Resonant top pair searches at the LHC: a window to electroweak phase transition

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DG, Kaladharan, Wu arxiv:2108.05356 and arxiv:2206.08381

Resonant top pair searches

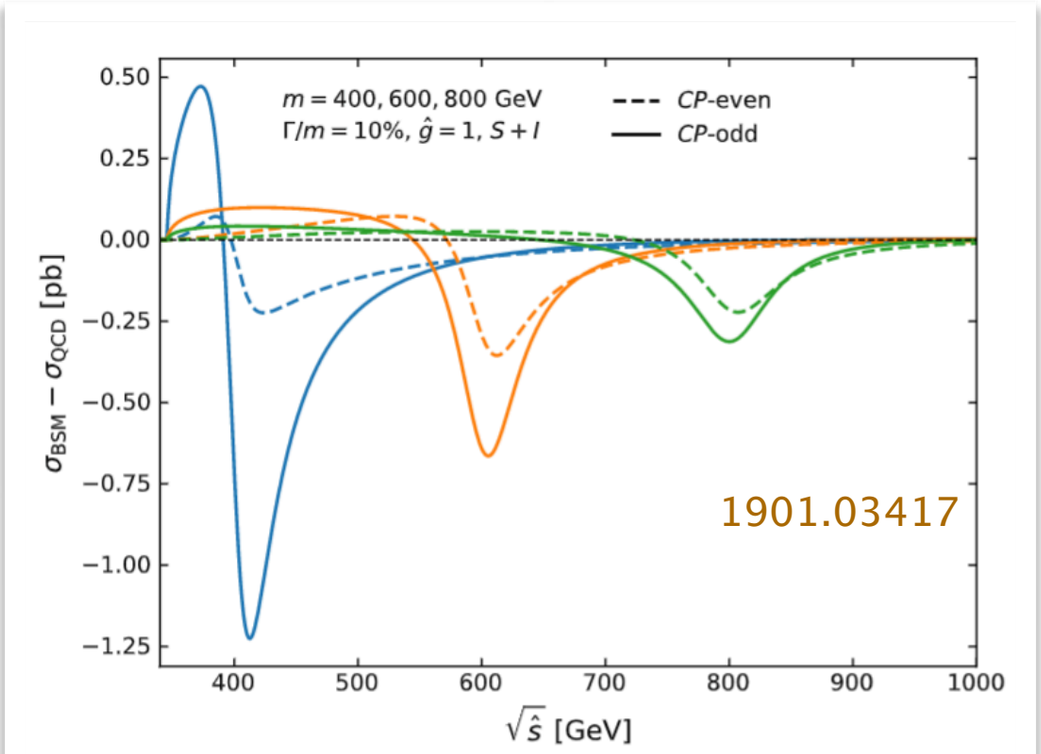
- Resonant top pair production is a relevant signature for many BSM frameworks:

  2HDM, SM+singlet, combinations of singlet and doublet fields, extra dimensions…

  Branco, Ferreira, Lavoura, Rebelo, Sher, Silva 2011; Muhlleitner, Sampaio, Santos, Wittbrodt 2017

- gg→H/A→tt channel: interesting signature with large signal/background interference

  Gaemers, Hoogeveen ’84
  Dicus, Stange, Willenbrock ’94
  Frederix, Maltoni ’07
  ATLAS – arXiv:1804.10823
  CMS – arXiv:1908.01115

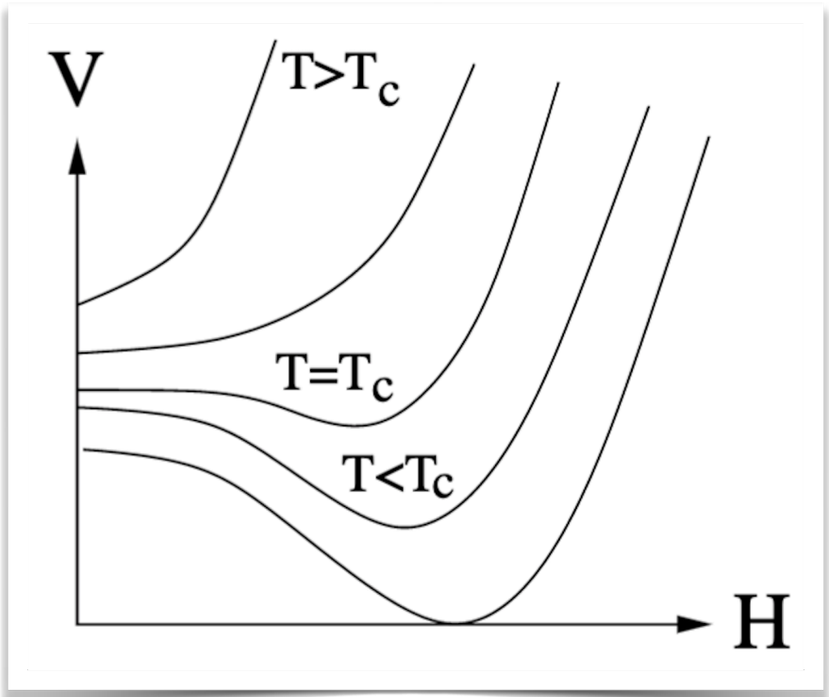


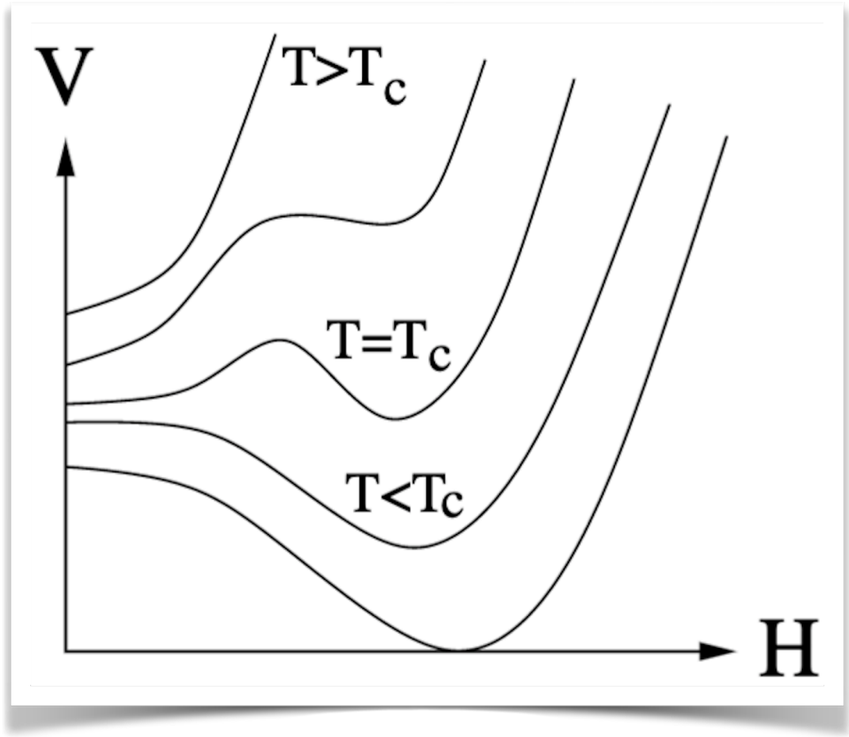
- **Resonant top pair searches can be a window to electroweak phase transition**

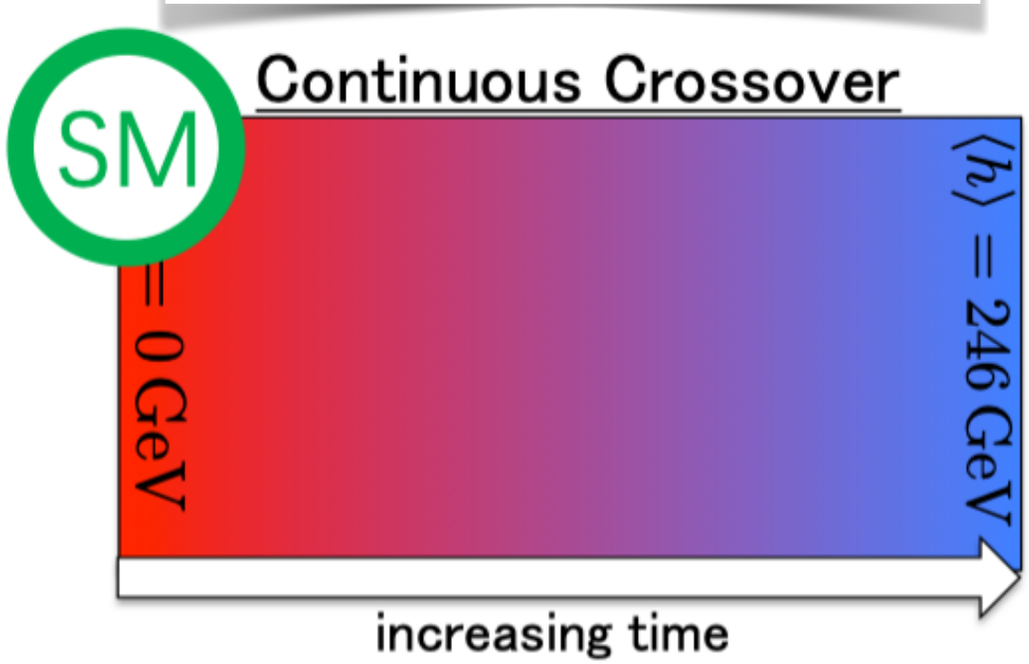
  DG, Kaladharan, Wu arxiv:2108.05356 and arxiv:2206.08381

Thermal history of our Universe

- What is the order of the Electroweak Phase Transition?







