The 2019 International Workshop on Baryon and Lepton Number Violation (**BLV2019**)

IFT (Madrid), 21-24 October 2019

Exotic Higgs Boson Searches at the LHC

Asma Hadef

University of Science and Technology of China

on behalf of ATLAS and CMS collaborations

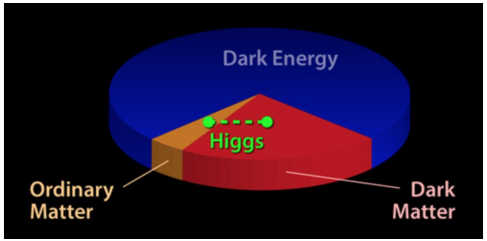
Outline

Introduction

In the **Standard Model (SM):** only **1 complex Higgs doublet** is responsible for electroweak symmetry breaking (the one neutral CP even Higgs boson ***h***).

The **ATLAS** and **CMS** experiments at the Large Hadron Collider discovered a new particle, with a mass of **125 GeV** and properties **compatible** with that predicted for the Higgs boson by the Standard Model.

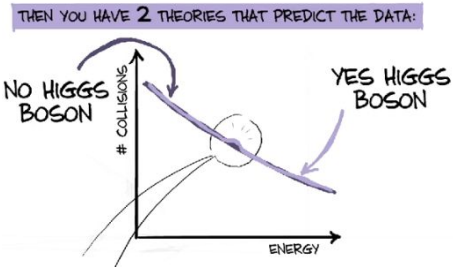
However, SM is <u>not complete</u>: for example, there is no acceptable Dark Matter (**DM**) candidate included in the SM.



Many beyond SM (BSM) models have been developed, to overcome the limitations of the SM:

- **Two Higgs Doublet Models** (**2HDM**): Leads to five physical states: H+, H- , A (neutral CP-odd pseudo-scalar), H and h (neutral CP-even scalars).
- **Minimal Supersymmetric Standard Model** (**MSSM**) solution to "hierarchy problem" ($m_h << m_{Planck}$) and DM candidates.
- Other models: Higgs as a **composite particle**, Higgs-**portal**, an **additional electroweak singlet** to the doublet Higgs field of the SM, etc.

Strategy



exotic Higgs searches at LHC

not covered in this talk

- Directly from decays of **neutral** and **charged Higgs** e.g. through **Flavour Changing Neutral Currents** (**FCNC**).

- Study indirectly by interpreting measured mass and couplings of Higgs (125) in extensions of the standard model.

❑ **Neutral Higgs searches:** many searches including b- associated and gg-fusion production with VV, bb, ττ , μμ decays etc.

❑ **Charged Higgs searches**: many searches including production in top decays with decay to τν, cs,..

Search in typical 2HDM scenarios

1.1. searches for charged Higgs

1.2. search for heavy neutral Higgs

1.3. Run 2 BSM Higgs exclusion in the hMSSM

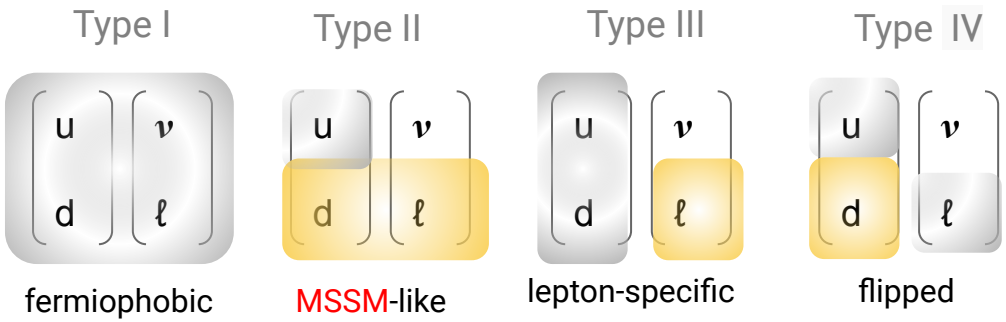
1.4. HL-LHC prospects for the MSSM Higgs sector

h	H	A	$H^{\pm}$
scalar	scalar	pseudo-scalar	charged

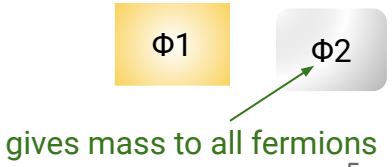
2 Higgs Doublet Models (2HDM)

Higgs sector of **2HDM** models described by 6 parameters:

- 4 Higgs masses: m_h , m_H , m_A , m_{H+-} .
- **tan β**: ratio of vacuum expectation values **vev**.
- **α**: mixing angle between the two neutral CP even states h,H.



Assume observed Higgs m_h=125.5 GeV is the light Higgs boson h in 2HDM models



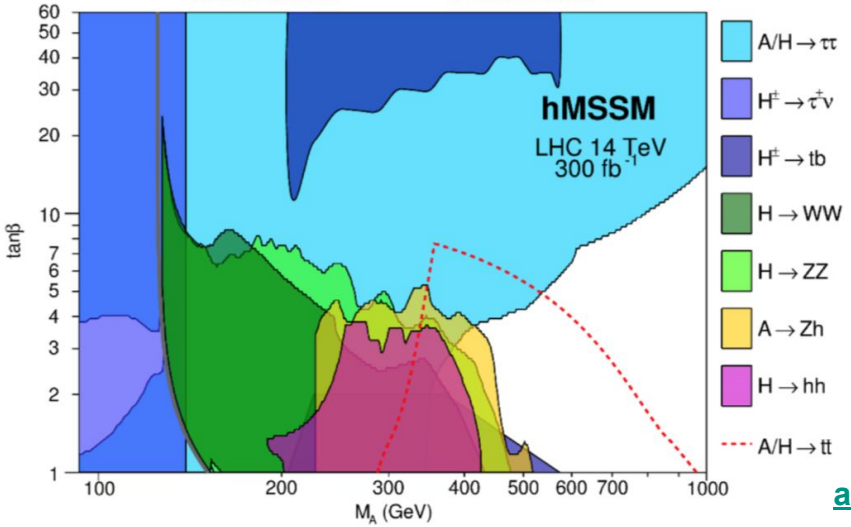
Search in typical 2HDM scenarios

1.1. searches for charged Higgs
1.2. search for heavy neutral Higgs
1.3. Run 2 BSM Higgs exclusion in the hMSSM
1.4. HL-LHC prospects for the MSSM Higgs sector

h	H	A	$H^{\pm}$
scalar	scalar	pseudo-scalar	charged

Scenarios for MSSM Higgs boson searches at the LHC

- **hMSSM scenario:** m_h fixed; all SUSY particles are heavy.
- **m_h^{mod} scenario:** m_h is close to the mass of the one observed at the LHC.
- **New benchmarks:** six new scenarios proposed in August 2018 (**Mh125**, **MH125**,***M125($\tilde{\chi}$)***, etc.).



Theory projections for 2 σ sensitivity

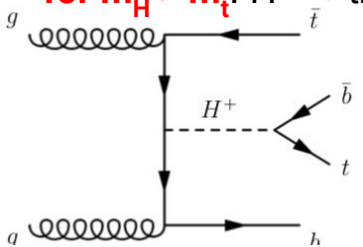
arXiv:1502.05653

***A/H → τ+τ−* and *A/H → tt* are important channels at mid- to high-mA**

Searches for charged Higgs $H^{\pm}/H^{\pm\pm}$

dominant production/decay modes

for $m_H > m_t$: $H^{\pm} \to tb$

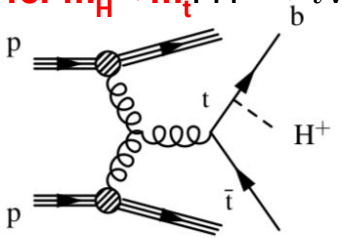


$\sigma \times \mathcal{B} < 9.25$ to 0.005 pb.

