

Analyzing a CP-odd Higgs at 95 GeV in the 2HDMS at future e^+e^- colliders

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February 19, 2026

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 - Two-Higgs-Doublet-Model + Singlet (2HDMS)
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- SM gauge group: $SU(3)_C \times SU(2)_L \times U(1)_Y$
- Gauge invariance requires massless gauge bosons, but W^\pm and Z are massive
- **Higgs mechanism:** EWSB breaks $SU(2)_L \times U(1)_Y \rightarrow U(1)_{em}$
- One complex doublet $\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$ with 4 DOF
→ 3 Goldstone bosons (W_L^\pm, Z_L) + 1 physical scalar (H)
- Couplings $g_{HVV} \propto m_V^2/v$, $g_{Hff} \propto m_f/v$,
 $\lambda_{HHH} = 3m_H^2/v$
- $v = 246.22$ GeV and $m_H = 125.09$ GeV measured, Higgs sector is fully determined, no additional free parameters → minimal sector

SM shortcomings:

- Baryon asymmetry
- Neutrino oscillations
- Dark matter
- Hierarchy problem

⇒ Motivates
BSM models with
**extended Higgs
sectors**

- Two $SU(2)_L$ doublets Φ_1, Φ_2 with a complex singlet S :

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{1}{\sqrt{2}}(v_1 + \rho_1 + i\eta_1) \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{1}{\sqrt{2}}(v_2 + \rho_2 + i\eta_2) \end{pmatrix}, \quad S = \frac{1}{\sqrt{2}}(v_S + \rho_S + i\eta_S)$$

- $\tan \beta = v_2/v_1$, v_S : singlet vacuum expectation value

- **Symmetries:**

- \mathbb{Z}_2 : $\Phi_1 \rightarrow \Phi_1, \Phi_2 \rightarrow -\Phi_2, S \rightarrow S$ (suppresses FCNCs)
- \mathbb{Z}_3 : $\Phi_1 \rightarrow \Phi_1, \Phi_2 \rightarrow e^{2\pi i/3}\Phi_2, S \rightarrow e^{-2\pi i/3}S$

- **Physical Higgs states:**

h_1, h_2, h_3 (CP-even); $a_1 \equiv a_{95}, a_2$ (CP-odd); H^\pm (charged)

- **Type II Yukawa structure:** up-type quarks couple to Φ_2 , down-type quarks and leptons to Φ_1 (as in the MSSM)

- **CP-even mixing** ($\alpha_1, \alpha_2, \alpha_3$):

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = Z^H \begin{pmatrix} \rho_1 \\ \rho_2 \\ \rho_3 \end{pmatrix}, \quad Z^H = \begin{pmatrix} c_1 c_2 & s_1 c_2 & s_2 \\ -(c_1 s_2 s_3 + s_1 c_3) & c_1 c_3 - s_1 s_2 s_3 & c_2 s_3 \\ -(c_1 s_2 c_3 - s_1 s_3) & -(c_1 s_3 + s_1 s_2 c_3) & c_2 c_3 \end{pmatrix}$$

where $c_i = \cos \alpha_i$, $s_i = \sin \alpha_i$

- **CP-odd mixing** (α_4):

$$\begin{pmatrix} a_1 \\ a_2 \end{pmatrix} = Z^A \begin{pmatrix} \eta \\ \eta_S \end{pmatrix}, \quad Z^A = \begin{pmatrix} \cos \alpha_4 & \sin \alpha_4 \\ -\sin \alpha_4 & \cos \alpha_4 \end{pmatrix}$$

α_4 controls the doublet–singlet composition of a_{g5}

- **Alignment limit:**

$$\alpha_3 = (\beta - \alpha_1 - \pi/2 + \varepsilon) \cdot \text{sign}(\alpha_2) \xrightarrow{\varepsilon \rightarrow 0} h_1 \approx h_{\text{SM}}$$

Couplings in the 2HDMS

Coupling modifiers defined as ratio to SM: $\kappa_X^{h_i} \equiv g_X^{h_i, 2HDMS} / g_X^{h_i, SM}$

- **Gauge boson couplings** (CP-even only):

$$\kappa_V^{h_i} = Z_{i1}^H \cos \beta + Z_{i2}^H \sin \beta, \quad \sum_{i=1}^3 (\kappa_V^{h_i})^2 = 1$$

- **Yukawa couplings** (Type II):

$$\kappa_u^{h_i} = \frac{Z_{i2}^H}{\sin \beta}, \quad \kappa_d^{h_i} = \frac{Z_{i1}^H}{\cos \beta}; \quad \kappa_u^{a_i} = \frac{Z_{i1}^A}{\tan \beta}, \quad \kappa_d^{a_i} = Z_{i1}^A \tan \beta$$

- **Trilinear Higgs couplings:**

$$\kappa_{hhh} = \frac{\lambda_{h_1 h_1 h_1}}{\lambda_{hhh}^{SM}}, \quad \kappa_{haa} = \frac{\lambda_{h_1 a_95 a_95}}{\lambda_{hhh}^{SM}}$$

95 GeV Diphoton “Excess”

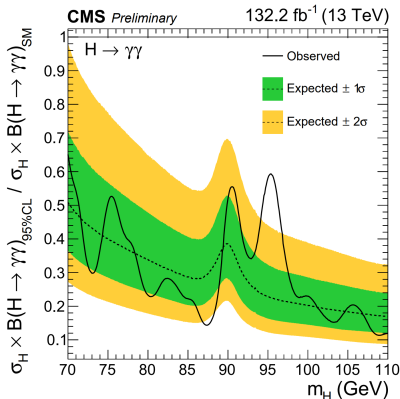
- Indications of excess in $H \rightarrow \gamma\gamma$ at ~ 95 GeV:

$$\mu_{\gamma\gamma}^{\text{CMS}} = 0.33_{-0.12}^{+0.19} \quad (\sim 2.9\sigma)$$
$$\mu_{\gamma\gamma}^{\text{ATLAS}} = 0.18_{-0.10}^{+0.10} \quad (\sim 1.7\sigma)$$

