Some studies in 2HDM benchmarking

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with a lot of input from Oscar Stål and Robert Harlander

Introduction

- There is some difficulty in getting points in the 2HDM parameter space, which fulfil theoretical constraints such as unitarity, perturbativity and potential stability
  - Just try a simple scan yourself and you will understand what I mean here; demonstrated also in previous discussions in this group
- Oscar suggested to try the following
  - Assume some degeneracy in the higgs boson masses
  - Then try to fine tune the m12 parameter such that the model is valid

The assumption of higgs mass degeneracy is motivated: precision electroweak measurements suggest that for a light h at least 2 of the H/A/H+ are approximately degenerate in mass

2HDM Scans: Method

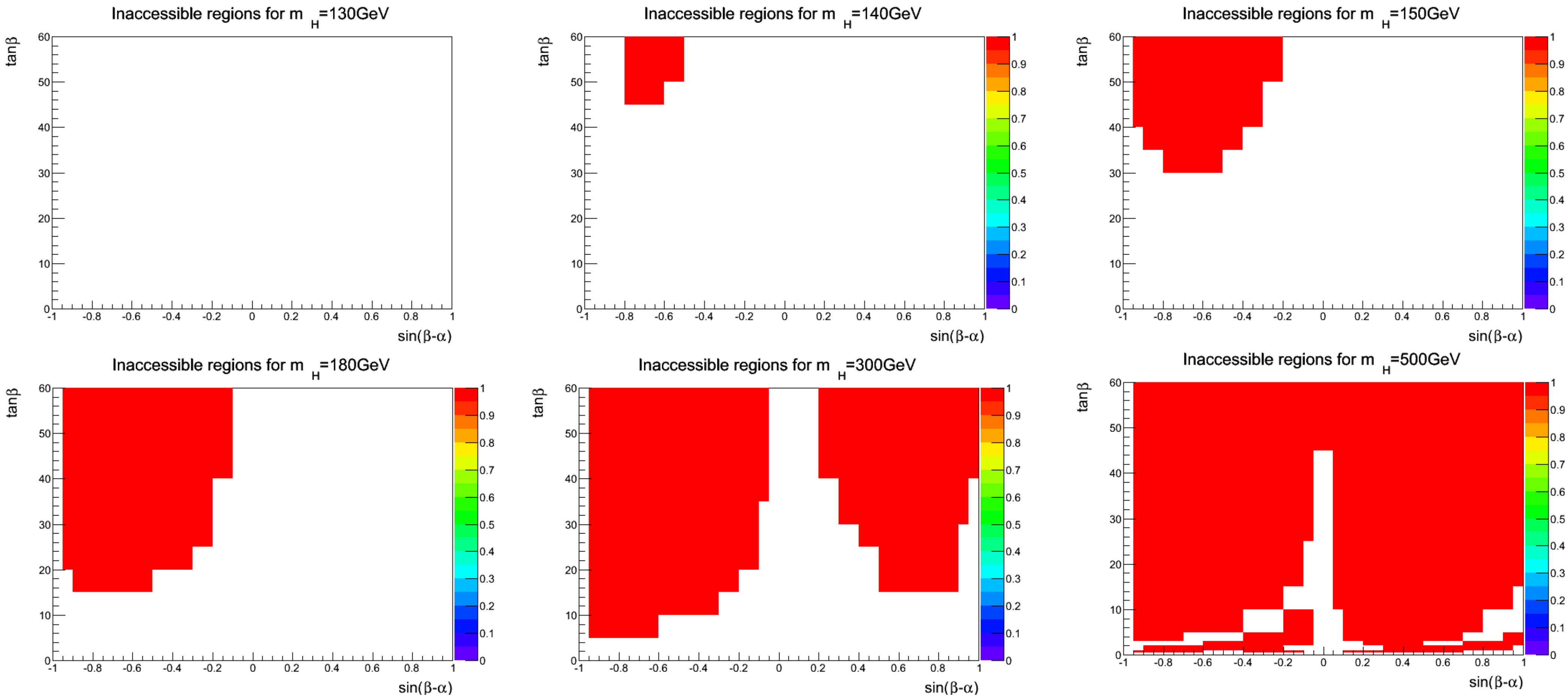
- I have tried to implement Oscar's suggestion
  - randomly choosing m_{12} such that $0 < \lambda_1 < 10$ (D13 from PRD67,07519)
  - Masses $m_H = m_A = m_{H+}$
- In this way we can get a lot of points, but not all of them
- Besides, m_{12} is different in each of them

