

# 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
  - The electroweak  $\rho$  parameter
  - 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

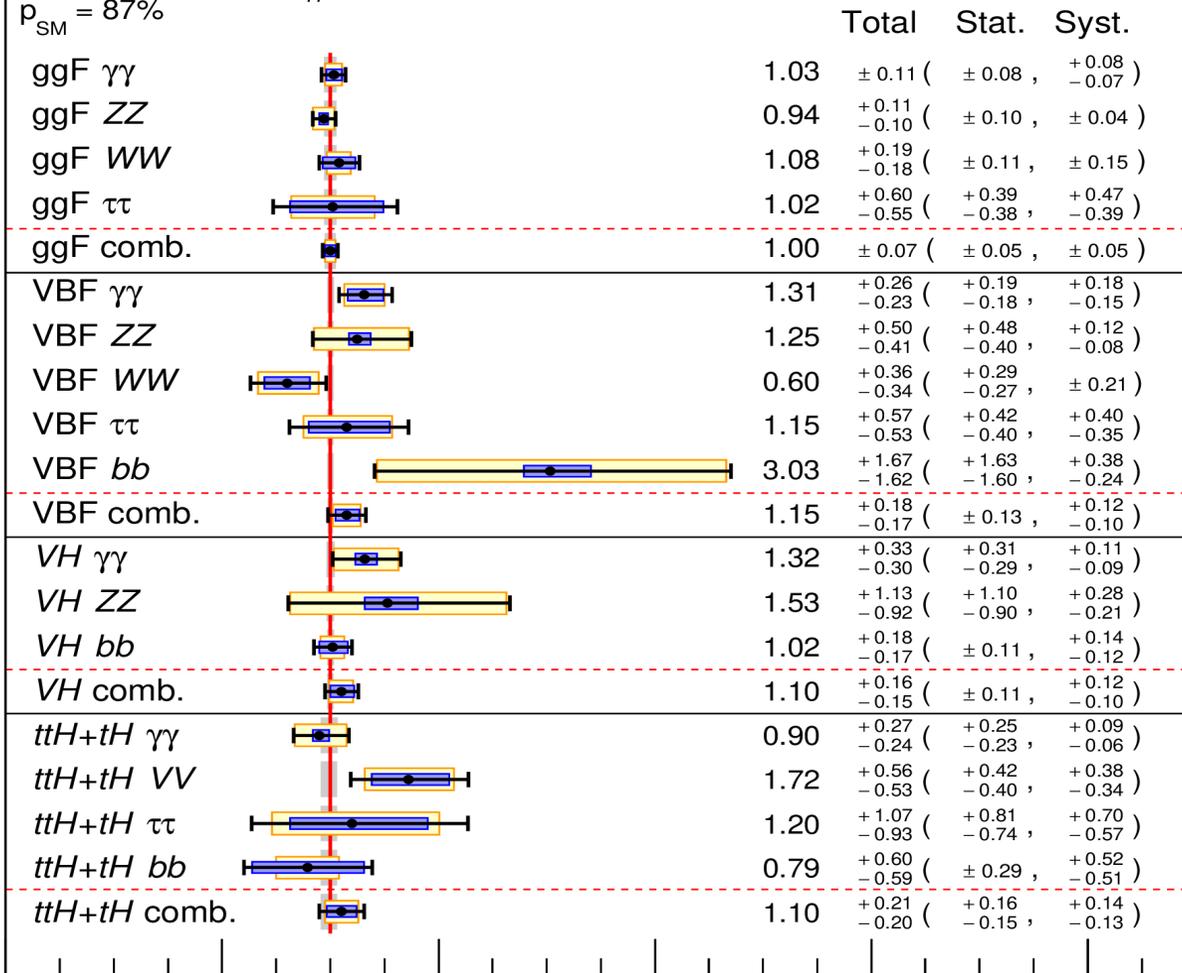
# Where we stand today

- Electroweak symmetry breaking yields Goldstone bosons that provide the longitudinal components of the massive W and Z gauge bosons.
- A priori, one could have imagined a plethora of possible dynamical models that produce the required Goldstone bosons.
- Remarkably, the simplest possible model, a self interacting complex doublet of elementary scalar fields (which yields a physical scalar particle — the Standard Model 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.

**ATLAS Preliminary**

$\sqrt{s} = 13 \text{ TeV}, 24.5 - 139 \text{ fb}^{-1}$   
 $m_H = 125.09 \text{ GeV}, |y_H| < 2.5$   
 $p_{\text{SM}} = 87\%$

