Search for BSM Higgs Signatures at the LHC

Hale Sert

on behalf of CMS & ATLAS Collaborations

Istanbul University

PIC 2021, Aachen

14-17 September 2021

RWTH Aachen University

Physics Institute III B | RWTH AACHEN UNIVERSITY

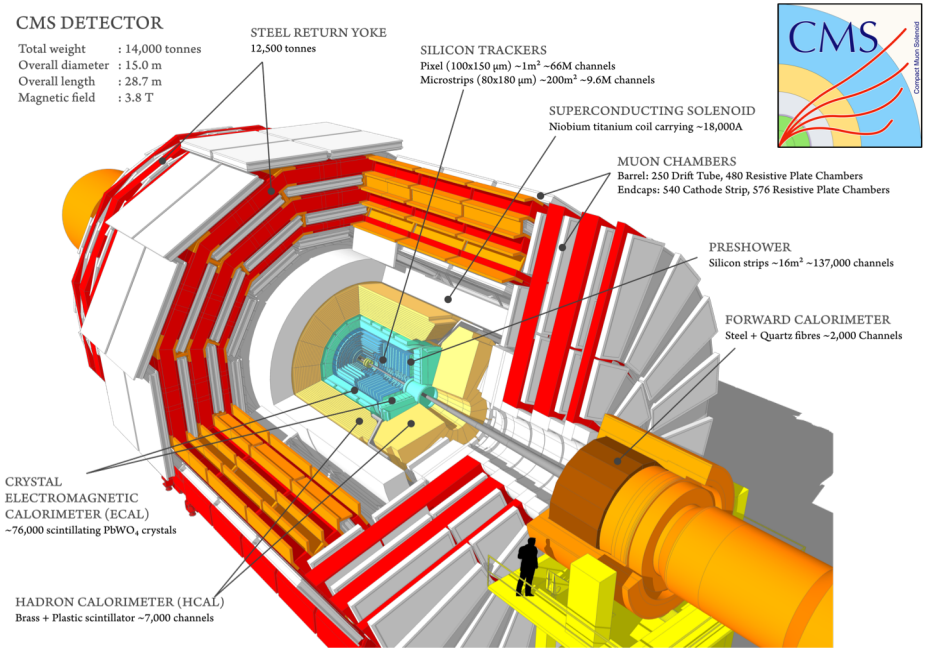
Physics in Collision

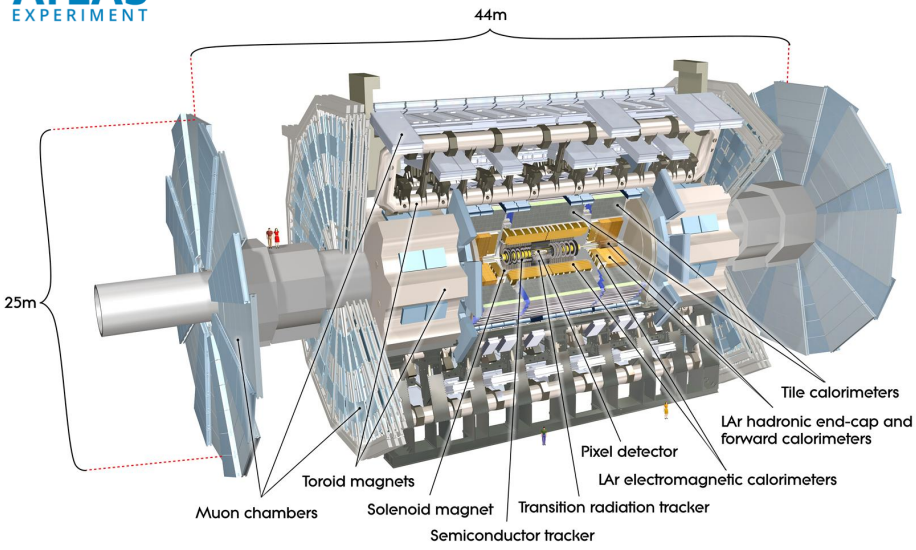
40th International Symposium on Physics in Collision

RWTH Aachen University, Aachen, Germany | September 14-17, 2021

Outline

- The Higgs boson (H) was discovered in 2012 by the ATLAS and CMS collaborations
- The measured properties have so far been in agreement with the SM predictions





- Have we observed the Higgs boson of the Standard Model?
- What else it could be?
- How to search for the BSM Higgs signatures at the LHC?

Some of Beyond the SM Theories

- The main extension of the SM is the addition of a Higgs doublet! (2HDM, MSSM)
  - In the Standard Model: one complex Higgs doublet => 1 Higgs boson, h
  - In extended models: two complex Higgs doublets => 5 Higgs bosons, $h, H, A, H^{\pm}$

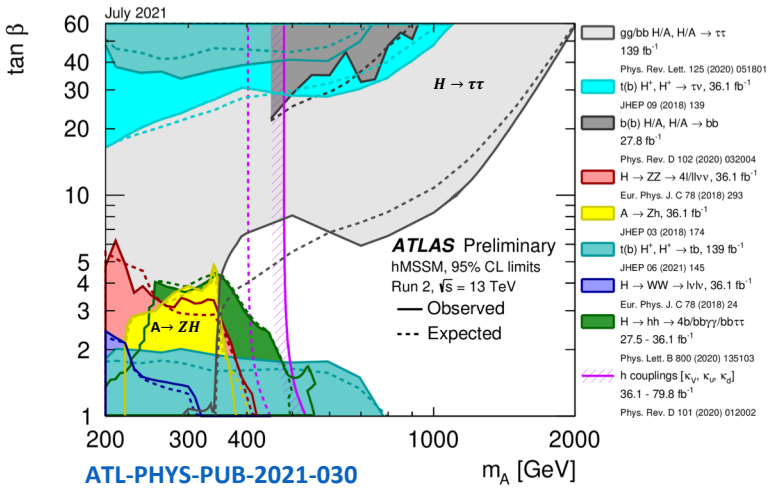
@2HDM

- It has four types, depending on the way the two $SU(2)_L$ doublets are coupled to the fermion sector:
  - Type I: the $SU(2)_L$ doublets couple to both up- and down-type fermions equally
  - Type II: one doublet couples exclusively to up-type and the other exclusively to down-type fermions

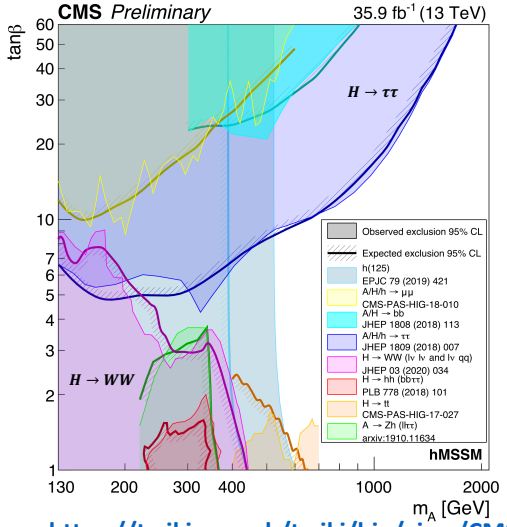
@MSSM (Type II 2HDM)

- The Higgs sector of MSSM is determined at tree level by only two parameters
  - M_A and $\tan\beta$

  where $1 < \tan\beta = v_2/v_1 < 60$



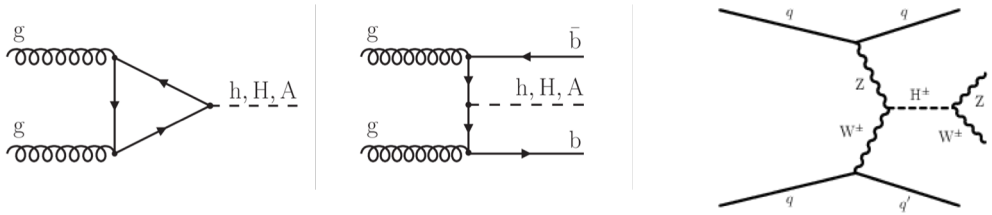
ATL-PHYS-PUB-2021-030



https://twiki.cern.ch/twiki/bin/view/CMSPublic/SummaryResultsHIG

Beyond the SM Higgs Searches

- BSM theories predict new additional Higgs bosons that trigger **searches for** those **additional bosons**
  - CP even Higgs boson
  - CP odd A boson
  - Charged Higgs bosons, H^+, H^-



- The self coupling of the Higgs boson is also predicted in the SM. **The double Higgs boson production** is one of the way to search for it. Any deviation from the SM would be an indication of new physics.
  - Non-resonant production
  - Resonant production

