BSM Higgs

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BSM?

BSM Higgs

Decays of h_{125} into exotic (or higly suppressed) signatures

- $h \to aa$
- $h \to$ meson + γ
- $h \to \ell\ell'$
- $h \to$ dark photons
- …

Searches for new Higgs bosons

- High mass H
- $H^{\pm}$
- A (pseudoscalar)
- H^{++}

- Large interplay between models
  - Sometimes more useful to think about topologies before models
- Division somewhat arbitrary

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Large group of analyses

Will only pick a few instructive and interesting ones

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The Higgs sector in the SM

Minimal request is one electroweak doublet

$$\phi = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_0 + i\phi_3 \end{pmatrix}$$

- Necessary to provide mass (L polarization) to $W^{\pm}$ and Z
- The extra d.o.f. originates the Higgs scalar

Many of the BSM scenarios deal with extra singlets/doublets/triplets

Disclaimer

Extending Higgs doublet necessary (not sufficient!) in many BSM scenarios

SUSY, DM, EWPT, …

A perfect candle: many different theories need complicated Higgs sector

It can also just be that nature is non-minimal (shocker…)

Different people gravitate(d) around this topic for different reasons

From experimental point of view though better to think in terms of additional d.o.f. an extension provides

Next-to-minimal-ish: 2HDM

Additional electroweak doublet (optional: plus a singlet)

$$\phi = \frac{1}{\sqrt{2}}\begin{pmatrix}\phi_1 + i\phi_2 \\ \phi_3 + i\phi_4\end{pmatrix} \quad \phi' = \frac{1}{\sqrt{2}}\begin{pmatrix}\phi_5 + i\phi_6 \\ \phi_7 + i\phi_8\end{pmatrix}$$

At least 5 degrees of freedom available

➔ **CP-even (h, H) CP-odd (A), $H^{\pm}$**

With few assumptions, free parameters of the theory: m_h, m_H, m_A, $m_{H\pm}$, tanβ, α

α is the mixing parameter between h and H

$$\tan(\beta) = \frac{< \varphi >_0}{< \varphi' >_0}$$

Necessary(-ish) but NOT sufficient
Sideways Standard Model!

Difficult to produce common benchmarks

→ Extensive work within the LHC HXSWG

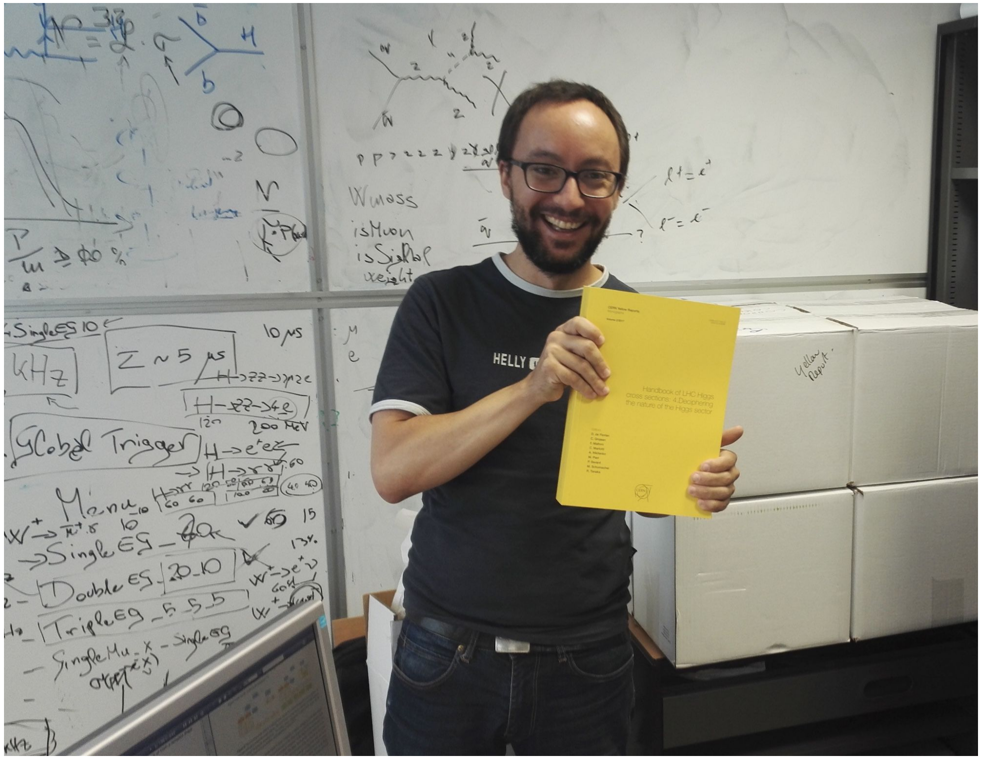
Parameters can be constrained in particular incarnations of 2HDM

→ In MSSM, d.o.f. reduced to two parameters → m_A and tanβ

YR4: Deciphering the Higgs sector

870 pages, a large fraction dedicated to Extended Higgs sector

A massive endeavour…



Couplings in 2HDM

All mass eigenstates couple to both h and H in all configurations, but couplings depend on model

	Type I	Type II	Lepton-specific	Flipped
ξ_h^u	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
ξ_h^d	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
ξ_h^ℓ	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$
ξ_H^u	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$
ξ_H^d	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$
ξ_H^ℓ	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\cos\alpha/\cos\beta$	$\sin\alpha/\sin\beta$

Different scaling of up and down fermions

Different scaling of leptons and quarks

Different scaling of up and down quarks, leptons flipped

$$g_{h,VV} \propto \sin(\beta-\alpha) \qquad g_{H,VV} \propto \cos(\beta-\alpha)$$

Typical topologies

Signatures depend on mass hierarchy and coupling structure

High mass:

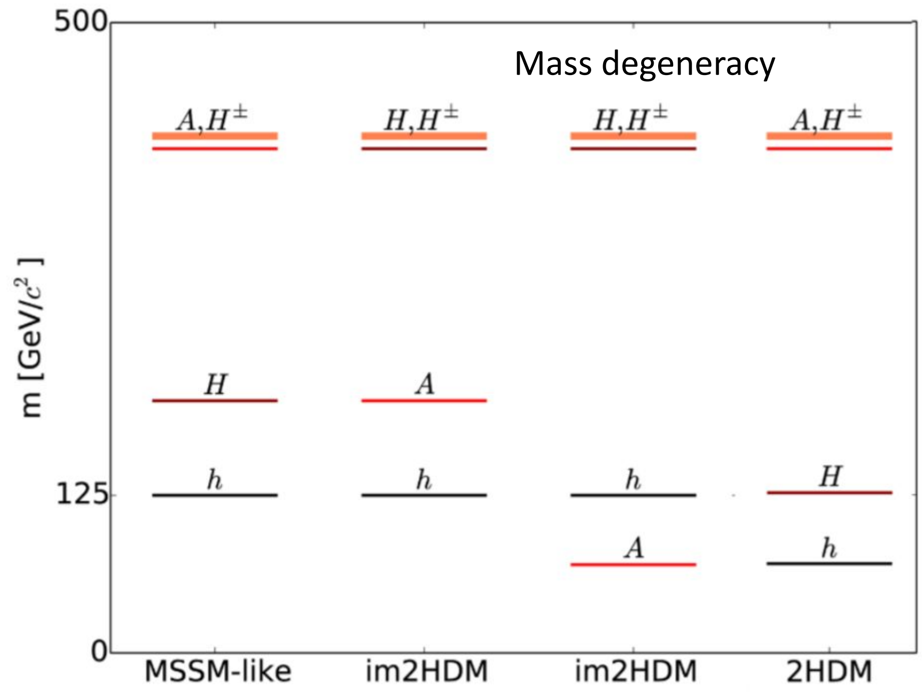
- $H \longrightarrow hh$, $H^{\pm} \longrightarrow W^{\pm}Z$, $H \longrightarrow AZ$, $A \longrightarrow Zh$, $H \rightarrow tt$ …

Mid-high mass:

- $A/H \longrightarrow \tau\tau/bb/\mu\mu/WW/ZZ$

Low mass:

- $A \longrightarrow \tau\tau/bb/\mu\mu$
- Overlap with low mass pseudoscalar (see later)



A/H → ττ

[Phys. Rev. Lett. 125 (2020) 051801]

Search in $\tau_{lep}\tau_{had}$ and $\tau_{had}\tau_{had}$ channels in range [0.2,2.5] TeV