200 GeV to 3 TeV.

JHEP 11 (2018) 085

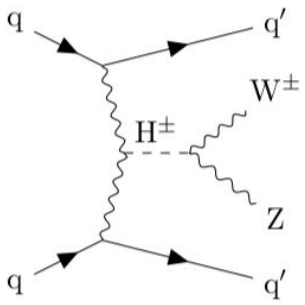
for $m_H < m_t$: $H^{\pm} \to \tau\nu$



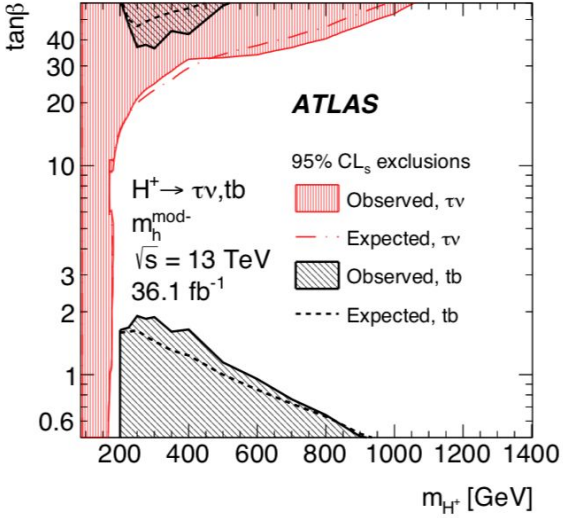
$\sigma \times \mathcal{B} < 5$ to 0.005 pb

80 GeV to 3 TeV

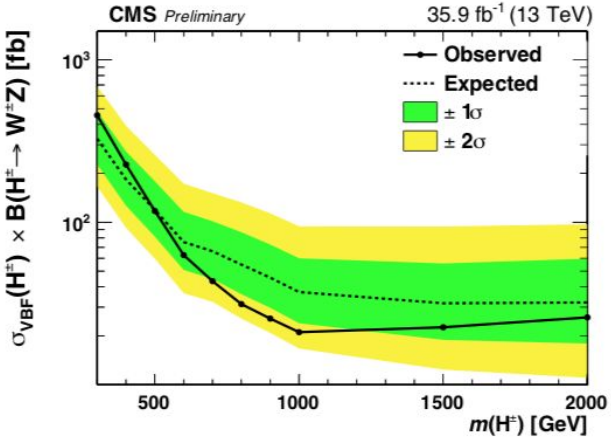
$H^{\pm} \to WZ$



CMS-CR-2018-261

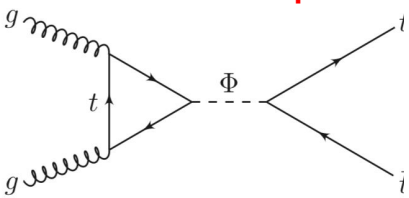


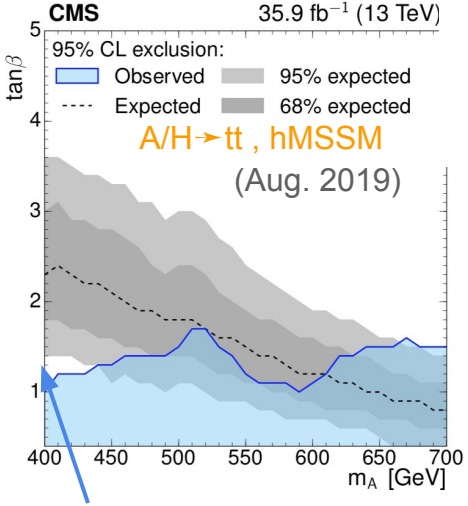
At low tanβ, the strongest limits are from the *tb* final state, whereas the exclusions at high tanβ and low *H+* masses are obtained from the τν final state.



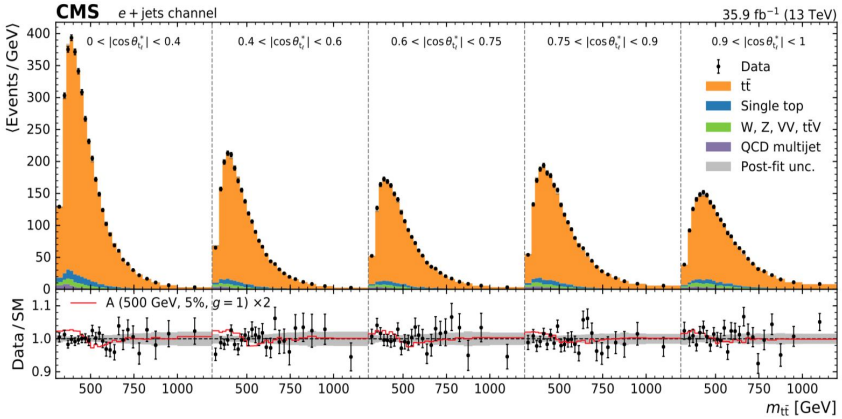
Search for heavy neutral Higgs A/H

A/H → tt : dominant and sensitive at low tanβ





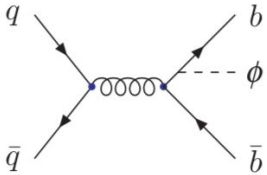
deviation compatible with an A boson at ~400 GeV is observed (1.9 σ global significance)

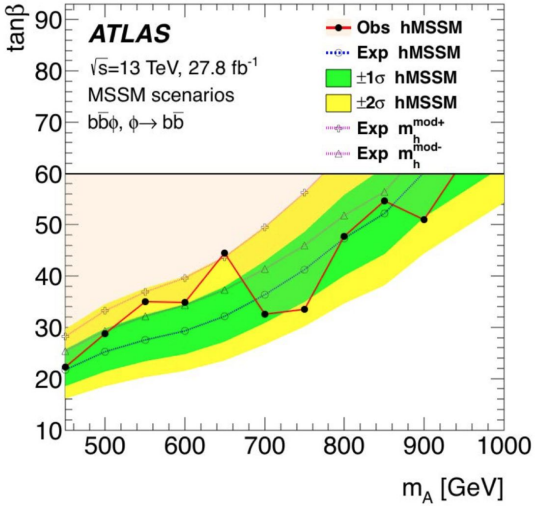


The invariant mass of the reconstructed tt system as well as angular variables sensitive to the spin of the new boson are used to search for the signal, while taking into account the interference with the standard model tt production.

