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IGGS 2024
Uppsala, Sweden
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Composite Higgs

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HIGGS 2024

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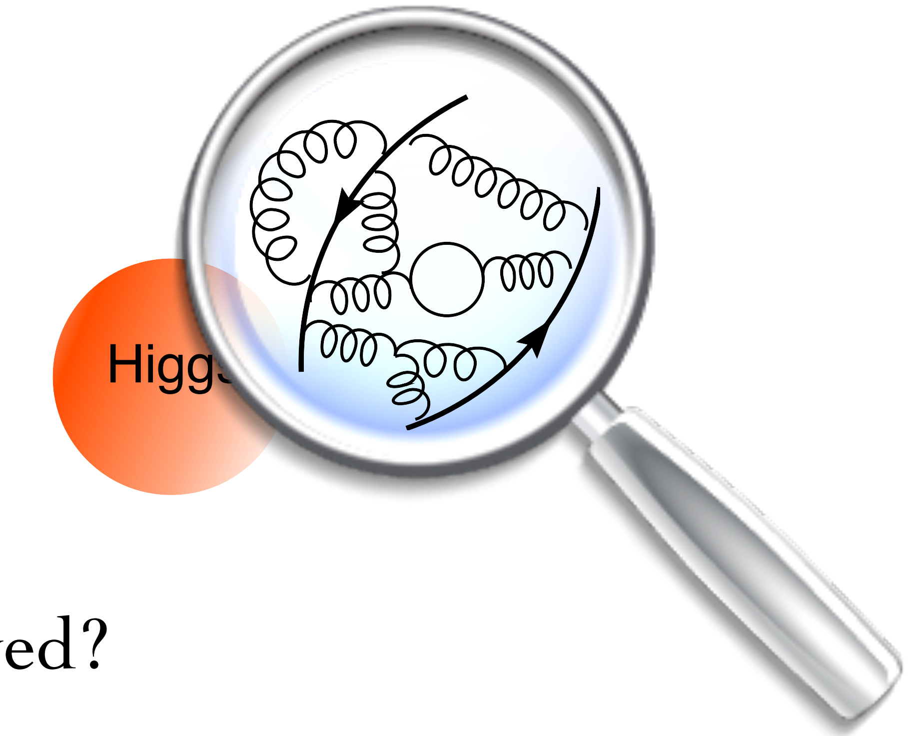
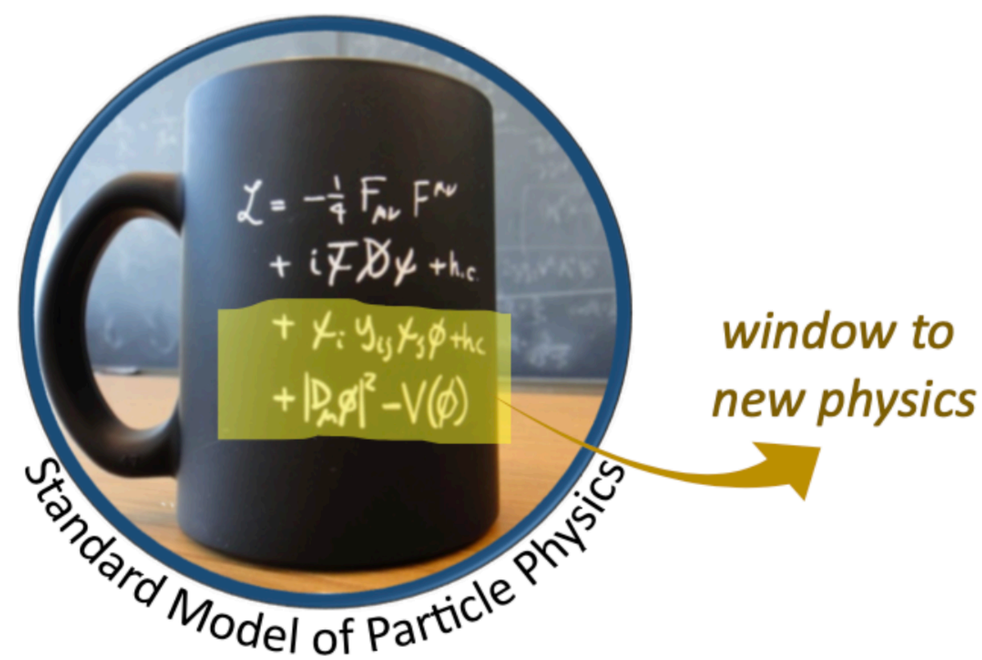
Open fundamental questions

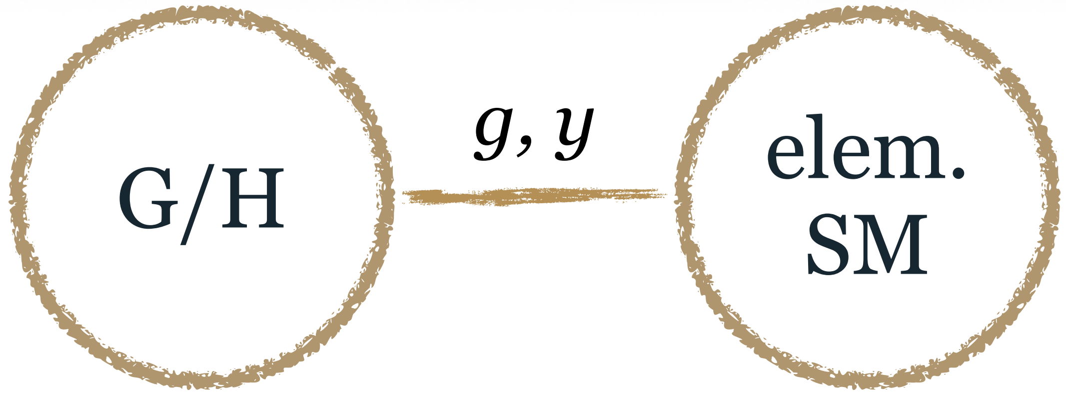
- Is it the SM Higgs?
- Is it small mass “natural"?
- Is it an elementary or composite particle?
- Is it unique?
- Is it the first supersymmetric particle ever observed?
- Is it the only responsible for the masses of all the elementary particles?
- Is it a portal to a hidden world?



The SM is a “partial" description of the Nature, it could be part of a more general theory which will manifest itself at energies higher than the ones explored till now



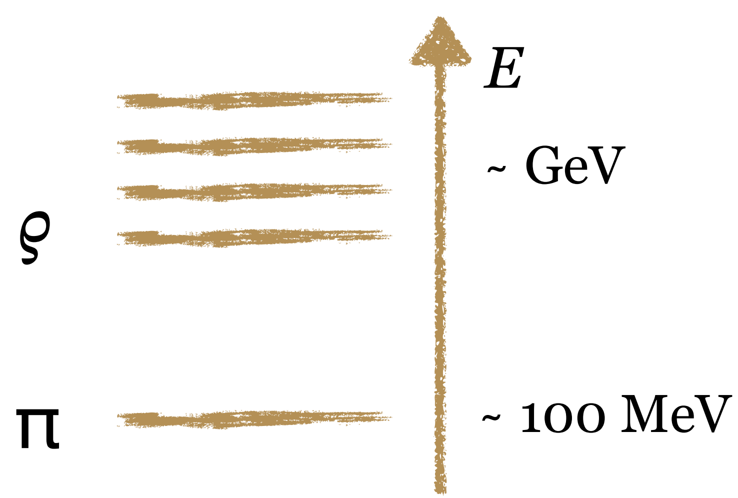
Higgs as a Composite pseudo Nambu Goldstone Boson



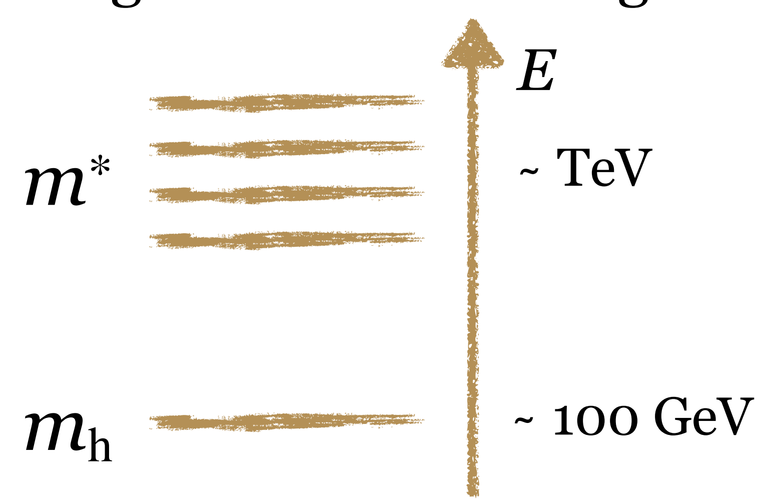
The basic idea:
Higgs as Goldstone boson of G/H in a strong sector

(Georgi, Kaplan '80s)

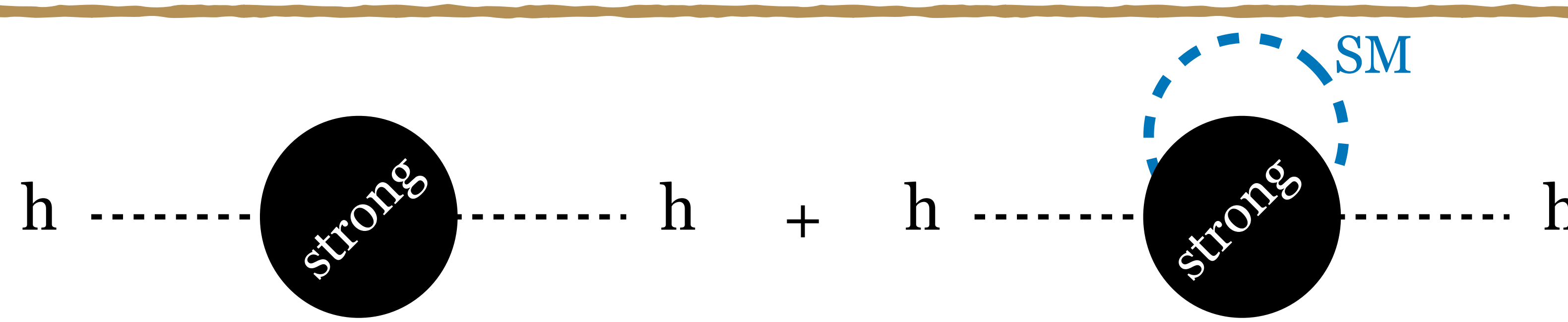
Inspired by QCD where one observes that the (pseudo) scalars are the lightest states



the Higgs could be a kind of pion arising from a new strong sector



Higgs mass =



because it's a Goldstone

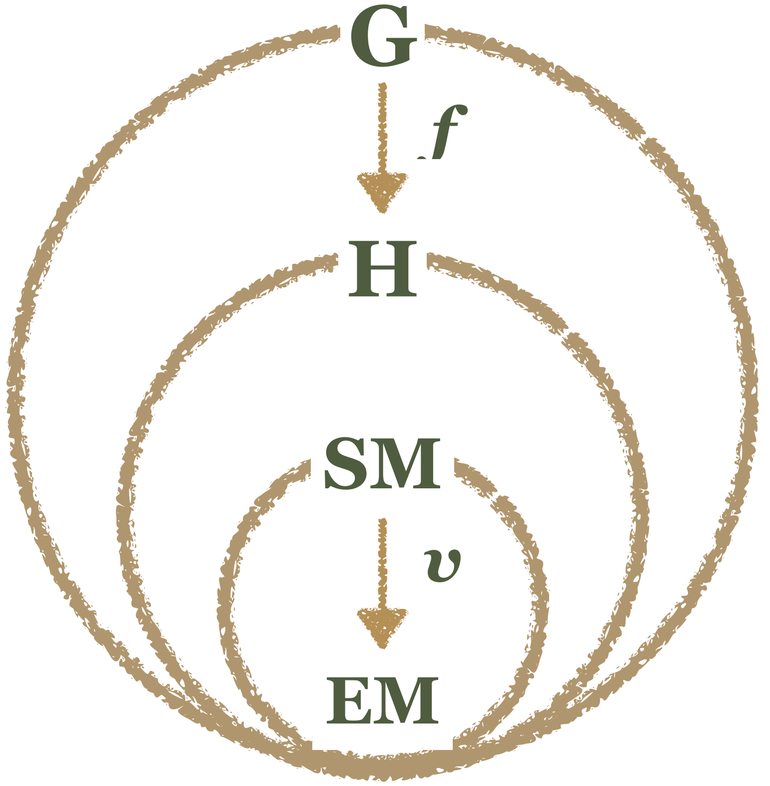
Mass protected by the global QCD symmetry

Basic rules for explicit composite pNGB models

☑ Need to choose the correct G → H (spontaneous) breaking at f (~ TeV) to have the required NGBs (≥ 4)

☑ Need to break H (explicitly, so pNGBs) via g_0 (gauge) and Y (Yukawa) couplings to generate the one-loop effective potential for EWSB

☑ Need to include new composite resonances from the confining strong dynamics



Composite Higgs Models

Elementary sector		**Strong sector**
$A_\mu, \psi \in SU(2) \times U(1)$	$\longleftrightarrow$ $\mathscr{L}_{\text{mix}} = g_0 A_\mu J^\mu_\rho + \Delta \bar{\psi} \Psi$	$\rho_\mu, \Psi \in G_{\text{strong}}$

Composite Higgs Models

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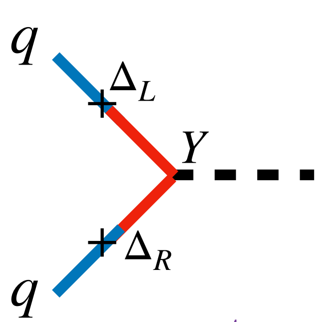
partial compositeness

Linear elementary-composite fermion mixings

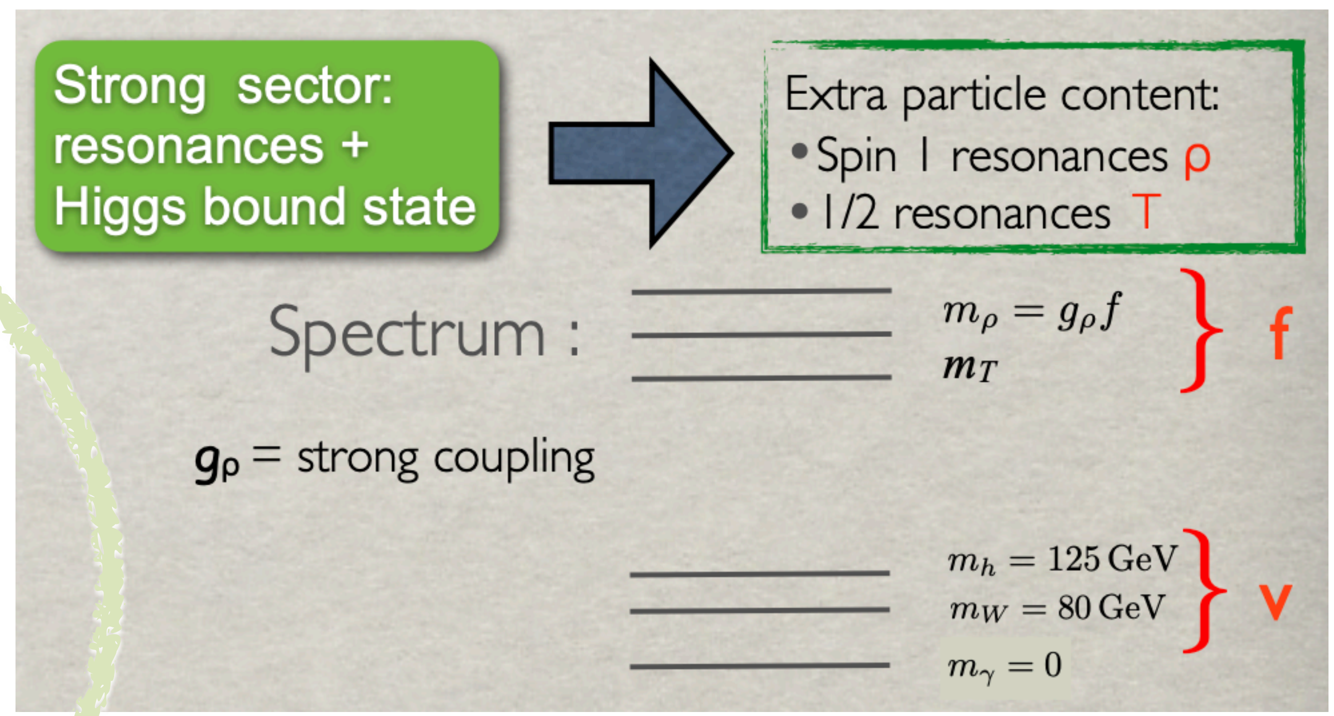
→ for the 3rd generation quarks

$$\Delta_R \bar{q}_R \mathscr{O}_L + \Delta_L \bar{q}_L \mathscr{O}_R + Y \bar{\mathscr{O}}_L H \mathscr{O}_L$$



top Yukawa couplings

$$m_t \sim \frac{v}{\sqrt{2}} \frac{\Delta_{t_L}}{m_T} \frac{\Delta_{t_R}}{m_{\tilde{T}}} \frac{Y_T}{f}$$



SM hierarchies are generated by the mixings:
light quarks mostly elementary, top mostly composite

Extended Composite Higgs Models

Models with a larger Higgs structure with respect to the SM have been largely discussed
Supersymmetry requires two Higgs doublets with specific Yukawa and potential terms
2HDMs offer a rich phenomenology in EW and flavour physics

Look for a pNGB realisation of extended Higgs scenarios

The structure of the Higgs sector is determined by the coset G/H

G	H	PGB	
SO(5)	SO(4)	4=(2,2)	→ Minimal = One dobulet
SO(6)	SO(5)	5=(2,2)+(1,1)	→ Doublet + Singlet
SO(6)	SO(4)xSO(2)	8=(2,2)+(2,2)	→ Two Doublets
SO(7)	SO(6)	6=(2,2)+(1,1)+(1,1)	
	G_2	7=(1,3)+(2,2)	
...	...	...	

