2HDM Benchmarking in ATLAS

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Introduction

- ATLAS has already presented in this meeting benchmark proposals, which were made in cooperation with Oscar Stall
  - See presentations here

https://indico.cern.ch/getFile.py/access?contribId=0&resId=0&materialId=slides&confId=258273

https://indico.cern.ch/getFile.py/access?contribId=3&resId=0&materialId=slides&confId=249197

- We have recently made public a note for ECFA HL-LHC workshop which contains a demonstration:

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2013-016/

2HDM Parameter Space

- 2HDM parameter space is large. Under certain assumptions it can be reduced to 7 “free” parameters for the CP-conserving 2HDM with softly broken Z2 symmetry
  - Masses: m_h, m_H, m_A, m_{H+}
  - Angles: tanβ , cos(β – α) or sin(β – α)
  - Z_2 symmetry breaking term: m_{12}^2

$$V(\Phi_1,\Phi_2) = m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 - (m_{12}^2\Phi_1^\dagger\Phi_2 + \text{h.c}) + \frac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \frac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2)$$

$$+\lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \{\frac{1}{2}\lambda_5(\Phi_1^\dagger\Phi_2)^2 + [\cancel{\lambda_6(\Phi_1^\dagger\Phi_1)} + \cancel{\lambda_7(\Phi_2^\dagger\Phi_2)}](\Phi_1^\dagger\Phi_2) + \text{h.c}\}$$

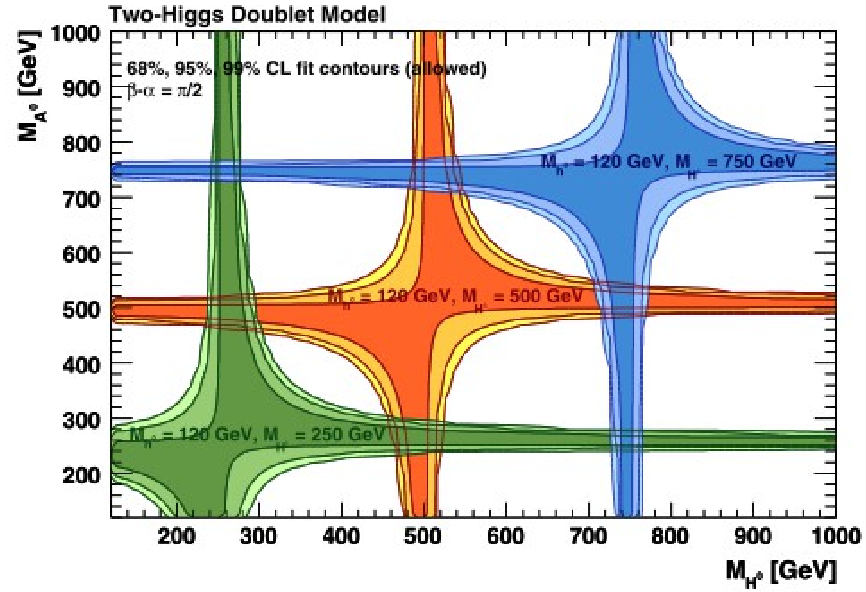
There is sign ambiguity of the α angle. In ATLAS we have chosen to use cos(β – α) and set in in the range -1≤ cos(β – α) ≤ 1. With this convention we have: 0 ≤ sin(β – α) ≤ 1

2HDM Parameter Space

- Notice that the SM-like limit (weak decoupling limit) of the model is $\cos(\beta - \alpha) \rightarrow 0$
- Choices for the parameters can be driven by physics assumptions
  - Lightest CP-even Higgs, h, is the one discovered at the LHC, i.e. $m_h = 125$ GeV
    - In principle we can think of considering the heavy CP-even Higgs as the one discovered; we need to think a little bit more there on how to define a sound benchmark in that case

How to select parameters (I)

- The masses of the additional Higgs bosons are not completely free parameters
  - Electroweak precision tests tells us that large mass splittings are disfavoured (they change ρ too much)
  - We further expect that the mass splitting is not large due to simple considerations of the potential parameters (and even more if you consider more carefully theory constraints)



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$$m_H^2 - m_A^2 = v^2\left[\lambda - \lambda_A + \frac{\hat{\lambda} c_{\beta-\alpha}}{s_{\beta-\alpha}}\right]$$

How to select parameters (II)

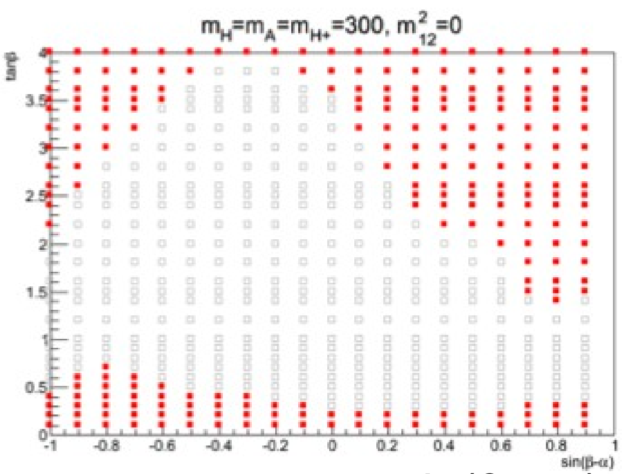
- From the discussion in the previous slide, we can say that the most natural choice for the heavy Higgs masses is to assume that they are degenerate
  - In the following we will assume: $m_H = m_A = m_{H+}$
  - A caveat for this argument is that for $m_{H+} \approx 200 - 300$ GeV or less some 2HDM types are constrained by experiment and besides there is an effect on $h \rightarrow \gamma\gamma$, so we may need to start mH+ from e.g. 300 or 350 GeV. This is not absolutely necessary and doesn't violate the general idea of mass degeneracy

