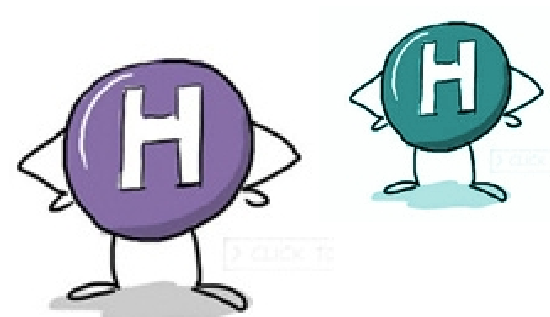
# Signs of New Higgses @ LHC

## (Enlarging the scope of LHC (multi)Higgs searches)





Jose Miguel No
IFT-UAM/CSIC, Madrid


MultiHiggs 2018
05/09/18

UNIVERSIDAD AUTONOMA DE MADRID

Instituto de Física Teórica UAM-CSIC

Comunidad de Madrid

WHY?

# Motivating more Higgses...

- Multi-Higgs (multi-scalar) appear in many solutions to Higgs Naturalness: SUSY (MSSM, NMSSM...), Composite Higgs, Neutral Naturalness

- Rich phenomenology

- Early Universe implications

WHY?

# Motivating more Higgses...

- ➔ Multi-Higgs (multi-scalar) appear in many solutions to Higgs Naturalness: SUSY (MSSM, NMSSM...), Composite Higgs, Neutral Naturalness

- ➔ Rich phenomenology

- ➔ Early Universe implications

WHY?

# Motivating more Higgses...

- Multi-Higgs (multi-scalar) appear in many solutions to Higgs Naturalness: SUSY (MSSM, NMSSM...), Composite Higgs, Neutral Naturalness

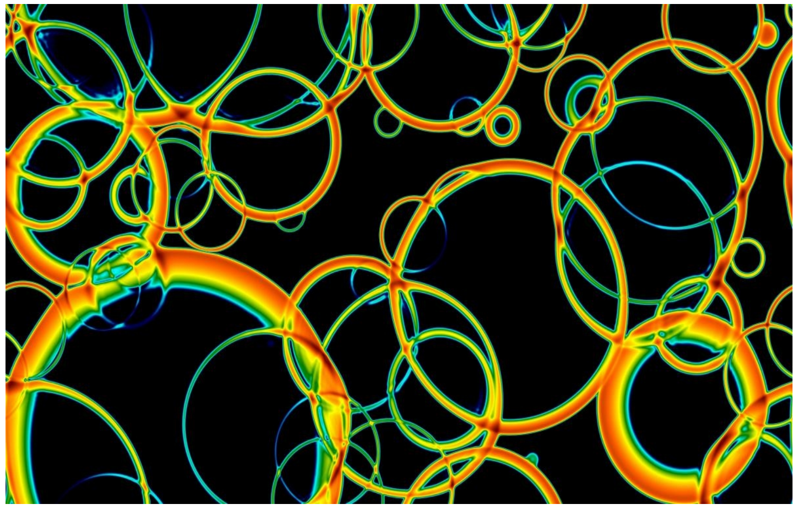
- Rich phenomenology

- Early Universe implications → Electroweak Phase Transition

Cosmological Relics from the EW Epoch?

Gravitational Wave Signal

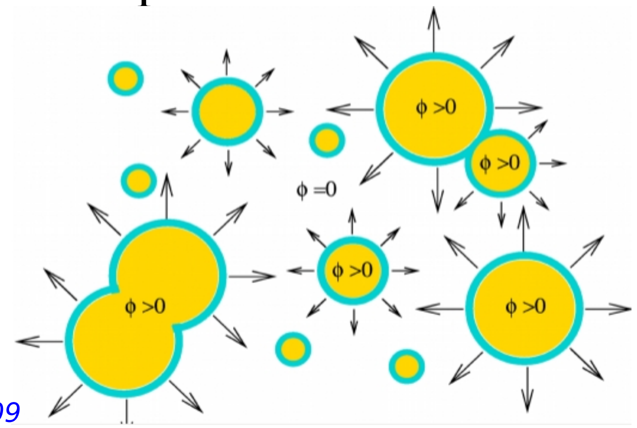
Matter-Antimatter asymmetry (EW Baryogenesis)



Courtesy of D. Weir

*Hindmarsh, Huber, Rummukainen, Weir, PRD **92** (2015) 123009*

Sourced by bubble collisions & subsequent plasma motions



WHY?

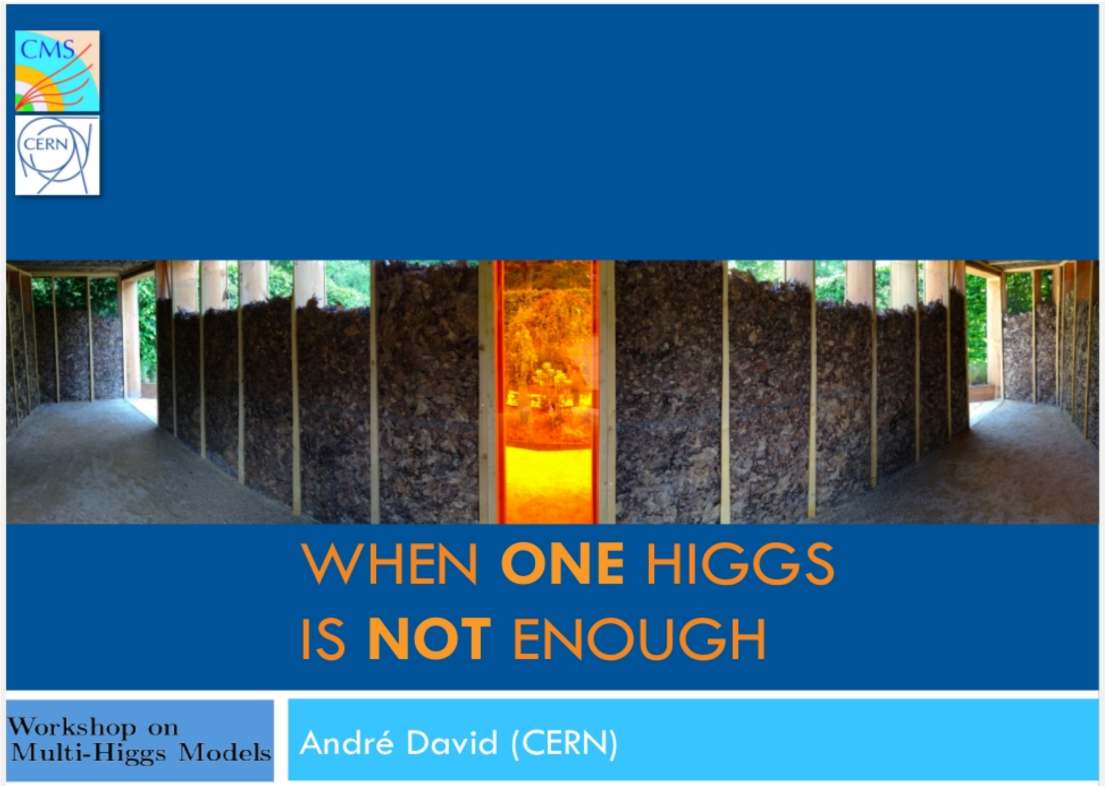
# Motivating more Higgses...

- ➔ Multi-Higgs (multi-scalar) appear in many solutions to Higgs Naturalness: SUSY (MSSM, NMSSM...), Composite Higgs, Neutral Naturalness

- ➔ Rich phenomenology

- ➔ Early Universe implications → Electroweak Phase Transition

  Cosmological Relics from the EW Epoch?



# BSM Higgs searches @ LHC

(e.g. ATLAS)

## Filter Documents

*Select the desired keywords to filter the results.*

*Selections within a section row are combined with a logical OR, while selections among different section rows are combined with a logical AND.*

Global Selections: Show All | Deselect All | Show Latest 20

CM Energy: 7 TeV | 8 TeV | 13 TeV | 14 TeV

Higgs physics: Higgs to 2 photons | Higgs to Z+photon | Higgs to 4 lepton | Higgs to 2 muons | Higgs to tautau | Higgs to ZZ | Higgs to WW | Higgs to bb | Higgs to cc | Higgs to invisible | Higgs to meson+photon | Gluon fusion production | VH production | bbH production | bH production | tH production | ttH production | Di-Higgs production | Off-shell Higgs | H(125) measurements | Mass measurement | Coupling measurements | Simplified template cross-section | Pseudo-observables | Exotic Higgs decays | Exotic Higgs production | **BSM Higgs searches** | Charged Higgs searches | kappa | NMSSM | Spin / CP

I will focus on neutral scalars:

- ➔ H → VV (WW, ZZ)
- ➔ A → Z h
- ➔ H → h h
- ➔ H/A → f f (ττ, bb)
- ➔ H/A → γγ
- …

| | | | | | |
|---|---|---|---|---|---|
| Search BSM H->hh->bb tau tau and hh->bb tau tau | Submitted to PRL | 01-AUG-18 | 13 | 36 $fb^{-1}$ | Documents \| 1808.00336 \| Inspire Internal |
| Search BSM H->hh->WW gamma gamma and hh->WW gamma gamma | Submitted to Eur. Phys. J. C | 23-JUL-18 | 13 | 36 $fb^{-1}$ | Documents \| 1807.08567 \| Inspire Internal |
| Search BSM H+ -> tau nu | Submitted to JHEP | 20-JUL-18 | 13 | 36.1 $fb^{-1}$ | Documents \| 1807.07915 \| Inspire Internal |
| Search BSM H->hh->bb gamma gamma and hh->bb gamma gamma | Submitted to JHEP | 13-JUL-18 | 13 | 36.1 $fb^{-1}$ | Documents \| 1807.04873 \| Inspire Internal |
| Search BSM h(125)->2a->4b | Submitted to JHEP | 19-JUN-18 | 13 | 36 $fb^{-1}$ | Documents \| 1806.07355 \| Inspire Internal |
| W/Z/Hgamma search 13 TeV 2016 | Phys. Rev. D 98 (2018) 032015 | 04-MAY-18 | 13 | 36 $fb^{-1}$ | Documents \| 1805.01908 \| Inspire HepData \| Briefing \| Internal |
| HH search bbbb 13 TeV 2016 | Submitted to JHEP | 17-APR-18 | 13 | 36 $fb^{-1}$ | Documents \| 1804.06174 \| Inspire HepData \| Internal |
| Search BSM H->ZZ->4l and llvv | Eur. Phys. J. C 78 (2018) 293 | 18-DEC-17 | 13 | 36.1 $fb^{-1}$ | Documents \| 1712.06386 \| Inspire Internal |
| VH search semi-leptonic 13 TeV 2016 | JHEP 03 (2018) 174 | 17-DEC-17 | 13 | 36.1 $fb^{-1}$ | Documents \| 1712.06518 \| Inspire HepData \| Internal |
| Search BSM H->WW->lvlv | Eur. Phys. J. C 78 (2018) 24 | 03-OCT-17 | 13 | 36.1 $fb^{-1}$ | Documents \| 1710.01123 \| Inspire Internal |
| Search BSM A/H/Z->tautau | JHEP 01 (2018) 055 | 21-SEP-17 | 13 | 36 $fb^{-1}$ | Documents \| 1709.07242 \| Inspire Internal |

