# Reflections on Scalars at the Weak Scale and Beyond


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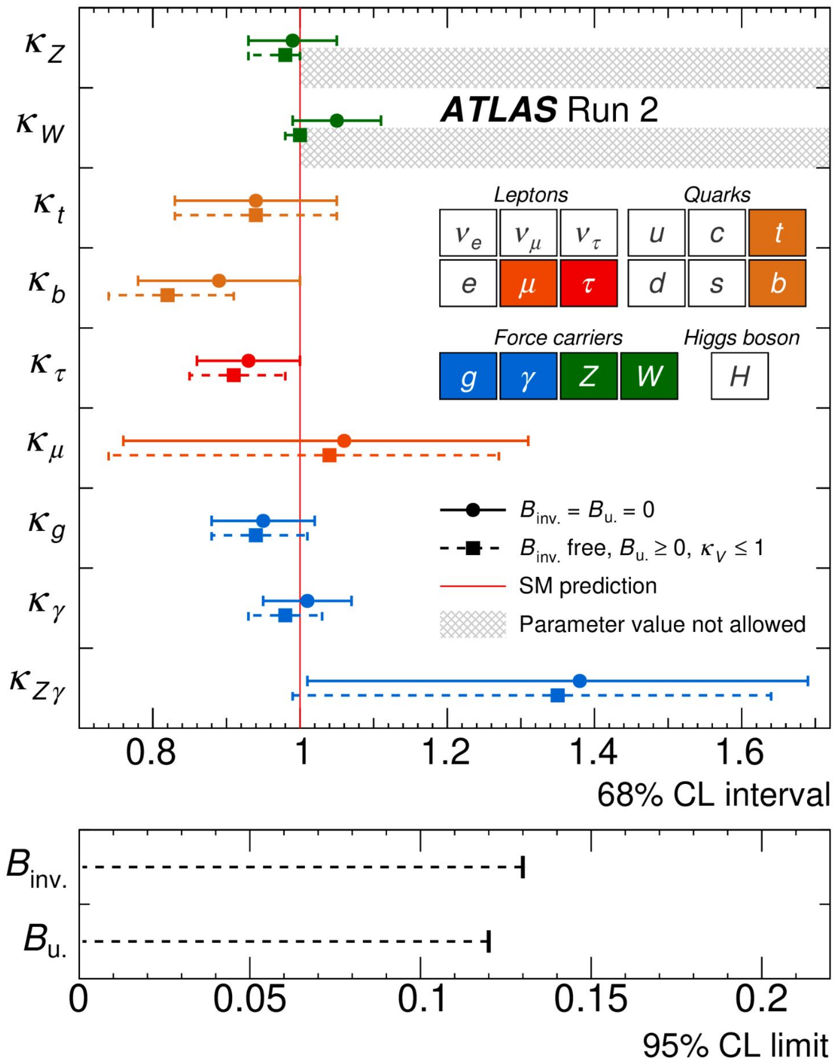
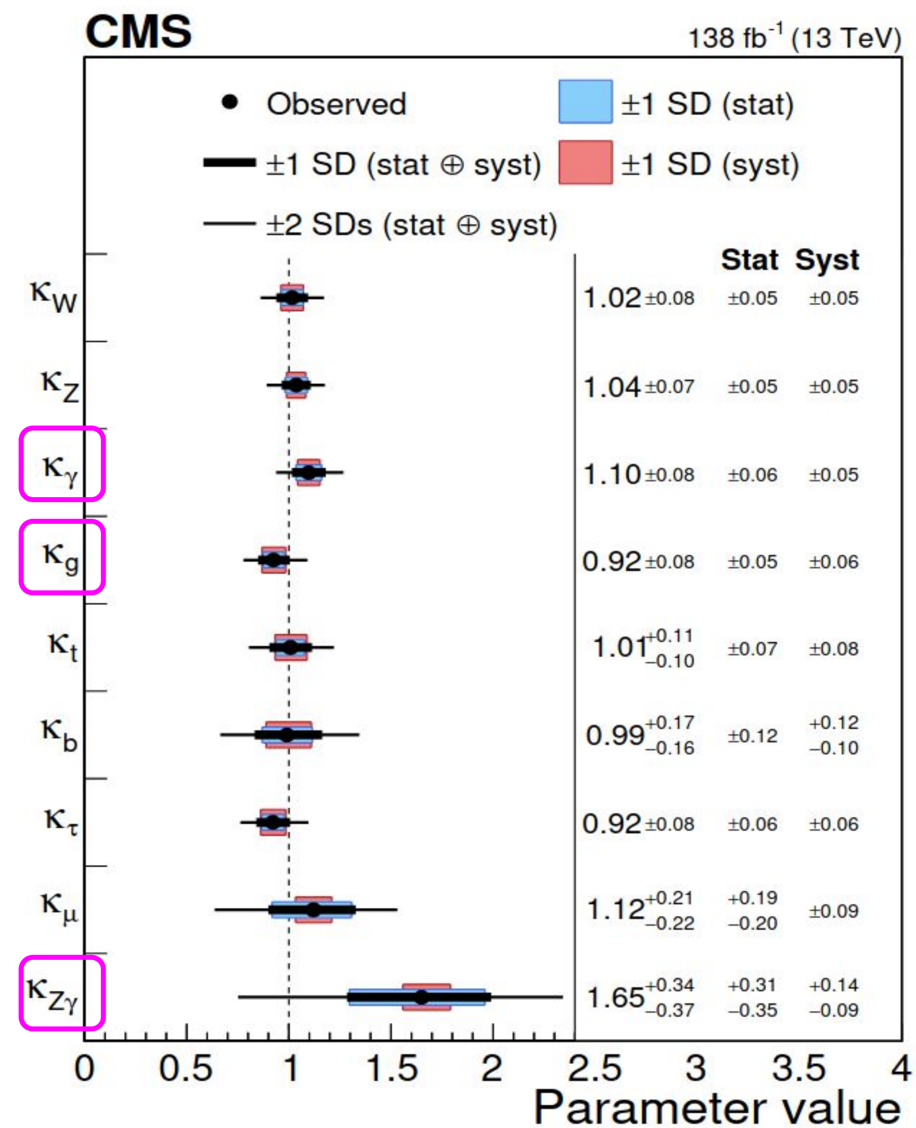
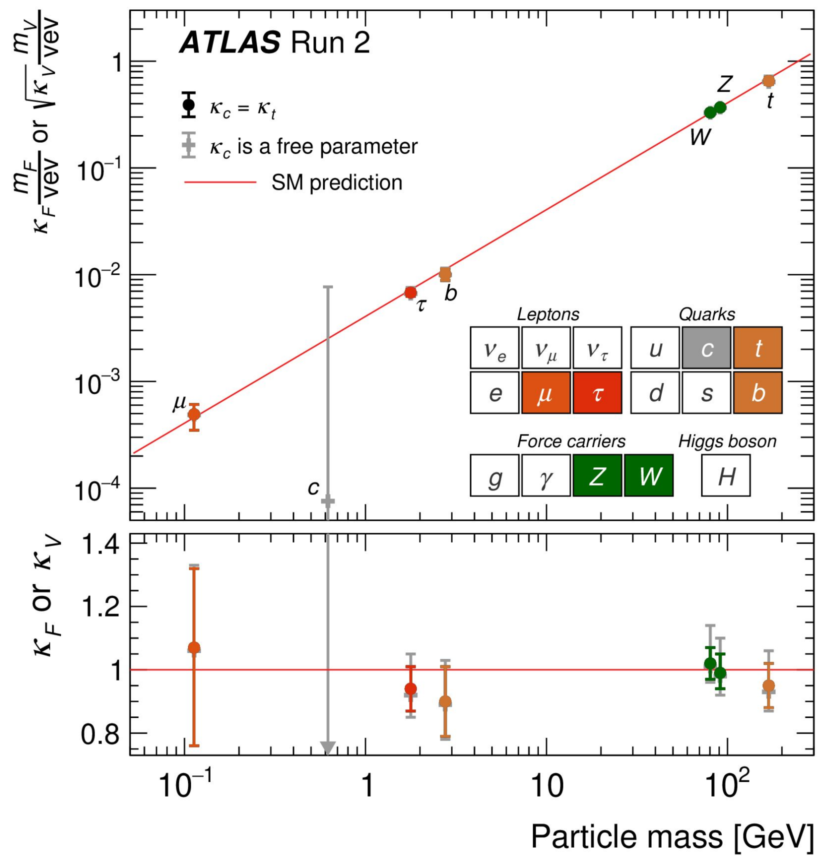
# ATLAS and CMS Fit to Higgs Couplings

## Departure from SM predictions of the order of few tens of percent allowed at this point.

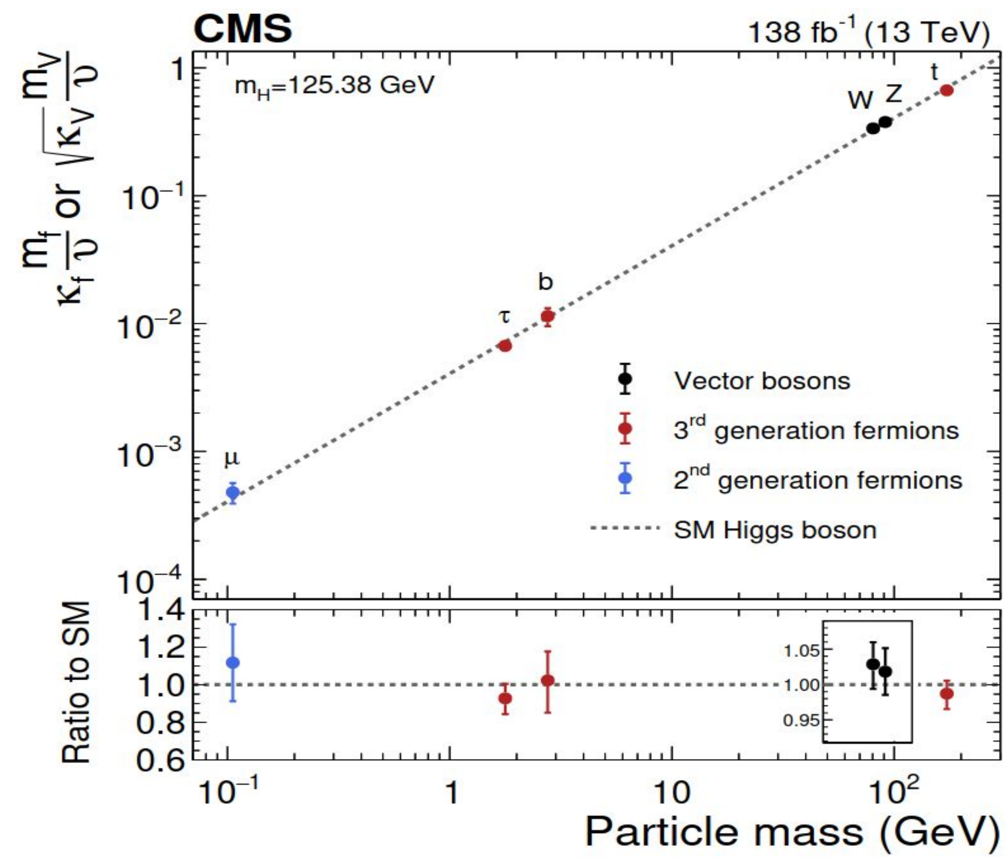


## Correlation between masses and couplings consistent with the Standard Model expectations




### H couplings vs particle mass






$$g_{hf\bar{f}} = \frac{m_f}{v}, \qquad g_{hVV} = \frac{m_V^2}{v}$$

All these coupling that are constrained at the 10 percent level, will be constrained at the few percent level at the end of the LHC era

T. Vickey

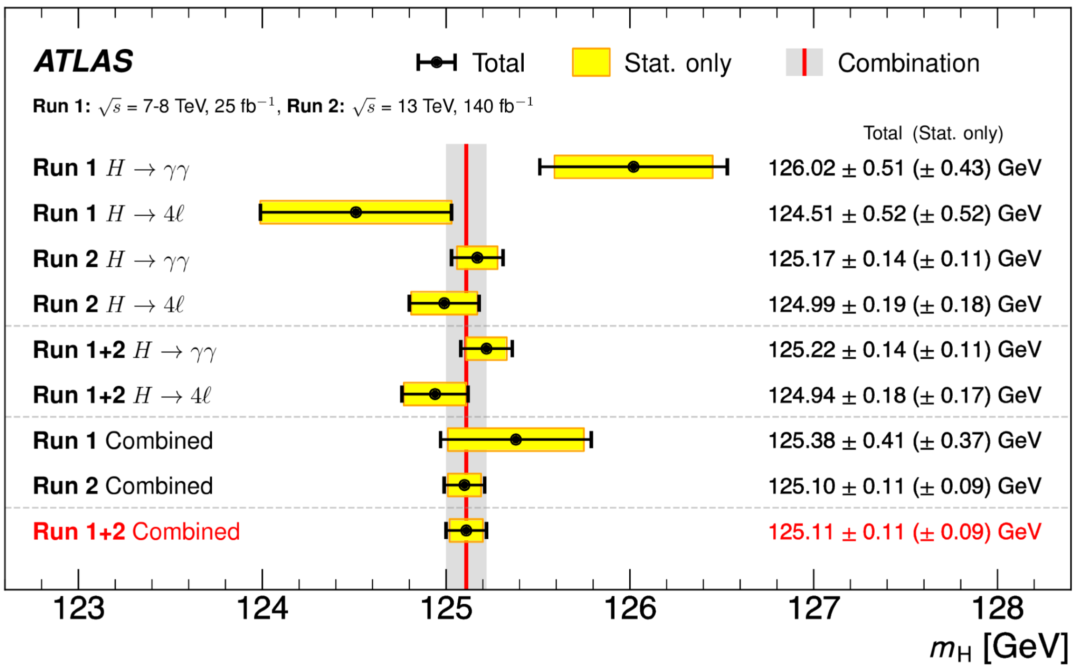
arXiv:2308.04775

# Higgs Boson Mass Combination

- Measurement combines the latest results in the H → ZZ* → 4ℓ and H → γγ decay channels
- Result based on 140 $fb^{-1}$ of pp collision data collected at a center of mass energy of 13 TeV during Run-2

**Full Run-2 result:** $m_H = 125.10 \pm 0.09\,(\text{stat.}) \pm 0.07\,(\text{syst.}) = 125.10 \pm 0.11\,\text{GeV}$

**Run-1 + Run-2 result:** $\boxed{m_H = 125.11 \pm 0.09\,(\text{stat.}) \pm 0.06\,(\text{syst.}) = 125.11 \pm 0.11\,\text{GeV}}$