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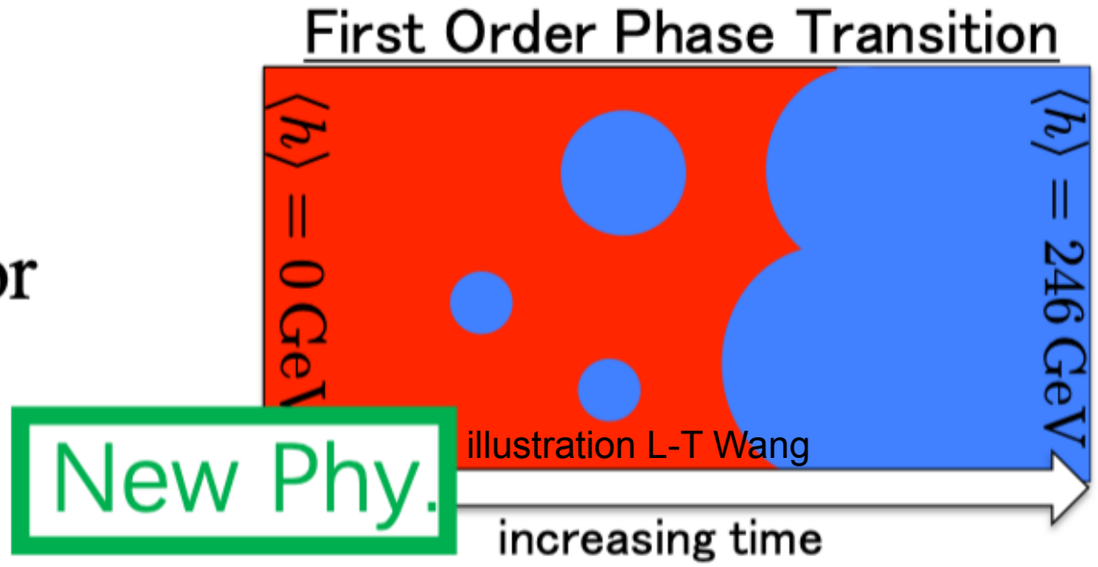
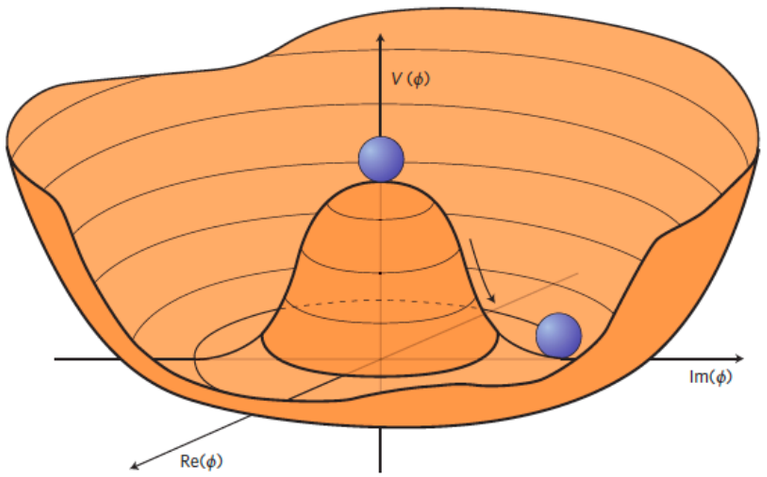
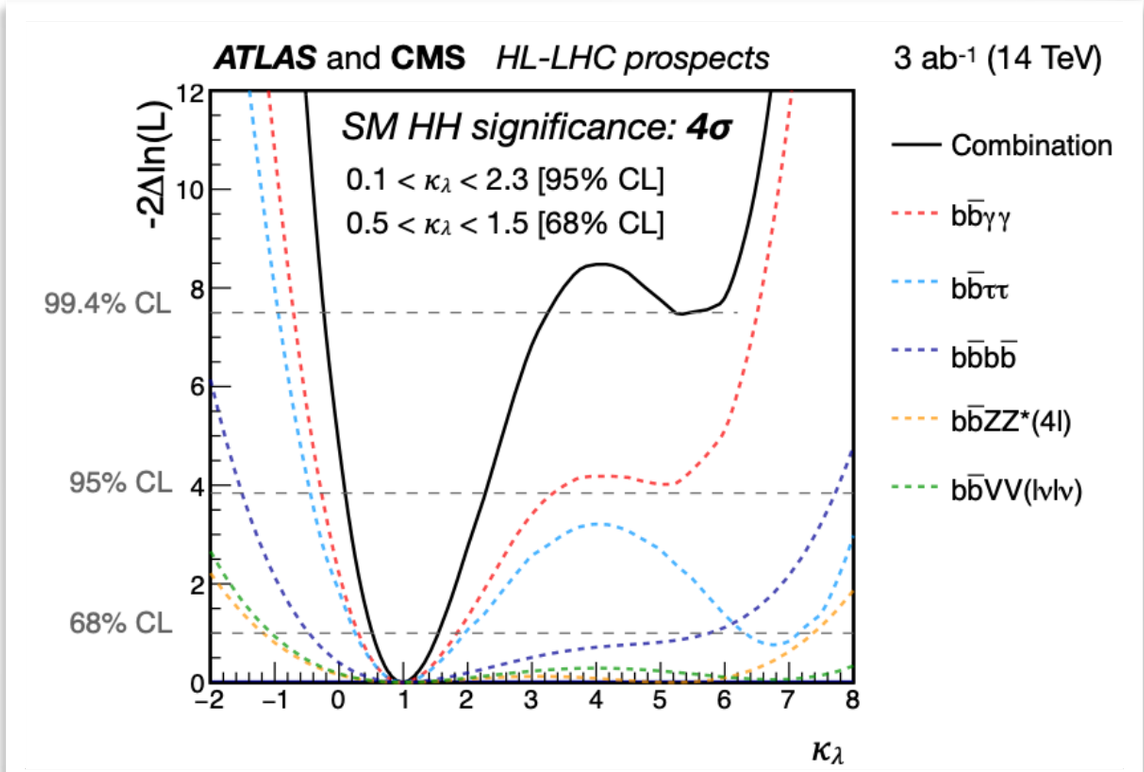


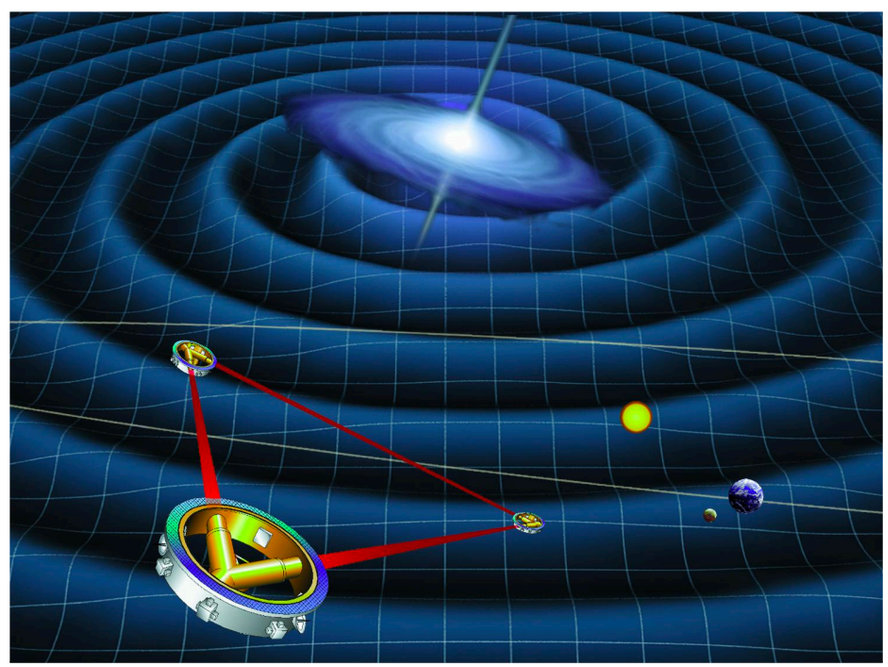
Higgs Potential: Collider & GW Complementarity

- Strong first order phase transition at EW scale typically requires novel degrees of freedom close to EW scale, displaying sizable interactions with the Higgs boson