# BSM Higgs searches @ LHC

Design (& perform!) LHC searches to probe new regions of parameter space

- ~~H → VV (WW, ZZ)~~
- ~~A → Z h~~
- ~~H → h h~~
- H/A → f f (ττ, bb)
- H/A → γγ

...

**If *h* is SM-like:**

"Traditional" BSM Higgs searches not (as) effective

e.g. 2HDM alignment

Enlarging the scope of

# BSM Higgs searches @ LHC

Enlarging the scope of

# BSM Higgs searches @ LHC

This talk...

❶ $A \rightarrow Z\,h$ ·········➤ $A \rightarrow Z\,H\,/\,H \rightarrow Z\,A$

❷ $H \rightarrow h\,h$ ·········➤ $H \rightarrow A\,A$

➔ Require sizeable mass splitting among BSM scalars

➔ Here focus on 2HDM as perfect illustration
(but other scenarios possible, e.g. NMSSM)

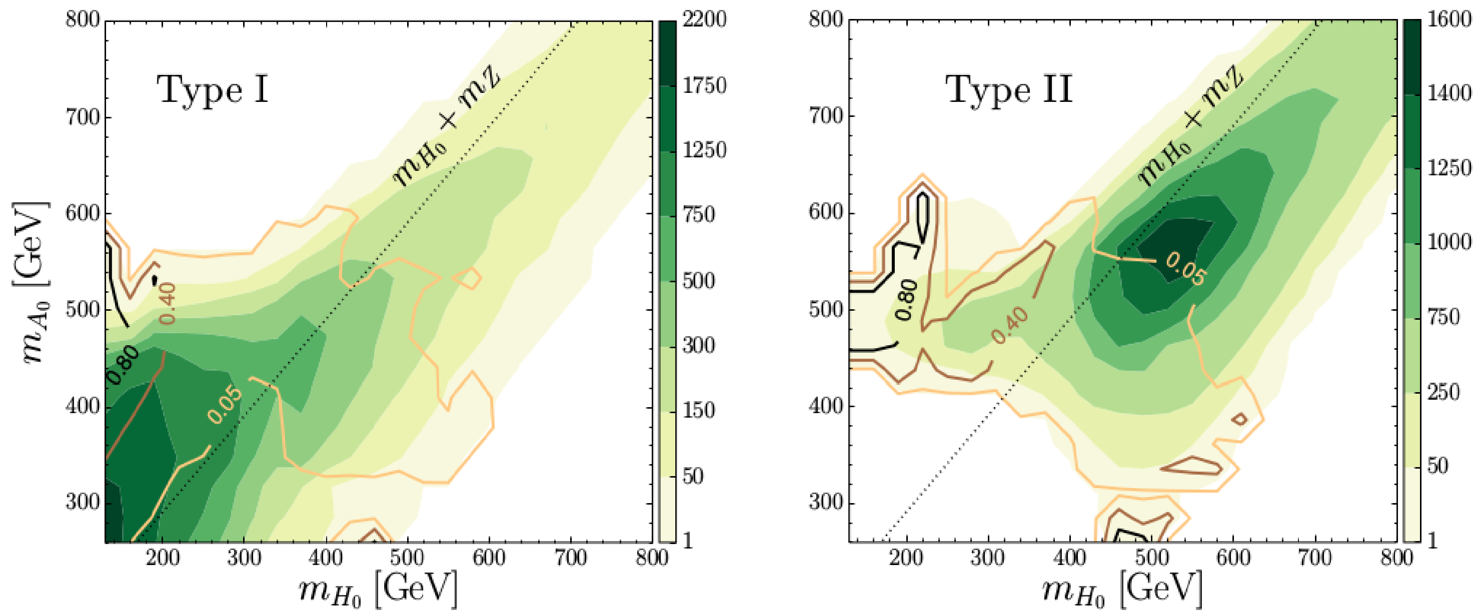
➔ "Traditional" LHC search: we eliminate restriction to SM Higgs mass window

WHY?

**Sizeable mass splitting among BSM scalars** ➔ *Hierarchical* 2HDM

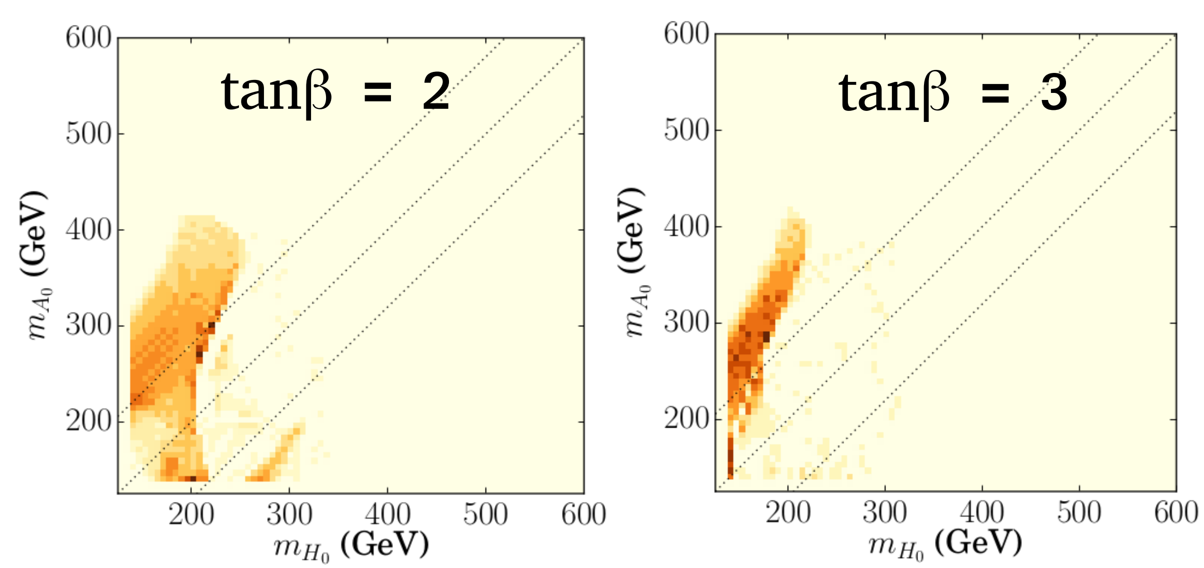
- Large 2HDM mass splittings favour strong EWPT → EW baryogenesis, GWs

*Dorsch, Huber, JMN, JHEP **1310** (2013) 029*
*Dorsch, Huber, Mimasu, JMN, Phys. Rev. Lett. **113** (2014) 211802*
*Basler, Krause, Muhlleitner, Wittbrodt, Wlotzka, JHEP **1702** (2017) 121*
*Dorsch, Huber, Mimasu, JMN, JHEP **1712** (2017) 086*




Perturbative EWPT studies now backed up by lattice simulations

*Andersen, Gorda, Helset, Niemi, Tenkanen, Tranberg, Vuorinen, Weir, arXiv:1711.09849*
*Gorda, Helset, Niemi, Tenkanen, Weir, arXiv:1802.05056*



WHY?

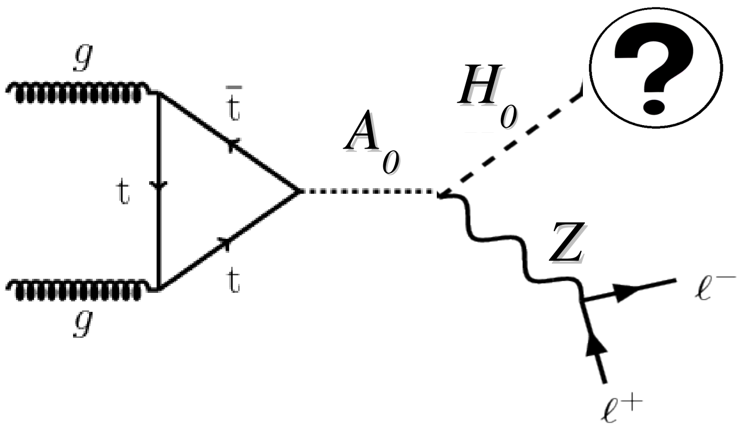
**Sizeable mass splitting among BSM scalars** ➔ *Hierarchical* 2HDM

- Large 2HDM mass splittings favour strong EWPT → EW baryogenesis; → GWs

- Important impact on BSM Higgs phenomenology → New decay modes (new avenues for LHC searches)

  Dorsch, Huber, Mimasu, JMN, Phys. Rev. Lett. **113** (2014) 211802
  Coleppa, Kling, Su, JHEP **1409** (2014) 161

e.g. $A_0 \to H_0\, Z$



WHY?

