Collider and gravitational wave signals for electroweak phase transition

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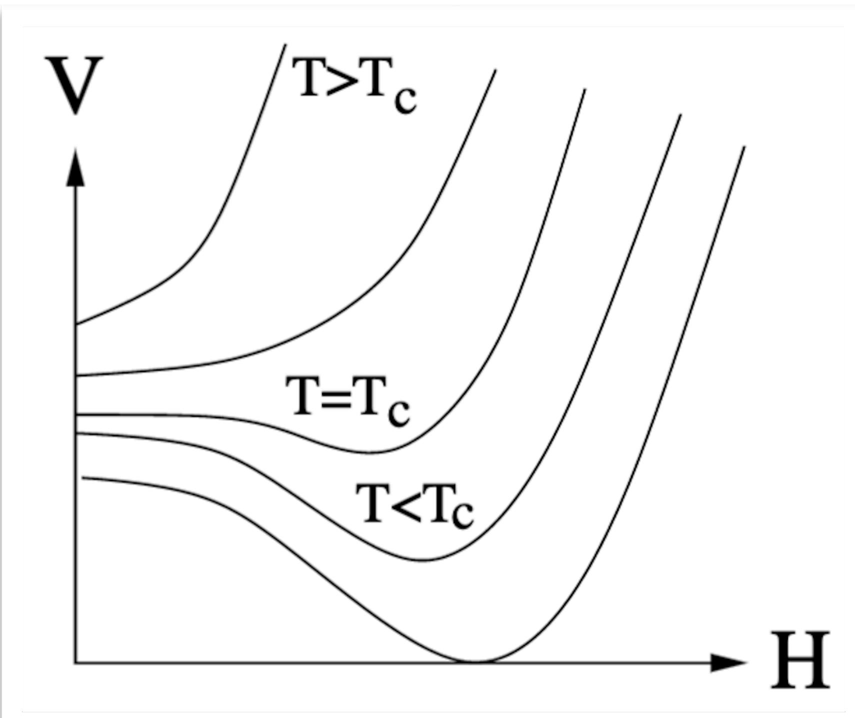
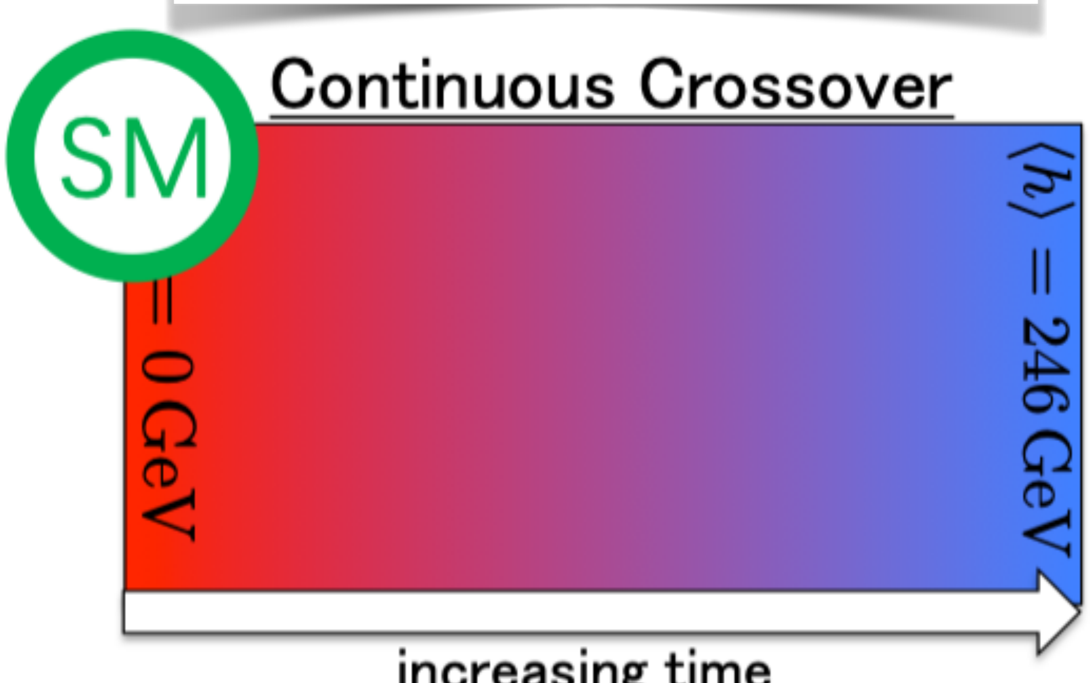
Dorival Gonçalves

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

Thermal history of our Universe

- What is the order of the Electroweak Phase Transition?





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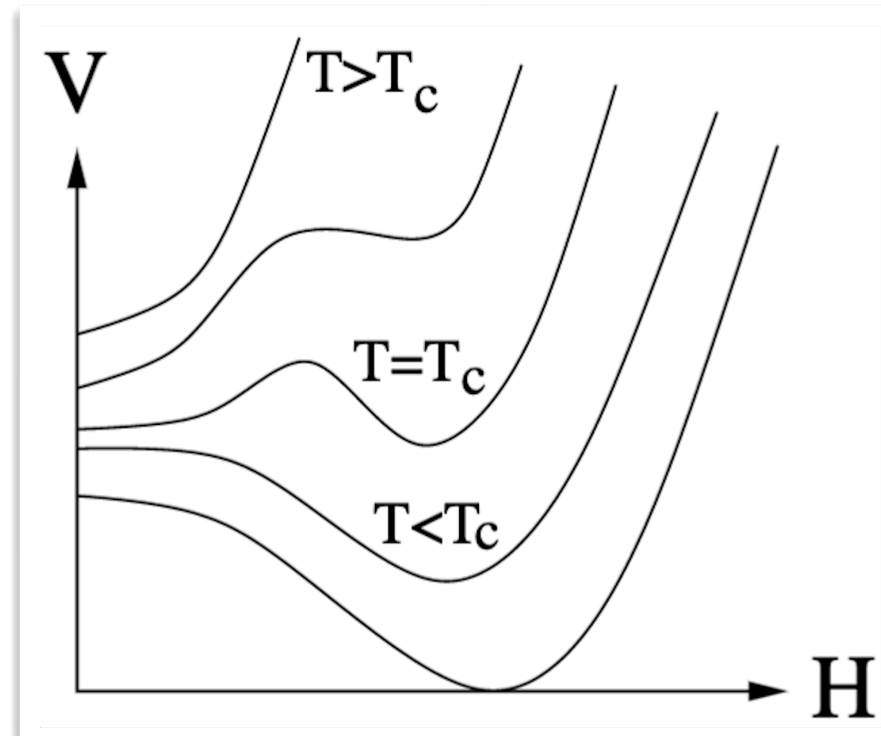
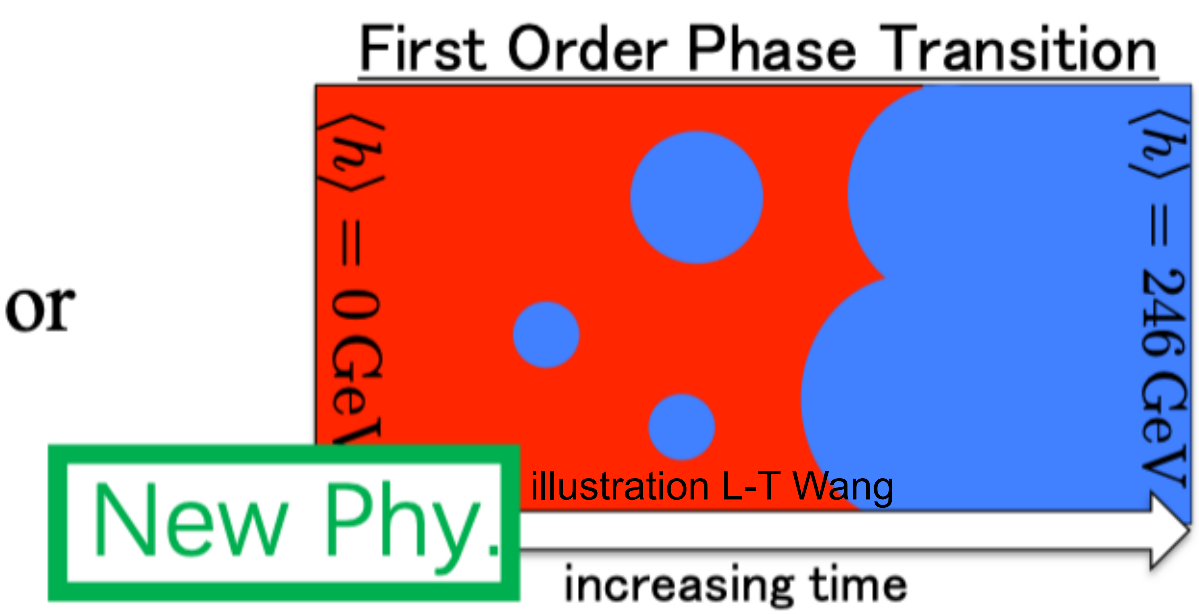
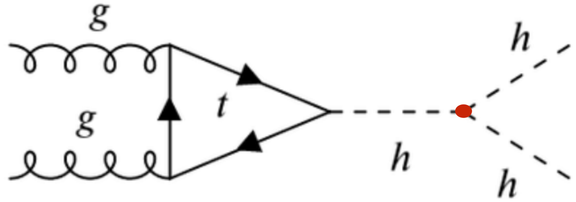
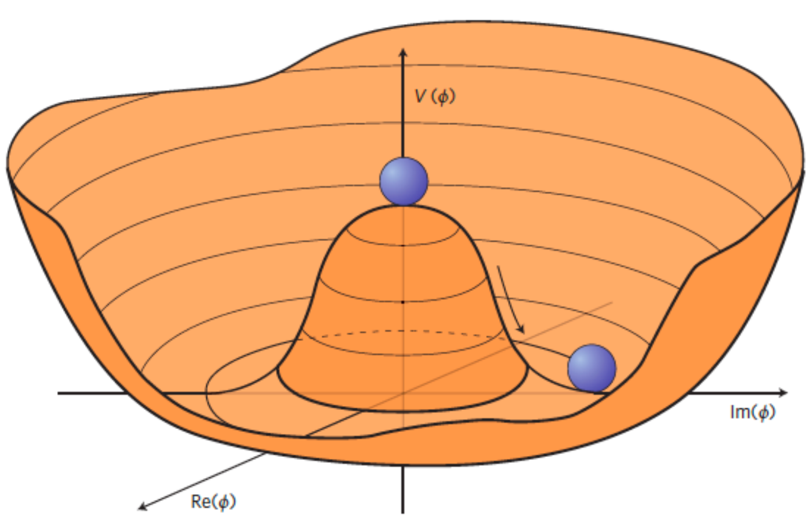


