Chasing 2HDM via electroweak corrections at e^+e^- colliders

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Remote from Les Houches

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MARIE CURIE ACTIONS

Precision BSM Phenomenology

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

Pia Bredt, Tatsuya Banno, Marius Höfer, Syuhei Iguro, Wolfgang Kilian, Yang Ma, Jürgen Reuter, **Hantian Zhang**

arXiv: 2509.05421

Q: can precision discover new physics?

What kind of new physics?

- **First of all: additional Higgs, e.g. in two-Higgs-doublet model (2HDM)**

Actively searched model
Scalar sector is less constrained

Provide strong first-order phase transition for baryogenesis and gravitational wave

Low-energy scalar sector of SUSY models

2HDM

Resolve vacuum metastability issue

Simple, yet phenomenologically rich

Hints from flavour anomalies in R_D and $R_{D^{(*)}}$

[**Iguro**, Phys.Rev.D 105 (2022) 9, 095011]
[Blanke, **Iguro**, **Zhang**, JHEP 06 (2022) 043]

Hints from electroweak-scale excesses at the LHC

[**Iguro**, Kitahara, Omura, **Zhang**, Phys.Rev.D 107 (2023) 7, 075017]

See also talks by Andres Crivellin and Jingya Zhu

Where to search for 2HDM?

- **Indirect search in Higgs production at e^+e^- colliders, as direct search at the LHC is difficult**

Electroweak (EW) corrections can enhance new physics signals

Different 2HDM models can yield similar signals at NLO EW in Higgs production

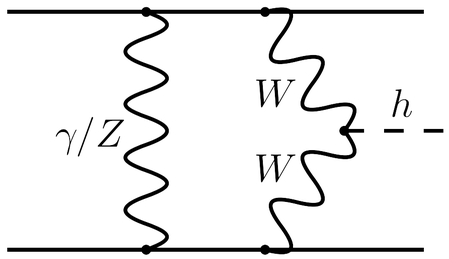
$\mathbb{Z}_2$**-symmetric 2HDM with CP-conserving Higgs potential** contains SM Higgs h, charged $H^{\pm}$, neutral CP-even H and CP-odd A, with additional parameters $\{c_{\beta\alpha}\ t_\beta,\ \lambda_5,\ m_H,\ m_A,\ m_{H^\pm}\}$

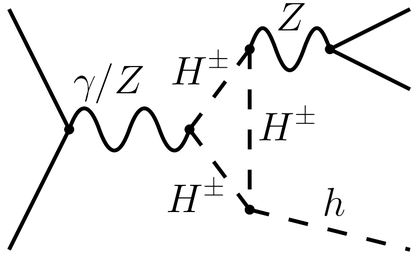
$c_{\beta\alpha} \equiv \cos(\beta-\alpha)$: control h-H mixing

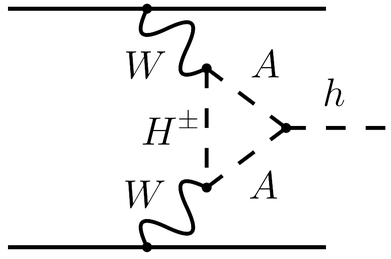
$t_\beta \equiv \tan(\beta)$: ratio between two vevs $\quad$ λ_5: scalar self-coupling

Higgs plus neutrino-pair production $e^+e^- \to h\nu\bar{\nu}$

- $e^+e^- \to Zh$ is well-studied at full NLO EW in 2HDM and SUSY [Aiko, Kanemura, Mawatari, 21'; Anisha, Arco, Di Noi, Englert, Mühlleitner, 25'; Heinemeyer, Paßehr, Schappacher, 25']
- $e^+e^- \to h\nu\bar{\nu}$ is major Higgs production at $\sqrt{s} > 500$ GeV, and $\sim 50\,\%$ of Zh cross section at $\sqrt{s} = 365$ GeV, but much larger than Zh-mediated $e^+e^- \to h\ell\bar{\ell}$
- No full NLO EW BSM study for $e^+e^- \to h\nu\bar{\nu}$ before [arXiv: 2509.05421]







Computational framework

Widely-used one-loop amplitude provider
in NNLO community

OpenLoops2

Buccioni, Lang, Lindert, Maierhöfer, Pozzorini, **Zhang**, Zoller
Eur.Phys.J.C 79 (2019) 10, 866

OpenLoops algorithm + On-the-fly reduction
+ analytic expansion (+ rational terms)

