

# Summary of the NMSSM subgroup

## Theory:

Ulrich Ellwanger (Orsay), Maggie Muhlleitner (KIT), Nausheen Shah (Wayne)

## Experiment:

ATLAS: Nikolaos Rompotis (Liverpool),  
CMS: Daniel Winterbottom (Imperial College)

# Structure of the subgroup

- Where to find us

[https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHWG3?redirectedfrom=LHCPhysics.LHCXSWG3#NMSSM\\_Higgs](https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHWG3?redirectedfrom=LHCPhysics.LHCXSWG3#NMSSM_Higgs)

<https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHWGNMSSM>

- Contact: [lhc-higgs-nmssm-convener@cern.ch](mailto:lhc-higgs-nmssm-convener@cern.ch)

ATLAS	CMS	THEORY		
<a href="#">Nikolaos Rompotis (Liverpool)</a>	<a href="#">Daniel Winterbottom (IC)</a>	<a href="#">Ulrich Ellwanger (IJClab Orsay)</a>	<a href="#">Margarete Mühlleitner (KIT)</a>	<a href="#">Nausheen Shah (Wayne)</a>

- Latest recommendations:

<https://twiki.cern.ch/twiki/bin/view/LHCPhysics/NMSSMBenchmarksNov2021bbbb>

<https://twiki.cern.ch/twiki/bin/view/LHCPhysics/NMSSMBenchmarksNov2021tautaugamgam>

<https://twiki.cern.ch/twiki/bin/view/LHCPhysics/NMSSMBenchmarksMarch2020>

# Mode of operation

- NMSSM = MSSM + singlet
  - At the beginning of the LHC, NMSSM related searches usually focused on light pseudo-scalars
  - For the last years this subgroup is interested mostly in multi-Higgs final states and cascade-like signatures
- Benchmarking
  - MSSM style of benchmarking had been considered in the past, but the opinion prevailed that the NMSSM phase space is too complicated for a useful simple benchmark
  - Instead of that the group shows maximum cross sections times BR for specific signatures

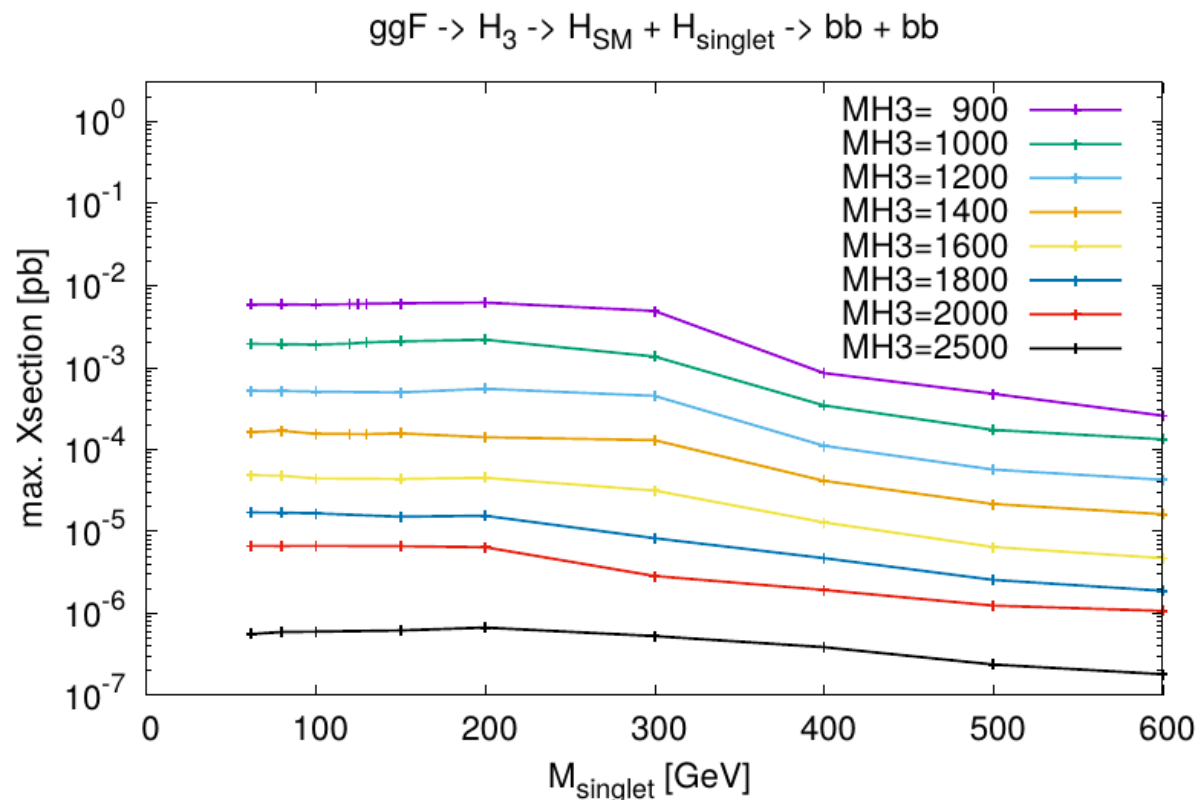
# Example of benchmark

- $ggF \rightarrow H_3 \rightarrow H_{SM} + H_{\text{singlet}}$  with  $H_{SM} \rightarrow bb/\tau\tau$  and  $H_{\text{singlet}} \rightarrow bb$

