Cosmology, Astrophysics, Theory and Collider Higgs 2024 conference
(CATCH22+2)

1-5 May 2024

Dublin Institute for Advanced Studies (DIAS)

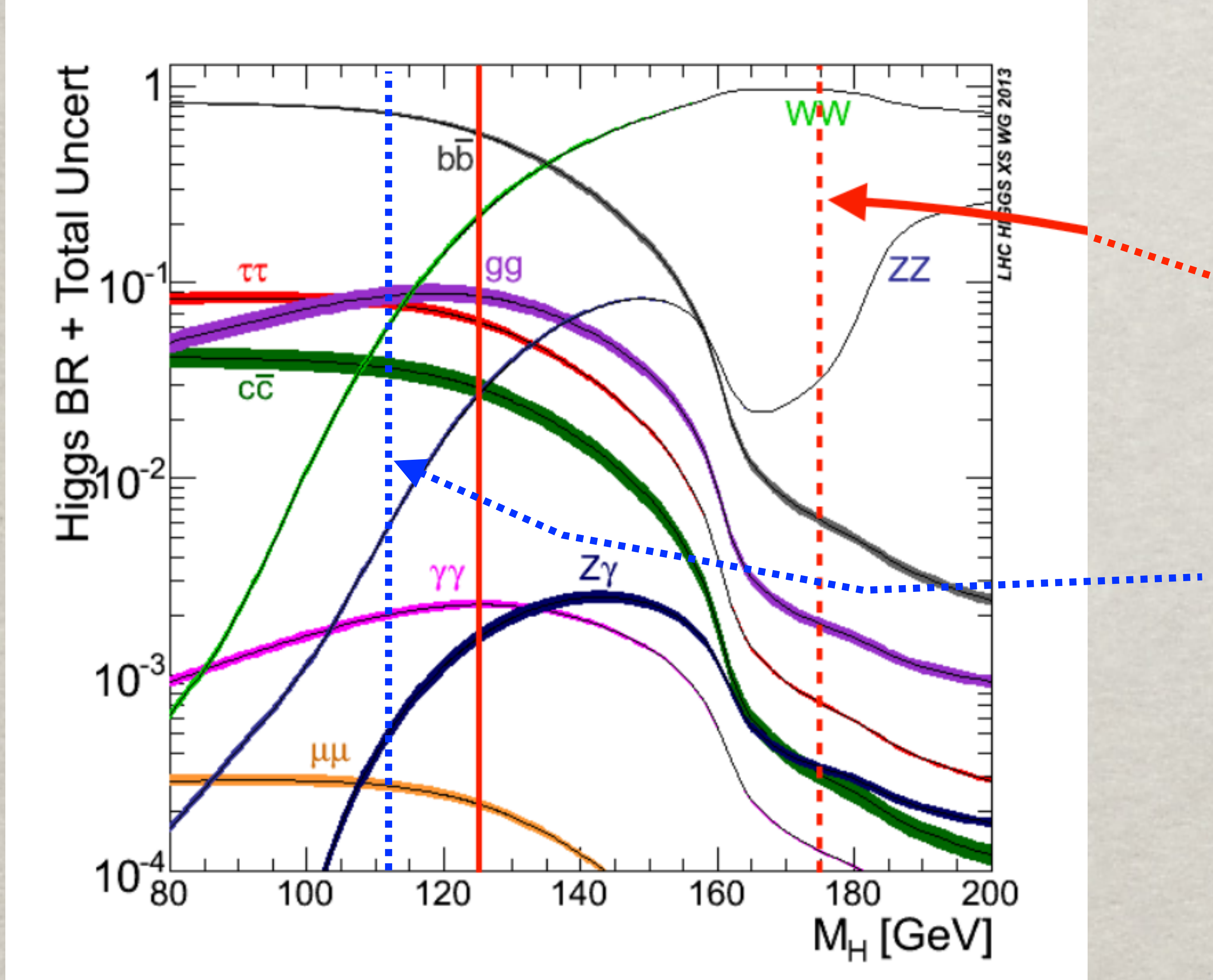
Collider-Cosmology Synergy for Strong Dynamics Signals

Stefania De Curtis

INFN and University of Florence
Galileo Galilei Institute for Theoretical Physics

On July 4th, 2012 the ATLAS and CMS collaborations finally announced the discovery of the Higgs boson … 48 years after its theoretical prediction (1964)

The value of the Higgs mass lies in a lucky spot



for a 50 GeV heavier Higgs only two basic decay channels WW and ZZ

for a 10 GeV lightest Higgs the WW and ZZ decay channels would have been impossible so far

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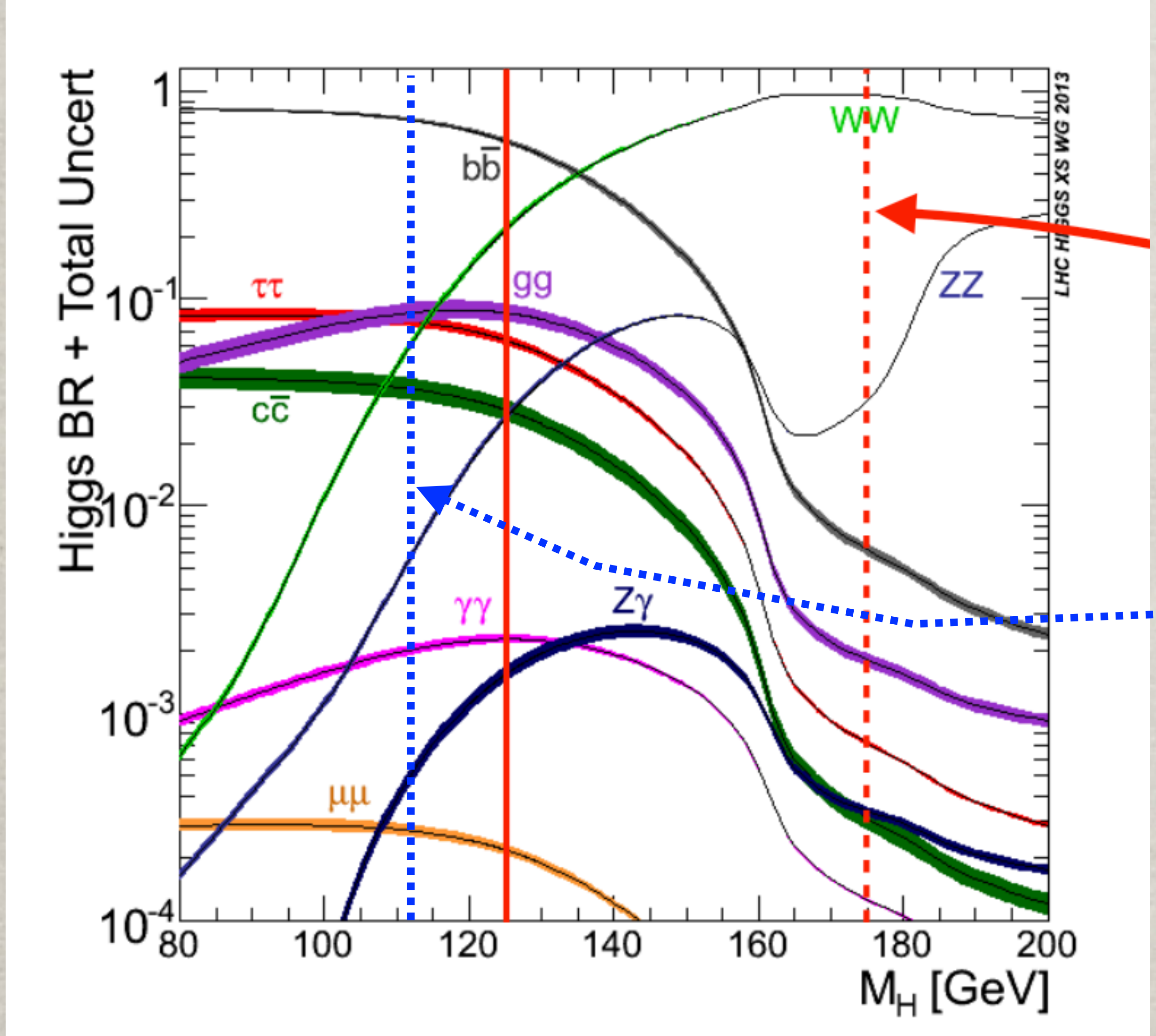
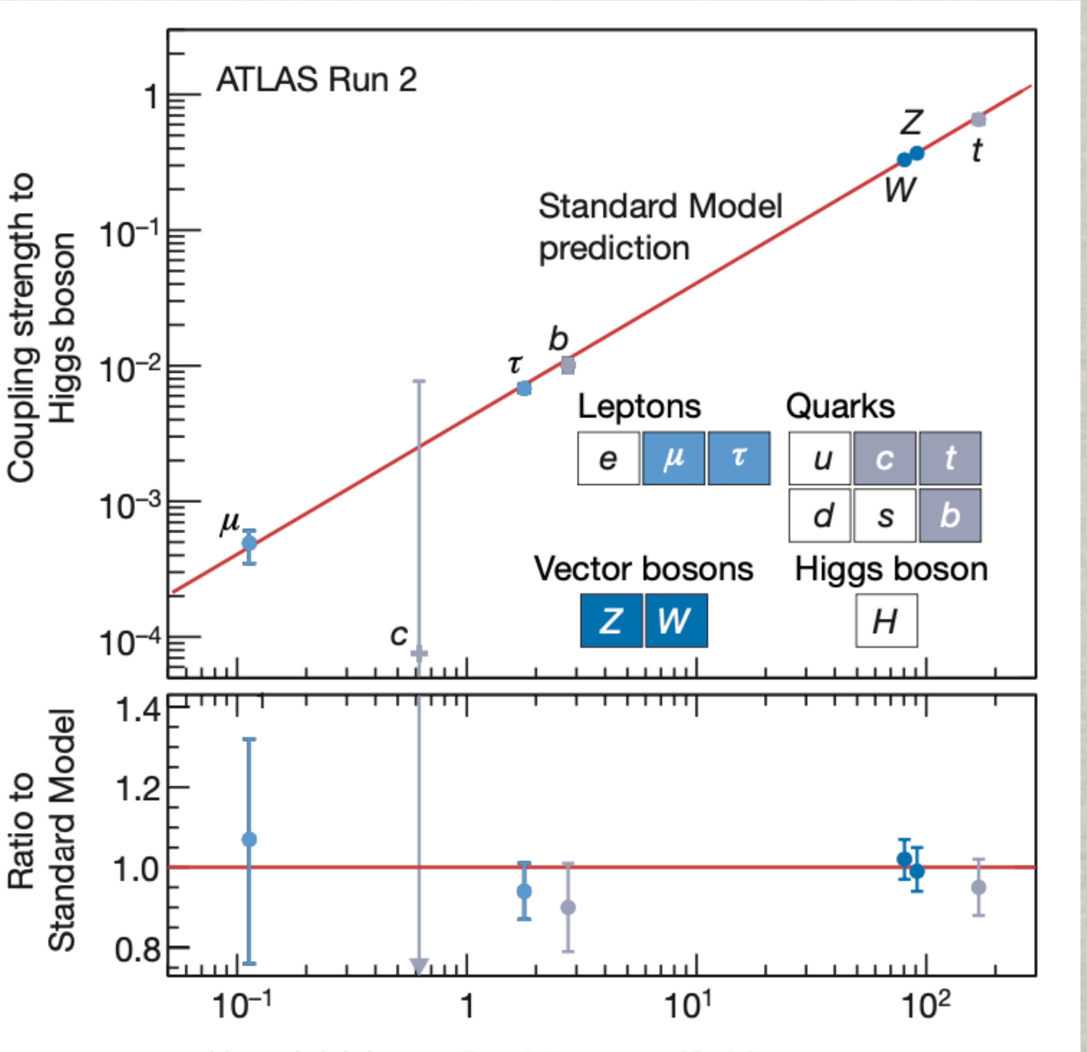
Measured coupling strengths to Higgs boson

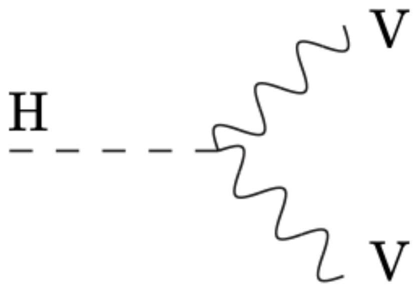




Nature, 607, 2022

The red straight line shows the excellent agreement with the SM prediction but…. several important couplings, like hhh are still very weakly constrained or **yet to be measured** like the ones to **light quarks**

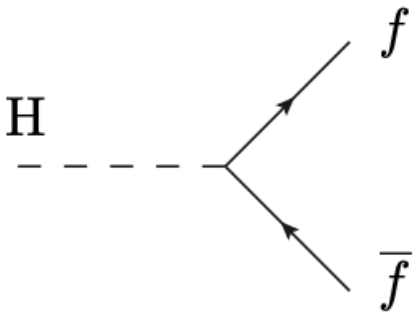
Pillars of Higgs Physics at Colliders



$$\frac{2m_V^2}{v}$$

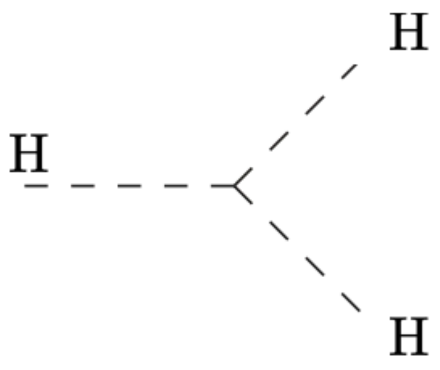
$$|D_\mu \phi|^2$$

This term could not exist without a vev



$$\frac{m_f}{v}$$

$$\bar{\psi}_i y_{ij} \psi_j \phi + h.c.$$



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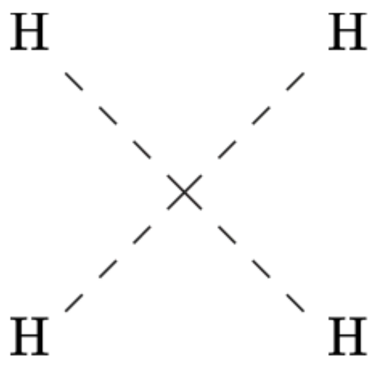
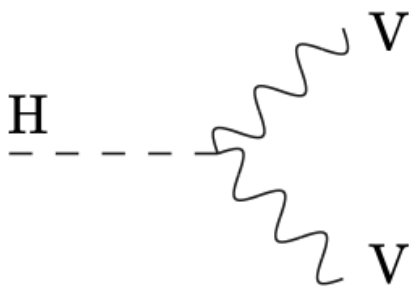


$$\frac{3m_H^2}{v^2}$$

$$V(\phi)$$

Pillars of Higgs Physics at Colliders



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$\kappa_{W,Z}$	Current	HL-LHC
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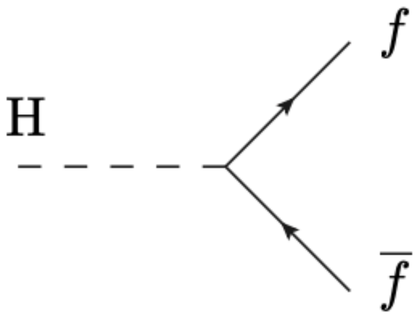

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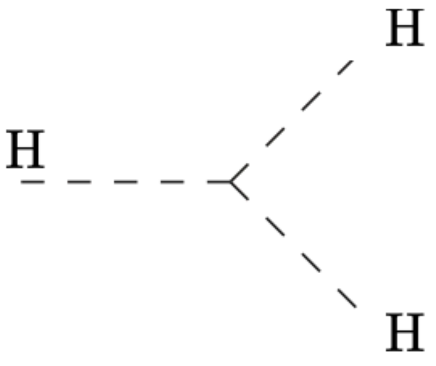

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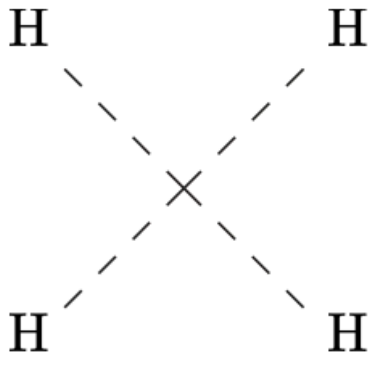

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Marumi Kado, IFAE 2024

$$\kappa_X = \frac{g_{hXX}}{g_{hXX}^{\mathrm{SM}}}$$

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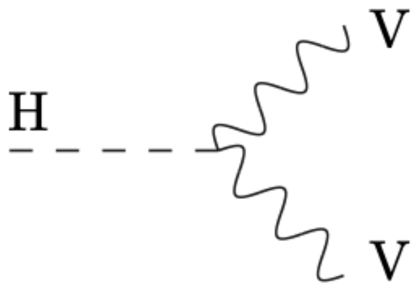

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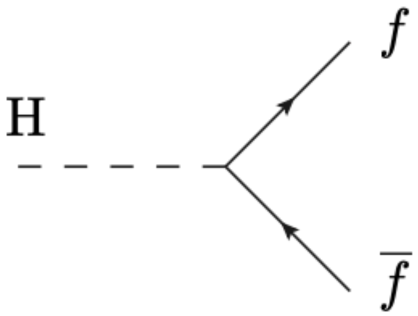

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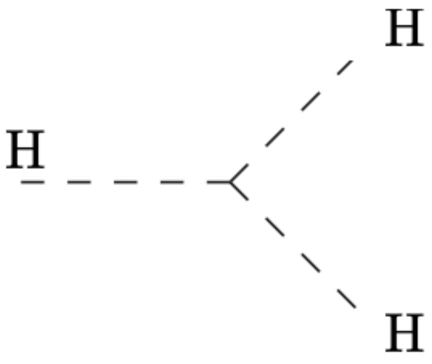
κ_t	11%	3.4%
κ_b	11%	3.7%
κ_τ	8%	1.9%



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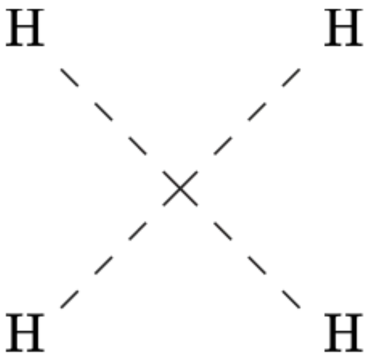

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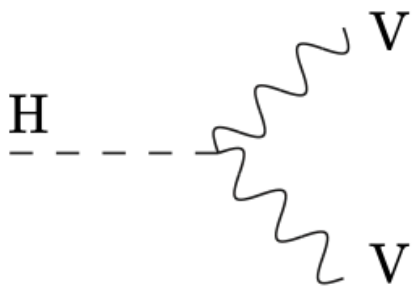

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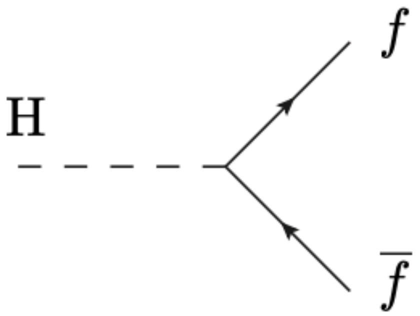

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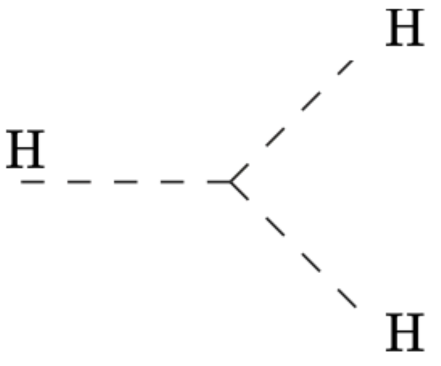

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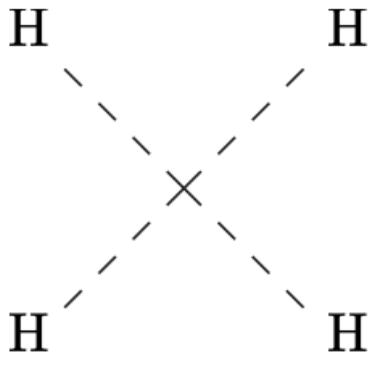

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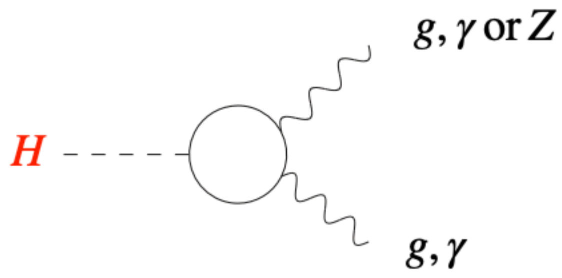
Probing new particles through loops in production and decays!



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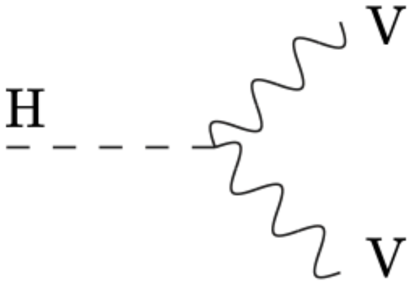

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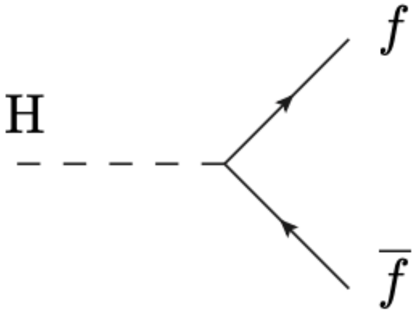

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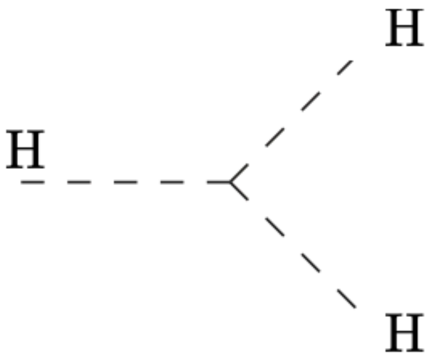

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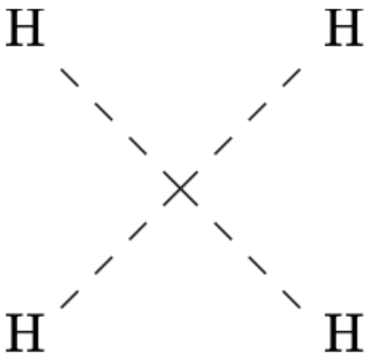

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SM

$$V(\phi) = \mu^2 \phi^* \phi + \lambda (\phi^* \phi)^2$$

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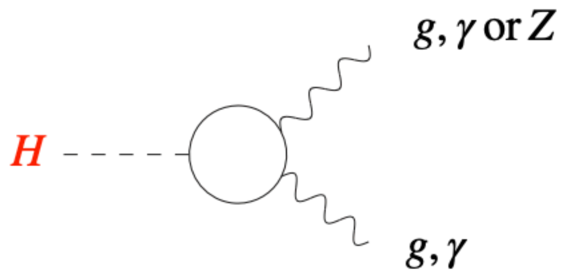

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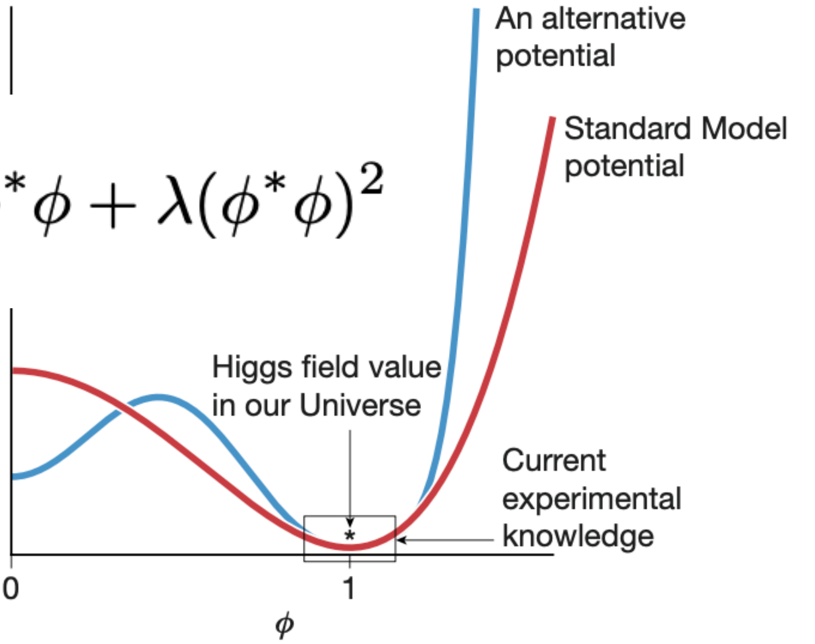

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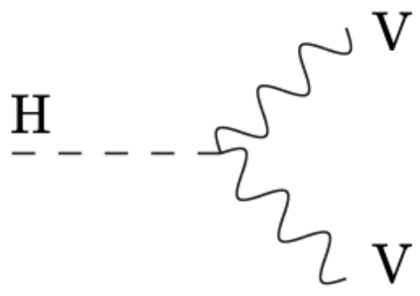
Salam, Wang, Zanderighi *Nature* 607 (2022) 7917

Pillars of Higgs Physics at Colliders



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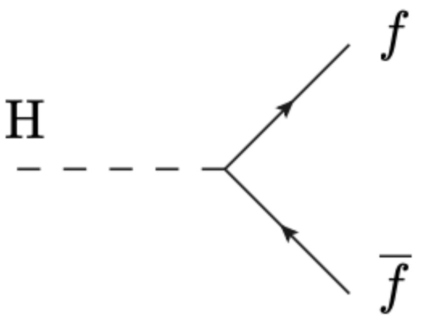

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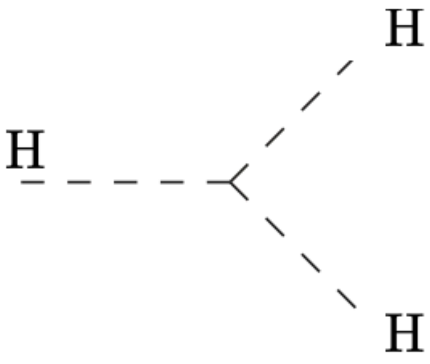

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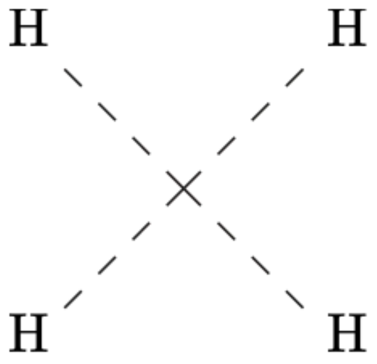

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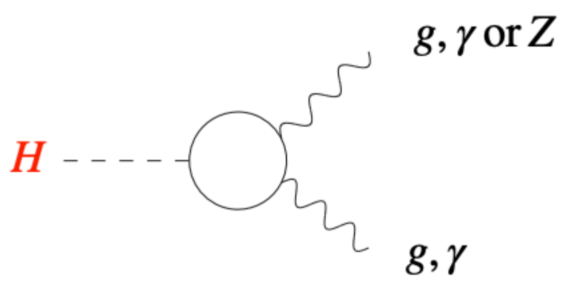

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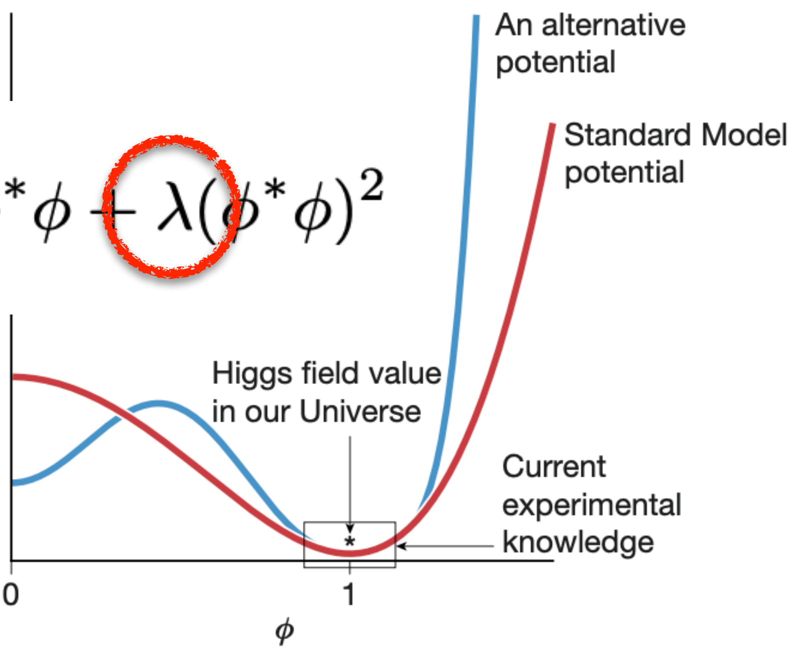

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At HL-LHC

κ_λ **~50%**

Salam, Wang, Zanderighi *Nature* 607 (2022) 7917

di-Higgs production and Higgs self coupling

Both during Run 3 of the LHC and the HL-LHC phase, a target process will be di-Higgs production as it provides a unique and direct probe of the Higgs boson self-coupling and a sensitive probe to BSM scenarios

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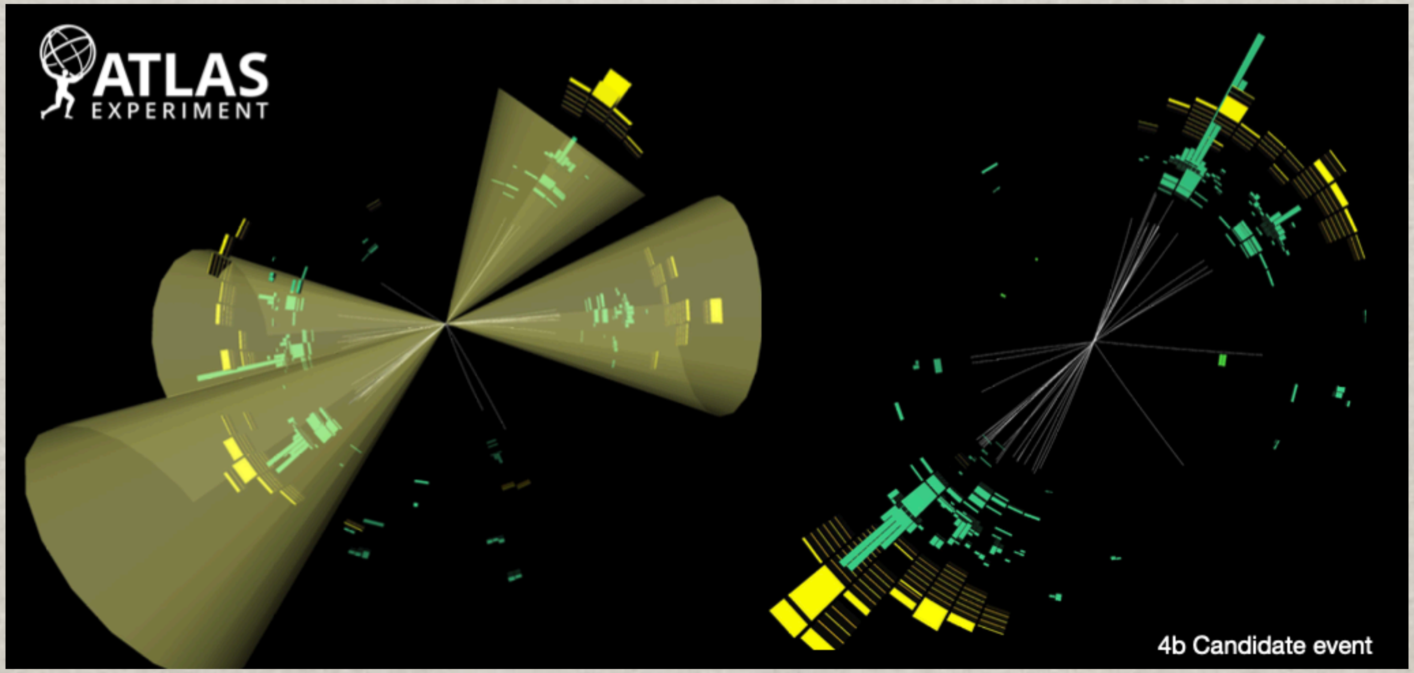
Very small cross section ~1000 times smaller than Higgs production
Huge challenge !