General-purpose
Monte Carlo generator

Whizard

Kilian, Ohl, **Reuter**
Eur.Phys.J.C 71 (2011) 1742

One-loop amplitude provider
with BSM models

Recola2

Denner, Lang, Uccirati
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For this study $e^+e^- \to h\,\nu\bar{\nu}$:

FKS subtraction

Massive electron beam set up

ISR effect is included in NLO real corrections

ISR beyond NLO is $\sim 0.2\,\%$ for $\sqrt{s} \geq 365$ GeV

Cross checks to [Denner, Dittmaier, Roth, Weber, 03'] for $e^+e^- \to h\,\nu\bar{\nu}$ in SM

to HAWK [Denner, Dittmaier, Kallwait, Mück, 14'] for $pp \to h\,\mu^+\nu_\mu$ in 2HDM

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OpenLoops algorithm + On-the-fly reduction
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Highly efficient and precise one-loop provider
in QCD and EW @ (N)NLO

BSM support: 2HDM and HiggsPO at LHC

Greljo, Isidori, Lindert, Marzocca, **Zhang**
Eur.Phys.J.C 77 (2017) 12, 838

Extensively used in, e.g. **NNLOJET** **MATRIX**

NNLOJET collaboration
arXiv: 2503.22804

See talk by Xuan Chen

General-purpose
Monte Carlo generator

Whizard

Kilian, Ohl, **Reuter**
Eur.Phys.J.C 71 (2011) 1742

Rational terms at two loops
Pozzorini, **Zhang**, Zoller, JHEP 05 (2020) 077

One-loop amplitude provider
with BSM models

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Denner, Lang, Uccirati
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Support SM and BSM models at NLO
e.g. 2HDM, HEFT,
Higgs singlet and triplet extension

Total and differential cross sections (benchmark)

[Bredt, Banno, Höfer, Iguro, Kilian, Ma, Reuter, **Zhang**, arXiv: 2509.05421]

Type I 2HDM

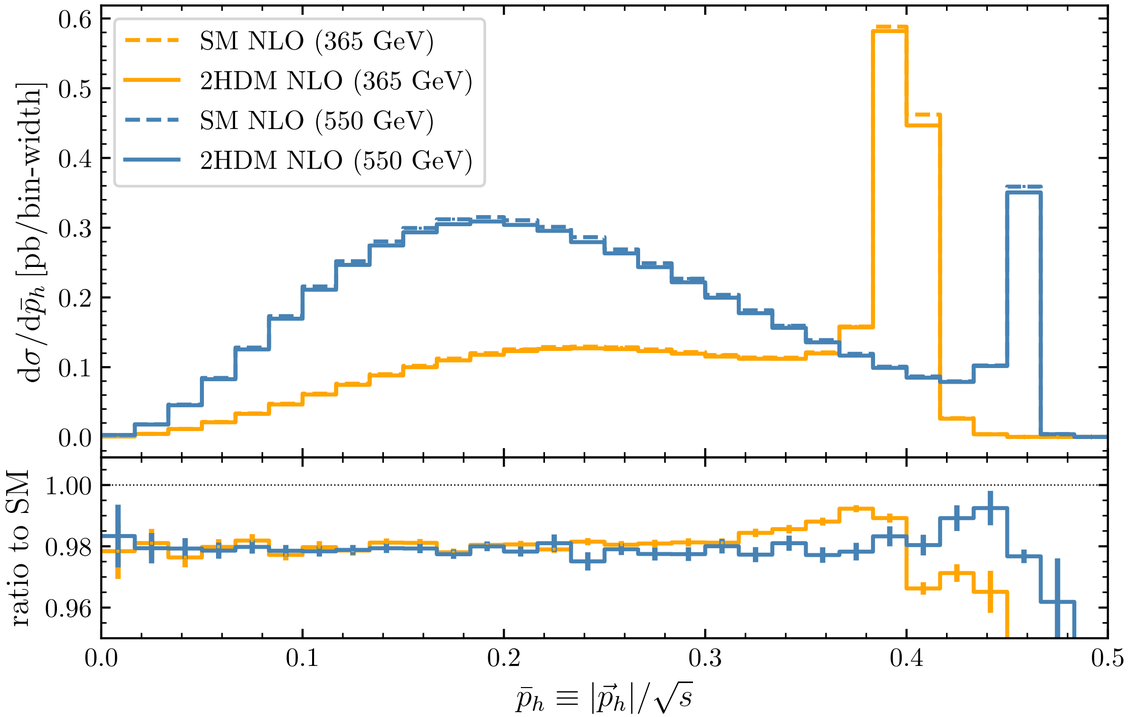
Benchmark point: $m_H = m_{H^\pm} = 400\,\text{GeV}$, $m_A = 435\,\text{GeV}$, $c_{\beta\alpha} = 0.037$, $t_\beta = 1.88$, $\lambda_5 = -2.54$