—●— Total     Stat.     Syst.     SM

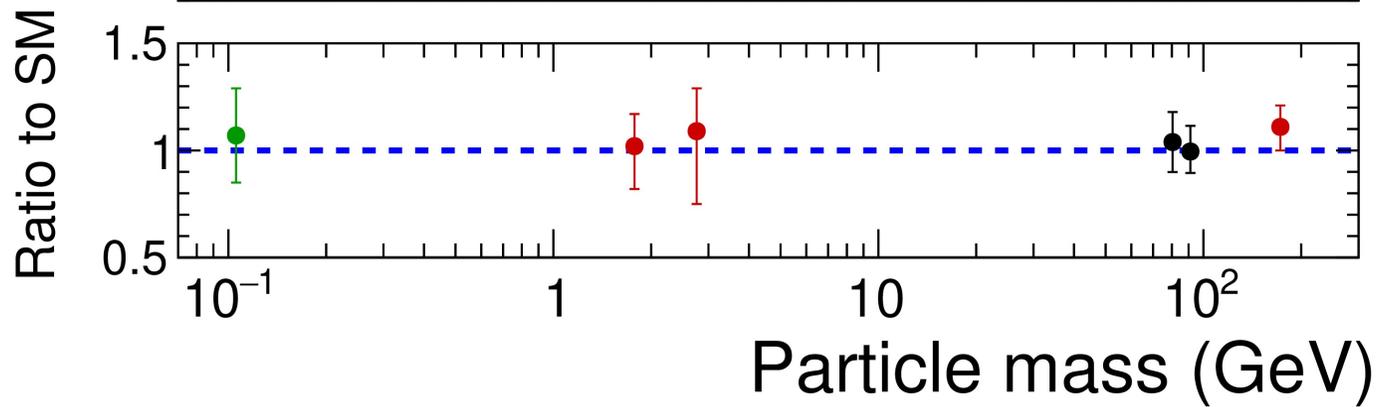
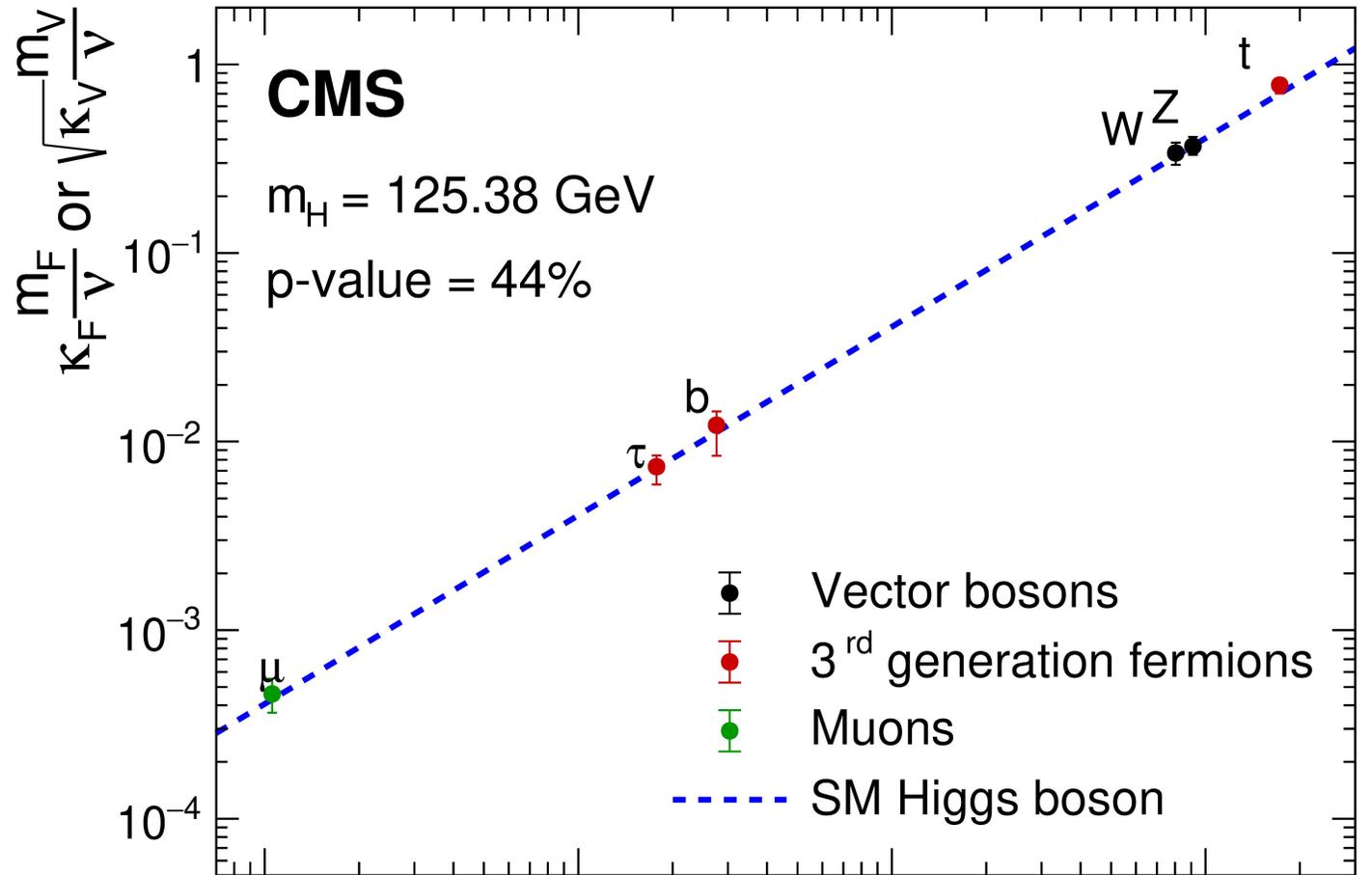


$\sigma \times B$  normalized to SM

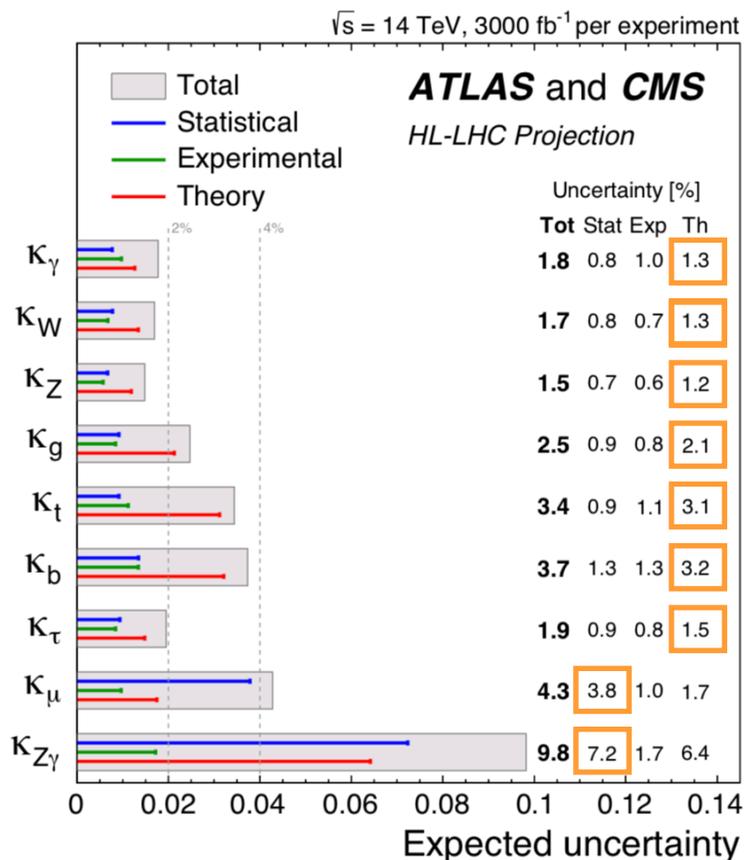
Taken from ATLAS collaboration,  
ATLAS-CONF-2020-027

Cross sections times branching fraction for ggF, VBF, VH and  $t\bar{t}H+tH$  production in each relevant decay mode, normalized to their Standard Model (SM) predictions. The values are obtained from a simultaneous fit to all channels. The cross sections of the ggF,  $H \rightarrow b\bar{b}$ , VH,  $H \rightarrow WW^*$  and VH,  $H \rightarrow \tau\tau$  processes are fixed to their SM predictions. Combined results for each production mode are also shown, assuming SM values for the branching fractions into each decay mode. The black error bars, blue boxes and yellow boxes show the total, systematic, and statistical uncertainties in the measurements, respectively. The gray bands show the theory uncertainties in the predictions. The level of compatibility between the measurement and the SM prediction corresponds to a p-value of  $p_{\text{SM}}=87\%$ , computed using the procedure outlined in the text with 16 degrees of freedom.