Example from mH = 130 GeV; in this case all points are ok for any sba and tanb

mH	tanb	cba	sba	mA	mCh	lam	lamA	lamF	lam1	m12_2	Val
130	0.5	0.3122	-0.9500	130.0	130.0	124.57	-1026.10	0.00	0.35	-2664.3202	0
130	1.0	0.3122	-0.9500	130.0	130.0	124.57	-1026.10	0.00	1.29	-23068.0618	0
130	2.0	0.3122	-0.9500	130.0	130.0	124.57	-1026.10	0.00	5.76	-26722.6896	0
130	3.0	0.3122	-0.9500	130.0	130.0	124.57	-1026.10	0.00	3.89	-2374.5681	0
130	5.0	0.3122	-0.9500	130.0	130.0	124.57	-1026.10	0.00	0.41	3126.7020	0
130	10.0	0.3122	-0.9500	130.0	130.0	124.57	-1026.10	0.00	3.01	1488.8567	0
130	15.0	0.3122	-0.9500	130.0	130.0	124.57	-1026.10	0.00	0.19	1111.3785	0
130	20.0	0.3122	-0.9500	130.0	130.0	124.57	-1026.10	0.00	0.78	830.8731	0
130	25.0	0.3122	-0.9500	130.0	130.0	124.57	-1026.10	0.00	2.12	661.5569	0
130	30.0	0.3122	-0.9500	130.0	130.0	124.57	-1026.10	0.00	4.07	549.1962	0
130	35.0	0.3122	-0.9500	130.0	130.0	124.57	-1026.10	0.00	3.63	473.5388	0
130	40.0	0.3122	-0.9500	130.0	130.0	124.57	-1026.10	0.00	3.70	415.4118	0
130	45.0	0.3122	-0.9500	130.0	130.0	124.57	-1026.10	0.00	3.81	369.8823	0
130	50.0	0.3122	-0.9500	130.0	130.0	124.57	-1026.10	0.00	4.19	333.1772	0

2HDM Scans: Failed Points

- Scans aren't successful all the time: failure to get valid point is denoted by coloured part on the plot



2HDM Scans: m_{12} fine tuning

- The fact that we couldn't find points in all plots doesn't necessarily mean that there aren't valid points at all
  - Evidence for high level of fine tuning needed for m_{12}
  - It is also clear that you cannot get for the same m_{12} all the range of tanβs

mH	cba	sba	m12_2	tanb=1.0	tanb=5.0	tanb=10.0	tanb=15.0	tanb=20
130	0.3122	-0.9500	800.0000	0	FAILED	FAILED	FAILED	FAILED
130	0.3122	-0.9500	830.0000	0	FAILED	FAILED	FAILED	0
130	0.3122	-0.9500	840.0000	0	FAILED	FAILED	FAILED	FAILED
130	0.3122	-0.9500	900.0000	0	FAILED	FAILED	FAILED	FAILED
130	0.3122	-0.9500	1000.0000	0	FAILED	FAILED	FAILED	FAILED
130	0.3122	-0.9500	1100.0000	0	FAILED	FAILED	0	FAILED
130	0.3122	-0.9500	1200.0000	0	FAILED	FAILED	FAILED	FAILED
130	0.3122	-0.9500	1300.0000	0	0	FAILED	FAILED	FAILED
130	0.3122	-0.9500	1400.0000	0	0	FAILED	FAILED	FAILED
130	0.3122	-0.9500	1500.0000	0	0	0	FAILED	FAILED
130	0.3122	-0.9500	1600.0000	0	0	0	FAILED	FAILED

extreme fine tuning

mH	tanb	cba	sba	mA	mCh	lam	lamA	lamF	lam1	m12_2	Validate
140	40.0	0.6000	-0.8000	140.0	140.0	1431.26	-1112.68	0.00	7.22	445.0000	FAILED
140	40.0	0.6000	-0.8000	140.0	140.0	1431.26	-1112.68	0.00	6.16	446.0000	FAILED
140	40.0	0.6000	-0.8000	140.0	140.0	1431.26	-1112.68	0.00	5.11	447.0000	FAILED
140	40.0	0.6000	-0.8000	140.0	140.0	1431.26	-1112.68	0.00	4.05	448.0000	0
140	40.0	0.6000	-0.8000	140.0	140.0	1431.26	-1112.68	0.00	2.99	449.0000	FAILED
140	40.0	0.6000	-0.8000	140.0	140.0	1431.26	-1112.68	0.00	1.93	450.0000	FAILED

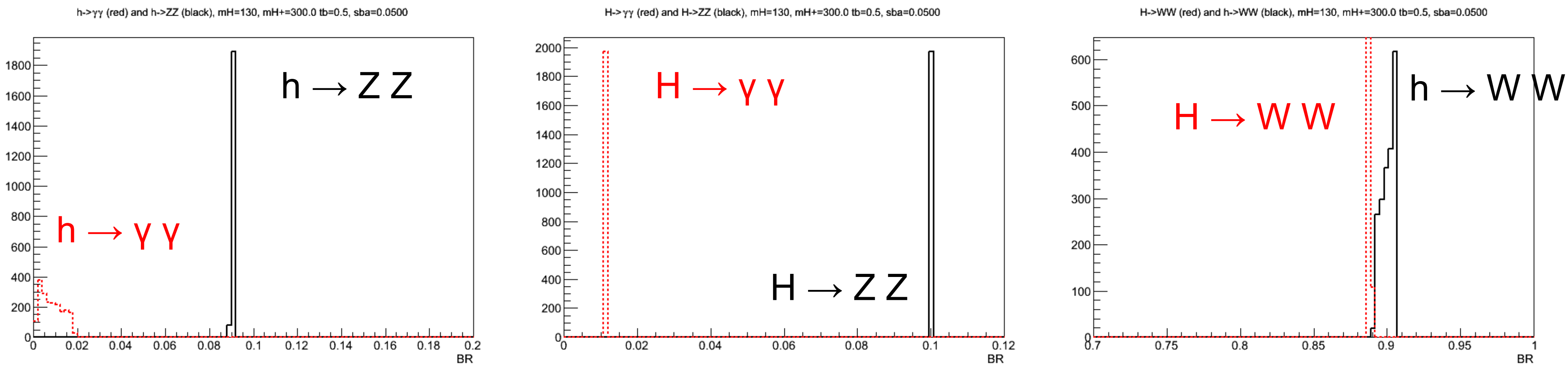
Does m_{12} value matter?