Multiple Higgs decay channels investigated: bb, $\gamma\gamma$, $\tau\tau$, WW

Reached a sensitivity to exclude at 95% CL di-Higgs production 2-3 times higher than expected in the SM

Analyses performance improved by ~50% w.r.t. earlier the Run 2



more than 100K events will be produced at HL-LHC

Still 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

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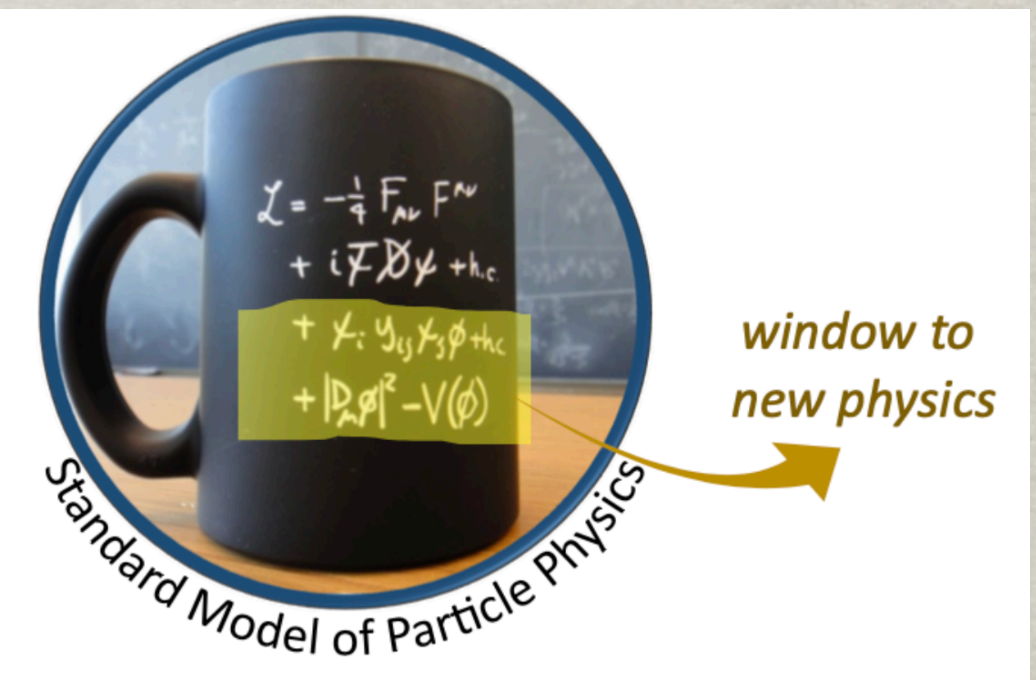
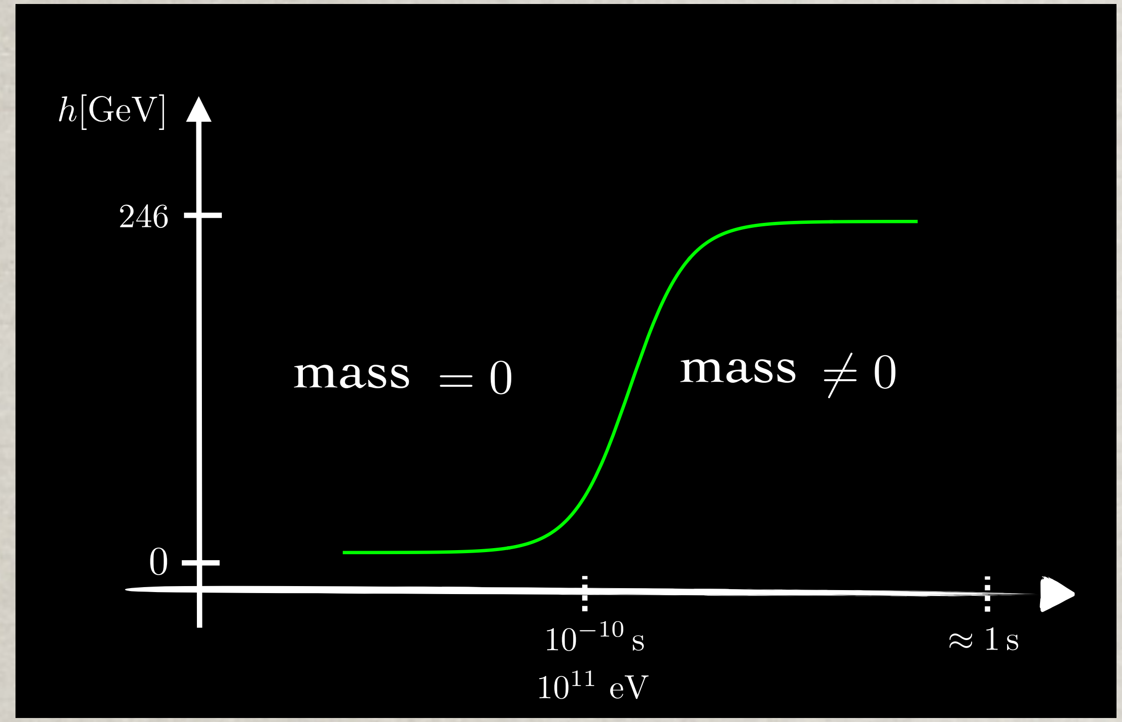
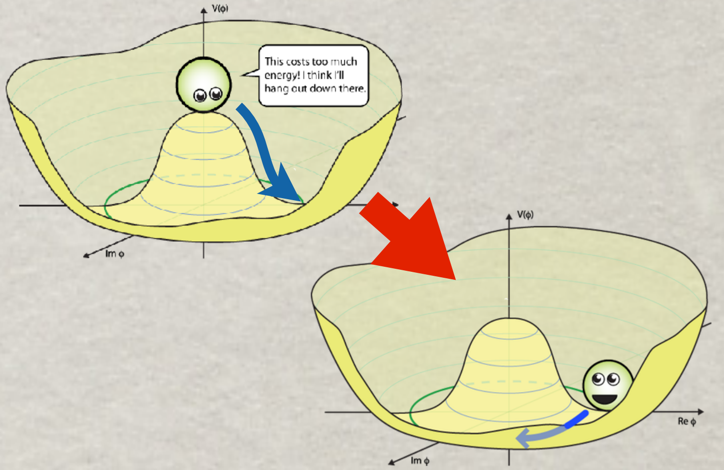


The Higgs and the Universe Evolution

The EW phase transition is responsible for mass generation



When the Higgs moved to the minimum of the potential it generated a cosmological phase transition



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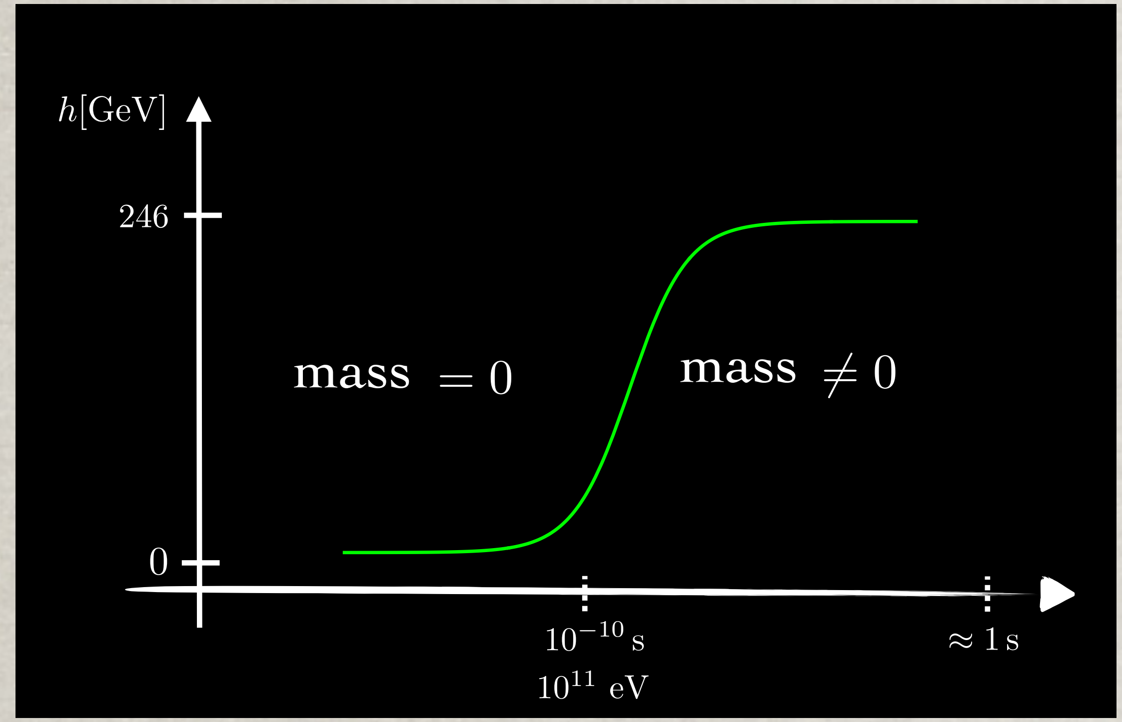

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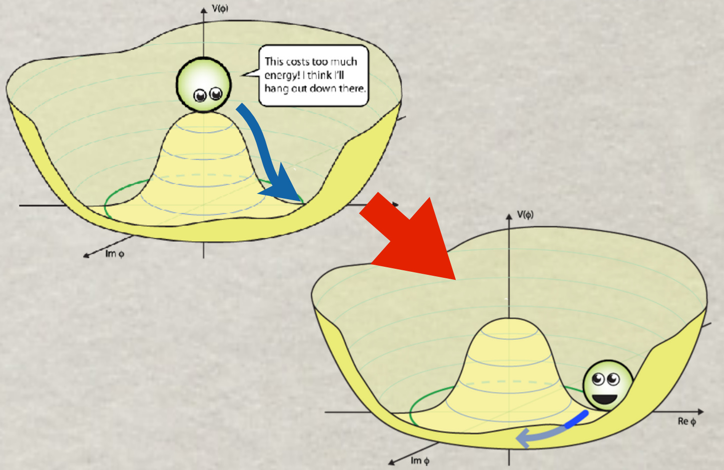
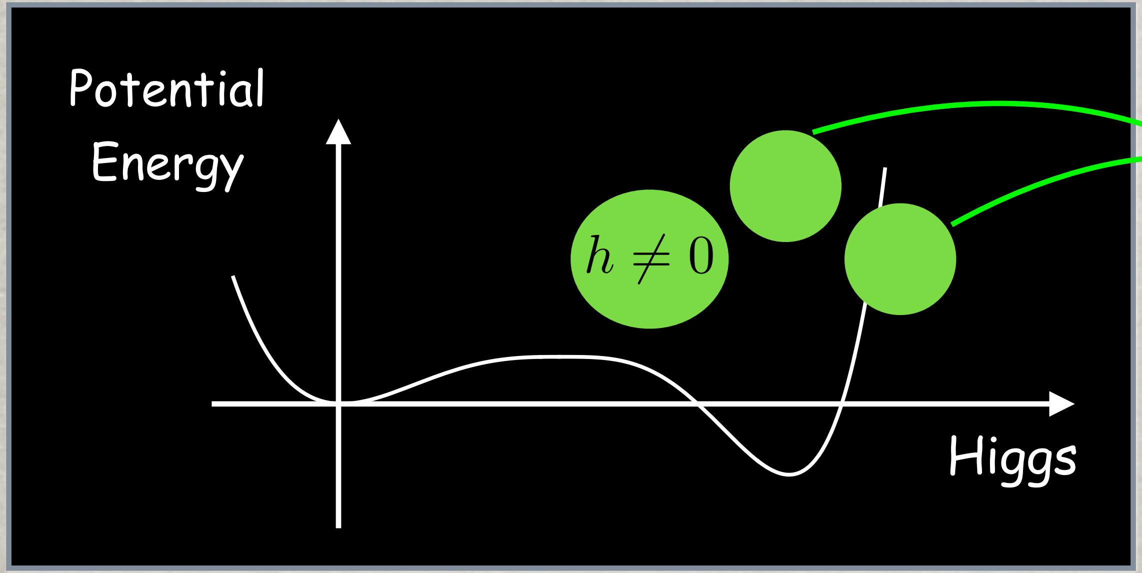


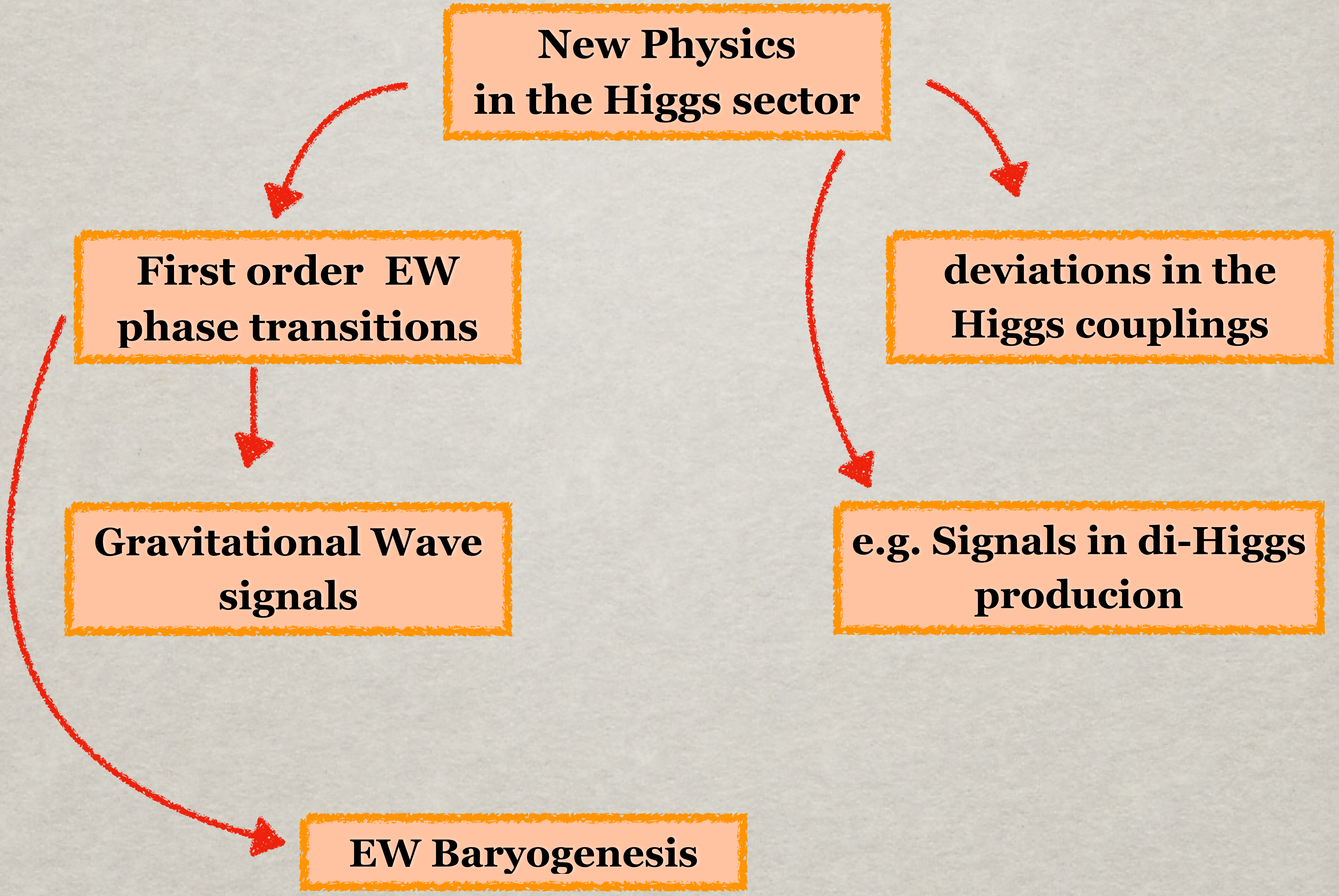
The EW transition starts at the bubble nucleation temperature, and can trigger Baryogenesis

Difficult within the SM
—> explore BSM solutions



new fields?
new dynamics?

New Physics in the Early Universe



New Physics
in the Higgs sector

First order EW
phase transitions

Gravitational Wave
signals

EW Baryogenesis

deviations in the
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e.g. Signals in di-Higgs
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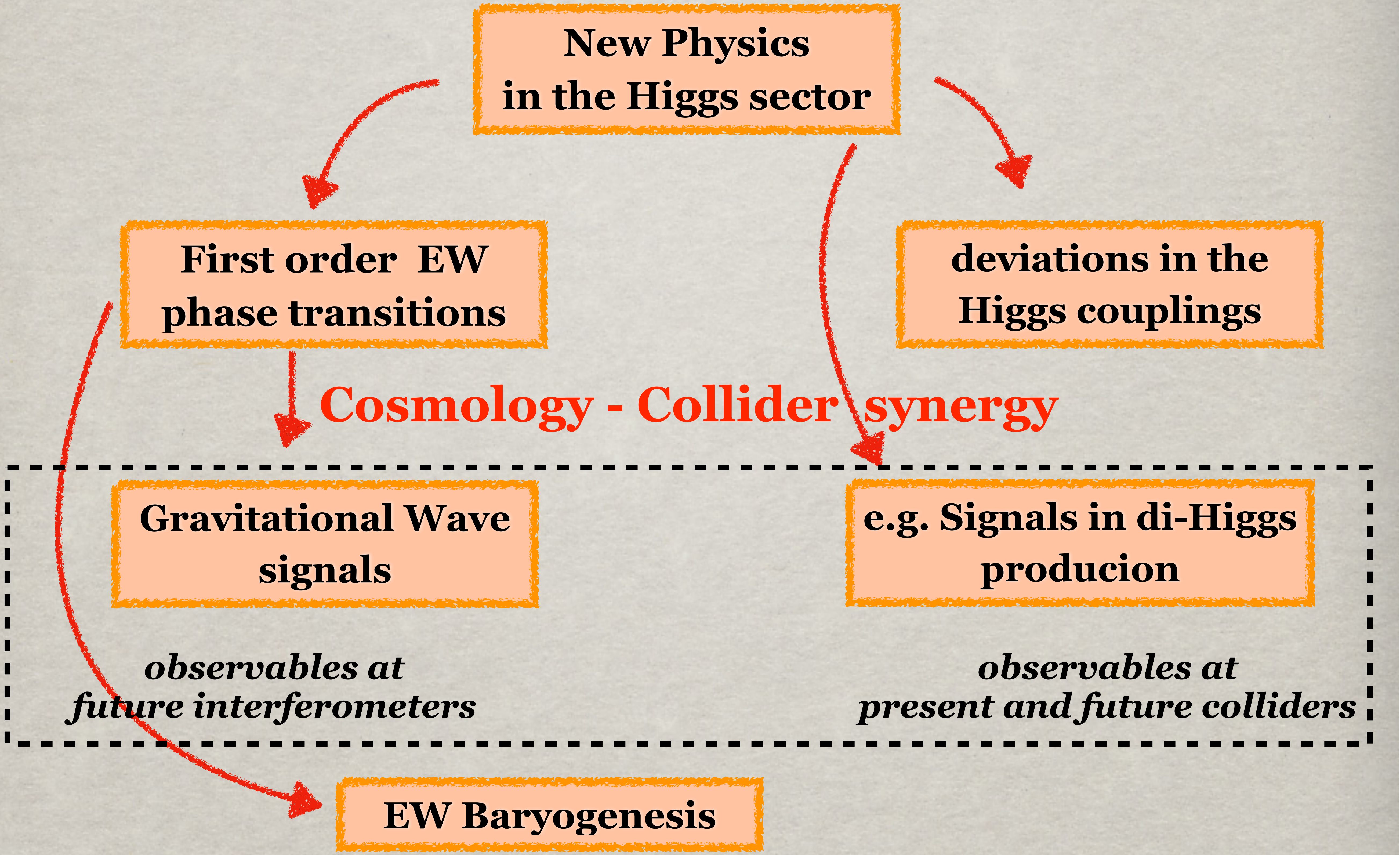


New Physics in the Higgs sector

First order EW phase transitions

deviations in the Higgs couplings

Cosmology - Collider synergy

Gravitational Wave signals

e.g. Signals in di-Higgs producion

observables at future interferometers

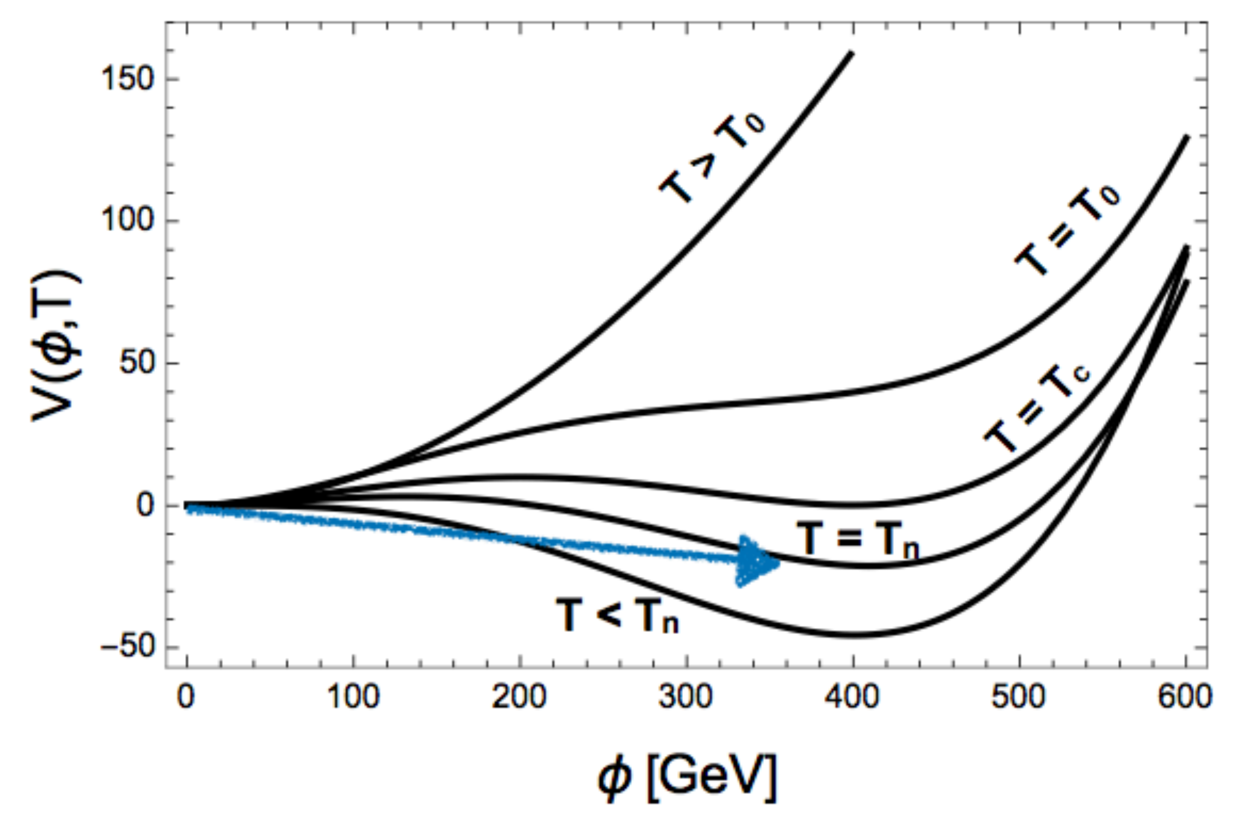
observables at present and future colliders