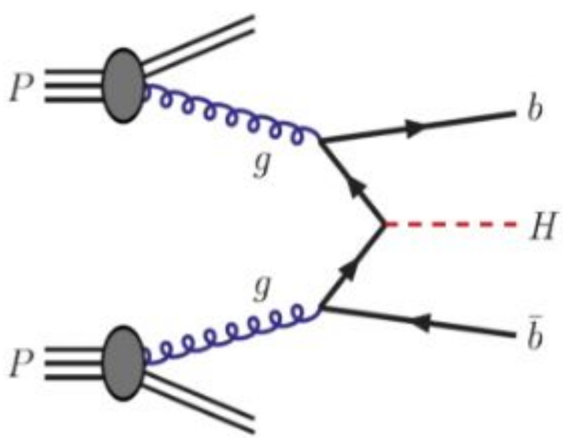
→ Single lepton triggers ~ 25 GeV, single τ around 150 GeV

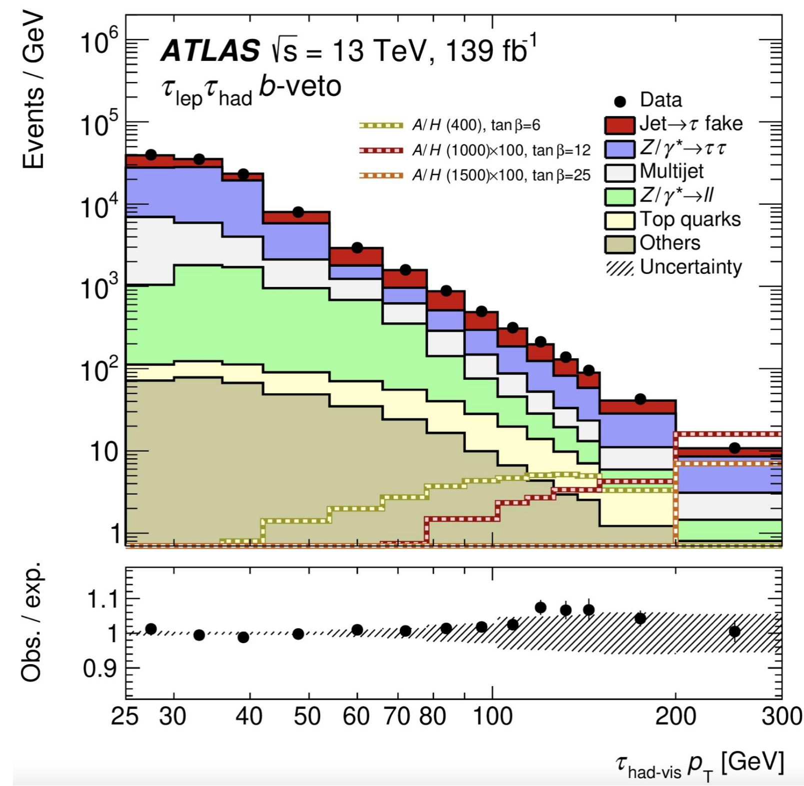
"Bump" hunting over the transverse mass spectrum defined with missing energy

$$m_T^{\mathrm{tot}} = \sqrt{(p_T^{\tau_1} + p_T^{\tau_2} + E_T^{\mathrm{miss}})^2 - (\boldsymbol{p}_T^{\tau_1} + \boldsymbol{p}_T^{\tau_2} + \boldsymbol{E}_T^{\mathrm{miss}})^2}$$

