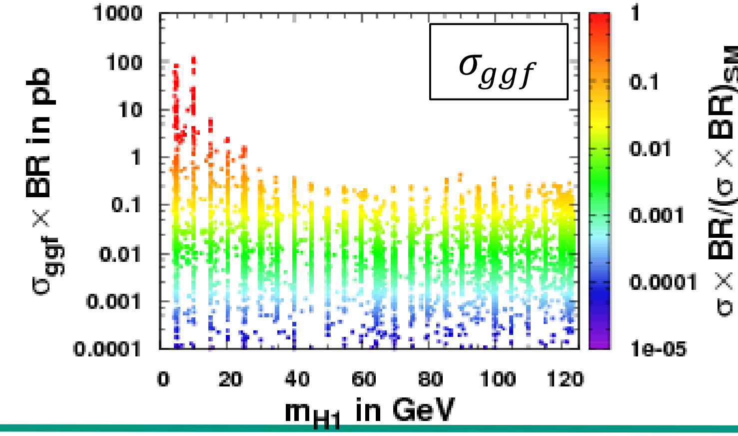


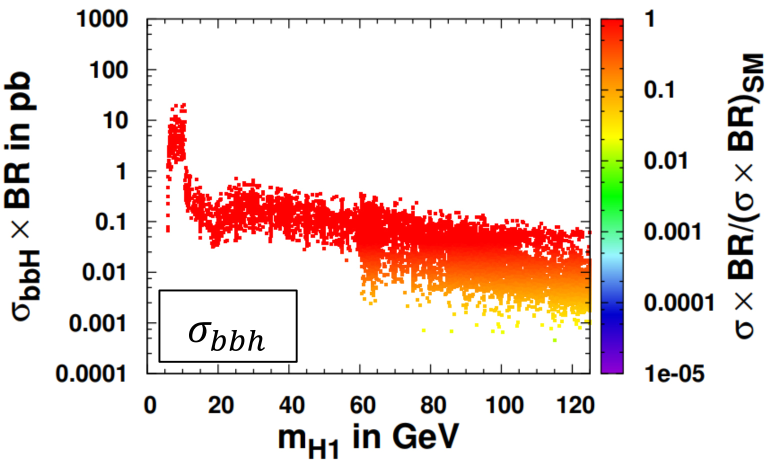
Discovery potential for tau final states @14TeV

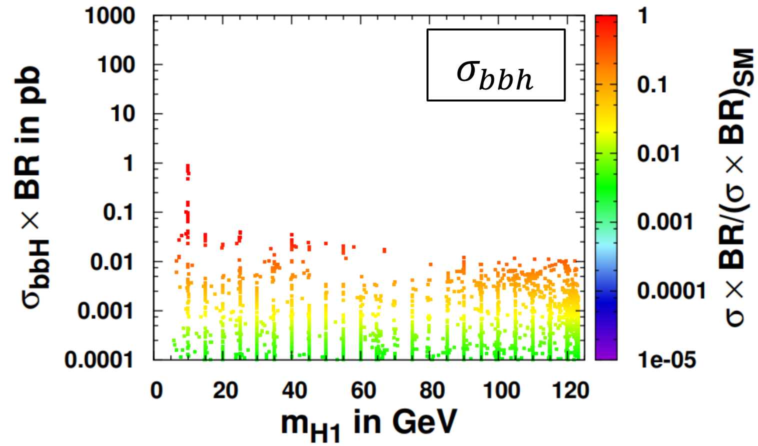
Region I – large $\lambda, \kappa,$ small $tan\beta$



Region II – small $\lambda, \kappa,$ large $tan\beta$







Region II: XS has large allowed range because of zero crossing of S_{11}.

