Probing CP-violation and Thermal History of our Universe with Higgs Physics

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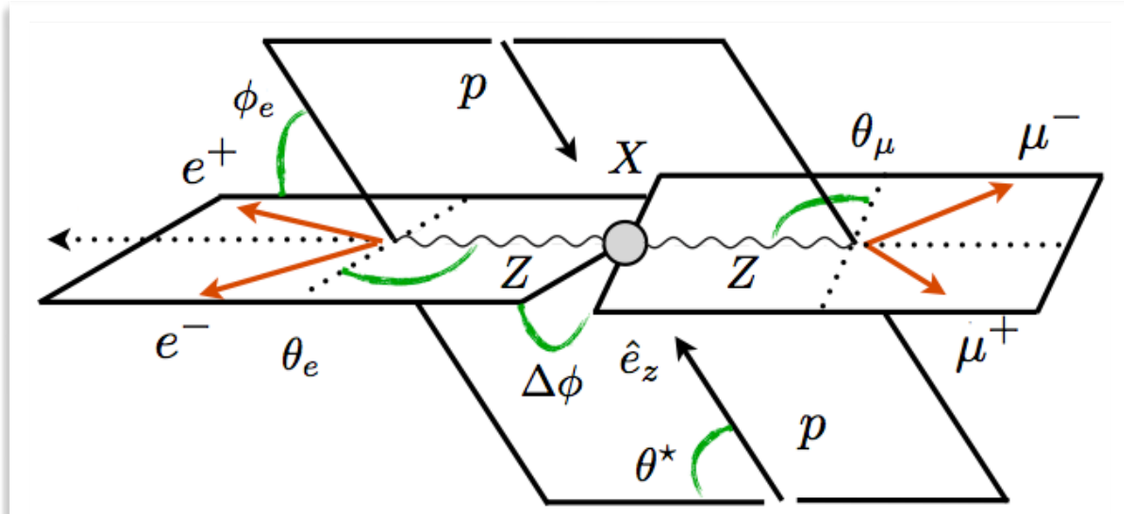
CP-violation

- At LHC CPV HVV interaction is already extensively tested (clean target H→4leptons)

4l: Gritsan, Melnikov, Schulze, et al '12

WBF: Englert, **DG**, Mawatari, Plehn '12

$$\mathcal{L}_0 = g_1^{(0)}\, HV_\mu V^\mu - \frac{g_2^{(0)}}{4}\, H\, V_{\mu\nu} V^{\mu\nu} - \frac{g_3^{(0)}}{4}\, A\, V_{\mu\nu}\tilde{V}^{\mu\nu}$$



- While CP-odd HVV is loop suppressed, CP-odd Hff can manifest at tree-level:
  - → Mixture possible in some models, e.g., 2HDM
  - → Not excluded from Higgs measurements
  - → Top quark is an obvious candidate

$$\mathcal{L} \supset -\frac{m_f}{v} K h \bar{f} (\cos\alpha + i\gamma_5 \sin\alpha) f$$

ttH: Buckley, **DG** (PRL '15)

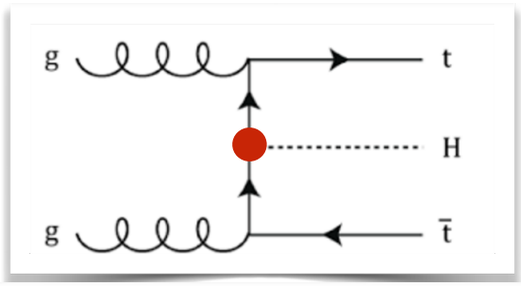
GF: Dolan, Harris, Jankowiak, Spannowsky 14'

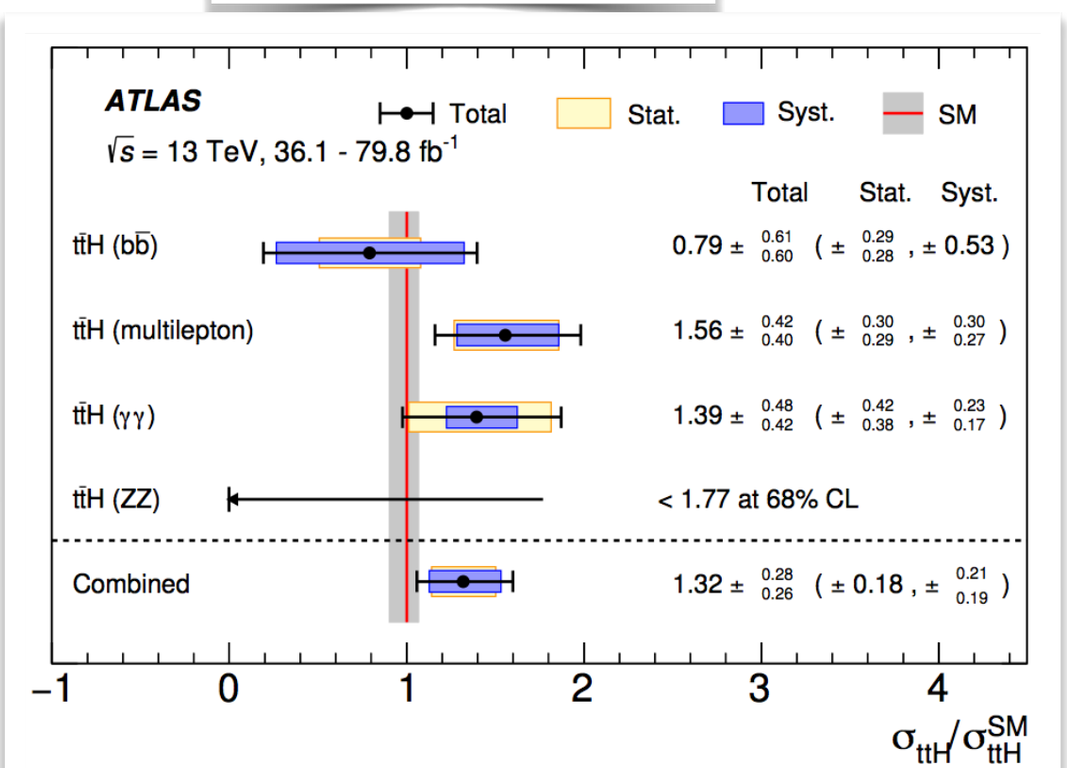
taus: Harnik, Martin, Okui, Primulando, Yu 13'

See also Ellis, Hwang, Sakurai, Takeuchi '13; Boudjemaa, Godbole, Guadagnoli,Mohan '15

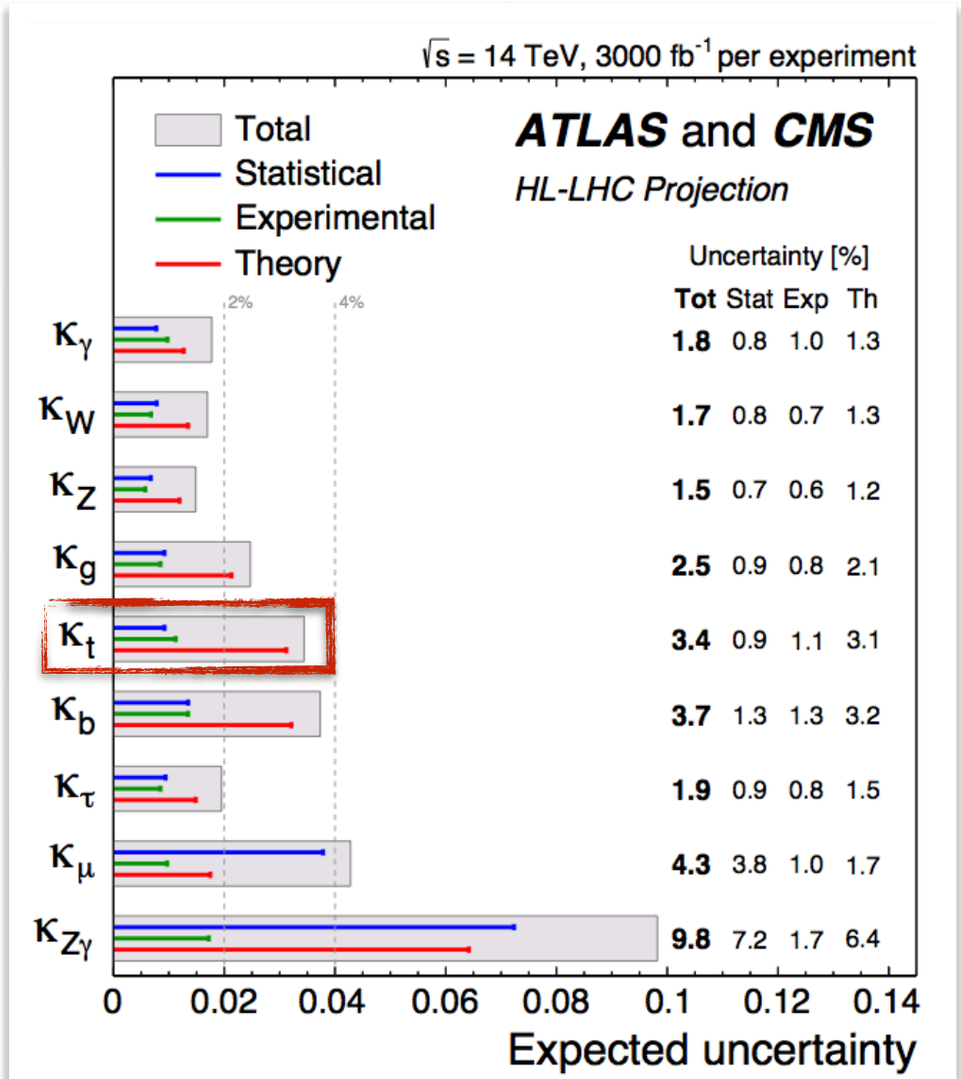
Direct CP measurement of Higgs-top coupling

