# Collider probes of a first order phase transition

based on arxiv 2309.17431

Kateryna Radchenko

in collaboration with Thomas Biekötter, Sven Heinemeyer, Jose Miguel No,
María Olalla Olea Romacho and Georg Weiglein

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# Motivation

- Open issues in the SM create the need for BSM physics that can answer to fundamental questions:
    - nature of dark matter, Baryon Asymmetry of the Universe (BAU), hierarchy problem, unification problem, masses of the neutrinos, strong CP problem, ...

- The central role of the Higgs makes models with extended Higgs sectors especially appealing:

  → the two Higgs Doublet Model (2HDM) is a simple extension that can accommodate a **first order EW phase transition**, a necessary condition for electroweak baryogenesis

In this talk: we analyze the capability of new $A \to ZH$ searches in the $\ell^+\ell^- tt/\,\nu\nu bb$ final states to probe regions of the 2HDM that feature a strong first order electroweak phase transition (SFOEWPT), their complementarity with other collider searches and future space based gravitational wave detectors

# Phase Transitions in a nutshell

- The Higgs mechanism requires **spontaneous symmetry breaking** but its origin remains a mystery

- In the SM the evolution from a symmetric vacuum to the EW vacuum happens through a smooth crossover, given the Higgs mass at ~ 125 GeV [Kajantie, Laine, Rummukainen, Shaposhnikov: arXiv: 9605288 ]

- In BSM models a **strong first order phase transition** can be accommodated:

  motivation : it is a necessary condition for electroweak baryogenesis :

  - what?: a mechanism to dynamically explain BAU

  - why?: it provides a mechanism to depart from thermal equilibrium
    → one of the Sakharov conditions, together with B violation and C/CP violation

# Phase Transitions in a nutshell

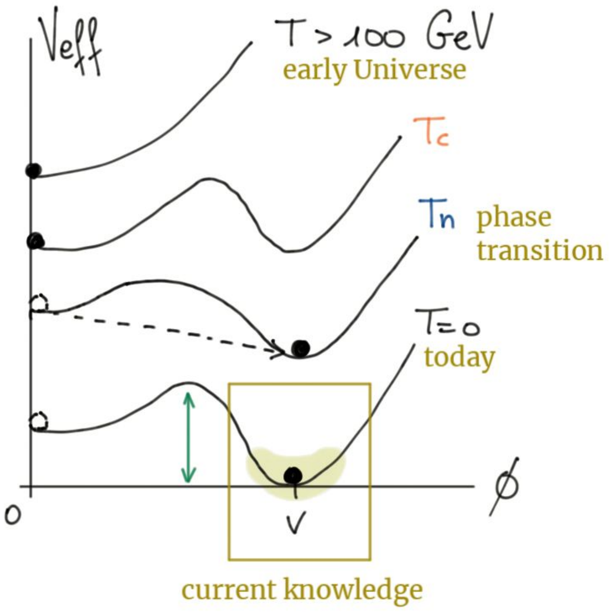
- In BSM models a **strong first order** phase transition can be accommodated:

The vacuum transitions from a symmetric phase to a broken (EW) phase as the universe cools down
It requires an energy barrier in the effective potential:

$$V_{\text{eff}} = \boxed{V_{\text{tree}} + V_{\text{CW}} + V_{\text{CT}}} + V_{\text{T}} + V_{\text{daisy}}$$

potential at T = 0

[Coleman, Weinberg, 1973]
[Dolan, Jackiw, 1974]
[Arnold, Espinosa, 1996]

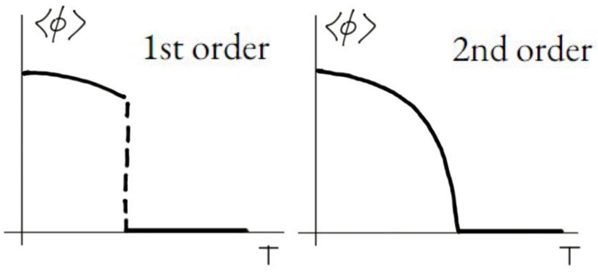


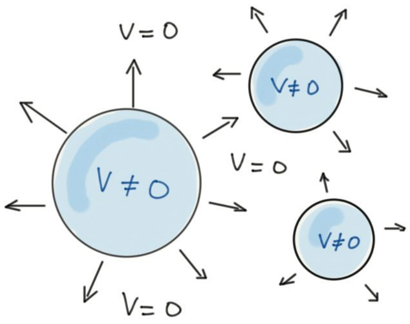
# Phase Transitions in a nutshell

- In BSM models a **strong** first order **phase transition** can be accommodated

  A first order transition provides violent conditions for bubble nucleation that are needed to depart from thermal equilibrium.

  Sphaleron processes are suppressed in the bubbles so the b-asymmetry generated outside through the scattering of the plasma against the bubble walls is not washed out once it enters inside the expanding bubble




[Gorbunov, Rubakov, 2011]
[Morrissey, Ramsey-Musolf: arXiv: 1206.2942 ]

# Phase Transitions in a nutshell

- In BSM models a **strong** **first order phase transition** can be accommodated

  Only a strong phase transition can lead to a successful electroweak baryogenesis!
  The transition is sufficiently strong when the vev at the bubble nucleation time is larger than the temperature (related to the rate of sphaleron transitions in the broken phase and avoids the washout of the asymmetry):

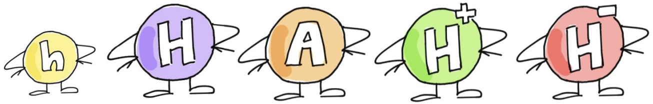
$$\xi_n = \frac{v_n}{T_n} \gtrsim 1$$

  **Phenomenological consequences** include sizable deviations in the trilinear Higgs coupling measurable at the LHC and potentially detectable gravitational wave (**GW**) signal in the frequency range of the space based telescope LISA, together with direct searches for the heavier scalars

# The 2HDM model

[T. D. Lee (1973) Physical Review , Branco, Ferreira et al: arXiv: 1106.0034 ]

- **CP conserving** 2HDM with two complex doublets: $\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{v_1+\rho_1+i\eta_1}{\sqrt{2}} \end{pmatrix}, \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{v_2+\rho_2+i\eta_2}{\sqrt{2}} \end{pmatrix}$




- **Softly broken $\mathbb{Z}_2$ symmetry** ($\Phi_1 \rightarrow \Phi_1$; $\Phi_2 \rightarrow -\Phi_2$ ) entails 4 Yukawa types