ArXiv:1908.01115

bbH → bb : sensitive to type II and IV at high tanβ

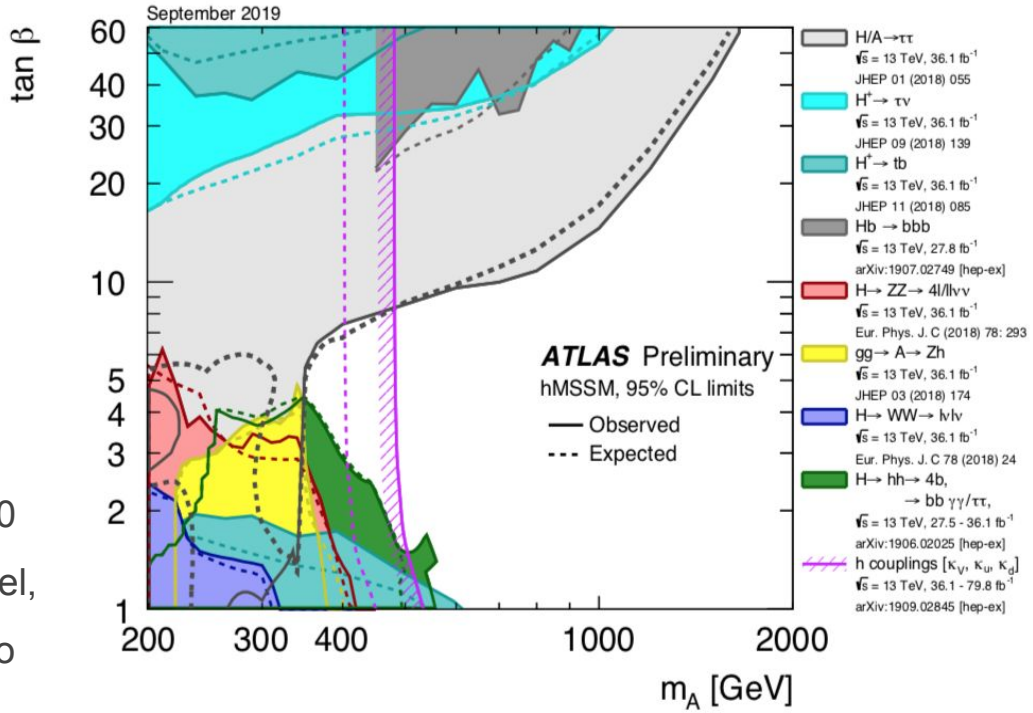




ArXiv:1907.02749

Run 2 BSM Higgs exclusion in the hMSSM

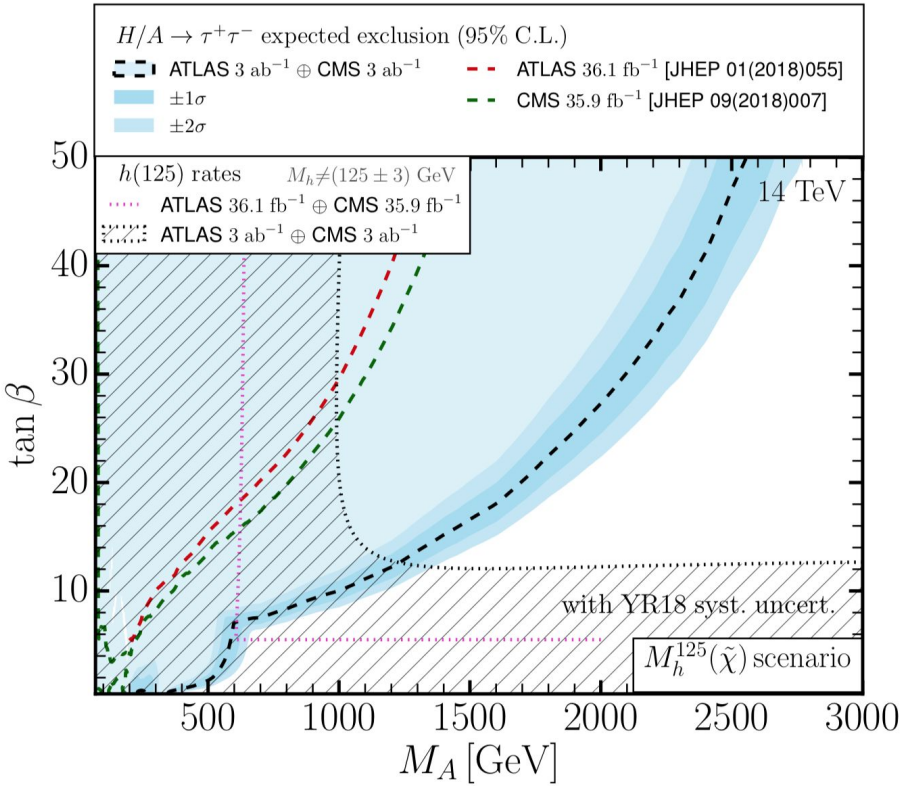
- A large number of channels have been included, even some of the di-Higgs channels.
- Also includes BSM interpretation of SM Higgs couplings limits.
- The ττ final state covers the largest phase space.
- H/A→ $t\bar{t}$ is probed by CMS from 400 to 700 GeV and excludes, at 95% confidence level, the region with values of tan *β* below 1.0 to 1.5.



Summary in the mA vs tan β combination plot (hMSSM)

HL-LHC prospects for the MSSM Higgs sector

- Heavy Higgs masses below 1 TeV will be completely probed.
- In the $M125(\tilde{\chi})$ scenario the $H/A \to \tau^+\tau^-$ reach is weakened due to additional H/A decay modes to light neutralinos and charginos, $H/A \to \tilde{\chi}\tilde{\chi}$.
- Dedicated experimental searches for these decays would be highly complementary and may improve the coverage in the moderate tan β region.



arXiv:1902.00134

Search in less typical scenarios

1.1. search for light neutral A in *b(b)A→ττ*

1.2. Search for $H \rightarrow \mu\mu$

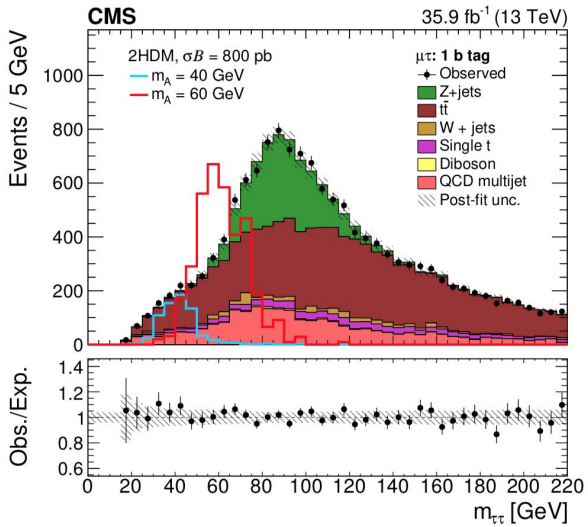
1.3. search for *heavy H* to *ww*

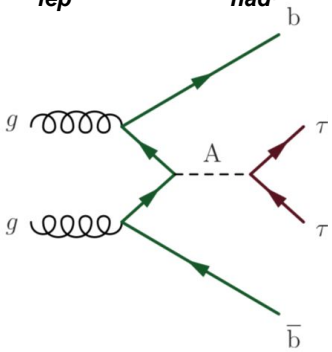
1.4. Higgs Pair Production

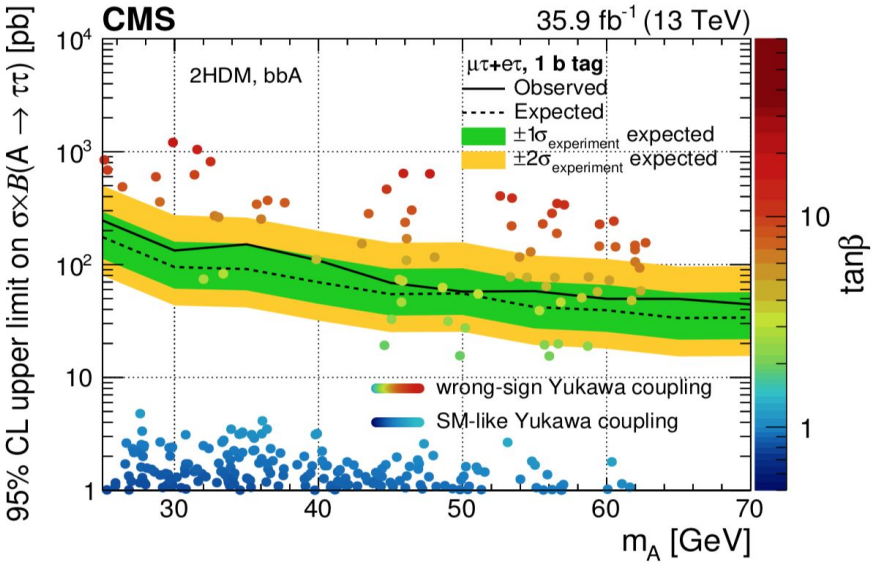
Search for light neutral A in b(b)A → $\tau\tau$

sensitive to type II and III, for high tanβ

search for light Higgs with an m_A ranging from 20 to 70 GeV and A decaying to a pair of τ leptons (one τ_{lep} and one τ_{had}).







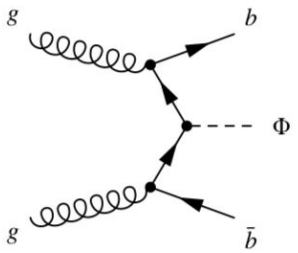
***JHEP 05*(2019)210**

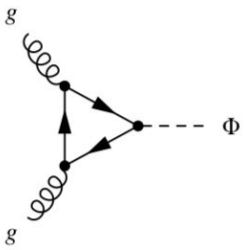
The data are consistent with the background-only hypothesis of the SM.