N_{bjet} categorization to exploit different production mechanisms

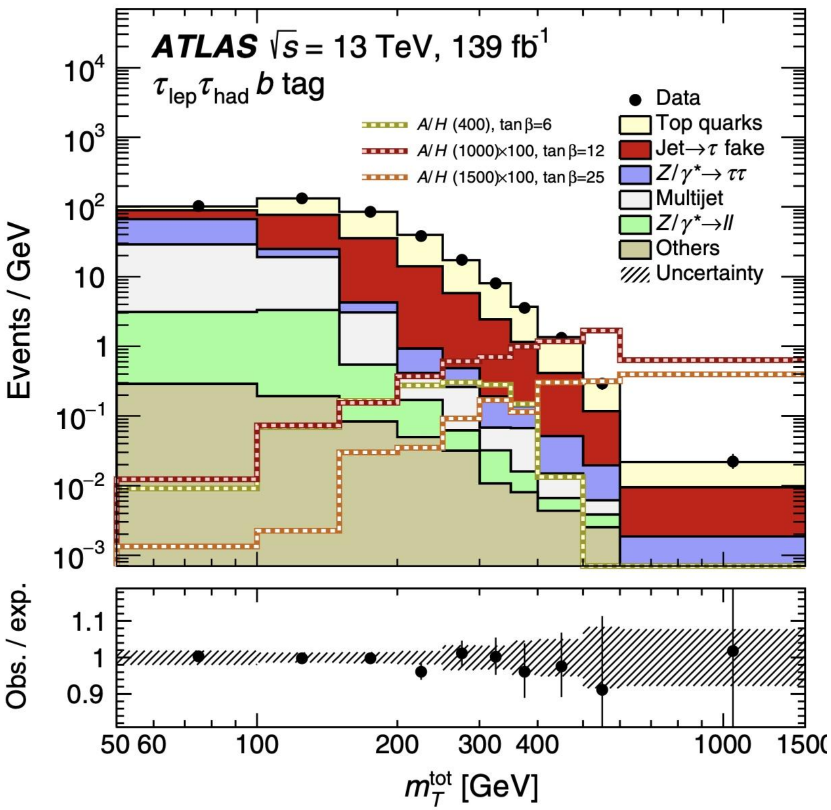
→ Dependence on tanβ for both b and τ

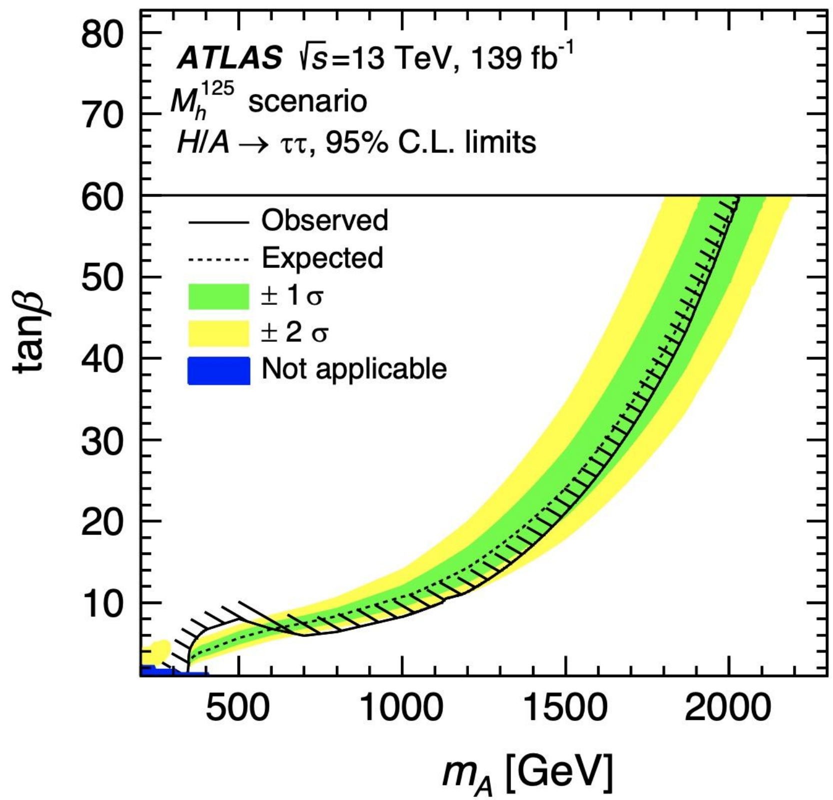




A/H → ττ

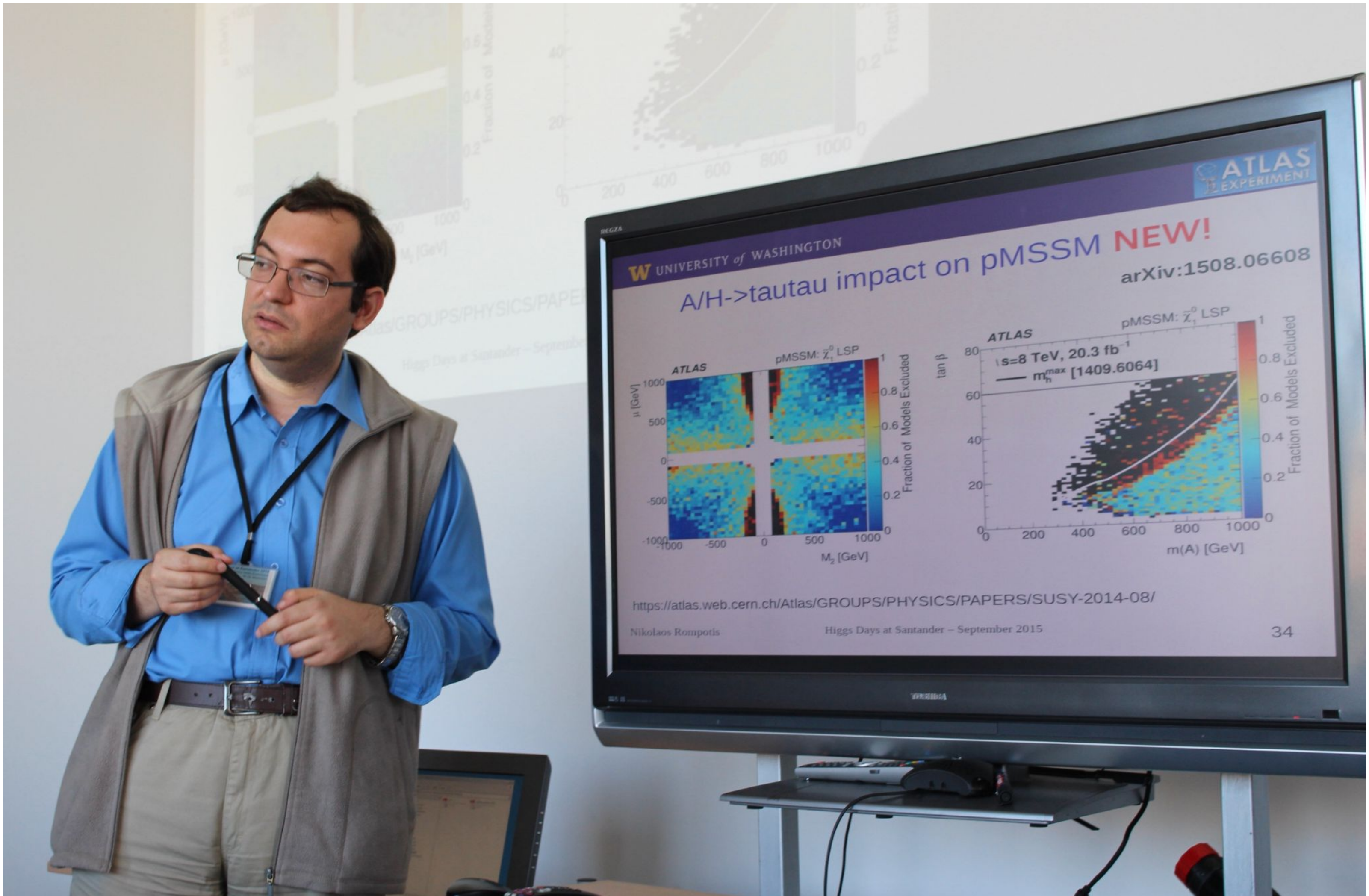
[Phys. Rev. Lett. 125 (2020) 051801](#)





Source	ggF (400 GeV)	ggF (1 TeV)	bbH (400 GeV)	bbH (1 TeV)
Tau id. efficiency	0.14	0.16	0.12	0.08
Tau energy scale	0.33	0.09	0.22	0.03
Z+jets bkg. modeling	0.27	0.19	0.08	0.04
Mis-id. $\tau_{\text{had-vis}}$ bkg.	0.22	0.01	0.14	0.03
Others	0.09	0.04	0.11	0.02
Total	0.54	0.28	0.45	0.13

A new hope


ATLAS EXPERIMENT
UNIVERSITY of WASHINGTON
A/H->tautau impact on pMSSM NEW!
arXiv:1508.06608
ATLAS
pMSSM: $\tilde{\chi}_1^0$ LSP
Fraction of Models Excluded
M2 [GeV]
$\sqrt{s}$=8 TeV, 20.3 fb^{-1}
m_h^{max} [1409.6064]
m(A) [GeV]
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/SUSY-2014-08/
Nikolaos Rompotis
Higgs Days at Santander – September 2015
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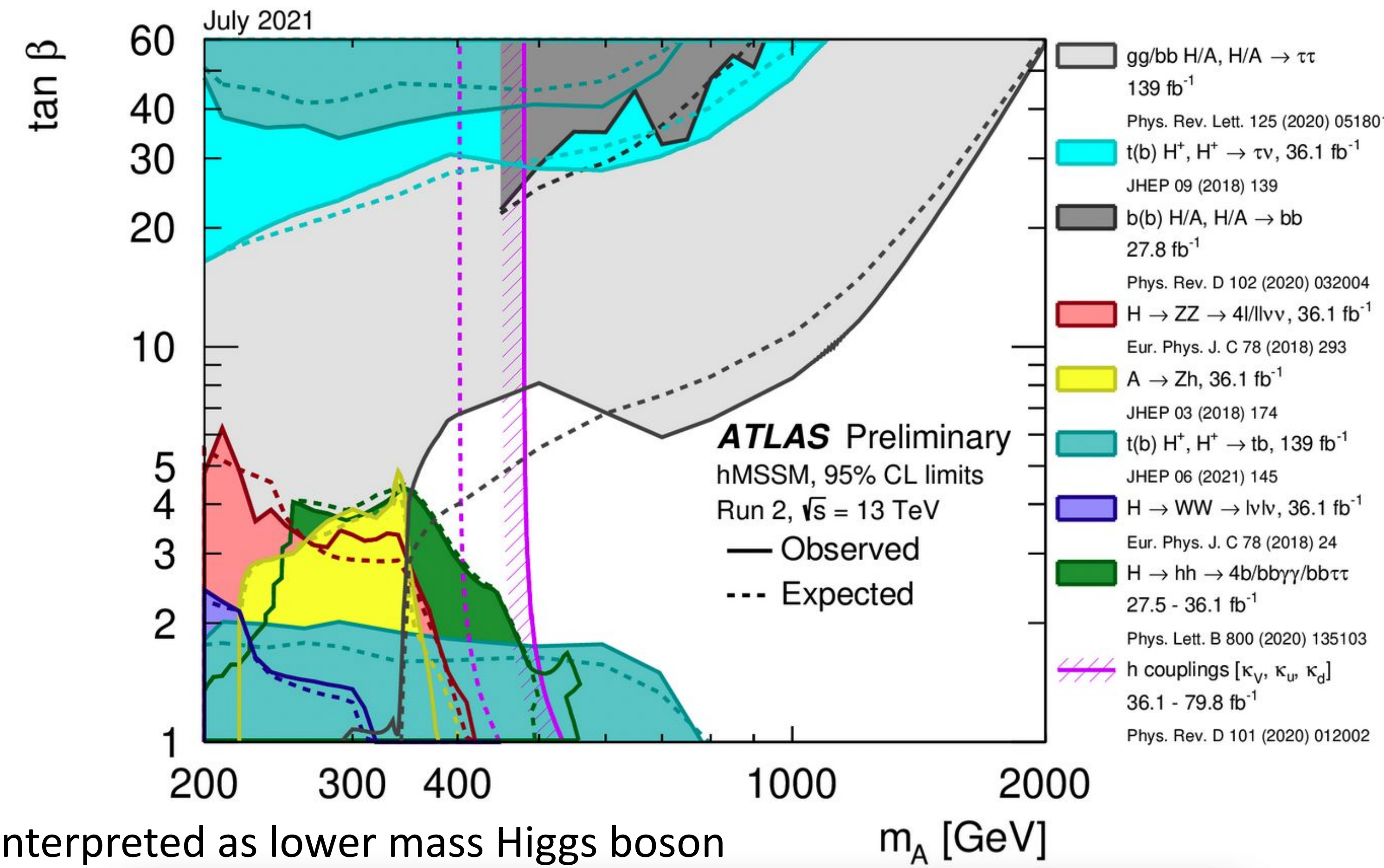
Combining into hMSSM

ATL-PHYS-PUB-2021-030



hMSSM:

- h_{125} interpreted as lower mass Higgs boson
- CP conserving Higgs sector
- Superpartners too heavy to contribute to production and decay

Strong limit provided by constraints from h_{125}

2HDM + S

Common extension (see for example NMSSM)