- Combined signal strength:

$$\mu_{\gamma\gamma}^{\text{combined}} = 0.24_{-0.08}^{+0.09} \quad (\sim 3.1\sigma)$$

- LEP: mild $b\bar{b}$ excess at similar mass (not included since $g_{ZZa_{95}} = 0$)
- Interpretation: $a_1 \equiv a_{95}$ as **CP-odd** pseudoscalar in the 2HDMS



CMS diphoton mass distribution
arXiv:2405.18149

Theoretical:

- **Perturbative unitarity:** scattering amplitudes remain perturbative
- **Boundedness from below:** potential is bounded for large field values
- **Vacuum stability (EVADE):** EW vacuum is the global minimum

Experimental:

- **HiggsSignals:** h_1 properties compatible with 125 GeV measurements
- **HiggsBounds:** BSM Higgs bosons not excluded by direct searches at 95% CL
- **95 GeV excess:** a_{95} reproduces observed diphoton signal
- **STU:** EW precision data satisfied

Circular (e.g. FCC-ee):

- High luminosity from continuous circulation
- Energy limited by synchrotron radiation

Linear (e.g. ILC, CLIC, LCF):

- Higher \sqrt{s} accessible
- Beam polarization:
 $P_{e^-} = -80\%$, $P_{e^+} = +30\%$

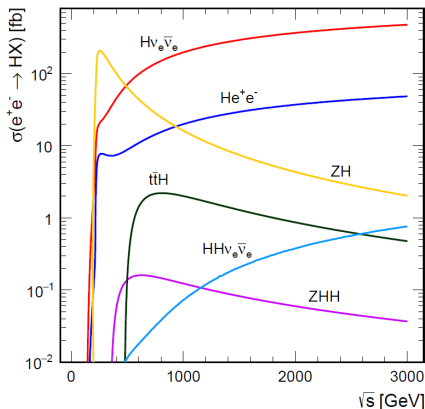
Advantages over pp :

- Clean initial state: \sqrt{s} , polarization known
- No QCD background/pile-up/PDF uncertainties
- Higgs-Strahlung $e^+e^- \rightarrow HZ$: Higgs analysis independent of decay mode
- Polarized beams enhance/suppress specific helicities

ILC: \sqrt{s} up to 1 TeV with beam polarization,
ideal for trilinear coupling measurements

Higgs Production at e^+e^- Colliders

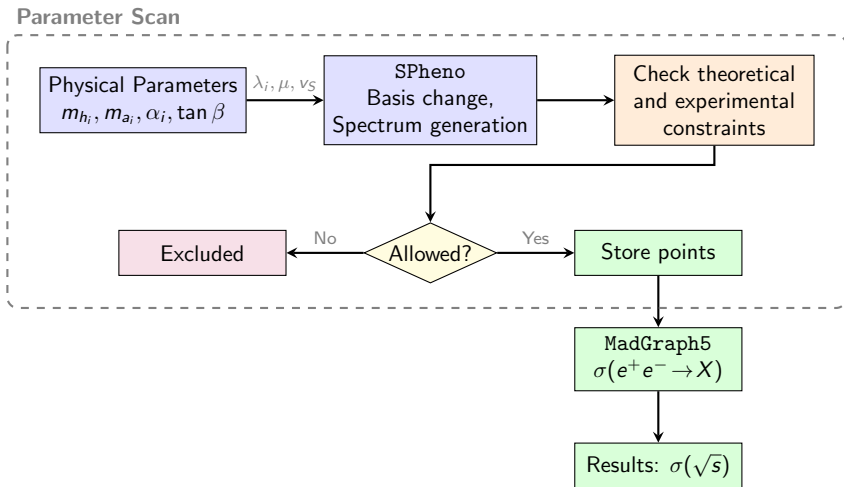
- Measurement of λ_{hhh} requires di-Higgs production
- ZHH : accessible at moderate \sqrt{s} , but $1/s$ fall-off
- $\nu\bar{\nu}HH$ (WW -fusion): log. growth, dominant above 1 TeV
- Circular colliders limited to ~ 365 GeV \rightarrow insufficient for WW -fusion di-Higgs
- Linear colliders at 1 TeV provide access to $\nu\bar{\nu}$ channels



Cross-sections for various $e^+e^- \rightarrow HX$ processes as a function of \sqrt{s}

arXiv:1910.11775

Analysis Workflow



Scanned parameters:

- $\tan \beta \in [0.5, 1.5]$, $\alpha_4 \in [1.7, 3\pi/4]$
- $\alpha_1 \in [0, \pi/2]$, $\alpha_2 \in [0, \pi/4]$
- $m_{h_2}, m_{h_3}, m_{a_2}, m_{H^\pm} \in [200, 1500] \text{ GeV}$, $v_S \in [10, 1500] \text{ GeV}$
- Alignment parameter $\varepsilon \in [0, 0.12]$

Fixed parameters:

- $m_{h_1} = 125.09 \text{ GeV}$, $m_{a_1} = 95.4 \text{ GeV}$
- $m_{H^\pm} = m_{h_3}$ (to satisfy *STU* constraints)
- $\mu = 1000$

Derived parameters:

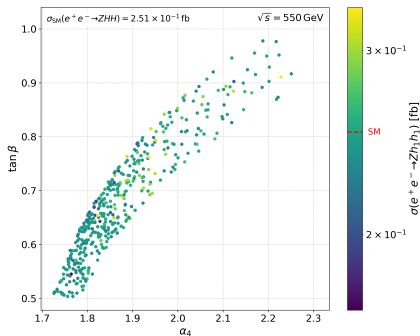
- From alignment:
$$\alpha_3 = (\beta - \alpha_1 - \pi/2 + \varepsilon) \cdot \text{sign}(\alpha_2)$$

