Triplet Higgs Scenarios

Jack Gunion
U.C. Davis

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Higgs-like LHC Signal

- **Fits with MVA CMS suggest we are heading towards the SM, but it could simply be a "decoupling" limit of a more complicated model.**

- **Still, there are discrepancies between ATLAS and CMS that are reduced if CiC CMS is right — both ATLAS and CMS agree on enhanced $\gamma\gamma$ rate relative to SM.**

- **Further, both experiments have enhanced $\gamma\gamma$ rate in VBF.**

- **ZZ and WW rates are quite SM-like in CMS, but slightly enhanced in ATLAS data.**

- **ATLAS has a Higgs mass discrepancy between the ZZ and the $\gamma\gamma$ final**

state.

- **The big questions:**

  1. **If the deviations from a single SM Higgs survive what is the model?**
  2. **If they do survive, how far beyond the "standard" model must we go to describe them?**
  3. **If they don't survive, must it be the SM or the decoupling limit of an extended Higgs sector or could considerable complexity underlie an apparently SM-like signal?**
  4. **It seems that whether or not the signal appears to be a single SM-like Higgs boson, it could nonetheless come from several overlapping Higgs bosons.**

The Models

1. **2HDM**

   There are certainly parameter choices, especially in Type I model for which all signal strengths are SM-like despite being from both $h + A$, but also enhancements are possible.

2. **NMSSM**

   Same story: $h_1 + h_2$ can combine to give either SM-like net signal or enhancement relative to SM.

3. **Higgs-radion**

   The $\gamma\gamma$ and gg couplings of the radion are anomalous and this opens up non-2HDM situations when the Higgs and radion physical eigenstates are degenerate.

4. **Higgs-triplet**

   Is there a sensible version in which triplets actually play a significant role and yet one gets a fairly SM-like state?

Based on Higgs Triplets in the Standard Model (J.F. Gunion, R. Vega, and J. Wudka)

Triplets Introduction

- **It is well-known that models with only Higgs doublets (and, possibly, singlets) provide the most straightforward extensions of the SM that satisfy $\rho \approx 1$ and the absence of flavor-changing neutral currents.**

- **However, there are many more complicated possibilities.**

- **Conventional left-right symmetric models are often constructed using a Higgs sector containing several triplet representations.**

  In those models, it is necessary to assign a very small vacuum expectation value to the neutral member of the left-handed triplet in order to avoid unacceptable corrections to ρ at tree level.

- **However, it is certainly not necessary to go to left-right symmetric extensions of the SM in order to consider Higgs triplet fields.**

  Even within the context of the SM a Higgs sector with Higgs triplet as well as doublet fields can be considered.

  Large tree-level deviations of the electroweak ρ parameter from unity can be avoided by two means:

1. the neutral triplet fields can be given vacuum expectation values that are much smaller than those for the neutral doublet fields; or
2. the triplet fields and the vacuum expectation values of their neutral members can be arranged so that a custodial $SU(2)$ symmetry is maintained at tree level.
   It is this latter type of model that we consider here.

By custodial $SU(2)$ at the tree level we mean simply that the hypercharges Y and vacuum expectation values V of all the Higgs multiplets are chosen so that $\rho = 1$ is maintained.

One might hope that a model could be constructed that maintains a custodial $SU(2)$ when loop corrections are included.

However, there are always one-loop corrections associated with interactions of the Z that violate custodial symmetry and, in fact, ρ always receives infinite corrections and simply becomes an input parameter in the renormalization process.

Equivalently, m_W and m_Z are separately renormalized and must both be treated as inputs/measurables in the renormalization process.

A number of models of type 2, with a custodial $SU(2)$ symmetry at tree level, have been proposed in the literature.

In particular, we focus on the model constructed by Georgi and Machacek (GM).

This model was considered in greater depth by Chanowitz and Golden (CG), who showed that a Higgs potential for the model could be constructed in such a way that it preserves the tree-level custodial $SU(2)$ symmetry.