LHC searches: di-Higgs or heavy resonant searches



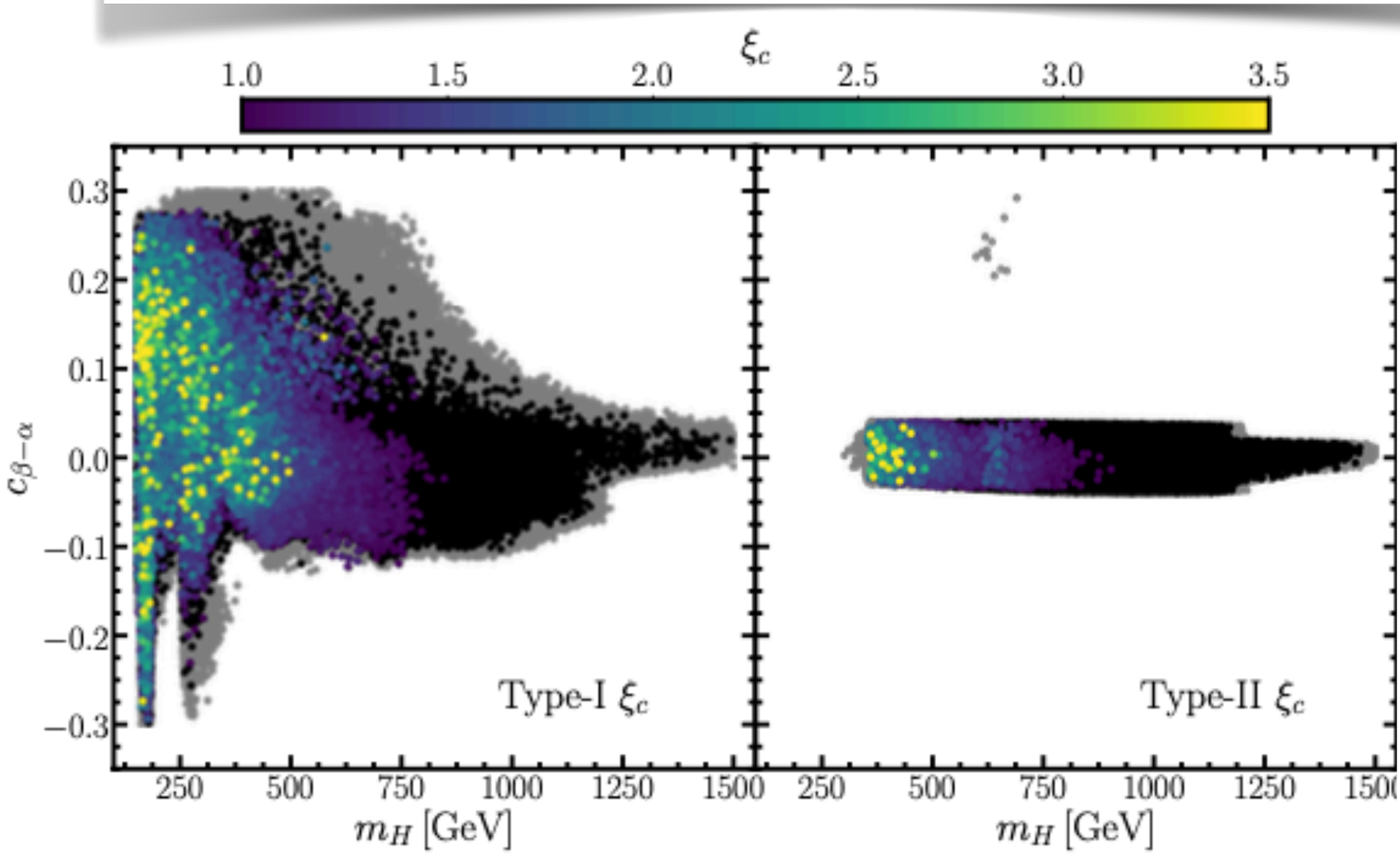




For $T_* \sim 100$ GeV, GW frequency (redshifted to today) ~ mHz

Signal in sensitivity band of future space-based GW detector **LISA**

Strong first-order phase transition in the 2HDM



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Dorsh, Huber, No 13'; Ramsey-Musolf '19

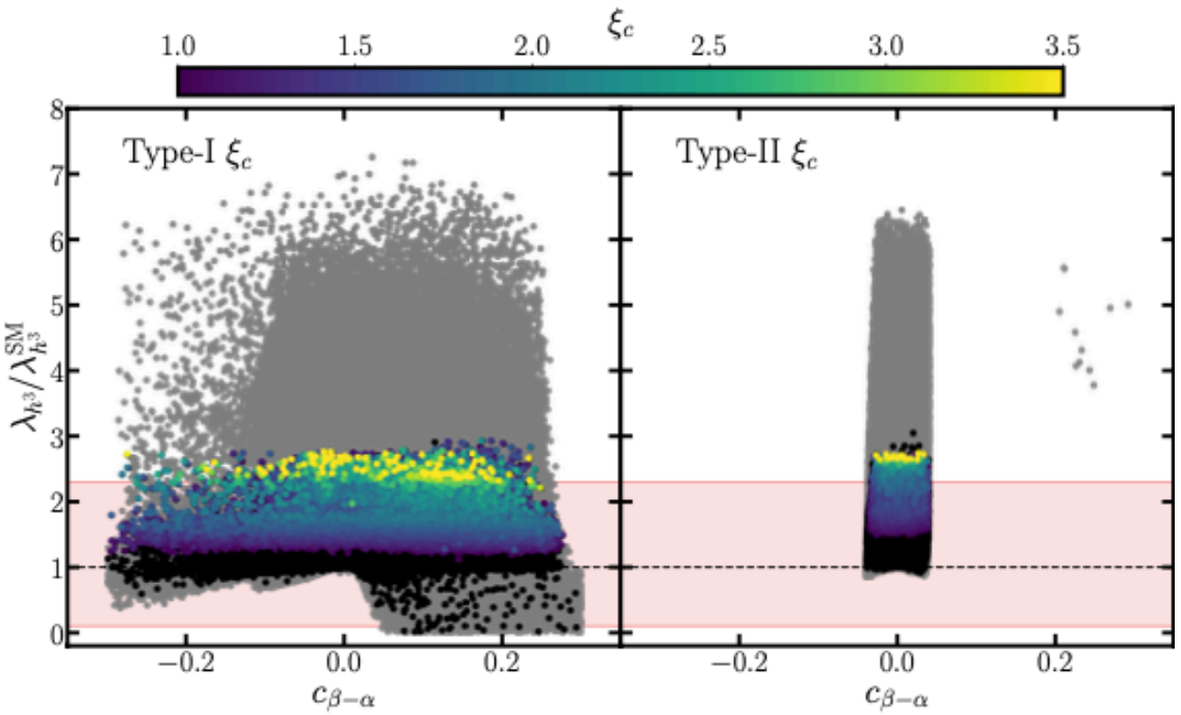
➡ Typically: the lighter the resonance, the higher the order parameter

$$\xi > 1 \;\rightarrow\; m_H \lesssim 750 \text{ GeV}$$

➡ Strong extra motivation for scalar searches at the LHC

Double Higgs searches

Non-resonant di-Higgs searches



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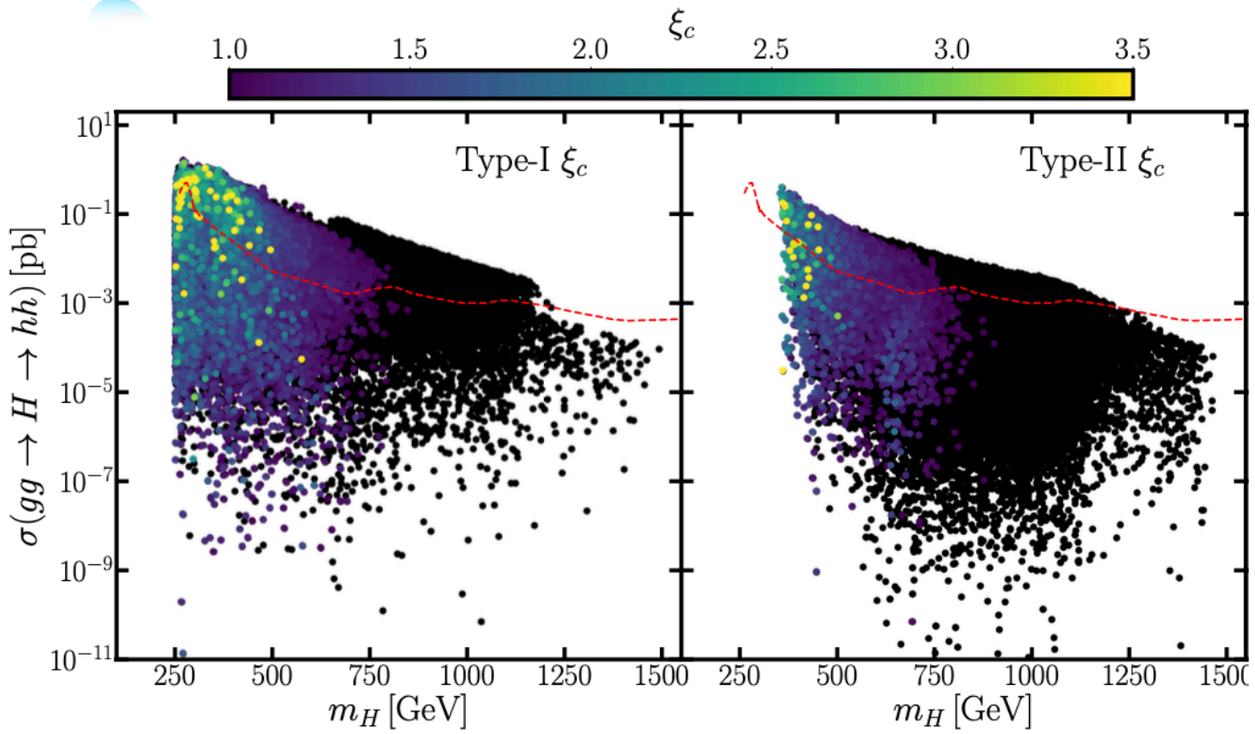
$$0.1 < \lambda_{h^3}/\lambda_{h^3}^{\rm SM} < 2.3$$

