Structure of the scalar sector

SM established as (an EFT) at least until the electroweak scale, but...
- Shape of the Higgs potential is still unknown! → only v and m₀ are known currently.
- No particular reason for the Higgs sector to be minimal, and many BSMS models predict additional scalars.
- One observable that can help find evidence for BSM is \( \delta \).

We show here some examples of results for \( \delta \):

- Two loops: Complete one-loop calculation available for 2HDMs, HSM, IDM, Structure of the scalar sector

Two-Higgs-Doublet Model (2HDM)

- Scalar potential of the CP-conserving 2HDM, with softly broken Z₂ symmetry

\[
V_{2HDM} = m_1^2|\Phi_1|^2 + m_2^2|\Phi_2|^2 - m_1^2|\Phi_1|^2 + \frac{\lambda_1}{2}|\Phi_1|^4 + \frac{\lambda_2}{2}|\Phi_2|^4 + \frac{\lambda_3}{2}|\Phi_1|^2|\Phi_2|^2 + \frac{\lambda_4}{2}|\Phi_1|^2|\Phi_1|^2 + \frac{\lambda_5}{2}|\Phi_2|^2|\Phi_2|^2 + \frac{\lambda_6}{2}|\Phi_1|^2|\Phi_2|^2
\]

Expand Higgs doublets as

\[
\Phi_i = \left( \begin{array}{c} \phi_i^0 \cr \phi_i^+ \end{array} \right) \text{ where } \left( \begin{array}{c} \phi_i^0 \\
\phi_i^+ \end{array} \right) = \left( \begin{array}{cc} c_i & -s_i \\
s_i & c_i \end{array} \right) \left( \begin{array}{c} \phi_i^0 \\
\phi_i^+ \end{array} \right)
\]

- Lagrangian mass parameters \( m_i^2 \), \( m_{ij} \) eliminated via tadpole equations (at each order in perturbation theory), and \( m_i^2 \) replaced by \( M^2 \equiv 2m_i^2/\sin 2\beta \) (soft breaking scale).
- Relate quartic couplings \( \lambda_i \) to mass parameters \( m_i, m_{ij}, m_{ik}, m_{jk} \) and CP-even mixing angle \( \alpha \) at tree-level as

\[
\lambda_i = -\frac{s_i^2 m_i^2 + s_i^2 m_j^2 + s_i^2 m_k^2}{v^2 s_i^2} + \frac{c_i^2 m_i^2}{v^2 c_i^2} + \frac{c_i^2 m_j^2}{v^2 c_i^2} + \frac{c_i^2 m_k^2}{v^2 c_i^2} + \lambda_i \frac{1}{v^2} \left[ -M^2 + 2m_i^2 + s_i^2 (m_{ij}^2 - m_i^2) \right]^{\frac{3}{2}}, \lambda_{ij} \lambda_{jk} \lambda_{ki} \frac{M^2 - m_i^2}{v^2}
\]

Additional (heavy) scalar masses can be written as \( m_i^2 = M^2 + \lambda_i v^2 \), where \( \lambda_i \) is some combination of the quartic couplings \( \lambda_i \).

What happens to the non-decoupling effects at two loops?

One loop

- Radiative corrections to \( \lambda_{HHH} \) in 2HDM first studied in [Kanemura, Kiyouno, Okada, Senaha, Yuan ‘92] and [Kanemura, Okada, Senaha, Yuan ‘94].
- Leading one-loop contributions (with \( n_{A,H} = 1, n_{A,H} = 2 \))

\[
\delta(\lambda_{HHH}) = -\frac{4\pi m_0}{16\pi^2} \sum_{H=H,H}= H m_0 \left( -M^2 \right) \phi_{H,A,H}^2
\]

- For small \( m_0 \) and large \( M \), the BSM corrections can become very large – \( \mathcal{O}(100\%) \) – without spoiling perturbativity → non-decoupling effects → can make EWPT become strongly 1st order.
- Complete one-loop calculation available for 2HDMs, HSM, IDM in \( \mathcal{O}(\alpha) \) [Kanemura, Kikuchi, Sakurai, Yagi ‘17].

Existing one-loop (and two-loop) works

<table>
<thead>
<tr>
<th>Scenario</th>
<th>( m_H ) (GeV)</th>
<th>( \delta ) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-loop</td>
<td>100</td>
<td>0.00</td>
</tr>
<tr>
<td>2-loops</td>
<td>100</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Our two-loop calculation: setup

- 2HDM with alignment, i.e. \( \alpha = \beta = \pi/2 \) → no mixing between \( H, A \).
- Effective potential approximation

\[
\delta(\lambda_{HHH}) = \left( \sum_{H=H,H}= H \right) \left( \frac{1}{16\pi^2} \right) \left( \frac{\partial^2 V}{\partial H^2} \right)
\]

- Leading contributions from heavy scalars and top quark
- \( \mathcal{O}(\alpha) \) and on-shell scheme calculations

Our two-loop calculation: preliminary results

We show here some examples of results for \( \delta = \Delta \lambda_{HHH}/\Delta \lambda_{HHH} = \Delta \lambda_{HHH}/\Delta \lambda_{HHH} = 1 \) in the OS scheme.