	$\sqrt{s} = 365\,\text{GeV}$		$\sqrt{s} = 550\,\text{GeV}$	
	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%

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

Alignment limit is $\cos(\beta - \alpha) = 0$

Sizable NLO effects even in alignment limit



Differential cross sections at NLO as a function of normalised Higgs three-momentum

Total and differential cross sections (benchmark)

[Bredt, Banno, Höfer, Iguro, Kilian, Ma, Reuter, **Zhang**, arXiv: 2509.05421]

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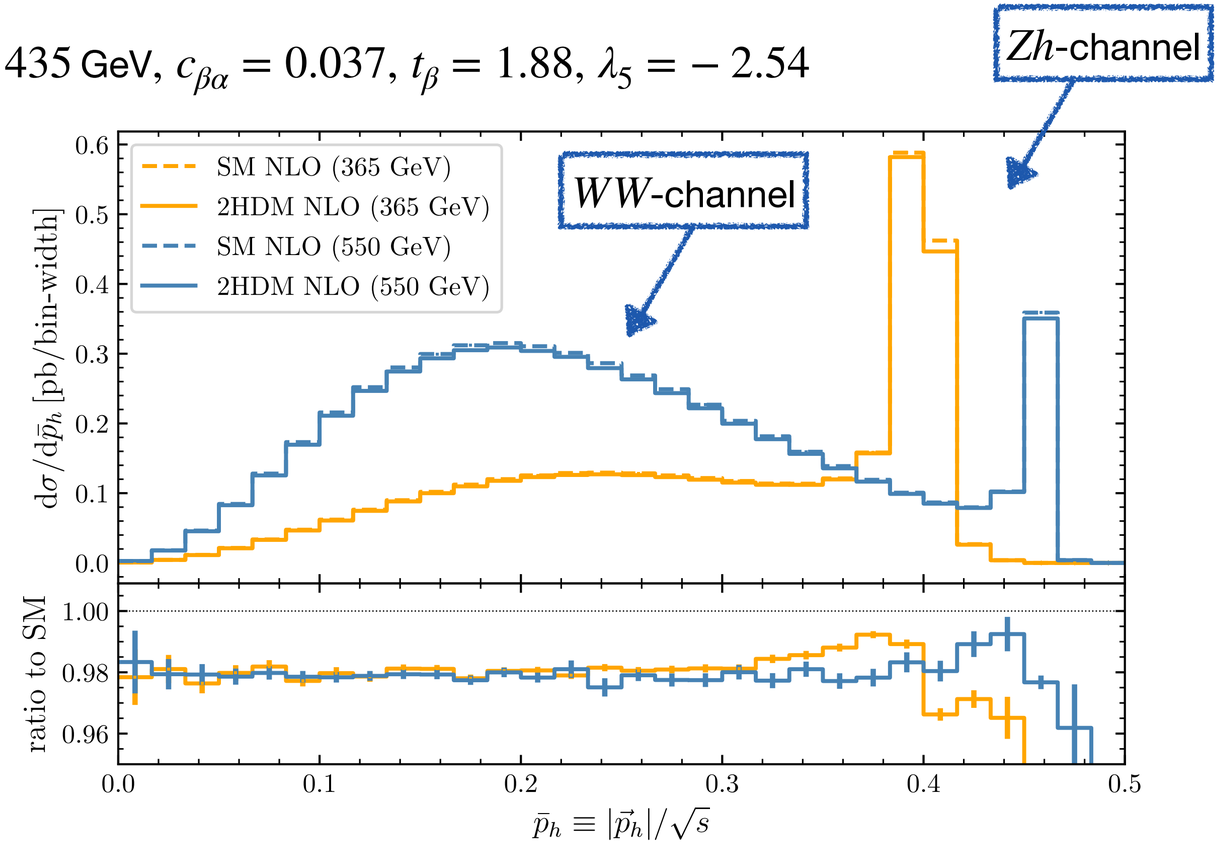


Differential cross sections at NLO as a function of normalised Higgs three-momentum