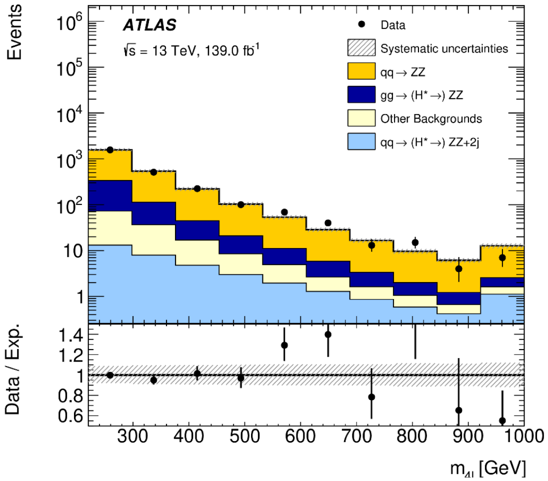


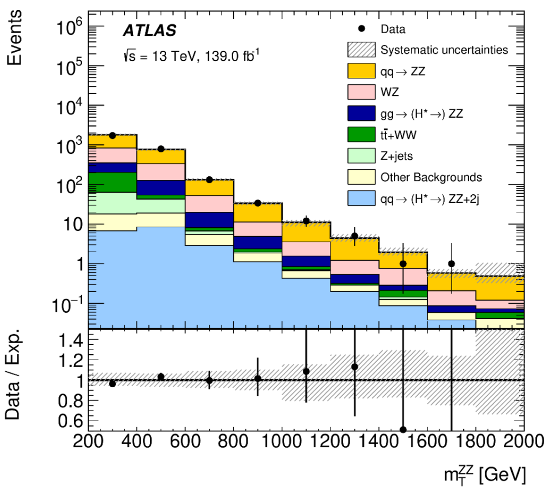

**Extremely precise measurement of the Higgs boson mass, with an uncertainty of only 110 MeV!**

T. Vickey

arXiv:2304.01532

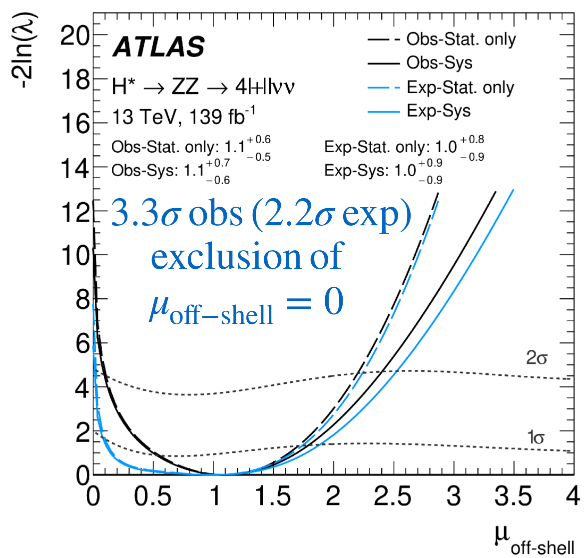
# Determination of the Higgs Boson Width



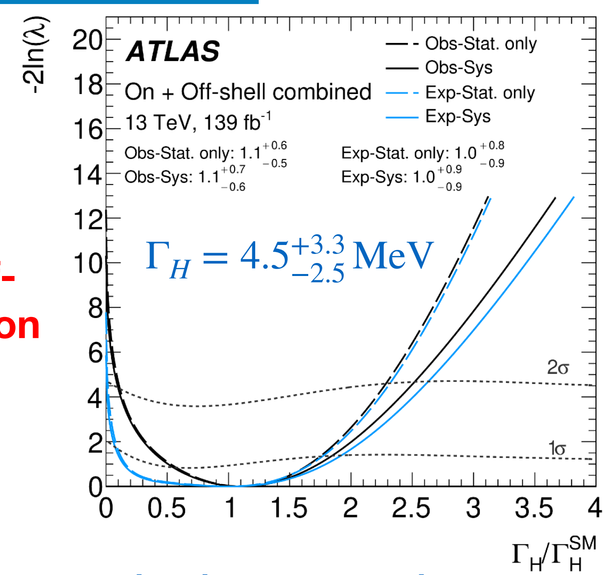




- Predicted Higgs width of 4.1 MeV is much smaller than the detector resolution
- This 4ℓ and 2ℓ 2ν ZZ combination exploits the independence of off-shell cross section on $\Gamma_H$ and relies on identical on-shell and off-shell Higgs couplings to determine $\Gamma_H$ from measurements of $\mu_{\text{off-shell}}$ and $\mu_{\text{on-shell}}$

$$\boxed{\sigma^{\text{on-shell}}_{gg\to H\to VV} \sim \frac{g^2_{ggH}g^2_{HZZ}}{m_H\Gamma_H} \qquad \sigma^{\text{off-shell}}_{gg\to H\to VV} \sim \frac{g^2_{ggH}g^2_{HZZ}}{m^2_{ZZ}}}$$




**Evidence for off-shell Higgs boson production!**



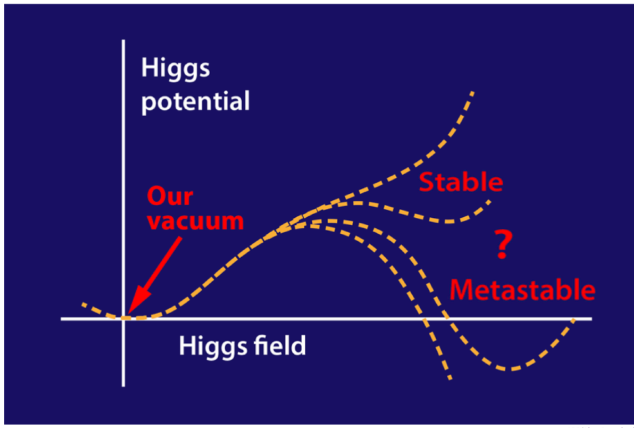

**NB: Neyman likelihood profiles shown; ~5-10% more conservative than asymptotic**

T. Vickey

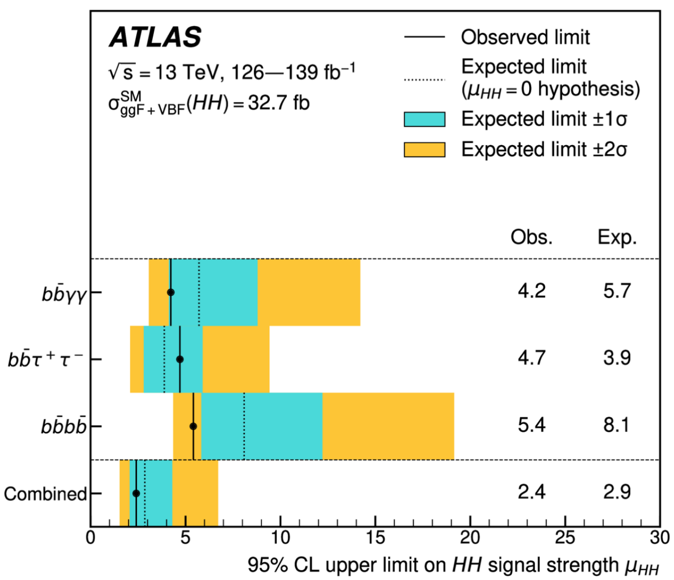
Phys. Lett. B 843 (2023) 137745

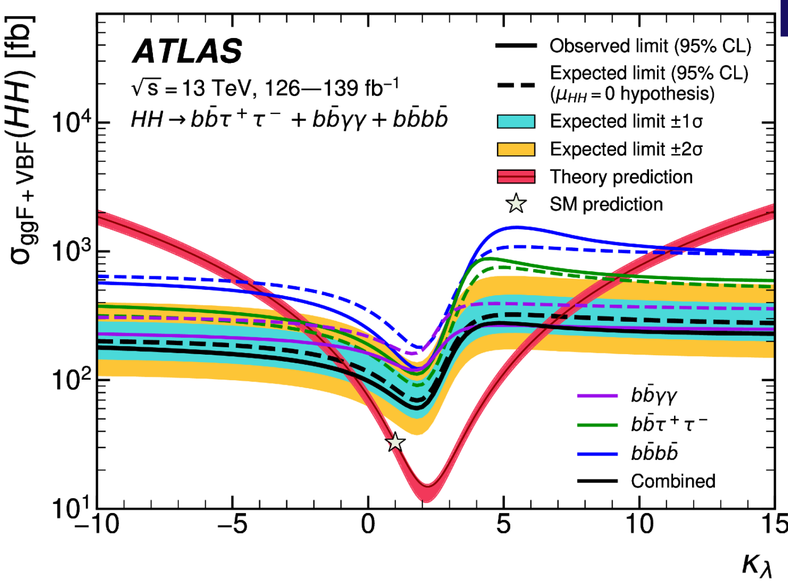
# ATLAS Higgs self-coupling results

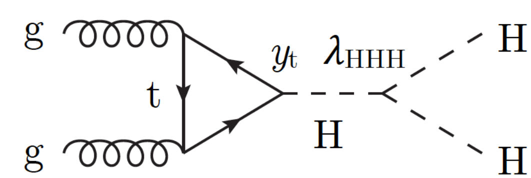
- Higgs self-interaction can be measured via HH production
  - $10^3$ times more rare than single Higgs processes
  - Allows us to probe the shape of the Higgs potential
- Many different channels analyzed
- Sensitivity better than 3x the SM




https://physics.aps.org/articles/v8/108



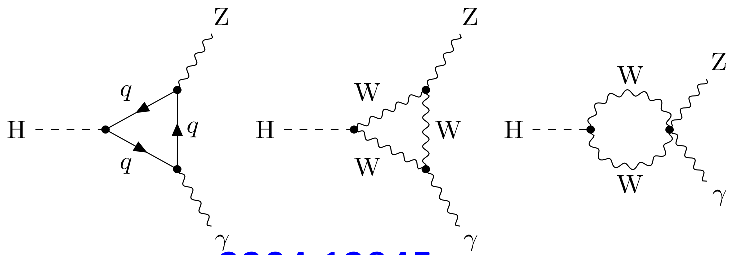



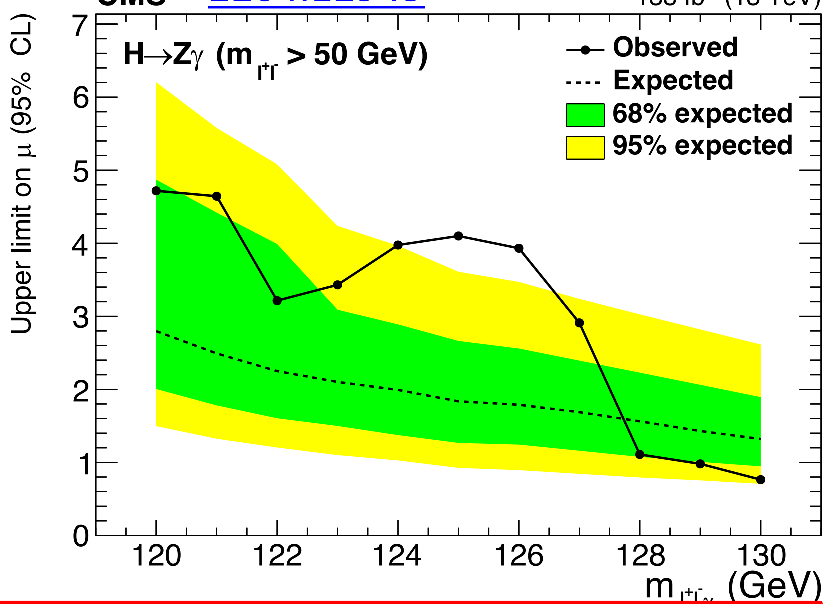



S. Tkaczyk

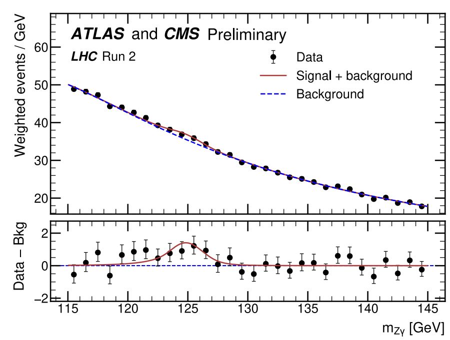
# Higgs Decay H → Zγ

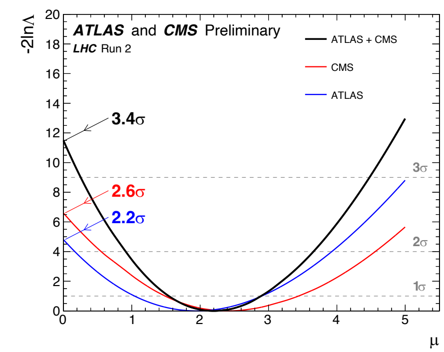
JHEP05(2023)233




- Similar to H→ γγ already reconstructed but rate reduction in Z→ $\ell\ell$ channel
- Sensitivity to BSM effects at the decay
- First example of combined ATLAS and CMS evidence of H →Zγ from previously published results




Signal strength μ for $M_h$=125.38 GeV: μ=2.4 ±0.9
Observed significance: **2.7** σ
Upper limit on μ: 4.1 Observed 1.8 Expected

Combined CMS and ATLAS first evidence for H → Zγ decay with observed significance: **3.4** σ (expected **1.6** σ)

Signal strength: μ=2.2 ±0.7
**1.9** σ compatibility with the SM prediction

# Why we should not be surprised

- There is a well known, amazing property of the SM as an effective field theory

- Take any sector with gauge invariant mass terms, which do not involve the Higgs v.e.v.

$$\mathcal{L} = -m_\phi^2 \phi^\dagger \phi + (M_\Psi \bar{\Psi} \Psi)$$

- The Appelquist-Carrazonne decoupling theorem says that as we push these gauge invariant masses up, the low energy effective theory will reduce to the Standard Model !

- The speed of decoupling depends on how these sector couple to the SM. In general, for a coupling κ to the Higgs, decoupling occurs when

$$\frac{k^2}{m_{\rm new}^2} \ll \frac{1}{v^2}$$

- Obviously decoupling doesn’t occur if the masses are proportional to the v.e.v.

- These properties are behind the EFT program.

# Why we should be surprised

- The Higgs potential suffers from a problem of stability under ultraviolet corrections, namely, given any sector that couples to the Higgs sector with gauge invariant masses, the Higgs mass parameter will be affected

$$\Delta m_H^2 \propto (-1)^{2S} \frac{k^2 N_g}{16\pi^2}\; m_{\rm new}^2$$

- These are physical corrections, regularization independent and shows that unless the new physics is lighter than the few TeV scale of very weakly coupled to the Higgs sector, the presence of particles with masses much larger than the weak scale mass parameter is hard to understand.

- This is particularly true in models that try to connect the Higgs with the ultraviolet physics, like Grand Unified Theories.

- In such a case, we need a delicate cancellation of corrections, that only an extension like Supersymmetry can provide.

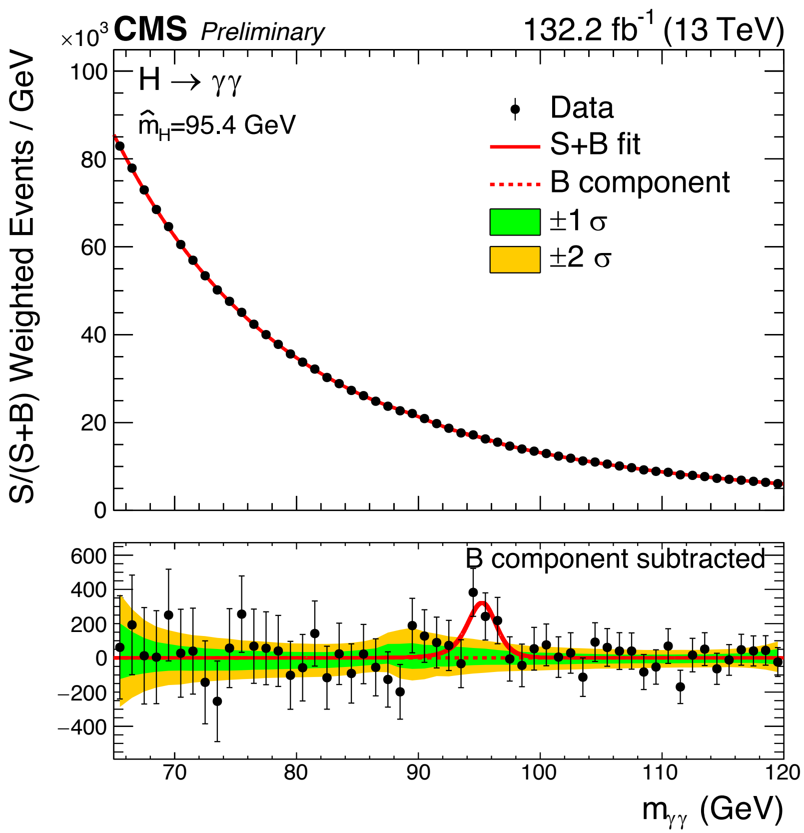
# Hints of New Scalars ?