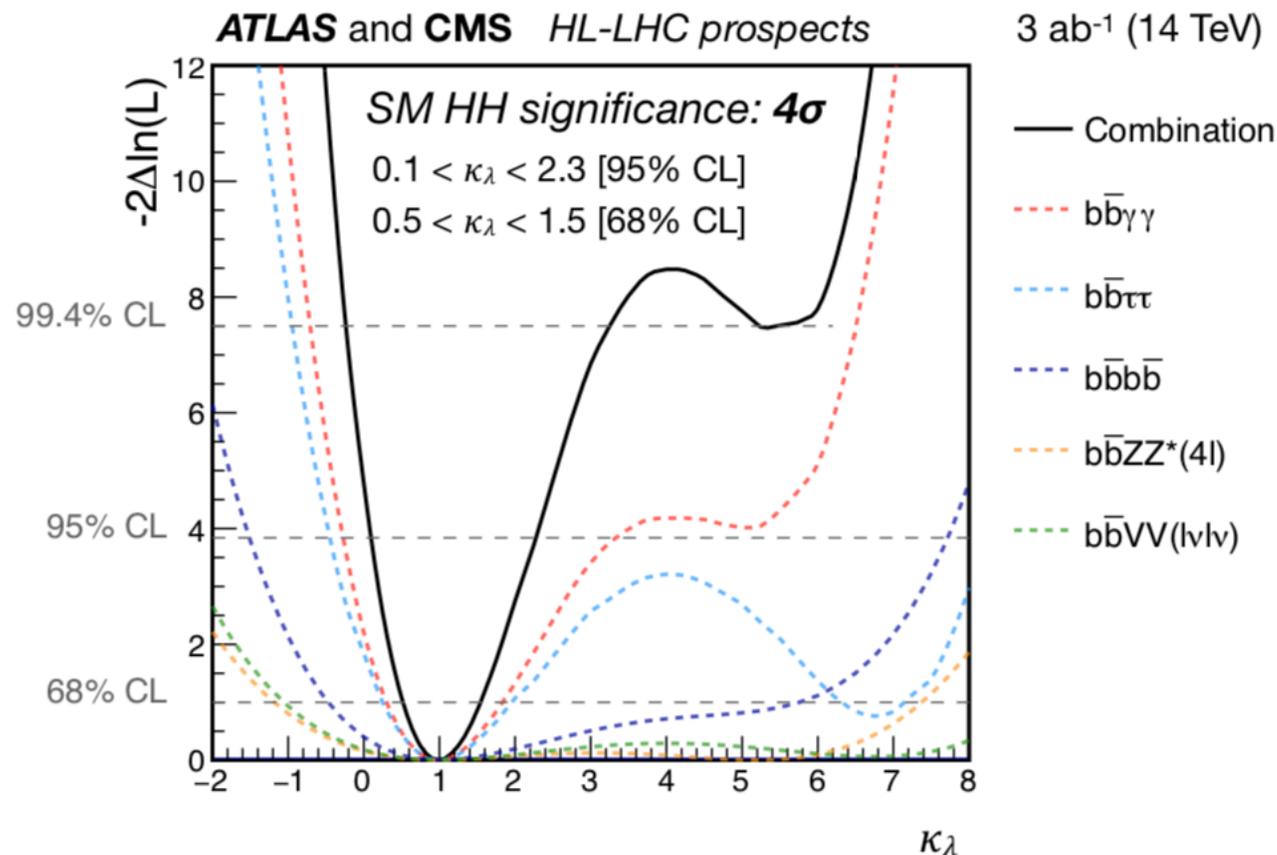
35.9-137 fb<sup>-1</sup> (13 TeV)



## Couplings



## Higgs boson self-coupling



The future

In addition for Higgs BSM searches a substantial amount of parameter space (and masses) to be covered

# Testing the SM using Higgs precision data—stepping beyond $\sigma \times \text{BR}$

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

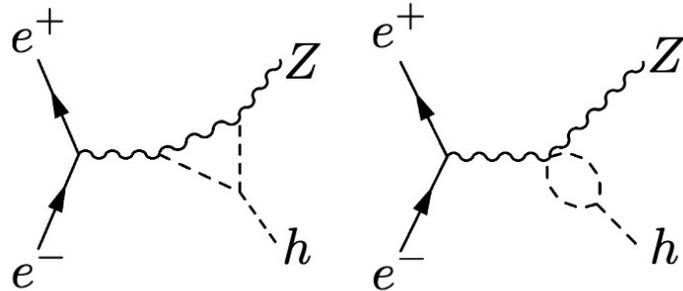


FIG. 1: NLO vertex corrections to the associated production cross section which depend on the Higgs self-coupling. These terms lead to a linear dependence on modifications of the self-coupling  $\delta_h$ .

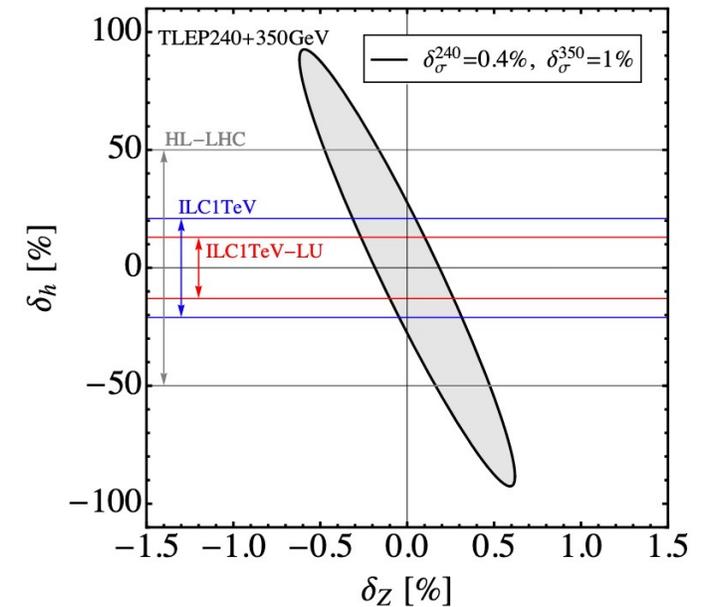
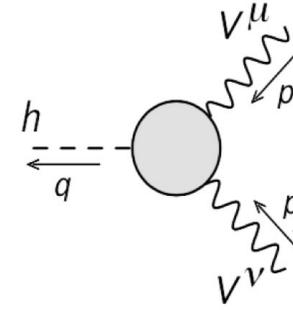


FIG. 3: Indirect  $1\sigma$  constraints possible in  $\delta_Z - \delta_h$  parameter space by combining associated production cross section measurements of 0.4% (1%-estimated) precision at  $\sqrt{s} = 240$  GeV, (350 GeV) in solid black. For large values of  $|\delta_h|$  this ellipse can only be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

➤ 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,  $\mathcal{L}_{\text{int}} = h Z_\mu Z^\mu$

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

$F_3$  corresponds to the CP-odd effective interaction,  $\mathcal{L}_{\text{eff}} = h F_{\mu\nu} \tilde{F}^{\mu\nu}$