Discovery potential for final states @14TeV

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- $\tau\tau$: in both Regions
- $\gamma\gamma$: in both Regions
- $Z\gamma$: for $m_{H1} > 95$ GeV
- WW/ZZ: for $m_{H1} > 80/90$ GeV, small because of phase space
- Double Higgs Production
- $A_1 A_1 / \tilde{\chi}_1^0 \tilde{\chi}_1^0$: XS x BR compatible to SM decay $\mathrm{H} \rightarrow \gamma\gamma$

For more details see backup slides and ***PLB782 (2018) 69-76***.

Other final states are small and $A_1 A_1 / \tilde{\chi}_1^0 \tilde{\chi}_1^0$ are only possible in a restricted parameter space where $m_{A1/\tilde{\chi}_1^0} < 0.5 m_{H1}$

NOTE: A_1 and $\tilde{\chi}_1^0$ masses are correlated, so both signatures happen in the same region of parameter space (see backup slides)

Upper bound for NMSSM double Higgs production BRs (if kinematically accessible)

	Region I large small	Region II small large
	80%	100%
	8%	1%
	7%	6%
	25%	0%
	30%	2%
	2.5%	0%
	35%	0%
	70%	5%
	2%	0.5%

See backup slides for corresponding BR plots

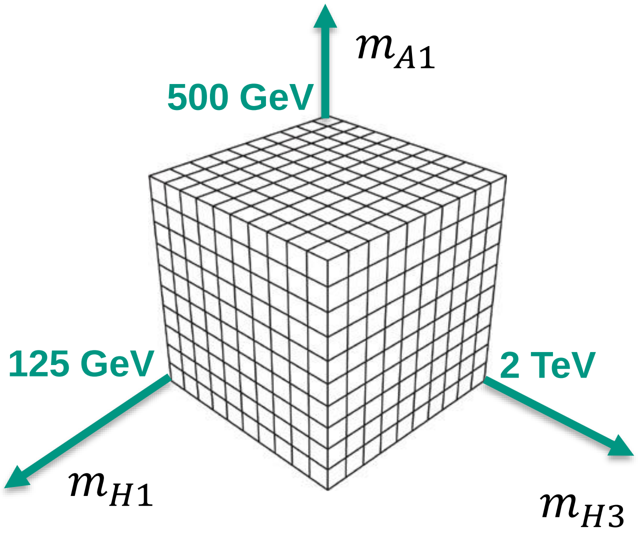
Dominant A_1 decay modes in bb, $\tau\tau$ and MET see backup slides

Reduction of the 6D Higgs mass space

- $H_3, H^{\pm}$ and A_2 are considerd to be degenerate in mass
- One observed 125 GeV Higgs with SM couplings

→ 3 undetermined free Higgs masses in the NSSM (3D)

- Provide 3D grid for unknown m_{H1}-m_{H3}- m_{A1} masses
- For each mass combination MINUIT* is used to determine corresponding NMSSM parameters



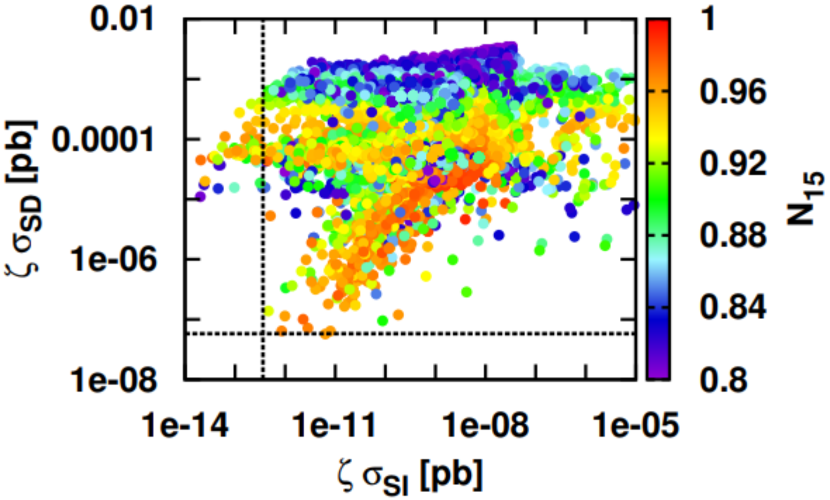
Efficient sampling of the parameter space and determination of the couplings

