Higgs Boson Physics—The View Ahead

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Outline

1. Higgs physics—where we stand today

2. Beyond the Standard Model (SM) Higgs boson

3. Constraints on Extended Higgs Sectors
   - A tale of two alignment mechanisms
   - Scalar sector CP violation

4. The Higgs sector as a portal to Beyond the SM (BSM) physics

5. Revisiting the Higgs Wishlist

Where we stand today

- A priori, one could have imagined a plethora of possible dynamical models that are responsible for electroweak symmetry breaking.

- Remarkably, the simplest possible model, a self-interacting complex doublet of elementary scalar fields [which yields a physical scalar particle — the Standard Model (SM) Higgs boson], is consistent with all current experimental data.

- A number of profound theoretical questions remain, which suggest that the complete story of electroweak symmetry breaking has not yet been written.

Summary of ATLAS Higgs boson data from Run 2 at the LHC

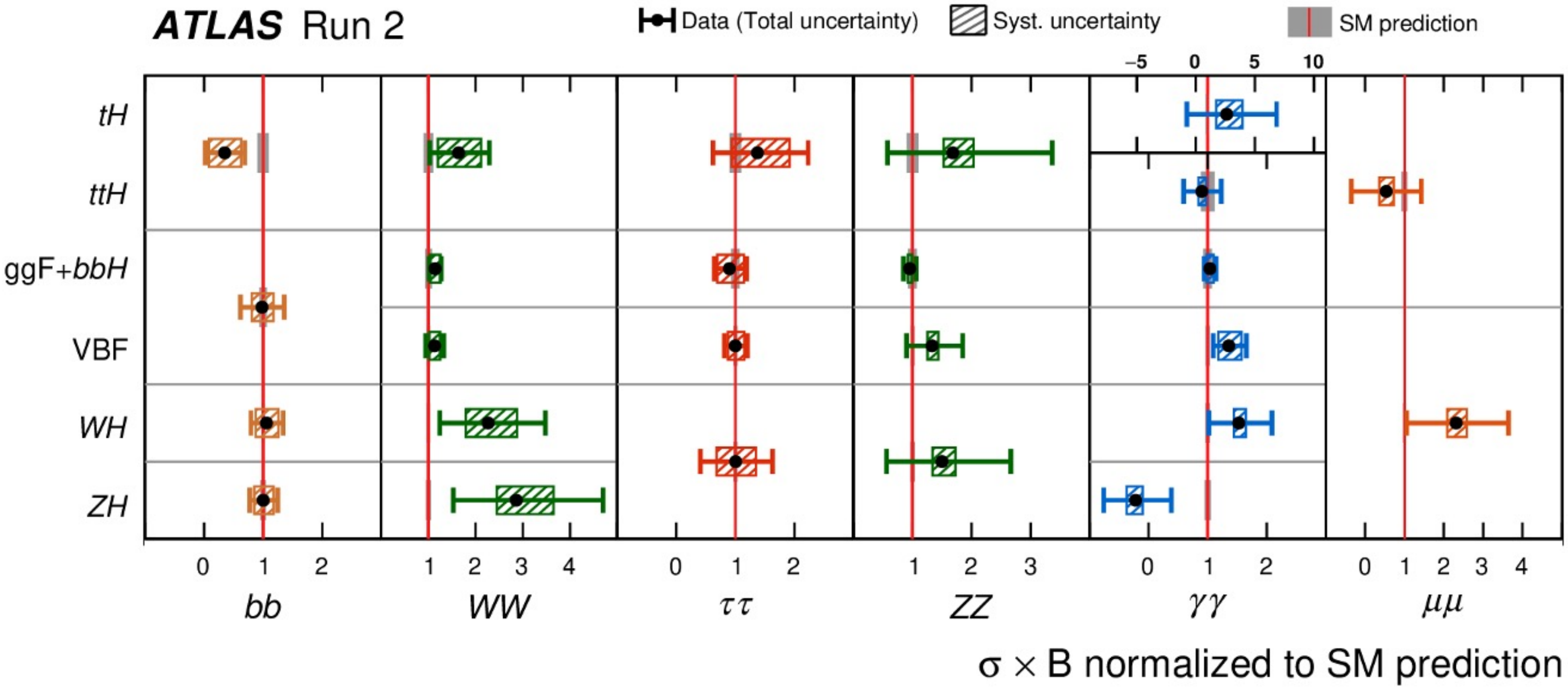
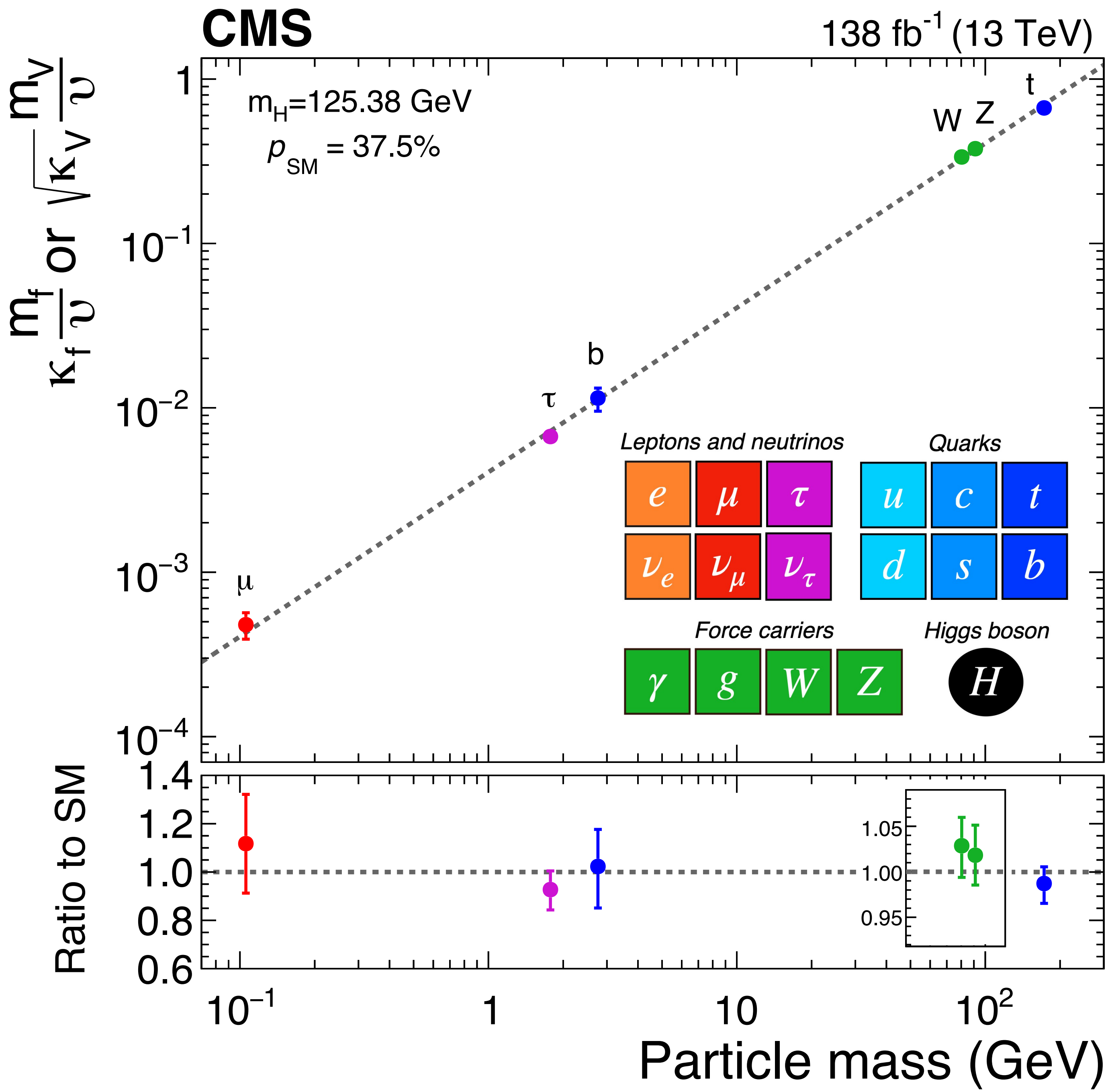


Fig. 3 | Ratio of observed rate to predicted standard model event rate for different combinations of Higgs boson production and decay processes. The horizontal bar on each point denotes the 68% confidence interval. The narrow grey bands indicate the theory uncertainties in the standard model (SM) cross-section multiplied by the branching fraction predictions. The p value for compatibility of the measurement and the SM prediction is 72%. $\sigma_i B_f$ is normalized to the SM prediction. Data are from ATLAS Run 2.



From the CMS webpage

Reduced Higgs coupling modifiers compared to their corresponding prediction from the Standard Model (SM). The error bars represent 68% CL intervals for the measured parameters. In the lower panel, the ratios of the measured coupling modifiers values to their SM predictions are shown.

Projections for HL-LHC

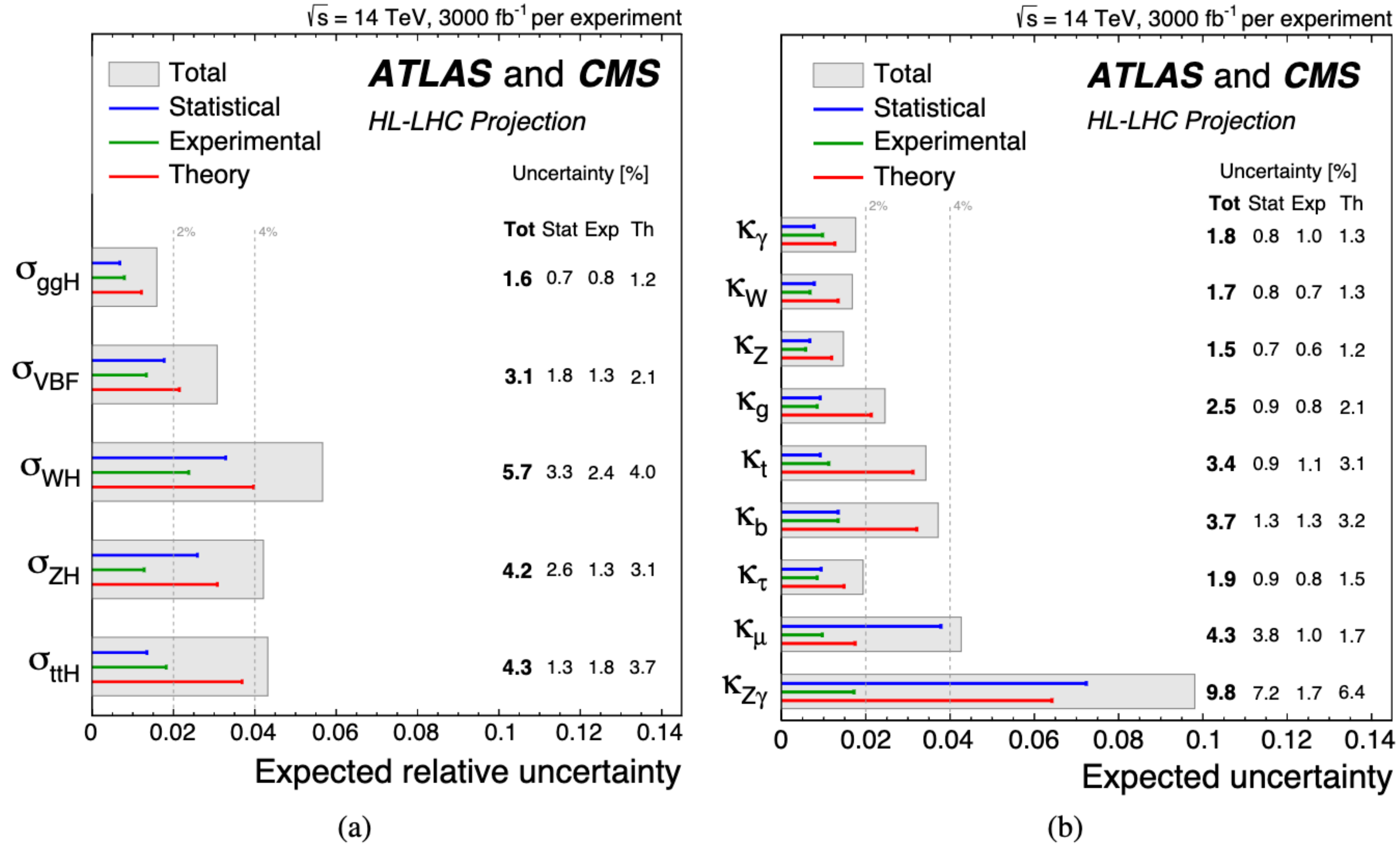


Figure 1: Summary plots showing the total expected uncertainties on (a) the per-production-mode cross-sections normalised to the SM predictions and (b) the coupling modifier parameters (κ), for the combination of ATLAS and CMS extrapolations. For each measurement, the total uncertainty is indicated by a grey box while the statistical, experimental and theory uncertainties are indicated by a blue, green and red line respectively. In addition, the numerical values are also reported. [3]