- Potential:

$$V_{\text{2HDM}} = m_{11}^2(\Phi_1^\dagger\Phi_1) + m_{22}^2(\Phi_2^\dagger\Phi_2) - m_{12}^2(\Phi_1^\dagger\Phi_2 + \Phi_2^\dagger\Phi_1) + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{\lambda_5}{2}((\Phi_1^\dagger\Phi_2)^2 + (\Phi_2^\dagger\Phi_1)^2),$$

- Free parameters: $m_h,\ m_H,\ m_A, m_{H^\pm}, m_{12}^2, \tan\beta, \cos(\beta-\alpha), v$

$\tan\beta = v_2/v_1$
$v^2 = v_1^2 + v_2^2 \sim (246\ \text{GeV})^2$

# The smoking gun signature

[Dorsch , Huber , Mimasu, No: arXiv:1405.5537 ]

- Couplings to fermions in the 4 types: $\mathcal{L}_{\text{Yuk}} = -\sum_{f=u,d,l} \frac{m_f}{v}\left[\xi_h^f \bar{f} f h + \xi_H^f \bar{f} f H + i\xi_A^f \bar{f}\gamma_5 f A\right]$

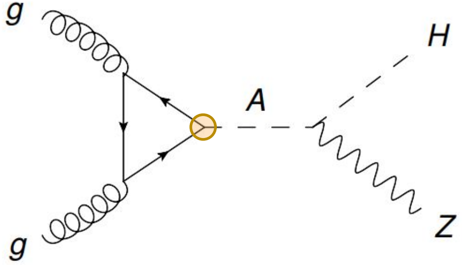
| | u-type | d-type | leptons | $\xi_A^u$ | $\xi_A^d$ |
|---|---|---|---|---|---|
| type I | $\Phi_2$ | $\Phi_2$ | $\Phi_2$ | $\cot\beta$ | $-\cot\beta$ |
| type II | $\Phi_2$ | $\Phi_1$ | $\Phi_1$ | $\cot\beta$ | $\tan\beta$ |
| type III (lepton-specific) | $\Phi_2$ | $\Phi_2$ | $\Phi_1$ | $\cot\beta$ | $-\cot\beta$ |
| type IV (flipped) | $\Phi_2$ | $\Phi_1$ | $\Phi_2$ | $\cot\beta$ | $\tan\beta$ |

- Smoking gun signature: $A \to ZH$ remains unsupressed in the **alignment limit** $(\cos(\beta-\alpha) \to 0)$ i.e. the Higgs at ~125 GeV has couplings to fermions and gauge bosons at tree level as in the SM

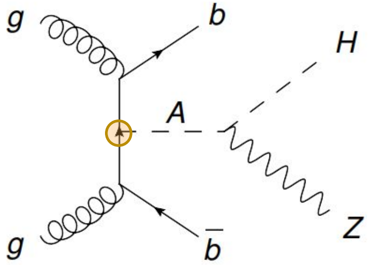
A production in all types:

$\propto 1/\tan^2\beta$

gluon fusion




b-associated




type II and IV : $\propto \tan^2\beta$

type I and III: $\propto 1/\tan^2\beta$

# Smoking gun searches

- Existing searches : $gg \to A \to ZH \to \ell^+\ell^- b\bar{b}$ at 13 TeV including 139 fb$^{-1}$

  [ATLAS: arXiv: 2011.05639] $b\bar{b} \to A \to ZH \to \ell^+\ell^- b\bar{b}$ at 13 TeV including 139 fb$^{-1}$

- New! : $gg \to A \to ZH \to \ell^+\ell^- t\bar{t}$ at 13 TeV including 140 fb$^{-1}$

  [ATLAS: arXiv: 2311.04033] $gg \to A \to ZH \to \nu\nu b\bar{b}$ at 13 TeV including 140 fb$^{-1}$

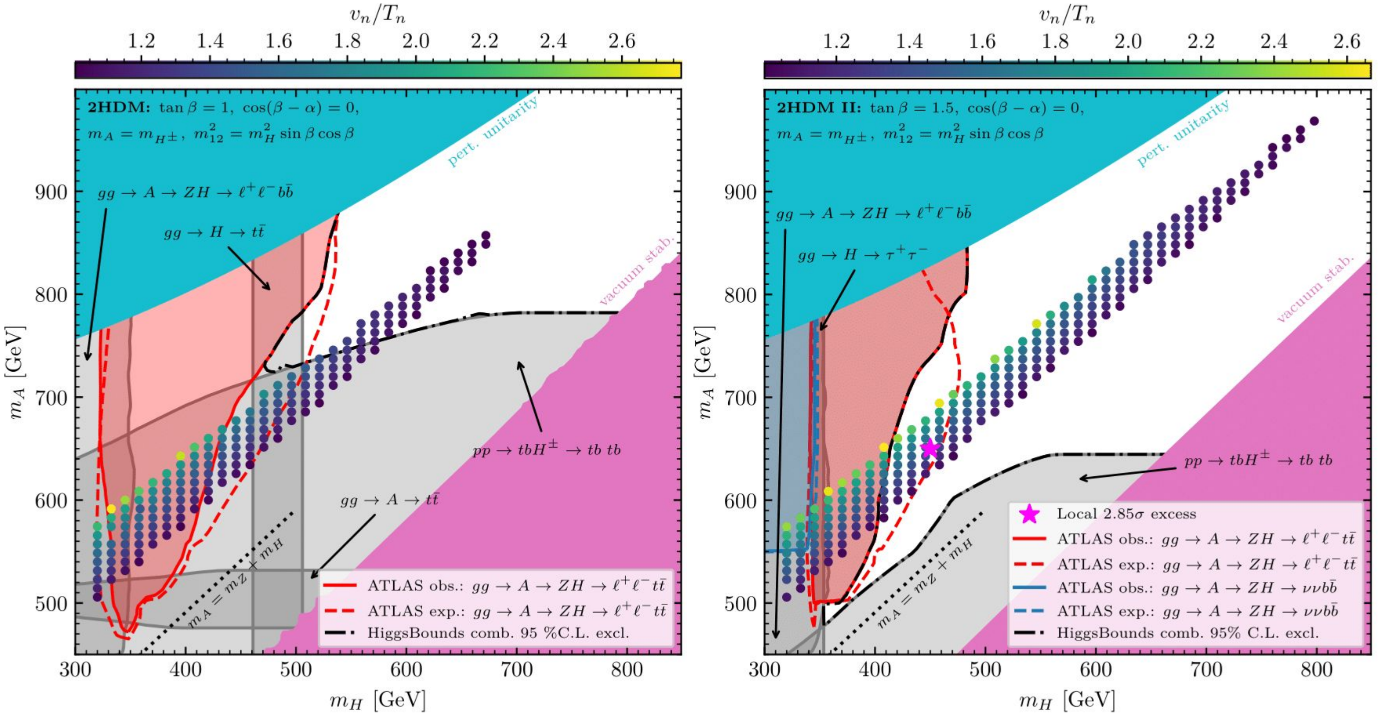
  $b\bar{b} \to A \to ZH \to \nu\nu b\bar{b}$ at 13 TeV including 140 fb$^{-1}$