New players in the game

Composite 2-Higgs Doublet Model (C2HDM)

J.Mrazek et al. '11; De Curtis,Moretti,Yagyu,Yildirim '16, De Curtis,Delle Rose,Moretti,Yagyu '18

- ☑ EWSB is driven by 2 Higgs doublets as pNGBs of SO(6)/SO(4)xSO(2). The unbroken group contains the custodial SO(4)

- ☑ Alignment conditions on the strong Yukawa couplings must be imposed to suppress FCNCs (composite version of an Aligned 2HDM Pich,Tuzón,'09)

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- The SM fields are linearly coupled to operators of the strong sector and explicitly break its symmetry
  A potential for the Higgses is radiatively generated, couplings and masses determined by the strong sector

- Fermion sector: embed the 3rd generation quarks into SO(6) reps. + linear couplings $\Delta_{L,R}$ between composite and elementary fermions (partial compositeness)

$$\begin{aligned}\mathcal{L}_{\rm mix} + \mathcal{L}_{\rm strong} &= \Delta^I_L \bar{q}^{\mathbf{6}}_L \Psi^I_R + \Delta^I_R \bar{t}^{\mathbf{6}}_R \Psi^I_L + h.c. \\ &+ \bar{\Psi}^I i \not{D} \Psi^I - \bar{\Psi}^I_L M^{IJ}_\Psi \Psi^J_R - \bar{\Psi}^I_L \left(Y^{IJ}_1 \Sigma + Y^{IJ}_2 \Sigma^2 \right) \Psi^J_R\end{aligned}$$

$$\Sigma = U_1 \Sigma_2 U_1^T$$

- Two heavy fermions' sextuplets ψ^J needed for an UV finite effective potential I,J=1,2

$$f, \quad \Delta_L^{1,2}, \quad \Delta_R^{1,2}, \quad Y_{1,2}^{IJ}, \quad M_\Psi^{IJ}, \quad I,J = 1,2$$

(partial compositeness for the top)

scale of compositeness, linear mixings, Yukawas, heavy fermion mass parameters

2-Higgs Doublets as pNGBs

Aligned 2HDM realised in a composite scenario

- Same physical Higgs states as in the elementary 2HDM: $h, H, A, H^{\pm}$ (h=SM-like Higgs)

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- CP-even states: h, H

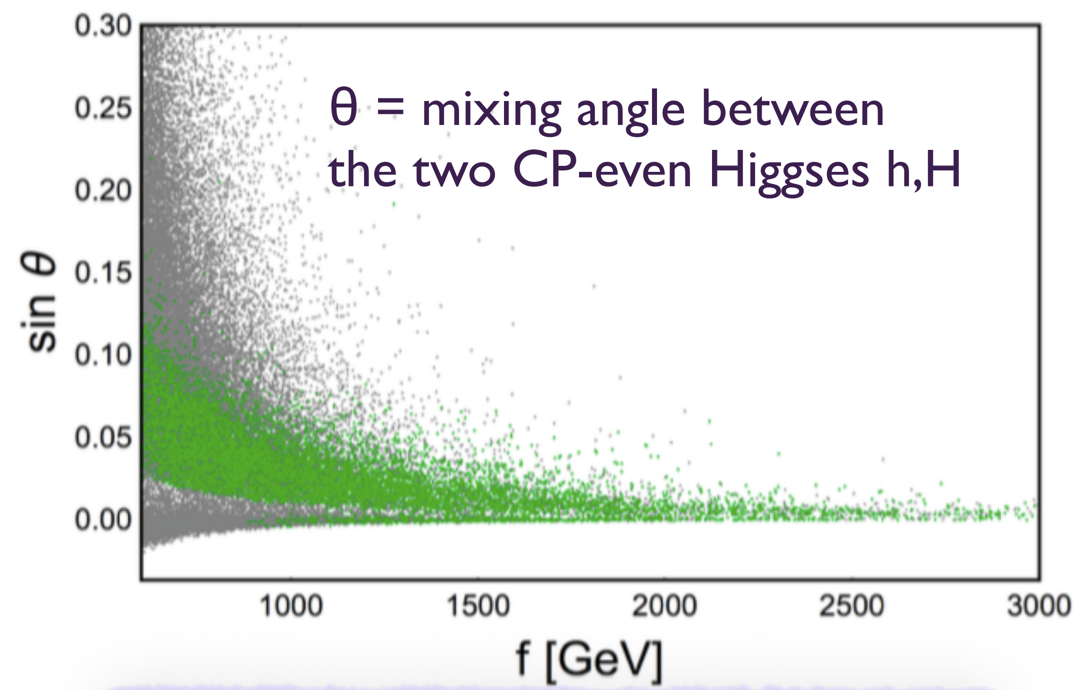
  $m_h \sim v \quad m_H \sim f + O(v) \qquad \xi = v^2/f^2$

  θ is predicted to be small: $O(\xi)$ for large f

- CP-odd states: $A, H^{\pm}$

  $m_A \sim m_{H^{\pm}} \sim f + O(v)$

$f \rightarrow \infty$ SM limit
$H, A, H^{\pm}$ decouple
$h \rightarrow h^{SM}$



green points satisfy the bounds from direct and indirect Higgs searches

tested against HiggsBounds and HiggsSignals

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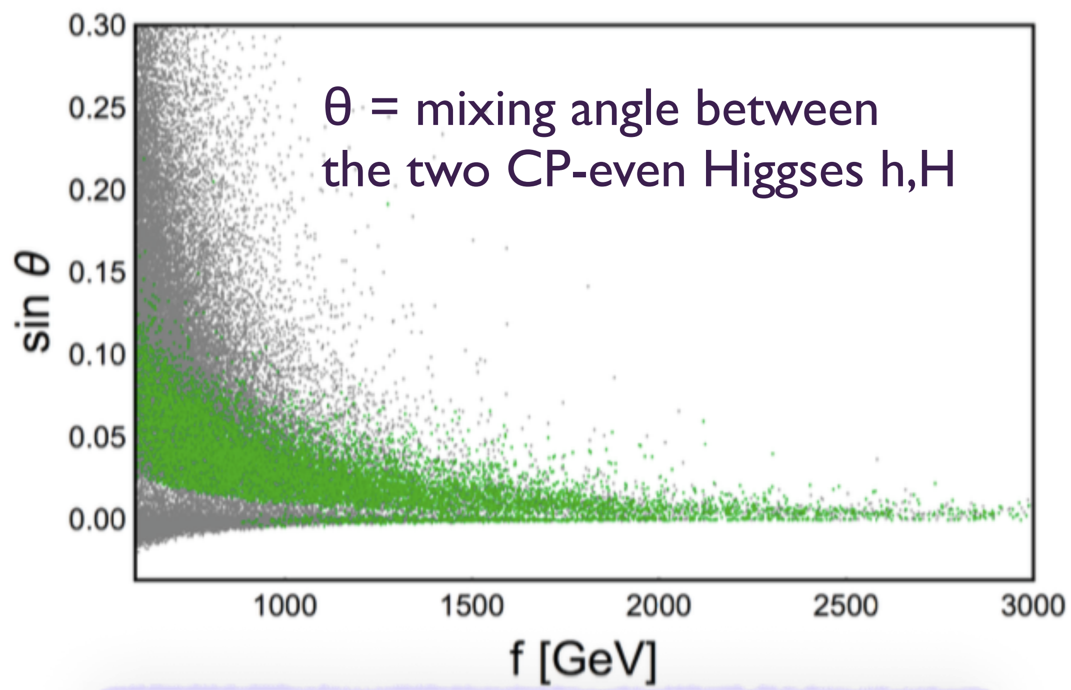

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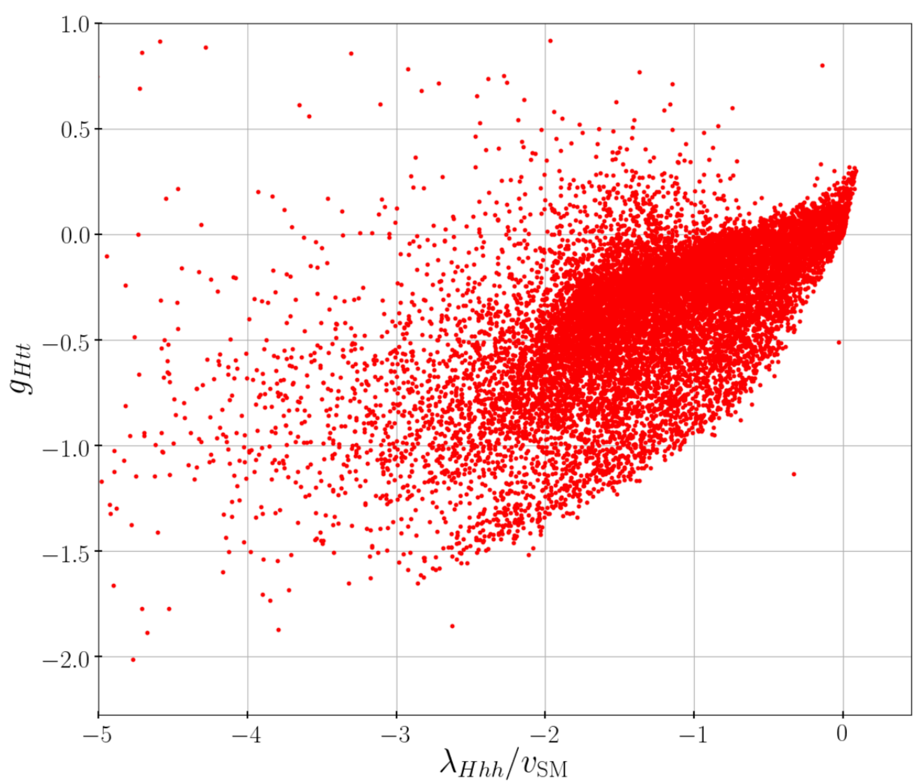


in the C2HDM the Higgs sector parameters are correlated and carry the imprint of compositeness

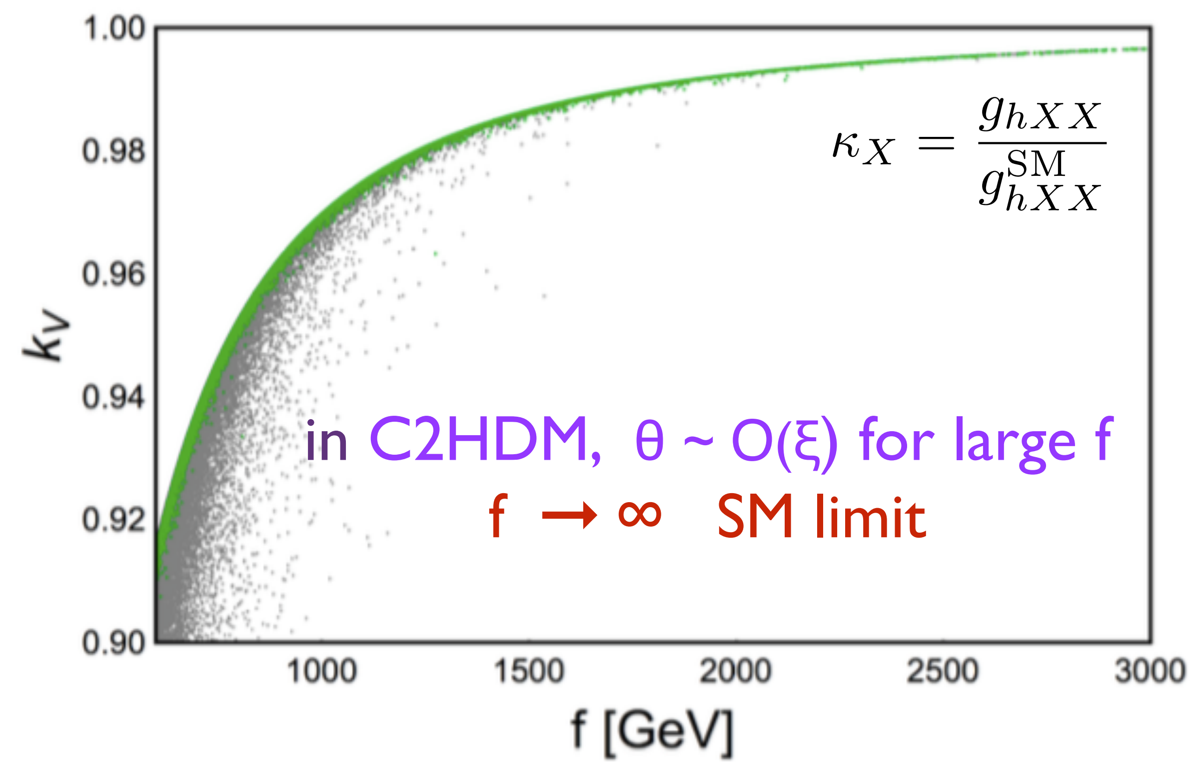
→ Ex: Htt and Hhh

C2HDM - facing the data

- h couplings to SM particles:

dictated by symmetries (as in QCD chiral Lagrangian) Ex: corrections of order ξ to the hVV couplings. Also modified by the mixing angle θ