Taken from:

Snowmass White Paper Contribution: Physics with the Phase-2 ATLAS and CMS Detectors

ATL-PHYS-PUB-2022-018 and CMS PAS FTR-22-001

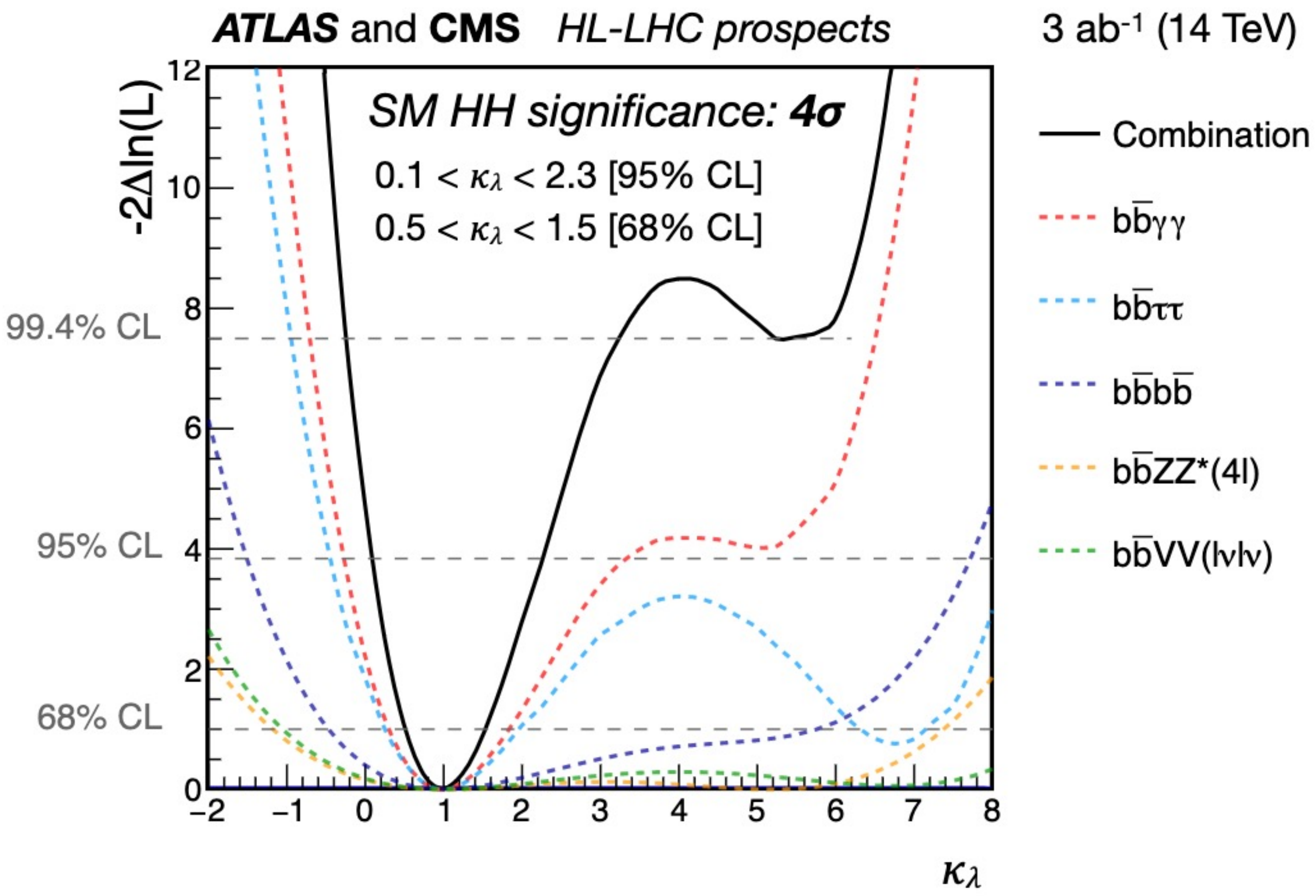


Figure 11: Negative-log-likelihood scan as a function of κ_λ, calculated by performing a conditional signal+background fit to the background and SM signal. The colored dashed lines correspond to the combined ATLAS and CMS results by channel, and the black line their combination. [3]

Testing the SM using Higgs precision data—stepping beyond $\sigma \times$ BR

- Differential cross sections of on-shell Higgs processes
- Off-shell Higgs boson exchange (tree level)
- Off-shell Higgs boson exchange (loop level)

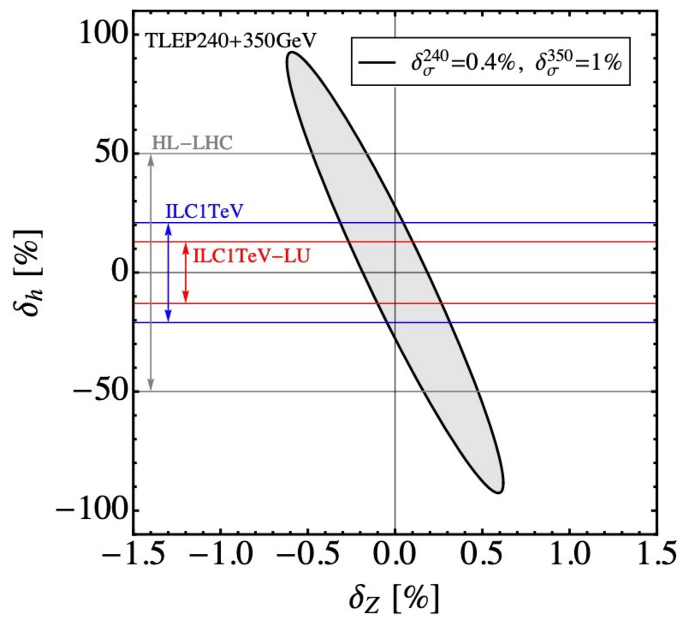


FIG. 3: Indirect 1σ constraints possible in $\delta_Z - \delta_h$ parameter space by combining associated production cross section measurements of 0.4% (1%-estimated) precision at $\sqrt{s} = 240$ GeV, (350 GeV) in solid black. For large values of $|\delta_h|$ this ellipse can only be considered qualitatively as the calculation is only valid to lowest order in δ_h. The different scales should be noted. Direct constraints possible at the high luminosity LHC and 1 TeV ILC (with LU denoting luminosity upgrade)

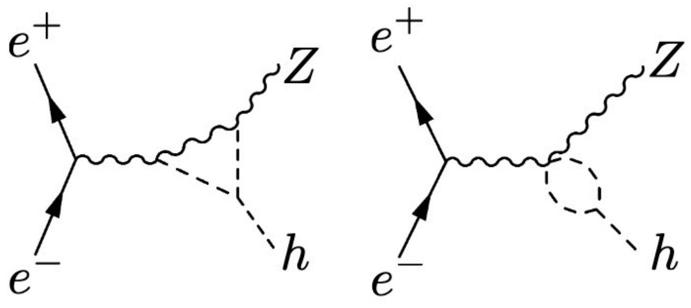
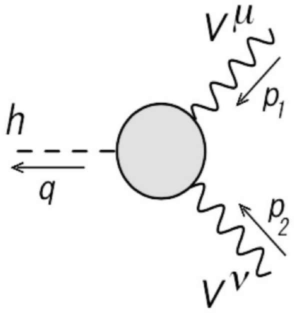


FIG. 1: NLO vertex corrections to the associated production cross section which depend on the Higgs self-coupling. These terms lead to a linear dependence on modifications of the self-coupling δ_h.

Taken from Matthew McCullough, arXiv:1312.3322

- Momentum dependent form factors



example: *h Z Z* vertex

$$T^{\mu\nu}(p_1, p_2) = F_1\, g^{\mu\nu} + F_2(p_1 \cdot p_2\, g^{\mu\nu} - p_1^\nu p_2^\mu) + F_3\, \epsilon^{\mu\nu\alpha\beta} p_{1\alpha} p_{2\beta}$$

where the form factors F_1, F_2 and F_3 depend on Lorentz invariant combinations of the kinematic variables.

F_1 corresponds to the tree-level SM interaction, $\mathcal{L}_{\rm int} = hZ_\mu Z^\mu$

F_2 corresponds to the CP-even effective interaction, $\mathcal{L}_{\rm eff} = hF_{\mu\nu}F^{\mu\nu}$

F_3 corresponds to the CP-odd effective interaction, $\mathcal{L}_{\rm eff} = hF_{\mu\nu}\widetilde{F}^{\mu\nu}$

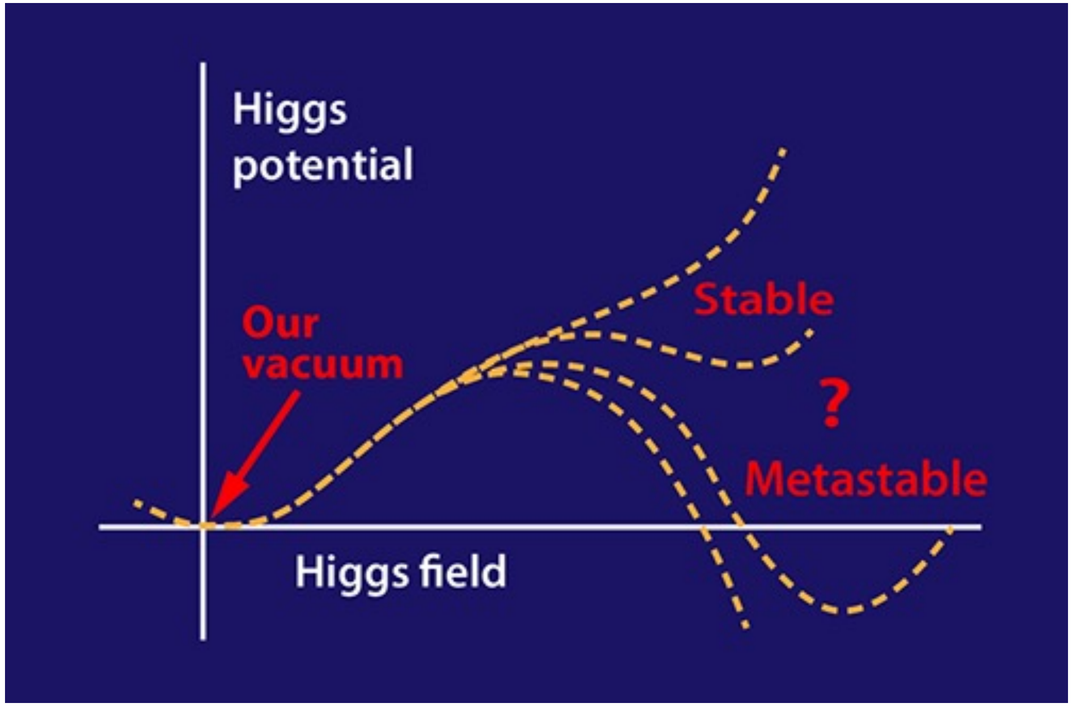
Caution: Higher dimensional operators in SMEFT may not account for all BSM Higgs phenomena if additional relatively light scalars exist.