- New physics could be also found in searches for exotic decays
  - Lepton Flavour Violating Decays, $H \rightarrow e\tau$
  - Decays to pseudo scalars, $H \rightarrow aa$
  - Decays to invisible particles, $H \rightarrow inv$

Searches for additional Higgs bosons

- CP even Higgs boson
- CP odd A boson
- Charged Higgs bosons, H^+, H^-

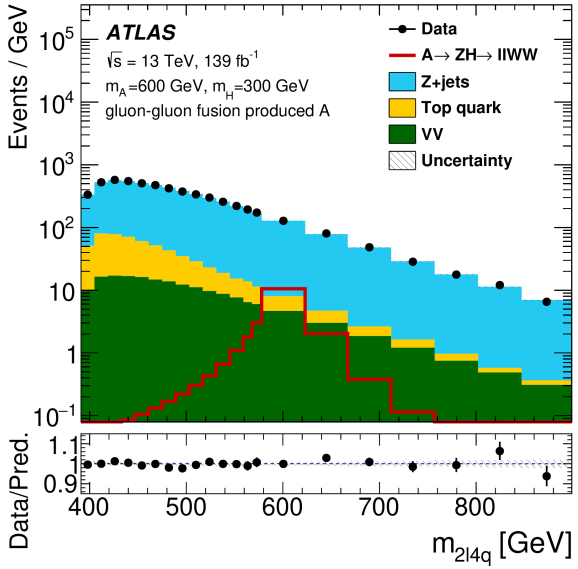
$A \rightarrow ZH$ Searches in ATLAS ($m_H > 125\ GeV$)

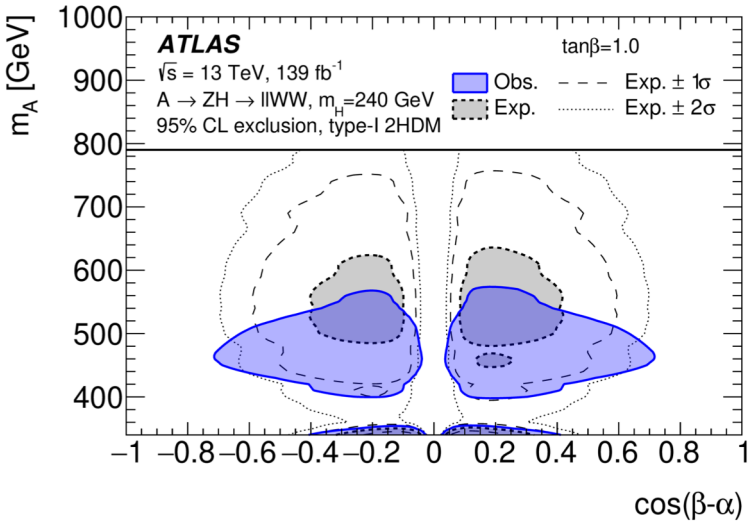
using the full Run 2 dataset

Eur. Phys. J. C. 81 (2021) 396

- A search is performed with the following mass ranges:
  - $230 < m_A < 800$ GeV and $130 < m_H < 700$ GeV for $\boldsymbol{H \rightarrow b\bar{b}}$, (ggF and b-associated production)
  - $300 < m_A < 800$ GeV and $200 < m_H < 700$ GeV for $\boldsymbol{H \rightarrow W^+W^-}$, W decays hadronically (ggF prod.)

  when $\mathbf{Z} \rightarrow \ell^+\ell^-$
- $m_{\ell\ell bb}$ and $\boldsymbol{m_{2\ell 4q}}$ distributions are used as final variables to discriminate signal from the backgrounds
- No significant deviation from the SM background predictions
- Observed upper bounds at 95% CL are set on the $\sigma_{prod} \times BR$





The results are interpreted in 2HDM phase spaces!

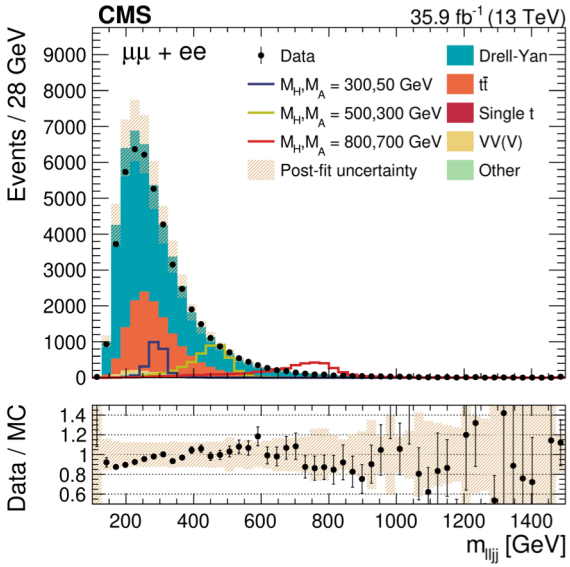
New: The $A \rightarrow ZH \rightarrow WW\ell\ell$ channel has not been explored previously at the LHC!
The mass range of $A \rightarrow ZH \rightarrow b\bar{b}\ell^+\ell^-$ is extended up to 2 TeV in ATLAS-CONF-2020-043

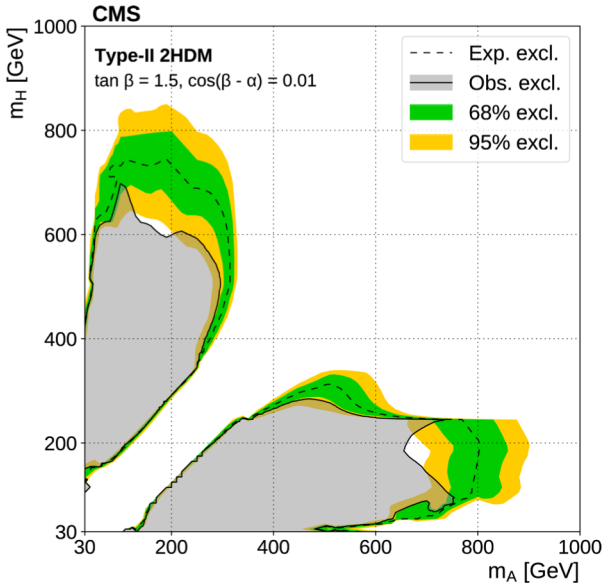
$A(H) \rightarrow ZH(A)$ Searches in CMS

using the 2016 dataset

JHEP 03 (2020) 055

- A H or A boson is searched in the mass range of $120 < m_H(m_A) < 1000$ and $30 < m_A(m_H) < 1000$ GeV, when $\boldsymbol{H(A)} \rightarrow \boldsymbol{b\bar{b}}$ and $\boldsymbol{Z} \rightarrow \ell\bar{\ell}$ with $\ell = e, \mu$
- $m^{inv.}_{\ell^+\ell^- b\bar{b}}$ are used to search for a resonant-like excess of events compatible with the H and A masses
- No significant deviations from the SM expectations are observed
- Model independent upper limits on $\sigma \times BR$ are set, and results are interpreted in type-II of 2HDM scenario
  - The interpretation in the all four type of 2HDM is done in Eur. Phys. J. C 79 (2019) 564





For tan β = 1.5 and cos(β −α) = 0.01,

- with mH > mA, regions in
  - $150 < m_H < 700$ GeV
  - $30 < m_A < 295$ GeV

alternatively

- with mH < mA, regions in
  - $30 < m_H < 280$ GeV
  - $150 < m_A < 700$ GeV

are excluded at 95% CL

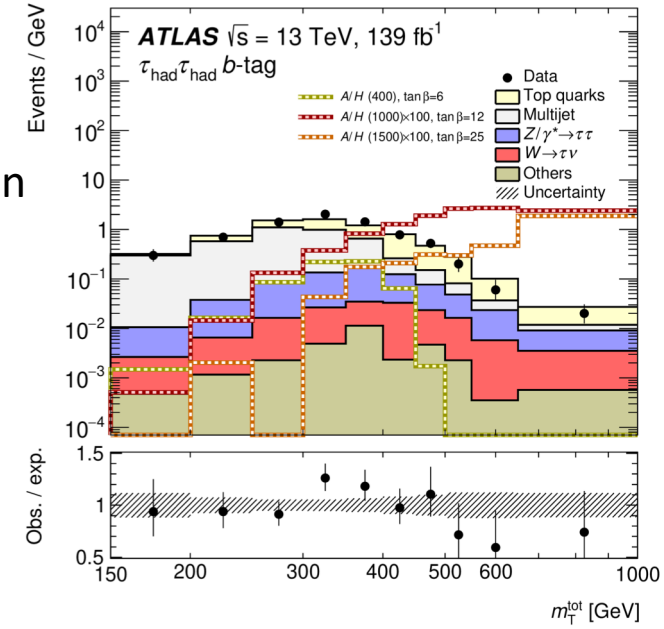
- A larger region of Type-II 2HDM parameter space is excluded compared to previous searches