Disentangle Zh and WW channels, allow simultaneous probes

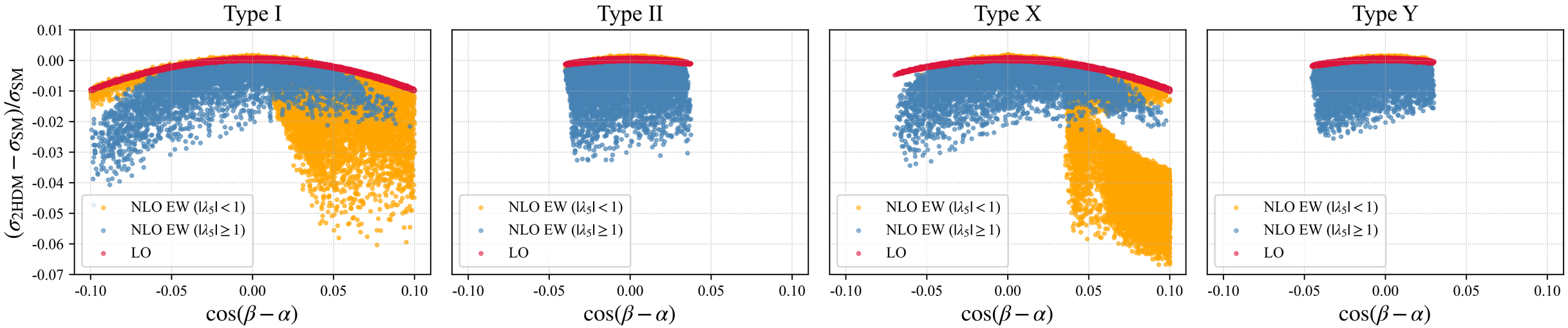
Comprehensive sensitivity analysis at $\sqrt{s} = 365$ GeV

[Bredt, Banno, Höfer, Iguro, Kilian, Ma, Reuter, **Zhang**, arXiv: 2509.05421]

160 000 allowed parameter points from **ScannerS** and **HiggsTools** (assuming $m_\phi \equiv m_H = m_{H^\pm} = m_A$) for type I, II, X, Y 2HDMs

Theory uncertainty in $(\sigma_{\text{2HDM}} - \sigma_{\text{SM}})$ is estimated to $0.7\,\%$

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



Relative differences between 2HDM and SM predictions in $c_{\beta\alpha}$-plane at $\sqrt{s} = 365$ GeV at LO (red) and NLO (orange for $|\lambda_5| < 1$, blue for $|\lambda_5| > 1$)

A combined (th+exp) uncertainty is estimated to be $0.92\,\%$

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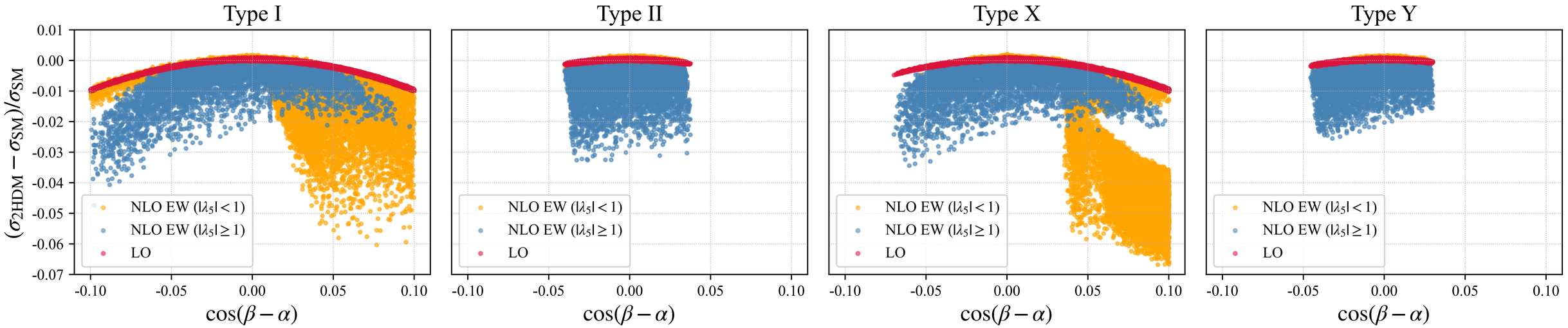