The choice for m_{12}^2

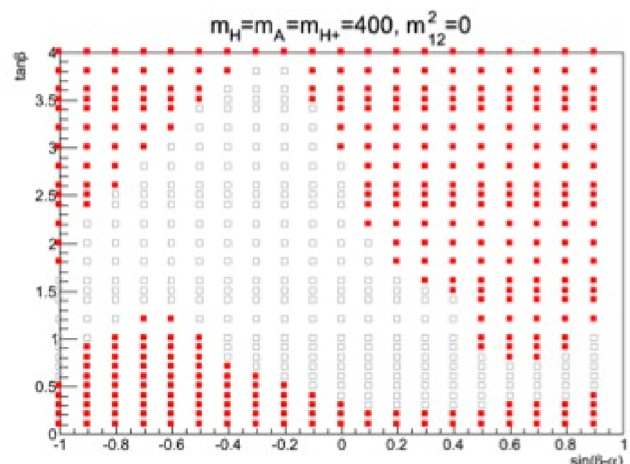
- The m_{12}^2 parameter can be also chosen in a less arbitrary way
  - Exact Z_2 symmetry: $m_{12}^2 = 0$
  - Z_2 symmetry MSSM-style broken: $m_{12}^2 = m_A^2 \tan\beta / (1 + \tan^2\beta)$
  - Reminder: m_{12}^2 choice affects theory constrains a lot

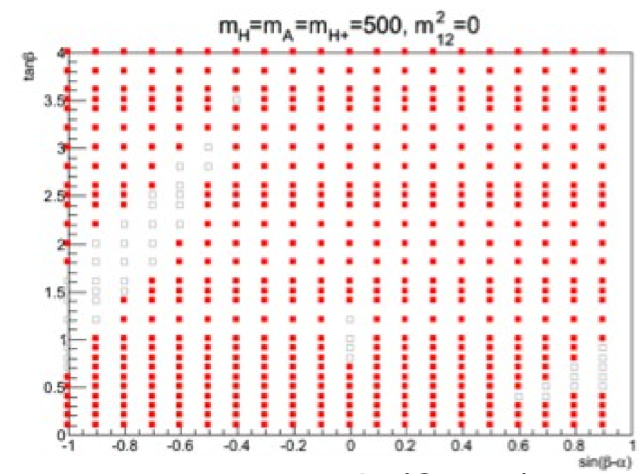
Example from the "Exact Z_2 symmetry case"

In red the theory inaccessible region; note the tan β scale in the y-axis: it is only till 4



tanβ





sin(β – α) sin(β – α) sin(β – α)

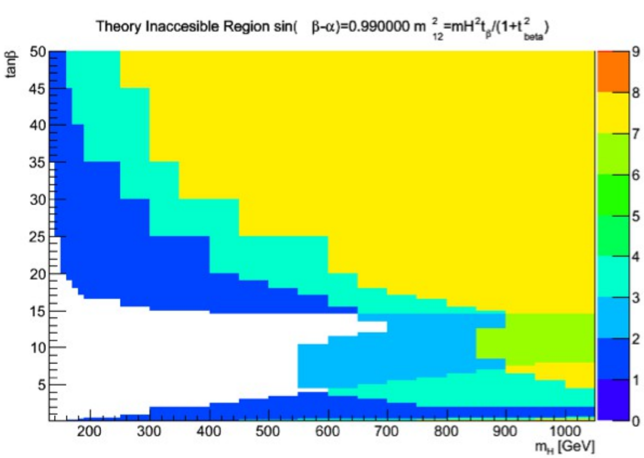
2HDMC was used for these plots

The choice for m_{12}^2

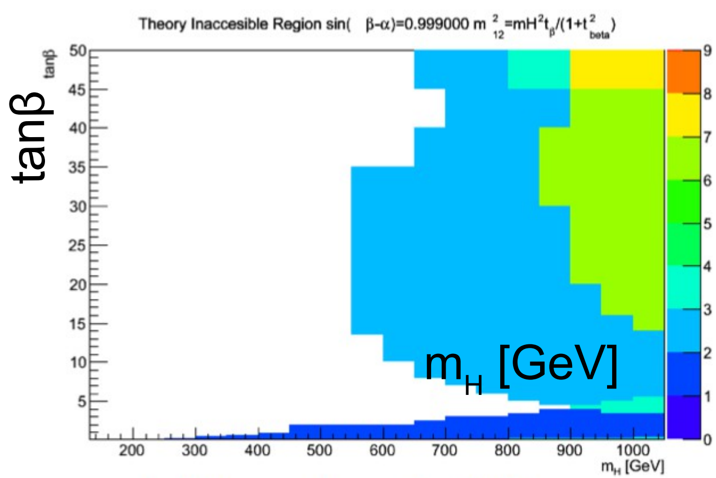
- An issue for the case with the exact Z_2 symmetry is that theory constrains a lot of the parameter space towards the weak decoupling limit
- This is not an issue at all if the Z_2 symmetry is broken as in the MSSM