- The m_{12} value of the potential mostly affects us due to the hH^+H^+ coupling

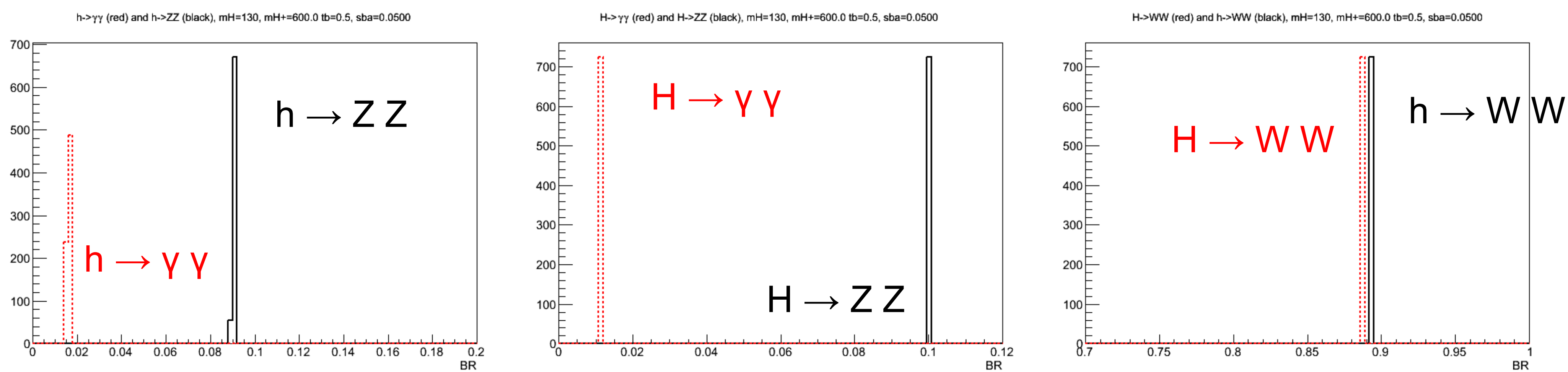
$$g_{hH^+H^+} = -\frac{1}{u}[(m_h^2 - \frac{m_{12}^2}{sin\beta cos\beta})\frac{cos(\beta+\alpha)}{sin\beta cos\beta} + (2m_{H^+}^2 - m_h^2)sin(\beta-\alpha)]$$

  - This mostly affects $h \rightarrow \gamma\,\gamma$ / W W BR
  - Examples in the next few slides

Does m_{12} value matter?

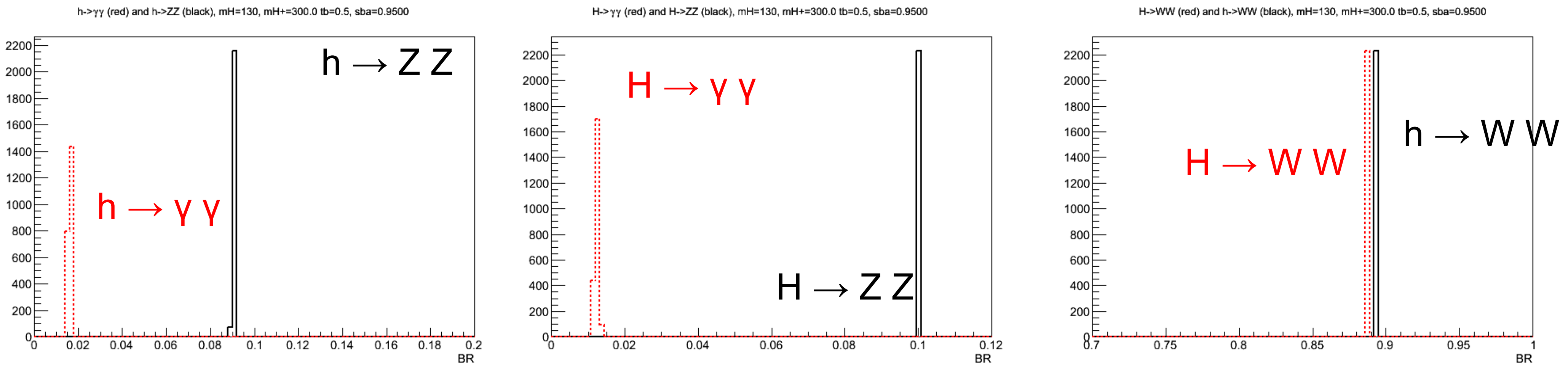


$m_A = m_H = 130$ GeV, $m_{H+} = 300$ GeV, $\tan\beta = 0.5$, $\sin(\beta - \alpha) = 0.05$



$m_A = m_H = 130$ GeV, $m_{H+} = 600$ GeV, $\tan\beta = 0.5$, $\sin(\beta - \alpha) = 0.05$

Does m_{12} value matter?