  * all of them now included in the public version of HiggsTools [HiggsTools Collaboration: arXiv: 2210.09332]

  [CMS PAS B2G-23-006] $gg \to A \to ZH \to Zt\bar{t}$ at 13 TeV including 138 fb$^{-1}$

- Other interesting searches: $H^\pm \to W^\pm H \to \ell^\pm \nu t\bar{t}$

# Constraints for low tanβ




> Colored regions excluded: vacuum stability (pink) and perturbative unitarity (cyan)

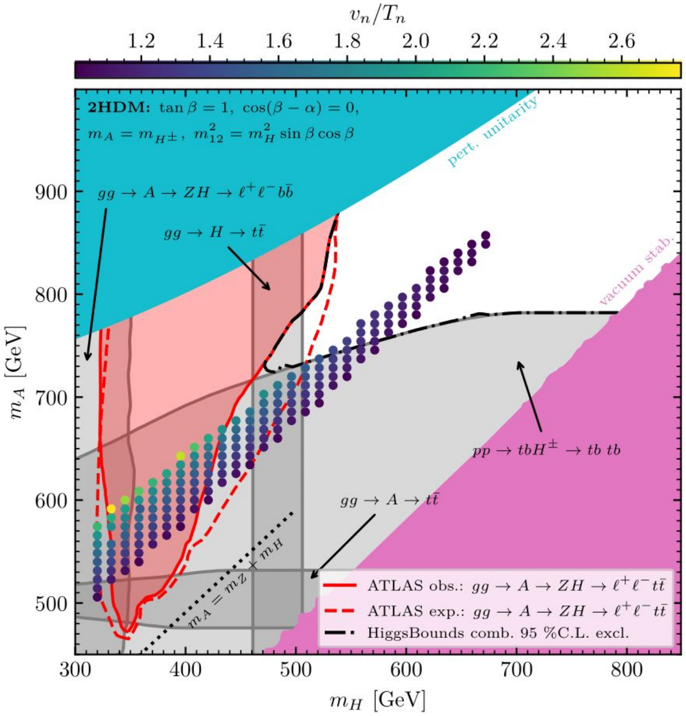
> Grey regions excluded by previous searches

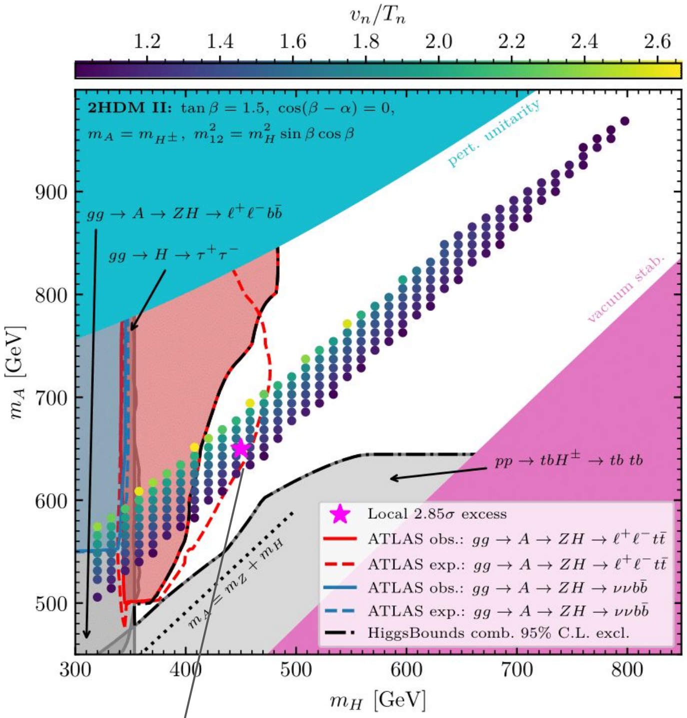
> Exclusion regions of **new searches** are colored in pale red ($\ell^+\ell^- tt$)/blue ($\nu\nu bb$)

> Black contour shows the combined exclusion limit of all the searches at 95% CL

> Colored dots indicate region yielding a FOEWPT

# Constraints for low tanβ




Local 2.85$\sigma$ excess at ($m_H$, $m_A$) ~ (450, 650) GeV not confirmed by CMS search

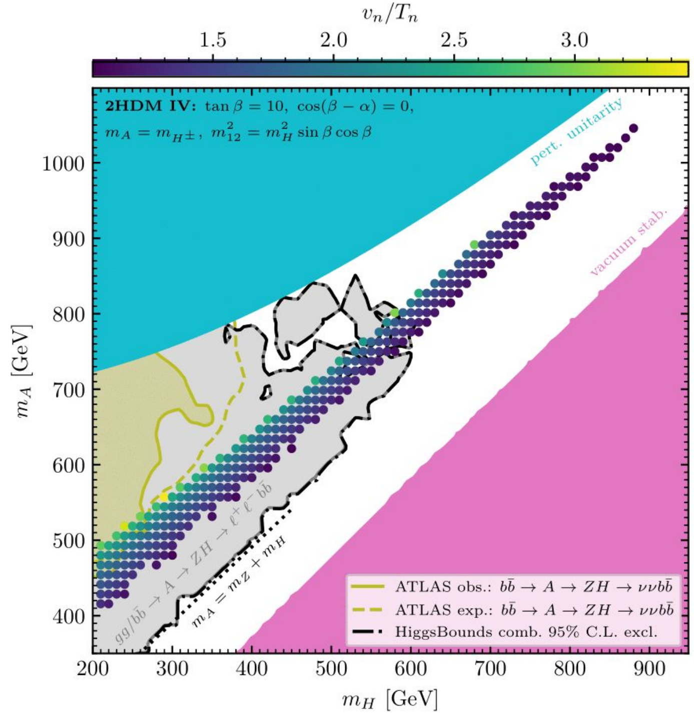
> Exclusion potential for masses above $2m_t$

> For tanβ = 1 the region with SFOEWPT is excluded by $H^\pm$ searches, although could be relaxed if $m_{H\pm} \neq m_A$

> For tanβ = 1.5 the region $H^\pm$ searches less sensitive, $A \to ZH \to \ell^+\ell^- tt$ partially **covers the unexplored SFOEWPT region**