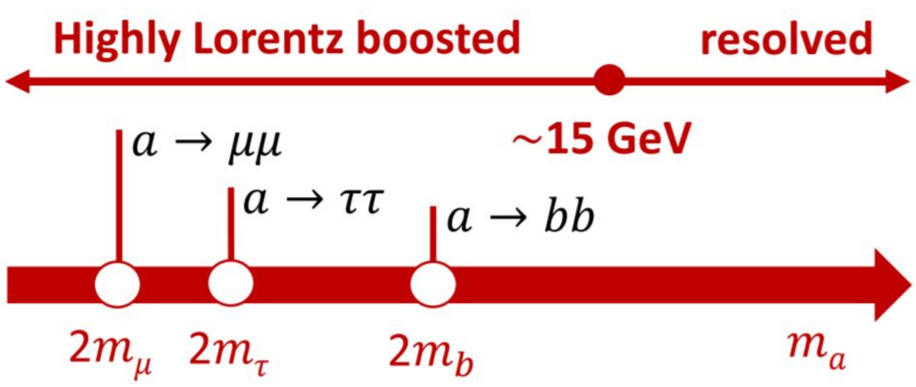
Helps solving the "μ-problem"

Add one singlet

$$\phi = \frac{1}{\sqrt{2}}\begin{pmatrix}\phi_1 + i\phi_2 \\ \phi_3 + i\phi_4\end{pmatrix} \quad \phi' = \frac{1}{\sqrt{2}}\begin{pmatrix}\phi_5 + i\phi_6 \\ \phi_7 + i\phi_8\end{pmatrix} \quad + \phi_S$$

Typically searched in a "lower" mass boson in μμ/ττ/bb

- Of particular interest in **h → aa** decays



h/H → aa → μμττ

Search for collimated dilepton pairs

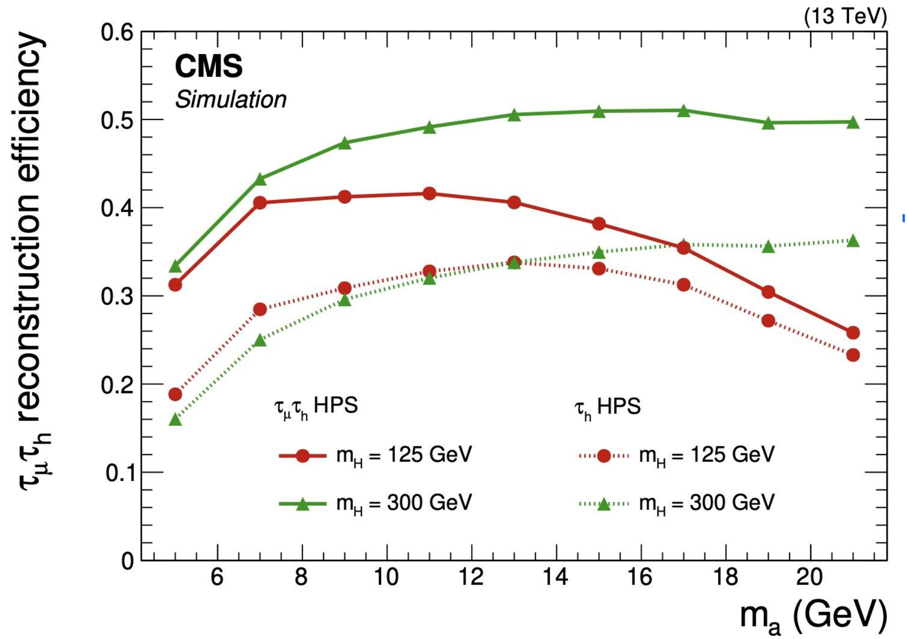
$3.6 < m_a < 21$ GeV

Require isolated μ trigger with $p_T > 24$ GeV

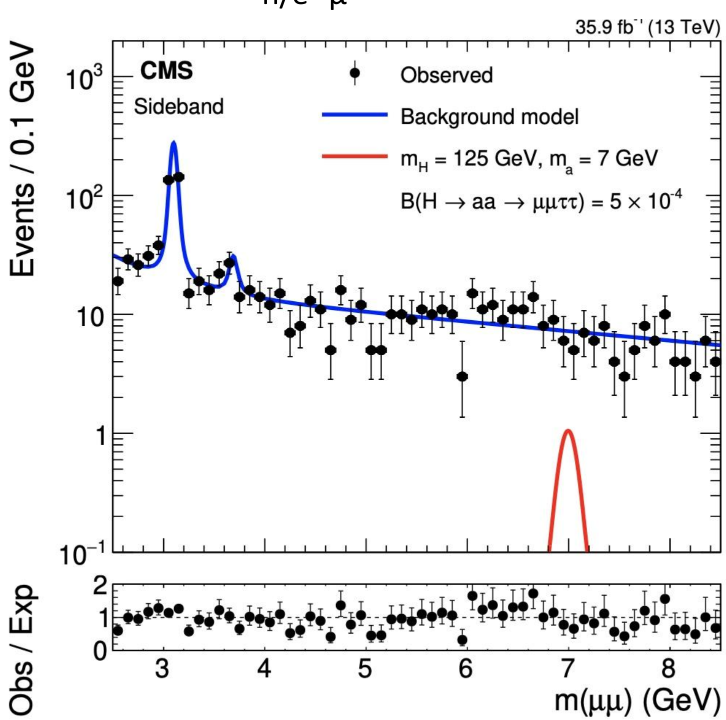
Custom τ-pair algo for collimated objects

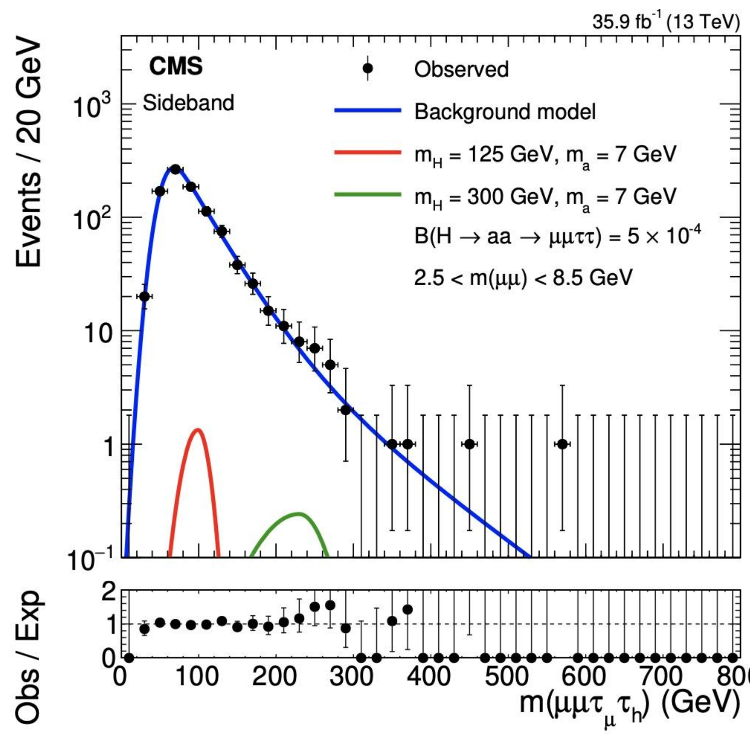
→ allow for a non-isolated μ in one τ decay