This has the implication that the custodial $SU(2)$ is maintained after higher-order loop corrections from Higgs self-interactions.

But, there is no way of avoiding the infinite ρ renormalization associated with the electroweak radiative corrections.

Nontheless, the GM model provides an attractive example of an extension of the SM Higgs sector which contains Higgs triplets but no other new physics.

We shall examine it with regard to the signatures and production mechanisms for the various Higgs bosons.

Basic Features and Couplings of the Higgs Bosons

- **In the GM model, the Higgs fields take the form**

$$\phi = \begin{pmatrix} \phi^{0*} & \phi^+ \\ \phi^- & \phi^0 \end{pmatrix} \quad \chi = \begin{pmatrix} \chi^0 & \xi^+ & \chi^{++} \\ \chi^- & \xi^0 & \chi^+ \\ \chi^{--} & \xi^- & \chi^{0\,*} \end{pmatrix}, \tag{1}$$

i.e. **one $Y = 1$ complex doublet, one real ($Y = 0$) triplet, and one $Y = 2$ complex triplet. We shall choose phase conventions for the fields such that $\phi^- = -(\phi^+)^*$, $\chi^{--} = (\chi^{++})^*$, $\chi^- = -(\chi^+)^*$, $\xi^- = -(\xi^+)^*$, and $\xi^0 = (\xi^0)^*$.**

- **At tree-level, the masses of the gauge bosons are determined by the kinetic energy terms of the Higgs Lagrangian, which take the form:**

$$\mathcal{L}_{kin} = \frac{1}{2}\mathrm{Tr}\left[(D_\mu\phi)^\dagger(D_\mu\phi)\right] + \frac{1}{2}\mathrm{Tr}\left[(D_\mu\chi)^\dagger(D_\mu\chi)\right]. \tag{2}$$

Here, $D_\mu\phi \equiv \partial_\mu\phi + ig\vec{W}\cdot\frac{\vec{\tau}}{2}\phi - ig'\phi B\frac{\tau_3}{2}$ and $D_\mu\chi \equiv \partial_\mu\chi + ig\vec{W}\cdot\vec{t}\chi - ig'\chi B t_3$, where the $\tau_i/2$ are the usual 2×2 representation matrices

of $SU(2)$ and the t_i are the 3×3 representation matrices for $SU(2)$ appropriate to the χ representation we have chosen:

$$t_1 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix} \quad t_2 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & -i & 0 \\ i & 0 & -i \\ 0 & i & 0 \end{pmatrix} \quad t_3 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -1 \end{pmatrix}. \tag{3}$$

- It is useful to consider the transformation of the ϕ and χ fields under $SU(2)_L \times SU(2)_R$,

$$\phi \to U_L \phi U_R^\dagger \qquad \chi \to U_L \chi U_R^\dagger, \tag{4}$$

where $U_{L,R} = \exp(-i\theta_{L,R}\hat{n}_{L,R} \cdot \vec{T}_{L,R})$, and the $\vec{T}_{L,R}$ generators are represented as specified above.

- The $SU(2)_L$ and $U(1)$ invariances of the Standard Model are to be associated with $\vec{T}_L$ and T_R^3 respectively.

  In particular, note that the $U(1)$ hypercharge associated with the B field is represented by right multiplication by the appropriate T_R^3 matrix (so that $Q = T_L^3 + T_R^3$).

- **The full $SU(2)_R$ group will be associated with the custodial symmetry required to have $\rho = 1$.**

  In particular, tree-level invariance for the gauge boson mass terms under the custodial $SU(2)_R$ is arranged by giving the χ^0 and ξ^0 the same vacuum expectation value.

  (However, since the hypercharge interaction with the B field breaks the custodial $SU(2)_R$, there are potentially infinite contributions to $\rho - 1$ at one-loop. We shall return to this issue later.)

