Higgs Hunting 2016 Theory Summary Talk

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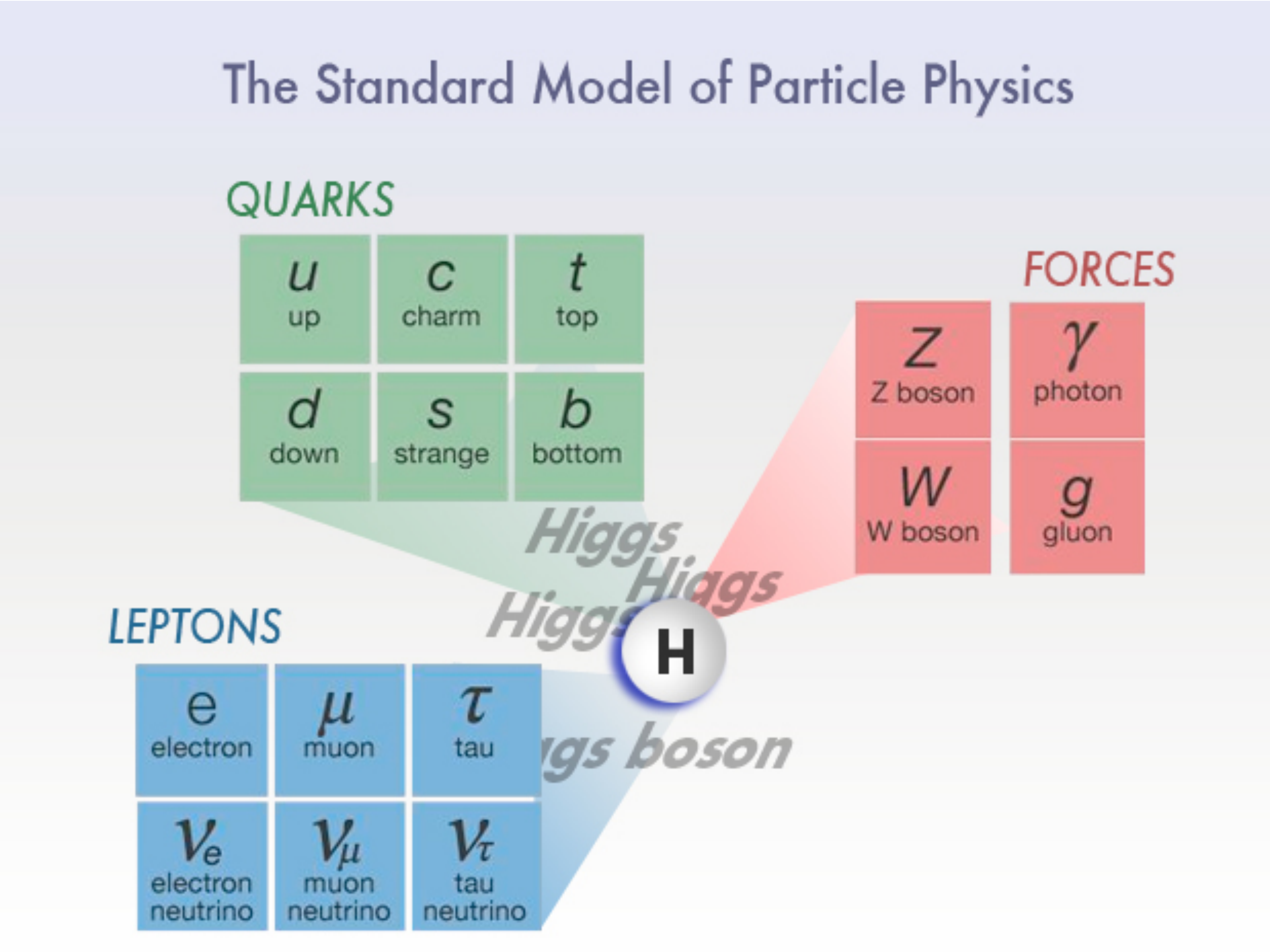
LPNHE, Paris

2 September 2016

With the discovery of the Higgs boson on 4 July 2012, the Standard Model is triumphant.


The Standard Model of Particle Physics
QUARKS
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electron neutrino
ν_μ
muon neutrino
ν_τ
tau neutrino
H
Higgs
Higgs
Higgs
Higgs boson

But, theorists are never satisfied!

(we tend to whine a lot)

peggy lee

is that all there is ?

Be careful what you ask for…


Donald J. Trump
@realDonaldTrump
Follow

Is that all there is? We need a new President - FAST!

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5:16 PM - 6 Dec 2015

Back to the Higgs boson…

Why were we expecting more than just the Higgs boson of the Standard Model?

Some phenomena must necessarily lie outside of the Standard Model (SM).

- Neutrinos are not massless.
- Dark matter is not accounted for.
- There is no explanation for the baryon asymmetry of the universe.
- The solution to the strong CP puzzle lies outside of the SM.
- Gauge coupling unification does not quite work (is this some hint?)
- There is no explanation for the inflationary period of the very early universe.
- The gravitational interaction is omitted.

New high energy scales must exist where new degrees of freedom and/or more fundamental physics reside. Let Λ denote the energy scale at which the SM breaks down.

Predictions made by the SM depend on a number of parameters that must be taken as input to the theory. These parameters are sensitive to ultraviolet (UV) physics, and since the physics at very high energies is not known, one cannot predict their values.

However, one can determine the sensitivity of these parameters to the UV scale Λ.

In the 1930s, it was already appreciated that a critical difference exists between bosons and fermions. Fermion masses are logarithmically sensitive to UV physics. Ultimately, this is due to the chiral symmetry of massless fermions, which implies that

$$\delta m_f \sim m_f \ln(\Lambda^2/m_f^2)$$

No such symmetry exists for bosons (in the absence of supersymmetry), and consequently we expect quadratic sensitivity of the boson squared-mass to UV physics,

$$\delta m_B^2 \sim \Lambda^2$$

JULY 1, 1939 PHYSICAL REVIEW VOLUME 56

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

V. F. WEISSKOPF
University of Rochester, Rochester, New York
(Received April 12, 1939)

In 1939, Weisskopf announces in the abstract to this paper that "the self-energy of charged particles obeying Bose statistics is found to be quadratically divergent"….

…. and concludes that in theories of elementary bosons, new phenomena must enter at an energy scale of order m/e (e is the relevant coupling)—the first application of naturalness.

which is about 10^{-58} times smaller than the classical electron radius. The "critical length" of the positron theory is thus infinitely smaller than usually assumed.

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 $W_{st} \sim e^2h/(mca^2)$ 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.

The tyranny of naturalness

In the SM the Higgs scalar potential,

$$V(\Phi) = -\mu^2(\Phi^\dagger\Phi) + \tfrac{1}{2}\lambda(\Phi^\dagger\Phi)^2\,,$$

where $\mu^2 = \frac{1}{2}\lambda v^2$ in terms of the vacuum expectation value v of the Higgs field. The parameter μ^2 is quadratically sensitive to Λ. Hence, to obtain $v = 246$ GeV in a theory where $v \ll \Lambda$ requires a significant fine-tuning of the ultraviolet parameters of the fundamental theory.