Final state is $\mu\mu\tau_{h/e}\tau_\mu$



JHEP 08 (2020) 139



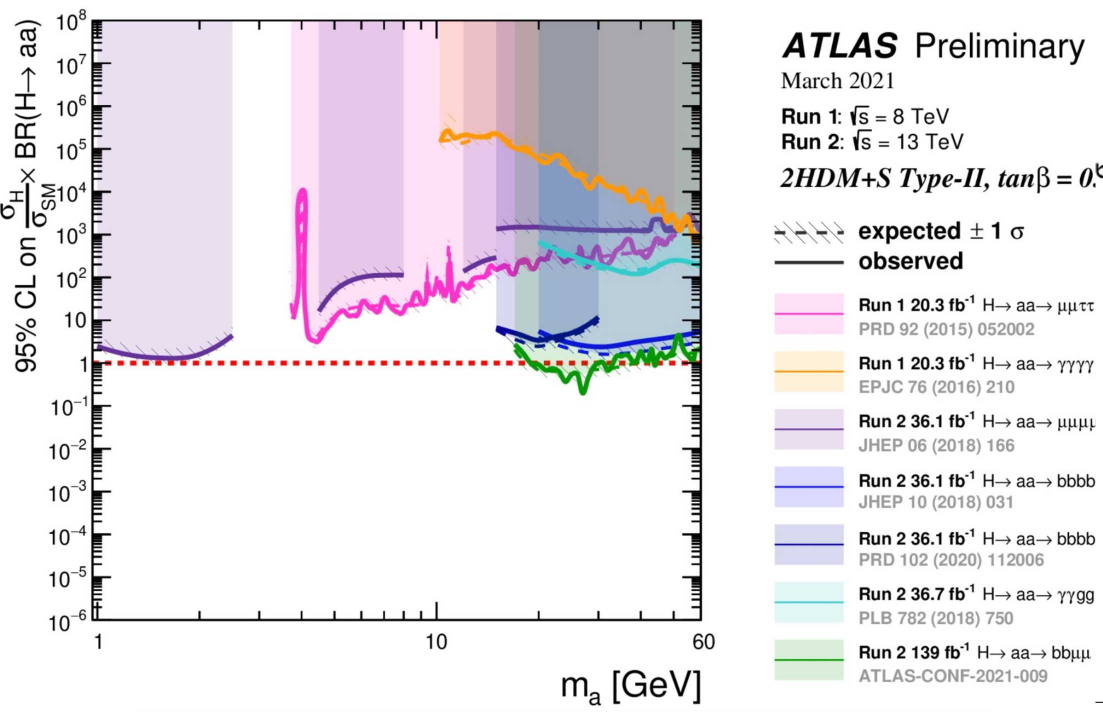


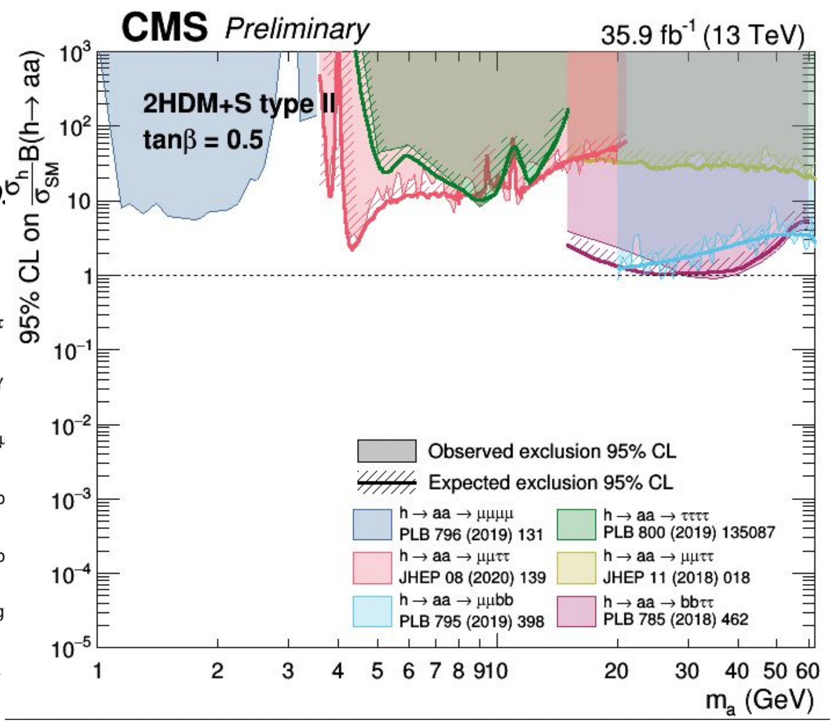
2HDM+S h⟶ aa combination

ATL-PHYS-PUB-2021-008

tanβ = 0.5

Run2Summary@HDMS





All topologies necessary to fully investigate the spectrum

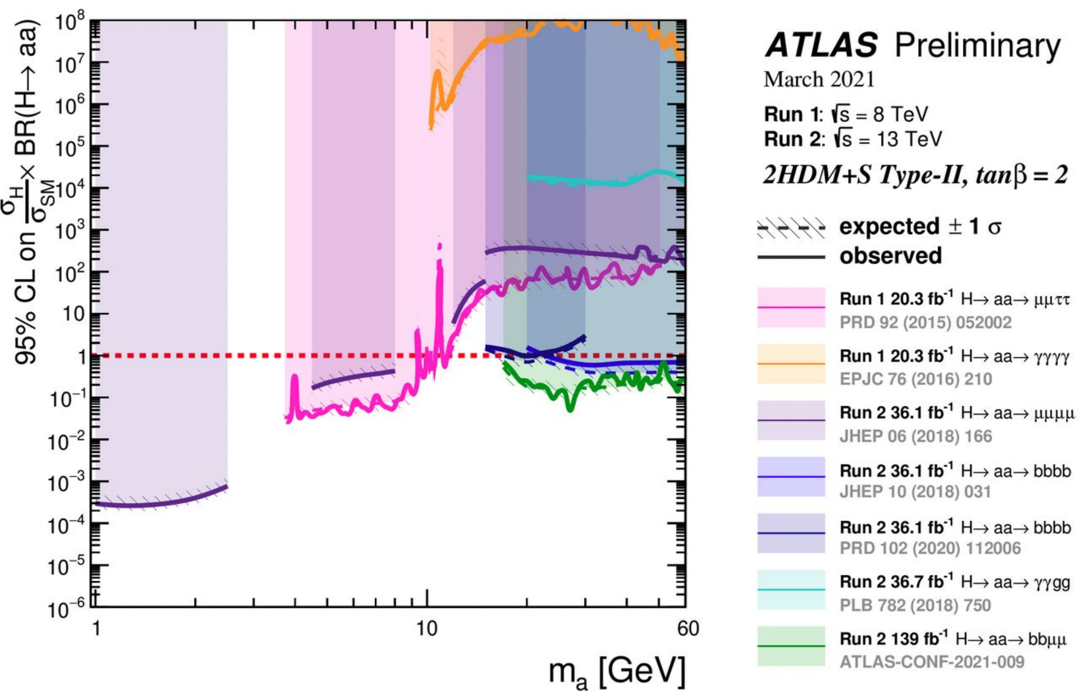
Most are statistically limited

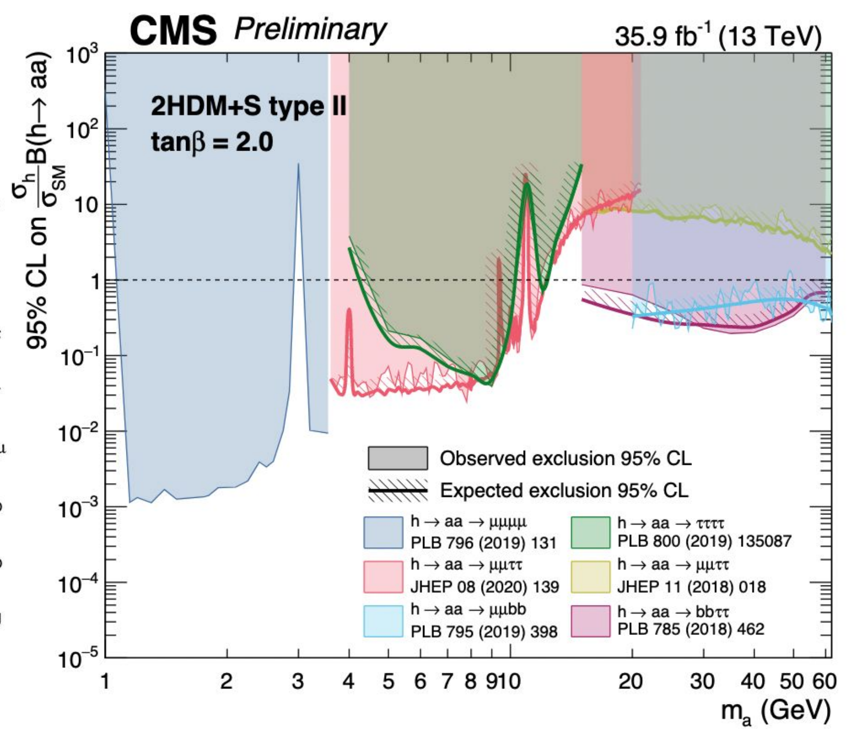
2HDM+S h⟶ aa combination

ATL-PHYS-PUB-2021-008

tanβ = 2

Run2Summary@HDMS





All topologies necessary to fully investigate the spectrum
Most are statistically limited
Strong dependence on tanβ and sign choice for couplings