- **We define $\langle\chi^0\rangle = \langle\xi^0\rangle = b$, and also take $\langle\phi^0\rangle = a/\sqrt{2}$. It will be convenient to use the notation:**

$$v^2 \equiv a^2 + 8b^2, \quad c_H \equiv \frac{a}{\sqrt{a^2+8b^2}}, \quad s_H \equiv \sqrt{\frac{8b^2}{a^2+8b^2}}, \tag{5}$$

where c_H and s_H are the cosine and sine of a doublet-triplet mixing angle.

We will also employ the subsidiary fields:

$$\begin{aligned} \phi^0 &\equiv \sqrt{\tfrac{1}{2}}(\phi^{0r} + i\phi^{0i}), \qquad \chi^0 \equiv \sqrt{\tfrac{1}{2}}(\chi^{0r} + i\chi^{0i}), \\ \psi^\pm &\equiv \sqrt{\tfrac{1}{2}}(\chi^\pm + \xi^\pm), \qquad \zeta^\pm \equiv \sqrt{\tfrac{1}{2}}(\chi^\pm - \xi^\pm), \end{aligned} \tag{6}$$

for the complex neutral and charged fields, respectively.

- The $W^\pm$ and Z are given mass by absorbing the Goldstone bosons

$$G_3^\pm = c_H\phi^\pm + s_H\psi^\pm, \qquad G_3^0 = i(-c_H\phi^{0i} + s_H\chi^{0i}). \tag{7}$$

- The gauge boson masses so obtained are:

$$m_W^2 = m_Z^2\cos^2\theta_W = \tfrac{1}{4}g^2v^2. \tag{8}$$

- The remaining physical states can be classified according to their transformation properties under the custodial $SU(2)$.

  One finds a five-plet $H_5^{++,+,0,-,--}$, a three-plet $H_3^{+,0,-}$ and two singlets, H_1^0 and $H_1^{0\prime}$.

  The compositions of the H states are:

$$\begin{aligned} H_5^{++} &= \chi^{++} \\ H_5^{+} &= \zeta^{+} \\ H_5^{0} &= \frac{1}{\sqrt{6}}(2\xi^0 - \sqrt{2}\chi^{0r}) \end{aligned}$$

$$
\begin{aligned}
H_3^+ = &\quad c_H\psi^+ - s_H\phi^+ \\
H_3^0 = &\quad i(c_H\chi^{0i} + s_H\phi^{0i}) \\
H_1^0 = &\quad \phi^{0r} \\
H_1^{0\prime} = &\quad \frac{1}{\sqrt{3}}(\sqrt{2}\chi^{0r} + \xi^0).
\end{aligned}
\tag{9}
$$

(According to our phase conventions, $H_5^{--} = (H_5^{++})^*$, $H_5^- = -(H_5^+)^*$, $H_3^- = -(H_3^+)^*$, and $H_3^0 = -(H_3^0)^*$.)

- However, not all these states need be mass eigenstates.

  Only the doubly-charged $H_5^{++,--}$ and, for appropriately chosen phases, the H_3^0 cannot mix.

  In general, the remaining neutral Higgs can mix with one another, as can the singly-charged Higgs, depending upon the precise structure of the Higgs potential.

  The masses and compositions of the mass eigenstates are determined by the quartic interactions among the Higgs fields ϕ and χ.

  However, as we have already mentioned, it is desirable to choose the Higgs potential in such a way that it preserves the custodial $SU(2)$ symmetry.

  In this case, the 5-plet and 3-plet states cannot mix with one another or with the singlets;

the only possible mixing is between H_1^0 and $H_1^{0\,\prime}$.

This latter mixing depends upon the parameters of the Higgs potential, and can range from zero to maximal.

For the moment, we shall adopt the language of zero mixing.

Thus, we shall give results for couplings using the fields defined in Eq. (9).

