Can we discover a light singlet-like NMSSM Higgs boson at the LHC?

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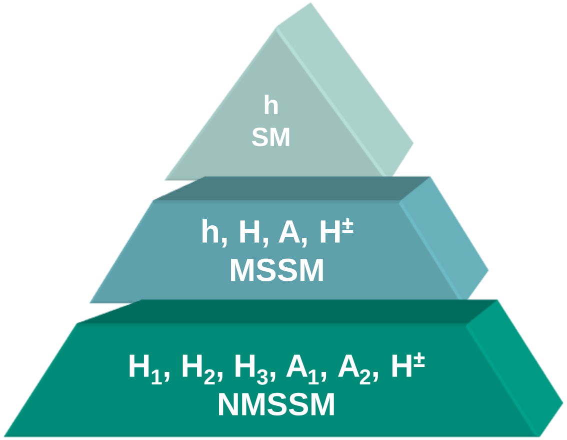


h
SM

h, H, A, $H^\pm$
MSSM

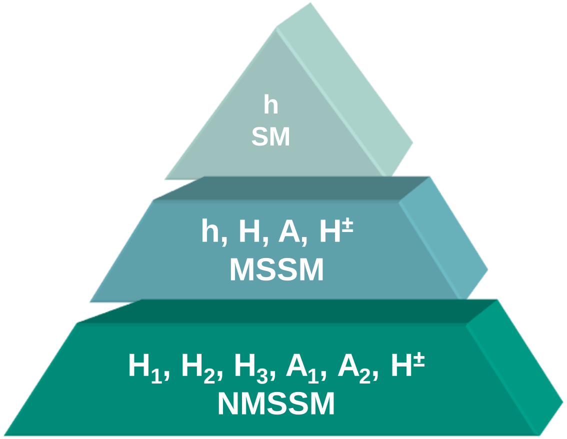
$H_1, H_2, H_3, A_1, A_2, H^\pm$
NMSSM

Parameters MSSM vs. NMSSM

- **NMSSM has one additional Higgs singlet**

  → additional terms in superpotential leads to more free parameters and leads to modification in the Higgs and neutralino sector

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



h
SM

h, H, A, H±
MSSM

H_1, H_2, H_3, A_1, A_2, H±
NMSSM

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

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

CMSSM

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

Semi CNMSSM

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

Problem with scanning NMSSM parameter space

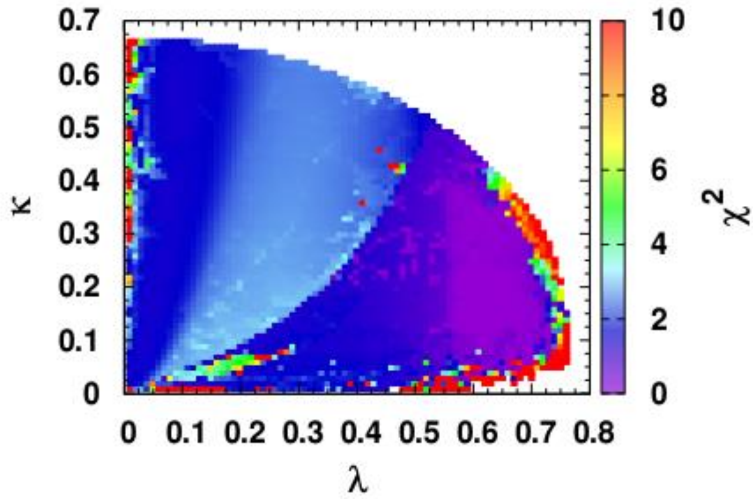
- **large parameter space**
- **parameters are highly correlated, so random scan of parameter space very inefficient without correlation matrix**
- **we do not know the correlation matrix**

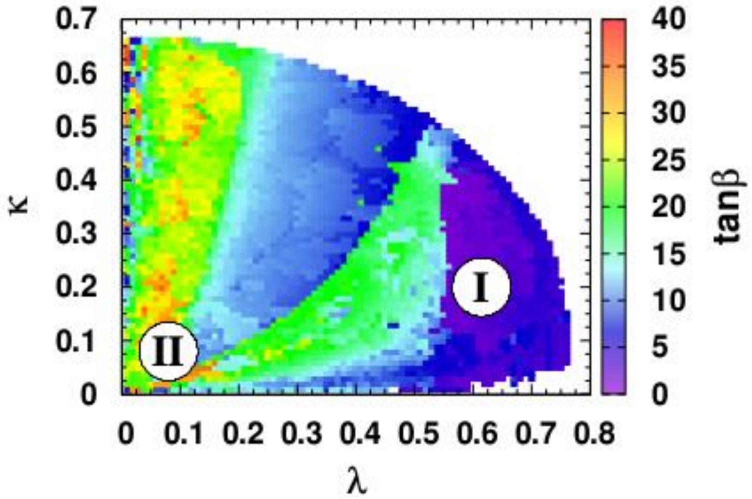
How to solve?

Idea: if we would have measured all the Higgs masses, would we be able to determine the parameters?

Result: yes, but not necessarily a unique solution

χ^2 Function has no unique solution





$$M_H^2 \approx \underbrace{M_Z^2 \cos^2 2\beta + \Delta_{\tilde{t}}}_{\text{CMSSM}} + \underbrace{\lambda^2 v^2 \sin^2 2\beta - \frac{\lambda^2}{\kappa^2}(\lambda - \kappa \sin 2\beta)^2}_{\text{NMSSM specific}}$$

In NMSSM the mixing with singlet increases Born term by large couplings at small $tan\beta$ (Region I) or by a combination of small couplings and large $tan\beta$ (Region II)

Region I: $\boldsymbol{\lambda}$-κ large, tanβ small → large NMSSM specific contribution

Region II: $\boldsymbol{\lambda}$-κ small, tan β large → CMSSM like

Idea: scan Higgs mass space instead of parameters

6 parameters spanning the **6D** parameter space: $\tan\beta, \lambda, \kappa, A_\lambda, A_\kappa, \mu_{eff}$

NMSSMTools

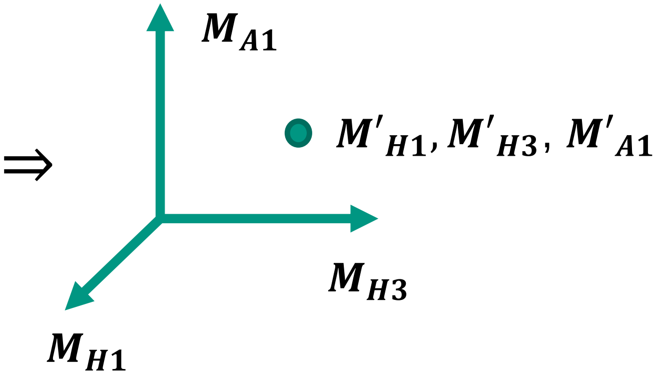
6 Higgs masses spanning the 6D parameter space:
$M_{H1}, M_{H2}, M_{H3}, M_{A1}, M_{A2}, M_{H^\pm}$

+

Fit Constraints:
$M_{H2} = 125\ GeV,\ M_{H1} = M'_{H1},$
$M_{A1} = M'_{A1},\ M_{H3} = M_{A2} = M_{H^\pm} = M'_{H3},$
for a given point $M'_{H1}, M'_{H3}, M'_{A1}$ in 3D

$\Rightarrow$

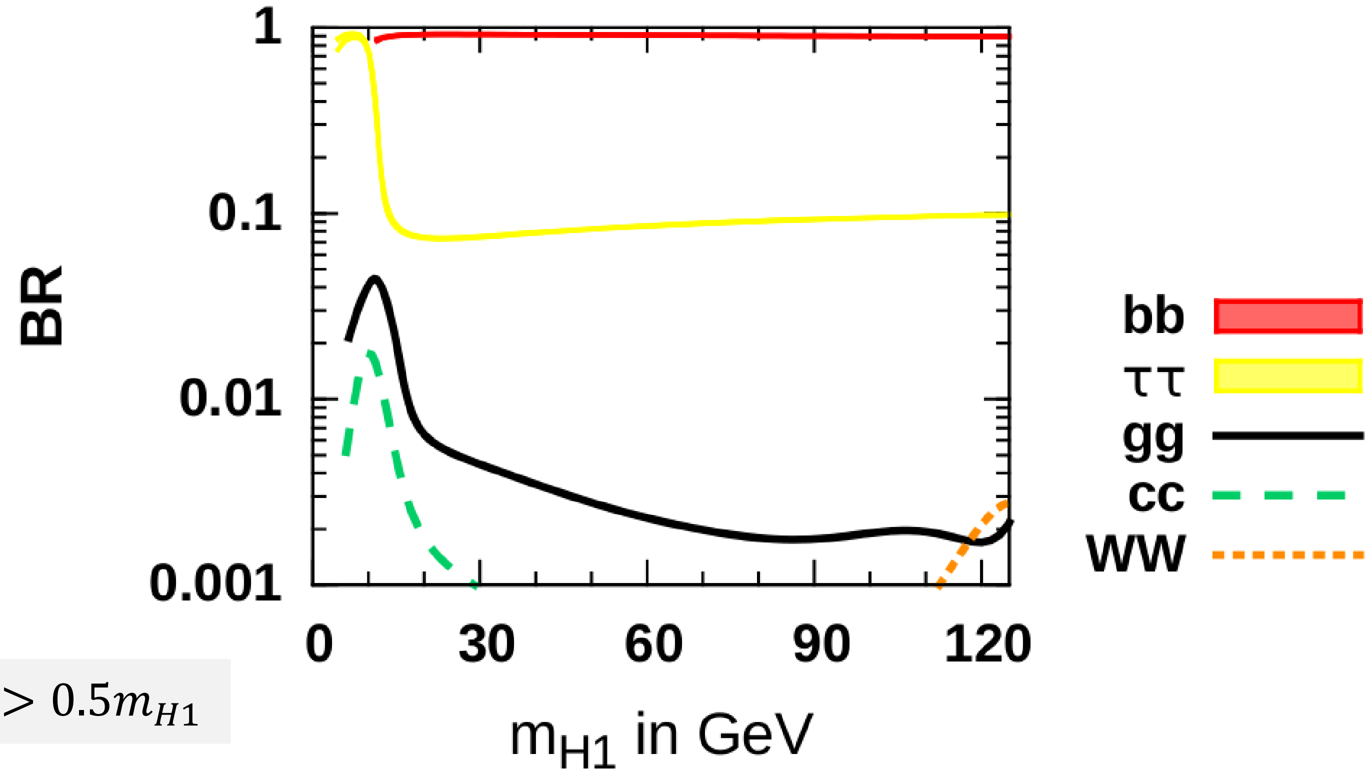
3D



Why: Higgs masses hardly correlated and more constraints, if we assume the decoupling limit with all heavy Higgs masses to be close to degenerate

BRs for light (singlet-like) Higgs boson

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



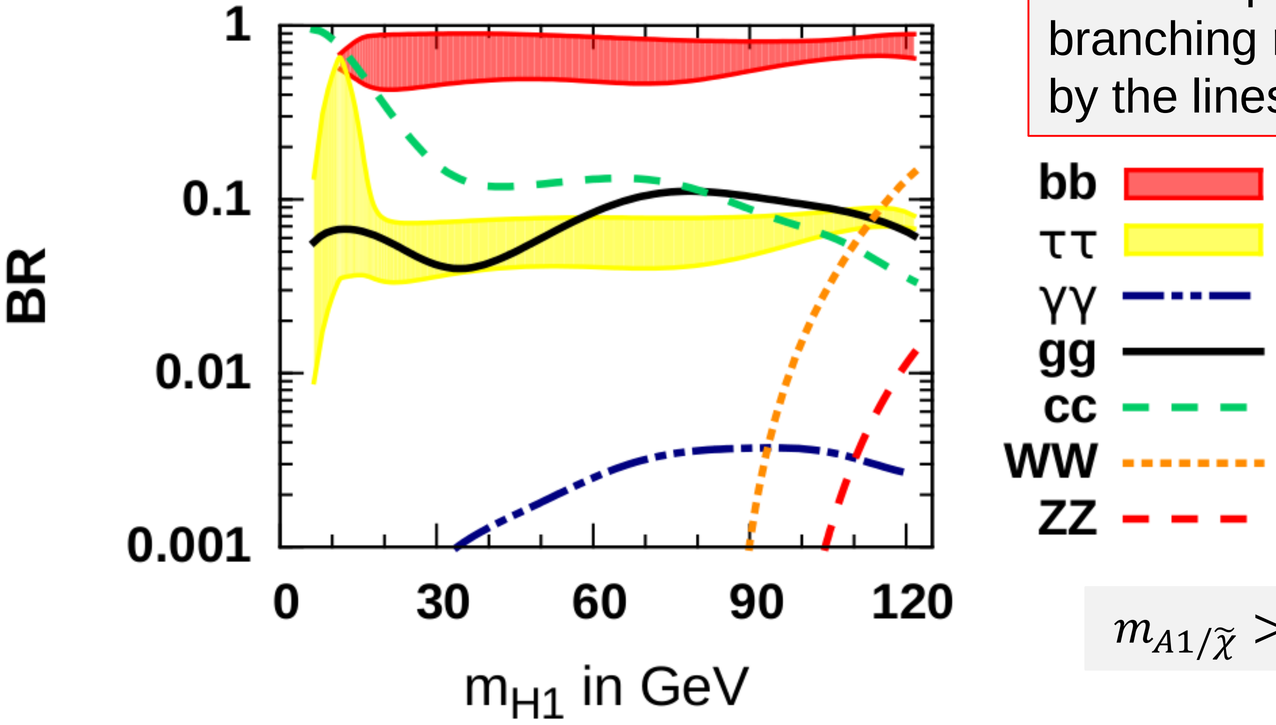
$m_{A1/\tilde{\chi}} > 0.5 m_{H1}$

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

BRs for light (singlet-like) Higgs boson

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

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



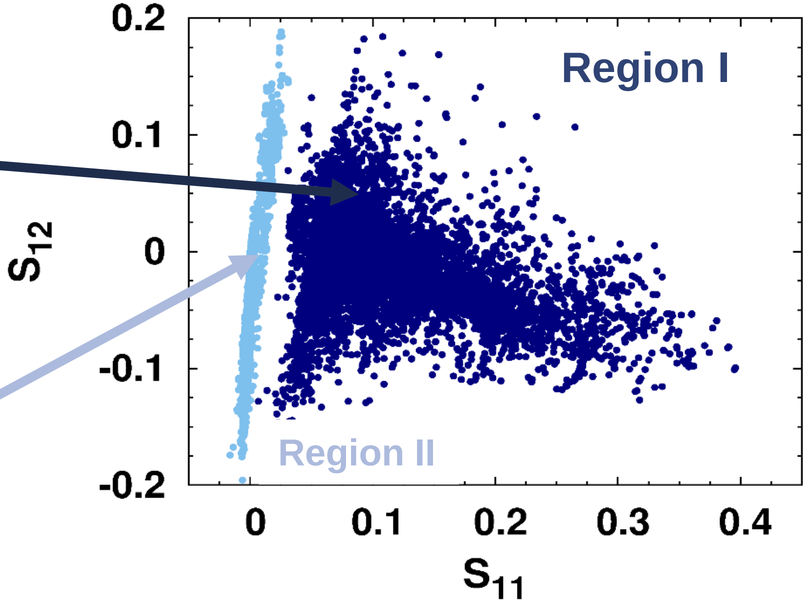
$$m_{A1/\tilde{\chi}} > 0.5 m_{H1}$$

MSSM-like Region different BRs compared to SM due to zero crossing of S_{11} leading to broad allowed bands for BRs.

