Collider and gravitational wave signals for electroweak phase transition

Dorival Gonçalves

Gonçalves, Kaladharan, Wu (PRD 2022, PRD 2023, PRD 2023)

Mitchell conference on Collider, DM, and Neutrino physics
Texas A&M - 24th May 2024

Entanglement and Bell's Inequalities with boosted top quark pairs

May 17, 2023, 3:20 PM

25m

Hawking Auditorium (Texas A&M University)

Speaker

Dorival Gonçalves (Oklahoma State University)

Understanding Jet Charge

May 17, 2023, 4:40 PM

25m

Hawking Auditorium (Texas A&M University)

Speaker

Andrew Larkoski (UCLA)

Beyond Kinematics for Optimal Hadronic Top Quark Polarimetry

May 23, 2024, 9:25 AM

25m

Hawking Auditorium (Mitchell Institute, Texas A&M University)

Speaker

Zhongtian Dong (University of Kansas)

arXiv:2405.xxxxx Dong, Gonçalves, Kong, Larkoski, Navarro

Collider and gravitational wave signals for electroweak phase transition

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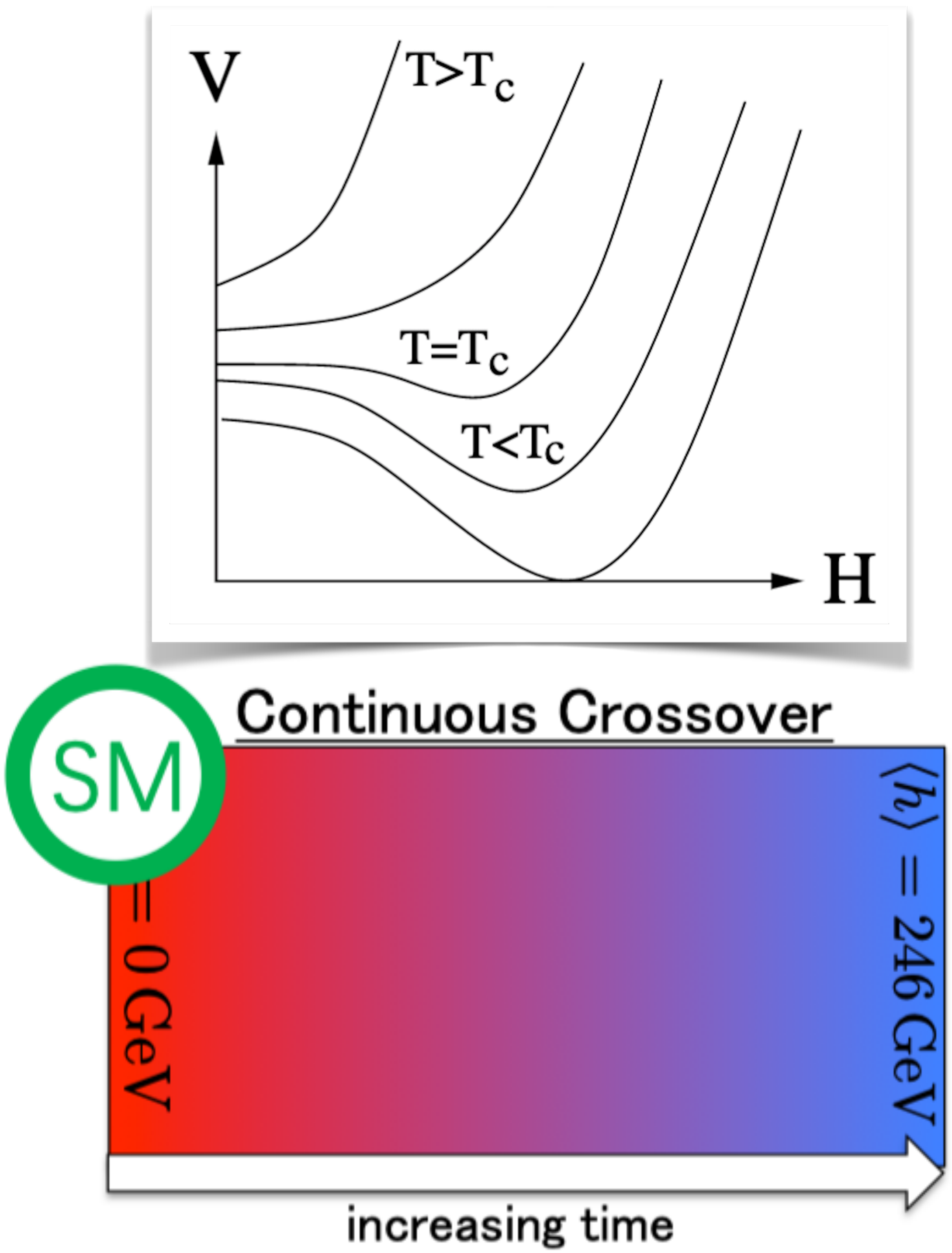
Thermal history of our Universe

- What is the order of the Electroweak Phase Transition?



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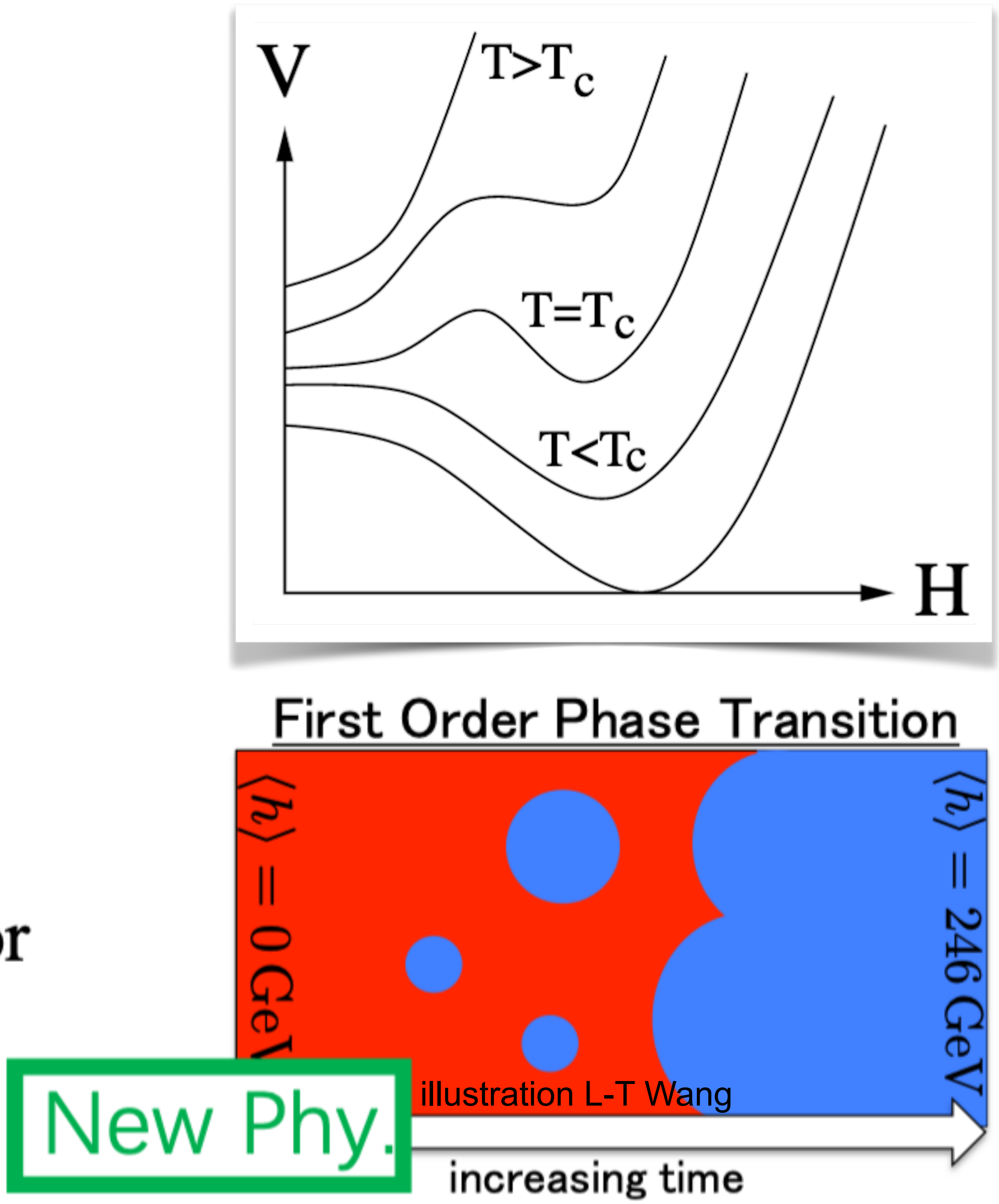
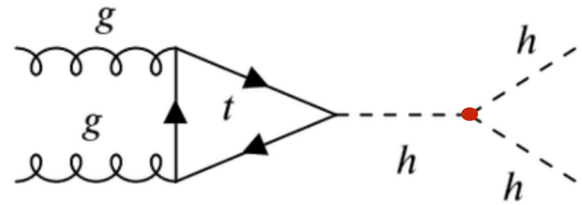
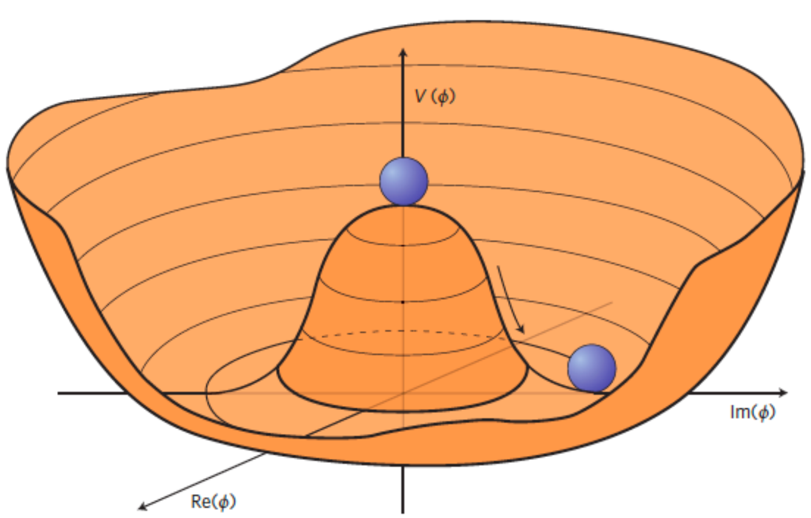
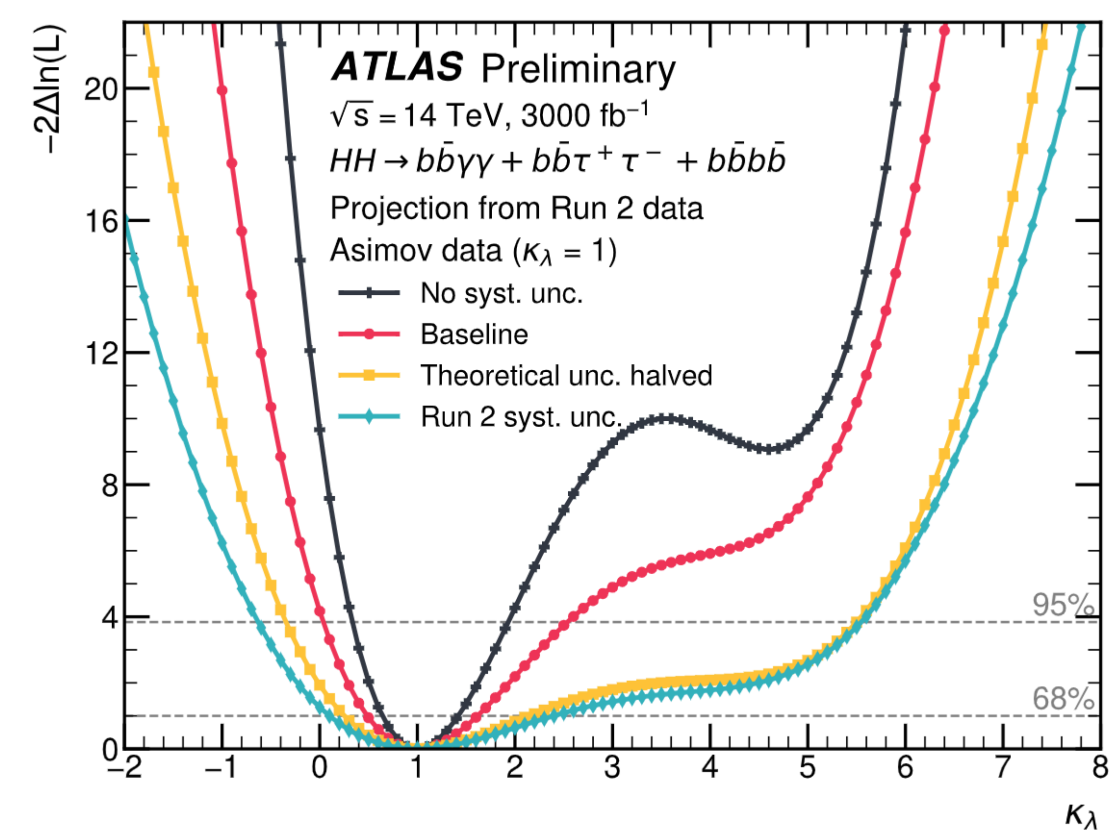