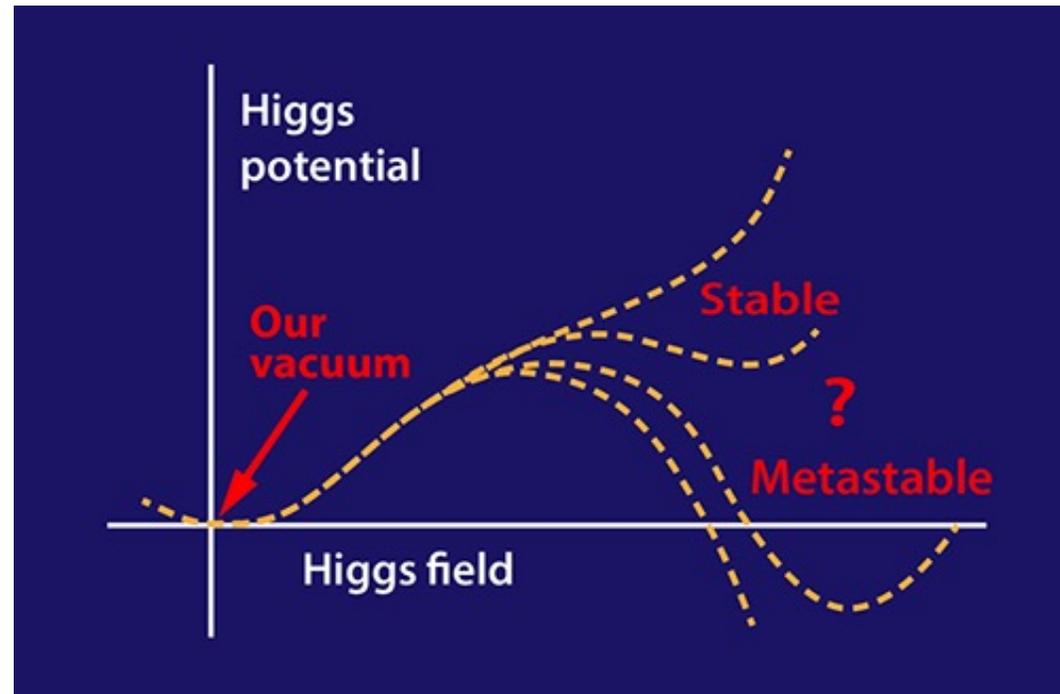
**Caution:** Higher dimensional operators in SMEFT may not account for all BSM Higgs phenomena if additional relatively light scalars exist.

# Is the electroweak vacuum of the SM stable?

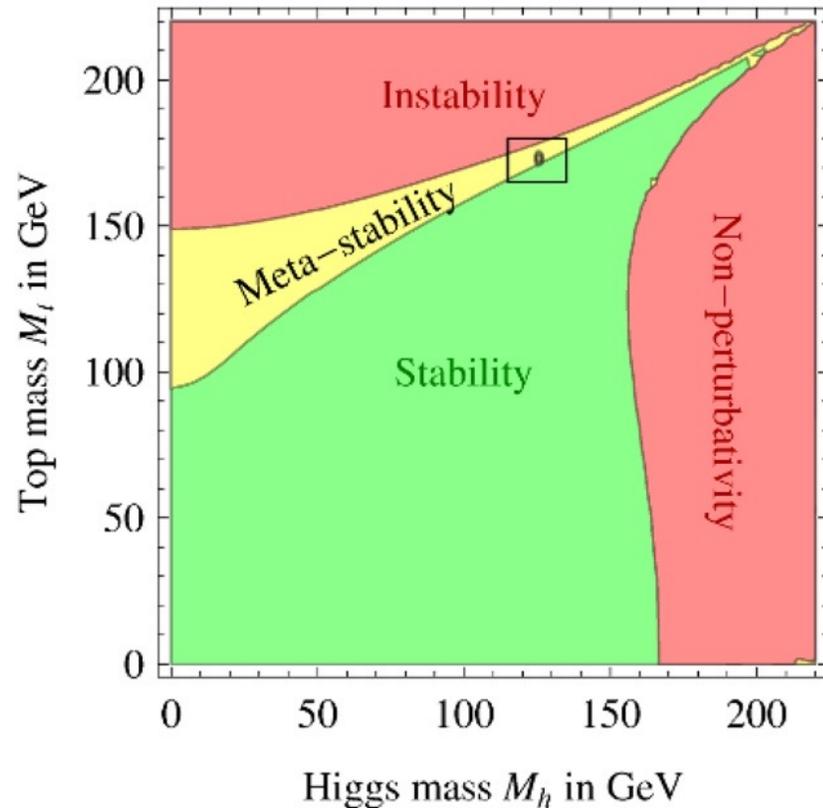
The Higgs field of the SM has a local minimum at  $\langle\Phi\rangle=246$  GeV. However, it is possible that a second minimum develops at very large field values. For field values larger than the Planck scale,  $M_{\text{PL}} = 10^{19}$  GeV (in units of  $c=1$ ), calculations within the SM are not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

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

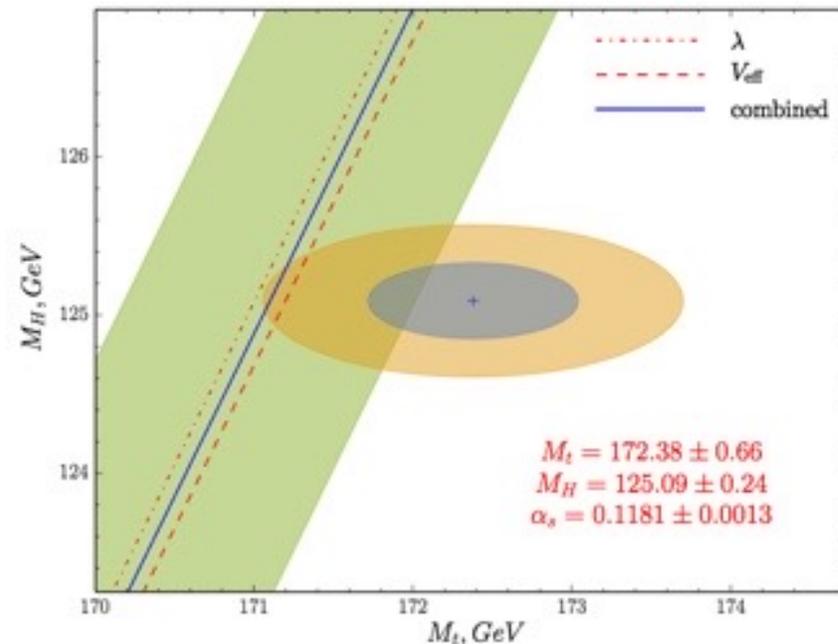
(figure courtesy of A. Kusenko)



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  $M_{\text{PL}}$ .



However, for a slightly lower value of  $m_t$  (compared to the central PDG value), stability up to  $M_{\text{PL}}$  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 BSM physics. Is such BSM physics accessible at the LHC or at future collider facilities?