Couplings to fermions and allowed range for Higgs mixing elements

S_{11} large and positive in Region I

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



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

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

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

Couplings to fermions and allowed range for Higgs mixing elements

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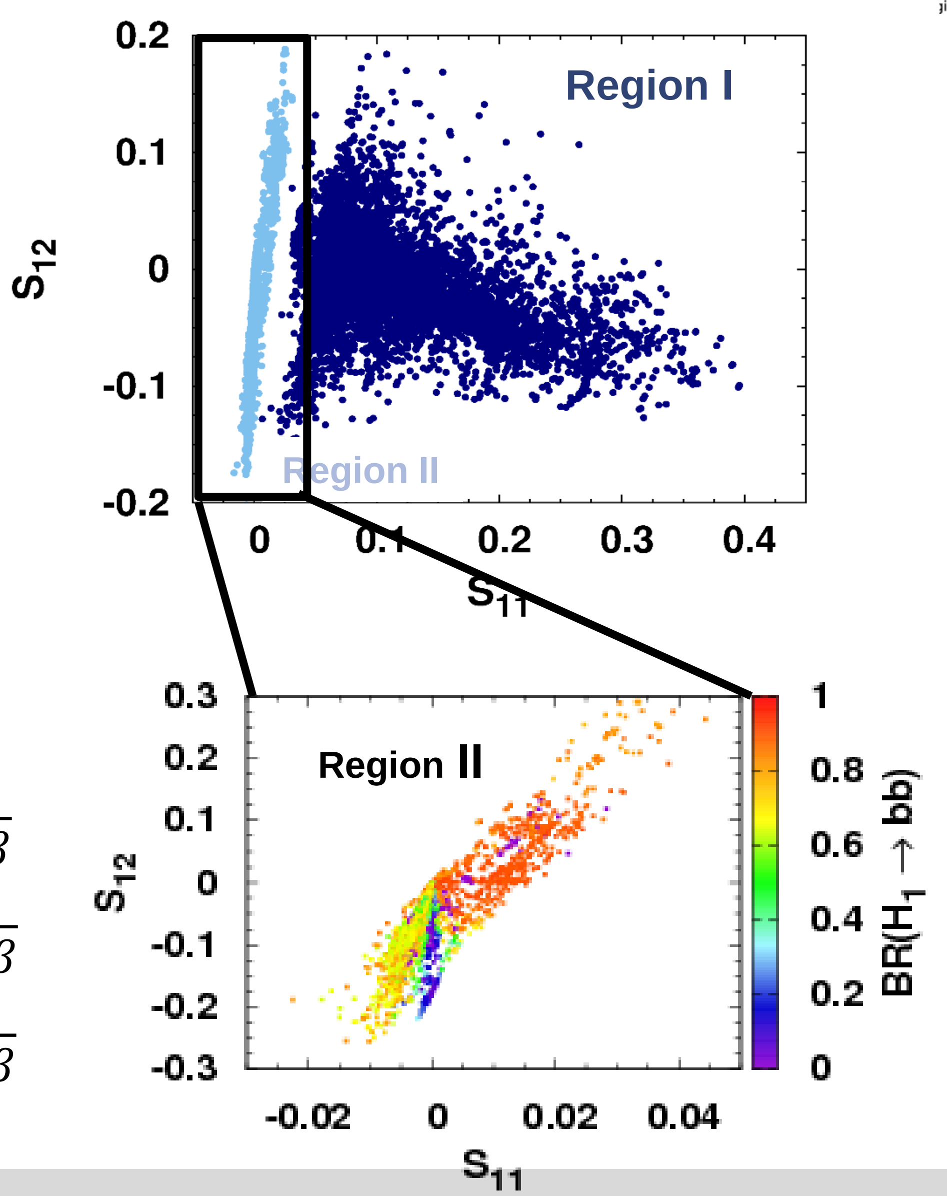
$$H_i \tau_L \tau_R^c : -\frac{h_\tau}{\sqrt{2}} S_{i1} \qquad h_\tau = \frac{m_\tau}{v \cos\beta}$$



Discovery potential for final states @14TeV

- $\tau\tau$: 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
- $A_1A_1/\ \tilde{\chi}_1^0\,\tilde{\chi}_1^0$: XS x BR compatible to SM decay $\mathrm{H} \rightarrow \gamma\gamma$

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See details for $\tau\tau$ and double Higgs Production on backup slides.

Other final states are small and $A_1A_1/\ \tilde{\chi}_1^0\ \tilde{\chi}_1^0$ 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)

Summary

- **Project 6D parameter space on 3D Higgs parameter space to allow efficient sampling with full coverage**

- **We find two regions where the Higgs mass constraints are fulfilled, called Region I (NMSSM-like) and II (MSSM-like)**

The phase space of a light Higgs boson below 125 GeV allows comparable XS @14TeV with the observed SM Higgs boson in many discovery channels like $\tau\tau$ and $\gamma\gamma$ for both regions for the whole H_1 mass range although H_1 is singlet-like

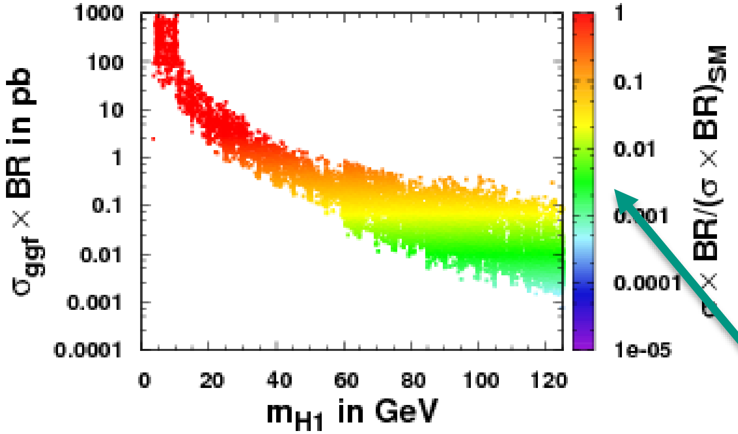
- **We provide benchmark points (see backup, 1712.02531) for different H_1 masses and discovery channels which allows a detailed simulation and studies of the background and efficiencies**

Backup

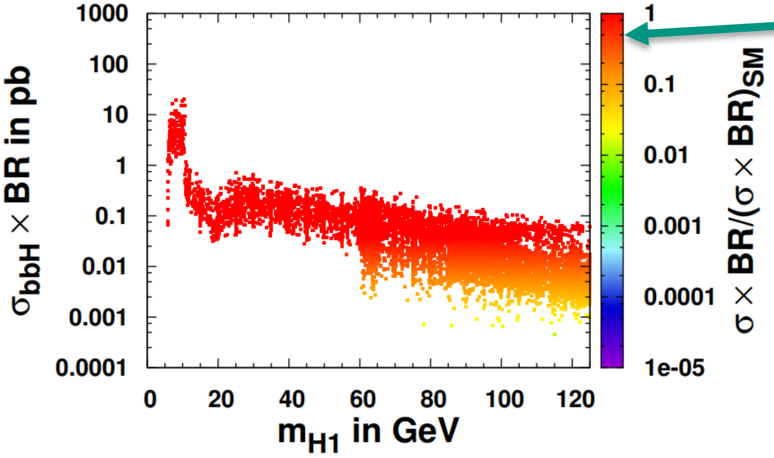
Discovery potential for tau final states @14TeV

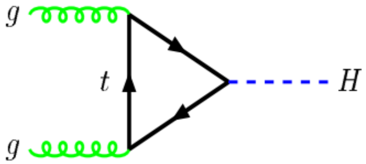
Region I – large $\lambda, \kappa,$ small $tan\beta$

σ_{ggf}



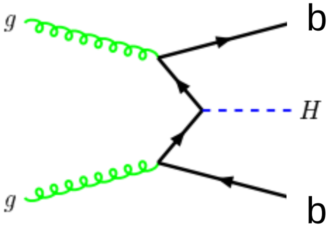
σ_{bbh}





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

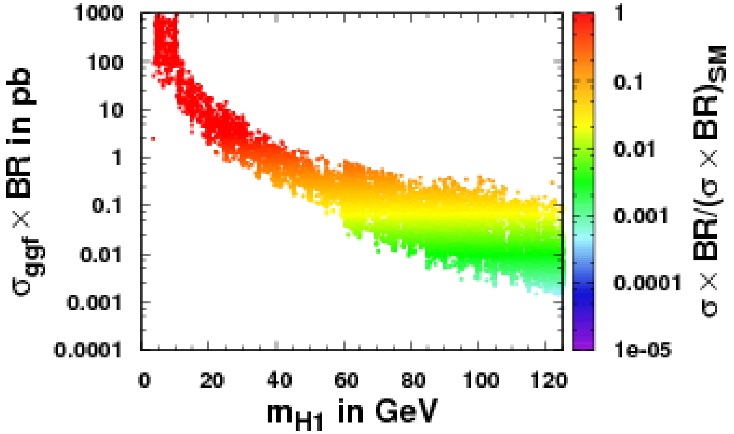
Red means 20-100%$(\sigma \times BR)_{SM}$ and **green** 1‰-1%$(\sigma \times BR)_{SM}$



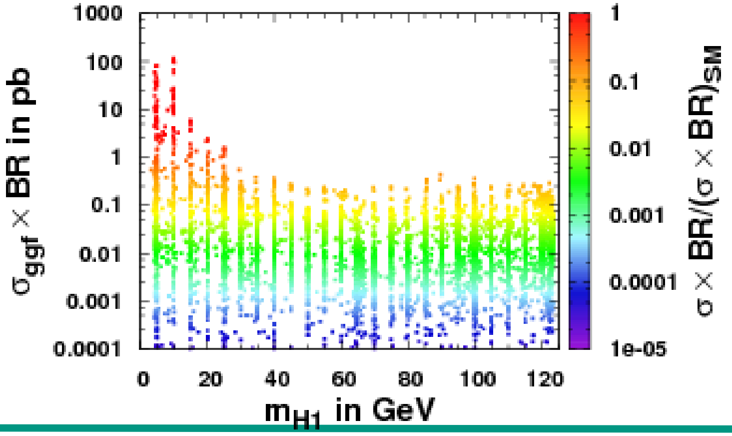
Discovery potential for tau final states @14TeV

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

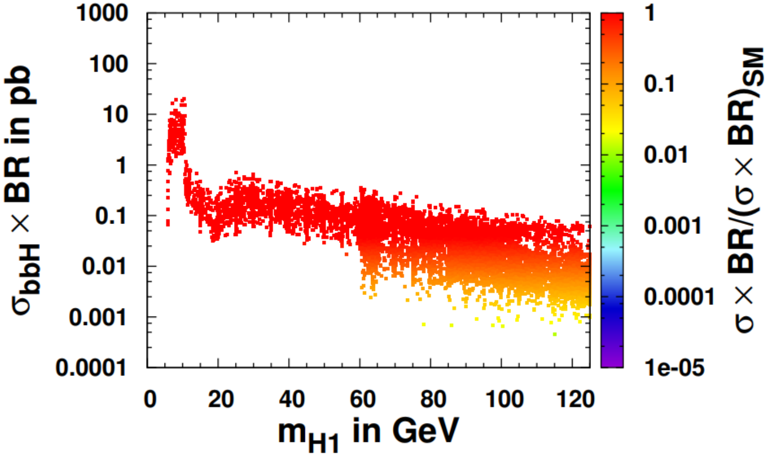
σ_{ggf}

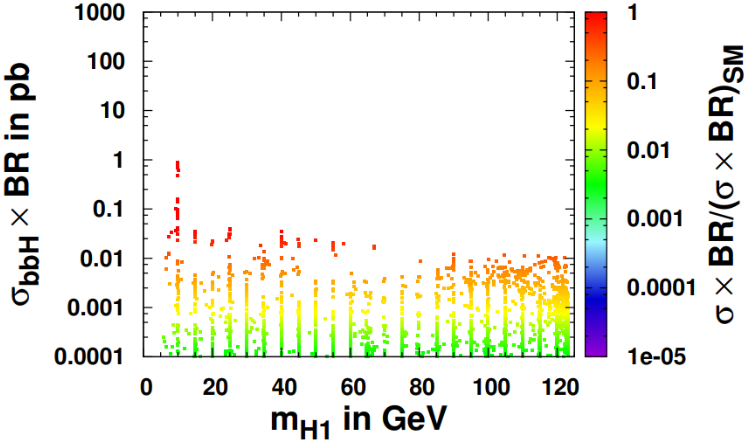


Region II – small λ, κ, large $tan\beta$



σ_{bbh}





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

Possible double Higgs production channels (if kinematically accessible)

- Lightest scalar Higgs boson

$$\boxed{H_1 \rightarrow A_1 A_1}$$

- Second lightest scalar Higgs boson

$$\boxed{\begin{array}{l} H_2 \rightarrow A_1 A_1 \\ H_2 \rightarrow H_1 H_1 \end{array}}$$

- Third scalar Higgs boson

$$\boxed{\begin{array}{l} H_3 \rightarrow A_1 A_1 \\ H_3 \rightarrow H_1 H_1 \\ H_3 \rightarrow H_2 H_2 \\ H_3 \rightarrow H_1 H_2 \end{array}}$$