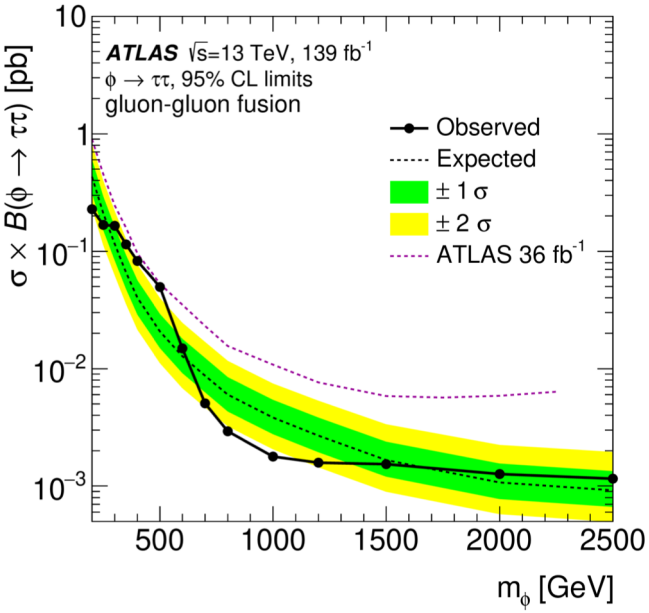
$H/A \rightarrow \tau\bar{\tau}$ Searches in ATLAS

using the full Run 2 dataset

Phys. Rev. Lett. 125, 051801 (2020)

- A search for H or A bosons over the mass range $0.2 < m_{H/A} < 2.5$ TeV is performed in the $\tau^+\tau^-$ decay with $\tau_{lep}\tau_{had}$ and $\tau_{had}\tau_{had}$ final state
- Both gluon fusion and b-associated production modes are considered
- m_T^{tot} is used as discriminating variable
- The events are classified in b-tag and b-veto categories
- The data are in good agreement with the SM bkg prediction
- Model independent upper limits are obtained





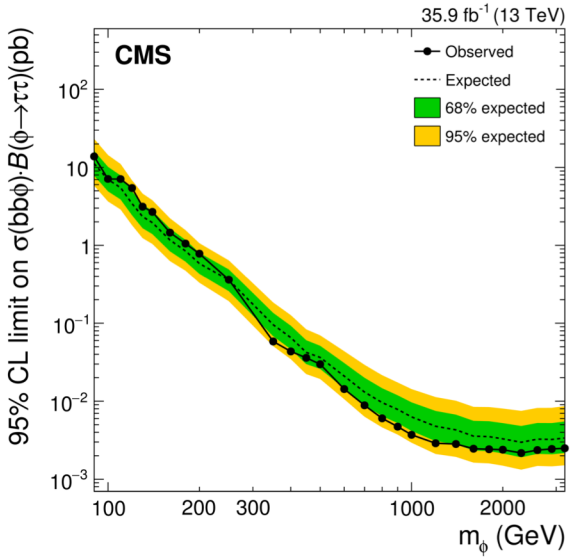
- The sensitivity and explored mass range are significantly increased, especially in the mass range 0.7–2.5 TeV!
- The results are interpreted in MSSM scenarios

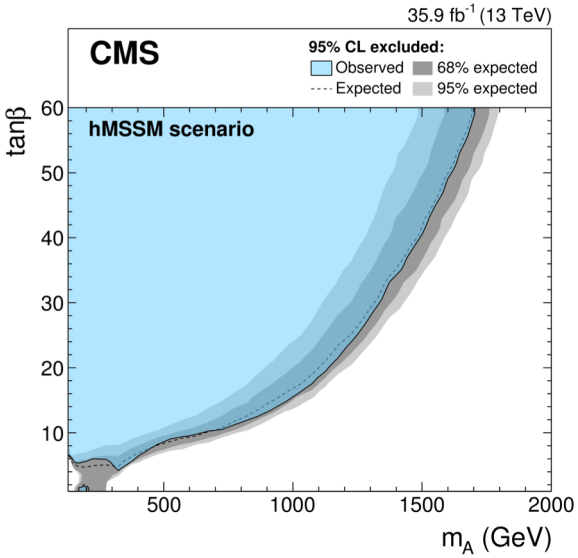
$H/A \rightarrow \tau\bar{\tau}$ Searches in CMS

using the 2016 dataset

JHEP 09 (2018) 007

- A heavy Higgs boson is searched in the mass range of $90 < m_{\phi} < 3200$ GeV in $\phi \rightarrow \tau\bar{\tau}$
  - In the channels of $e\mu, e\tau_h, \mu\tau_h$ and $\tau_h\tau_h$
- Higgs boson production in association with b quarks is considered to enhance sensitivity!
- Discriminating variable: $m_T^{tot} = \sqrt{m_T^2(p_T^{\tau_1}, p_T^{\tau_2}) + m_T^2(p_T^{\tau_1}, p_T^{\tau miss}) + m_T^2(p_T^{\tau_2}, p_T^{\tau miss})}$, where $m_T = \sqrt{2p_T p_T'[1 - \cos(\Delta\phi)}$
- The events are classified in b-tag and no b-tag categories in general
- No significant deviation has been observed





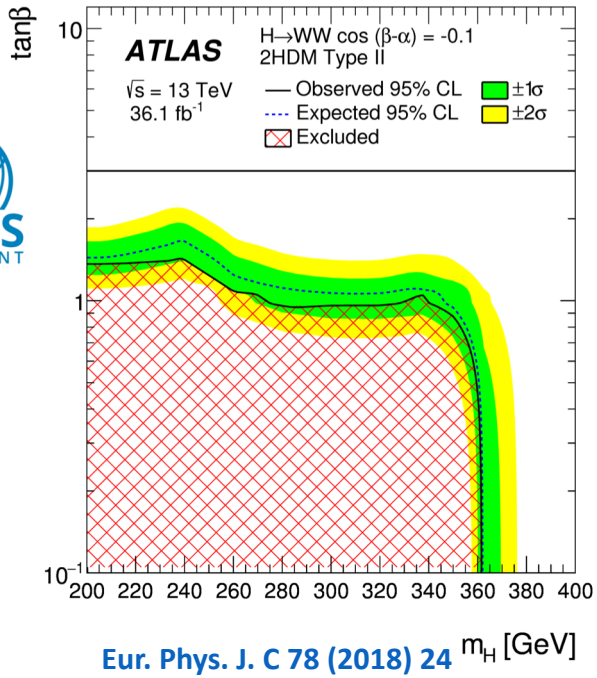
Model independent limits are set in σ × BF (ϕ → τ τ)

- These range from 15 pb to 2.5 fb for production in association with b quarks
- Exclusion regions are determined in tan β − mA plane for specific scenarios

$H \rightarrow W^+W^-$ Searches in ATLAS & CMS

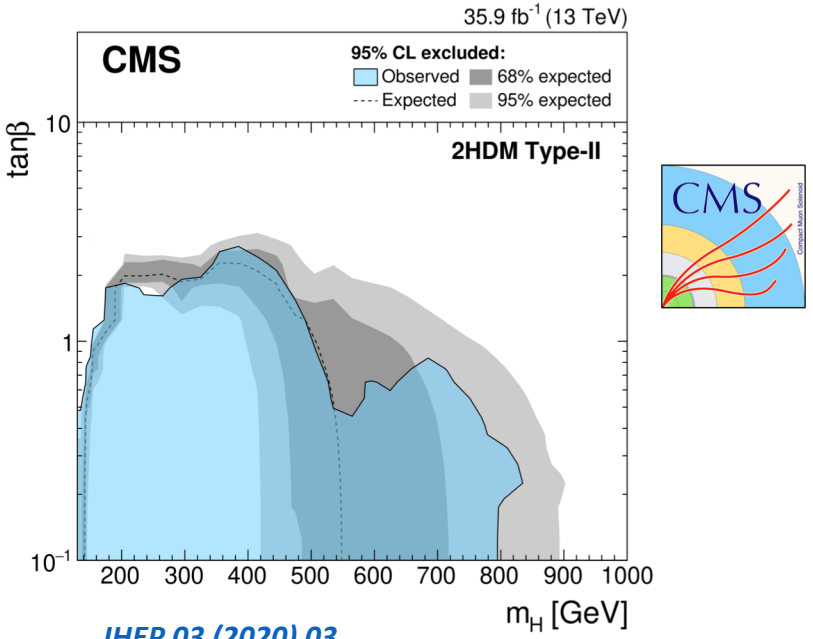
using the 2016 dataset

- Mass range of $0.2 < m_H < 5$ TeV
- In $e\nu\mu\nu$ final state
- Quark-antiquark annihilation or gluon-gluon and vector boson fusion processes are studied