Indeed, the one-loop contribution to the squared-mass parameter μ^2 would be expected to be of order $(g^2/16\pi^2)\Lambda^2$. Setting this quantity to be of order of v^2 (to avoid an *unnatural* fine-tuning of the tree-level parameter and the loop contribution) yields

$$\Lambda \simeq 4\pi v/g \sim \mathcal{O}(1\ \mathrm{TeV})$$

A *natural* theory of electroweak symmetry breaking (EWSB) would seem to require new physics at the TeV scale to govern the EWSB dynamics.

Origin of the electroweak scale ?

- Naturalness is restored by supersymmetry which ties the bosons to the more well-behaved fermions [talks by Wagner and Carena].

- The Higgs boson is an approximate Goldstone boson—the only other known mechanism for keeping an elementary scalar light. Example: neutral naturalness [talks by Redigolo and Greco].

- The Higgs boson is a composite scalar, with an inverse length of order the TeV-scale [talks by Greco and Carena].

- The TeV-scale is chosen by some vacuum selection mechanism [talks by Dvali and de Lima].

- It's just fine-tuned. Get over it!

What next at the LHC ?

- Experimentalists---Of course, keep searching for new physics beyond the Standard Model (BSM)

- Theorists---Find new ways BSM physics (which might provide natural relief) can be hiding at the TeV-scale

But, if no signals for BSM physics emerge soon, what then?

When asked : what I intend to work on if no hints of BSM physics show up in Run 2 of the LHC, I say: “the Higgs sector, of course!”

After all, we have only recently discovered a most remarkable particle that seems to be like nothing that has ever been seen before---an elementary scalar boson. Shouldn’t we probe this state as thoroughly as possible and explore its properties?

The three really big questions

1. Are there additional Higgs bosons to be discovered? (To paraphrase I.I. Rabi, “who ordered that?”) If fermionic matter is non-minimal why shouldn’t scalar matter also be non-minimal?

2. If we measure the Higgs properties with sufficient precision, will deviations from SM-like Higgs behavior be revealed?

3. The operator $H^\dagger H$ is the unique relevant operator of the SM that is a Lorentz invariant gauge group singlet. As such, does it provide a “Higgs portal” to BSM physics that is neutral with respect to the SM gauge group?

This is not to say that other questions with potential connections to Higgs physics are less important. Some of these questions have been touched on at this meeting.

- Connections with neutrinos [talk by Bonilla]
- Connections with cosmology [talks by Baldes and Lebedev]
- Connections with baryogenesis [talk by Baldes]

The precision Higgs program requires important contribution from theorists

- Improved perturbative computations (N…NLO) of Higgs production and decay [talks by Boughezal, Krauss, Dreyer and Caola]

- New techniques for extracting Higgs properties (Examples: Higgs width [talk by Roentsch]; Yukawa couplings of first and second generation quarks [talks by Koenig, Azatov and Stamou]; Higgs self-couplings [talk by Panico]; coefficients of higher dimensional operators of the Higgs Effective Field Theory [talks by Ghezzi, Biekotter and Riva])

The Higgs portal may play an important role in theories of dark matter [talk by Lebedev]

Do more Higgs bosons mean more fine-tuning?

There are many examples in which natural explanations of the EWSB scale employ BSM physics with extended Higgs sectors. The MSSM (which employs two Higgs doublets) is the most well known example of this type, but there are many other such examples.

If you give up on naturalness, or employ e.g. vacuum selection, it has been argued that it may be difficult in some cases to accommodate more than one Higgs doublet at the electroweak scale.

However, it is possible to construct "partially natural" extended Higgs sectors in which the electroweak vev is fine-tuned (as in the SM), but additional scalar masses are related to the electroweak scale by a symmetry.

The partially natural two-Higgs doublet model

The 2HDM scalar potential

$$V = m^2\left(\Phi_1^\dagger\Phi_1 + \Phi_2^\dagger\Phi_2\right) + \tfrac{1}{2}\lambda\left[(\Phi_1^\dagger\Phi_1)^2 + (\Phi_2^\dagger\Phi_2)^2\right] + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2)$$
$$+\lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \left\{\tfrac{1}{2}\lambda_5(\Phi_1^\dagger\Phi_2)^2 + \text{h.c.}\right\},$$

possesses two discrete symmetries,

$$\begin{aligned}\mathbb{Z}_2^m: &\quad \Phi_1 \Longleftrightarrow \Phi_2,\\ \mathbb{Z}_2^i: &\quad \Phi_1 \Longleftrightarrow -\Phi_1, \quad \Phi_2 \Longleftrightarrow \Phi_2,\end{aligned}$$

and one fine-tuned squared-mass parameter m^2.

The discrete symmetries of the scalar potential cannot be successfully implemented in the Higgs-fermion Yukawa interactions in the 2HDM extension of the SM. However, if one adds vector-like fermion top partners, then one can extend the discrete symmetries such that top quarks transform into their top partners.

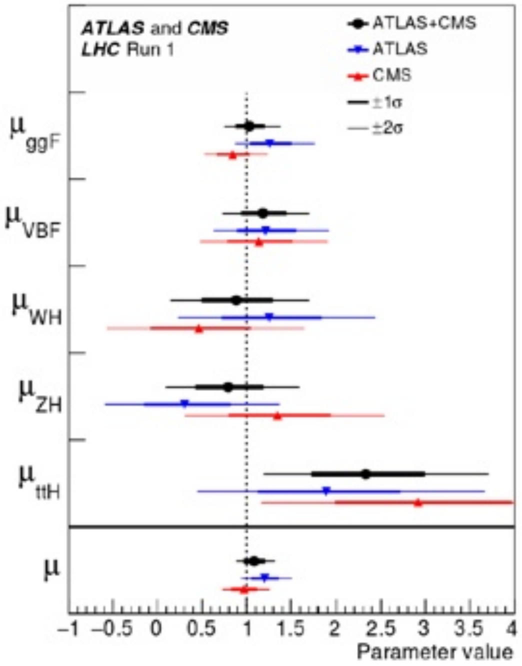
To construct a successful model, one will need to introduce a bare mass M for the top partners, which will softly break one of the two discrete symmetries. We assume that this soft-breaking is generated at a cutoff scale Λ. This re-introduces some fine-tuning (which grows with M), although it is not quadratically sensitive to Λ. The end result is that the top partners should not be too heavy (good for LHC discovery!).