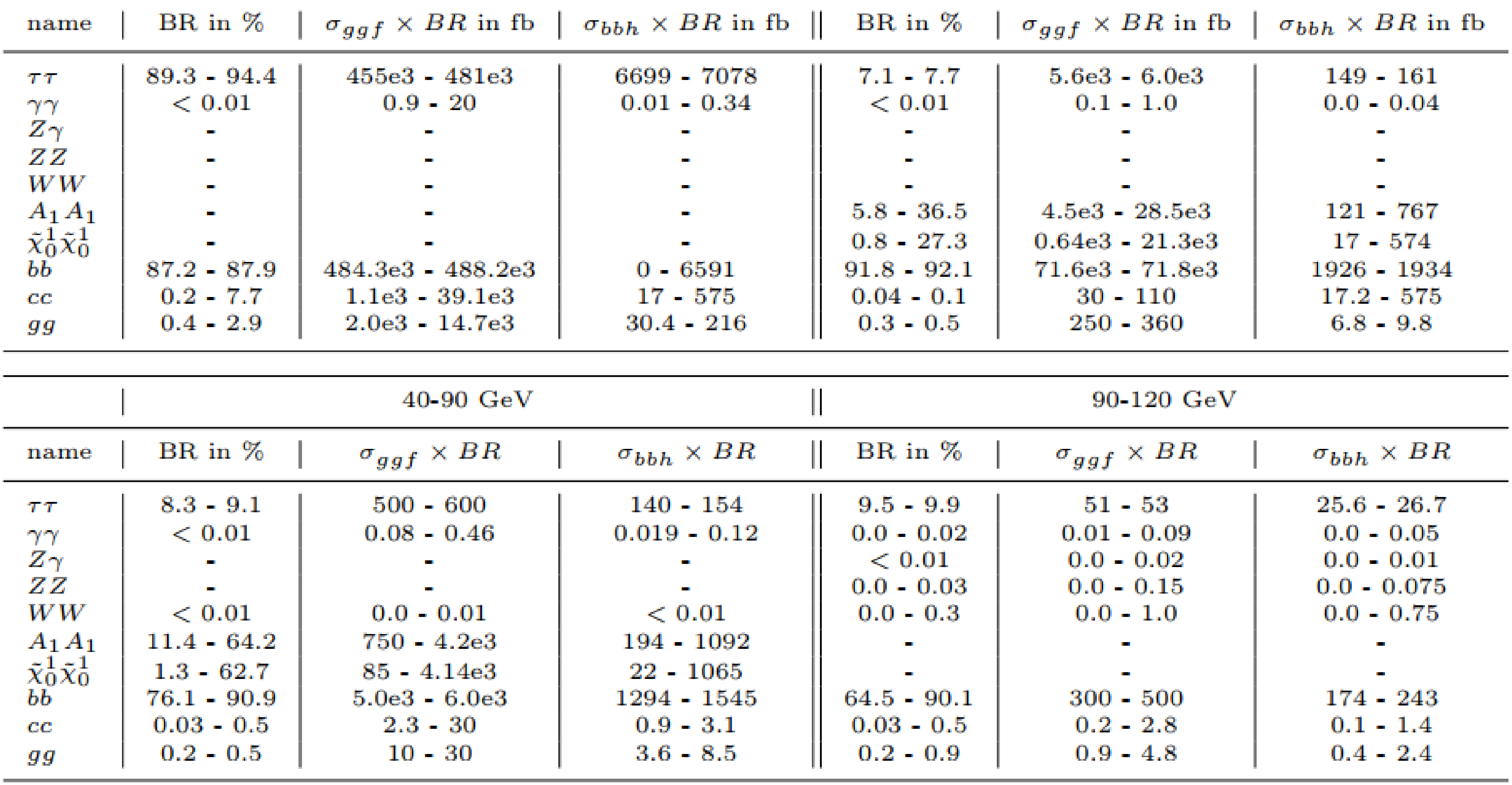
- Second pseudo-scalar Higgs boson

$$\boxed{\begin{array}{l} A_2 \rightarrow A_1 H_1 \\ A_2 \rightarrow A_1 H_2 \end{array}}$$

See backup slides for corresponding BR plots and upper limits
Dominant A_1 decay modes in bb, $\tau\tau$ and MET see backup slides

Summary of Higgs boson branching ratios (SI)

For comparison of the discovery channels the XS x BR for the 125 GeV Higgs boson are for the ggf channel γγ : 112 fb, ZZ : 1321 fb, Zγ : 76 fb, τ τ : 3090 fb and for the bbh channel γγ : 1.3 fb, ZZ : 15.4 fb, Zγ : 0.8 fb, τ τ : 36 fb.

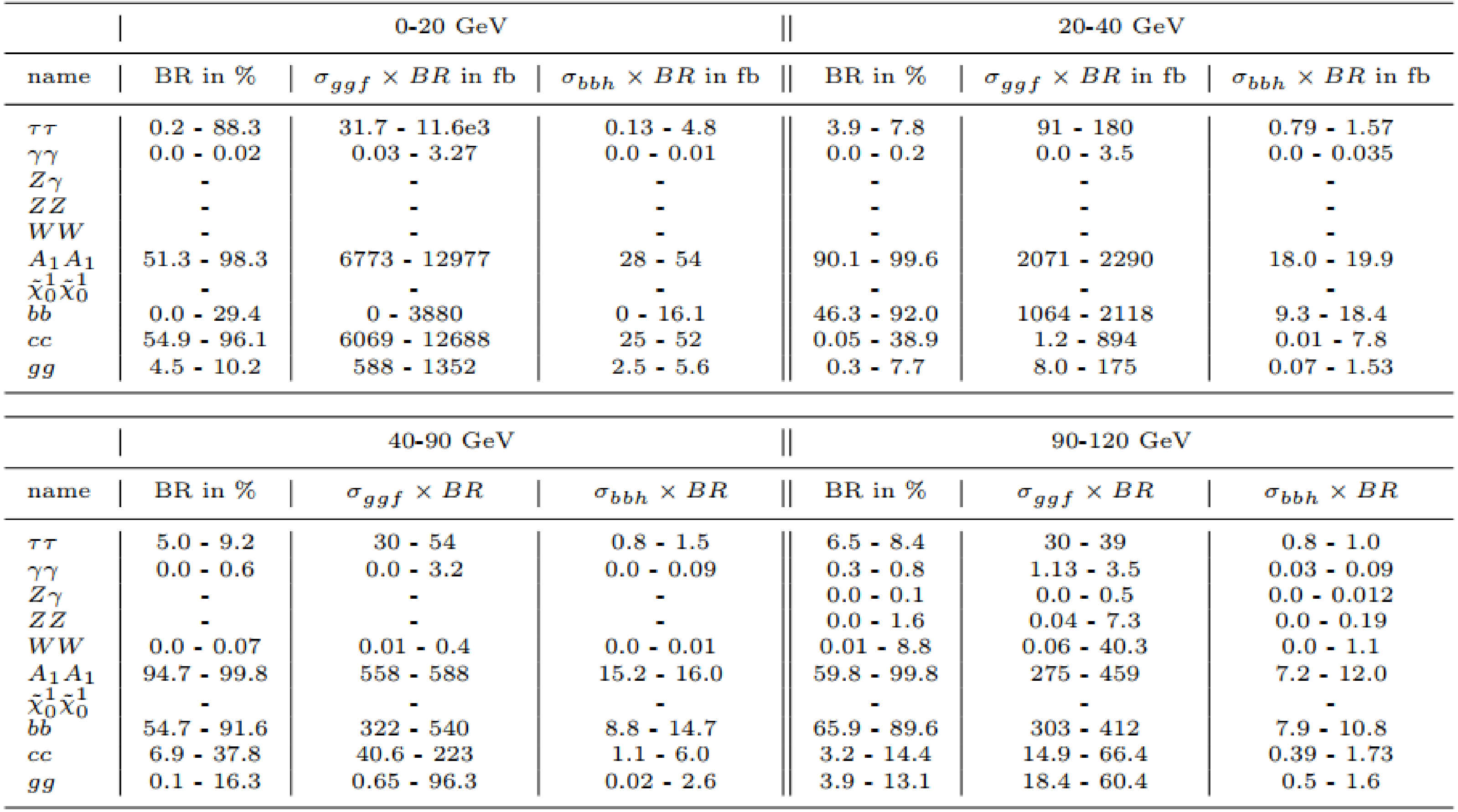


name	BR in %	$\sigma_{ggf} \times BR$ in fb	$\sigma_{bbh} \times BR$ in fb	BR in %	$\sigma_{ggf} \times BR$ in fb	$\sigma_{bbh} \times BR$ in fb
$\tau\tau$	89.3 - 94.4	455e3 - 481e3	6699 - 7078	7.1 - 7.7	5.6e3 - 6.0e3	149 - 161
$\gamma\gamma$	< 0.01	0.9 - 20	0.01 - 0.34	< 0.01	0.1 - 1.0	0.0 - 0.04
$Z\gamma$	-	-	-	-	-	-
ZZ	-	-	-	-	-	-
WW	-	-	-	-	-	-
A_1A_1	-	-	-	5.8 - 36.5	4.5e3 - 28.5e3	121 - 767
$\tilde{\chi}_0^1\tilde{\chi}_0^1$	-	-	-	0.8 - 27.3	0.64e3 - 21.3e3	17 - 574
bb	87.2 - 87.9	484.3e3 - 488.2e3	0 - 6591	91.8 - 92.1	71.6e3 - 71.8e3	1926 - 1934
cc	0.2 - 7.7	1.1e3 - 39.1e3	17 - 575	0.04 - 0.1	30 - 110	17.2 - 575
gg	0.4 - 2.9	2.0e3 - 14.7e3	30.4 - 216	0.3 - 0.5	250 - 360	6.8 - 9.8

	40-90 GeV			90-120 GeV		
name	BR in %	$\sigma_{ggf} \times BR$	$\sigma_{bbh} \times BR$	BR in %	$\sigma_{ggf} \times BR$	$\sigma_{bbh} \times BR$
$\tau\tau$	8.3 - 9.1	500 - 600	140 - 154	9.5 - 9.9	51 - 53	25.6 - 26.7
$\gamma\gamma$	< 0.01	0.08 - 0.46	0.019 - 0.12	0.0 - 0.02	0.01 - 0.09	0.0 - 0.05
$Z\gamma$	-	-	-	< 0.01	0.0 - 0.02	0.0 - 0.01
ZZ	-	-	-	0.0 - 0.03	0.0 - 0.15	0.0 - 0.075
WW	< 0.01	0.0 - 0.01	< 0.01	0.0 - 0.3	0.0 - 1.0	0.0 - 0.75
A_1A_1	11.4 - 64.2	750 - 4.2e3	194 - 1092	-	-	-
$\tilde{\chi}_0^1\tilde{\chi}_0^1$	1.3 - 62.7	85 - 4.14e3	22 - 1065	-	-	-
bb	76.1 - 90.9	5.0e3 - 6.0e3	1294 - 1545	64.5 - 90.1	300 - 500	174 - 243
cc	0.03 - 0.5	2.3 - 30	0.9 - 3.1	0.03 - 0.5	0.2 - 2.8	0.1 - 1.4
gg	0.2 - 0.5	10 - 30	3.6 - 8.5	0.2 - 0.9	0.9 - 4.8	0.4 - 2.4

Summary of Higgs boson branching ratios (SII)

For comparison of the discovery channels the XS x BR for the 125 GeV Higgs boson are for the ggf channel γγ : 112 fb, ZZ : 1321 fb, Zγ : 76 fb, τ τ : 3090 fb and for the bbh channel γγ : 1.3 fb, ZZ : 15.4 fb, Zγ : 0.8 fb, τ τ : 36 fb.



	0-20 GeV			20-40 GeV		
name	BR in %	$\sigma_{ggf} \times BR$ in fb	$\sigma_{bbh} \times BR$ in fb	BR in %	$\sigma_{ggf} \times BR$ in fb	$\sigma_{bbh} \times BR$ in fb
$\tau\tau$	0.2 - 88.3	31.7 - 11.6e3	0.13 - 4.8	3.9 - 7.8	91 - 180	0.79 - 1.57
$\gamma\gamma$	0.0 - 0.02	0.03 - 3.27	0.0 - 0.01	0.0 - 0.2	0.0 - 3.5	0.0 - 0.035
$Z\gamma$	-	-	-	-	-	-
ZZ	-	-	-	-	-	-
WW	-	-	-	-	-	-
A_1A_1	51.3 - 98.3	6773 - 12977	28 - 54	90.1 - 99.6	2071 - 2290	18.0 - 19.9
$\tilde{\chi}_0^1\tilde{\chi}_0^1$	-	-	-	-	-	-
bb	0.0 - 29.4	0 - 3880	0 - 16.1	46.3 - 92.0	1064 - 2118	9.3 - 18.4
cc	54.9 - 96.1	6069 - 12688	25 - 52	0.05 - 38.9	1.2 - 894	0.01 - 7.8
gg	4.5 - 10.2	588 - 1352	2.5 - 5.6	0.3 - 7.7	8.0 - 175	0.07 - 1.53

	40-90 GeV			90-120 GeV		
name	BR in %	$\sigma_{ggf} \times BR$	$\sigma_{bbh} \times BR$	BR in %	$\sigma_{ggf} \times BR$	$\sigma_{bbh} \times BR$
$\tau\tau$	5.0 - 9.2	30 - 54	0.8 - 1.5	6.5 - 8.4	30 - 39	0.8 - 1.0
$\gamma\gamma$	0.0 - 0.6	0.0 - 3.2	0.0 - 0.09	0.3 - 0.8	1.13 - 3.5	0.03 - 0.09
$Z\gamma$	-	-	-	0.0 - 0.1	0.0 - 0.5	0.0 - 0.012
ZZ	-	-	-	0.0 - 1.6	0.04 - 7.3	0.0 - 0.19
WW	0.0 - 0.07	0.01 - 0.4	0.0 - 0.01	0.01 - 8.8	0.06 - 40.3	0.0 - 1.1
A_1A_1	94.7 - 99.8	558 - 588	15.2 - 16.0	59.8 - 99.8	275 - 459	7.2 - 12.0
$\tilde{\chi}_0^1\tilde{\chi}_0^1$	-	-	-	-	-	-
bb	54.7 - 91.6	322 - 540	8.8 - 14.7	65.9 - 89.6	303 - 412	7.9 - 10.8
cc	6.9 - 37.8	40.6 - 223	1.1 - 6.0	3.2 - 14.4	14.9 - 66.4	0.39 - 1.73
gg	0.1 - 16.3	0.65 - 96.3	0.02 - 2.6	3.9 - 13.1	18.4 - 60.4	0.5 - 1.6