Is the electroweak vacuum of the SM stable?

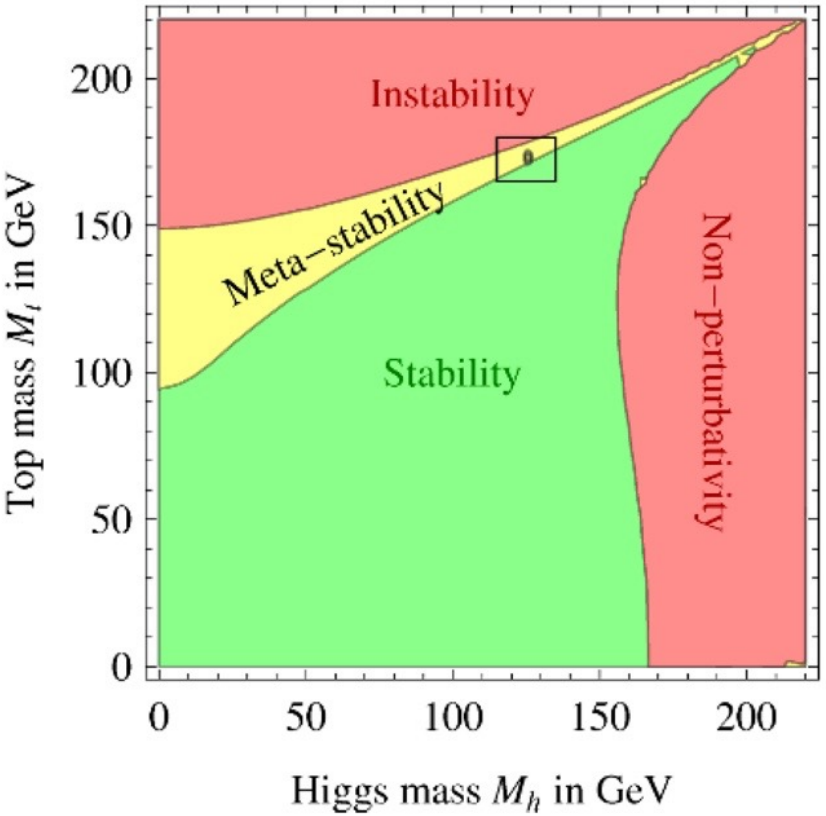
The Higgs field of the SM has a local minimum at $<\Phi>$=246 GeV. However, it is possible that a second minimum develops at very large field values. For field values larger than the Planck scale, M_{PL} = 10^{19} GeV (in units of $c=1$), calculations within the SM are not reliable, as gravitational effects can no longer be neglected.

However, below M_{PL} one can reliably compute the shape of the SM scalar potential to determine whether our vacuum is stable.

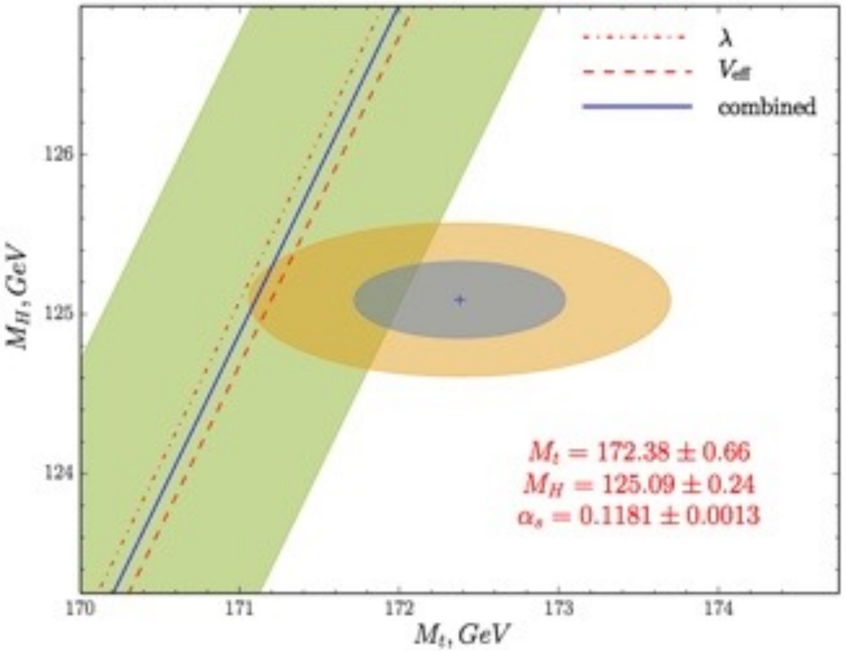
(figure courtesy of A. Kusenko)



Detailed calculations by G.Degrassi, S. Di Vita, J. Elias-Miro, J.R. Espinosa, G.F. Giudice, G. Isidori and A. Strumia (2012)—see figure below on the left, and a subsequent treatment by A.V. Bednyakov, B.A. Kniehl, A.F. Pikelner and O.L. Veretin (2015)—see figure below on the right, suggest that the electroweak vacuum is metastable, with a lower secondary minimum below M_{PL} .



However, for a slightly lower value of m_t (compared to the central PDG value), stability up to M_{PL} is recovered.



Key questions for Higgs physics

- Do the Higgs properties deviate from those of the SM Higgs boson?

- Are there additional Higgs scalars beyond the SM Higgs boson?
  - Keep in mind that the fermion and gauge boson sectors of the SM are far from being of minimal form ("Who ordered that?"). So why shouldn't the the scalar sector be non-minimal as well?

- Are the dynamics of electroweak symmetry breaking natural due to new physics beyond the SM (BSM)…
  - ...while retaining the elementarity of the Higgs boson?
  - …while revealing the composite nature of the Higgs boson?

- The operator $\Phi^\dagger\Phi$ is an electroweak singlet, and thus can be a portal to a dark sector governed by BSM physics. Is such BSM physics accessible at the LHC or at future collider facilities?

Nathaniel Craig posed seven questions at the LCWS-2023 conference last week

A few comments on the seven questions of N. Craig:

- A key goal of future Higgs studies is to establish the presence of Higgs boson self-interactions. The possible contributions of BSM physics to the triple Higgs boson coupling can in some cases lead to significant corrections to the predicted SM value despite the SM-like values of the Higgs couplings to vector bosons and fermions.

- The Yukawa force is established for the third generation of fermions with the observation of the hbb and h$\tau\tau$ couplings. Establishing the Higgs boson couplings to second generation fermions could provide some clues to the flavor puzzle.

- By causality, Craig is referring to locality, unitarity, and analyticity constraints on effective field theory (EFT) corrections to the SM, which are reflected by positivity bounds on some higher dimensional EFT coefficients.

- Is electroweak symmetry realized in Nature? In contrast to SMEFT, electroweak symmetry is only realized nonlinearly in HEFT.

Why haven't we discovered BSM physics?

1. New particles are too heavy. Due to *heavy-mass decoupling* (HMD), the effects of these new particles with masses of $O(\Lambda)$ on the SM are suppressed, typically of $O(v^2/\Lambda^2)$.

2. New particles interact too weakly. Due to *feeble-interaction decoupling* (FID), the effects of these new particles (which may have masses well below the electroweak scale) are strongly suppressed due to their extraordinarily weak coupling to the SM.

3. In the absence of HMD or FID, one must still be able to extract a significant signal above SM backgrounds. Perhaps the BSM physics is hidden in plain sight.

Remarkably, Higgs physics provides examples of all three possibilities.

Beyond the SM Higgs Boson

- The observed Higgs boson could be a composite of more fundamental particles (the energy scale where the composite nature is revealed would most likely lie above 1 TeV).

- A closely related possibility—the Higgs boson is a pseudo-Goldstone boson generated by new dynamics (whose energy scale would most likely lie above 1 TeV).

- The observed Higgs boson is one (probably the lightest) member of the scalar sector, in which case additional scalars (multiple generations or flavors) remain to be discovered in the exploration of the TeV energy scale.

Motivations for Extended Higgs Sectors

- Extended Higgs sectors can modify the electroweak phase transition and facilitate baryogenesis.
- Extended Higgs sectors can enhance vacuum stability.
- Extended Higgs sectors can provide a dark matter candidate.
- Extended Higgs sectors can be employed to provide a solution to the strong CP problem ($\Longrightarrow$ axion)
- Models of new physics beyond the SM often require additional scalar Higgs states. E.g., two Higgs doublets are required in the minimal supersymmetric extension of the SM (MSSM).

Extended Higgs Sectors are Highly Constrained

- The electroweak ρ parameter is very close to 1.

- One neutral Higgs scalar of the extended Higgs sector must be SM-like (and identified with the Higgs boson at 125 GeV).

- At present, only one Higgs scalar has been observed.

- Higgs-mediated flavor-changing neutral currents (FCNCs) are suppressed.

- Scalar sector CP-violation has not yet been observed (with implications for electric dipole moments).

- Charged Higgs exchange at tree level (e.g. in $\bar{B} \to D^{(*)}\tau^-\overline{\nu}_\tau$) and at one-loop (e.g. in $b \to s\gamma$) can significantly constrain the charged Higgs mass and the Yukawa couplings.

The ρ-parameter constraint on extended Higgs sectors

Given that the electroweak ρ-parameter is very close to 1, it follows that a Higgs multiplet of weak-isospin T and hypercharge Y must satisfy,[1]

$$\rho \equiv \frac{m_W^2}{m_Z^2 \cos^2\theta_W} = 1 \qquad \Longleftrightarrow \qquad (2T+1)^2 - 3Y^2 = 1\,,$$

independently of the Higgs vacuum expectation values (vevs). The simplest solutions are Higgs singlets $(T,Y)=(0,0)$ and hypercharge-one complex Higgs doublets $(T,Y)=(\frac{1}{2},1)$. For example, the latter is employed by the two Higgs doublet model (2HDM).

More generally, one can achieve $\rho=1$ by fine-tuning if

$$\sum_{T,Y}\left[4T(T+1)-3Y^2\right]|V_{T,Y}|^2 c_{T,Y} = 0\,,$$

where $V_{T,Y} \equiv \langle\Phi(T,Y)\rangle$ is the scalar vev, and $c_{T,Y}=1$ for complex Higgs representations and $c_{T,Y}=\frac{1}{2}$ for real $Y=0$ Higgs representations.

[1] Y is normalized such that the electric charge of the scalar field is $Q = T_3 + Y/2$.

SM-like Higgs boson with suppressed Higgs-mediated FCNCs: A tale of two alignment mechanisms

1. Higgs field alignment

In the limit in which one of the Higgs mass eigenstate fields is approximately aligned with the direction of the scalar doublet vacuum expectation value (vev) in field space, the tree-level properties of the corresponding scalar mass eigenstate approximate those of the SM Higgs boson.

2. Flavor alignment

The quark mass matrices derive from the Higgs-fermion Yukawa couplings when the neutral Higgs fields acquire vevs. Flavor alignment arises when the diagonalization of the quark mass matrices simultaneously diagonalize the neutral Higgs quark interactions, implying the absence of tree-level Higgs-mediated FCNCs.