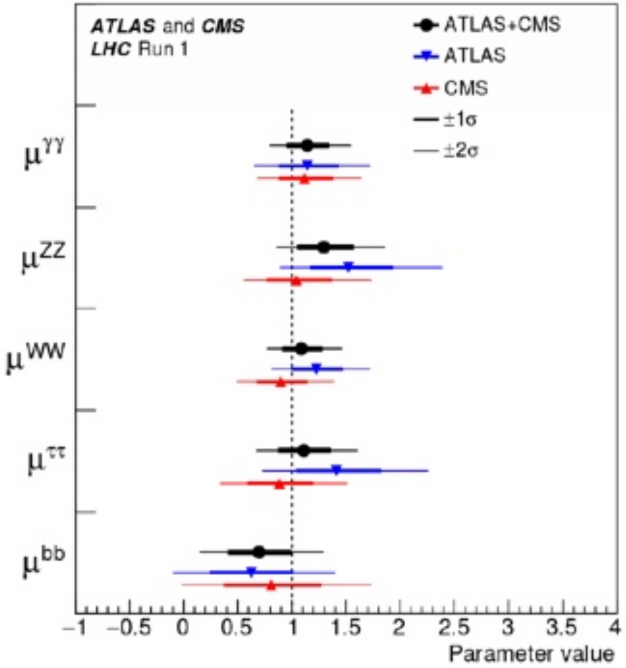
(For details, see P. Draper, H.E. Haber and J. Ruderman, JHEP 06 (2016) 124)

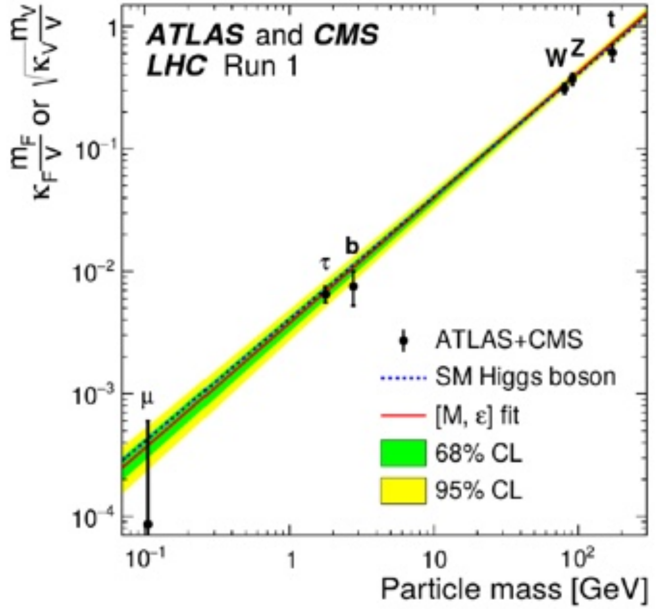
Introduction:

What's next for Higgs Physics?

- The 125 GeV Higgs boson has been discovered (7+8) TeV) and rediscovered (13 TeV)
- There are some deviations, but well within the current uncertainties
  - ➔ No *striking* discrepancies from the SM have been observed so far







- The LHC experiments must continue to test the SM predictions for the Higgs sector
  - ➔ Increase the precision of the measurements
  - ➔ Search for rare and BSM signatures

We already know that the observed Higgs boson is SM-like. Thus any model of BSM physics, including models of extended Higgs sectors must incorporate this observation.

For models of extended Higgs sectors, a SM-like Higgs boson can be achieved in a particular limit of the model called the alignment limit [talks by Carena and Wagner].

The 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 vevs (in order to preserve U(1)$_{\rm EM}$),

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

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

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

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

and $H_2, H_3, \ldots, H_n$ are the other linear combinations such that $\langle H_i^0\rangle = 0$.

That is H_1^0 is aligned with the direction of the Higgs vev in field space. 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. This is the exact alignment limit.

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

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

and/or

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

Although the alignment limit is most naturally achieved in the decoupling regime, it is possible to have a SM-like Higgs boson without decoupling. In the latter case, the masses of the additional scalar states could lie below ~ 500 GeV and be accessible to LHC searches.

Extending the SM Higgs sector with a singlet scalar

The simplest example of an extended Higgs sector adds a real scalar field S. The most general renormalizable scalar potential (subject to a $\mathbb{Z}_2$ symmetry to eliminate linear and cubic terms) is

$$\mathcal{V} = -m^2\Phi^\dagger\Phi - \mu^2 S^2 + \tfrac{1}{2}\lambda_1(\Phi^\dagger\Phi)^2 + \tfrac{1}{2}\lambda_2 S^2 + \lambda_3(\Phi^\dagger\Phi)S^2\,.$$

After minimizing the scalar potential, $\langle\Phi^0\rangle = v/\sqrt{2}$ and $\langle S\rangle = x/\sqrt{2}$. The squared-mass matrix of the neutral Higgs bosons is

$$\mathcal{M}^2 = \begin{pmatrix} \lambda_1 v^2 & \lambda_3 vx \\ \lambda_3 vx & \lambda_2 x^2 \end{pmatrix}\,.$$

The corresponding mass eigenstates are h and H with $m_h \leq m_H$. An approximate alignment limit can be realized in two different ways.

- $x \gg v$. This is the *decoupling limit*, where h is SM-like and $m_H \gg m_h$.
- $|\lambda_3|x \ll v$. Then h is SM-like if $\lambda_1 v^2 < \lambda_2 x^2$. Otherwise, H is SM-like.

The Higgs mass eigenstates are explicitly defined via

$$\begin{pmatrix} h \\ H \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \sqrt{2}\,\mathrm{Re}\;\Phi^0 - v \\ \sqrt{2}\,S - x \end{pmatrix},$$

where

$$\lambda_1 v^2 = m_h^2 \cos^2\alpha + m_H^2 \sin^2\alpha\,,$$

$$\lambda_2 x^2 = m_h^2 \sin^2\alpha + m_H^2 \cos^2\alpha\,,$$

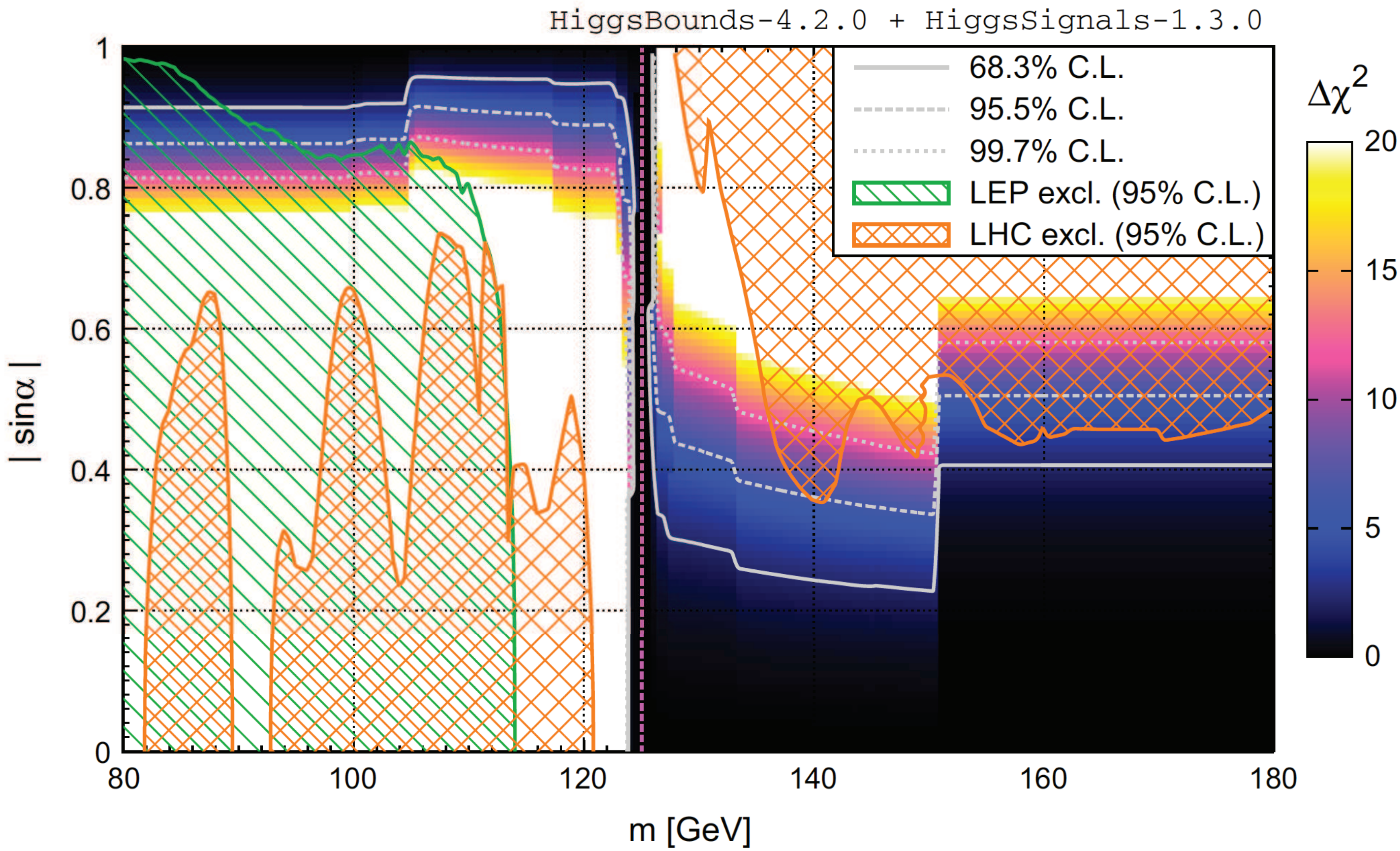
$$\lambda_3 xv = (m_H^2 - m_h^2)\sin\alpha\cos\alpha\,.$$

