# **Midterm talk**: CP-odd Higgs at 95 GeV in the 2HDMS

Ayla Tutuș

**Supervisors:** Prof. Gudrid Moortgat-Pick, Prof. Sven Heinemeyer

**In collaboration with:** Daniel Schieber, Cheng Li

University of Hamburg
II. Institute for Theoretical Physics

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# Motivation

- The Standard Model (SM) Higgs sector is incomplete!
- Possible extensions: Two-Higgs-Doublet Models (2HDM), specifically Type-II
- In the singlet extension of the 2HDM, the 2HDMS, a **CP-odd scalar $\mathbf{A_{95}}$** can arise!
- Model can potentially acommodate the observed excess at $\sim$ 95 GeV (ATLAS, CMS)
- **Goal:** Test if 2HDMS Type II can accomodate that excess and if so, study production channels of such an $A_{95}$ in $e^+e^-$ collisions at the ILC and future colliders

# 2HDMS (Singlet extension)

- Model: two Higgs doublets $\Phi_1$, $\Phi_2$ and one **complex** singlet $S$
- Symmetries:
  - $\mathbb{Z}_2$: $\Phi_1 \to \Phi_1$, $\Phi_2 \to -\Phi_2$ (suppresses FCNCs)
  - $\mathbb{Z}_3$: $\Phi_1 \to \Phi_1$, $\Phi_2 \to e^{2\pi i/3}\Phi_2$, $S \to e^{-2\pi i/3}S$

    (restricts singlet interactions and allows trilinear terms)
- Physical Higgs states:
  - CP-even: $h_1$, $h_2$, $h_3$

    $\to$ One of these (typically $m \sim 125$ GeV) is SM-like
  - CP-odd: $a_1$, $a_2$ (light $= A_{95}$)
  - Charged: $H^\pm$
- Fields:
  - $\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{1}{\sqrt{2}}(v_1 + \rho_1 + i\eta_1) \end{pmatrix}$
  - $\Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{1}{\sqrt{2}}(v_2 + \rho_2 + i\eta_2) \end{pmatrix}$
  - $S = \frac{1}{\sqrt{2}}(v_S + \rho_S + i\eta_S)$
  - Electroweak constraint: $v_1^2 + v_2^2 = v^2 = (246.22\ \text{GeV})^2$

# 2HDMS (Singlet extension)

- Key parameters:
  - $\tan\beta = v_2/v_1, \quad v_S$
  - **CP-even mixing angles:** $\alpha_1$, $\alpha_2$, $\alpha_3$ (parametrize mixing matrix $R$); the CP-even mass eigenstates are related to the gauge eigenstates via:

$$(h_1, h_2, h_3)^T = R(\alpha_1, \alpha_2, \alpha_3) \cdot (\rho_1, \rho_2, s)^T$$

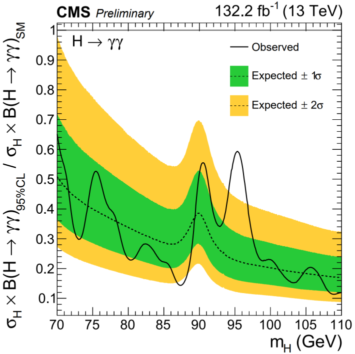
$$R = \begin{pmatrix} c_{\alpha_1} c_{\alpha_2} & s_{\alpha_1} c_{\alpha_2} & s_{\alpha_2} \\ -(c_{\alpha_1} s_{\alpha_2} s_{\alpha_3} + s_{\alpha_1} c_{\alpha_3}) & c_{\alpha_1} c_{\alpha_3} - s_{\alpha_1} s_{\alpha_2} s_{\alpha_3} & c_{\alpha_2} s_{\alpha_3} \\ -(c_{\alpha_1} s_{\alpha_2} c_{\alpha_3} - s_{\alpha_1} s_{\alpha_3}) & -(c_{\alpha_1} s_{\alpha_3} + s_{\alpha_1} s_{\alpha_2} c_{\alpha_3}) & c_{\alpha_2} c_{\alpha_3} \end{pmatrix}$$

  where $c_{\alpha_i} = \cos\alpha_i$, $s_{\alpha_i} = \sin\alpha_i$

- **CP-odd mixing angle:** $\alpha_4$ (controls doublet–singlet mixing of CP-odd states)
- physical Higgs masses:
  - fixed:$m_{h_2} = 125$ GeV (SM-like), $m_{a_1} = 95$ GeV (light $A_{95}$) $m_{a_2}$, $m_{H_\pm}$

