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

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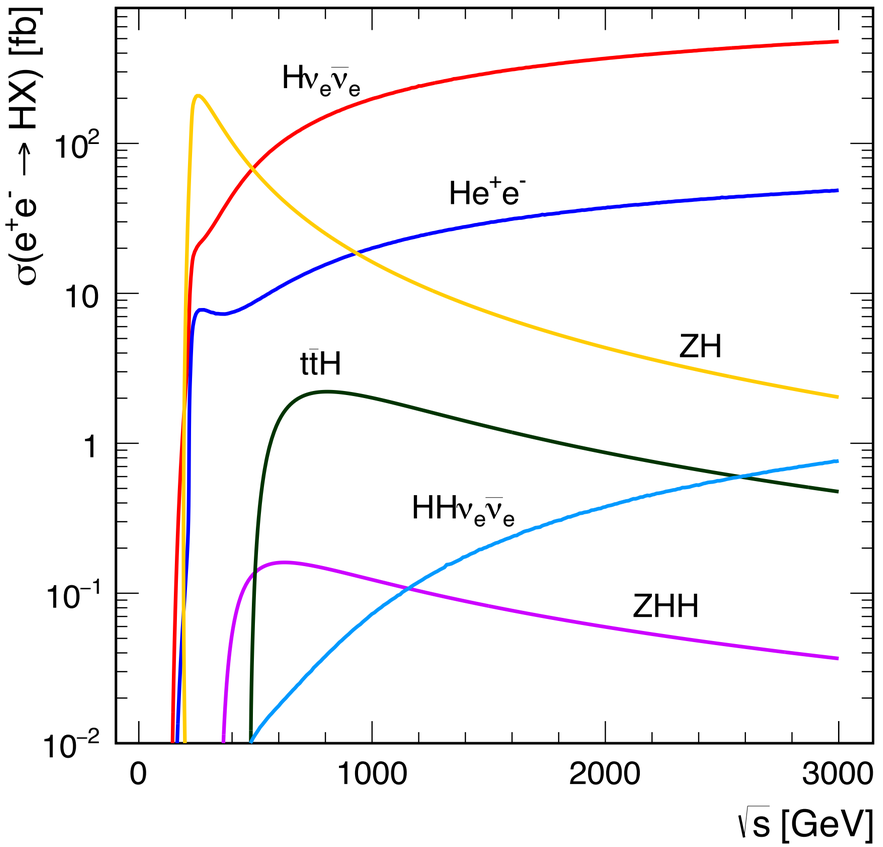
https://yangphy.github.io/

Higgs production at e^+e^- Higgs factories

Higgs production channels in the Standard Model



1608.07538: Higgs Physics at the CLIC Electron-Positron Linear Collider

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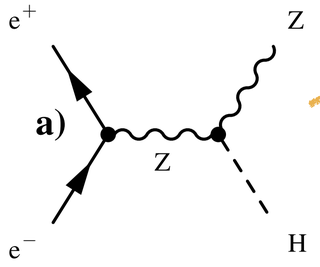
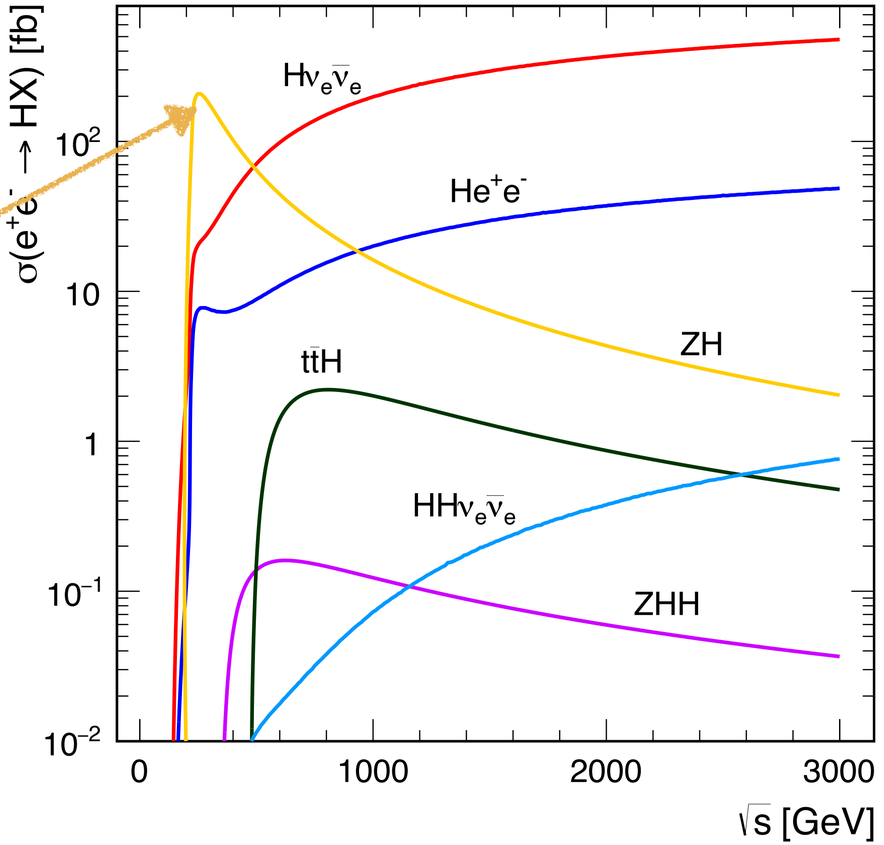
Higgs-strahlung