$k_V \simeq (1-\xi/2)\cos\theta$ V=W,Z $\xi = v^2/f^2$



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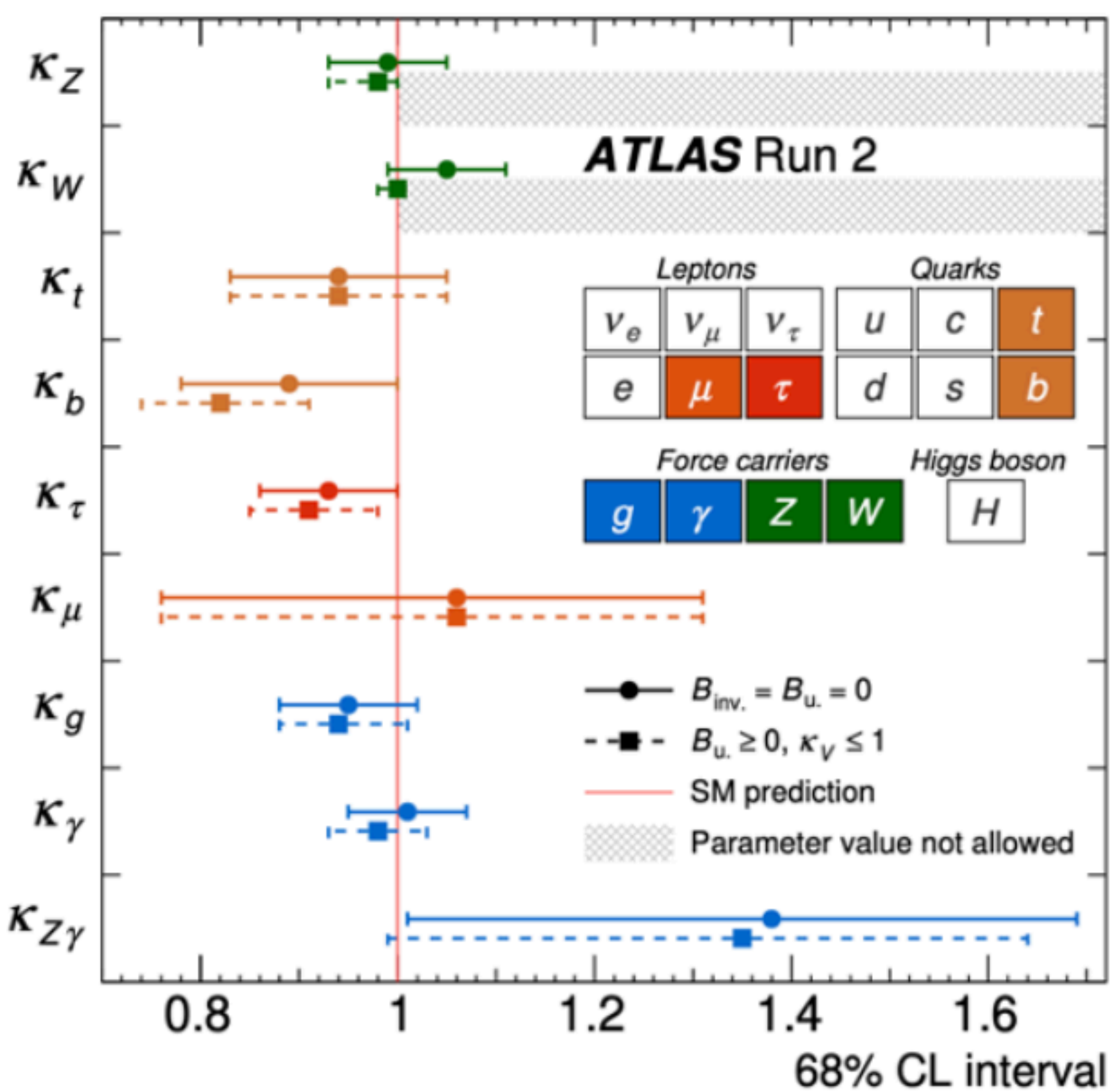

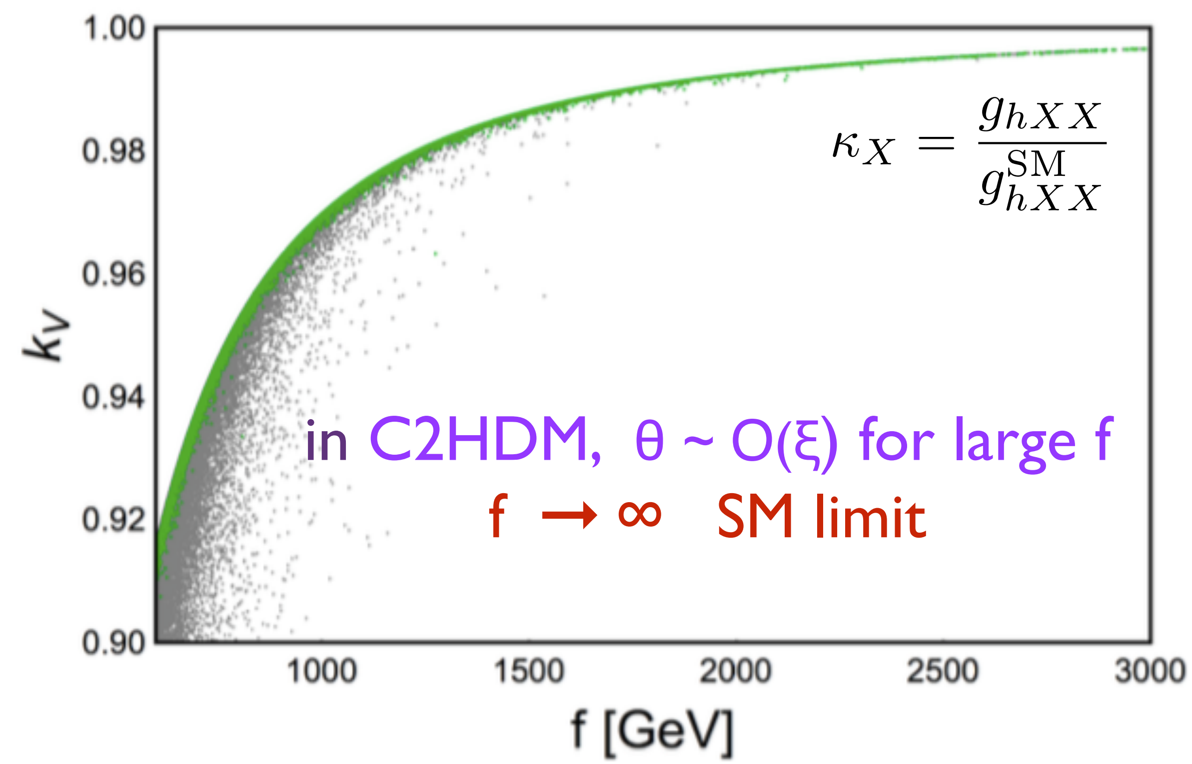

green points satisfy the present bounds

NOW: the Higgs couplings are constrained at 10-20% level

ξ ≤ 0.1 f ≥ 750 GeV

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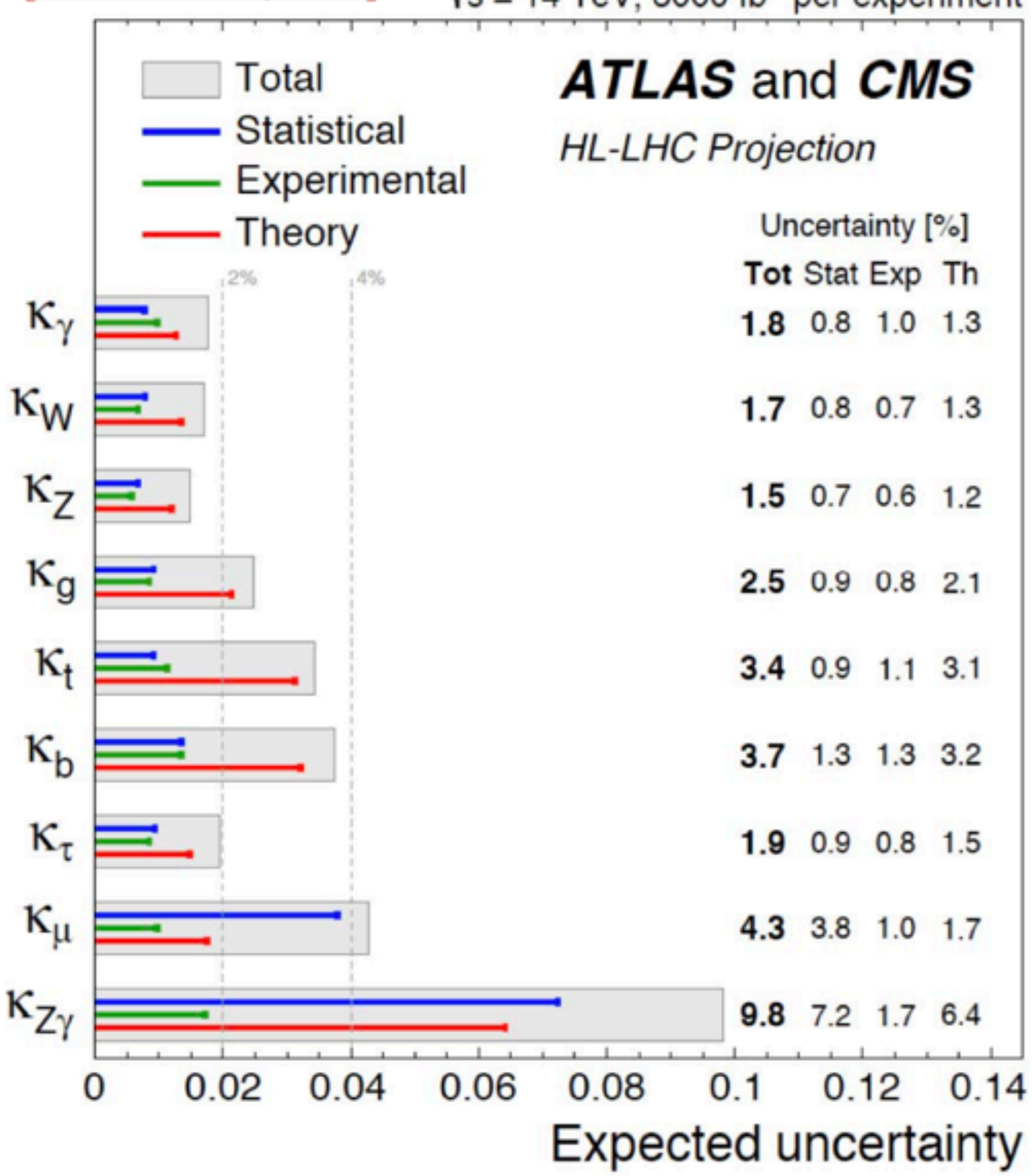
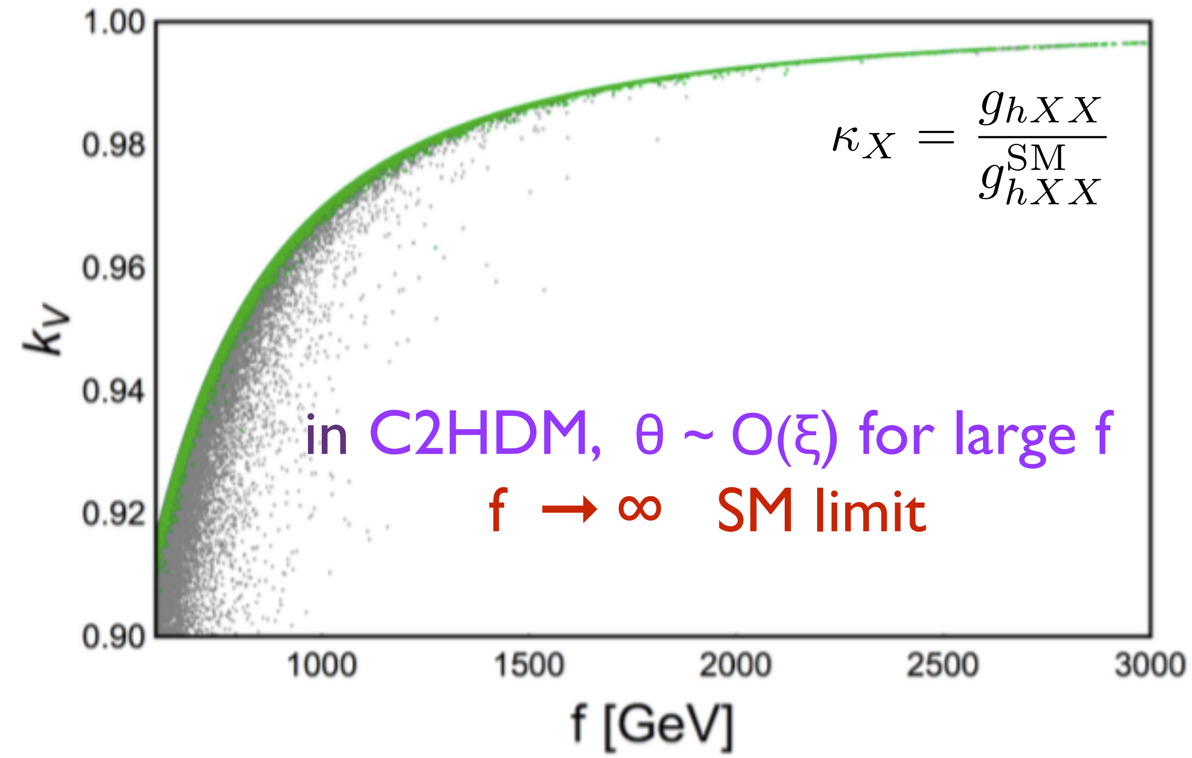
[De Blas et al., 2020]



	Tot	Stat	Exp	Th
κ_γ	1.8	0.8	1.0	1.3
κ_W	1.7	0.8	0.7	1.3
κ_Z	1.5	0.7	0.6	1.2
κ_g	2.5	0.9	0.8	2.1
κ_t	3.4	0.9	1.1	3.1
κ_b	3.7	1.3	1.3	3.2
κ_τ	1.9	0.9	0.8	1.5
κ_μ	4.3	3.8	1.0	1.7
$\kappa_{Z\gamma}$	9.8	7.2	1.7	6.4



in C2HDM, $\theta \sim O(\xi)$ for large f

f $\to \infty$ SM limit

green points satisfy the present bounds

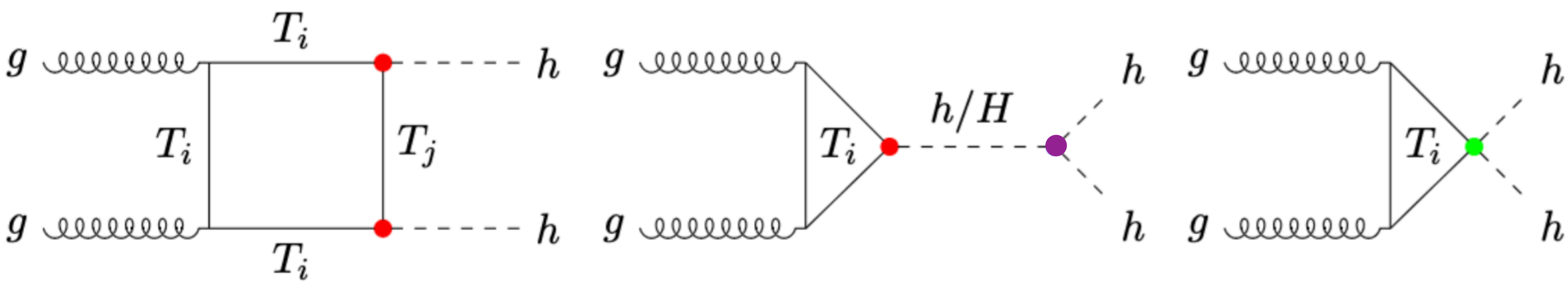
HL-LHC : the Higgs couplings will be constrained at 2-4% level

$\xi \leq 0.04$ f $\geq$ 1200 GeV

CHMs NOT ruled out

Can di-Higgs production at LHC reveal the underlying EWSB?