Type	Process
Z-associated	$e^+e^- \rightarrow Zh_1h_1$ $e^+e^- \rightarrow Za_{95}a_{95}$
ν -associated	$e^+e^- \rightarrow \nu_e\bar{\nu}_e h_1h_1$ $e^+e^- \rightarrow \nu_e\bar{\nu}_e a_{95}a_{95}$
top-Yukawa	$e^+e^- \rightarrow t\bar{t}h_1$ $e^+e^- \rightarrow t\bar{t}a_{95}$

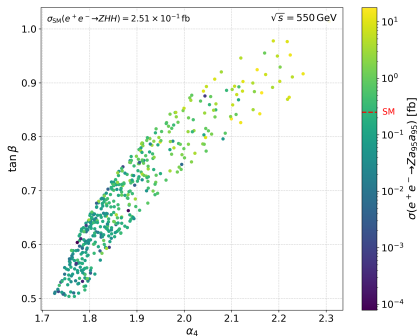
- $\sqrt{s} = 550$ GeV and 1 TeV
- Compare h_1 and a_{95} processes
- ILC polarization
(P_{e^-}, P_{e^+}) = (-80%, +30%)
- Subprocess decomposition via custom diagram filter

Results – Z-Associated Cross-sections

$$e^+e^- \rightarrow Zh_1h_1 \quad (550 \text{ GeV})$$



$$e^+e^- \rightarrow Za_{95}a_{95} \quad (550 \text{ GeV})$$

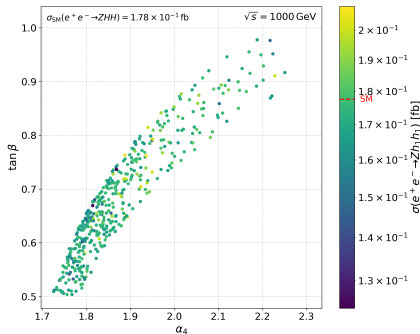


- $\sim 0.2\text{--}0.3 \text{ fb}$ @ 550 GeV
- near SM value 0.25 fb

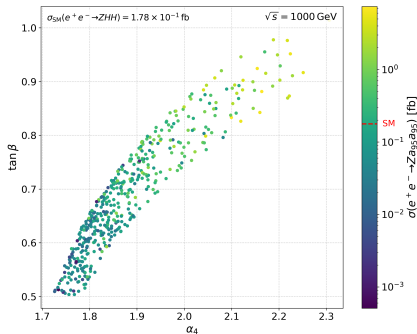
- $\mathcal{O}(10^{-4})\text{--}\mathcal{O}(10) \text{ fb}$ @ 550 GeV
- $Za_{95}a_{95}$ exceeds SM ZHH towards higher α_4 and $\tan\beta$

Results – Z-Associated Cross-sections

$$e^+e^- \rightarrow Zh_1h_1 \text{ (1 TeV)}$$



$$e^+e^- \rightarrow Za_{95}a_{95} \text{ (1 TeV)}$$

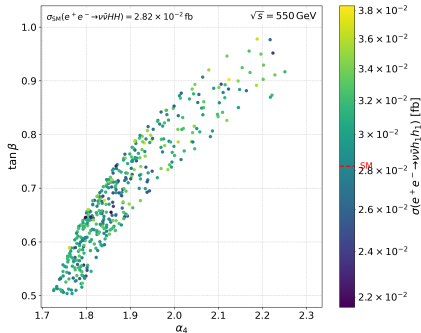


- $\sim 0.13\text{--}0.2 \text{ fb @ 1 TeV}$
- near SM value 0.18 fb
- $1/s$ suppression at higher energies

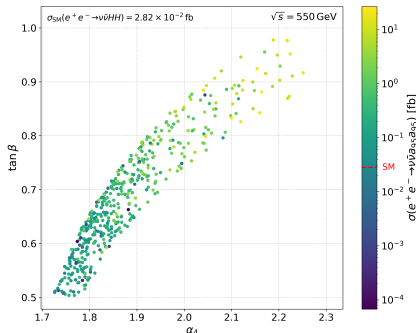
- $\mathcal{O}(10^{-3})\text{--}\mathcal{O}(1) \text{ fb @ 1 TeV}$
- $1/s$ suppression at higher energies

Results – Neutrino-Associated Cross-sections

$$e^+e^- \rightarrow \nu\bar{\nu}h_1h_1 \quad (550 \text{ GeV})$$



$$e^+e^- \rightarrow \nu\bar{\nu}a_{95}a_{95} \quad (550 \text{ GeV})$$

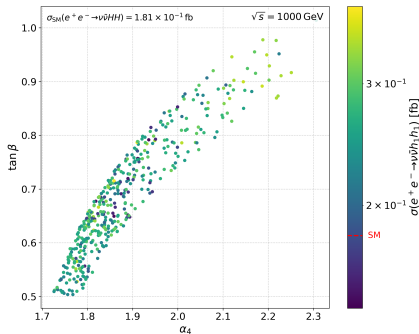


- $\sim 0.022\text{--}0.038$ fb @ 550 GeV
- near SM value 0.028 fb

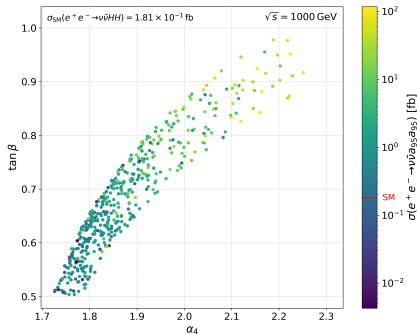
- up to $\mathcal{O}(10)$ fb @ 550 GeV

Results – Neutrino-Associated Cross-sections

$$e^+e^- \rightarrow \nu\bar{\nu}h_1h_1 \text{ (1 TeV)}$$



$$e^+e^- \rightarrow \nu\bar{\nu}a_{95}a_{95} \text{ (1 TeV)}$$

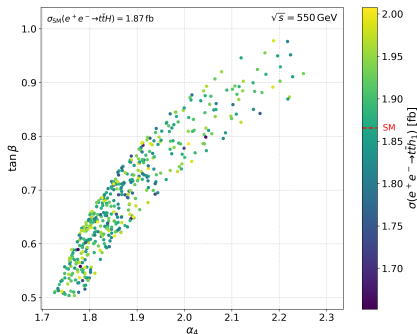


- $\sim 0.2\text{--}0.3$ fb @ 1 TeV
- Order-of-magnitude increase at 1 TeV from *WW*-fusion growth