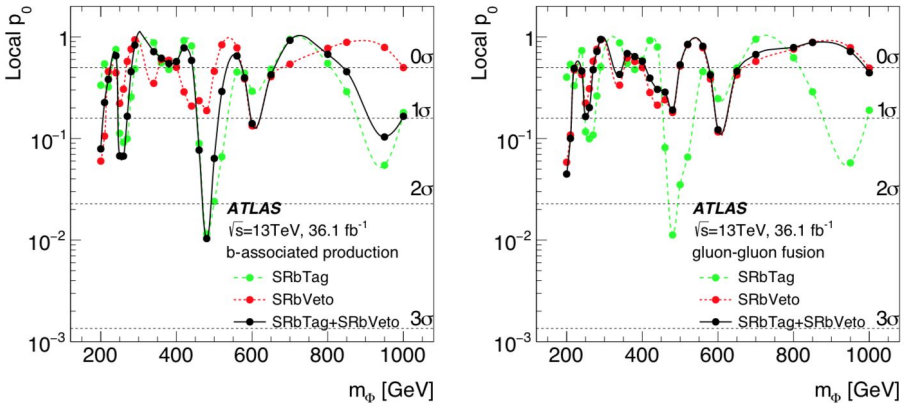
- Models with wrong-sign Yukawa couplings have cross section several orders of magnitude higher than the current limit.
- Models with tanβ > 3 are excluded.

Search for H → μμ

- Search for a massive scalar narrow resonances with and without *b*-tagged jets in the range 0.2-1 TeV.

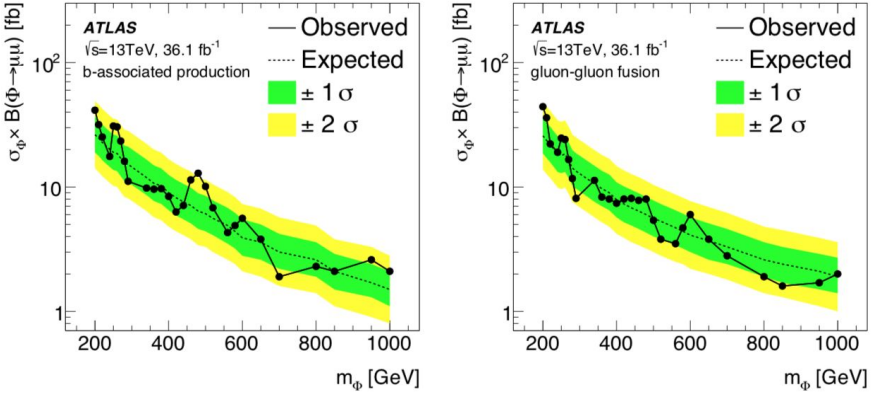






arXiv:1901.08144

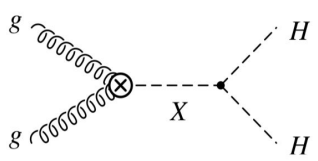
- No significant excess is observed in ATLAS with 36 fb-1 data at 13 TeV.
- A limit is set on the cross section times branching ratio for *b*-quark associated production and gluon–gluon fusion between 1.9 and 41 fb and 1.6 and 44 fb respectively, which is consistent with expectations.

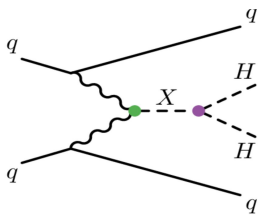


Higgs Pair Production

ATLAS: arXiv:1906.02025

Higgs boson pairs are a key signature of heavy new particle decays in several scenarios BSM in the mass range 260–3000 GeV.



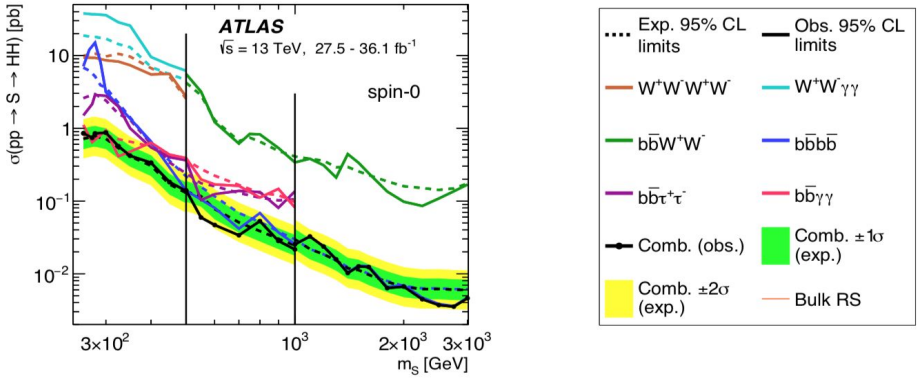


Six final states combined to set limits on:

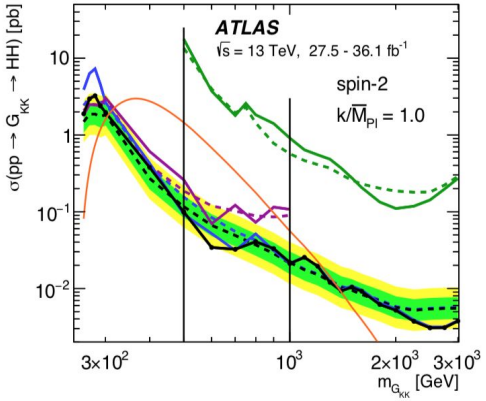
- **Spin-0 heavy scalar** (Heavy Higgs in 2HDM and EWK-Singlet Models).
- **Spin-2 heavy particle** (Randall- Sundrum Graviton).

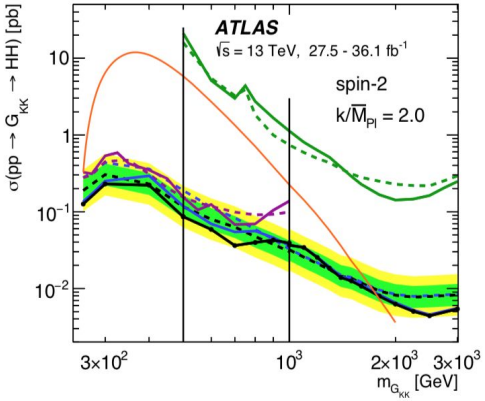
New: Generic inclusive search in the mass range 260-1000 GeV with broad and narrow resonance using HH → bbbb via VBF channel (see backup).

spin-0 heavy scalar



spin-2 KK graviton





Beyond 2HDM

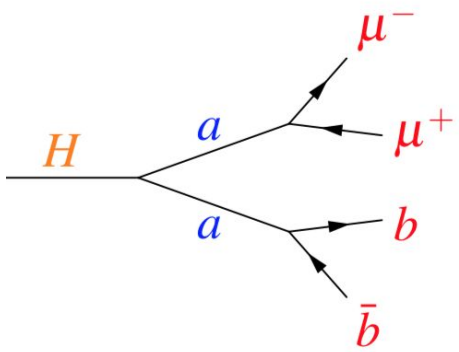
1.1. 2HDM+S signatures

1.2. Invisible Higgs decays

1.3. HL-LHC prospects for invisible Higgs

2HDM+S signatures at LHC

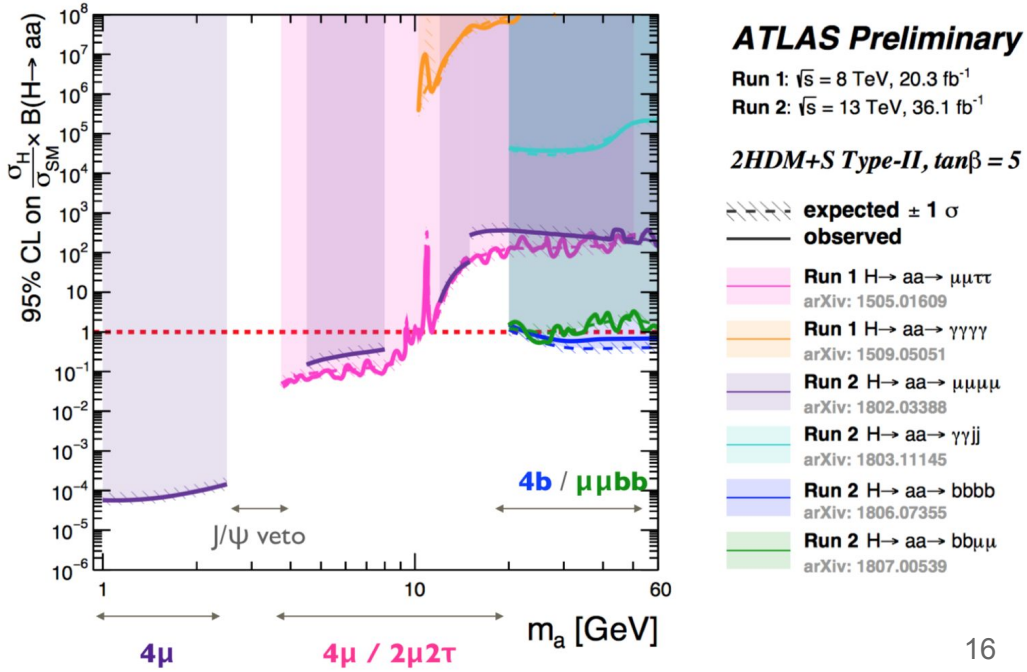
- Search for the decay of Higgs bosons into two light pseudoscalar Higgs bosons "**a**" (**NMSSM**).
- This search is aimed at the **ma > mτ** region.