> $H^\pm \to W^\pm H$ would play a role in the uncovered region

# Constraints for high tanβ




> Gluon fusion A production is suppressed for large tanβ

> **b associated production** is more efficient in types II and IV

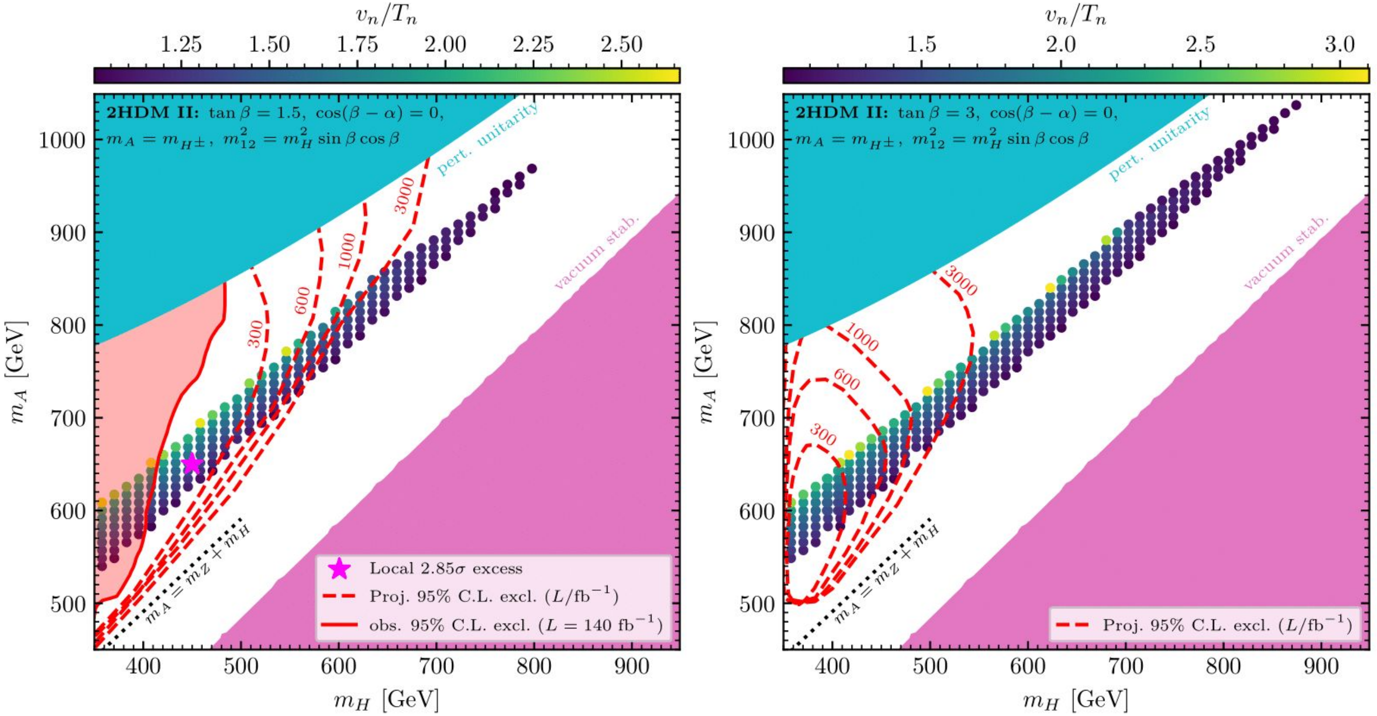
> BR(H→ tt) is very suppressed so the new b associated search is competing with the old searches in the $\ell^+\ell^- bb$ final state, which has a larger exclusion potential than the new search with decays into neutrinos

> *νν*bb reach larger $m_A$ (up to 1.2 TeV) which would surpass the lepton decay mode in models where a larger mass splitting between $m_{H\pm}$ and $m_A$ is allowed

> In general, **for large tanβ the lepton decay mode is more promising** independently of the 2HDM scenario, but other searches gain sensitivity for tanβ ≳ 15

# Future prospects

$$\sigma^{\text{exp. 95\% CL}}_{\text{proj.}}(\mathcal{L}, m_H, m_A) = \sigma^{\text{exp. 95\% CL}}_{\text{Run 2}}(m_H, m_A)\sqrt{\frac{140\ \text{fb}^{-1}}{\mathcal{L}}}$$



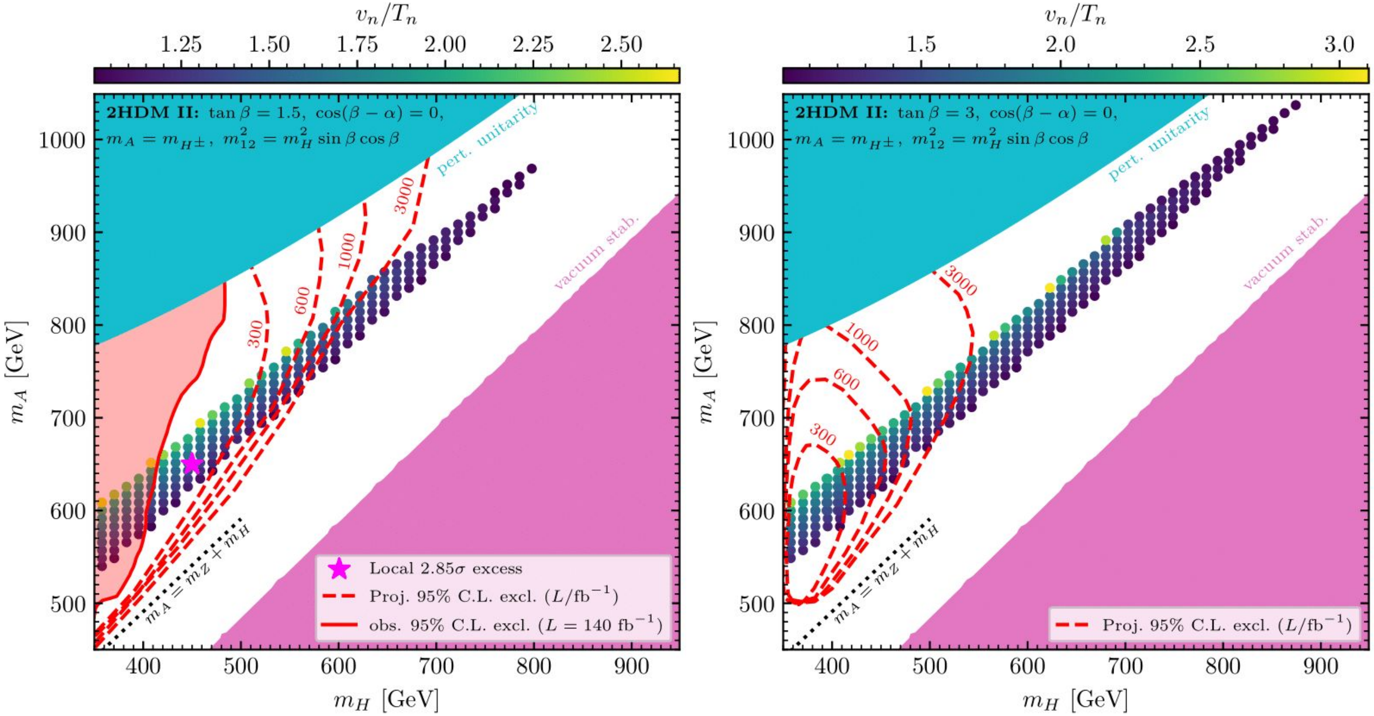

> Future discovery reach of the smoking gun search above the di-top threshold

> Limits obtained by rescaling the expected cross section limits reported in the new search