* F. James and M. Roos, Comput.Phys.Commun. 10 (1975) 343-367

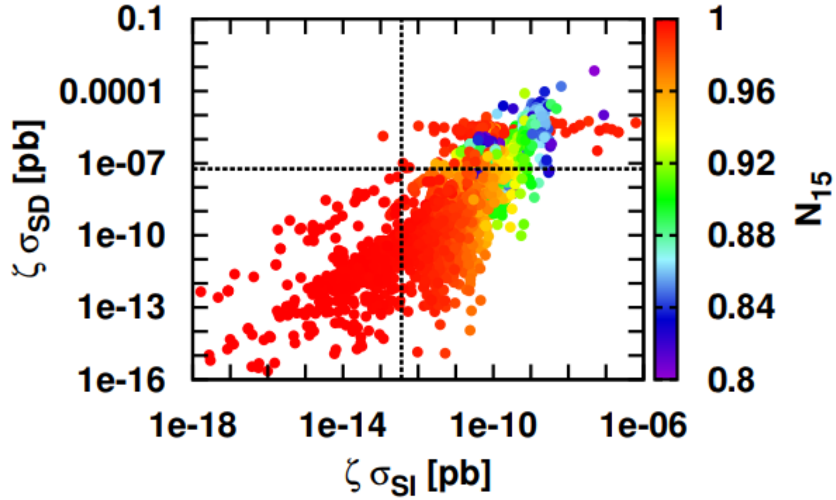
Efficient sampling of Parameter Space - Example

- Dividing the axis of the 3D space into X~100 bin require a total of X^3 Minuit fits, which is quite feasible instead of random sampling in the 6D parameters of the Higgs parameters
- E.g. efficient sampling of parameter space allows to find points in parameter space which will elude the future searches for dark matter at the Darwin experiment

Scenario I (large λ, κ, small $\tan\beta$)



Scenario II (small λ, κ, large $\tan\beta$)