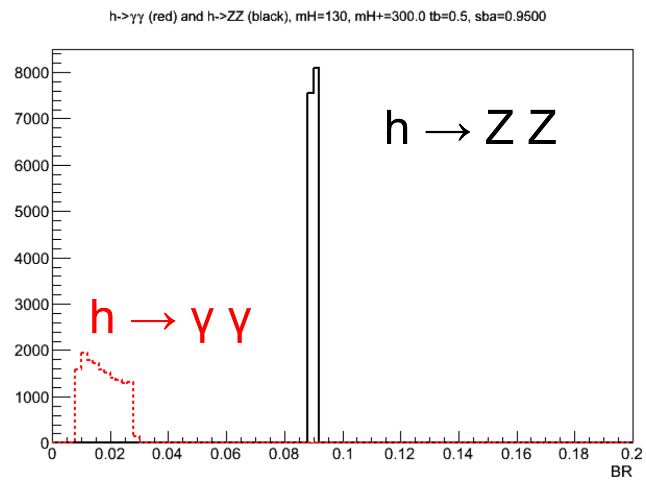
$m_A = m_H = 130$ GeV, $m_{H+} = 300$ GeV, $\tan\beta = 0.5$, $\sin(\beta - \alpha) = 0.95$

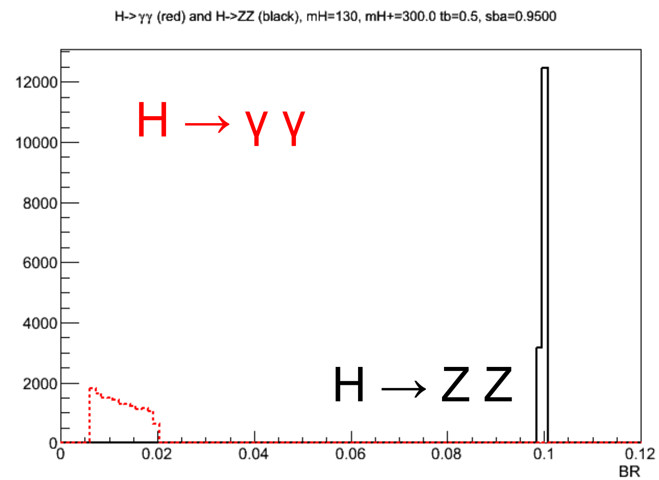
These plots show that if we know that there are m_{12} choices that lead to valid models, then we can find a high m_{H+} limit such that the observables are independent of the m_{12} choice.

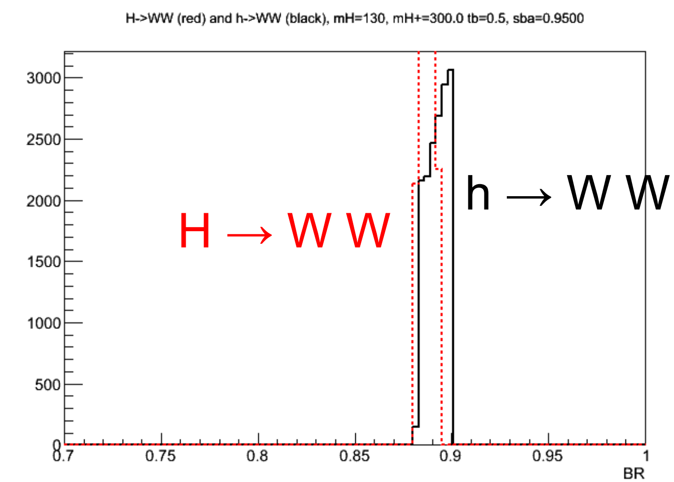
Question: what do we get if we ignore the theoretical constraints? If we know somehow that there is at least one m_{12} choice that makes the model valid then if we perform calculations using a random m_{12} what do we get?

Does m_{12} value matter?

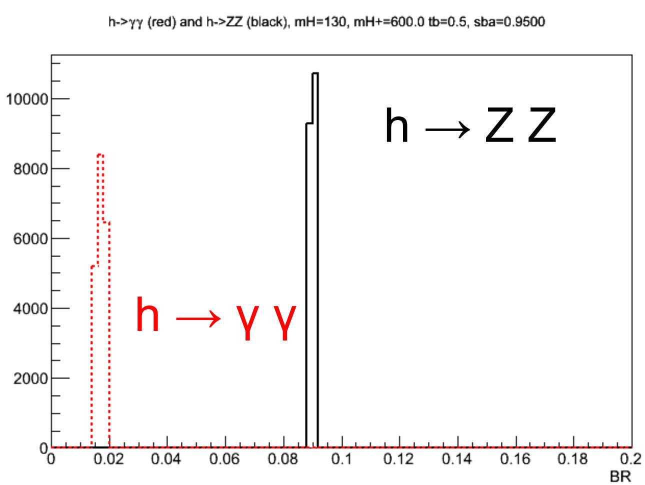
removing the requirement that the model passes theoretical constraints