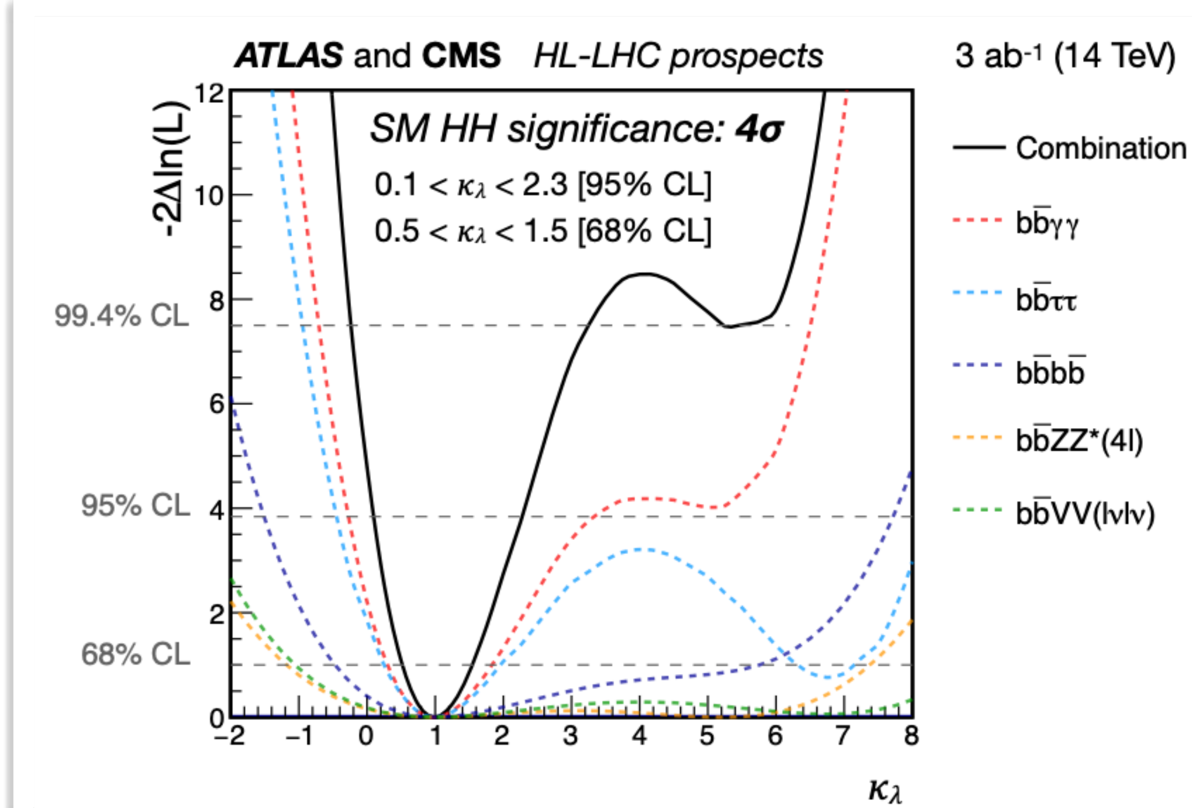


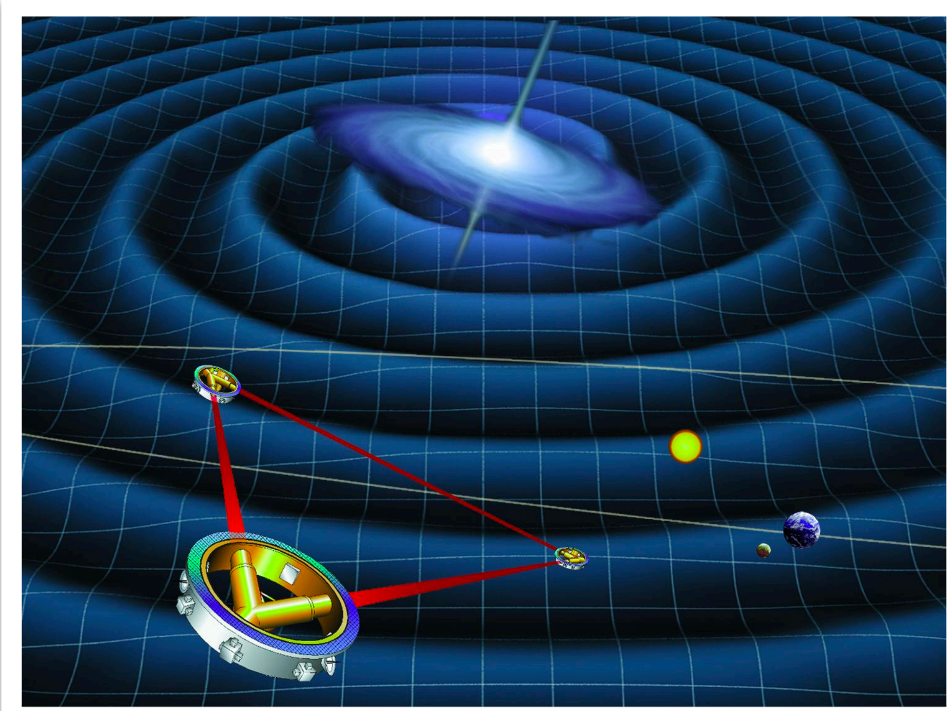
Higgs Potential: Collider & GW Complementarity



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







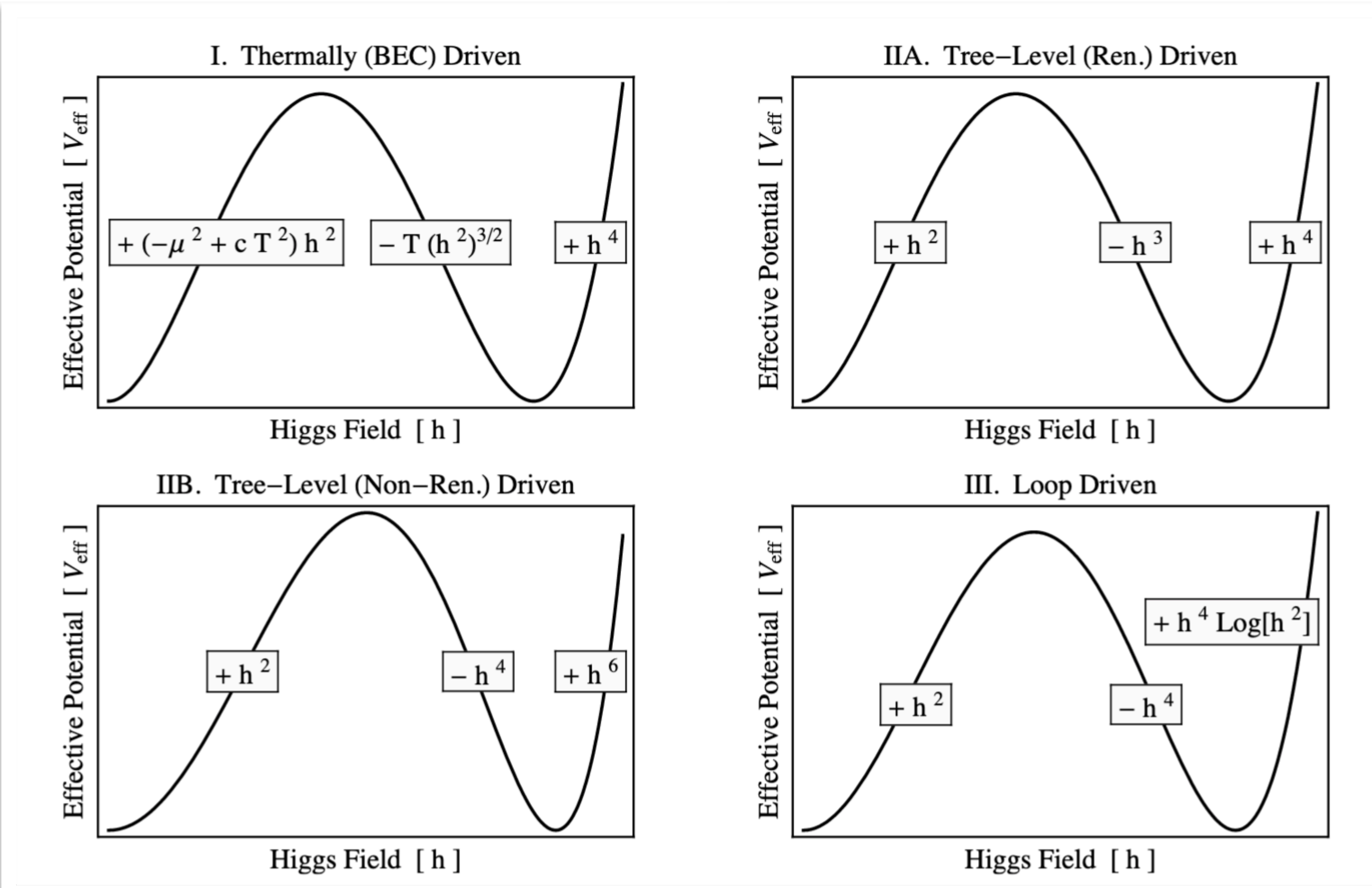
- For $T_* \sim 100$ GeV, GW frequency (redshifted to today) ~ mHz