240 GeV FCC-ee/CEPC
250 GeV ILC



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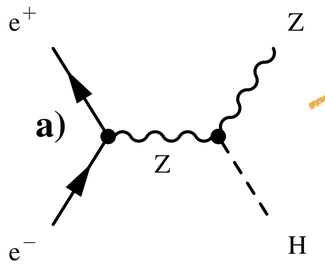

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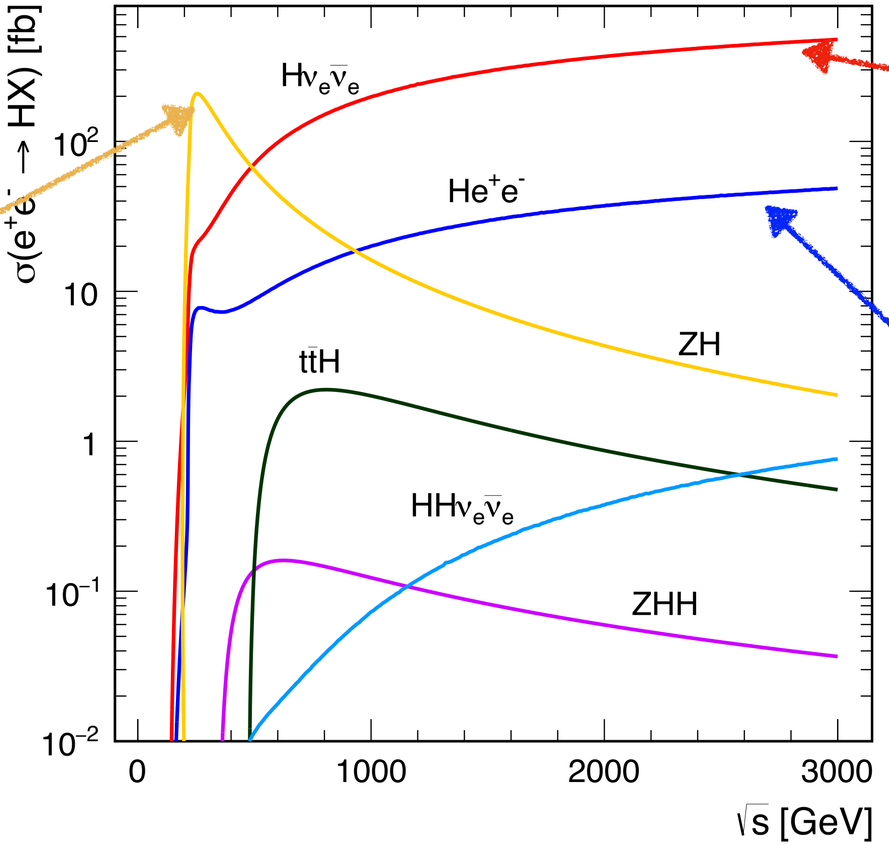
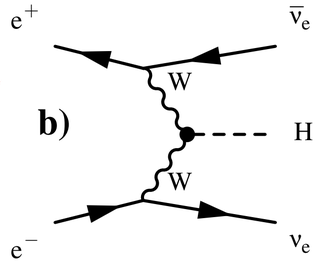
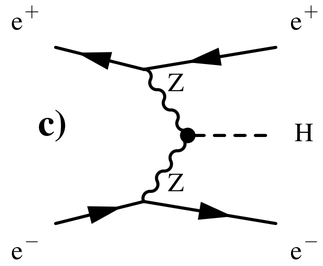