Signals of New Physics in gg → hh



T_i = t,T's with Q=2/3

INGREDIENTS: modified h couplings, s-channel H exchange, new heavy tops in the loops, new quartic hhTT (typical of pNGBs)

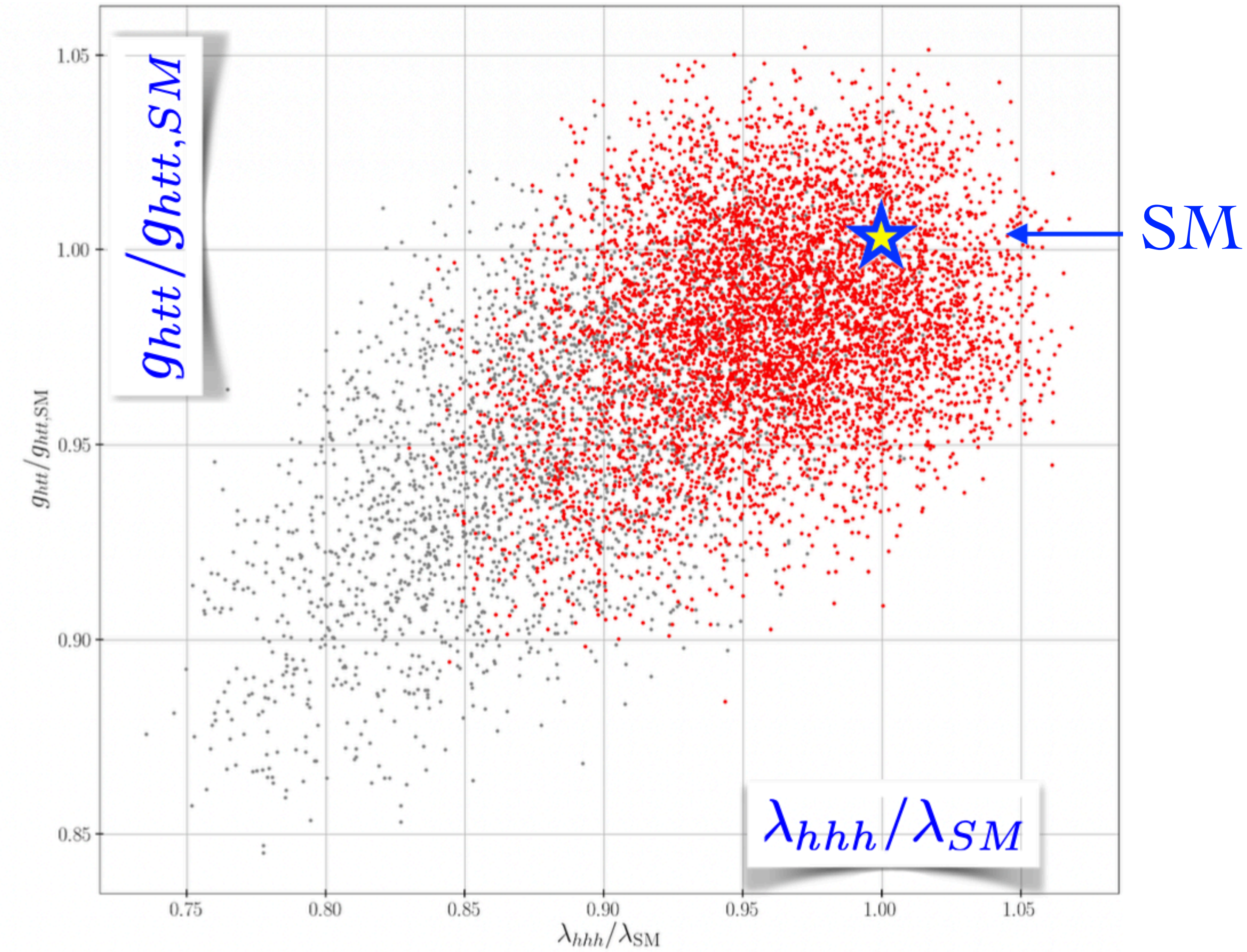
In C2HDM both resonant and non-resonant modes yield to a change in the integrated cross-section and to peculiar kinematic features in its differential distributions

h-top Yukawa and h-trilinear couplings in the C2HDM

scan over the model parameters $700 \leq f(\mathrm{GeV}) \leq 3000$, $0 \leq \Delta, Y, M_\psi \leq 10f$

with the constraints to reconstruct v_{SM}, m_h, m_{top} exp. values, and $M_T \geq 1.3$ TeV

the grey points are **excluded** by the present **direct** and **indirect Higgs searches** (enforced with HiggsBounds and HiggsSignals)



deviations up to 10% in g_{htt} and 15% in λ_{hhh}

Numerical analysis

De Curtis, Delle Rose, Egle, Mühlleitner, Moretti, Sakurai, 2310.10471

The di-Higgs production cross sections through gluon fusion are computed by adapting the public code **HPAIR** (M. Spira), that has been extended to include the C2HDM

INCLUSIVE RESULTS

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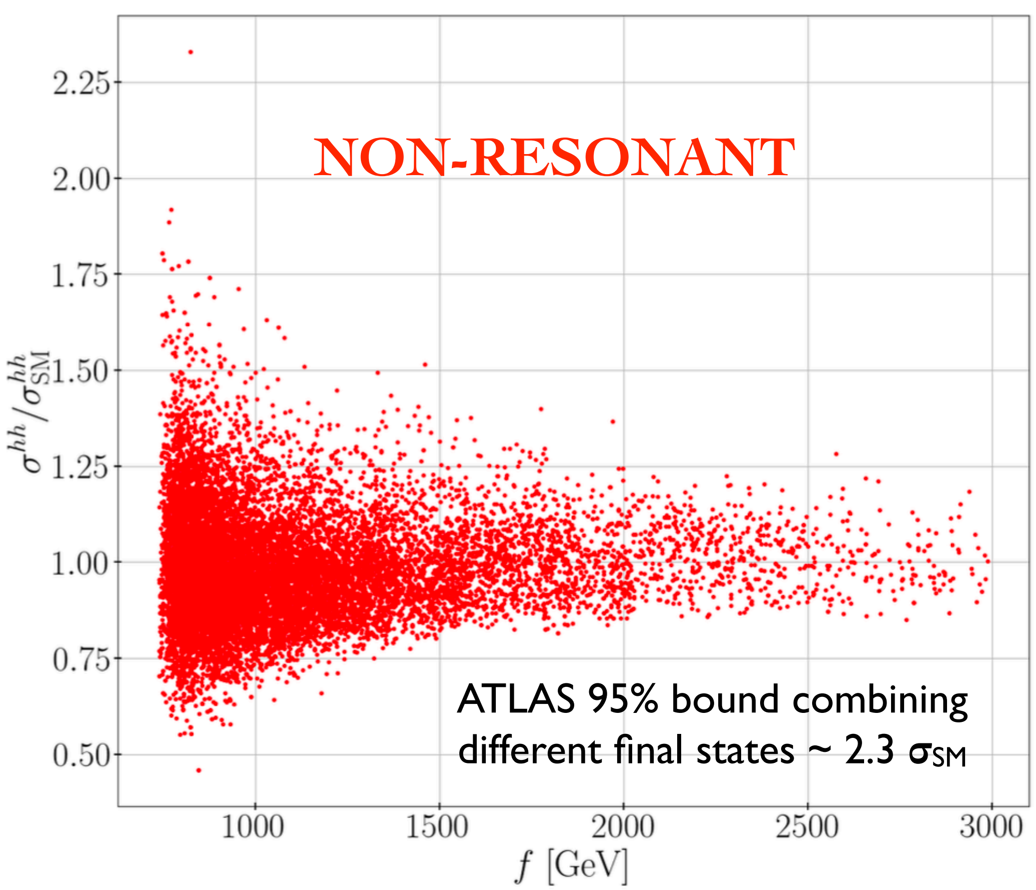
INCLUSIVE RESULTS

NON-RESONANT: $\mathbf{M_H < 2\, m_h}$ + cases with **suppressed resonant contribution** (small H couplings, large m_H, large Γ_H, destructive interferences between diagrams)

$\sigma(gg \to H) \times BR(H \to hh)/\sigma(gg \to hh) < 0.1$



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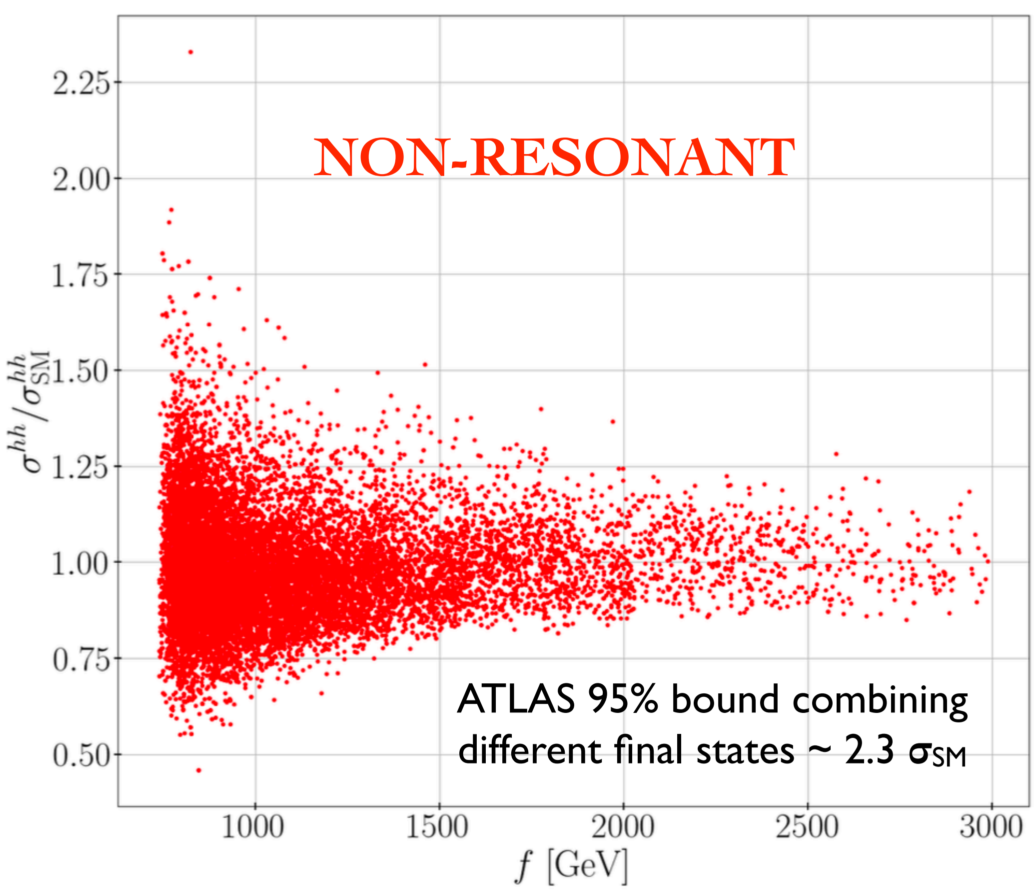
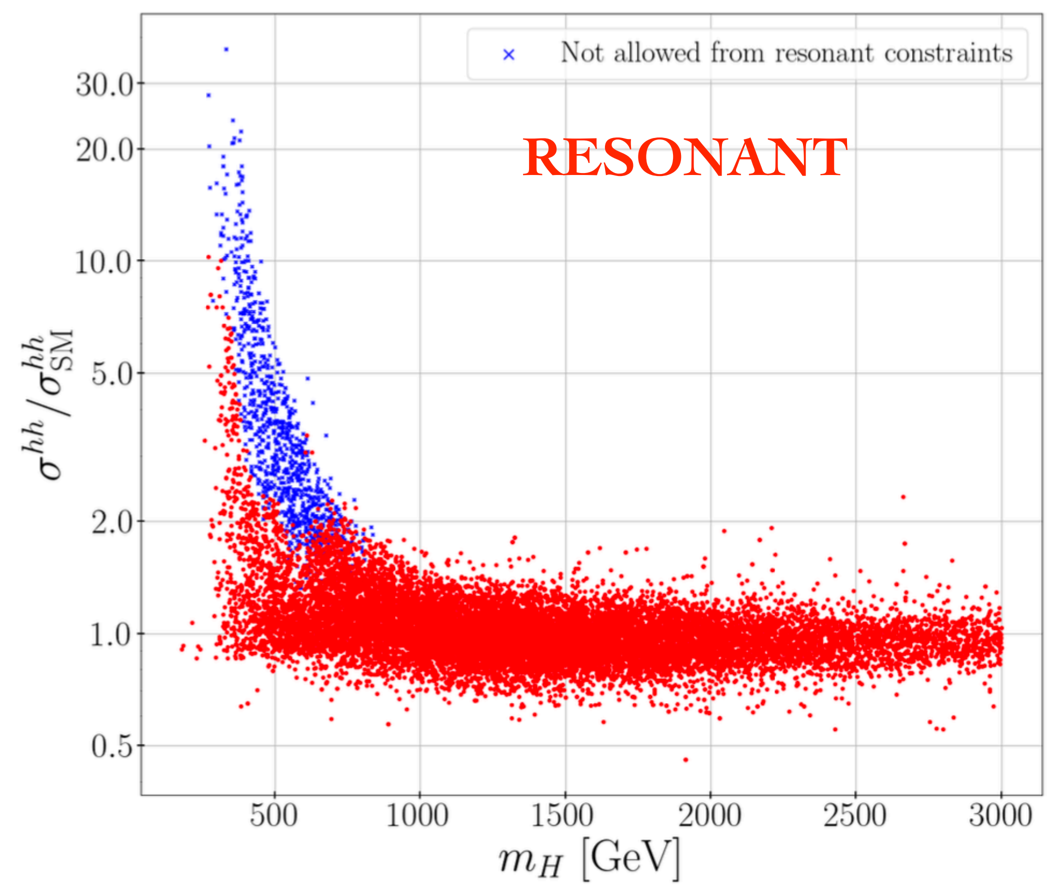
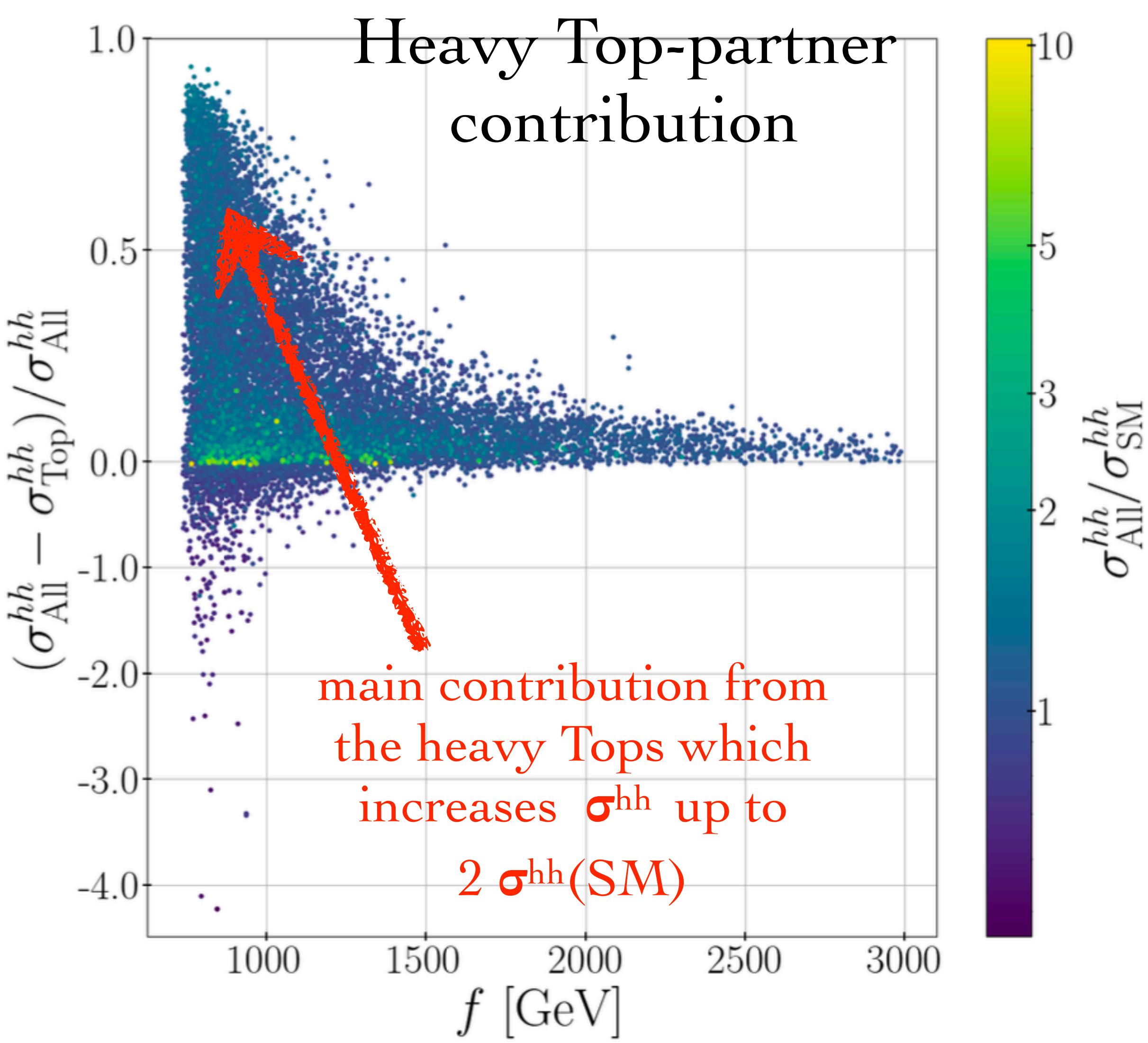
RESONANT: $M_H > 2\, m_h$