Why we are interested in the NMSSM

- **MSSM**

Loop corrections Δ_{rad} $< m_Z^2$

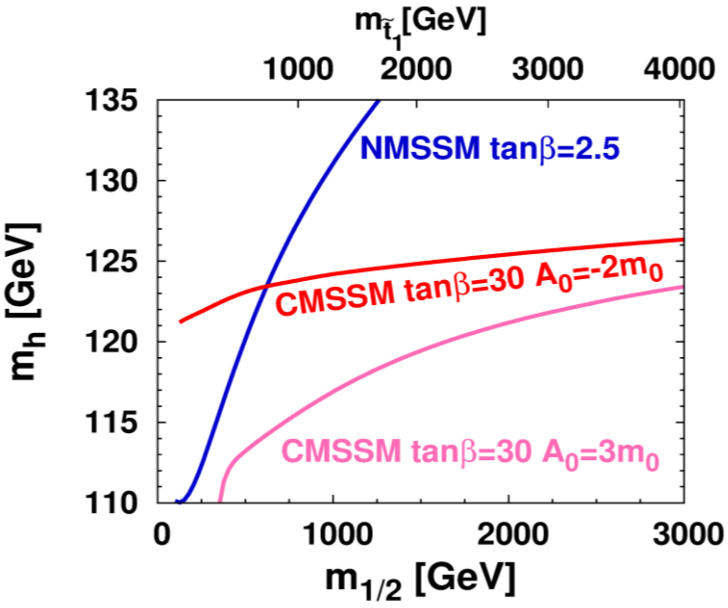
$$\underbrace{m_h^2}_{m_h^2 \approx m_Z^2 \cos^2 2\beta + \frac{3}{(4\pi)^2}\frac{m_t^4}{v^2}\left[\ln\frac{m_{\tilde t}^2}{m_t^2} + \frac{X_t^2}{m_{\tilde t}^2}\left(1 - \frac{X_t^2}{12 m_{\tilde t}^2}\right)\right]} \approx \underbrace{m_Z^2 \cos^2 2\beta}_{} + \boxed{\frac{3}{(4\pi)^2}\frac{m_t^4}{v^2}\left[\ln\frac{m_{\tilde t}^2}{m_t^2} + \frac{X_t^2}{m_{\tilde t}^2}\left(1 - \frac{X_t^2}{12 m_{\tilde t}^2}\right)\right]}$$

- **NMSSM: Mixing with singlet**

$$m_h^2 \approx \boxed{\lambda^2 v^2 \sin^2 2\beta +} M_Z^2 \cos^2 2\beta + \Delta_{rad}$$

Ellwanger, arXiv 1108.0157

Increases Higgs mass for large values of λ already at Born level



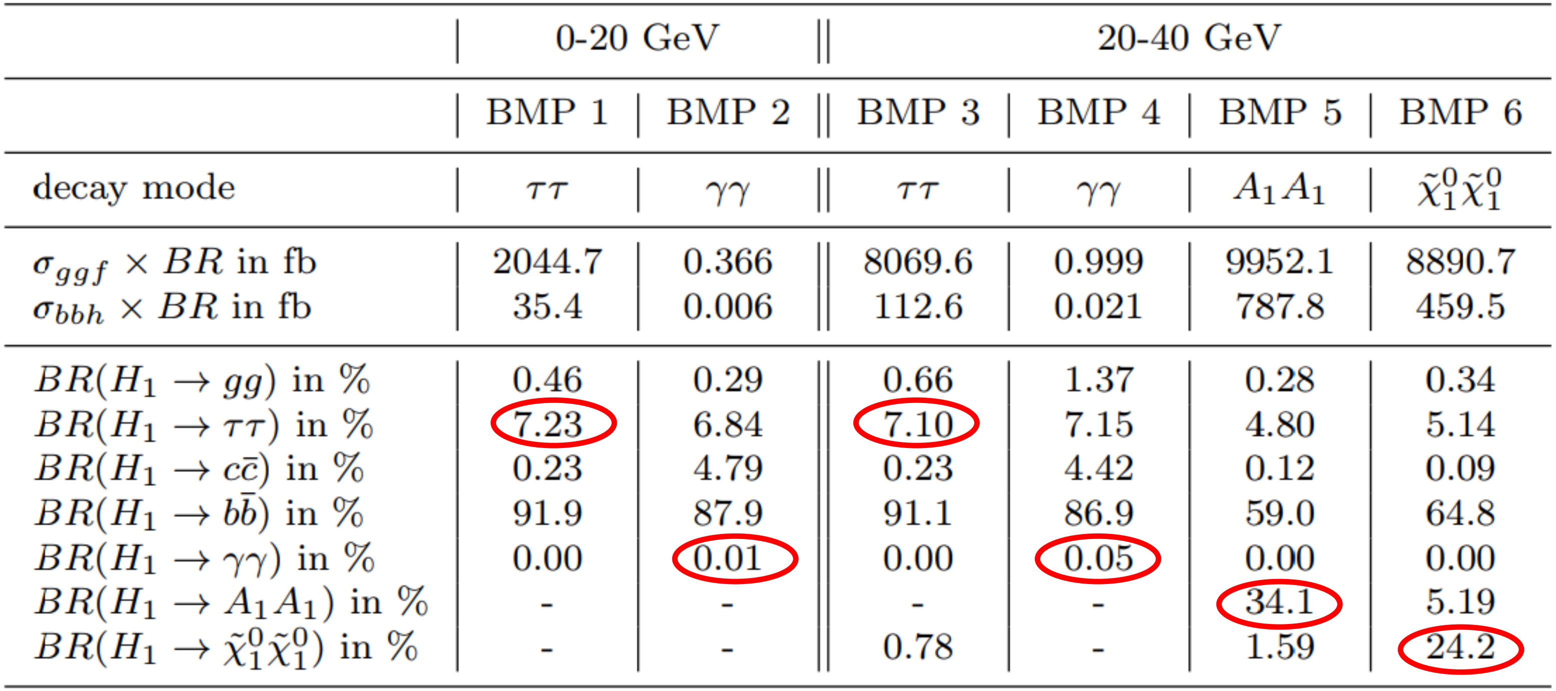
NMSSM: m_h=125 GeV for TeV instead of multi-TeV stops

χ^2 Function $\chi^2_{tot} = \chi^2_{H_1} + \chi^2_{H_2} + \chi^2_{H_3} + \chi^2_{LEP} + \chi^2_{\boldsymbol{LHC}}$

- $\chi^2_{H_1} = \frac{(m_{H_1} - m_{grid,H_1})^2}{\sigma^2_{H_1}}$
  - m_{grid,H_1} : Chosen point in the 3D mass space
  - m_{H_1}: below observed Higgs boson, $\sigma^2_{H_1}$ set to 2 GeV
- $\chi^2_{H_2} = \frac{(m_{H_2} - m_{obs})^2}{\sigma^2_{SM}} + \sum_i \left(c^i_{H_2} - c_{obs}\right)^2 / \sigma^2_{coup}$
  - 125 GeV Higgs boson with SM couplings , $c^i_{H_2}$: reduced couplings of H_2, ratio of couplings of H_2 to particle $i = f_u, f_d, W, Z, \gamma$. Observed coupling c_{coup} agree within 10% with the SM couplings, so $\sigma^2_{coup} = 0.1$.
- $\chi^2_{H_3/A_1} = \frac{(m_{H_3/A_1} - m_{grid,H_3/A_1})^2}{\sigma^2_{H_3/A_1}}$
- 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

Benchmark Points for different mass ranges

- BMPs have been selected to have a maximal cross section times branching ratio for the corresponding decay mode

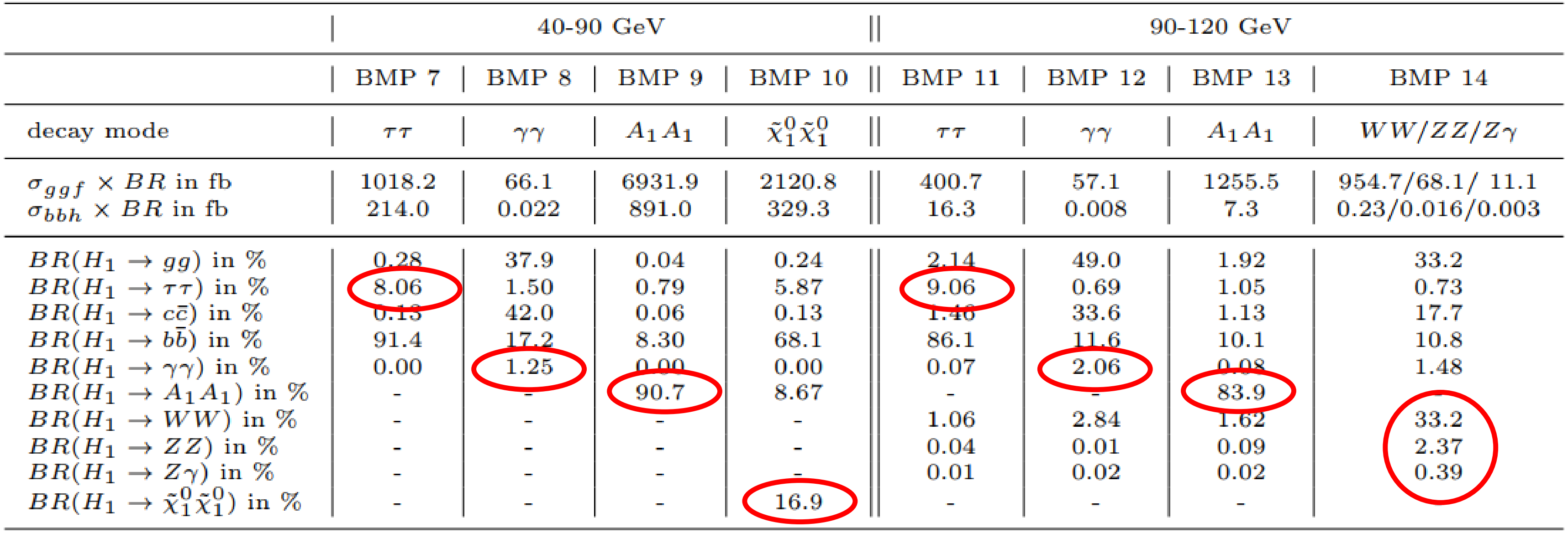


	0-20 GeV		20-40 GeV			
	BMP 1	BMP 2	BMP 3	BMP 4	BMP 5	BMP 6
decay mode	$\tau\tau$	$\gamma\gamma$	$\tau\tau$	$\gamma\gamma$	A_1A_1	$\tilde{\chi}_1^0\tilde{\chi}_1^0$
$\sigma_{ggf} \times BR$ in fb	2044.7	0.366	8069.6	0.999	9952.1	8890.7
$\sigma_{bbh} \times BR$ in fb	35.4	0.006	112.6	0.021	787.8	459.5
$BR(H_1 \to gg)$ in %	0.46	0.29	0.66	1.37	0.28	0.34
$BR(H_1 \to \tau\tau)$ in %	7.23	6.84	7.10	7.15	4.80	5.14
$BR(H_1 \to c\bar{c})$ in %	0.23	4.79	0.23	4.42	0.12	0.09
$BR(H_1 \to b\bar{b})$ in %	91.9	87.9	91.1	86.9	59.0	64.8
$BR(H_1 \to \gamma\gamma)$ in %	0.00	0.01	0.00	0.05	0.00	0.00
$BR(H_1 \to A_1A_1)$ in %	-	-	-	-	34.1	5.19
$BR(H_1 \to \tilde{\chi}_1^0\tilde{\chi}_1^0)$ in %	-	-	0.78	-	1.59	24.2

See backup slides for corresponding mass spectrum

Benchmark Points for different mass ranges

- BMPs have been selected to have a maximal cross section times branching ratio for the corresponding decay mode



	40-90 GeV				90-120 GeV			
	BMP 7	BMP 8	BMP 9	BMP 10	BMP 11	BMP 12	BMP 13	BMP 14
decay mode	$\tau\tau$	$\gamma\gamma$	$A_1 A_1$	$\tilde{\chi}_1^0 \tilde{\chi}_1^0$	$\tau\tau$	$\gamma\gamma$	$A_1 A_1$	$WW/ZZ/Z\gamma$
$\sigma_{ggf} \times BR$ in fb	1018.2	66.1	6931.9	2120.8	400.7	57.1	1255.5	954.7/68.1/ 11.1
$\sigma_{bbh} \times BR$ in fb	214.0	0.022	891.0	329.3	16.3	0.008	7.3	0.23/0.016/0.003
$BR(H_1 \to gg)$ in %	0.28	37.9	0.04	0.24	2.14	49.0	1.92	33.2
$BR(H_1 \to \tau\tau)$ in %	8.06	1.50	0.79	5.87	9.06	0.69	1.05	0.73
$BR(H_1 \to c\bar{c})$ in %	0.13	42.0	0.06	0.13	1.46	33.6	1.13	17.7
$BR(H_1 \to b\bar{b})$ in %	91.4	17.2	8.30	68.1	86.1	11.6	10.1	10.8
$BR(H_1 \to \gamma\gamma)$ in %	0.00	1.25	0.00	0.00	0.07	2.06	0.08	1.48
$BR(H_1 \to A_1 A_1)$ in %	-	-	90.7	8.67	-	-	83.9	-
$BR(H_1 \to WW)$ in %	-	-	-	-	1.06	2.84	1.62	33.2
$BR(H_1 \to ZZ)$ in %	-	-	-	-	0.04	0.01	0.09	2.37
$BR(H_1 \to Z\gamma)$ in %	-	-	-	-	0.01	0.02	0.02	0.39
$BR(H_1 \to \tilde{\chi}_1^0 \tilde{\chi}_1^0)$ in %	-	-	-	16.9	-	-	-	-