A SM-like Higgs boson with or without "decoupling"

1. The decoupling limit (an example of HMD)

In the decoupling limit, there is a new mass parameter, $M \gg v$, such that all physical Higgs masses with one exception are of $\mathcal{O}(M)$. The Higgs boson, with $m_h \sim \mathcal{O}(v)$, is SM-like, due to approximate Higgs field alignment.

2. Higgs alignment limit without decoupling (an example of FID)

In models of alignment with suppressed scalar mixing, the masses of all Higgs scalars, both SM-like and non-SM-like, can be of $\mathcal{O}(v)$. The absence (suppression) of scalar mixing is due to an exact (approximate) symmetry or the result of a finely tuned scalar potential.

An example of HMD and FID in the two Higgs doublet model (2HDM)

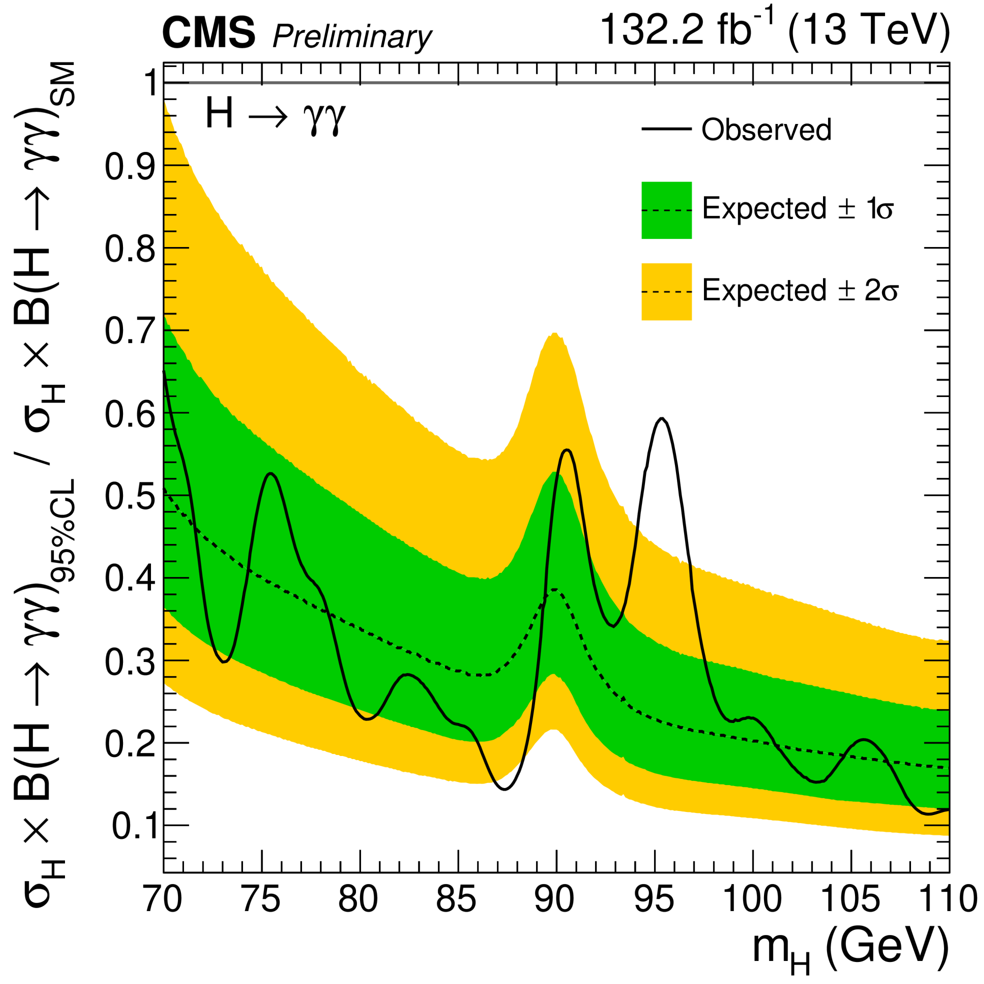
Consider the *Higgs basis* with doublet scalar fields H_1 and H_2 where the vev (v=246 GeV) resides entirely in H_1. The scalar potential is given by:

$$\begin{aligned}\mathcal{V} = {} & Y_1 H_1^\dagger H_1 + Y_2 H_2^\dagger H_2 + [Y_3 H_1^\dagger H_2 + \text{h.c.}] \\ & + \tfrac{1}{2} Z_1 (H_1^\dagger H_1)^2 + \tfrac{1}{2} Z_2 (H_2^\dagger H_2)^2 + Z_3 (H_1^\dagger H_1)(H_2^\dagger H_2) + Z_4 (H_1^\dagger H_2)(H_2^\dagger H_1) \\ & + \left\{ \tfrac{1}{2} Z_5 (H_1^\dagger H_2)^2 + \big[Z_6 (H_1^\dagger H_1) + Z_7 (H_2^\dagger H_2)\big] H_1^\dagger H_2 + \text{h.c.} \right\} ,\end{aligned}$$

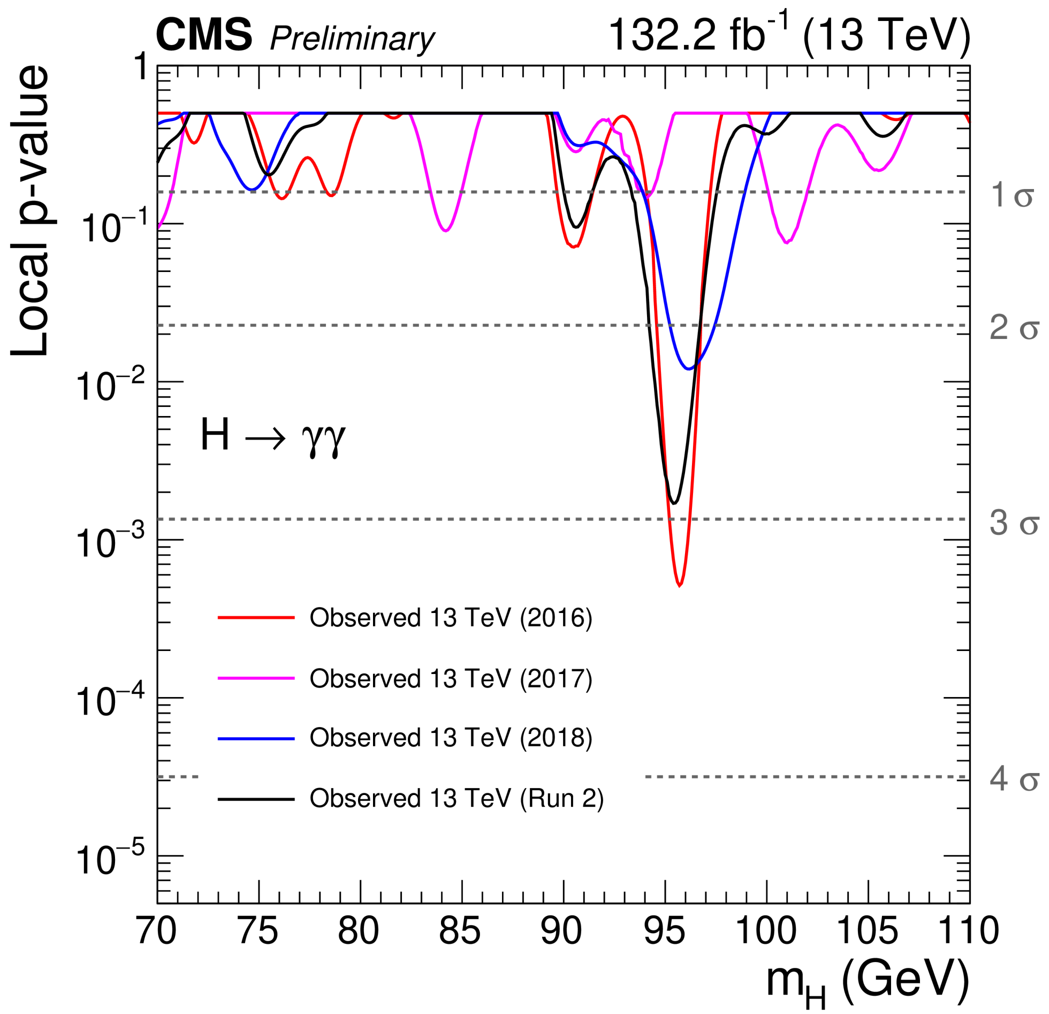
- The potential minimum conditions fix $Y_1 = -v^2 Z_1/2$ and $Y_3 = -v^2 Z_6/2$
- The heavy-mass decoupling limit (HMD) corresponds to $Y_2 \gg v^2$
- Higgs alignment without heavy-mass decoupling corresponds to $|Z_6| \ll 1$ (i.e., FID)

In both cases, the 2HDM will contain a neutral scalar that resembles the SM Higgs boson.

BSM Higgs physics hidden in plain sight?



Expected and observed exclusion limits (95% CL, in the asymptotic approximation) on the product of the production cross section and branching fraction into two photons for an additional SM-like Higgs boson, from the analysis of the combined data from 2016, 2017, and 2018. The inner and outer bands indicate the regions containing the distribution of limits located within ±1 and 2σ, respectively, of the expectation under the background-only hypothesis.



The observed local *p*-values for an additional SM-like Higgs boson as a function of m_H, from the analysis of the data from 2016, 2017, 2018, and their combination. Taken from CMS-PAS-HIG-20-002 (20 March 2023).

Exhibiting Higgs field alignment in the 2HDM

Physical 2HDM scalars: three neutral scalars h_1, h_2 and h_3 and a charged pair $H^{\pm}$
Higgs basis mixing parameters: q_{k1} and q_{k2} (k=1,2,3)

$$\mathcal{L}_{VVH} = \left(g m_W W_\mu^+ W^{\mu -} + \frac{g}{2\cos\theta_W} m_Z Z_\mu Z^\mu\right) \sum_k q_{k1} h_k$$

$$\begin{aligned}
\mathcal{L}_{\rm Yuk} = &-\frac{1}{v}\sum_k \overline{D}\left\{q_{k1} M_D + \frac{v}{\sqrt{2}}\left[q_{k2}\rho^{D\dagger} P_R + q_{k2}^* \rho^D P_L\right]\right\} D h_k \\
&-\frac{1}{v}\sum_k \overline{U}\left\{q_{k1} M_U + \frac{v}{\sqrt{2}}\left[q_{k2}^*\rho^{U} P_R + q_{k2} \rho^{U\dagger} P_L\right]\right\} U h_k \\
&-\left\{\overline{U}\left[K\rho^{D\dagger} P_R - \rho^{U\dagger} K P_L\right] D H^+ + \text{h.c.}\right\},
\end{aligned}$$

In the Higgs alignment limit,

$$q_{11} = q_{22} = -i q_{32} = 1\,,$$

$$q_{21} = q_{31} = q_{12} = 0\,,$$

in which case h_1 coincides with the SM-like Higgs boson. Note the presence of FCNCs mediated by h_2 and h_3.

where $P_{R,L} \equiv \frac{1}{2}(1 \pm \gamma_5)$, $Q = U$ and D are three flavors of up and down quark fields, the M_Q are the 3×3 up and down-type diagonal quark mass matrices, K is the CKM mixing matrix and the ρ^Q are generic complex 3×3 matrices.