Light Higgs production cross section

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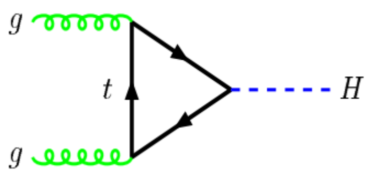
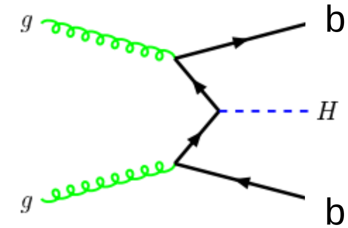
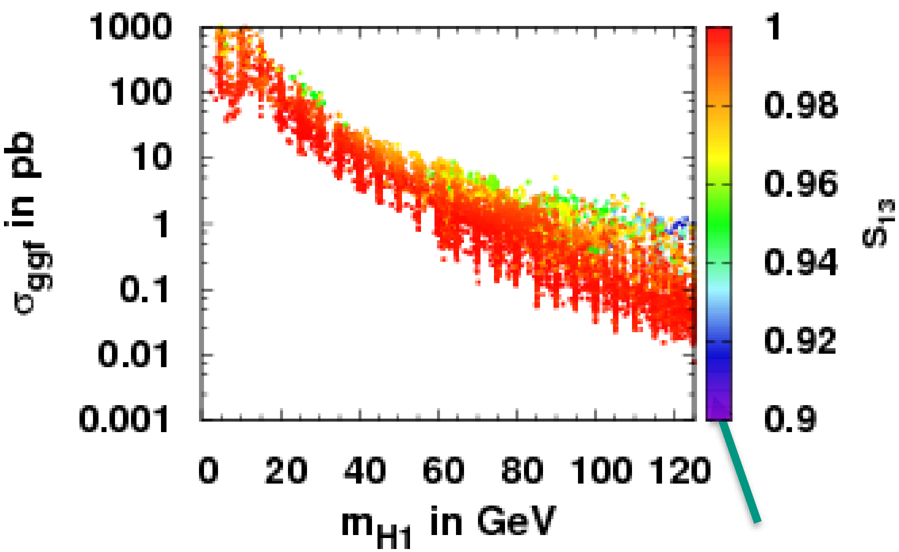
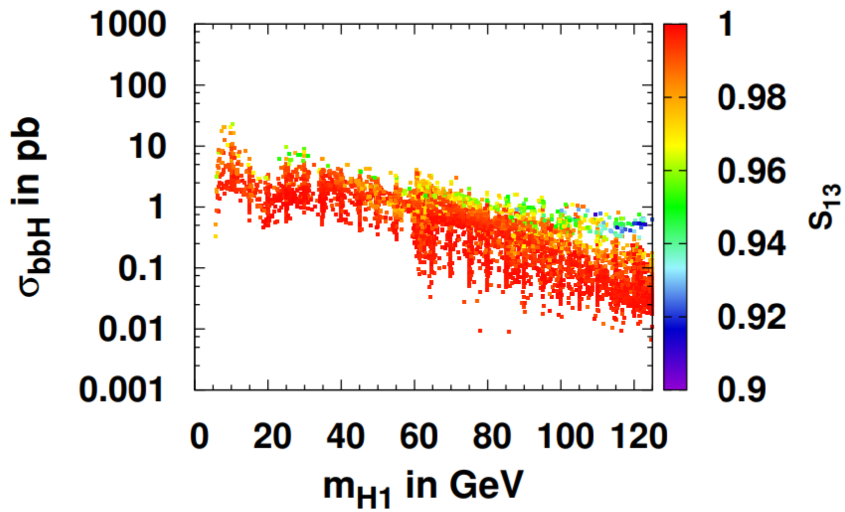
Region I – large $\lambda, \kappa,$ small $tan\beta$