- From the Higgs boson couplings to fermions and vector bosons we can determine the basic phenomenological features of the Higgs sector of the model.

- Regarding the fermion couplings, there are two possible types.
  1. First, there are the standard Yukawa couplings of the doublet Higgs field to fermion-antifermion channels
  2. The only other possible couplings are ones closely analogous to those required in order to produce a "see-saw" mechanism for generating neutrino masses in left-right symmetric models; namely, couplings of the triplet Higgs fields (with $Y = 2$) to the lepton-lepton channels.
     Such couplings lead to Majorana masses for the neutrinos and there are strong limits, as a result of which these couplings have no phenomenological impact on the LHC Higgs physics.

- Returning to the standard doublet fermion-antifermion interactions, we see that all tree-level Higgs boson couplings to fermion-antifermion channels are determined by the overlap of the mass eigenstate Higgs fields with the doublet field.

One finds that the $H_5^{++,--}$, $H_5^{+,-}$, H_5^0, and $H_1^{0\prime}$ states have no such overlap, and that only the $H_3^{+,-}$, H_3^0 and H_1^0 will have tree-level fermion-antifermion couplings.

The Feynman rules for the various couplings are given below (to be multiplied by an overall factor of i):

$$\begin{aligned} g_{H_1^0 q\bar{q}} &= -\frac{g m_q}{2 m_W c_H} \quad (q = t, b), \\ g_{H_3^0 t\bar{t}} &= +\frac{g m_t s_H}{2 m_W c_H}\gamma_5, \\ g_{H_3^0 b\bar{b}} &= -\frac{g m_b s_H}{2 m_W c_H}\gamma_5, \\ g_{H_3^- t\bar{b}} &= \frac{g s_H}{2\sqrt{2} m_W c_H}\Big[m_t(1+\gamma_5) - m_b(1-\gamma_5)\Big], \end{aligned} \tag{10}$$

where third-generation notation is employed for the quarks.

Analogous expressions hold for the couplings to leptons.

- It is possible that $b \gtrsim a$, so that most of the mass of the W and Z comes from the triplet vacuum expectation values.

In this case, the doublet vacuum expectation value $a/\sqrt{2}$ is much smaller than in the SM, and the Yukawa couplings of the doublet to the fermions must be much larger than in the SM in order to obtain the experimentally determined quark masses.

Then, the Higgs bosons that do couple to fermions have much larger fermion-antifermion pair couplings and decay widths than in the SM.

- Most interesting, however, are the couplings to vector bosons. The Feynman rules for these are specified for the states of Eq. (9) as follows (we drop an overall factor of $ig_{\mu\nu}$):

$$\begin{aligned}
H_5^{++}W^-W^- : &\quad \sqrt{2}gm_W s_H \\
H_5^{+}W^-Z : &\quad -gm_W s_H/c_W \\
H_5^{+}W^-\gamma : &\quad 0 \\
H_5^{0}W^-W^+ : &\quad (1/\sqrt{3})gm_W s_H \\
H_5^{0}ZZ : &\quad -(2/\sqrt{3})gm_W s_H c_W^{-2} \\
H_1^{0}W^-W^+ : &\quad gm_W c_H \\
H_1^{0}ZZ : &\quad gm_W c_H c_W^{-2} \\
H_1^{0\prime}W^-W^+ : &\quad (2\sqrt{2}/\sqrt{3})gm_W s_H \\
H_1^{0\prime}ZZ : &\quad (2\sqrt{2}/\sqrt{3})gm_W s_H c_W^{-2}
\end{aligned} \tag{11}$$

where s_W and c_W are the sine and cosine of the standard electroweak angle, respectively.

Several features of these couplings should be noted.

1. First, there are no couplings of the H_3 Higgs multiplet members to vector bosons.
2. Second, we observe that the SM is regained in the limit where $s_H \to 0$, in which case the H_1^0 plays the role of the SM Higgs and has SM couplings, not only to VV channels as seen in Eq. (11), but also to $f\bar{f}$ channels, Eq. (10).