Vector-boson-fusion (VBF)



WW fusion



ZZ fusion

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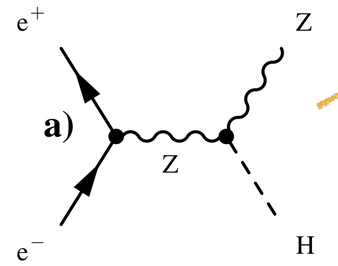

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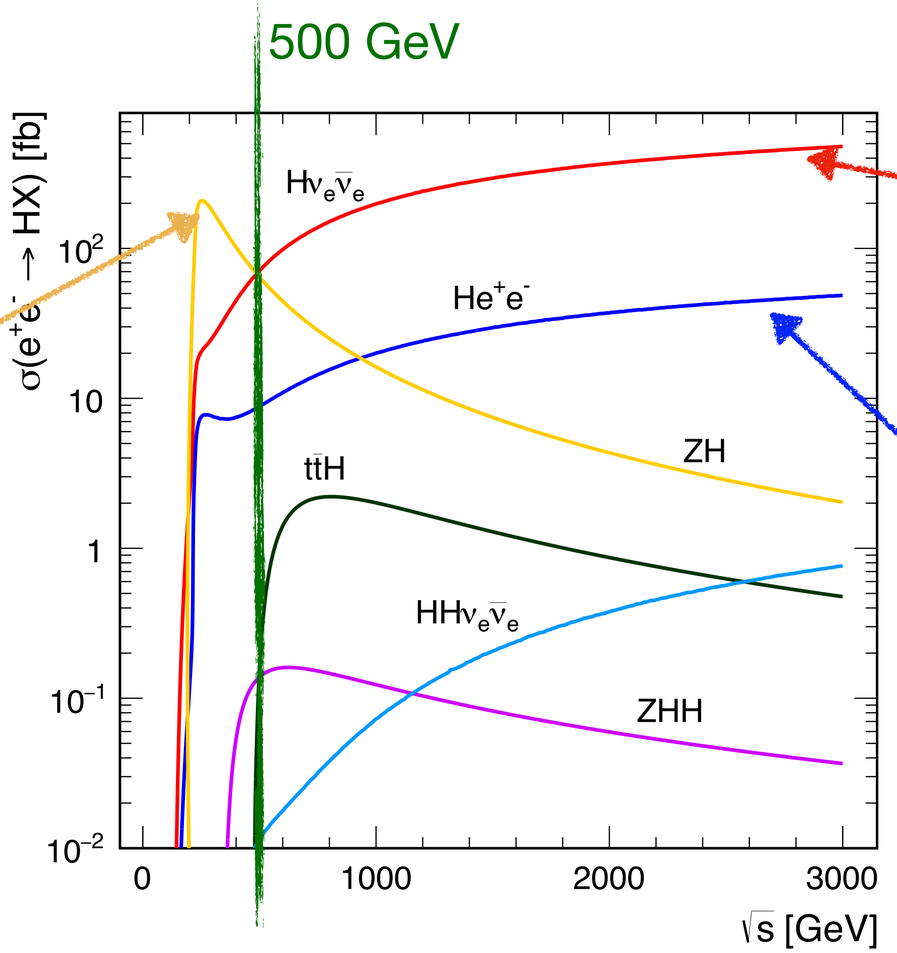

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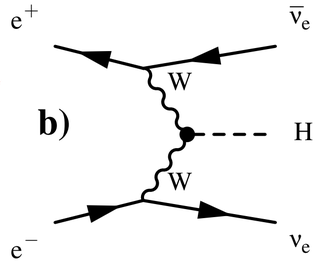

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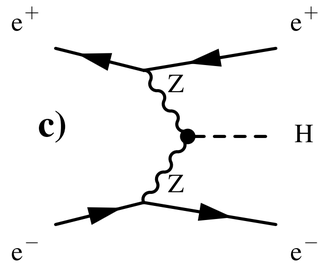