Eur. Phys. J. C 78 (2018) 24

- Mass range of $0.2 < m_H < 3$ TeV
- In $2\ell 2\nu$ and $\ell\nu 2q$ final states
- Gluon and vector boson fusion production modes are considered



JHEP 03 (2020) 03

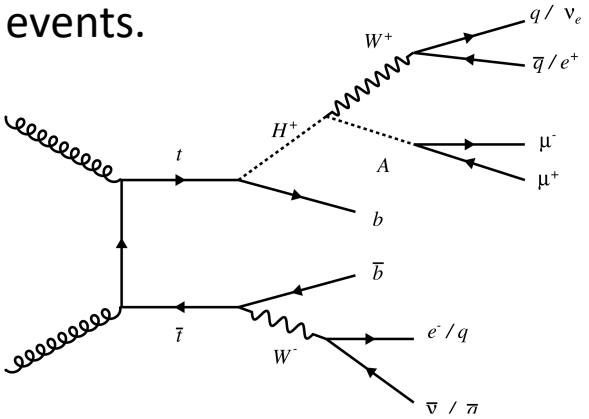
- The data is consistent with the SM expectation
- Model independent limits are obtained and results are interpreted in 2HDM

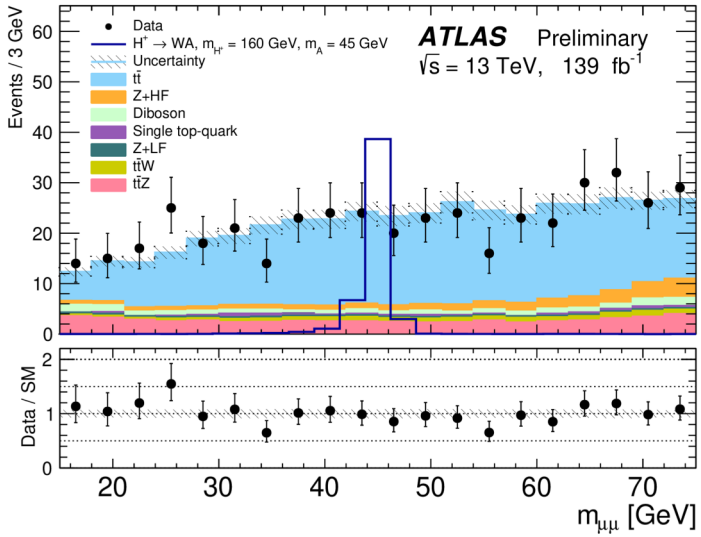
Search for $H^{\pm} \to W^{\pm}A \to W^{\pm}\mu\mu$

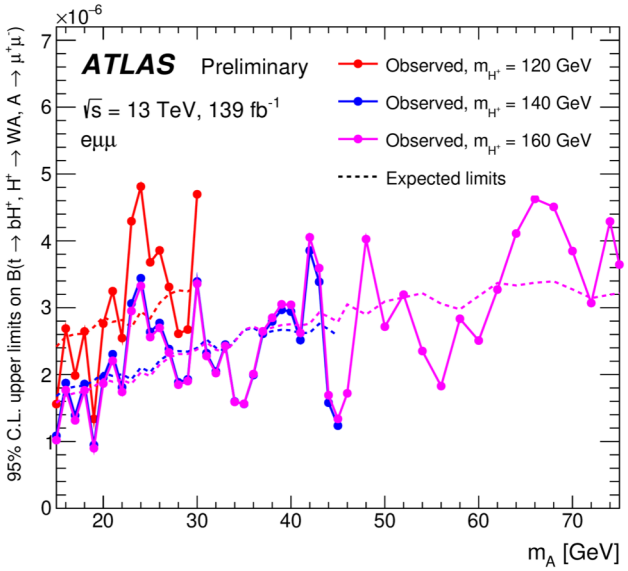
using the full Run 2 dataset

ATLAS-CONF-2021-047

- A search is performed for $H^{\pm} \to W^{\pm}A$, when $A \to \mu\mu$ in $t\bar{t}$ events.
- The mass ranges are
  - $100 < m_{H^{\pm}} < 160$ GeV and
  - $15 < m_A < 75$ GeV
- An excess in the $\mu\mu$ invariant mass spectrum is searched
- No excess has been found, upper limits on $\sigma \times BR$ are set







- New: The first ATLAS searches in this production and decay channel!

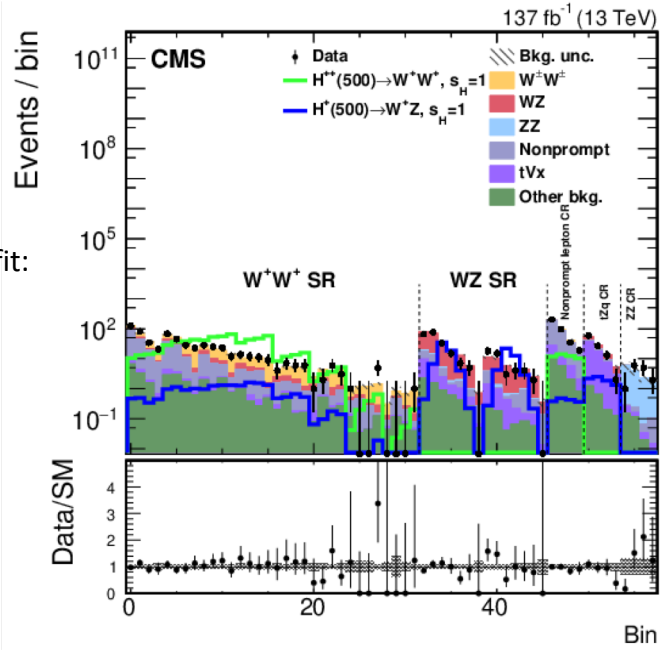
$H^{\pm\pm} \to W^{\pm} W^{\pm}$ and $H^{\pm} \to W^{\pm}Z$

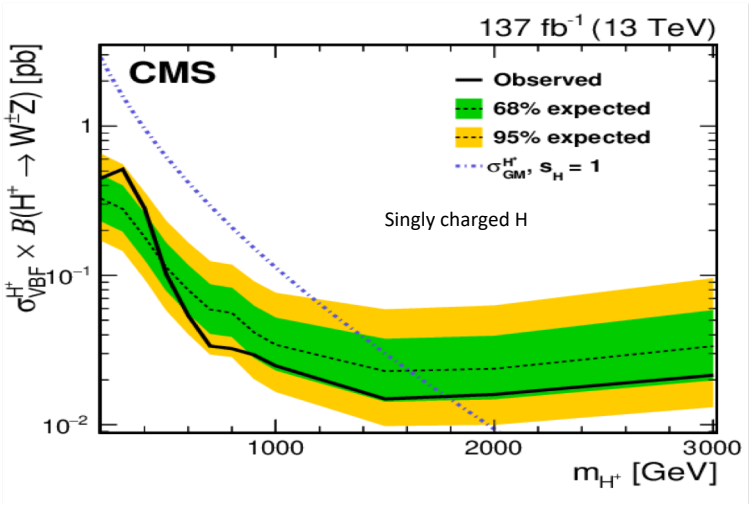
using the full Run 2 dataset

Eur. Phys. J. C (2021) 81:723

- The search is performed for the VBF production of $H^{\pm\pm}$ and $H^{\pm}$ over mass range: $200 < m_{H^{\pm\pm}}/m_{H^{\pm}} < 3000$ GeV in leptonic decays of $W^{\pm} W^{\pm}$ and $W^{\pm}$Z
- The $W^{\pm} W^{\pm}$ and $W^{\pm}$Z channels are simultaneously studied using the di-boson transverse mass m_T and dijet invariant mass m_{jj} distributions

Distributions for the bins used in the simultaneous fit:





- No excess of events with respect to the SM background predictions is observed.
- Model independent upper limits at 95% CL are reported on the $\sigma \times BR$ for VBF production of charged Higgs bosons