- ttH channel observation (2018):





- Expected HL-LHC precisions:



- Opportunity: direct measure Higgs-top CP structure at the LHC

$$\mathcal{L} \supseteq -\frac{m_t}{v} K \bar{t} \left(\cos\alpha + i\gamma_5 \sin\alpha\right) t \; H$$

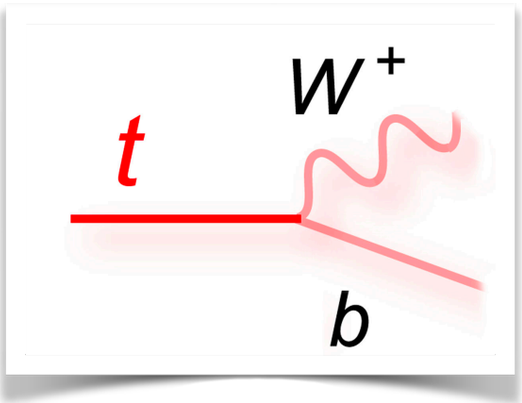
Top Quark is Unique

- Decays before it hadronizes or its spin flips

$$\tau_{top} \approx 5 \times 10^{-25} s$$

$$\tau_{had} \approx 2 \times 10^{-24} s$$

$$\tau_{flip} \approx 10^{-21} s$$



- Top polarization directly observable via angular distributions of its decay products

$$\frac{1}{\Gamma_f}\frac{d\Gamma_f}{d\cos\theta_f} = \frac{1}{2}(1 + \omega_f \cos\theta_f)$$

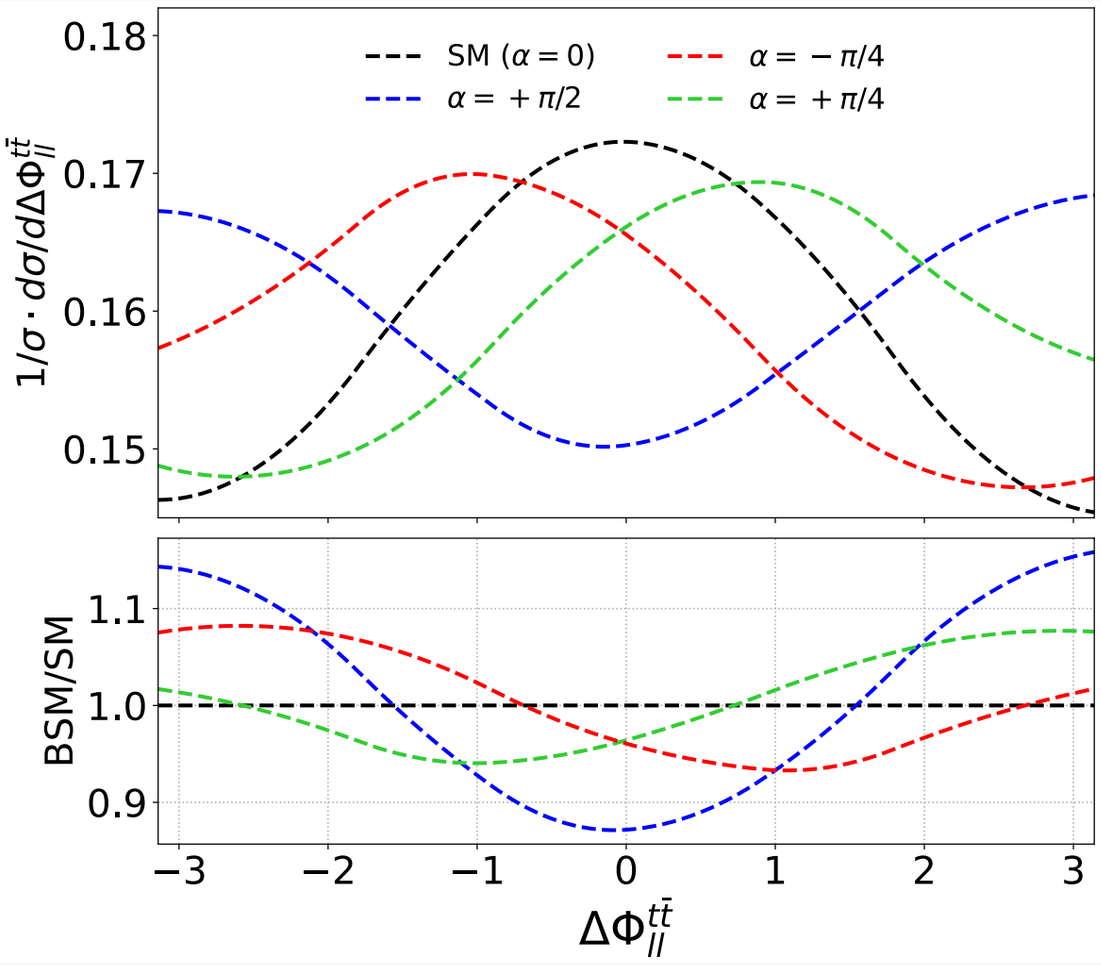
	$l^+, \bar{d}$	b	$\bar{\nu}, u$
ω_f	1	-0.4	-0.3