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Our experimental colleagues :

- Produce the as many Higgs as they can - higher luminosities
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“How about BSM ?”

e.g. MadGraph5_aMC@NLO

Higgs physics beyond the SM

2HDM as a benchmark

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 $R_{D^{(*)}}$

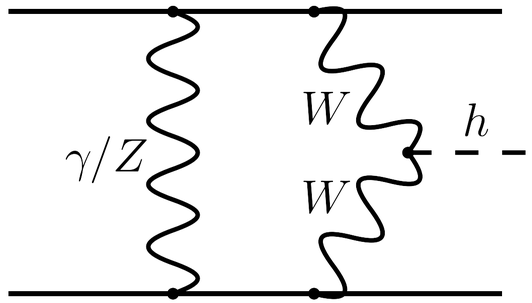
Hints from electroweak-scale excesses at the LHC

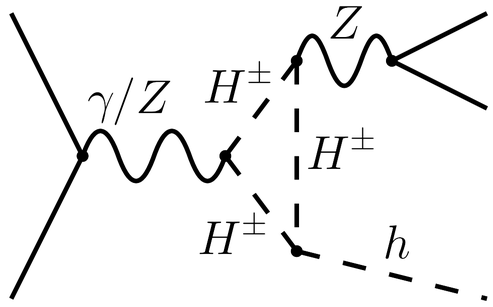
EW Loops for 2HDM at e^+e^- Higgs factories

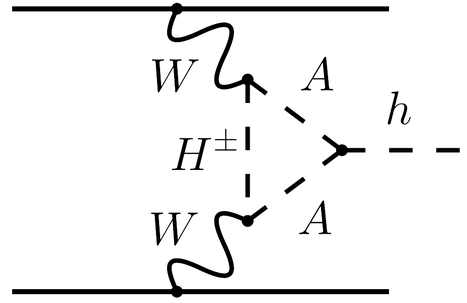
- For FCC-ee: $e^+e^- \to ZH$ has been well studied NLO in 2HDM and SUSY

  Aiko, Kanemura, Mawatari, 21'; Anisha, Arco, Di Noi, Englert, Mühlleitner, 25'; Heinemeyer, Paßehr, Schappacher, 25'

- $e^+e^- \to H\nu\bar{\nu}$:
  - LO production rate~50% to $e^+e^- \to ZH$ at 365 GeV, and dominates at $\sqrt{s} > 500$ GeV
  - The first 2HDM analysis is done in 2509.05421







How is it achieved ?

Our friends and competitor: Whizard

General-purpose
Monte Carlo generator

Whizard

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

How is it achieved ?

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)

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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