$H^{\pm\pm} \to W^{\pm} W^{\pm}$ and $H^{\pm} \to W^{\pm}Z$

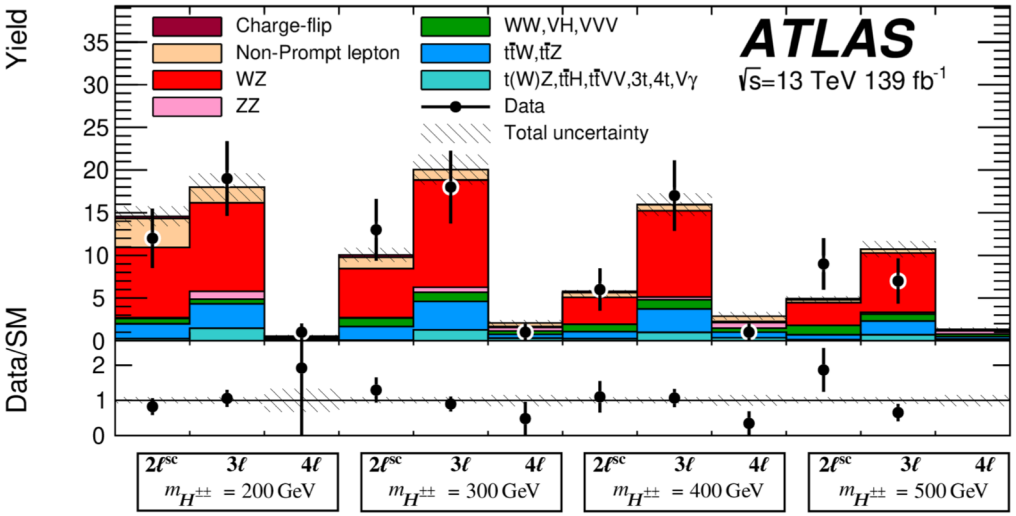
using the full Run 2 dataset

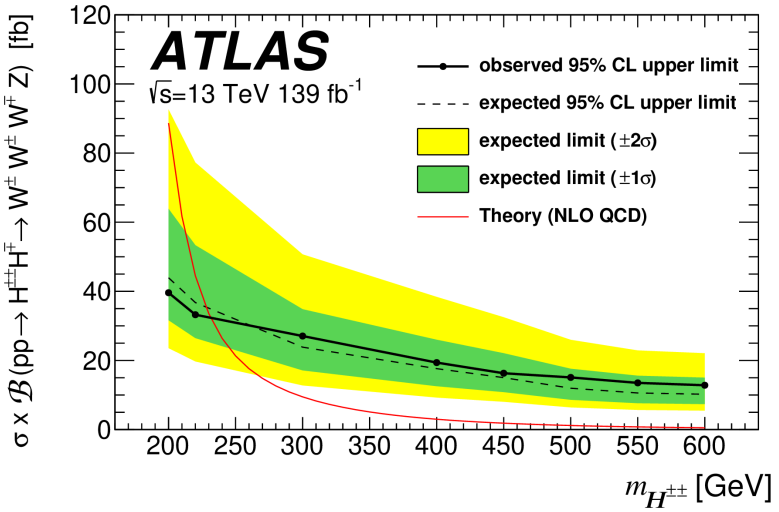
JHEP06 (2021) 146

The search is performed in the mass range of $200 < m_{H^{\pm\pm}} < 600$ GeV

- In final states of two same charge leptons (SC) ($2\ell^{SC}$), three leptons (3ℓ) or four leptons (4ℓ)

New: The associated production of $H^{\pm\pm}$ and $H^{\pm}$ bosons is explored!



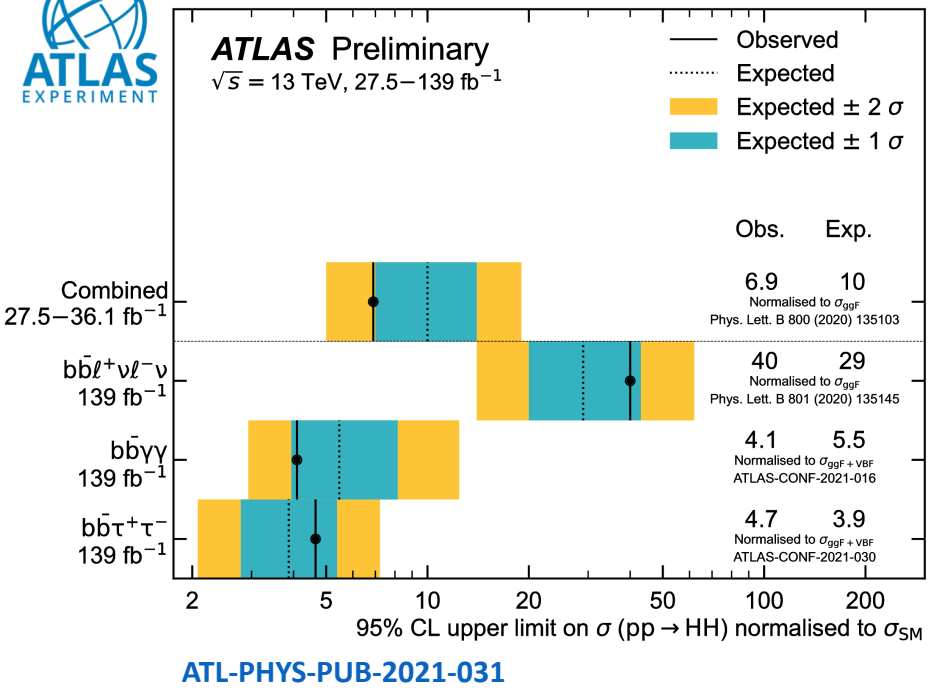


- No significant deviation from the SM predictions was observed
- $H^{\pm\pm}$ bosons are excluded at 95% CL up to 230 GeV for the associated production mode
- The limit on the $H^{\pm\pm}$ boson mass implies a constraint on the $H^{\pm}$ boson mass
  - which is at most 5 GeV different from the $H^{\pm\pm}$ mass
- Upper limits on the associated production $\sigma \times BR$ range from 40 to 10 fb

Searches for double Higgs boson production

- Non-resonant production
- Resonant production

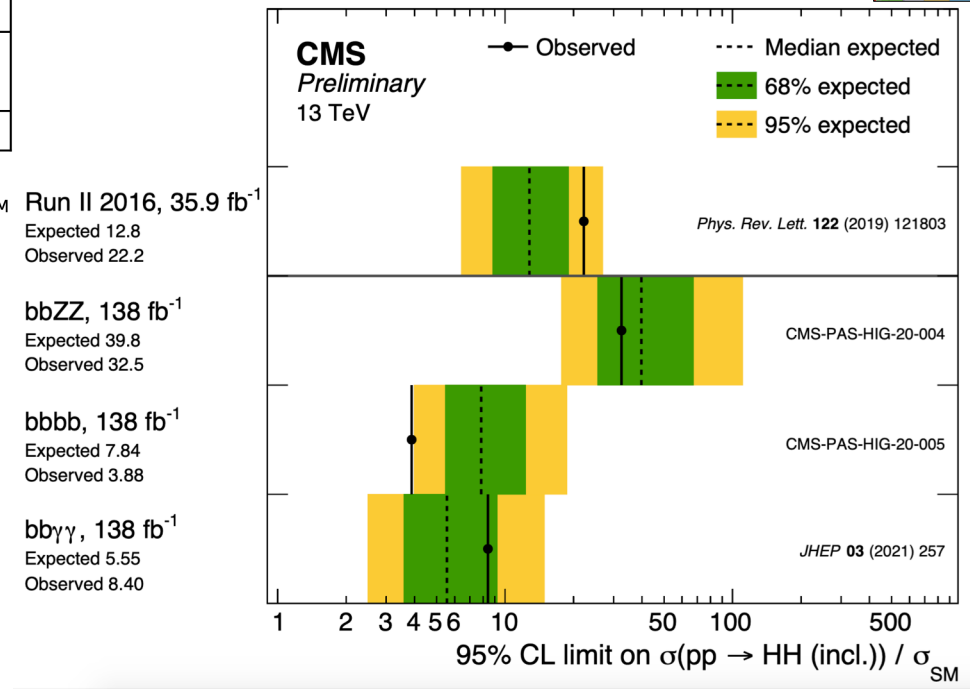
Double Higgs Boson Production Searches



ATL-PHYS-PUB-2021-031

- Non-resonant HH production cross-section to the Standard Model prediction

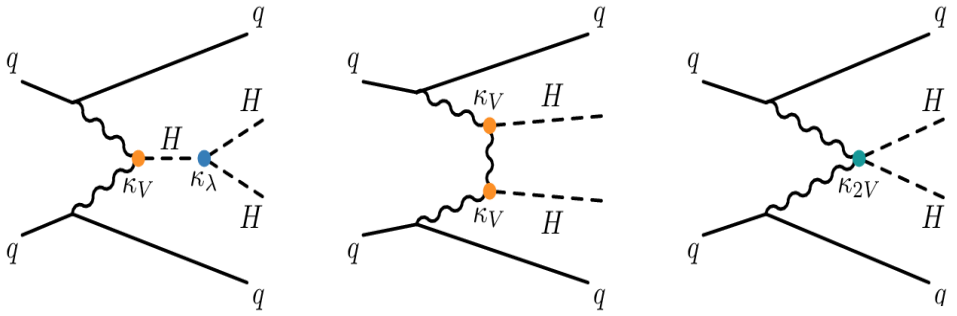
https://twiki.cern.ch/twiki/bin/view/CMSPublic/SummaryResultsHIG