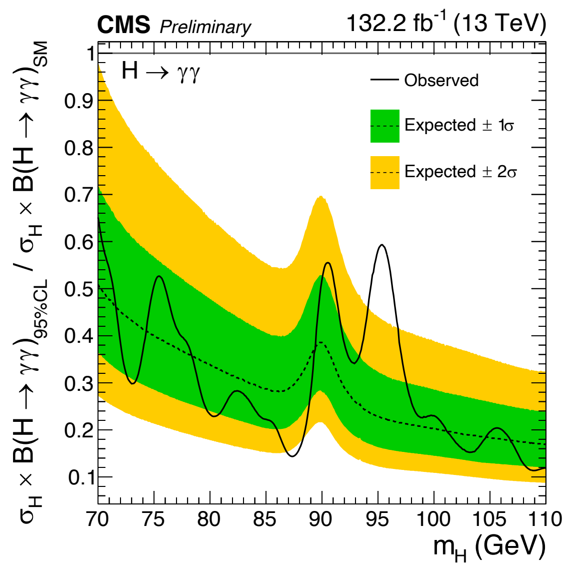
S. Tkaczyk

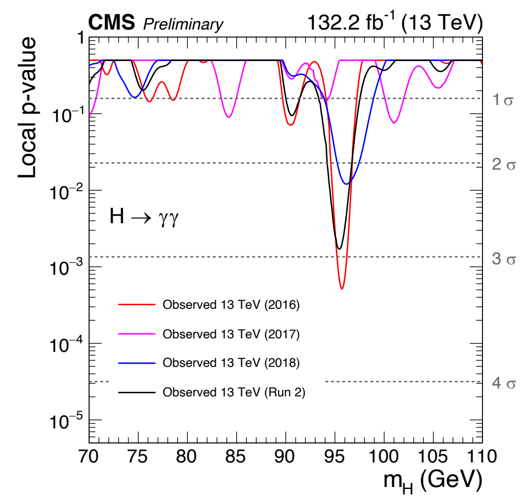
# Search for Light H → γγ

[CMS-PAS-HIG-020-002](CMS-PAS-HIG-020-002)

Search for additional light H → γγ decays below H(125)




Data compatible with background-only-hypothesis
Observed Upper Limit on σ x BF : from 73 to 15 fb-1
Largest deviation M=**94.5** GeV w/ Local (Global) **2.9**(**1.3**)σ

ATLAS results not inconsistent with the CMS excess, arXiv:2306.03889

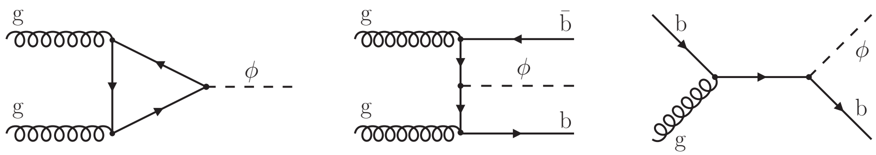
KOTLARSKI, BANK

S. Tkaczyk

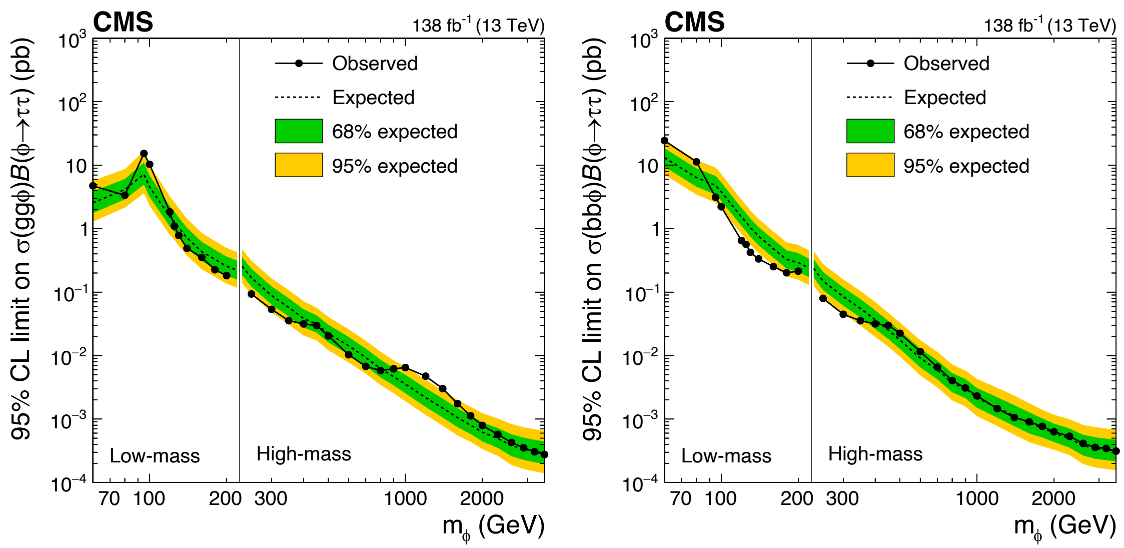
# Search for neutral higgs $\phi$

JHEP07(2023)073

Neutral higgs $\phi$ in ggF or in association with b-quark(s)



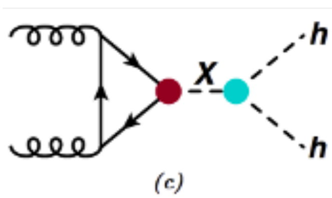

$\phi \rightarrow \tau\tau$ in lepton or hadron decays



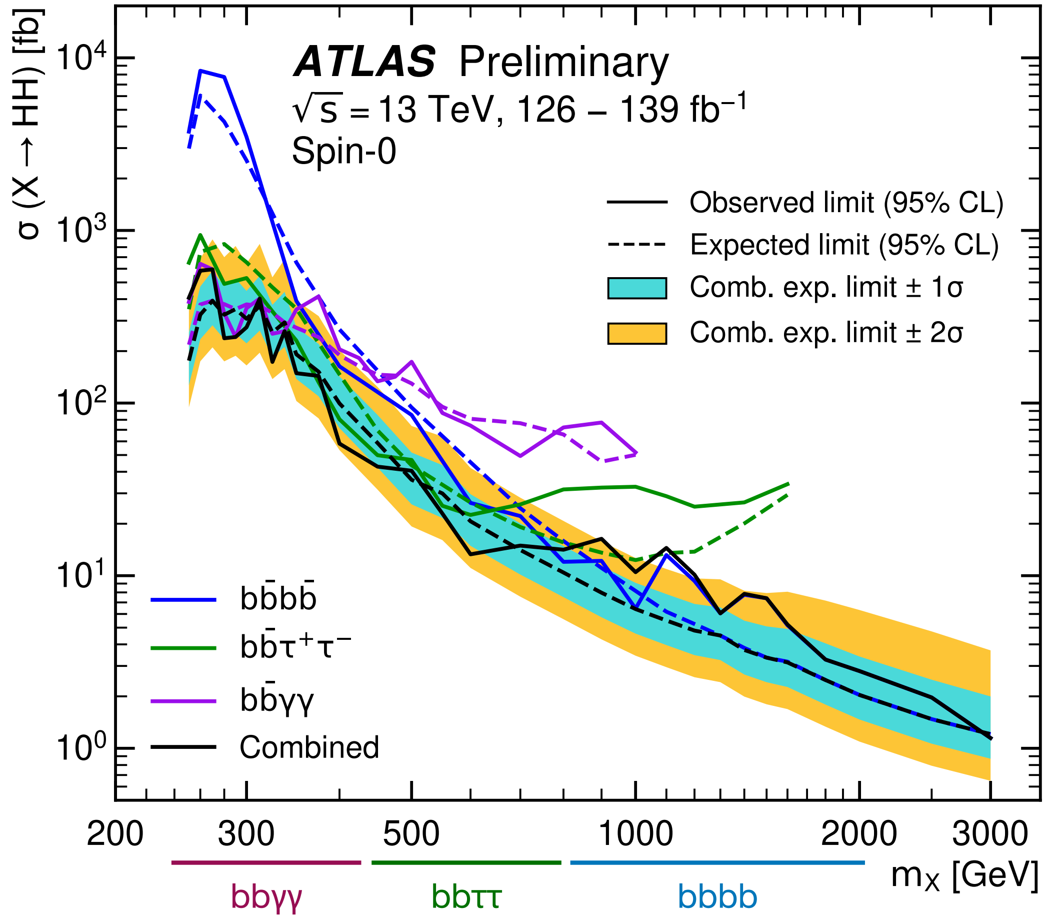

Limits set [60 - 3500 GeV] ranging from 10pb to 0.3fb
e.g. two excesses in gg$\phi$ at 0.1 and 1.2 TeV with ~3$\sigma$

In MSSM scenarios $M_h^{125}$ & $M_{h,\,EFT}^{125}$ additional Higgs bosons with masses below 350 GeV excluded

# Resonant Di-Hiogs Production




Local Excess at 1.1—1.2 TeV




Other Interesting Excesses : A (650 GeV) -> H (450 GeV) Z
A(650 GeV) -> h (95 GeV) Z
H,A (400 GeV) —> t tbar, tau tau
A(610 GeV) —> H(290 GeV) Z

arXiv:2302.13697

# Simple Framework for analysis of coupling deviations
# 2HDM : General Potential

- General, renormalizable potential has seven quartic couplings, with three of them, given in the last line, may be complex.

$$
\begin{aligned}
V &= m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - (m_{12}^2 \Phi_1^\dagger \Phi_2 + h.c.) \\
&+ \frac{\lambda_1}{2} (\Phi_1^\dagger \Phi_1)^2 + \frac{\lambda_2}{2} (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) \\
&+ \left[ \frac{\lambda_5}{2} (\Phi_1^\dagger \Phi_2)^2 + \lambda_6 (\Phi_1^\dagger \Phi_1)(\Phi_1^\dagger \Phi_2) + \lambda_7 (\Phi_2^\dagger \Phi_2)(\Phi_1^\dagger \Phi_2) + h.c. \right] ,
\end{aligned}
$$

- In general, it is assumed that lambda 6 and 7 are zero, since this condition appears naturally in models with flavor conservation. However, this condition is basis dependent and it is not necessary.

- We will therefore concentrate on the general 2HDM, with all quartic couplings different from zero. As it is well known an important parameter in these models is

$$\tan\beta = \frac{v_2}{v_1}$$

# $Z_2$ symmetric case : Motivation

- In 2HDM, one can define independent Yukawa couplings for each charge eigenstate fermion sector

$$Y_1^{ij} \bar{\Psi}_L^i H_1 \psi_R^j + Y_2^{ij} \bar{\Psi}_L^i H_2 \psi_R^j + h.c.$$

- Here the Yukawas are 3x3 matrices in flavor space

- This leads to a mass matrix

$$M = Y_1 \frac{v_1}{\sqrt{2}} + Y_2 \frac{v_2}{\sqrt{2}}$$

- The problem is that, contrary to the SM, diagonalization of this mass matrix does not lead to diagonal terms for the Yukawa interactions and there is in general dangerous flavor violation interactions the Higgs sector.

- This may be avoided by a simple parity symmetry, where for instance

$$H_1 \to H_1, \quad H_2 \to -H_2, \quad L \to L, \quad R \to \pm R$$

- This marries even scalar fields with even fermion fields and odd with odd and kills the flavor violating interactions while keeping

$$\lambda_6 = \lambda_7 = 0$$

- However, in a complete theory these couplings could be generated at the loop level, and it is interesting to consider the general case.

# Higgs Basis

- An interesting basis for the phenomenological analyses of these models is the Higgs basis

$$H_1 = \Phi_1 \cos\beta + \Phi_2 \sin\beta$$
$$H_2 = \Phi_1 \sin\beta - \Phi_2 \cos\beta$$

$$H_1 = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + \phi_1^0 + iG^0) \end{pmatrix}, \quad H_2 = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(\phi_2^0 + ia^0) \end{pmatrix}$$

- The field $\phi_1^0$ is therefore associated with the field direction that acquires a vacuum expectation value and acts as a SM-like Higgs

- The behavior of the neutral mass eigenstates depend on the projection on the fields in this basis.

- Typically, it is the lightest neutral Higgs boson that behaves like the SM-like Higgs. The case in which one can identify the state $\phi_1^0$ with the mass eigenstate is called alignment.

- In the alignment limit the tree-level couplings agree with the SM ones. Large departures from the alignment limit are heavily restricted by LHC measurements.