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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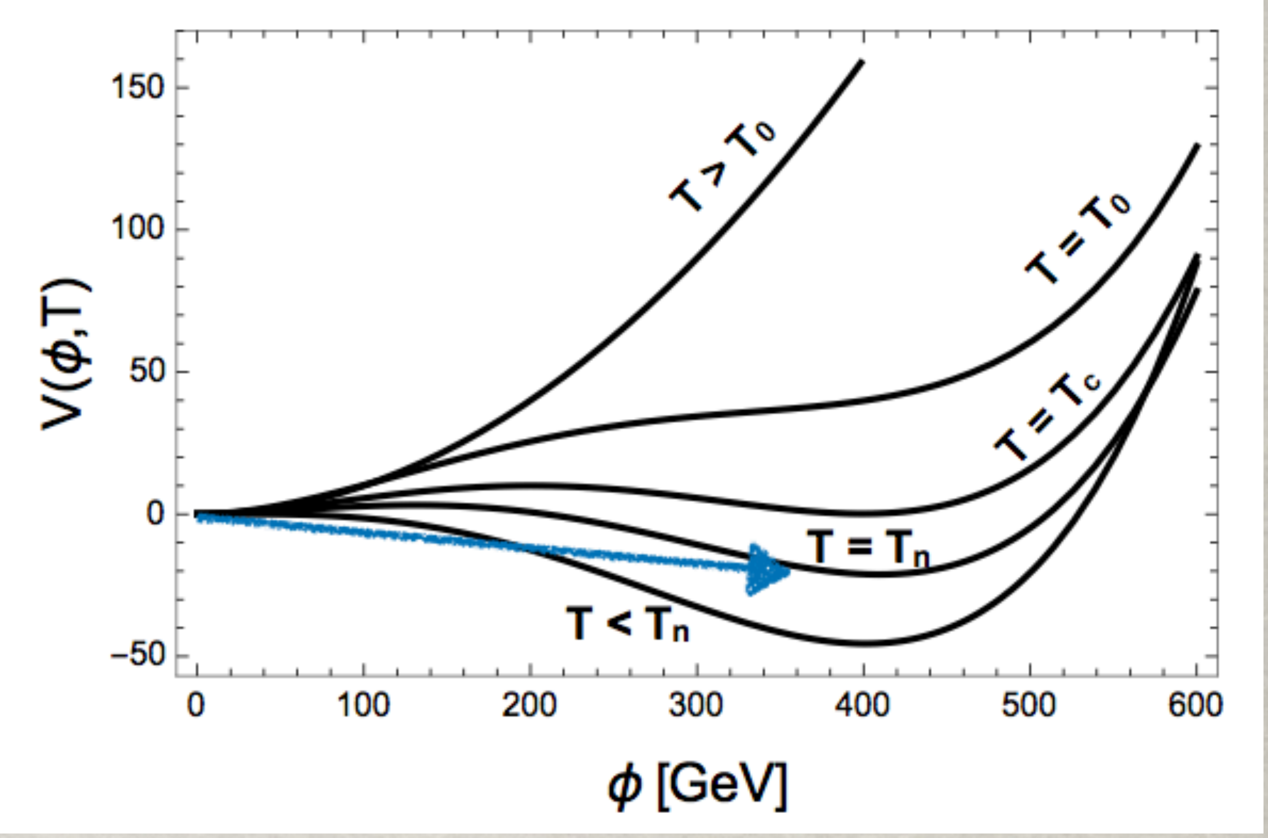
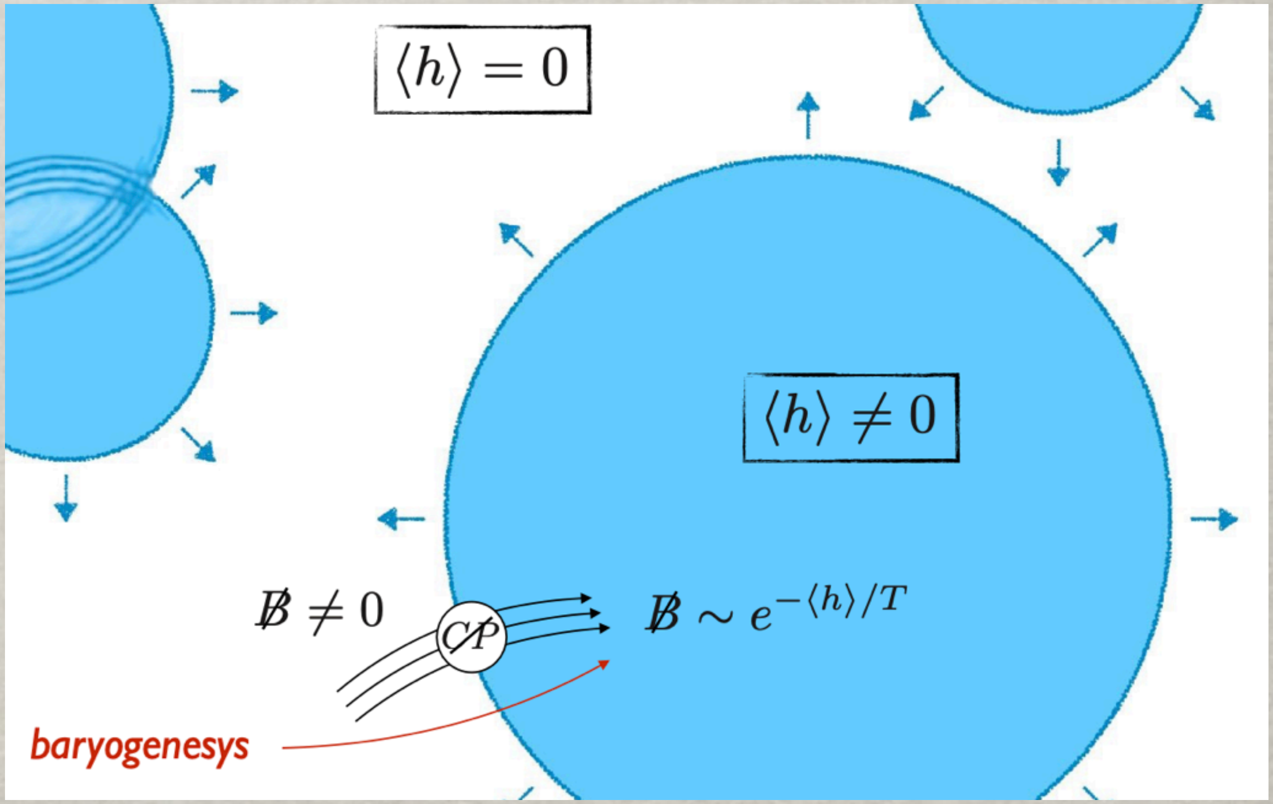


Sakharov Conditions for Baryogenesis

- ☑ Barion number violation
- ☑ C and CP violation
- ☑ **Out of equilibrium dynamics:** (strong) 1^{st} order phase transition



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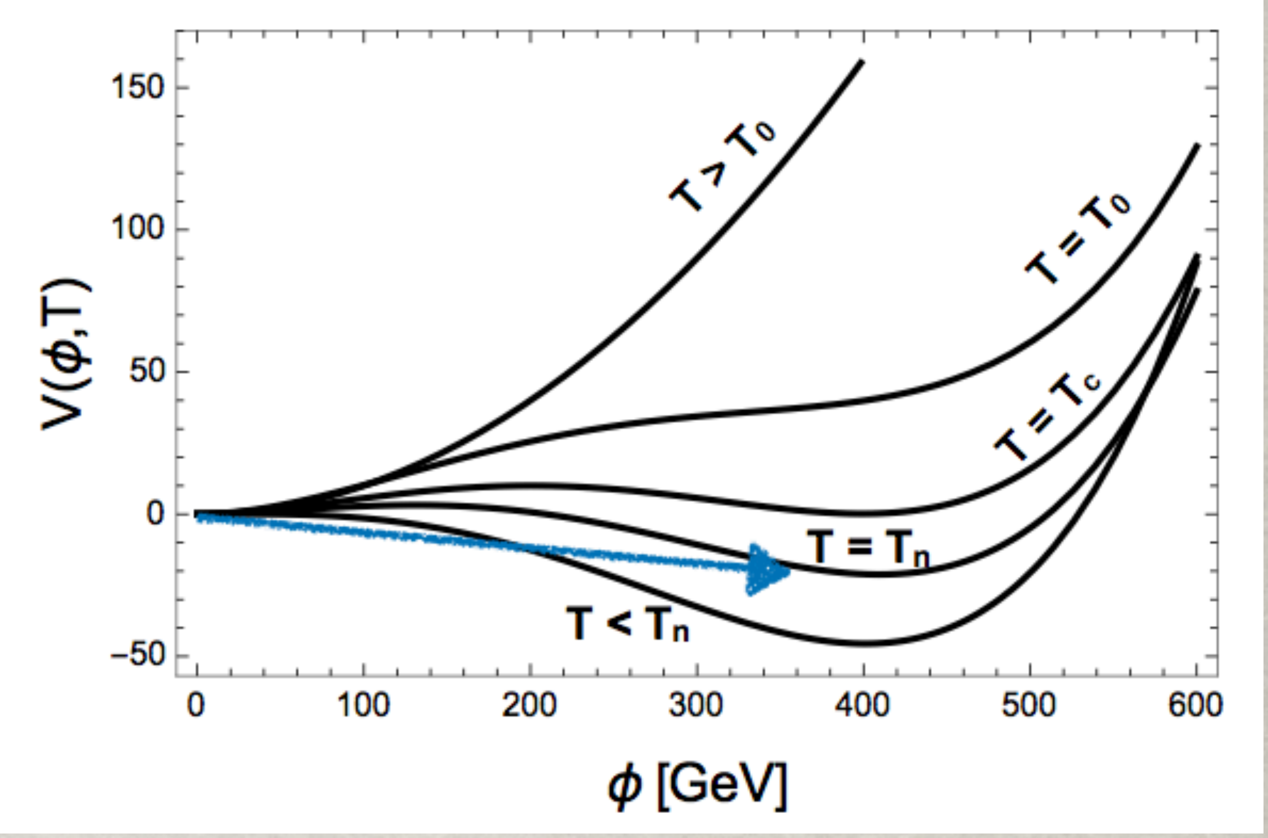

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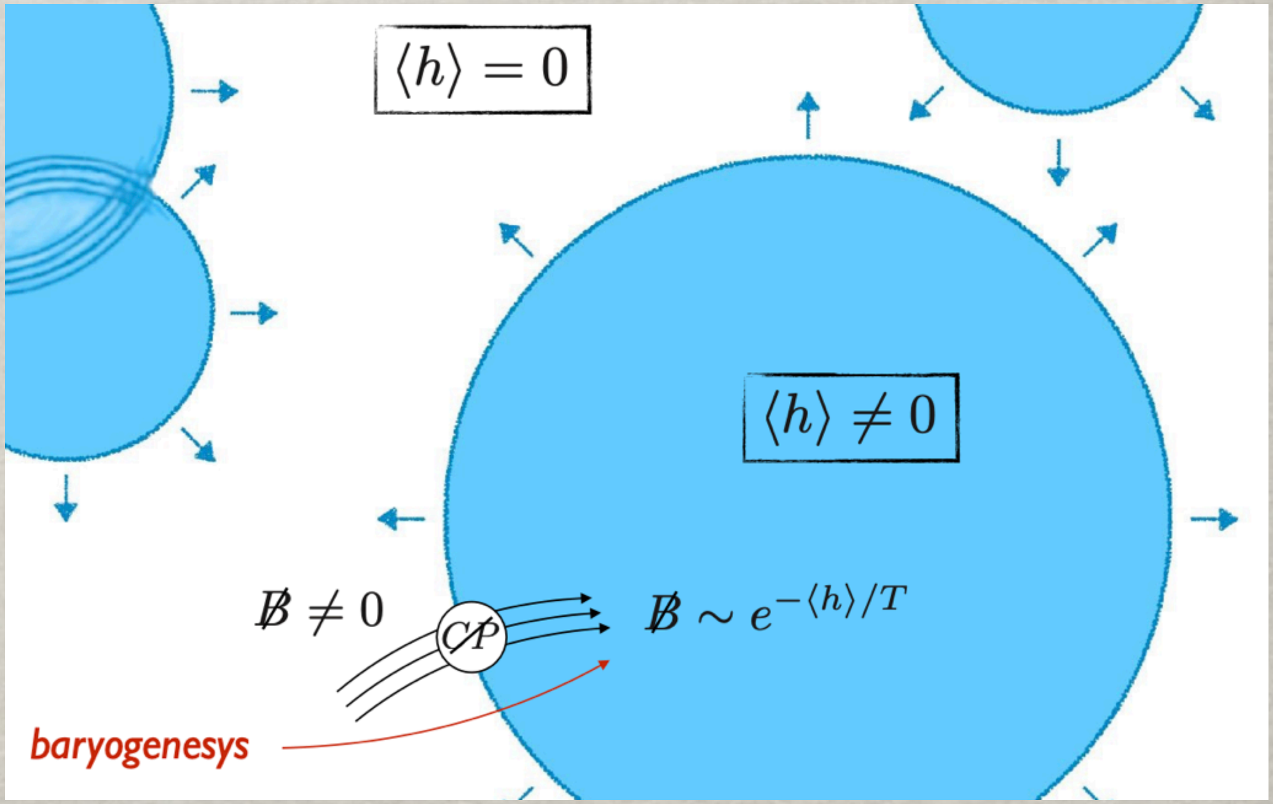

In the SM phase transition is a smooth crossover, also not enough CP violation from CKM → **NP needed !!**

The SM + scalar singlet

(Espinosa,Konstandin,Riva '11)

Higgs + singlet effective potential (Z_2 symmetric) in the high-temperature limit

$$V(h,\eta,T) = \frac{\mu_h^2}{2}h^2 + \frac{\lambda_h}{4}h^4 + \frac{\mu_\eta^2}{2}\eta^2 + \frac{\lambda_\eta}{4}\eta^4 + \frac{\lambda_{h\eta}}{2}h^2\eta^2 + \left(c_h\frac{h^2}{2} + c_\eta\frac{\eta^2}{2}\right)T^2$$

thermal corrections

thermal masses (count the dof coupled to the scalars)

$$c_h = \frac{1}{48}(9g^2 + 3g'^2 + 12y_t^2 + 24\lambda_h + 2\lambda_{h\eta}) \qquad c_\eta = \frac{1}{12}(4\lambda_{h\eta} + \lambda_\eta)$$

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portal interaction

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$$V(h,\eta,T) = \frac{\mu_h^2}{2}h^2 + \frac{\lambda_h}{4}h^4 + \frac{\mu_\eta^2}{2}\eta^2 + \frac{\lambda_\eta}{4}\eta^4 + \underbrace{\boxed{\frac{\lambda_{h\eta}}{2}h^2\eta^2}}_{\text{portal interaction}} + \underbrace{\left(c_h\frac{h^2}{2} + c_\eta\frac{\eta^2}{2}\right)T^2}_{\text{thermal corrections}}$$

thermal masses (count the dof coupled to the scalars)

$$c_h = \frac{1}{48}(9g^2 + 3g'^2 + 12y_t^2 + 24\lambda_h + 2\lambda_{h\eta}) \qquad c_\eta = \frac{1}{12}(4\lambda_{h\eta} + \lambda_\eta)$$

☑ EW symmetry restored at very high T: <h, η> = (0,0)

☑ Two interesting patterns of symmetry breaking (as the Universe cools down):

1. (0,0) → (v,0) one-step PhT
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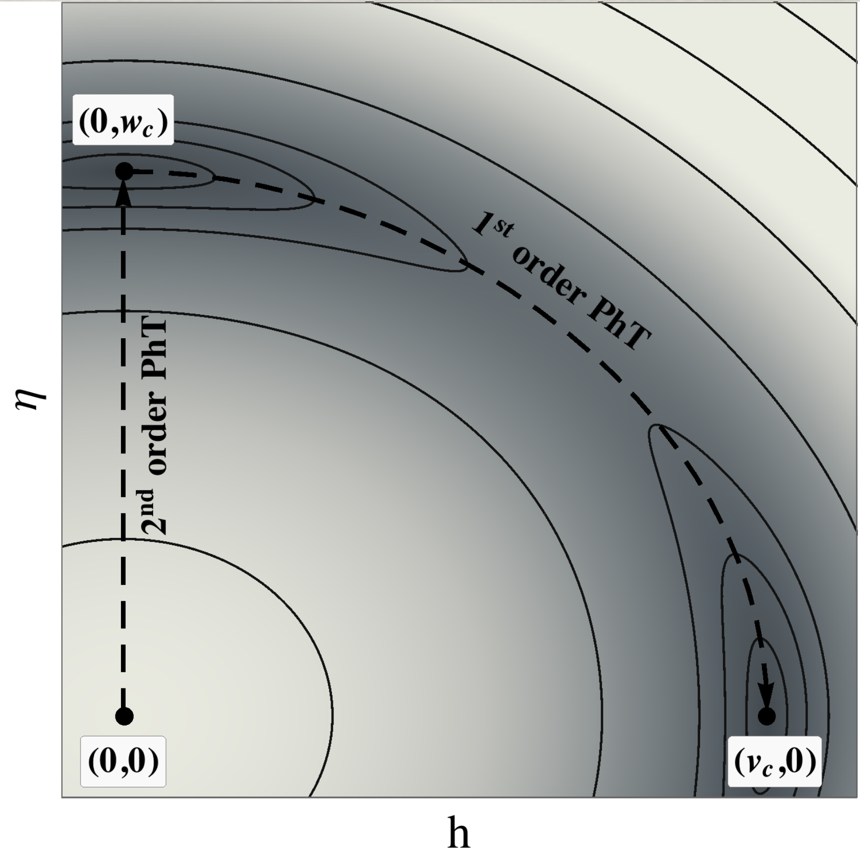

darker color corresponds to deeper potential

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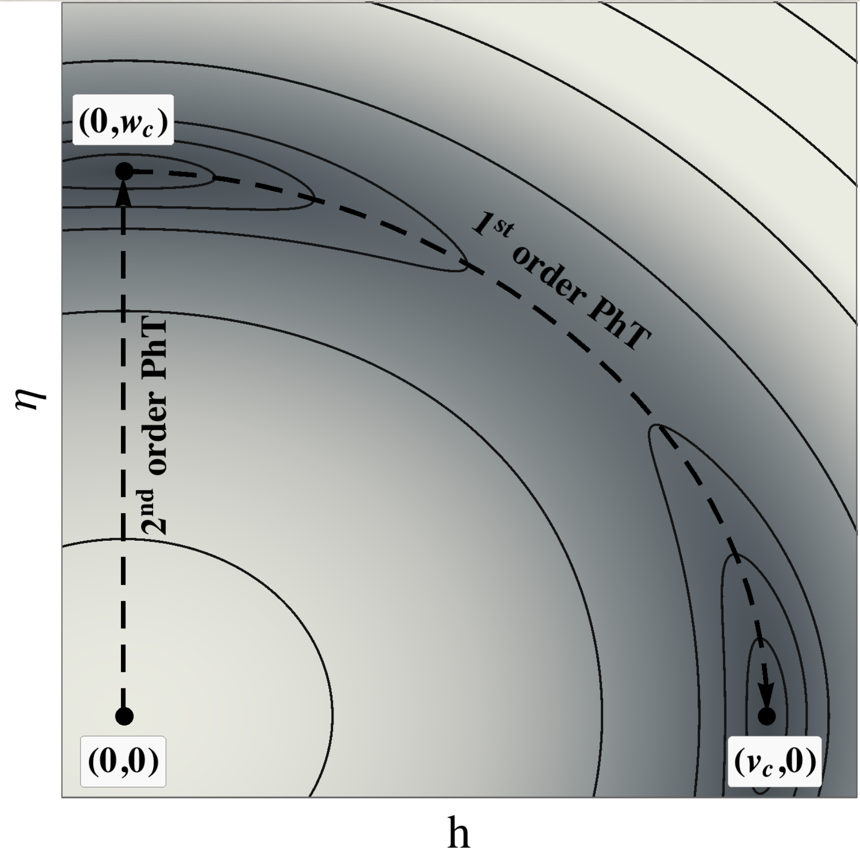
Is it possible to realise it in a CHM scenario based on SO(6)/SO(5)?

extended pNGB Higgs sector with an extra scalar singlet



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Composite Dynamics in the Early Universe
Properties of the EWPhT

(De Curtis,Delle Rose,Panico,2019)

H+ η pNGBs of SO(6) -> SO(5)

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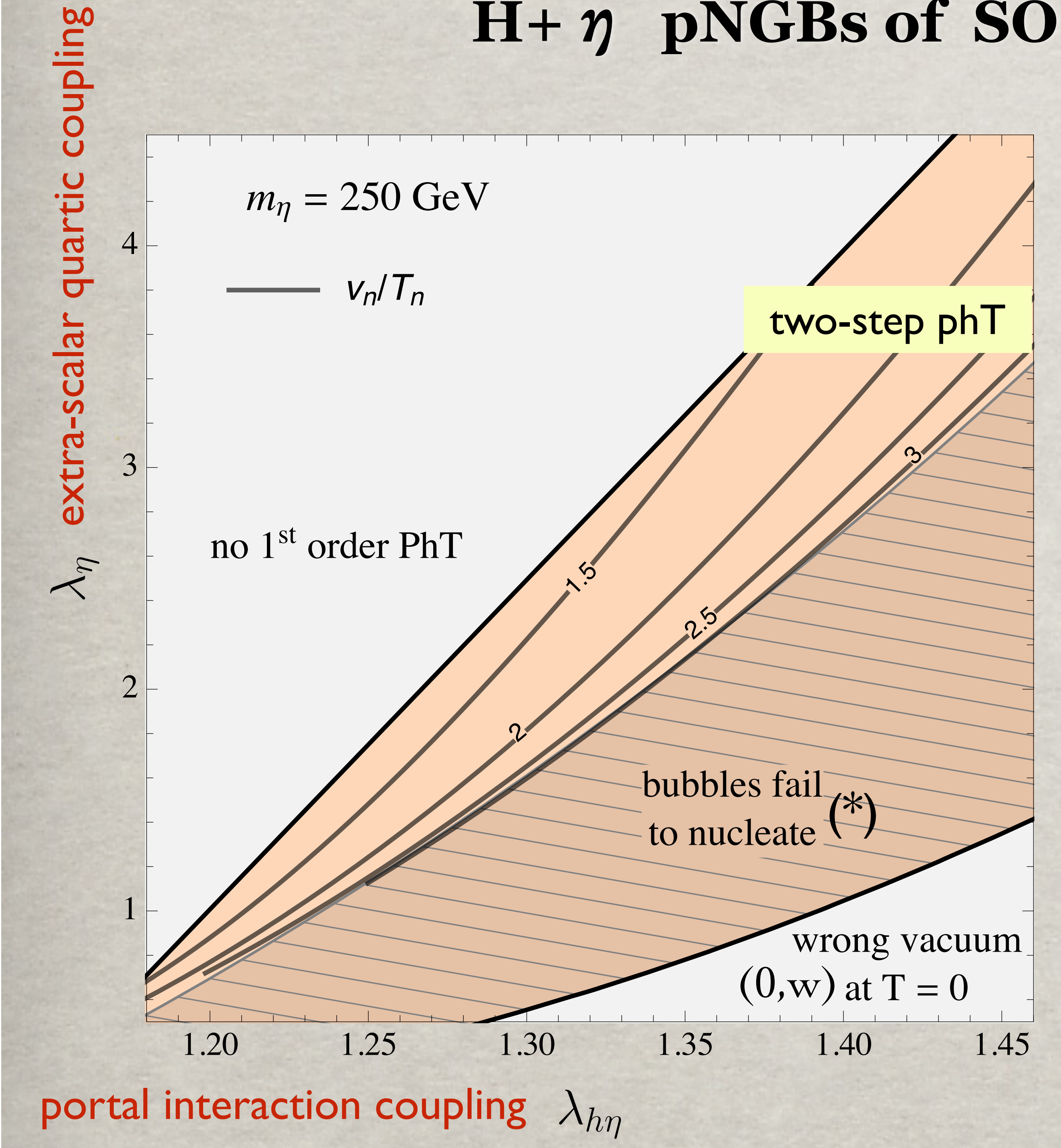

The EWPhT starts at $T_n < T_c$ determined by requiring: Probability of nucleation of bubbles / Hubble volume ~ 1

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

(*) 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

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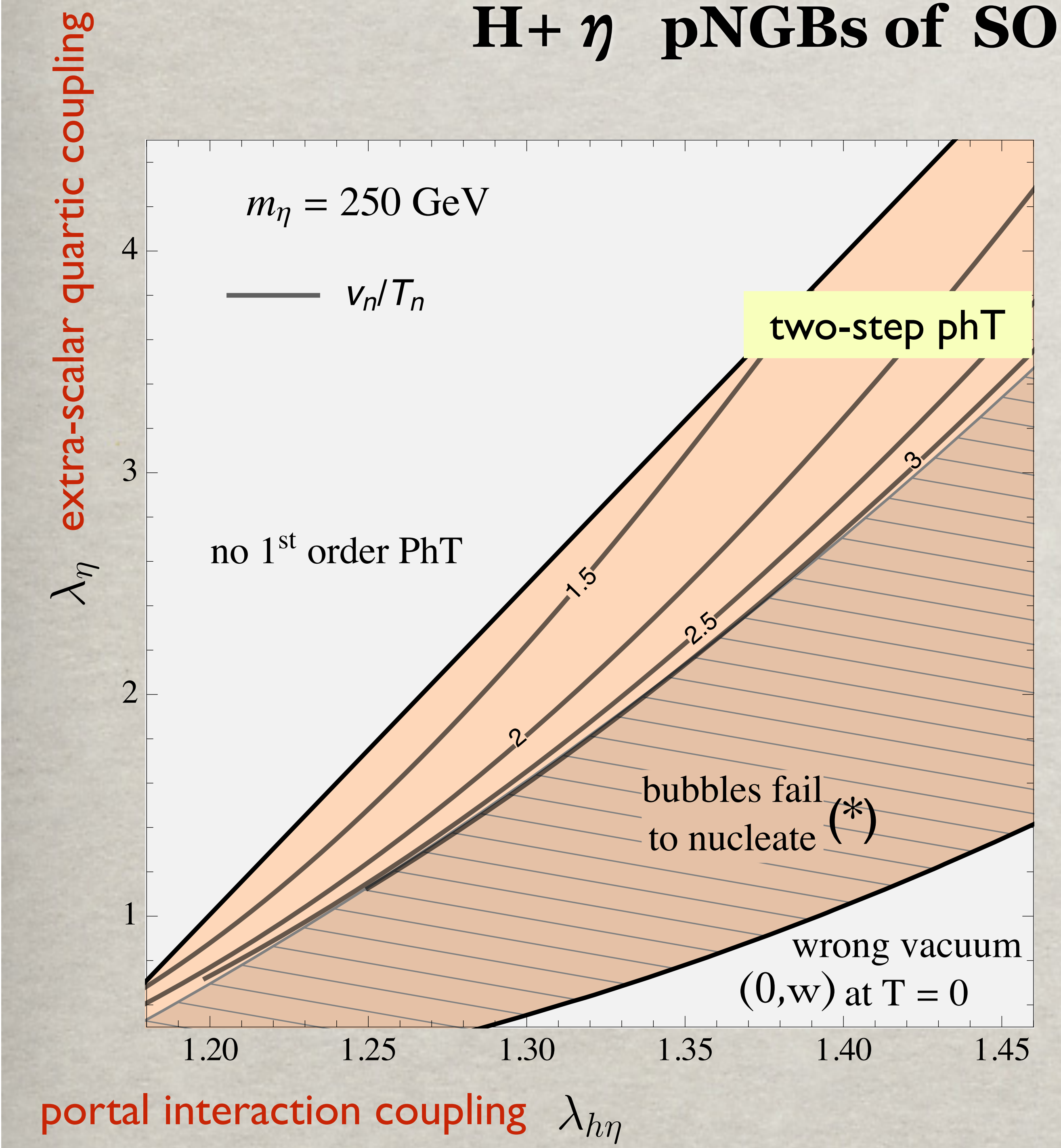

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—— Strength of the phase transition
v_n/T_n ($v_n = \langle h \rangle |_{T_n}$)
a crucial parameter for EWBG

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

(*) 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

EW Baryogenesis

☑ The out-of-equilibrium dynamics fulfils only one of the Sakharov's conditions to realise baryogengesis → a strong source of CP is also needed to explain the observed baryon asymmetry

(Espinosa,Gripaios,Kostandin,Riva,'12)

BONUS

☑ An additional source of CP is present in CHMs due to the non-linear dynamics of the GBs → ex: dimension 5 operator $\eta h \bar{t}_L t_R$ can have a complex coefficient

$$\mathcal{O}_t = y_t \left(1 + i\frac{b}{f}\eta\right) \frac{h}{\sqrt{2}} \bar{t}_L t_R + \text{h.c.} \qquad m_q = |m_q(v,w)|\, e^{i\theta(w)} \qquad v \equiv \langle h \rangle , w \equiv \langle \eta \rangle$$

☑ It induces a phase in the top mass which becomes physical during the EW phase transition at T ≠ 0 when η changes its VEV. This is realised on the bubble walls during the two-step phase transition (0,0) → (0,w) → (v, 0)