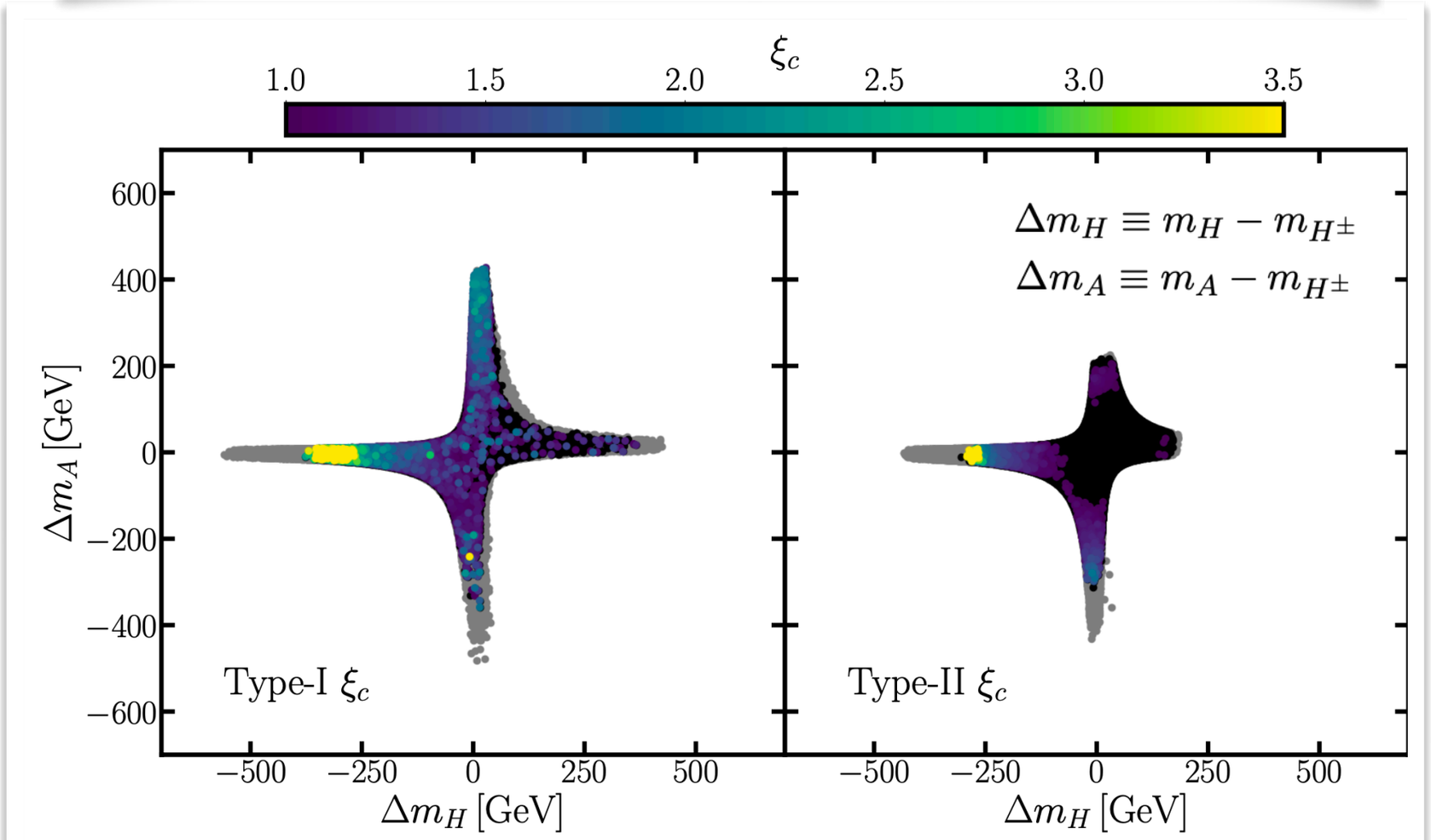
ATLAS+CMS projections

Resonant di-Higgs searches:



Limited precision prompts Higgs self-coupling as key benchmark for future colliders

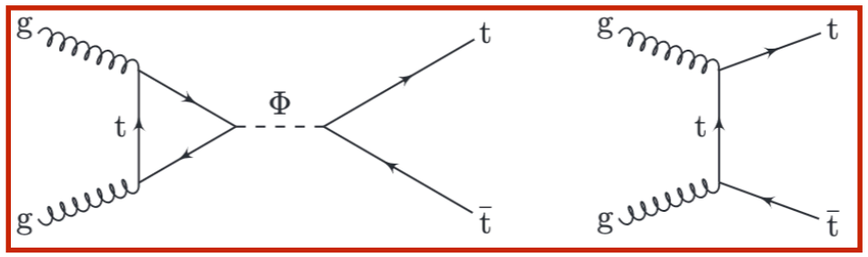
Mass Hierarchy for strong first-order phase transition

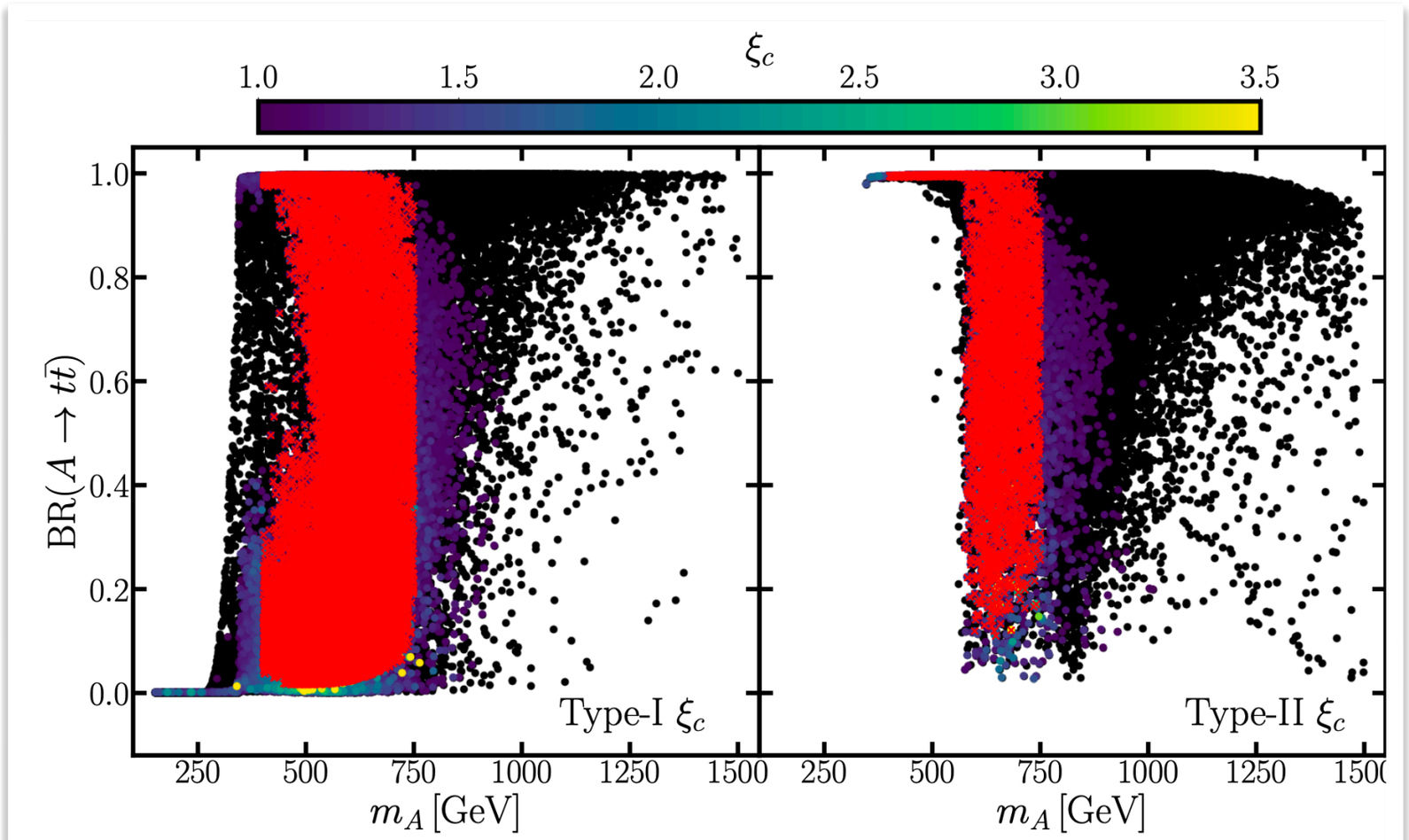


DG, Kaladharan, Wu '21; Dorsh, Huber, No 13'