See backup slides for corresponding mass spectrum

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

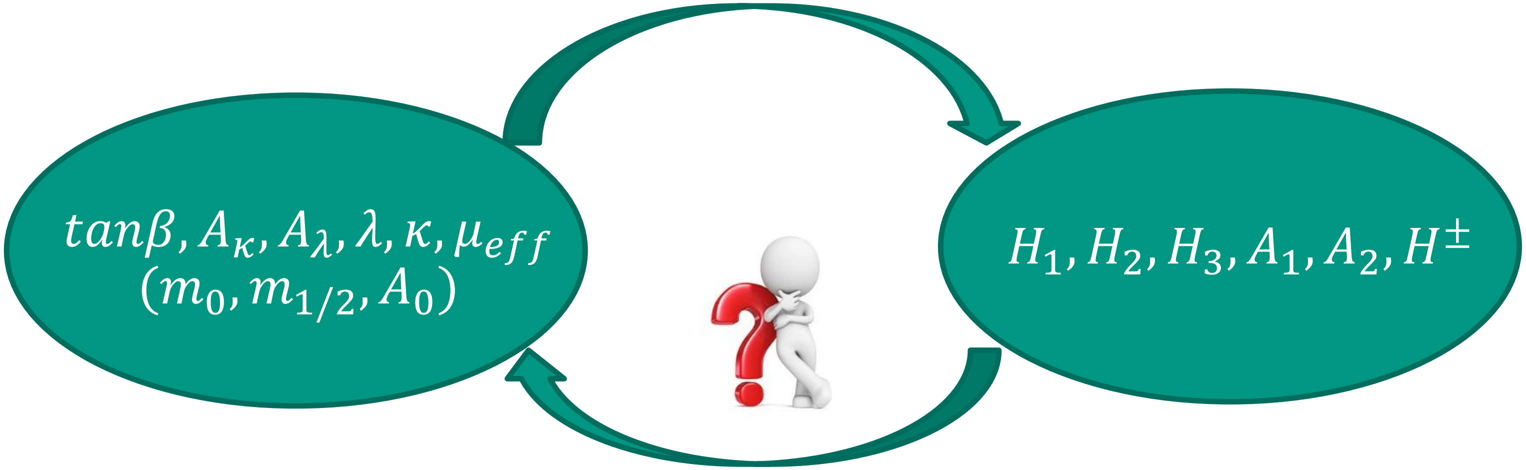
	Region I **large λ, κ, small $tan\beta$**	**Region II** **small λ, κ, large $tan\beta$**
$BR(H_1 \to A_1 A_1)$	80%	100%
$BR(H_2 \to A_1 A_1)$	8%	1%
$BR(H_2 \to H_1 H_1)$	7%	6%
$BR(A_2 \to A_1 H_1)$	25%	0%
$BR(A_2 \to A_1 H_2)$	30%	2%
$BR(H_3 \to A_1 A_1)$	2.5%	0%
$BR(H_3 \to H_1 H_1)$	35%	0%
$BR(H_3 \to H_1 H_2)$	70%	5%
$BR(H_3 \to H_2 H_2)$	2%	0.5%

See backup slides for corresponding BR plots
Dominant A_1 decay modes in bb, $\tau\tau$ and MET see backup slides

Principle Fitting procedure

- 6 free parameter (6D) are needed to describe the Higgs sector in the NMSSM consisting of 6 Higgs bosons (6D)

calculated with NMSSMTools*



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

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

Question: Can we invert the problem and fit the free couplings and NMSSM parameters for fixed Higgs masses to determine range for BRs?

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

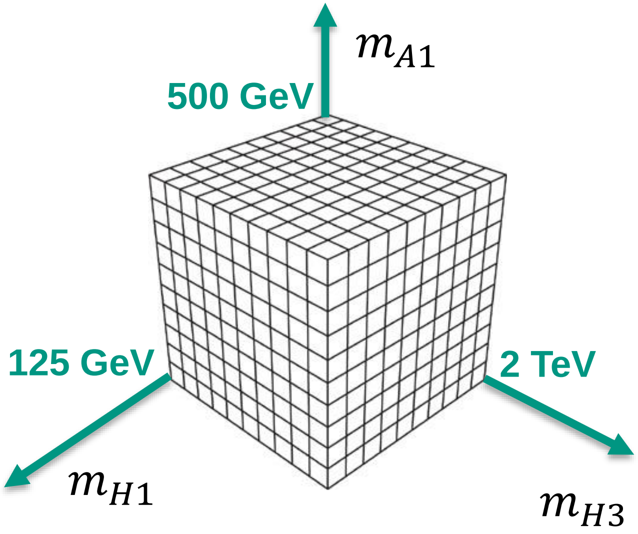
Reduction of the 6D Higgs mass space

- $H_3, H^{\pm}$ 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

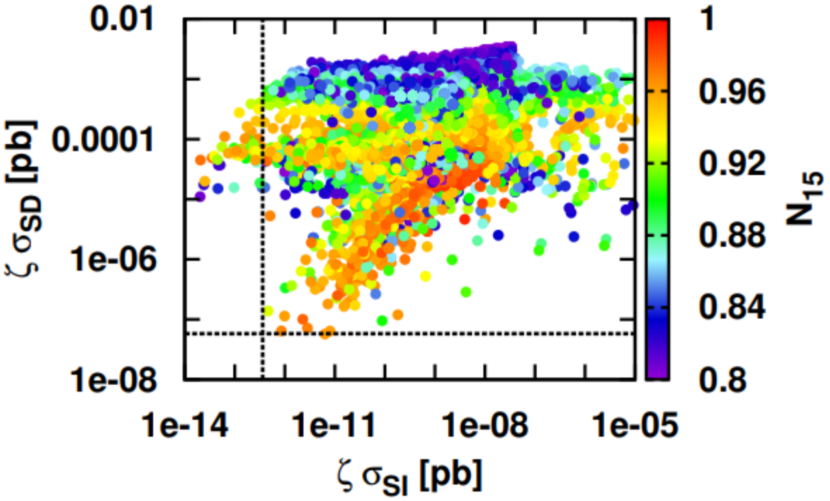
Efficient sampling of the parameter space and determination of the couplings



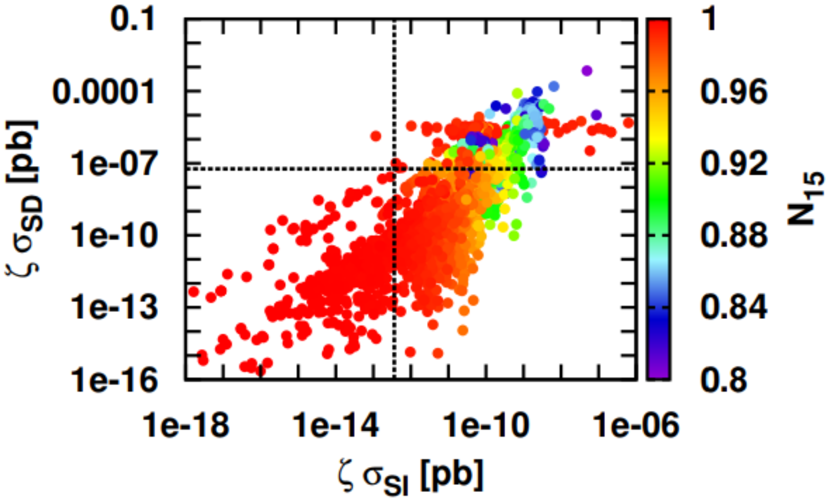
* F. James and M. Roos, Comput.Phys.Commun. 10 (1975) 343-367

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



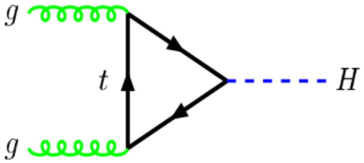
Scenario I (large λ, κ, small $\tan\beta$)

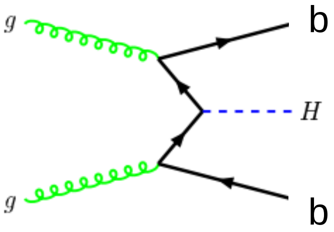


Scenario II (small λ, κ, large $\tan\beta$)

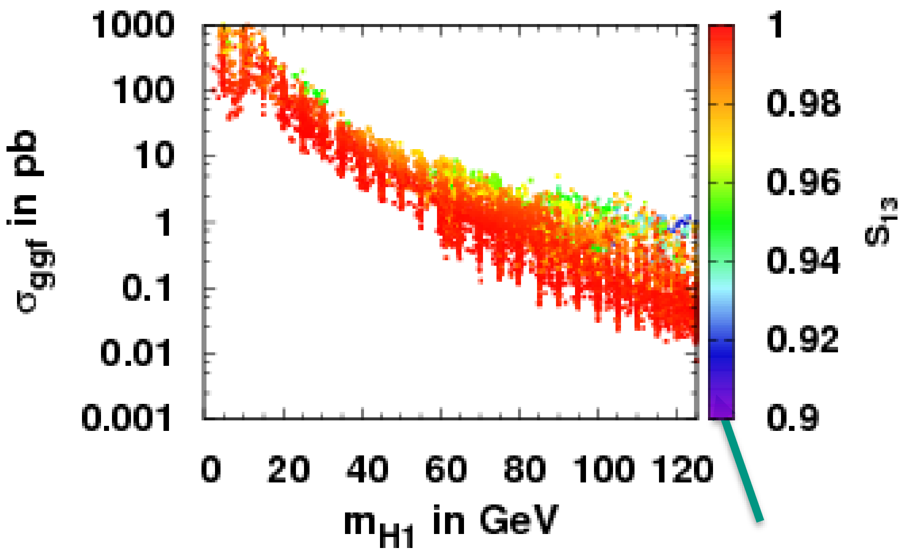
Light Higgs production cross section

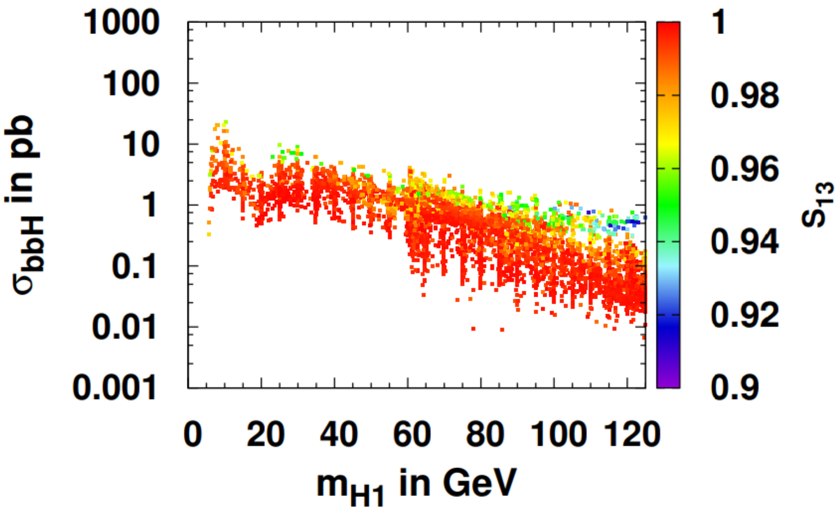
Region I – large $\lambda, \kappa,$ small $tan\beta$





$\sim tan\beta^2$



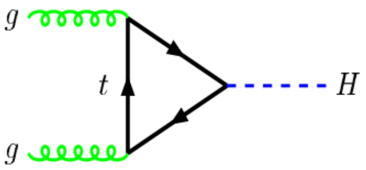


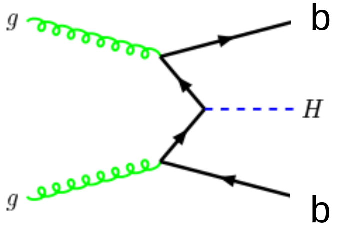
S_{13}: Singlet component of H_1

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

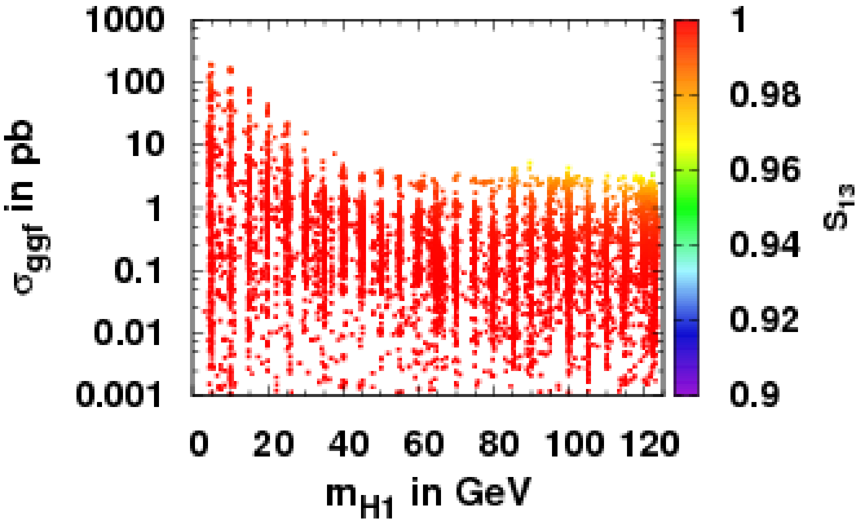
Light Higgs production cross section

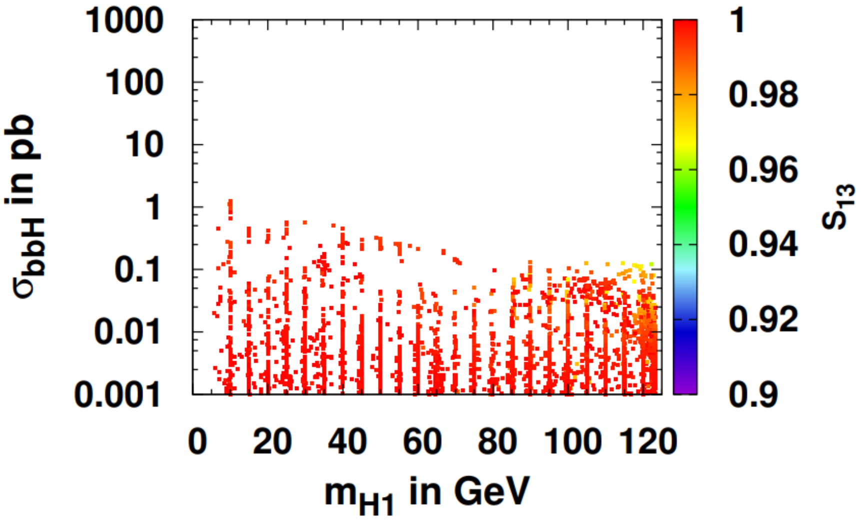
Region II – small $\lambda, \kappa,$ large $tan\beta$