Spin analyzing power: maximum for charged leptons

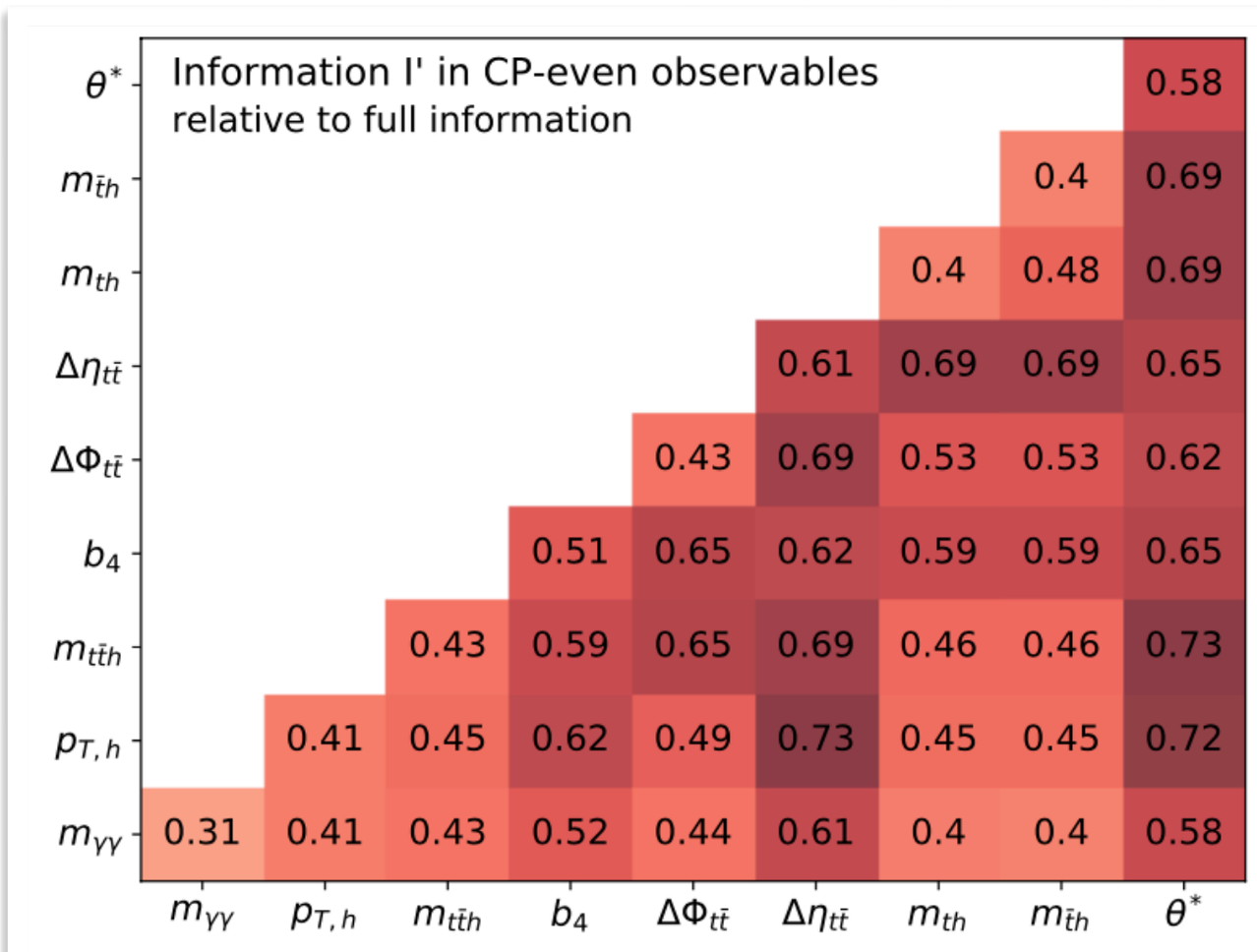
CP sensitive observables

- CPV observables best defined at the top pair rest frame:

$$d\sigma(gg \to t(n_t)\bar{t}(n_{\bar{t}})H) = \sin^2\alpha f_1(p_i.p_j) + \cos^2\alpha f_2(p_i.p_j) + \sin\alpha\cos\alpha \sum_l g(p_i.p_j)\epsilon_l$$



DG, Kong, Kim '18 & '21

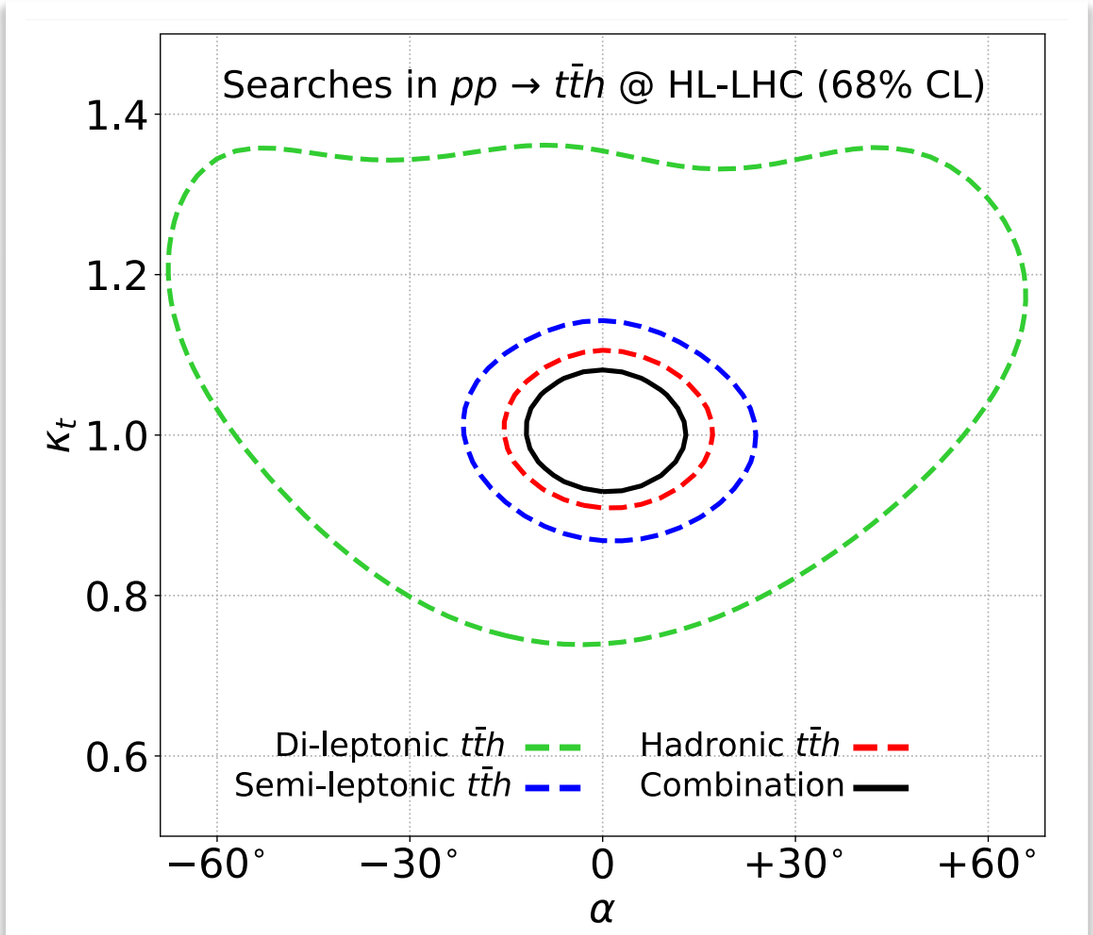


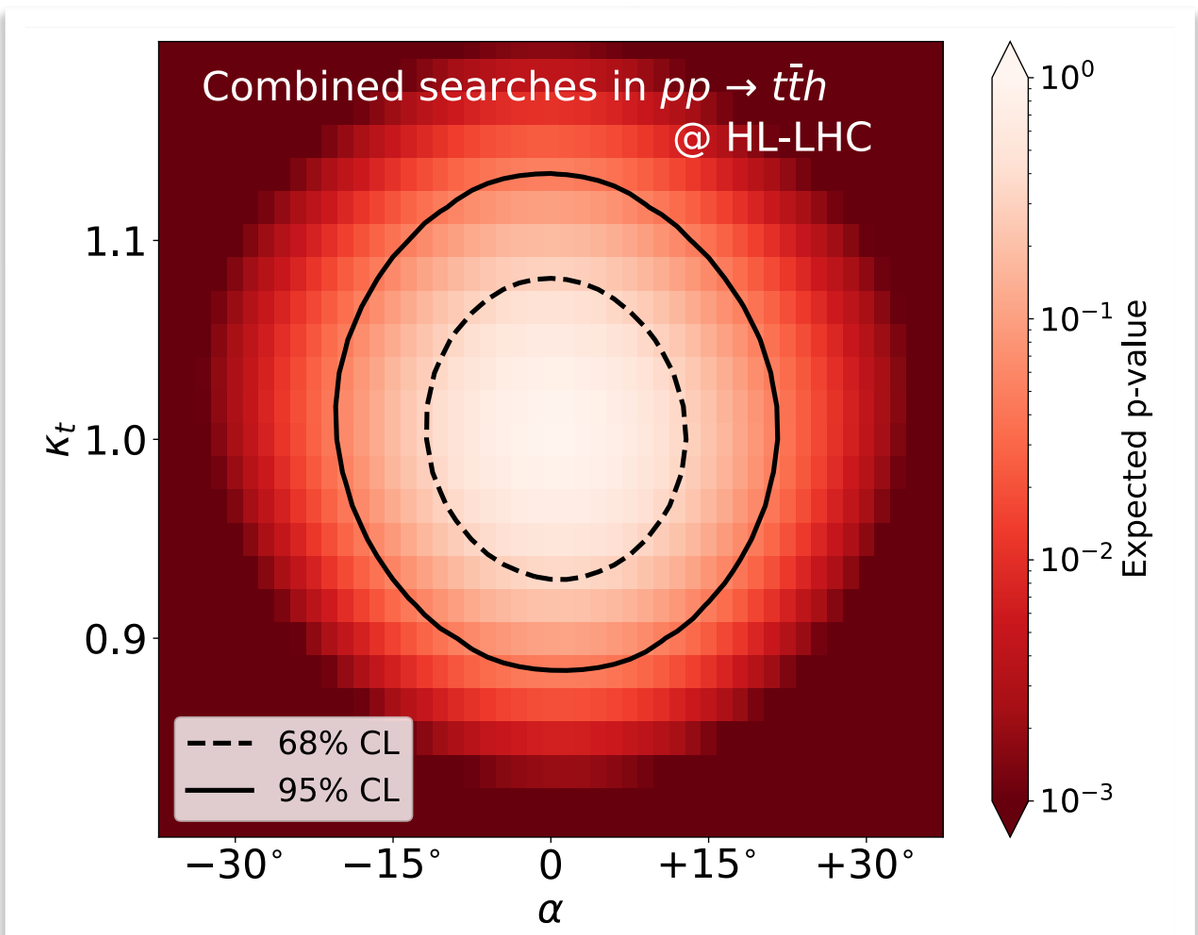
Barman, DG, Kling '21

Information increases with successive addition of observables ➡ **Multivariate analysis problem**