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

The Shape of the Higgs Potential

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

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

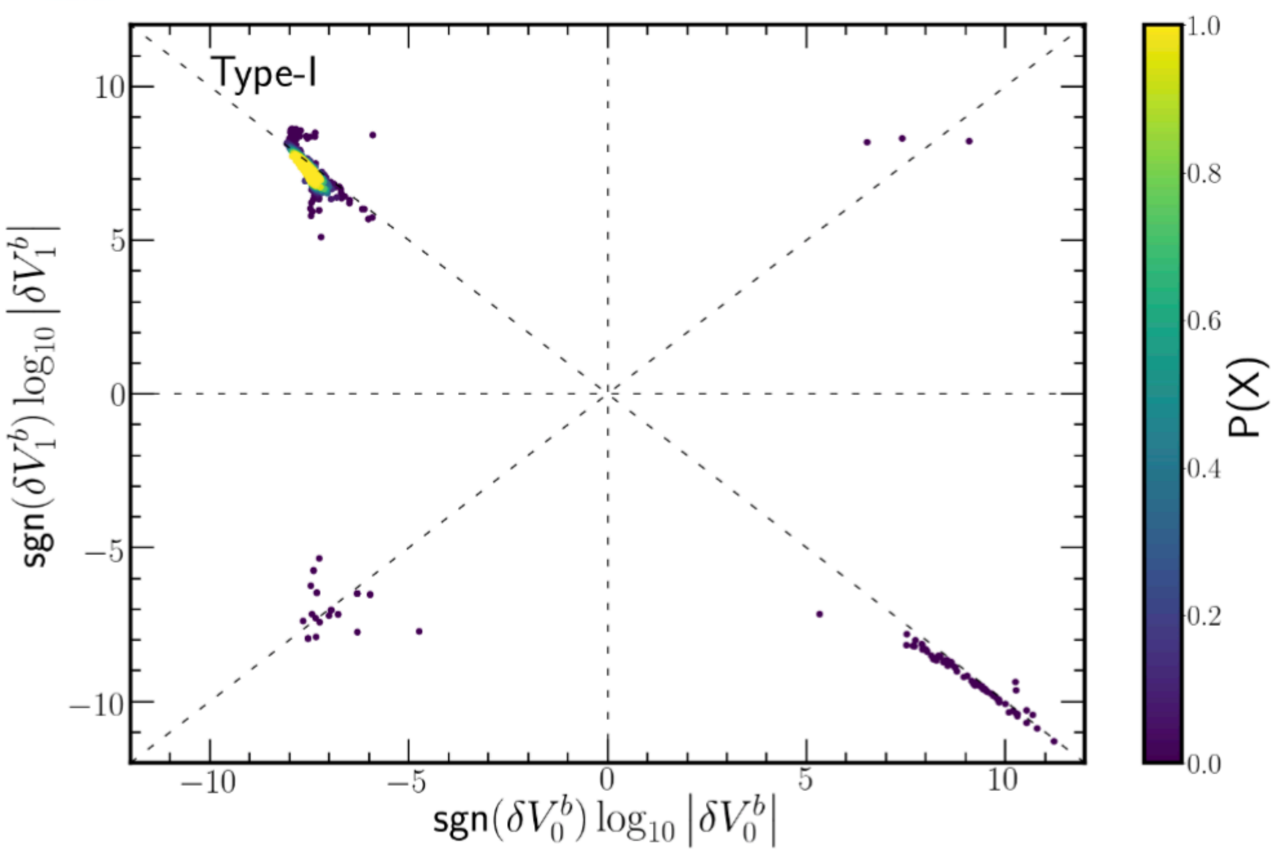


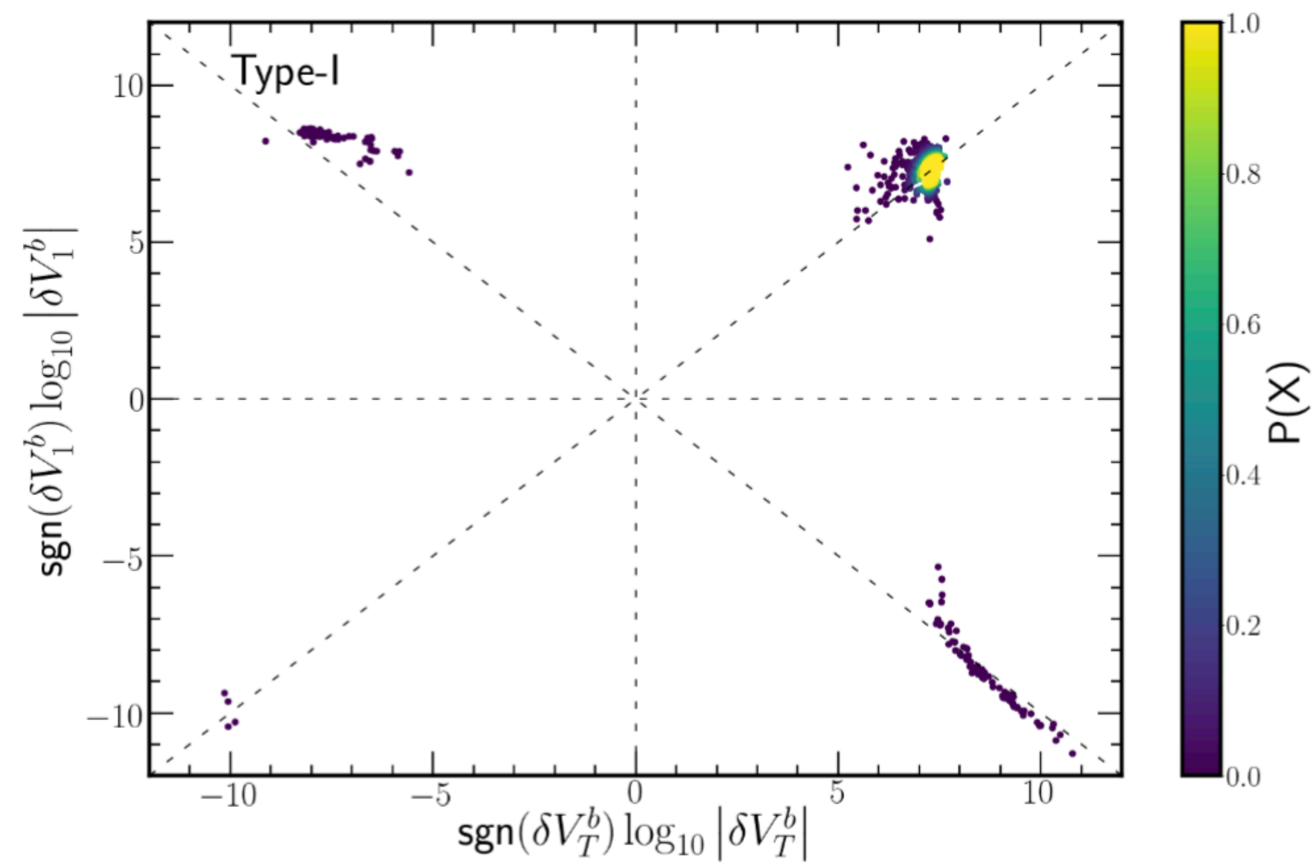
Chung,Long, L–T Wang '12

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

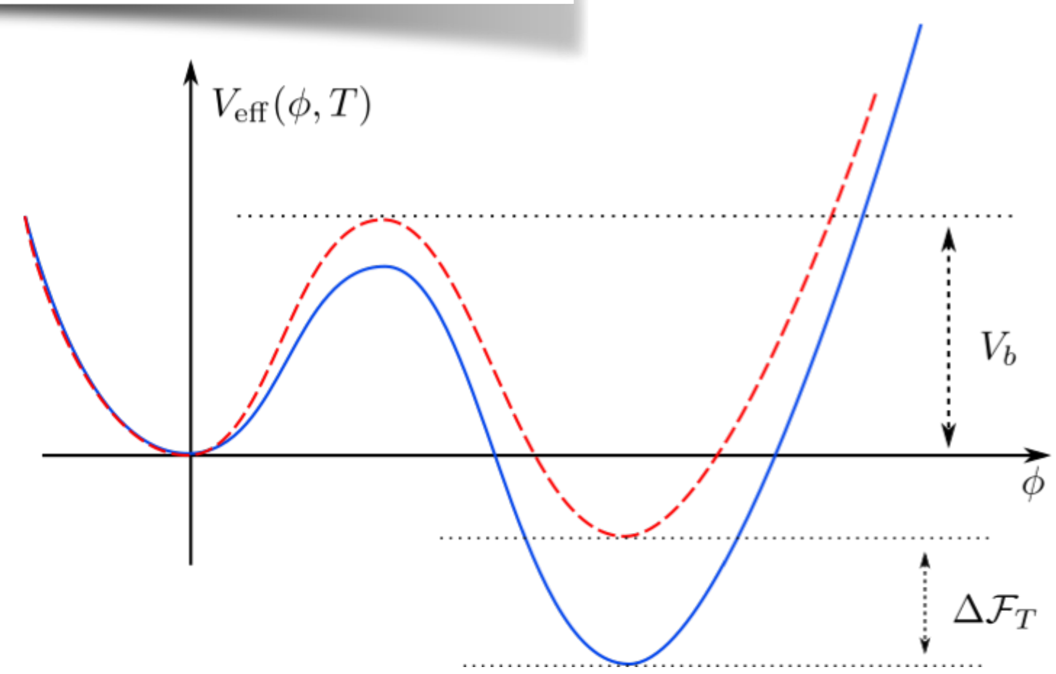
➡ Potential barrier induced by one-loop+thermal effects for more than 99% of points