Flavor alignment to avoid tree-level Higgs-mediated FCNCs

1. In the 2HDM, choose the ρ^F to be diagonal matrices (e.g., $\rho^F = a^F M_F$)

This requirement, if implemented generically, is not stable under RG evolution. The diagonality condition can be imposed either at:

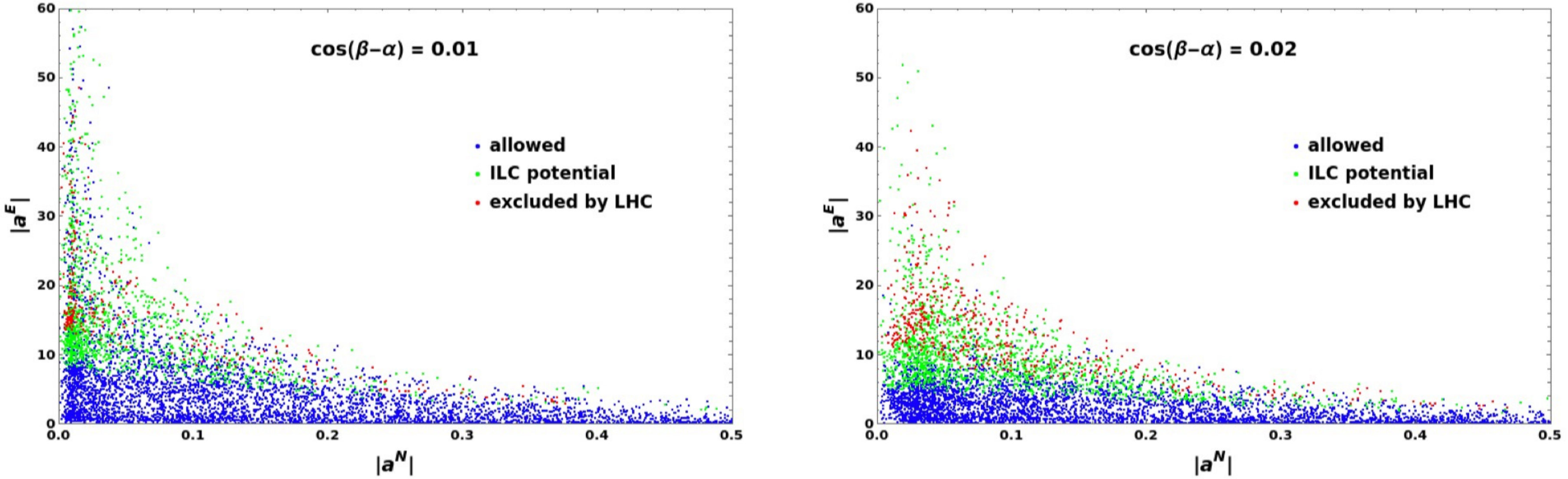
- the electroweak scale by fine-tuning [A. Pich and P. Tuzon, arXiv: 0908.1554]

  or

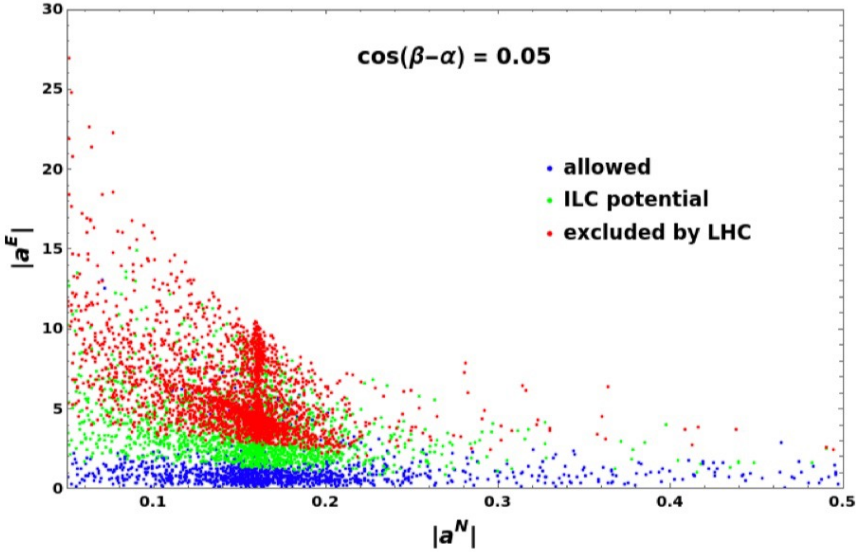
- at a very high energy scale, in which case tree-level Higgs-mediated FCNCs are generated at the electroweak scale and provide potential signals for discovery [S. Gori, H.E. Haber and E. Santos, **arXiv:1703.05873**]

2. In the 2HDM, impose a discrete symmetry on the Higgs Lagrangian such the the ρ^Q are diagonal. Different choices of the discrete symmetry yield the well-known Types I, II, X, and Y Yukawa couplings of the 2HDM.

Flavor alignment parameters: a^F, for F=U,D,N,E, where $\rho^F = a^F M_F$



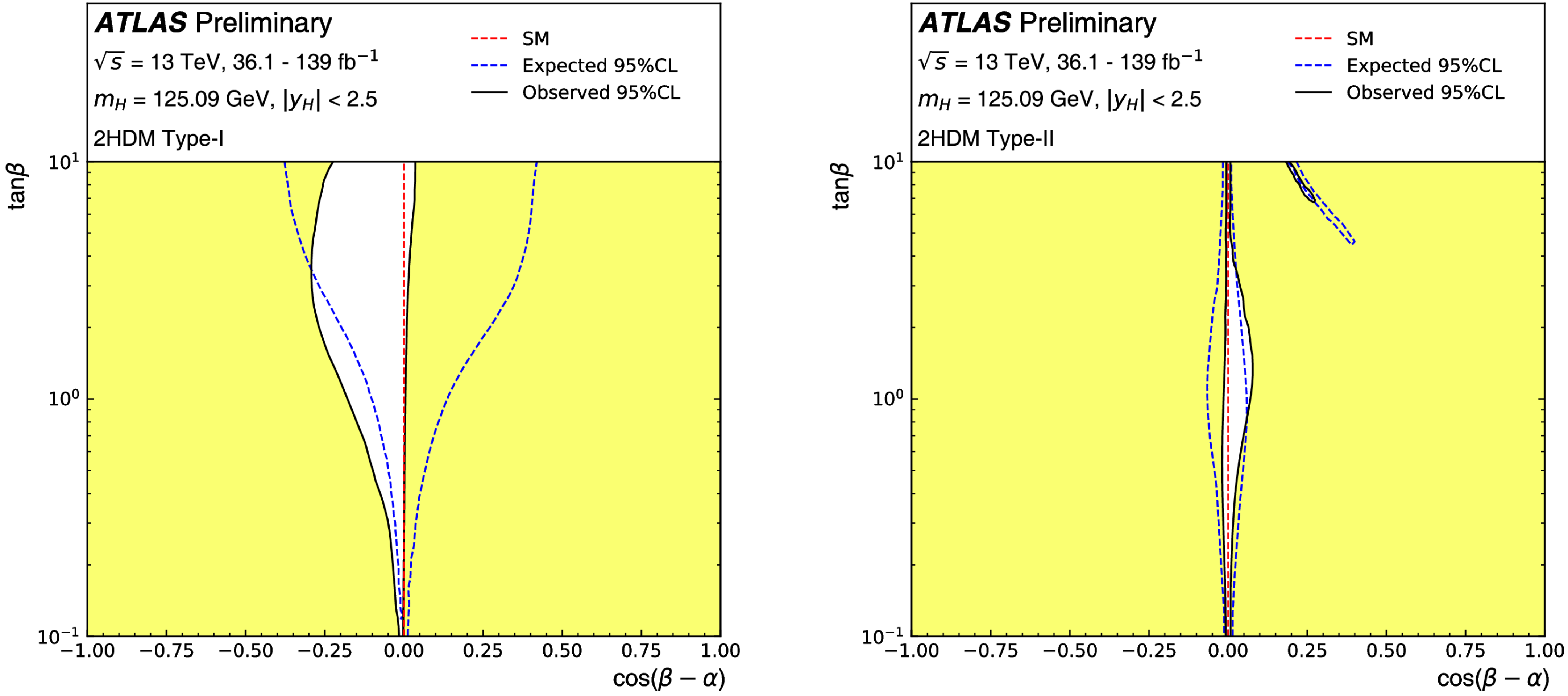
Figures taken from a forthcoming paper by S. Gori, H.E. Haber and E. Shahly.



Off-diagonal couplings of the neutral Higgs boson to $\tau\mu$ can be generated if flavor alignment is imposed at a very high energy scale $\boldsymbol{\Lambda}$, due to renormalization group evolution from $\boldsymbol{\Lambda}$ down to the energy scale of electroweak physics (100 GeV).

Figure 3: BR($h \to \mu\tau$) results for the case of $\cos(\beta-\alpha) = 0.01$ (left), 0.02 (right) and 0.05 (bottom) for fixed quark parameters $a^U = 0.1$ and $a^D = 1$. Green points indicate choices of the alignment parameters that lead to $h \to \mu\tau$ branching ratios that exceed the projected ILC upper bound of 2.3×10^{-4}, but are not yet excluded by LHC bounds. Red points are already excluded by LHC bounds and blue points remain unexcluded by both current experimental bounds and ILC projections.

LHC constraints on Higgs field 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. The observed best-fit values for cos(β - α) are -0.006 for the Type-I 2HDM and 0.002 for the Type-II 2HDM. Taken from ATLAS Collaboration, ATLAS-CONF-2021-053 (2 November 2021).