HL-LHC Projections

Recent $h \to \gamma\gamma$ study:



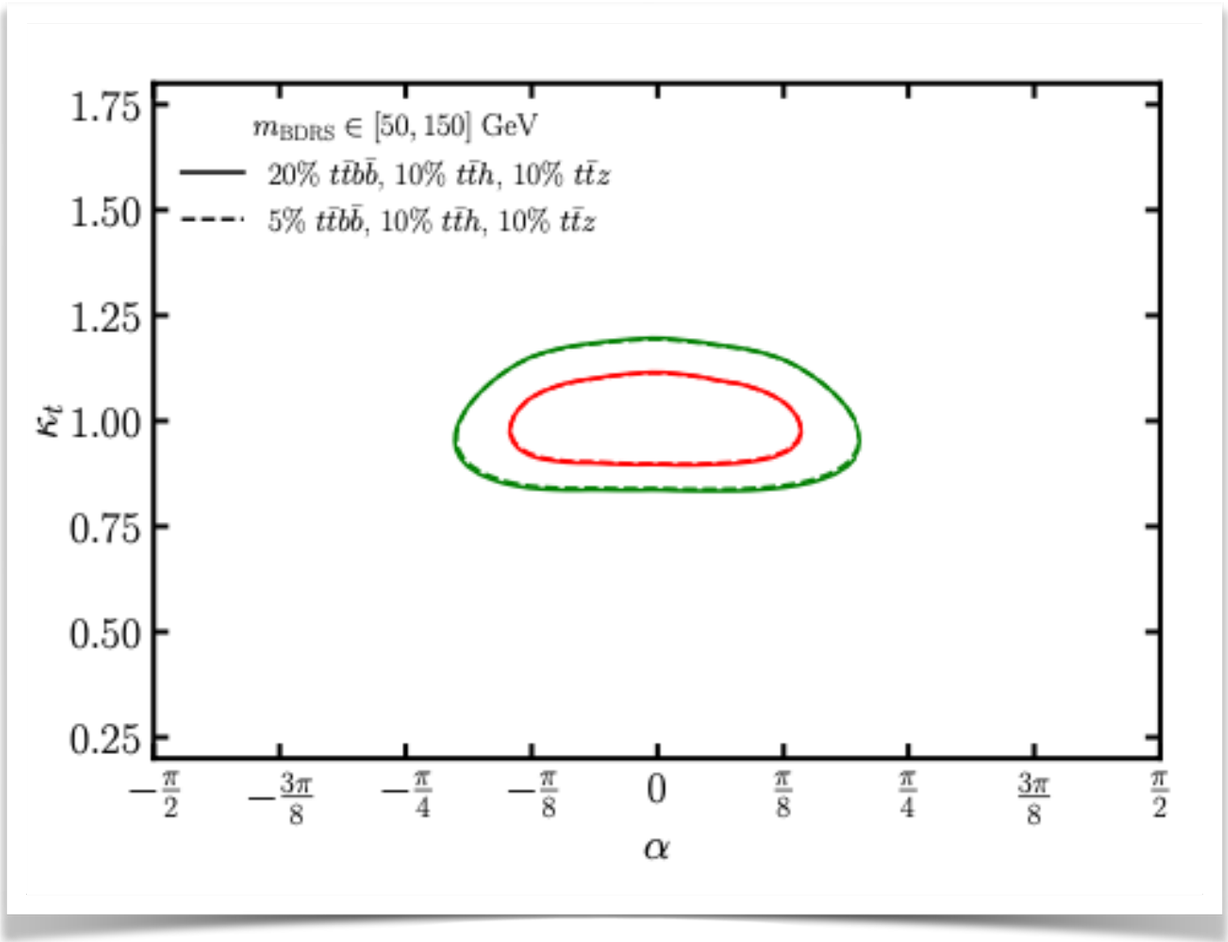


Barman, DG, Kling '21

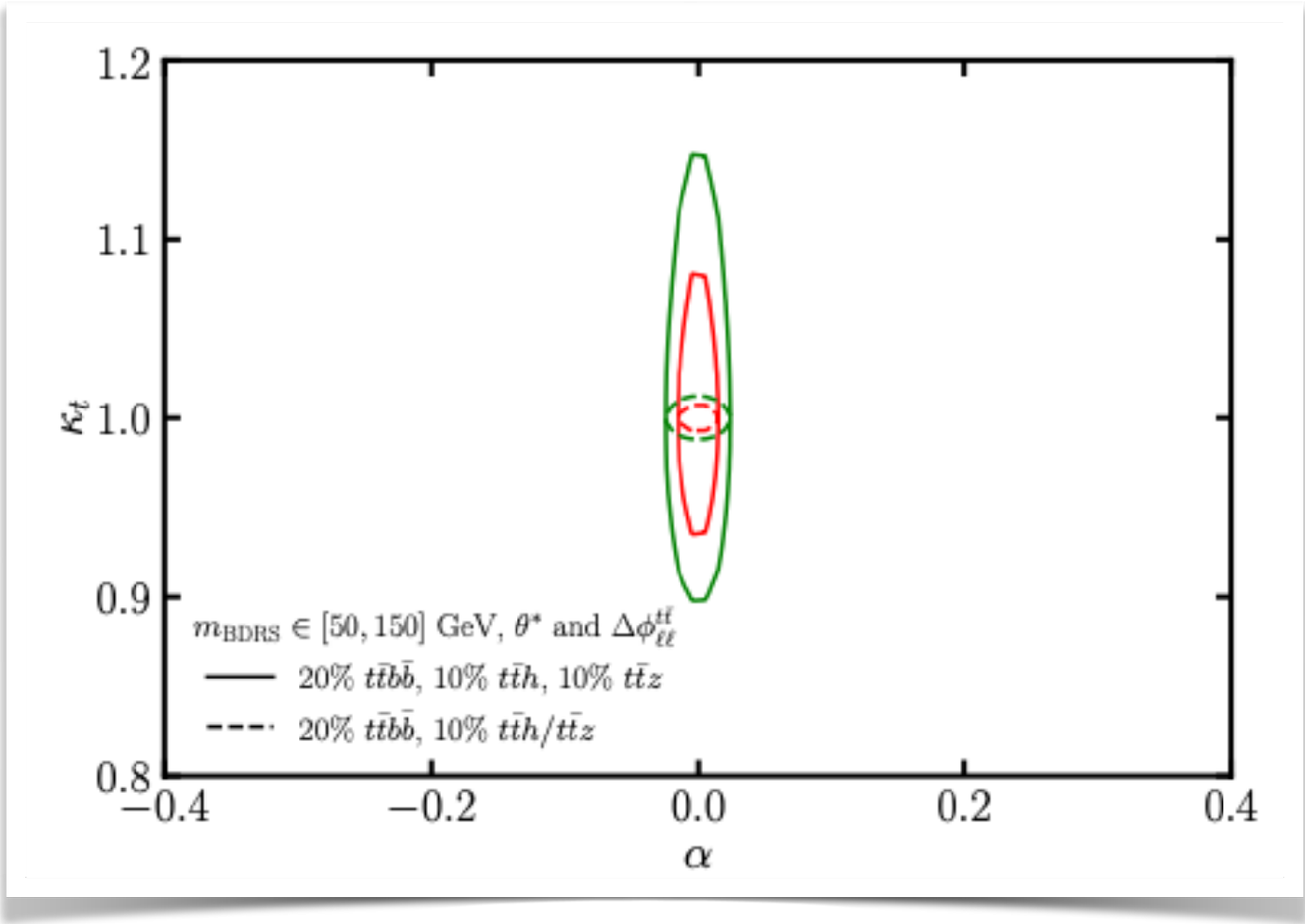
Higgs-top CP phase could be probed up to $\alpha \lesssim 13^\circ$