Higgs triplets

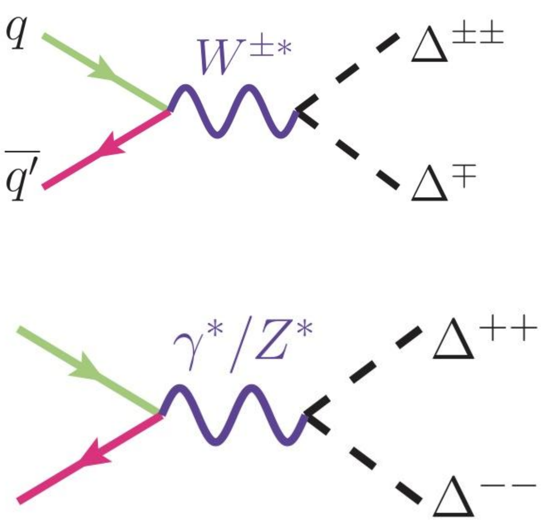
Higgs sector organized in triplets: a nice way to provide neutrino masses via type-II seesaw mechanism

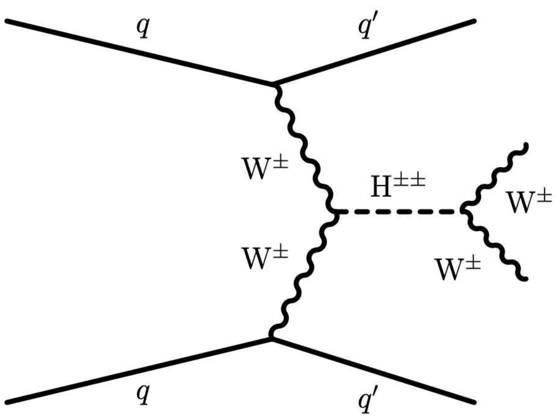
→ Generic forms suffer for large radiative corrections

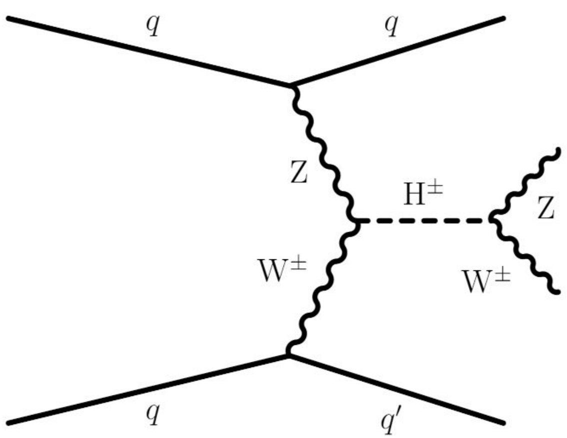
Georgi-Machacek: two triplets, one real and one complex

corrections preserved via custodial symmetry

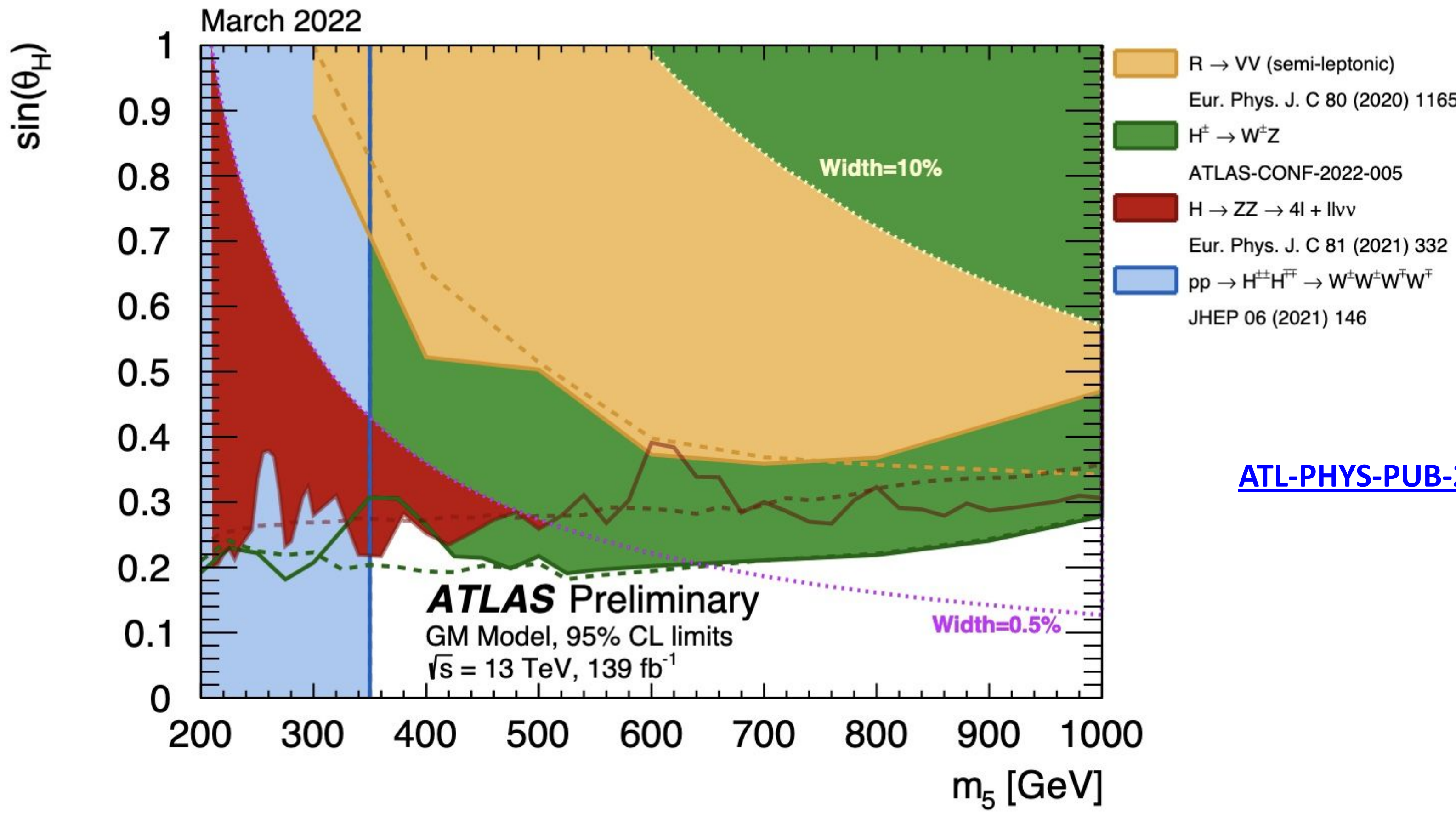
Model predicts several new single and double charged scalars