Higgs Potential: Collider & GW Complementarity



- LHC searches:
  - Higgs pair production
  - Heavy resonant searches

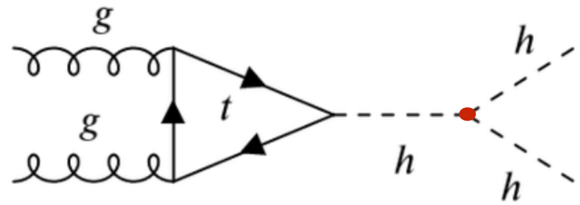


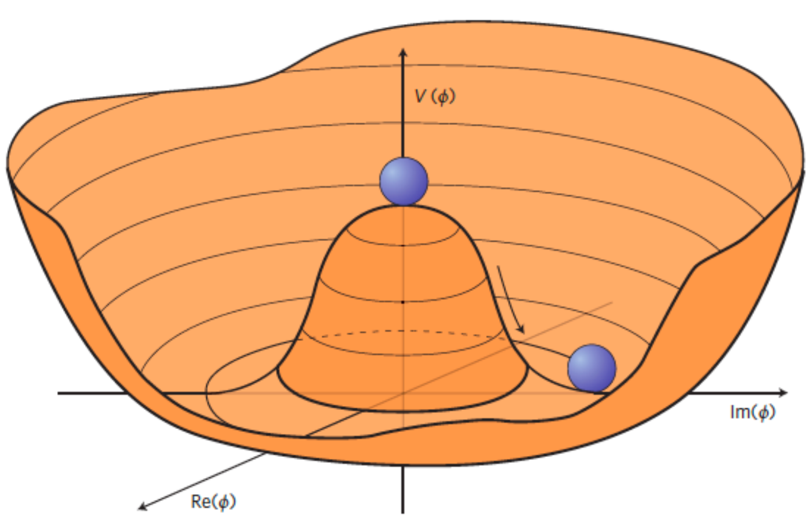


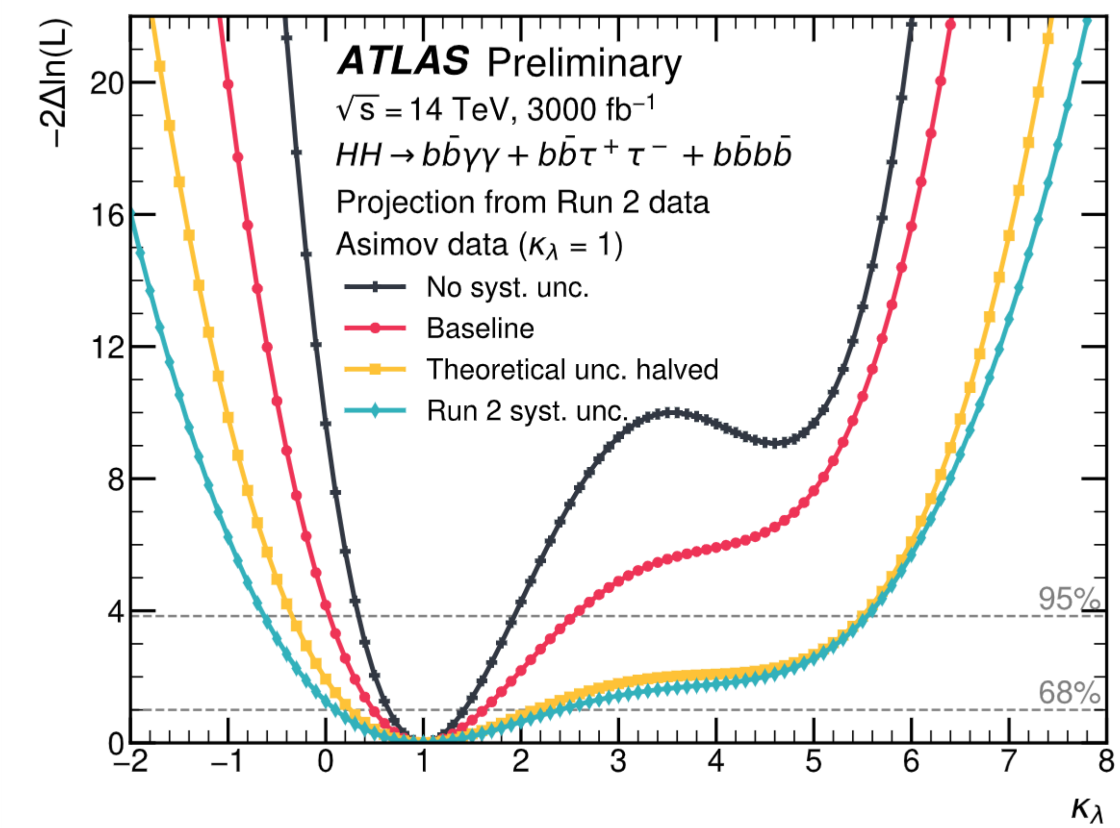
See talks by Viviana Cavaliere and Jason Veatch

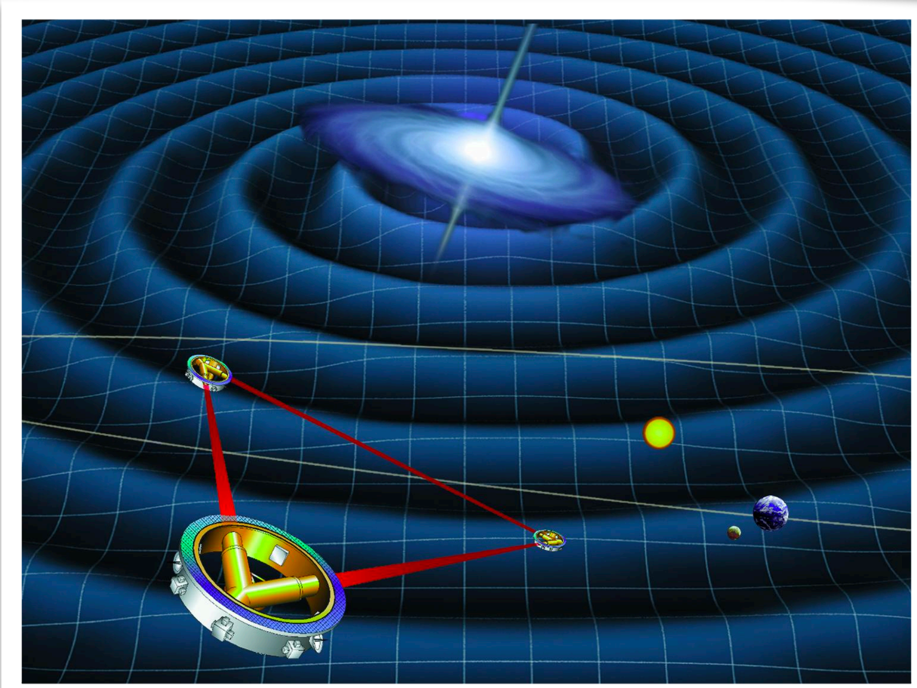
Higgs Potential: Collider & GW Complementarity

- LHC searches:
  - Higgs pair production
  - Heavy resonant searches









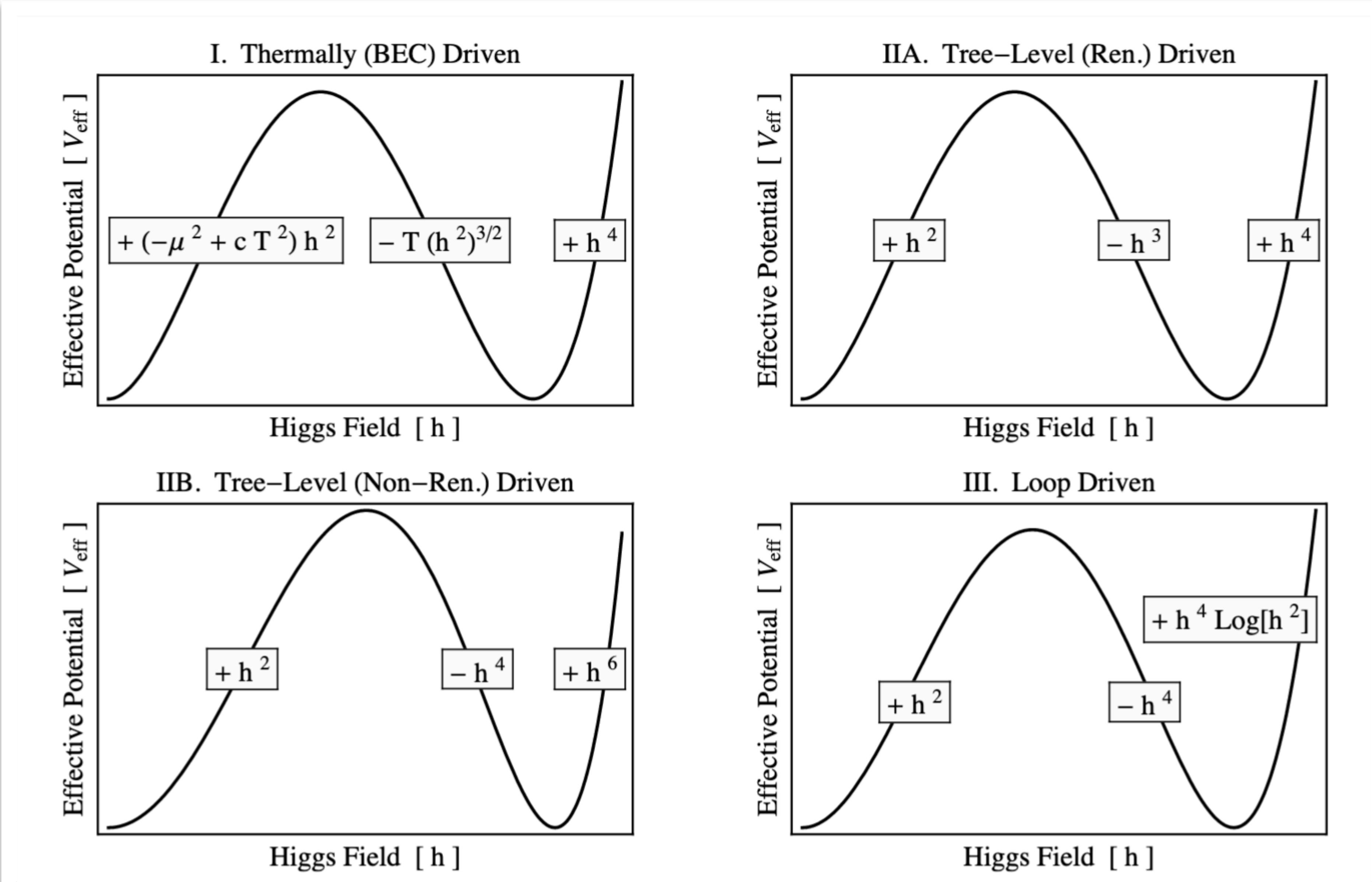
- For T_* ~ 100 GeV, GW frequency (redshifted to today) ~ mHz