HL-LHC & FCC-hh Projections

- Recent $h \to b\bar{b}$ study:



HL-LHC: $\alpha \lesssim 22^\circ$



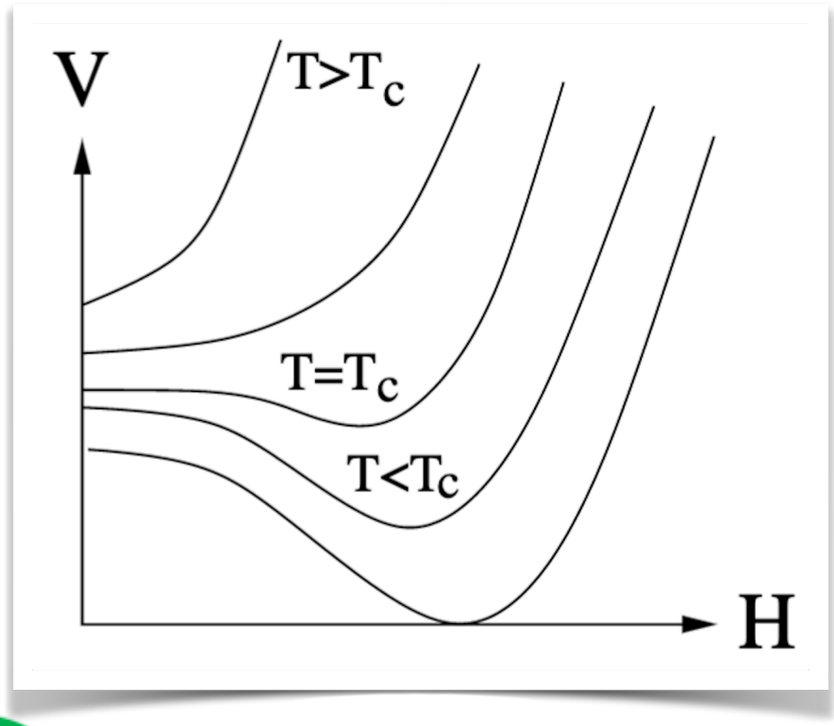
FCC-hh: $\alpha \lesssim 1^\circ$

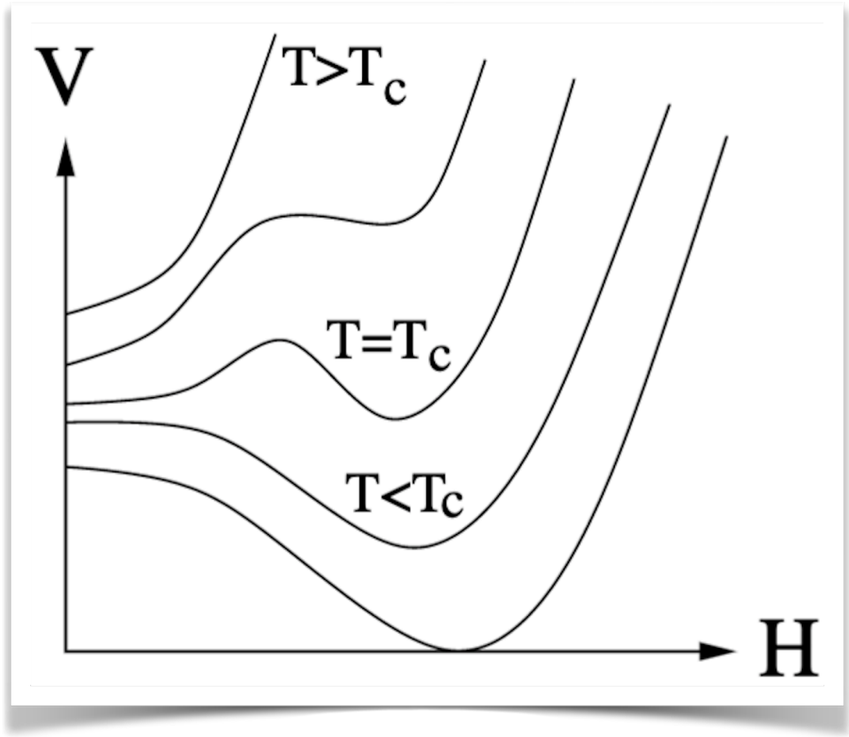
DG, Kong, Kim, Wu '21

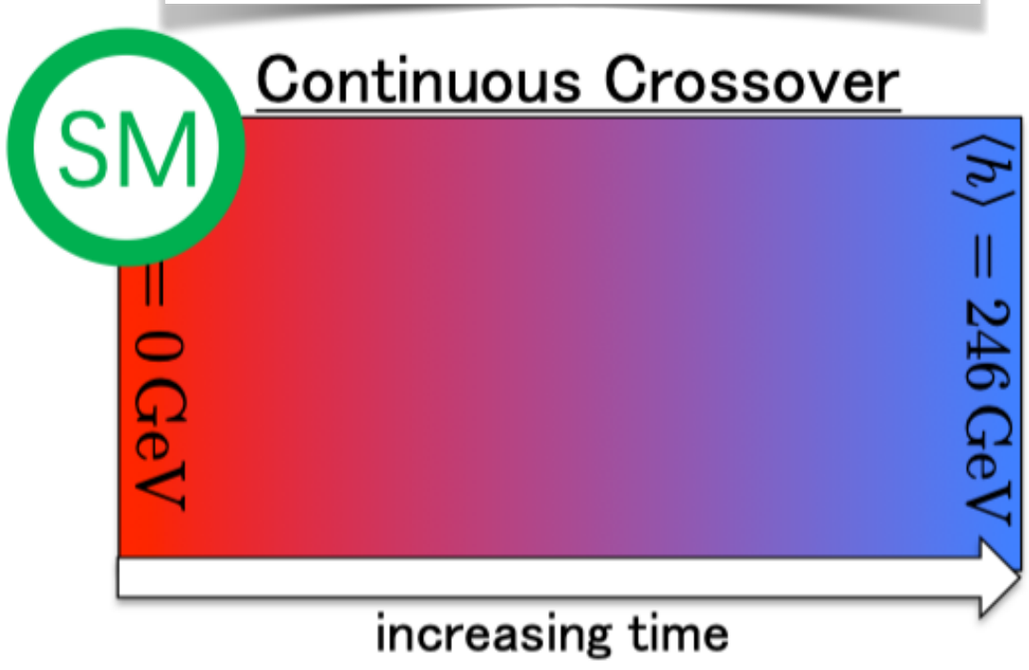
Mangano, Plehn, Reimitz, Schell, Shao '15

Thermal history of our Universe

- What is the order of the Electroweak Phase Transition?