# Mass Matrix in the Higgs Basis

- The neutral Higgs mass matrix takes a particularly simple form in the Higgs basis (Zi are the quartic couplings)

$$\mathcal{M}^2 = v^2 \begin{pmatrix} Z_1 & Z_6^R & -Z_6^I \\ Z_6^R & \frac{M_{H^\pm}^2}{v^2} + \frac{1}{2}(Z_4 + Z_5^R) & -\frac{1}{2}Z_5^I \\ -Z_6^I & -\frac{1}{2}Z_5^I & \frac{M_{H^\pm}^2}{v^2} + \frac{1}{2}(Z_4 - Z_5^R) \end{pmatrix}$$

- Two things are obvious from here. First, in the CP-conserving case, the condition of alignment, $Z_6 \ll 1$ implying small mixing between the lightest and heavier eigenstates is given by

$$\cos(\beta - \alpha) = -\frac{Z_6 v^2}{m_H^2 - m_h^2} \qquad \text{Decoupling}: \quad Z_6 v^2 \ll m_H^2$$

- Second, while in the alignment limit the real part of $Z_5$ contributes to the splitting of the two heavier mass eigenstates, its imaginary part contributes to the splitting and their mixing.

$$M_{h_3,h_2}^2 = M_{H^\pm}^2 + \frac{1}{2}(Z_4 \pm |Z_5|)v^2 \,.$$

$$m_h^2 = Z_1 v^2, \qquad m_h = 125 \text{ GeV}$$

Ivanov, Ferreira

# Symmetries of the SU(2)×U(1) 2HDM

**Higgs-Family Symmetries:**

**$Z_2$:** $\Phi_1 \to \Phi_1 \quad , \quad \Phi_2 \to -\Phi_2$

**U(1):** $\Phi_1 \to \Phi_1 \quad , \quad \Phi_2 \to e^{i\theta}\,\Phi_2 \qquad \theta \neq \{0\,,\,\pi\}$

**SO(3):** $\begin{pmatrix} \Phi_1 \\ \Phi_2 \end{pmatrix} \to U \begin{pmatrix} \Phi_1 \\ \Phi_2 \end{pmatrix} \qquad \forall_{U \in U(2)}$

**Generalized CP Transformations:**

**CP1:** $\Phi_1 \to \Phi_1^* \quad , \quad \Phi_2 \to \Phi_2^*$

**CP2:** $\Phi_1 \to \Phi_2^* \quad , \quad \Phi_2 \to -\Phi_1^*$

**CP3:** $\begin{pmatrix} \Phi_1 \\ \Phi_2 \end{pmatrix} \to \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \Phi_1^* \\ \Phi_2^* \end{pmatrix} \qquad 0 < \theta < \pi/2$

New symmetries arise when g1 = 0, 13 in total

Pfilatsis

# Symmetries of the 2HDM

**Each symmetry has a different impact on the scalar potential, originating models with different phenomenologies and a different number *N* of independent parameters:**

| Symmetry | $m_{11}^2$ | $m_{22}^2$ | $m_{12}^2$ | $\lambda_1$ | $\lambda_2$ | $\lambda_3$ | $\lambda_4$ | $\lambda_5$ | $\lambda_6$ | $\lambda_7$ | $N$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| CP1 | | | real | | | | | real | real | real | 9 |
| $Z_2$ | | | 0 | | | | | | 0 | 0 | 7 |
| U(1) | | | 0 | | | | | 0 | 0 | 0 | 6 |
| CP2 | | $m_{11}^2$ | 0 | | $\lambda_1$ | | | | | $-\lambda_6$ | 5 |
| CP3 | | $m_{11}^2$ | 0 | | $\lambda_1$ | | | $\lambda_1 - \lambda_3 - \lambda_4$ | 0 | 0 | 4 |
| $SO(3)$ | | $m_{11}^2$ | 0 | | $\lambda_1$ | | $\lambda_1 - \lambda_3$ | 0 | 0 | 0 | 3 |

**TABLE 1**

**Some of these symmetries have phenomenologically viable extensions to the Yukawa sector, thus becoming symmetries of the whole lagrangian, not simply of the potential ($Z_2$, U(1), CP1, CP2, CP3).**

**These symmetries may appear differently depending on the *choice of basis* for the 2HDM.**

Ferreira

# New 2HDM symmetries

**Combining the new relations between couplings ("$r_0$-symmetry")**

$$\{m_{11}^2 + m_{22}^2 = 0 \ , \ \ \lambda_1 = \lambda_2 \ , \ \ \lambda_6 = -\lambda_7\}$$

**with the other six symmetries, we obtain new 2HDM models, with new coupling relationships which are RG invariant to all orders.**

**We will designate the new symmetries with the prefix "0", so for instance, "0CP1" will refer to the application of the $r_0$ and CP1 symmetries, and "$0Z_2$" refers to the application of $r_0$ and $Z_2$.**

| Symmetry | $m_{11}^2$ | $m_{22}^2$ | $m_{12}^2$ | $\lambda_1$ | $\lambda_2$ | $\lambda_3$ | $\lambda_4$ | $\lambda_5$ | $\lambda_6$ | $\lambda_7$ |
|---|---|---|---|---|---|---|---|---|---|---|
| $r_0$ | | $-m_{11}^2$ | | | $\lambda_1$ | | | | | $-\lambda_6$ |
| 0CP1 | | $-m_{11}^2$ | real | | $\lambda_1$ | | | real | real | $-\lambda_6$ |
| $0Z_2$ | | $-m_{11}^2$ | 0 | | $\lambda_1$ | | | | 0 | 0 |
| 0U(1) | | $-m_{11}^2$ | 0 | | $\lambda_1$ | | | 0 | 0 | 0 |
| 0CP2 | 0 | 0 | 0 | | $\lambda_1$ | | | | | $-\lambda_6$ |
| 0CP3 | 0 | 0 | 0 | | $\lambda_1$ | | | $\lambda_1 - \lambda_3 - \lambda_4$ | 0 | 0 |
| $0SO(3)$ | 0 | 0 | 0 | | $\lambda_1$ | | $\lambda_1 - \lambda_3$ | 0 | 0 | 0 |

**TABLE 2**

No clear which symmetry transformations behind this relations !

OGREID

All Higgs masses proportional to the Higgs vev, therefore testable in the near future.

# 3HDMs

Talks by Ivanov, Keus and Rebello

Extended Symmetries

Possibility of incorporating CP Violation and Dark Matter

Rebello

S3 = Permutation Symmetry Group

$$\begin{pmatrix} h_1 \\ h_2 \\ h_S \end{pmatrix} = \begin{pmatrix} \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} & 0 \\ \frac{1}{\sqrt{6}} & \frac{1}{\sqrt{6}} & -\frac{2}{\sqrt{6}} \\ \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} \end{pmatrix} \begin{pmatrix} \phi_1 \\ \phi_2 \\ \phi_3 \end{pmatrix}$$

**doublet and singlet:** $\begin{pmatrix} h_1 \\ h_2 \end{pmatrix}, \quad h_S$ of $S_3$

$$V_2 = \mu_0^2 h_S^\dagger h_S + \mu_1^2 (h_1^\dagger h_1 + h_2^\dagger h_2),$$

$$\begin{aligned} V_4 = {} & \lambda_1 (h_1^\dagger h_1 + h_2^\dagger h_2)^2 + \lambda_2 (h_1^\dagger h_2 - h_2^\dagger h_1)^2 + \lambda_3 [(h_1^\dagger h_1 - h_2^\dagger h_2)^2 + (h_1^\dagger h_2 + h_2^\dagger h_1)^2] \\ & + \left\{ \lambda_4 \left[ (h_S^\dagger h_1)(h_1^\dagger h_2 + h_2^\dagger h_1) + (h_S^\dagger h_2)(h_1^\dagger h_1 - h_2^\dagger h_2) \right] + \text{h.c.} \right\} \\ & + \lambda_5 (h_S^\dagger h_S)(h_1^\dagger h_1 + h_2^\dagger h_2) + \lambda_6 [(h_S^\dagger h_1)(h_1^\dagger h_S) + (h_S^\dagger h_2)(h_2^\dagger h_S)] \\ & + \left\{ \lambda_7 \left[ (h_S^\dagger h_1)(h_S^\dagger h_1) + (h_S^\dagger h_2)(h_S^\dagger h_2) \right] + \text{h.c.} \right\} + \lambda_8 (h_S^\dagger h_S)^2. \end{aligned}$$

Das and Dey, 2014

No symmetry for the interchange of $h_1$ and $h_2$

$\lambda_4$ plays a special rôle

# Complex vacua, Spontaneous CP Violation

Table 1: Spontaneous CP violation

| Vacuum | $\lambda_4$ | SCPV | Vacuum | $\lambda_4$ | SCPV | Vacuum | $\lambda_4$ | SCPV |
|---|---|---|---|---|---|---|---|---|
| C-I-a | X | no | C-III-f,g | 0 | no | C-IV-c | X | yes |
| C-III-a | X | yes | C-III-h | X | yes | C-IV-d | 0 | no |
| C-III-b | 0 | no | C-III-i | X | no | C-IV-e | 0 | no |
| C-III-c | 0 | no | C-IV-a | 0 | no | C-IV-f | X | yes |
| C-III-d,e | X | no | C-IV-b | 0 | no | C-V | 0 | no |

- C-III-a $(0,\ \hat{w}_2 e^{i\sigma_2},\ \hat{w}_S)$;
- C-III-h $(\sqrt{3}\hat{w}_2 e^{i\sigma_2},\ \pm\hat{w}_2 e^{i\sigma_2},\ \hat{w}_S)$;
- C-IV-c $\left(\sqrt{1+2\cos^2\sigma_2}\,\hat{w}_2,\ \hat{w}_2 e^{i\sigma_2},\ \hat{w}_S\right)$;
- C-IV-f $\left(\sqrt{2+\frac{\cos(\sigma_1-2\sigma_2)}{\cos\sigma_1}}\,\hat{w}_2 e^{i\sigma_1},\ \hat{w}_2 e^{i\sigma_2},\ \hat{w}_S\right)$;

# $Z_2$-symmetric 3HDM with dark CPV

Keus

DM is protected by a $Z_2$ symmetry $(-,-,+)$:

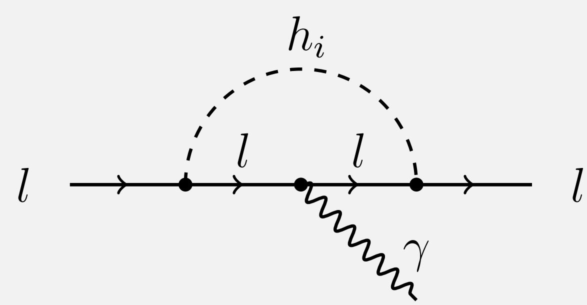
$$\phi_1 \to -\phi_1, \quad \phi_2 \to -\phi_2, \quad \text{SM fields} \to \text{SM fields}, \quad \phi_3 \to \phi_3$$

$Z_2$ symmetry respected by the vacuum $(0,0,v)$:

$$\phi_1 = \begin{pmatrix} H_1^+ \\ \frac{H_1+iA_1}{\sqrt{2}} \end{pmatrix}, \quad \phi_2 = \begin{pmatrix} H_2^+ \\ \frac{H_2+iA_2}{\sqrt{2}} \end{pmatrix}, \quad \phi_3 = \begin{pmatrix} G^+ \\ \frac{v+h+iG^0}{\sqrt{2}} \end{pmatrix}$$

Only $\phi_3$ can couple to fermions $\phi_u = \phi_d = \phi_e = \phi_3$ and $h_i = h$

$$\begin{aligned} -\mathcal{L}_{Yukawa} &= Y_u \bar{Q}'_L i\sigma_2 \phi_u^* u'_R \\ &+ Y_d \bar{Q}'_L \phi_d d'_R \\ &+ Y_e \bar{L}'_L \phi_e e'_R + \text{h.c.} \end{aligned}$$




**No contributions to electric dipole moments (EDMs)**

Observable heavy scalar DM

V. Keus, [Phys. Rev. D 101, 073007 (2020)]

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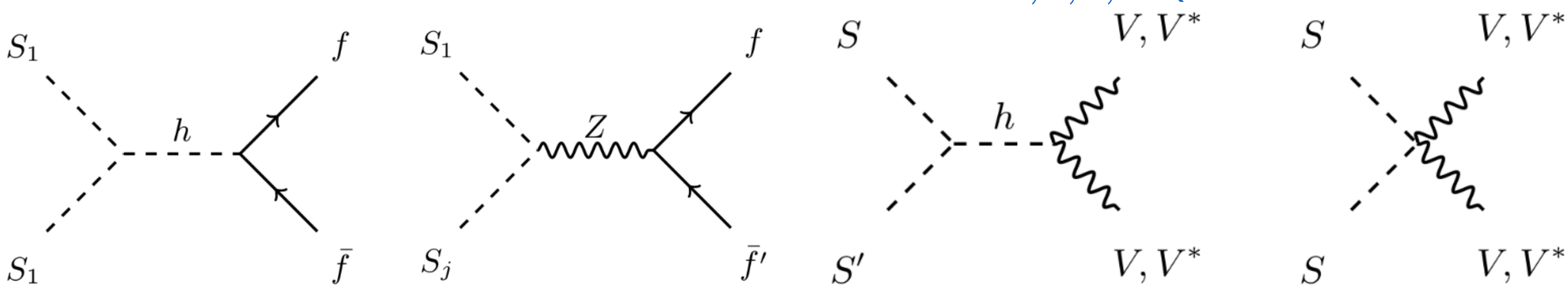
$Z_2$ symmetry respected by the vacuum $(0,0,v)$:

$$\phi_1 = \begin{pmatrix} H_1^+ \\ \frac{H_1+iA_1}{\sqrt{2}} \end{pmatrix}, \qquad \phi_2 = \begin{pmatrix} H_2^+ \\ \frac{H_2+iA_2}{\sqrt{2}} \end{pmatrix}, \qquad \phi_3 = \begin{pmatrix} G^+ \\ \frac{v+h+iG^0}{\sqrt{2}} \end{pmatrix}$$

DM candidate: the lightest CP-mixed state $S_{1,2,3,4}$ (mixtures of $H_{1,2}, A_{1,2}$)




**Tension released:** the extended dark sector allows for annihilations, co-annihilations and CP-violation!

V. Keus, S. F. King, S. Moretti, D. Sokolowska, et al., [JHEP 12, 014 (2016)]

# NHDMs

de Medeiros Varzielas

In MHDMs

$$\mathcal{L}^Y = -\sum_{k=1}^{N}\Big\{\bar{Q}'_L\,\left(Y_k^{d,\prime}\,H'_k\,d'_R + Y_k^{u,\prime}\,\tilde{H}'_k\,u'_R\right) + \bar{L}'_L\,Y_k^{e,\prime}\,H'_k\,e'_R + h.c.\Big\}\,.$$

Higgs Basis

$$H_1 = \frac{1}{\sqrt{2}}\begin{pmatrix}\sqrt{2}\,G^+ \\ v + S_1^0 + iG^0\end{pmatrix}\,,\quad H_{k>1} = \frac{1}{\sqrt{2}}\begin{pmatrix}\sqrt{2}\,S_k^+ \\ S_k^0 + iP_k^0\end{pmatrix}\,,$$

## Higgs Alignment

$$\begin{aligned}\mathcal{L}^Y = &-\left(1+\frac{S_1^0}{v}\right)\left(\bar{d}_L m_d d_R + \bar{u}_L m_u u_R + \bar{l}_L m_e e_R\right) \\ &-\frac{1}{v}\sum_{k=2}^{N}\left(S_k^0 + iP_k^0\right)\left(\bar{d}_L Y_k^d d_R + \bar{u}_L Y_k^u u_R + \bar{l}_L Y_k^e e_R\right) \quad \text{FCNC} \\ &-\frac{\sqrt{2}}{v}\sum_{k=2}^{N} S_k^+\left(\bar{u}_L V Y_k^d d_R - \bar{u}_R Y_k^{u,\dagger} V d_L + \bar{\nu}_L Y_k^e e_R\right) \\ &+ h.c.\,,\end{aligned}$$

de Medeiros Varzielas

$$Y_k^A \stackrel{!}{=} T_A Y_k^A T_A^\dagger ,$$

Alignment

$$\begin{pmatrix} Y_{11} & e^{i(\alpha_l-\beta_l)}\, Y_{12} & e^{i(\alpha_l-\gamma_l)}\, Y_{13} \\ e^{i(\beta_l-\alpha_l)}\, Y_{21} & Y_{22} & e^{i(\beta_l-\gamma_l)}\, Y_{23} \\ e^{i(\gamma_l-\alpha_l)}\, Y_{31} & e^{i(\gamma_l-\beta_l)}\, Y_{32} & Y_{33} \end{pmatrix} \stackrel{!}{=} \begin{pmatrix} Y_{11} & Y_{12} & Y_{13} \\ Y_{21} & Y_{22} & Y_{23} \\ Y_{31} & Y_{32} & Y_{33} \end{pmatrix}$$

$A_4, S_4, \Delta(54), \Sigma(36)$

$$V_0 = -m^2(\phi_1^\dagger\phi_1 + \phi_2^\dagger\phi_2 + \phi_3^\dagger\phi_3) + V_4 ,$$