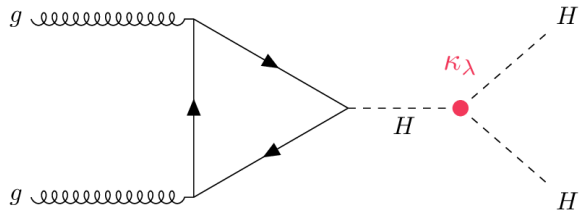


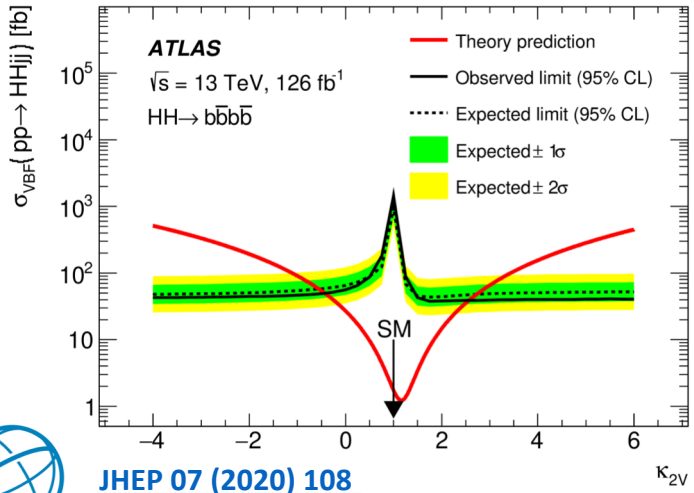
- Both ATLAS and CMS have single-channel analyses that are performing significantly better than the 2016 combined result!

Non-resonant Double Higgs Production

- Non-resonant analyses are used to set limits on predicted couplings (κ_λ, κ_{2V})

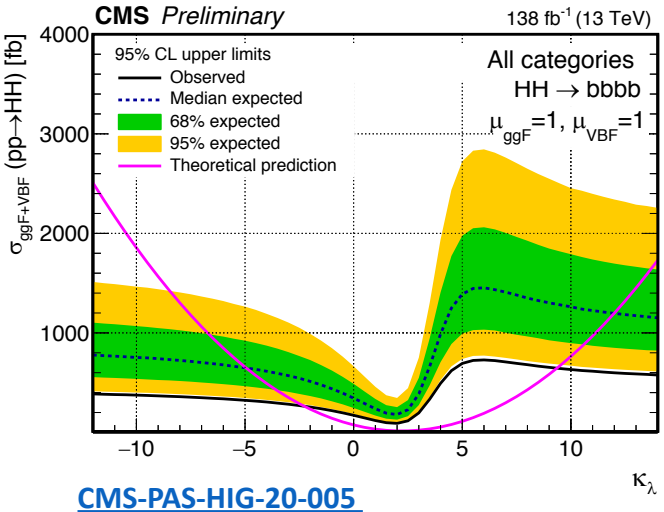






[JHEP 07 (2020) 108]

The observed excluded region corresponds to
$\kappa 2V < -0.43$ & $\kappa 2V > 2.56$

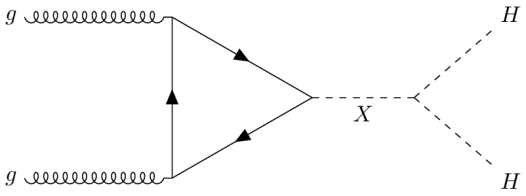


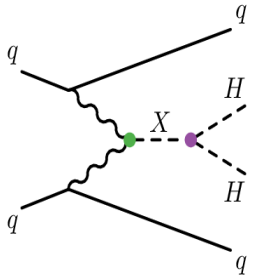
[CMS-PAS-HIG-20-005]

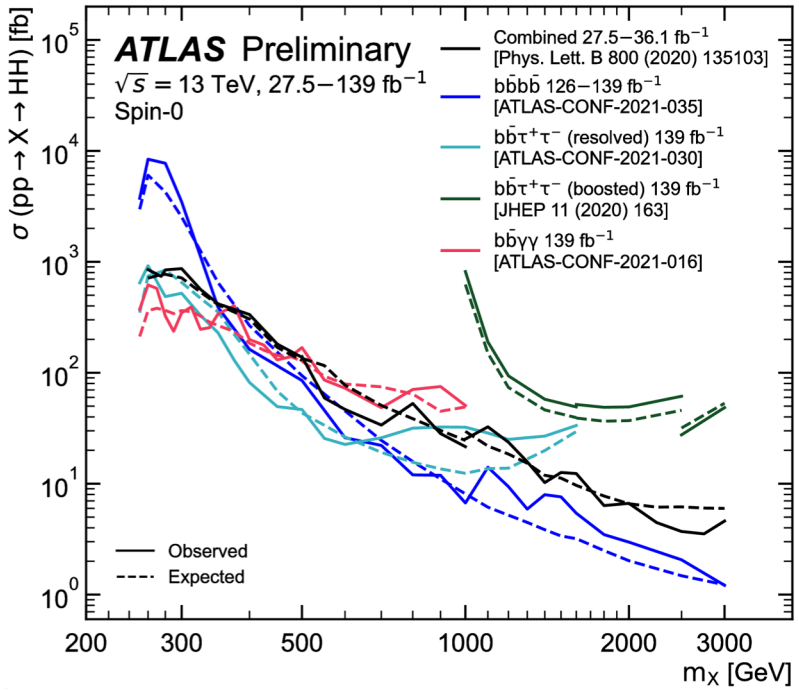
The value of κ_λ normalised to SM expectation is observed to be in the range of $-2.3 < \kappa_\lambda < 9.4$

Resonant Double Higgs Production

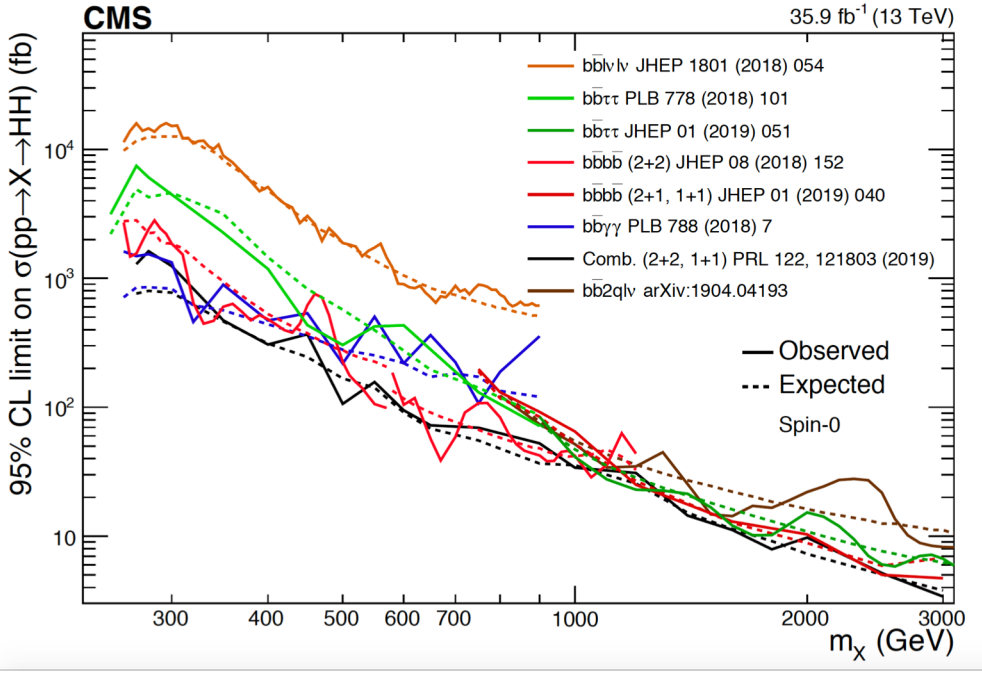
- The resonant production of double Higgs searches are also ongoing!