Example from the "MSSM-style broken Z_2 symmetry"

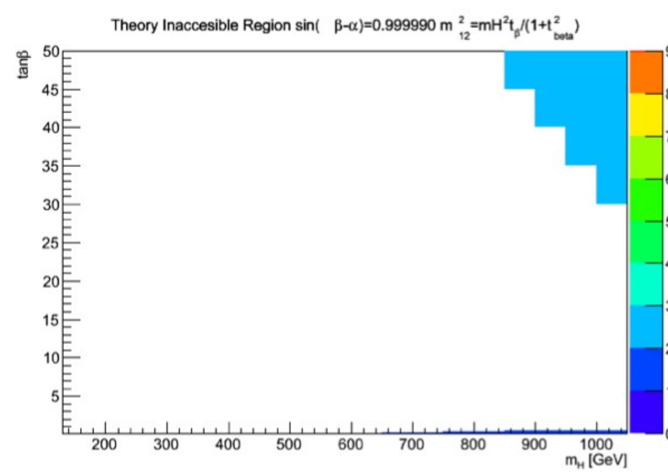
Coloured regions are theory inaccessible in the mH – tanβ plane; notice the y-axis tanβ range which is up to tan β = 50 !



$\sin(\beta - \alpha) = 0.99$



$\sin(\beta - \alpha) = 0.999$



$\sin(\beta - \alpha) = 0.99999$

2HDMC was used for these plots

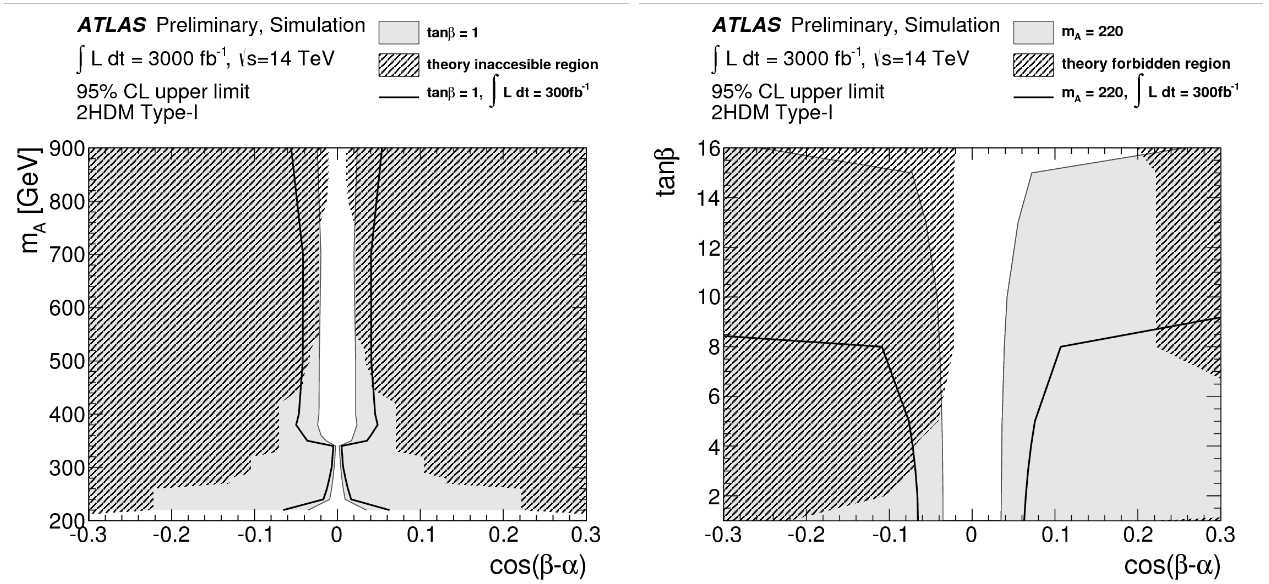
Results Presentation

- For the ATLAS ECFA HL-LHC results we have demonstrated the 2HDM scenario with the MSSM-style broken Z_2 symmetry
  - Quick summary: look for 2HDM A → Zh

Results presented on a 2D plane:

◊ mA – cos(β – α) for a given tan β

◊ tan β – cos(β – α) for given mA

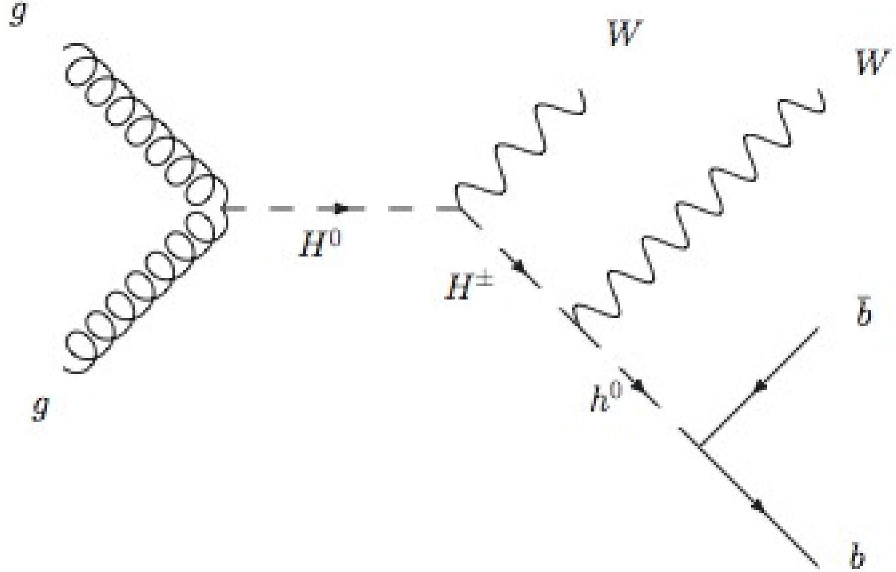


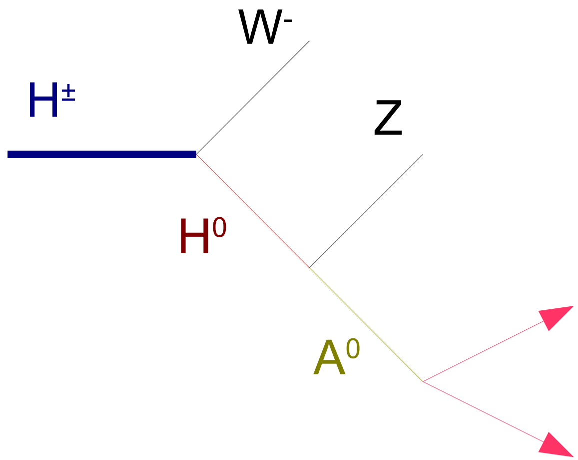
Benchmark Merits

- The benchmarks described here are not completely arbitrary
  - Mass degeneracy is motivated both experimentally and theoretically
  - The value of m_{12}^2 parameter is chosen assuming either an exact symmetry or the way it is broken in a very popular model, the MSSM
  - The benchmark can be used easily for a variety of final states: $H \rightarrow WW/ZZ$, $A \rightarrow Zh$, $H \rightarrow hh$, $H/A \rightarrow tt$, including charged Higgs decays

Benchmark Problems

- There is an important issue with this set of benchmark
  - It doesn't cover all possible signatures
  - Cascade decays are in principle possible and we may need to think more on a nice benchmark adequate for these cases. E.g. $H \to H^{\pm}W$, $A \to ZH$, … but also more complicated topologies like the following two diagrams:



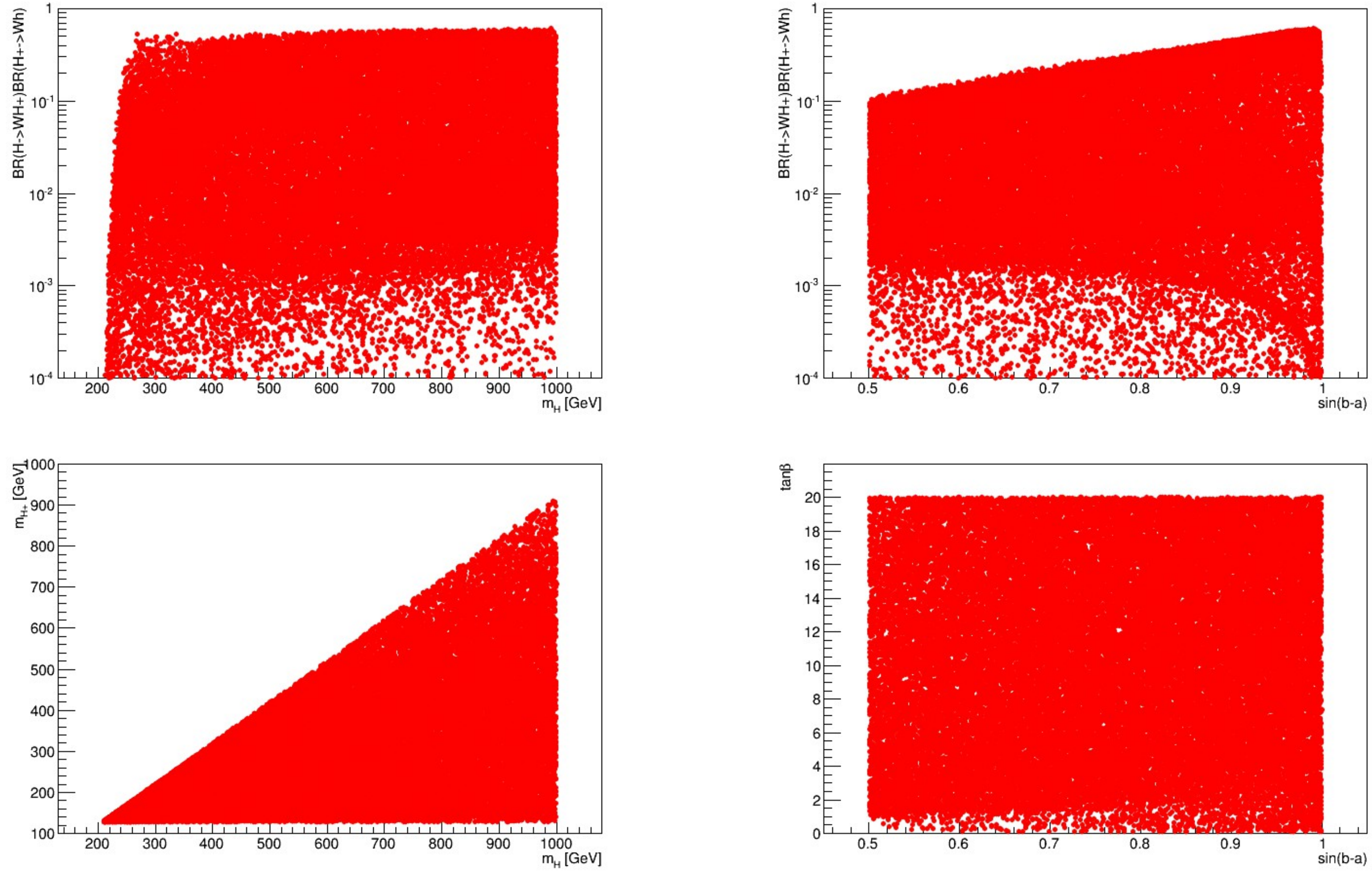


Cascades I

- Cascades (and whenever large mass splittings are required) have a lot of problems
- For a demonstration consider the following. Run 100K points by sampling randomly the 2HDM parameter space using m_H = 200 – 1000 GeV, $m_{H\pm}$ = 110 – (m_H – m_W), tanβ = 0.1 – 20, sin(β – α) = 0.5 – 1, m_A = m_H or $m_{H\pm}$ and consider valid points for the H → $WH^\pm$ → WWh chain
- Reminder of the theory constraints
  - Potential stability: there is no direction in the higgs fields in which the potential goes to –inf
  - Unitarity of the higgs-higgs scattering matrix (hep-ph/0508020): largest eigenvalue of the matrix is less than 16 π
  - Perturbativity of the quartic Higgs couplings (each of them is < 4 π)