$\sim tan\beta^2$





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}

Special BRs for light (singlet-like) Higgs boson

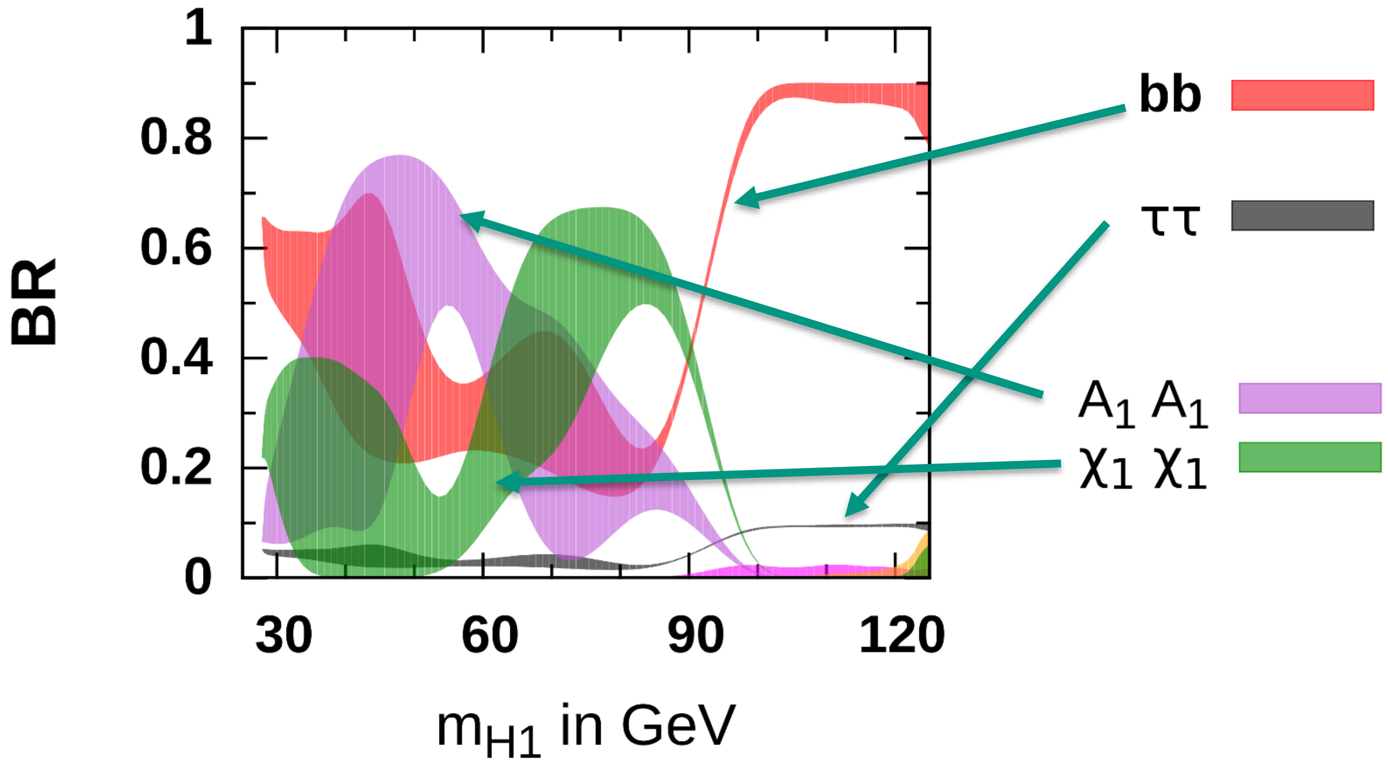
- Small region in parameter space where $\boldsymbol{m_{A_1} < 0.5\, m_{H1}}$ leads to dominant BR into light pseudo-scalar Higgs
- Light pseudo-scalar Higgs boson mass and lightest neutralino mass are correlated
- $\boldsymbol{m_{A_1} < 0.5\, m_{H1}}$ implies $\boldsymbol{m_{\tilde{\chi}_1^0} < 0.5\, m_{H1}}$

	Region I **large** $\lambda, \kappa,$ **small** $tan\beta$	**Region II** **small** $\lambda, \kappa,$ **large** $tan\beta$
$BR(H_1 \rightarrow A_1 A_1)$	0-80%	0-100%
$BR(H_1 \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0)$	0-70%	-

Light Neutralinos < $0.5\, m_{H1}$ not possible in Region II
→ Decays with MET only possible in Region I

BRs for light Higgs boson, if $m_{A_1} < 0.5\, m_{H1}$ (implies $m_{\tilde{\chi}_1^0} < 0.5\, m_{H1}$)

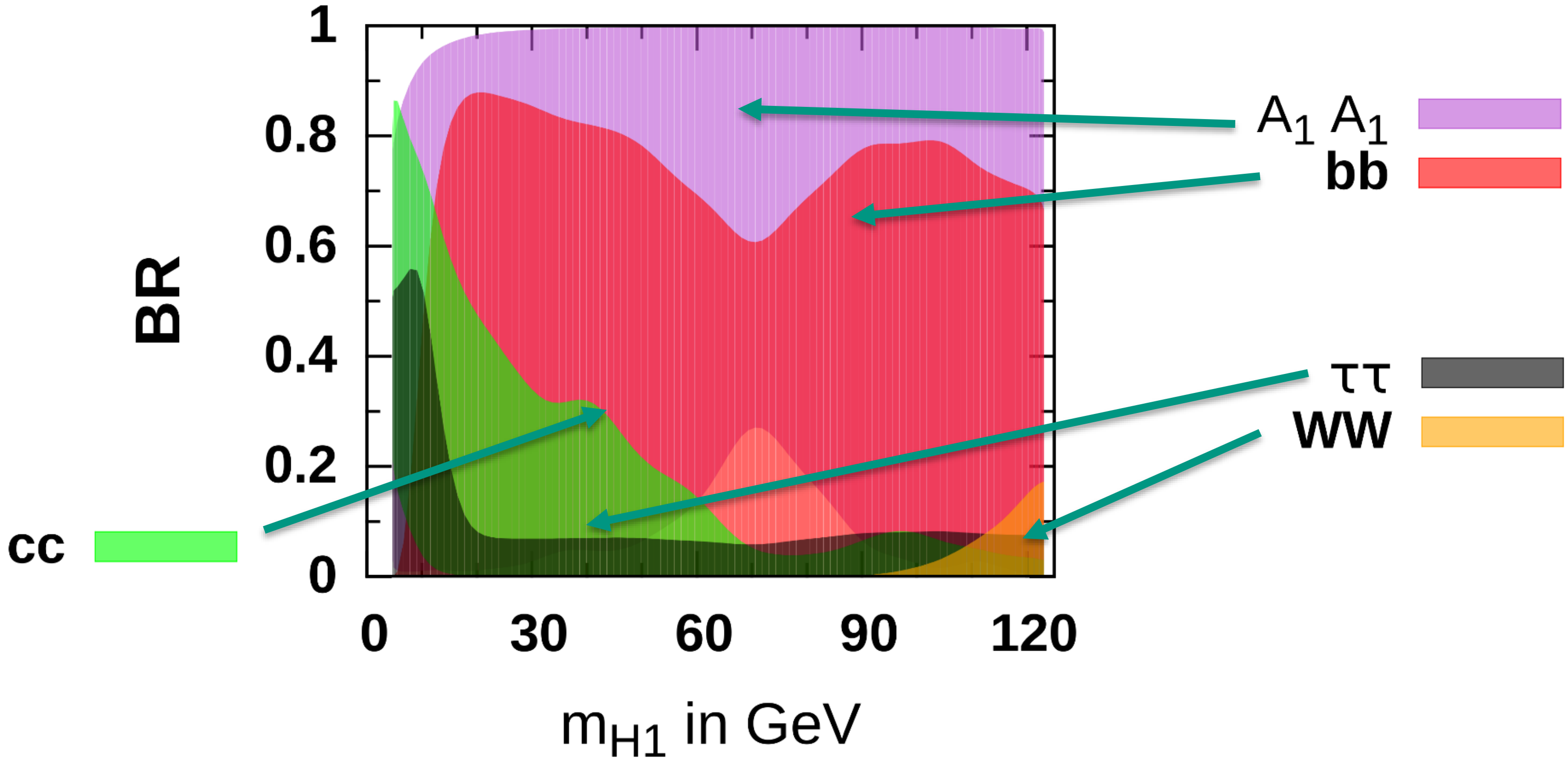
Region I – large $\lambda, \kappa,$ small $tan\beta$



Light pseudo-scalar Higgs boson mass and lightest neutralino mass are correlated

BRs for light Higgs boson, if $m_{A_1} < 0.5\, m_{H1}$

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



Light Neutralinos < $0.5\, m_{H1}$ not possible in Region II

NMSSM – neutralino sector

- **Mass matrix M_0 has an additional singlino component in NMSSM**

$$M_0 = \begin{pmatrix} \mathbf{M_1} & 0 & -\frac{g_1 v_d}{\sqrt{2}} & \frac{g_1 v_u}{\sqrt{2}} & 0 \\ 0 & \mathbf{M_2} & \frac{g_2 v_d}{\sqrt{2}} & -\frac{g_2 v_u}{\sqrt{2}} & 0 \\ -\frac{g_1 v_d}{\sqrt{2}} & \frac{g_2 v_d}{\sqrt{2}} & 0 & -\mu_{\mathrm{eff}} & -\lambda v_u \\ \frac{g_1 v_u}{\sqrt{2}} & -\frac{g_2 v_u}{\sqrt{2}} & -\mu_{\mathrm{eff}} & 0 & -\lambda v_d \\ 0 & 0 & -\lambda v_u & -\lambda v_d & \sqrt{2}\frac{\kappa}{\lambda}\mu_{eff} \end{pmatrix}$$

MSSM

NMSSM

$$M_1 \approx 0.4 m_{1/2}, M_2 \approx 0.8 m_{1/2}, M_3 \approx 2.7 m_{1/2}$$

Small ratio $\frac{\kappa}{\lambda}$ and small μ_{eff} needed

5x5 neutralino mixing matrix

$$\Rightarrow \quad \tilde{\chi}_1^0 = \tilde{B} + \tilde{W} + \tilde{H}_1 + \tilde{H}_2 + \tilde{S}$$

LSP and A1 < 60 GeV possible but small region in parameter space

BRs x XS for light Higgs Boson

(in comparison with 125 GeV Higgs Boson)

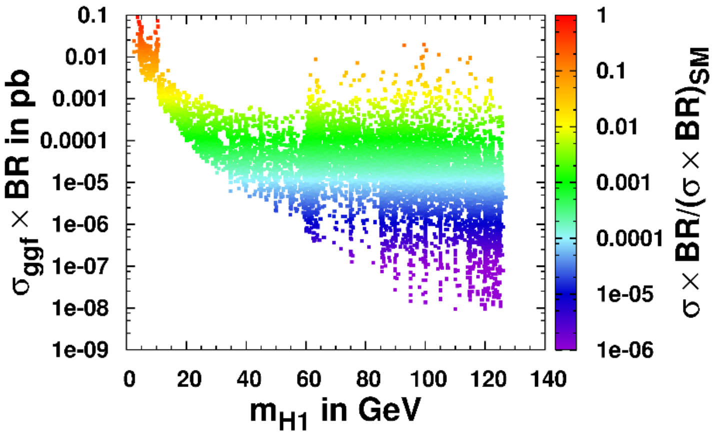
Discovery potential for γ final states

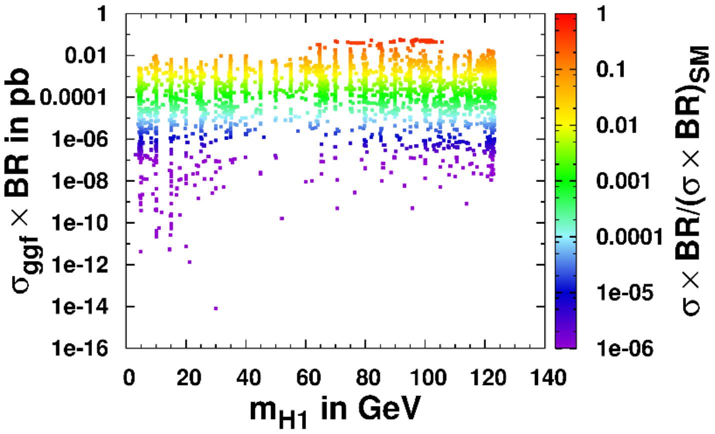
@14TeV

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

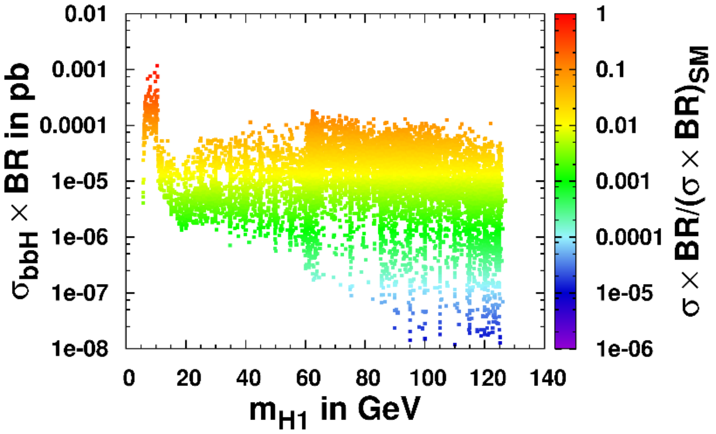
Region II – small $\lambda, \kappa,$ large $tan\beta$

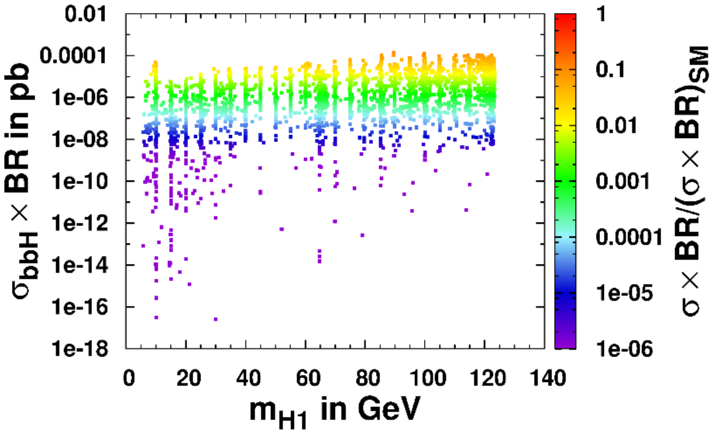
σ_{ggf}





σ_{bbh}





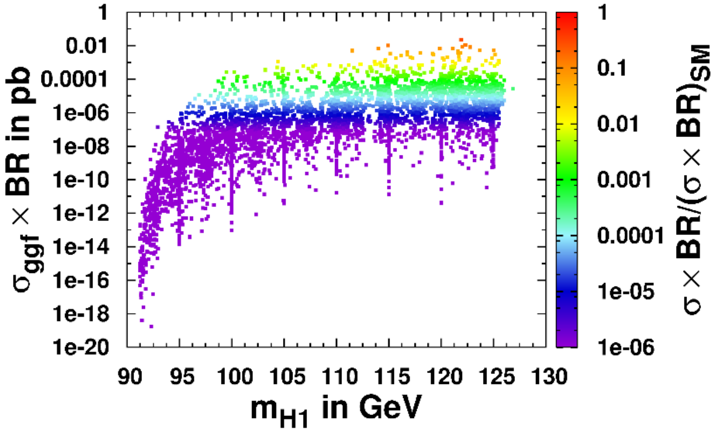
$\gamma\gamma$: in both Regions the whole mass range is accessible