Benchmark for the total/differential cross sections

Type I 2HDM

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

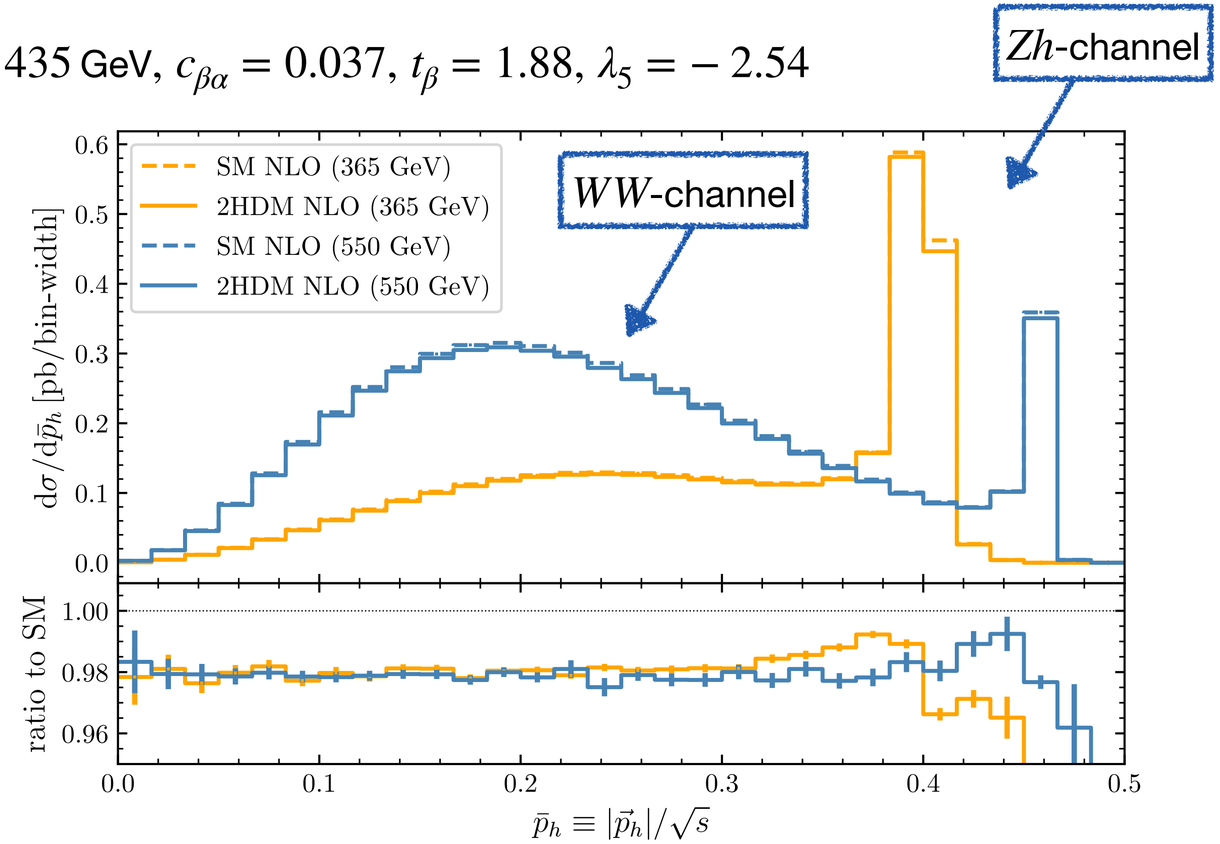
	$\sqrt{s} = 365\,\text{GeV}$		$\sqrt{s} = 550\,\text{GeV}$	
	LO [fb]	NLO EW [fb]	LO [fb]	NLO EW [fb]
SM	55.79	52.44(1)	97.82(1)	88.45(2)
2HDM	55.71	51.45(1)	97.67(1)	86.59(2)
Rel.Diff.	−0.1%	−1.9%	−0.2%	−2.1%
2HDM (aligned)	55.79	51.58(1)	97.81(1)	86.83(2)
Rel.Diff.	0.0%	−1.7%	0.0%	−1.8%

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

Bredt, Banno, Höfer, Iguro, Kilian, **Ma**, Reuter, Zhang, 2509.05421



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

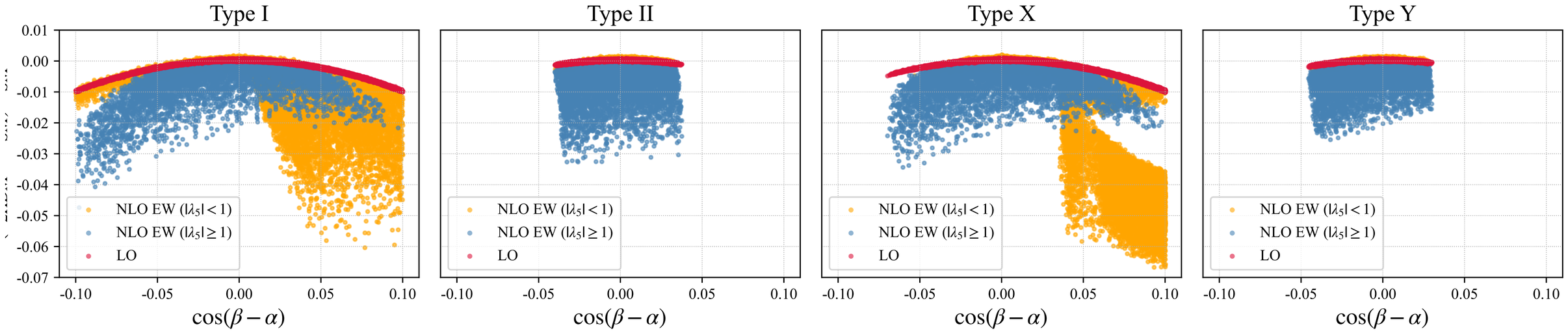
Disentangle Zh and WW channels, allow simultaneous probes