Leads automatically to Higgs Alignment

$A, A'$

Vev Alignmments

$B, C$

$$\begin{aligned} m^2_{h_{SM}} &= 2\lambda_1 v^2 = 2m^2 , \\ m^2_{H^\pm} &= \frac{1}{2}\lambda_2 v^2 \quad \text{(double degenerate)} , \\ m^2_h &= \frac{1}{2}\lambda_3 v^2 \quad \text{(double degenerate)} , \\ m^2_H &= 3m^2_h = \frac{3}{2}\lambda_3 v^2 \quad \text{(double degenerate)} . \end{aligned}$$

$$\begin{aligned} m^2_{h_{SM}} &= 2(\lambda_1+\lambda_3) v^2 = 2m^2 , \\ m^2_{H^\pm} &= \frac{1}{2}(\lambda_2 - 3\lambda_3) v^2 \quad \text{(double degenerate)} , \\ m^2_h &= -\frac{1}{2}\lambda_3 v^2 \quad \text{(double degenerate)} , \\ m^2_H &= 3m^2_h = -\frac{3}{2}\lambda_3 v^2 \quad \text{(double degenerate)} \end{aligned}$$

NO SCPV

$$V_{\rm soft} = m_{11}^2\phi_1^\dagger\phi_1 + m_{22}^2\phi_2^\dagger\phi_2 + m_{33}^2\phi_3^\dagger\phi_3 + \left(m_{12}^2\,\phi_1^\dagger\phi_2 + m_{23}^2\,\phi_2^\dagger\phi_3 + m_{31}^2\,\phi_3^\dagger\phi_1 + h.c.\right)$$

N. Coyle, D. Rocha, C.W. ‘ 23

# General expression for neutral Higgs couplings in 2HDM

$$\boxed{\begin{aligned}\mathcal{L}_{h_1^0} &= -\frac{m_i}{v}\left[\sin(\beta-\alpha) - \frac{\cos(\beta-\alpha)}{(1+\Delta_i)}\left(\tan\beta - \frac{\Delta_i}{\tan\beta}\right)\right] h_1^0 \bar{f}_i f_i \\ &+ \left[\left(\frac{\mathrm{Re}(\bar{y}_2^{ij})}{\cos\beta\sqrt{2}}\cos(\beta-\alpha)(1-\delta^{ij}) + i\frac{\mathrm{Im}(\bar{y}_2^{ij})}{\cos\beta\sqrt{2}}\cos(\beta-\alpha)\right) h_1^0 \bar{f}_L^i f_R^j + h.c.\right]\end{aligned}}$$

$$\boxed{\begin{aligned}&= -\frac{m_i}{v}\left[\sin(\beta-\alpha) + \frac{\cos(\beta-\alpha)}{(1+\tilde{\Delta}_i)}\left(\frac{1}{\tan\beta} - \tilde{\Delta}_i\tan\beta\right)\right] h_1^0 \bar{f}_i f_i \\ &- \left[\left(\frac{\mathrm{Re}(\bar{y}_1^{ij})}{\sin\beta\sqrt{2}}\cos(\beta-\alpha)(1-\delta^{ij}) + i\frac{\mathrm{Im}(\bar{y}_1^{ij})}{\sin\beta\sqrt{2}}\cos(\beta-\alpha)\right) h_1^0 \bar{f}_L^i f_R^j + h.c.\right]\end{aligned}}$$

$$\boxed{M_d = U_L M U_R^\dagger} \qquad \boxed{\bar{y}_i = U_L y_i U_R^\dagger}$$

$$\boxed{\Delta_i = \frac{\mathrm{Re}(\bar{y}_2^{ii})}{\mathrm{Re}(\bar{y}_1^{ii})}\tan\beta} \qquad \tilde{\Delta}_i = \frac{1}{\Delta_i}$$

Higgs FCNC demands flavor as well as Higgs misalignment !

# Non-SM Higgs Coupling

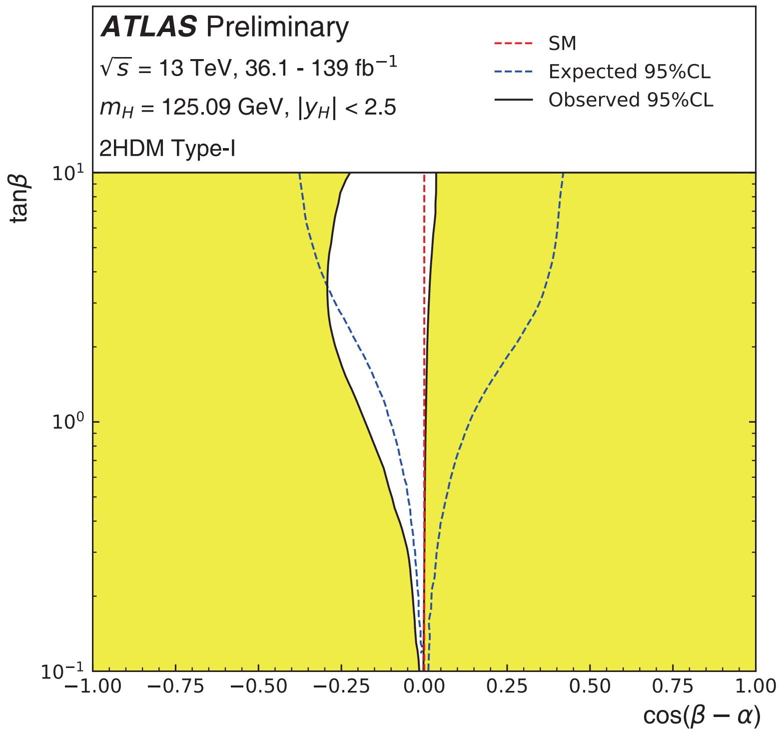
$$\mathcal{L}_{h_2^0} = -\frac{m_i}{v}\delta^{ij}\left[\cos(\beta-\alpha) + \left(\frac{\tan\beta}{1+\Delta_i} - \frac{\Delta_i}{\tan\beta(1+\Delta_i)}\right)\sin(\beta-\alpha)\right] h_2^0 \bar{f}_i f_i$$
$$+ \left[\left(\frac{\mathrm{Re}(\bar{y}_2^{ij})}{\sqrt{2}\cos\beta}(1-\delta^{ij})\sin(\beta-\alpha) + i\frac{\mathrm{Im}(\bar{y}_2^{ij})}{\sqrt{2}\cos\beta}\sin(\beta-\alpha)\right) h_2^0 \bar{f}_L^i f_R^j + h.c.\right]$$

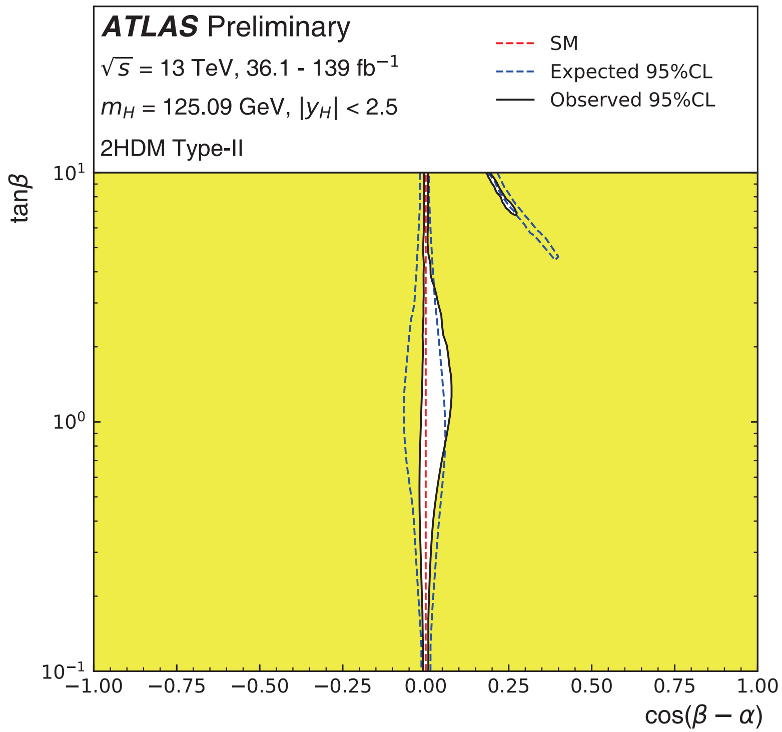
$$\mathcal{L}_{h_2^0} = -\frac{m_i}{v}\delta^{ij}\left[\cos(\beta-\alpha) - \left(\frac{1}{\tan\beta(1+\tilde{\Delta}_i)} - \frac{\tilde{\Delta}_i\tan\beta}{(1+\tilde{\Delta}_i)}\right)\sin(\beta-\alpha)\right] h_2^0 \bar{f}_i f_i$$
$$- \left[\left(\frac{\mathrm{Re}(\bar{y}_1^{ij})}{\sqrt{2}\sin\beta}(1-\delta^{ij})\sin(\beta-\alpha) + i\frac{\mathrm{Im}(\bar{y}_1^{ij})}{\sqrt{2}\sin\beta}\sin(\beta-\alpha)\right) h_2^0 \bar{f}_L^i f_R^j + h.c.\right]$$

Higgs alignment, of course, does not ensure flavor alignment in the non-standard Higgs sector

# We will keep in mind that the LHC favors and SM-like Higgs boson

## LHC constraints on Higgs alignment in the 2HDM



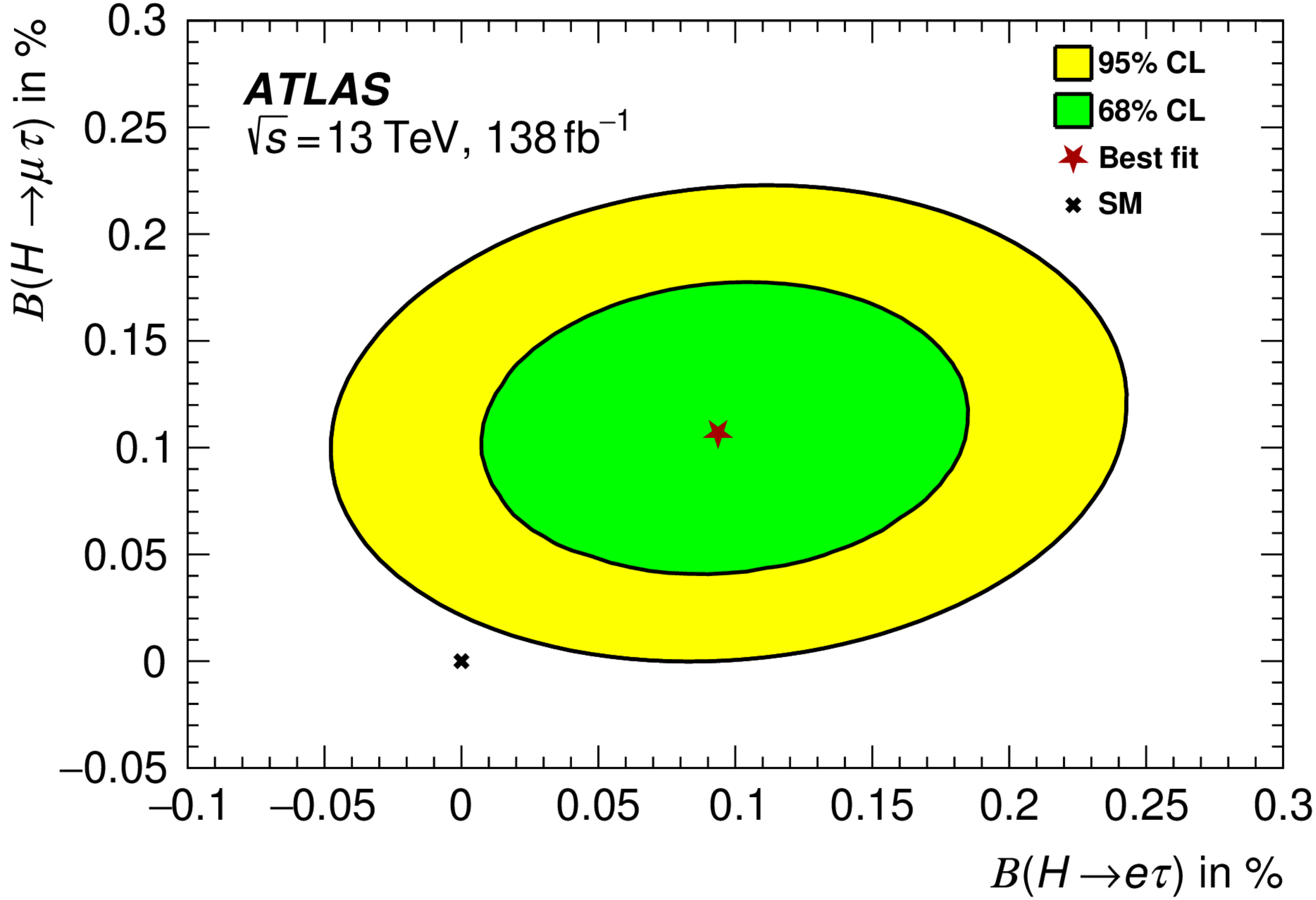




Regions excluded by fits to the measured rates of the productions and decay of the Higgs boson (assumed to be h of the 2HDM). Contours at 95% CL. ATLAS-CONF-2021-053

$$k_b = \sin(\beta - \alpha) + \frac{\cos(\beta - \alpha)}{\tan\beta}$$

$$k_b = \sin(\beta - \alpha) - \cos(\beta - \alpha)\tan\beta$$

# Possible flavor violation in Higgs decays

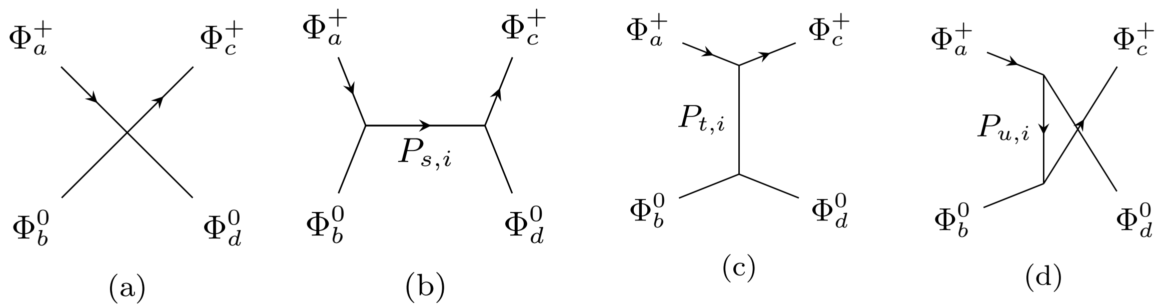



No hint from CMS, though : $BR(H \to \tau\mu, e) < 0.15\%$

Carena

# Entanglement Suppression and Alignment

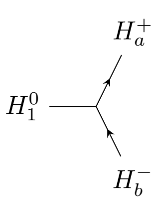
## Amplitude for $\Phi_a^+\Phi_b^0 \to \Phi_c^+\Phi_d^0$ in the broken phase



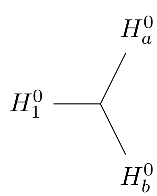

- Tree level contributions
- Gauge coupling turned off
- Yukawa couplings do not contribute at this order

We shall perform the calculation in the Higgs basis: such U(2) rotation - no mixing between $\Phi^0$ and $\Phi^+$ - corresponds to a single-qubit operation and does not change the entanglement power of the S-Matrix

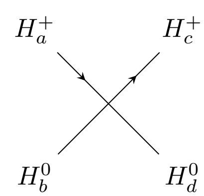
From the scalar potential the Feyman rules follow



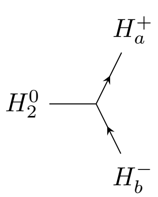

$$= \frac{iv}{\sqrt{2}}\begin{pmatrix} Z_1 & Z_6 \\ Z_6 & Z_3 \end{pmatrix}_{ab}$$