ATL-PHYS-PUB-2021-031



https://twiki.cern.ch/twiki/bin/view/CMSPublic/SummaryResultsHIG

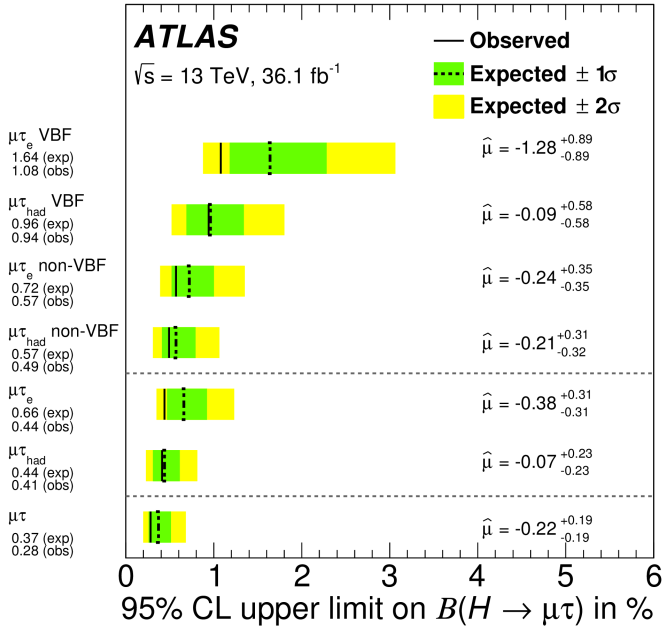
Searches for Exotic Decays

- Lepton Flavour Violating Decays, $H \rightarrow e\tau$
- Decays to pseudo scalars, $H \rightarrow aa$
- Decays to invisible particles, $H \rightarrow inv$

Lepton Flavour Violation Searches

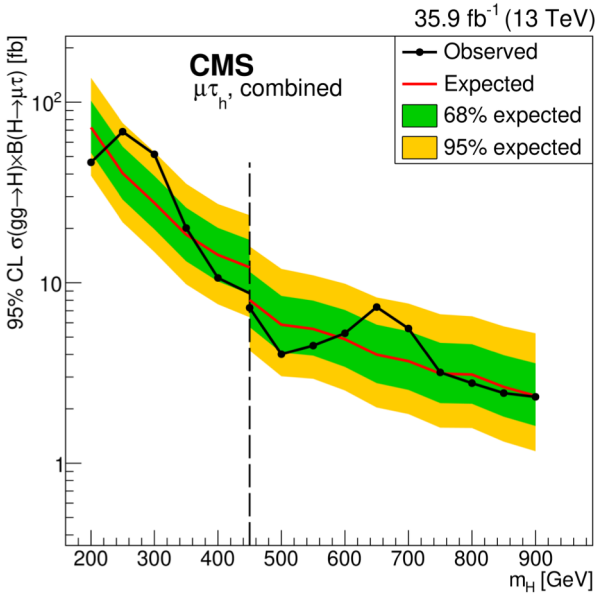
using 2016 dataset

- LFV is searched in $H \to \mu\tau$ and $H \to e\tau$
- BDT scores are used as final variables
- VBF and non-VBF categorizations



Phys. Lett. B 800 (2020) 135069

- LFV is searched in $H \to \mu\tau$ and $H \to e\tau$
- Collinear mass distributions are used as discriminating variable
  - $M_{col} = M_{vis}/\sqrt{x_\tau^{vis}}$, where x is the fraction of momentum carried by the visible decay products



JHEP 03 (2020) 103

- No excess is observed
- Upper limits on branching ratios and $\sigma \times BR$ are set
- Yukawa couplings are constrained

Summary

- Many Higgs searches are ongoing in beyond the SM theories
- Only a few representative results presented here - see the ATLAS and CMS public results pages for the full set:
  - ATLAS: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HDBSPublicResults
  - CMS: http://cms-results.web.cern.ch/cms-results/public-results/publications/HIG/SUS.html
    http://cms-results.web.cern.ch/cms-results/public-results/publications/HIG/EXO.html
- Both CMS and ATLAS results are in agreement
- No excess has been found yet
- Parameter spaces are constrained
- Run3 and Phase2 could be promising for BSM Higgs searches
  - An exciting area is upcoming at the LHC!

Thanks for your attention!

Backup

Beyond the SM Theories

@2HDM

- Free parameters of 2HDM
  - $m_h, m_H, m_A, m_{H^+}, \alpha, \tan\beta, m_{12}(\text{soft } Z_2 \text{ symmetry } (\text{H1} \rightarrow H1, H2 \rightarrow -H2) \text{ breaking parameter})$
  - The two angles α and β can be substituted by $\cos(\beta - \alpha)$ and $\tan\beta$ without loss of generality.
- It has four special types, depending on the way the two SU(2)L doublets are coupled to the fermion sector:
  - Type I: the SU(2)L doublets couple to both up- and down-type fermions equally
  - Type II: one doublet couples exclusively to up-type and the other exclusively to down-type fermions
  - Lepton specific: the quarks couple to one of the Higgs doublets and the leptons couple to the other
  - Flipped, with $\cos(\beta - \alpha) = 0$: the up-type quarks and leptons couple to one of the Higgs doublets, while the down-type quarks couple to the other

@MSSM

- There are many benchmark scenarios
  - hMSSM and M_h^{mod} benchmark scenarios
  - M_h^{125} benchmarks proposed in 2019 to be compatible with the Run 2 results are commonly used scenarios

@NMSSM: Next to MSSSM

- The theories can be further extended by a scalar
  - NMSSM: two complex Higgs doublets + one scalar complex singlet => 7 Higgs bosons $h, H_1, H_2, A_1, A_2, H^{\pm}$

@Heavy vector triplet (HVT) model

- which is a simplified model providing a broad phenomenological framework for heavy resonances coupling to SM fermions and bosons
- This model introduces heavy spin-1 particles, referred to as W' and Z'.

@ Technicolor, little Higgs, a more complex Higgs sector, warped extra dimensions

- predict the existence of heavy resonances that predominantly decay into pairs of bosons, including WH and ZH.

@ type-II see saw model,

- Predict 7 scalar bosons, $H^{\pm\pm}$, $H^{\pm}$, A^0, H^0 and h^0 after EWSB

Mass Hierarchies in 2HDM (JHEP03(2020)055)