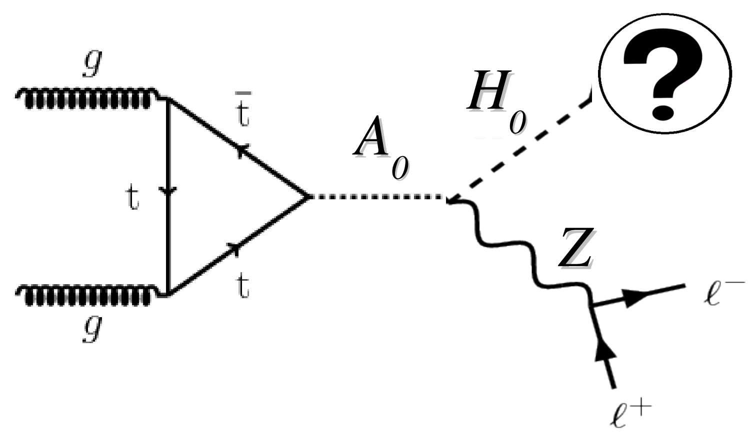
**Sizeable mass splitting among BSM scalars** ➔ *Hierarchical* 2HDM

- Large 2HDM mass splittings favour strong EWPT → EW baryogenesis; → GWs

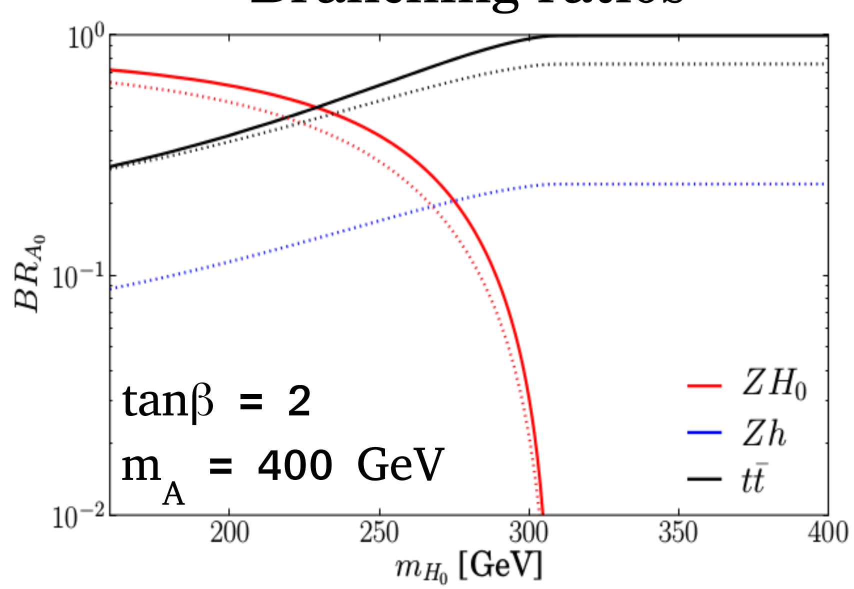
- Important impact on BSM Higgs phenomenology → New decay modes (new avenues for LHC searches)

*Dorsch, Huber, Mimasu, JMN, Phys. Rev. Lett.* ***113*** *(2014) 211802*
*Coleppa, Kling, Su, JHEP* ***1409*** *(2014) 161*

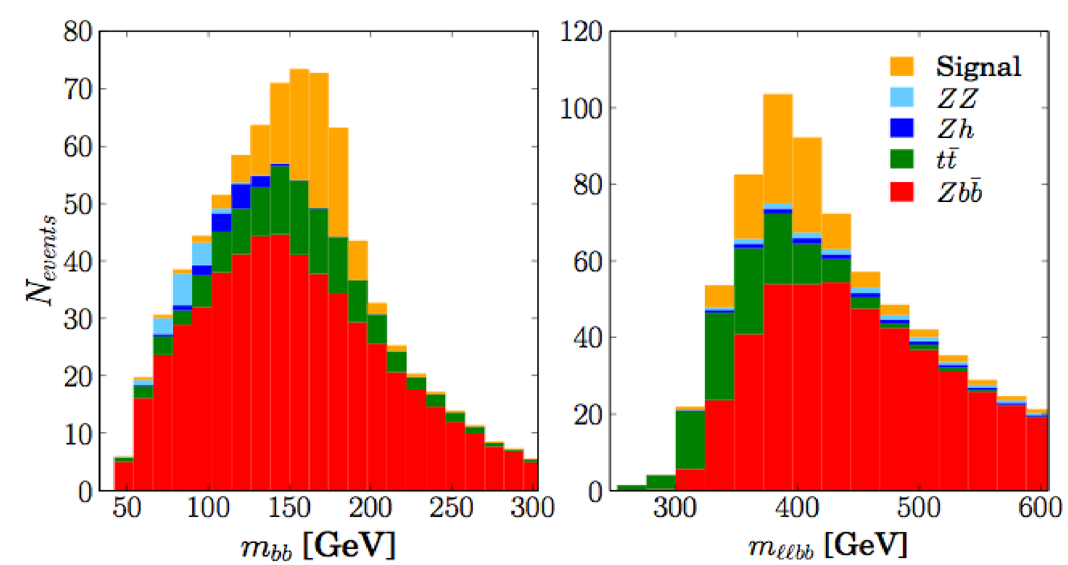
e.g. $A_0 \to H_0\, Z$




Branching ratios




Kinematics



# … and the search was performed!

Phys. Lett. B759 (2016) 369 (ArXiv:1603.02991)

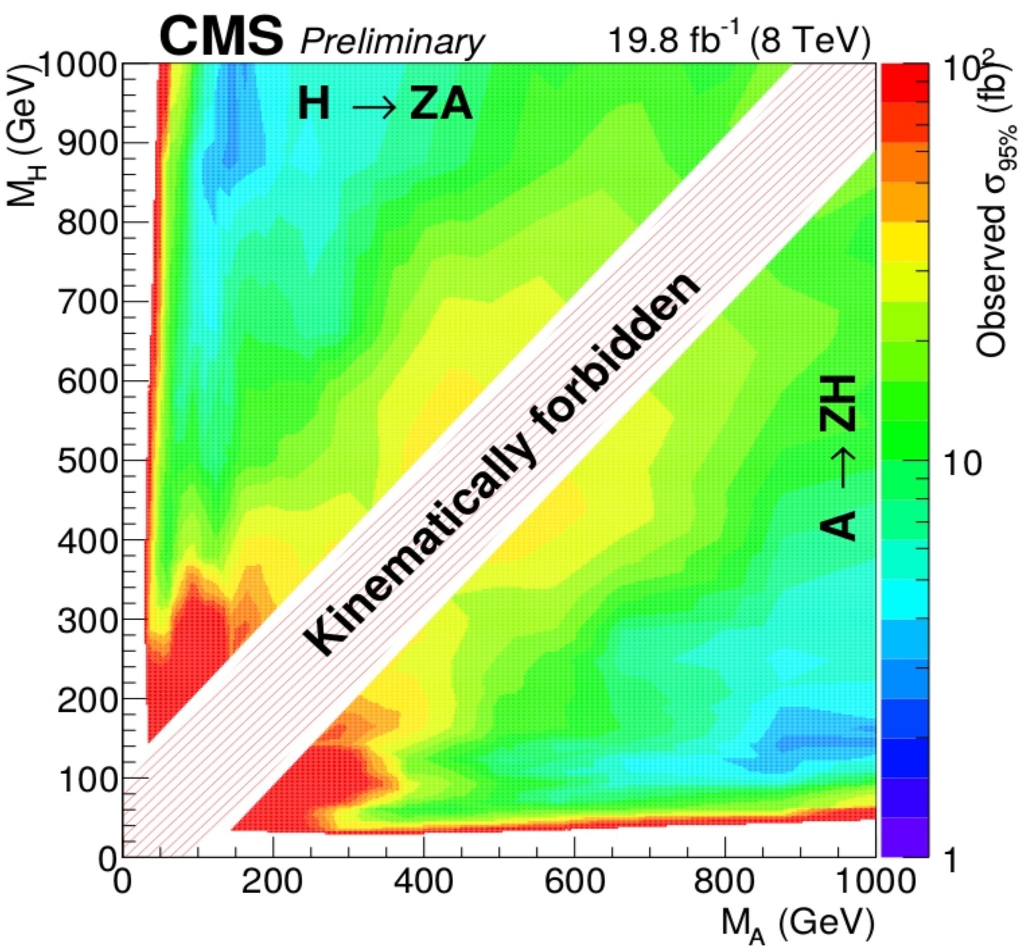
CMS-PAS-HIG-15-001

Search for H/A decaying into Z and A/H, with Z→ $\ell\ell$ and A/H→ bb or A/H→ $\tau\tau$