BSM sensitivity at FCC-ee $\sqrt{s} = 365$ GeV

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

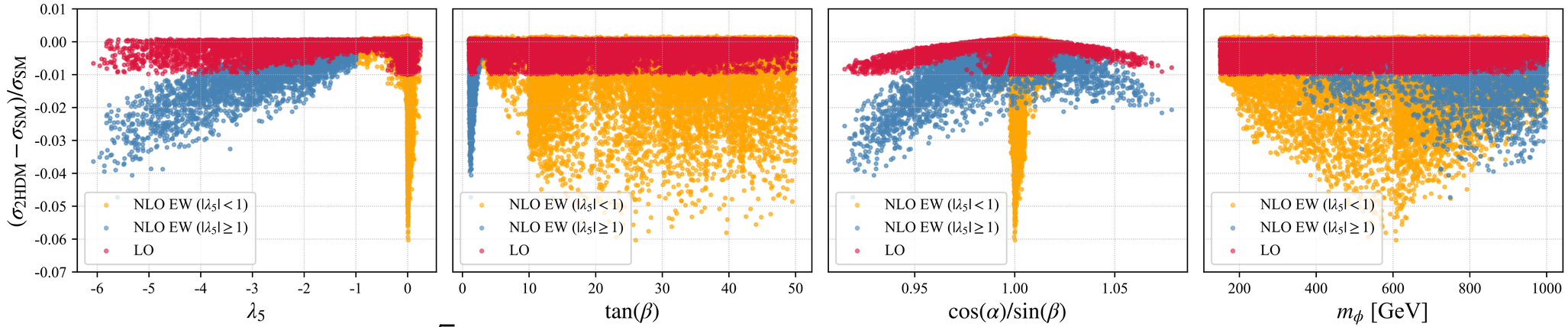


Relative differences between 2HDM and SM predictions in $c_{\beta\alpha}$-plane at $\sqrt{s} = 365$ GeV at LO (red) and NLO (orange for $|\lambda_5| < 1$, blue for $|\lambda_5| > 1$)

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

Bredt, Banno, Höfer, Iguro, Kilian, **Ma**, Reuter, Zhang, 2509.05421

BSM sensitivity at higher energies



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 $0.92\ \%$

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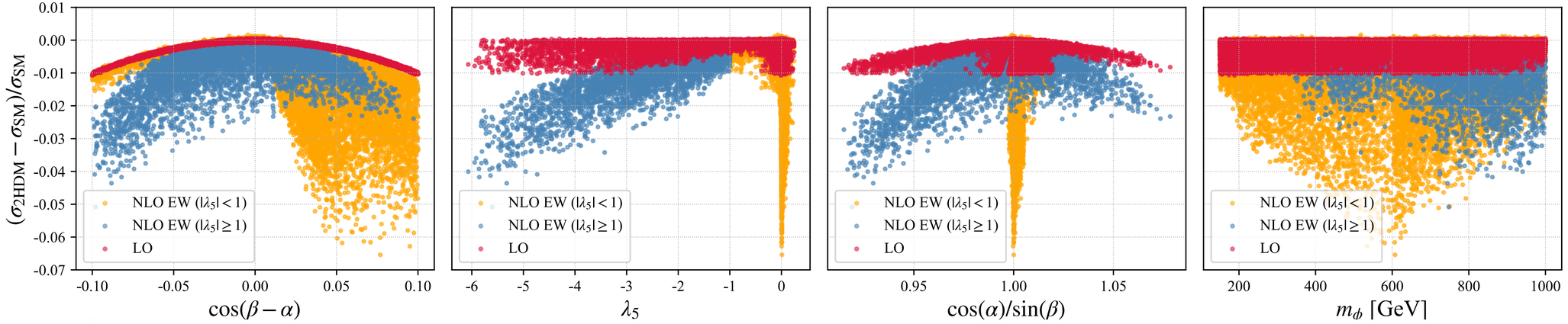

Type I 2HDM predictions at $\sqrt{s} = 550$ GeV. A combined (th+exp) uncertainty is estimated to be $0.85\ \%$

Comments

Our observation :

- 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

Our comments :

- At future e^+e^- colliders, the NLO EW will induce the BSM signals that are not present at LO
- **NLO EW will be a standard practice for BSM phenomenology** studies at next generation colliders

Our wish :

The next generation MC tool shall enable automated NLO EW even for BSM models