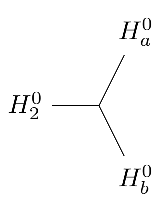

$$= \frac{iv}{\sqrt{2}}\begin{pmatrix} Z_1 & 2Z_6 \\ 2Z_6 & Z_5 \end{pmatrix}_{ab}$$




$$= i\begin{pmatrix} Z_1 & Z_6 & Z_6 & Z_5 \\ Z_6 & Z_3 & Z_4 & Z_7 \\ Z_6 & Z_4 & Z_3 & Z_7 \\ Z_5 & Z_7 & Z_7 & Z_2 \end{pmatrix}_{ab,cd}$$




$$= \frac{iv}{\sqrt{2}}\begin{pmatrix} Z_6 & Z_5 \\ Z_4 & Z_7 \end{pmatrix}_{ab}$$




$$= \frac{iv}{\sqrt{2}}\begin{pmatrix} Z_6 & Z_3+Z_4 \\ Z_3+Z_4 & Z_7 \end{pmatrix}_{ab}$$

**Recall:** $H_1^+ = G^+ \quad H_2^+ = H^+$

$$H_1^0 = \frac{H_{SM} + iG^0}{\sqrt{2}} \qquad H_2^0 = \frac{H_{NSM} + iA^0}{\sqrt{2}}$$

# S-Matrix Minimal Entanglement and Emerging Symmetry

Full amplitude:

$$iM_{ab,cd} = iM^0_{ab,cd} - \frac{v^2}{2}\sum_i \sum_{r=s,t,u} M^r_i{}_{ab,cd}\, P_{r,i}$$

$$M^s_i{}_{ab,cd} = M_{abi}M^*_{cdi}\ , \quad M^u_i{}_{ab,cd} = M_{adi}M^*_{cbi}$$

$$M^t_i{}_{ab,cd} = \sum_{j,k} \mathcal{R}_{ij}M_{ajc}(\mathcal{R}_{ik}M_{dkb,0})^* + \text{h.c.}\ ,$$

rotation matrix in the neutral sector

4-point contact interaction

$$P_{t,i} = i/(t - m^2_{0,i}) \text{ and } P_{r,i} = i/(r - m^2_{+,i}), \quad r = s, u.$$

$$m_{0,i} = \{m_h, m_H, 0, m_A\} \text{ and } m_{+,i} = \{m_{H^\pm}, 0\}$$

Every term should satisfy the conditions:

$$M_{11,11} + M_{22,22} = M_{12,12} + M_{21,21}\ ,$$
$$M_{11,22} = M_{12,21} = M_{21,12} = M_{22,11} = 0$$
$$M_{11,12} = M_{21,22}\ , \quad M_{11,21} = M_{12,22}\ .$$

➔

$$Z_1 = Z_2 = Z_3 \equiv Z$$
$$Z_i = 0\ , \quad i \neq 1,2,3$$
$$Y_1 = Y_2 \equiv Y = -Zv^2/2$$
$$Y_3 = 0$$

➔ $Z_6 = 0$

Alignment

This leads to the scalar potential with maximal SO(8) symmetry:

$$\mathcal{V} = Y(H_1^\dagger H_1 + H_2^\dagger H_2) + \frac{Z}{2}(H_1^\dagger H_1 + H_2^\dagger H_2)^2$$
$$= \frac{Z}{2}\left(\sum_{i=1,2}|H_i^0|^2 + G^+G^- + H^+H^- - \frac{v^2}{2}\right)^2$$

Acting on the 8 real components of the two doublets

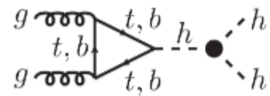
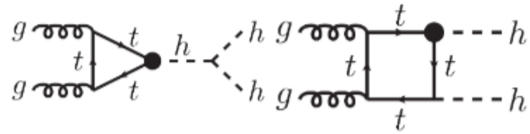
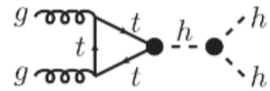
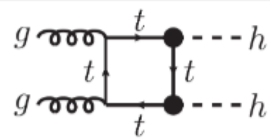
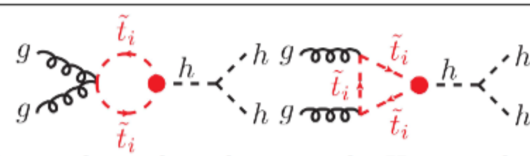
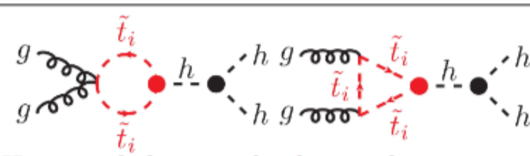
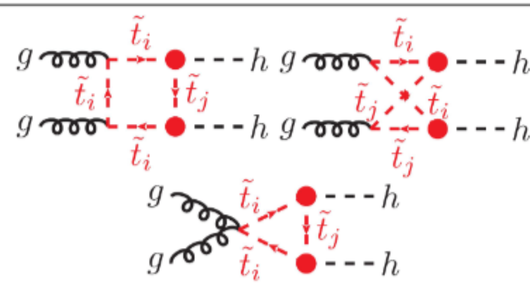
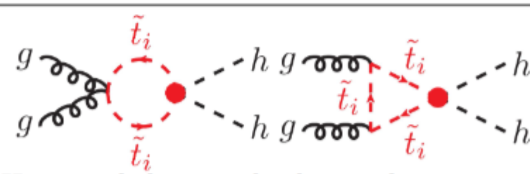
This is then broken spontaneously to SO(7) by the Higgs vev

MC, Low, Wagner, Xiao [2307.08112]

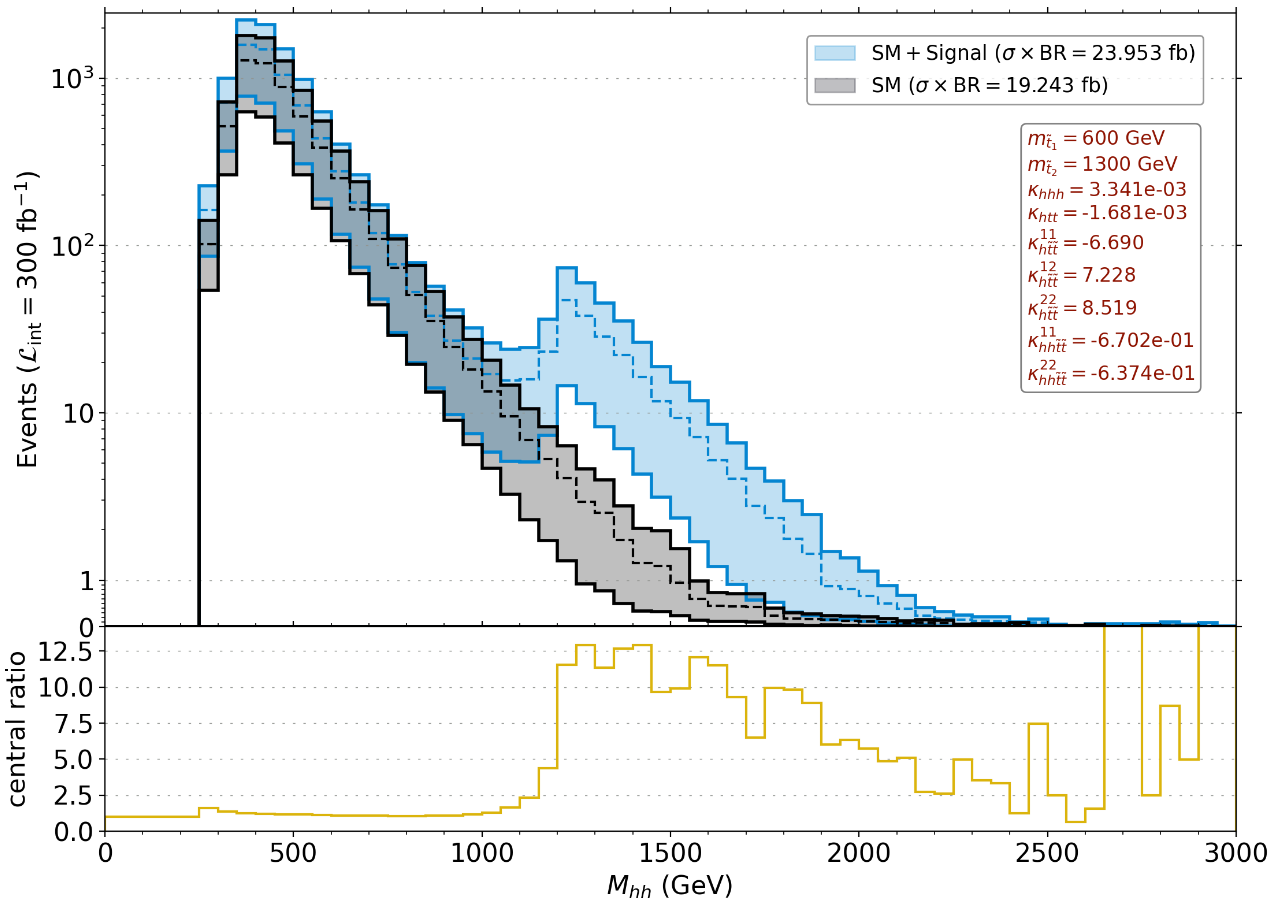
Moretti

# di-Higgs Production

Huang, Joglekar, Li, C.W.
arXiv:1711.05743

| | Topology type | Feynman diagrams | Amplitude |
|---|---|---|---|
| 1 | Modified Higgs trilinear coupling |  | $\mathcal{A}_i \propto \kappa_{hhh}$ |
| 2 | One modified Yukawa coupling |  | $\mathcal{A}_i \propto \kappa_{htt}$ |
| 3 | Modified Higgs trilinear coupling and modified Yukawa coupling |  | $\mathcal{A}_i \propto \kappa_{hhh}\kappa_{htt}$ |
| 4 | Two modified Yukawa couplings |  | $\mathcal{A}_i \propto \kappa_{htt}^2$ |
| 5 | Bubble and triangle with $h\tilde{t}\tilde{t}$ couplings |  | $\mathcal{A}_i \propto \kappa_{h\tilde{t}\tilde{t}}^{ii}$ |
| | This class of topologies involves only diagonal couplings between the Higgs and the squarks, due to the absence of FCNCs in strong interactions and the presence of one $h\tilde{t}\tilde{t}$ coupling. | | |
| 6 | Modified Higgs trilinear coupling + Bubble and triangle with $h\tilde{t}\tilde{t}$ coupling |  | $\mathcal{A}_i \propto \kappa_{hhh}\kappa_{h\tilde{t}\tilde{t}}^{ii}$ |
| | Only diagonal couplings between the Higgs and the squarks due to the strong interaction. | | |
| 7 | Triangle and box with two $h\tilde{t}\tilde{t}$ couplings |  | $\mathcal{A}_i \propto \lvert\kappa_{h\tilde{t}\tilde{t}}^{ij}\rvert^2$ |
| 8 | Bubble and triangle with $hh\tilde{t}\tilde{t}$ coupling |  | $\mathcal{A}_i \propto \kappa_{hh\tilde{t}\tilde{t}}^{ii}$ |
| | Only diagonal couplings between the Higgs and the squarks due to the strong interaction. | | |

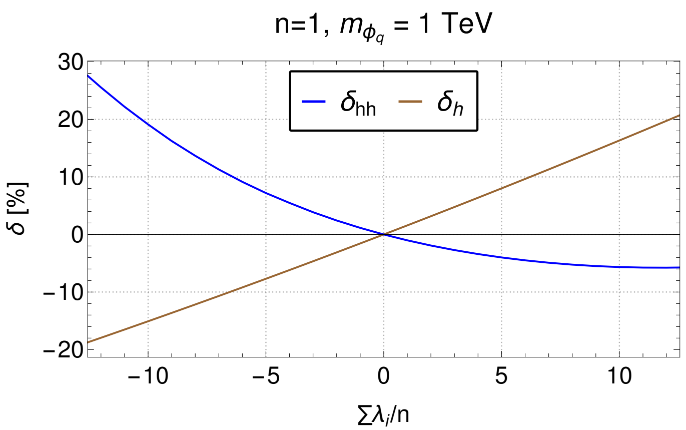
# The excess is larger than PDF and scale uncertainties

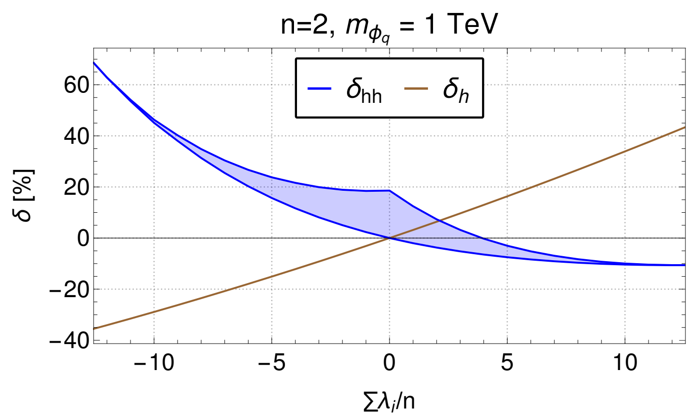



*Cinderella shoe plots*: high mass enhancement separates from SM background (LO here, ME@NLO analysis in progress) while low mass effect needs better systematics

# Single vs. di-Higgs (n=1 and n=2)

$\delta_h$ and $\delta_{hh}$ as a function of the averaged coupling $\left(\sum \lambda_k\right)/n$ for n=1 and n=2 and for a mass of 1 TeV. For this plot we have taken $-4\pi \leq \lambda_k \leq 4\pi$.



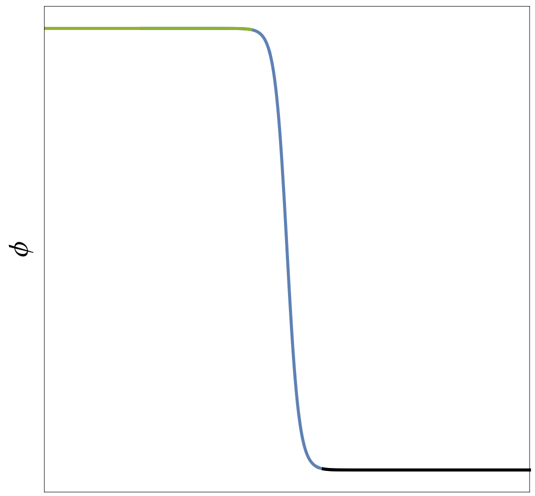

The complementarity between the dependence of $\delta_h$ and $\delta_{hh}$ w.r.t. the coupling $\lambda_k$ is very clear.

For n = 1 the $\delta_h$ and $\delta_{hh}$ values are lines while for n = 2 there is an allowed region for $\delta_{hh}$ due to the additional dependence on $\sum_k \lambda^2_k$.