- "**a → bb**" generally dominates.
- Other decays may also be significant depending on the model: **"a → μμ"**, **"a → ττ"**, **"a → γγ"** and **"a → gg"**.

ATL-PHYS-PUB-2018-045

Upper limit of **ma < 62.5 GeV** set by requirement of H → aa. Most searches sensitive down to 15–20 GeV.



Invisible Higgs decays

- Higgs can decay to DM through the Higgs portal model.
- Such decays produce long lived particles which escape undetected.
- They called "invisible" but can be inferred indirectly from final states with large E_T^{miss}.

$\mathcal{B}_{inv}$ at 95% CL; obs (expected)

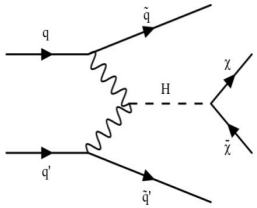
ATLAS	
Run 1	0.25 (0.27)
2015+2016	0.38 (0.21)
All	0.26 (0.17)

CMS	
Run 1+2015	0.23 (0.24)
2016	0.26 (0.20)
All	0.19 (0.15)

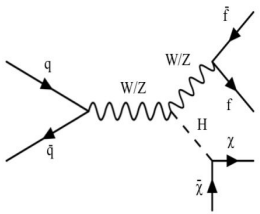
ATLAS: PRL 122 (2019) 231801

CMS: PLB 793 (2019) 520

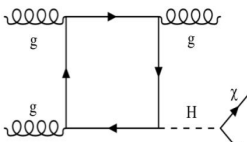
Searches for invisible decays of Higgs produced in VBF (CMS, ATLAS), in association with Z(ll) or Z/W(hadrons).



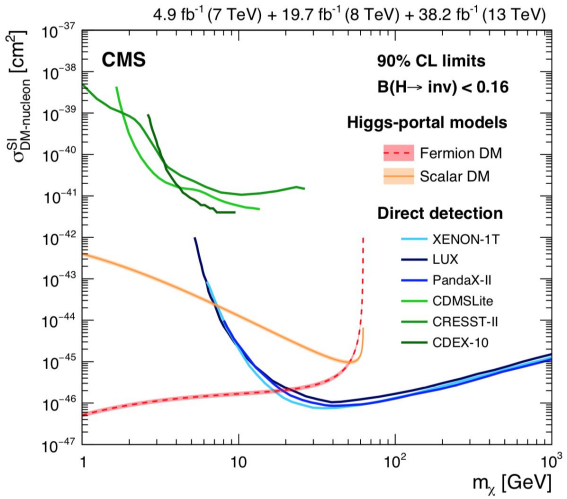
VBF



W/Z



ggF



90% CL upper limits on the spin-independent DM-nucleon scattering cross section in Higgs-portal models, assuming a scalar or fermion DM candidate.

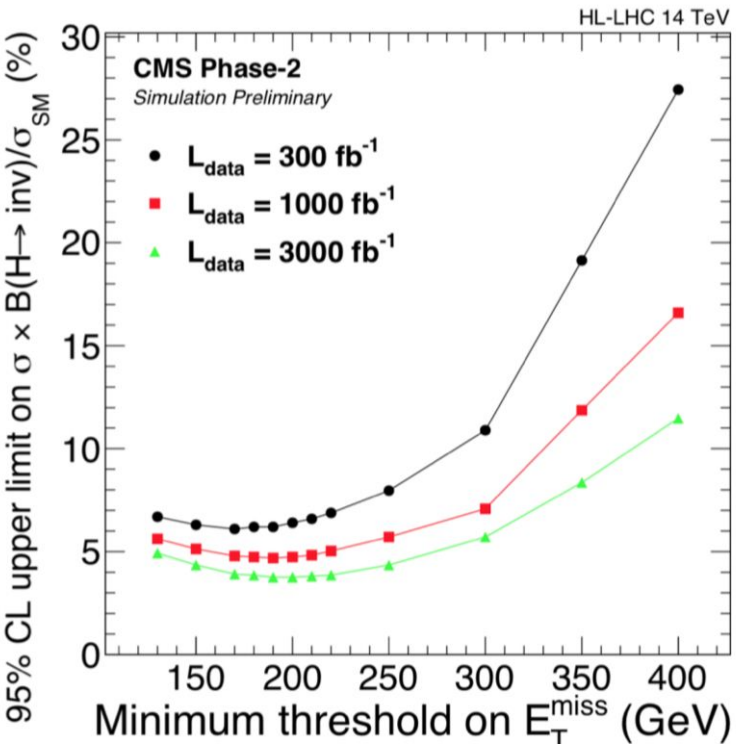
HL-LHC prospects for invisible Higgs

CMS projection for VBF: BR(H → inv) < 3.8%.

ATLAS projection for VH: BR(H → inv) < 8%.

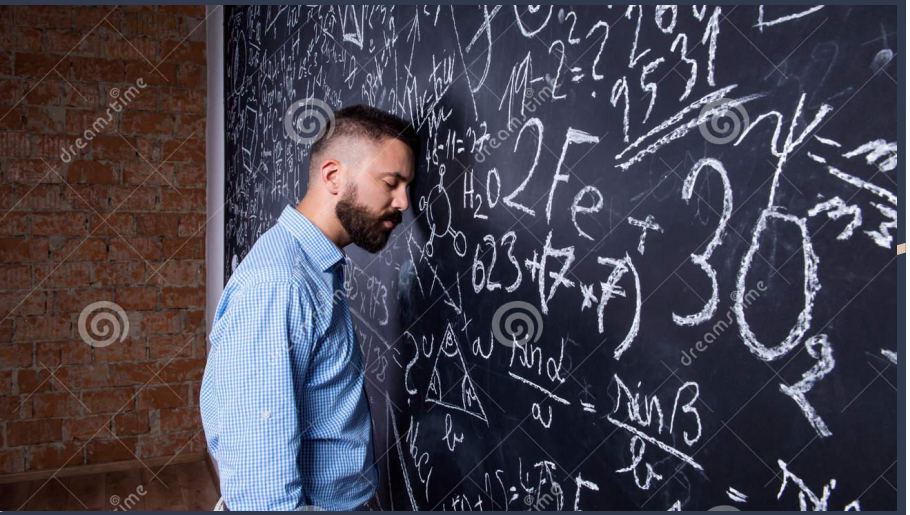
ATLAS has conducted a study to show the impact of pileup jets on the invisible Higgs branching ratio limit in the VBF channel [ATL-PHYS-PUB-2018-038, 2018].

the development of improved pileup jet mitigation will be an important development to empower the invisible Higgs decay analyses in the future.



arXiv:1902.00134

Conclusion



- ➔ No signs of deviations from SM so far, but still large room for data reconstruction and analysis improvements, new model testing, new data interpretation …
- ➔ Still there are small excesses which could grow .. To be watched out with more statistics.
- ➔ LHC Run2 potential still to be exploited.
- ➔ from Run3 to HL-LHC, a long path for a deep scrutiny of tiny effects.