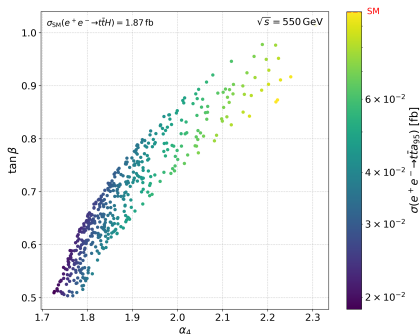
- up to $\mathcal{O}(10^2)$ fb @ 1 TeV
- **Largest cross-sections of all channels**, benefits from both *WW*-fusion topology *and* enhanced trilinear $h_1a_{95}a_{95}$ coupling

Results – Top-Associated Cross-sections

$$e^+e^- \rightarrow t\bar{t}h_1 \text{ (550 GeV)}$$



$$e^+e^- \rightarrow t\bar{t}a_{95} \text{ (550 GeV)}$$

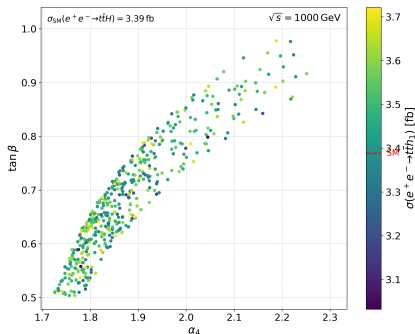


- $\sim 1.7\text{--}2.0$ fb @ 550 GeV
- closely distributed around SM value 1.87 fb

- $\sim 0.02\text{--}0.06$ fb @ 550 GeV
- slightly suppressed coupling $\kappa_{t\bar{t}a_{95}} \sim 0.35\text{--}0.65$

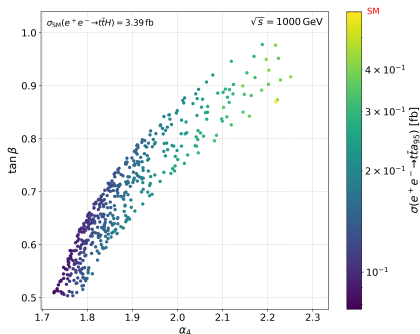
Results – Top-Associated Cross-sections

$$e^+e^- \rightarrow t\bar{t}h_1 \text{ (1 TeV)}$$



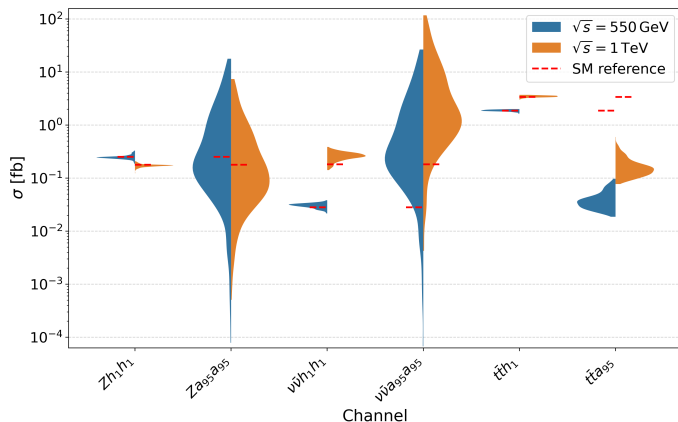
- $\sim 3.1\text{--}3.7 \text{ fb @ 1 TeV}$
- SM value 3.4 fb

$$e^+e^- \rightarrow t\bar{t}a_{95} \text{ (1 TeV)}$$



- $\sim 0.1\text{--}0.4 \text{ fb @ 1 TeV}$
- far below SM reference value

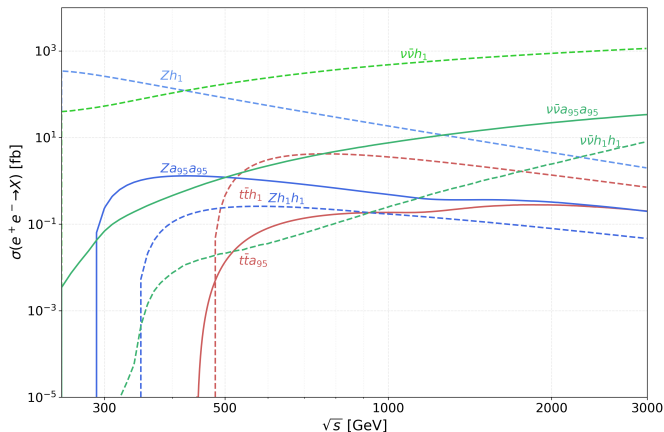
Results – Cross-section Summary



- **Most promising channels:** $\nu\bar{\nu}a_{95}a_{95}$ and $Za_{95}a_{95}$ (cross-sections can exceed SM di-Higgs by orders of magnitude!)
- a_{95} pair production is possible but not guaranteed, dependent on α_4 and $\tan\beta$
- h_1 -like channels (Zh_1h_1 , $\nu\bar{\nu}h_1h_1$, $t\bar{t}h_1$) remain near SM predictions, insufficient to distinguish 2HDMS from SM

Results – Energy Dependence (Benchmark Point)