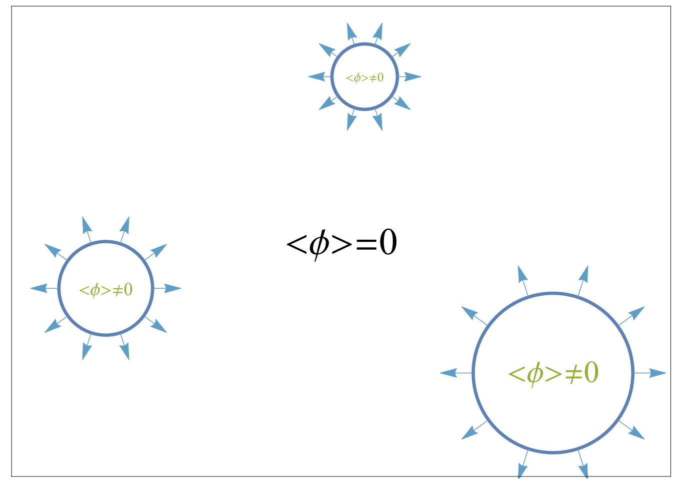
If single Higgs is very close to the SM value constraining $\sum \lambda_k /n$ to small values, any significant excess of di-Higgs production would provide a strong indication that n ≥ 2.

# Gravitational Waves from Cosmological Phase Transitions

Lewicki




$\Longrightarrow$




- Latent heat

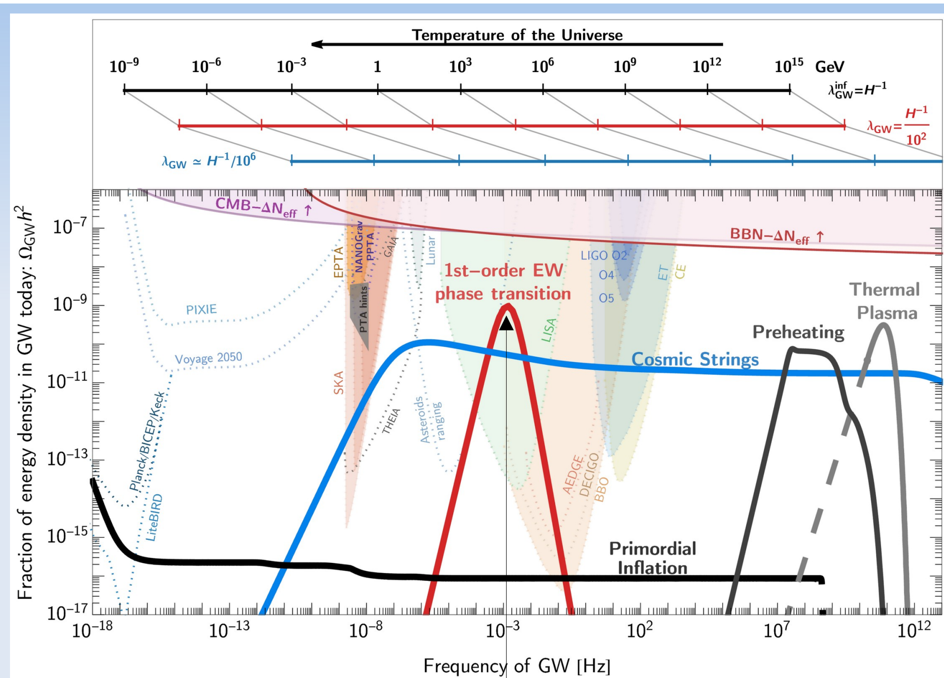
$$\alpha \approx \left. \frac{\Delta V - \frac{T}{4}\frac{\partial \Delta V}{\partial T}}{\rho_R} \right|_{T=T_*}, \quad \Delta V = V_f - V_t$$

- Average size of bubbles upon collision (Characteristic scale)

$$HR_* = (8\pi)^{\frac{1}{3}} \left(\frac{\beta}{H}\right)^{-1}$$

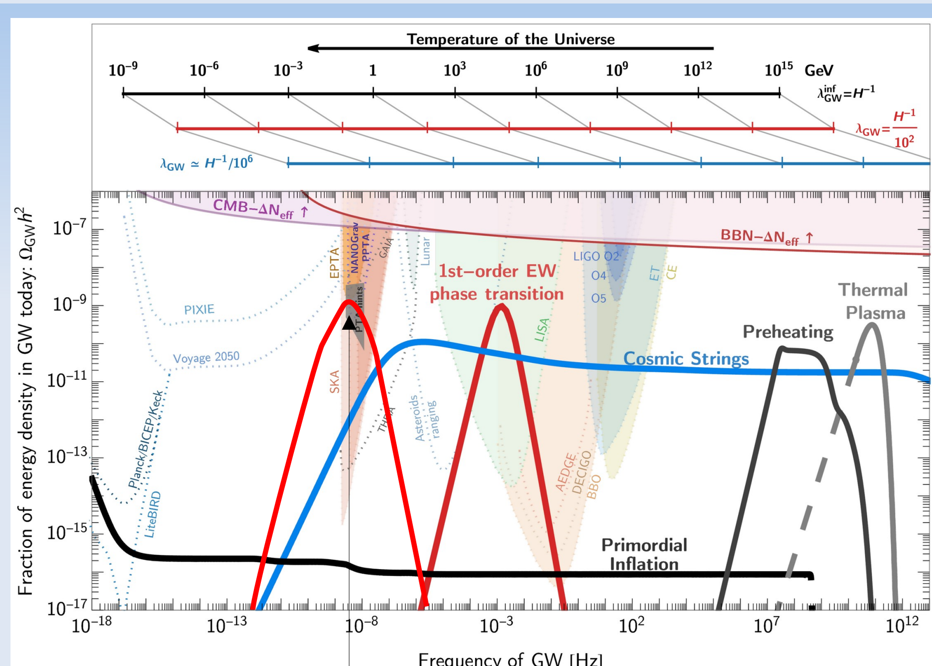
- collisions of bubble walls $\quad \Omega_{\rm col} \propto \Big( \kappa_{\rm col} \quad (HR_*)^2$

Kamionkowski '93, Konstandin '08 '17, Hindmarsh '18 '20, I ) '20 '22, Konstandin




courtesy of Peera Simakachor

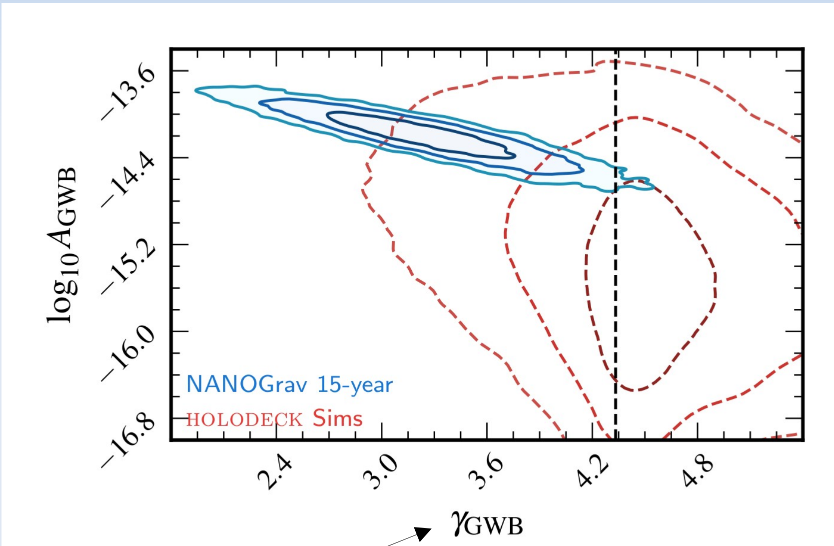
PT at around T ~ 100 GeV




PT at around T ~ 10 MeV

Konstandin

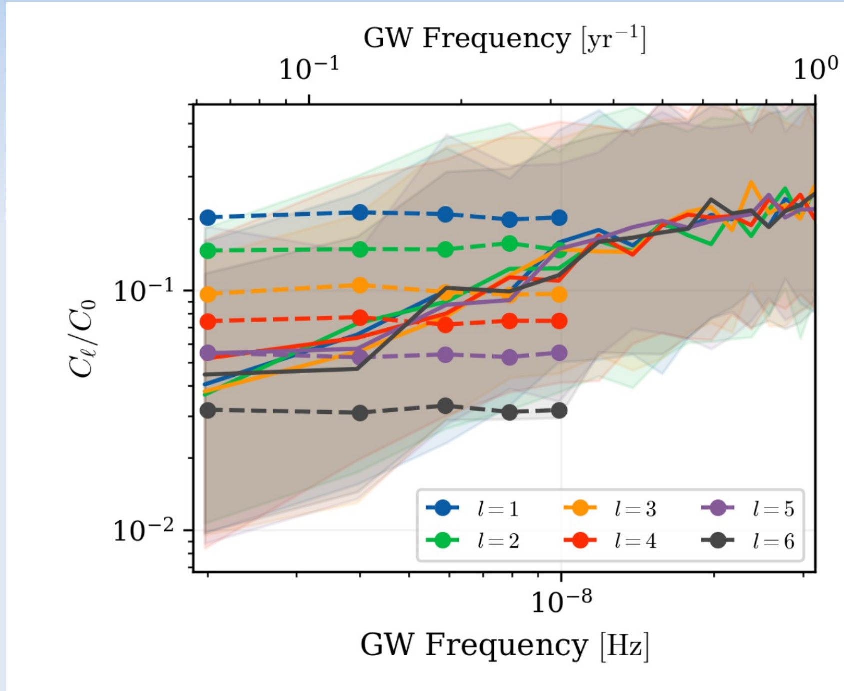
The currently favored interpretation is in terms of
a population of supermassive black hole mergers.
Still, the amplitude is on the low side and the spectrum seems a bit steep.



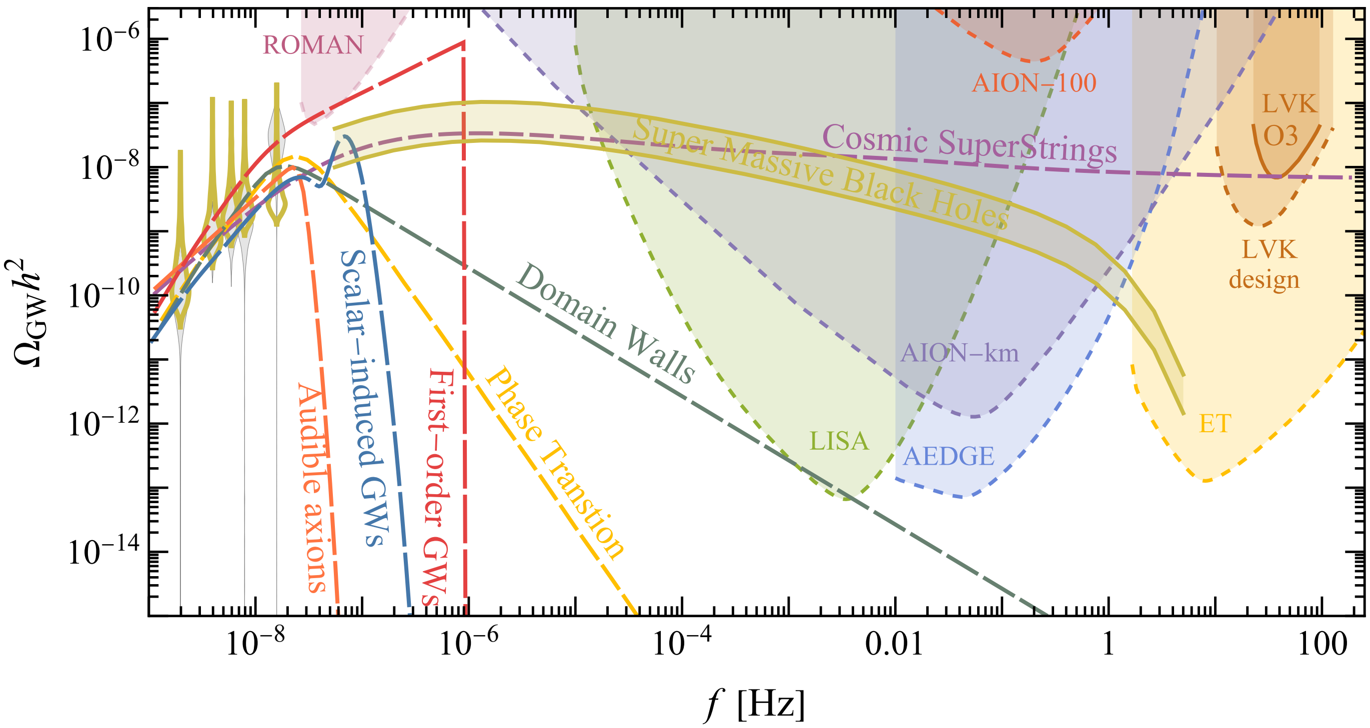

power law slope

*[NanoGrav 2023]*

No anisotropies have been found so far.

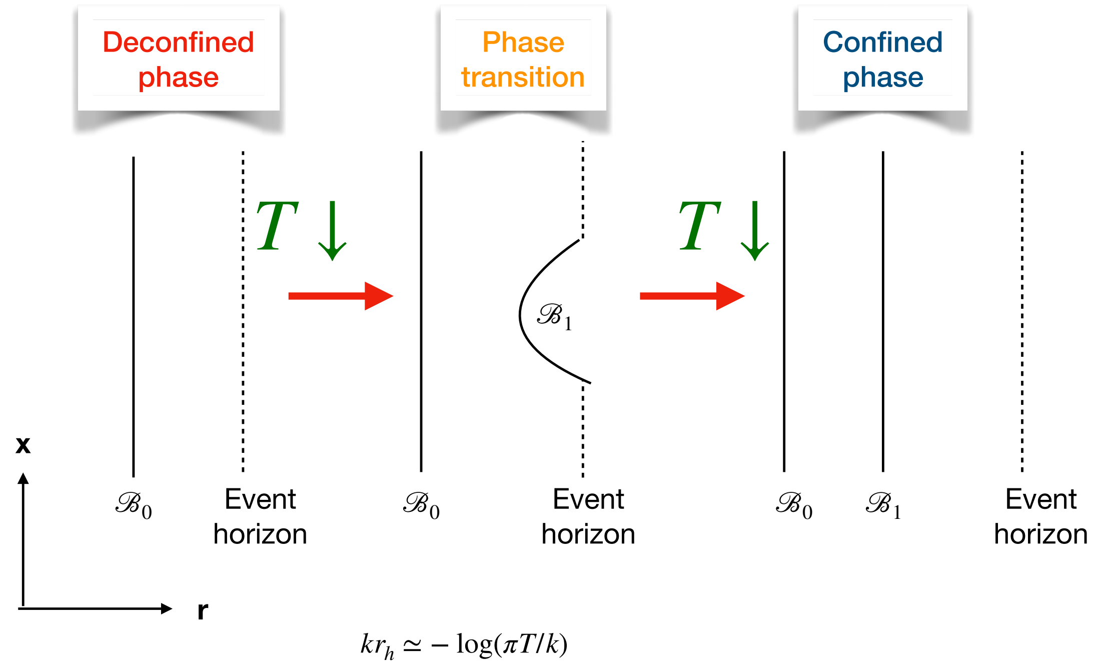


Lewicki



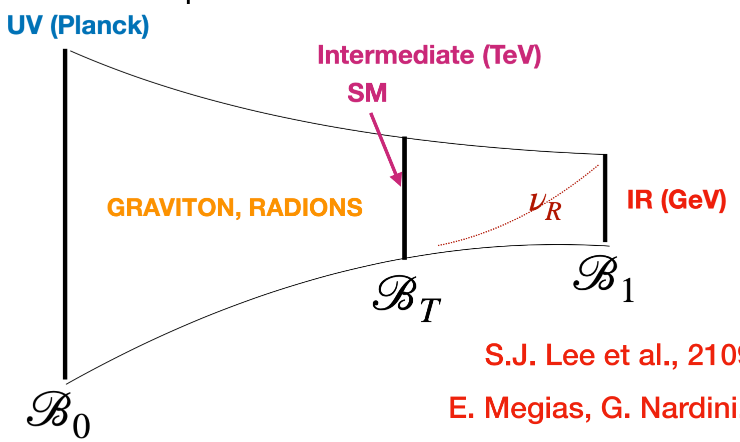

| Scenario | Best-fit parameters | ΔBIC |
|---|---|---|
| GW-driven SMBH binaries | $p_{\rm BH} = 0.25$ | 5.2 |
| GW + environment-driven SMBH binaries | $p_{\rm BH} = 1$<br>$\alpha = 3.8$<br>$f_{\rm ref} = 12$ nHz | (BIC = 57.3) |
| Cosmic (super)strings (CS) | $G\mu = 2 \times 10^{-12}$<br>$p = 6.3 \times 10^{-3}$ | -4.3<br>(2.5) |
| Phase transition (PT) | $T_* = 0.24$ GeV<br>$\beta/H = 6.0$ | -8.9<br>(-1.0) |
| Domain walls (DWs) | $T_{\rm ann} = 0.79$ GeV<br>$\alpha_* = 0.026$ | -8.8<br>(-1.5) |
| Scalar-induced GWs (SIGWs) | $k_* = 10^{7.6}$/Mpc<br>$A = 0.08$<br>$\Delta = 0.28$ | -5.4<br>(2.5) |
| First-order GWs (FOGWs) | $\log_{10} r = -16,\ n_{\rm t} = 2.9$<br>$T_{\rm rh} = 0.35$ GeV | -5.5<br>(2.4) |
| “Audible” axions | $m_a = 3.1 \times 10^{-11}$ eV<br>$f_a = 0.87\, M_{\rm P}$ | -7.7<br>(0.7) |