More material ...

Searches for charged Higgs $H^{\pm}/H^{\pm\pm}$

Process	Experiment	Ref [ ]	√s [TeV]	√L [fb^{-1}]
$H^{\pm} \rightarrow tb$	ATLAS	JHEP 11 (2018) 085	13	36.1
	CMS	CMS-PAS-HIG-18-004 CMS-PAS-HIG-18-015	13	35.9
$H^{\pm} \rightarrow \tau\nu$	ATLAS	JHEP 09 (2018) 139	13	36
	CMS	JHEP 07 (2019) 142	13	35.9
$H^{\pm} \rightarrow WZ$	CMS	CMS-CR-2018-261	13	35.9
$H^{\pm\pm} \rightarrow WW$	CMS	CMS-PAS-SMP-17-004	13	35.9

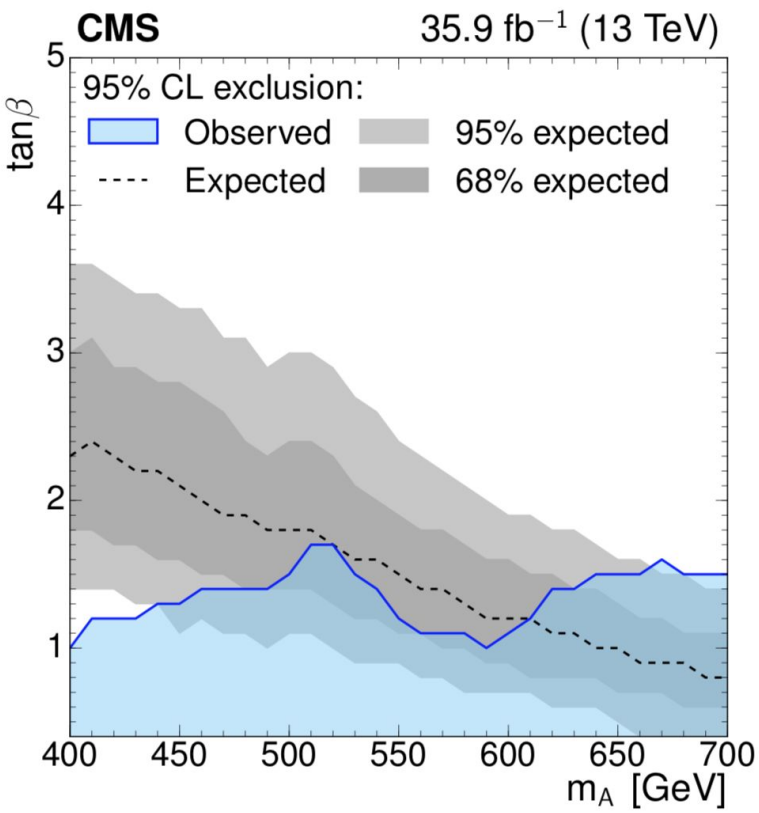
Search for heavy neutral Higgs A/H

Process	Experiment	Ref [ ]	√s [TeV]	√L [fb^{-1}]
A/H → tt	ATLAS	PRL119 (2017) 191803	8	20.3
	CMS	ArXiv:1908.01115	13	35.9
b(b)H -->bb, b(b)H -->$\tau\tau$	ATLAS	ArXiv:1907.02749 JHEP01(2018) 055	13	27.8 36.1
	CMS	JHEP08(2018)113 JHEP 09 (2018)007	13	35.9
(MSSM) H → $\mu\mu$	CMS	**arXiv:1907.03152**	13	35.9
A → ZH	ATLAS	**arXiv:1712.06518**	13	36
	CMS	CMS-PAS-HIG-18-023	13	35.9

Run 2 BSM Higgs exclusion in the hMSSM

H/A→ $t\bar{t}$ is probed by CMS from 400 to 700 GeV and excludes, at 95% confidence level, the region with values of tan β below 1.0 to 1.5

Exclusion in the (mA , tan β) plane of the hMSSM. The inner (dark gray) band and the outer (light gray) band indicate the regions containing 68 and 95%, respectively, of the distri- bution of constraints expected under the background-only hypothesis. The observed excluded region is indicated by the blue shaded area. Both H and A boson signals are included with masses and widths that correspond to a given point in the plane.

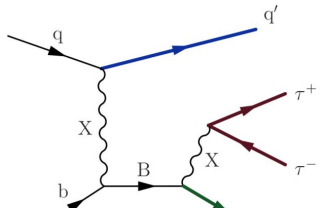


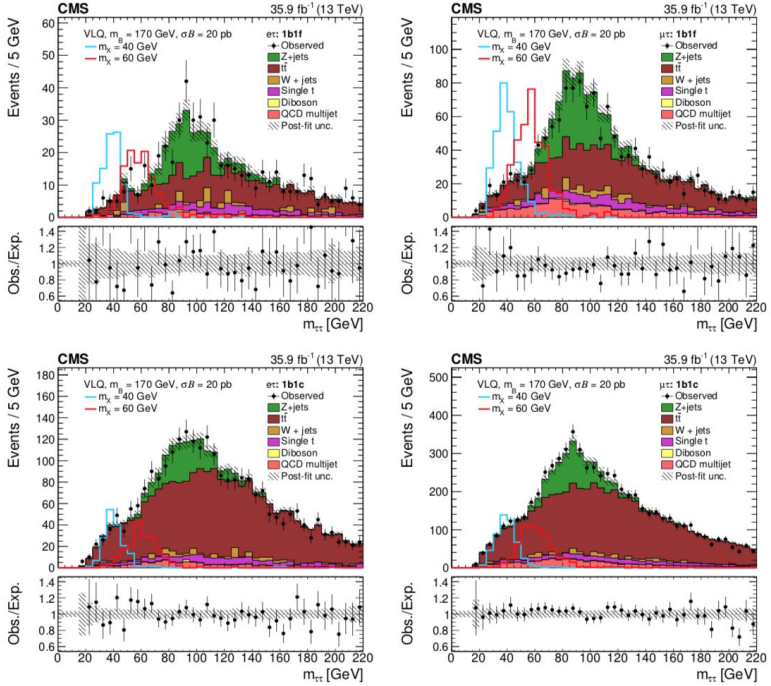
CMS: arXiv:1908.0111

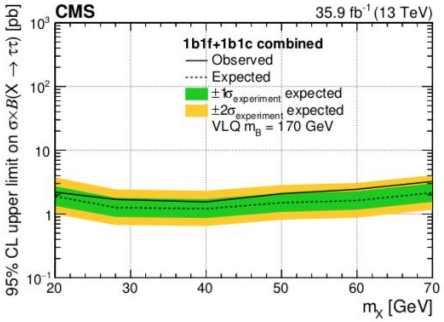
Search for light neutral A in b(b)A → $\tau\tau$

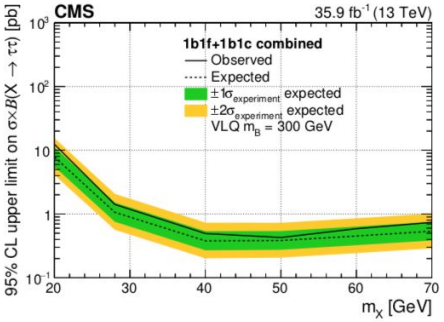
JHEP 05(2019)210

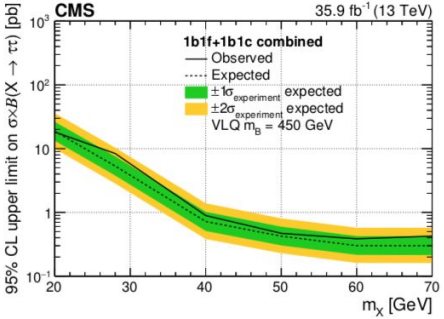
In addition to 2HDM model, there is also another model describes a low-mass boson X decaying to a τ-lepton pair in a process where the X boson is created through the decay of a vector-like quark (VLQ).