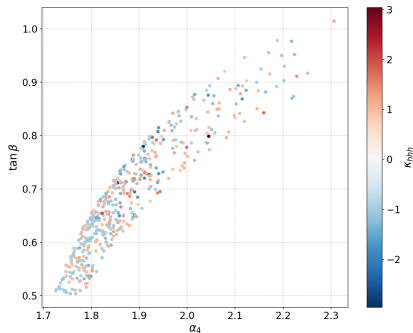
$$\tan \beta = 0.82, \alpha_4 = 1.97$$



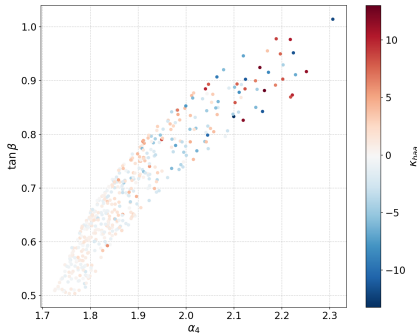
- Higgs-Strahlung: early threshold, $1/s$ fall-off
- WW -fusion: logarithmic growth with \sqrt{s}
- $\nu\bar{\nu}a_{95}a_{95}$ surpasses $Za_{95}a_{95}$ at ~ 500 GeV, exceeds 10 fb above 1 TeV

Results – Trilinear Couplings

$\kappa_{h_1 h_1 h_1}$ in the $(\alpha_4, \tan \beta)$ plane



$\kappa_{h_1 a_{95} a_{95}}$ in the $(\alpha_4, \tan \beta)$ plane



● $\kappa_{h_1 h_1 h_1} \in [-2.96, +3.04]$

● $\kappa_{h_1 a_{95} a_{95}} \in [-13.22, +12.98]$

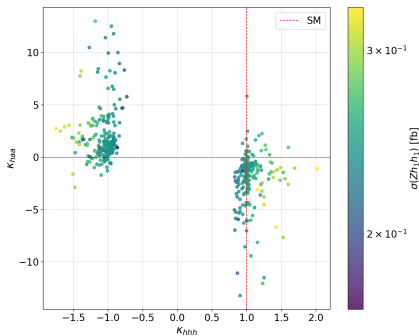
● stronger couplings towards higher α_4 and $\tan \beta$

Note: $\kappa_{h_{aa}}$ normalized to $\lambda_{hhh}^{\text{SM}}$, effective vertex strength differs by

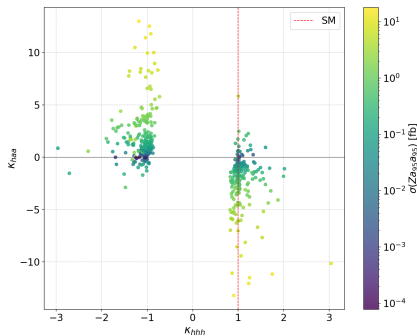
factor 3 because of symmetry factors for identical particles ($3! = 6, 2! = 2$).

Results – $\kappa_{h_1 h_1 h_1}$ vs. $\kappa_{h_1 a_{95} a_{95}}$

Colored by $\sigma(Zh_1 h_1)$



Colored by $\sigma(Za_{95} a_{95})$

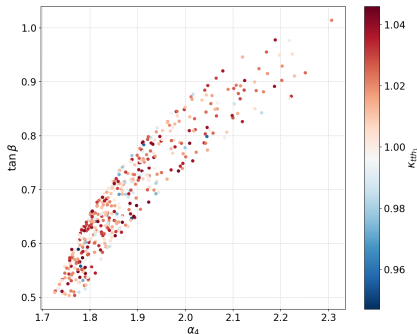


- larger $|\kappa_{h_1 h_1 h_1}| \rightarrow$ higher $\sigma(Zh_1 h_1)$
- gap at $|\kappa_{h_1 h_1 h_1}| < 1$ from alignment and experimental constraints

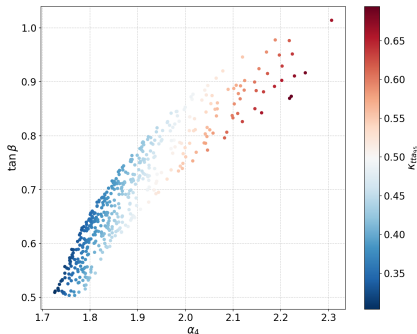
- larger $|\kappa_{h_1 a_{95} a_{95}}| \rightarrow$ higher $\sigma(Za_{95} a_{95})$

Results – Top-Yukawa Couplings

κ_{tth_1} in the $(\alpha_4, \tan\beta)$ plane



$\kappa_{tta_{95}}$ in the $(\alpha_4, \tan\beta)$ plane

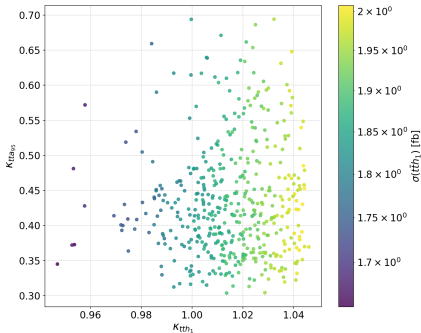


- $\kappa_{tth_1} \in [0.96, 1.04]$
- alignment forces near-SM values

- $\kappa_{tta_{95}} \in [0.35, 0.65]$
- slightly suppressed

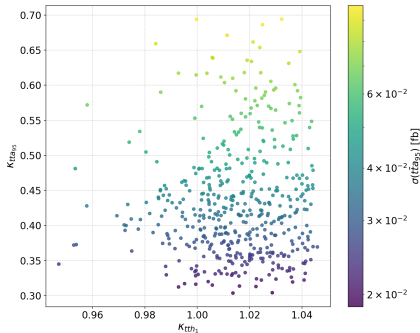
Results – $\kappa_{t\bar{t}h_1}$ vs. $\kappa_{t\bar{t}a_{95}}$

Colored by $\sigma(t\bar{t}h_1)$



- larger $|\kappa_{t\bar{t}h_1}|$ correlates with higher $\sigma(t\bar{t}h_1)$

Colored by $\sigma(t\bar{t}a_{95})$



- larger $|\kappa_{t\bar{t}a_{95}}|$ correlates with higher $\sigma(t\bar{t}a_{95})$