# The 95 GeV excess

- Experimental hints for an additional Higgs-like scalar around 95 GeV:
  - CMS/ATLAS (Run II): di-photon channel ($\gamma\gamma$), local excess near 95 GeV
  - LEP: excess in $b\bar{b}$ final state around 96 GeV
- Only the CMS/ATLAS $\gamma\gamma$ excess is considered in this analysis
  - CMS: $\mu_{\gamma\gamma}^{\text{CMS}} = 0.33^{+0.19}_{-0.12}$ (local significance: $\sim 3.1\sigma$)
  - ATLAS: $\mu_{\gamma\gamma}^{\text{ATLAS}} = 0.23^{+0.17}_{-0.16}$ (l.s.: $\sim 2.2\sigma$)
  - Combined: $\mu_{\gamma\gamma}^{\text{combined}} = 0.24^{+0.09}_{-0.08}$ (l.s.: $\sim 3.5\sigma$)
- Focus on light CP-odd Higgs that is singlet-like — CP-even also possible, but not considered here




arxiv:2405.18149

# Analysis Setup

Tools used:

1. **HiggsTools:** apply **experimental** constraints (HiggsBounds + HiggsSignals)
2. **Theoretical** constraints (applied separately): unitarity, BFB, vacuum stability (**EVADE**)
3. **MadGraph5:** compute $e^+e^-$ cross sections

**Beam polarization setting (ILC parameters):** $P_{e^-} = -80\%$, $P_{e^+} = +30\%$

# Analysis Strategy

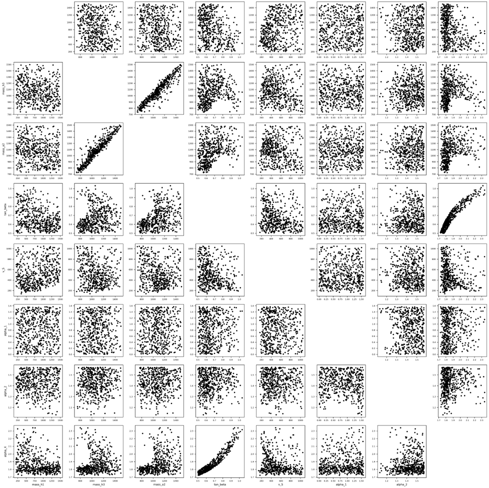
1. Fix $m_{a_1} = 95.4$ GeV
2. Generate random 2HDMS parameter points
3. Filter using HiggsTools, enforce constraints
4. Generate SPheno spectrum files
5. Use MadGraph5 to compute cross sections for selected processes at ILC with :
   - $e^+e^- \to t\bar{t}A_{95}$, $\nu\bar{\nu}A_{95}$, $ZA_{95}$, etc.
6. Plot $\tan\beta$ vs. $\alpha_4$ scans and compare channels

# Constraint regions

- **Theoretical constraints:** unitarity, boundedness from below (BfB), vacuum stability
- **Experimental constraints:** electroweak precision tests (STU), HiggsBounds, HiggsSignals, embed 95 GeV excess
- Use **HiggsTools** framework: combines HiggsBounds and HiggsSignals
- Only points in the final region (pass all constraints) are considered **allowed** for scans

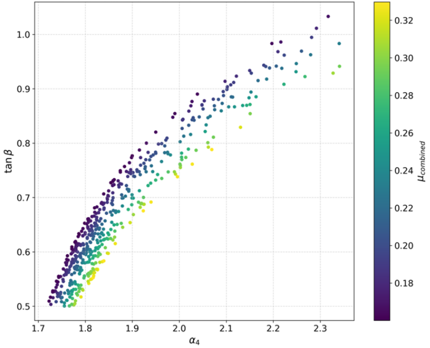
# Results – Parameter Scan

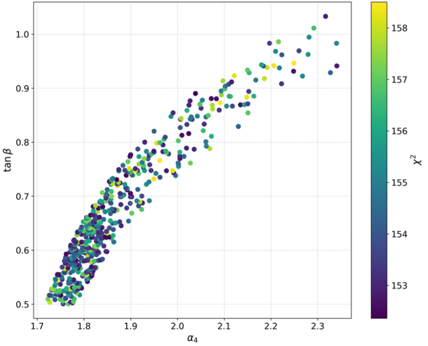
- Full 2HDMS parameter scan shown
- Observed strong correlations:
    - $m_{a_2}$ vs. $m_{h_3}$
    - $\tan\beta$ vs. $\alpha_4$
- Note: $m_{a_2} > m_{a_1}$ due to mass ordering
- Focus on $\tan\beta$ and $\alpha_4$ because they control the A95 couplings to SM particles