# Elementary scalar fields portend an energy scale associated with new phenomena that is close at hand.

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## On the Self-Energy and the Electromagnetic Field of the Electron

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(Received April 12, 1939)

The charge distribution, the electromagnetic field and the self-energy of an electron are investigated. It is found that, as a result of Dirac's positron theory, the charge and the magnetic dipole of the electron are extended over a finite region; the contributions of the spin and of the fluctuations of the radiation field to the self-energy are analyzed, and the reasons that the self-energy is only

logarithmically infinite in positron theory are given. It is proved that the latter result holds to every approximation in an expansion of the self-energy in powers of  $e^2/hc$ . The self-energy of charged particles obeying Bose statistics is found to be quadratically divergent. Some evidence is given that the "critical length" of positron theory is as small as  $h/(mc) \cdot \exp(-hc/e^2)$ .

The situation is, however, entirely different for a particle with Bose statistics. Even the Coulombian part of the self-energy diverges to a first approximation as  $W_{st} \sim e^2 h / (mca^2)$  and requires a much larger critical length that is  $a = (hc/e^2)^{-\frac{1}{2}} \cdot h / (mc)$ , to keep it of the order of magnitude of  $mc^2$ . This may indicate that a theory of particles obeying Bose statistics must involve new features at this critical length, or at energies corresponding to this length; whereas a theory of particles obeying the exclusion principle is probably consistent down to much smaller lengths or up to much higher energies.

# 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 ( $\Rightarrow$  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  $\rho$  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.
- Higgs sector CP-violation has not yet been observed (with implications for electric dipole moments).
- Charged Higgs exchange at tree level (e.g. in  $\bar{B} \rightarrow D^{(*)} \tau^- \bar{\nu}_\tau$ ) and at one-loop (e.g. in  $b \rightarrow s \gamma$ ) can significantly constrain the charged Higgs mass and the Yukawa couplings.

## The $\rho$ -parameter constraint on extended Higgs sectors

Given that the electroweak  $\rho$ -parameter is very close to 1, it follows that a Higgs multiplet of weak-isospin  $T$  and hypercharge  $Y$  must satisfy,<sup>1</sup>

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

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

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

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.

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

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

$$(T, Y; c): \Phi=(\frac{1}{2}, 1; 1), X=(1, 2; 1), T=(1, 0; \frac{1}{2})$$

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

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  $hVV$  coupling that is *larger* than the corresponding SM value

# 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.

## The Higgs field alignment limit: approaching the SM Higgs boson

Consider an extended Higgs sector with  $n$  hypercharge-one Higgs doublets  $\Phi_i$  and  $m$  additional singlet Higgs fields  $\phi_i$ .

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

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

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

## The Higgs basis

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

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

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

That is  $H_1^0$  is **aligned** in field space with the direction of the Higgs vacuum expectation value (vev). Thus, if  $\sqrt{2} \operatorname{Re}(H_1^0) - v$  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,  $\sqrt{2} \operatorname{Re}(H_1^0) - v$  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  $\sqrt{2} \operatorname{Re}(H_1^0) - v$  with other neutral scalars are suppressed.

# Higgs field alignment with or without decoupling

## 1. The decoupling limit

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

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.

# 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  $q_{k2}$  ( $k=1,2,3$ )

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

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

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  $3 \times 3$  up and down-type diagonal quark mass matrices,  $K$  is the CKM mixing matrix and the  $\rho^Q$  are generic complex  $3 \times 3$  matrices.

# Flavor alignment to avoid tree-level Higgs-mediated FCNCs

1. In the 2HDM, choose the  $\rho^Q$  to be diagonal matrices.

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  $\rho^Q$  are diagonal. Different choices of the discrete symmetry yield the well-known Types I, II, X and Y Yukawa couplings of the 2HDM.

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  $\cos(\beta - \alpha) = 0$ .

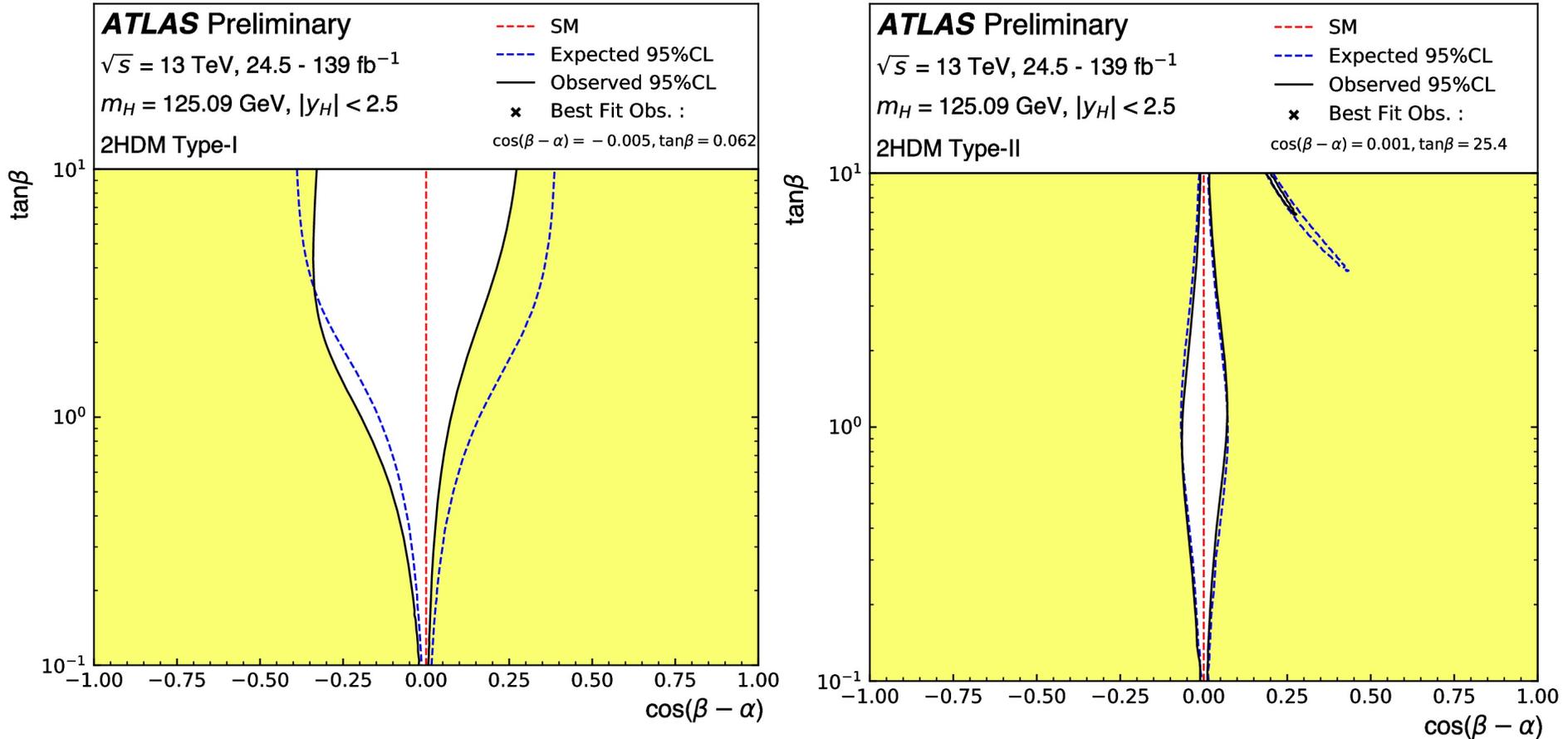
The Type I and II Yukawa couplings  $\rho^U$  and  $\rho^D$  are diagonal matrices

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

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

$\tan \beta = v_2/v_1$  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,  $\alpha$  is the CP-even Higgs mixing angle.