<https://twiki.cern.ch/twiki/bin/view/LHCPhysics/NMSSMBenchmarksNov2021bbbb>

Maximum cross sections times BR from an NMSSM parameter scan respecting constraints from:

- SM Higgs measurements in the kappa framework
- mass theoretical uncertainty
- BSM searches at the LHC
- LEP constraints
- B-physics
- dark matter direct detection



# Latest updates from theory

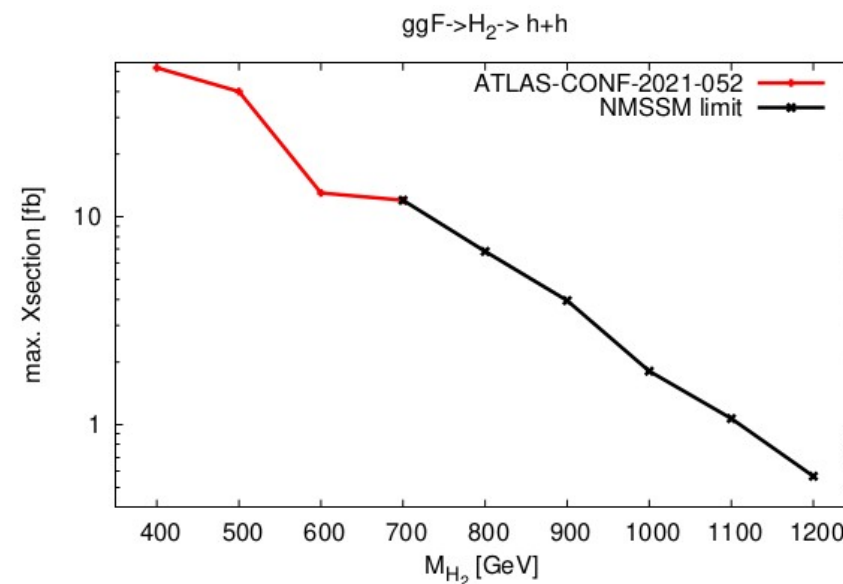
- Di-Higgs production:  $ggF \rightarrow H_2 \rightarrow H_{SM} H_{SM}$

- Within the NMSSM parameter space satisfying bounds from SM Higgs properties, B-physics, dark matter, searches by ATLAS/CMS

- Xsection maximal for  $H_2$  = strong mixture of  $H_S$  and  $H_{MSSM}$

- For  $M_{H_2} < \sim 700$  GeV: limited by the search for  $bb + bb, \tau\tau, \gamma\gamma$  final states in ATLAS-CONF-2021-052