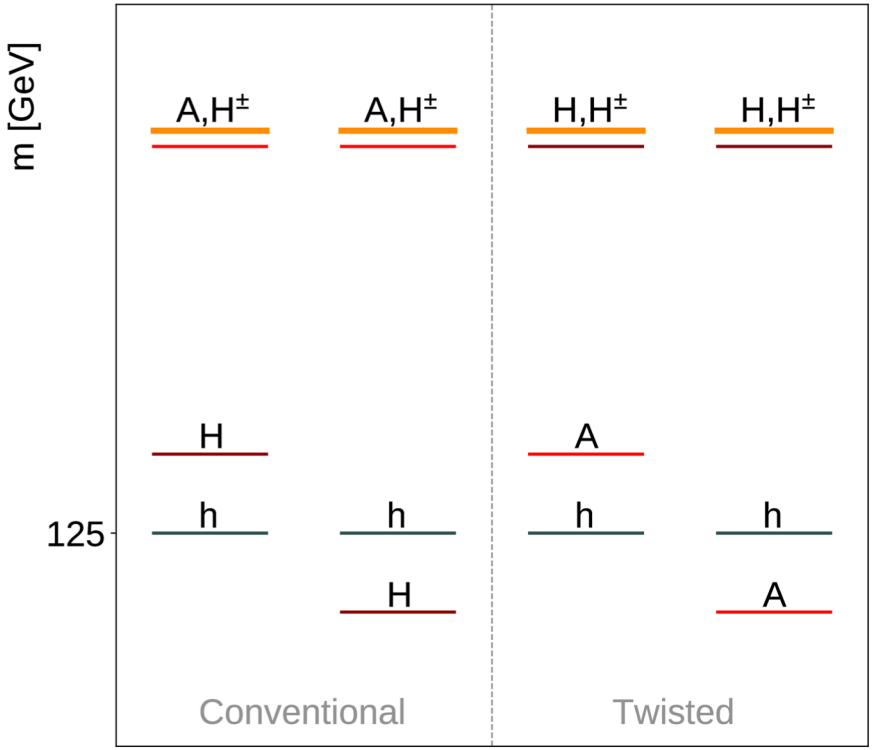
Conventional,

- where A is degenerate in mass with the charged scalars; and

Twisted,

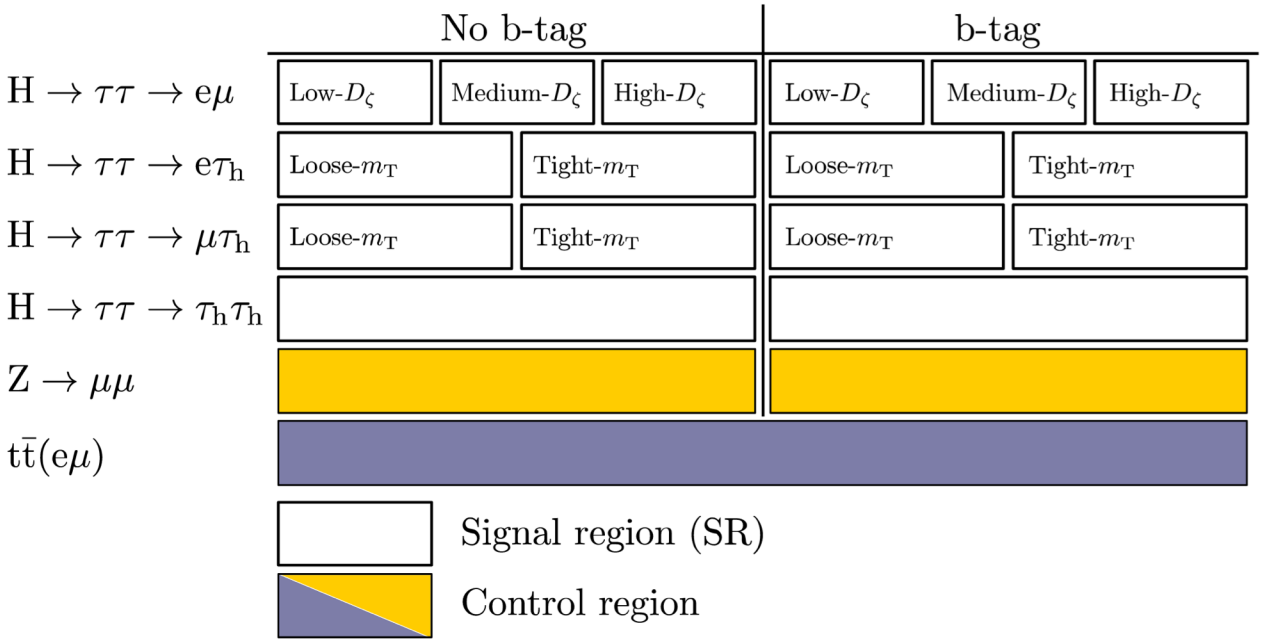
- where H is degenerate in mass with the charged scalars.

In both scenarios, the lighter of the A and H bosons can be either heavier or lighter than the observed Higgs boson h(125).



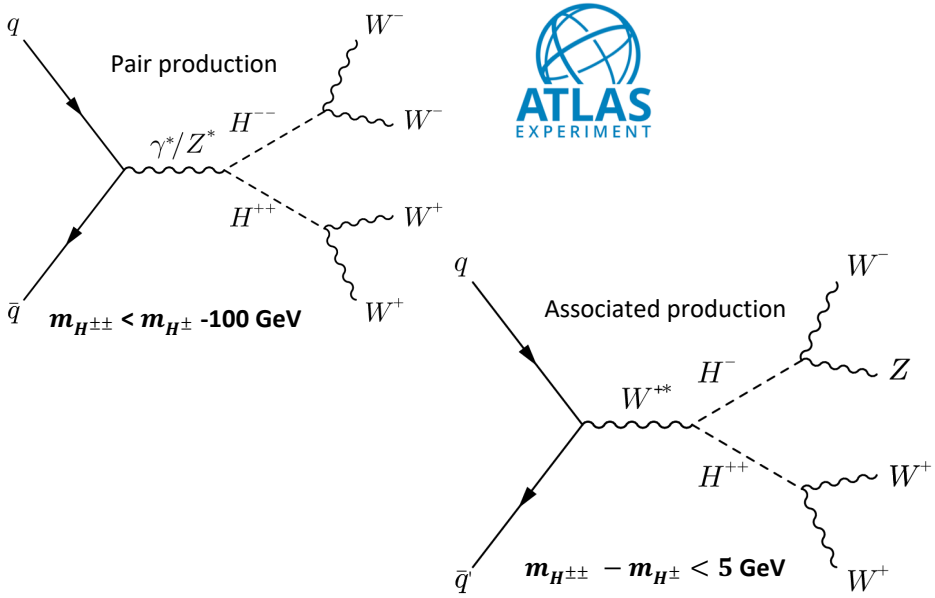
$H/A \rightarrow \tau\bar{\tau}$ Searches in CMS

- The classification:



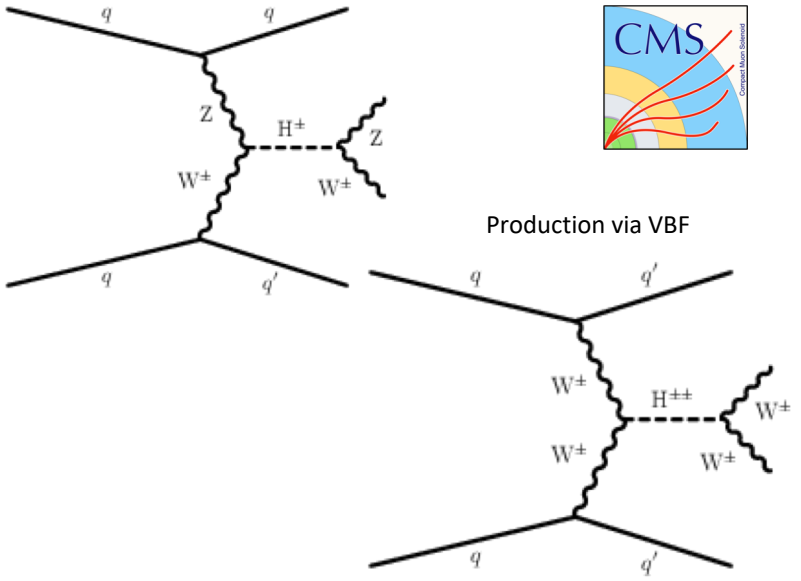
Charged Higgs Boson Searches

- *ATLAS*



- $H^{\pm\pm}$ is proposed in type-II see saw model.

- *CMS*



- The charged bosons are produced via VBF in the Georgi—Machacek (GM) model

$H^{\pm\pm} \to W^{\pm} W^{\pm}$ and $H^{\pm} \to W^{\pm}Z$

using the full Run 2 dataset

Variable	$W^{\pm}W^{\pm}$	WZ
Leptons	2 leptons, $p_T > 25/20$ GeV	3 leptons, $p_T > 25/10/20$ GeV
p_T^j	>50/30 GeV	>50/30 GeV
$\lvert m_{\ell\ell} - m_Z \rvert$	>15 GeV (ee)	<15 GeV
$m_{\ell\ell}$	>20 GeV	—
$m_{\ell\ell\ell}$	—	>100 GeV
p_T^{miss}	>30 GeV	>30 GeV
b jet veto	Required	Required
τ_h veto	Required	Required
$\max(z_\ell^*)$	<0.75	<1.0
m_{jj}	>500 GeV	>500 GeV
$\lvert \Delta\eta_{jj} \rvert$	>2.5	>2.5

- The Georgi—Machacek (GM) model, includes both real and complex triplets, that preserves a global symmetry SU(2)L ×SU(2)R, which is broken by the Higgs VEV to the diagonal subgroup SU(2)L+R.
- Thus, the tree-level ratio of the W and Z boson masses is protected against large radiative corrections.
- In this model, singly (doubly) charged Higgs bosons that decay to W and Z bosons (same-sign W boson pairs) are produced via vector boson fusion (VBF).
- The charged Higgs bosons H± and H±± in the GM model are degenerate in mass (denoted as mH5) at tree level
- Production and decays of the H5 states depend on the two parameters mH5 and sH, where s2H characterizes the fraction of the W boson mass squared generated by the vacuum expectation value of the triplet fields.