Combining on the H_5 plane



ATL-PHYS-PUB-2022-008

H5plane benchmark from the LHCHXWG YR4

Very little dependence on h_{125}

Recasting of several analyses into this model

Conclusions

The complete structure of the Higgs sector remains an open question

It can be a powerful tool to hint at what BSM theories are viable

Extended Higgs sector is still a large topic of research with rich topologies

- Overlaps nicely with other BSM searches

Experimentally, lots of issues to overcome

Pushes our detectors and techniques to their limit

Combination among collaborations still an open question

Backup

h/H → aa → μμττ

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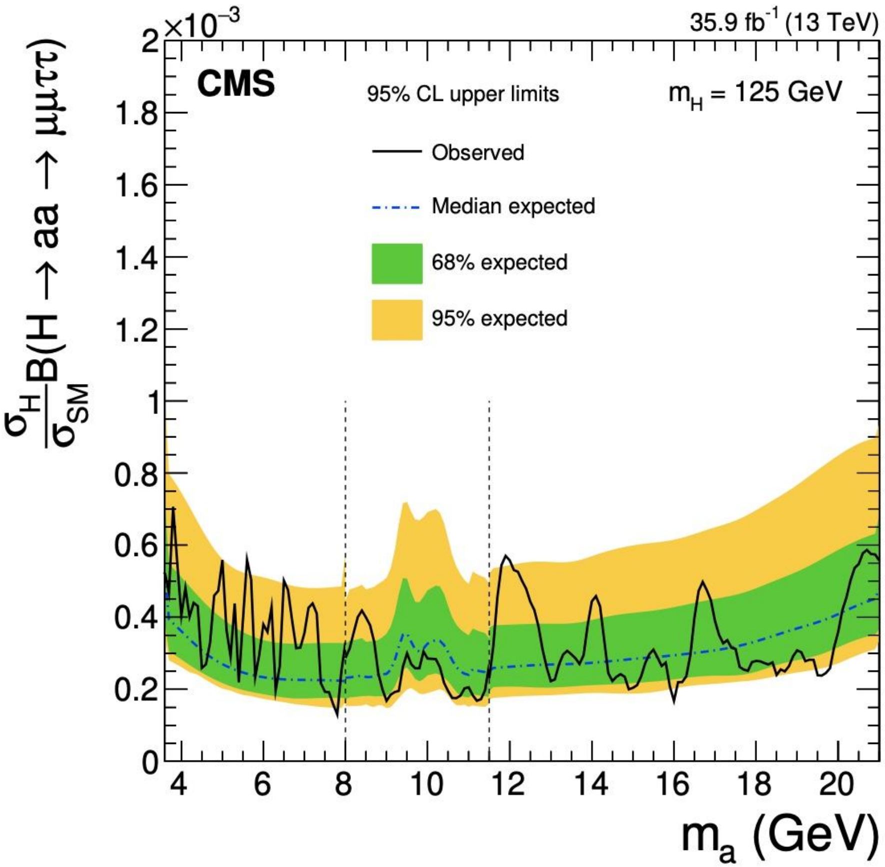
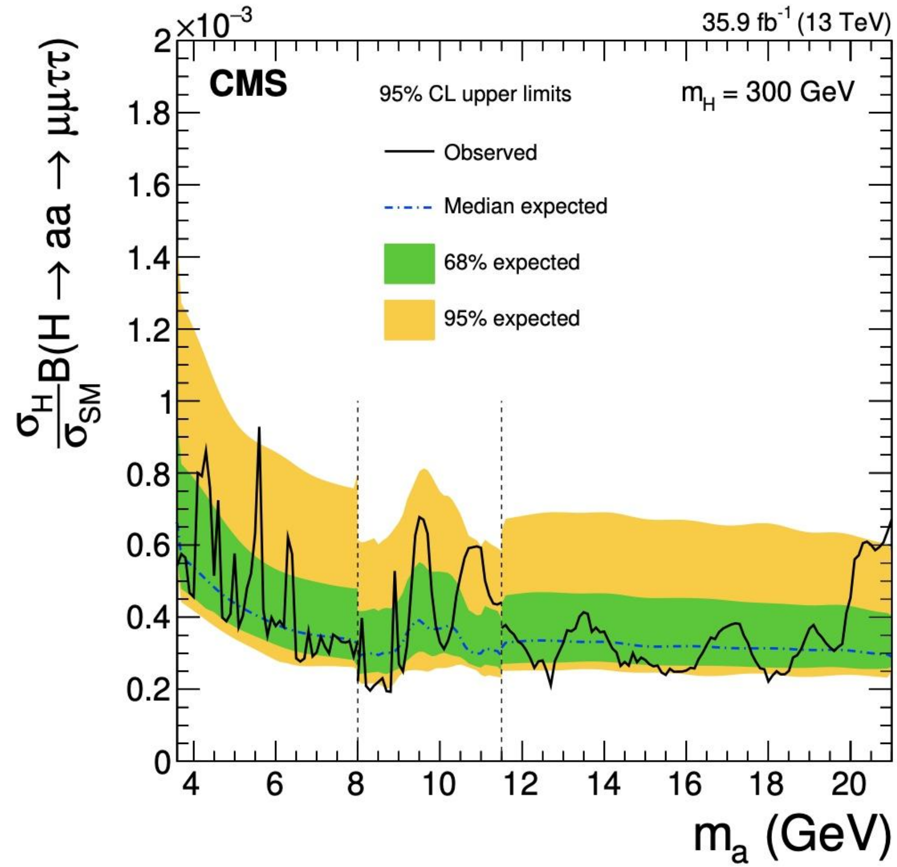


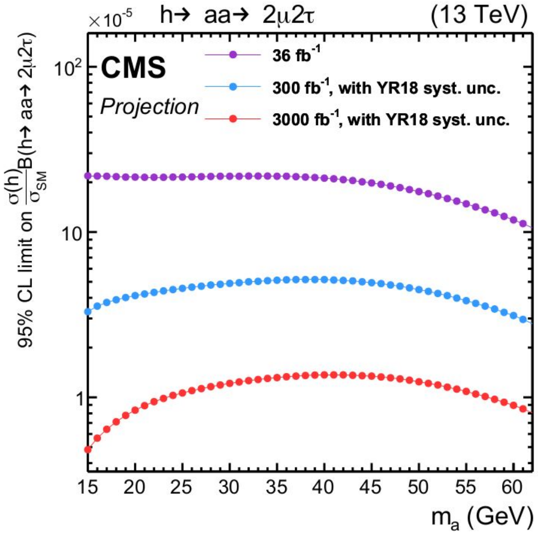


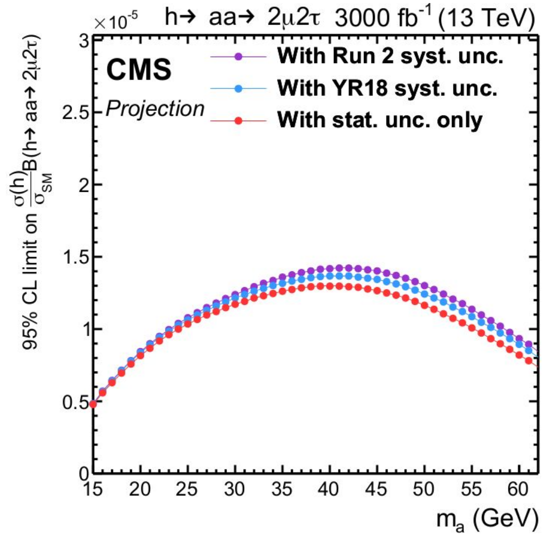
2HDM+S at HL-LHC

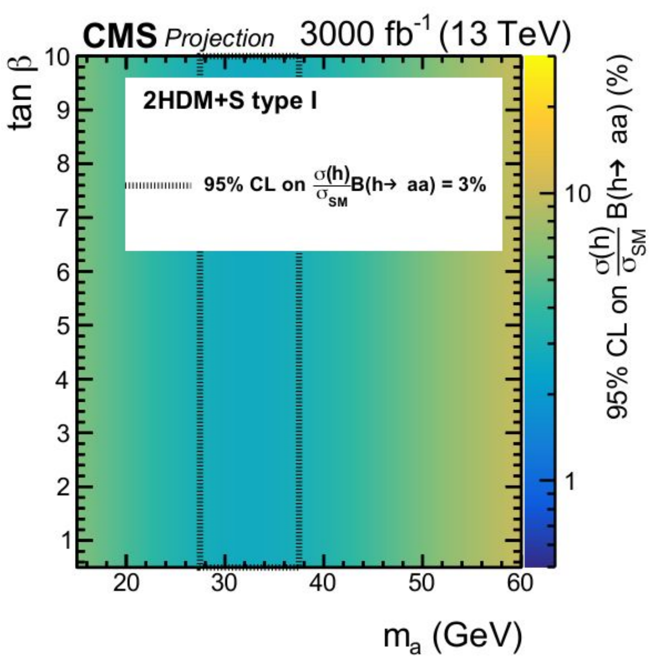
CMS-FTR-18-035

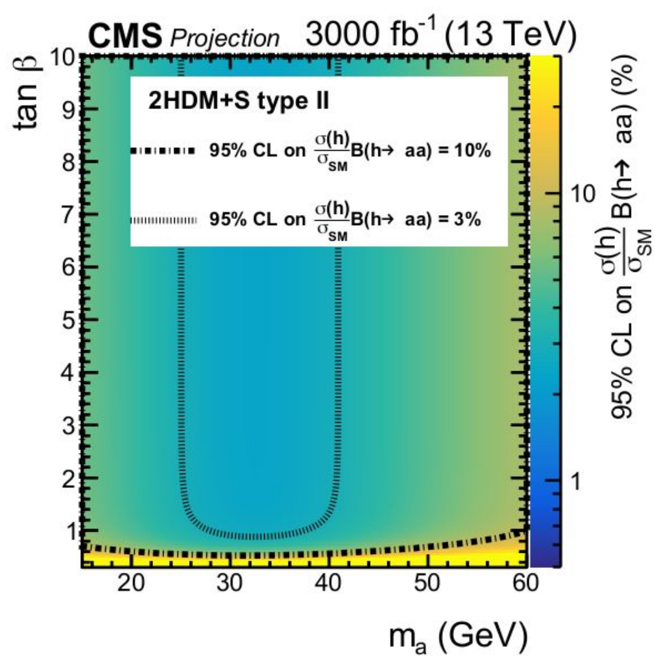
Projections for h⟶ aa⟶ 2μ2τ and 2b2τ channels