For more information see also:  
arXiv:2203.05049

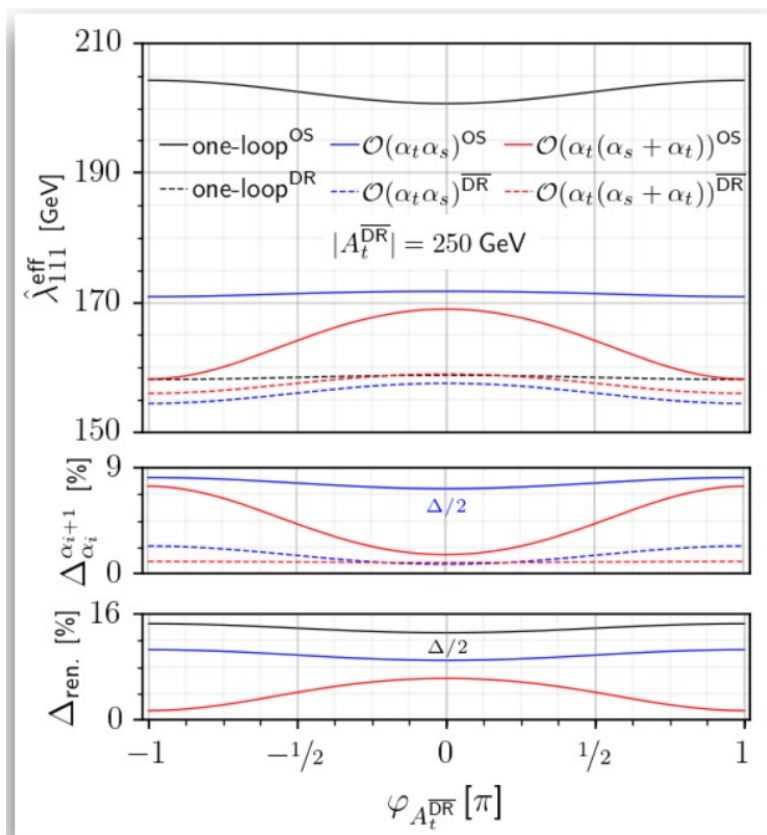


Slide by Ulrich Ellwanger

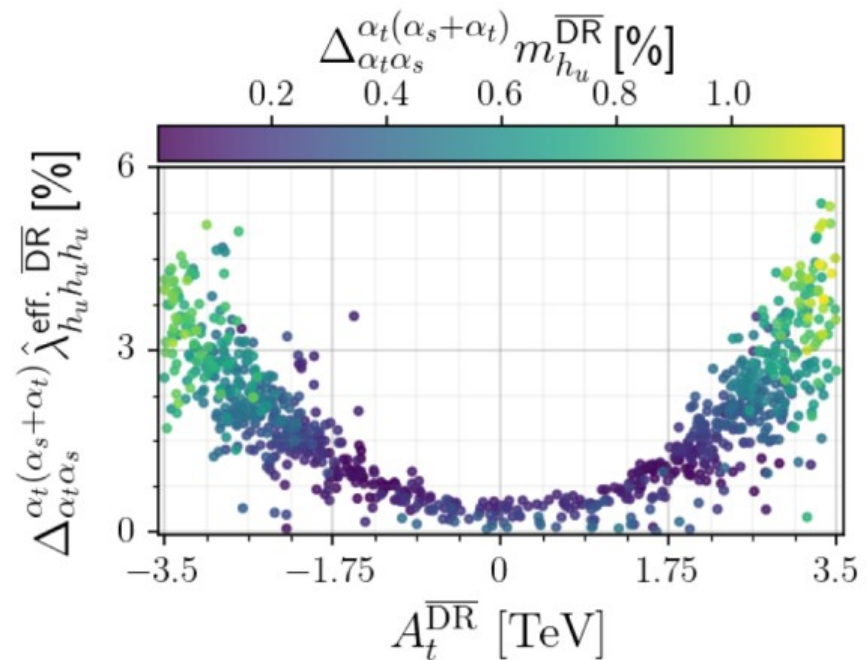
# Latest updates from theory

- $O(\alpha_t^2)$  Corrections to Trilinear Higgs Self-Coupling

$\lambda_{HHH}$  and  $M_{HH}$  related through Higgs potential  $\rightarrow$  same precision required;  
 $\lambda_{HHH}$  enters Higgs-to-Higgs decays and Higgs pair production



[Borschensky, Dao, Gabelmann, MM, Rzehak, '22]

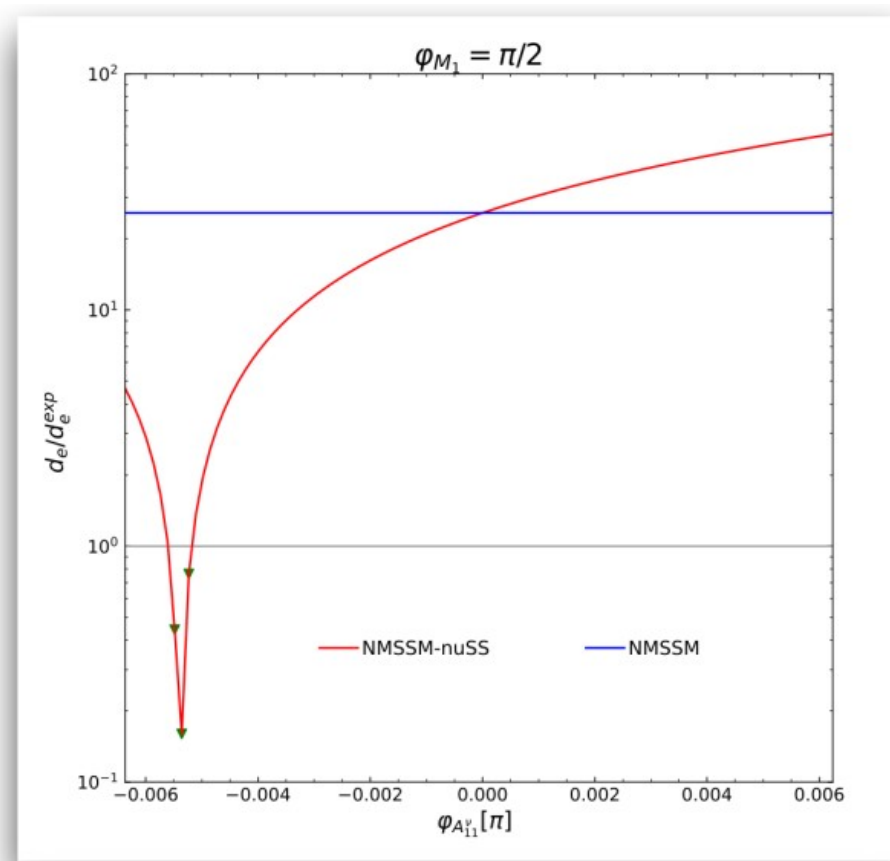
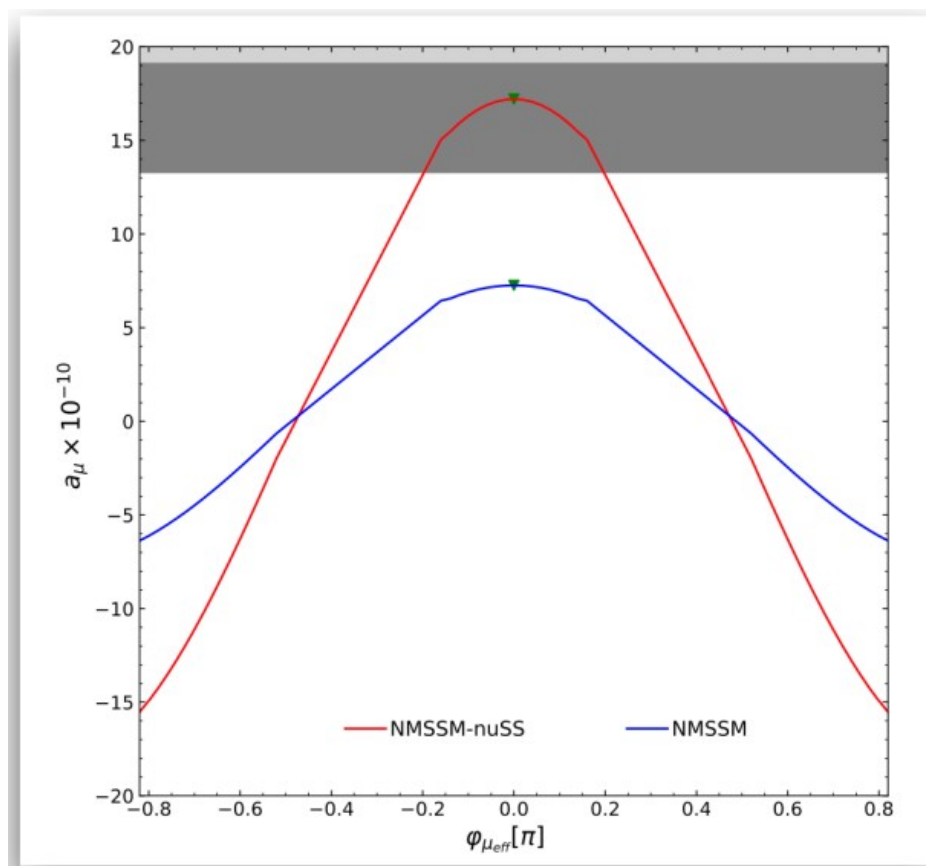