> For tanβ =1.5 LHC will be able to probe $m_A$ up to 700 GeV $m_H$ up to 1 TeV, covering largely the region yielding a SFOEWPT → test of BAU (realisable for small tanβ) [Fromme, Huber, Seniuch: arXiv: 0605.242]

# Future prospects

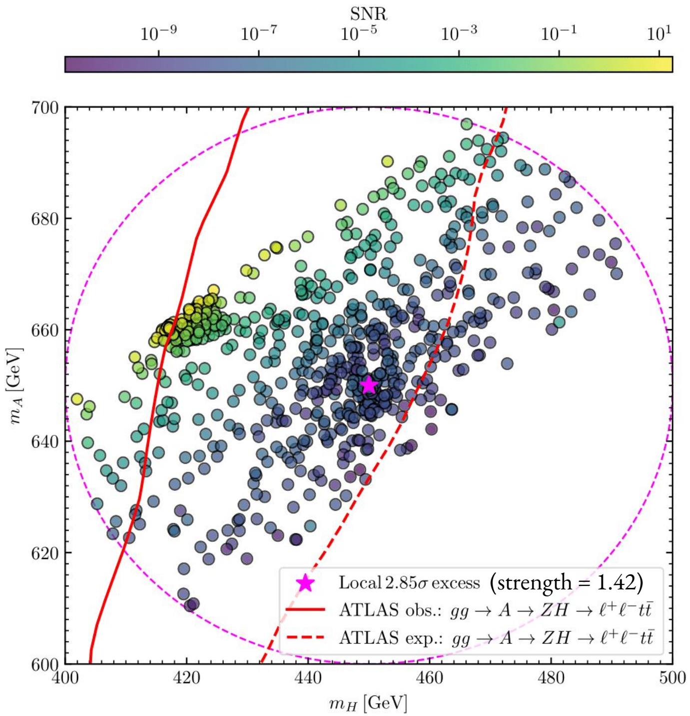
$$\sigma^{\text{exp. 95\% CL}}_{\text{proj.}}(\mathcal{L}, m_H, m_A) = \sigma^{\text{exp. 95\% CL}}_{\text{Run 2}}(m_H, m_A)\sqrt{\frac{140\ \text{fb}^{-1}}{\mathcal{L}}}$$




> For tanβ = 1.5 all the points that would yield a detectable GW signal would be probed at HL-LHC

> For tanβ = 3 the search $A \to ZH \to \ell^+\ell^- tt$ starts to probe the FOEWPT region but it cannot probe it fully. It is is the only search that can probe the parameter space in this tanβ regime

# Complementarity with a GW signal




Assuming: $v_\mathrm{w} = 0.6$ and 7 years of operation

> A stochastic GW signal is detectable at a GW observatory if its **signal to noise ratio** (SNR) is greater than 1:

$$\mathrm{SNR} = \sqrt{\mathcal{T} \int_{-\infty}^{+\infty} \mathrm{d}f \left[ \frac{h^2\Omega_{\mathrm{GW}}(f)}{h^2\Omega_{\mathrm{Sens}}(f)} \right]^2}$$

> Since the SNR is very sensitive to the masses of the scalars, we allow for a 50 GeV mass window around the excess → SNR spans over several orders of magnitude

> The poor mass resolution of the excess and the sharp dependence of the SNR on it prevents a decisive conclusion on the sensitivity of LISA to this scenario

> The absence of a signal at the LHC poses severe and definitive constraints on the possible GW signal from an EWPT but not the other way around

# Conclusions

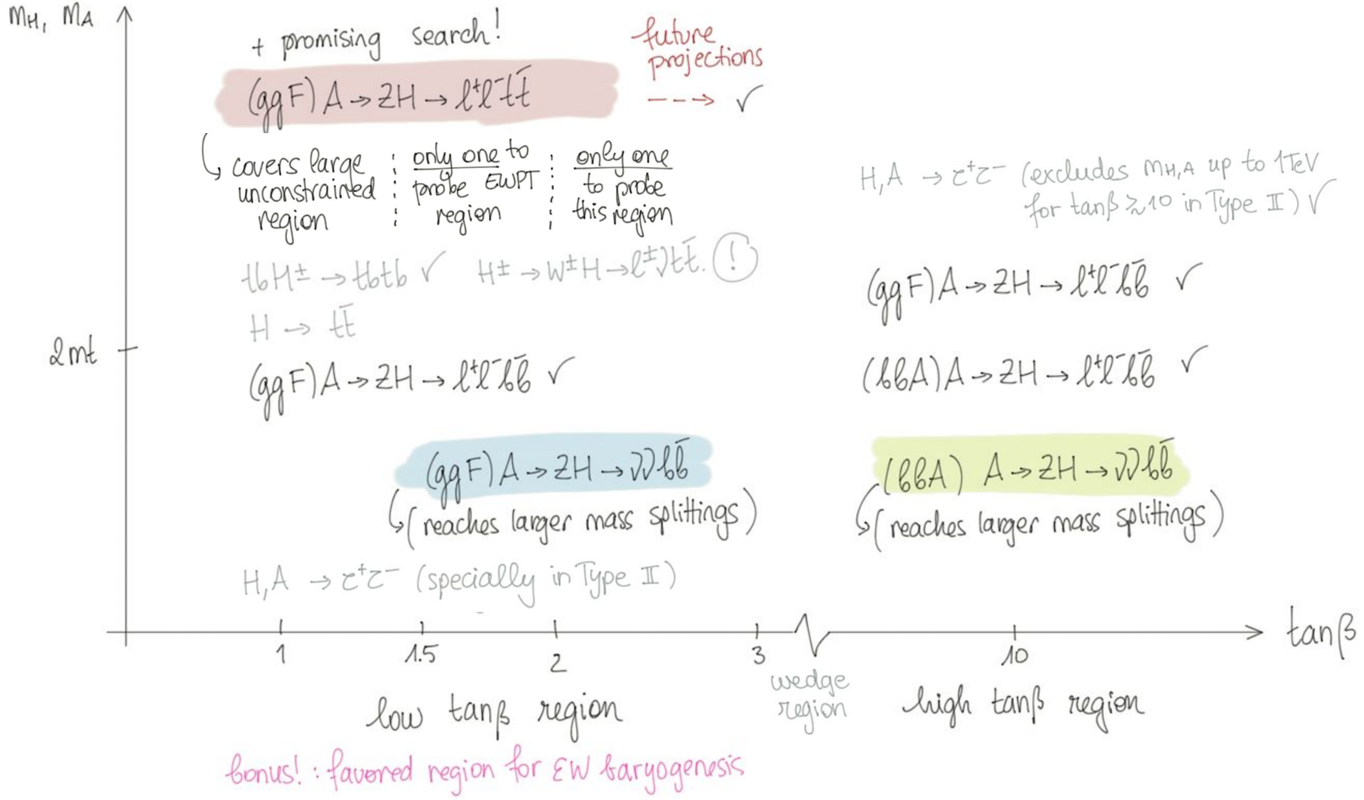
- 2HDM mass splittings between scalars ↔ large quartic couplings: good for SFOEWPT but bad for perturbative unitarity and EWPO, can be probed by the smoking gun search because $(m_A - m_H) > m_Z$