The CMS Collaboration

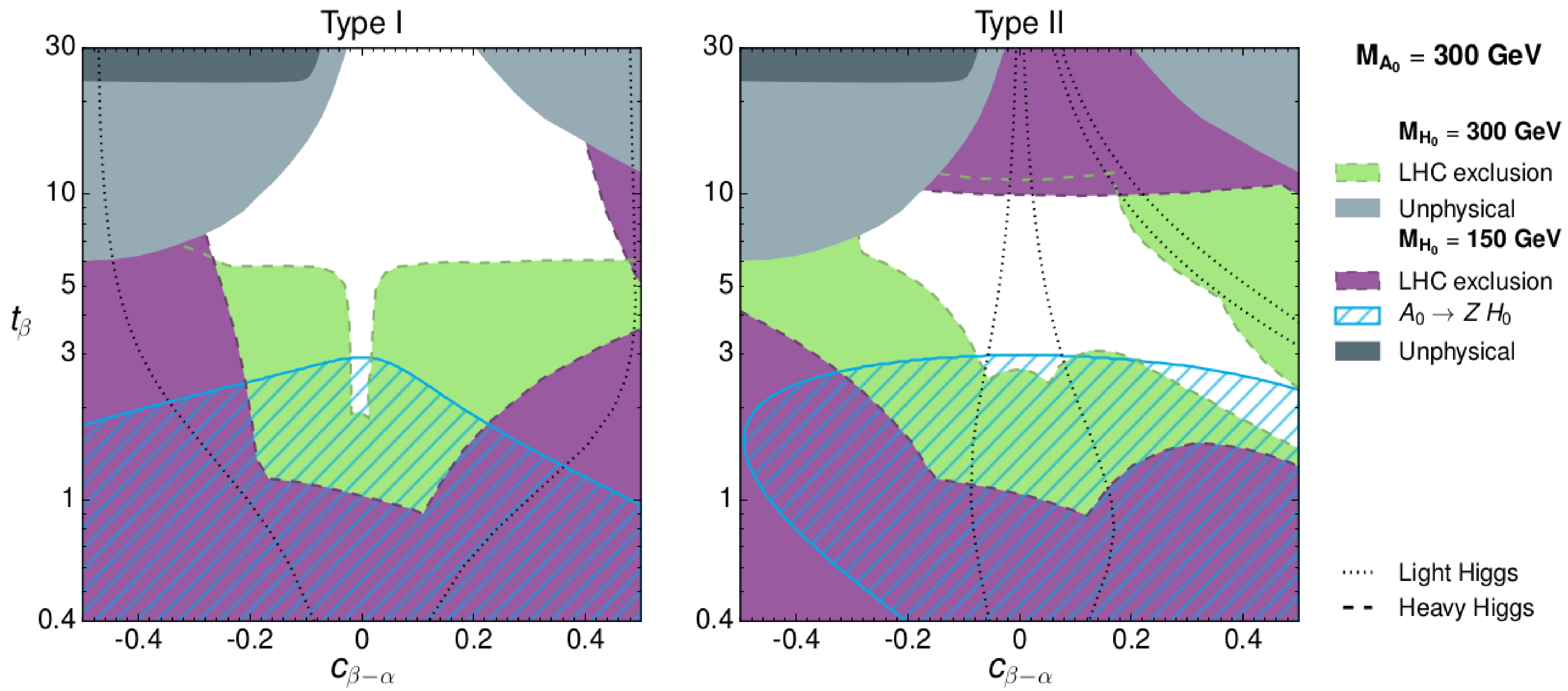
One important motivation for 2HDMs is that these models provide a way to explain the asymmetry between matter and anti-matter observed in the Universe [4, 5]. Another important motivation is Supersymmetry [6], which is a theory that falls in the broad class of 2HDMs. Axion models [7], which would explain how the strong interaction does not violate the CP symmetry, would give rise to an effective low-energy theory with two Higgs doublets. Finally, it has also been recently noted [8] that certain realizations of 2HDMs can accommodate the muon $g-2$ anomaly [9] without violating the present theoretical and experimental constraints.

In the most general case 14 parameters are necessary to describe the scalar sector in a 2HDM. However, only 6 free parameters remain once the so-called $Z_2$ symmetry is imposed to suppress flavor changing neutral currents, in agreement with experimental observations, and the values of the mass of the recently discovered Higgs boson (125 GeV) and the electroweak vacuum expectation value (246 GeV) are assumed. The compatibility of a 125 GeV SM-like Higgs boson with 2HDMs is possible in the so-called alignment limit. In such a limit, one of the CP-even scalars, h or H, is identified with the 125 GeV Higgs boson and the condition $cos(\beta-\alpha) \approx 0$ or $sin(\beta-\alpha) \approx 0$ is satisfied, where $\tan\beta$ and $\alpha$ are, respectively, the ratio of the vacuum expectation values, and the mixing angle of the two Higgs doublets. A recent theoretical study [5] has shown that, in this limit, a large mass splitting (>100 GeV) between the A and H bosons would favor the electroweak phase transition that would be at the origin of the baryogenesis process in the early Universe, thus explaining the currently observed matter-antimatter asymmetry in the Universe. In such a scenario, the most frequent decay mode of the pseudoscalar A boson would be A→ZH.



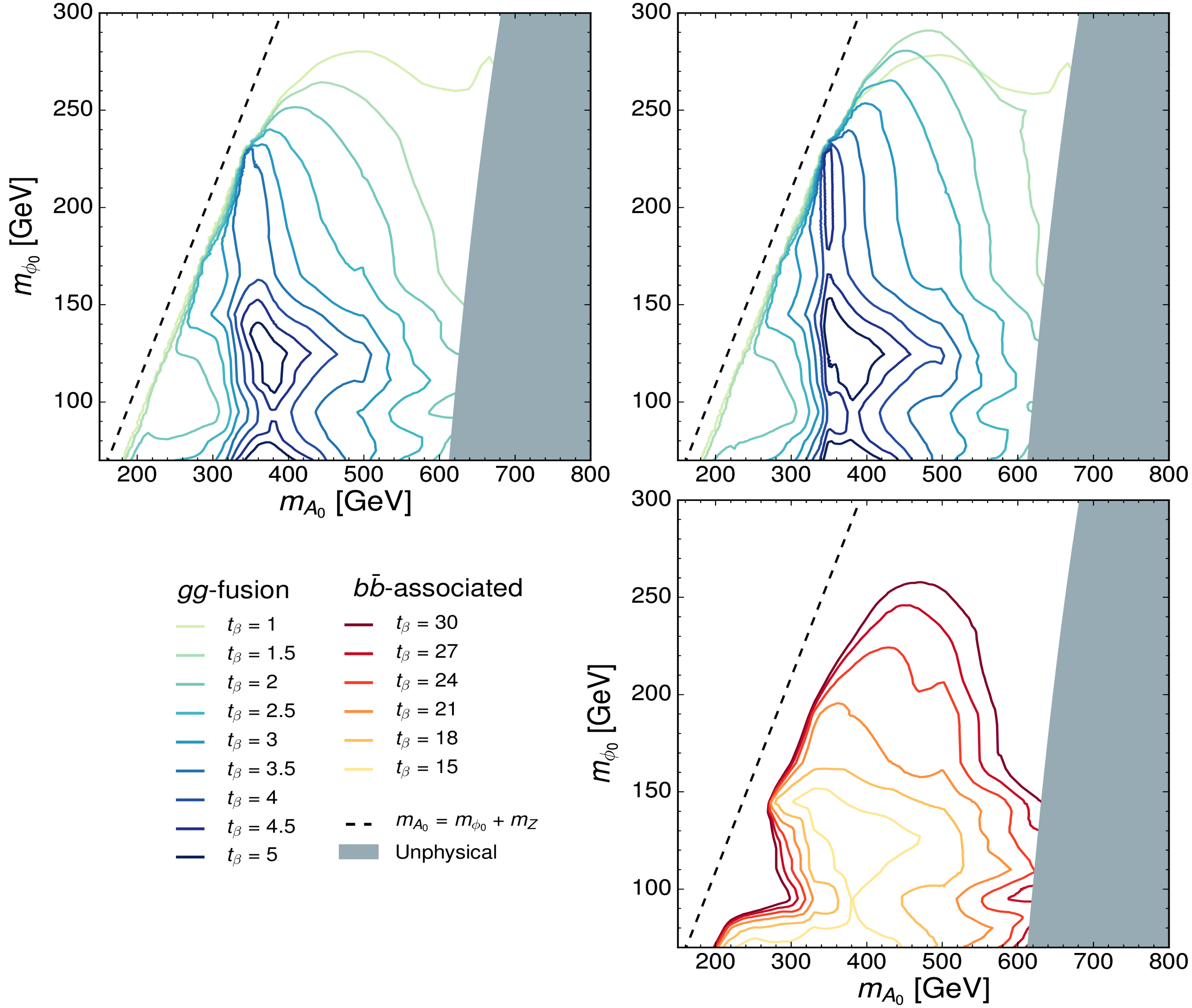
# Impact of A → Z H BSM Higgs search (LHC Run 1)

*Dorsch, Huber, Mimasu, JMN, Phys. Rev. D**93** (2016) 115033*



# Impact of A → Z H BSM Higgs search (LHC Run 1)

Dorsch, Huber, Mimasu, JMN, Phys. Rev. D**93** (2016) 115033




2HDM alignment

# … and for **13** TeV, ATLAS as well.

## Search for a heavy Higgs boson decaying into a $Z$ boson and another heavy Higgs boson in the $\ell\ell bb$ final state in $pp$ collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

The ATLAS Collaboration *

ARTICLE INFO

*Article history:*
Received 4 April 2018
Received in revised form 15 June 2018
Accepted 4 July 2018
Available online 11 July 2018
Editor: W.-D. Schlatter

ABSTRACT

A search for a heavy neutral Higgs boson, $A$, decaying into a $Z$ boson and another heavy Higgs boson, $H$, is performed using a data sample corresponding to an integrated luminosity of 36.1 fb$^{-1}$ from proton–proton collisions at $\sqrt{s} = 13$ TeV recorded in 2015 and 2016 by the ATLAS detector at the Large Hadron Collider. The search considers the $Z$ boson decaying to electrons or muons and the $H$ boson into a pair of $b$-quarks. No evidence for the production of an $A$ boson is found. Considering each production process separately, the 95% confidence-level upper limits on the $pp \to A \to ZH$ production cross-section times the branching ratio $H \to bb$ are in the range of 14–830 fb for the gluon–gluon fusion process and 26–570 fb for the $b$-associated process for the mass ranges 130–700 GeV of the $H$ boson and 230–800 GeV of the $A$ boson. The results are interpreted in the context of two-Higgs-doublet models.