- Due to the preference for large mass hierarchy among the scalar modes, it is likely that at least one of the scalar states be above the top-quark pair threshold: Favors gg→H/A→tt searches
- $m_H < m_{H^\pm} \approx m_A$: most favorable region for SFOEWPT
  Favors BSM searches via $A \to ZH$ channel

gg→H/A→tt: HL-LHC projection





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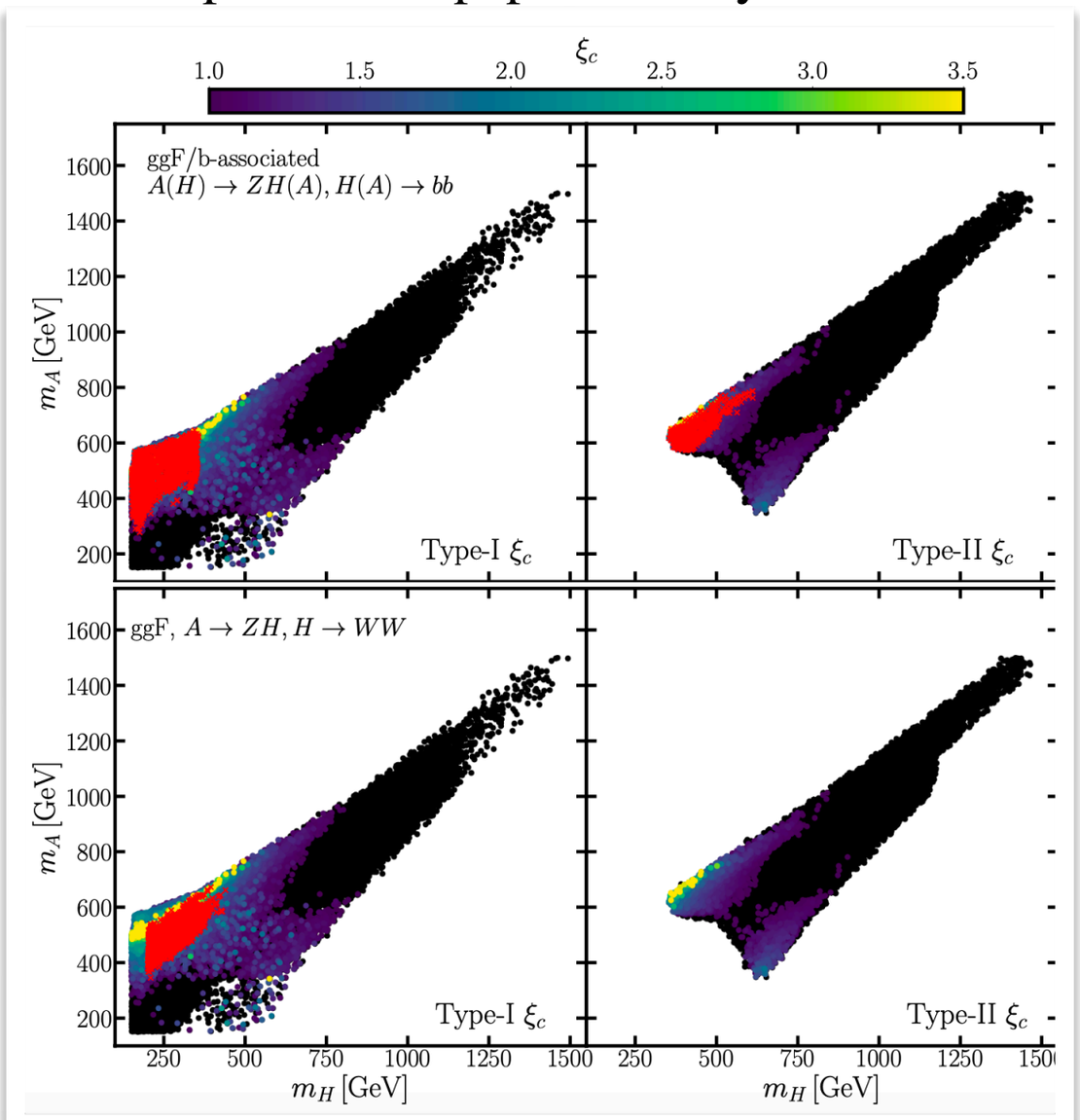
➡ gg→H/A→tt searches can play a leading role to probe the strong first order EWPT regime
They will be specially important in the type-2 2HDM, as it presents typically heavy scalar masses

Searches via pp→ZH/A: HL-LHC projection

- A(H)→ZH(A): widely discussed channel in the context of EWPT Dorsh, Huber, No 13'

Until last year, theoretical and experimental papers mostly focus on H/A→bb and H→WW searches



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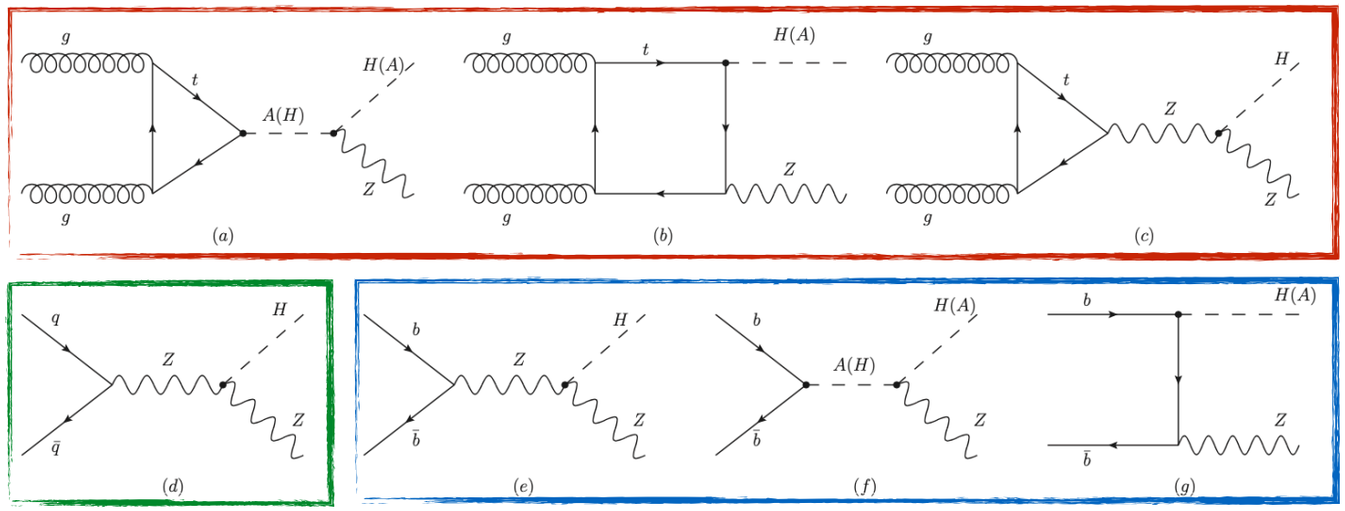
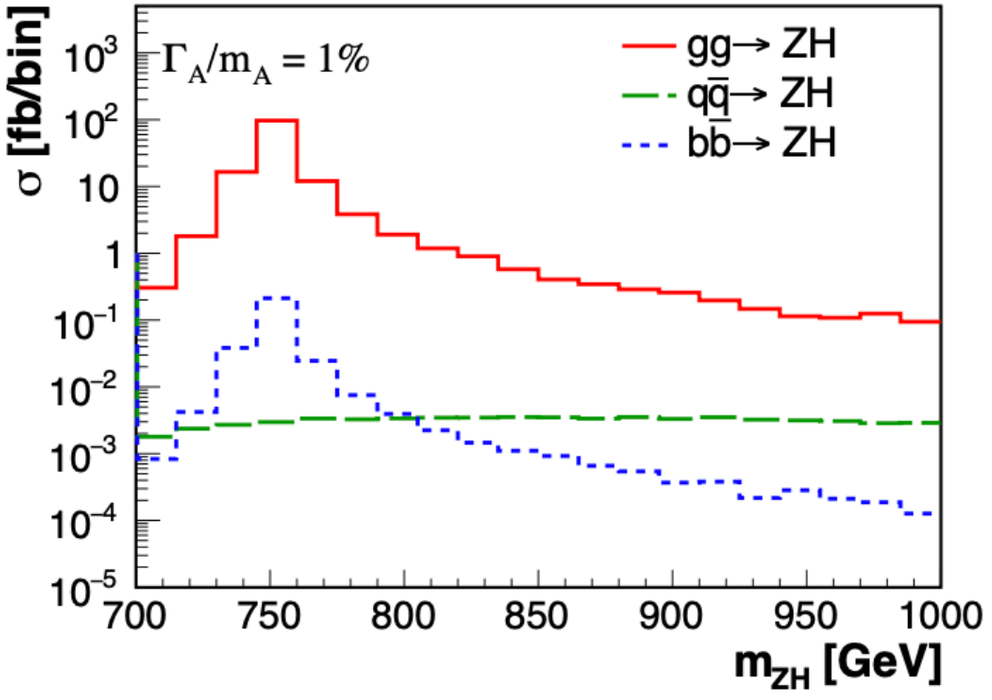
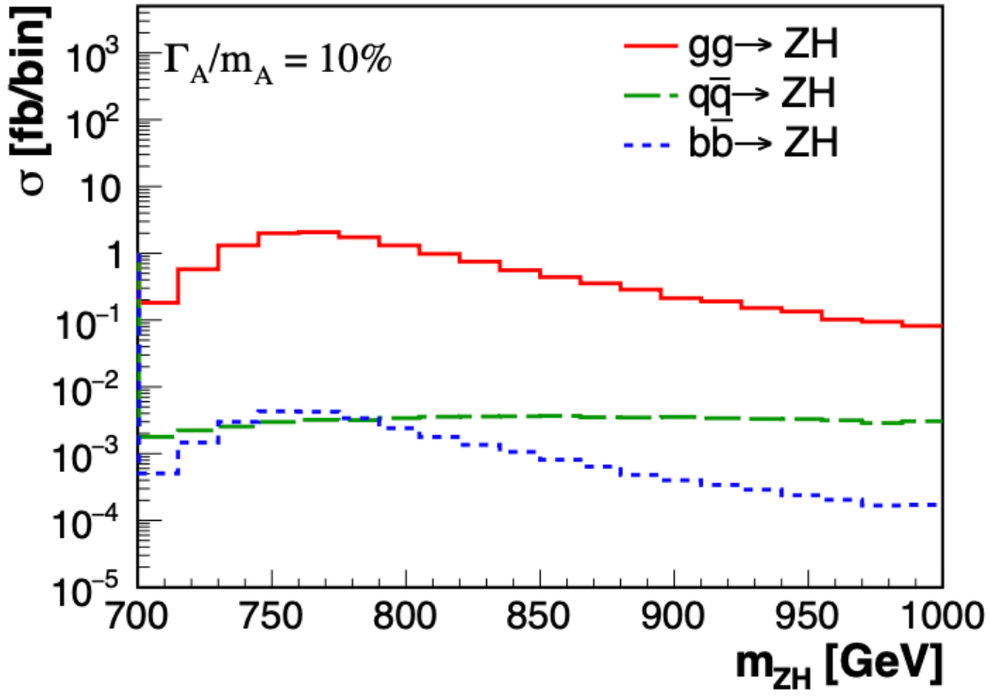
ATLAS-CONF-2023-034