Slide by Maggie Muhlleitner

# Latest updates from theory

- Anomalous magnetic moment (AMM), electric dipole moment (EDM); CP-violating NMSSM

[Thi Nhung Dao, Duc Ninh Le, MMM,'22]



# Latest updates from theory

- NMSSM SM - like  $h_{125}$

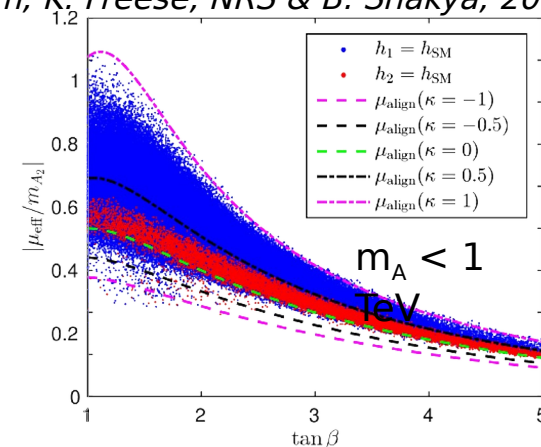
*M. Carena, H. Haber, I. Low, NRS & C. Wagner, 2015*

$$\lambda_{\text{alt}}^2 = \frac{m_h^2 - M_Z^2 c_{2\beta}}{v^2 s_{2\beta}^2}$$

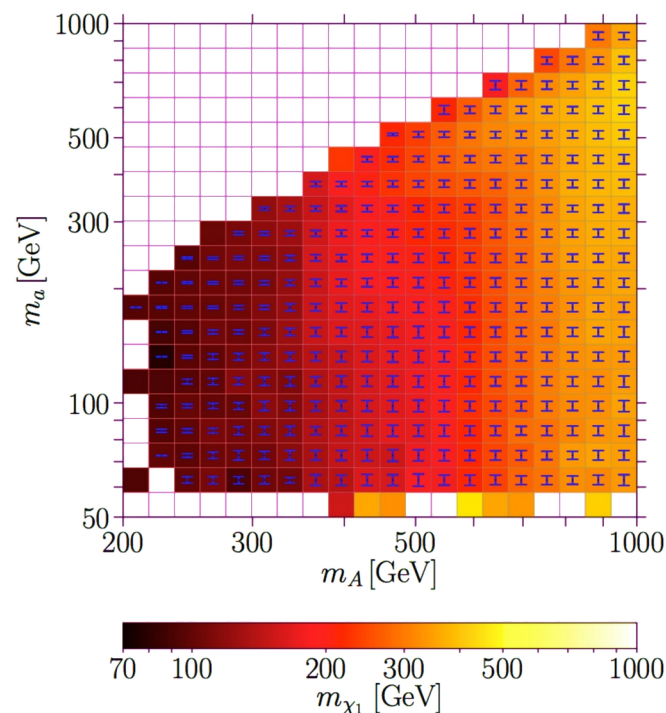
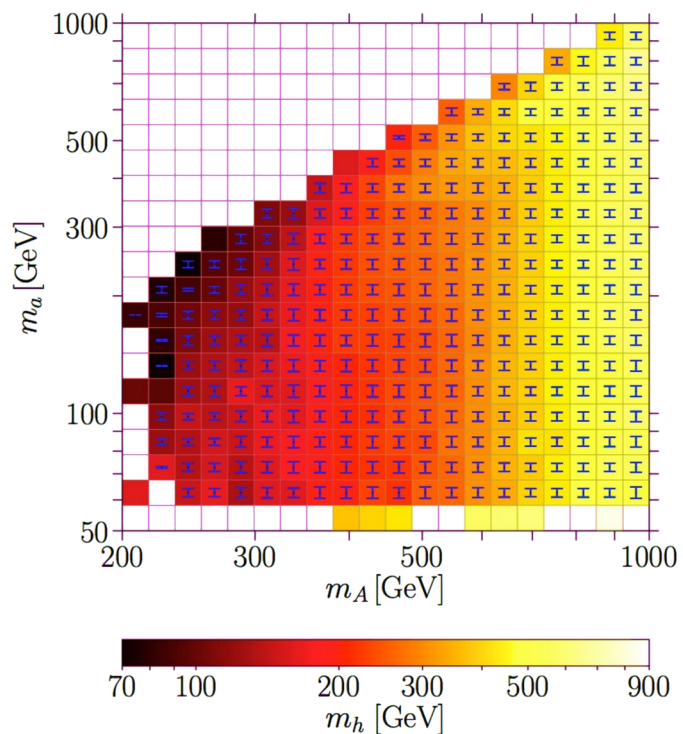
$$1 - \frac{m_A^2}{4\mu^2} s_{2\beta}^2 - \frac{\kappa}{2\lambda} s_{2\beta} = 0$$