$\sim tan\beta^2$



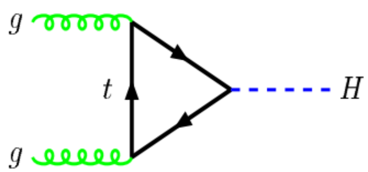


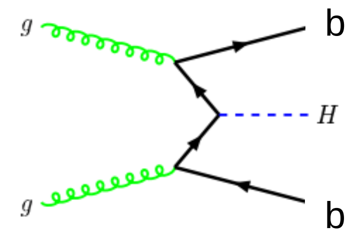
S_{13}: Singlet component of H_1

Small $tan\beta$ value leads to dominant ggf XS

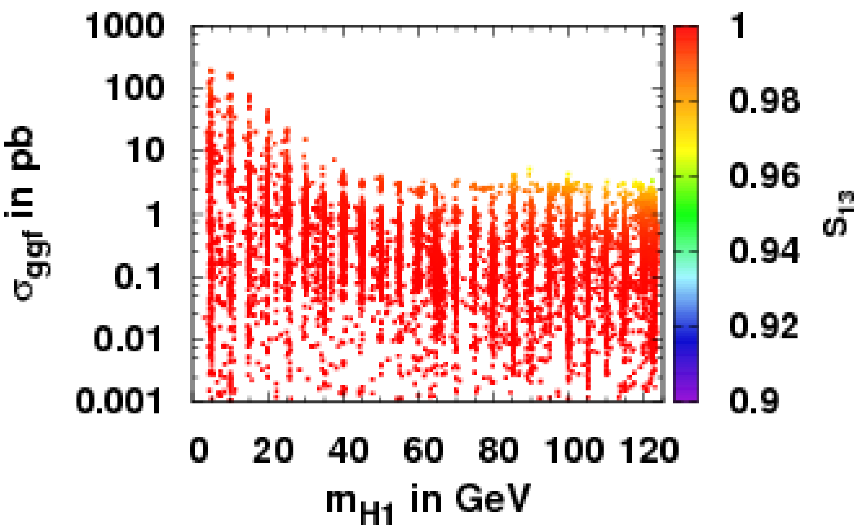
Light Higgs production cross section

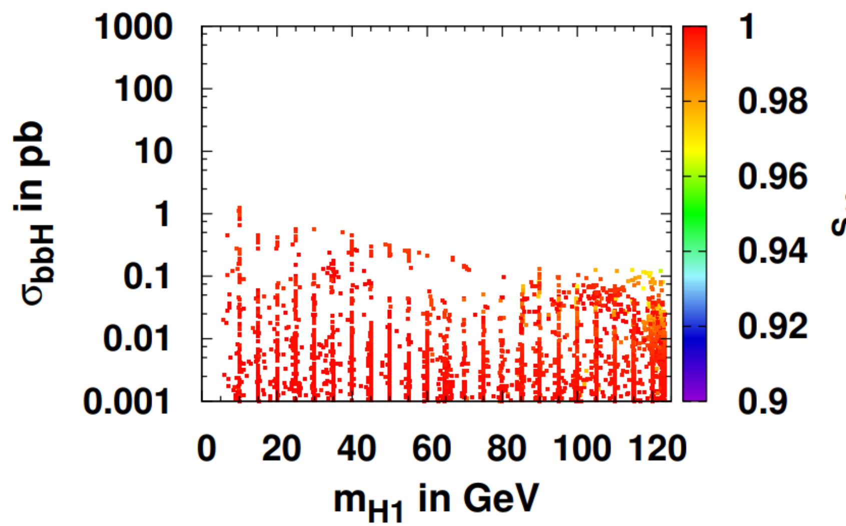
Region II – small $\lambda, \kappa,$ large $tan\beta$





$\sim tan\beta^2$





No $tan\beta$ enhancement for bbH XS and large spread
→ Coupling not only proportional to $tan\beta$ but also Higgs mixing matrix elements S_{11} and S_{12}

BRs x XS for light Higgs Boson

(in comparison with 125 GeV Higgs Boson)

Discovery potential for γ final states

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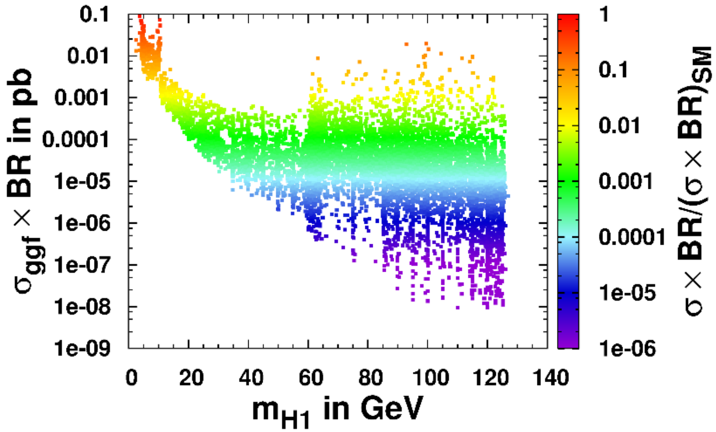
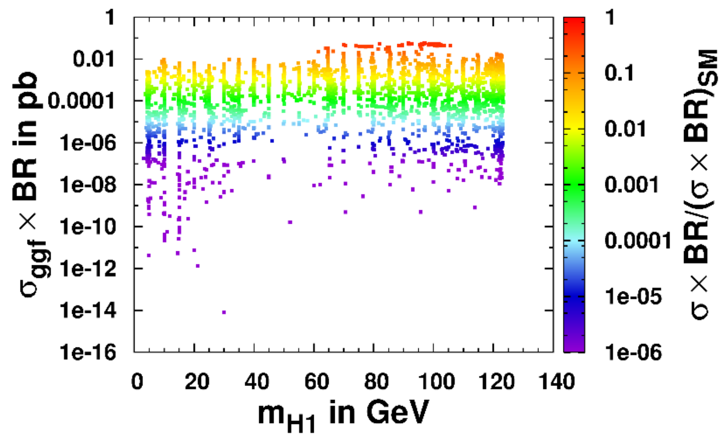
Region I – large $\lambda, \kappa,$ small $tan\beta$