   However, in this model with custodial $SU(2)$ symmetry, there is no intrinsic need for s_H to be small.
3. A third important observation is that when $s_H \neq 0$ there is a non-zero $H_5^+ W^- Z$ coupling, in contrast to the absence of such a coupling of the charged Higgs in any model containing only Higgs doublets (and singlets).

   In fact, one can demonstrate that any model containing triplet or higher Higgs representations with a neutral field member that has a non-zero vacuum expectation value, and that simultaneously yields $\rho = 1$ at tree-level, must have at least one charged Higgs with non-zero coupling to the WZ channel.
4. Finally, we emphasize the remarkable dichotomy between the H_5 and the H_3 multiplets:

   ignoring for the moment the HV and HH type channels, at tree level the former couple and decay only to vector boson pairs, while the latter couple and decay only to fermion-antifermion pairs.

- Let us now turn to the potential for the Higgs sector. It is the most general form of the Higgs sector potential subject to the requirements that it preserve the custodial $SU(2)$ and that it be invariant under $\chi \to -\chi$. The latter requirement is imposed for the sake of simplicity, in order to eliminate cubic terms in the potential, but we believe that it does not significantly alter the phenomenology of the model. In our notation the potential is written as:

$$\begin{aligned} V_{Higgs} = \quad & \lambda_1(\mathrm{Tr}\phi^\dagger\phi - c_H^2 v^2)^2 + \lambda_2(\mathrm{Tr}\chi^\dagger\chi - \tfrac{3}{8}s_H^2 v^2)^2 \\ + \quad & \lambda_3(\mathrm{Tr}\phi^\dagger\phi - c_H^2 v^2 + \mathrm{Tr}\chi^\dagger\chi - \tfrac{3}{8}s_H^2 v^2)^2 \\ + \quad & \lambda_4(\mathrm{Tr}\phi^\dagger\phi\mathrm{Tr}\chi^\dagger\chi - 2\sum_{ij}\mathrm{Tr}[\phi^\dagger\tau_i\phi\tau_j]\mathrm{Tr}[\chi^\dagger t_i\chi t_j]) \\ + \quad & \lambda_5(3\mathrm{Tr}[\chi^\dagger\chi\chi^\dagger\chi] - [\mathrm{Tr}\chi^\dagger\chi]^2)\,, \end{aligned} \tag{12}$$

where the ϕ and χ fields were defined in Eq. (1), the τ_i are the usual Pauli matrices, and the t_i are the $SU(2)$ triplet representation matrices. From this potential we obtain the Higgs boson masses and couplings.

As stated earlier, all members of the 5-plet have the same mass as do all members of the 3-plet. These masses are:

$$m^2_{H_5} = 3(\lambda_5 s^2_H + \lambda_4 c^2_H)v^2, \quad m^2_{H_3} = \lambda_4 v^2. \tag{13}$$

In general, the H^0_1 and $H^{0\,\prime}_1$ can mix according to the mass-squared matrix:

$$\mathcal{M}^2_{H^0_1, H^{0\,\prime}_1} = \begin{pmatrix} 8c^2_H(\lambda_1+\lambda_3) & 2\sqrt{6}s_H c_H \lambda_3 \\ 2\sqrt{6}s_H c_H \lambda_3 & 3s^2_H(\lambda_2+\lambda_3) \end{pmatrix} v^2 \,. \tag{14}$$

Clearly, the mixing between H^0_1 and $H^{0\,\prime}_1$ vanishes in the limit of $\lambda_3 \to 0$. In this limit, there are only four Higgs potential parameters and the four independent Higgs boson masses can be used to determine them uniquely. More generally, specifying the masses of the four Higgs boson mass eigenstates leaves one undetermined parameter in the potential.