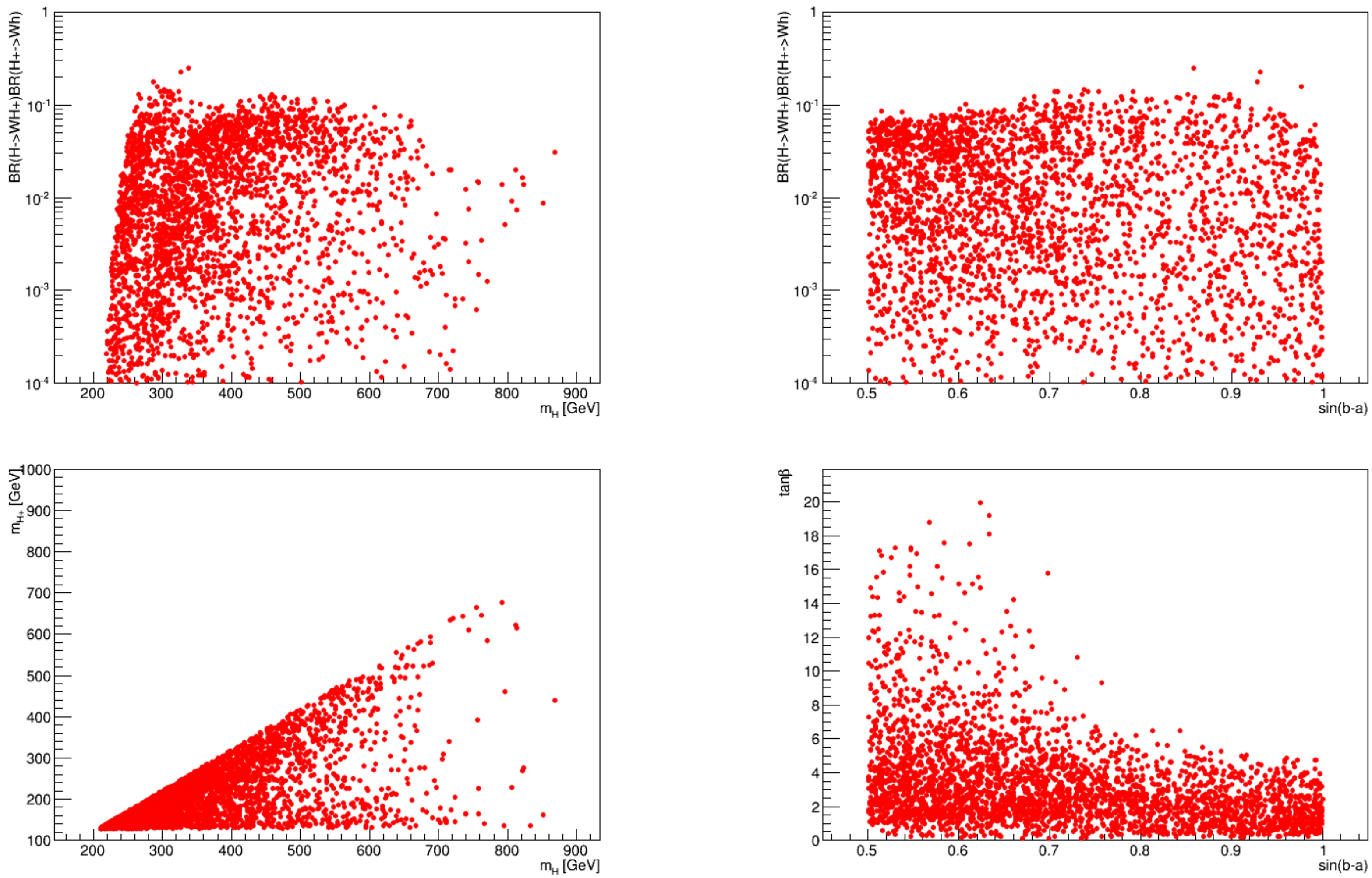
Cascades II

Demanding potential stability: ~43K points are valid out of 100K



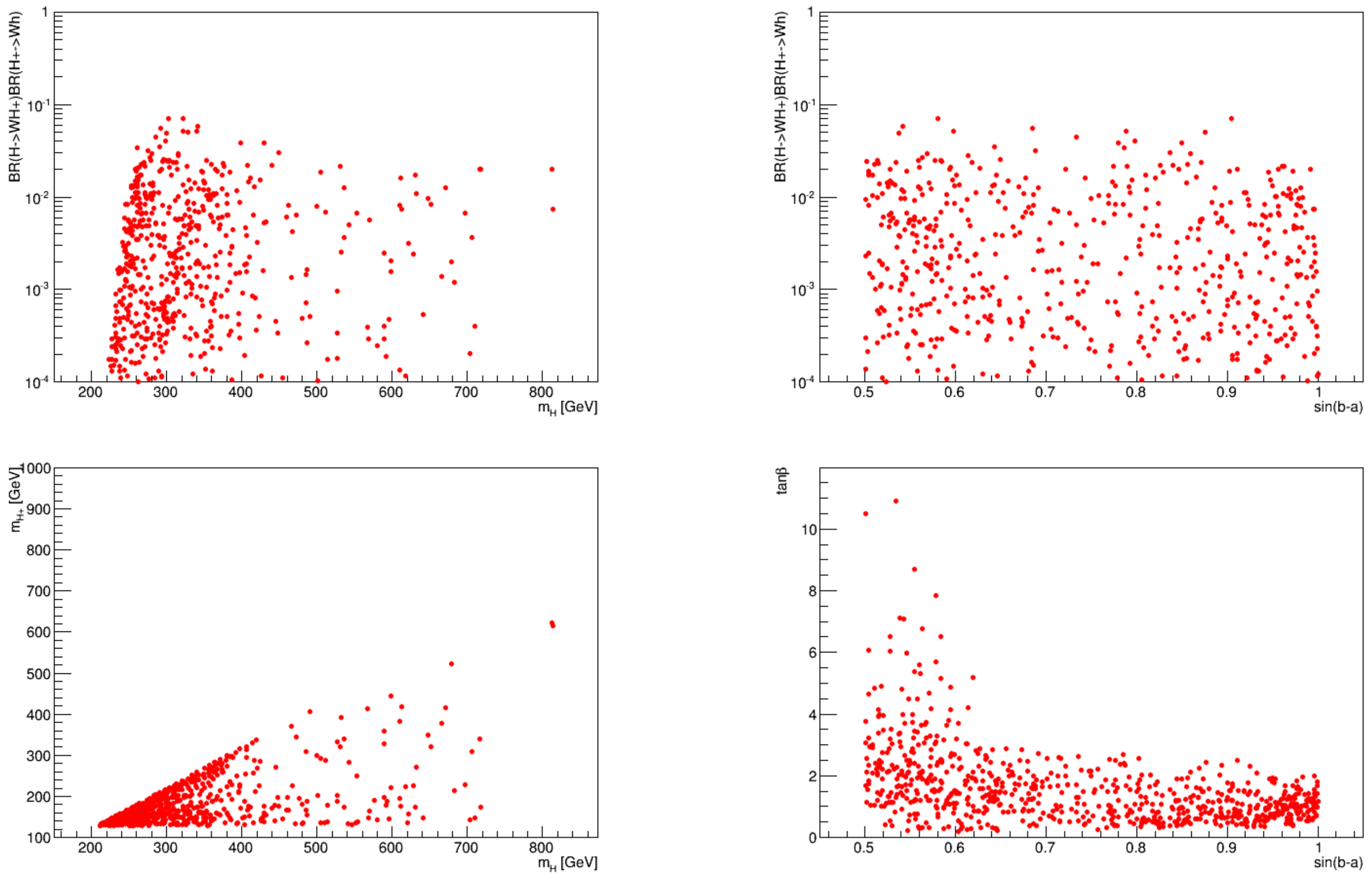
Cascades III

Demanding also unitarity of Higgs-Higgs scattering matrix: ~4K points are valid out of 100K