- $A \rightarrow ZH \rightarrow \ell^+\ell^- tt$ has the potential to further probe the relevant regions for FOEWPT in the 2HDM specially for $1.5 \lesssim \tan\beta \lesssim 3$ above the di-top production threshold

- It is the only search to target the so far unexplored regions for $\tan\beta > 2$ and the regions featuring a FOEWPT for $\tan\beta \sim 1.5$

- No clear statement can be made about the GW signature but the interplay between collider and astrophysical experiments would play a crucial role in the inquiry of the EW symmetry breaking mechanism

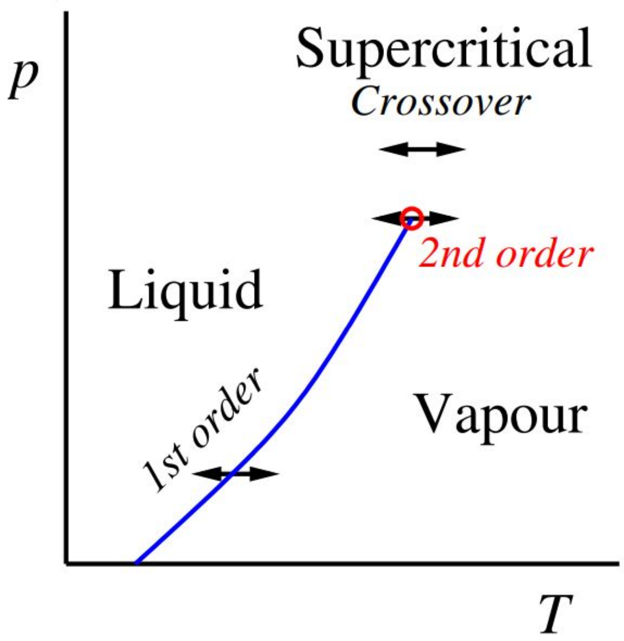
# Summary



$m_H, m_A$
+ promising search!
(ggF) $A \to ZH \to \ell^+\ell^- t\bar{t}$
future projections
- - -> ✓
covers large unconstrained region
only one to probe EWPT region
only one to probe this region
$tbH^\pm \to tbtb$ ✓
$H^\pm \to W^\pm H \to \ell^\pm \nu t\bar{t}$ (!)
$H \to t\bar{t}$
$2m_t$
(ggF) $A \to ZH \to \ell^+\ell^- b\bar{b}$ ✓
(ggF) $A \to ZH \to \nu\nu b\bar{b}$
(reaches larger mass splittings)
$H, A \to \tau^+\tau^-$ (specially in Type II)
$H, A \to \tau^+\tau^-$ (excludes $m_{H,A}$ up to 1TeV for $\tan\beta \gtrsim 10$ in Type II) ✓
(ggF) $A \to ZH \to \ell^+\ell^- b\bar{b}$ ✓
(bbA) $A \to ZH \to \ell^+\ell^- b\bar{b}$ ✓
(bbA) $A \to ZH \to \nu\nu b\bar{b}$
(reaches larger mass splittings)
1
1.5
2
3
10
$\tan\beta$
wedge region
low $\tan\beta$ region
high $\tan\beta$ region
bonus! : favored region for EW baryogenesis

# Backup

# Water vs SM phase diagram



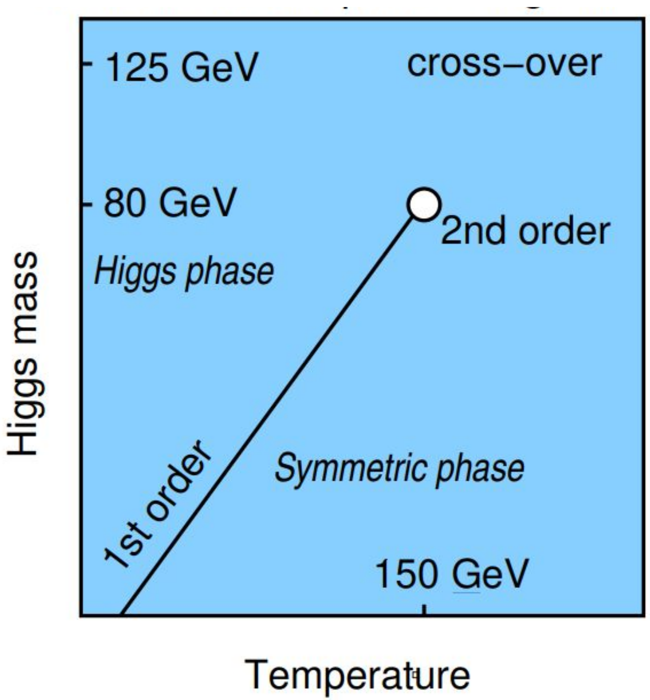




Image by: [Hindmarsh, Lüben, Lumma, Pauly: arXiv: 2008.09136 ]

# thdmTools: a python package to explore the 2HDM

[Bieköter, Heinemeyer, No, Radchenko, Romacho, Weiglein: arxiv:2309.17431 ]