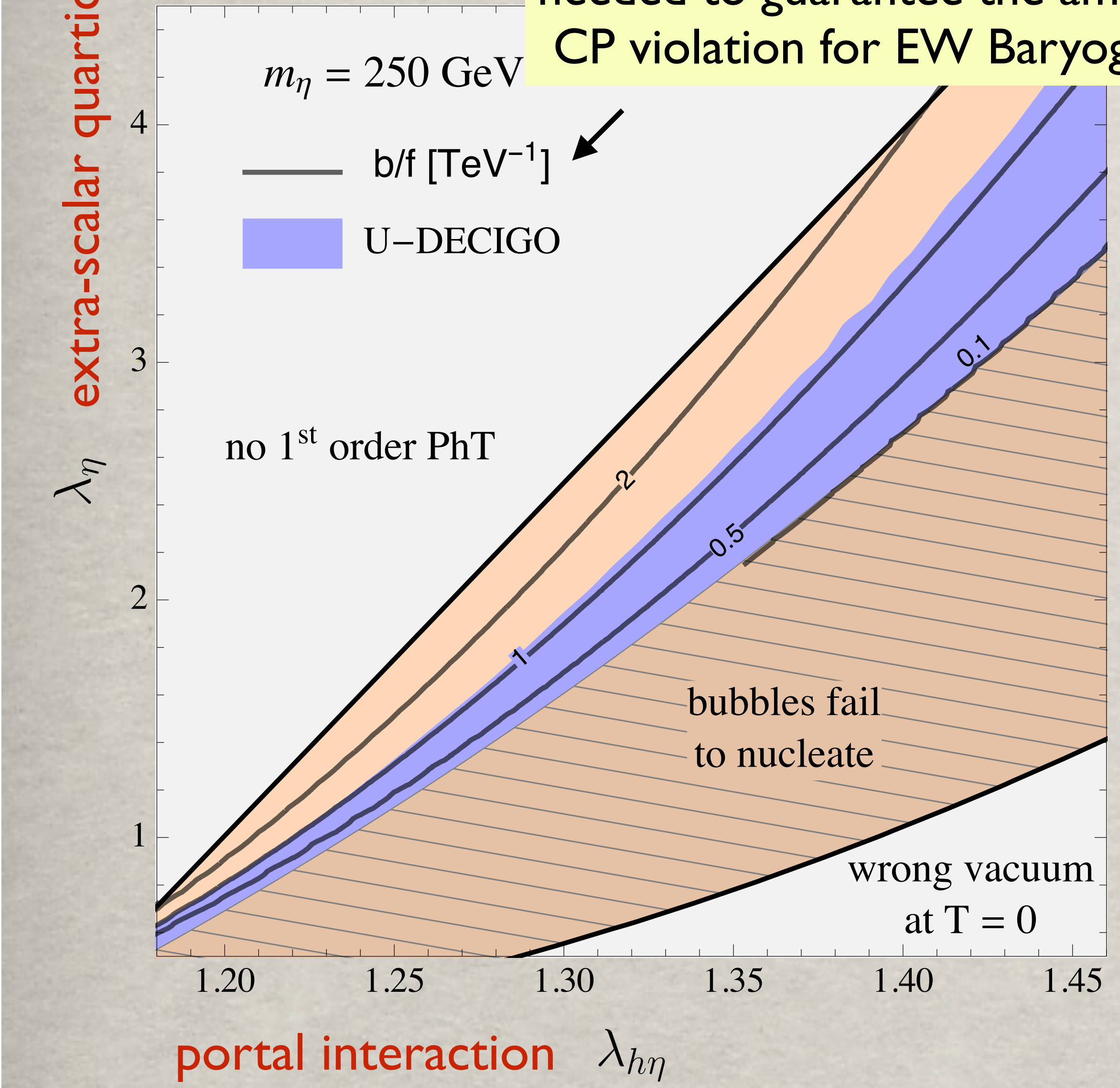
if w = 0 at T = 0, no constrains on the EDM

☑ The baryon asymmetry depends on the variation of the phase of the top mass, the strength of the PhT, the bubble width, the bubble wall velocity. To reproduce the observed baryon asymmetry $(n_B - n_{\bar{B}})/n_\gamma \simeq 6 \times 10^{-10}$ b/f ≲ TeV^{-1} is enough

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

extra-scalar quartic coupling



portal interaction coupling

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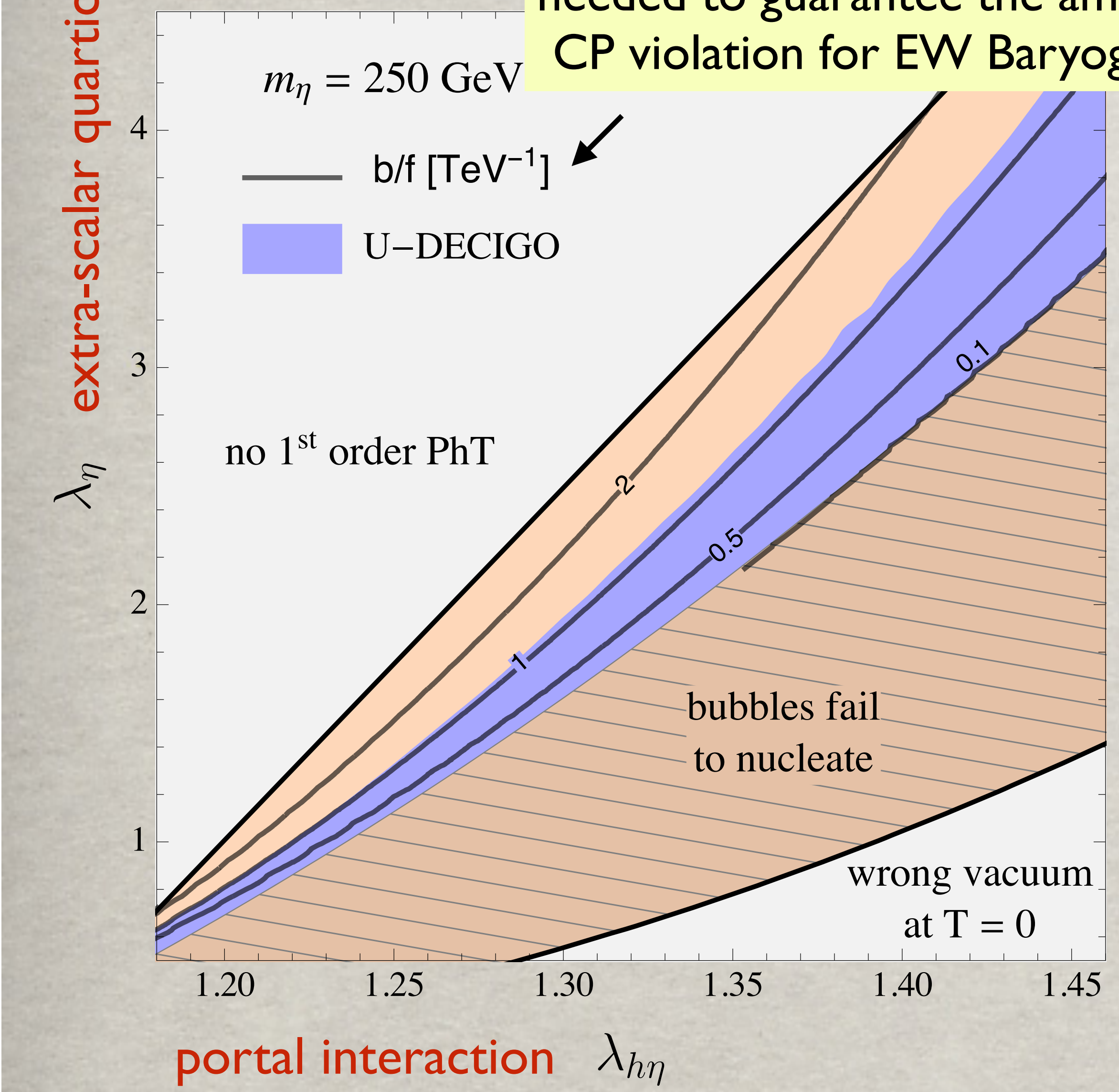


extra-scalar quartic coupling

portal interaction coupling

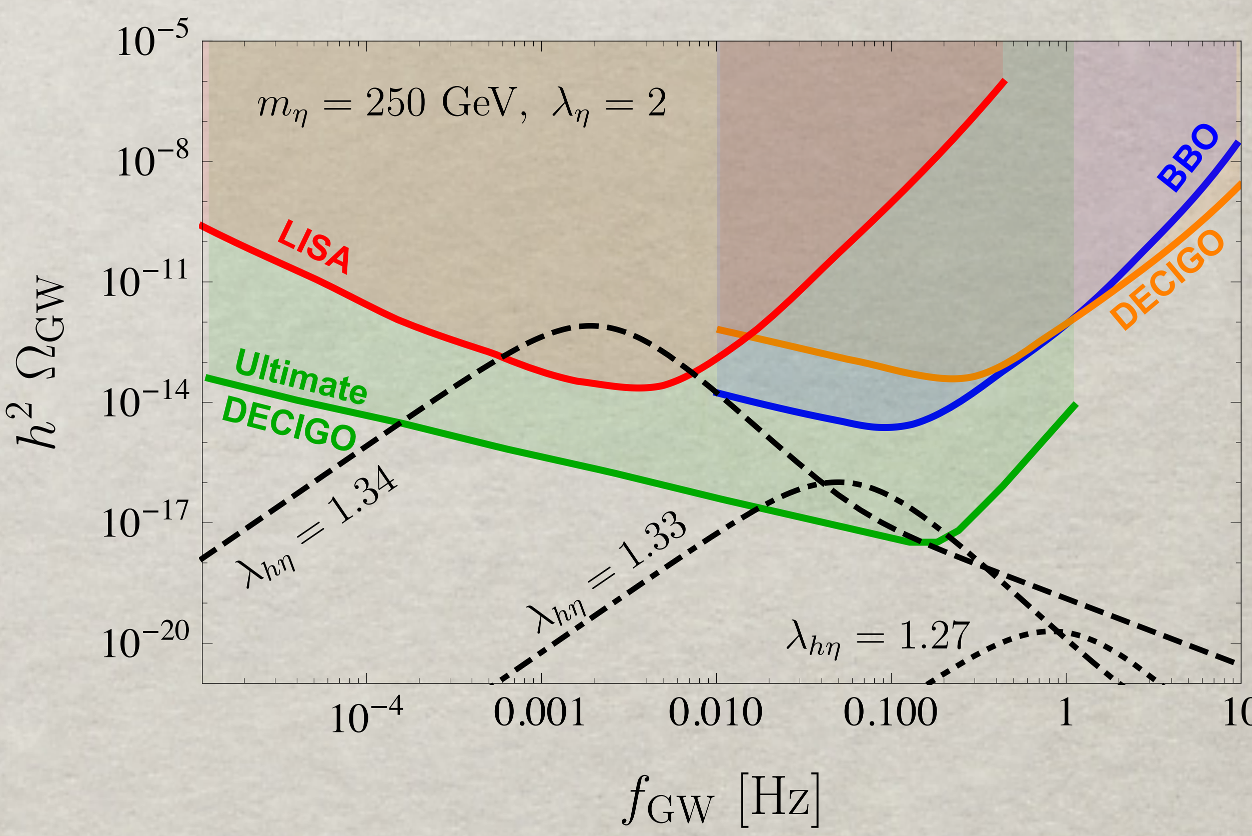
The bubbles expand, collide incoherently …

Stochastic Background of GW's :

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

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

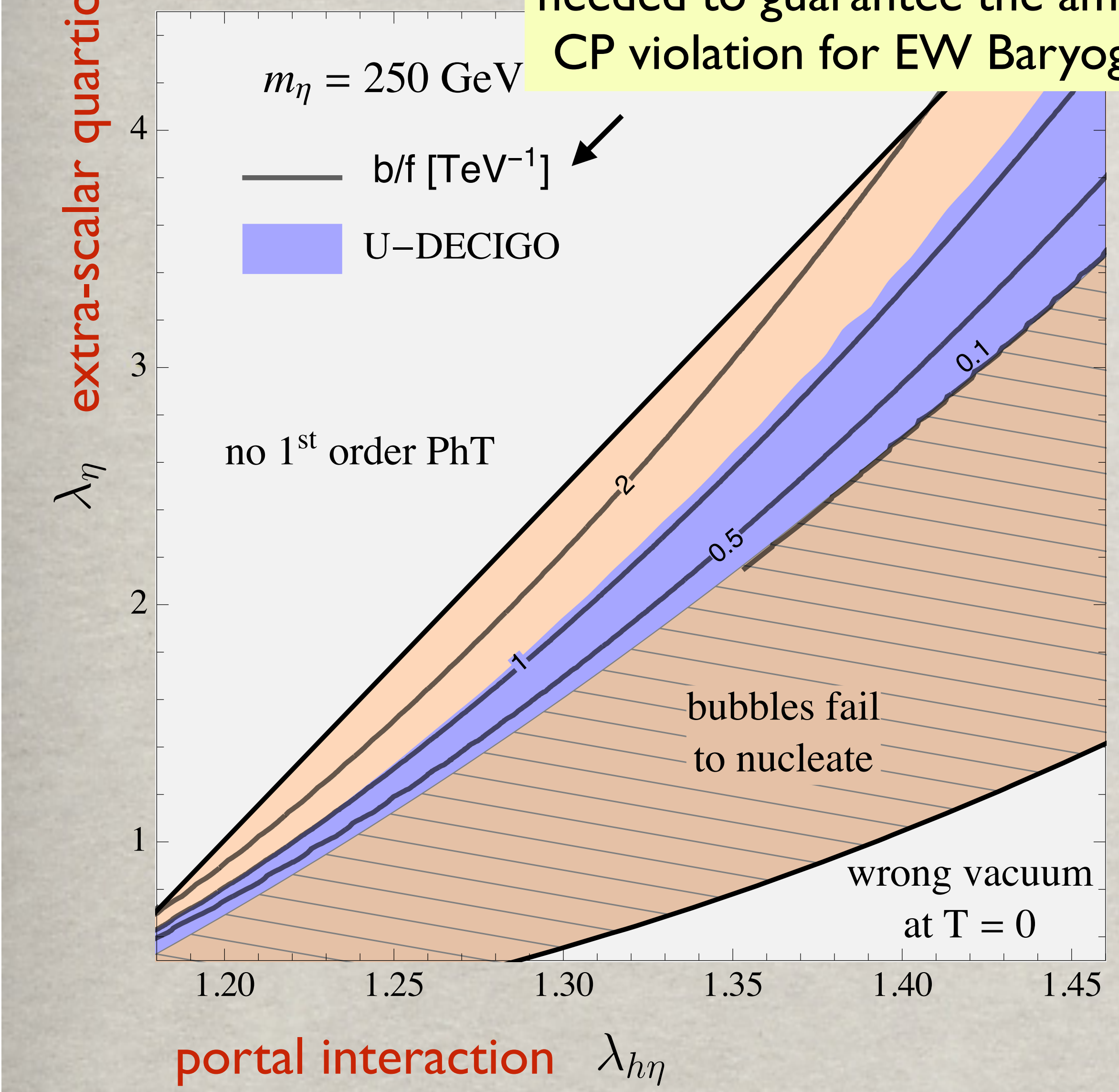
Gravitational Wave Spectrum



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

same region where the EWBG could be achievable

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



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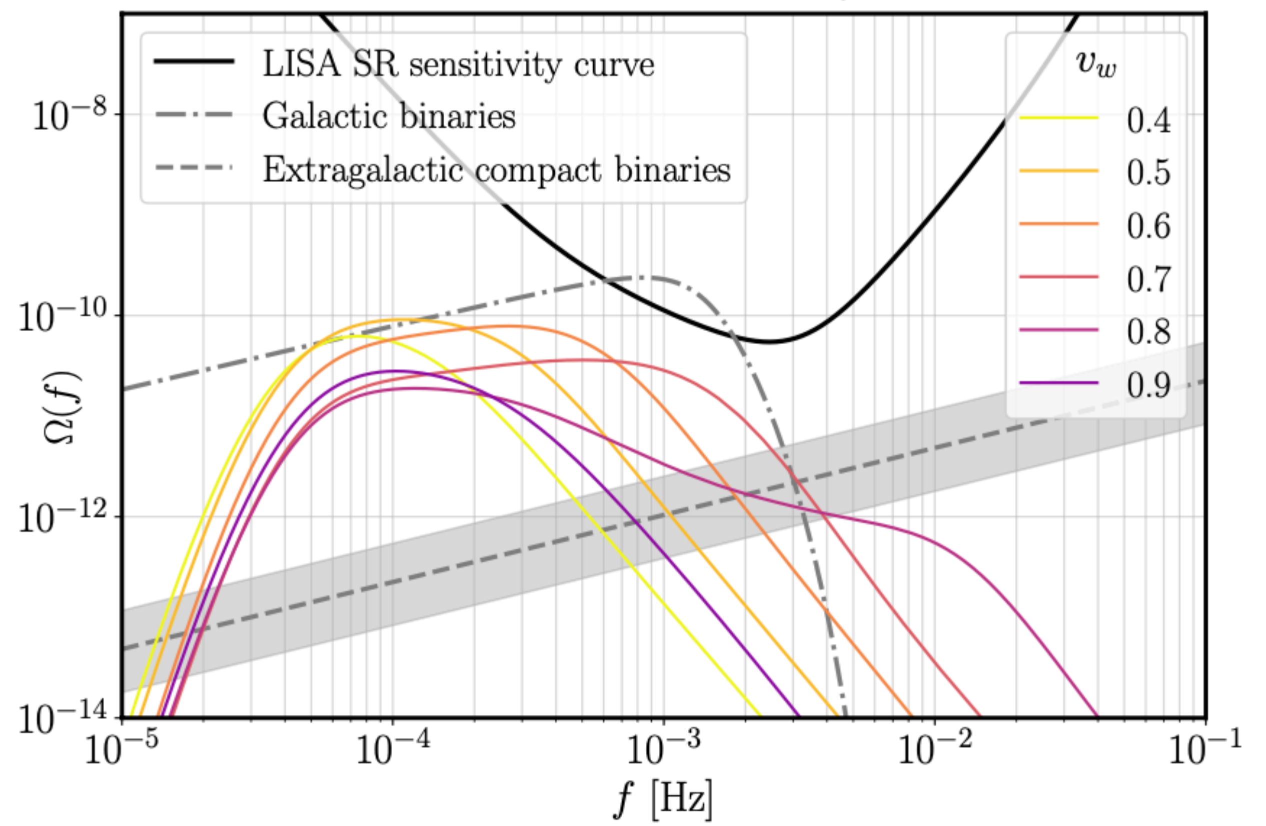
Gowling, Hindmarsh, 2019



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 xx(2024)

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). Alignment conditions on the strong Yukawa couplings must be imposed to suppress FCNCs (composite version of an Aligned 2HDM)

- ☑ 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: linear couplings $\Delta_{L,R}$ between composite and elementary fermions (partial compositeness for the top). Composite heavy fermions T with Q=2/3,-1/3,5/3

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scale of compositeness,

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

strong coupling, linear mixings, Yukawas, heavy fermion mass parameters

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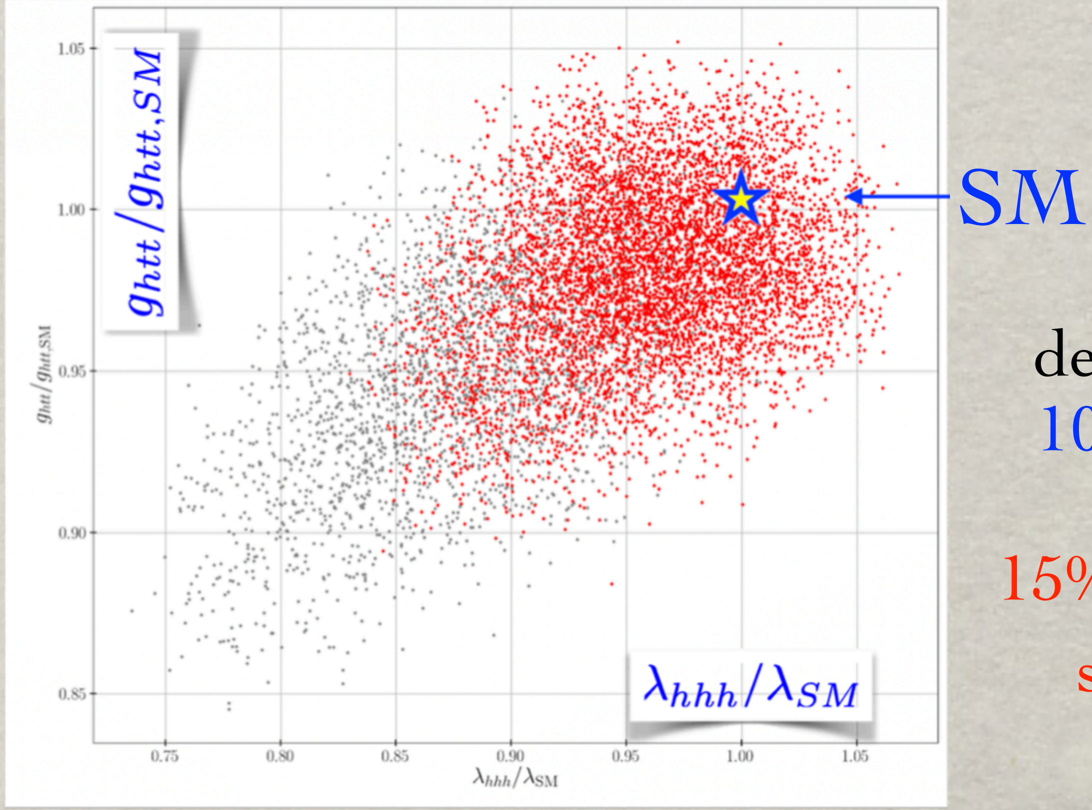
scan over the model parameters

$750 \leq f(\mathrm{GeV}) \leq 3000$, $2 \leq g_\rho \leq 10$,

$-10f \leq \Delta, Y, M_\psi \leq 10f$

with the constraints to reconstruct

v_{SM}, m_h, m_{top} and $M_T \geq 1.3$ TeV

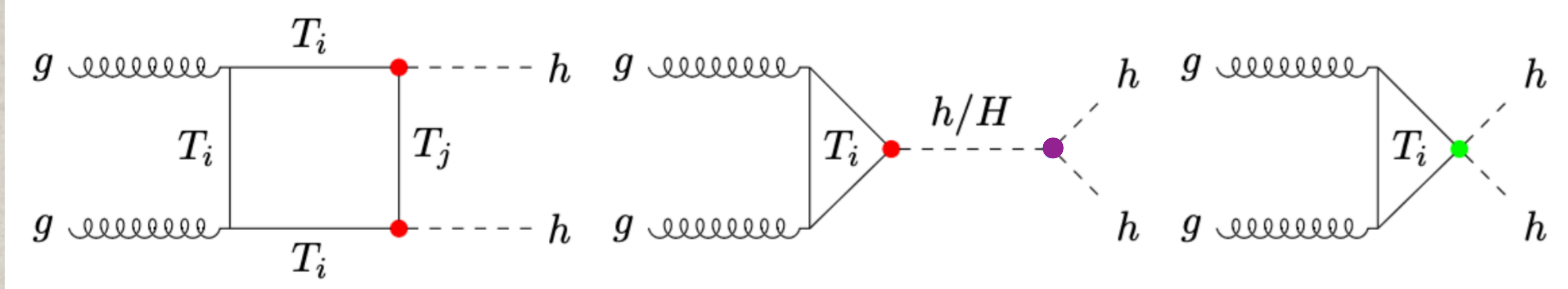


the grey points are excluded by the present direct and indirect Higgs searches (HiggsBounds and HiggsSignals Tools)

deviations up to
10% in g_{htt} top Yukawa
15% in λ_{hhh} Higgs self-coupling

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)

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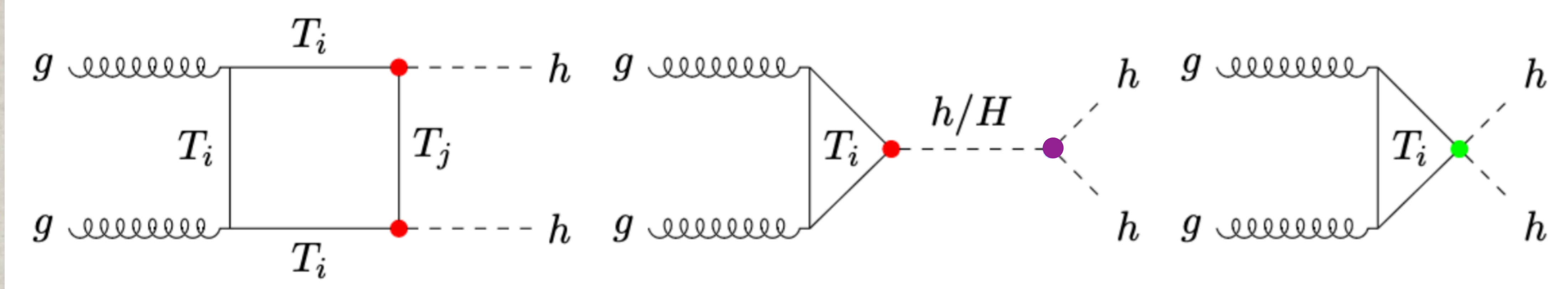

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In C2HDM both resonant and non-resonant modes yield to a change in the integrated cross-section and to peculiar kinematic features in its differential distributions

New topologies from the interference with loops of new heavy tops lead to a modification of the line-shape and a local maximum at ~ 2 m_T

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

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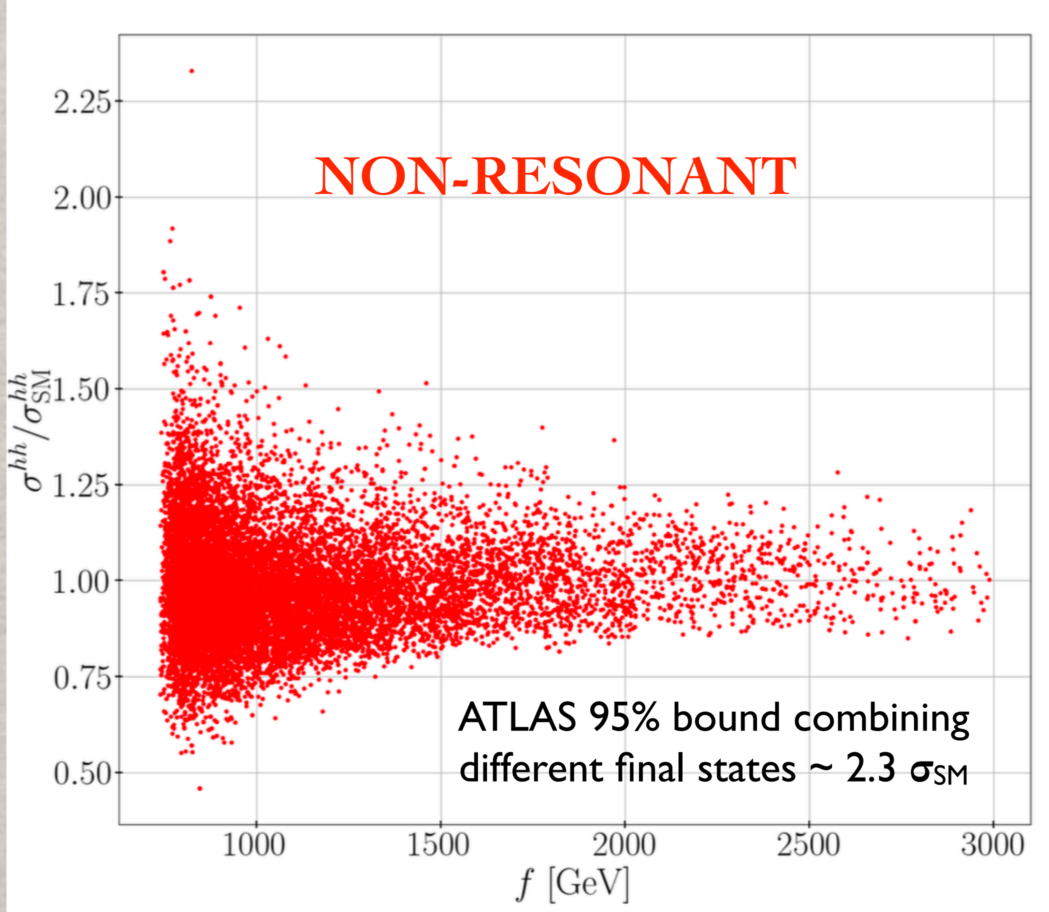
$\sigma(gg \to H) \times BR(H \to hh)/\sigma(gg \to hh) < 0.1$