- 2HDMS Type II can accommodate the 95 GeV diphoton excess as a CP-odd pseudoscalar a_{95} while satisfying all theoretical and experimental constraints
- Cross-sections computed for Z-associated, neutrino-associated and top-Yukawa channels at $\sqrt{s} = 550$ GeV and 1 TeV with ILC beam polarizations
- $\nu\bar{\nu}a_{95}a_{95}$ **yields the largest cross-sections** ($\mathcal{O}(10^1\text{--}10^2)$ fb), driven by WW -fusion and enhanced trilinear $h_1a_{95}a_{95}$ coupling
- Subprocess $h_1 \rightarrow a_{95}a_{95}$ dominates in both $Za_{95}a_{95}$ and $\nu\bar{\nu}a_{95}a_{95}$
- a_{95} pair production is viable across a significant portion of the allowed parameter space, but depends strongly on α_4 and $\tan\beta$
- $\kappa_{tth_1} \approx 1$ (alignment), $\kappa_{tta_{95}}$ suppressed

- Overall analysis of a_{95} production at e^+e^- colliders, study accessibility of a_{95}
- Identify regions of 2HDMS parameter space where a_{95} pair production could be observed at e^+e^- colliders; how to probe inaccessible regions?
- CP-even interpretation of 95 GeV excess (h_{95}) for comparison
- Include higher-order corrections (currently NLO with MadGraph5)
- LHC Run 3 data: updated constraints on 95 GeV signal strength
- Broader parameter scan ranges and additional production channels

Thank you for listening!

$$\begin{aligned} V_{2\text{HDMS}} = & m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - m_{12}^2 (\Phi_2^\dagger \Phi_1 + \text{h.c.}) + \frac{\lambda_1}{2} (\Phi_1^\dagger \Phi_1)^2 + \frac{\lambda_2}{2} (\Phi_2^\dagger \Phi_2)^2 \\ & + \lambda_3 (\Phi_1^\dagger \Phi_1) (\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2) (\Phi_2^\dagger \Phi_1) + m_S^2 S^\dagger S \\ & + \lambda'_1 (S^\dagger S) (\Phi_1^\dagger \Phi_1) + \lambda'_2 (S^\dagger S) (\Phi_2^\dagger \Phi_2) + \frac{\lambda''_3}{4} (S^\dagger S)^2 \\ & + \frac{\mu_{S1}}{6} (S^3 + S^{\dagger 3}) + \mu_{12} (S \Phi_1^\dagger \Phi_2 + S^\dagger \Phi_2^\dagger \Phi_1) \end{aligned}$$

Theoretical constraints:

- **Perturbative unitarity:** lower bounds on couplings: $|\lambda_i| < 8\pi$
- **Boundedness from below (BFB):** potential $V \rightarrow +\infty$ for $|\Phi_i|, |S| \rightarrow \infty$
- **Vacuum stability (EVADE):** electroweak vacuum is the global minimum and must preserve electric charge and CP-symmetry
- **STU parameters:** $\chi_{STU}^2 < 5.99$ (95% CL); $m_{H^\pm} \approx m_{h_3}$

Experimental constraints:

- **HiggsSignals:** compatibility with 125 GeV measurements:
 $|\chi^2 - \chi_{SM}^2| < 5.99$
- **HiggsBounds:** parameter point not excluded by direct searches at 95% CL
- **95 GeV diphoton excess:** $\chi_{95}^2 < 1$

Checking order: Unitarity \rightarrow BFB \rightarrow STU \rightarrow Vacuum stability
 \rightarrow HB \rightarrow HS \rightarrow 95 GeV excess

Backup: Why $\sqrt{s} = 550$ GeV?

The direct measurement in $e^+e^- \rightarrow t\bar{t}H$ production requires a center-of-mass energy of at least 500 GeV. The cross section rises sharply around that energy; raising the center-of-mass energy to 550 GeV enhances the production rate by a factor or approximately four and the measurement of the $t\bar{t}H$ coupling by a factor two. Several groups have performed detailed full-simulation studies at center-of-mass energies ranging from 500 GeV to 1.4 TeV [526, 527, 525]. With 4 ab^{-1} at 550 GeV, a precision of 2.8% is expected on the top Yukawa coupling, which could improve to 1% with 8 ab^{-1} at 1 TeV. Measurements at multiple center-of-mass energies and with different beam polarizations can further characterize the $t\bar{t}H$ coupling [528].

ILC Report to Snowmass 2021

arXiv:2203.07622

- $e^+e^- \rightarrow t\bar{t}H$ requires $\sqrt{s} \geq 2m_t + m_H \approx 470$ GeV
- Cross-section rises sharply:
 - 500 \rightarrow 550 GeV: production rate increases by factor ~ 4
 - $t\bar{t}H$ coupling measurement improves by factor ~ 2
- 550 GeV also provides a sufficient phase space for $\nu\bar{\nu}a_{g5}a_{g5}$ (onset of WW -fusion)

Masses (GeV):

$m_{h_1} = 125.09$	$m_{a_1} = 95.4$
$m_{h_2} = 835.6$	$m_{a_2} = 1082.8$
$m_{h_3} = 1010.6$	$m_{H^\pm} = 1010.6$

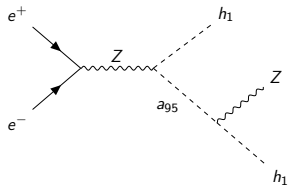
Mixing angles and other parameters:

$\tan \beta = 0.82$	$\alpha_1 = 0.41$
$\alpha_2 = 1.39$	$\alpha_3 = -1.27$
$\alpha_4 = 1.97$	$v_S = 392.4 \text{ GeV}$
$\mu = 1000 \text{ GeV}$	

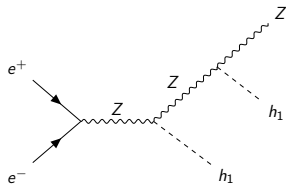
Cross-sections (fb):

Process	550 GeV	1 TeV
$Zh_1 h_1$	0.26	0.17
$Za_{95} a_{95}$	1.11	0.48
$\nu\bar{\nu} a_{95} a_{95}$	1.68	7.52

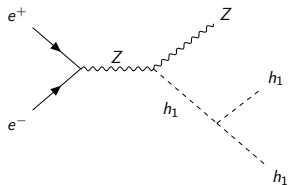
Backup: Subprocesses (Zh_1h_1)



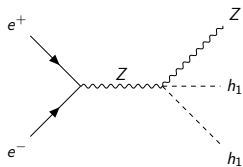
Intermediate $a_{95} \rightarrow Zh_1$: negl.