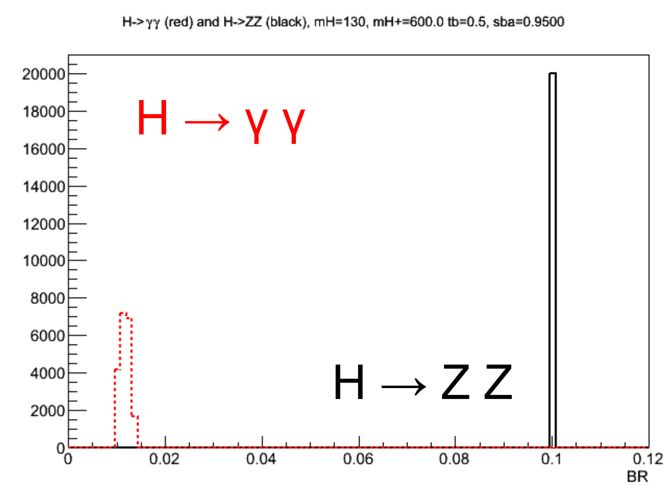


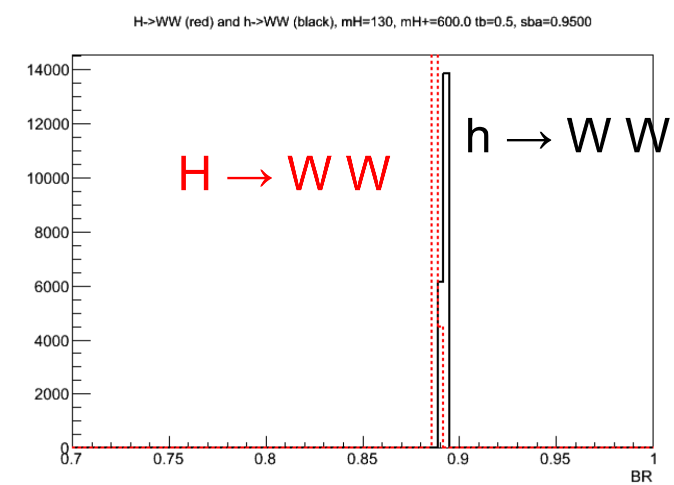




$m_A = m_H = 130$ GeV, $m_{H+} = 300$ GeV, $\tan\beta = 0.5$, $\sin(\beta - \alpha) = 0.95$







$m_A = m_H = 130$ GeV, $m_{H+} = 600$ GeV, $\tan\beta = 0.5$, $\sin(\beta - \alpha) = 0.95$

Some Numbers

```
mH = mA = 130 GeV, tan b = 0.5,  sin(b-a) = 0.05-------------------------------------------------------------------------
    ZZ mean     sigma sigma/mean  WW mean    sigma sigma/mean gamgam mean sigma  sigma/mean
h:   0.0878 (  0.0041   4.62%)    0.8712 (  0.0402   4.62%)    0.0410 (  0.0443 108.08%)     mH+=130GeV

h:   0.0908 (  0.0004   0.49%)    0.9007 (  0.0045   0.49%)    0.0085 (  0.0049  57.90%)     mH+=300GeV
h:   0.0841 (  0.0071   8.41%)    0.8347 (  0.0702   8.41%)    0.0812 (  0.0773  95.24%)     mH+=300GeV, no theo cons

h:   0.0901 (  0.0001   0.07%)    0.8935 (  0.0006   0.06%)    0.0164 (  0.0006   3.89%)     mH+=600GeV
h:   0.0897 (  0.0016   1.82%)    0.8896 (  0.0162   1.82%)    0.0207 (  0.0178  85.97%)     mH+=600GeV, no theo cons
h:   0.0900 (  0.0006   0.66%)    0.8926 (  0.0058   0.66%)    0.0174 (  0.0064  36.96%)     mH+=1000GeV, no theo cons
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
H:   0.1003 (  0.0002   0.16%)    0.8903 (  0.0014   0.16%)    0.0094 (  0.0016  16.59%)     mH+=130GeV

H:   0.1001 (  0.0000   0.03%)    0.8886 (  0.0003   0.03%)    0.0113 (  0.0003   2.52%)     mH+=300GeV
H:   0.1001 (  0.0003   0.30%)    0.8882 (  0.0027   0.30%)    0.0117 (  0.0030  25.19%)     mH+=300GeV, no theo cons

H:   0.1001 (  0.0000   0.00%)    0.8883 (  0.0000   0.00%)    0.0117 (  0.0000   0.22%)     mH+=600GeV
H:   0.1001 (  0.0001   0.07%)    0.8883 (  0.0007   0.07%)    0.0117 (  0.0007   6.24%)     mH+=600GeV, no theo cons
H:   0.1001 (  0.0000   0.03%)    0.8883 (  0.0002   0.03%)    0.0117 (  0.0003   2.24%)     mH+=1000GeV, no theo cons

mH = mA = 130 GeV, tan b = 0.5,  sin(b-a) = 0.95-------------------------------------------------------------------------
    ZZ mean     sigma sigma/mean  WW mean    sigma sigma/mean gamgam mean sigma  sigma/mean
h:   0.0901 (  0.0001   0.06%)    0.8936 (  0.0006   0.06%)    0.0163 (  0.0006   3.79%)     mH+=300GeV
h:   0.0900 (  0.0005   0.58%)    0.8926 (  0.0052   0.58%)    0.0174 (  0.0057  32.83%)     mH+=300GeV, no theo cons

h:   0.0900 (  0.0000   0.01%)    0.8929 (  0.0001   0.01%)    0.0171 (  0.0001   0.39%)     mH+=600GeV
h:   0.0900 (  0.0001   0.14%)    0.8928 (  0.0013   0.14%)    0.0172 (  0.0014   8.22%)     mH+=600GeV, no theo cons
h:   0.0900 (  0.0000   0.05%)    0.8928 (  0.0005   0.05%)    0.0172 (  0.0005   2.95%)     mH+=1000GeV, no theo cons
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
H:   0.1000 (  0.0000   0.05%)    0.8875 (  0.0004   0.05%)    0.0125 (  0.0005   3.61%)     mH+=300GeV
H:   0.1000 (  0.0004   0.41%)    0.8877 (  0.0036   0.41%)    0.0123 (  0.0040  32.53%)     mH+=300GeV, no theo cons

H:   0.1001 (  0.0000   0.00%)    0.8882 (  0.0000   0.00%)    0.0118 (  0.0000   0.39%)     mH+=600GeV
H:   0.1001 (  0.0001   0.10%)    0.8882 (  0.0009   0.10%)    0.0118 (  0.0010   8.26%)     mH+=600GeV, no theo cons
H:   0.1001 (  0.0000   0.04%)    0.8882 (  0.0003   0.04%)    0.0117 (  0.0003   2.97%)     mH+=1000GeV, no theo cons

mH = mA = mH+ = 600 GeV, tan b = 0.5---------------------------------------------------------------------------------------
h:   0.0897 (  0.0016   1.82%)    0.8896 (  0.0162   1.82%)    0.0207 (  0.0178  86.13%)  sin(b-a) = 0.05, no theo cons
h:   0.0900 (  0.0000   0.00%)    0.8924 (  0.0000   0.00%)    0.0177 (  0.0000   0.13%)  sin(b-a) = 0.95
h:   0.0900 (  0.0001   0.14%)    0.8928 (  0.0013   0.14%)    0.0172 (  0.0014   8.21%)  sin(b-a) = 0.95, no theo cons

H:   0.2063 (  0.0867  42.05%)    0.4261 (  0.1792  42.05%)    0.0000 (  0.0000   -%    )  sin(b-a) = 0.05, no theo cons
H:   0.3256 (  0.0007   0.21%)    0.6725 (  0.0014   0.21%)    0.0000 (  0.0000   -%    )  sin(b-a) = 0.95
H:   0.1108 (  0.0967  87.24%)    0.2290 (  0.1997  87.24%)    0.0000 (  0.0000   -%    )  sin(b-a) = 0.95, no theo cons
```