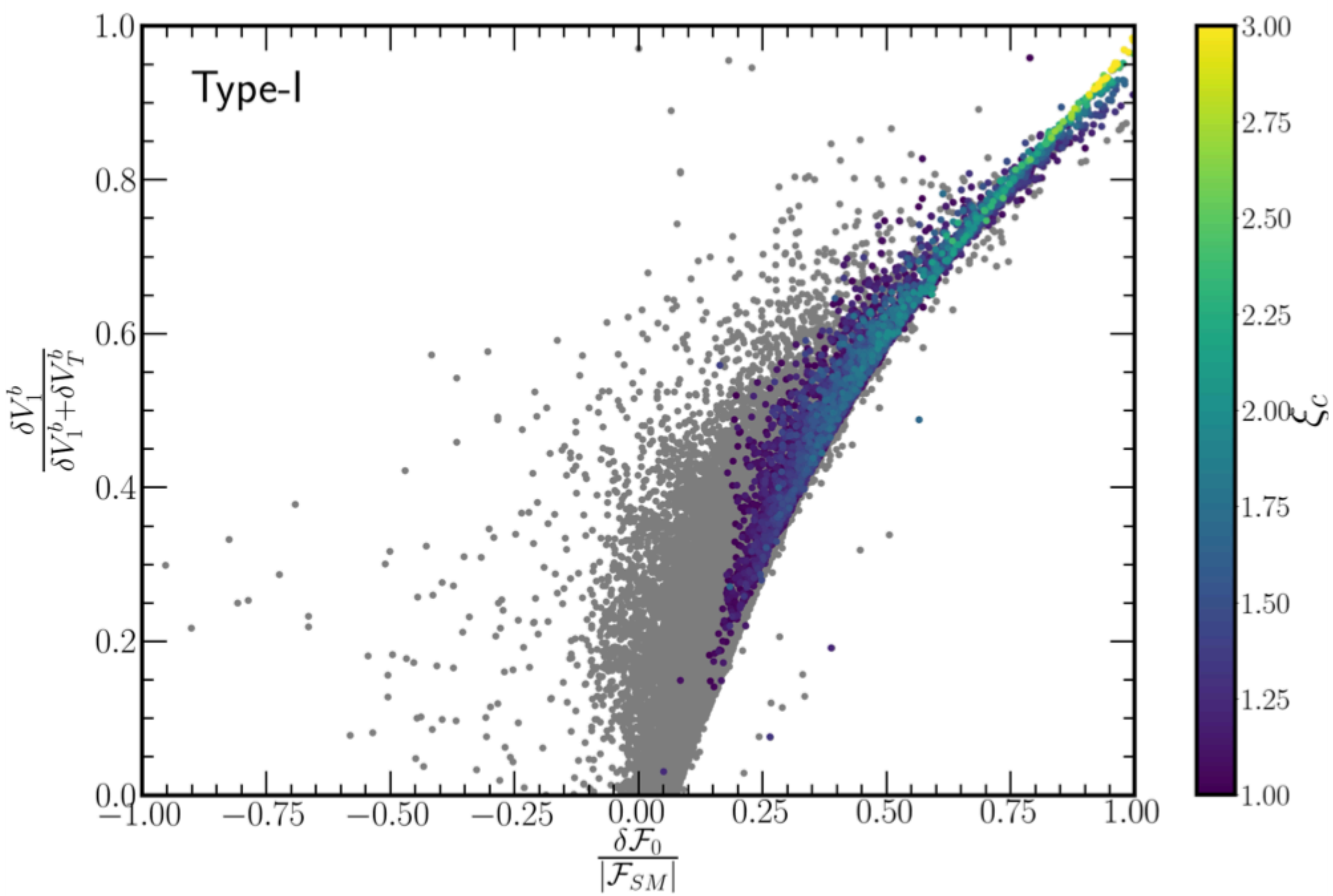
The Shape of the Higgs Potential

- **Vacuum Upliftment:**

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

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

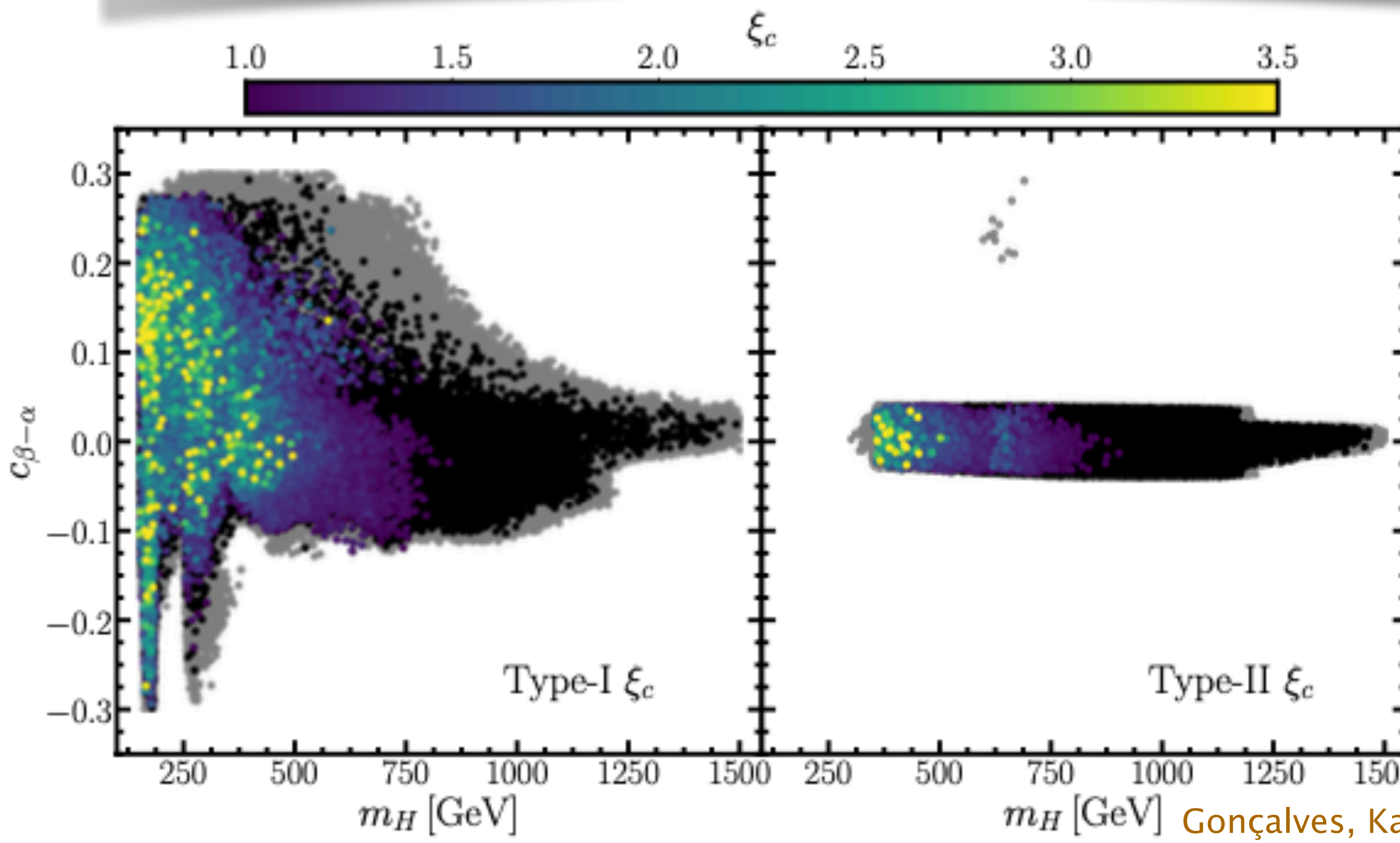




$$\xi_c \equiv \frac{v_c}{T_c}$$

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

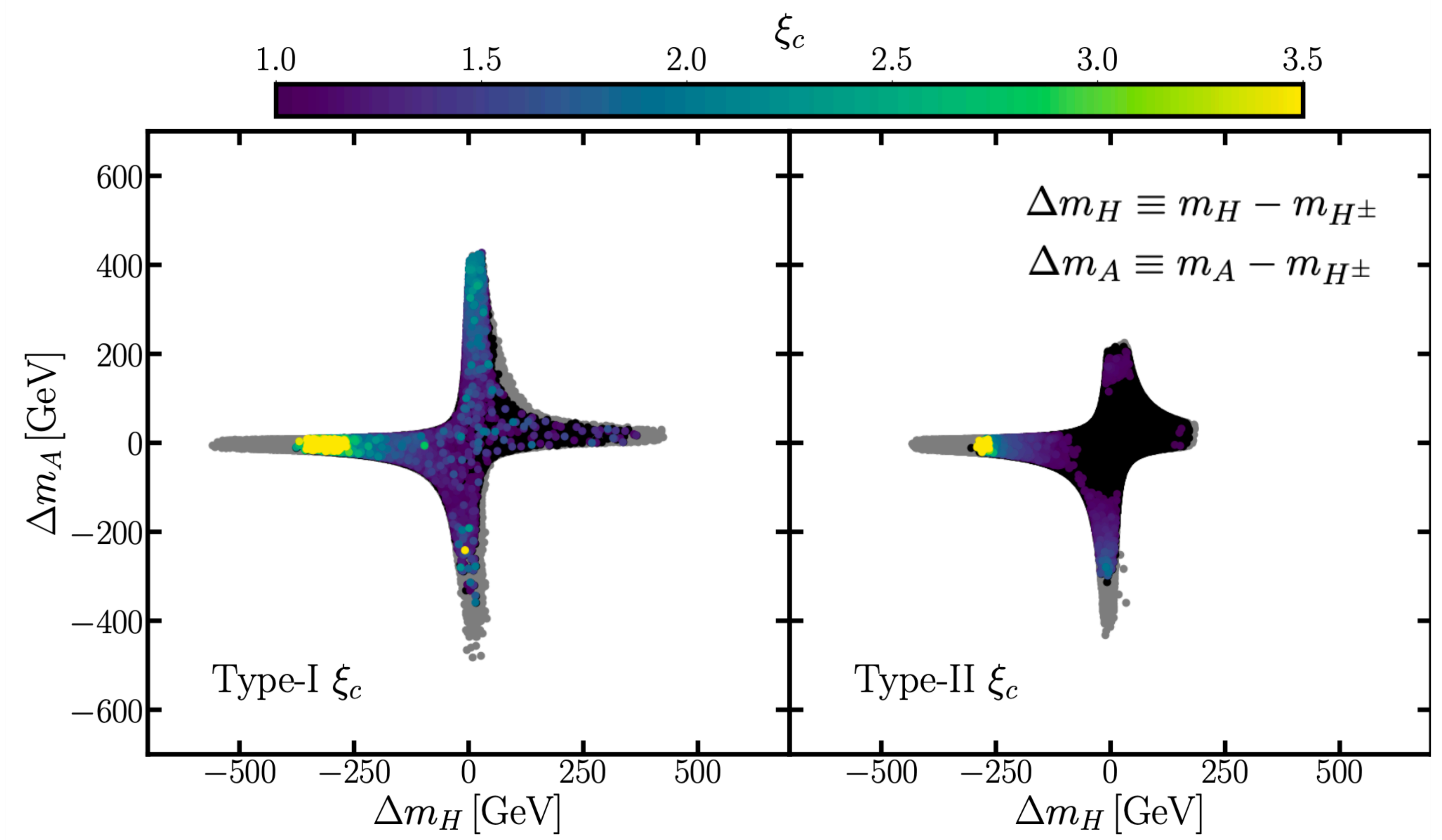
Strong first-order phase transition in the 2HDM



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'