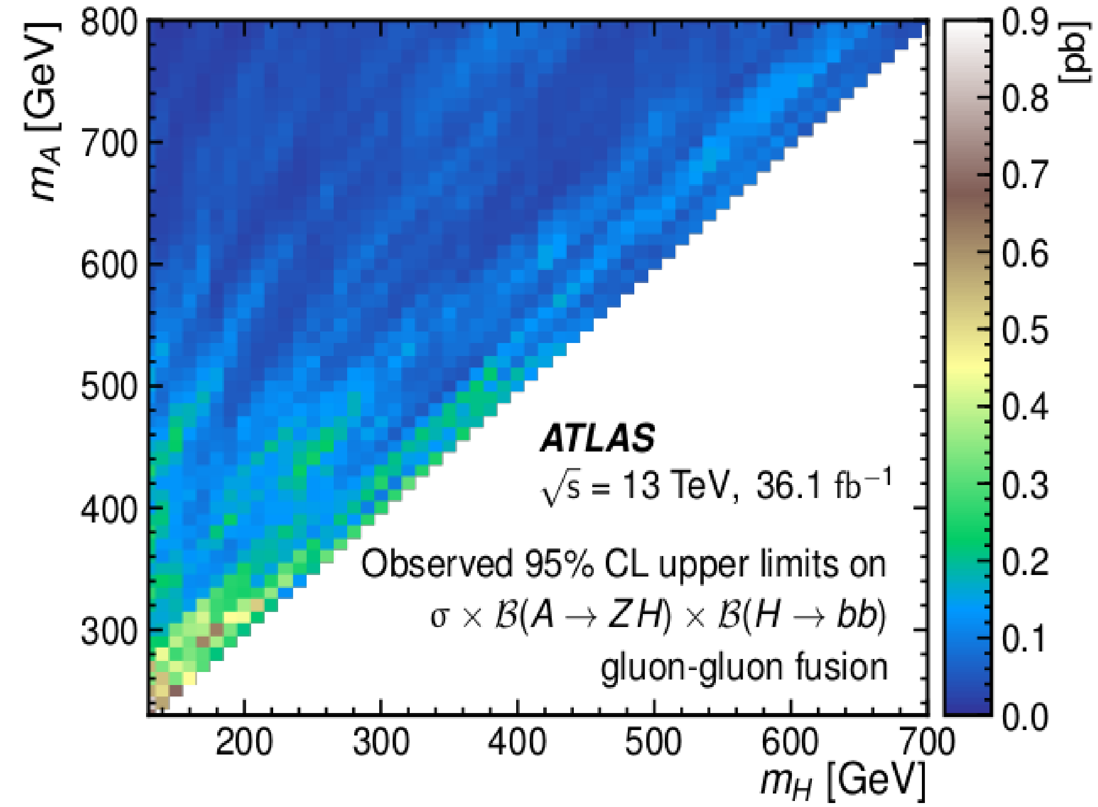


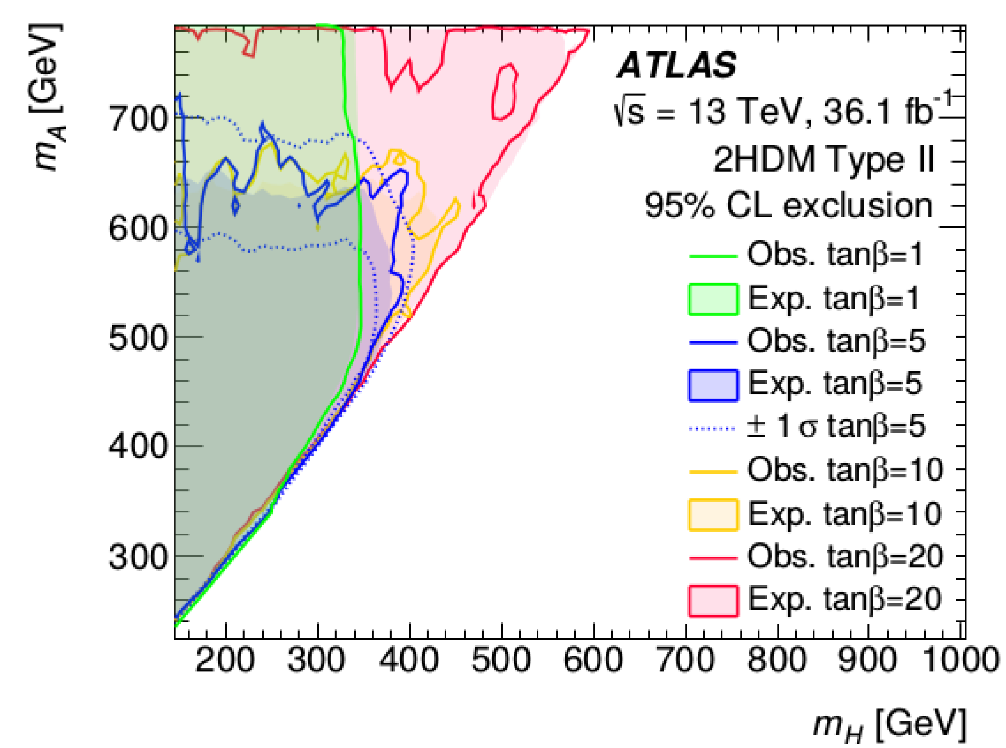
**1. Introduction**

After the discovery of a Higgs boson at the Large Hadron Collider (LHC) [1,2], one of the most important remaining questions is whether the recently discovered particle is part of an extended scalar sector or not. Additional Higgs bosons appear in all models with an extended scalar sector, such as the two-Higgs-doublet model (2HDM) [3,4]. Such extensions are motivated by, and included in, several new physics scenarios, such as supersymmetry [5], dark matter [6] and axion [7]models, electroweak baryogenesis [8] and neutrino mass models [9].

The addition of a second Higgs doublet leads to five Higgs bosons after electroweak symmetry breaking. The phenomenology

This assumption of mass degeneracy is relaxed in this Letter by assuming $m_A > m_H$. Such a case is motivated by electroweak baryogenesis scenarios in the context of the 2HDM [21–24]. For 2HDM electroweak baryogenesis to occur, the requirement $m_A > m_H$ is favoured [21]for a strong first-order phase transition to take place in the early universe. The $A$ boson mass is also bounded from above to be less than approximately 800 GeV, whereas the lighter CP-even Higgs boson, $h$, is required to have properties similar to those of a Standard Model (SM) Higgs boson and is assumed to be the Higgs boson with mass of 125 GeV that was discovered at the LHC [21]. Under such conditions and for large parts of the 2HDM parameter space, the CP-odd Higgs boson, $A$, decays into $ZH$ [25,21]. The production of the $A$ boson in the relevant 2HDM parameter space proceeds mainly through gluon–gluon fusion and



… inverting the mass ordering: $m_A > m_H \rightarrow m_H > m_A$

… inverting the mass ordering: $m_A > m_H \rightarrow m_H > m_A$

▶ $A \rightarrow Z\ H$ and $H \rightarrow Z\ A$ yield “same” LHC search

## ... inverting the mass ordering: $m_A > m_H \rightarrow m_H > m_A$

- $A \rightarrow Z\, H$ and $H \rightarrow Z\, A$ yield "same" LHC search

- For sufficient splitting, $H \rightarrow A\, A$ also possible: competing decay modes
  - $H \rightarrow Z\, A$ (gauge coupling)
  - $H \rightarrow A\, A$ (scalar potential coupling)

- If $H \rightarrow A\, A$ dominant decay mode, should be searched for @ LHC!
  (Potential LHC discovery mode for both H and A)

## … inverting the mass ordering: $m_A > m_H \rightarrow m_H > m_A$

- $A \rightarrow Z\ H$ and $H \rightarrow Z\ A$ yield "same" LHC search

- For sufficient splitting, $H \rightarrow A\ A$ also possible: competing decay modes
  - $H \rightarrow Z\ A$ (gauge coupling)
  - $H \rightarrow A\ A$ (scalar potential coupling)

- If $H \rightarrow A\ A$ dominant decay mode, should be searched for @ LHC!
  (Potential LHC discovery mode for both H and A)

In 2HDM, $H \rightarrow A\ A$ dominant (over $H \rightarrow Z\ A$) generally violates stability and/or unitarity

## … inverting the mass ordering: $m_A > m_H \rightarrow m_H > m_A$

- $A \rightarrow Z\ H$ and $H \rightarrow Z\ A$ yield "same" LHC search

- For sufficient splitting, $H \rightarrow A\ A$ also possible: competing decay modes
  - $H \rightarrow Z\ A$ (gauge coupling)
  - $H \rightarrow A\ A$ (scalar potential coupling)

- If $H \rightarrow A\ A$ dominant decay mode, should be searched for @ LHC!
  (Potential LHC discovery mode for both H and A)

In 2HDM, $H \rightarrow A\ A$ dominant (over $H \rightarrow Z\ A$) generally violates stability and/or unitarity

$H \rightarrow A\ A$ can dominate for larger Higgs sectors (2HDM + S, 3HDM…)

# Let's do something about it!

## Enlarging the scope of LHC resonant di-Higgs searches

Reinterpret 13 TeV CMS resonant di-Higgs search $p\,p \to H \to h\,h \to 4b$
(CMS-PAS-HIG-17-009)

with C. Vernieri (CMS), D. Barducci, J. Zurita, K. Mimasu

- Several kinematical properties depend only on mass ratio $m_H / m_h$
  *Gouzevitch, Oliveira, Rojo, Rosenfeld, Salam, Sanz, JHEP **1307** (2013) 148*

  If known selection efficiencies for $H \to h\,h$, possible to extend analysis to mass plane $(m_H, m_A)$