The SM-like Higgs must be approximately $\sqrt{2}\,\mathrm{Re}\;\Phi^0 - v$.
If h is SM-like, then $m_h^2 \simeq \lambda_1 v^2$ and

$$|\sin\alpha| = \frac{|\lambda_3|vx}{\sqrt{(m_H^2 - m_h^2)(m_H^2 - \lambda_1 v^2)}} \simeq \frac{|\lambda_3|vx}{m_H^2 - m_h^2} \ll 1\,,$$

If H is SM-like, then $m_H^2 \simeq \lambda_1 v^2$ and

$$|\cos\alpha| = \frac{|\lambda_3|vx}{\sqrt{(m_H^2 - m_h^2)(\lambda_1 v^2 - m_h^2)}} \simeq \frac{|\lambda_3|vx}{m_H^2 - m_h^2} \ll 1\,.$$



Taken from T. Robens and T. Stefaniak, Eur. Phys. J. **C75**, 104 (2015).

Theoretical structure of the 2HDM

Consider the most general renormalizable 2HDM potential,

$$\begin{aligned}\mathcal{V} &= m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 - [m_{12}^2\Phi_1^\dagger\Phi_2 + \text{h.c.}] + \tfrac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1)^2 \\ &\quad + \tfrac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) \\ &\quad + \left\{\tfrac{1}{2}\lambda_5(\Phi_1^\dagger\Phi_2)^2 + \left[\lambda_6(\Phi_1^\dagger\Phi_1) + \lambda_7(\Phi_2^\dagger\Phi_2)\right]\Phi_1^\dagger\Phi_2 + \text{h.c.}\right\} .\end{aligned}$$

After minimizing the scalar potential, assume that $\langle\Phi_i^0\rangle = v_i$ (for $i = 1, 2$).

Define the Higgs basis fields,

$$H_1 = \begin{pmatrix} H_1^+ \\ H_1^0 \end{pmatrix} \equiv \frac{v_1^*\Phi_1 + v_2^*\Phi_2}{v}, \qquad H_2 = \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix} \equiv \frac{-v_2\Phi_1 + v_1\Phi_2}{v},$$

such that $\langle H_1^0\rangle = v/\sqrt{2}$ and $\langle H_2^0\rangle = 0$. The Higgs basis is uniquely defined up to an overall rephasing, $H_2 \to e^{i\chi}H_2$.

In the Higgs basis, the scalar potential is given by:

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

where Y_1, Y_2 and $Z_1, \ldots, Z_4$ are real and uniquely defined, whereas Y_3, Z_5, Z_6 and Z_7 are complex and transform under the rephasing of H_2,

$$
[Y_3, Z_6, Z_7] \to e^{-i\chi} [Y_3, Z_6, Z_7] \quad \text{and} \quad Z_5 \to e^{-2i\chi} Z_5 \,.
$$

Physical observables must be independent of χ.

After minimizing the scalar potential, $Y_1 = -\frac{1}{2} Z_1 v^2$ and $Y_3 = -\frac{1}{2} Z_6 v^2$.

Remark: Generically, the Z_i are $\mathcal{O}(1)$ parameters.

Type I and II Higgs-quark Yukawa couplings in the 2HDM

In the Φ_1–Φ_2 basis, the 2HDM Higgs-quark Yukawa Lagrangian is:

$$-\mathscr{L}_{\rm Y} = \overline{U}_L \Phi_i^{0\,*} h_i^U U_R - \overline{D}_L K^\dagger \Phi_i^- h_i^U U_R + \overline{U}_L K \Phi_i^+ h_i^{D\,\dagger} D_R + \overline{D}_L \Phi_i^0 h_i^{D\,\dagger} D_R + {\rm h.c.}\,,$$

where K is the CKM mixing matrix, and there is an implicit sum over i. The $h^{U,D}$ are 3×3 Yukawa coupling matrices.

In order to naturally eliminate tree-level Higgs-mediated FCNC, we shall impose a discrete symmetry to restrict the structure of $\mathscr{L}_{\rm Y}$.

Under the discrete symmetry, $\Phi_1 \to +\Phi_1$ and $\Phi_2 \to -\Phi_2$, which restricts the form of the scalar potential by setting $m_{12}^2 = \lambda_6 = \lambda_7 = 0$.Two different choices for how the discrete symmetry acts on the fermions then yield:

- Type-I Yukawa couplings: $h_1^U = h_1^D = 0$,

- Type-II Yukawa couplings: $h_1^U = h_2^D = 0$.

If the discrete symmetry is unbroken, then the scalar potential and vacuum are automatically CP-conserving (and all scalar potential parameters and the Higgs vevs can be chosen real).

Actually, it is sufficient for the discrete symmetry to be broken softly by taking $m_{12}^2 \neq 0$. In this case, an additional source of CP-violation will be present if $\mathrm{Im}(\lambda_5^*[m_{12}^2]^2) \neq 0$. Nevertheless, Higgs-mediated FCNC effects remain suppressed.

Note that the parameter

$$\tan\beta \equiv \frac{v_2}{v_1},$$

is now meaningful since it refers to vacuum expectation values with respect to the basis of scalar fields where the discrete symmetry has been imposed.

The alignment limit in the CP-conserving 2HDM

We take $m_{12}^2 \neq 0$ and impose a Type-I or II structure of the Higgs–quark interactions. For simplicity, we assume CP-conservation, in which case all scalar potential parameters of the Higgs basis can be chosen real.