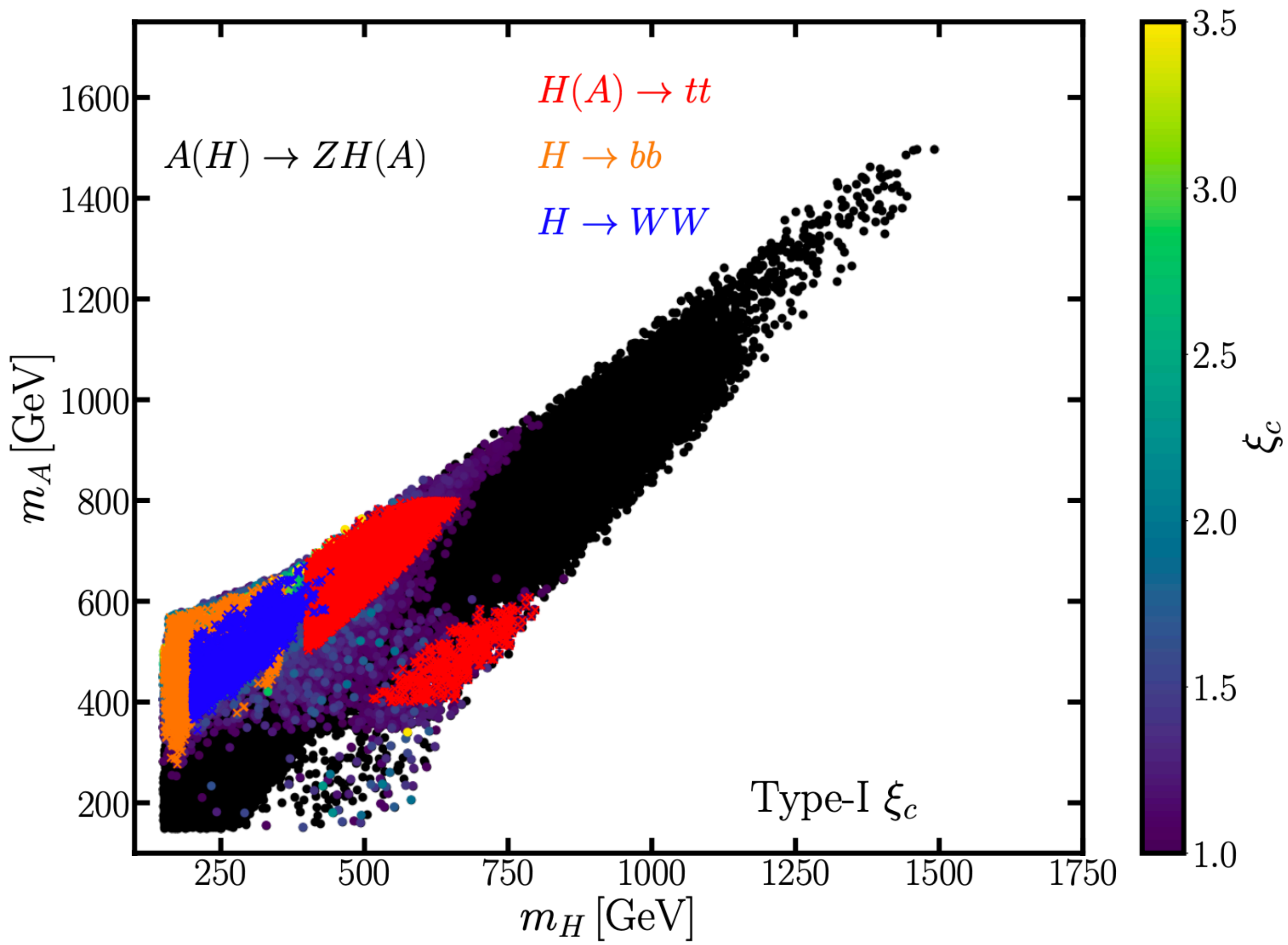
- Due to the preference for large mass hierarchy among the scalar modes, it is likely that at least one of the scalar states be above the top-quark pair threshold: Favors gg→H/A→tt searches
- $m_H < m_{H^\pm} \approx m_A$: most favorable region for SFOEWPT
  Favors BSM searches via $A \to ZH$ channel

Top Pair Resonant Searches via pp→ZH/A

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

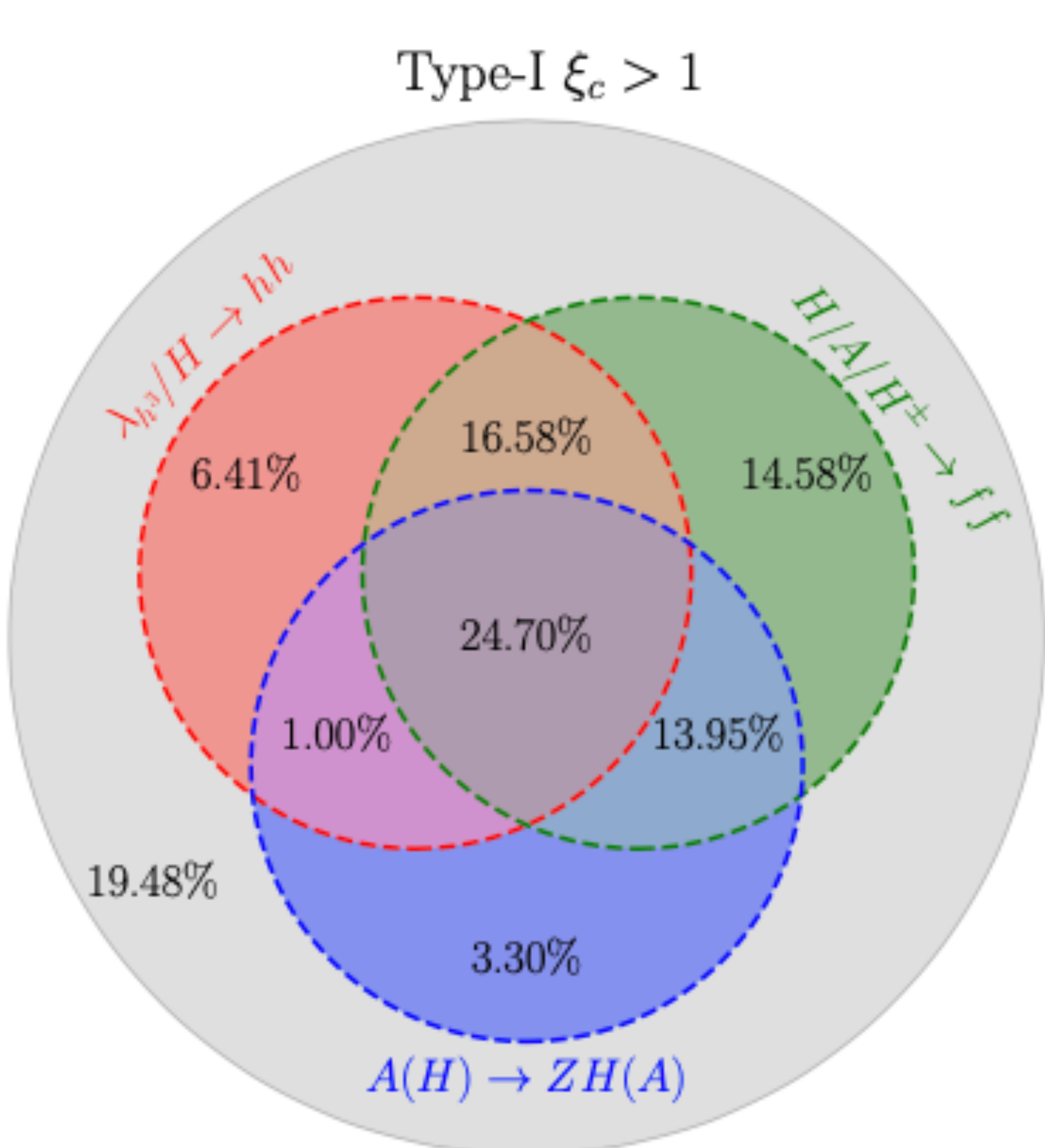
  See e.g., arXiv:2011.05639 and arXiv:1911.03781