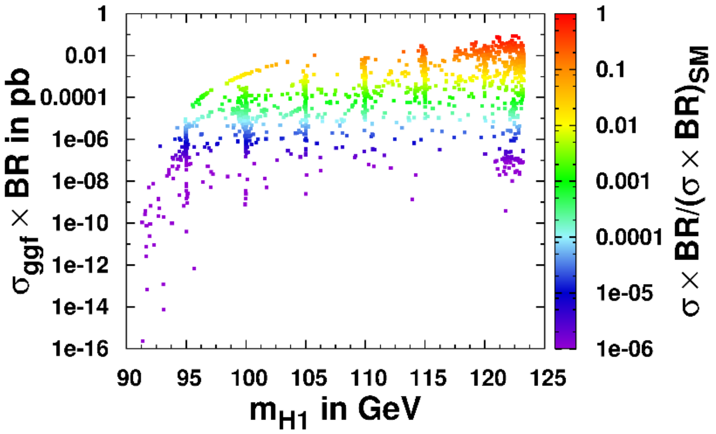
Discovery potential for $Z\gamma$ final states @14TeV

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

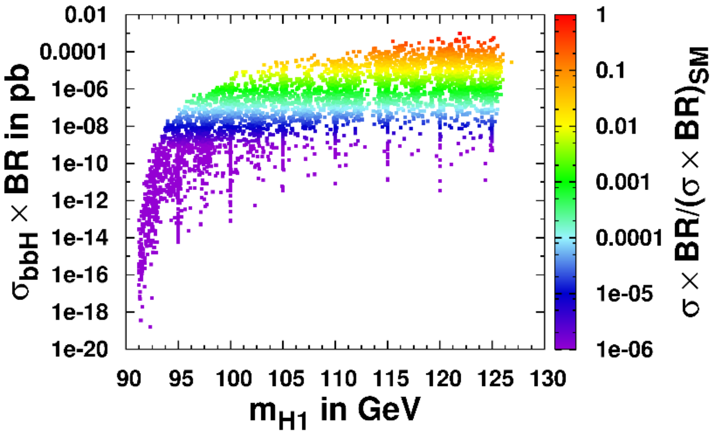
Region II – small $\lambda, \kappa,$ large $tan\beta$

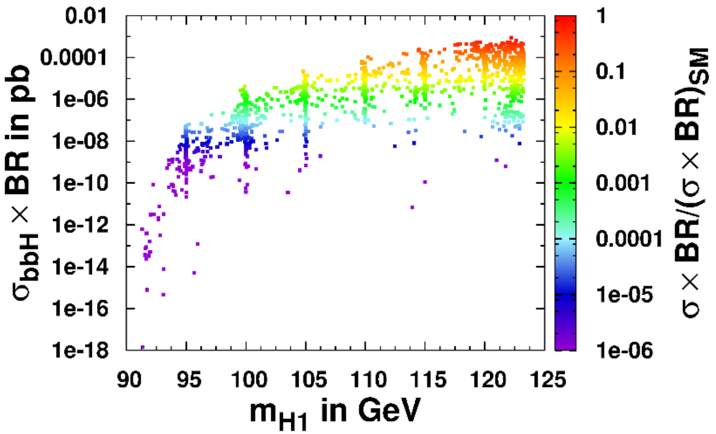
σ_{ggf}





σ_{bbh}





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

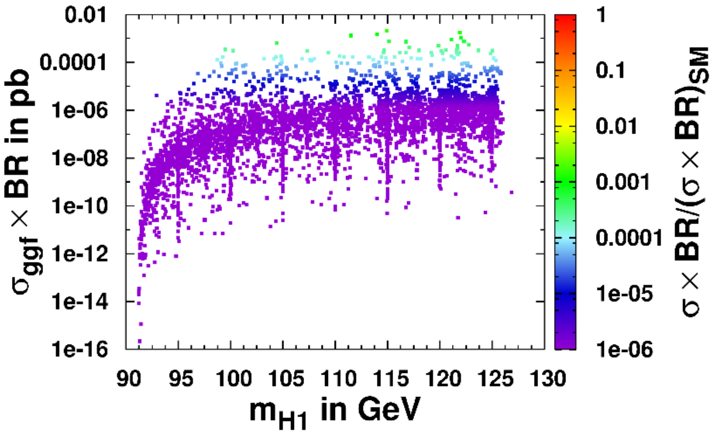
Discovery potential for Z final states

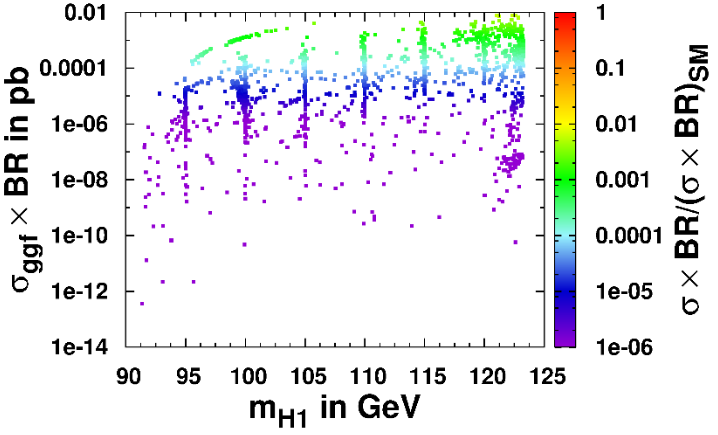
@14TeV

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

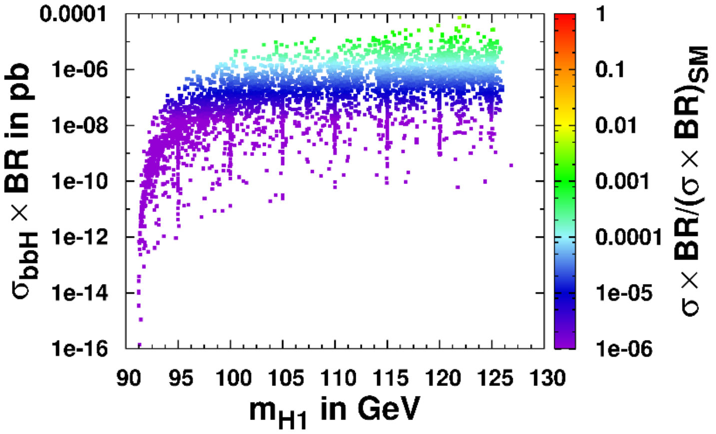
Region II – small $\lambda, \kappa,$ large $tan\beta$

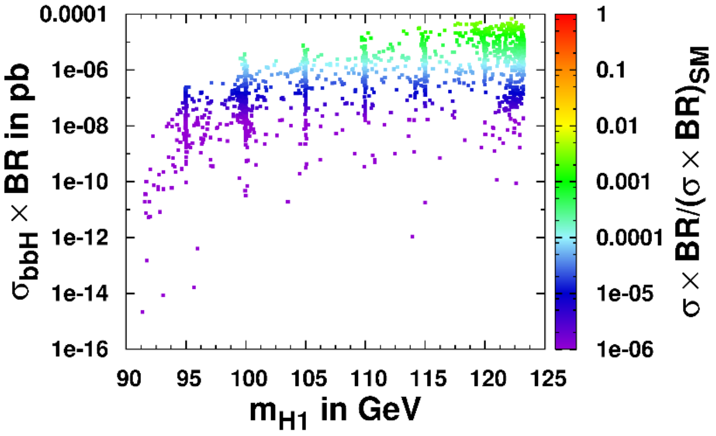
σ_{ggf}





σ_{bbh}



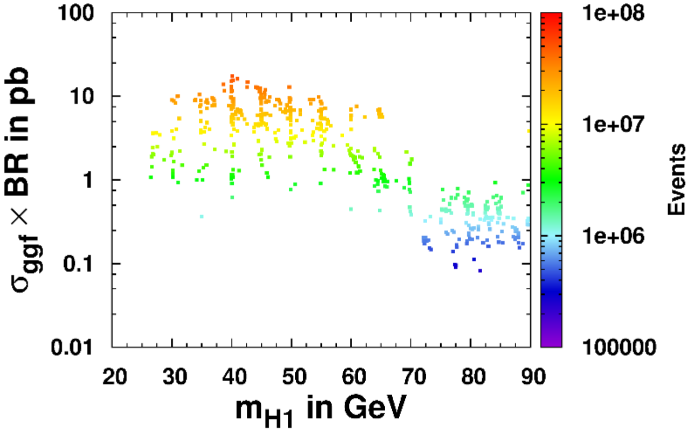


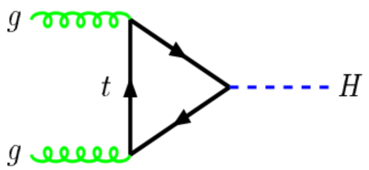
ZZ: for mass range above the maximal ratio is 1 ‰ because of phase space

Discovery potential for A_1 final states @14TeV

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

σ_{ggf}

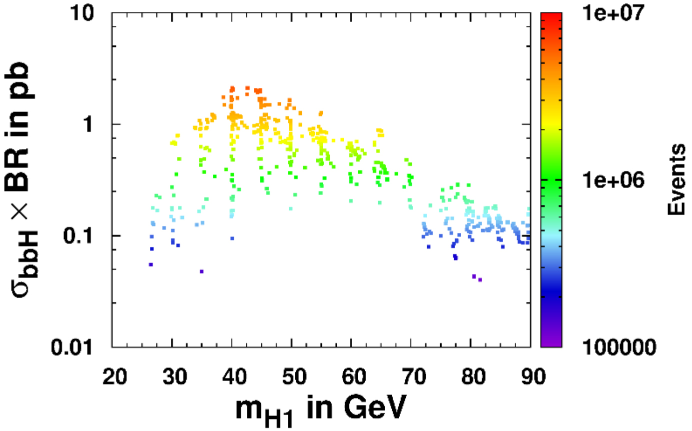


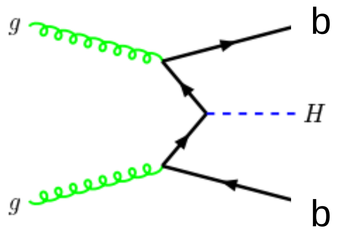


Events for SM Higgs in $\gamma\gamma$ and $\epsilon = 1 \longrightarrow N_{ggf} \sim 0.3e6$

Color coding corresponds to the number of events for $\mathcal{L}_{int} = 3000 fb^{-1}$

σ_{bbh}





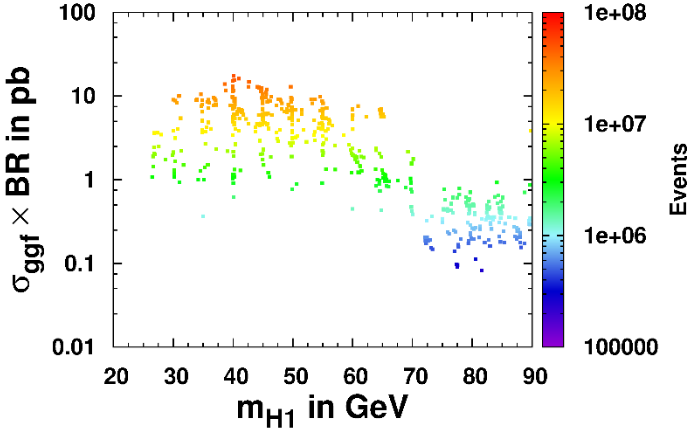
Events for SM Higgs in $\gamma\gamma$ and $\epsilon = 1 \longrightarrow N_{ggf} \sim 4e3$

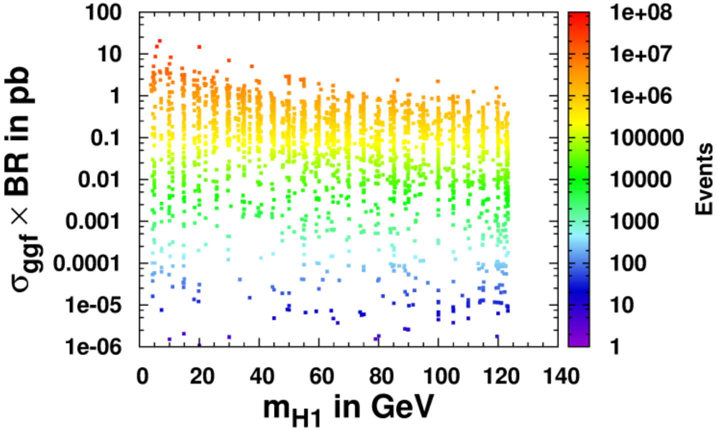
Discovery potential for A_1 final states @14TeV

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

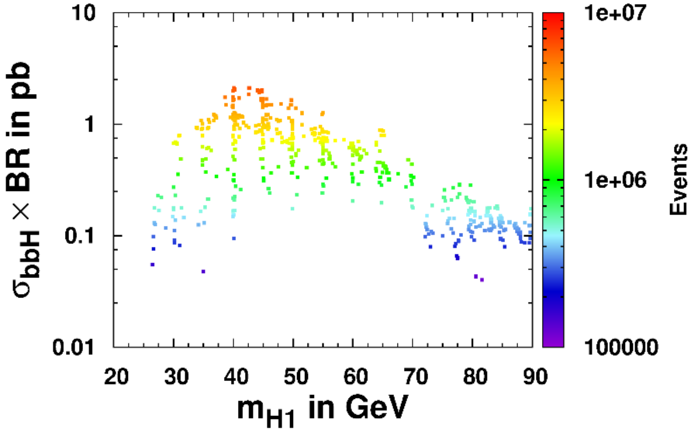
Region II – small $\lambda, \kappa,$ large $tan\beta$