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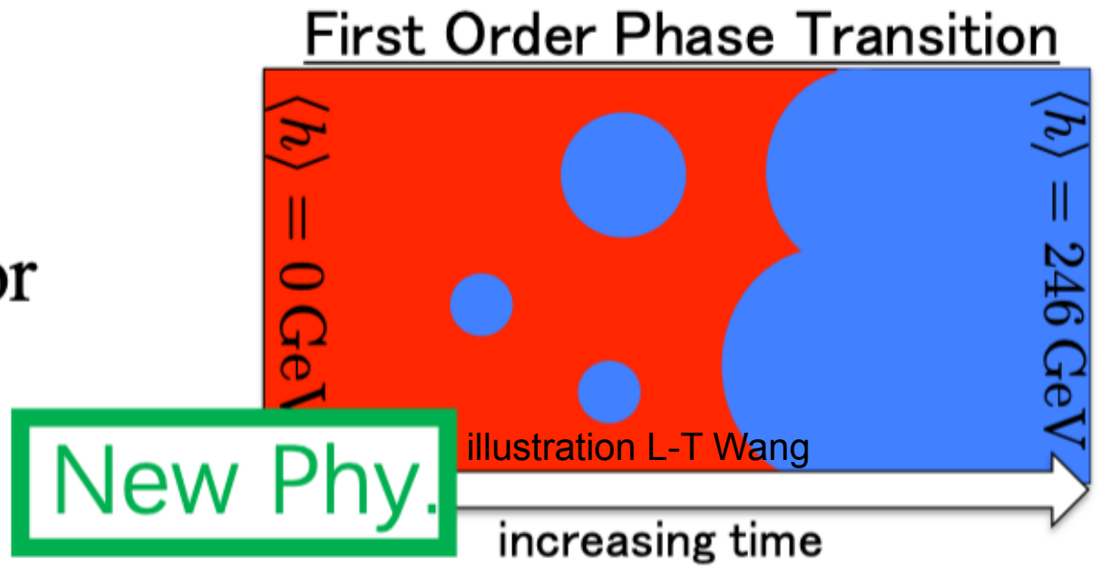
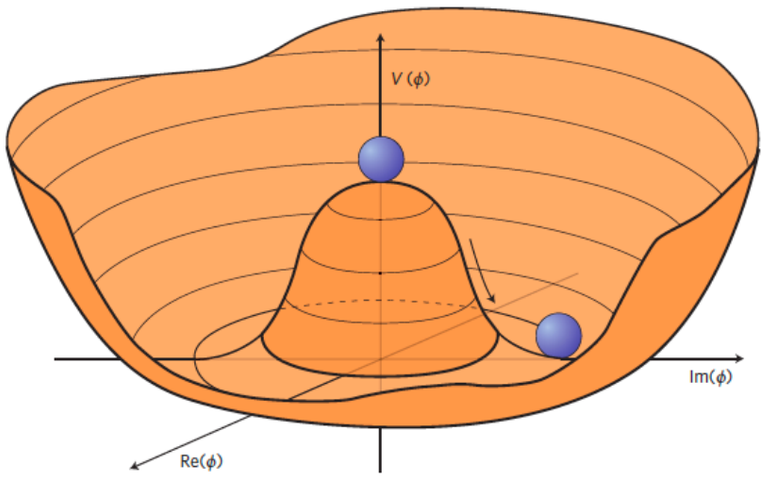
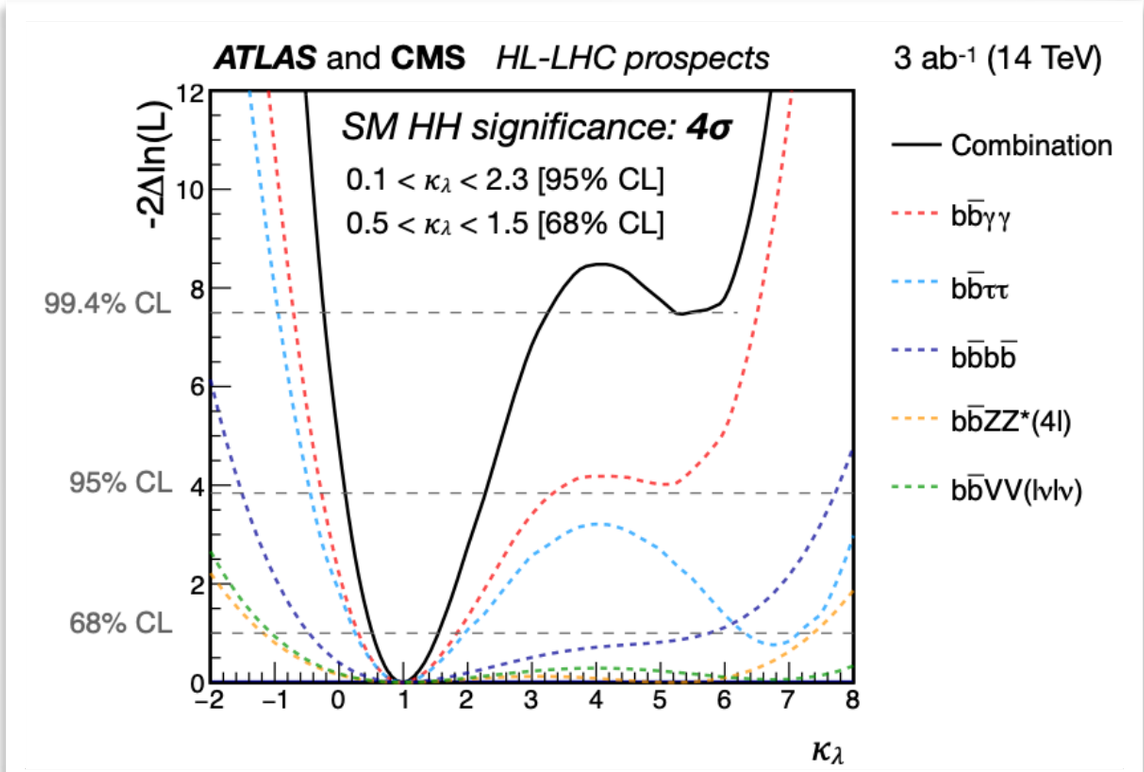
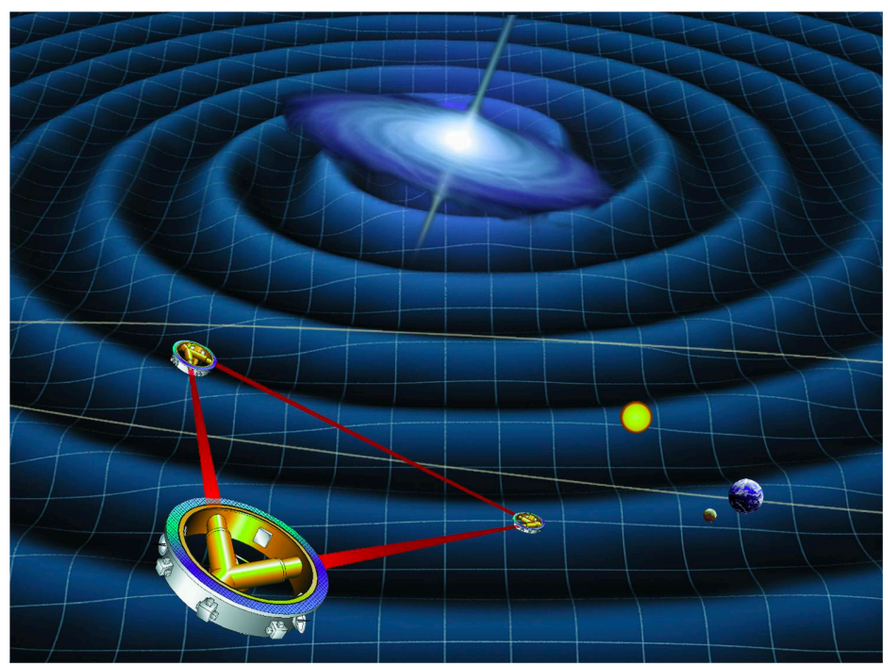