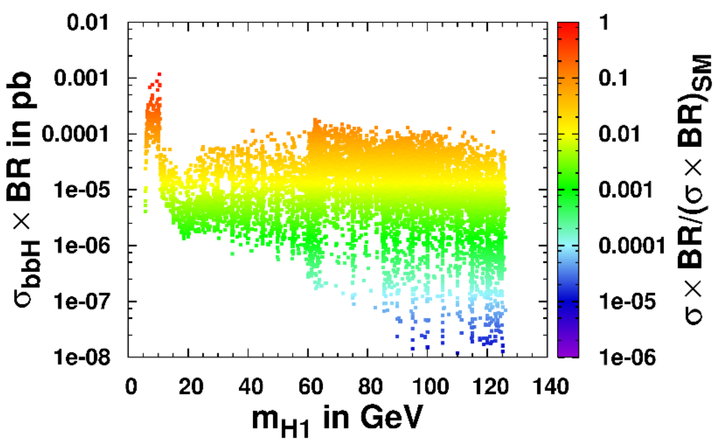
Region II – small $\lambda, \kappa,$ large $tan\beta$

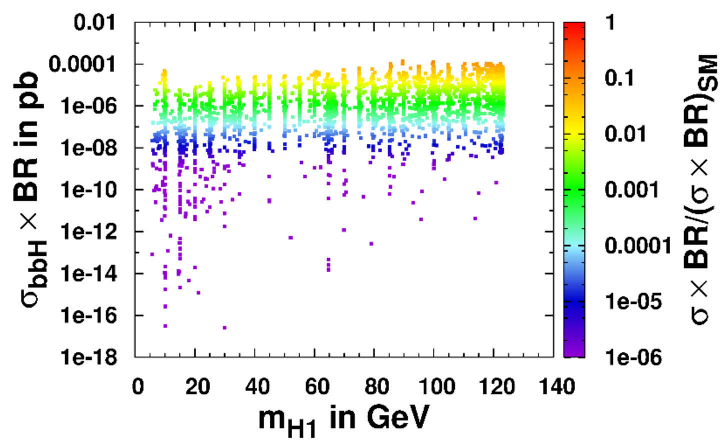
σ_{ggf}





σ_{bbh}





$\gamma\gamma$: in both Regions the whole mass range is accessible

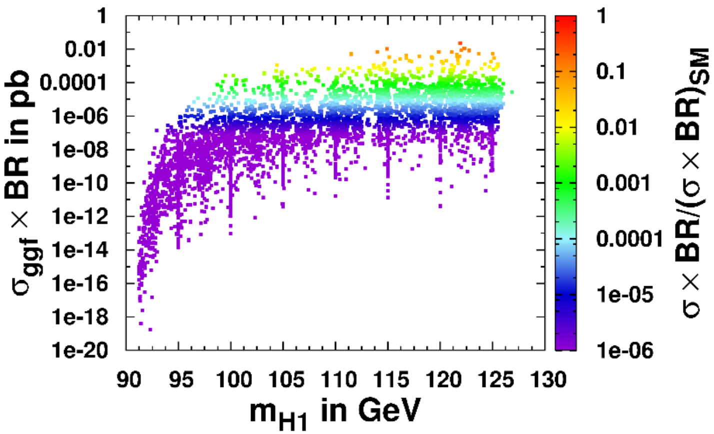
Discovery potential for $Z\gamma$ final states