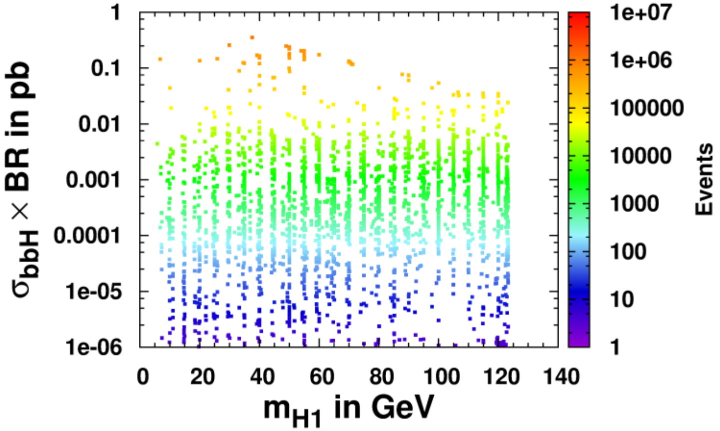
σ_{ggf}





σ_{bbh}



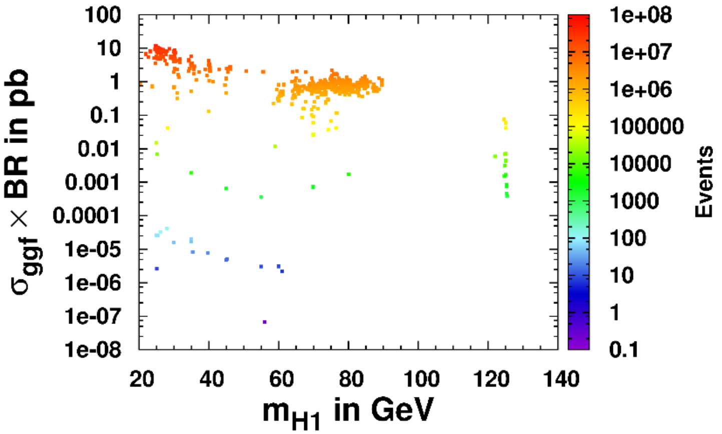


A_1A_1: number of events N of the order of 1e7 for both production modes if kinematically allowed

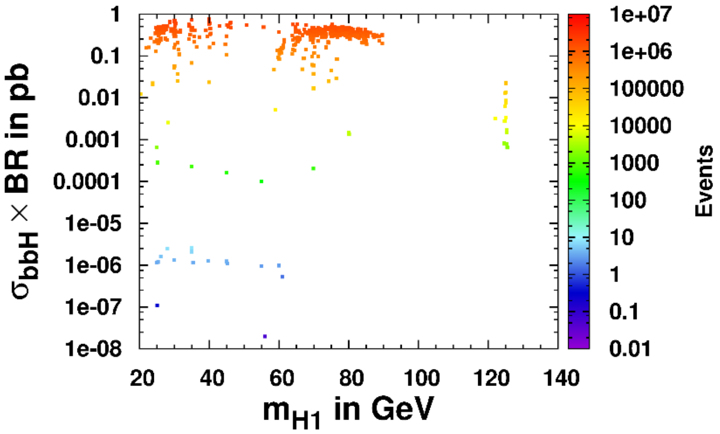
Discovery potential for MET final states @14TeV

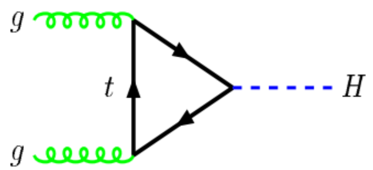
Region I – large λ, κ, small $tan\beta$

σ_{ggf}



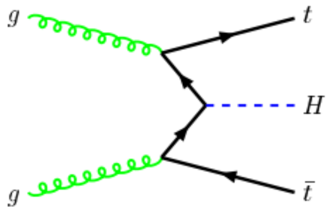
σ_{bbh}





Events for $\gamma\gamma$ and $\epsilon = 1 \longrightarrow N_{ggf} \sim 0.3e6$

Color coding corresponds to the number of events for $\mathcal{L}_{int} = 3000 fb^{-1}$



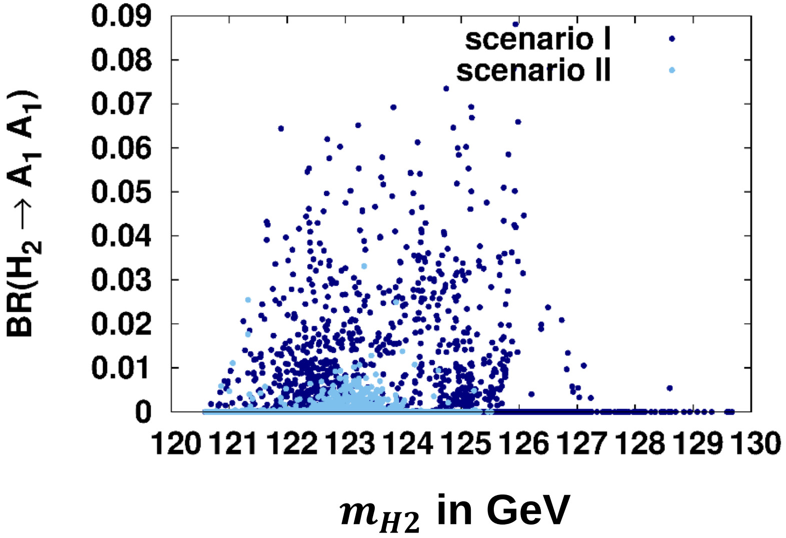
Events for $\gamma\gamma$ and $\epsilon = 1 \longrightarrow N_{ggf} \sim 4e3$

$\tilde{\chi}_1^0 \tilde{\chi}_1^0$: number of events N of the order of 1e7 for both production modes only possible for Region I

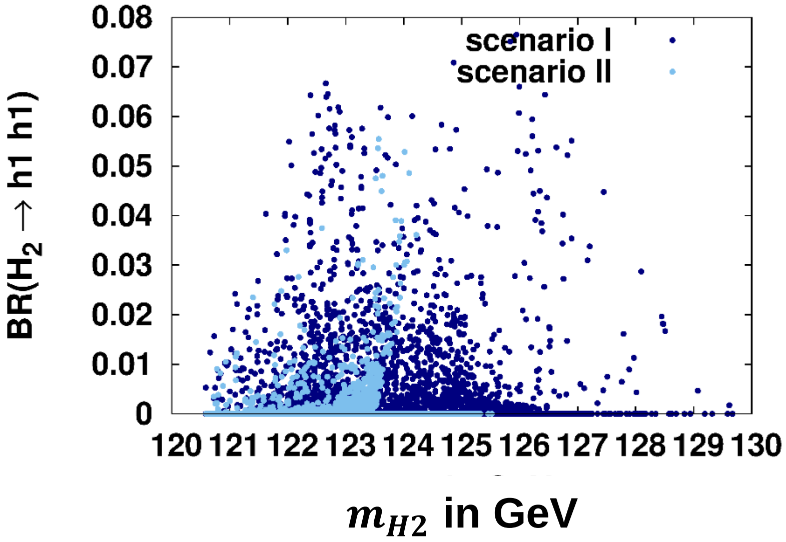
NMSSM double Higgs production BRs

Double Higgs production in H_2 decays

- $BR(H_2 \to A_1 A_1)$

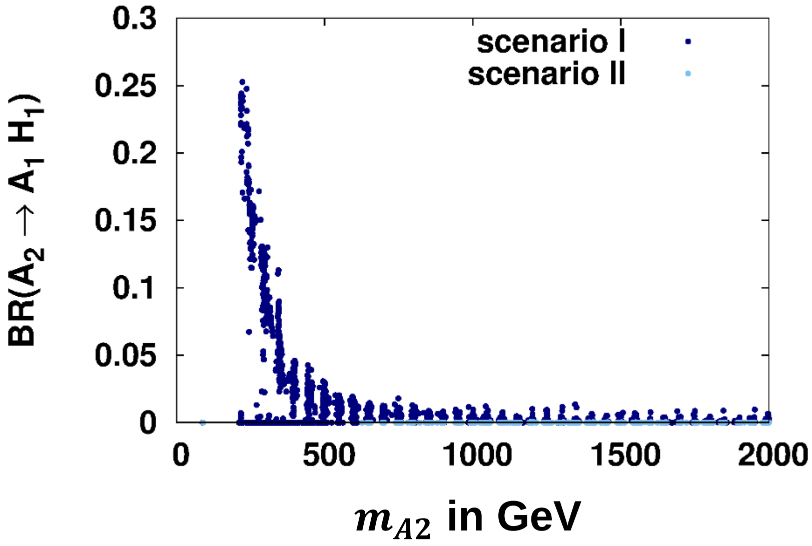


- $BR(H_2 \to H_1 H_1)$

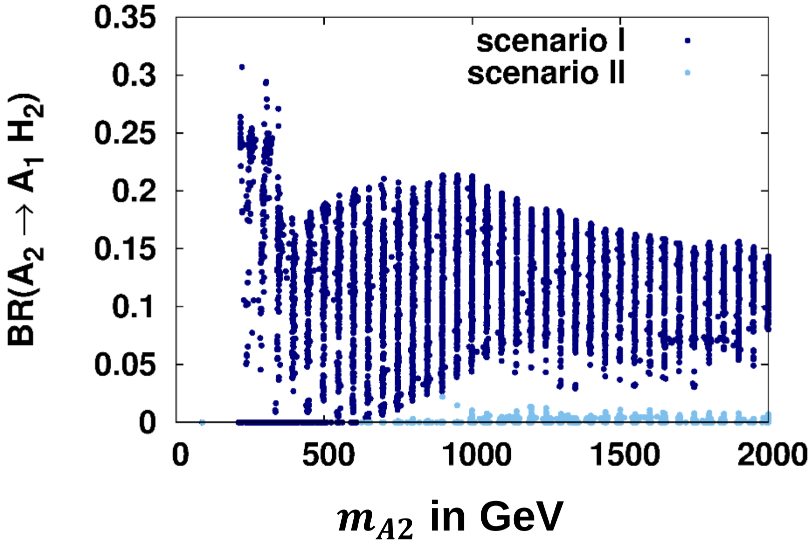


Double Higgs production in A_2 decays

- $BR(A_2 \rightarrow A_1 H_1)$

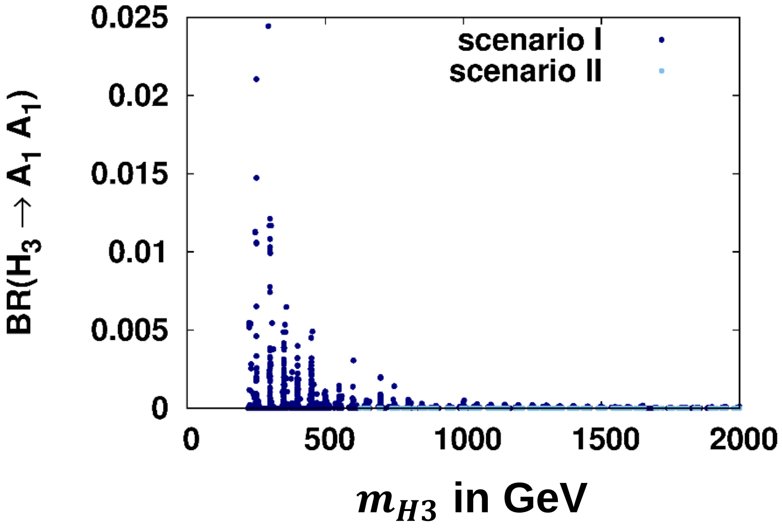


- $BR(A_2 \rightarrow A_1 H_2)$

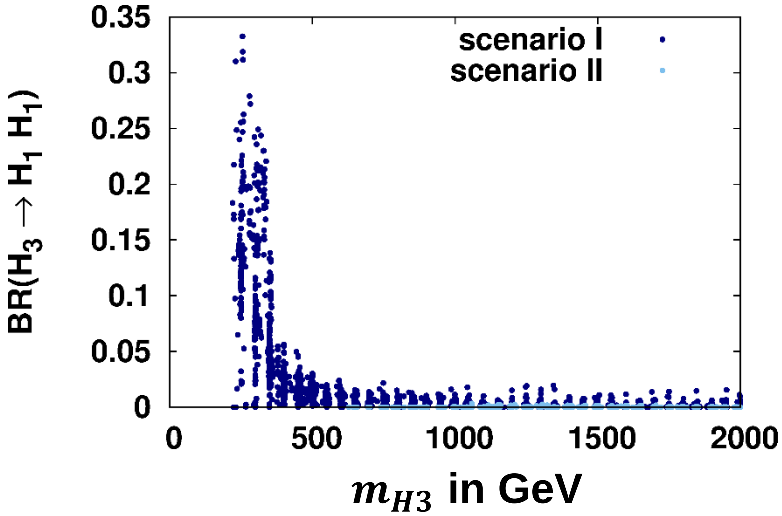


Double Higgs production in H_3 decays

- $BR(H_3 \rightarrow A_1 A_1)$

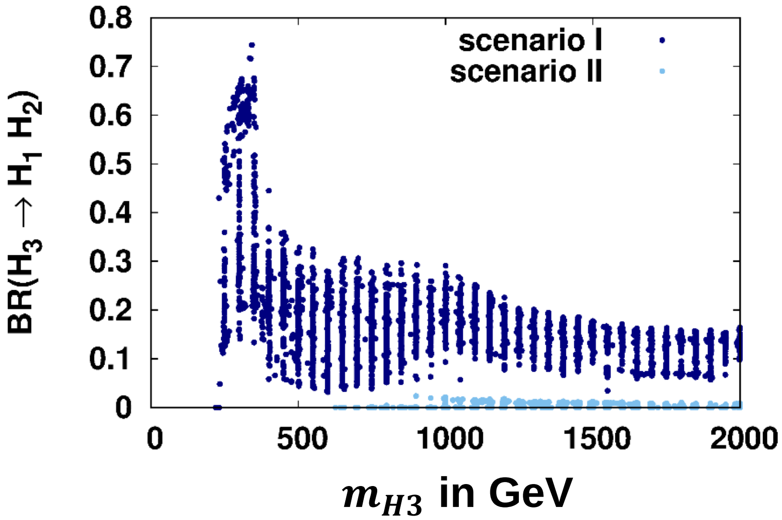


- $BR(H_3 \rightarrow H_1 H_1)$



Double Higgs production in H_3 decays

- $BR(H_3 \to H_1 H_2)$



- $BR(H_3 \to H_2 H_2)$