Fingerprinting nonminimal Higgs sectors

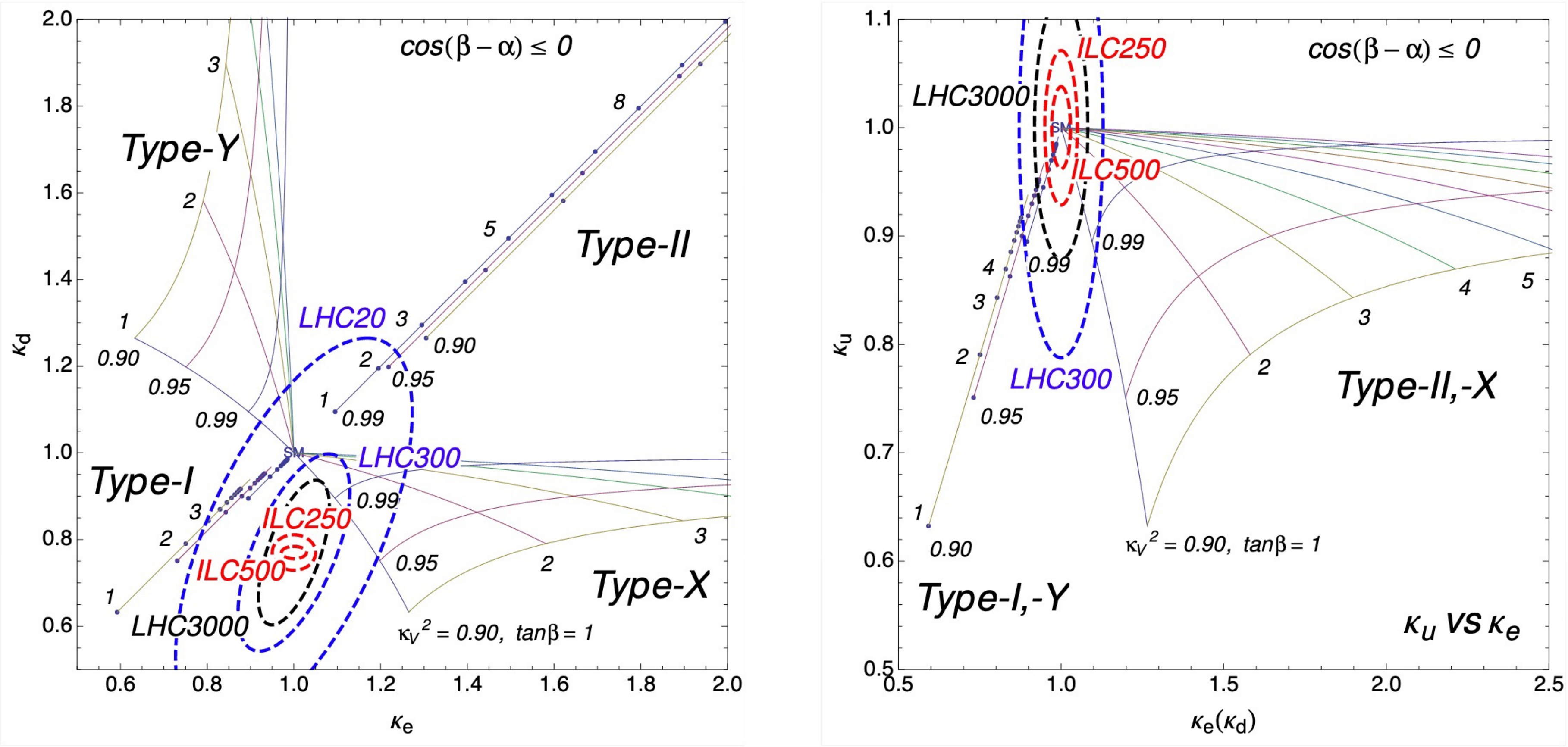
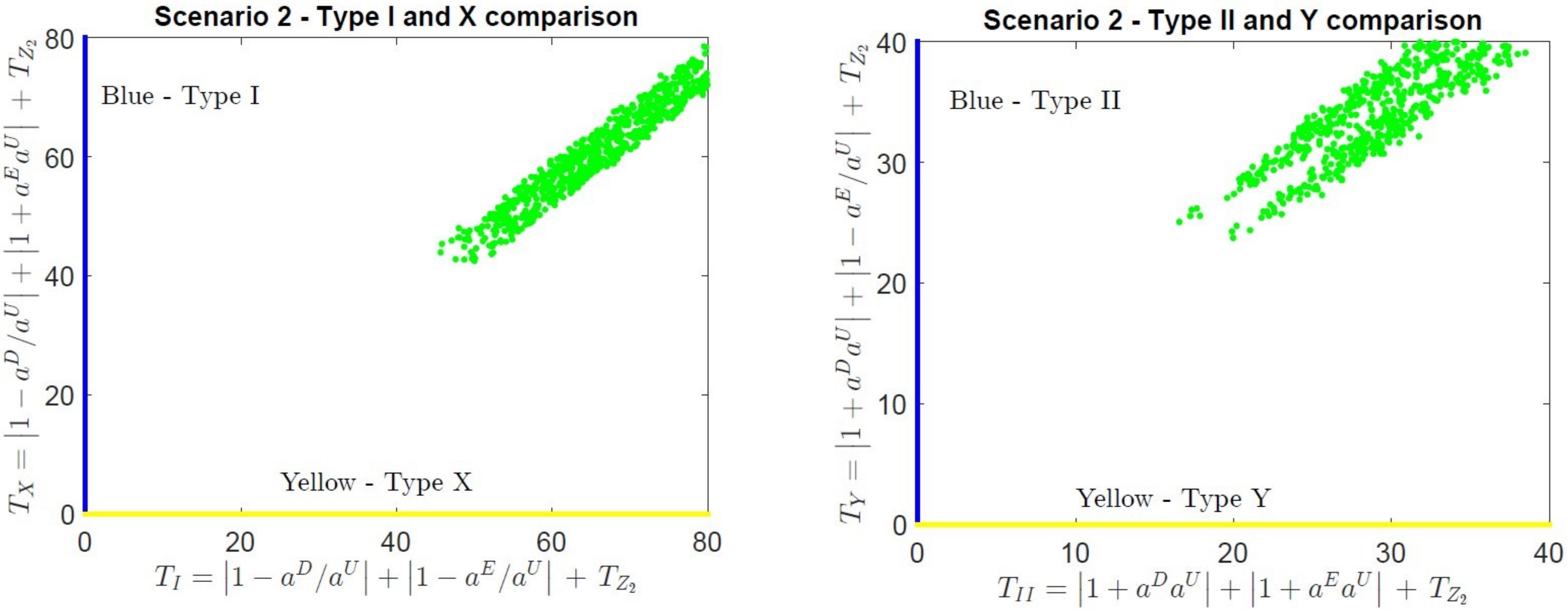


FIG. 10: The scaling factors for the Yukawa interaction of the SM-like Higgs boson in THDMs in the case of $\cos(\beta-\alpha) < 0$.

Taken from S. Kanemura, K. Tsumura, K. Yagyu and H. Yokoya, arXiv: 1406.3294

Assuming Yukawa interactions of Types I, II, X or Y may be too strong an assumption.

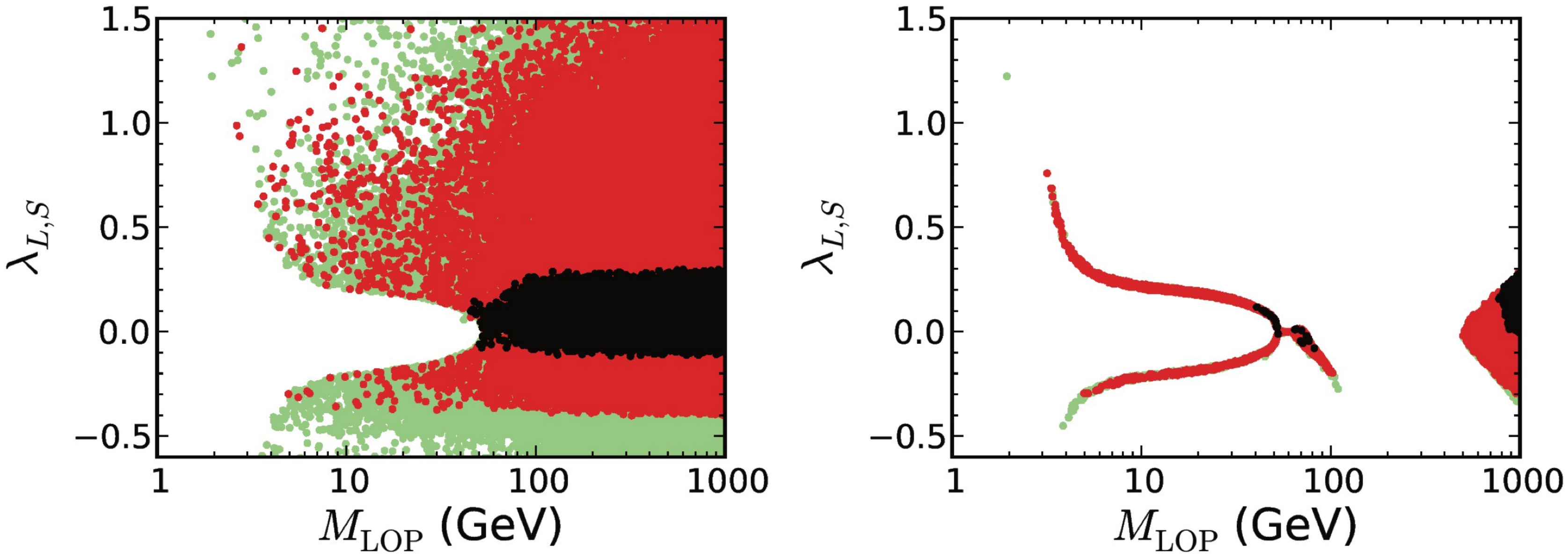
Example: an attempt to find 2HDM model points consistent with an ATLAS excess above background in a search for A → $\tau\,\tau$ and a CMS excess above background in a search for A → t t, for m_A = 400 GeV.



Taken from J.M. Connell, P. Ferreira, and H.E. Haber, arXiv: 2302.13697

A neutral scalar dark matter candidate—the inert doublet model (IDM)

The IDM is a 2HDM in which the scalar potential in the Higgs basis exhibits an exact $\mathbf{Z_2}$ discrete symmetry. All fields of the IDM—gauge bosons, fermions and the Higgs basis field H_1 are even under $\mathbf{Z_2}$. Only the Higgs basis field H_2 is $\mathbf{Z_2}$-odd. Hence, there is no mixing between H_1 and H_2. That is, Higgs field alignment is exact. The lightest $\mathbf{Z_2}$-odd particle (LOP) residing in H_2 is a candidate for the dark matter.



The viable IDM parameter space projected on the $(M_{\rm LOP}\,,\,\lambda_{L,S})$ plane imposing only the upper limit (left) and the upper and lower limits (right) of the WMAP range, $0.1018 \leq M_{\rm LOP}h^2 \leq 0.1234$. The green points correspond to all valid points in the scan, while the red and black regions show the points which remain valid when the model satisfies stability and perturbativity up to a scale $\Lambda = 10^4$ GeV and the GUT scale $\Lambda = 10^{16}$ GeV, respectively. Taken from A. Goudelis, B. Herrmann and O. Stål, JHEP **1309** (2013) 106.

Note: deviations from SM Higgs properties can arise at one-loop (e.g., $H^\pm$ loop corrections to $h \to \gamma\gamma$).

CP violation originating from the scalar sector

- Expected in any extended Higgs sector. Since CP-violation via the CKM matrix is already present, to turn off CP-violation effects that can arise via the scalar potential (or via the Yukawa couplings without additional symmetries) requires a fine-tuning of parameters [D. Fontes, M. Loschner, J.C. Romao and J.P. Silva, arXiv: 2103.05002]

- Strongly constrained by experimental limits on the electric dipole moment of the electron [for recent work, see W. Altmannshofer, S. Gori, N. Hamer and H.H. Patel, arXiv: 2009.01258]

- Interesting phenomenological features of the complex 2HDM
  - P-even, C-odd phenomena originating from the bosonic sector
  - P-odd, C-even phenomena originating from the Yukawa sector

Scalar mediated P-even CP-violating signals

Look for tree-level processes (production and/or decay) that are sensitive to bosonic processes that survive in the Higgs alignment limit. In the 2HDM, there are four classes of processes (involving trilinear couplings) whose simultaneous observation would constitute a detection of P-even CP violation:

1. $h_2 H^+ H^-\,, \quad h_3 H^+ H^-\,, \quad Z h_2 h_3\,,$
2. $h_2 h_k h_k\,, \quad h_3 H^+ H^-\,, \quad Z h_2 h_3\,, \quad$ (for $k = 2$ or 3),
3. $h_3 h_k h_k,\,, \quad h_2 H^+ H^-\,, \quad Z h_2 h_3\,, \quad$ (for $k = 2$ or 3),
4. $h_2 h_k h_k\,, \quad h_3 h_\ell h_\ell\,, \quad Z h_2 h_3\,, \quad$ (for $k, \ell = 2$ or 3).

Above, h_1 is the SM-like Higgs boson and h_2 (h_3) is the would-be CP-even (CP-odd) neutral scalar if CP were conserved. Detection of such signals requires a multi-TeV lepton collider. For more details, see H.E. Haber, V. Keus and R. Santos, arXiv:2206.09643.