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

The Shape of the Higgs Potential

$$V_{\rm eff} = V_0 + V_1 + V_T$$

- **Barrier formation:** tree vs. one-loop vs. thermally induced barrier

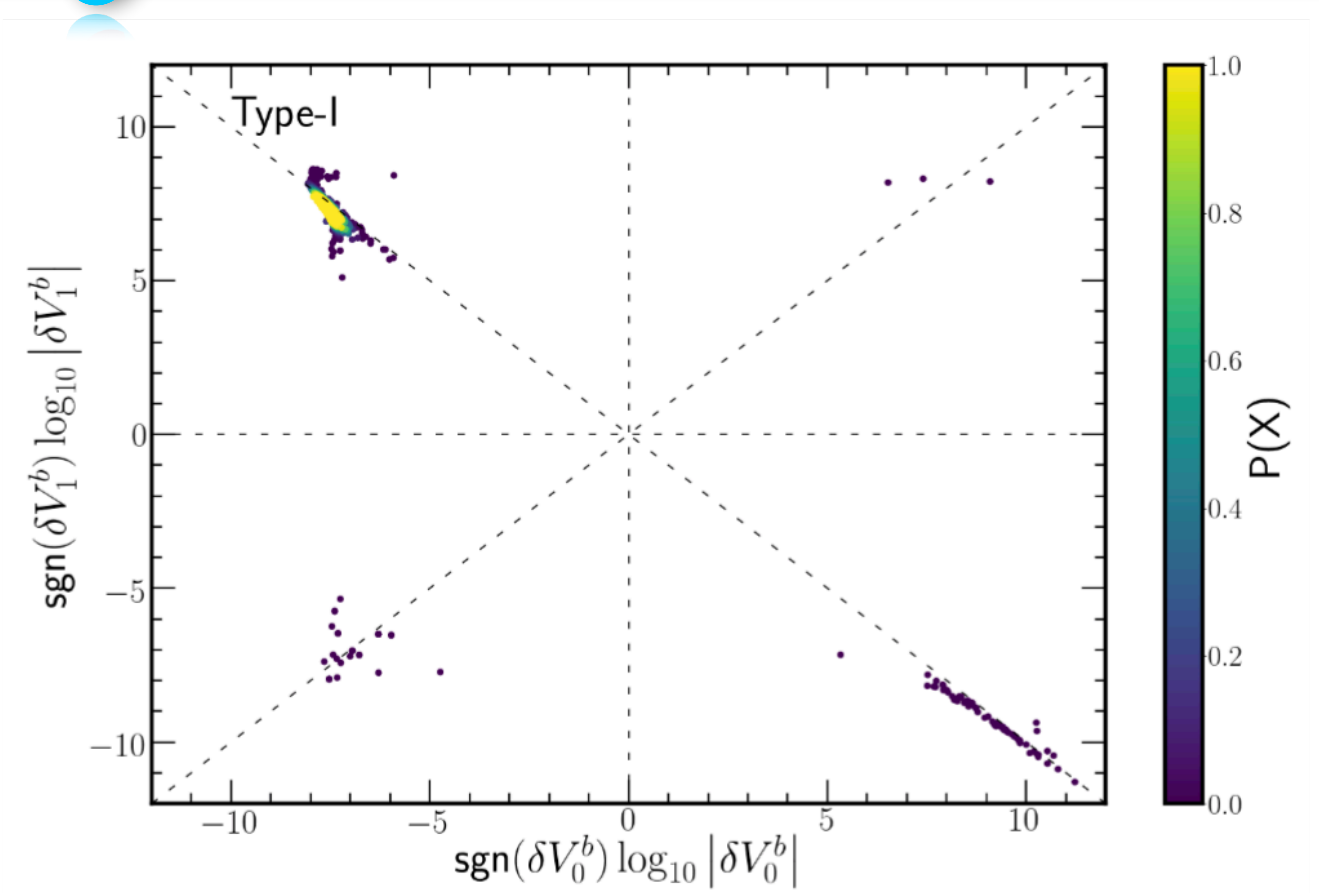


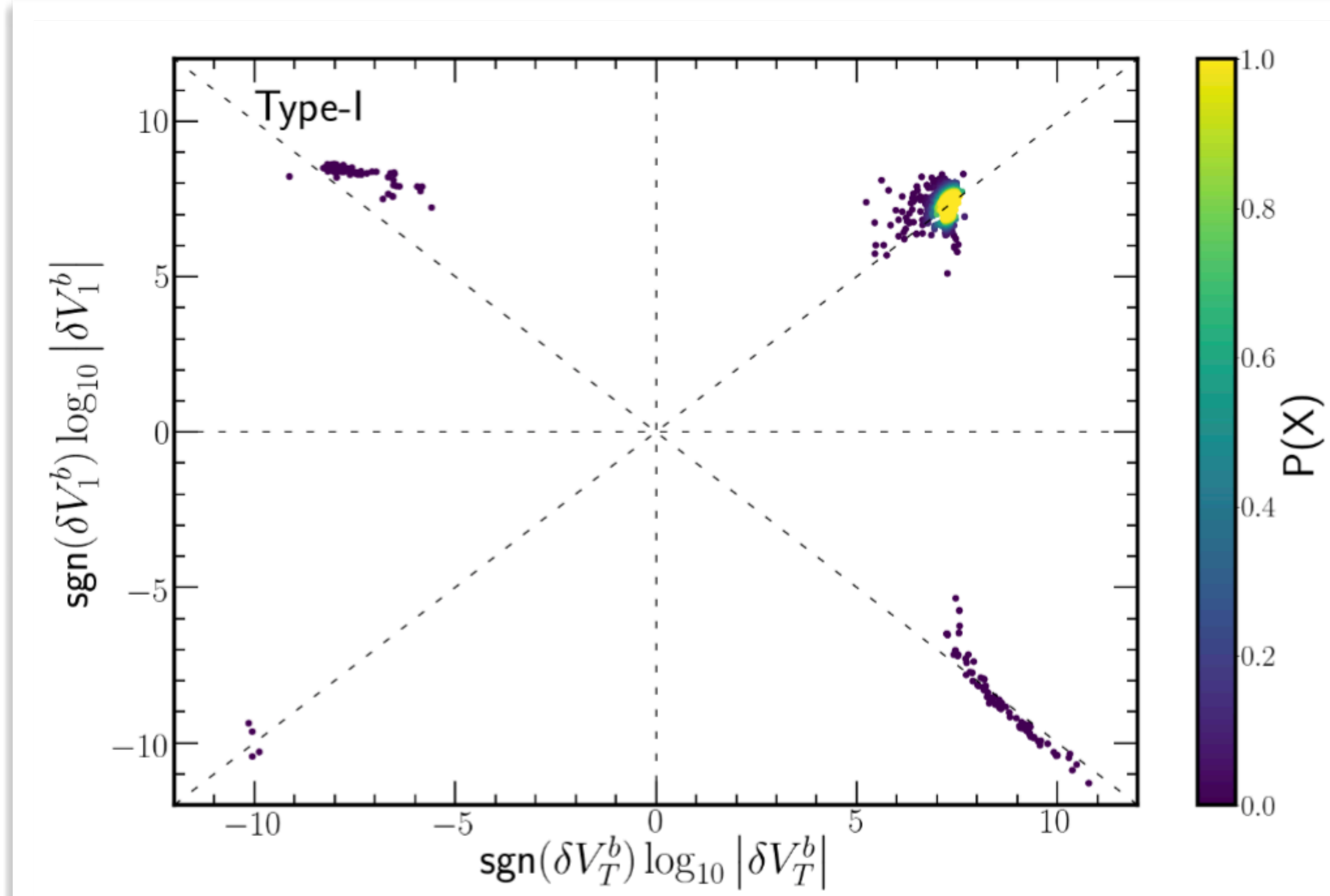
Chung,Long, L-T Wang '12

The Shape of the Higgs Potential

$$V_{\text{eff}} = V_0 + V_1 + V_T$$

- **Barrier formation:** tree vs. one-loop vs. thermally induced barrier
- 2HDM





DG, Kaladharan, Wu PRD 22

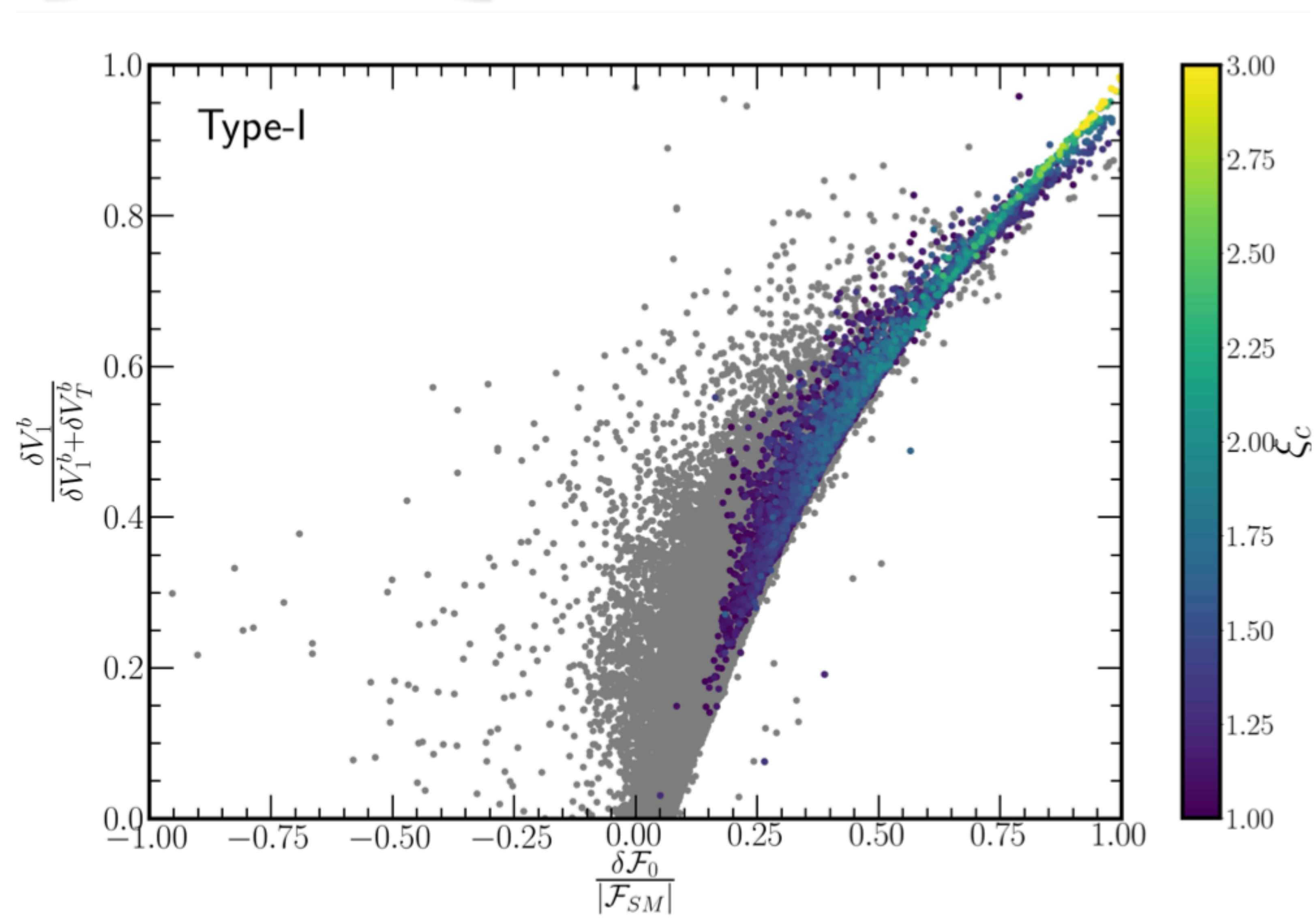
→ Potential barrier induced by one-loop+thermal effects for more than 99% of points

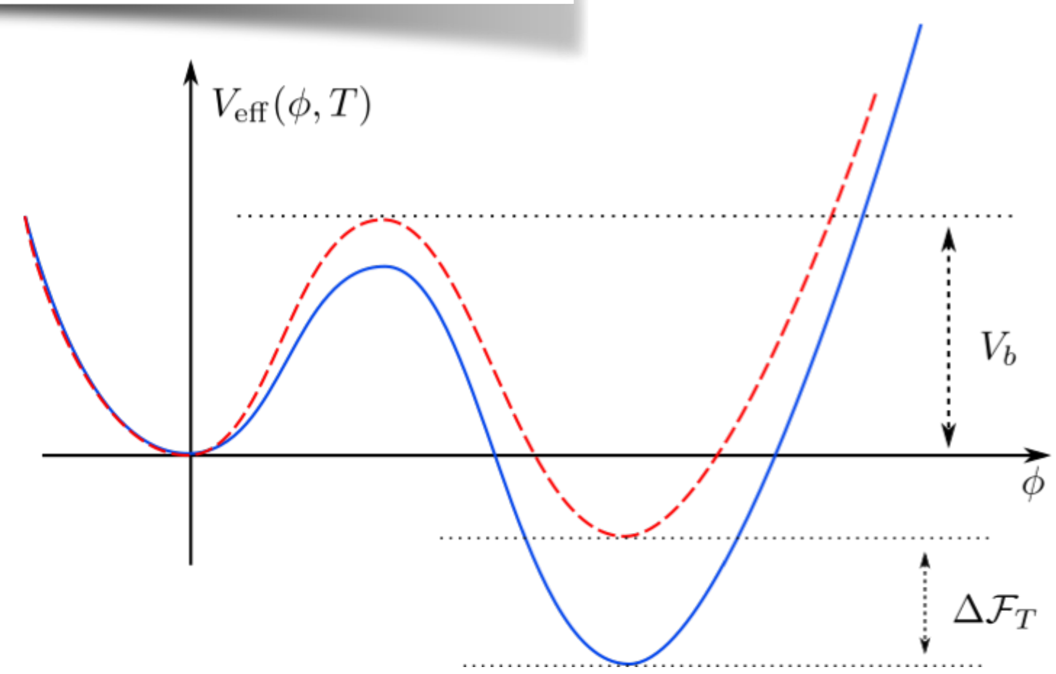
The Shape of the Higgs Potential

- **Vacuum Upliftment:**

$$\frac{\Delta\mathcal{F}_0}{|\mathcal{F}_0^{SM}|} \equiv \frac{\mathcal{F}_0 - \mathcal{F}_0^{SM}}{|\mathcal{F}_0^{SM}|}$$