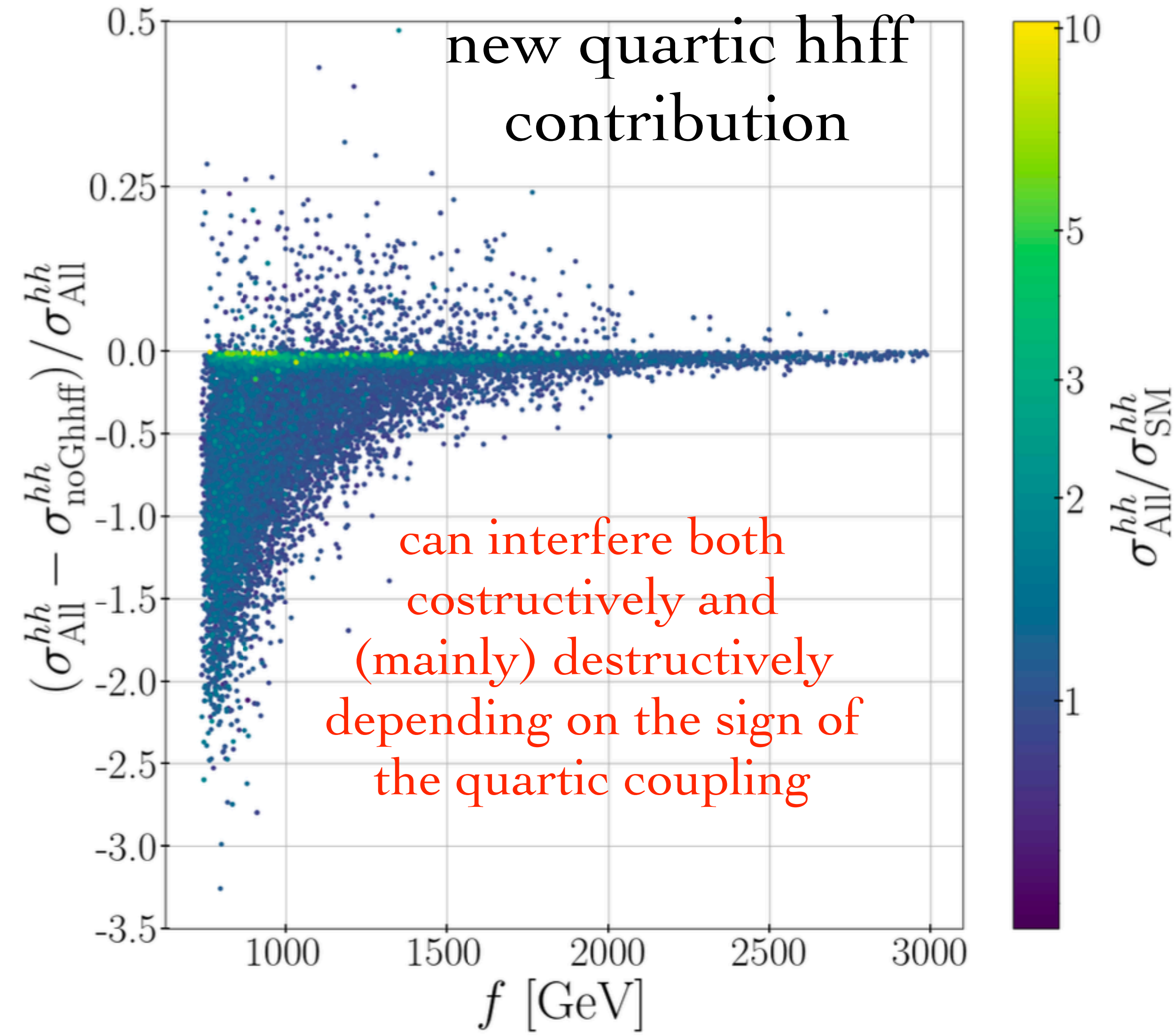
compare with the exp. limits on resonant di-Higgs production obtained in the narrow width approximation (points with $\Gamma_H/M_H > 5\%$ are not excluded)





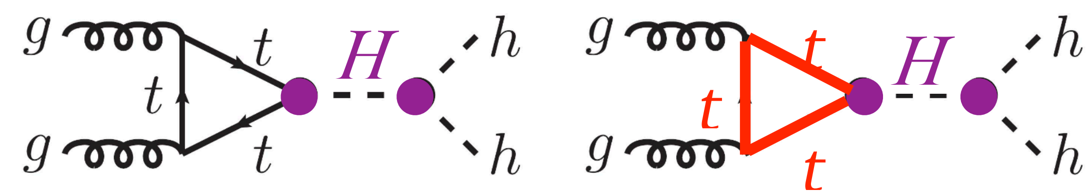
Impact of new C2HDM effects (not present in 2HDM)





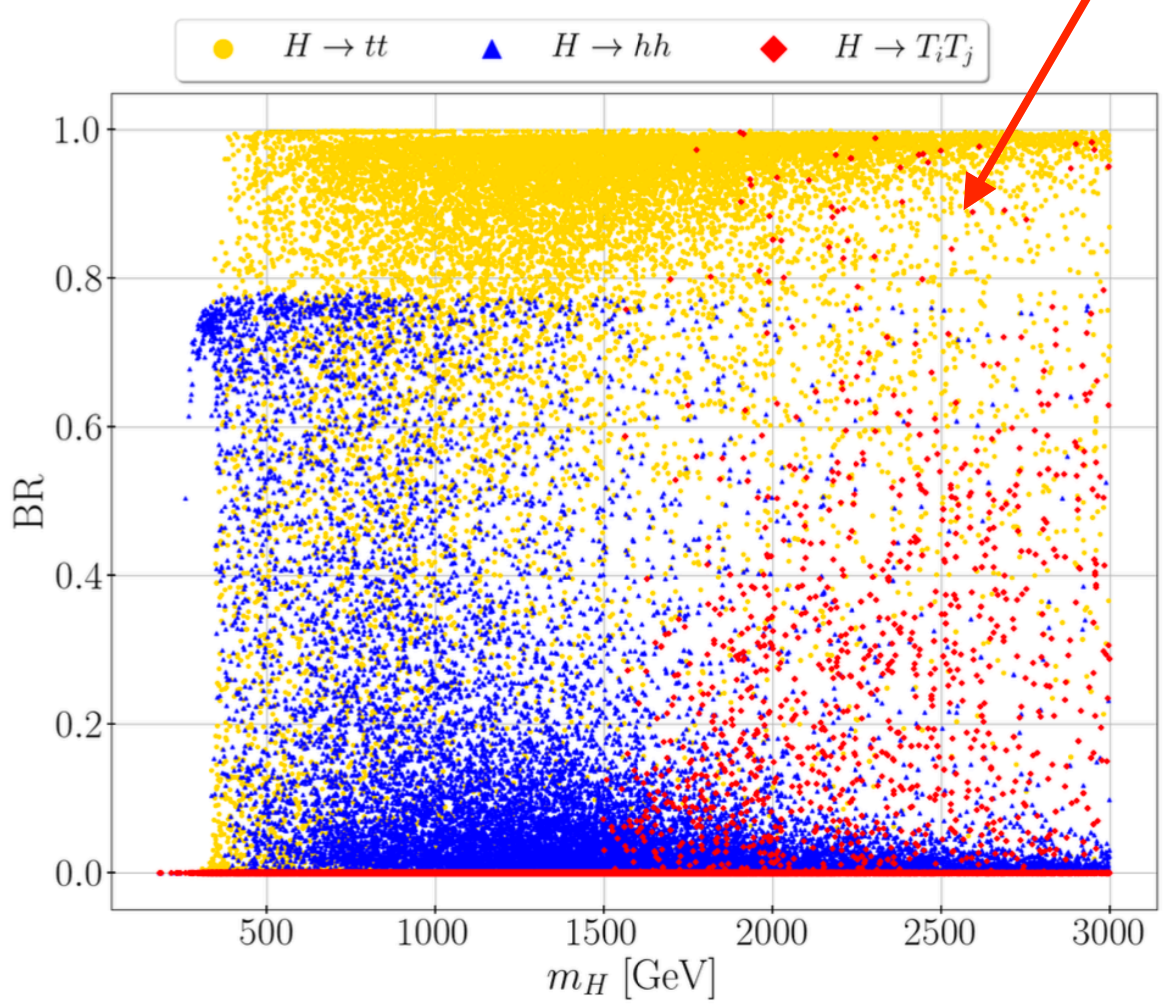
The largest cross-sections are the resonant ones (yellow and green BPs) are not affected by heavy Tops and new quartic terms

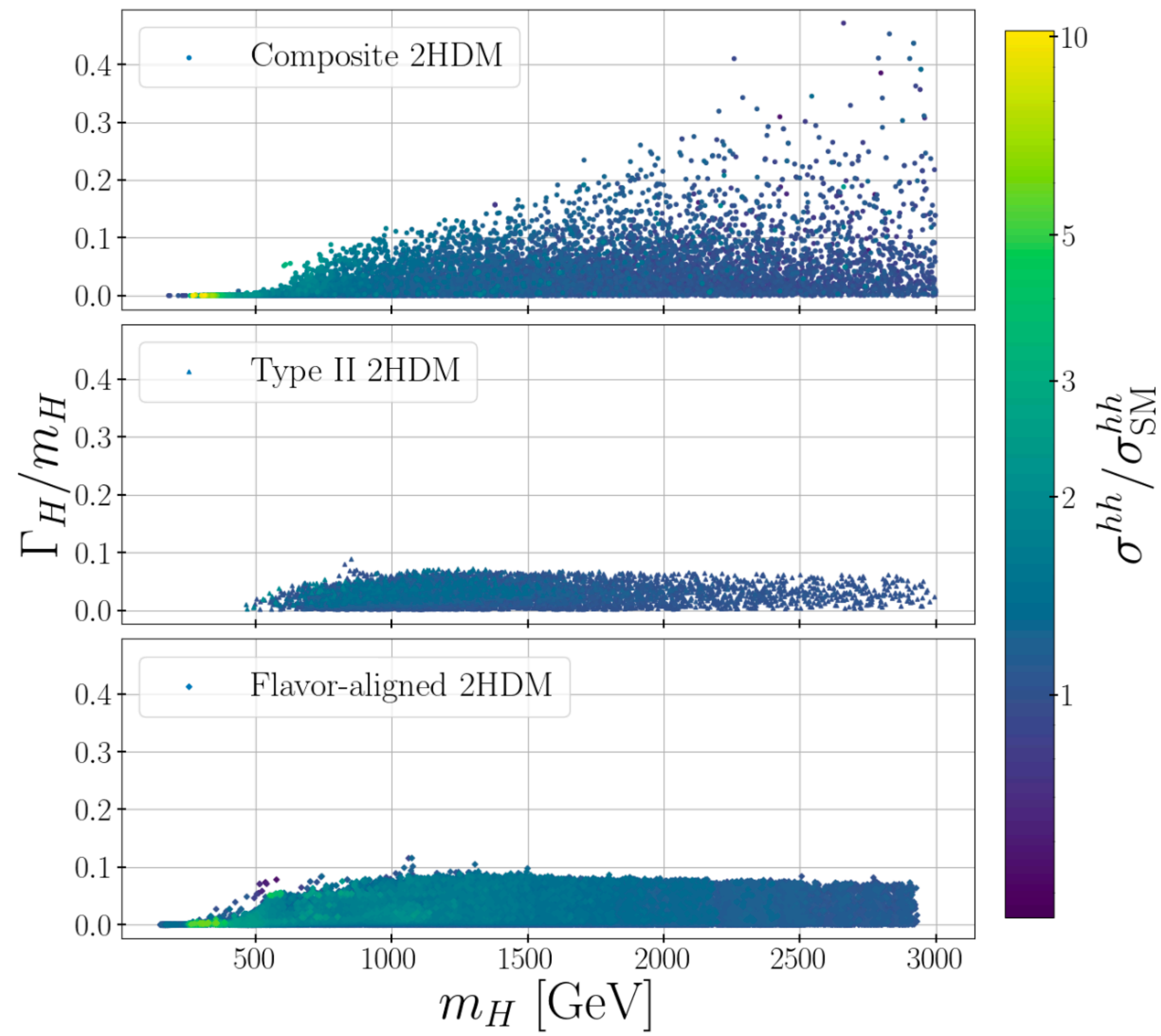
H contribution



the **heavy Higgs H** can have a **sizeable BR in $T_9T_{8,7}$**

T_9=top, $T_{8,7}$= lightest heavy tops

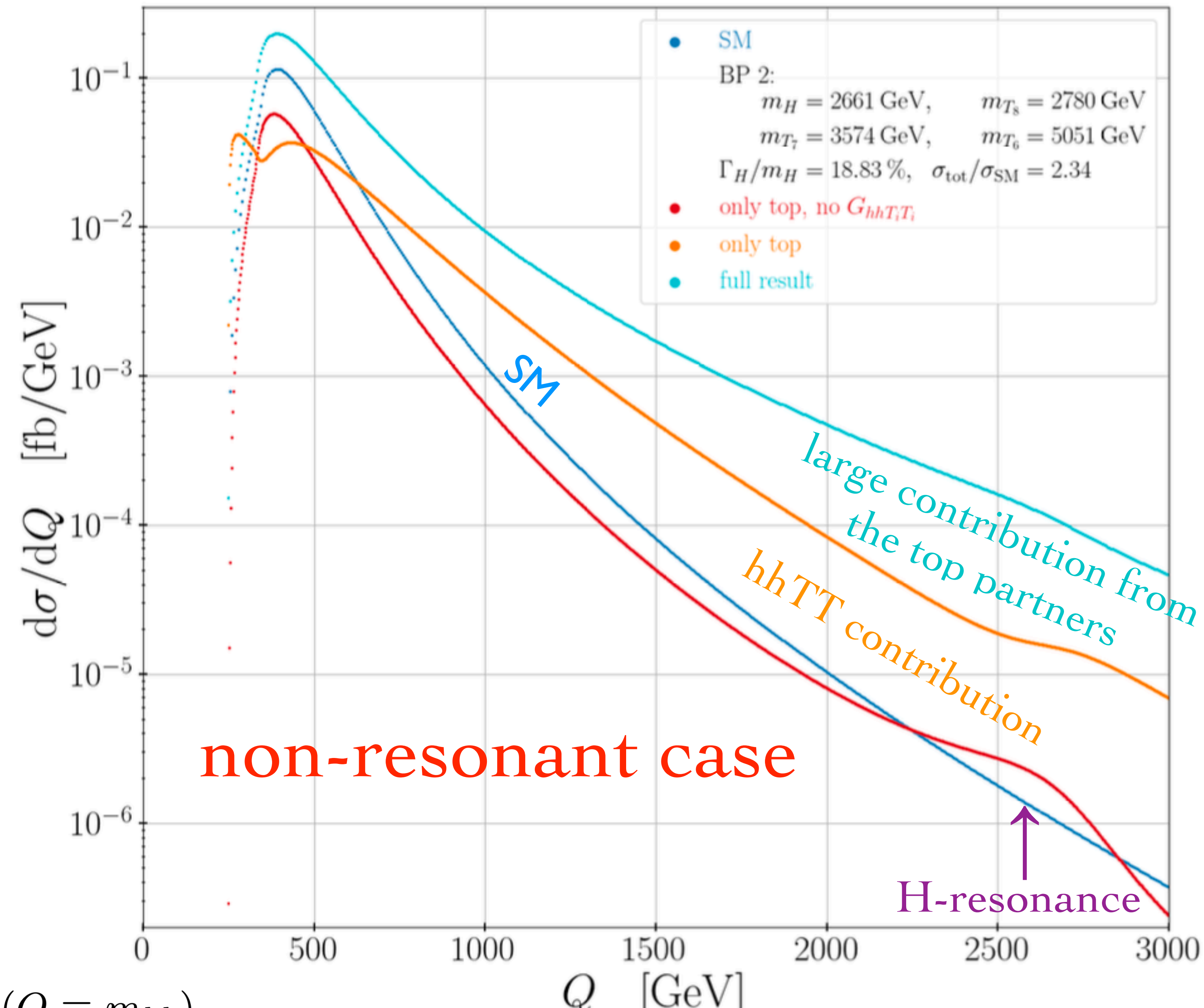




Peculiar feature of the C2HDM: Γ_H/M_H can be ~10-20%

di-Higgs production in C2HDM - invariant mass distributions

1. modified hhh (κ_λ) and tth (κ_t) couplings → small deviations
2. additional H contributions → present in several BSM schemes (MSSM, 2HDM, …)
3. additional heavy top contributions ($t' = T_i$, $i = 1,\ldots, 8$) → naturally present in CHMs
4. quartic tthh coupling (since h is pNGB) → naturally present in CHMs