# LHC constraints on Higgs field alignment in the 2HDM



Regions of the  $(\cos(\beta - \alpha), \tan \beta)$  plane of the 2HDM with Type-I and Type-II Yukawa couplings, excluded by fits to the measured rates of Higgs boson production and decays. Contours at 95% CL, defined in the asymptotic approximation by  $-2 \ln \Lambda = 5.99$ , are drawn for both the data and the expectation for the SM Higgs sector. Taken from ATLAS-CONF-2020-027 (29 July 2020).

# Fingerprinting nonminimal Higgs sectors

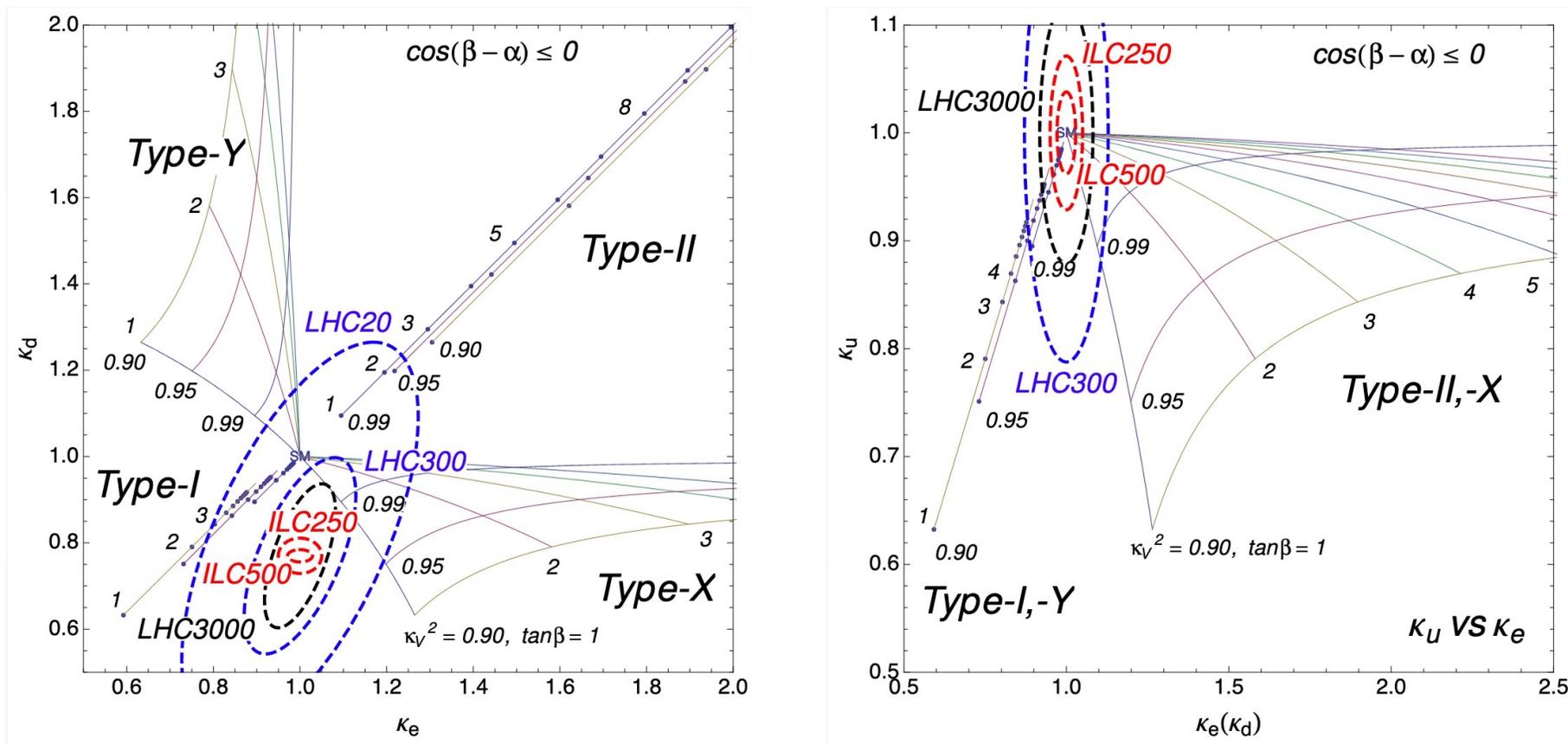
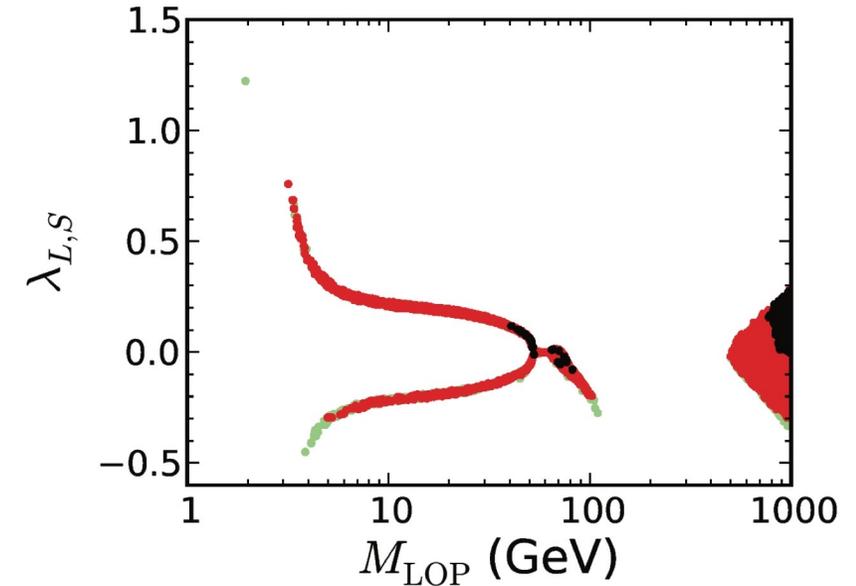
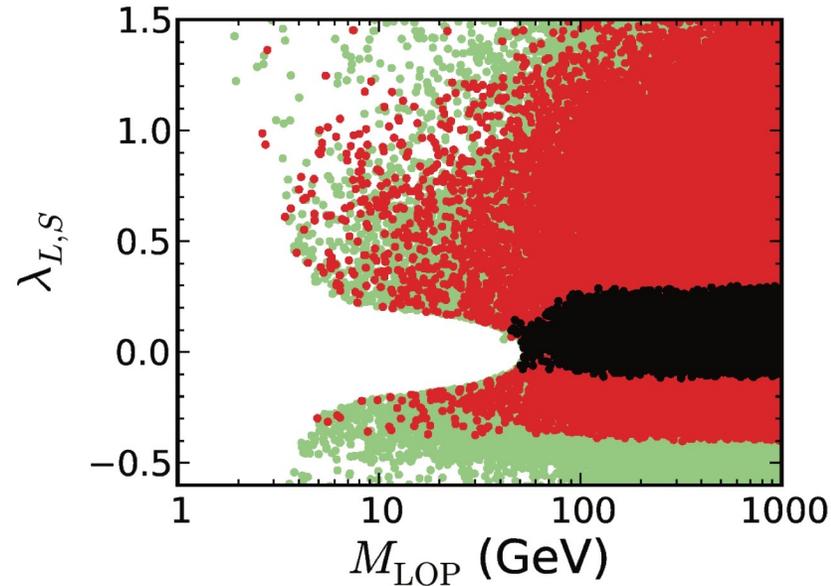