Biekotter, Heinemeyer, No, Radchenko, Romacho, Weiglein '23

Top Pair Resonant Searches via pp→ZH/A







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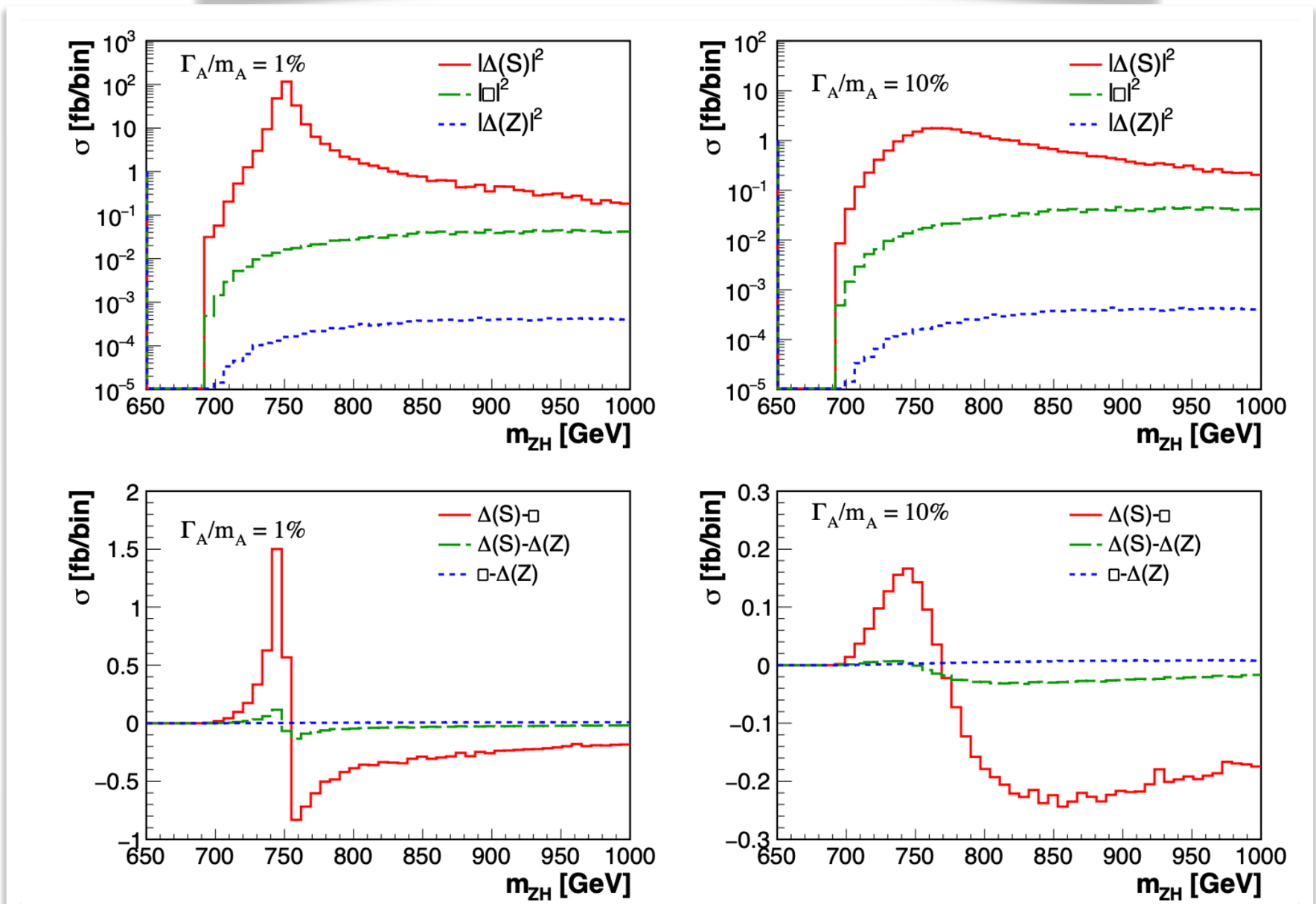
Type-1 2HDM with $c_{\beta-\alpha} \approx 0.3,\ m_H = 600$ GeV, $m_A = 750$ GeV, and $t_\beta = 1$

Gluon fusion gg→ZH/A



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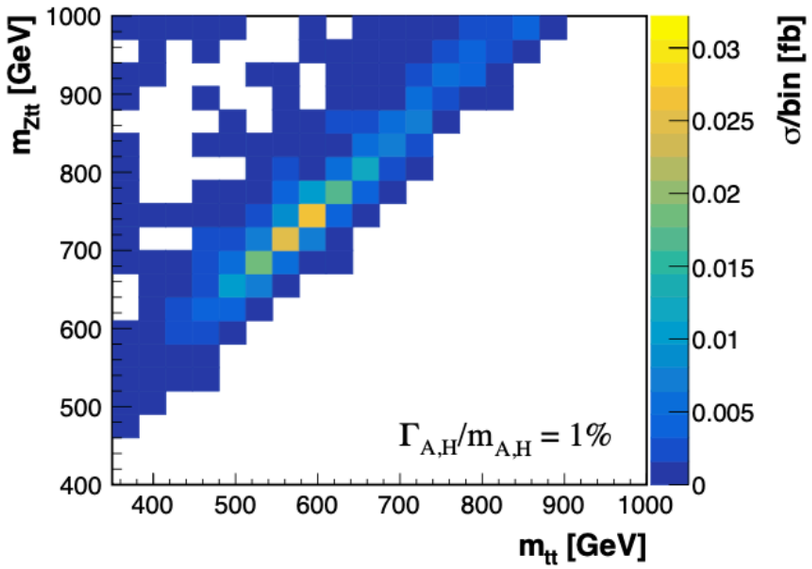
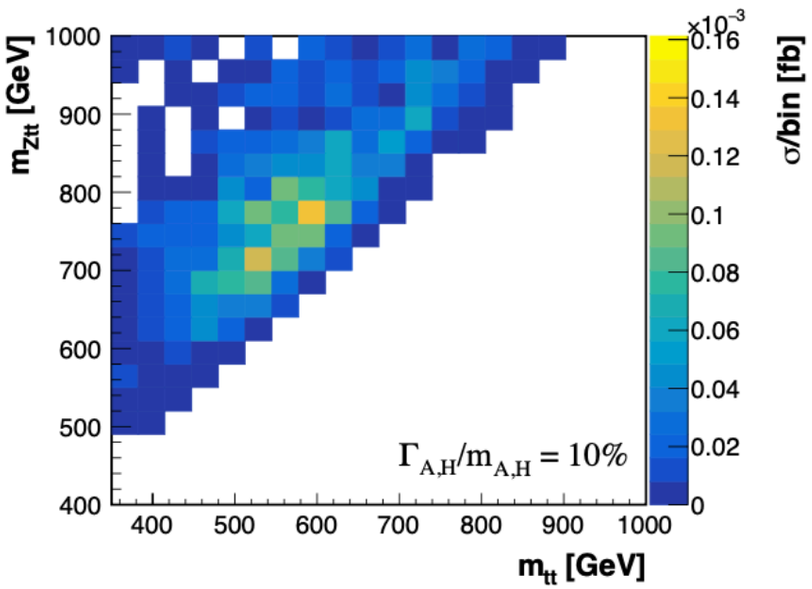
Type-1 2HDM with $c_{\beta-\alpha} \approx 0.1,\ m_H = 600$ GeV, $m_A = 750$ GeV, and $t_\beta = 1$