$$\mathcal{F}_0 \equiv V_{\text{eff}}(v_1, v_2, T=0) - V_{\text{eff}}(0,0,T=0)$$

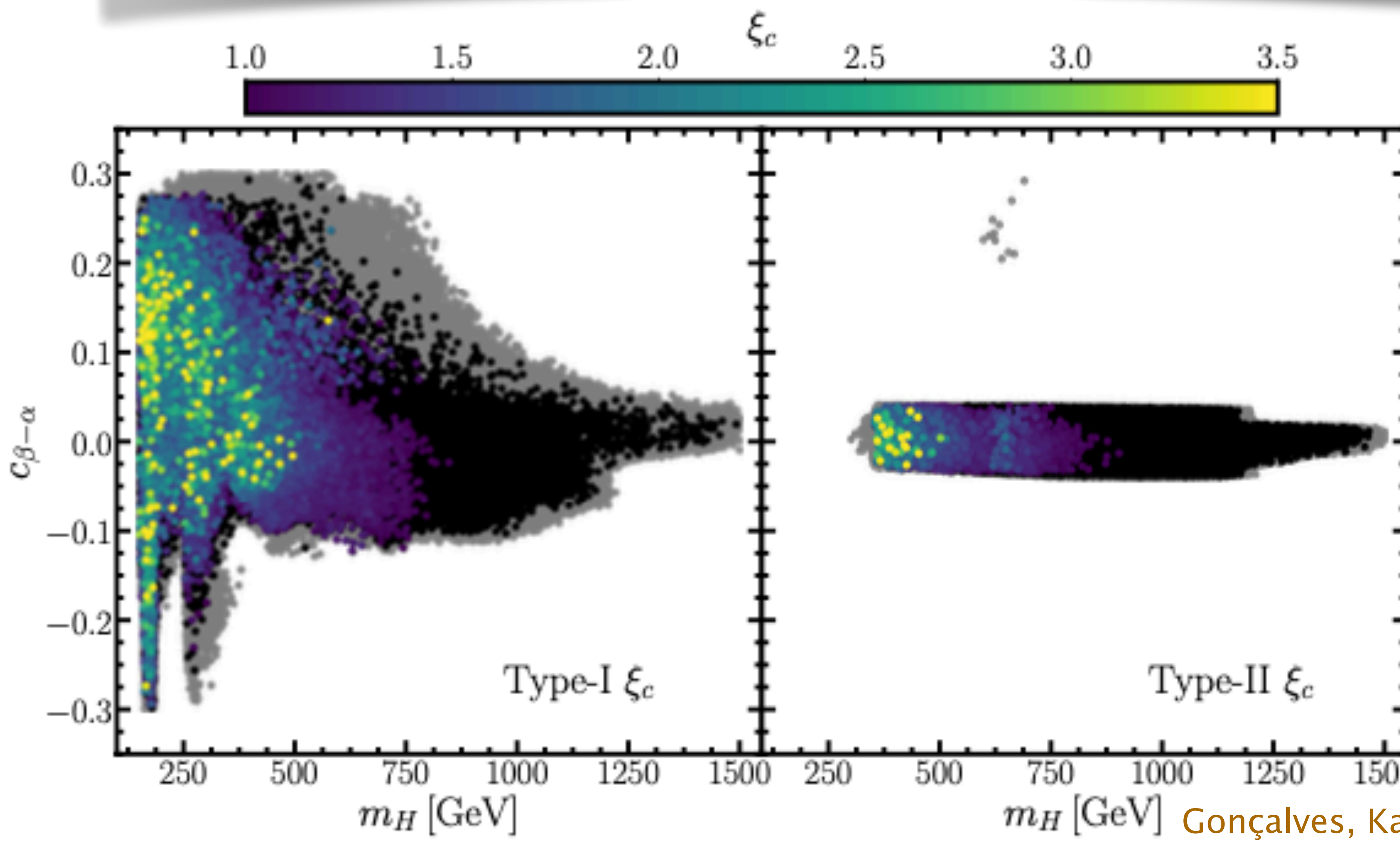




$$\xi_c \equiv \frac{v_c}{T_c}$$

DG, Kaladharan, Wu PRD 22; Dorsh, Huber, No 13’

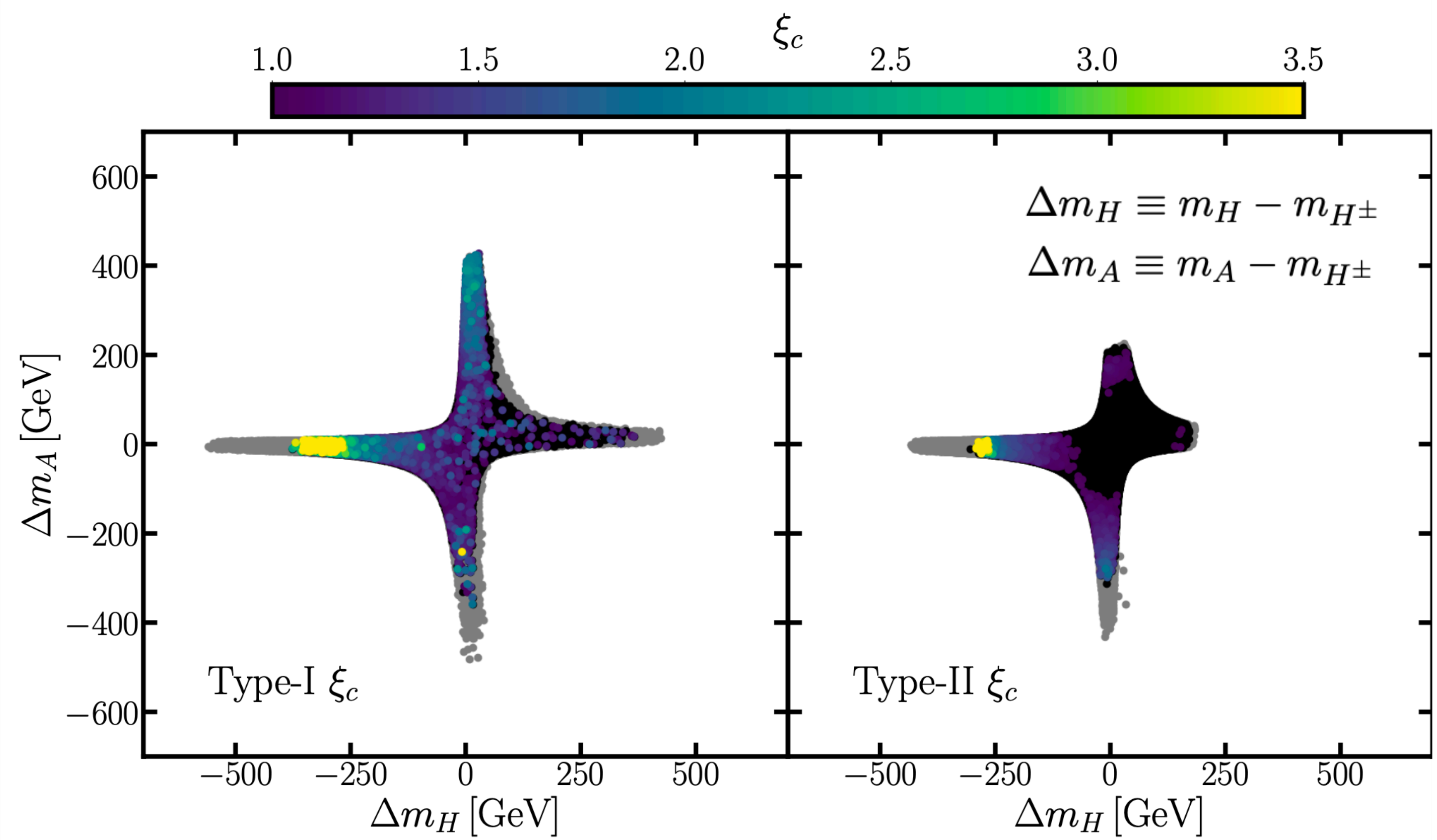
Strong first-order phase transition in the 2HDM



Gonçalves, Kaladharan, Wu (PRD, 2022)
Gonçalves, Kaladharan, Wu (PRD, 2023)
Ramsey-Musolf '19

- Typically: the higher the order parameter, the lighter the resonance
  $\xi > 1 \;\rightarrow\; m_H \lesssim 750$ GeV
- Strong extra motivation for scalar searches at the LHC

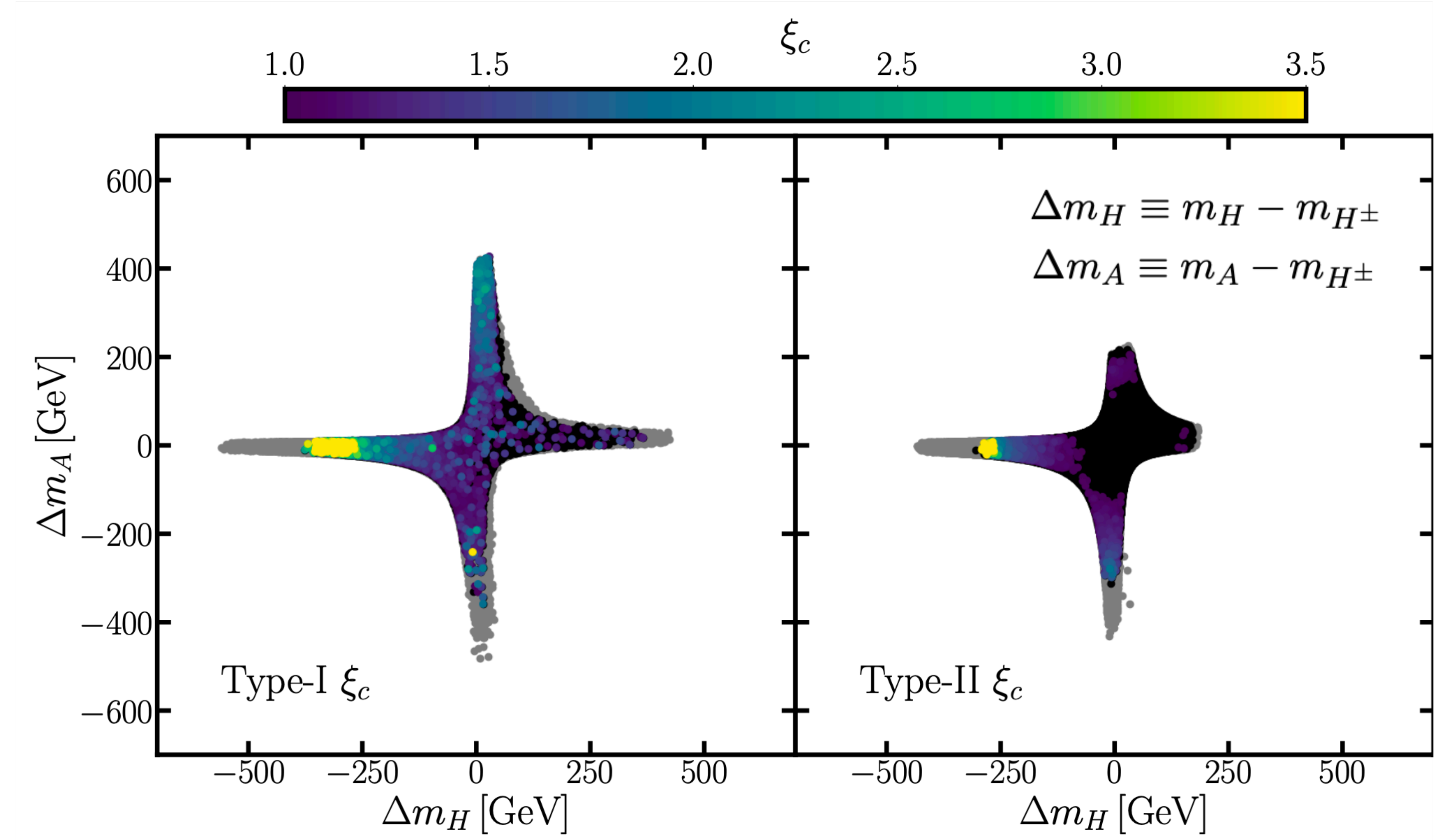
Mass Hierarchy for strong first-order phase transition



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: <u>Favors gg→H/A→tt searches</u>
- $m_H < m_{H^\pm} \approx m_A$: most favorable region for SFOEWPT
  <u>Favors BSM searches via $A \to ZH$ channel</u>