The CP-odd Higgs boson is $A = \sqrt{2}\,\mathrm{Im}\,H_2^0$ with $m_A^2 = Y_2 + \frac{1}{2}(Z_3 + Z_4 - Z_5)v^2$. After eliminating Y_2 in favor of m_A^2, the CP-even Higgs squared-mass matrix with respect to the Higgs basis states, $\{\sqrt{2}\,\mathrm{Re}\,H_1^0 - v\,,\, \sqrt{2}\,\mathrm{Re}\,H_2^0\}$ is given by,

$$\mathcal{M}_H^2 = \begin{pmatrix} Z_1 v^2 & Z_6 v^2 \\ Z_6 v^2 & m_A^2 + Z_5 v^2 \end{pmatrix} .$$

The CP-even Higgs bosons are h and H with $m_h \leq m_H$. An approximate alignment limit can be realized in two different ways.

1. $m_A^2 \gg (Z_1 - Z_5)v^2$. This is the *decoupling limit*, where h is SM-like and $m_A \sim m_H \sim m_{H^\pm} \gg m_h$.

2. $|Z_6| \ll 1$. h is SM-like if $m_A^2 + (Z_5 - Z_1)v^2 > 0$. Otherwise, H is SM-like.

In particular, the CP-even mass eigenstates are:

$$\begin{pmatrix} H \\ h \end{pmatrix} = \begin{pmatrix} c_{\beta-\alpha} & -s_{\beta-\alpha} \\ s_{\beta-\alpha} & c_{\beta-\alpha} \end{pmatrix} \begin{pmatrix} \sqrt{2}\,\mathrm{Re}\; H_1^0 - v \\ \sqrt{2}\,\mathrm{Re}\; H_2^0 \end{pmatrix},$$

where $c_{\beta-\alpha} \equiv \cos(\beta-\alpha)$ and $s_{\beta-\alpha} \equiv \sin(\beta-\alpha)$ are defined in terms of the mixing angle α that diagonalizes the CP-even Higgs squared-mass matrix when expressed in the original basis of scalar fields, $\{\sqrt{2}\,\mathrm{Re}\,\Phi_1^0 - v_1\,,\ \sqrt{2}\,\mathrm{Re}\,\Phi_2^0 - v_2\}$.

Since the SM-like Higgs must be approximately $\sqrt{2}\,\mathrm{Re}\,H_1^0 - v$, it follows that

- h is SM-like if $|c_{\beta-\alpha}| \ll 1$,
- H is SM-like if $|s_{\beta-\alpha}| \ll 1$.

The case of a SM-like H necessarily corresponds to alignment without decoupling.

Remark: Although the tree-level couplings of $\sqrt{2}\,\mathrm{Re}\;H_1^0 - v$ coincide with those of the SM Higgs boson, the one-loop couplings can differ due to the exchange of non-minimal Higgs states (if not too heavy). For example, the $H^\pm$ loop contributes to the decays of the SM-like Higgs boson to $\gamma\gamma$ and γZ.

The alignment limit in equations

The CP-even Higgs squared-mass matrix yields,

$$Z_1 v^2 = m_h^2 s_{\beta-\alpha}^2 + m_H^2 c_{\beta-\alpha}^2\,,$$

$$Z_6 v^2 = (m_h^2 - m_H^2) s_{\beta-\alpha} c_{\beta-\alpha}\,,$$

$$Z_5 v^2 = m_H^2 s_{\beta-\alpha}^2 + m_h^2 c_{\beta-\alpha}^2 - m_A^2\,.$$

If h is SM-like, then $m_h^2 \simeq Z_1 v^2$ and

$$|c_{\beta-\alpha}| = \frac{|Z_6| v^2}{\sqrt{(m_H^2 - m_h^2)(m_H^2 - Z_1 v^2)}} \simeq \frac{|Z_6| v^2}{m_H^2 - m_h^2} \ll 1\,,$$

If H is SM-like, then $m_H^2 \simeq Z_1 v^2$ and

$$|s_{\beta-\alpha}| = \frac{|Z_6| v^2}{\sqrt{(m_H^2 - m_h^2)(Z_1 v^2 - m_h^2)}} \simeq \frac{|Z_6| v^2}{m_H^2 - m_h^2} \ll 1\,.$$

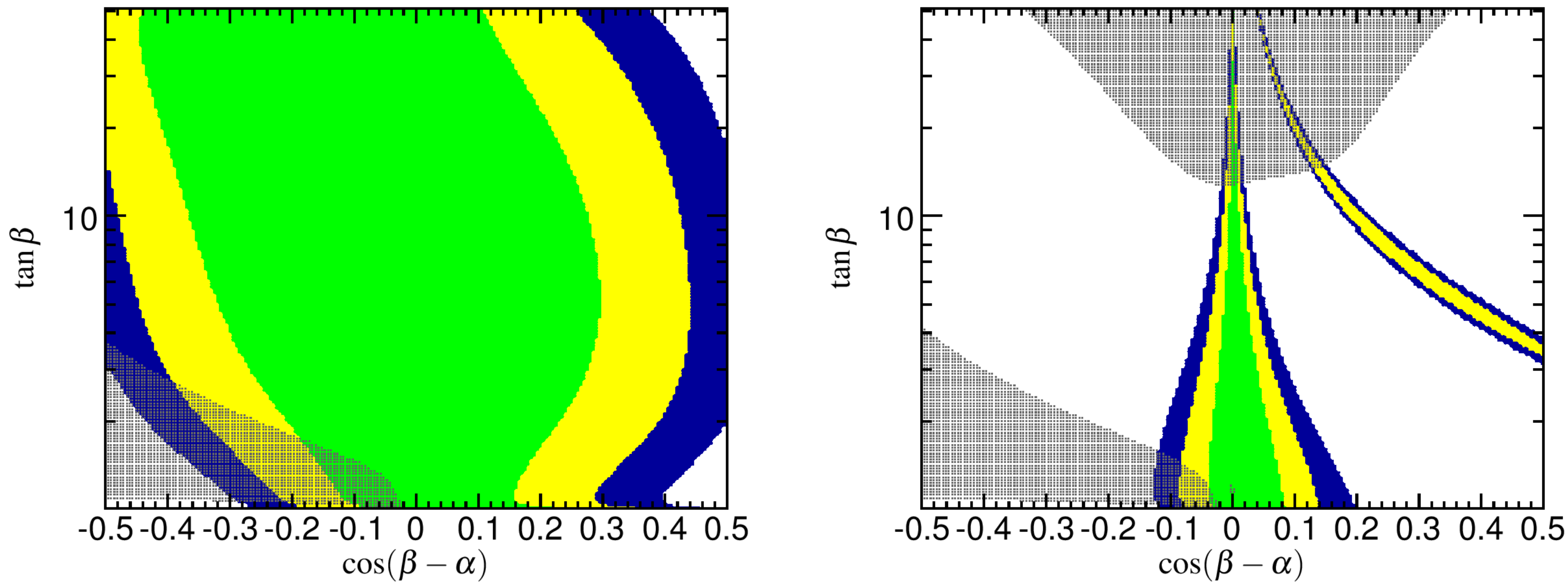
Higgs interaction	2HDM coupling	approach to alignment limit
hVV	$s_{\beta-\alpha}$	$1-\frac{1}{2}c^2_{\beta-\alpha}$
hhh	*	$1+2(Z_6/Z_1)c_{\beta-\alpha}$
hH^+H^-	*	$\frac{1}{3}\left[(Z_3/Z_1)+(Z_7/Z_1)c_{\beta-\alpha}\right]$
$hhhh$	*	$1+3(Z_6/Z_1)c_{\beta-\alpha}$
$h\overline{D}D$	$s_{\beta-\alpha}\mathbb{1}+c_{\beta-\alpha}\rho^D_R$	$\mathbb{1}+c_{\beta-\alpha}\rho^D_R$
$h\overline{U}U$	$s_{\beta-\alpha}\mathbb{1}+c_{\beta-\alpha}\rho^U_R$	$\mathbb{1}+c_{\beta-\alpha}\rho^U_R$