Some Numbers

- Conclusions (I)
  - As we increase m_{H+} the γ γ BR sensitivity on m_{12} decreases, but how strong this sensitivity is depends on sin(β–α)
  - Releasing the theoretical constraint of m_{12} gives similar mean values for the BR, but larger variations, which become less significant depending on m_{H+} and sin(β – α)
  - If we are not affected by γ γ channels the dependence is in general very small => different statements about direct searches and constraints from h125 properties
  - Warning: these conclusions assume that
    - we can extrapolate from the values that we have chosen for m_H, m_A etc
    - there are no values of m_{12} for which we can get completely different behaviour from the average
    - for each point there is at least one valid m_{12} choice

Some Numbers

- Conclusions (II)
  - Direct searches ($H \rightarrow WW/ZZ$): Assuming high enough m_{H+} (e.g. m_{H+} > 600 GeV) the full $\sin(\beta - \alpha)$ space is available and it doesn't matter whether your choice of m_{12} fulfils theoretical constraints at least for low m_H (<~500 GeV)
  - Indirect constraints from h125 properties:
    - For valid points and adequate high m_{H+} we can get some small dependence vs m_{12} which is up the few % level depending on $\sin(\beta - \alpha)$ but also the A, H mass choice
    - If we remove the theoretical constraints there is some tension for to have variations in the $\gamma\gamma$ BR which is of order 10%
    - Note that if you are interested only on $h \rightarrow WW/ZZ$ then the dependence is much smaller (from sub-% to few %)

Conclusions for Benchmarking

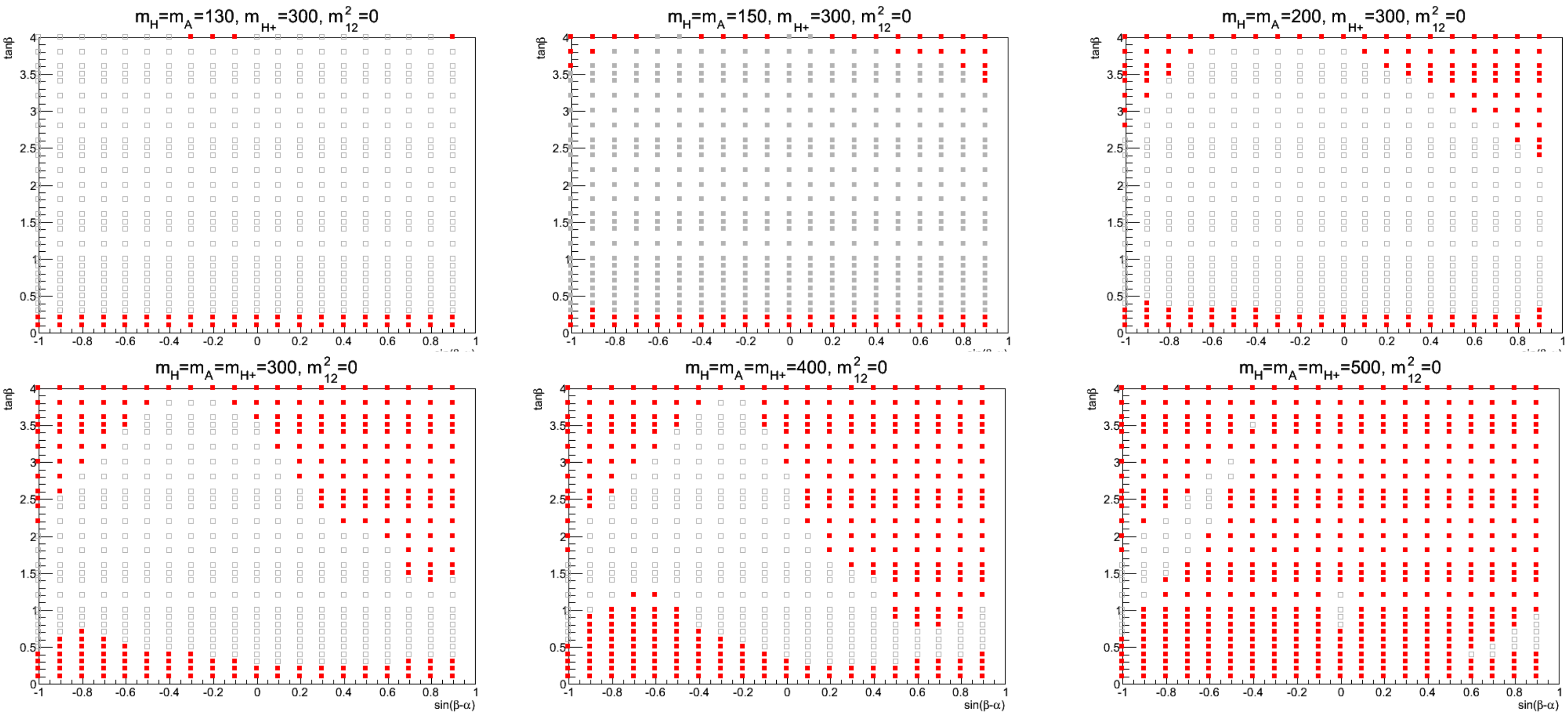
- There seem to be 3 easy ways for benchmarking
  - For direct searches for low mass $H \rightarrow WW/ZZ$ m_{12} and theoretical constraints in practice are most probably not so relevant
  - For cases where there is dependence on m_{12} we can define
    - **“$m_{12} = 0$” benchmarks:** easy to define but limited phase-space due to theoretical constraints to low tan β and low m_H
    - **“$\sin(\beta - \alpha) \rightarrow 1$” benchmark:** SM-like limit; it is most probably easier to find some way to fine-tune m_{12} such that the model is valid; hope to be able to access high m_H too