FIG. 10: The scaling factors for the Yukawa interaction of the SM-like Higgs boson in THDMs in the case of  $\cos(\beta - \alpha) < 0$ .

Taken from S. Kanemura, K. Tsumura, K. Yagyu and H. Yokoya, arXiv: [1406.3294](https://arxiv.org/abs/1406.3294)

# 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  $(M_{\text{LOP}}, \lambda_{L,S})$  plane imposing only the upper limit (left) and the upper and lower limits (right) of the WMAP range,  $0.1018 \leq M_{\text{LOP}} h^2 \leq 0.1234$ . 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  $h \rightarrow \gamma\gamma$ ).

# CP violation originating from the scalar sector

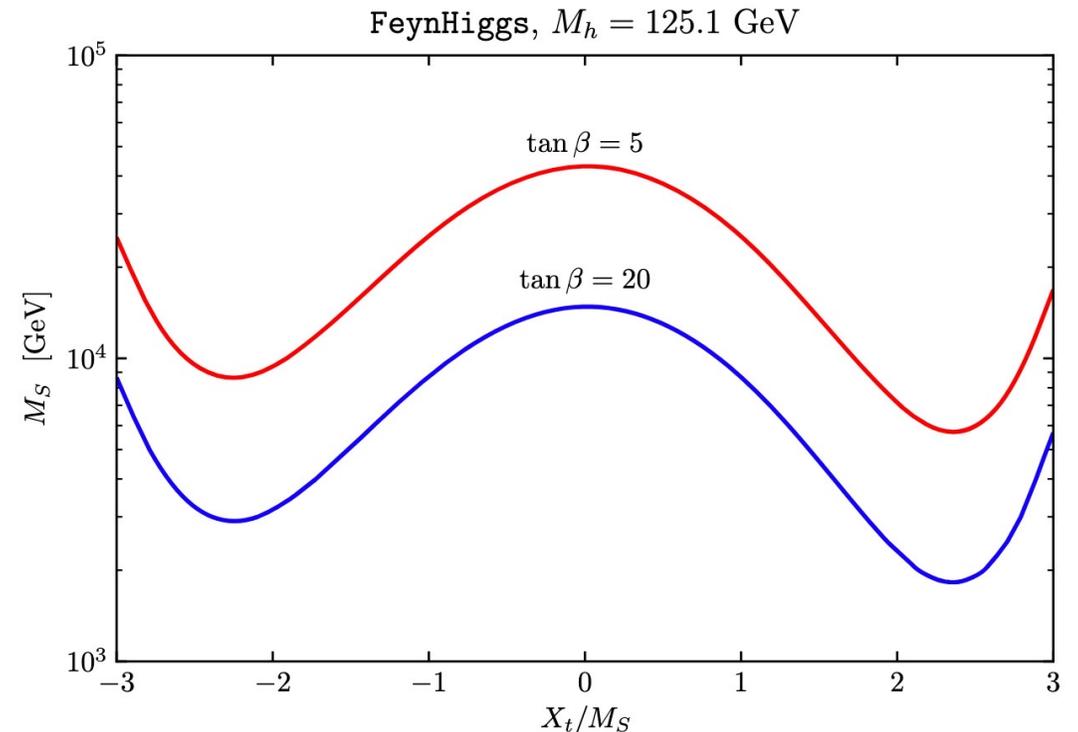
- Expected in any extended Higgs sector. Since CP-violation via the CKM matrix is already present, to turn off CP-violation effects that can arise via the scalar potential (or via the Yukawa couplings without additional symmetries) requires a fine-tuning of parameters [D. Fontes, M. Loschner, J.C. Romao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

# 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.



**Fig. 2** Values of the SUSY mass parameter  $M_S$  and of the stop mixing parameter  $X_t$  (normalized to  $M_S$ ) that lead to the prediction  $M_h = 125.1$  GeV, in a simplified MSSM scenario with degenerate SUSY masses, for  $\tan \beta = 20$  (blue) or  $\tan \beta = 5$  (red)

## 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  $\lambda$  plays a significant role in determining the Higgs mass. Remarkably, approximate Higgs field alignment is achieved for  $\lambda = \lambda_{\text{alt}}$ .