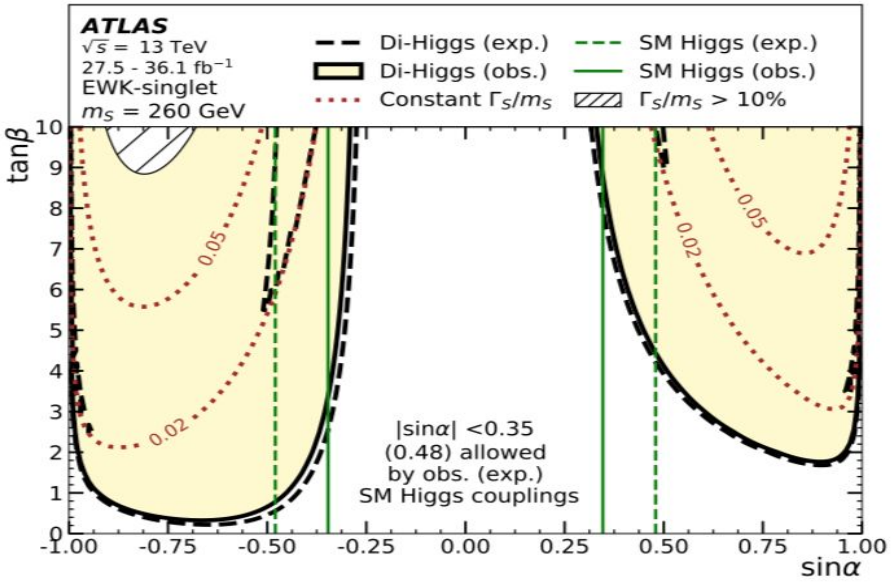


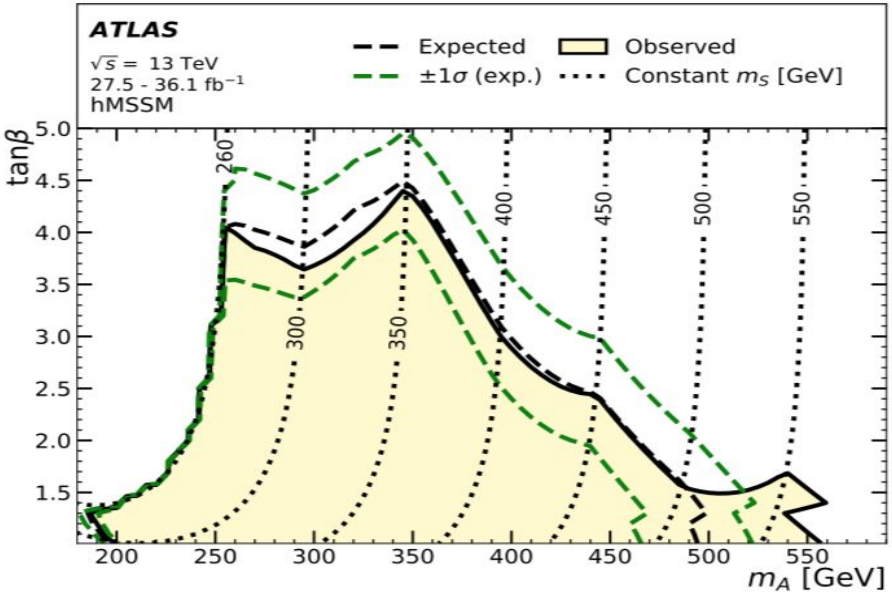




Higgs Pair Production

Constrained the EWK-Singlet Model in the (*m*S, sin α) and the (sin α, tan β) parameter spaces and the hMSSM Model in the (*m*A, tan β).





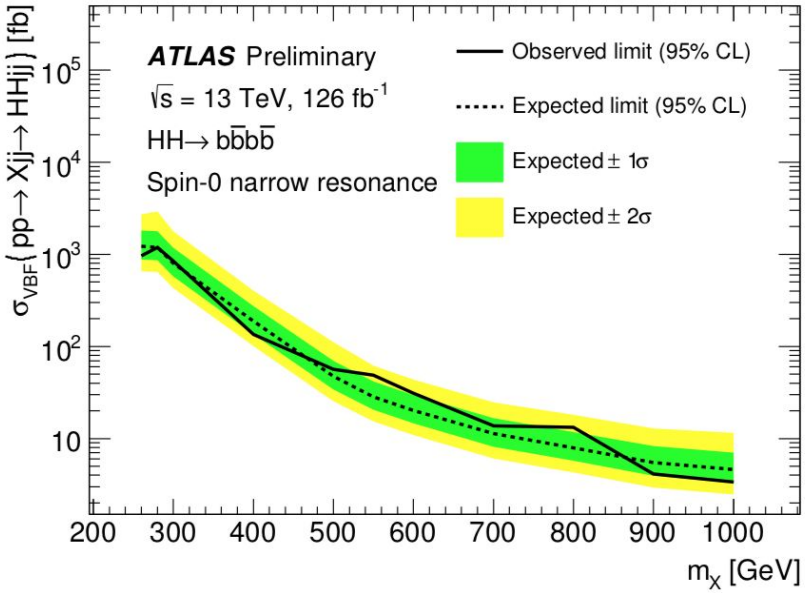
ATLAS: arXiv:1906.02025

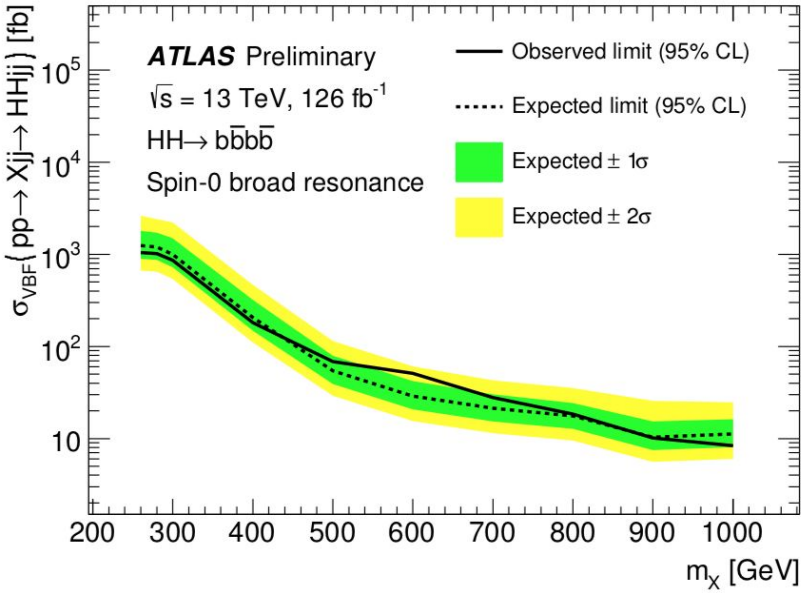
Higgs Pair Production: HH → bbbb

Generic inclusive search for 260< mX <1000 GeV:

1. broad resonance with tanβ = 2.0 and sin (β − α) = 0.6 .
2. narrow resonance with a fixed width of 4 MeV.

ATLAS-CONF-2019-030





Lepton Flavour violating Higgs decays

The presence of LFV Higgs boson couplings would allow $\tau \rightarrow \mu$ and $\tau \rightarrow e$ to proceed via a virtual Higgs boson.

See Tomas Davidek's talk on Lepton flavor violating searches at the LHC

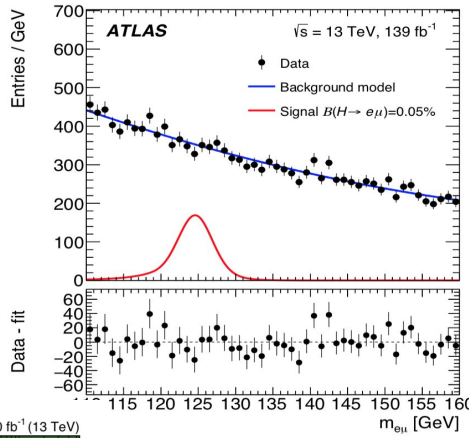
These decays are forbidden in the SM but occur in many new physics scenarios (SUSY,composite Higgs, or Randall– Sundrum models,...)