Caveats:
→ there is no consideration of potential effects of m_{12} in the production cross section, assuming that if the BRs are ok then the production is ok too
→ so far I have provided no evidence in support of a way to access high m_H (>500 GeV)

"m_{12}=0" Benchmark

- In the following I will show some studies on the m_{12}=0 benchmark

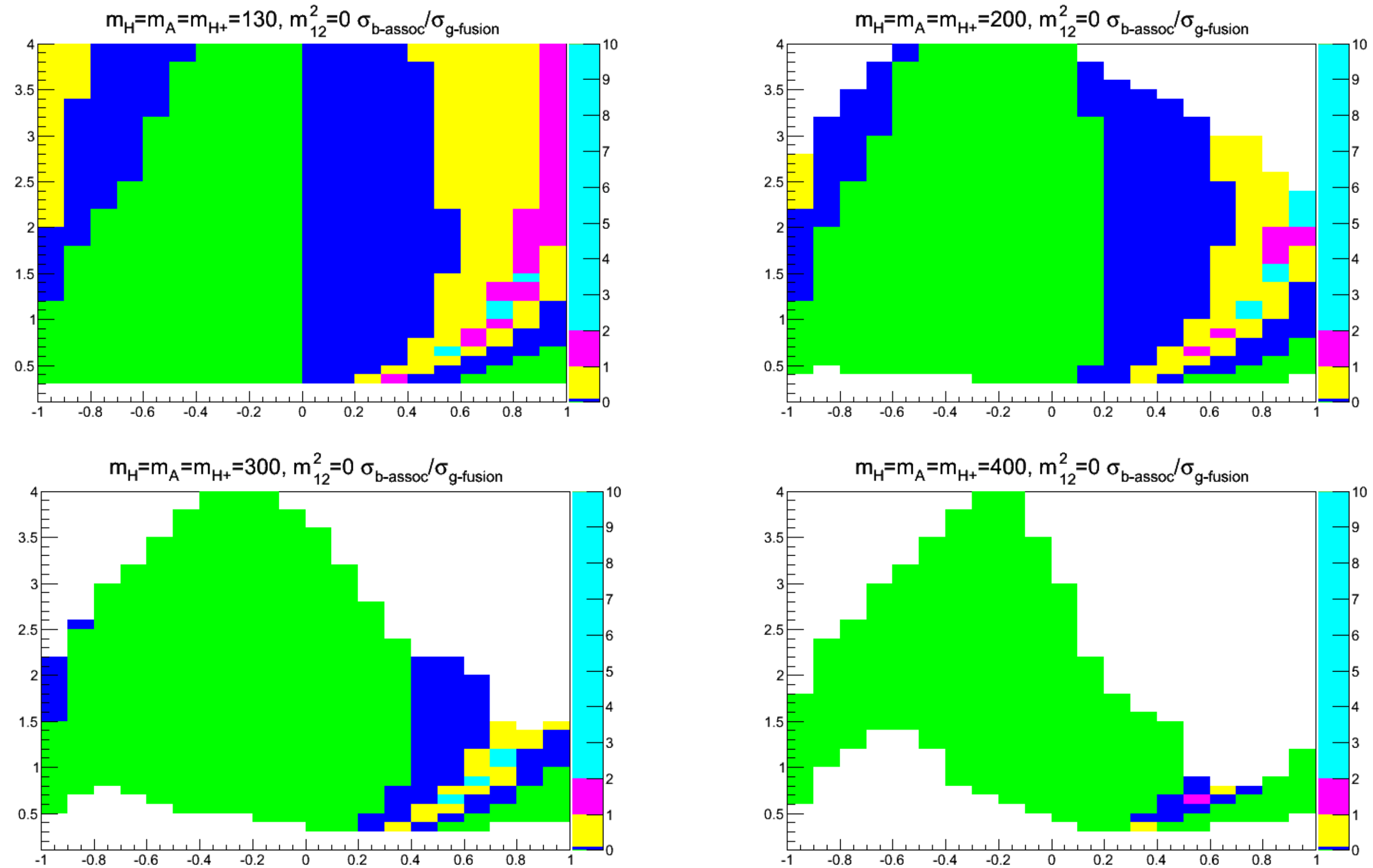
Red points denote configurations with failing some theoretical constraint