Cascades IV

Demanding also g(φφφφ) < 4 π: ~1K points are valid out of 100K



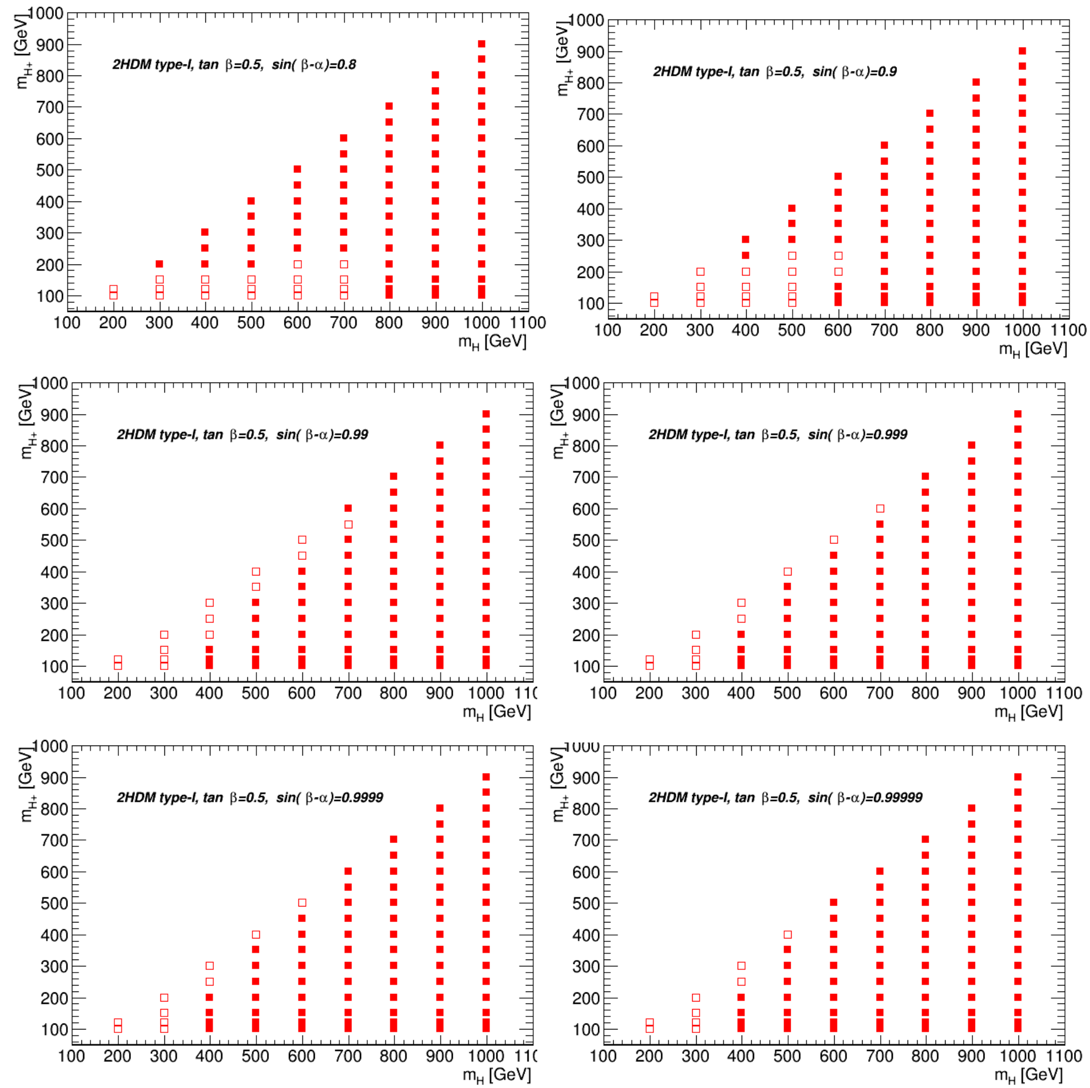
Cascade Benchmarking

- Towards a benchmark definition
  - Simple trial: m_H, $m_{H\pm}$ tan β, sin(β – α) free ; $m_A = m_{H\pm}$; most points are not valid; rather incomplete study, since it doesn't include a production cross section X BR study, only examines theory accessibility