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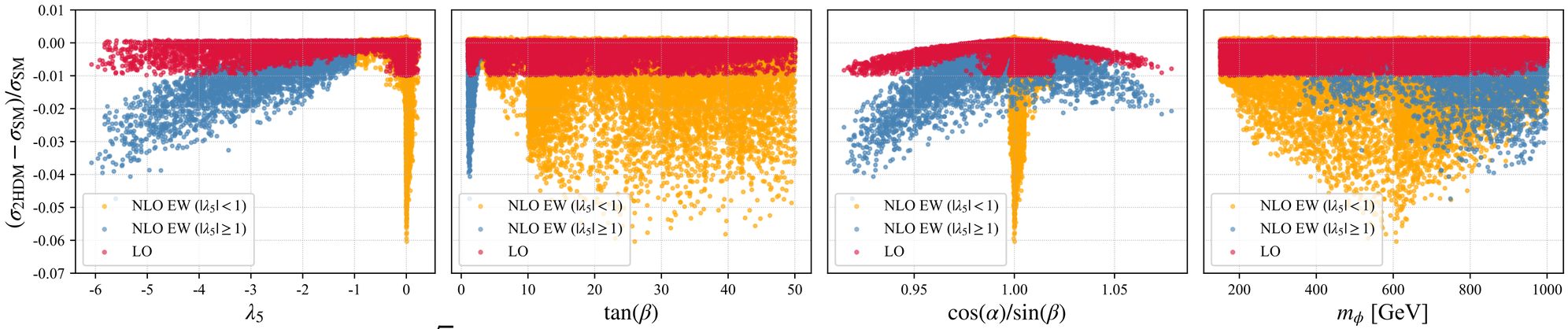
QCD corrections beyond NLO EW in G_μ scheme are small [Wang, Yang, Zhou, 21; Sun, Feng Jia, Sang, 17']
ISR effect beyond NLO is small [Denner, Dittmaier, Roth, Weber, 03']
Missing SM higher-order corrections do not contribute to theory uncertainty in $(\sigma_{\rm 2HDM} - \sigma_{\rm SM})$

Precise model-type discrimination requires NNLO EW in 2HDM

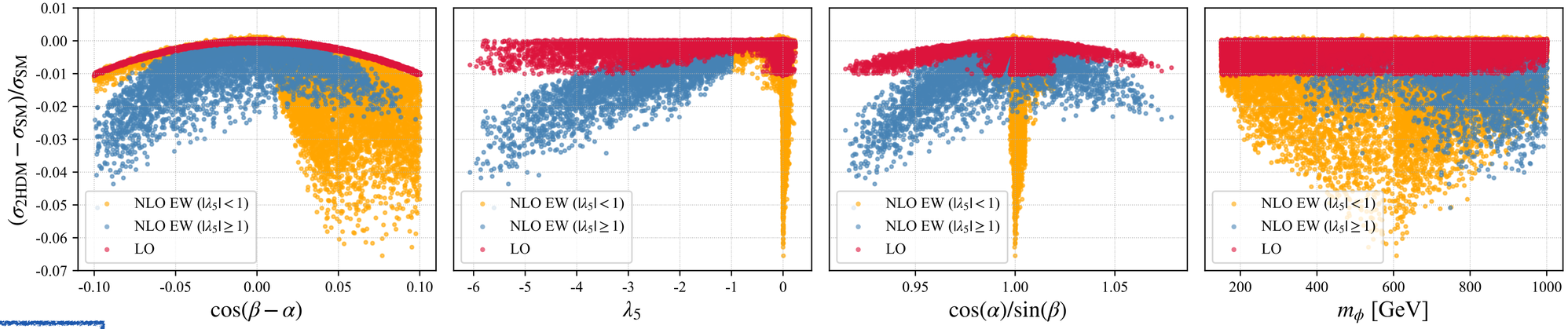
Comprehensive sensitivity analysis at $\sqrt{s} = 365$ and 550 GeV

[Bredt, Banno, Höfer, Iguro, Kilian, Ma, Reuter, **Zhang**, arXiv: 2509.05421]



Type I 2HDM predictions at $\sqrt{s} = 365$ GeV at LO (red) and NLO (orange for $|\lambda_5| < 1$, blue for $|\lambda_5| > 1$) for $|c_{\beta\alpha}| < 0.1$

A combined (th+exp) uncertainty is estimated to be $0.92\,\%$



$\sqrt{s} = 550$ GeV case is slightly pronounced in sensitivity but cross sections are larger

Type I 2HDM predictions at $\sqrt{s} = 550$ GeV. A combined (th+exp) uncertainty is estimated to be $0.85\,\%$

Summary

Precision can discover new physics!

- **Precision BSM phenomenology at e^+e^- colliders** [arXiv: 2509.05421]
  - EW corrections are powerful probe to explore extended Higgs sector (in $e^+e^- \to h\nu\bar{\nu}$)
  - Observe several-percent NLO-enhanced difference (up to $6 \sim 7\,\% > 5\sigma$) between 2HDM and SM cross sections, even in alignment limit (up to $2 \sim 3\,\% > 2\sigma$)
  - Highlight discovery potential of precision studies at e^+e^- colliders for new physics searches