NMSSMTools scans with consistent  $h_{125}$  pheno

*S. Baum, K. Freese, NRS & B. Shakya, 2017*



*S. Baum, N.R.S, K. Freese, 2019*

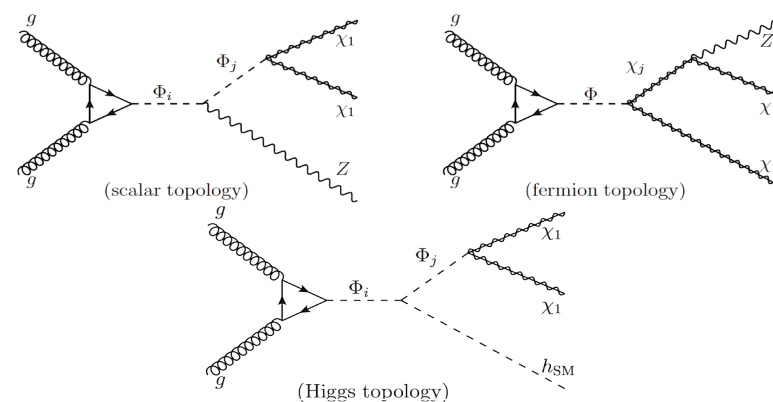


Slide from Nausheen Shah

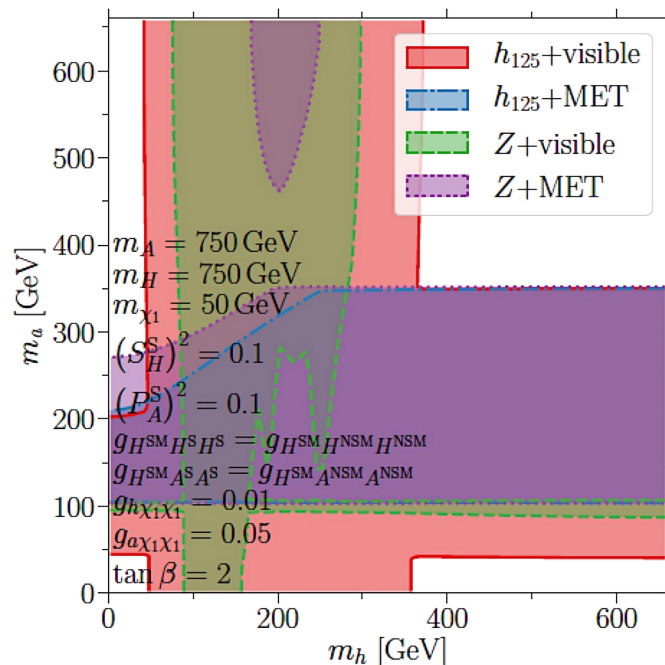
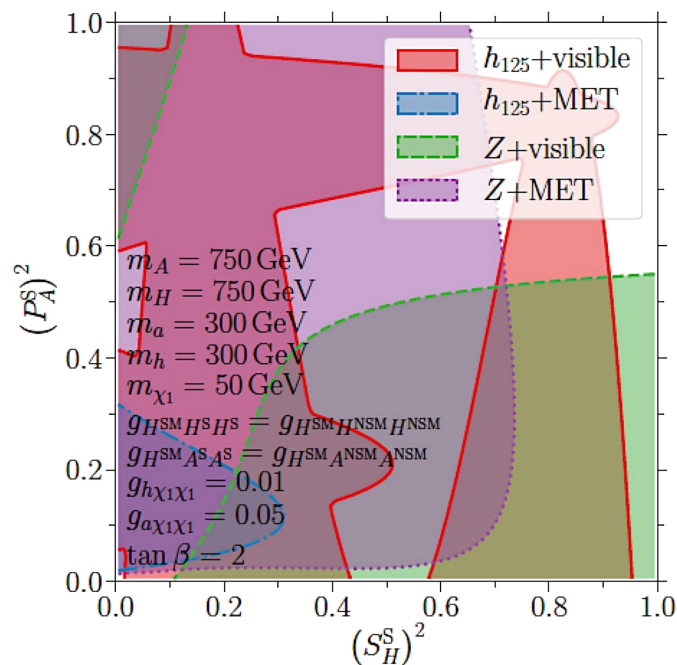