Analyses are completely statistically limited





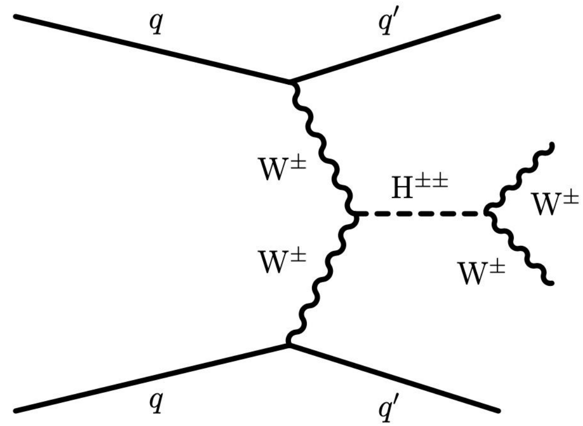




BR limits will mostly get to < 10%

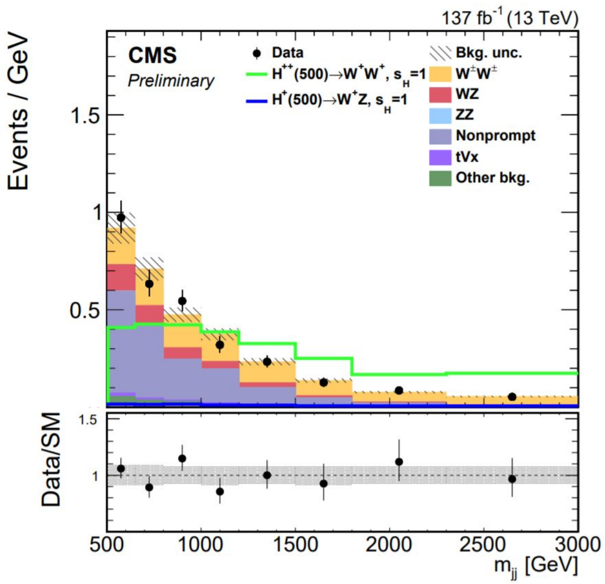
Difficult to be competitive at future (lepton) colliders

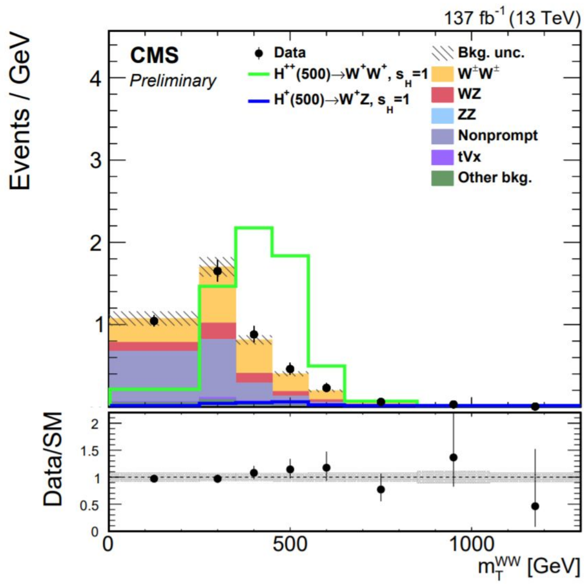
$H^{+(+)} \rightarrow$ vector bosons

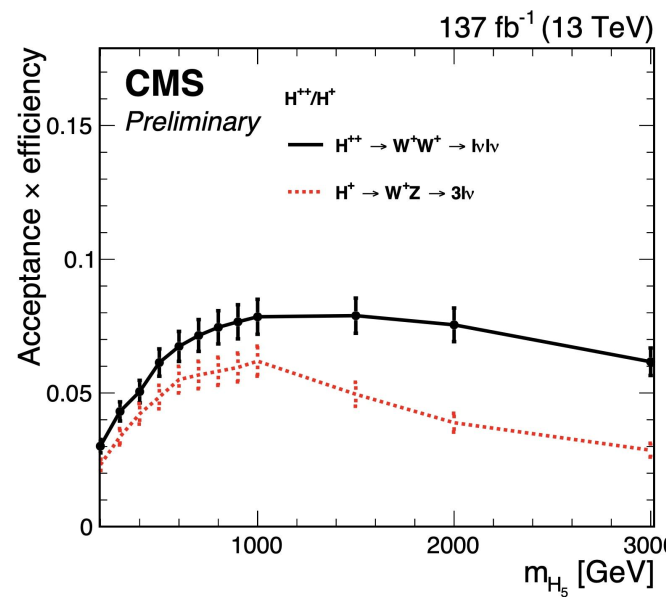


- VBF $H^+ \rightarrow W^+Z$ and $H^{++} \rightarrow W^+W^+$ in leptonic decays
- Mass degeneracy
  - $\rightarrow$ simultaneous search in $200 < m_{H5} < 2000$ GeV range
- tt, tZq and ZZ backgrounds estimated from data
- inverting b-tag and same-sign selections
- Fit m_{jj}, m_T^{VV}

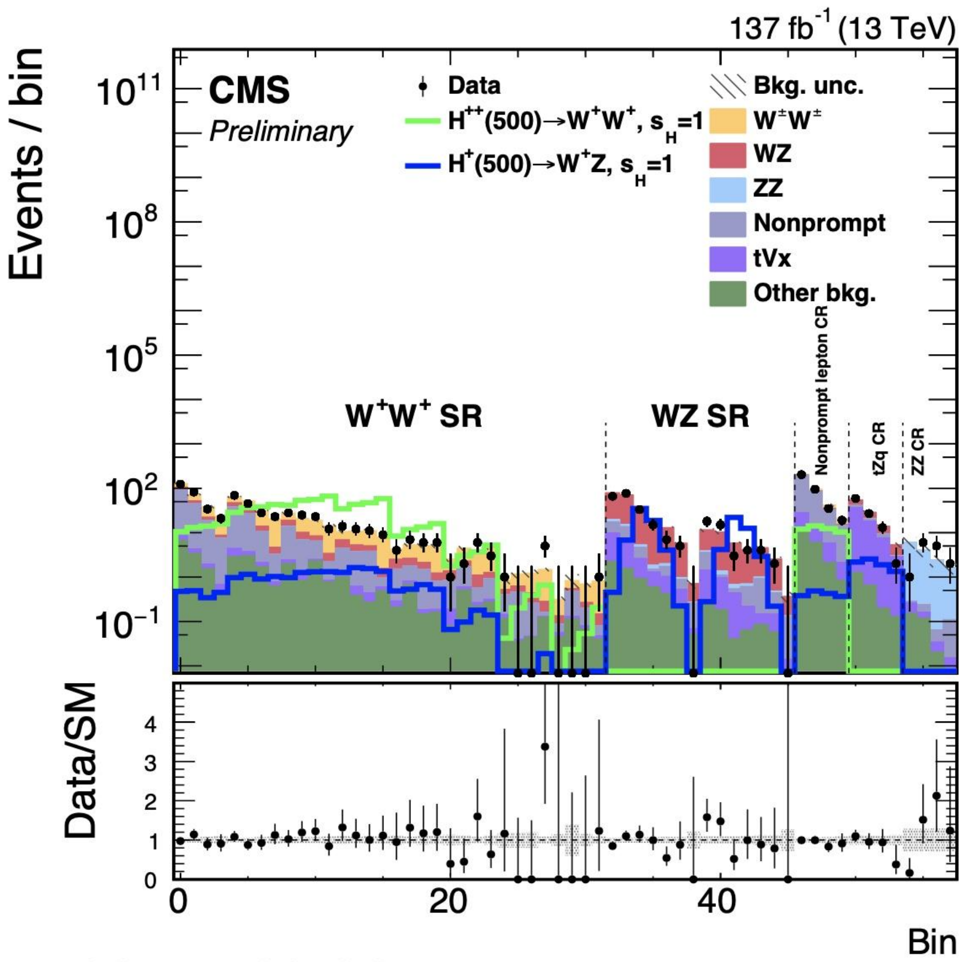
$$m_T^{VV} = \sqrt{\left(\sum_i E_i\right)^2 - \left(\sum_i p_{z,i}\right)^2}$$







$H^{+(+)} \rightarrow$ vector bosons



Source of uncertainty	$\Delta\mu$ background-only
Integrated luminosity	0.002
Lepton measurement	0.003
JES and JER	0.003
Pileup	0.001
b tagging	0.001
Trigger	0.001
Limited sample size	0.005
Nonprompt rate	0.002
$W^\pm W^\pm$/WZ rate	0.014
Other prompt background rate	0.002
Signal rate	—
Total systematic uncertainty	0.016
Statistical uncertainty	0.021
Total uncertainty	0.027

$H^{+(+)} \to$ vector bosons