NON-RESONANT

ATLAS 95% bound combining different final states ~ 2.3 σ_{SM}

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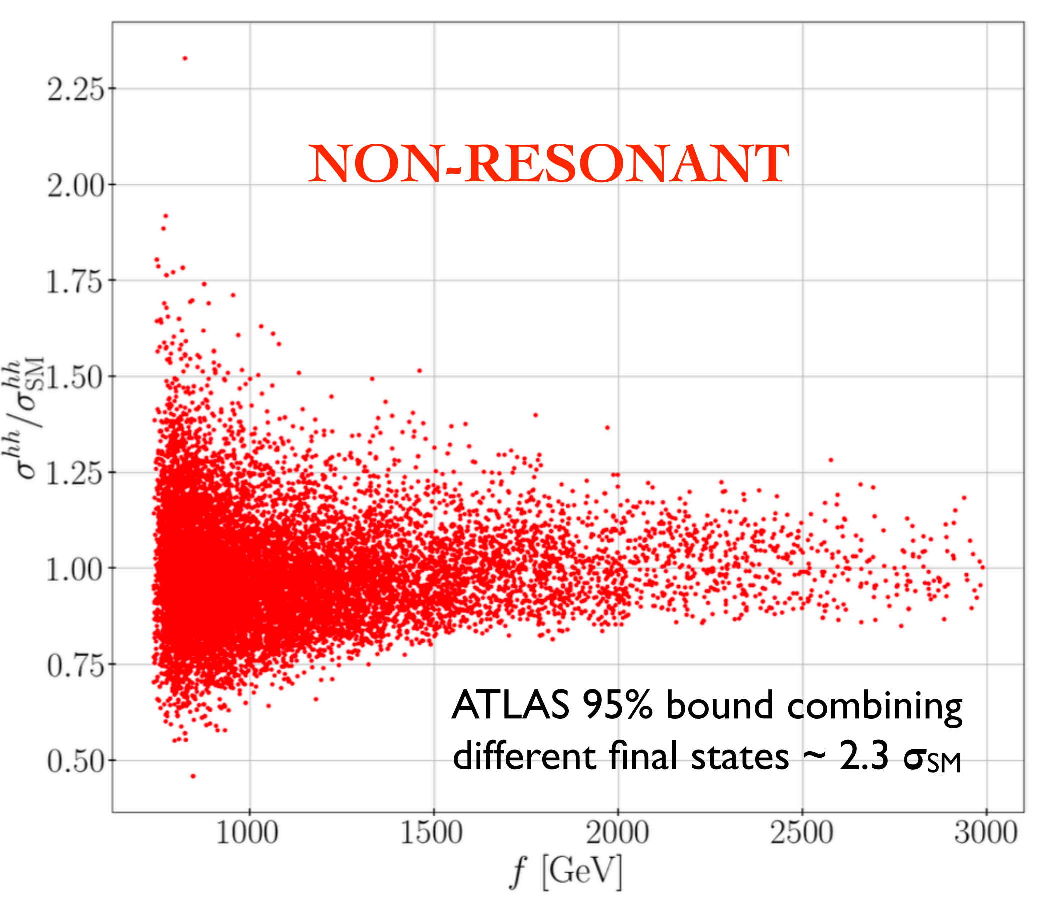
RESONANT: $\mathbf{M_H > 2\, m_h}$

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)



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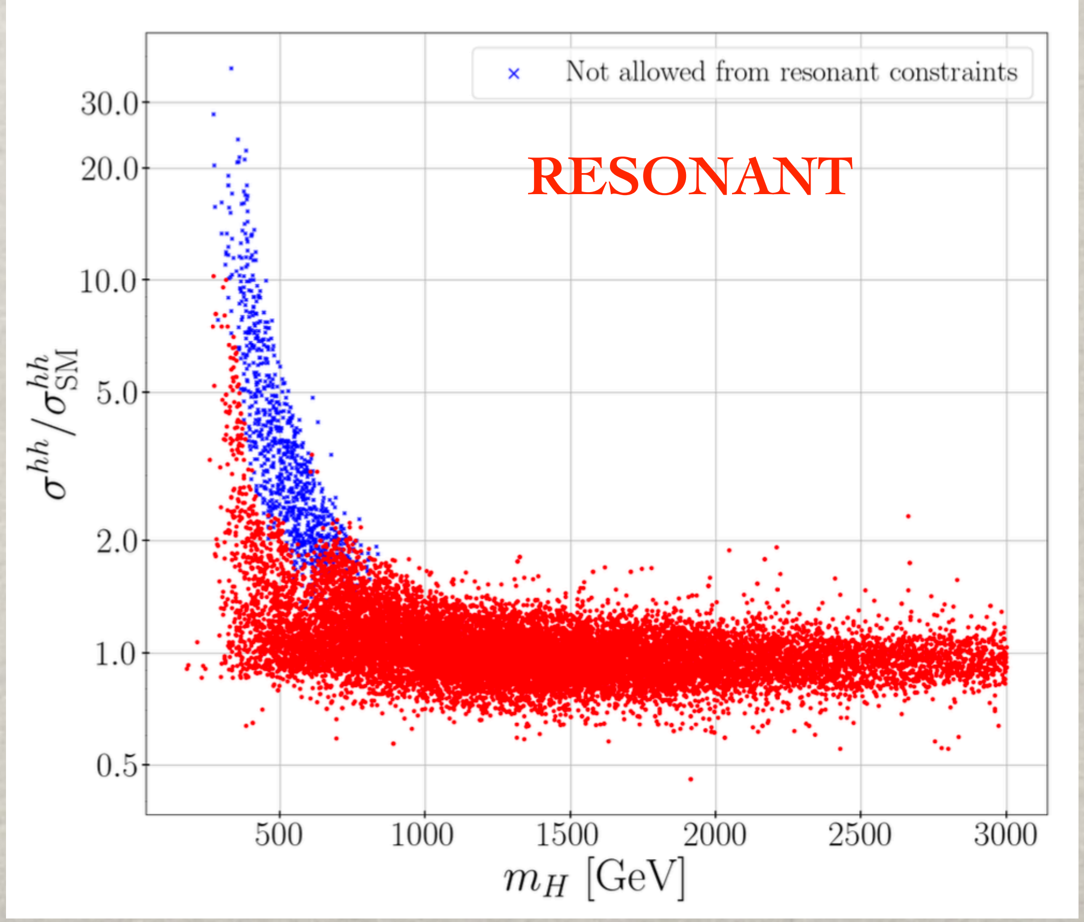
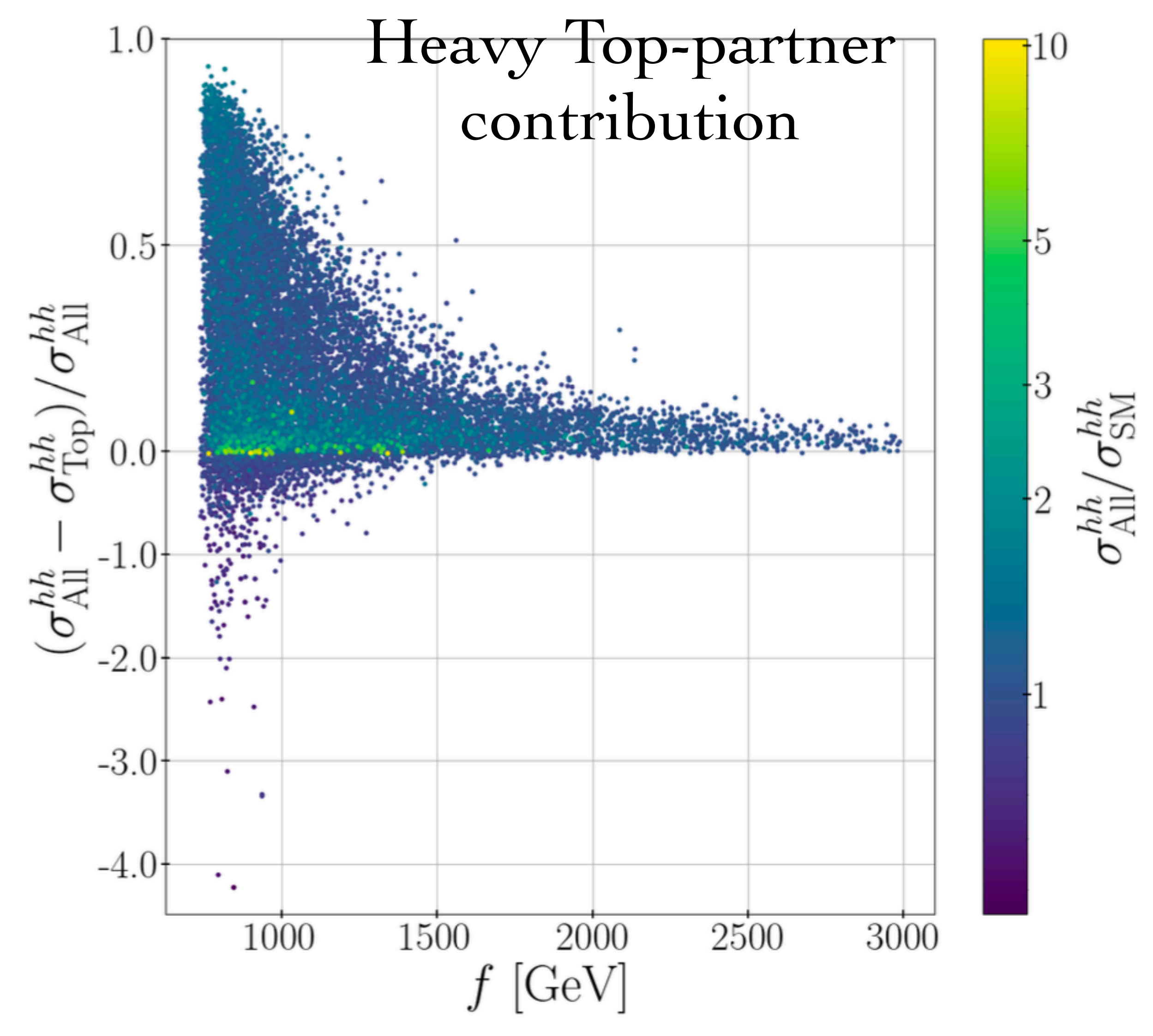
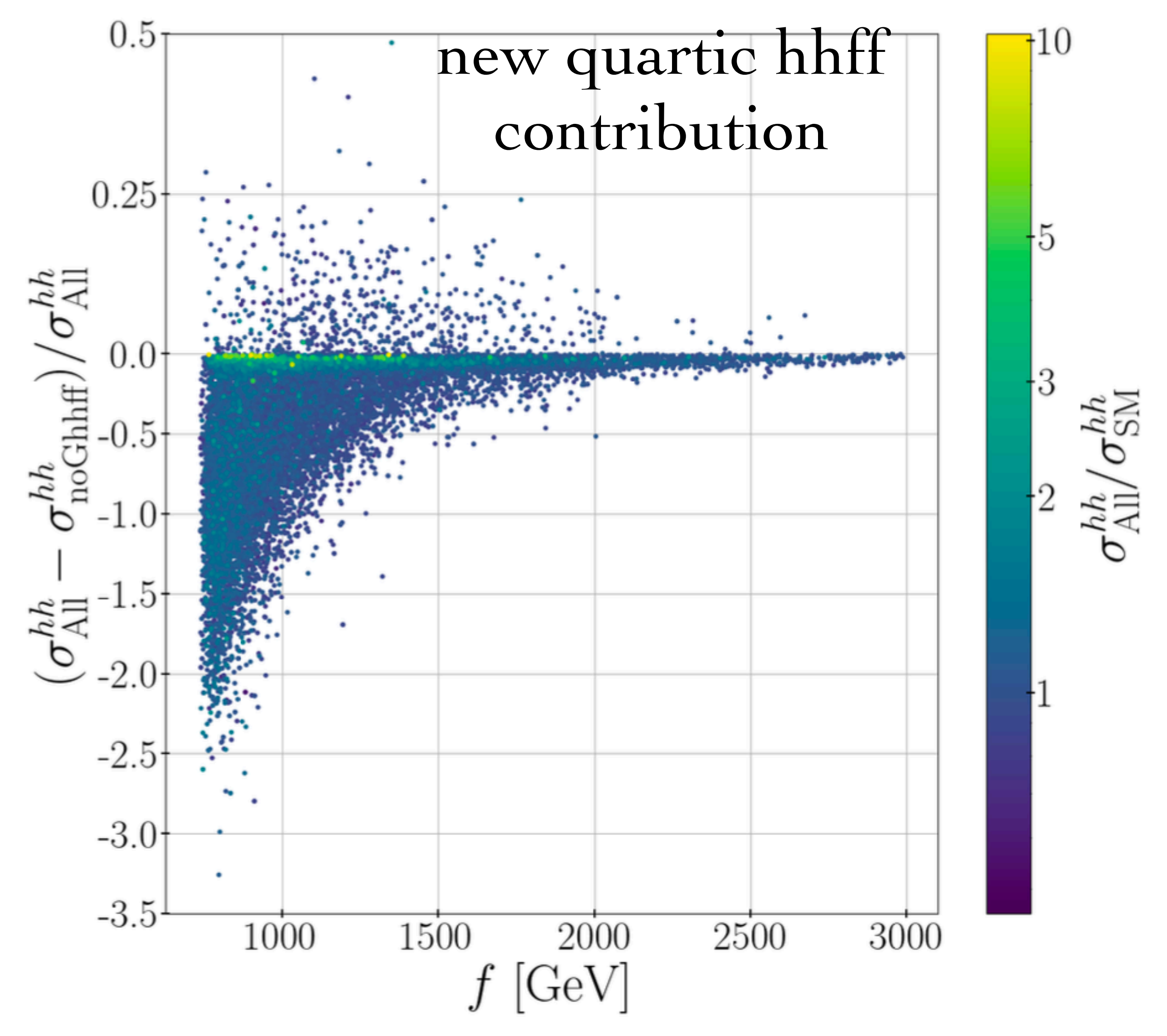


Impact of new C2HDM effects (not present in 2HDM)



Heavy Top-partner contribution



new quartic hhff contribution

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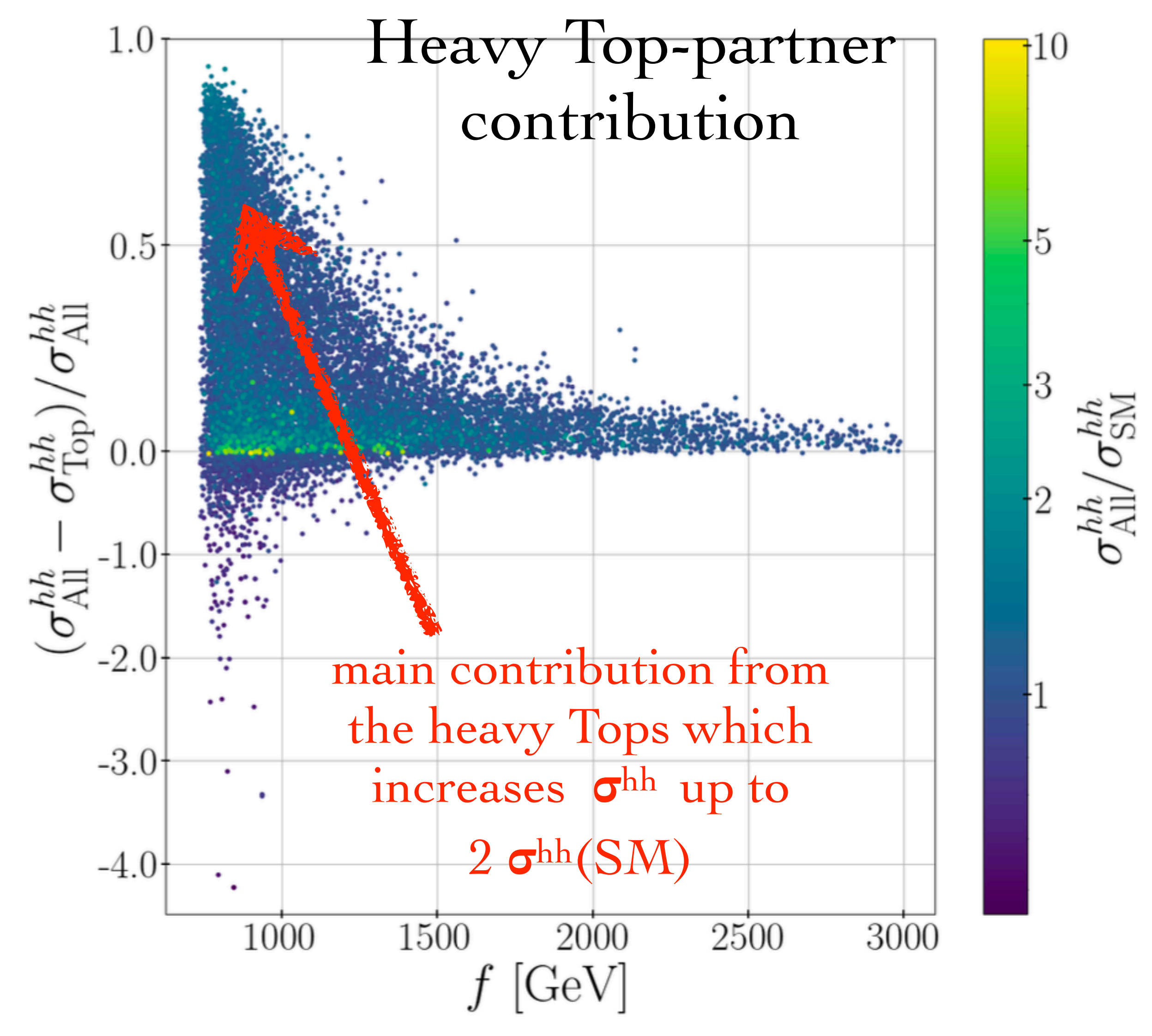
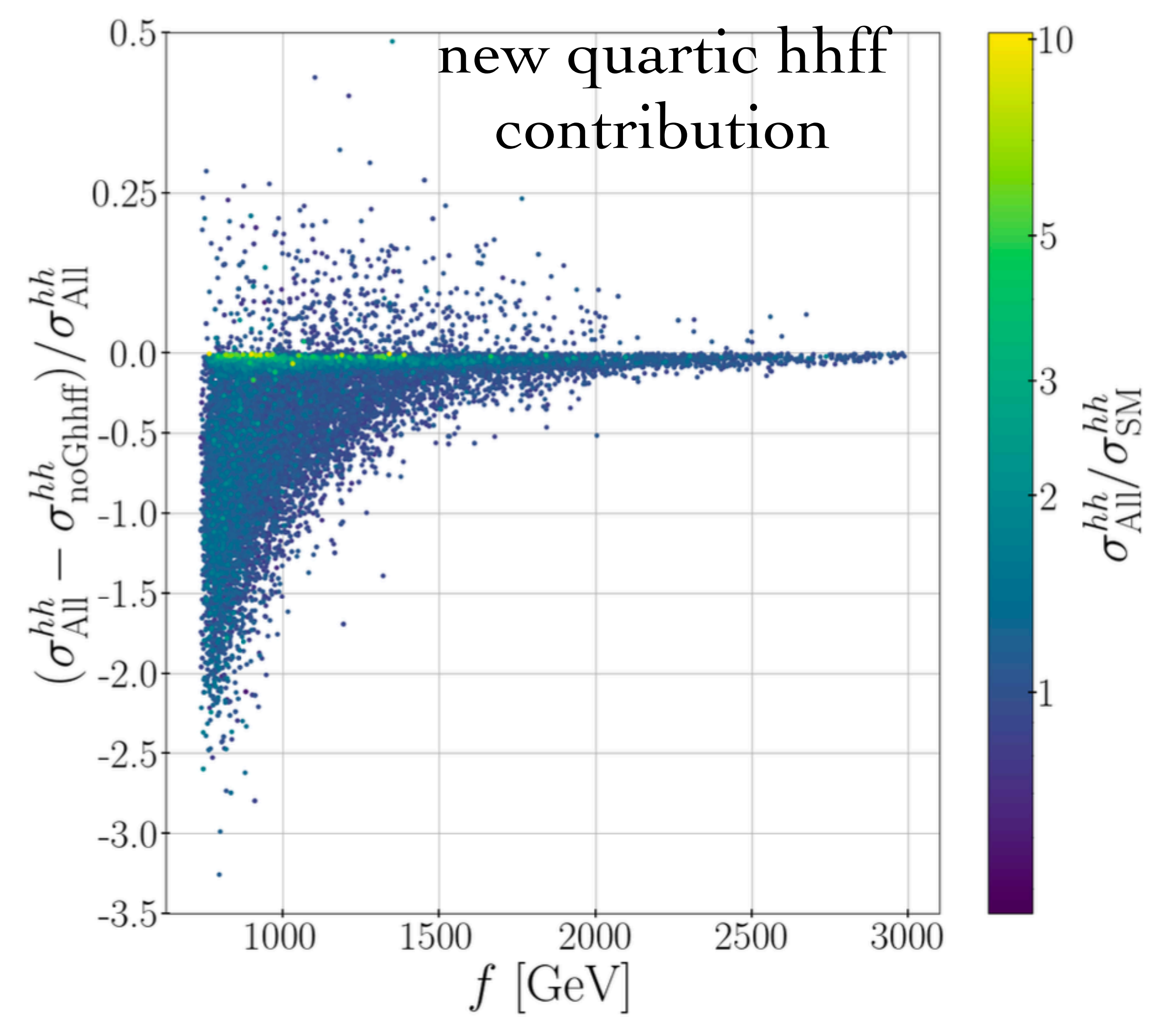


Heavy Top-partner contribution

main contribution from the heavy Tops which increases σ^{hh} up to 2 σ^{hh}(SM)



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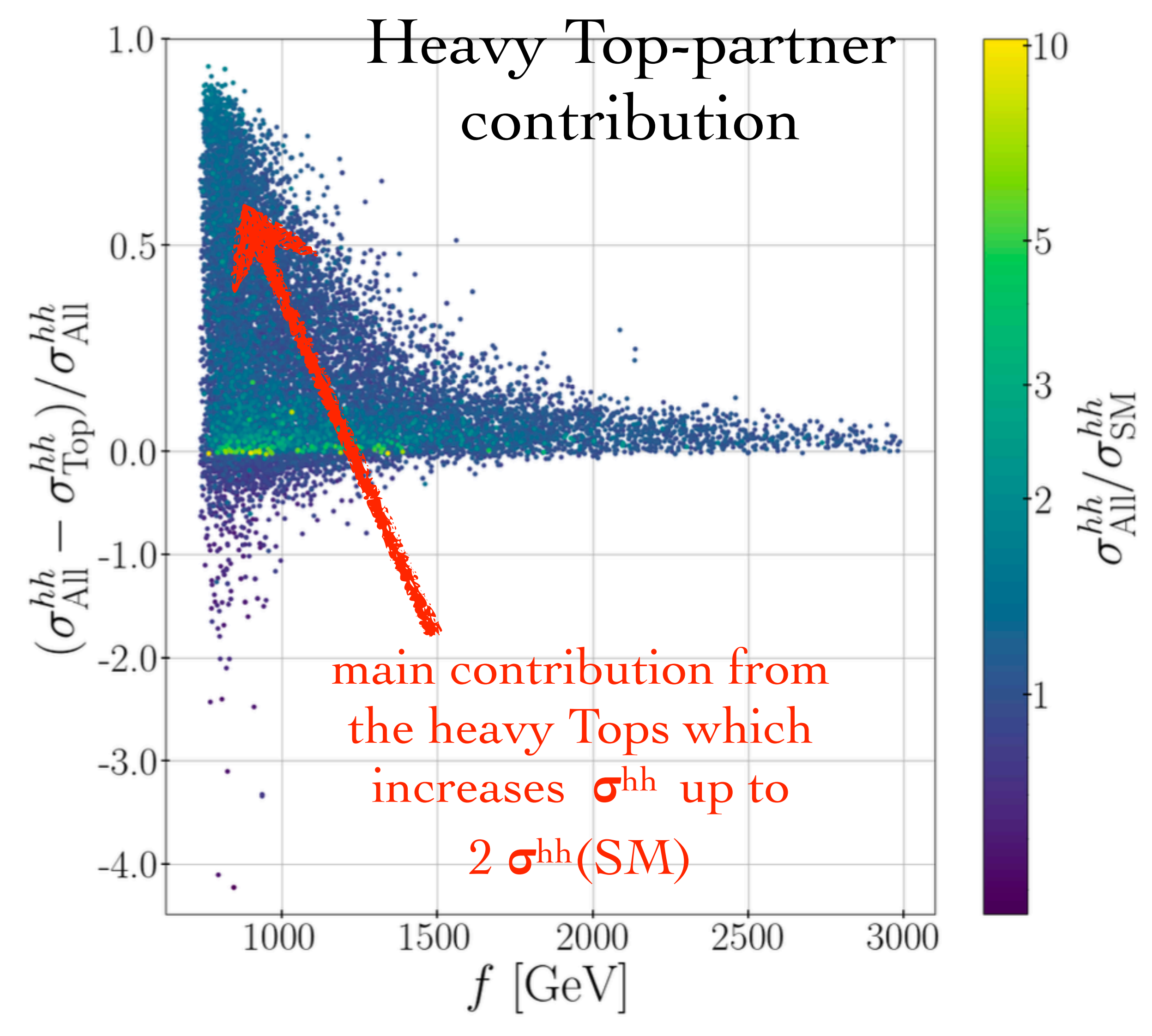