# Latest updates from theory

- Cascade decays due to the presence of additional Higgs particles with visible and invisible decays



S. Baum & NRS, 2018  
S. Baum & NRS, 2019



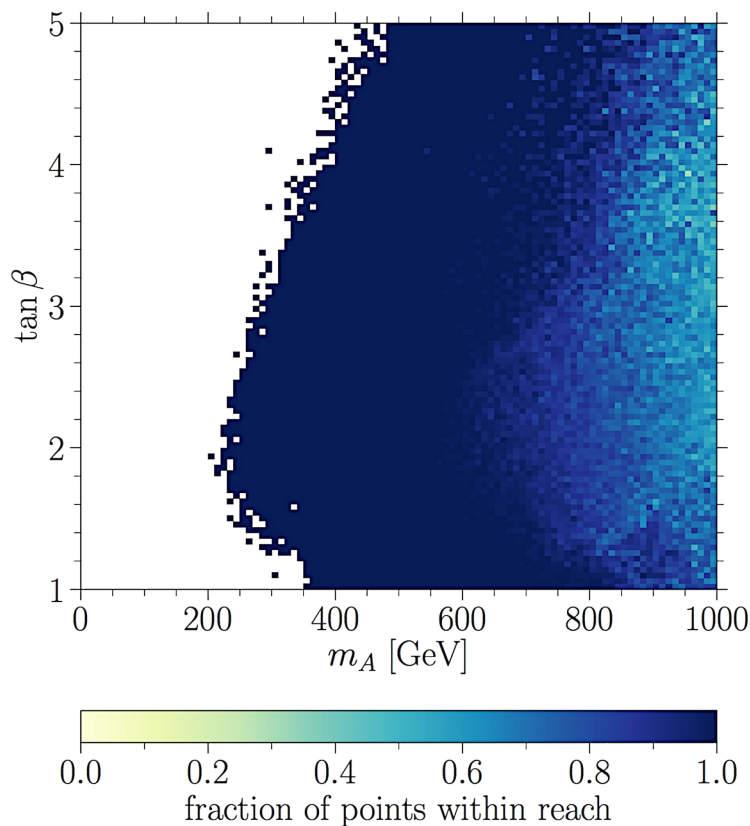
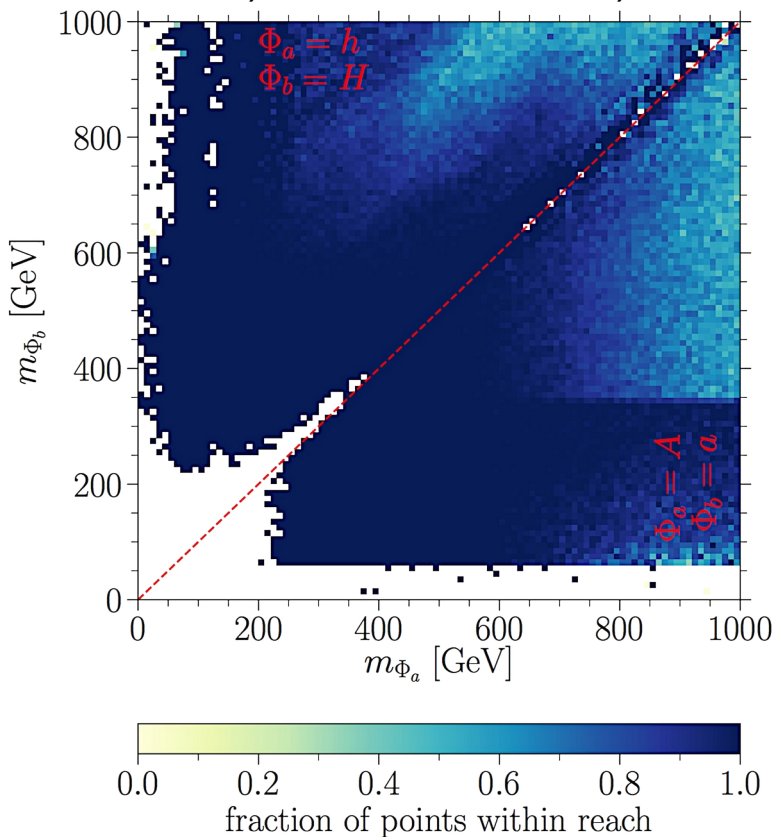
Future reach of the different Higgs Cascade search modes at the LHC with  $L = 3000 \text{ fb}^{-1}$  of data.

Slide from Nausheen Shah

# Latest updates from theory

- NMSSM: 2HDM+S + SUSY: Heavy Higgs Direct Searches & Cascades!