$(Q \equiv m_{hh})$

$m_H \sim 2.6$ TeV

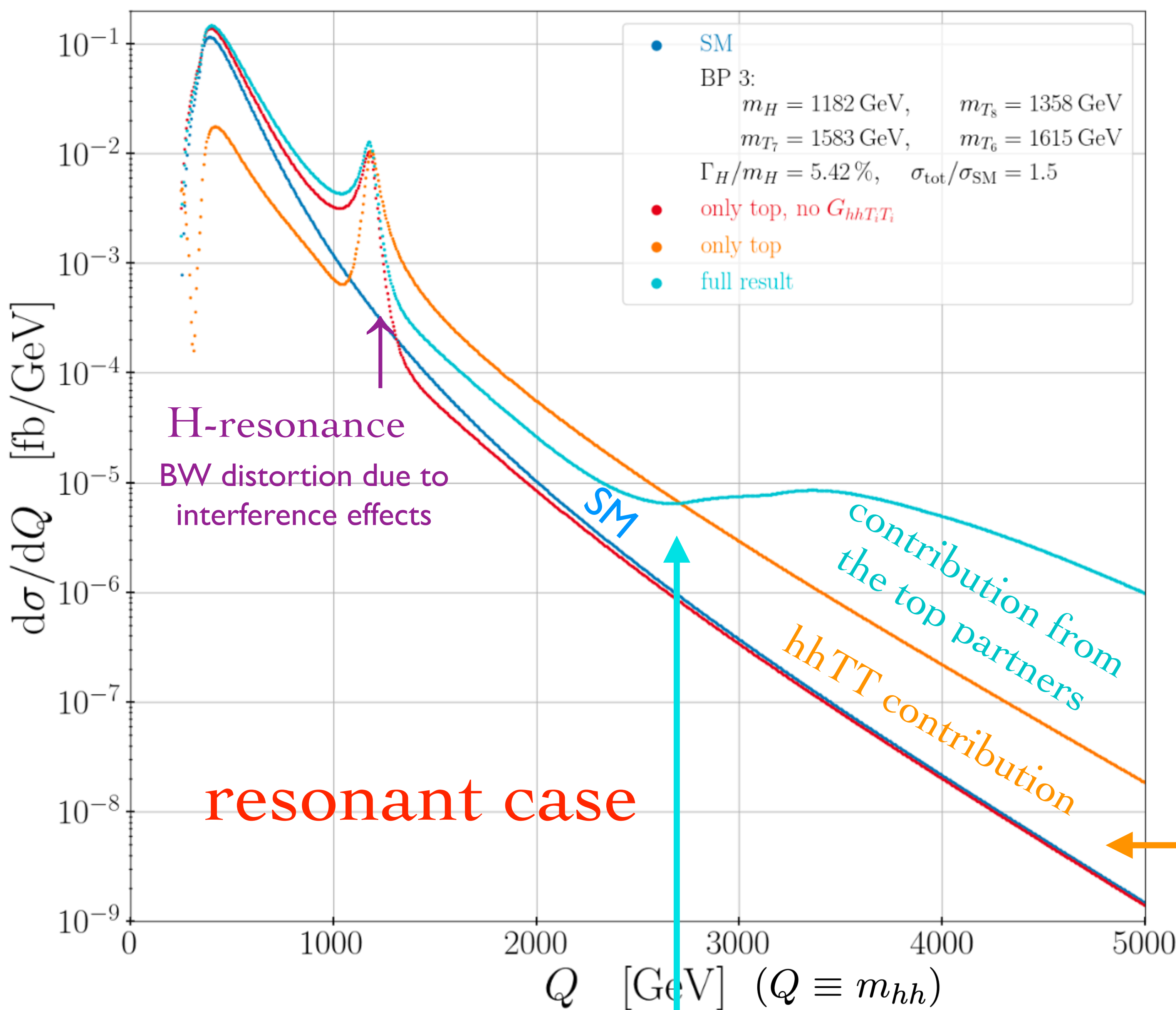
$\Gamma_H/m_H \sim 19\%$

Large Width

$m_T > 2.7$ TeV

$\sigma_{tot}/\sigma_{SM} = 2.34$

di-Higgs production in C2HDM - invariant mass distributions



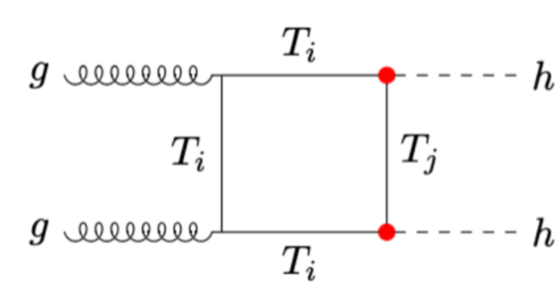
$\sigma_{\rm tot}/\sigma_{\rm SM} = 1.5$

$m_H \sim 1.2$ TeV
$\Gamma_H/m_H \sim 5.4\%$

$m_T > 1.3$ TeV

destructive interference before the peak and constructive interference after the peak

start to see the threshold shape at 2MT induced by boxes



di-Higgs production in C2HDM - invariant mass distributions

The results of the present analysis are primarily of theoretical nature and serve to demonstrate that a computable framework exists within composite scenarios that can eventually be tested experimentally

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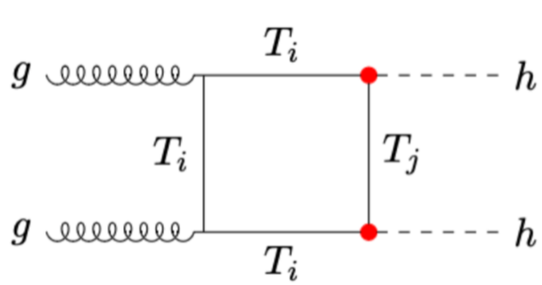

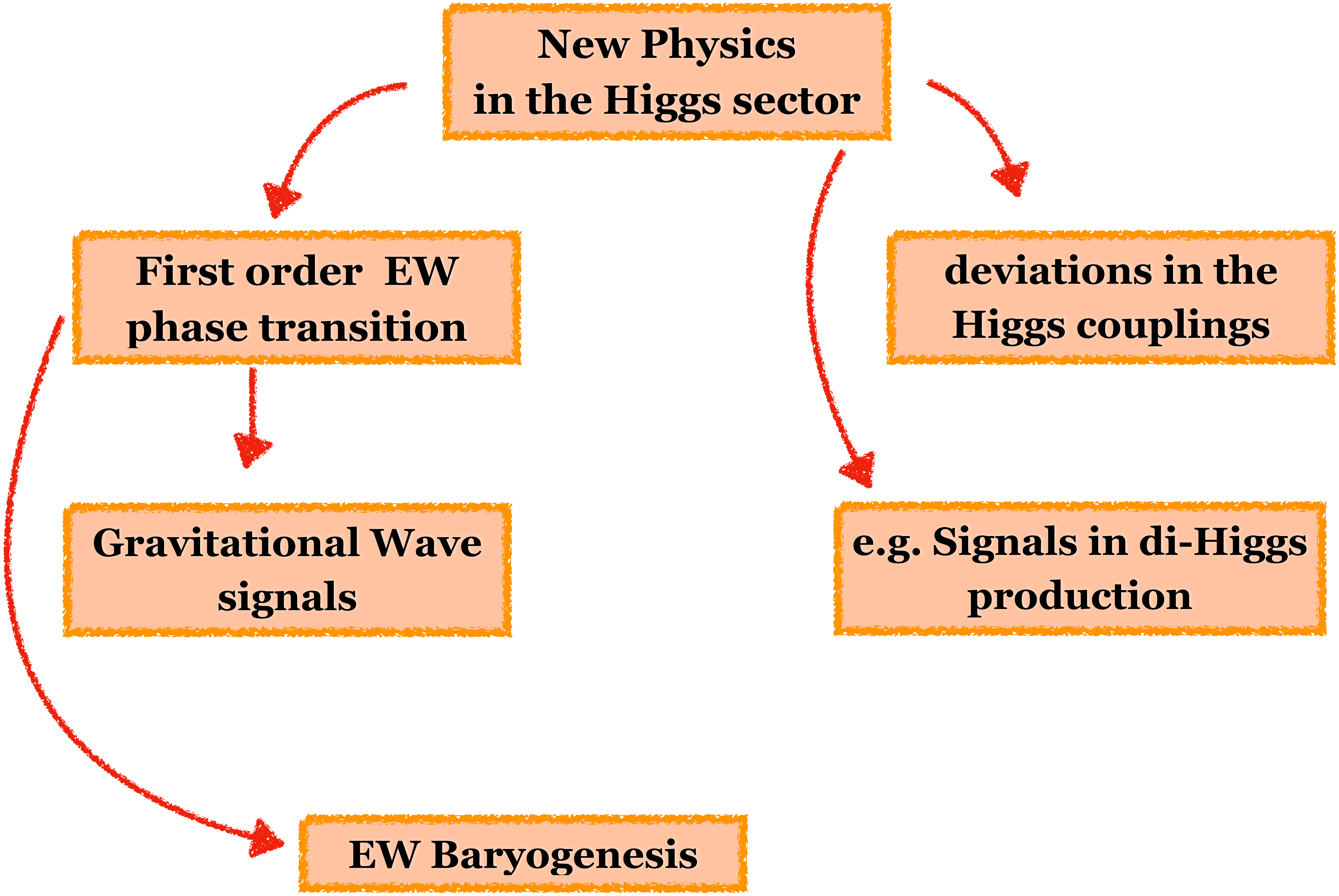
New Physics
in the Higgs sector
First order EW
phase transition
deviations in the
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Gravitational Wave
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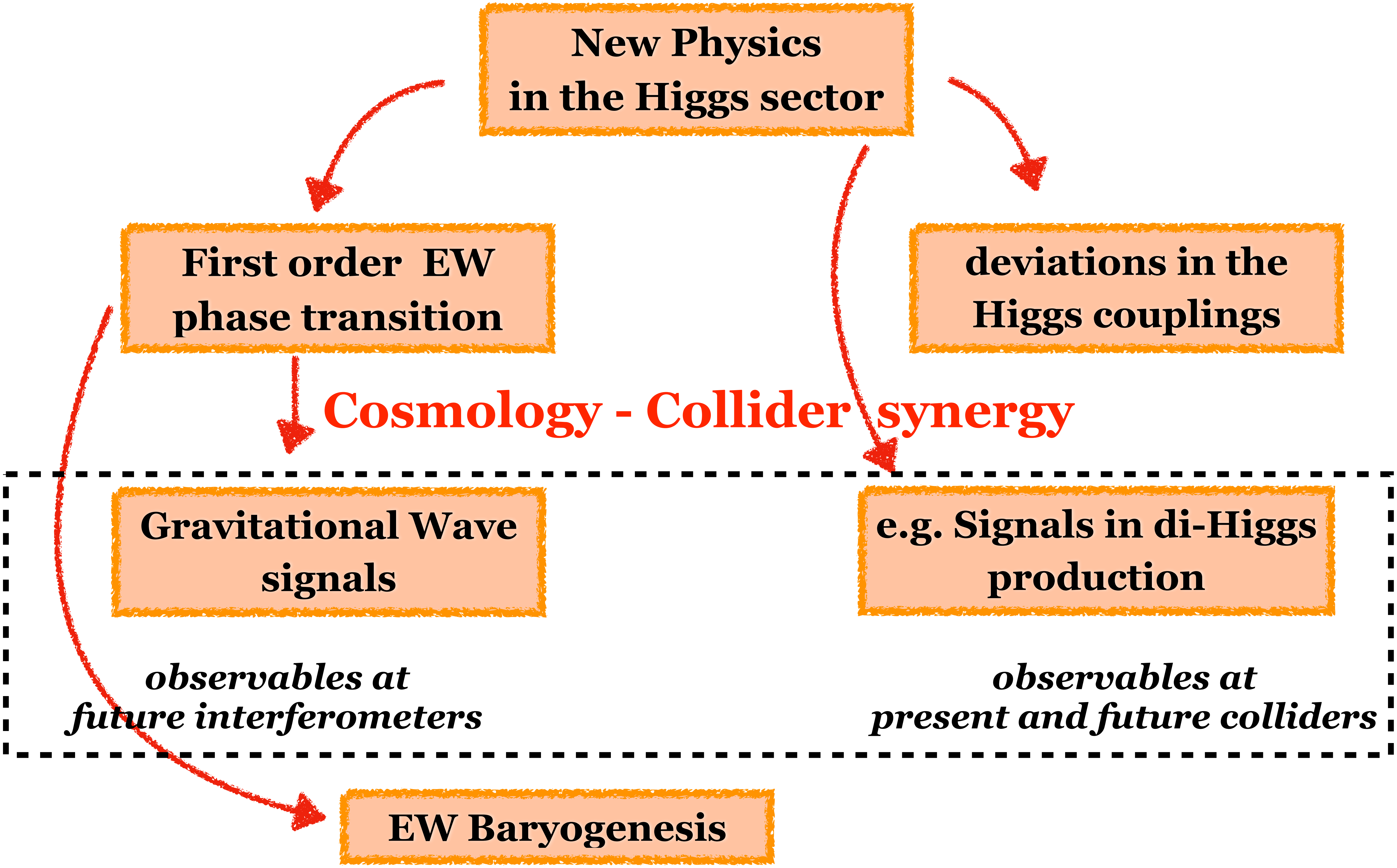
e.g. Signals in di-Higgs
production
EW Baryogenesis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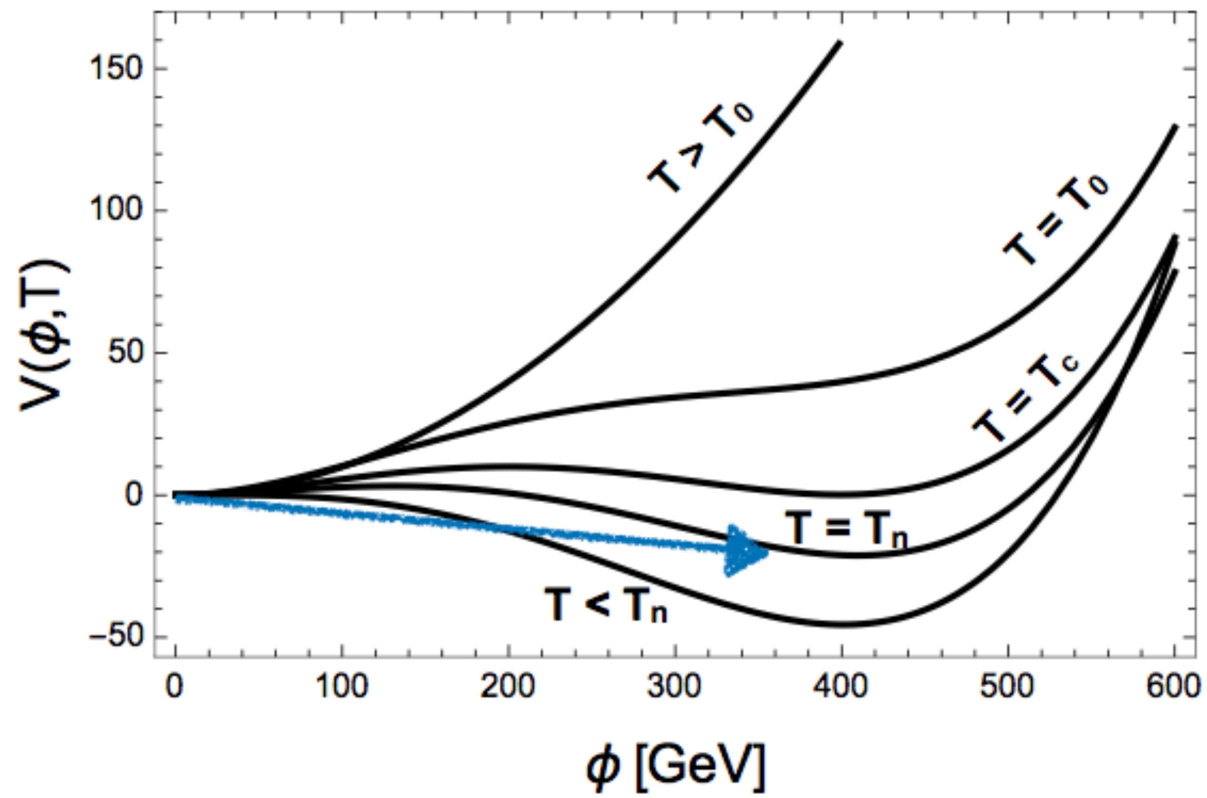
EW Baryogenesis