Type I and II 2HDM couplings of the SM-like Higgs boson h normalized to those of the SM Higgs boson, in the alignment limit. The hH^+H^- coupling given above is normalized to the SM hhh coupling. The scalar Higgs potential is taken to be CP-conserving. For the fermion couplings, D is a column vector of three down-type fermion fields (either down-type quarks or charged leptons) and U is a column vector of three up-type quark fields. In the third column, the first non-trivial correction to alignment is exhibited. Finally, complete expressions for the entries marked with a * can be found in H.E. Haber and D. O'Neil, Phys. Rev. D **74**, 015018 (2006) [Erratum: ibid. D **74** (2006) 059905].

$$\text{Type I}: \qquad \rho^D_R=\rho^U_R=\mathbb{1}\cot\beta\,,$$

$$\text{Type II}: \qquad \rho^D_R=-\mathbb{1}\tan\beta\,, \qquad \rho^U_R=\mathbb{1}\cot\beta\,.$$

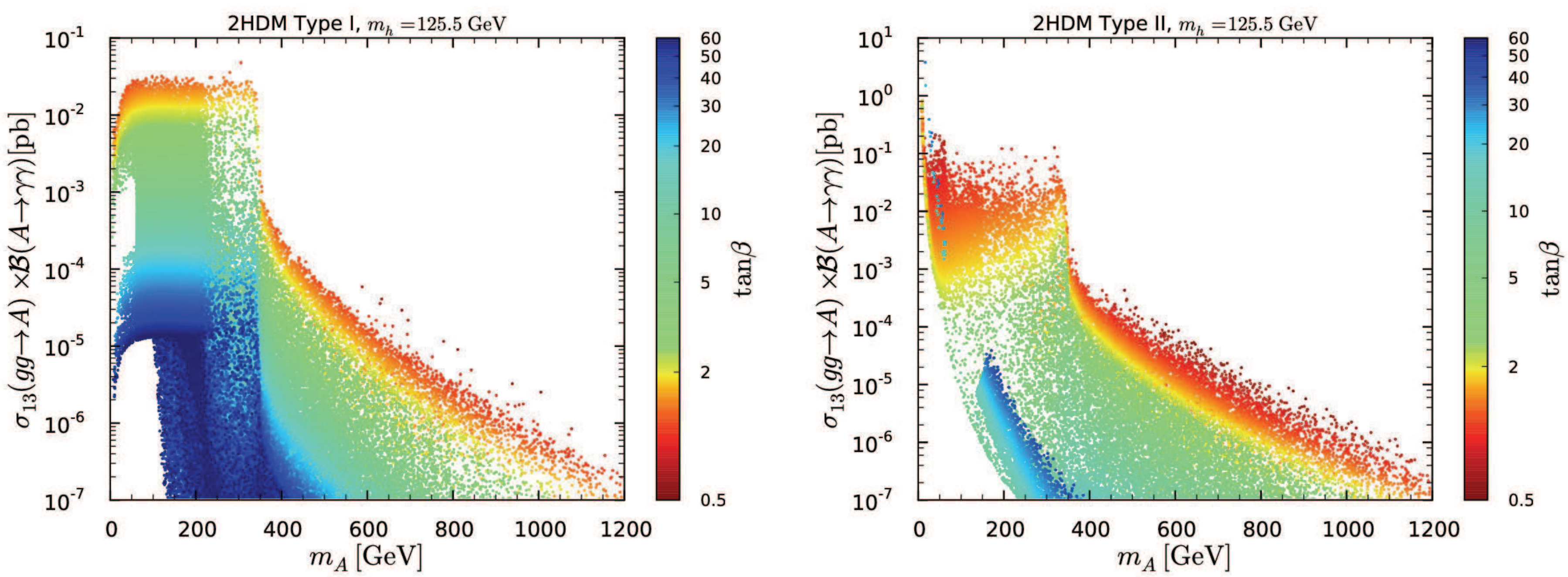
Constraints on Type-I and II 2HDMs from Higgs data



Direct constraints from LHC Higgs searches for Type-I (left) and Type-II (right) 2HDM with $m_H = 300$ GeV with $m_h = 125$ GeV, $Z_4 = Z_5 = -2$ and $Z_7 = 0$. Colors indicate compatibility with the observed Higgs signal at $1\,\sigma$ (green), $2\,\sigma$ (yellow) and $3\,\sigma$ (blue). Exclusion bounds at 95% C.L. from the non-observation of the additional Higgs states overlaid in gray. From H.E. Haber and O. Stål, Eur. Phys. J. C **75**, 491 (2015) [Erratum: ibid., **76**, 312 (2016)].

Projections for future LHC running

Sample results are shown below for the search for A in gg-fusion, scanned over Type-I and II 2HDM parameter spaces, assuming that $|\cos(\beta - \alpha)| \leq 0.14$ (which guarantees that the observed Higgs boson is SM-like).*



Cross sections times branching ratio in Type I (left panels) and in Type II (right panels) for $gg \to A \to \gamma\gamma$ at the 13 TeV LHC as functions of m_A with $\tan\beta$ color code.

*See J. Bernon, J.F. Gunion, H.E. Haber, Y. Jiang and S. Kraml, Phys. Rev. D **92**, 075004 (2015).

The alignment limit of the Higgs sector of the MSSM

The MSSM values of Z_1 and Z_6 (including the leading one-loop corrections):

$$Z_1 v^2 = m_Z^2 c_{2\beta}^2 + \frac{3v^2 s_\beta^4 h_t^4}{8\pi^2}\left[\ln\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12M_S^2}\right)\right],$$

$$Z_6 v^2 = -s_{2\beta}\left\{m_Z^2 c_{2\beta} - \frac{3v^2 s_\beta^2 h_t^4}{16\pi^2}\left[\ln\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t(X_t+Y_t)}{2M_S^2} - \frac{X_t^3 Y_t}{12M_S^4}\right]\right\}.$$

where $M_S^2 \equiv m_{\tilde{t}_1} m_{\tilde{t}_2}$, $X_t \equiv A_t - \mu\cot\beta$ and $Y_t = A_t + \mu\tan\beta$.

Note that $m_h^2 \leq Z_1 v^2$ is consistent with $m_h \simeq 125$ GeV for suitable choices for M_S and X_t. Exact alignment (i.e., $Z_6 = 0$) can now be achieved due to an accidental cancellation between tree-level and loop contributions,†

$$m_Z^2 c_{2\beta} = \frac{3v^2 s_\beta^2 h_t^4}{16\pi^2}\left[\ln\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t(X_t+Y_t)}{2M_S^2} - \frac{X_t^3 Y_t}{12M_S^4}\right].$$

†See M. Carena, H.E. Haber, I. Low, N.R. Shah and C.E.M. Wagner, Phys. Rev. D **91**, 035003 (2015).