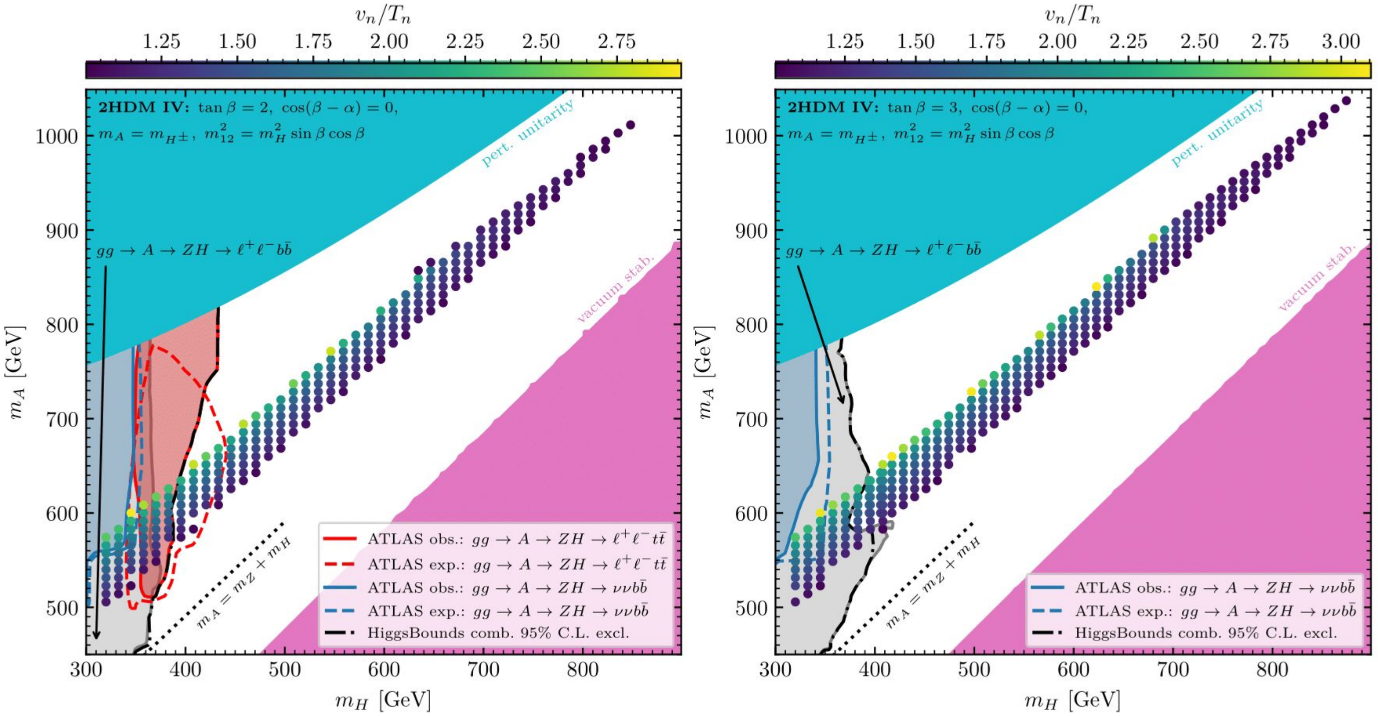
- **EWPO**: impose a condition on the Higgs boson masses: $(m_{H\pm}-m_H) \sim 0$ and/or $(m_{H\pm}-m_A) \sim 0$
  in our scenarios $m_{H\pm} = m_A$

- Theoretical:
  **(N)LO Unitarity**: from the $2 \rightarrow 2$ processes scattering amplitude
  [Cacchio, Chowdhury, Eberhardt, Murphy: arXiv:1609.01290]
  **Stability**: tree level boundedness from below of the potential
  [Bhattacharyya, Das: arXiv:1507.06424]

- Collider searches and measurements:
  **HiggsBounds**: experimental limits from direct searches
  **HiggsSignals**: signal strength of the 125 GeV Higgs
  [HiggsTools Collaboration: arXiv: 2210.09332]

- **Flavour observables**: $B \rightarrow X_s\gamma$ and $B_s \rightarrow \mu\mu$ (SuperIso) *not considered in this project
  [Mahmoudi: arXiv:0808.3144]

# Constraints for low tanβ part II

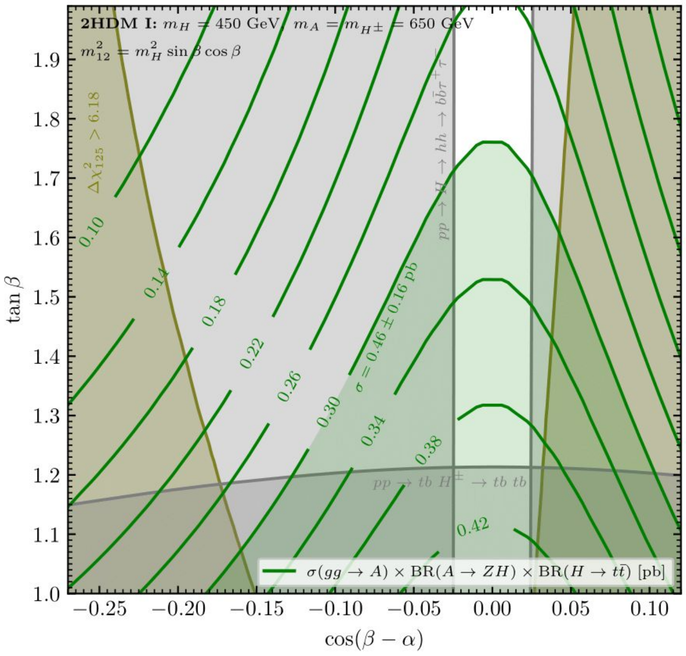


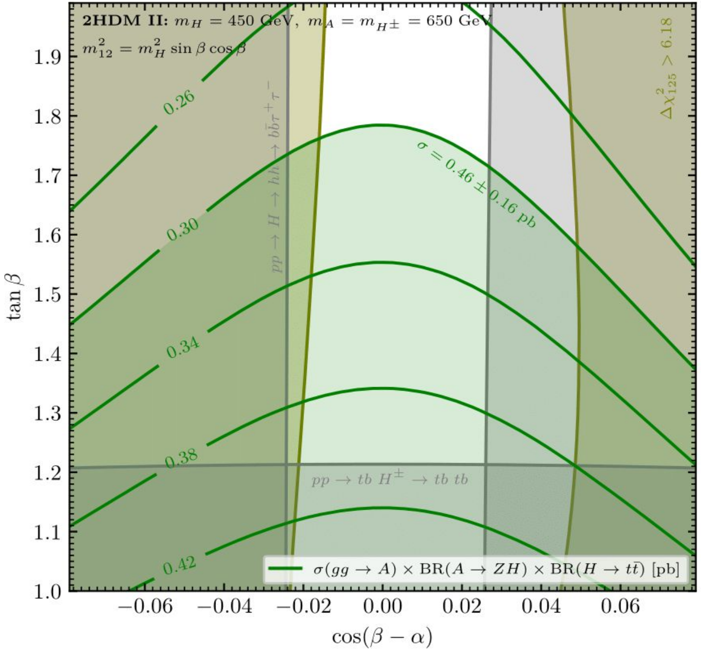

> Focusing on Type IV because $H \to bb$ is enhanced w.r.t I and III and $H \to \tau^+\tau^-$ excludes large regions in II