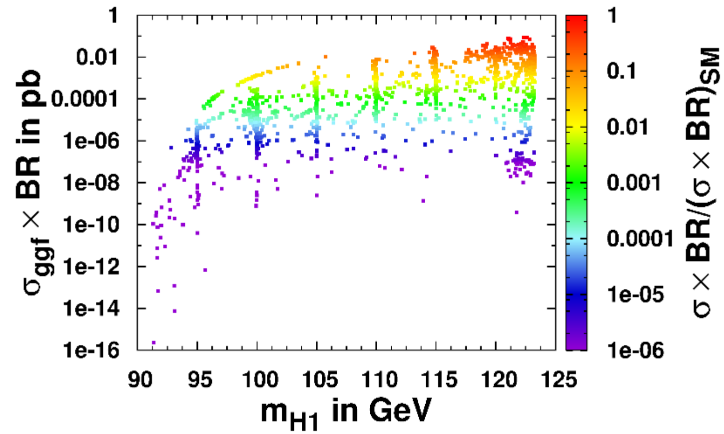
@14TeV

Region I – large $\lambda, \kappa,$ small $tan\beta$

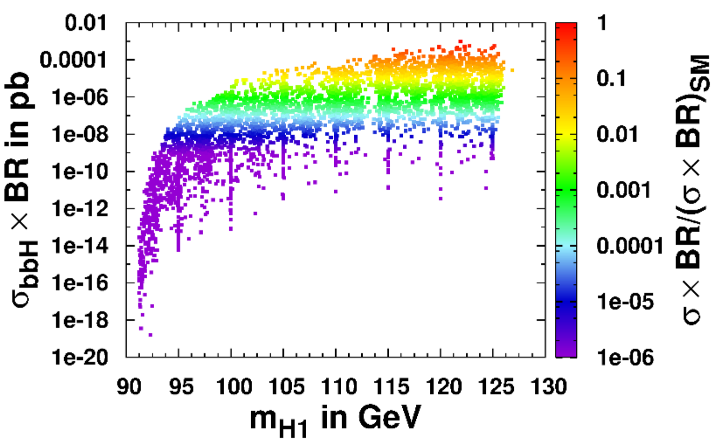
Region II – small $\lambda, \kappa,$ large $tan\beta$