Mass Hierarchy for strong first-order phase transition

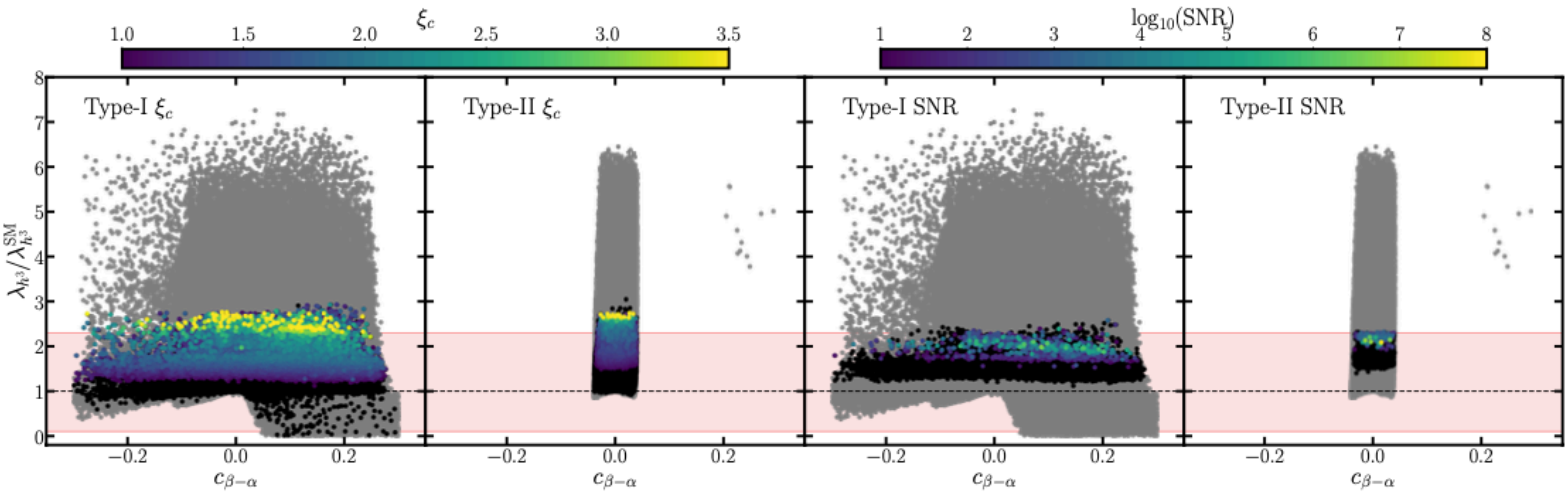


DG, Kaladharan, Wu '21; Dorsh, Huber, No 13'

➡ $m_H \approx m_{H^\pm} \approx m_A$ region leads to depleted number of SFOEWPT points. Due to the charged Higgs mass constraint $m_{H^\pm} > 580$ GeV, the type-II 2HDM displays further suppression for this region in comparison to type-I.

Collider & GW complementarity

Non-resonant di-Higgs searches:



DG, Kaladharan, Wu ‘21

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

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

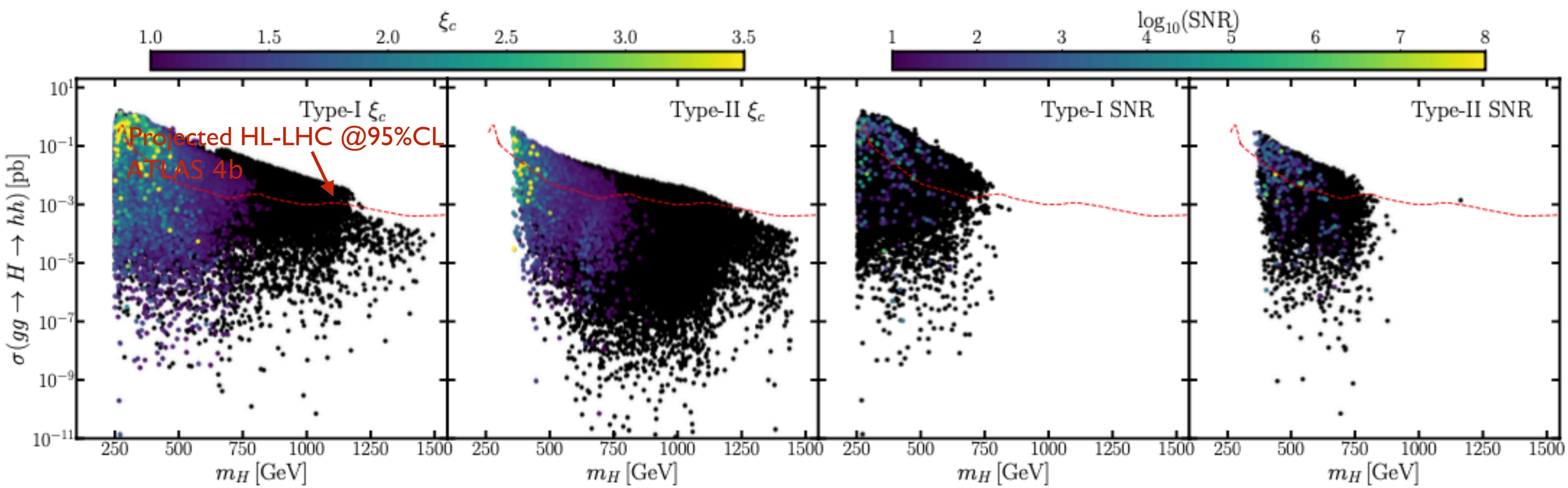
ATLAS+CMS projections from European strategy

→ While HL-LHC sensitive to SFOEWPT with ξ_C>2.5, LISA sensitive to GW signals in complementary regime ξ_C<2.5

Collider & GW complementarity

- **Resonant di-Higgs searches:**

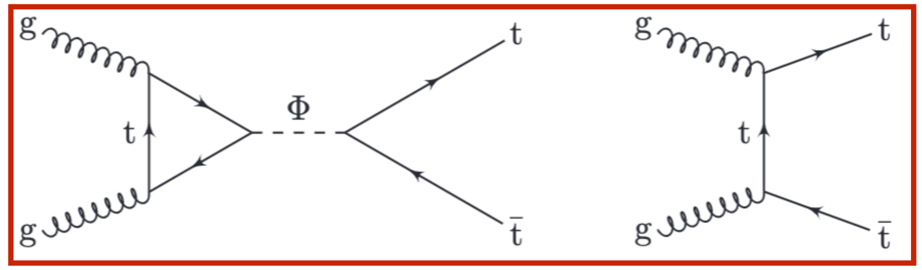
$\xi_c > 1 \;\rightarrow\; m_H \lesssim 750$ GeV: $pp \rightarrow H \rightarrow hh$ searches is favored at LHC

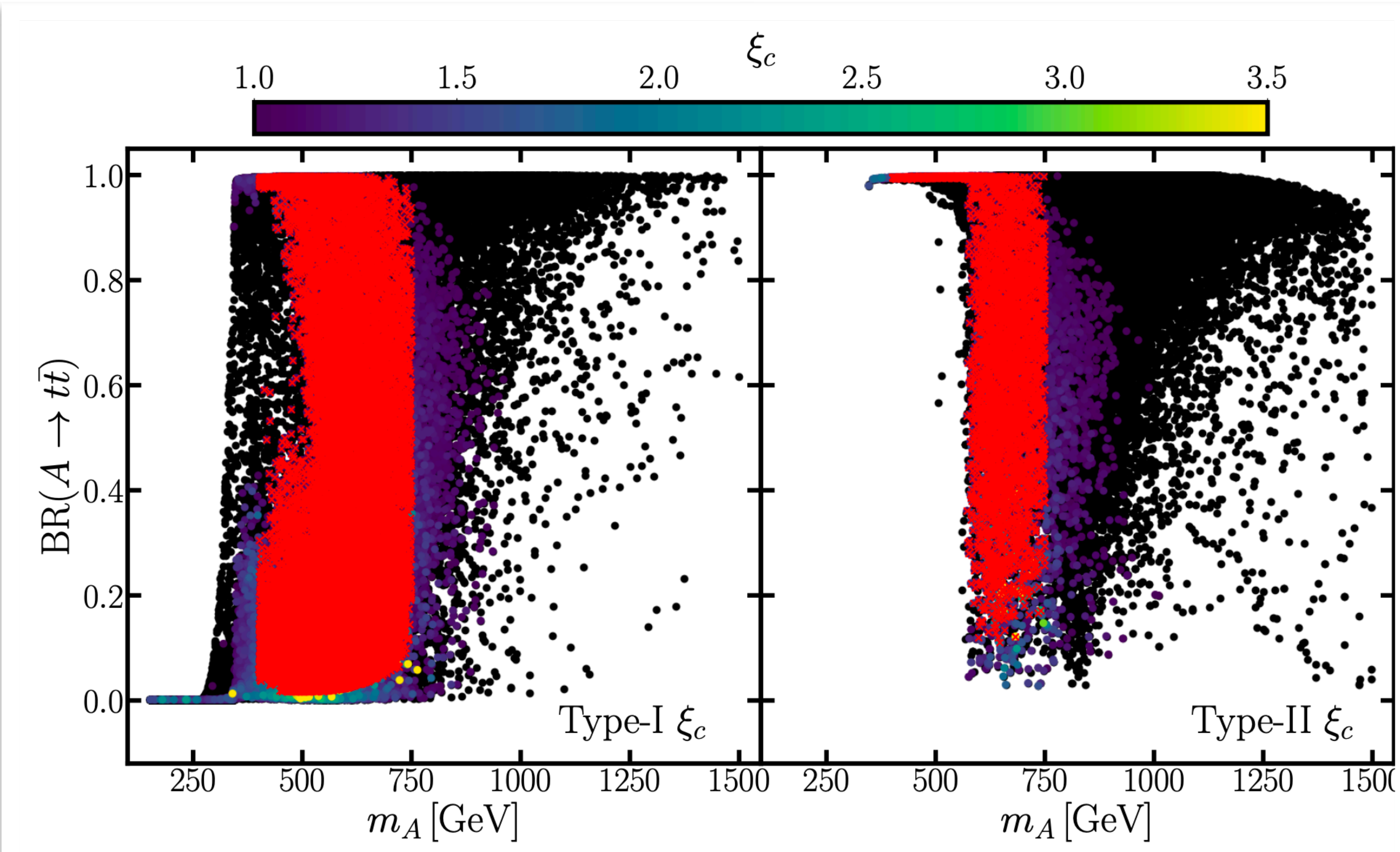


DG, Kaladharan, Wu '21

➡ While HL-LHC sensitive to SFOEWPT with large ξ_c, LISA sensitive to GW signals in complementary regime