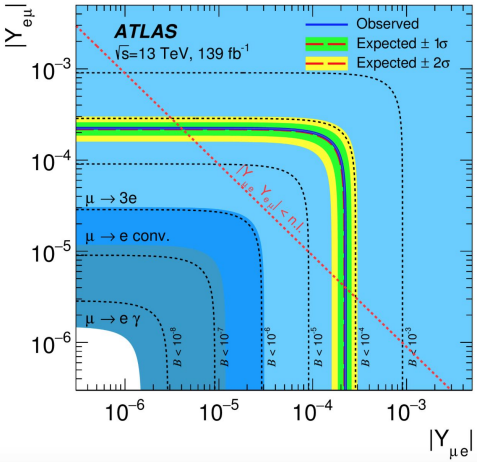
Process	Experiment	Ref [ ]	√s [TeV]	√L [fb^{-1}]
$H \rightarrow e\tau$	ATLAS	arXiv:1907.06131	13	36.1
	CMS	arXiv:1712.07173	13	35.9
$H \rightarrow \mu\tau$	ATLAS	arXiv:1907.06131	13	36.1
	CMS	arXiv:1712.07173	13	35.9
$H \rightarrow e\mu$ $H \rightarrow e\mu$	ATLAS	arXiv:1909.10235	13	139
	CMS	arXiv:1607.03561	8	19.7

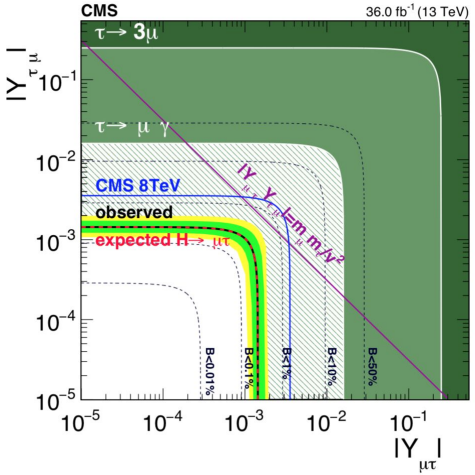
Lepton Flavour violating Higgs decays

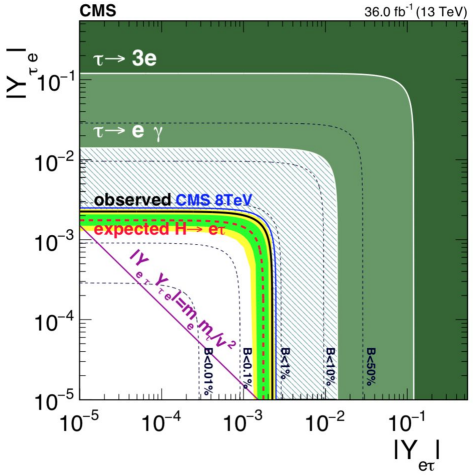
H → eμ with full Run2 stat. (new)

- 8 categories of events corresponding to different meμ resolution
- Combined fit of to the meμ binned spectra
- Background (mainly from top-events) from data (sidebands)







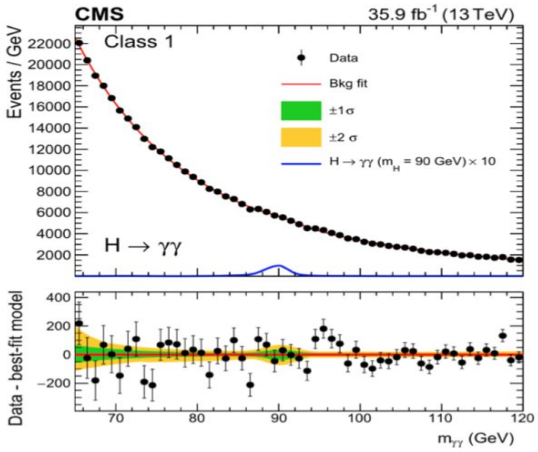


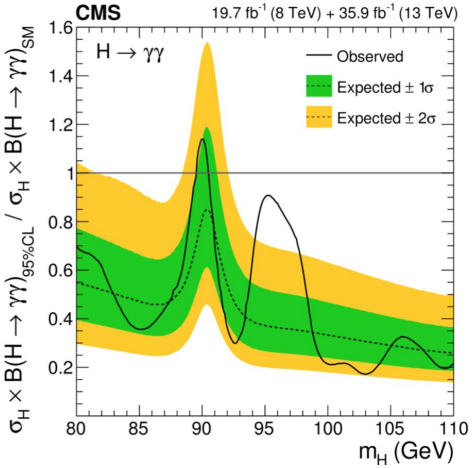
Process	ATLAS	CMS
H → eτ	0.47% (0.34%)	0.61% (0.37%)
H → $\mu\tau$	0.28% (0.37%)	0.25% (0.25%)
H → eμ	0.0061% (0.0058%)	0.035% (0.048%)

SM-like H → γγ in intermediate mass

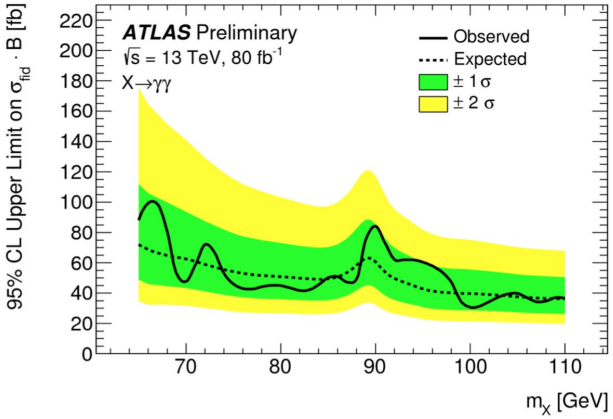
- Several models predict new resonances below the Higgs mass:
  - Additional scalar in 2HDM.
  - Axion-like particles.

- Search for a narrow spin-0 resonances in the range 70-110 GeV.
- Analyses based on SM H->γγ.





- Small excess seen at 95.3 GeV in CMS: 2.8σ local with 8 + 13 TeV (20 + 36 fb-1) data.
- Very minor excess in ATLAS with 13 TeV (80 fb-1) data.
- A limit is set on the fiducial cross section between 80 and 40 fb by ATLAS experiment.



Search for heavy H → WW

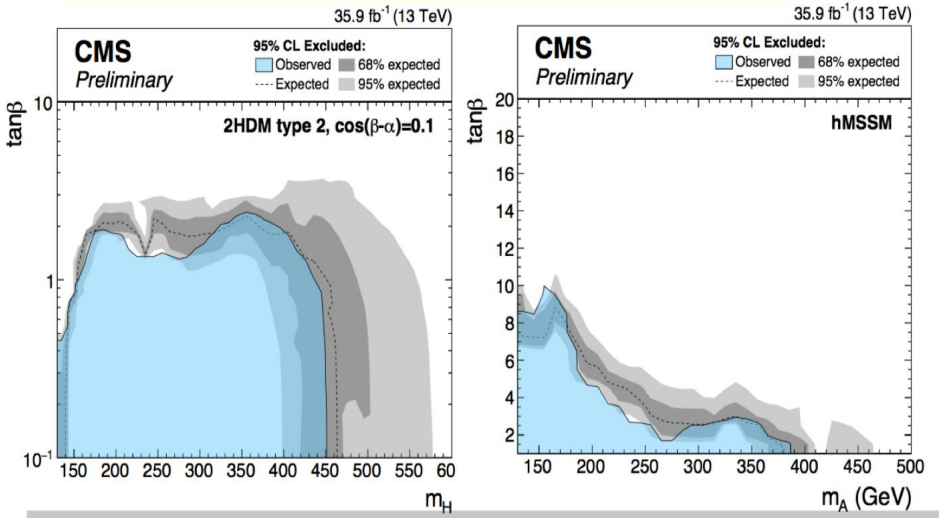
H → WW strongly suppressed in the alignment limit of 2HDM

A ➛ ZZ are forbidden (at tree level) if the CP symmetry is assumed

several analyses in the past; the most recent preliminary by CMS (similar results of ATLAS on the corresponding data set **36fb-1 at 13 TeV**) based on ***semi-leptonic and leptonic channels***

mass range investigated 200 GeV to 3 TeV

a limited region of the parameter space is probed by this channel



CMS: CMS-PAS-HIG-17-033