Double HS: 26.2% (SM: 13.9%)

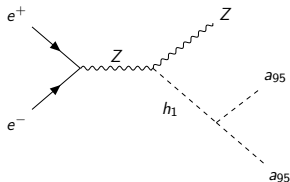


$h_1 \rightarrow h_1h_1$: 12.9% (SM: 9.6%)

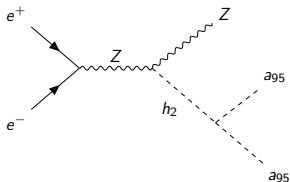


Quartic ZZh_1h_1 : 30.5% (SM: 33.1%)

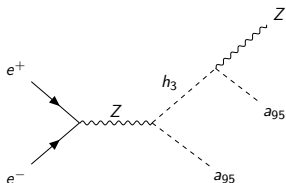
Backup: Subprocesses ($Za_{95}a_{95}$)



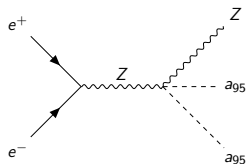
$h_1 \rightarrow a_{95} a_{95}$: **103.4%**



$h_2 \rightarrow a_{95} a_{95}$: 0.2%



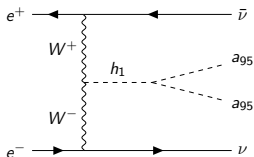
$h_i \rightarrow Z a_{95}$: *negl.*



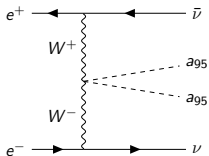
Quartic $ZZ a_{95} a_{95}$: 0.2%

Interference: -3.9% \Rightarrow $h_1 \rightarrow a_{95} a_{95}$ overwhelmingly dominant

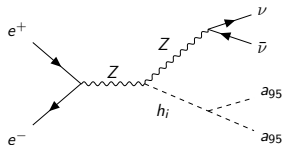
Backup: Subprocesses ($\nu\bar{\nu}a_{95}a_{95}$)



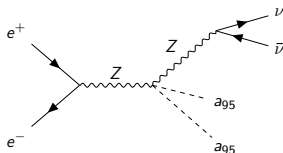
WW-fusion, $h_1 \rightarrow a_{95}a_{95}$: 101.9%



Quartic $W^+W^-a_{95}a_{95}$: 0.2%



Z-med. $h_i \rightarrow a_{95}a_{95}$: 4.5%

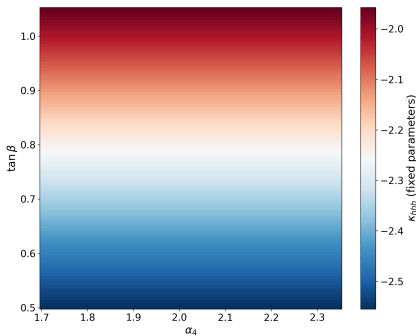


Quartic $ZZa_{95}a_{95}$: negl.

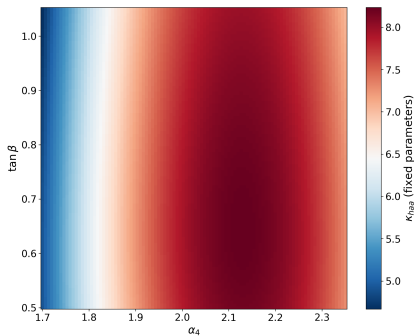
Interference: $-6.6\% \Rightarrow$ WW-fusion $h_1 \rightarrow a_{95}a_{95}$ overwhelmingly dominant

Backup: Trilinear Couplings (Benchmark Point)

$\kappa_{h_1 h_1 h_1}$ (only vary α_4 and $\tan \beta$)



$\kappa_{h_1 a_{95} a_{95}}$ (only vary α_4 and $\tan \beta$)

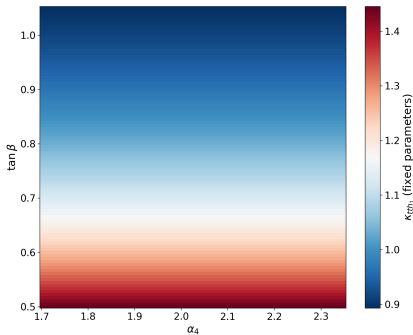


- independent of α_4
- stronger coupling towards lower $\tan \beta$

- depends on α_4 through Z^A mixing

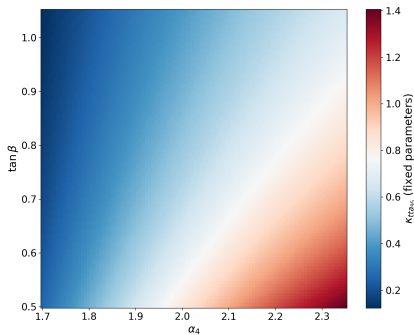
Backup: Top-Yukawa Couplings (Benchmark Point)

κ_{tth_1} (only vary α_4 and $\tan\beta$)