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

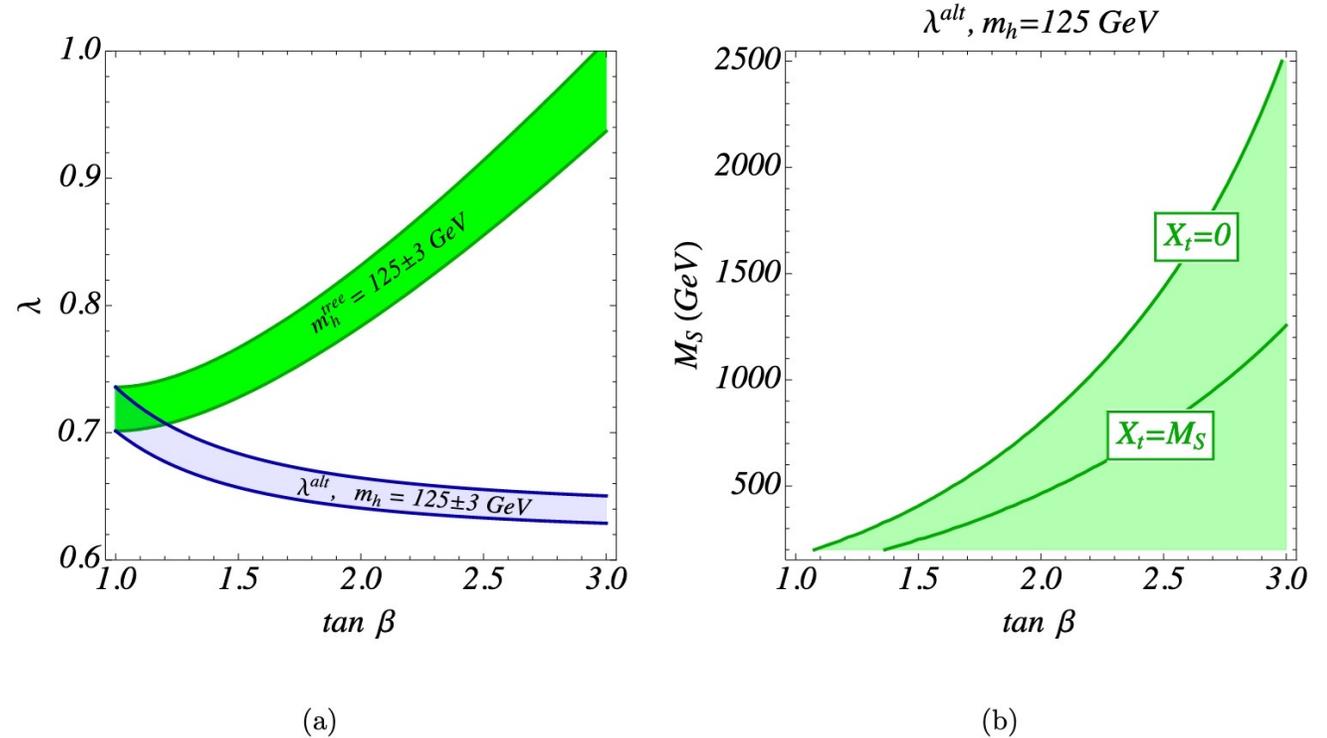


FIG. 2: Left panel : The blue shaded band displays the values of  $\lambda$  as a function of  $\tan \beta$ , necessary for alignment for  $m_h = 125 \pm 3 \text{ GeV}$ . Also shown in the figure as a green band are values of  $\lambda$  that lead to a tree-level Higgs mass of  $125 \pm 3 \text{ GeV}$ . Right panel : Values of  $M_S$  necessary to obtain a  $125 \text{ GeV}$  mass for values of  $\lambda$  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](https://arxiv.org/abs/1510.09137)

# Many other BSM scenarios

Many models inspired by naturalness considerations [see N. Craig's SSI lecture], but one can entertain more general scenarios. SMEFT 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.

The screenshot shows the website for the "Higgs Identification (Minipgm)" workshop. The header includes the UC Santa Barbara logo and the Kavli Institute for Theoretical Physics name. A navigation bar contains links for HOME, DIRECTORY, ACTIVITIES, PROPOSE ACTIVITY, APPLY, FOR VISITORS, ONLINE TALKS, and OUTREACH. The main content area features the workshop title, a partnership note with the Kavli Foundation, and a list of coordinators: Nima Arkani-Hamed, Andy Haas, Howard Haber, Ian Low, and Vivek Sharma. A detailed paragraph describes the workshop's purpose, focusing on the discovery of a new boson at the LHC and the need to measure its quantum numbers and interaction strengths. A sidebar on the right includes a 3D plot of a potential well, a credit to Luis Álvarez-Gaumé & John Ellis, and the Kavli Foundation logo. Below the main text, there are sections for DATES (Dec 10, 2012 - Dec 21, 2012) and QUICK LINKS (Wikispace, Online Talks, Photos). The footer contains copyright information, the NSF logo, and the UC Santa Barbara logo.

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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

THE KAVLI FOUNDATION

**DATES**  
Dec 10, 2012 - Dec 21, 2012

**QUICK LINKS**

- Wikispace
- Online Talks
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➤ Is the observable Higgs state responsible for the unitarization of  $W_L W_L$  scattering?

$$\begin{aligned}
 W_L W_L \rightarrow W_L W_L, Z_L Z_L, h Z_L &\Rightarrow g_{hWW}, g_{hZZ} \\
 W_L W_L \rightarrow t\bar{t} &\Rightarrow g_{ht\bar{t}}
 \end{aligned}$$

For example, in an  $SU(2) \times U(1)$  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<sup>1</sup>

$$\begin{aligned}
 \sum_{\text{CP-even } k} g_{W^+W^-\phi_k^0}^2 &= g^2 m_W^2, \\
 \sum_{\text{CP-even } k} g_{ZZ\phi_k^0}^2 &= \frac{g^2 m_Z^2}{\cos^2 \theta_W}, \\
 \sum_{\text{CP-even } k} g_{W^+W^-\phi_k^0} g_{kff}^S &= -\frac{1}{2} g^2 m_f.
 \end{aligned}$$

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

<sup>1</sup>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 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 ( $\Lambda_{\text{BSM}}$ )?
- How reliable is the determination of  $\Lambda_{\text{BSM}}$ , and how is this quantity related to a measurable quantity?
- How many standard deviations are required for the deviations to be convincing [cf.  $(g-2)_\mu$ ,  $A_L$ ,  $A_{\text{FB}}(b)$ ]?

➤ Fate of the Higgs self-coupling  $\lambda(Q)$  as  $Q \rightarrow M_{\text{PL}}$  ?

- ❑ Is the Higgs vacuum stable or metastable?
- ❑ What is the theoretical origin of  $\lambda$ ?

How does BSM physics impact these questions?

- For example, in the MSSM,  $\lambda$  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  $\mu$  problem.
- An more accurate computation of the Higgs mass to reduce the uncertainty below 1 GeV.

# Nine years later, here is my (woefully incomplete) list of 22 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 ( $h \rightarrow ZZ^* \rightarrow \nu\bar{\nu}\nu\bar{\nu}$ )? How well can we constrain  $\text{BR}(h \rightarrow \text{invisible})$ ?

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. Will convincing data emerge that points to a composite nature of  $h$ ?

## 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. How close is the extended scalar sector to the Higgs field alignment limit and what is the mechanism that explains this?
3. Does unitarization of  $W_L W_L$  scattering require additional scalars from an extended scalar sector? (Or is  $h(125)$  sufficient?)
4. 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?
5. Are there new sources of CP violation associated with the extended scalar sector? Can these be experimentally observed (and the source be identified)?

6. Is the metastability of the SM vacuum modified when the additional scalars are taken into account?
7. Do neutral scalars comprise a significant fraction of the dark matter?
8. Beyond the scalar sector, can one identify any associated BSM phenomena?
9. 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?
10. Will quark/lepton flavor off-diagonal couplings of neutral scalars be observed?
11. Will the Higgs portal reveal evidence for a dark sector?
12. Do axions or axion like particles exist? What is the connection of such light weakly coupled particles to the scalars associated with the electroweak scale?
13. Will the extended Higgs sector reveal evidence for substructure?

Concerning the items listed on the Higgs wishlist, here are two questions suitable for Snowmass deliberations:

- What are the optimal set of future experimental facilities that provide the best chance of addressing the issues raised in the Higgs wishlist?
- Compare and contrast the strengths and weaknesses of various proposed future facilities in addressing the key questions of Higgs physics.