gg→H/A→tt: HL-LHC projection

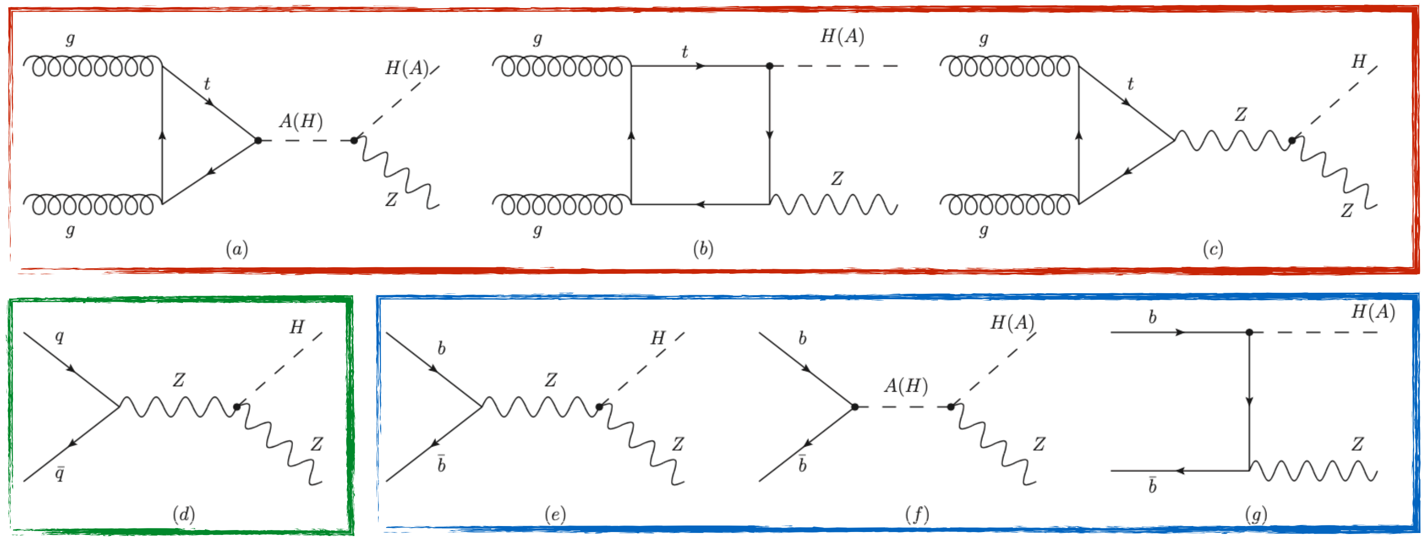


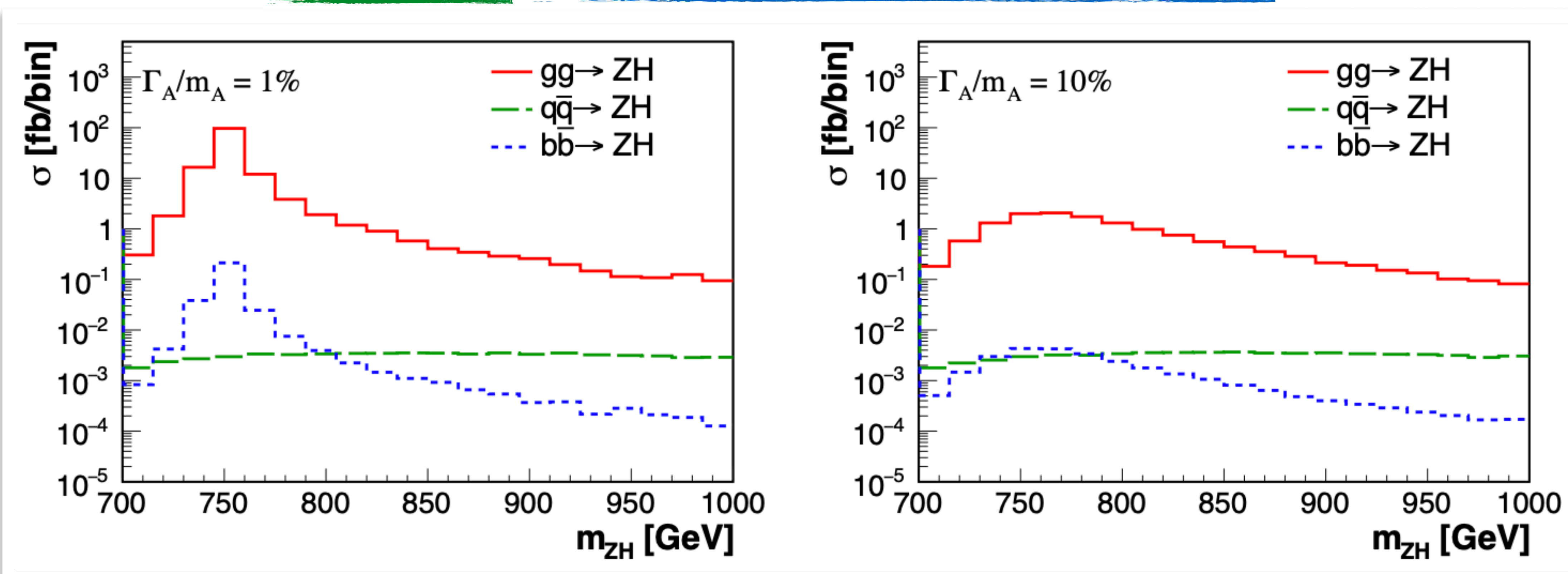


DG, Kaladharan, Wu '21

- 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

Top Pair Resonant Searches via pp→ZH/A



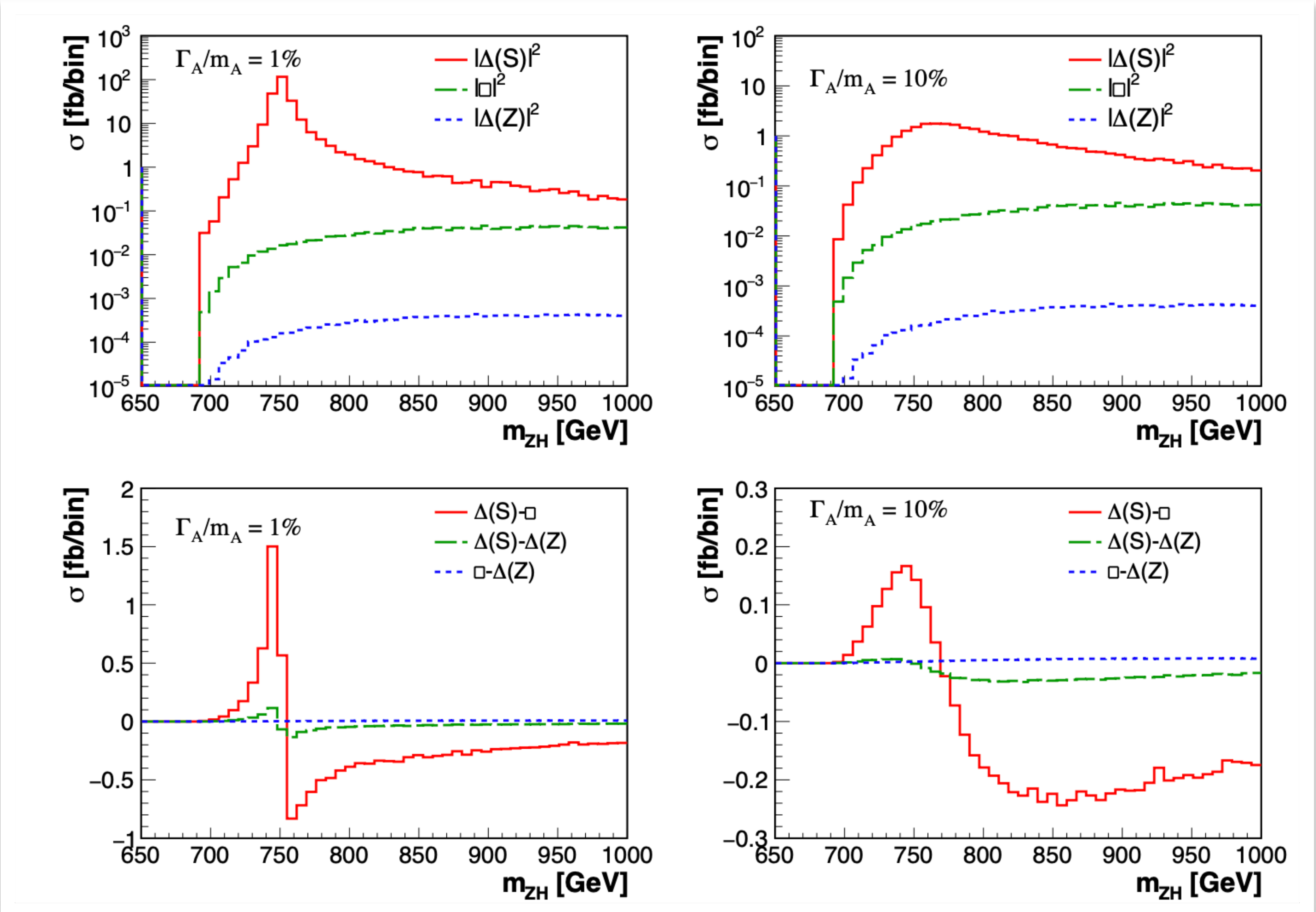


DG, Kaladharan, Wu ’22

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

CMS-PAS-B2G-23-006, see talk by Hyunyong Kim

Gluon fusion gg→ZH/A



DG, Kaladharan, Wu ’22

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

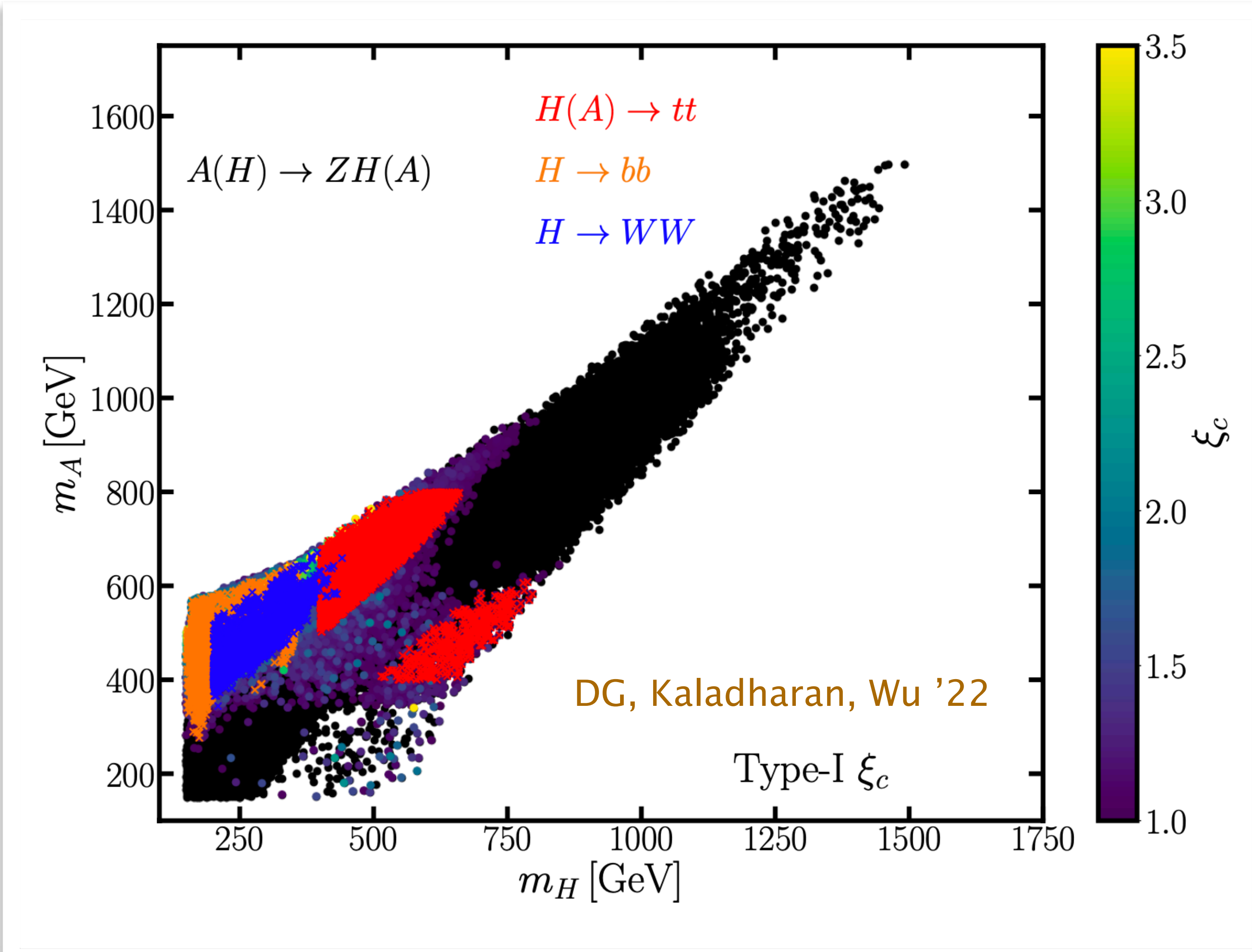
Interference between signal and ttZ background generates subleading effects for allowed 2HDM parameter space