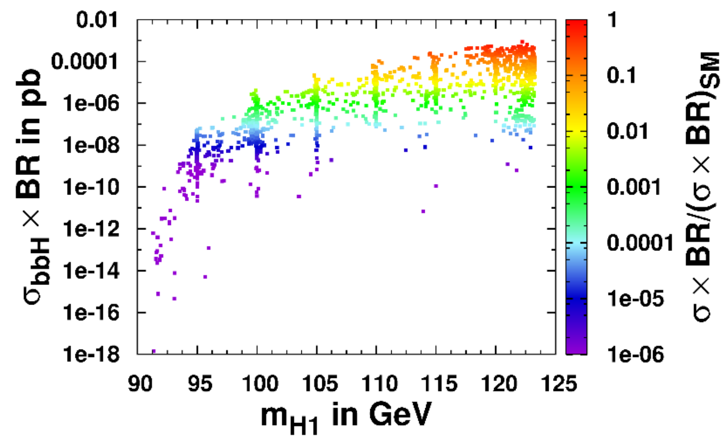
σ_{ggf}





σ_{bbh}





$Z\gamma$: in both Regions the mass range above 95 GeV is accessible

Discovery potential for Z final states

@14TeV

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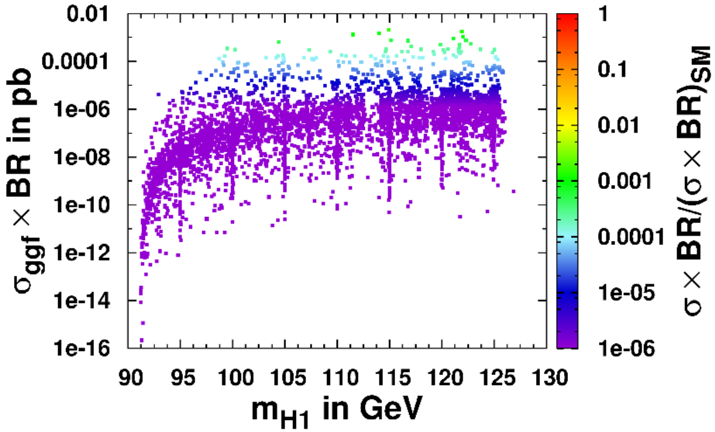
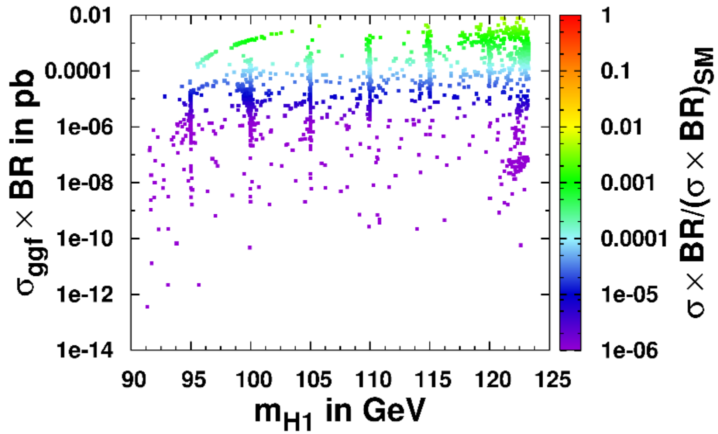
Region I – large λ, κ, small $tan\beta$

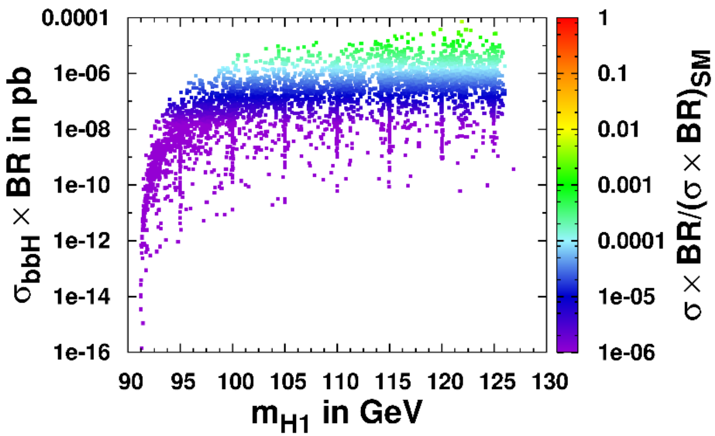
Region II – small λ, κ, large $tan\beta$

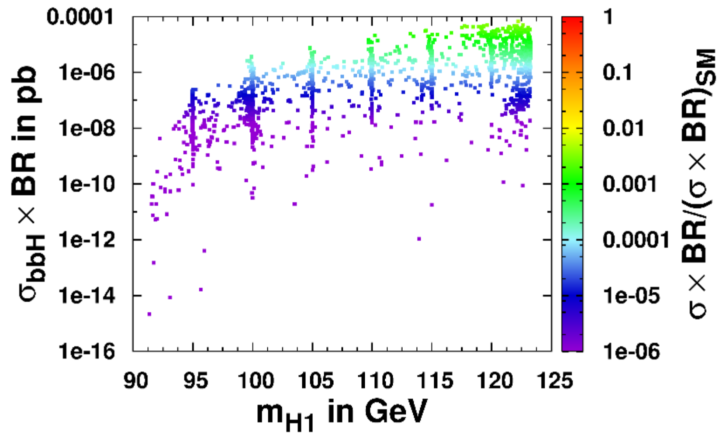
σ_{ggf}





σ_{bbh}





ZZ: for mass range above the maximal ratio is 1 ‰ because of phase space