> Manifestation of the **wedge region** in 2HDM: 2 ≲tanβ ≲8 hard to probe

> Above the di top threshold the smoking gun search with **tt decay is the only search** that can probe the parameter space but only for **tanβ < 3**

# Local 2.85$\sigma$ excess at $(m_H, m_A)$ ~ (450, 650) GeV



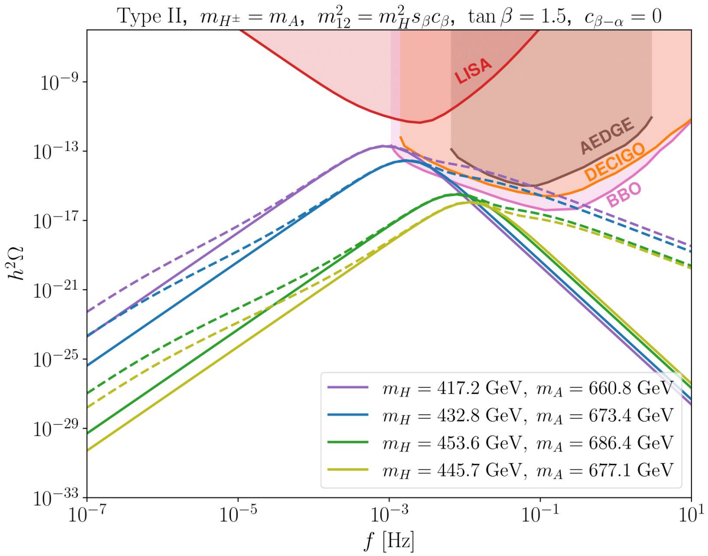

$$\sigma(gg \to A) \times \mathrm{BR}(A \to ZH) \times \mathrm{BR}(H \to t\bar{t}) = 0.46 \pm 0.16 \text{ pb}$$

> Green shaded region correspond to a description of the excess within 1$\sigma$

> A **description of the excess is possible** in all types close to the alignment limit

> The cross section diminishes away from the alignment limit because other decay modes of $H$ (to $VV$ or $hh$) become relevant

# Complementarity with a GW signal



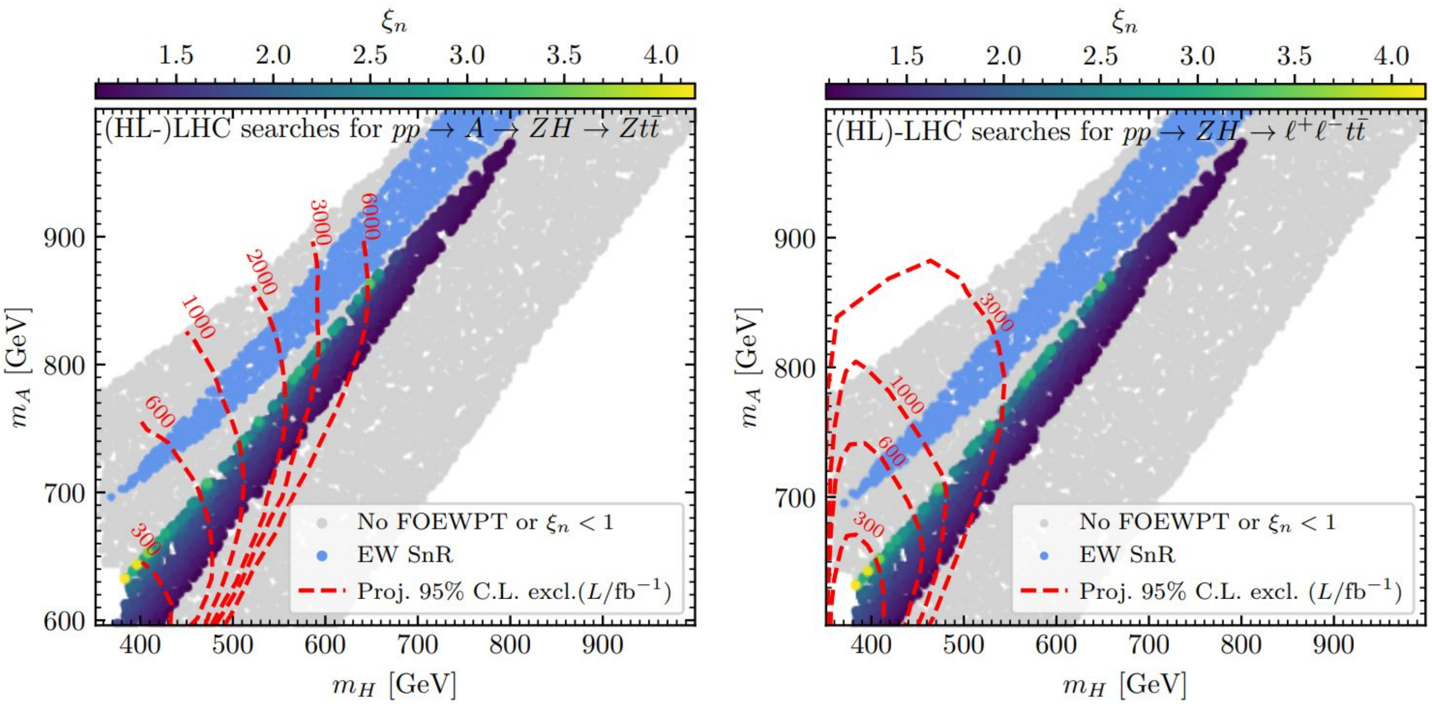

Solid lines: sound wave contribution $h^2\Omega_{sw}$
Dashed lines: sound wave + turbulence $h^2\Omega_{sw}+h^2\Omega_{turb}$

> We analyze the **GW spectra** for the point with the largest SNR ratio in the previous scan and 3 more points with up to 10% deviation in the mass

> For small deviations in the masses the peak amplitudes of the GW signals quickly drop to values below the experimental sensitivity of the proposed GW detectors

> If a BSM signal was detected at the LHC, a mass resolution at the percent level would be required to draw conclusions about the detectability of a GW signal → space based astronomy could become a tool to sharpen the precision of particle physics

# Comparison to previous CMS projections




[Biekötter, Heinemeyer, No, Romacho, Weiglein: arxiv:2208.14466]