Top Pair Resonant Searches via pp→ZH/A

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

→ 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

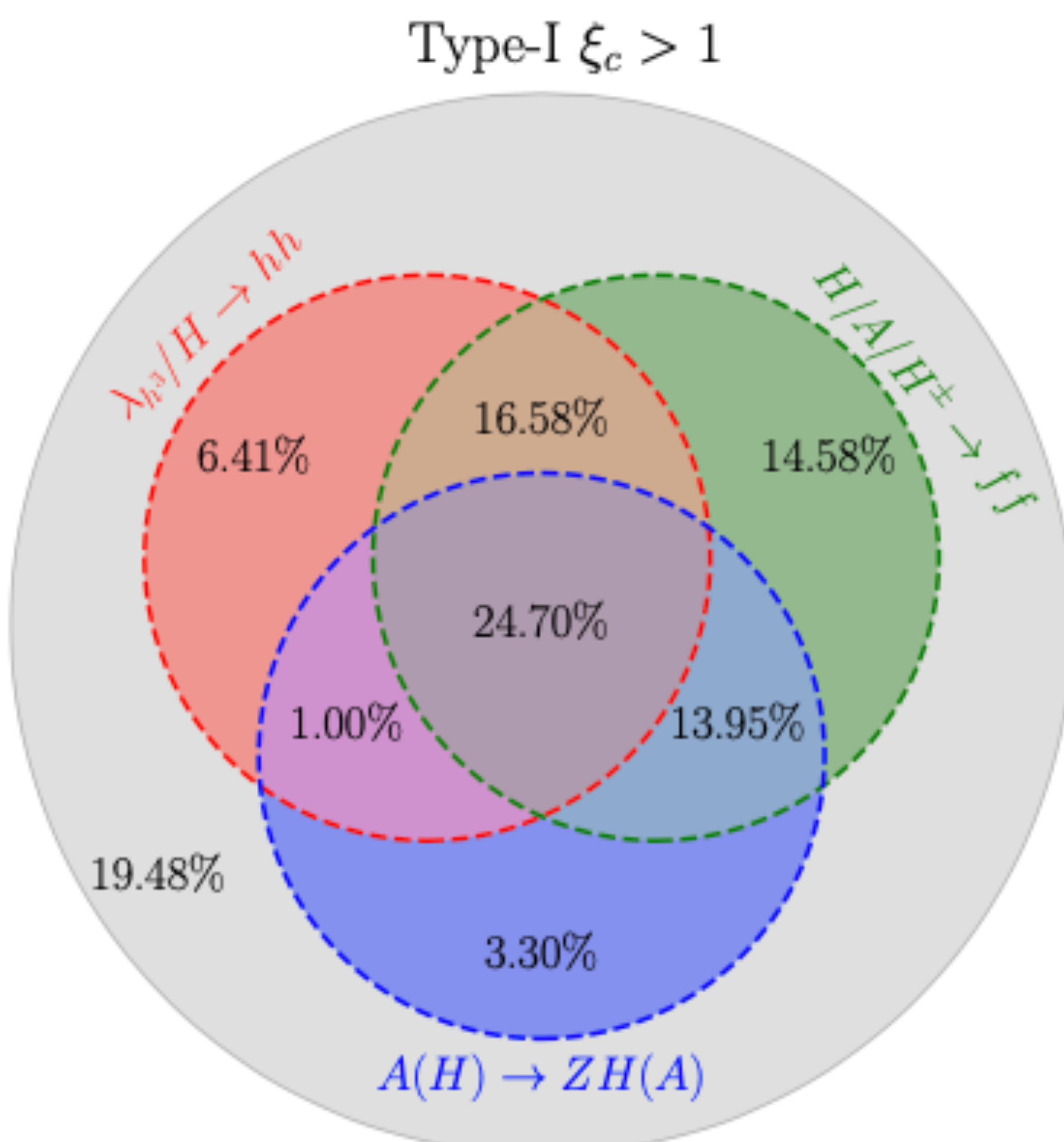
CMS-PAS-B2G-23-006
See talk by Hyunyong Kim



ATLAS-CONF-2023-034

Smoking gun signatures at the HL-LHC

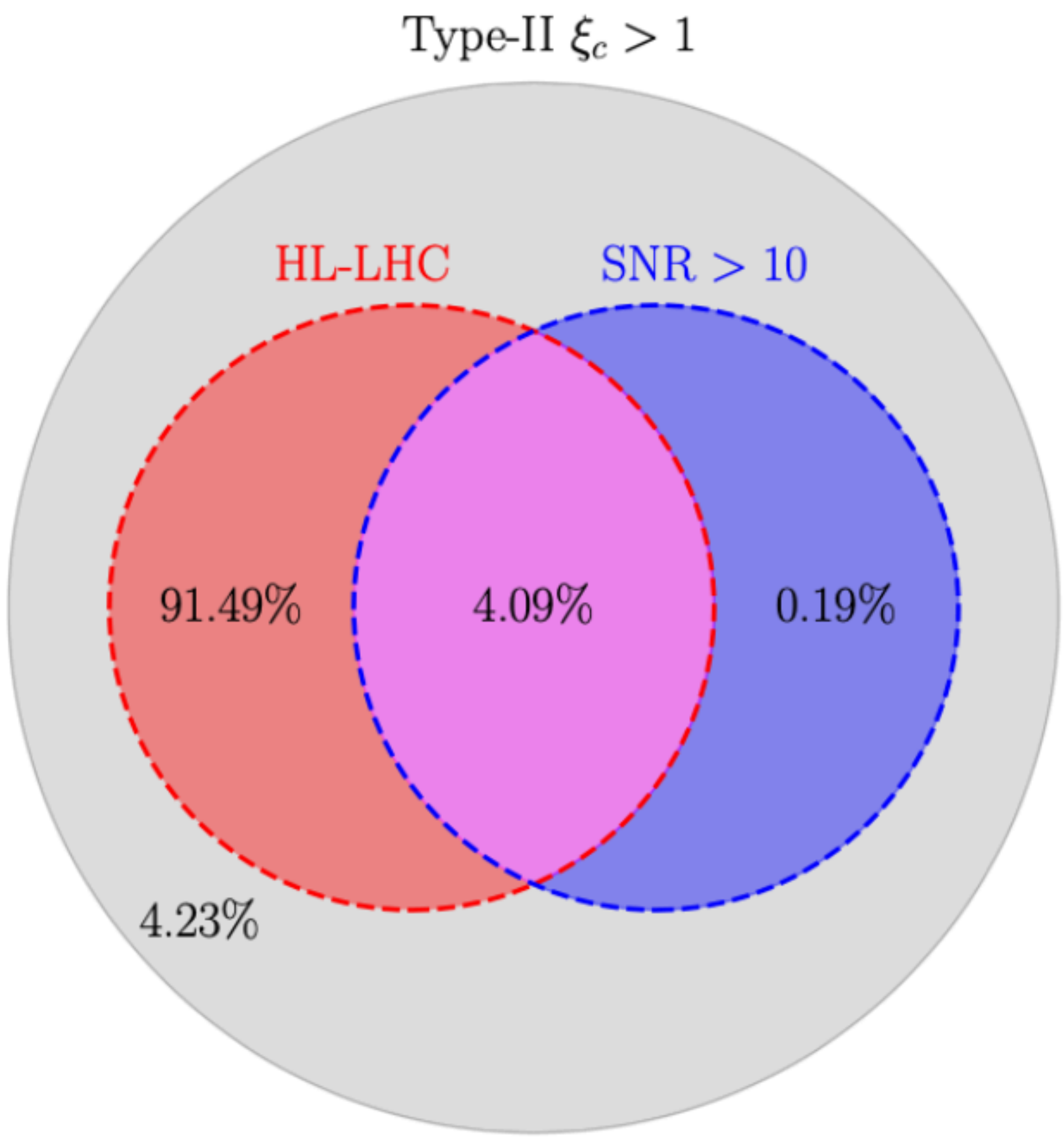
- Complementarity of the Higgstrahlung searches with other relevant classes of searches at the HL-LHC



Gonçalves, Kaladharan, Wu (PRD, 2022)
Gonçalves, Kaladharan, Wu (PRD, 2023)
Gonçalves, Kaladharan, Wu (PRD, 2023)

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

Collider & GW complementarity



Gonçalves, Kaladharan, Wu (PRD, 2022)
Gonçalves, Kaladharan, Wu (PRD, 2023)
Gonçalves, Kaladharan, Wu (PRD, 2023)

- 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
- Requirement for small scalar masses to induce vacuum upliftment play crucial role for sizable HL-LHC sensitivity

Summary

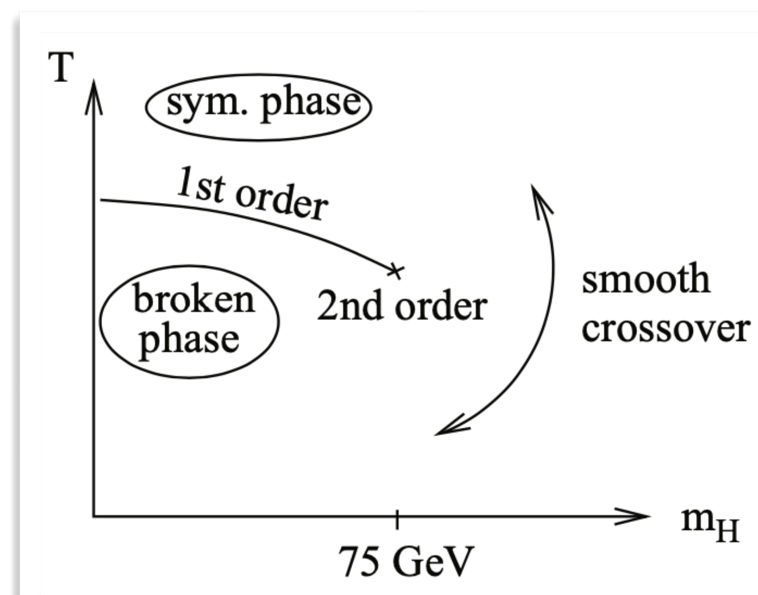
Thermal history of EWSB could have profound consequences for particle physics and cosmology

- The strength of phase transition is correlated with the upliftment of the true vacuum with respect to the symmetric one at zero temperature
- 2HDM leads to rich phase transition, favoring SFOEWPT below TeV scale
- Typically, as the order parameter increases, the resonance becomes lighter

  Strong extra motivation for scalar searches at the LHC!

- Smoking gun signatures for SFOEWPT at HL-LHC:

  $H,A \to t\bar{t}$, di-Higgs, and $A(H) \to ZH(A)$



U.S. DEPARTMENT OF ENERGY

Work in collaboration with

Ajay Kaladharan (OSU)

Yongcheng Wu
(Faculty Nanjing Normal University)

2HDM: Parameter Space Scan

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

- Theoretical and experimental constraints:

→ Perturbative unitarity

→ Boundedness from below

→ Vacuum stability

→ Electroweak precision constraints (S/T/U)