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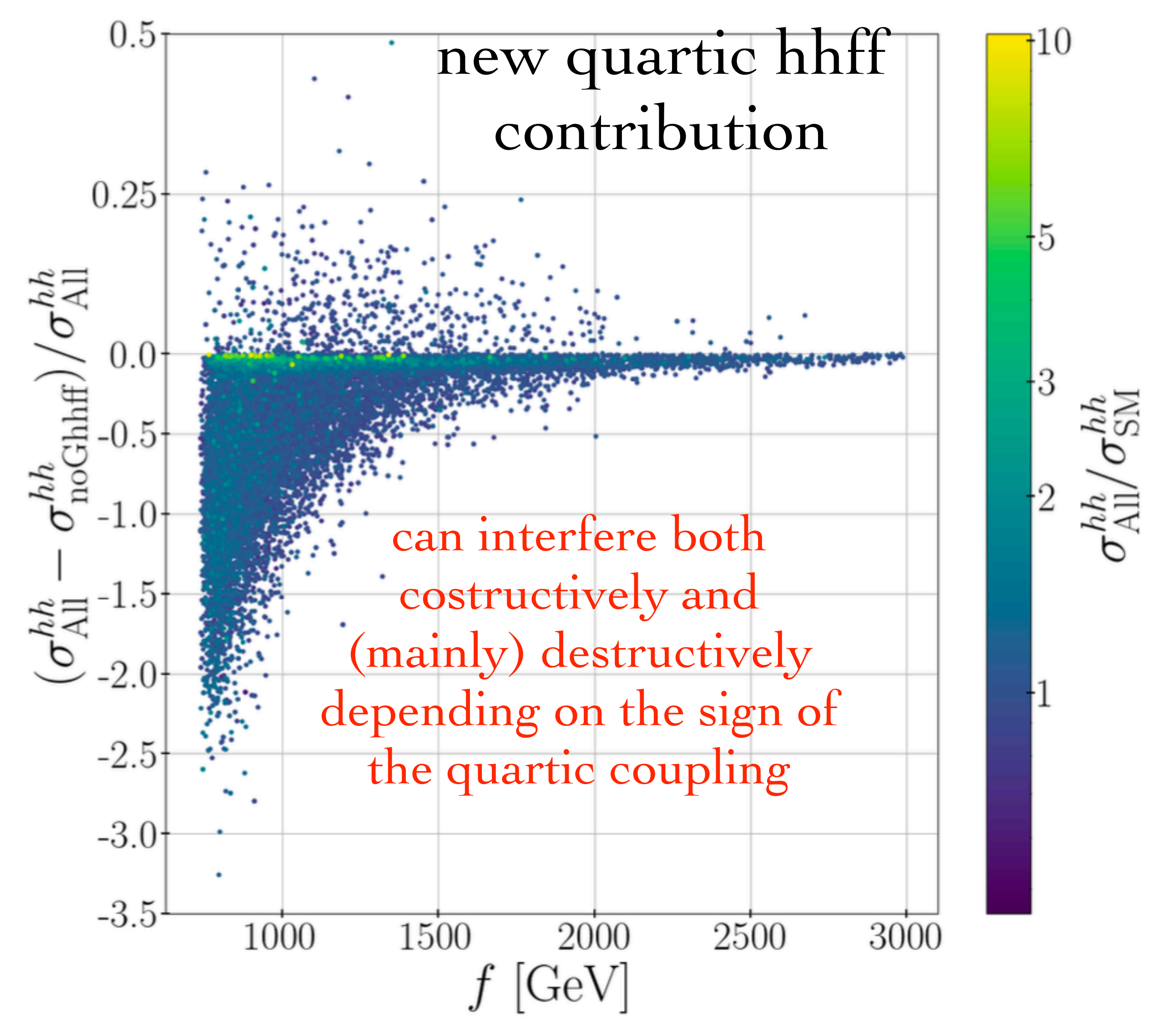
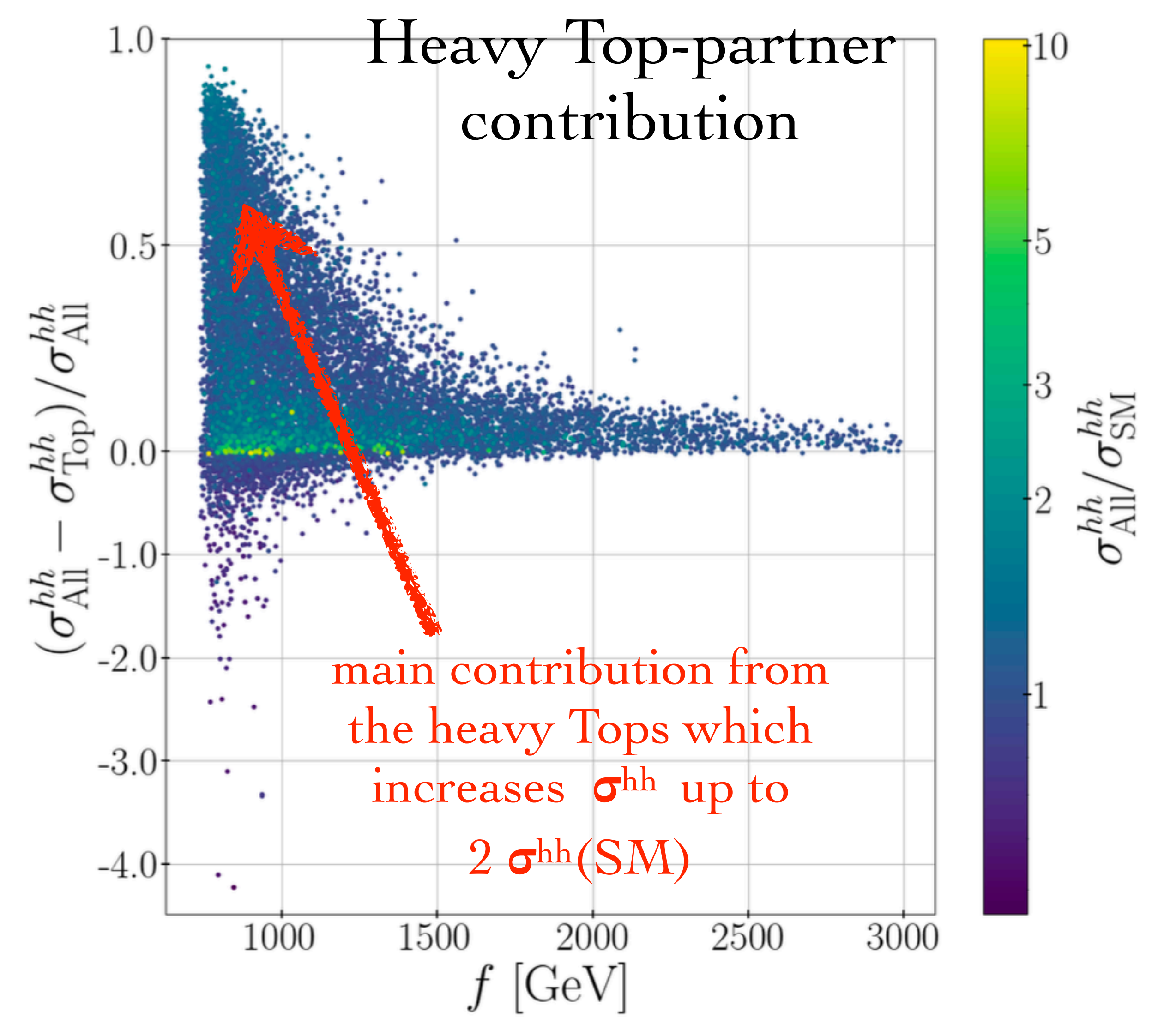


new quartic hhff contribution

can interfere both costructively and (mainly) destructively depending on the sign of the quartic coupling

Impact of new C2HDM effects (not present in 2HDM)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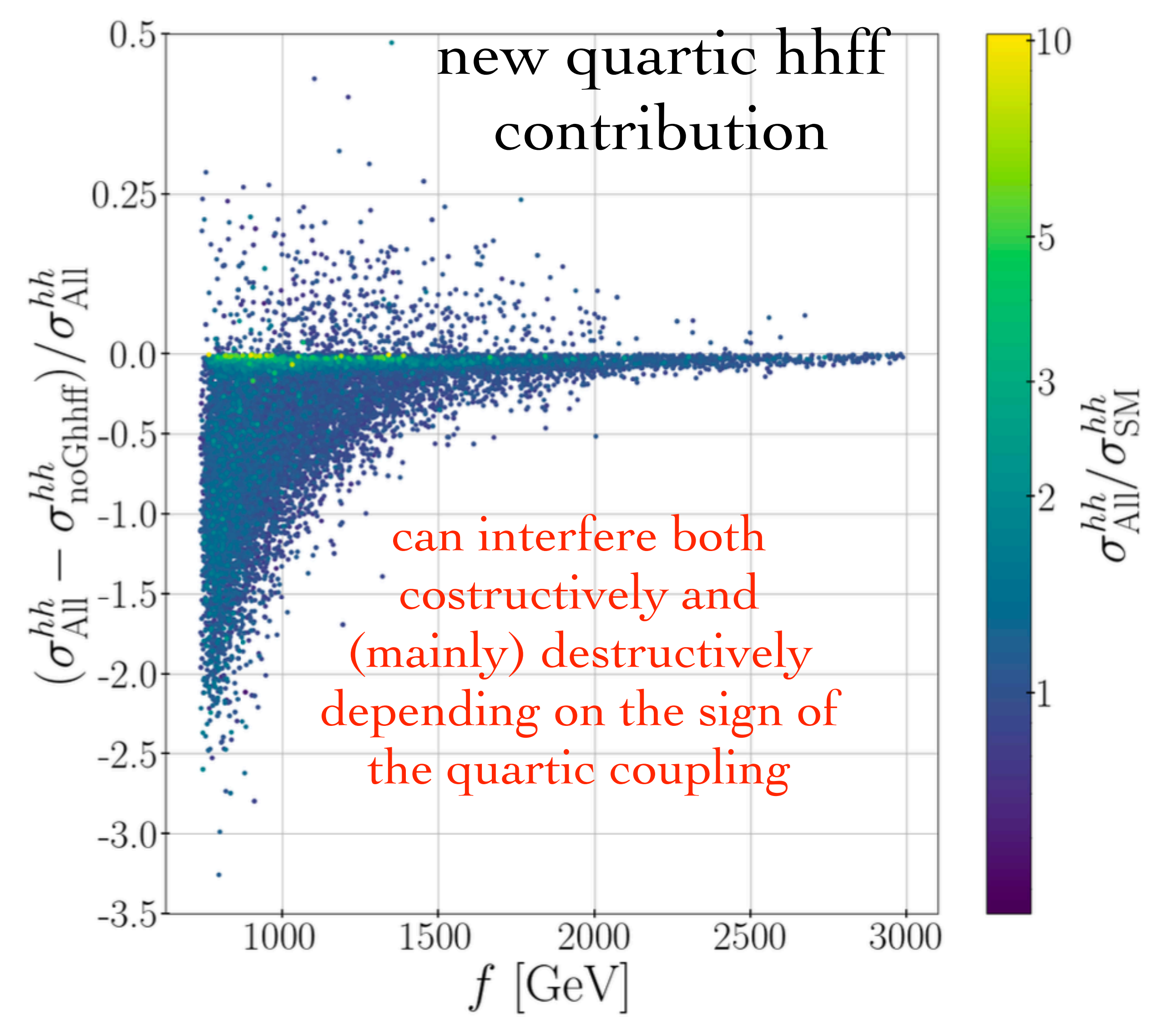
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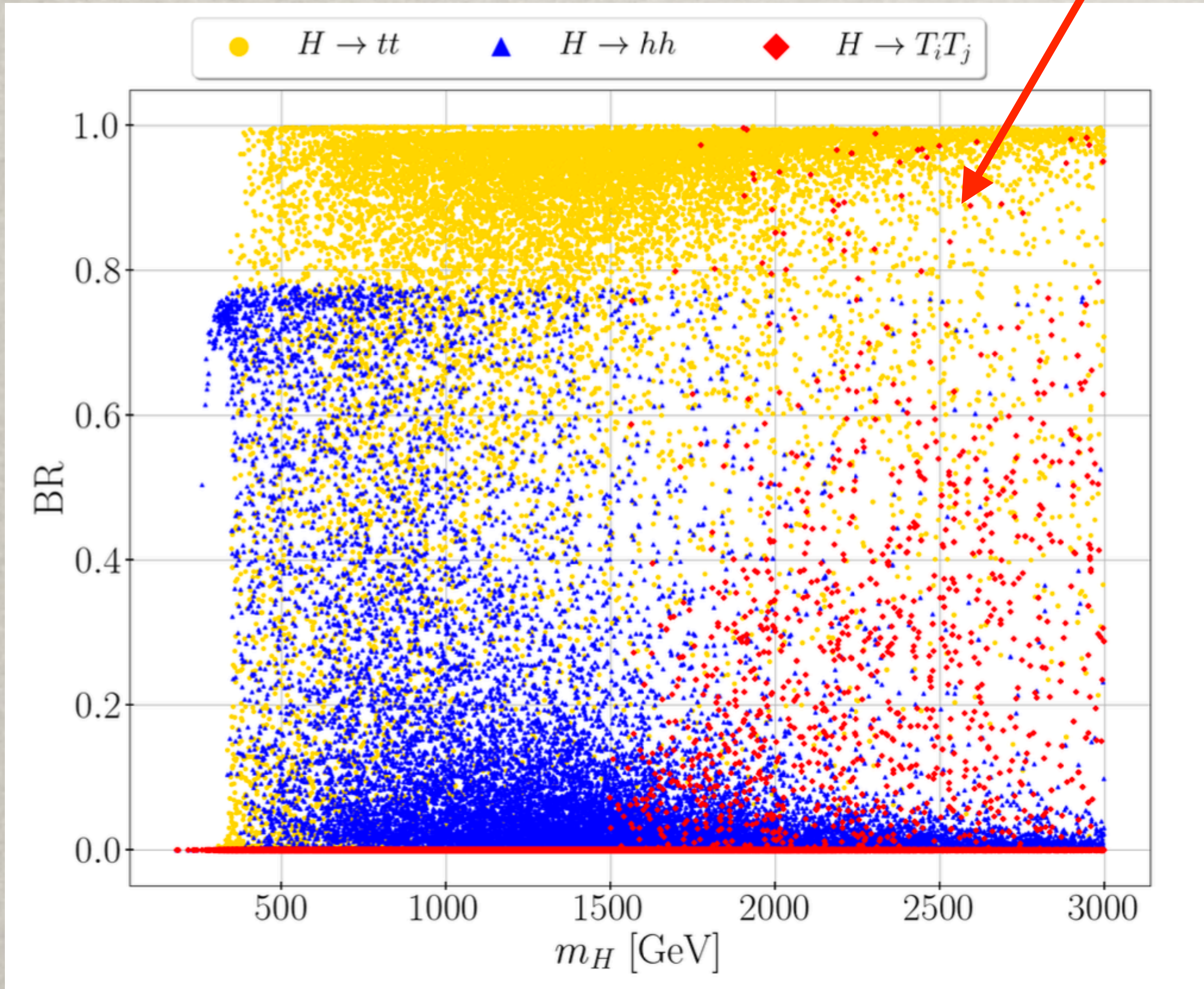
The largest cross-sections are the resonant ones (yellow and green BPs) are not affected by heavy Tops and new quartic terms

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



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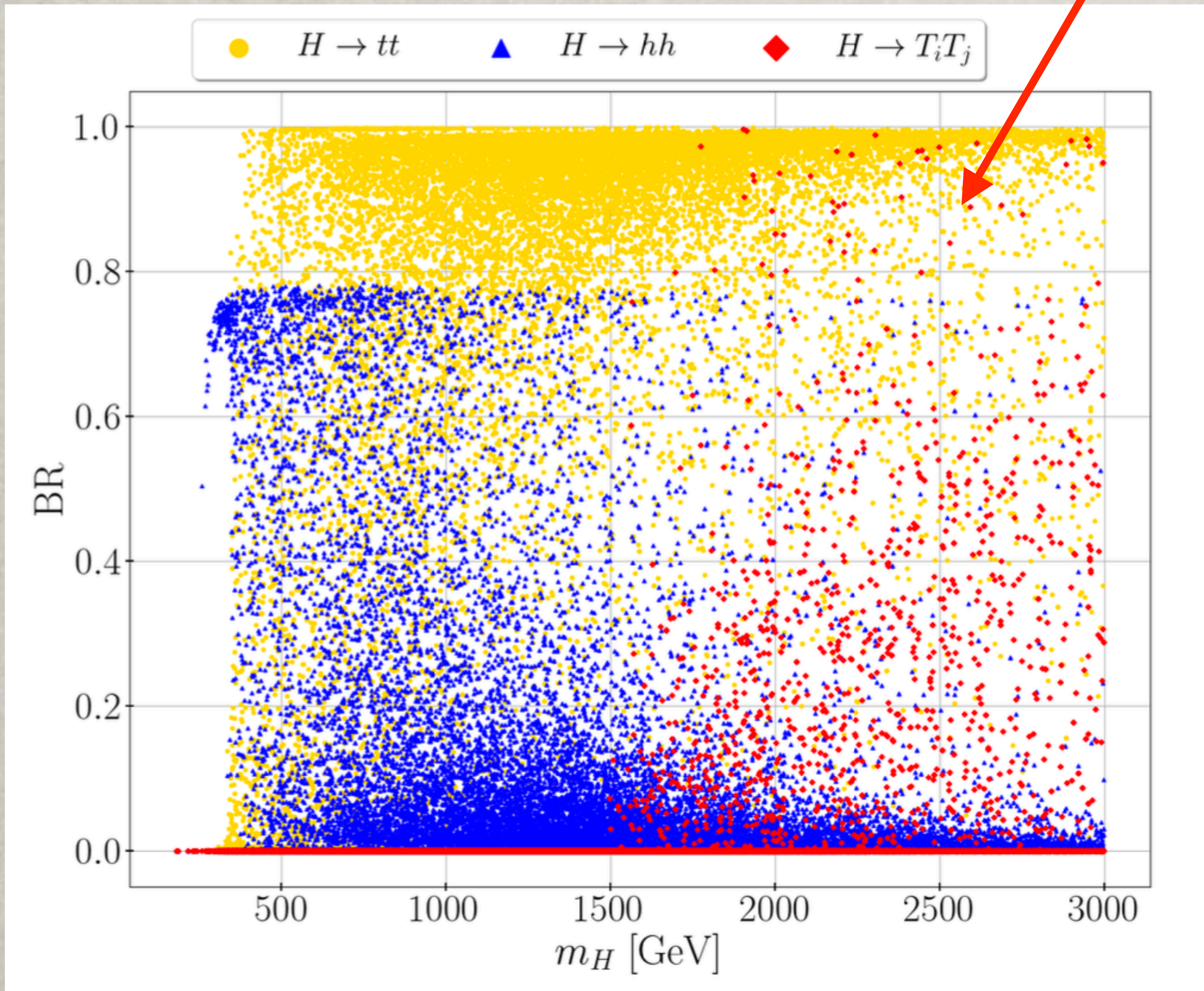
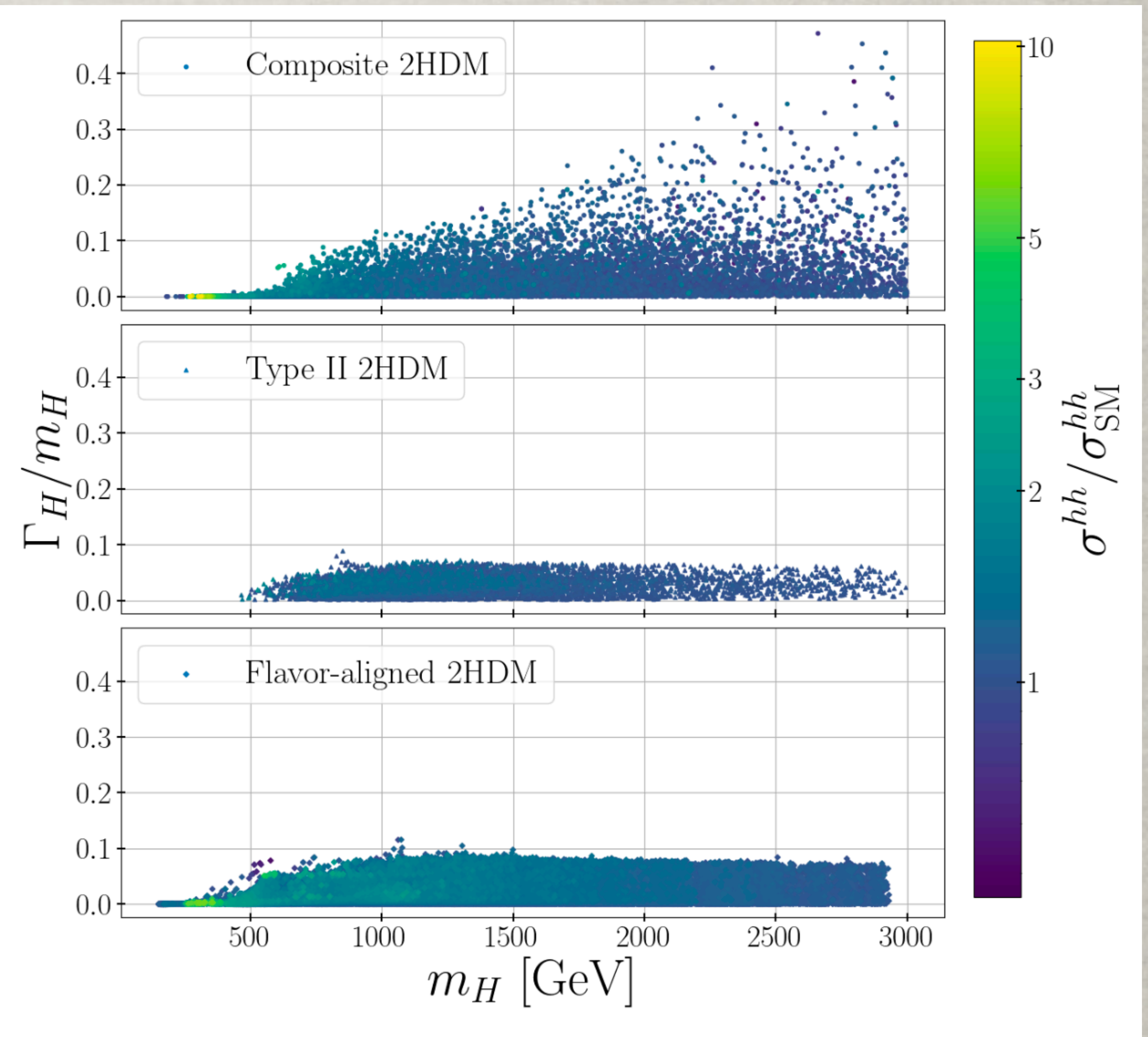


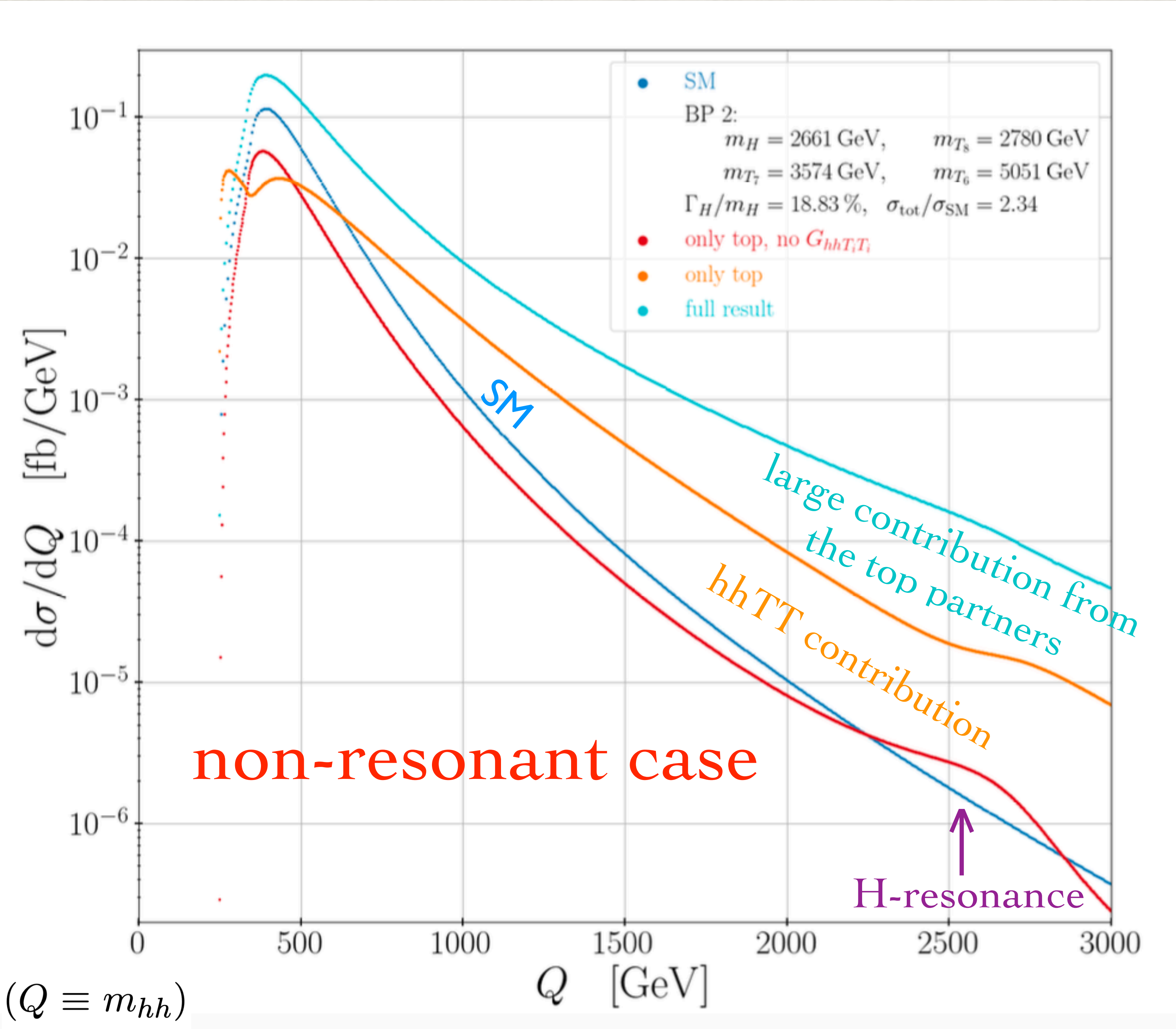


Peculiar feature of the C2HDM: Γ_H/M_H can be ~10-20%

enhancement of σ_{hh}, great impact on the shape modification of the differential distributions due to the large interference effects

di-Higgs production in C2HDM - invariant mass distributions

1. modified hhh (k_λ), tth couplings (k_t) → small deviations
2. H contribution → present in several BSM schemes (MSSM, 2HDM, ..)
3. Heavy Tops' contributions ($t' = T_i$ i=1,..,8) + quartic tthh → naturally present in CHMs



large contribution from the top partners

hhTT contribution

non-resonant case

H-resonance

$(Q \equiv m_{hh})$

$m_H \sim 2.6$ TeV

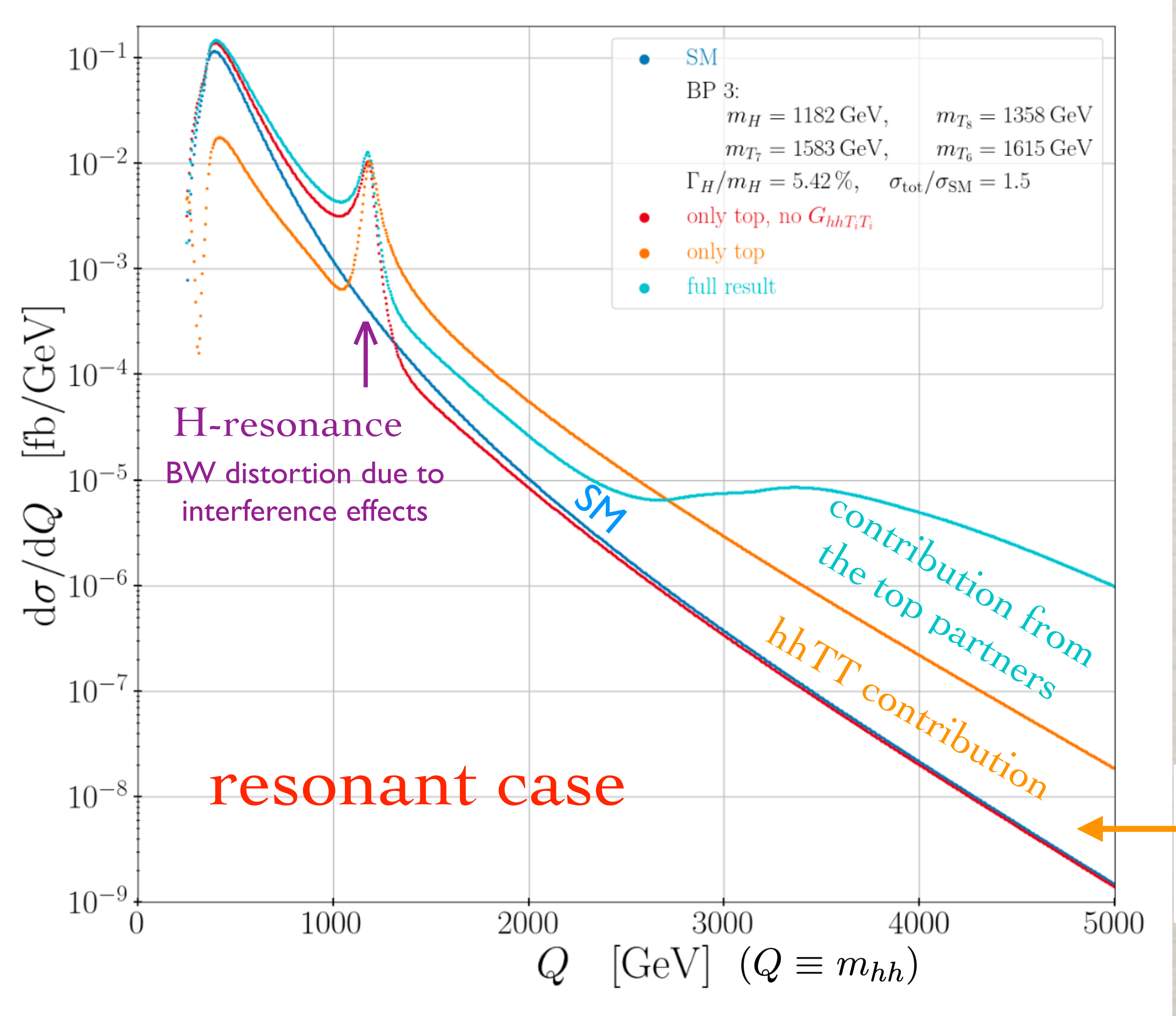
$\Gamma_H/m_H \sim 19\%$

Large Width

$m_T > 2.7$ TeV

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

di-Higgs production in C2HDM - invariant mass distributions



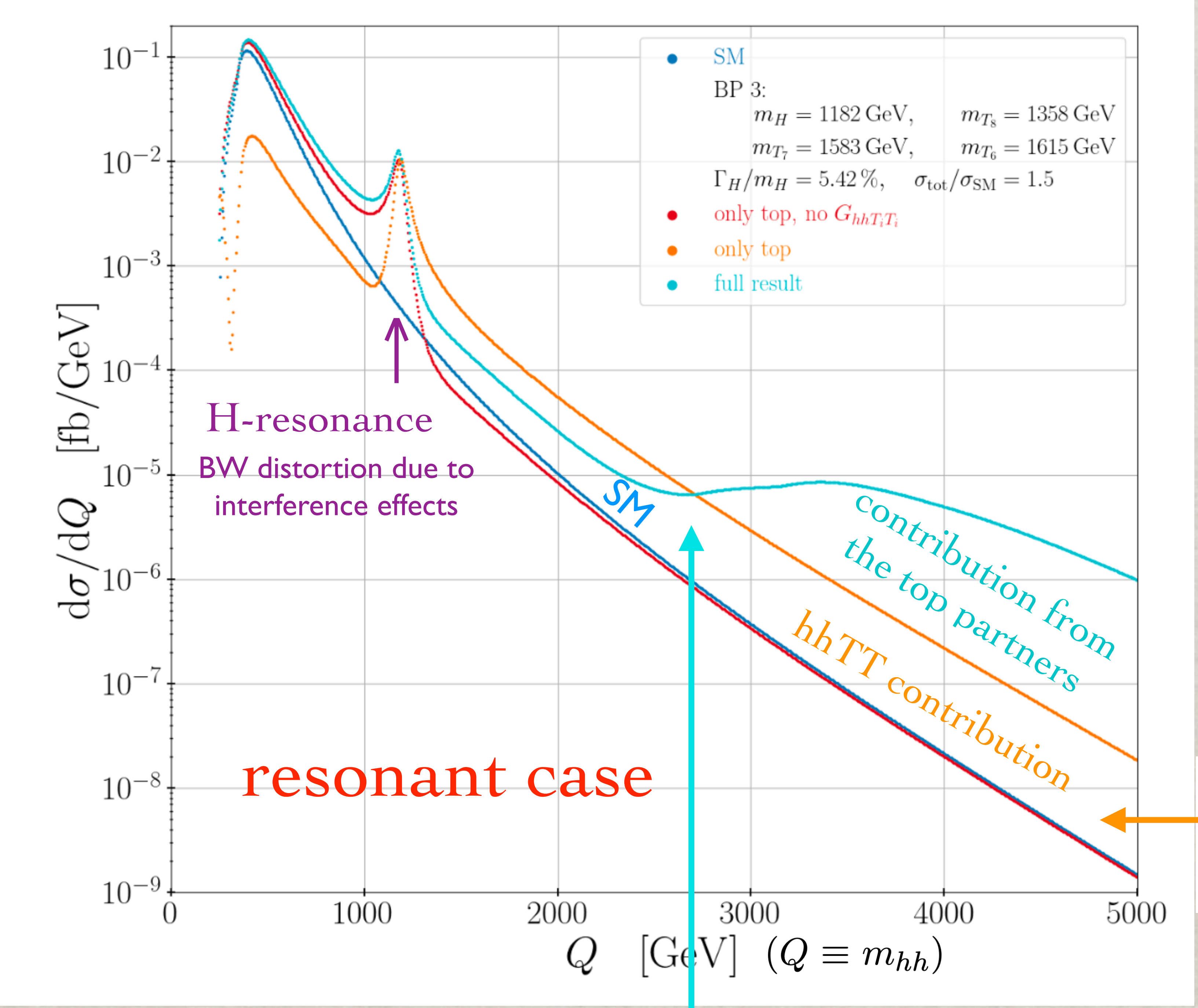
$\sigma_{\rm tot}/\sigma_{\rm SM} = 1.5$