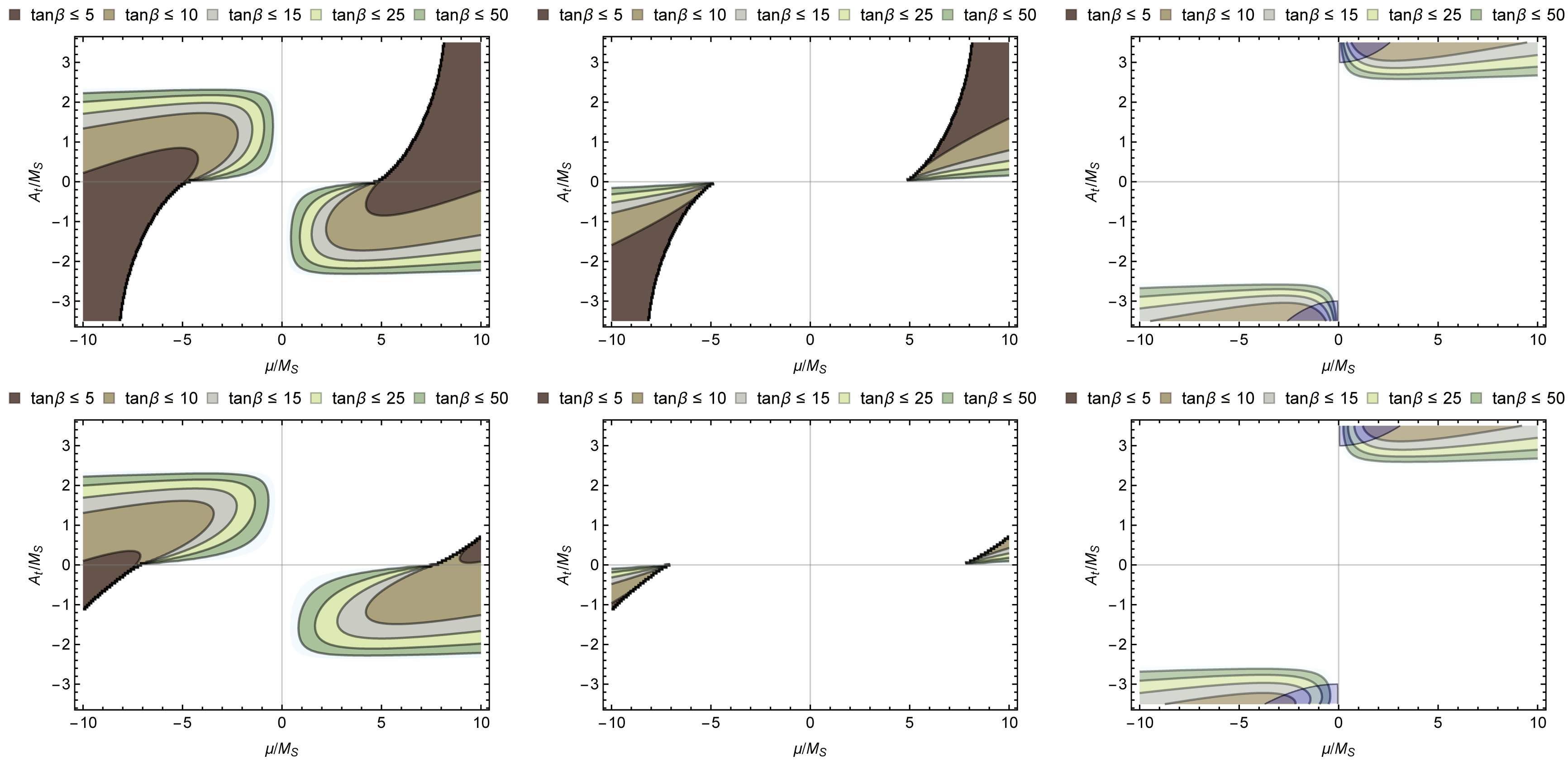
The alignment condition is then achieved by (numerically) solving a 7th order polynomial equation for $t_\beta \equiv \tan\beta$ (where $\widehat{A}_t \equiv A_t/M_S$ and $\widehat{\mu} \equiv \mu/M_S$),[‡]

$$M_Z^2 t_\beta^4(1-t_\beta^2) - Z_1 v^2 t_\beta^4(1+t_\beta^2) + \frac{3m_t^4\widehat{\mu}(\widehat{A}_t t_\beta - \widehat{\mu})(1+t_\beta^2)^2}{4\pi^2 v^2}\left[\tfrac{1}{6}(\widehat{A}_t t_\beta - \widehat{\mu})^2 - t_\beta^2\right] = 0\,.$$

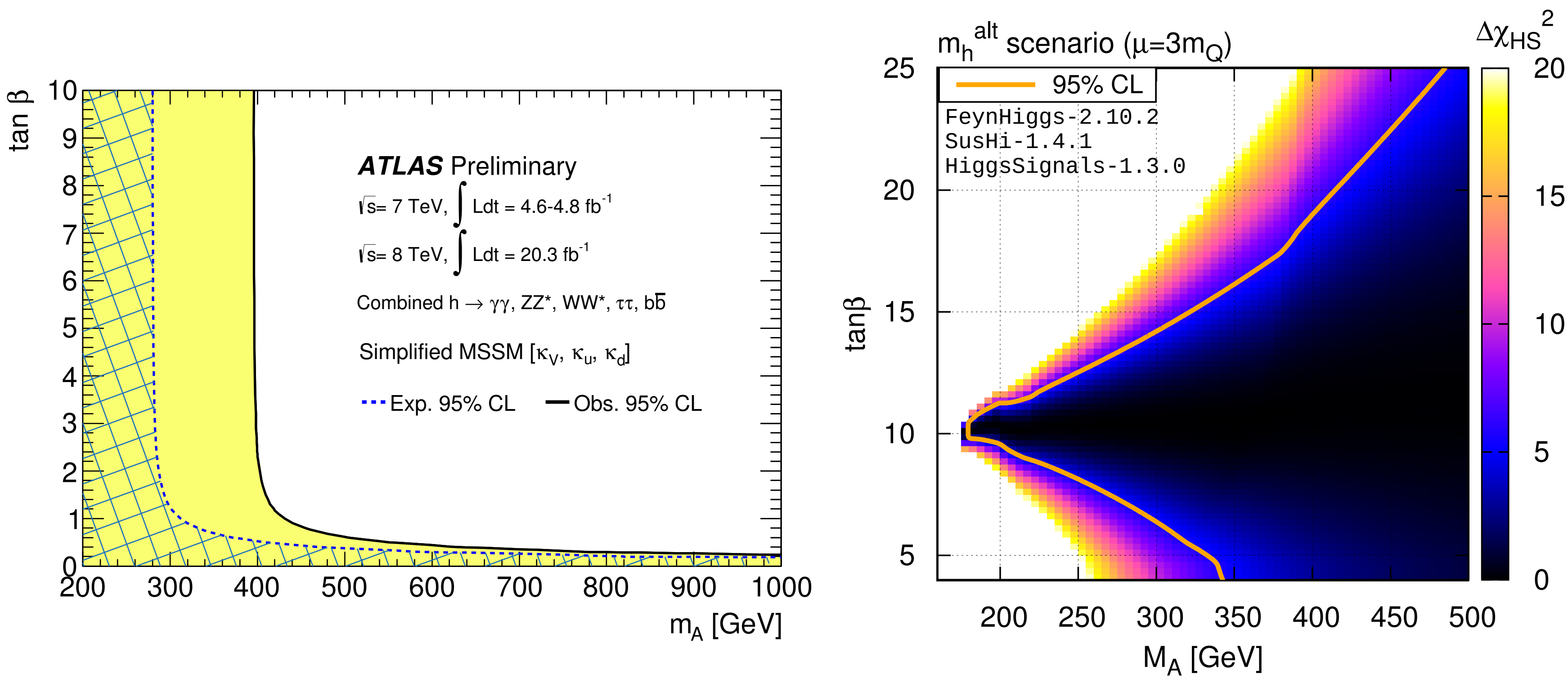
<u>*REMARK*</u>: Normally, we identify h as the SM-like Higgs boson. However, in the alignment limit there exist parameter regimes, corresponding to the case of $m_A^2 + (Z_5 - Z_1)v^2 < 0$ (where the radiatively corrected Z_1 and Z_5 are employed), in which H is the SM-like Higgs boson. In either case, $Z_1 v^2$ is the (approximate) squared mass of the SM-like Higgs boson.