→ Flavor constraints

→ Higgs signal strengths and heavy scalar searches

ScannerS

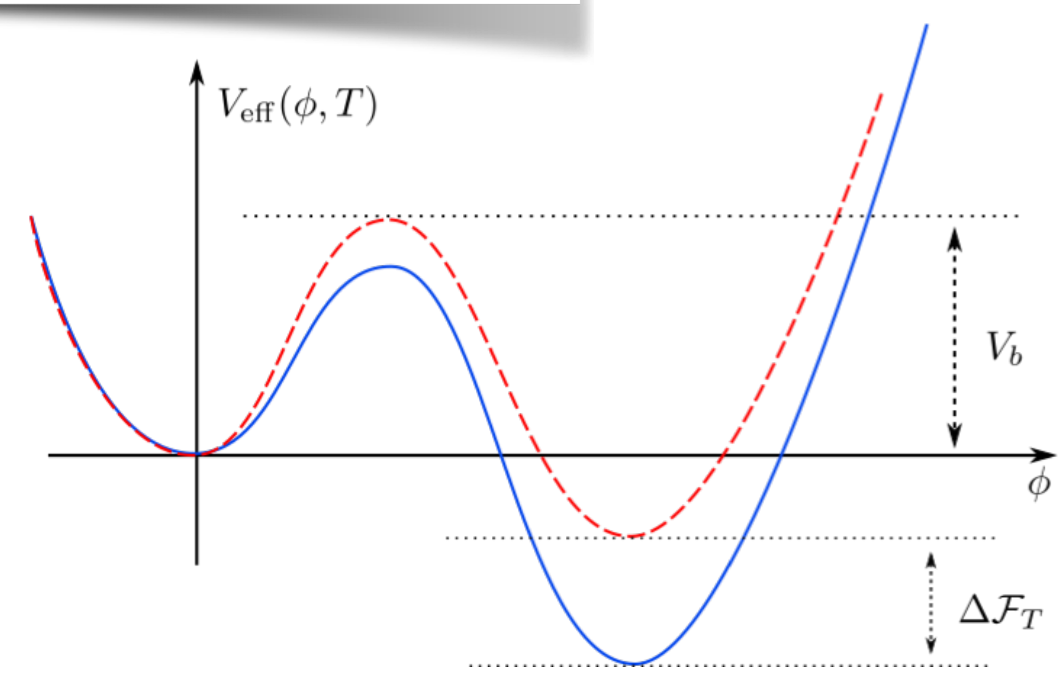
HiggsBounds & HiggsSignals

The Shape of the Higgs Potential

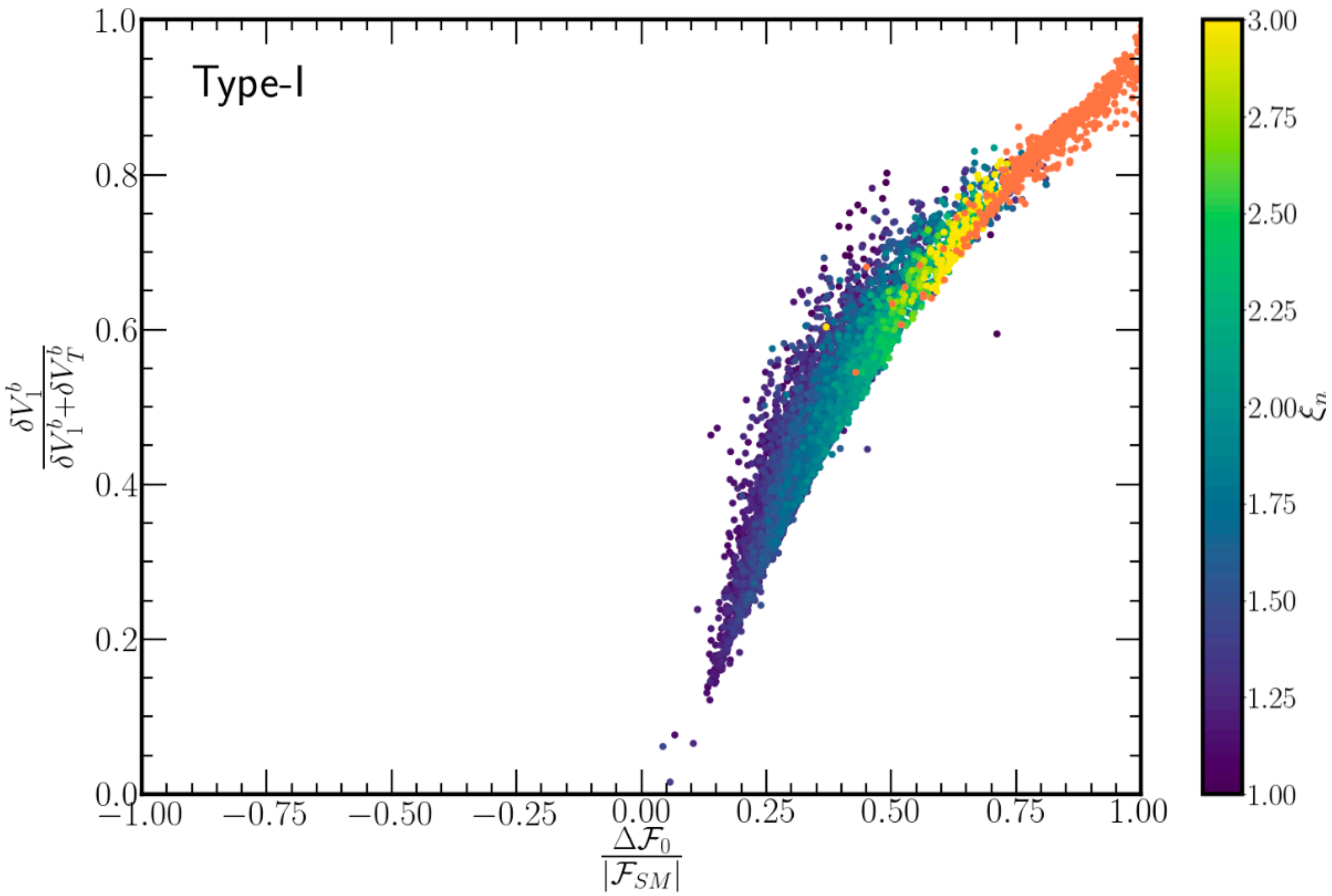
- **Vacuum Upliftment:**

$$\frac{\Delta\mathcal{F}_0}{|\mathcal{F}_0^{\rm SM}|} \equiv \frac{\mathcal{F}_0 - \mathcal{F}_0^{\rm SM}}{|\mathcal{F}_0^{\rm SM}|}$$

$$\mathcal{F}_0 \equiv V_{\rm eff}(v_1, v_2, T=0) - V_{\rm eff}(0,0,T=0)$$



- C2HDM displays the same general profile:



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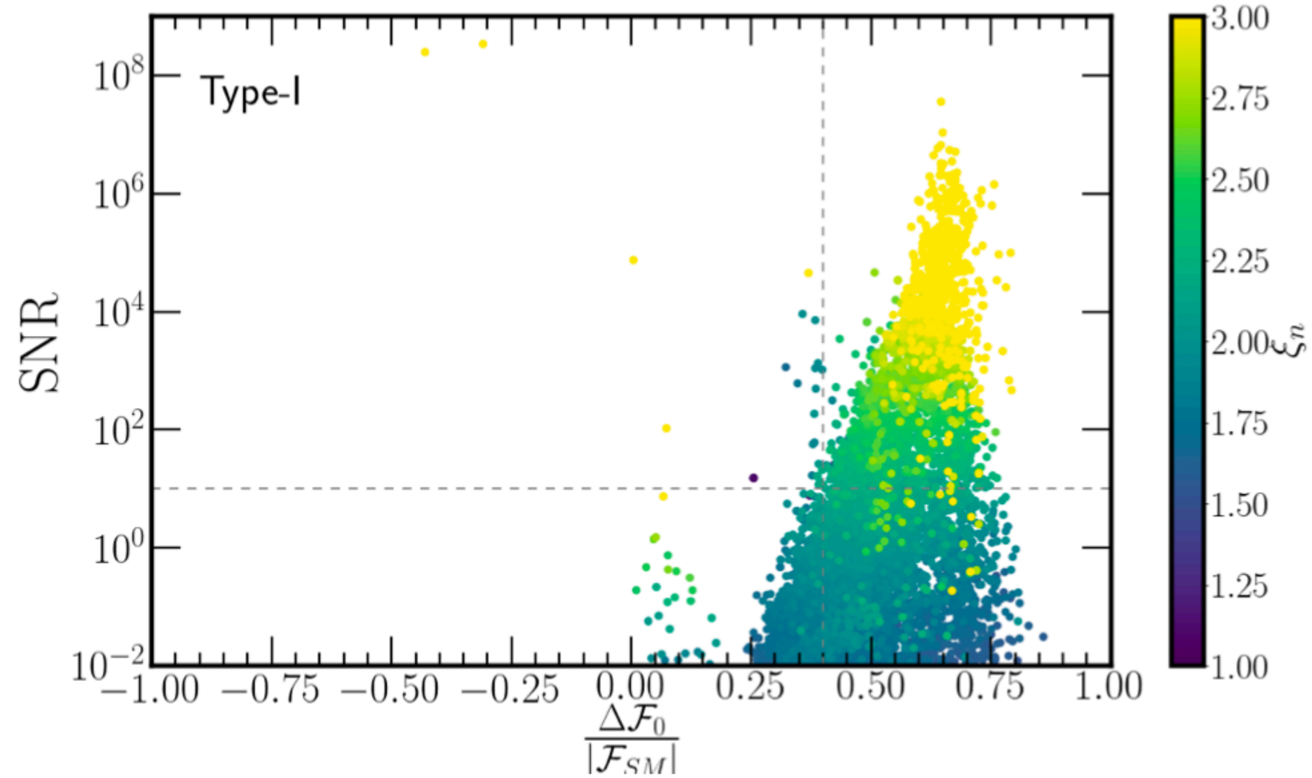


FIG. 3: SNR versus $\Delta\mathcal{F}_0/\mathcal{F}_0^{\mathrm{SM}}$ color coded with ξ_n for the Type I parameter point with $\xi_n > 1$. The dotted line in the plot corresponds to an SNR value of 10, serving as the threshold above which LISA can probe the parameter points.

The Shape of the Higgs Potential

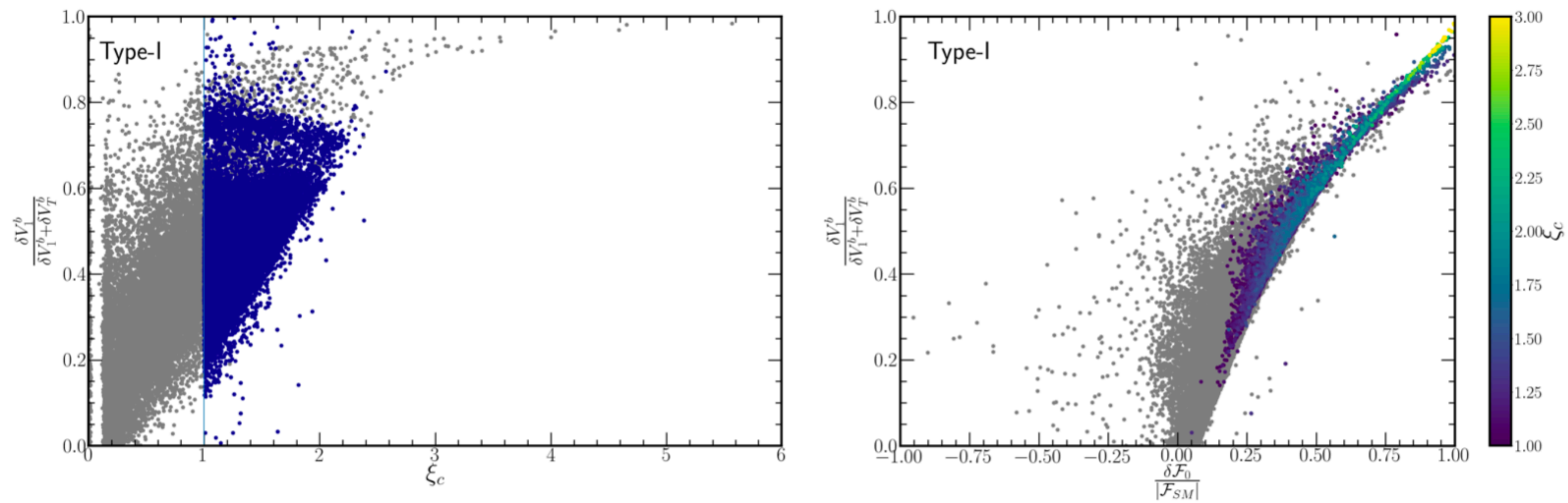
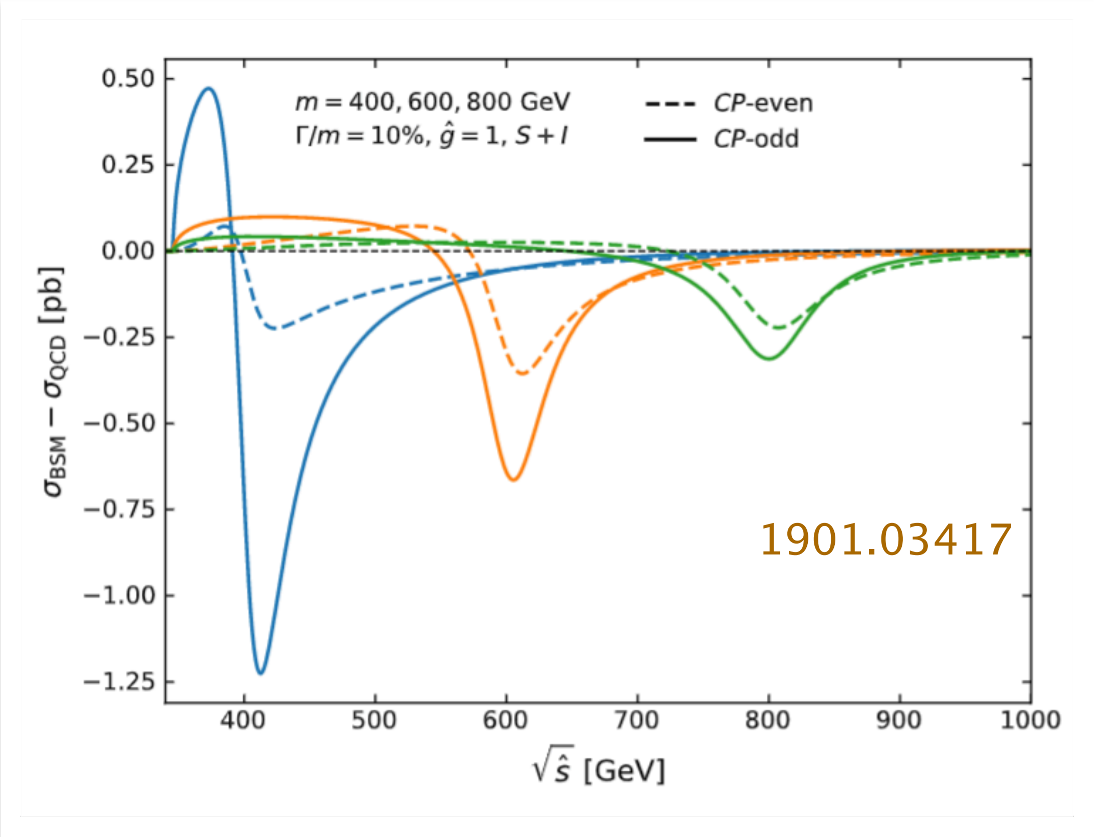


FIG. 3: Left panel: the ratio $\frac{\delta V_1^b}{\delta V_1^b+\delta V_T^b}$ for the barrier at T_c versus ξ_c. Blue denotes the points with $\xi_c > 1$ and have nucleation temperature, while gray represents points with first-order phase transition. Right panel: the ratio $\frac{\delta V_1^b}{\delta V_1^b+\delta V_T^b}$ for the barrier at T_c versus $\delta\mathcal{F}_0/\mathcal{F}_0^{\rm SM}$ color coded with ξ_c. Gray denotes all first-order phase transition points. We assume the type-I 2HDM, focusing on the most probable region in Fig. 2, where the barrier is generated by the one-loop and thermal corrections $\delta V_1^b, \delta V_T^b > 0$.

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