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

$m_T > 1.3$ TeV

destructive interference before the peak and constructive interference after the peak

di-Higgs production in C2HDM - invariant mass distributions



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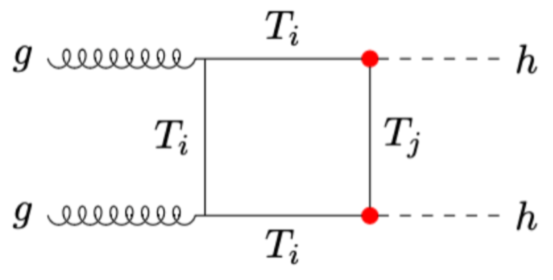
start to see the threshold shape at 2MT induced by boxes



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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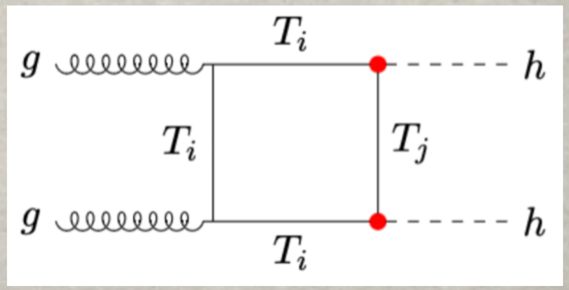
$\Gamma_H/m_H \sim 5.4\%$

$m_T > 1.3$ TeV

destructive interference before the peak and constructive interference after the peak

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



Conclusions

☑ 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

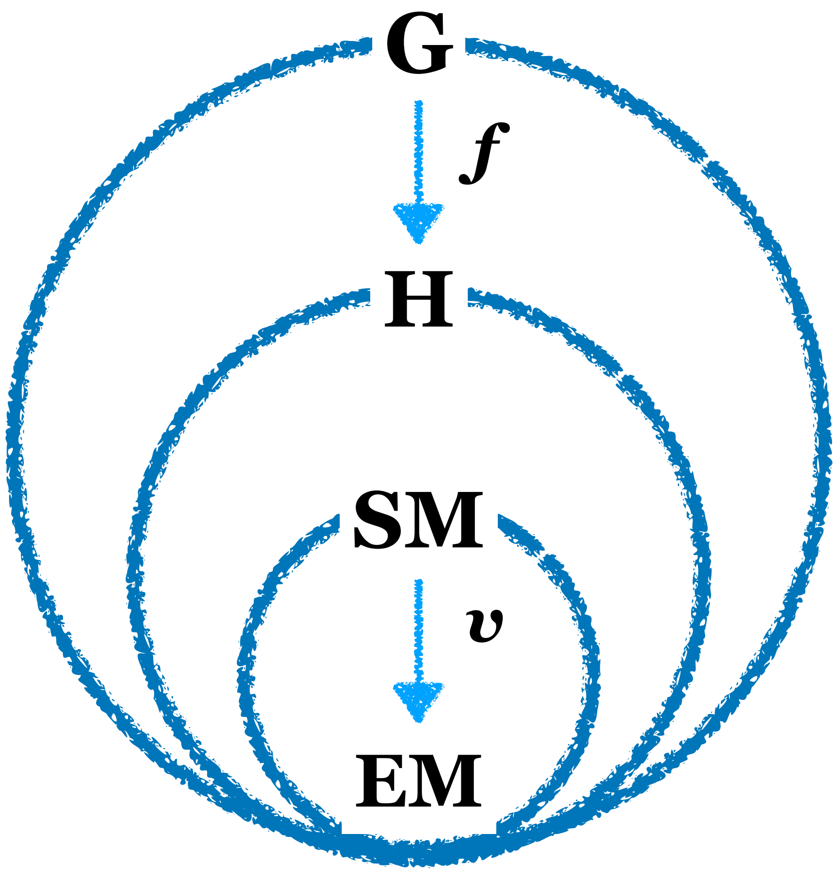
☑ Composite Higgs models (while addressing the naturalness problem), can account for such interesting features

☑ Shown in this talk: (i) a 2-step strong 1st order EWPhT associated to EW baryogenesis can be naturally realised (here within SO(6)->SO(5) CHM) (ii) effects on the gg → hh process lead to peculiar features due to: coupling modifications, new resonance exchange, heavy fermions in the loops and the extra quartic couplings (here for a C2H2M)

Very promising interplay between gravity-wave and collider experiments to detect signals from a possible underlying strong dynamics and disentangle among different BSM schemes

BACKUP SLIDES

Basic rules for Composite NGB Higgs models



☑ a global symmetry G above f (~ TeV) is spontaneously broken down to a subgroup H

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

☑ H should contain the custodial group

☑ the number of NGBs (dim G - dim H) must be larger than (or at least equal to) 4

☑ the symmetry G must be explicitly broken to generate the mass for the (otherwise massless) NGBs

Composite Higgs Models

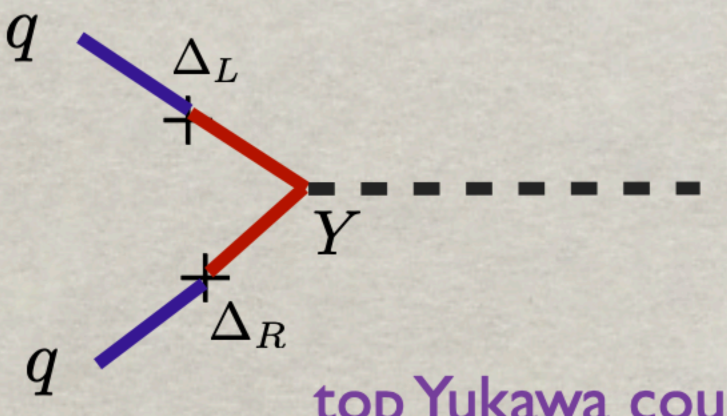
Elementary Sector		**Strong Sector**
$A_\mu, \psi \in SU(2) \times U(1)_Y$	$\mathcal{L}_{\text{mix}} = g_0 A_\mu J^\mu_\rho + \Delta \bar{\psi} \Psi$	$\rho_\mu, \Psi \in G_{\text{strong}}$
$g_0 < 1$		m_ρ, $1 < g_\rho < 4\pi$

partial compositeness

Linear elementary-composite fermion mixings

→ for the 3rd generation quarks

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



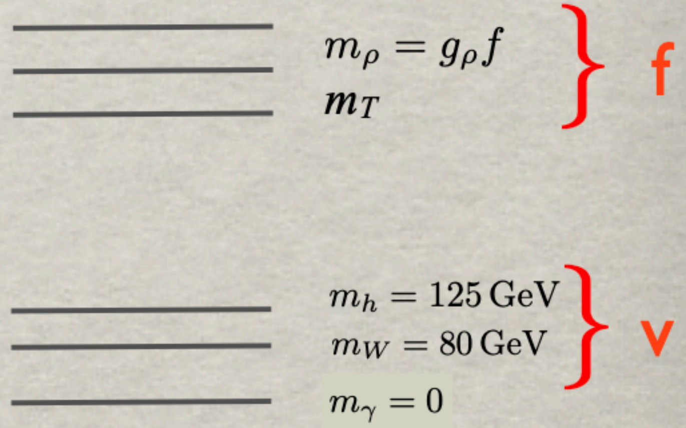
top Yukawa coupling

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

Strong sector: resonances + Higgs bound state

Extra particle content:
- Spin 1 resonances ρ
- 1/2 resonances T

Spectrum :



g_ρ = strong coupling

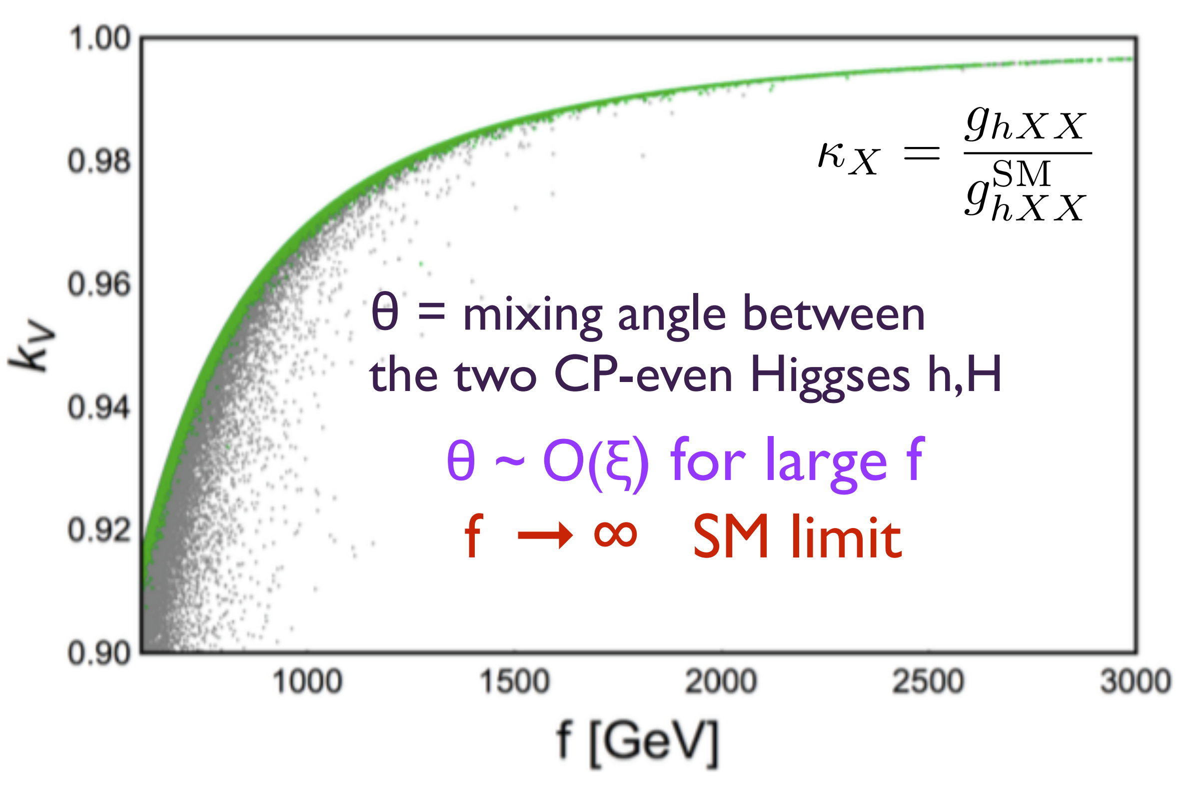
SM hierarchies are generated by the mixings:
light quarks mostly elementary, top mostly composite

C2HDM - facing the data

- h couplings to SM particles:

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 $\xi = v^2/f^2$

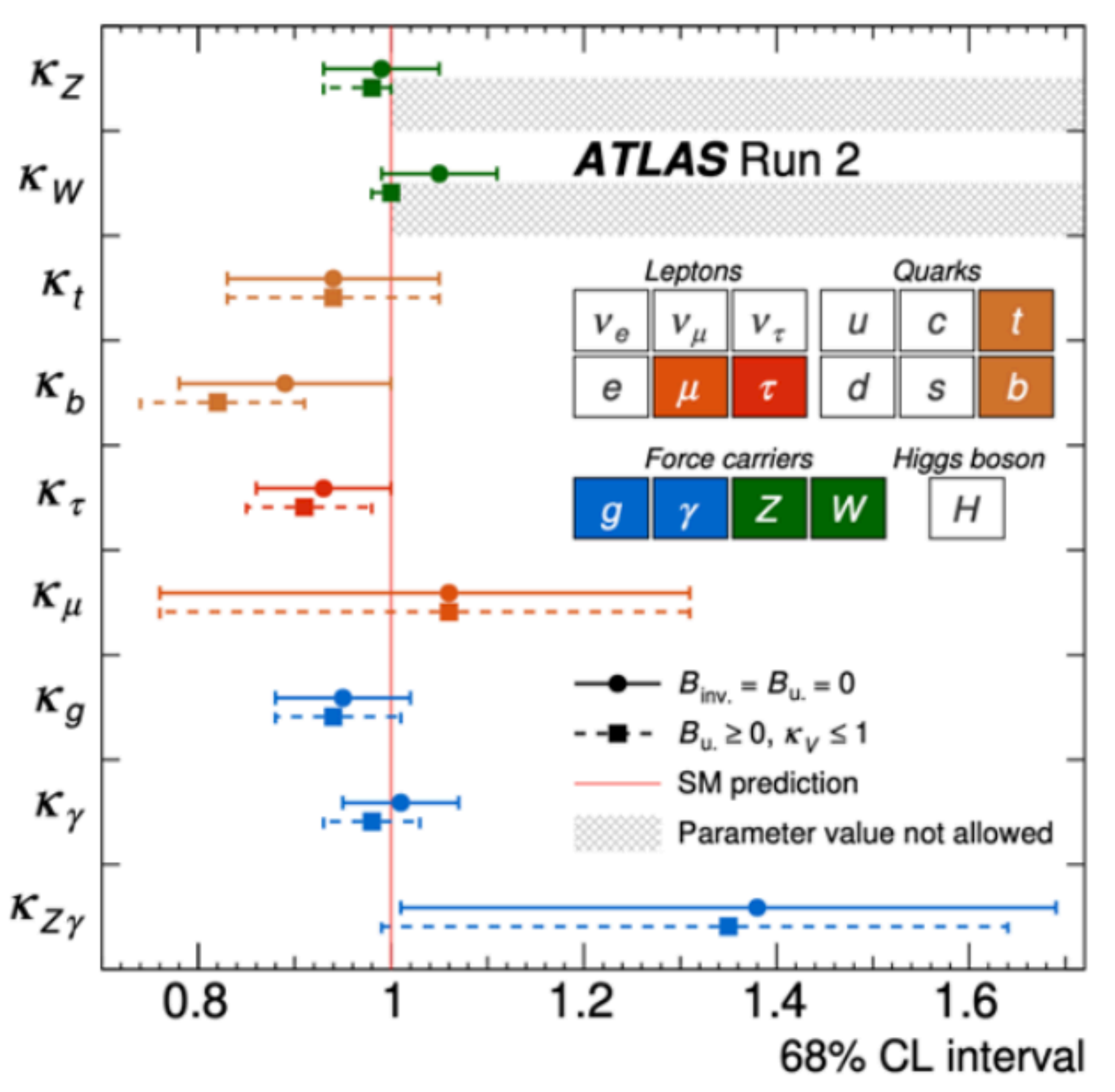


$$\kappa_X = \frac{g_{hXX}}{g^{SM}_{hXX}}$$

θ = mixing angle between
the two CP-even Higgses h,H

θ ~ O(ξ) for large f
f ⟶ ∞ SM limit

green points satisfy the present bounds
tested against HiggsBounds and HiggsSignals packages



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

$\xi \leq 0.1$ $f \geq 750$ GeV

C2HDM - facing the data

- h couplings to SM particles:

corrections of order ξ to the hVV couplings.
Also modified by the mixing angle θ

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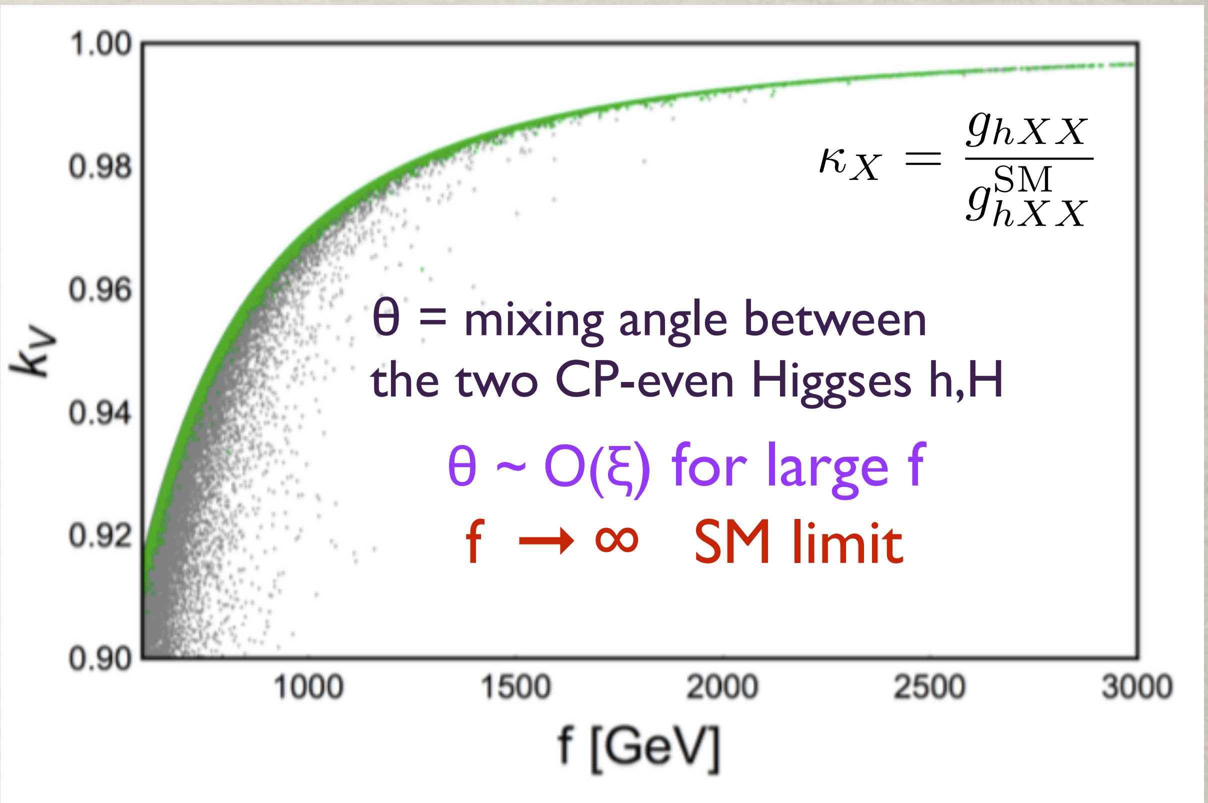

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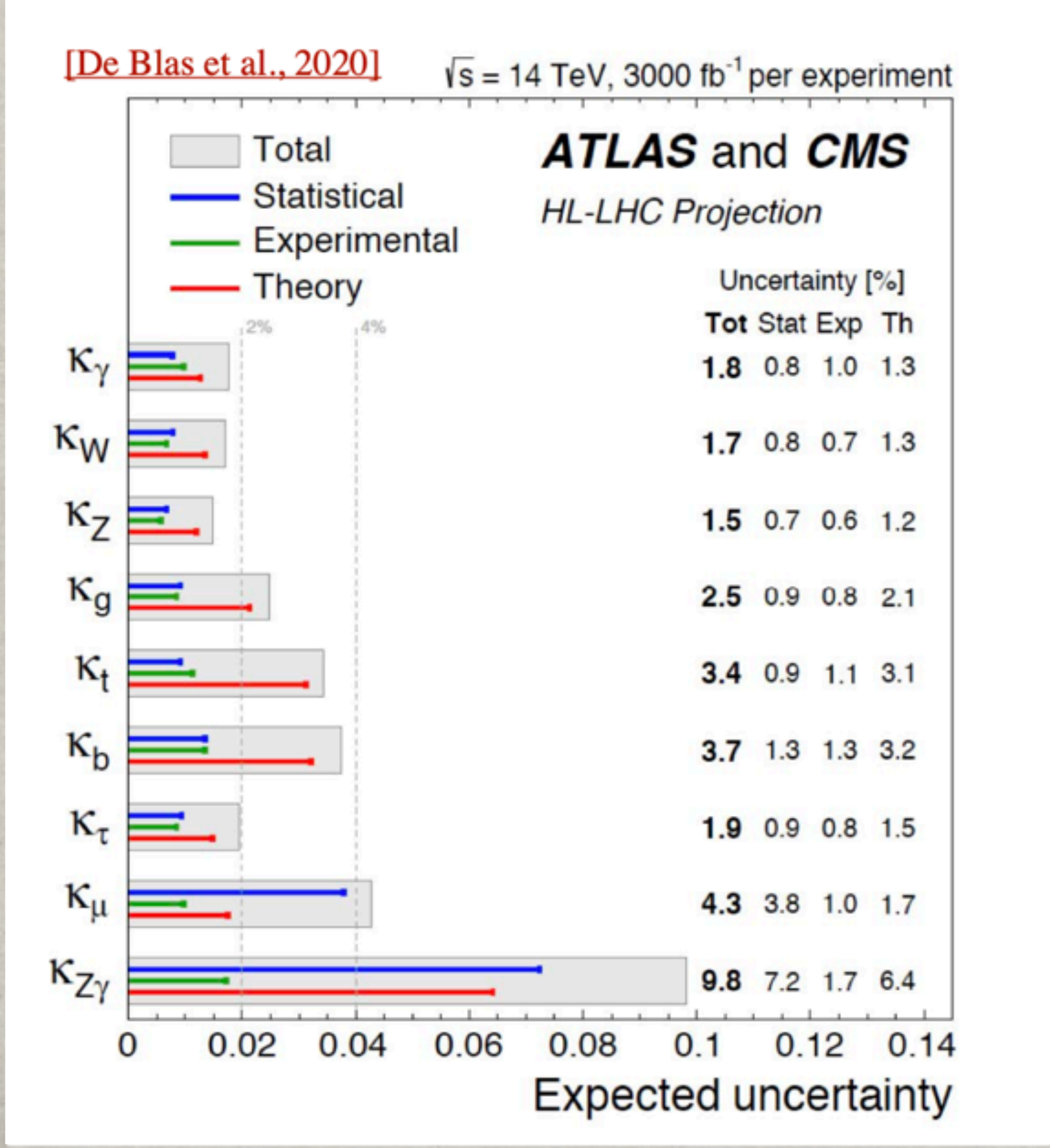


[De Blas et al., 2020]

$\sqrt{s}$ = 14 TeV, 3000 fb^{-1} per experiment

Uncertainty [%]

	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

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

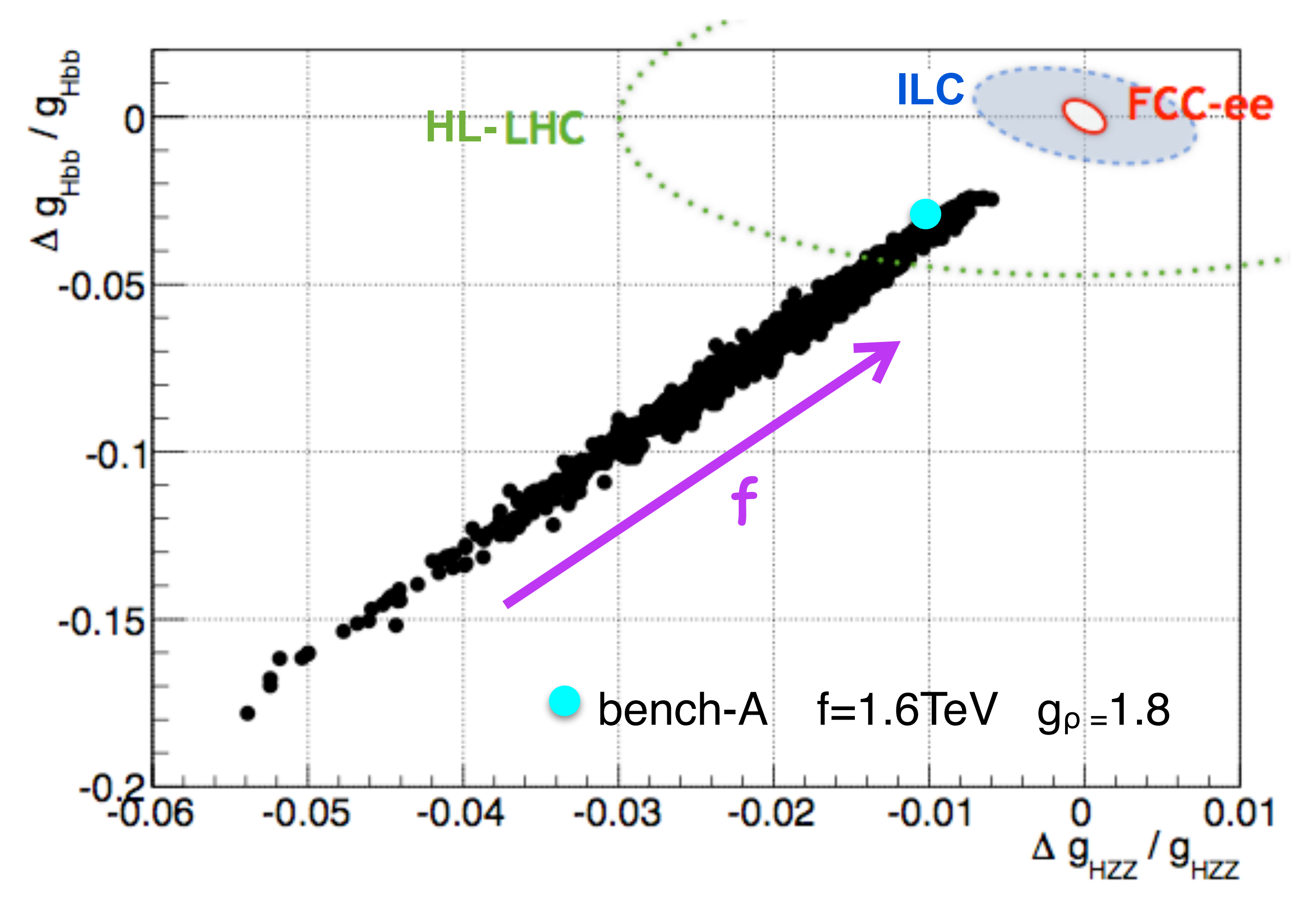
$\xi \leq 0.04$ $f \geq 1200$ GeV

CHMs
NOT
ruled out

CHM: Higgs coupling deviations

Deviations for HZZ and Hbb couplings in the 4DCHM compared with the relative precision expected at HL-LHC, ILC, FCC-ee