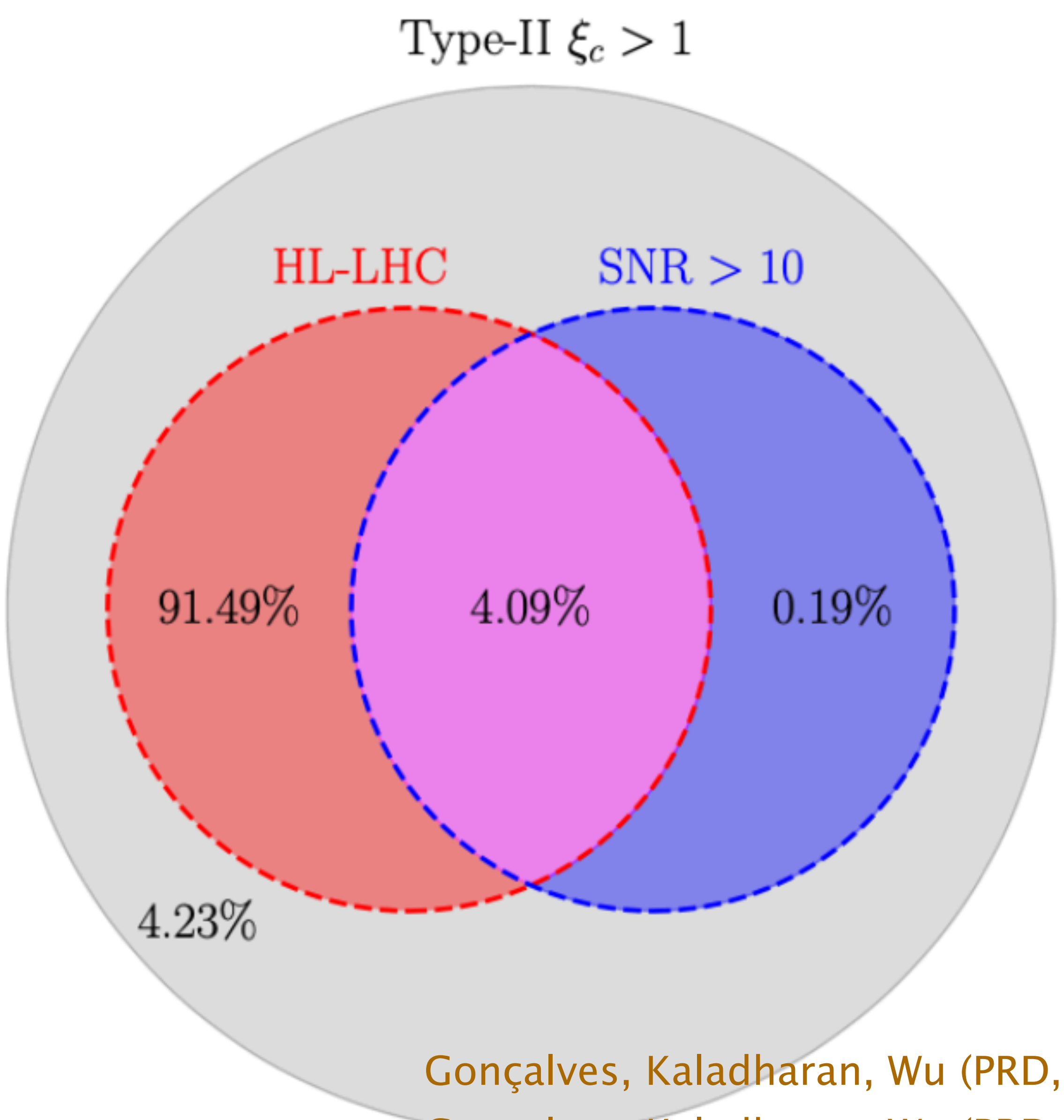
→ Above top-quark pair threshold the H/A → tt is typically dominant decay, leading to strong limits, and extending the sensitivity to strong first-order phase transition regime



DG, Kaladharan, Wu ’22; Biekotter, Heinemeyer, No, Radchenko, Romacho, Weiglein ’23

Collider & GW complementarity





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

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

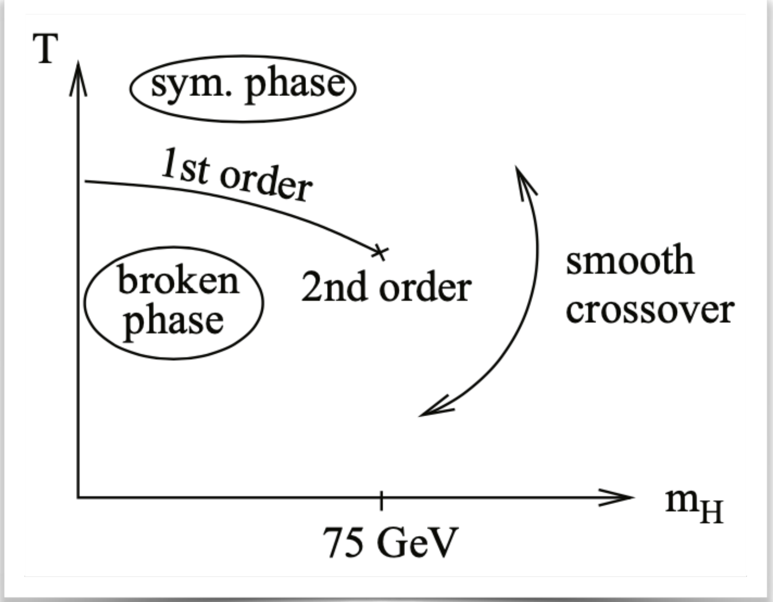
Summary

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

- 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!

- H, A→ tt: smoking gun signature for SFOEWPT at HL-LHC with gluon fusion and Higgstrahlung production



U.S. DEPARTMENT OF ENERGY

Work in collaboration with

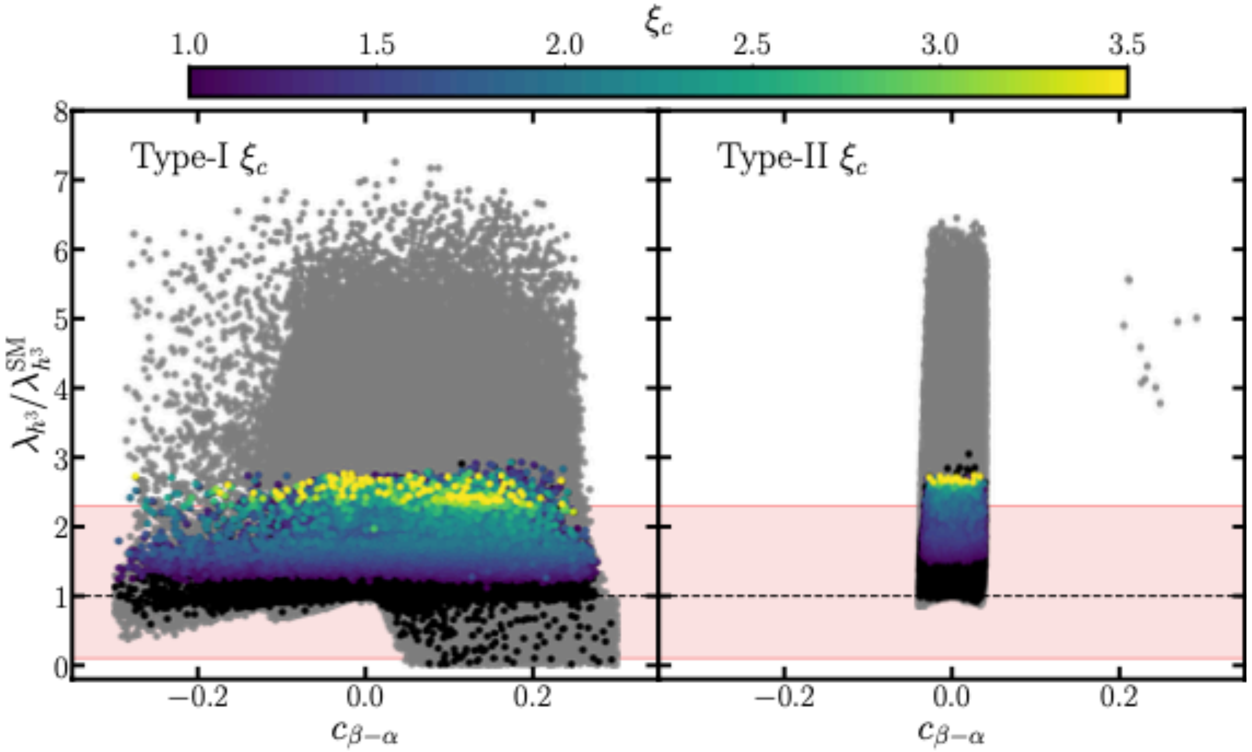
Ajay Kaladharan (OSU)