*S. Baum, NRS & K. Freese, 2019*



Optimistic assumptions:  
~90% probed with  
3000 fb<sup>-1</sup>

Slide from  
Nausheen Shah

$(\max[\mu_{\text{Curr. Lim.}}^{<37 \text{ fb}^{-1}} (\text{conventional})] > 0.01 \text{ or } \max[\mu_{\text{Proj.}}^{3000 \text{ fb}^{-1}} (\text{Higgs cascades})] > 0.1)$

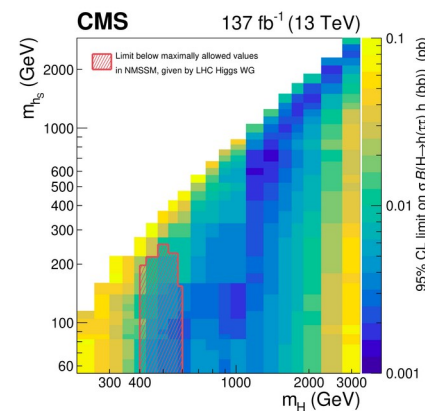
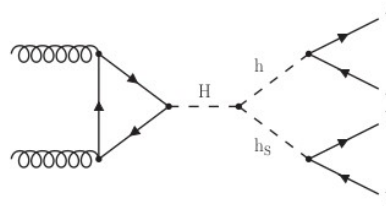
# Relevant experimental results

- In general, di-Higgs results, especially (but not restricted to) those including two bosons of different masses in the final state, can use these benchmarks to show whether or not they constrain NMSSM
- So far the benchmarks have been used by 3 CMS results

We would like to advertise to the experimental colleagues interested in such signatures that they can check whether their results are relevant for NMSSM. The group provides numbers in our twikis to get some idea; if more scans are needed contact us and we will produce them for you.

First result ever to use our benchmarks in 2021 (presented in the last workshop)

[arxiv:2106.10361](https://arxiv.org/abs/2106.10361)



# Selection of latest CMS results

- Di-H125 results

$HH \rightarrow 4W/2W2\tau/4\tau$  [arxiv:2206.10268](#)

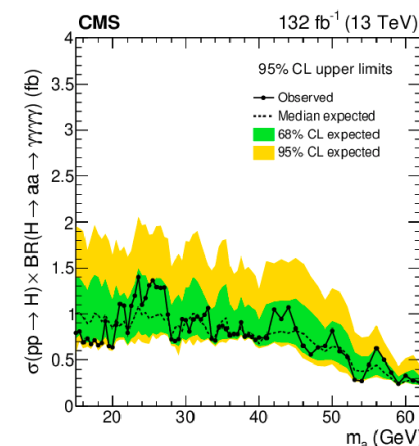
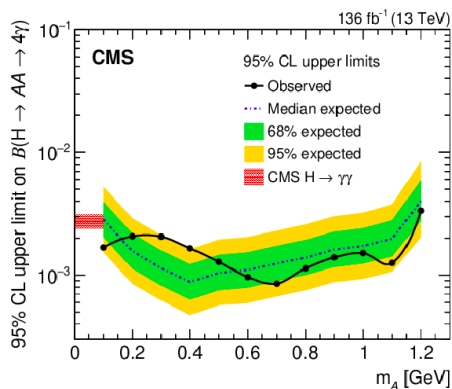
- Light particles

$H \rightarrow aa \rightarrow 4\gamma$  [arXiv:2208.01469](#)

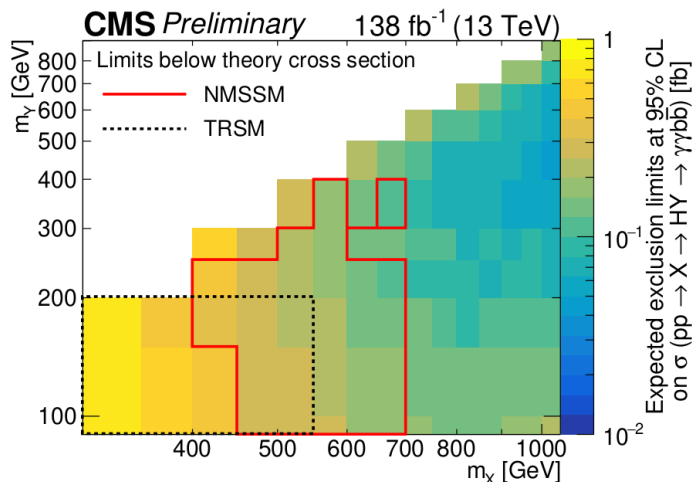
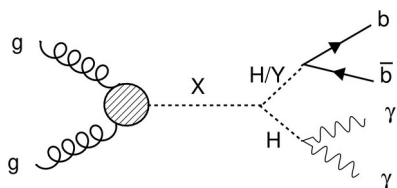
$H \rightarrow aa \rightarrow bb\mu\mu$  [HIG-21-021](#)

- multi-Higgs results / cascades

$H \rightarrow AA \rightarrow 4\gamma$  (2 merged  $\gamma\gamma$  pairs)  
[arxiv:2209.06197](#)