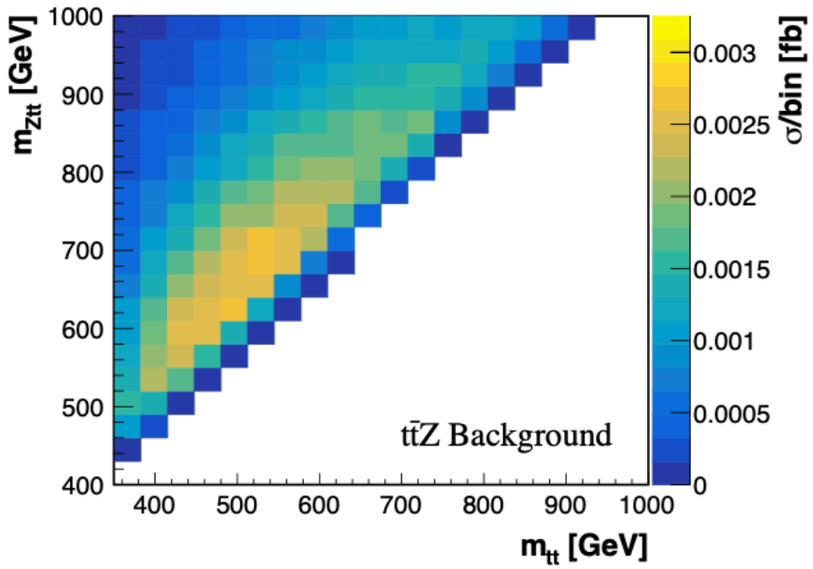
Interference between signal and ttZ background generates subleading effects for allowed 2HDM parameter space

Top Pair Resonant Searches via pp→ZH/A

- 14 TeV LHC focusing on the semi-leptonic top pair final state
- Leading background arises from ttZ production







$t_\beta = 1,\ c_{\beta-\alpha} = 0.1$

$m_A = 750$ GeV, $m_H = 600$ GeV

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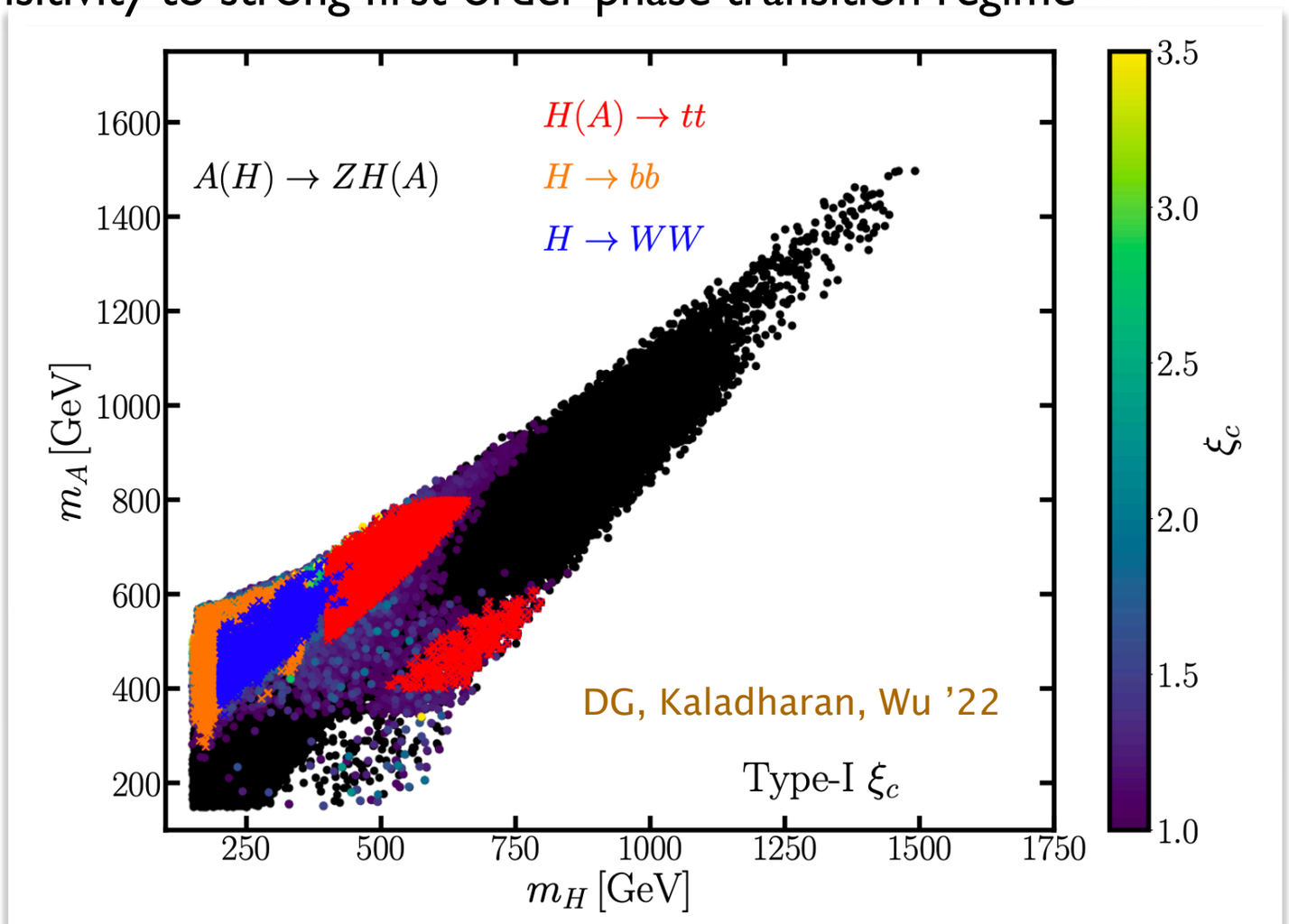
Top Pair Resonant Searches via pp→ZH/A

- pp→ZH/A searches mostly account for H/A→bb and H→WW (sensitivity $m_{H,A} < 350$ GeV)

  See e.g., arXiv:2011.05639 and arXiv:1911.03781

- Above top-quark pair threshold the H/A → tt is typically dominant decay, leading to strong limits, and extending the sensitivity to strong first-order phase transition regime



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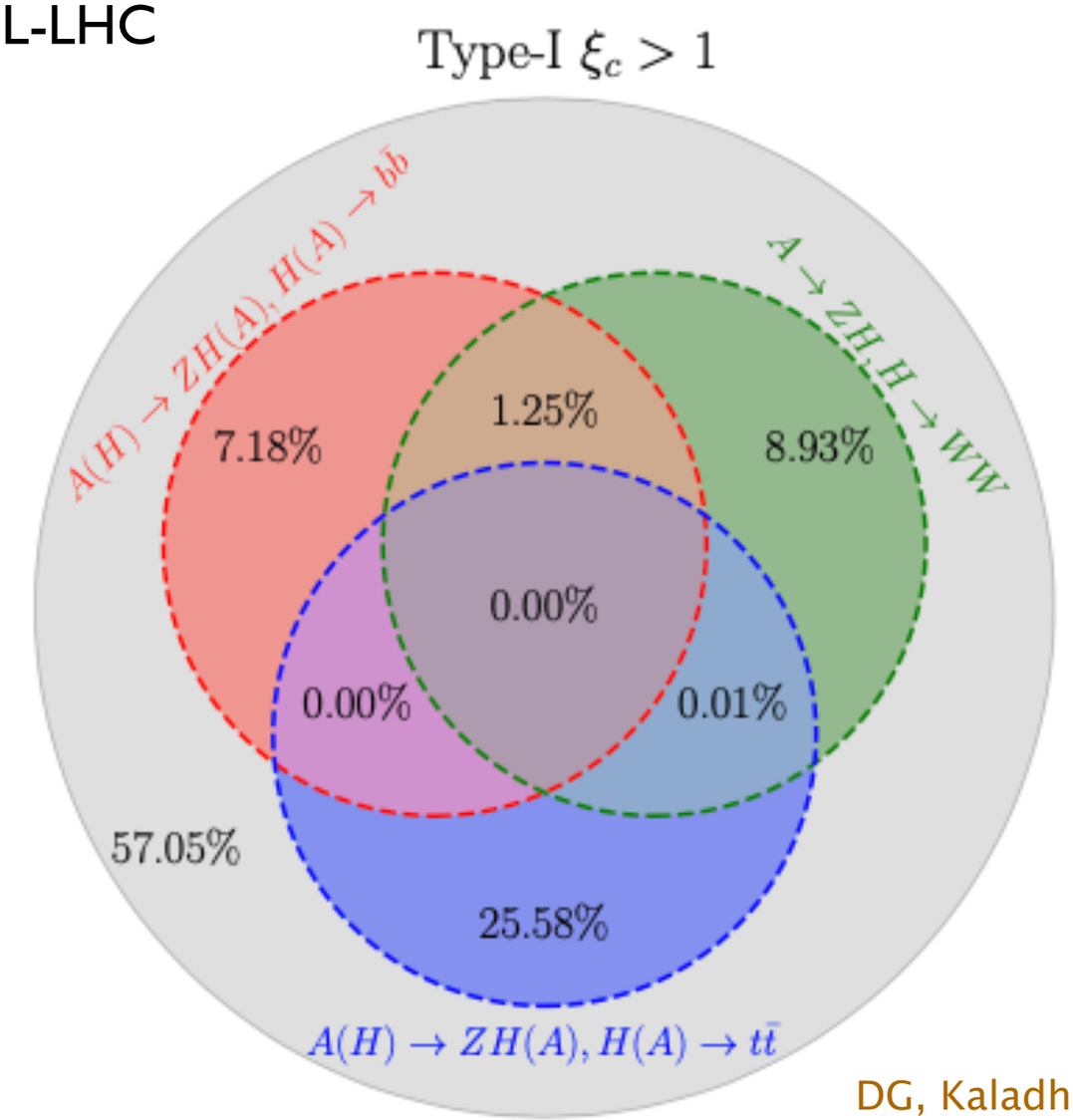
Biekotter, Heinemeyer, No, Radchenko, Romacho, Weiglein '23