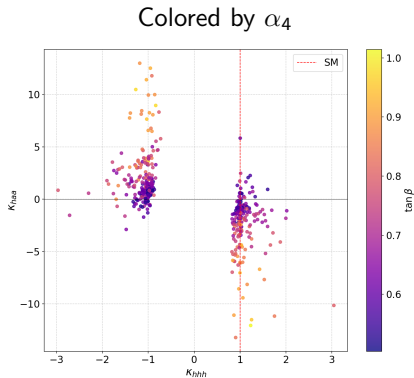
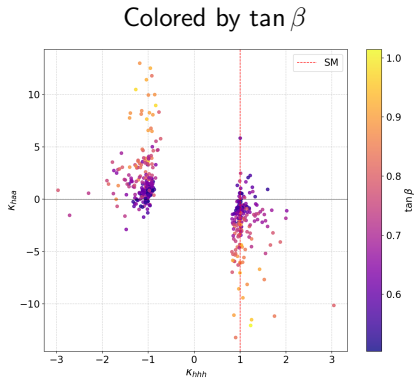
- stronger for lower $\tan\beta$

$\kappa_{tta_{95}}$ (only vary α_4 and $\tan\beta$)



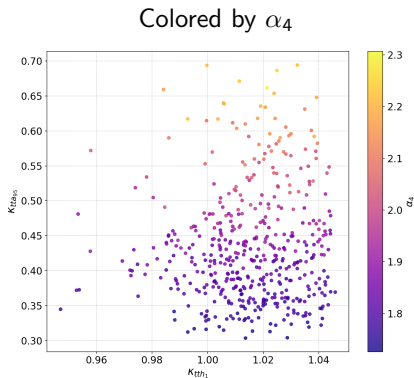
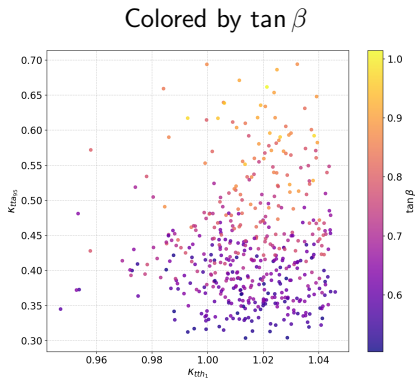
- stronger for lower $\tan\beta$
and higher α_4

Backup: $\kappa_{h_1 h_1 h_1}$ vs. $\kappa_{h_1 a_{95} a_{95}}$



Larger $|\kappa_{h_1 a_{95} a_{95}}|$ correlated with higher α_4 and $\tan \beta$

Backup: κ_{tth_1} vs. $\kappa_{tta_{95}}$



- No strong correlation between κ_{tth_1} and $\kappa_{tta_{95}}$
- Stronger $\kappa_{tta_{95}}$ for higher $\tan\beta$ and higher α_4

Backup: $\kappa_{tta_{95}}$ Coupling scaling

CP-odd top-Yukawa coupling (Type II):

$$\kappa_{tta_{95}} = -\cot \beta \cos \alpha_4$$

Contributing factors:

- $\cot \beta$ from up-type Yukawa structure in Type II 2HDMS
- $\cos \alpha_4 = Z_{11}^A$ from CP-odd mixing matrix

Scan ranges:

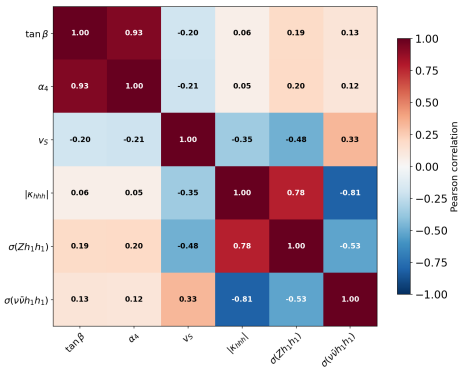
$$\begin{aligned}\tan \beta \in [0.5, 1.5] &\Rightarrow \cot \beta \in [0.67, 2.0] \\ \alpha_4 \in [1.7, 3\pi/4] &\Rightarrow |\cos \alpha_4| \in [0.13, 0.71] \\ \Rightarrow |\kappa_{tta_{95}}|_{\max} &\approx 1.41, \quad |\kappa_{tta_{95}}|_{\min} \approx 0.09\end{aligned}$$

But observed range: $\kappa_{tta_{95}} \in [0.35, 0.65]$ (below 1, suppressed)

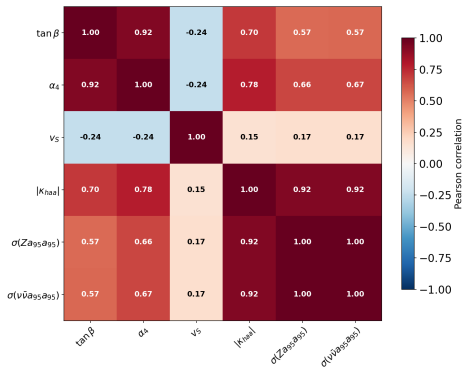
- Experimental constraints (HiggsSignals, 95 GeV excess) seem to exclude regions where $\cot \beta$ and $|\cos \alpha_4|$ are simultaneously large
- The suppression is a consequence of the allowed parameter space, not physical

Backup: Correlation Matrices – Trilinear Couplings

$h_1 h_1 h_1$ sector



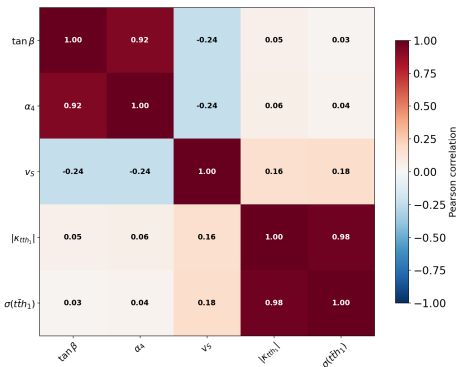
$h_1 a_{95} a_{95}$ sector



$$\text{Pearson correlation: } r = \frac{\sum(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum(x_i - \bar{x})^2 \sum(y_i - \bar{y})^2}}$$

Backup: Correlation Matrices – Top-Yukawa Couplings

$t\bar{t}h_1$ sector



$t\bar{t}a_{95}$ sector