Yongcheng Wu (Faculty Nanjing)

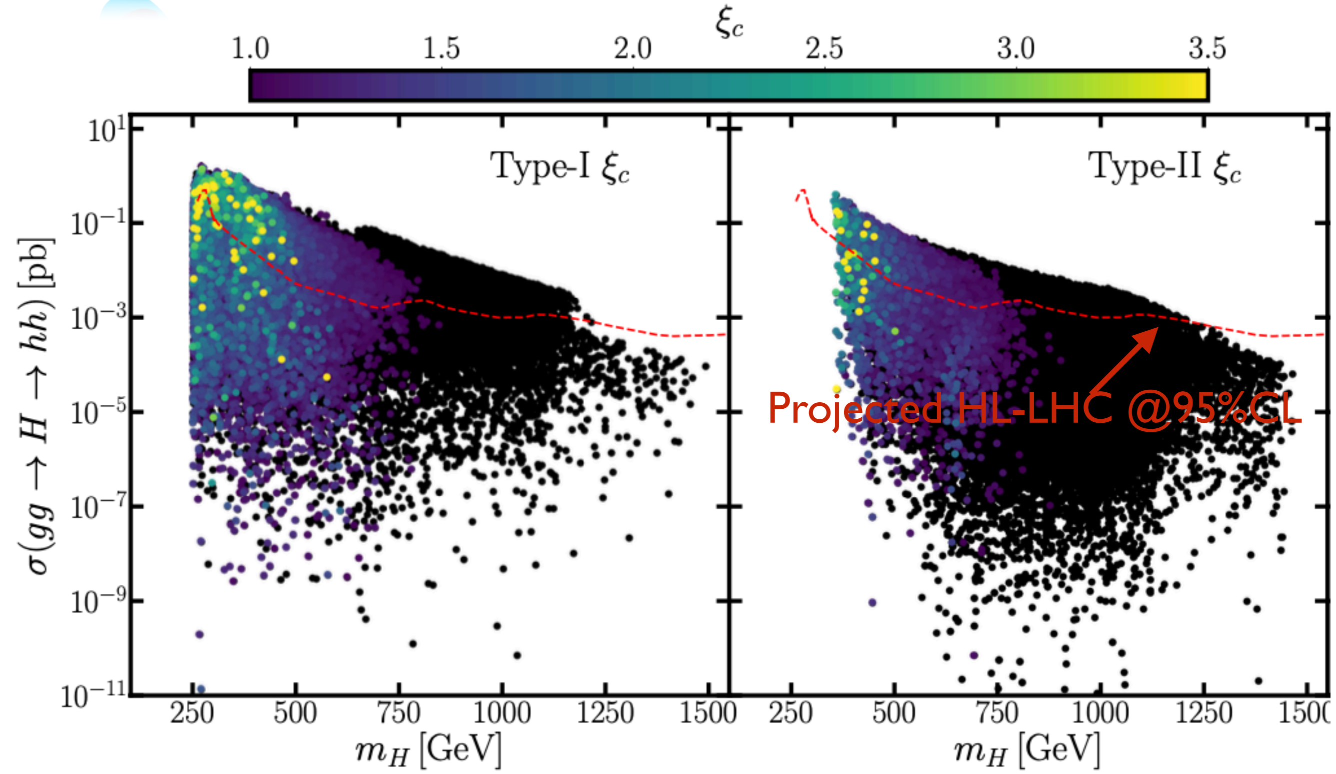
See his talk at DPF-Pheno:
“PBH formation from first-order phase transition”

Backup

Non-resonant di-Higgs searches



Resonant di-Higgs searches:



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

ATLAS+CMS projections

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

2HDM: Parameter Space Scan

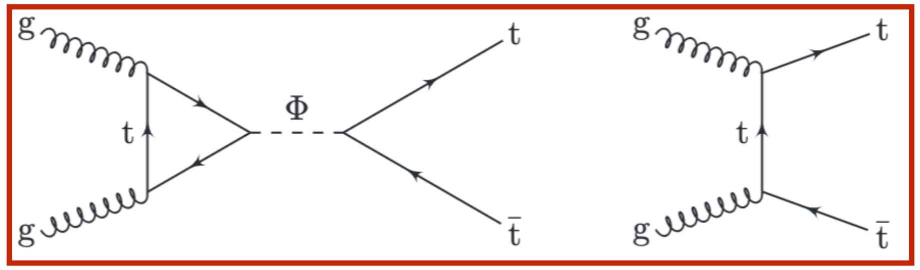
$$\tan\beta \in (0.8, 25)\,, \quad m_{12}^2 \in (10^{-3}, 10^5)\,\text{GeV}^2\,, \quad m_H \in (150, 1500)\,\text{GeV}\,,$$
$$\cos(\beta-\alpha) \in (-0.3, 0.3)\,, \quad m_A \in (150, 1500)\,\text{GeV}\,, \quad m_{H^\pm} \in (150, 1500)\,\text{GeV}.$$

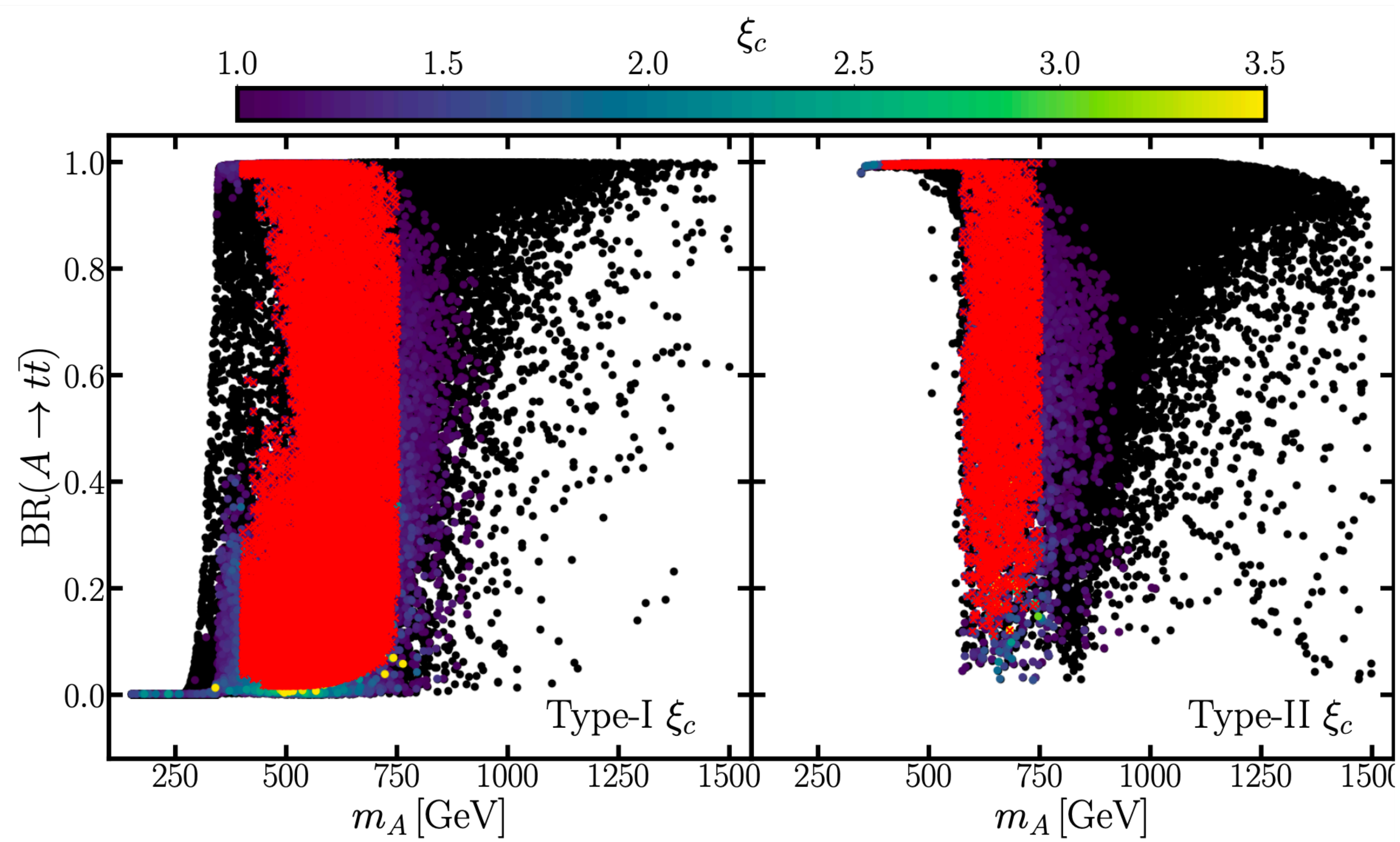
- Theoretical and experimental constraints:
  - → Perturbative unitarity
  - → Boundedness from below
  - → Vacuum stability
  - → Electroweak precision constraints (S/T/U)
  - → Flavor constraints
  - → Higgs signal strengths and heavy scalar searches