Higgs Potential: Collider & GW Complementarity



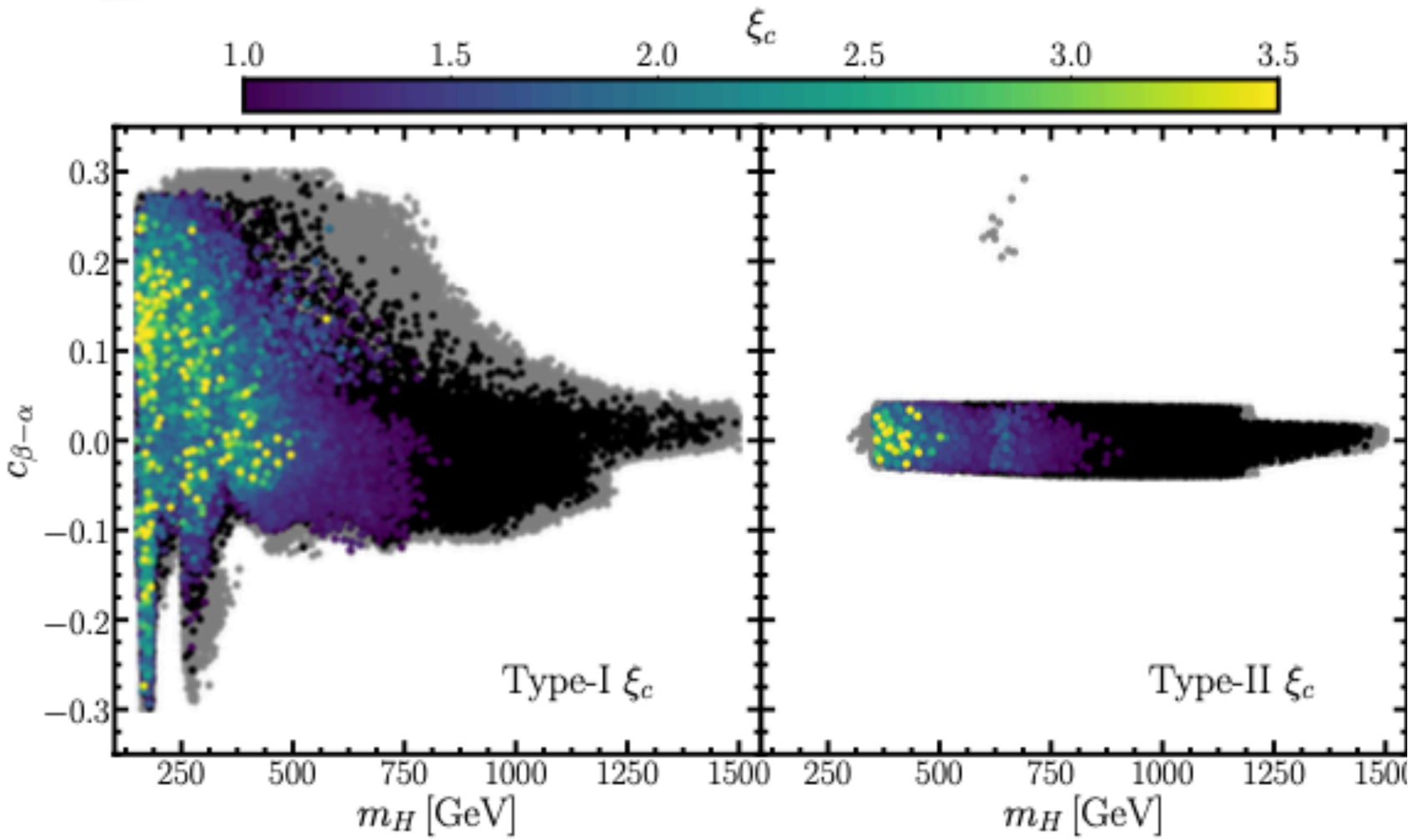




For $T_* \sim 100$ GeV, GW frequency (redshifted to today) ~ mHz

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

Collider & GW complementarity



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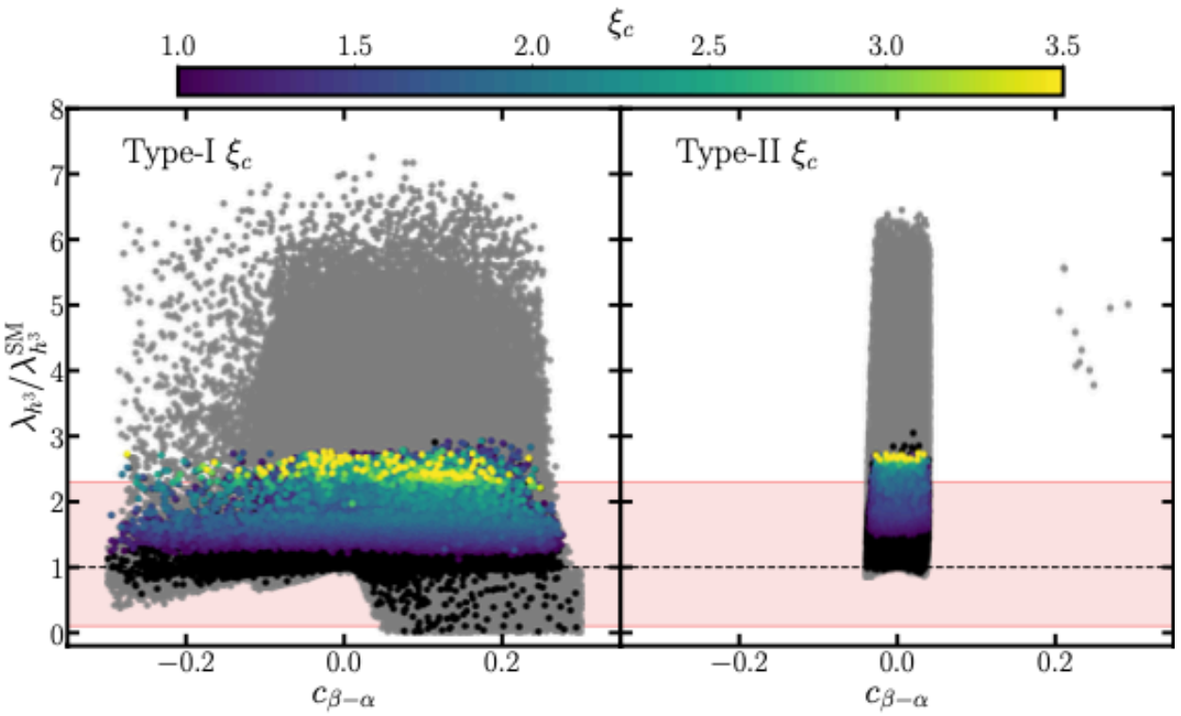
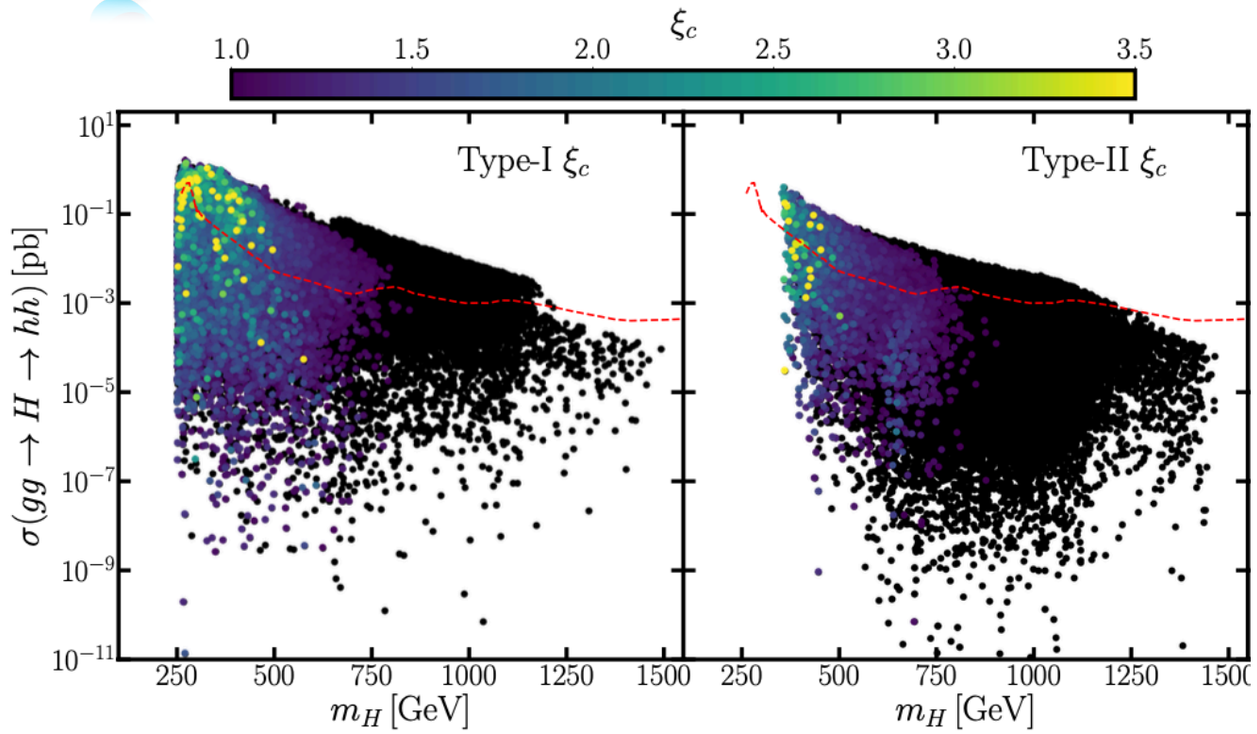
- Analytical behavior of $\Delta\mathcal{F}_0/|\mathcal{F}_0|$ favors lower mass scalars
- → Typically: the lighter the resonance, the higher the order parameter
- → $\xi_c > 1 \;\rightarrow\; m_H \lesssim 750$ GeV: EFT analysis is disfavored at LHC
- → Strong extra motivation for scalar searches at the LHC

Collider & GW complementarity

Non-resonant di-Higgs searches



Resonant di-Higgs searches:



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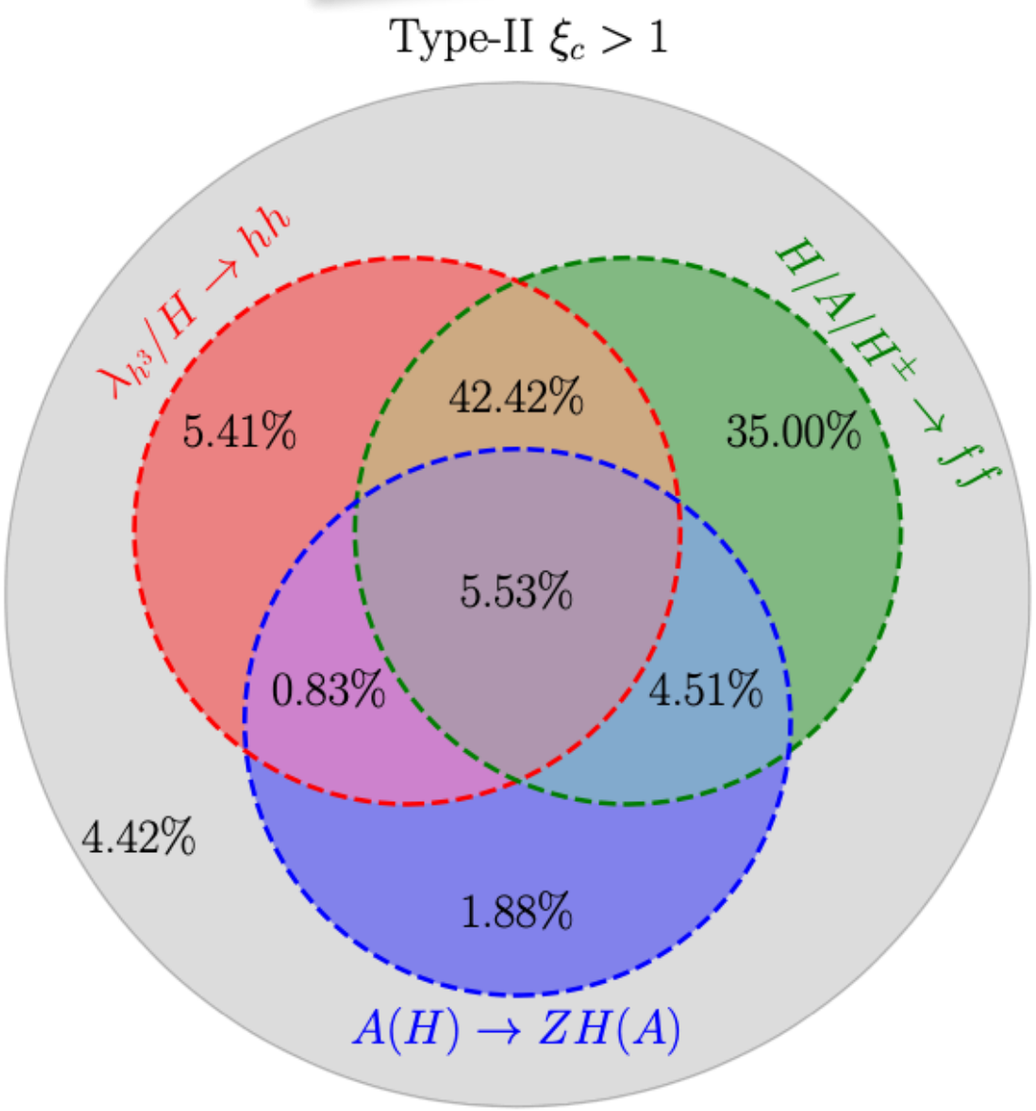
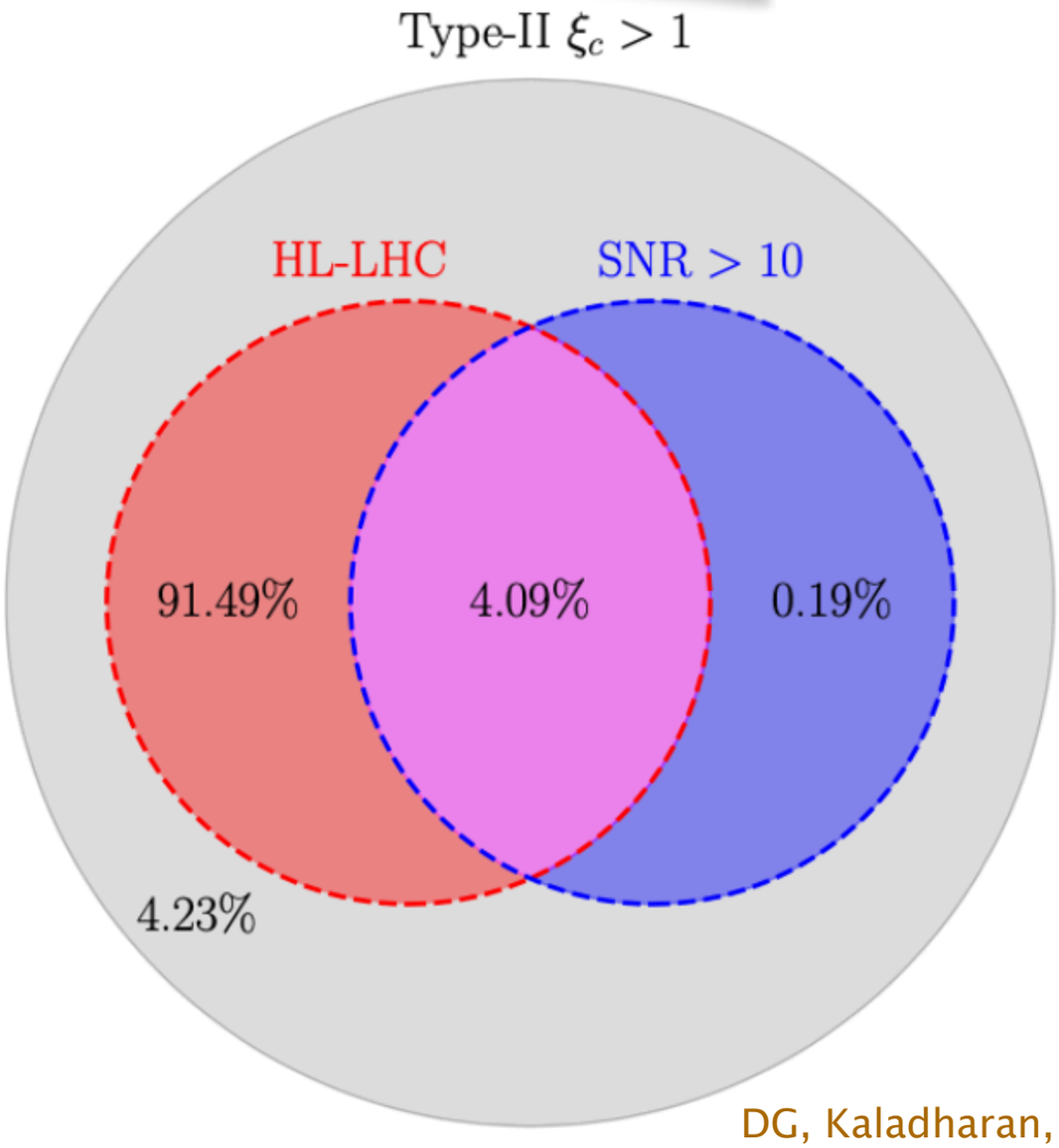
$$0.1 < \lambda_{h^3}/\lambda_{h^3}^{\rm SM} < 2.3$$

ATLAS+CMS projections

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

Collider & GW complementarity





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- Smoking gun signature for SFOEWPT at HL-LHC: (H, A, $H^\pm \to$ tt, tb) followed by di-Higgs searches
- Widely discussed channel A(H) → ZH(A) is still relevant, whereas, to smaller fraction of parameter space
- 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

The search for new sources of CPV and understanding the thermal history of EWSB are cornerstones for the LHC program (and forthcoming experiments, such as LISA, FCC,…)

- Higgs-top coupling can naturally display larger CP-phases than HVV
  - → Direct probe: ttH channel
  - → Multivariate analysis problem. t-quark polarization uplifts analysis from raw rate to polarization study

See talk by Rahool Barman for more details

- Thermal history of EWSB is a crucial challenge for particle physics and cosmology
  - → Well-motivated 2HDM leads to rich phase transition, favoring SFOEWPT below TeV scale.
  - → Smoking gun signature for SFOEWPT at HL-LHC: ($H, A, H^{\pm} \to tt, tb$)

See talk by Ajay Kaladharan for more details

Work in collaboration with

KC Kong (Kansas)

Felix Kling (DESY)

Kim Jeoghan (CBNU-Korea)

Ajay Kaladharan (OSU)

Rahool K. Barman (OSU)

Yongcheng Wu (OSU -> Faculty Nanjing)

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