P-even, CP-violating signals via loop effects

One can indirectly probe the P-even, CP-violating phenomena via loop contributions to the ZZZ and ZW^+W^-form factors.[§]

$$\Gamma_V^{\alpha\beta\mu}(q,\bar{q},P) = f_1^V(\bar{q}-q)^\mu g^{\alpha\beta} - \frac{f_2^V}{m_W^2}(\bar{q}-q)^\mu P^\alpha P^\beta + f_3^V\left(P^\alpha g^{\mu\beta} - P^\beta g^{\mu\alpha}\right)$$
$$+ i f_4^V\left(P^\alpha g^{\mu\beta} + P^\beta g^{\mu\alpha}\right) + i f_5^V \epsilon^{\mu\alpha\beta\rho}(\bar{q}-q)_\rho$$
$$- f_6^V \epsilon^{\mu\alpha\beta\rho} P_\rho - \frac{f_7^V}{m_W^2}(\bar{q}-q)^\mu \epsilon^{\alpha\beta\rho\sigma} P_\rho(\bar{q}-q)_\sigma .$$

The form factor f_4^V is the unique form factor that is P-conserving and CP-violating. In the exact Higgs alignment limit, a nonzero scalar contribution to f_4 requires at least three neutral scalars beyond the SM-like Higgs boson.[¶]

[§]Applications to the CP-violating 2HDM can be found in Grzadkowski, Ogreid and Osland, arXiv:1603.01388.

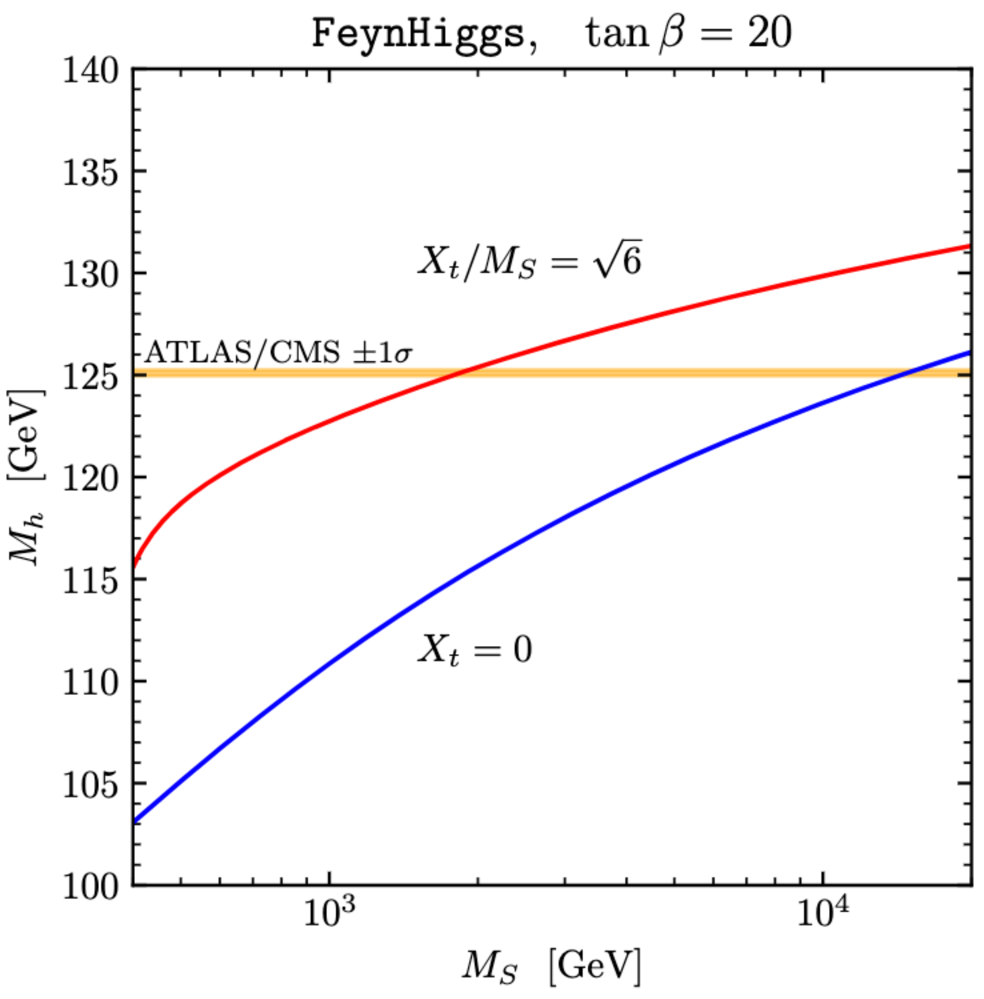
[¶]Note that there are two triangle diagrams with internal scalars that contribute at one loop order to the ZW^+W^- form factors, consisting of an $H^+H^-h_j$ and an $h_jh_kH^+$ loop, with corresponding ZH^+H^- and Zh_jh_k vertices, respectively. Only the latter can contribute to the P-even, CP-violating form factor f_4.

The Higgs boson as a portal to BSM physics

1. Supersymmetry (SUSY)

The MSSM employs a 2HDM Higgs sector and provides a (potentially) natural framework for electroweak symmetry breaking. The observed Higgs mass of 125 GeV is a prediction of the MSSM as a function of MSSM parameters.

The most recent precision Higgs mass calculations suggest that the SUSY scale M_S may be out of reach of LHC searches.



Taken from P. Slavich, S. Heinemeyer, et al., arXiv:2012.15629

2. Non-minimal SUSY models

In the NMSSM, the superpotential contains a term $\lambda H_U H_D N$, where N is a singlet superfield. The parameter λ plays a significant role in determining the Higgs mass. Remarkably, approximate Higgs field alignment is achieved for $\lambda = \lambda^{alt}$.

This scenario provides a much richer phenomenology for future LHC searches.

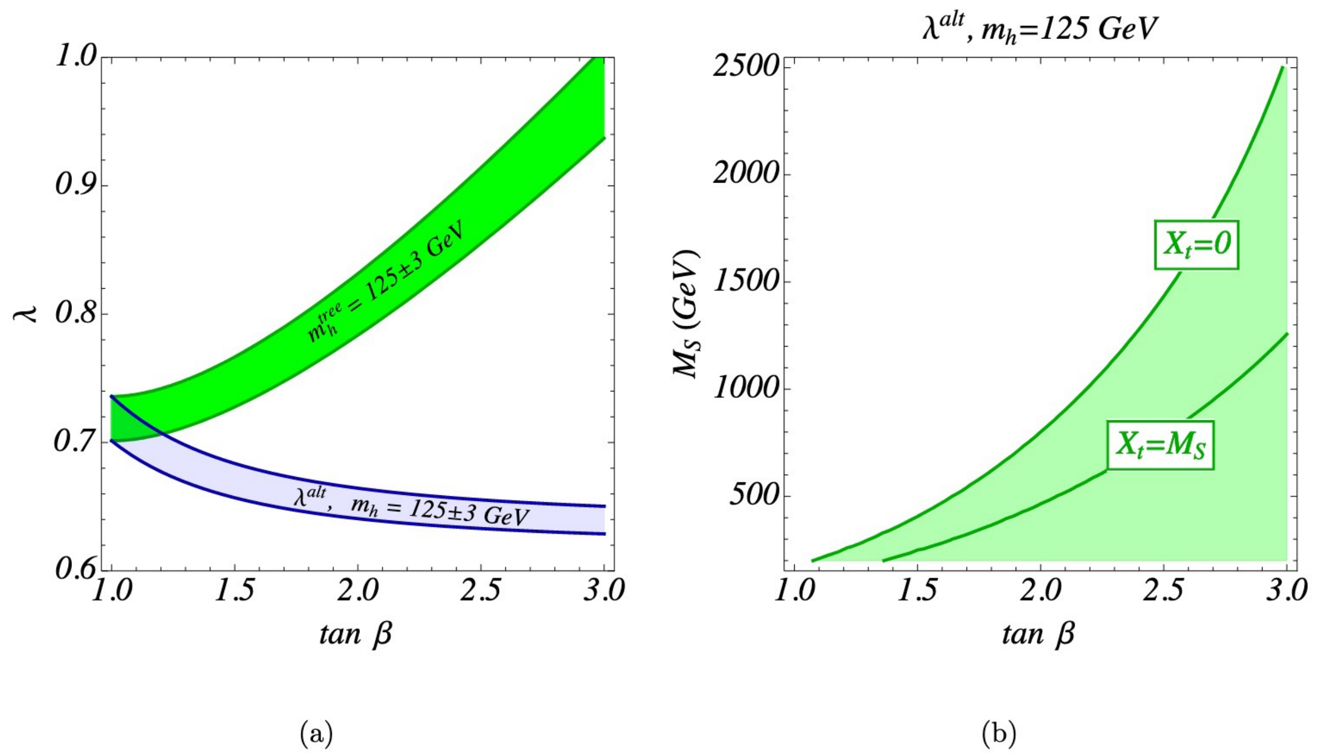


FIG. 2: *Left panel : The blue shaded band displays the values of* λ *as a function of* $\tan\beta$, *necessary for alignment for* $m_h = 125 \pm 3$ GeV. *Also shown in the figure as a green band are values of* λ *that lead to a tree-level Higgs mass of* 125 ± 3 GeV. *Right panel : Values of* M_S *necessary to obtain a 125* GeV *mass for values of* λ *fixed by the alignment condition and stop mixing parameter* $X_t = 0$ *and* $X_t = M_S$. *The dominant two-loop corrections are included.*

Taken from M. Carena, H.E. Haber, I. Low, N. Shah and C.E.M. Wagner, arXiv:1510.09137

Many other BSM scenarios

There are many other models inspired by naturalness, but one can also entertain more general scenarios. SMEFT (and more generically HEFT) provides a model independent approach for probing BSM physics.

- Supersymmetry
- The Higgs boson as a pseudo-Goldstone boson
- Composite Higgs models
- Higgs boson as a component of an extra-dimensional gauge field
- Higgs portal to the dark sector
- Cosmological scalars

Early universe history (inflation, electroweak phase transition) provide an independent motivation for BSM Higgs physics. Future gravitational wave experiments open up a new avenue for exploration.

Revisiting the Higgs Wishlist

I co-organized a KITP Rapid Response Workshop, "Higgs Identification" in December 2012, in response to the discovery of the Higgs boson earlier that year.

Participants of the workshop drew up a Higgs wishlist consisting of a list of theory questions and a separate list addressed to the LHC experimentalists (trying to clarify the early Higgs data).

The theory questions posed are still relevant.

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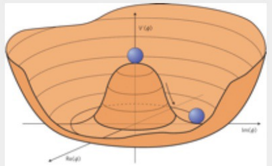
Higgs Identification (Minipgm)

in partnership with the **Kavli Foundation**.

Coordinators: Nima Arkani-Hamed, Andy Haas, Howard Haber, Ian Low, Vivek Sharma

On July 4, 2012 CERN announced the discovery of a new boson at the Large Hadron Collider. Both the ATLAS and CMS collaborations independently observe the new boson with a mass at around 125 GeV, with properties crudely approximating those predicted for the Higgs boson of the Standard Model of particle physics. It is crucial to measure the quantum numbers and interaction strengths of the new particle, and compare to the detailed predictions for the Higgs boson made by the Standard Model. This will have a direct impact on searches for new phenomena at the LHC and beyond, and provide essential insights into the nature of possible new physics. In particular, searches for new particles can shed light on whether "naturalness" is relevant as a guiding principle for physics at the TeV scale.

This rapid response workshop aims at bringing together theorists, with expertise in collider phenomenology, Standard Model processes, and theories and models of TeV-scale physics beyond the Standard Model, and experimentalists working on the LHC Higgs analyses, to examine the status of the Higgs data as of December, 2012 and to assess its implications for future experimental and theoretical studies. New physics models that could explain any observed deviations from the Standard Model predictions or be ruled out by the current data set will be explored in detail, and suggestions will be developed for further improvements to the LHC Higgs data analyses. In addition, the workshop will evaluate the benefits of various strategies for precision Higgs experimental studies at future facilities such as higher energy and/or luminosity runs at the LHC and a Higgs factory at a future lepton collider.