ScannerS

HiggsBounds & HiggsSignals

gg→H/A→tt: HL-LHC projection





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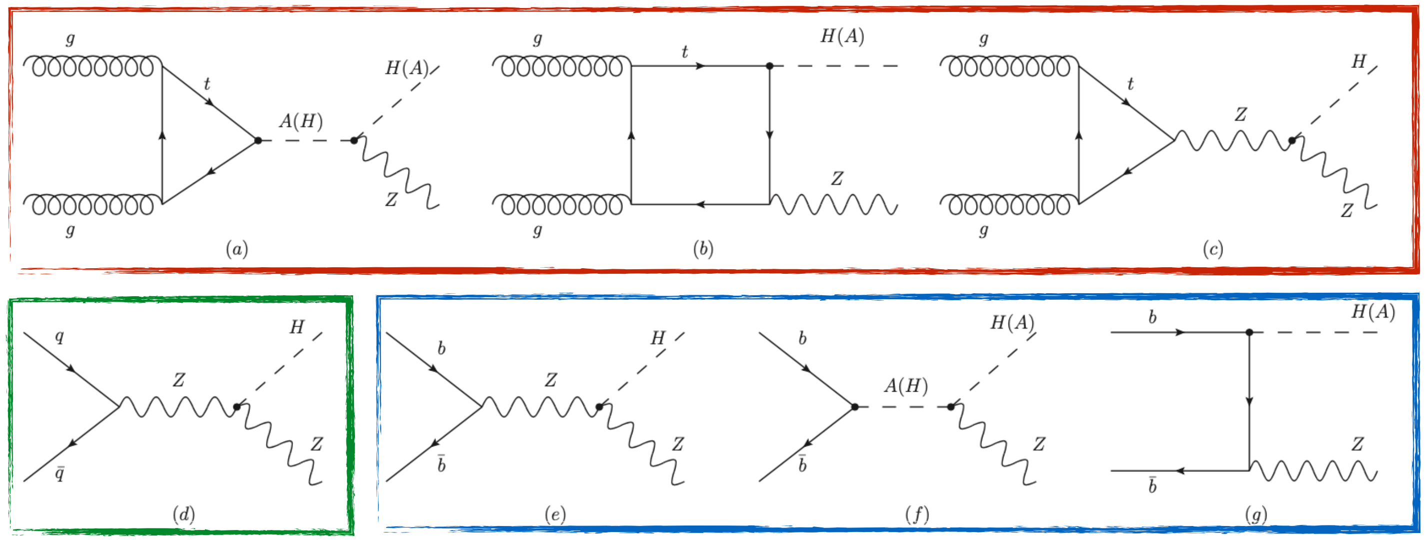
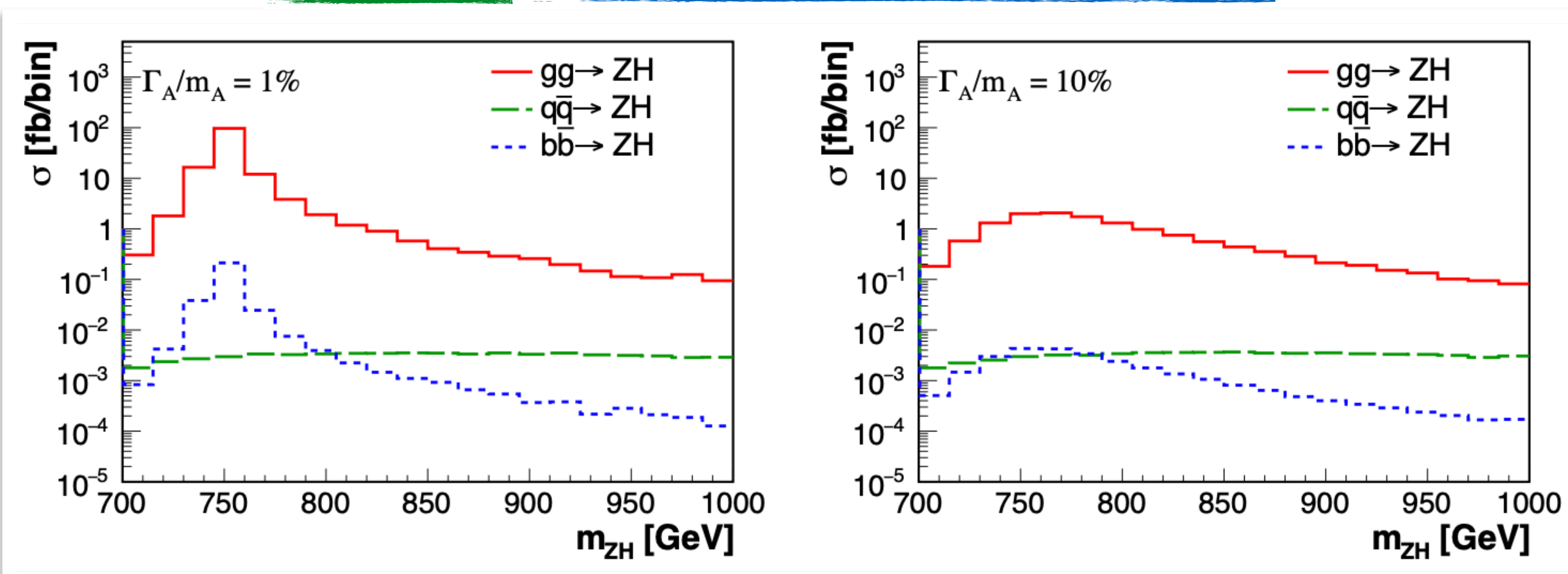
gg→H/A→tt searches can play a leading role to probe the strong first order EWPT regime

They will be specially important in the type-2 2HDM, as it presents typically heavy scalar masses

Top Pair Resonant Searches via pp→ZH/A





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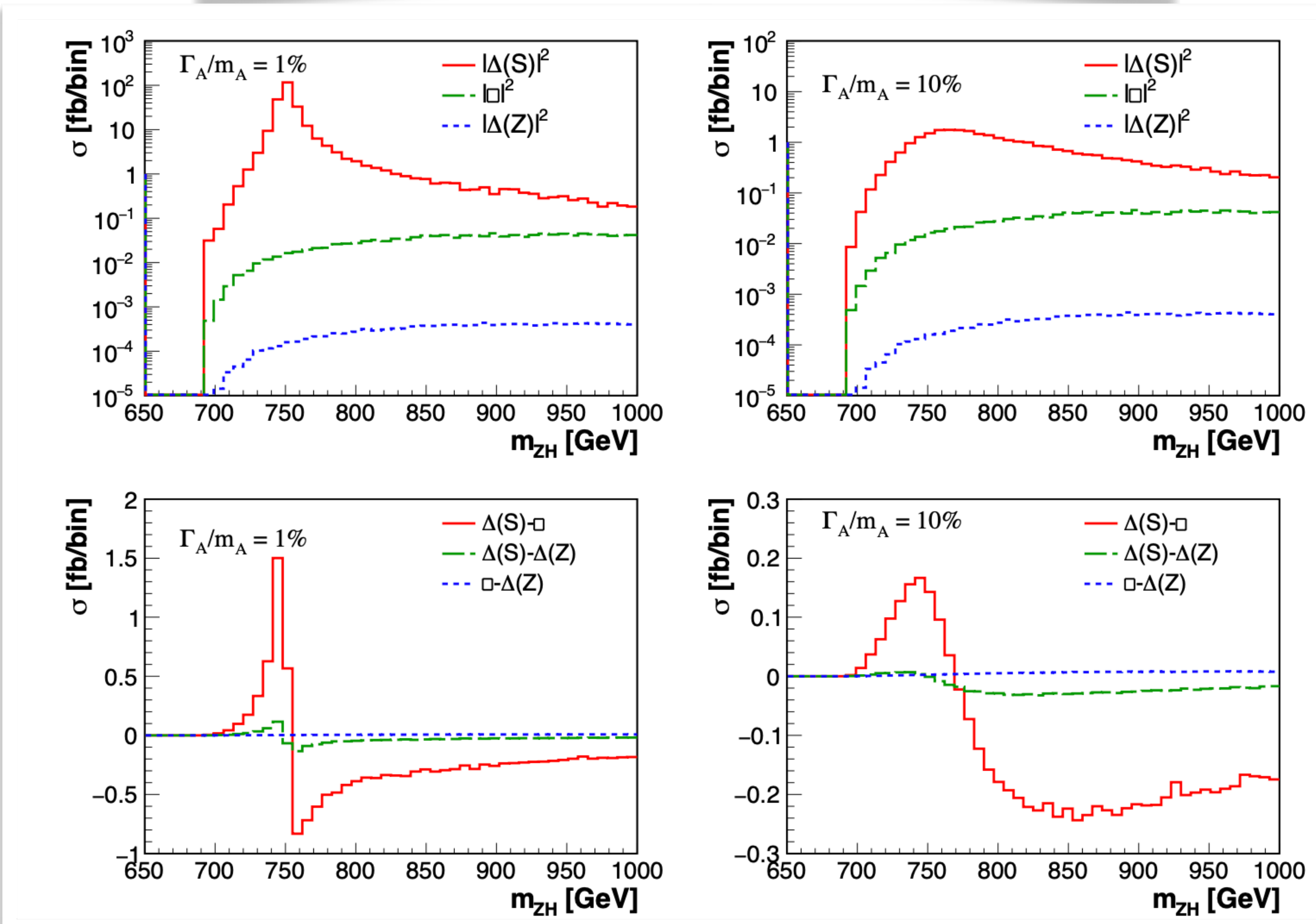
Type-1 2HDM with $c_{\beta-\alpha} \approx 0.3,\ m_H = 600$ GeV, $m_A = 750$ GeV, and $t_\beta = 1$

Gluon fusion gg→ZH/A



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

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