Chasing the two-Higgs-doublet model via electroweak corrections at e^+e^- colliders

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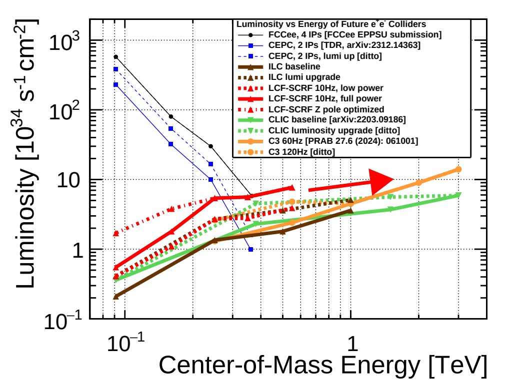
Introduction

- Future e^+e^- colliders (FCC-ee, CEPC, ILC/LCF and CLIC) can determine Higgs properties at EW scale with permille accuracy
- We show that 2HDM can induce percent-level deviations from SM through EW corrections to $e^+e^- \to h\nu\bar{\nu}$ at e^+e^- colliders



[Linear Collider Vision Collaboration, 2025]

Two-Higgs-doublet model (2HDM)

$\mathbb{Z}_2$-symmetric 2HDM: SM + second Higgs doublet

- a simple extension of SM, 2HDM is contained in MSSM
- Five physical Higgs

h (SM-like), H (heavy CP-even), A (CP-odd), $H^{\pm}$ (charged)

- Free parameters

$m_H,\ m_A,\ m_{H^\pm}$: BSM Higgs mass

$\cos(\beta-\alpha)$: mixing angle between h and H

$\tan(\beta)$: ratio of two vevs

λ_5: scalar self coupling

- The alignment limit, $\cos(\beta-\alpha)=0$ → h behaves exactly like SM Higgs
- Four type Yukawa, type-I, II, X, Y (determined by $\mathbb{Z}_2$ charge)

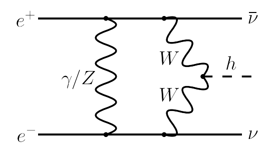
Target process: $e^+e^- \to h\nu\bar{\nu}$

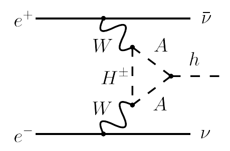
$e^+e^- \to Zh$ is well investigated at full NLO in 2HDM (and SUSY)

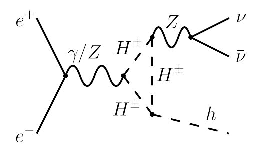
[Xie et al., 2021; Aiko, Kanemura, and Mawatari, 2021; Arco et al., 2025; Heinemeyer, Paßehr, and Schappacher, 2025]

We focus on $e^+e^- \to h\nu\bar{\nu}$

- Full NLO EW study in BSM theories is still missing
- Cross section is one order of magnitude larger than $e^+e^- \to h\ell\bar{\ell}$, at $\sqrt{s} = 365, 550\ \mathrm{GeV}$
- Cross section is mainly contributed by Zh-production and WW-fusion, and is dominated by WW-fusion at higher energy







Total cross section

Total cross sections for $e^+e^- \to h\nu\bar{\nu}$ in SM and type-I 2HDM benchmark without cuts.

Relative difference: $(\sigma_{\text{2HDM}} - \sigma_{\text{SM}})/\sigma_{\text{SM}}$

Benchmark: $m_H = m_{H^\pm} = 400$ GeV, $m_A = 435$ GeV, $\cos(\beta-\alpha) = 0.03734$, $\tan(\beta) = 1.88$, $\lambda_5 = -2.54$

Benchmark point is allowed by theoretical and experimental constraints based on `ScannerS + HiggsTools`

Computational tools: `Whizard + Recola2/OpenLoops2`

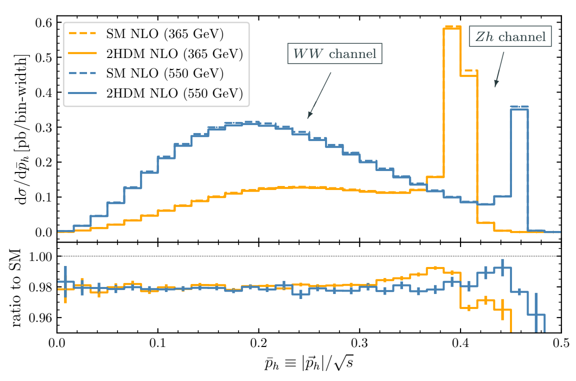
	$\sqrt{s} = 365$ GeV		$\sqrt{s} = 550$ GeV	
	LO [fb]	NLO EW [fb]	LO [fb]	NLO EW [fb]
SM	55.79	52.44(1)	97.82(1)	88.45(2)
2HDM	55.71	51.45(1)	97.67(1)	86.59(2)
Rel.Diff.	−0.1%	−1.9%	−0.2%	−2.1%
2HDM (aligned)	55.79	51.58(1)	97.81(1)	86.83(2)
Rel.Diff.	0.0%	−1.7%	0.0%	−1.8%

(Future e^+e^- colliders will provide permille-level accuracy)

NLO EW corrections are a sensitive probe of the 2HDM, even in the alignment limit

Differential cross section

Differential cross sections at NLO as a function of the normalized Higgs three-momentum $\bar{p}_h$