From the above results for the Higgs boson masses, we see that if all the λ_i are similar in magnitude and $s_H \to 0$ (implying that the doublet field is primarily responsible for the W and Z masses), then the lightest Higgs boson is predominantly composed of $H^{0\,\prime}_1$, *a mixture of triplet fields*.

In the other extreme, $c_H \to 0$ (implying that the triplet fields are responsible for giving the W and Z their mass) and the lightest Higgs boson is predominantly H^0_1, *the real part of the neutral doublet field*.

This is clearly an amusing systematic structure, in that the lightest Higgs boson is always the one that has the least to do with the symmetry breaking mechanism.

Therefore, unitarity requirements for the VV scattering processes and precision electroweak constraints impose significant constraints upon the heavier of the two.

In other words, the H_1^0 and $H_1^{0\,\prime}$ are likely to be light enough to be interesting for the 126 GeV LHC signal. and they can mix if $\lambda_3 \neq 0$.

LHC data?

- The only way to get a single Higgs that couples to both $q\bar{q}$ and VV is to have the H_1^0 as part of the actual eigenstate, which I denote by H.

- But, $H_1^0 - H_1^{0\prime}$ mixing is also a possibility, just not pure $H_1^{0\prime}$.

- The mass matrix allows anything so let's just take a mixture of

$$H = \cos\alpha H_1^0 + \sin\alpha H_1^{0\prime}. \tag{15}$$

  Then, the couplings of the H relative to the SM are:

$$C_q = Hq\bar{q} = \frac{\cos\alpha}{c_H}, \qquad C_V = HVV = c_H\cos\alpha + \frac{2\sqrt{2}}{\sqrt{3}} s_H \sin\alpha\,. \tag{16}$$

- Note that if we require $C_q = 1$ then $\cos\alpha = c_H$.

  If we plug this into C_V we find $c_H^2 = 1$ is required if we demand $C_V = 1$.

  (There are, however, some $\pm$ signs that could arise.)

- **An interesting question is what is the situation if C_V or C_q or both deviated from unity.**