# Let's do something about it!

## Enlarging the scope of LHC resonant di-Higgs searches

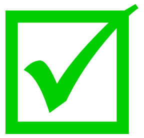
Reinterpret 13 TeV CMS resonant di-Higgs search $p\,p \to H \to h\,h \to 4b$
(CMS-PAS-HIG-17-009)

with C. Vernieri (CMS), D. Barducci, J. Zurita, K. Mimasu

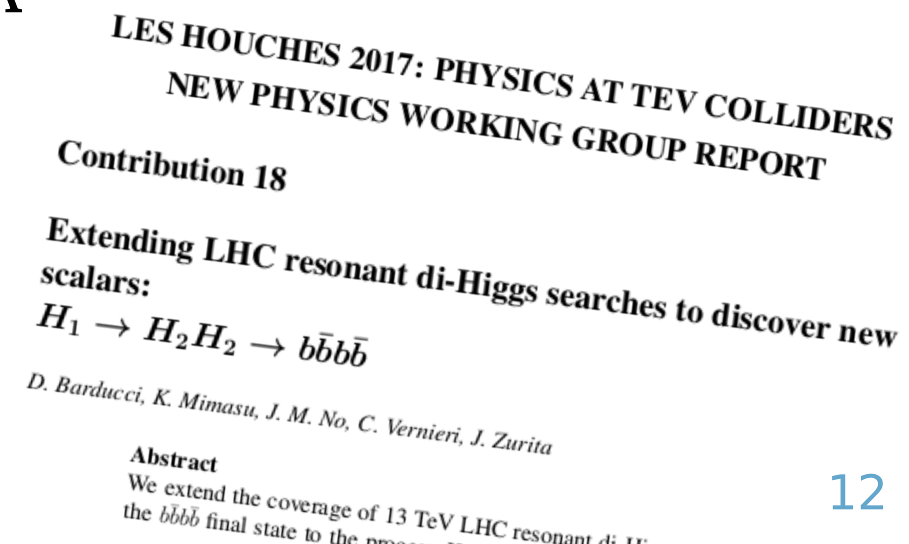
- Several kinematical properties depend only on mass ratio $m_H / m_h$
  Gouzevitch, Oliveira, Rojo, Rosenfeld, Salam, Sanz, JHEP **1307** (2013) 148

  If known selection efficiencies for $H \to h\,h$, possible to extend analysis to mass plane $(m_H, m_A)$

### GOALS:

❶ Extend $H \to h\,h$ 13 TeV CMS search to $H \to A\,A$
+ Derive prospective LHC sensitivities 

❷ 2HDM, NMSSM interpretation 



LES HOUCHES 2017: PHYSICS AT TEV COLLIDERS
NEW PHYSICS WORKING GROUP REPORT

Contribution 18

**Extending LHC resonant di-Higgs searches to discover new scalars:**
$H_1 \to H_2 H_2 \to b\bar{b}b\bar{b}$

*D. Barducci, K. Mimasu, J. M. No, C. Vernieri, J. Zurita*

**Abstract**
We extend the coverage of 13 TeV LHC resonant di-H...

## Reinterpreting 13 TeV CMS p p → X → h h → 4b search (CMS-PAS-HIG-17-009)

- **Initial event selection:** 4 b-tagged jets with $|\eta| < 2.4$ and $P_T > 30$ GeV + 2 jets w. $P_T > 90$ GeV OR $P_T > 45$ GeV

Low Mass Region (LMR) $m_X \in [250, 620]$ GeV

Medium Mass Region (MMR) $m_X \in [550, 1200]$ GeV

# Reinterpreting 13 TeV CMS $p\,p \to X \to h\,h \to 4b$ search (CMS-PAS-HIG-17-009)

▶ **Initial event selection:** 4 b-tagged jets with $|\eta| < 2.4$ and $P_T > 30$ GeV + 2 jets w. $P_T > 90$ GeV OR $P_T > 45$ GeV

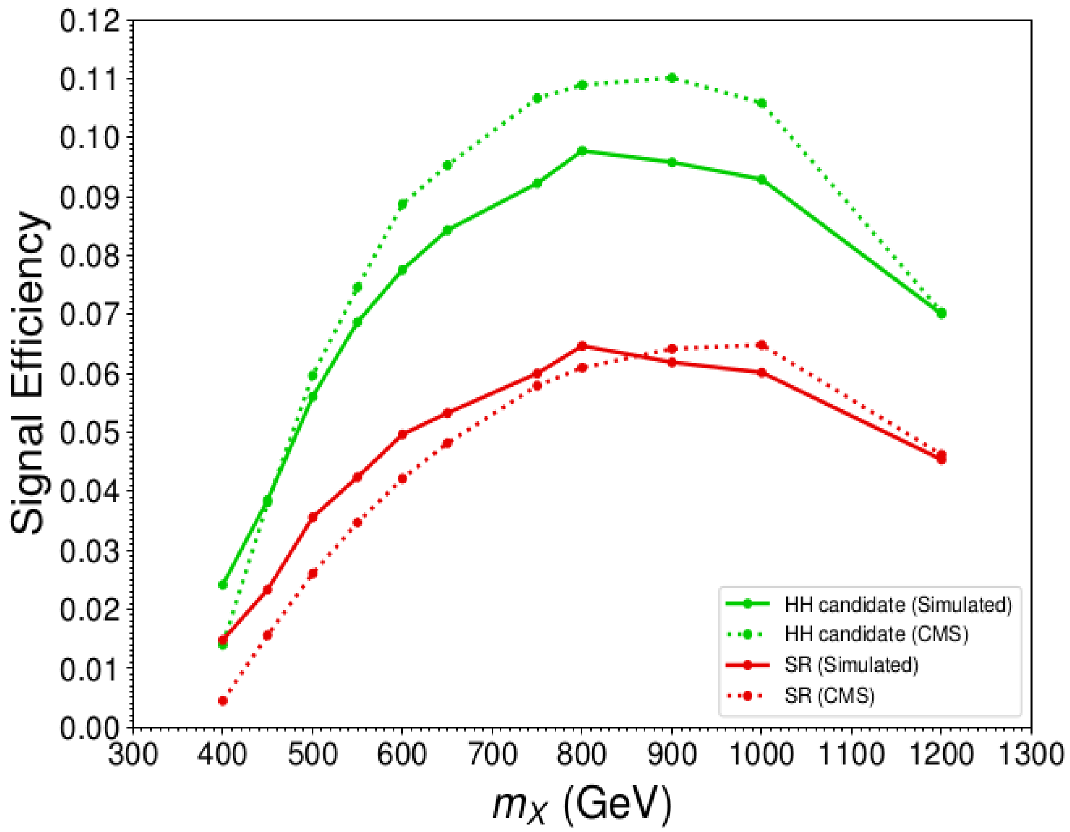
Low Mass Region (LMR) $m_X \in [250, 620]$ GeV

Medium Mass Region (MMR) $m_X \in [550, 1200]$ GeV

▶ **"HH" selection (MMR):** Two b-jet pairs w. $\Delta R_{bb} < 1.5$

▶ **Signal Region selection:** $\chi < 1$

$$\chi = \sqrt{\left(\frac{m_{h_1} - C}{R}\right)^2 + \left(\frac{m_{h_2} - C}{R}\right)^2} \qquad (C, R) = (115, 23)\ \text{GeV}$$




First, we need to reproduce CMS efficiencies!

## Reinterpreting 13 TeV CMS p p → X → h h → 4b search
(CMS-PAS-HIG-17-009)

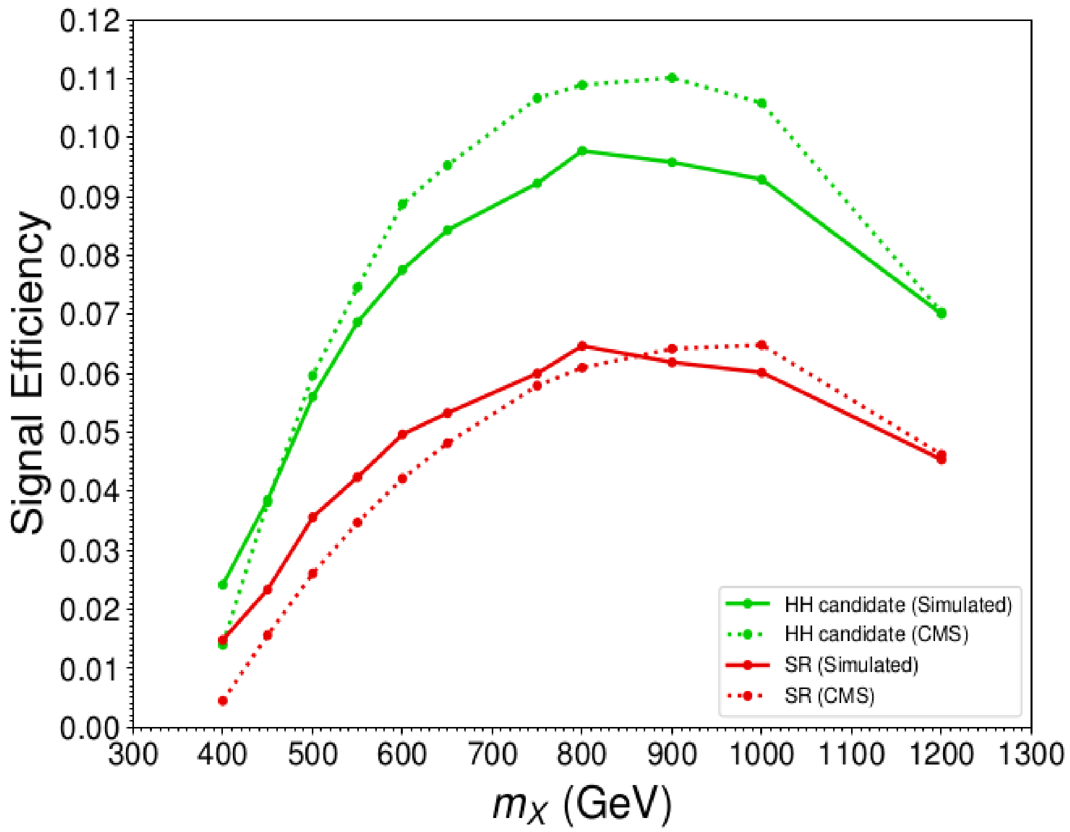
- **Initial event selection:** 4 b-tagged jets with $|\eta| < 2.4$ and $P_T > 30$ GeV + 2 jets w. $P_T > 90$ GeV OR $P_T > 45$ GeV

Low Mass Region (LMR) $m_X \in [250, 620]$ GeV

Medium Mass Region (MMR) $m_X \in [550, 1200]$ GeV

- **"HH" selection (MMR):** Two b-jet pairs w. $\Delta R_{bb} < 1.5$
- **Signal Region selection:** $\chi < 1$

$$\chi = \sqrt{\left(\frac{m_{h_1} - C}{R}\right)^2 + \left(\frac{m_{h_2} - C}{R}\right)^2} \qquad (C, R) = (115, 23) \text{ GeV}$$