Leading two-loop corrections of $\mathcal{O}(\alpha_s h_t^2)$ can be obtained from the leading one-loop corrected results by replacing m_t with $m_t(\lambda)$, where $\lambda \equiv \left[m_t(m_t)M_S\right]^{1/2}$ in the one-loop leading log pieces and $\lambda \equiv M_S$ in the leading threshold corrections. Imposing $Z_6 = 0$ now leads to a 11th order polynomial equation in t_β that can be solved numerically.

[‡] P. Bechtle, H.E. Haber, S. Heinemeyer, O. Stål, T. Stefaniak, G. Weiglein and L. Zeune, in preparation.



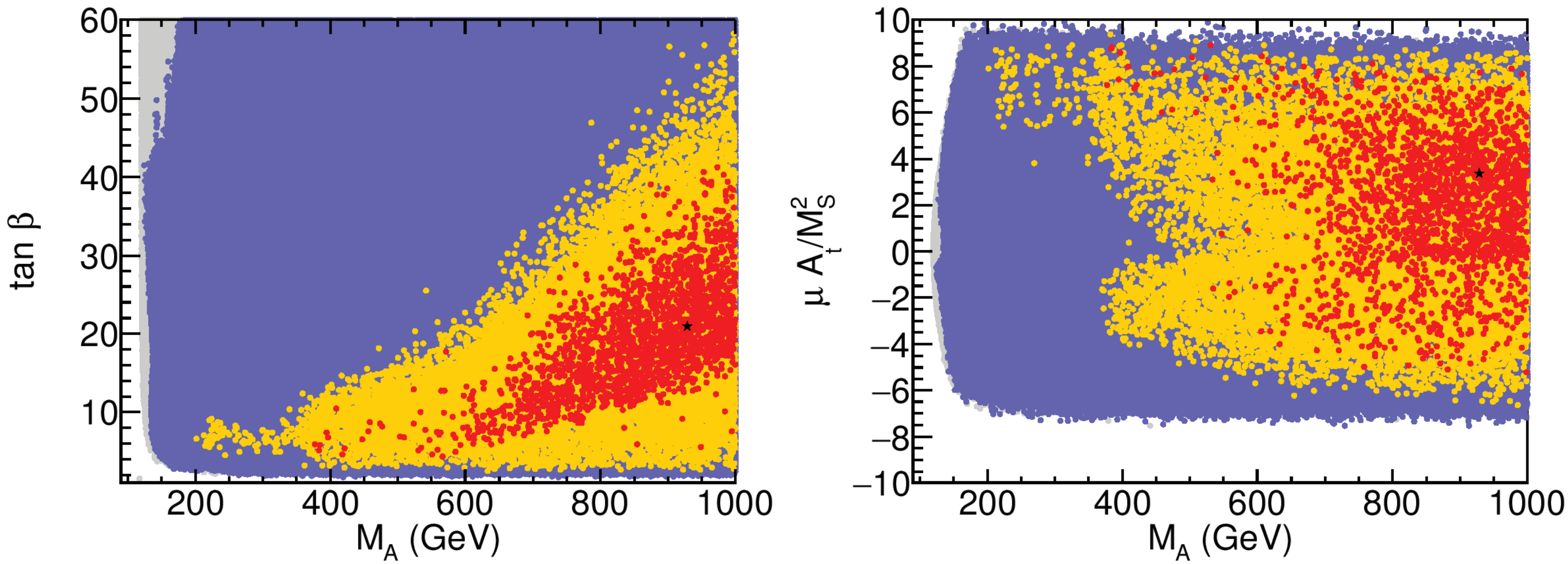
Contours of $\tan\beta$ corresponding to exact alignment, $Z_6 = 0$, in the $(\mu/M_S, A_t/M_S)$ plane. Z_1 is adjusted to give the correct Higgs mass. *Top*: Approximate one-loop result; *Bottom*: Two-loop improved result. Taking the top (bottom) three panels together, one can immediately discern the regions of zero, one, two and three values of $\tan\beta$ in which exact alignment is realized. In the overlaid blue regions we have (unstable) values of $|X_t/M_S| \geq 3$. (Taken from P. Bechtle, H.E. Haber, S. Heinemeyer, O. Stål, T. Stefaniak, G. Weiglein and L. Zeune, arXiv:1608.00638 [hep-ph].)



Left panel: Regions of the $(m_A, \tan\beta)$ plane excluded in a simplified MSSM model via fits to the measured rates of the production and decays of the SM-like Higgs boson h. Taken from ATLAS-CONF-2014-010.

Right panel: Likelihood distribution, $\Delta\chi^2_{\rm HS}$ obtained from testing the signal rates of h against a combination of Higgs rate measurements from the Tevatron and LHC experiments, obtained with `HiggsSignals`, in the alignment benchmark scenario of Carena et al. (op. cit.). From P. Bechtle, S. Heinemeyer, O. Stål, T. Stefaniak and G. Weiglein, EPJC **75**, 421 (2015).

Likelihood analysis: allowed regions in the $\tan\beta$–m_A plane



Preferred parameter regions in the $(M_A,\ \tan\beta)$ plane (left) and $(M_A,\ \mu A_t/M_S^2)$ plane (right), where $M_S^2 = m_{\tilde{t}_1} m_{\tilde{t}_2}$ and h is the SM-like Higgs boson, in a pMSSM-8 scan. Points that do not pass the direct constraints from Higgs searches from `HiggsBounds` and from LHC SUSY particle searches from `CheckMATE` are shown in gray. Applying a global likelihood analysis to the points that pass the direct constraints, the color code employed is red for $\Delta\chi_h^2 < 2.3$, yellow for $\Delta\chi_h^2 < 5.99$ and blue otherwise. The best fit point is indicated by a black star. (Taken from P. Bechtle, H.E. Haber, S. Heinemeyer, O. Stål, T. Stefaniak, G. Weiglein and L. Zeune, arXiv:1608.00638 [hep-ph].)

Conclusions

Pursuing Higgs physics into the future by theorists and experimentalists is likely to lead to profound insights into the fundamental theory of particles and their interactions.