Barducci, DC et al. JHEP 1309(2013)047



4DCHM black points

FCC-ee will be able to discover the 4DCHM bench-A ● with a 10σ significance!!

f = compositeness scale

$0.75 \leq f\ (\text{TeV}) \leq 1.6$

g_ρ = strong coupling

$1.5 \leq g_\rho \leq 3$

scan over the 4DCHM fermion parameters

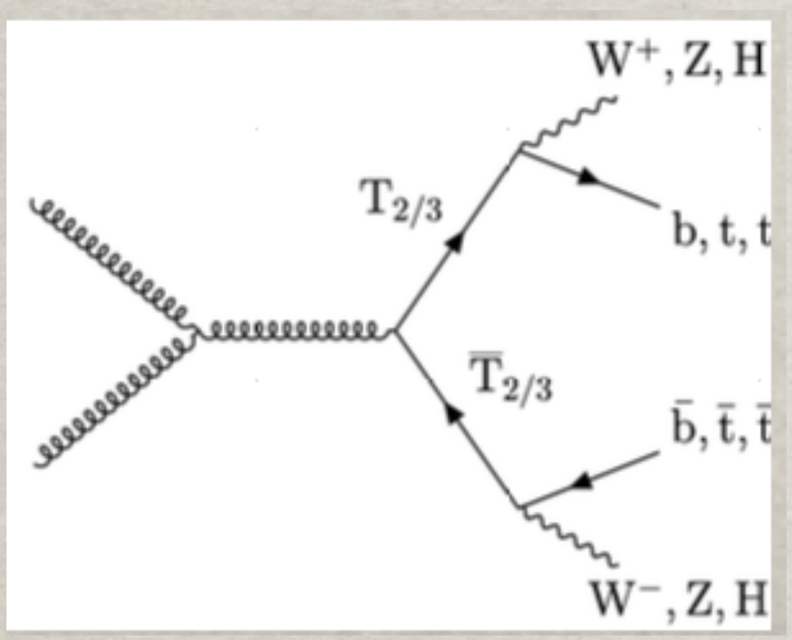
$$\frac{g_{HZZ}}{g_{HZZ}^{SM}} \sim \sqrt{1-\xi}$$

$$\frac{g_{Hbb}}{g_{Hbb}^{SM}} \sim \frac{1-2\xi}{\sqrt{1-\xi}} \qquad \xi = \frac{v^2}{f^2}$$

$\xi < 0.03$ after HL-LHC
$\xi < 0.008$ after ILC/CepC
$\xi < 0.002$ after FCC-ee

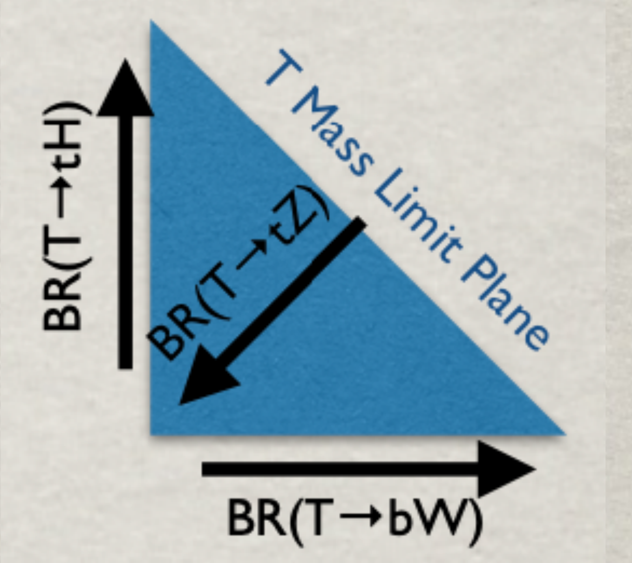
f > 5-6 TeV

Mass bounds on new heavy fermions: $T_{2/3}$, $B_{-1/3}$, $X_{5/3}$



Pair production searches set
σ x BR limits depending on
the extra-fermion mass and on
the BR assumption

← only SM decay channels →
considered

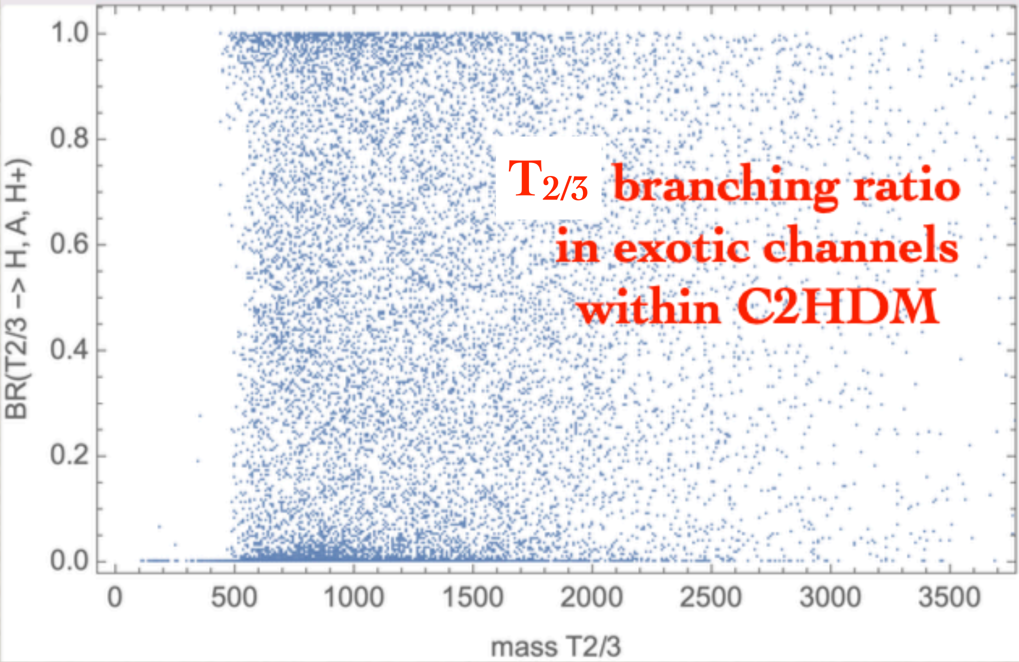


In C2HDM the $T_{2/3}$ can decay in Ht, At, $H^+\bar{b}$ with BR~1 thus softening the bounds based on the SM decay channel only

However, from a recent ATLAS analysis [hep-exp 2212.05263] seems difficult to allow $M_{T2/3} < 1.3$ TeV

Search for pair-produced vector-like quarks using events with exactly one lepton (e or μ), at least four jets including at least one b-tagged jet, and large missing transverse momentum

(upgrade of a previous analysis using 139 fb^{-1} and neural networks trained at several BRs)



A recasting of the bounds is under study

For the phenomenological analysis we take $M_{T2/3} \geq 1.3$ TeV

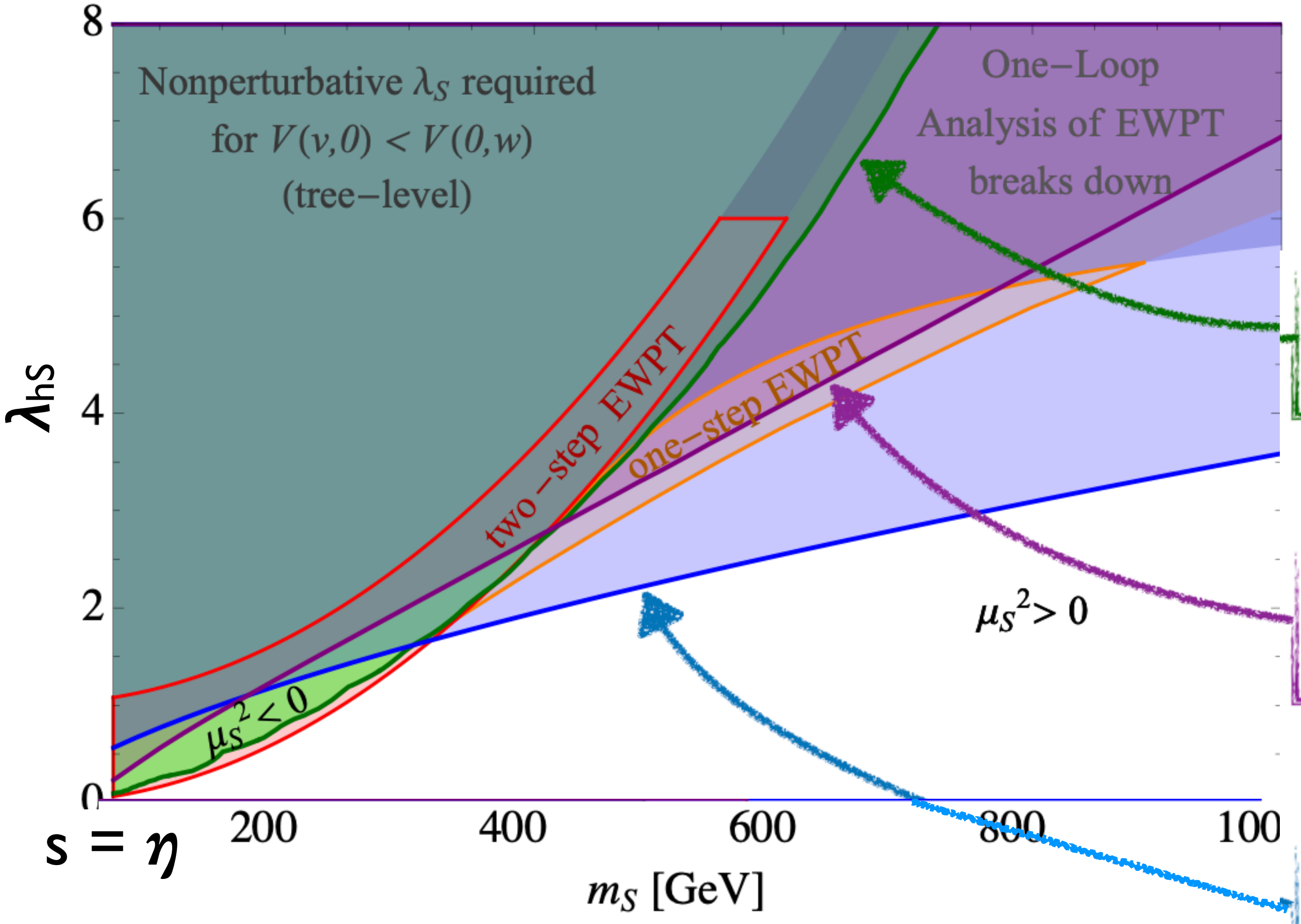
The SM + scalar singlet

phenomenology

☑ direct searches very challenging: need for a 100TeV collider.
interesting channel: qq -> qq ηη (VBF)

☑ indirect searches:

- modification to the triple Higgs coupling $$\lambda_3 = \frac{m_h^2}{2v} + \frac{\lambda_{h\eta}^3}{24\pi^2}\frac{v^3}{m_\eta^2} + \dots$$
- corrections to the Zh cross section at lepton colliders



s = η

Curtin, Meade, Yu, 2015

$S/\sqrt{B} > 2$ with VBF
accessed at FCC-hh with 30/ab

σ_{Zh} modified by more than 0.6%
accessed at FCC-ee

λ_3 modified by more than 10%
accessed at FCC-hh with 30/ab

Key features for a first-order PhT

S_3=bounce action

- ☑ Nucleation probability (per unit time and volume) **P**: $P = T^4 e^{-S_3/T}$
- ☑ Nucleation temperature **T_n**:

$$\int_{T_n}^{\infty} \frac{dT}{T} V_H^4 P \simeq O(1)$$

for phase transitions at the EW scale
$S_3/T_n \approx 140$

- ☑ Vacuum expectation value in the broken phase at T_n: **v_n**
- ☑ Vacuum energy released in the plasma (strength) : $\alpha = \epsilon/\rho_{rad}$
- ☑ The (inverse) time duration of the phase transition: **β/H_n**

$$\frac{\beta}{H_n} = T \frac{d}{dT} \frac{S_3}{T}\bigg|_{T_n}$$

extracted from the solution of the bounce equation

$$\frac{d^2\phi}{dr^2} + \frac{2}{r}\frac{d\phi}{dr} = \nabla V(\phi, T)$$

$$d\phi/dr\,|_{r=0} = 0 \quad \phi\,|_{r=\infty} = 0$$

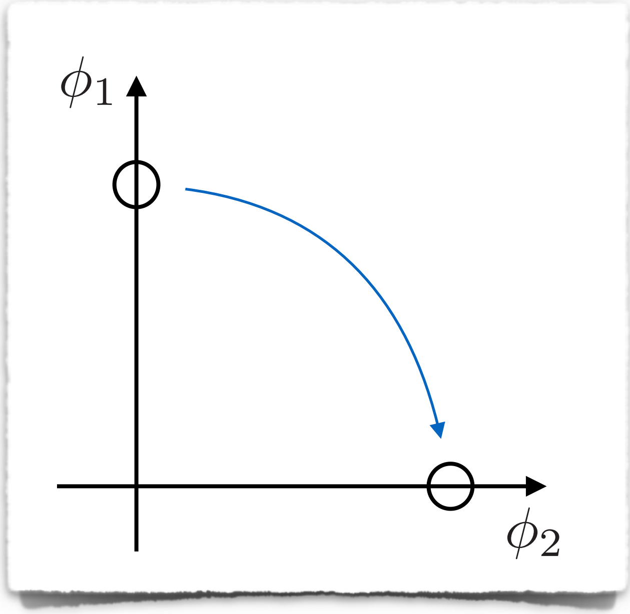
- ☑ Bubble wall velocity: **v_w**
- ☑ The thickness of the bubble wall: **Lw**

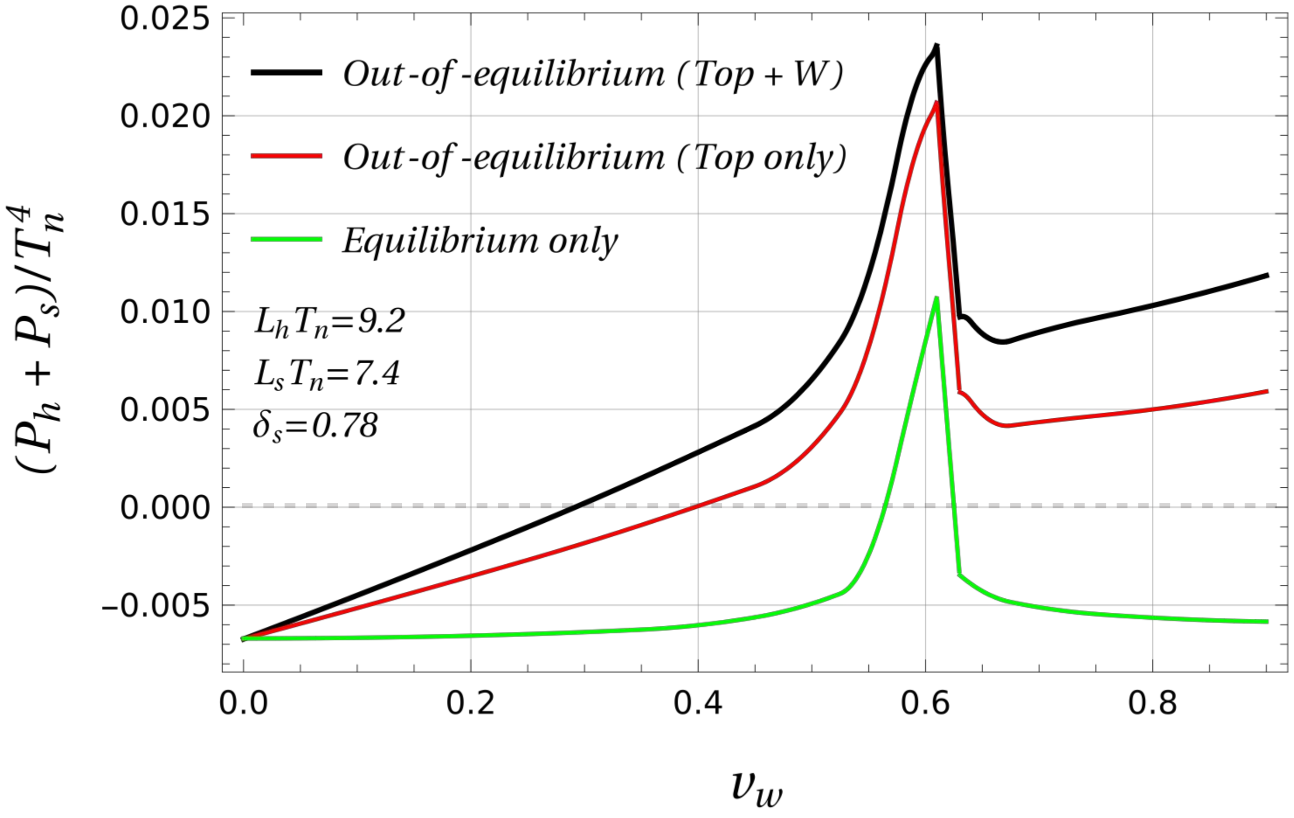
highly non-trivial: requires hydrodynamics
modelling of the bubble wall moving in the plasma

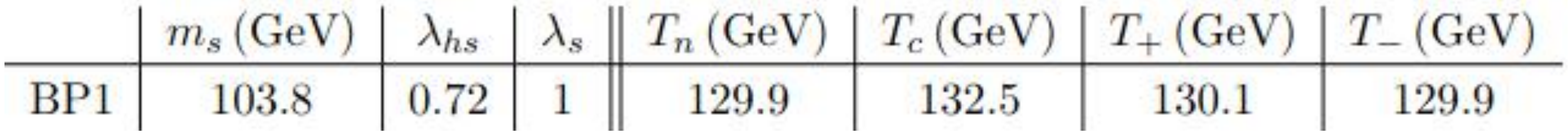
Determination of the wall speed

Delle Rose talk, Heidelberg 2024

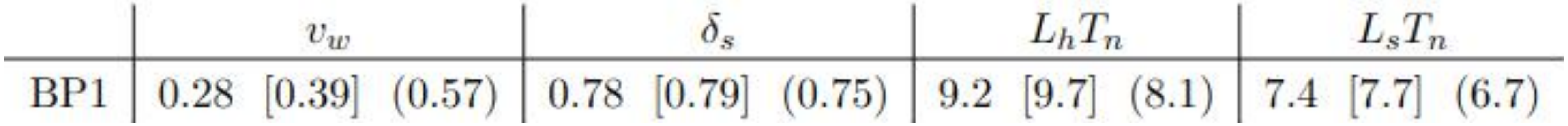
Benchmark scenario: SM + singlet







	m_s (GeV)	λ_{hs}	λ_s	T_n (GeV)	T_c (GeV)	T_+ (GeV)	T_- (GeV)
BP1	103.8	0.72	1	129.9	132.5	130.1	129.9



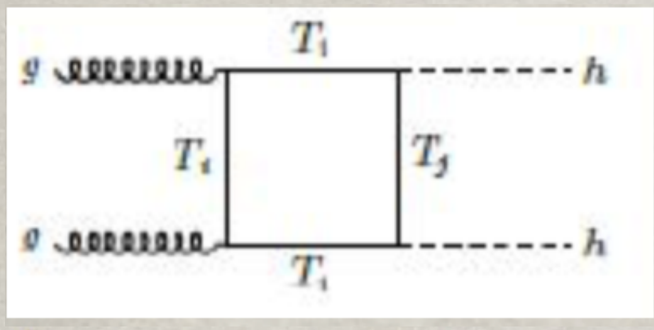
	v_w	δ_s	$L_h T_n$	$L_s T_n$
BP1	0.28 [0.39] (0.57)	0.78 [0.79] (0.75)	9.2 [9.7] (8.1)	7.4 [7.7] (6.7)

- *Peak corresponding to the Jouguet velocity*
- *Important corrections from out-of-equilibrium perturbations*
- *Sizeable corrections given by the W bosons*

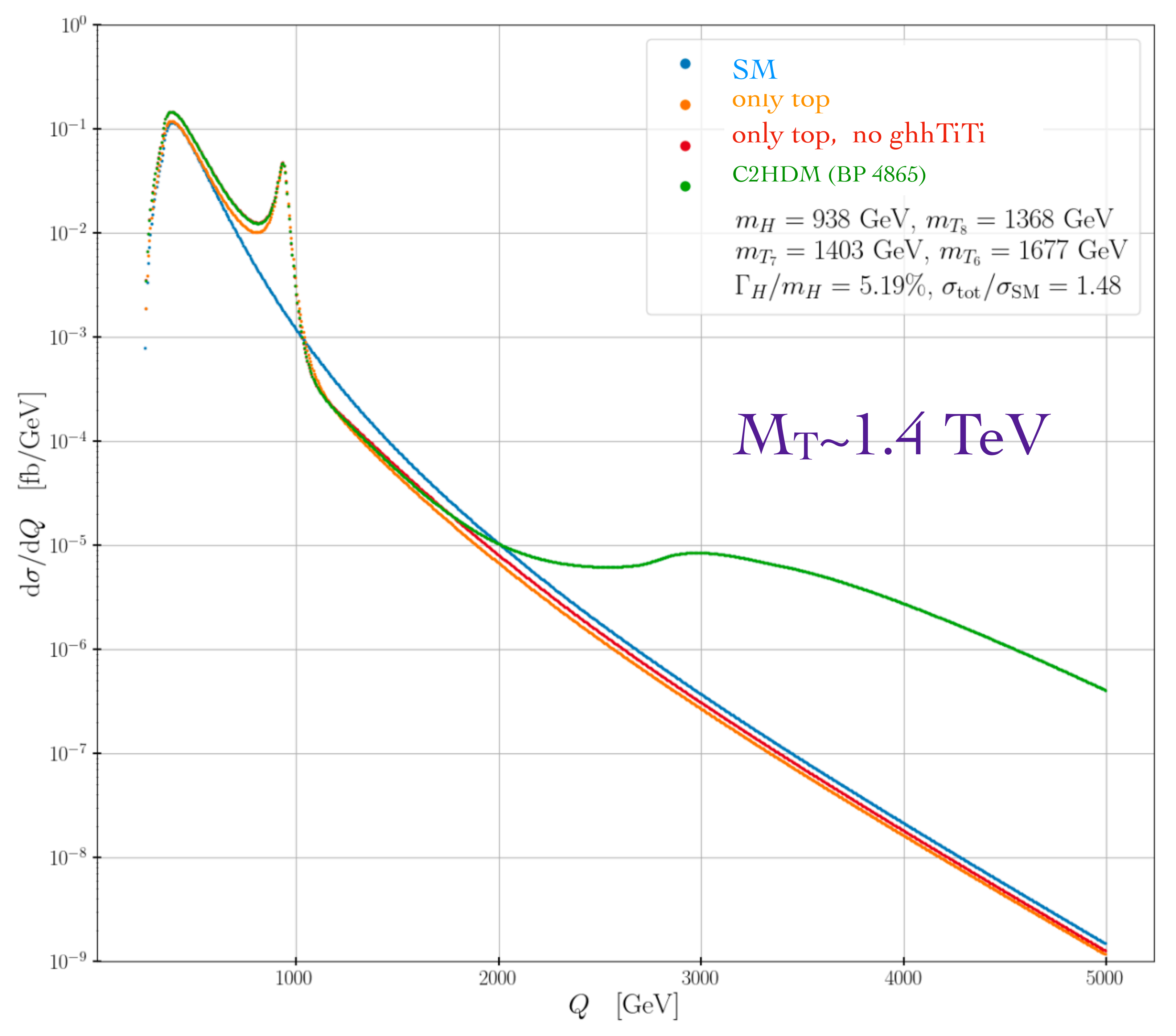
De Curtis, LDR, Guiggiani, Gil Muyor, Panico, 2024

di-Higgs production in C2HDM

Can we see the heavy tops' loop effects by looking at the invariant mass and/or p_t distributions?



Boxes can induce thresholds at $2M_T$ and low-mass tail, different from squark loop effects (PV functions, spin)



M_T~1.4 TeV

di-Higgs production in C2HDM

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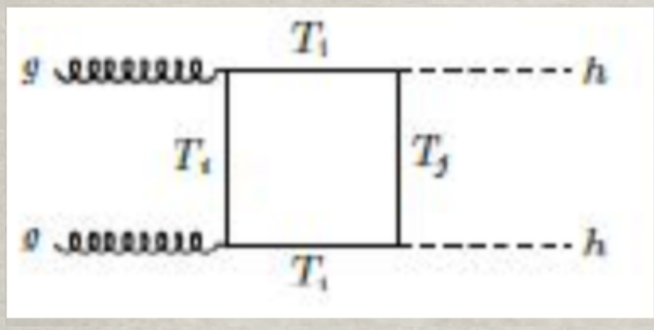

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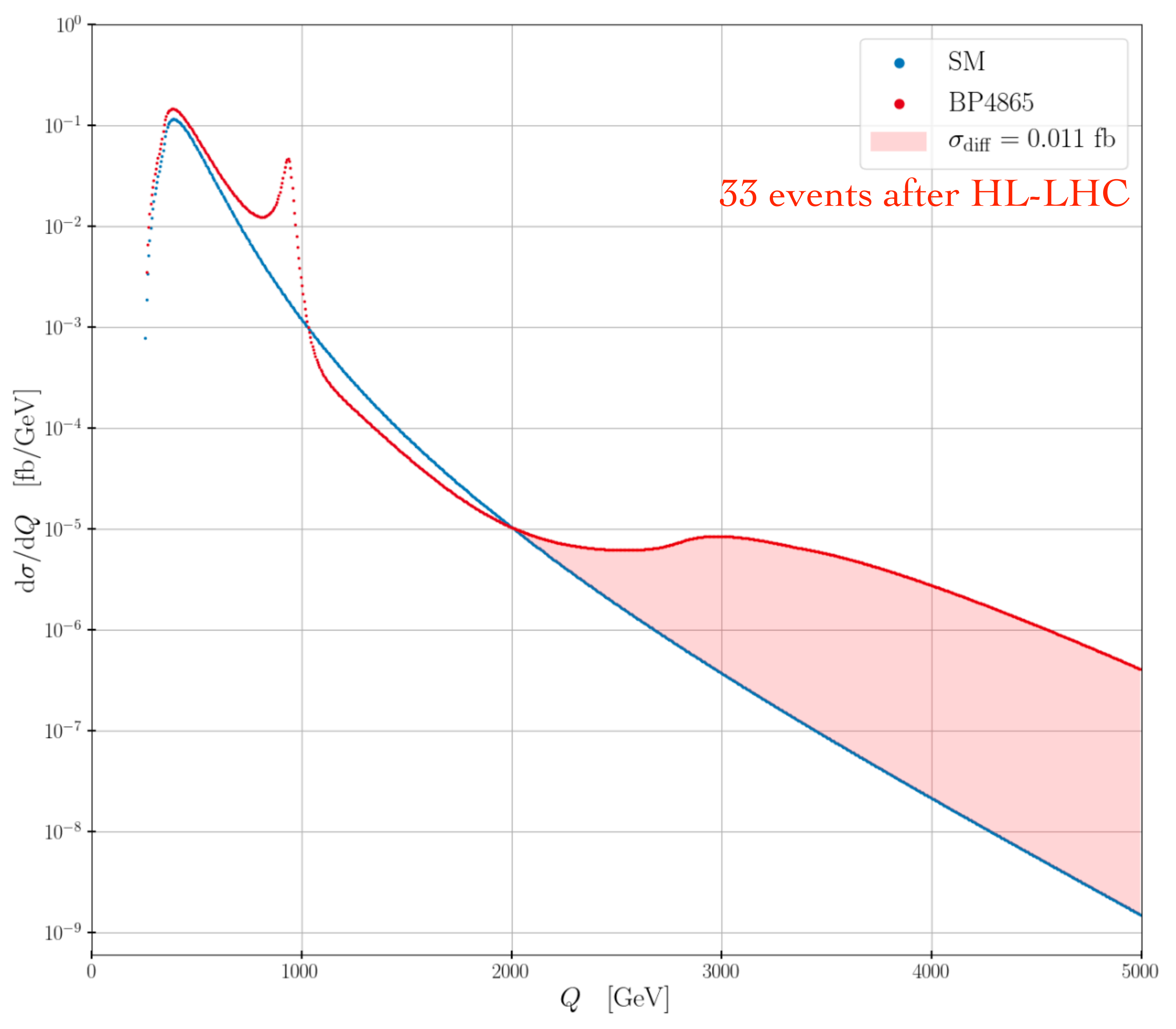

33 events after HL-LHC