"m_{12}=0": ggH vs bbH for type II

- In most of the relevant parameter space ggH dominates, but nevertheless there are some places where bbH is important

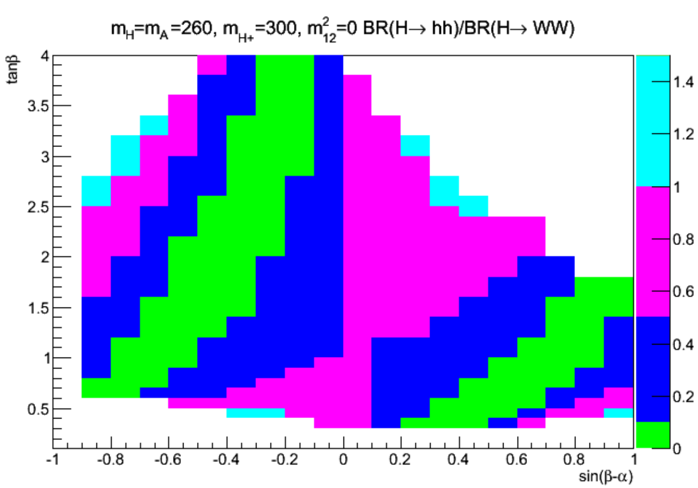
Color code:
green < 1%,
blue < 10%,
yellow < 100%,
magenta 100%-200%,
light blue > 200%

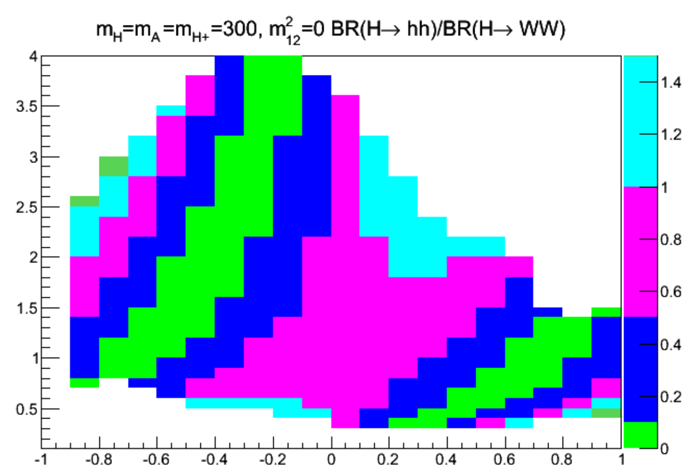


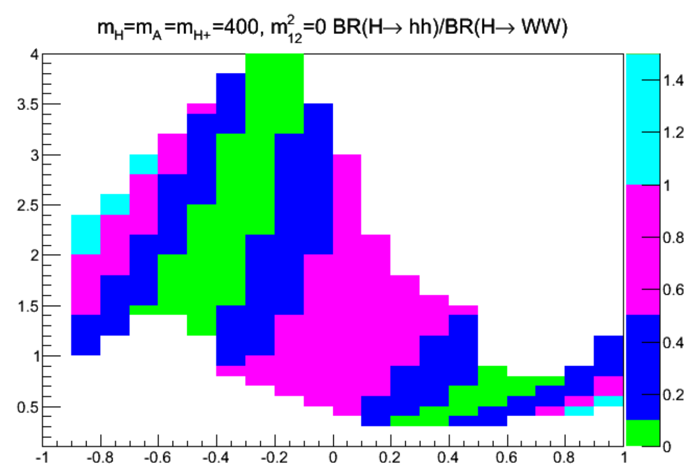
"m_{12}=0": other contributions to the signal

- There may be other decays that should be included in our signal. This may include
  - A → τ τ , H → h h, H^+ → Wh, A → Zh, A/H → tt, …
  - All these need to be checked

BR(H → hh) / BR(H → WW) for type II and various mass configurations. For large parts of the parameter space the H → hh is comparable to H → WW







Outlook & Conclusions

- Clearly defined benchmarks are needed for 2HDM studies suitable for direct searches and constraints from h125 properties
  - Choice of parameters may be non-trivial due to violation of theoretical constraints (unitarity, potential stability, pertubativity)
- We provided some evidence that it is possible to think of benchmarks for H → WW / ZZ, which are independent of such constraints for low mass mH (<500 GeV)
- For high mH and properties may be less straightforward to be convinced that there is an easy way to define such a benchmark
  - "m_{12}=0" and "sin(β – α) → 1" benchmarks may be a possible way out; nevertheless, there may be other ways too
- In any case we have to careful to evaluate the effect of signal production mechanisms and possible decay channels that come with the particular benchmark
  - e.g. H → hh is a significant channel for many configurations