First, we need to reproduce CMS efficiencies! ☑

# Reinterpreting 13 TeV CMS p p → X → h h → 4b search (CMS-PAS-HIG-17-009)

- **Initial event selection:** 4 b-tagged jets with $|\eta| < 2.4$ and $P_T > 30$ GeV + 2 jets w. $P_T > 90$ GeV OR $P_T > 45$ GeV

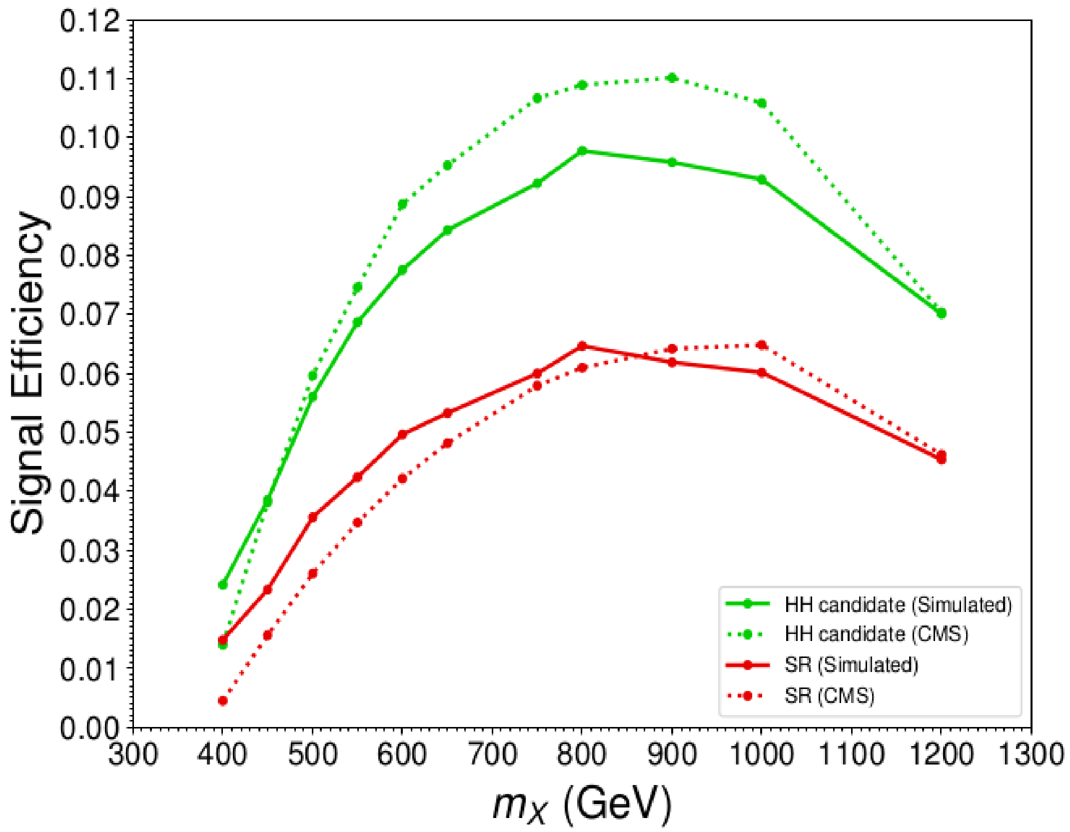
Low Mass Region (LMR) $m_X \in [250, 620]$ GeV

Medium Mass Region (MMR) $m_X \in [550, 1200]$ GeV

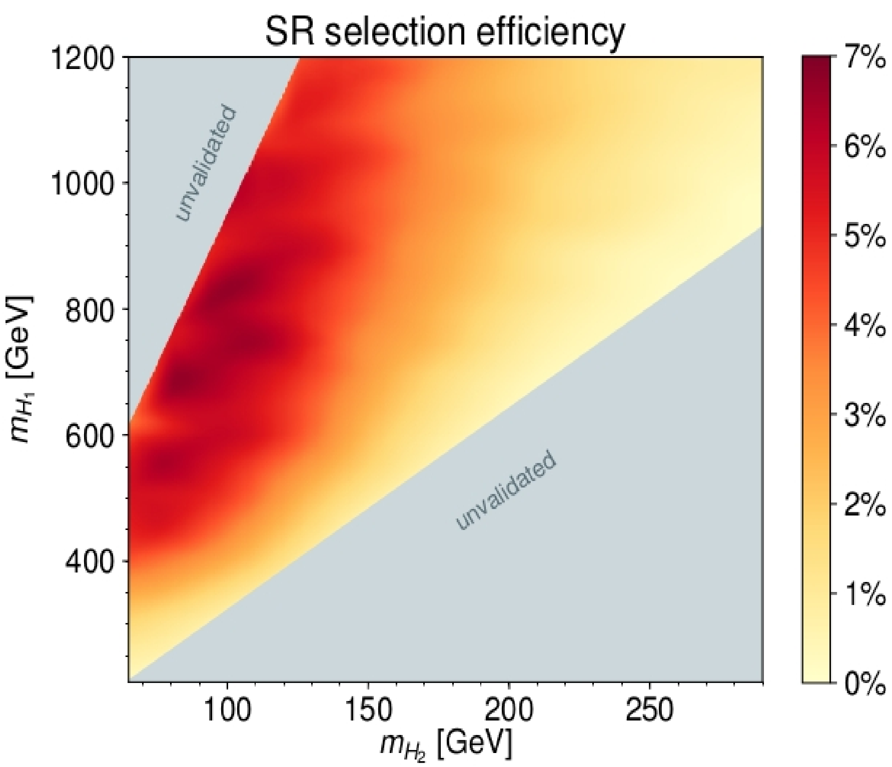
- **"HH" selection (MMR):** Two b-jet pairs w. $\Delta R_{bb} < 1.5$

- **Signal Region selection:** $\chi < 1$

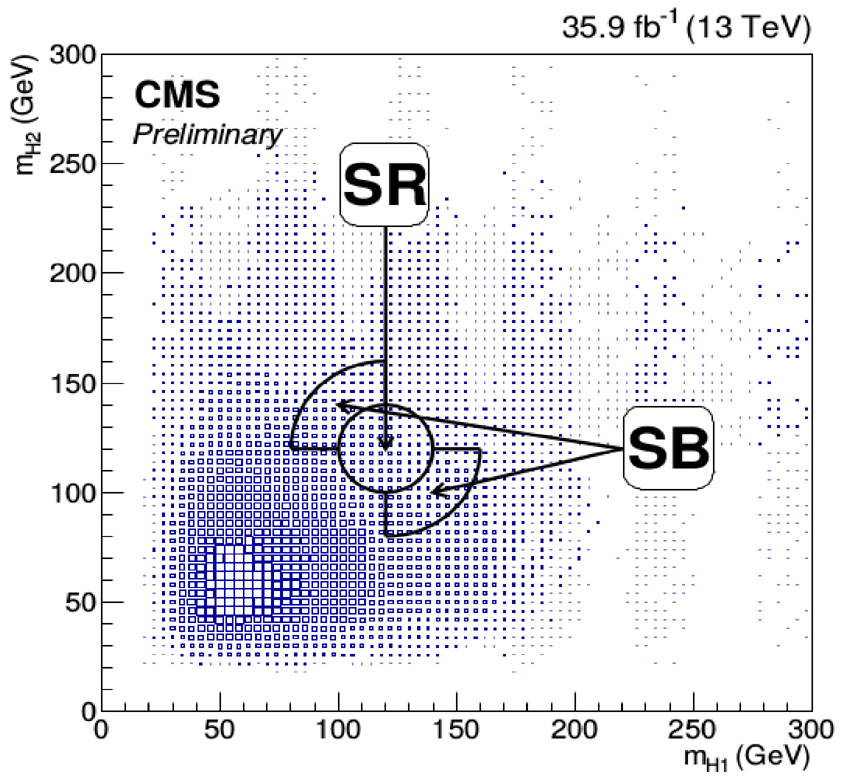
$$\chi = \sqrt{\left(\frac{m_{h_1} - C}{R}\right)^2 + \left(\frac{m_{h_2} - C}{R}\right)^2} \qquad (C, R) = (115, 23)\ \text{GeV}$$