Credits: Luis Álvarez-Gaumé & John Ellis Nature Physics 7, 2–3 (2011) doi:10.1038/nphys1874

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More than ten years later, here is my (woefully incomplete) list of 20 items that merit future study and clarification:

Concerning the *h*(125):

1. What are the coupling strengths of *h* to second generation quarks (c,s)?

2. Will we ever be able to determine the coupling strengths of *h* to first generation quarks (u,d) ? To gluons?

3. What will it take to measure the coupling strength of *h* to electrons?

4. Will sufficient precision ever exist to measure the invisible decay partial width expected in the SM $(h \to ZZ^* \to \nu\bar{\nu}\nu\bar{\nu})$? How well can we constrain BR(*h* → *invisible)?*

5. With what ultimate accuracy can one predict the properties (cross sections, partial widths, etc.) of the SM Higgs boson? What are the important missing higher order perturbative computations that need to be done?

6. To what extent (and with what accuracy) can one experimentally reconstruct the Higgs scalar potential? (How well can one determine the Higgs self-coupling?)

7. With what accuracy (and reliability) can one experimentally determine the total width of *h*?

8. Will experimental deviations from SM Higgs boson properties, if observed, be convincing? Will they reveal a new mass threshold for BSM physics?

9. Does the Higgs boson couple to a dark sector made up of new particles that are completely neutral with respect to the SM (the so-called “Higgs portal”)?

10. Will convincing data emerge that points to a composite nature of the Higgs boson?

Concerning Higgs physics beyond the Standard Model:

1. How many generations (or flavors) of scalars exists at or below the TeV scale and what are their electroweak quantum numbers?

2. Are there any new elementary scalars not yet discovered with masses below the mass of the SM-like Higgs boson? For example, do axion-like particles exist?

3. How small is the departure from the Higgs alignment limit, and what is the underlying mechanism that yields an approximate Higgs alignment?

4. Does unitarization of $W_L W_L$ scattering require additional scalars from an extended scalar sector? (Or is *h*(125) sufficient?)

5. How small is the departure from the flavor alignment limit of the neutral Higgs–fermion Yukawa couplings? Will quark/lepton flavor off-diagonal couplings of neutral scalars be observed?

6. Are there new sources of CP violation associated with the extended scalar sector? Can these be experimentally observed (and the sources identified)?

7. How does the extended scalar sector affect the electroweak phase transition? Does it permit electroweak baryogenesis? Does it play other significant roles in early universe cosmology (e.g., inflation)? Will future gravitational wave experiments shed any light on these matters?

8. If additional scalars are discovered, how will these discoveries impact the question of the stability of the electroweak vacuum?

9. Do neutral scalars comprise a significant fraction of the dark matter?

10. How does the scalar sector inform the identification of the BSM physics? Does this shine any light on the large gap from the TeV scale to the Planck scale?

Final thoughts

- Future Higgs studies have the potential for addressing many profound questions concerning the theory of fundamental particles and their interactions. With expectations of data samples that are 20 times larger than what has presently been analyzed, there are considerable opportunities for discoveries at the LHC during the next 10 to 15 years.

- Nevertheless, Nature may demand more precision than the LHC can ultimately provide. Therefore, it is critical that the particle physics community address the following question:

What are the optimal (realistic?) future experimental facilities that provide the best chance for addressing the questions raised in the Higgs wishlist?

Backup slides

Example: the Georgi-Machacek (G-M) model (complex doublet, complex triplet, real triplet scalars)

(T, Y; c): Φ=(½ , 1; 1), X=(1, 2; 1), T=(1, 0; ½)

If $V_{1,2} = V_{1,0}$ then $\sum_{T,Y}\left[4(T(T+1)-3Y^2\right]|V_{T,Y}|^2 c_{T,Y} = 4\left(|V_{1,0}|^2 - |V_{1,2}|^2\right) = 0,$ and it follows that ρ=1.

One can write down a custodial symmetric scalar potential that yields $V_{1,2} = V_{1,0}$ at tree-level. However, due to custodial symmetry violating hypercharge gauge and Yukawa interactions, one finds that custodial symmetry violating terms in the scalar potential are generated at the loop level and are divergent and require counterterms. That is, a custodial symmetric scalar potential must be unnaturally fine-tuned. There are two options:

- Accept the fine-tuning of the scalar potential.
- Impose the custodial symmetric scalar potential at a very high energy scale (imposed by a mechanism to be determined by the (unknown) ultraviolet completion, and use RG evolution to permit (hopefully) small custodial violation at the electroweak scale.

A few phenomenological interesting features of the G-M model:

- Doubly charged Higgs scalars
- Non-zero tree-level $H^{\pm} W^{\mp} Z$ vertex
- Possibility of an *hVV* couling that is *larger* than the corresponding SM value

The Higgs field alignment limit: approaching the SM Higgs boson

Consider an extended Higgs sector with n hypercharge-one Higgs doublets Φ_i and m additional singlet Higgs fields ϕ_i.

After minimizing the scalar potential, we assume that only the neutral Higgs fields acquire vacuum expectation values (in order to preserve $\mathrm{U}(1)_{\rm EM}$),

$$\langle\Phi_i^0\rangle = v_i/\sqrt{2}\,, \qquad\qquad \langle\phi_j^0\rangle = x_j\,.$$

Note that $v^2 \equiv \sum_i |v_i|^2 = 4m_W^2/g^2 = (246~{\rm GeV})^2$.

The Higgs basis

Define new linear combinations of the hypercharge-one doublet Higgs fields (the so-called *Higgs basis*). In particular,

$$H_1 = \begin{pmatrix} H_1^+ \\ H_1^0 \end{pmatrix} = \frac{1}{v}\sum_i v_i^* \Phi_i \,, \qquad \langle H_1^0 \rangle = v/\sqrt{2}\,,$$

and $H_2, H_3, \ldots, H_n$ are the other linear combinations of doublet scalar fields such that $\langle H_i^0 \rangle = 0$ (for $i = 2, 3, \ldots, n$).

That is H_1^0 is aligned in field space with the direction of the Higgs vacuum expectation value (vev). Thus, if $\sqrt{2}\,\mathrm{Re}(H_1^0) - v$ is a mass-eigenstate, then the tree-level couplings of this scalar to itself, to gauge bosons and to fermions are precisely those of the SM Higgs boson, h^0. This is the exact alignment limit.

A SM-like Higgs boson

In general, $\sqrt{2}\,\mathrm{Re}(H_1^0)-v$ is not a mass-eigenstate due to mixing with other neutral scalars. Nevertheless, a SM-like Higgs boson exists if either:

- the diagonal squared masses of the other Higgs basis scalar fields are all large compared to the mass of the observed Higgs boson (the so-called *decoupling limit*).

and/or

- the elements of the neutral scalar squared-mass matrix that govern the mixing of $\sqrt{2}\,\mathrm{Re}(H_1^0)-v$ with other neutral scalars are suppressed.

In the CP-conserving 2HDM, the neutral scalar fields are denoted by the CP-even fields h and H and a CP-odd field A. To conform with the conventions of the 2HDM literature, we identify

k	scalar	q_{k1}	q_{k2}
1	h	$\sin(\beta-\alpha)$	$\cos(\beta-\alpha)$
2	H	$\cos(\beta-\alpha)$	$-\sin(\beta-\alpha)$
3	A	0	i

In the Higgs field alignment limit, *h* is SM-like and $\cos(\beta-\alpha)=0$.

The Type I and II Yukawa couplings ρ^U and ρ^D are diagonal matrices

$$\frac{v}{\sqrt{2}}\rho^U = M_U \cot\beta\,, \quad \text{Types I and II,}$$

$$\frac{v}{\sqrt{2}}\rho^D = \begin{cases} M_D \cot\beta\,, & \text{Type I,} \\ -M_D \tan\beta\,, & \text{Type II.} \end{cases}$$

$\tan\beta = v_2/v_1$ is defined in the scalar field basis in which the discrete symmetries that define the Types I and II Yukawa couplings are manifestly realized. In this basis, α is the CP-even Higgs mixing angle.

The Higgs wishlist compiled by the participants of the KITP Rapid Response Workshop, “Higgs Identification”, in December 2012

➢Is the observable Higgs state responsible for the unitarization of $W_L W_L$ scattering?

$$W_L W_L \to W_L W_L, Z_L Z_L, h Z_L \quad \Rightarrow \quad g_{hWW}\,,\ g_{hZZ}$$
$$W_L W_L \to t\bar{t} \quad \Rightarrow \quad g_{ht\bar{t}}$$

For example, in an SU(2)×U(1) gauge theory with a CP-conserving Higgs sector, no doubly charged Higgs bosons and $\rho \equiv m_W^2/m_Z^2 \cos^2\theta_W = 1$, we have[1]

$$\sum_{\mathrm{CP-even}\ k} g^2_{W^+W^-\phi_k^0} = g^2 m_W^2\,,$$

$$\sum_{\mathrm{CP-even}\ k} g^2_{ZZ\phi_k^0} = \frac{g^2 m_Z^2}{\cos^2\theta_W}\,,$$

$$\sum_{\mathrm{CP-even}\ k} g_{W^+W^-\phi_k^0}\, g^S_{kff} = -\tfrac{1}{2} g^2 m_f\,.$$

Are these unitary sum rules saturated by the experimentally observed Higgs state?

[1] For more general results, see J.F. Gunion, H.E. Haber and J. Wudka, Phys. Rev. **D43**, 904 (1991).

- How close to the decoupling limit is the experimentally observed Higgs boson?

  - There are two decoupling limits:

    - Higgs sector decoupling: enters at tree-level
    - Decoupling of new BSM physics: enters at loop-level.

  - Higgs decoupling limit governs the mass scale of the non-minimal Higgs states.

  - BSM physics decoupling governs the mass scale of of the new BSM interactions.

Here, BSM physics refers to all new physics beyond the Standard Model with a possible extended Higgs sector.

➢ What if deviations from SM Higgs couplings are confirmed?

- ❑ If large deviations are detected is there a compelling source of new physics beyond the Standard Model that can account for the deviations? How can one discriminate among different choices of the BSM physics?

- ❑ If small deviations from SM couplings are eventually established (highly suggestive of the near-decoupling regime), what are the systematics of the deviations, and do they point to a particular BSM scenario and/or extended Higgs sector?

  - The answer is known in the pure 2HDM model [e.g. if CP is conserved, then deviations from decoupling depend on one parameter, $\cos(\beta-\alpha)$]. But, how to generalize? To include BSM effects, you must distinguish between tree and loop contributions that contribute to the deviations.

➢ Precision Higgs observables as a probe of new physics

- ❑ How well can the LHC do in the asymptotic limit?
- ❑ What is the value added by the ILC?
- ❑ If deviations from SM Higgs couplings are detected can one extract a value for the mass scale of the new physics (Λ_{BSM})?
- ❑ How reliable is the determination of Λ_{BSM}, and how is this quantity related to a measurable quantity?
- ❑ How many standard deviations are required for the deviations to be convincing [cf. $(g\text{-}2)_{\mu}$, A_L , $A_{FB}(b)$]?

➢ Fate of the Higgs self-coupling $\lambda(Q)$ as $Q \to M_{PL}$?

- ❑ Is the Higgs vacuum stable or metastable?

- ❑ What is the theoretical origin of λ?

How does BSM physics impact these questions?

- For example, in the MSSM, λ is determined by gauge couplings, and the Higgs vacuum is therefore stable.

- In other BSM models, the corresponding answers may not be so straightforward.

- Is the gauge hierarchy problem resolved by TeV-scale physics? If yes, does this new physics provide us with a more fundamental understanding of the origin of electroweak symmetry breaking?

Supersymmetry remains the favored candidate, but if and when new physics is discovered, avoid the temptation to drive a square peg into a round hole.

Nevertheless, the SUSY wishlist for Higgs physics includes:

- A resolution to the μ problem.

- An more accurate computation of the Higgs mass to reduce the uncertainty below 1 GeV.