Combined results

- Inclusion of top pair resonant searches via pp→ZH/A can boost sensitivity to strong first order phase transition regime at the HL-LHC



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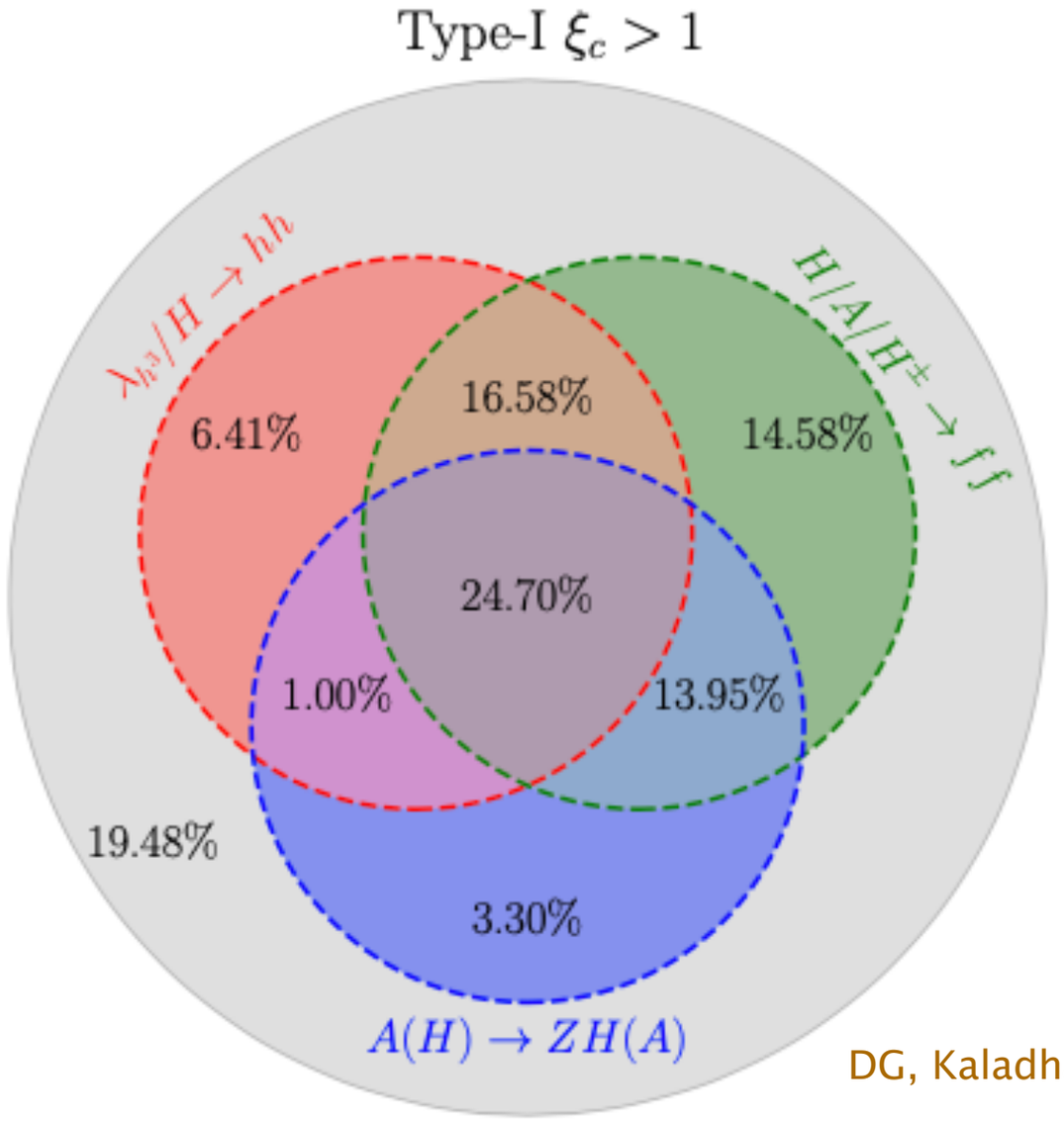
$$\tan\beta \in (0.8, 25)\,, \qquad m_{12}^2 \in (10^{-3}, 10^5)\,\text{GeV}^2\,, \qquad m_H \in (150, 1500)\,\text{GeV}\,,$$
$$\cos(\beta-\alpha) \in (-0.3, 0.3)\,, \qquad m_A \in (150, 1500)\,\text{GeV}\,, \qquad m_{H^\pm} \in (150, 1500)\,\text{GeV}.$$

Combined results

- Complementarity of the Higgstrahlung searches with other relevant classes of searches at the HL-LHC



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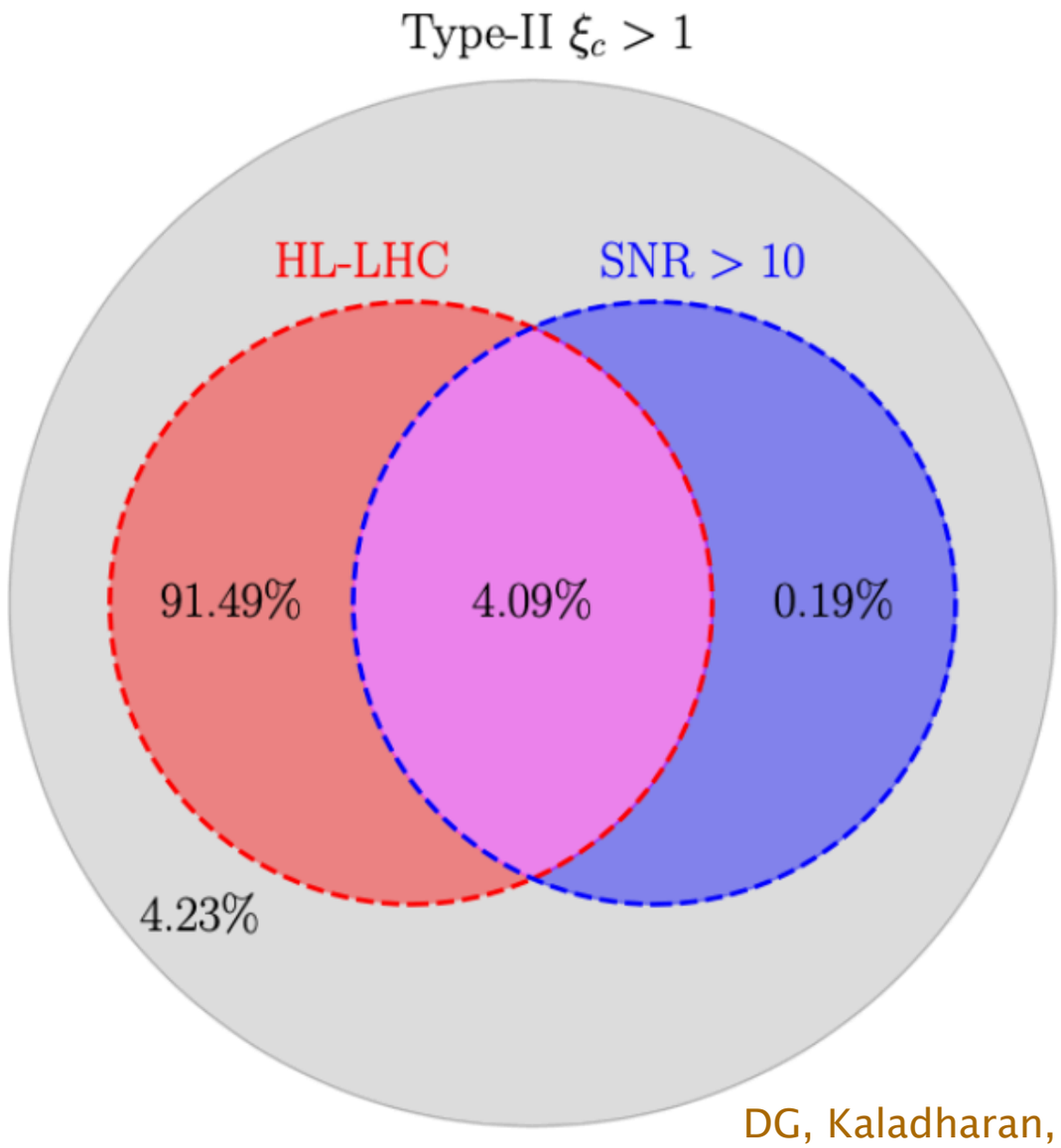
Collider & GW complementarity



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In contrast to HL-LHC, LISA is going to be sensitive to a significantly smaller parameter space region, whereas it renders to complementary sensitivities where correspondent LHC cross-section is suppressed

Summary

Thermal history of EWSB could have profound consequences for particle physics and cosmology

- Well-motivated 2HDM leads to rich phase transition, favoring SFOEWPT below TeV scale

  Strong extra motivation for scalar searches at the LHC!

- Gluon fusion and Higgstrahlung production with $H, A \to tt$ are smoking gun signatures for SFOEWPT at HL-LHC

- Higgstrahlung production with $H, A \to tt$ final state renders the largest sensitivity to $\xi_c > 1$ regime in the 2HDM, in comparison to other Higgstrahlung searches with $H/A \to bb$ and $H \to WW$

Work in collaboration with

Ajay Kaladharan (OSU)

Yongcheng Wu (OSU -> Faculty Nanjing)

DG, Kaladharan, Wu arxiv:2108.05356 and arxiv:2206.08381