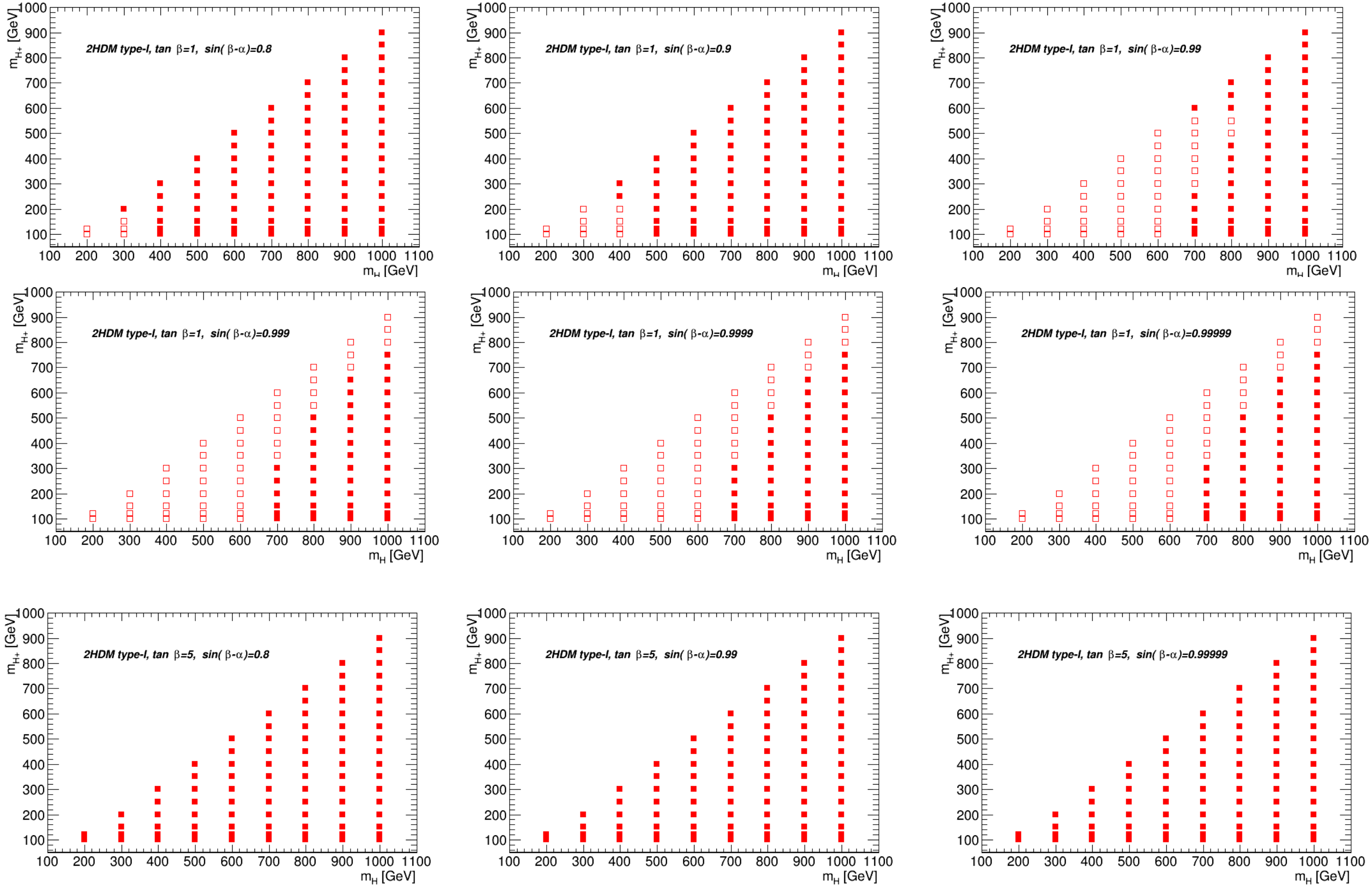
Open red rectangles indicate valid points

Some valid points can be get only for tan β ~ 1; no points at all for tan β = 5 or greater; there is also tendency to get more points at sin(β – α) ~ 1

In summary it is demonstrated that it is difficult to get a lot of points with simple benchmarking choices.

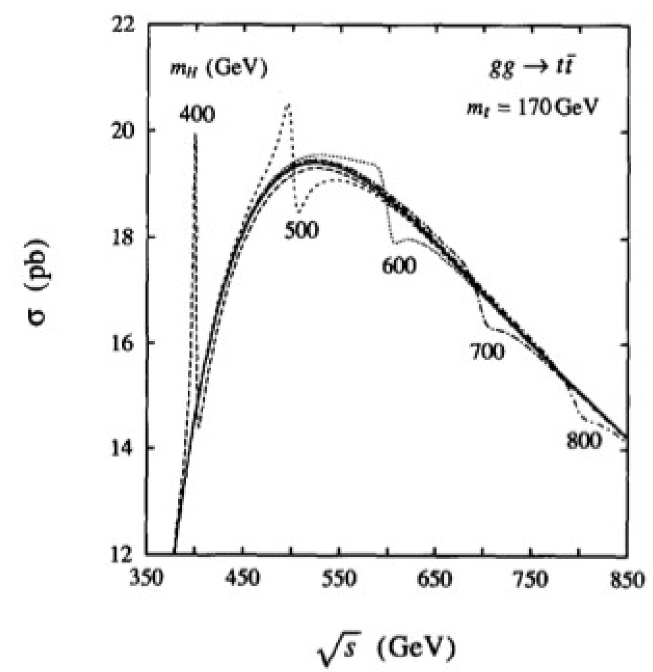


Cascade Benchmarking



A side question: Interference

- Interference effects may be important
  - A/H → tt is known to be affected with significant interference with gg → tt production
  - What about other channels? e.g. H → hh, is there any interference we have to worry about? If yes, how to treat it when generating MC samples?



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Conclusions

- ATLAS has already some public results using a 2HDM benchmark with simple choices of the parameters based on mass degeneracy and MSSM features
  - Heavy Higgses are degenerate as suggested by EWK precision tests and theory constraints
  - The Z2 symmetry of the Higgs potential is broken in the same way as in the MSSM
- The benchmark can be used in a large variety of final states
  - Not all of them: cascade type of signatures aren't covered; we have shown that there is some difficulty in getting lots of valid points in the parameter space using simple benchmarks
- Side question: we are interested in understanding how big the interference effect is for the various 2HDM signatures and how to simulate it in our MC samples