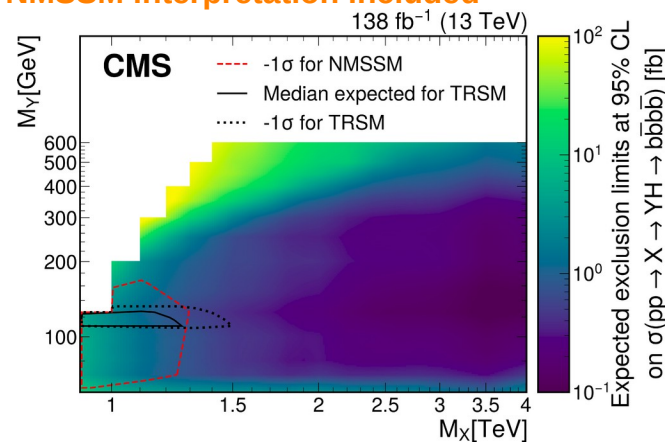


$X \rightarrow Y/H + H$  [HIG-21-011](#)  
NMSSM interpretation included



$X \rightarrow YH \rightarrow 4b$  [arxiv:2204.12413](#)

NMSSM interpretation included



# Selection of latest ATLAS results

- di-H125 results

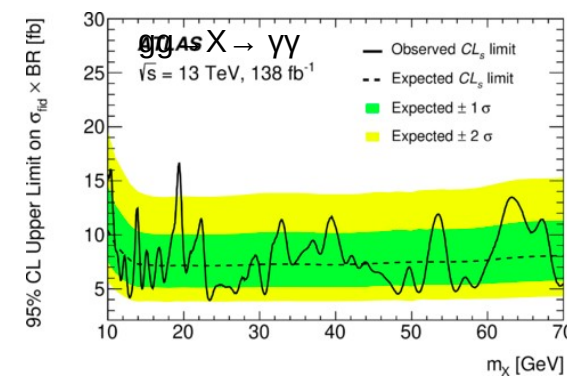
$H \rightarrow hh \rightarrow bb\tau\tau$  [arxiv:2209.10910](https://arxiv.org/abs/2209.10910)

$H \rightarrow hh \rightarrow bbbb$  [arxiv:2202.07288](https://arxiv.org/abs/2202.07288)

$H \rightarrow hh \rightarrow bby\gamma$  [arxiv:2112.11876](https://arxiv.org/abs/2112.11876)

- Light particles

Boosted di-photon resonances (10–70 GeV)  
[arxiv:2211.04172](https://arxiv.org/abs/2211.04172)

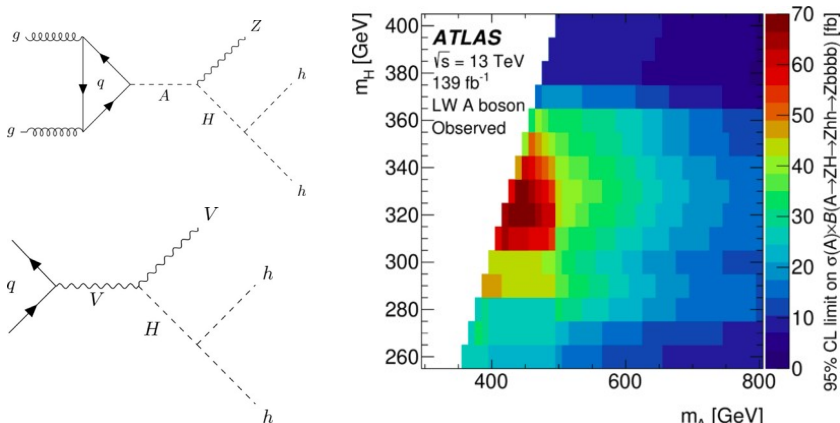


- multi-Higgs results / cascades

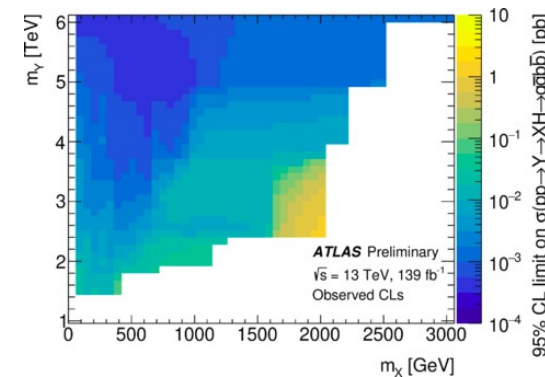
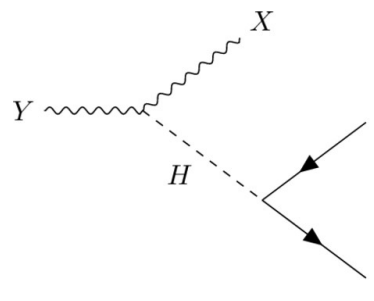
$X \rightarrow Zh/W\bar{h} \nu\nu b\bar{b}, l\bar{l} b\bar{b}, l\nu b\bar{b}$  [arxiv:2207.00230](https://arxiv.org/abs/2207.00230)

Z/W hh ( $\rightarrow 4b$ ) production [arXiv:2210.05415](https://arxiv.org/abs/2210.05415)

Includes Higgs cascades, 2HDM interpretations



$Y \rightarrow XH$  search (fully hadronic)  
 ATLAS-CONF-2022-045





# Conclusions

- Our subgroup provides theory predictions for NMSSM
  - Experimenters are encouraged to contact us if they think they can use the numbers we provide
  - The twiki benchmarks are just examples of possibilities and more points can be produced or more signatures can be explored upon request