Then, extrapolate to mass plane

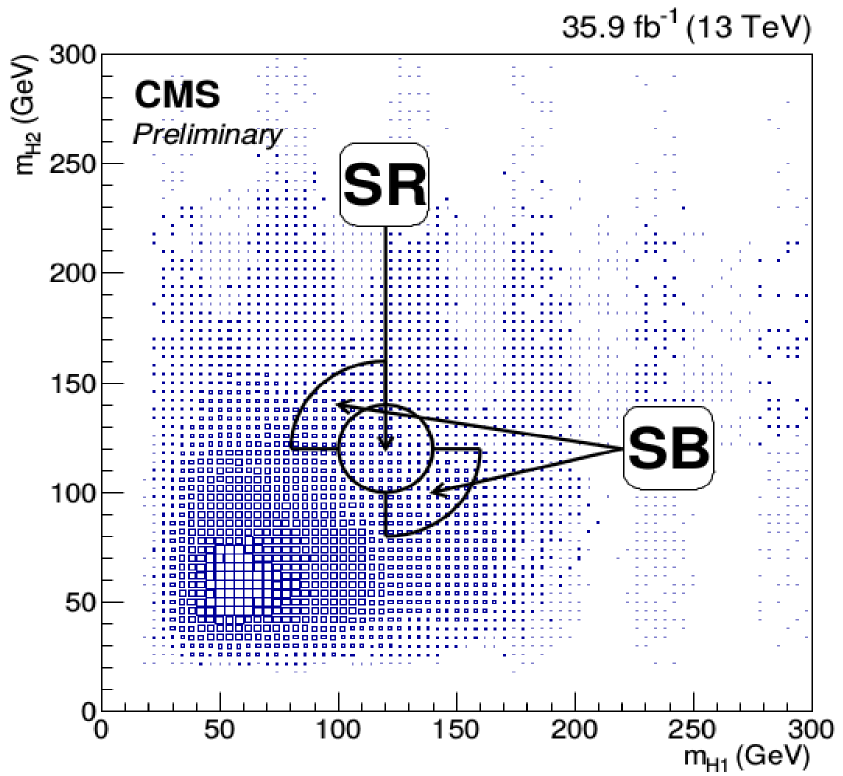


- Need SM background for projected XS sensitivity

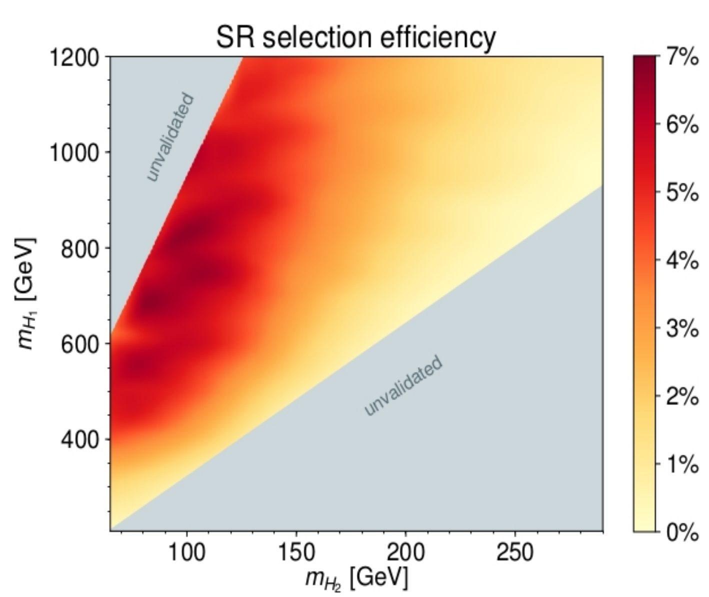


# Reinterpreting 13 TeV CMS p p → X → h h → 4b search
(CMS-PAS-HIG-17-009)

- Need SM background for projected XS sensitivity

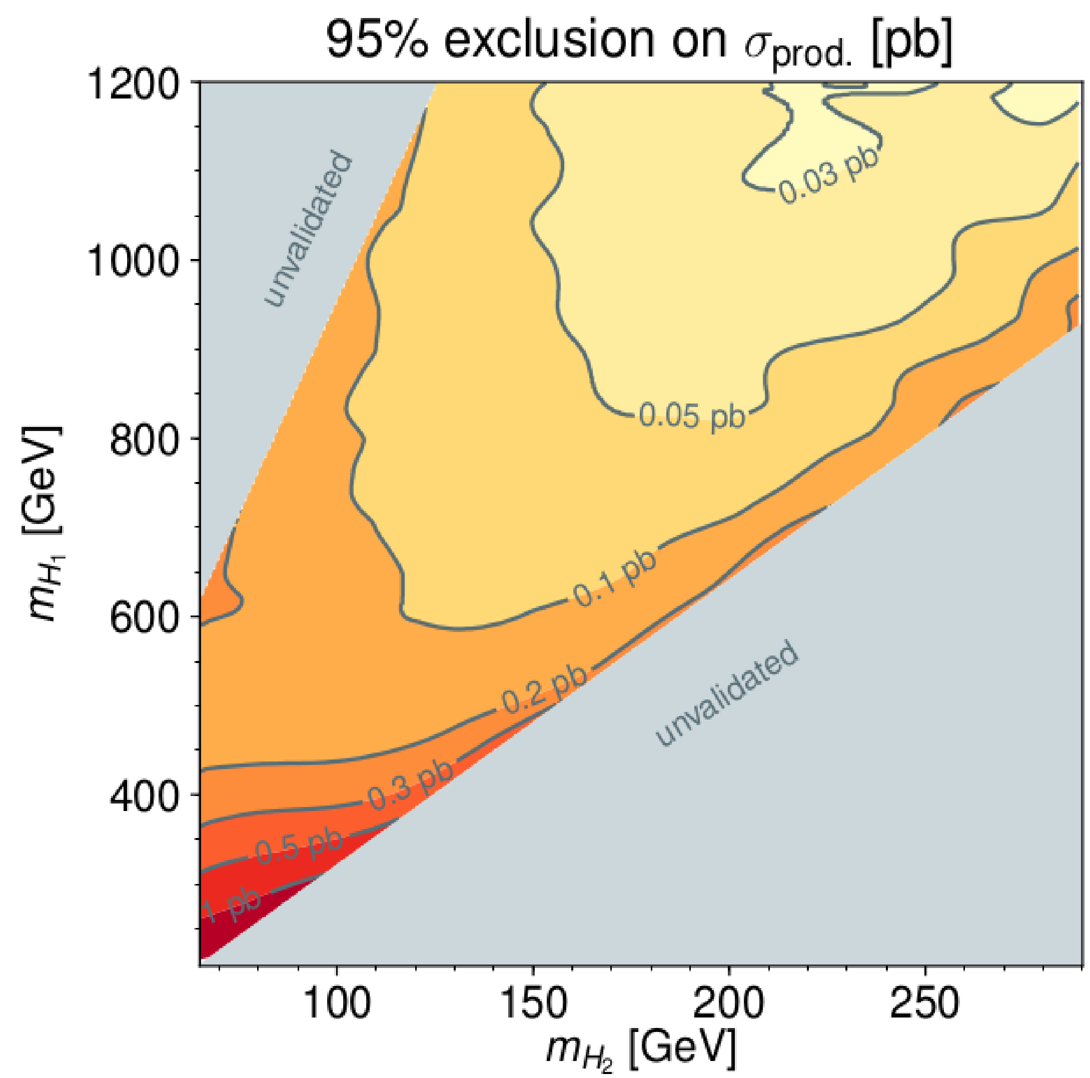



+




=

$p\ p \to H_1 \to H_2\ H_2 \to 4b$



Reinterpreting 13 TeV CMS p p → X → h h → 4b search (CMS-PAS-HIG-17-009)

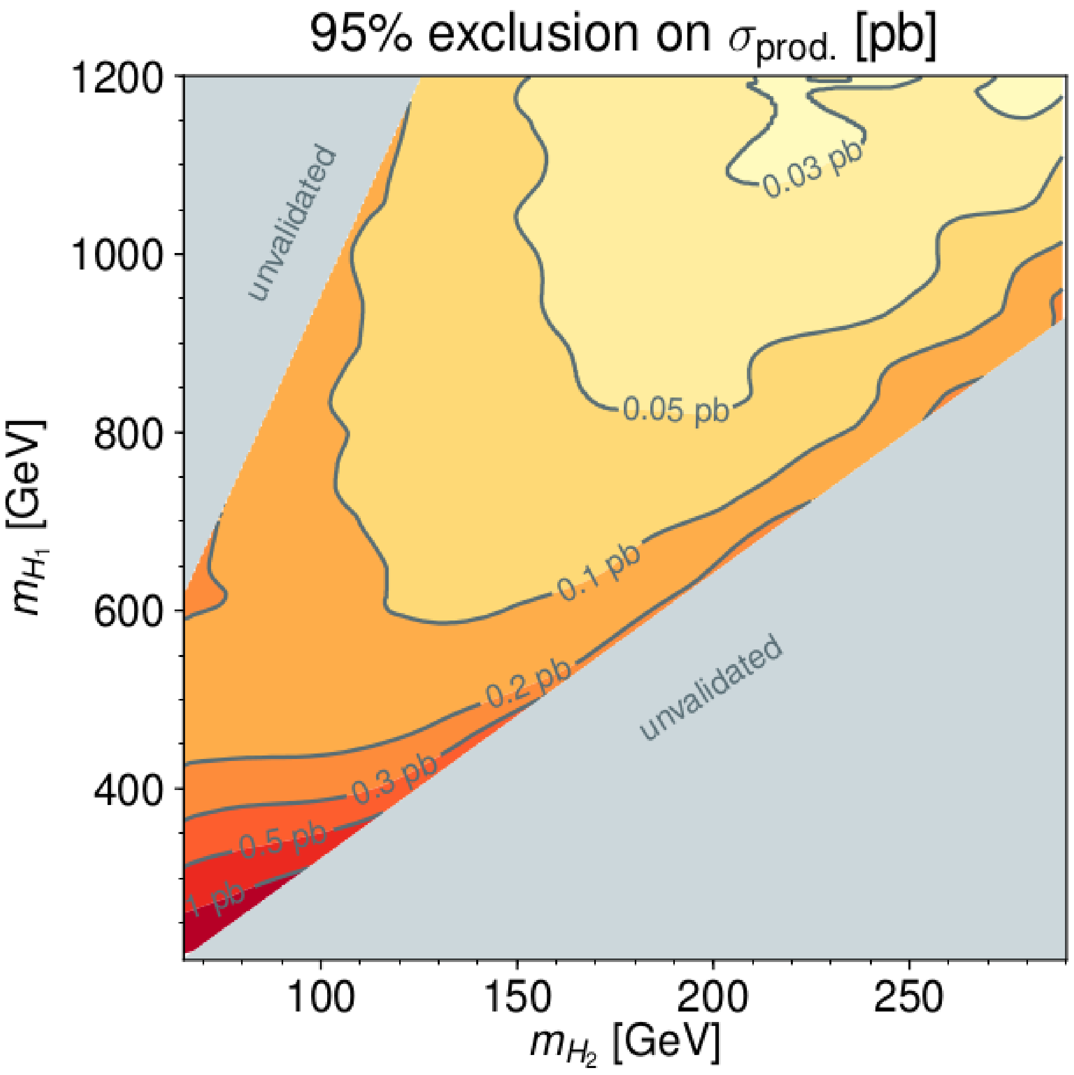
Search looks promising...

e.g. $m_H$ = 500 GeV, $m_A$ = 150 GeV

→ 95% CL XS Limit = 0.1 pb (H → Z A, A → bb)

→ 95% CL XS Limit ≃ 0.2 pb (H → A A, A → bb)

$p\,p \to H_1 \to H_2\,H_2 \to 4b$



Thank you!