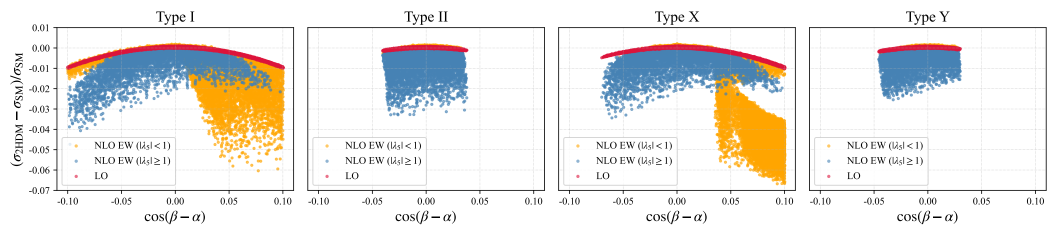
WW-fusion contribution increases with lower $\bar{p}_h$ and higher $\sqrt{s}$

The separation of two channels allows simultaneous new physics probes

Relative difference and NLO EW effects

Relative difference between SM and 2HDM for type-I, II, X and Y at $\sqrt{s} = 365 \text{ GeV}$

160k allowed parameter: $m_\phi = m_H, m_A, m_{H^\pm}, \cos(\beta - \alpha), \tan(\beta), \lambda_5$



Theoretical uncertainty is estimated to be 0.7%
Experimental uncertainty will reach 0.6% at $\sqrt{s} = 365 \text{ GeV}$ with 4.3 ab^{-1} } combined 0.92%

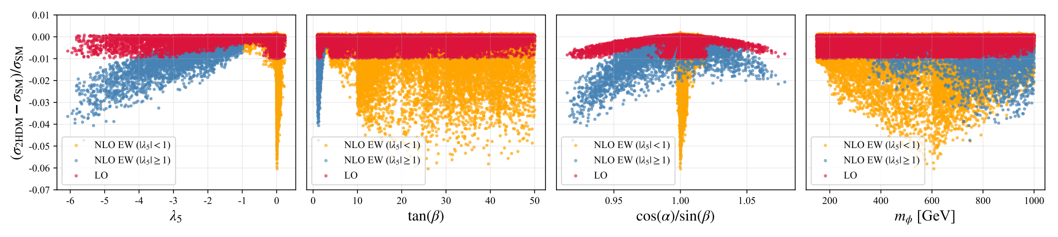
[Linear Collider Vision Collaboration, 2025]

Deviations can reach -6% to -7%

Evan in the alignment limit, these deviations can reach -2% to -3%

NLO EW effects and other parameters

Type I 2HDM predictions in the $\lambda_5, \tan(\beta), \cos(\alpha)/\sin(\beta), m_\phi$ parameter planes



There is no clear correlation between the NLO effects and $m_\phi, \tan(\beta)$

→ Calculating NLO effects in the UV-complete theory is important

Summary

Based on arXiv:2509.05421

- First full NLO EW study of $e^+e^- \to h\nu\bar{\nu}$ in 2HDM
- NLO effects induce deviations of several percent between SM and 2HDM, even in the alignment limit
- These effects are observable, providing new opportunities for BSM searches at future e^+e^- colliders

Backup

2HDM potential and Yukawa

Higgs potential (CP-conserving)

$$
\begin{aligned}
V = \; & m_1^2 \Phi_1^\dagger \Phi_1 + m_2^2 \Phi_2^\dagger \Phi_2 - m_{12}^2 \left(\Phi_1^\dagger \Phi_2 + \Phi_2^\dagger \Phi_1 \right) \\
& + \frac{\lambda_1}{2} \left(\Phi_1^\dagger \Phi_1 \right)^2 + \frac{\lambda_2}{2} \left(\Phi_2^\dagger \Phi_2 \right)^2 + \frac{\lambda_3}{2} \left(\Phi_1^\dagger \Phi_1 \right) \left(\Phi_2^\dagger \Phi_2 \right) \\
& + \frac{\lambda_4}{2} \left(\Phi_1^\dagger \Phi_2 \right) \left(\Phi_2^\dagger \Phi_1 \right) + \frac{\lambda_5}{2} \left[\left(\Phi_1^\dagger \Phi_2 \right)^2 + \left(\Phi_2^\dagger \Phi_1 \right)^2 \right]
\end{aligned}
$$

$\mathbb{Z}_2$ charge assignments ($+$ is $\mathbf{Z}_2$-even, $-$ is $\mathbf{Z}_2$-odd)

	Φ_1	Φ_2	Q	u_R	d_R	L	e_R
type-I	$+$	$-$	$+$	$-$	$-$	$+$	$-$
type-II	$+$	$-$	$+$	$-$	$+$	$+$	$+$
type-X	$+$	$-$	$+$	$-$	$-$	$+$	$+$
type-Y	$+$	$-$	$+$	$-$	$+$	$+$	$-$

Theoretical uncertainty

We employed different renormalization schemes between SM and 2HDM

- SM: G_μ scheme
- 2HDM: on-shellscheme for mixing angles
- λ_5: $\overline{\text{MS}}$ scheme

This causes 0.7% theoretical uncertainty at $\sqrt{s} = 365\ \text{GeV}$ in $(\sigma_{\text{2HDM}} - \sigma_{\text{SM}})/\sigma_{\text{SM}}$

To reduce this uncertainty, we need NLO EW corrections in 2HDM

(higher-order SM corrections cancel)

Parameter constraints

Theoretical constraints

- Perturbative unitarity
- Boundedness from below
- Electroweak vacuum stability

Experimental constraints

- Electroweak precision observables
- Flavor-changing processes
- Direct searches at the LHC and LEP