Strong EW Phase Transition can trigger Baryogenesis

Thermal History

- ☑ The EW symmetry is restored at $T > T_0$ below T_0 a new (local) minimum appears
- ☑ At a critical T_c the two minima are degenerate and separated by a barrier (two phases coexist)
- ☑ The transition starts at the bubble nucleation temperature $T_n < T_c$



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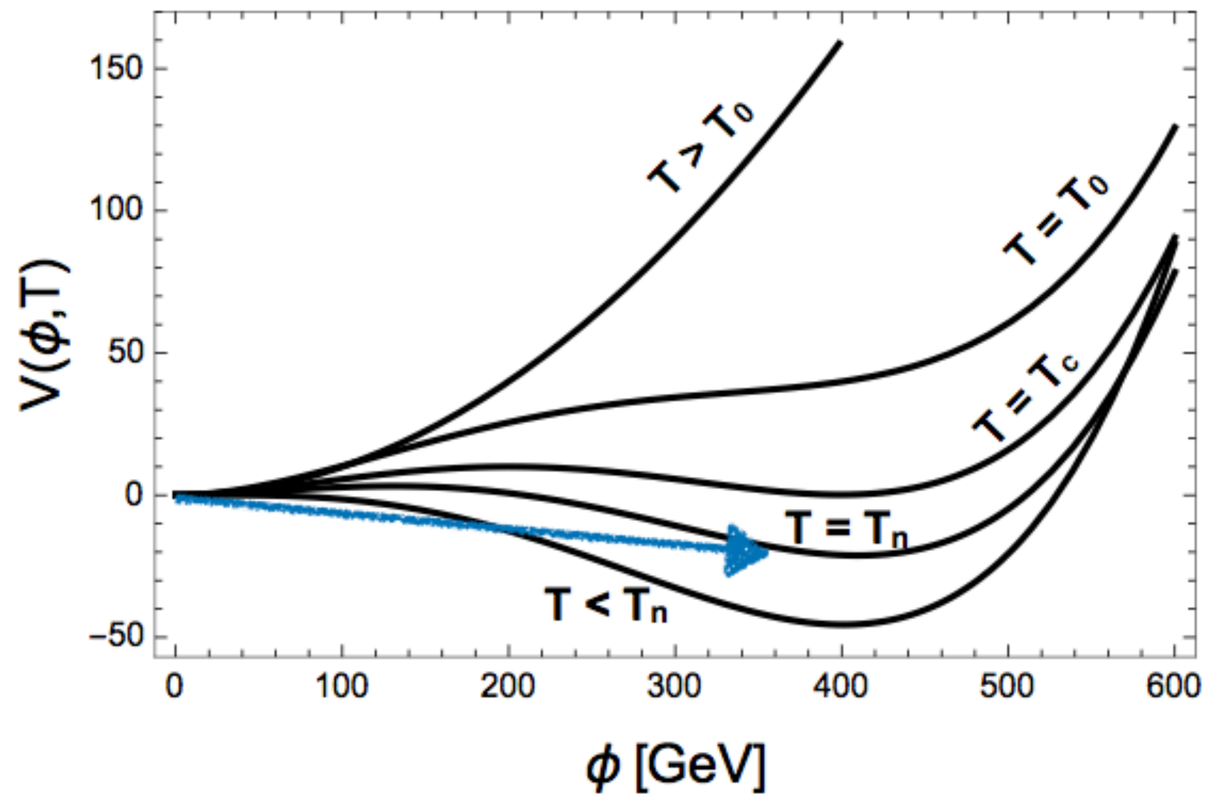
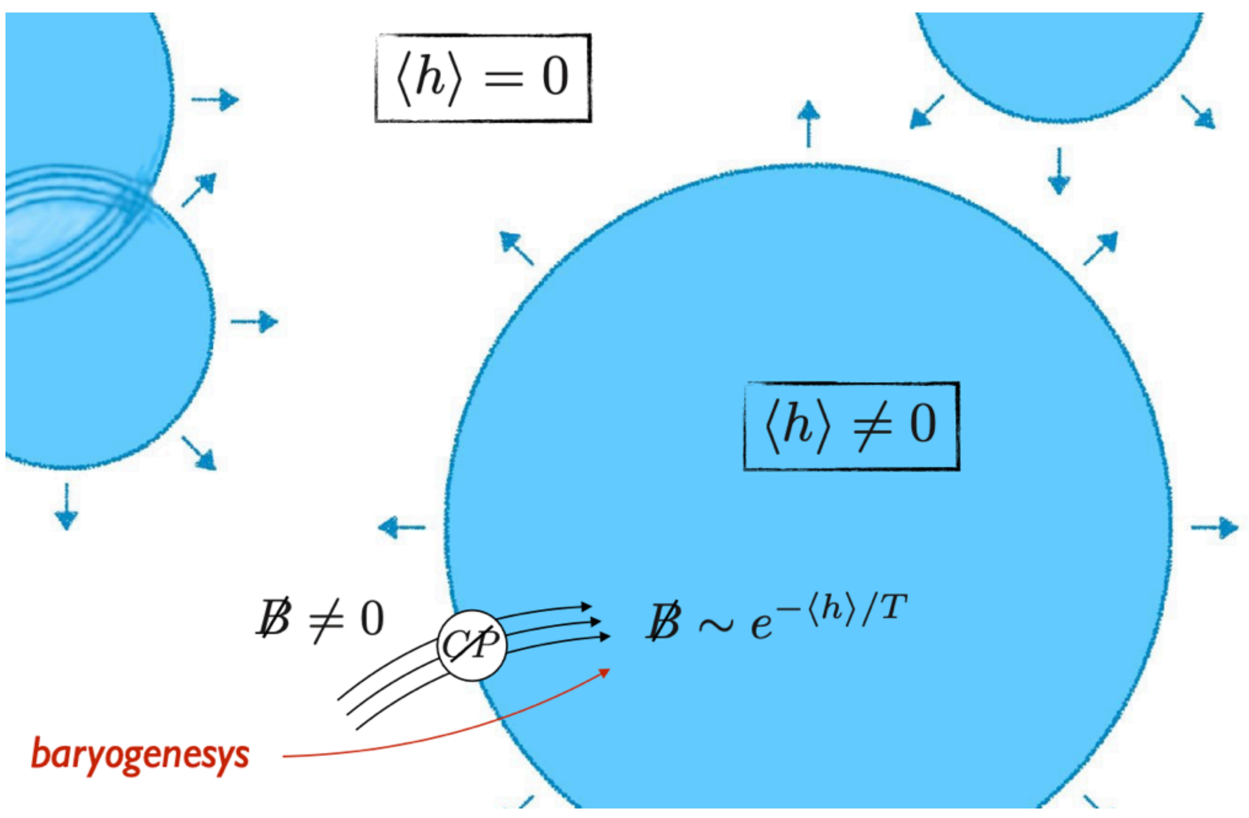


Sakharov Conditions for Baryogenesis

- Baryon number violation
- C and CP violation
- **Out of equilibrium dynamics:**
  (strong) 1st order phase transition

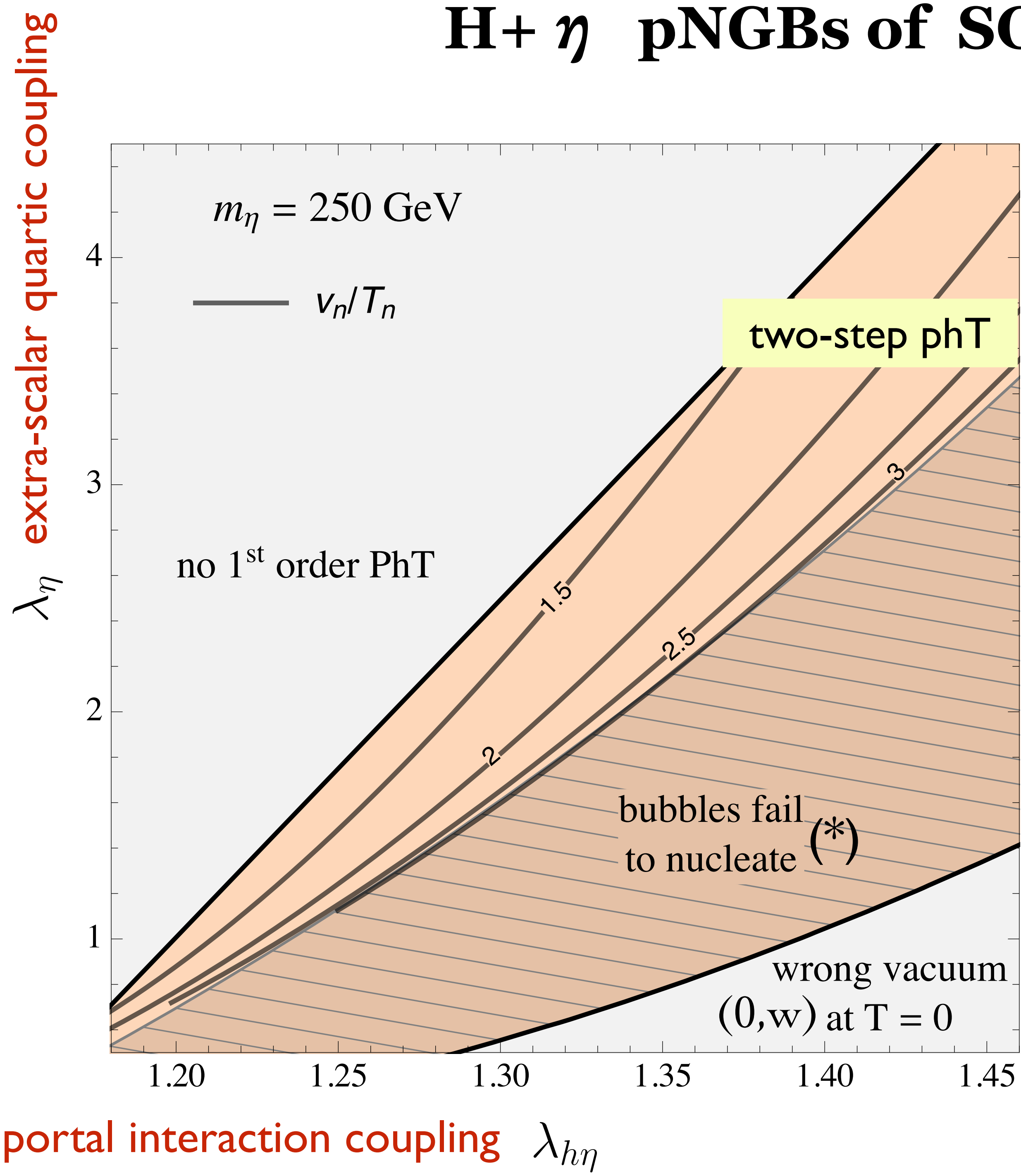


In the SM phase transition is a smooth crossover, also not enough CP violation from CKM → **NP needed !!**

Composite Dynamics in the Early Universe
Properties of the EWPhT

H+ η pNGBs of SO(6) -> SO(5)

(De Curtis, Delle Rose, Panico, 2019)



(*) the rate of bubble formation does not balance the Hubble expansion (ex. $\lambda_{h\eta}$ too large produces a high barrier) and no EWSB occurs

The EWPhT starts at $T_n < T_c$ determined by requiring: Rate of nucleation of bubbles / Hubble volume ~ 1

The computation of T_n requires solving (numerically) a two-field bounce equation (use CosmoTransition package)

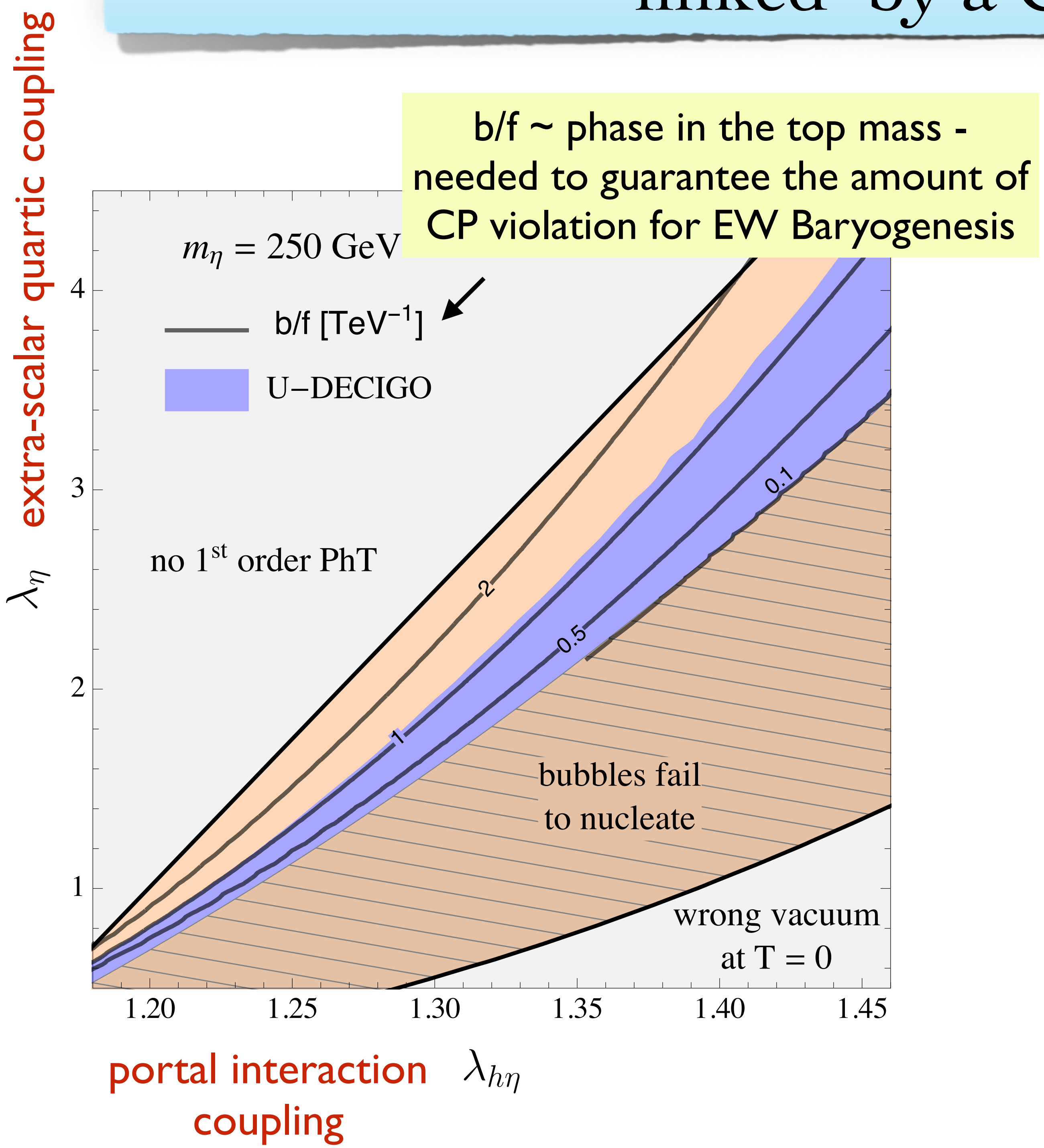
—— Strength of the phase transition

v_n/T_n ($v_n = \langle h \rangle|_{T_n}$)