Quiros




- A complete theory could be one with an intermediate brane at the TeV, where the SM is localized, and thus providing an explanation of the hierarchy problem

- The comparison with PTA data is the same as it only depends on the $\mathscr{B}_1$ brane




S.J. Lee et al., 2109.10938

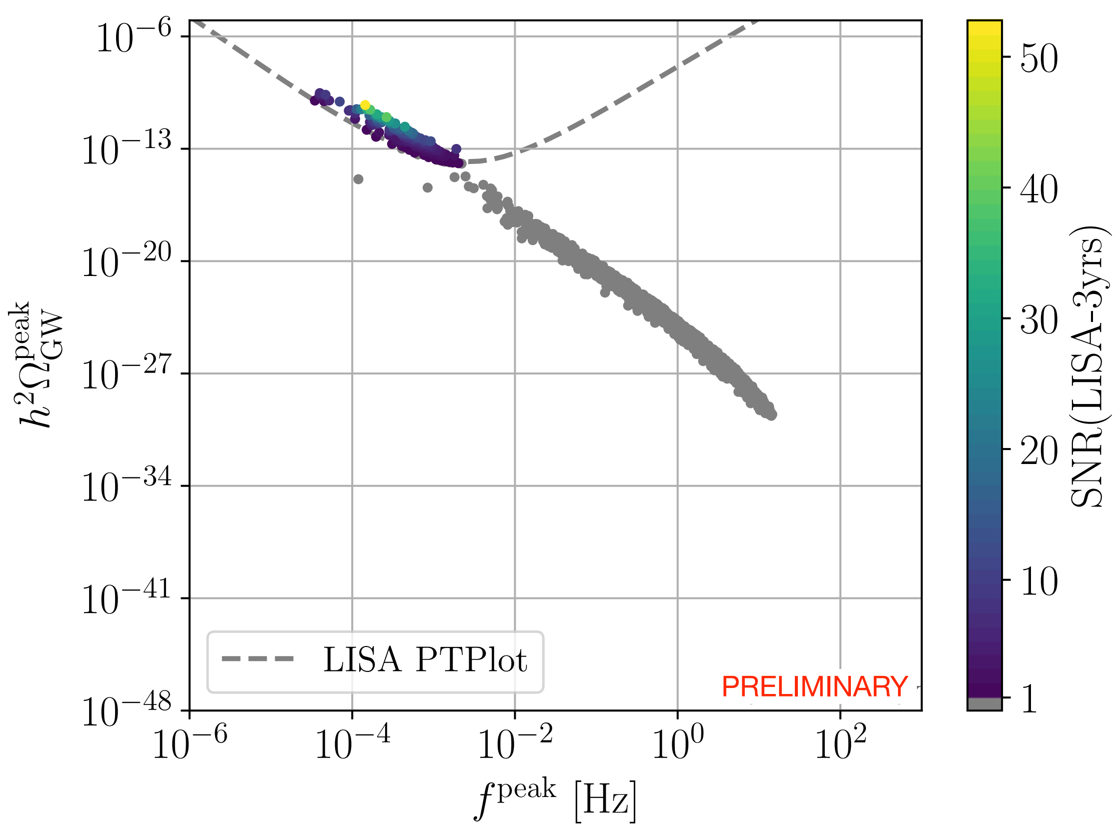
E. Megias, G. Nardini, M.Q., 2306.17071

Muhlleitner

$$f^{\text{peak}} = 26 \times 10^{-6}\, \frac{\beta}{H} \left( \frac{1}{(8\pi)^{\frac{1}{3}} \max(v_b,\, c_s)} \right) \left( \frac{T_*}{100\,\text{GeV}} \right) \left( \frac{g_*}{100} \right)^{\frac{1}{6}} \text{Hz}$$

$$h^2\Omega_{\text{GW}}^{\text{peak}} = 4 \times 10^{-7} \left( \frac{100}{g_*} \right)^{\frac{1}{3}} \begin{cases} \frac{(8\pi)^{1/3}\max(v_b, c_s)}{\beta/H} \left( \frac{\kappa\alpha}{1+\alpha} \right)^2 & \text{if} \quad H\tau_{\text{sh}} \simeq 1 \\ \frac{2}{\sqrt{3}} \left( \frac{(8\pi)^{1/3}\max(v_b, c_s)}{\beta/H} \right)^2 \left( \frac{\kappa\alpha}{1+\alpha} \right)^{3/2} & \text{if} \quad H\tau_{\text{sh}} < 1 \end{cases}$$

## GW from (S)FOEWPT in ‚CP in the Dark'




[Biermann,MM, Santos,Viana]

CP conservation at T=0

CP violation at the phase transition

BSMPTv3

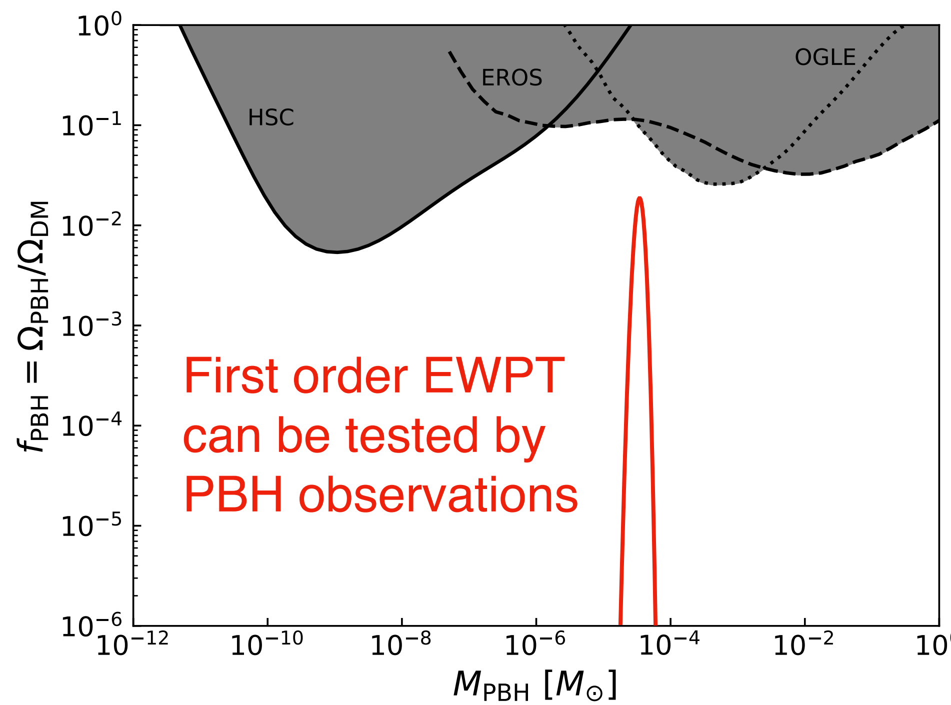
# PBH from 1st OEWPT

K. Hashino, SK, T. Takahashi, 2021
K. Hashino, SK, T. Takahashi, M. Tanaka 2023

Mass of PBH from EWPT is determined by $t_{PBH}$

$$M_{\rm PBH} \approx \frac{4\pi}{3} H^{-3}(t_{\rm PBH})\rho_c = 4\pi H^{-1}(t_{\rm PBH})$$

$$\boxed{M_{\rm PBH} \sim 10^{-5} M_\odot}$$




Microlensing observations

Subaru HSC https://hsc.mtk.nao.ac.jp/ssp
OGLE http://ogle.astrouw.edu.pl/

Future observations

PRIME 2023~ http://www-ir.ess.sci.osaka-u.ac.jp/prime/index.html
Roman 2026~ https://roman.gsfc.nasa.gov

$f_{\rm PBH}$ is constrained by $10^{-4}$

Using far infrared rays: sensitive to the microlensing from center galaxy

# Strongly 1st OPT

Kanemura

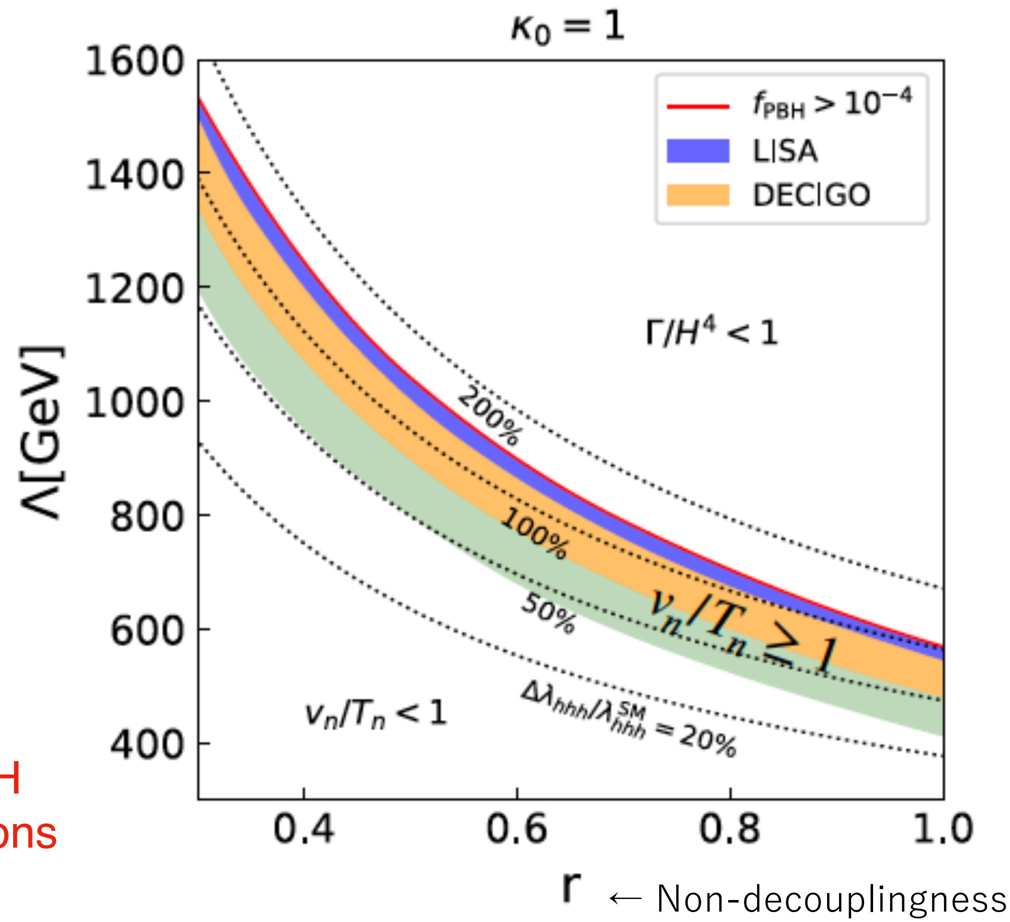
## Parameter region

Sphaleron decoupling $\boxed{\frac{\varphi_c}{T_c} \gtrsim 1}$

Bubble nucleation completion $\boxed{\left.\frac{\Gamma}{H^4}\right|_{T=T_t} \simeq 1}$

- PBH (red)
- GW (LISA)
- GW (DECIGO)
- Only $\Delta\lambda_{hhh}$ (HL-LHC, ILC, ⋯)

First order EWPT can be explored by PBH observations in addition to GW observations and collider experiments



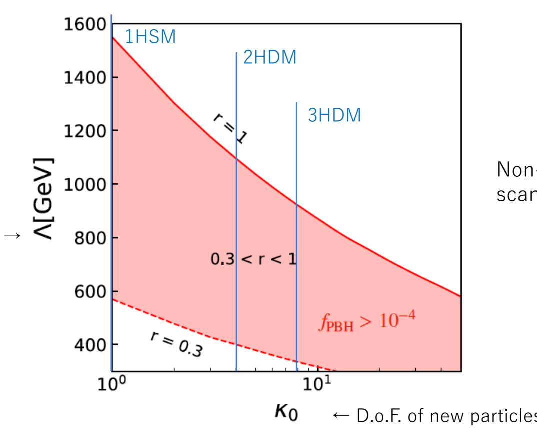

$$V(\phi, 0) = \frac{m^2}{2}(\phi^\dagger\phi) + \frac{\lambda}{4}(\phi^\dagger\phi)^4 + \sum_{n=1}^{\infty} \frac{c_{2n+4}}{2^{(n+2)}\Lambda^{2n}} (\phi^\dagger\phi)^{n+2}$$

$$\lambda_3 = \frac{3m_h^2}{v}\left(1 + \frac{8v^2}{3m_h^2}\sum_{n=1}^{\infty}\frac{n(n+1)(n+2)c_{2n+4}v^{2n}}{2^{n+2}\Lambda^{2n}}\right)$$

Huang, Joglekar, Li, Wagner, arXiv:1512.00068

## Parameter Regions testable by PBH

Scale of new particles →




Non-decouplingness r scanned
0.3 < r < 1

# Conclusions

- Precision Higgs measurement show a good agreement of all couplings with respect to the SM expectations, including a single scalar Higgs boson.
- Extra Higgs Doublet/Singlet Models and extensions provide a good effective field theory to the study of LHC data.
- Light non-standard Higgs bosons demand alignment in field space of the mass eigenstates with the directions acquiring vev's. Some flavor alignment also required.
- New scalars may have an impact on the Standard Higgs phenomenology, and open the window for a discovery at the LHC.
- They can also be relevant in cosmological phase transitions, which may be probed by the search for new physics, the analysis of the Higgs potential, the detection of gravitational waves and primordial black holes.
- Overall, extra scalars provide a plethora of new phenomena that may be probed in the near future and remains as one of the most exciting phenomena in physics in the years to come.

Pilaftsis Theorem : No matter what you did,

Apostolos did it first

Pilaftsis Theorem : No matter what you did,

Apostolos did it first. And better.