Allowed points (=passing all constraints)

# Results – $\tan\beta$ vs. $\alpha_4$



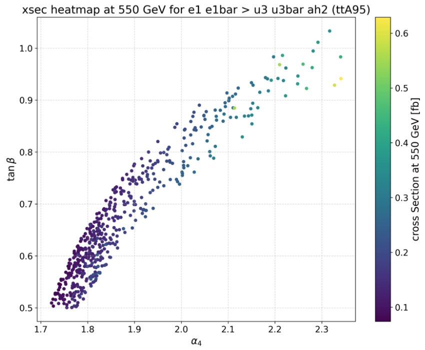



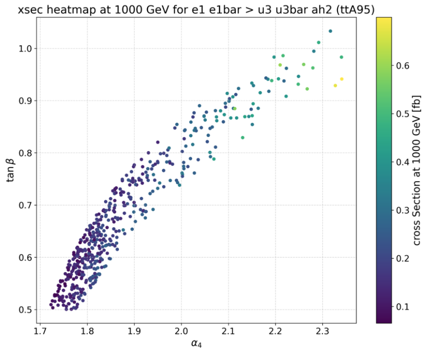

- heatmaps for $\tan\beta$ vs. $\alpha_4$ with their respective $\mu_{combined}$ (left) and $\chi^2$ values (right)
- $\mu_{\text{combined}}$ is the combined Higgs diphoton signal strength given by

$$\mu_{\text{combined}} = \frac{\sigma(pp \to A_{95}) \times \text{BR}(A_{95} \to \gamma\gamma)}{\sigma_{\text{SM}} \times \text{BR}_{\text{SM}}}$$

- $\chi^2$ is computed by HS, compares predicted and observed Higgs rates incl. the $\gamma\gamma$ excess

# Results – $\tan\beta$ vs. $\alpha_4$

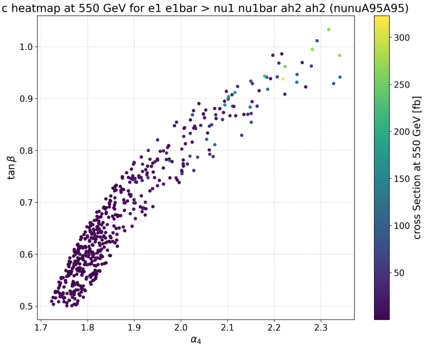


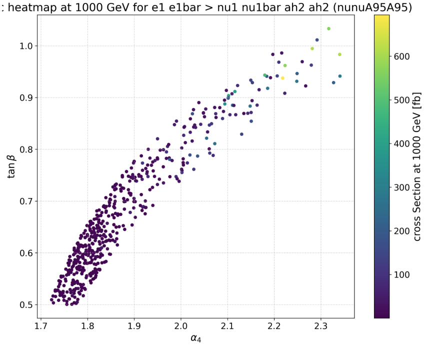




- $\tan\beta$ vs. $\alpha_4$ with cross sections for $t\bar{t}A_{95}$
- studied at energies $\sqrt{s} = 550$ GeV and 1000 GeV (energy choices based on ILC staging scenarios[1])

[1] See LC Vision document: `https://arxiv.org/abs/2203.07622`

# Results – $\tan\beta$ vs. $\alpha_4$




- $\tan\beta$ vs. $\alpha_4$ with cross sections for $\nu\bar{\nu}A_{95}A_{95}$
- Observations:
  - High cross sections for $ttA_{95}$ (strong top coupling)
  - 0 for e.g. $ZA_{95}$ (no coupling between CP-odd A and Z)

# Summary and Outlook

**Summary:**

- $A_{95}$ is motivated by experimental excesses and can be regarded as a theoretically allowed scenario within extended Higgs sectors
- Performed parameter scan in 2HDMS after enforcing experimental and theoretical constraints
- Identified $\tan\beta$ and $\alpha_4$ as key parameters
- Computed cross sections with MadGraph for $A_{95}$ production
- Visualized dependencies between key parameters
- Most promising production channel: $t\bar{t}A_{95}$

**Outlook:**

- More investigations in the parameter space and coupling properties of different channels
- Study possible decays of $A_{95}$
- Compare with CP-even $h_{95}$ in the 2HDMS

Thank you for listening!