a crucial parameter for EWBG

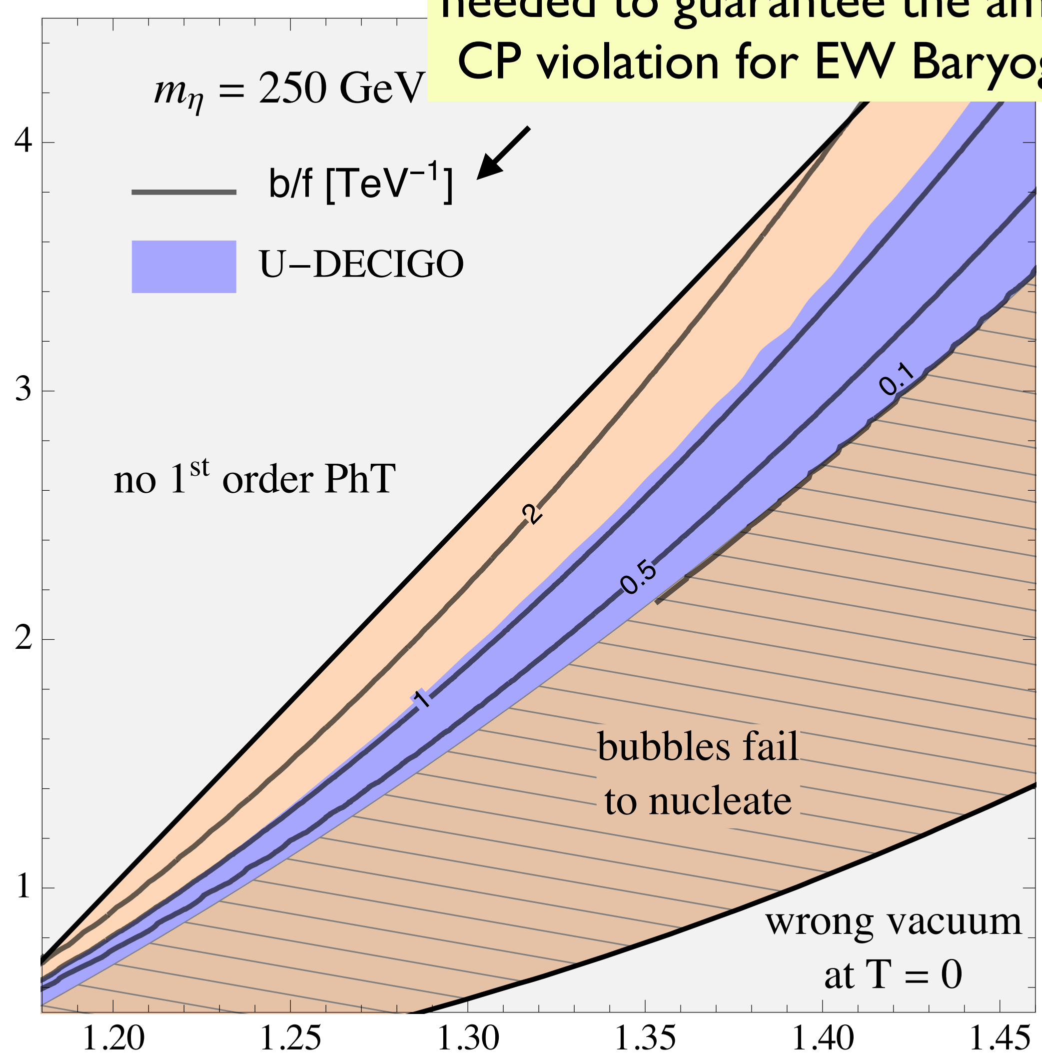
T_n is one of the parameter characterising the amplitude and the frequency peak of the GW spectrum

Strong EWPhT, EWBG and GW spectrum linked by a CHM scenario



Strong EWPhT, EWBG and GW spectrum linked by a CHM scenario

b/f ~ phase in the top mass - needed to guarantee the amount of CP violation for EW Baryogenesis



portal interaction coupling $\lambda_{h\eta}$

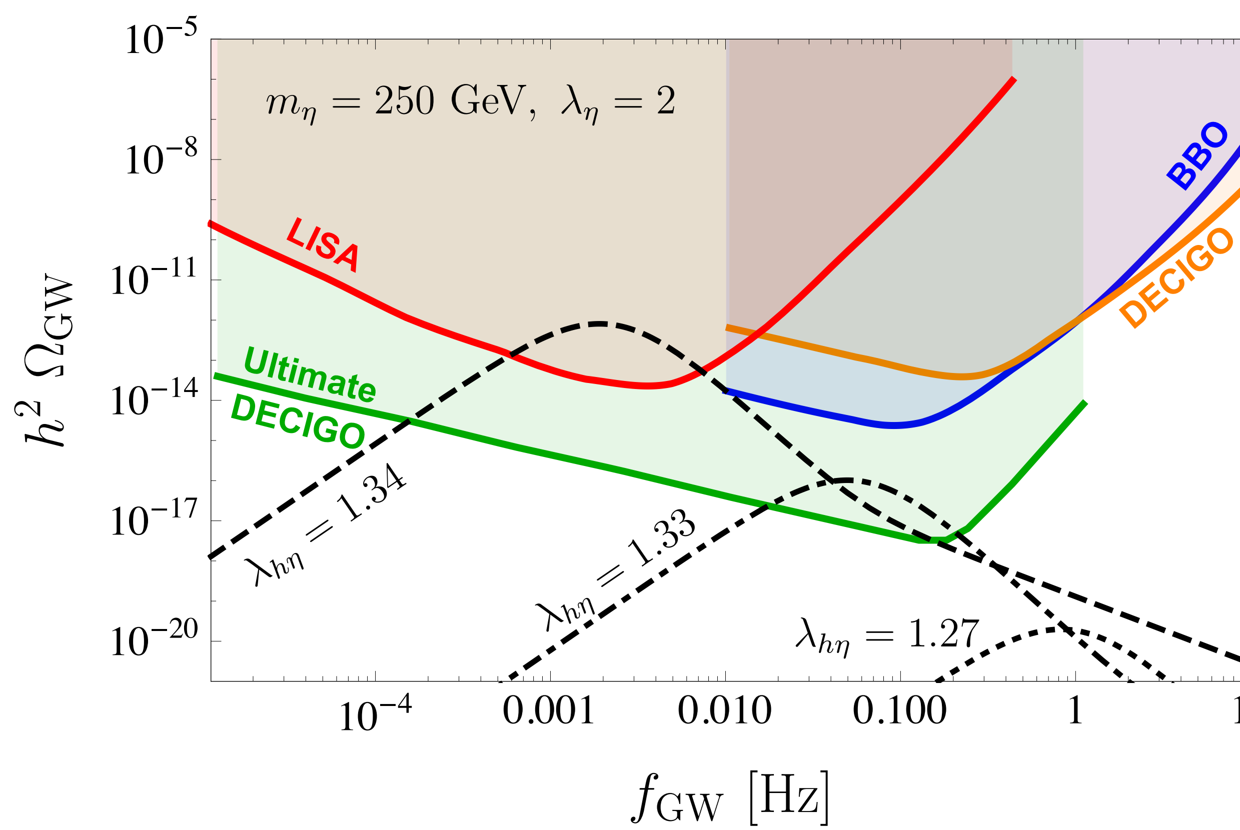
The bubbles expand, collide incoherently …

Stochastic Background of GW's :

(bubble collisions, sound waves in the plasma, magnetohydrodynamic turbulence effects)

(Grojean,Servant '06, Caprini,Durrer,Servant '08,'09)

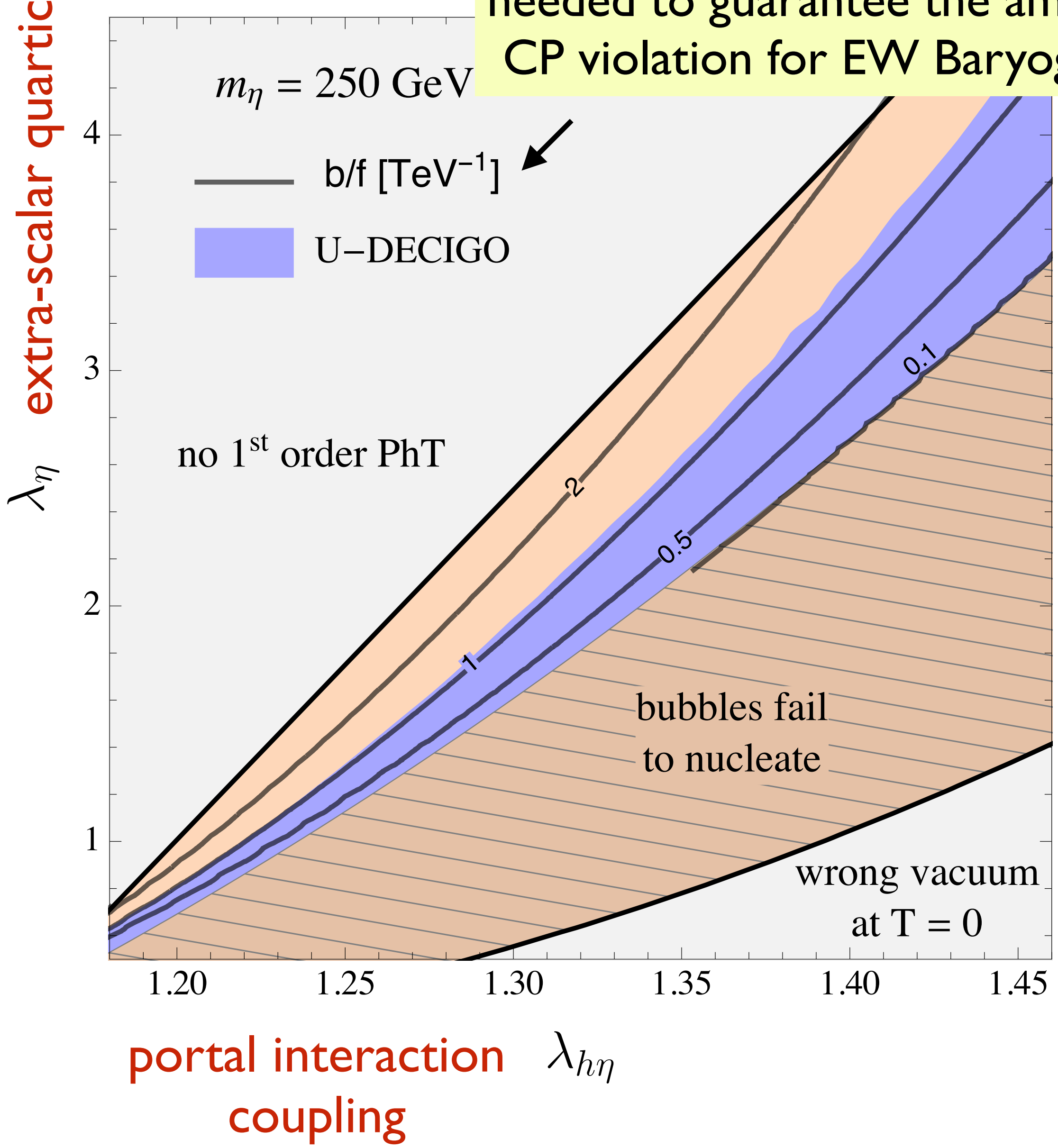
Gravitational Wave Spectrum



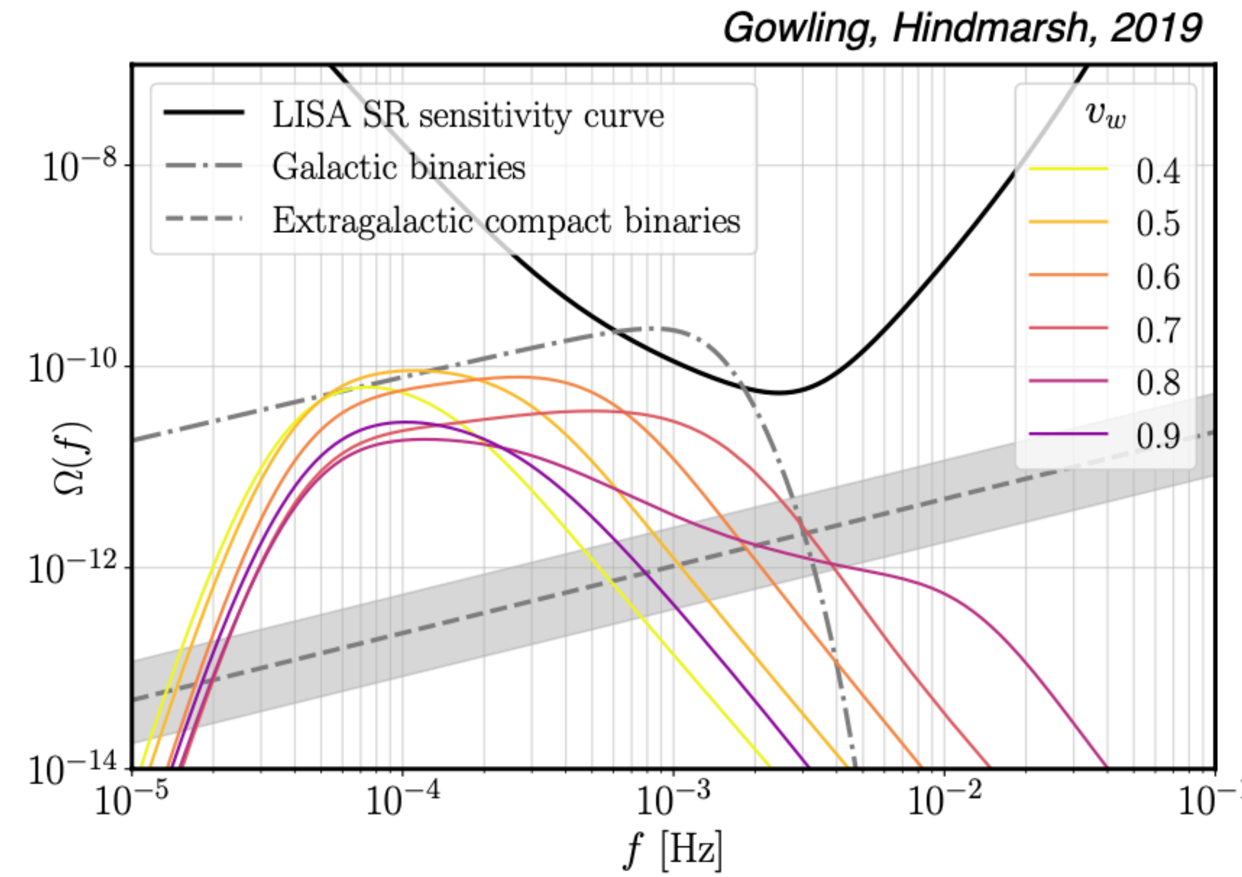
same region where the EWBG could be achievable

peak frequencies within the sensitivity reach of future experiments for a significant part of the parameter space

Strong EWPhT, EWBG and GW spectrum linked by a CHM scenario



b/f ~ phase in the top mass - needed to guarantee the amount of CP violation for EW Baryogenesis



the wall speed has a strong effect on the shape of the power spectrum

Can be determined by solving the Boltzmann equation which describes the plasma dynamics and its interactions with the bubble wall

De Curtis, Delle Rose, Guiggiani, Mayor, Panico JHEP 03(2022),163; JHEP 05(2023),194; JHEP 05(2024) 009

Conclusions

☑ di-Higgs production is a target process for the LHC, within the SM it is the experimental signature of the Higgs self-interaction, but also a probe for BSM scenarios

☑ We analysed $gg \rightarrow hh$ within the C2HDM with an approach which enables to disentangle the different NP ingredients: coupling modifications, new resonance exchange, heavy fermions in the loops, and the extra quartic couplings

☑ Sizeable effects both in the **integrated cross-section** and in the **differential distributions** open the prospect of **using di-Higgs production at the LHC as a probe for NP** with the possibility to **disentangle among different BSM schemes**

☑ New Physics in the Higgs sector can provide 1st order EWPhT, thus signals of gravitational waves and EW baryogenesis, along with modifications to the Higgs couplings and signatures at colliders