- **some plots appear below.**

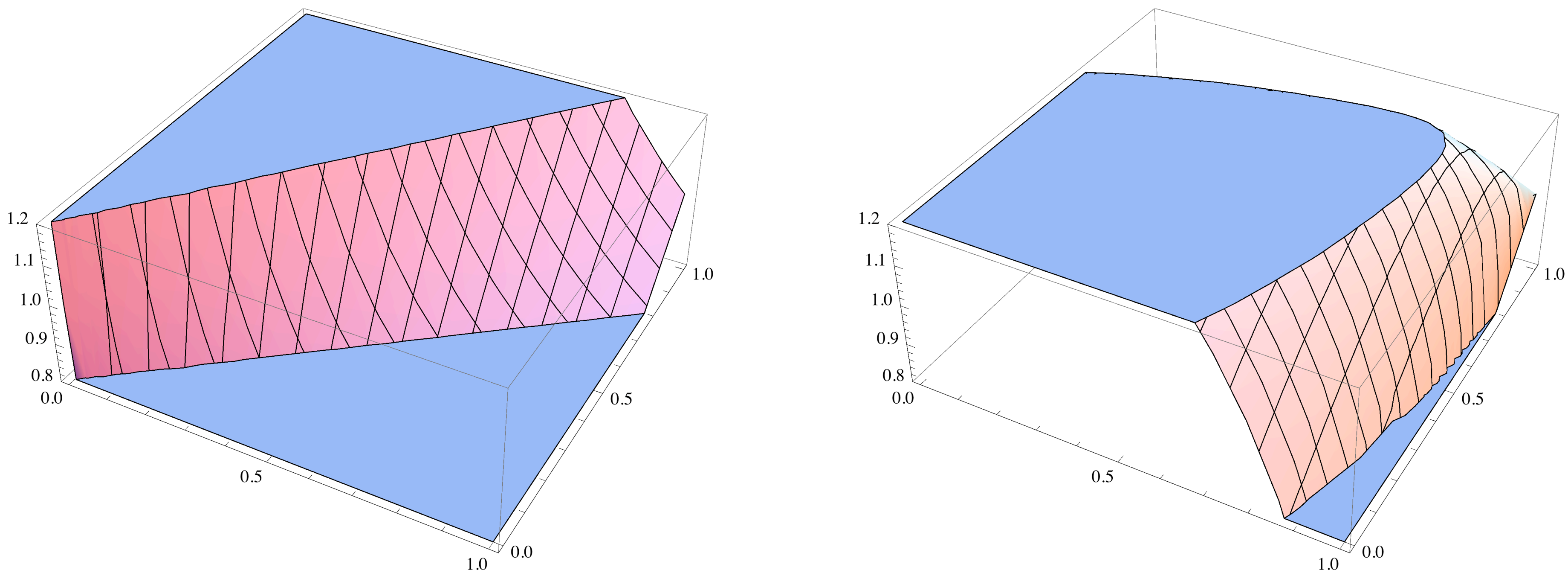

Figure 1: We plot C_q (left) and C_V (right) in the plane of $\cos\alpha$ (left axis) and c_H (right axis). Note SM limit when $c_H \to 1$ for which $\cos\alpha \to 1$ also.

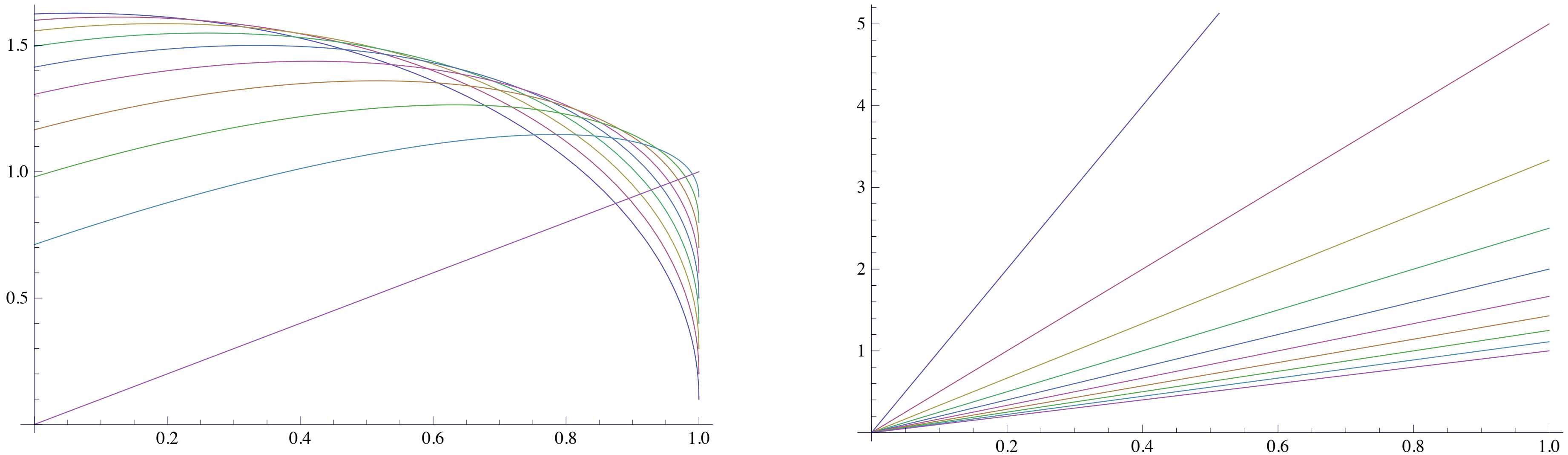

Figure 2: **We plot C_V (left) and C_q (right) as a function of $\cos\alpha$ for fixed values of $c_H = 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0$.**