Karlsruhe Institute of Technology Institute for Theoretical Physics

Probing SFOEWPT scenarios in 2HDM with FCC-ee/CEPC

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Based on arXiv: 2506.18555 , with

Francisco Arco, Stefano Di Noi, Christoph Englert, Margarete Mühlleitner

[JHEP 10 (2025) 179]

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Motivation

- Origin of the baryon asymmetry of the universe (BAU) remains an open problem.

$$\eta_b \equiv \frac{n_b - n_{\bar{b}}}{n_\gamma} \simeq 6.1 \times 10^{-10}$$ Planck 2018

- Electroweak baryogenesis requires three Sakharov conditions Sakharov '67
  - Baryon number violation (BNV)
  - CP violation
  - Departure from thermal equilibrium

- In SM

BNV Interactions ✓

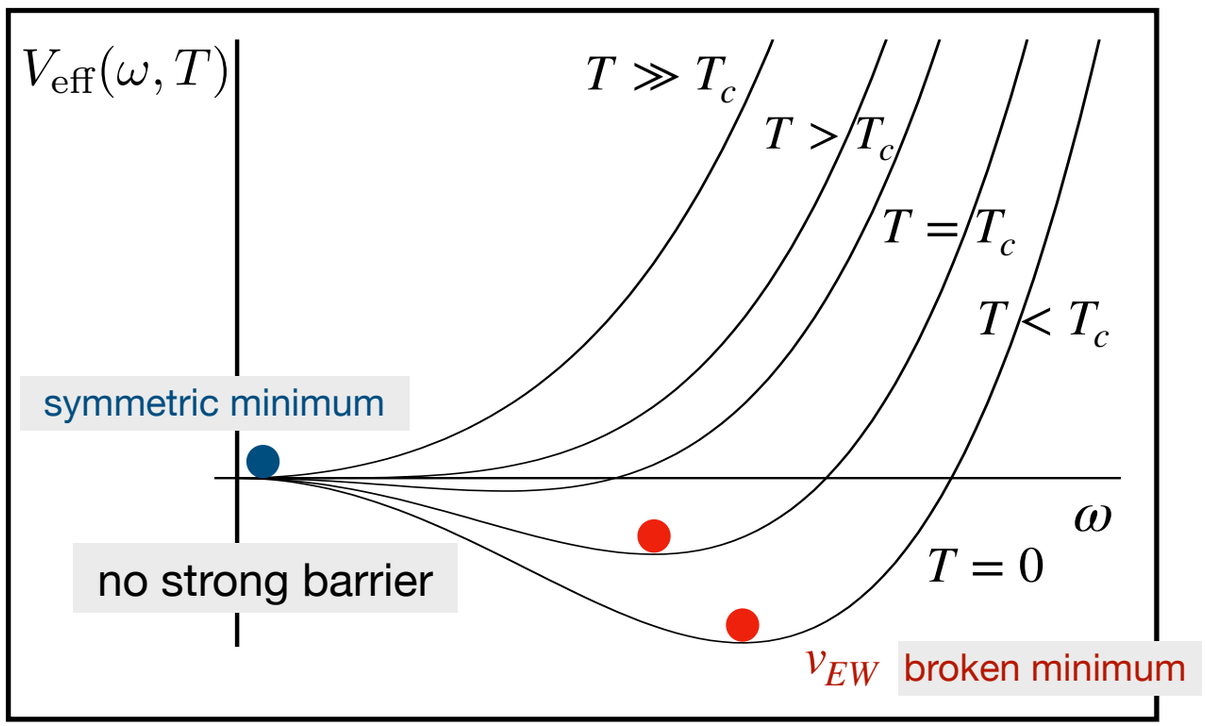
CP Violation ✓ but too small ✗

Departure from thermal equilibrium ✗

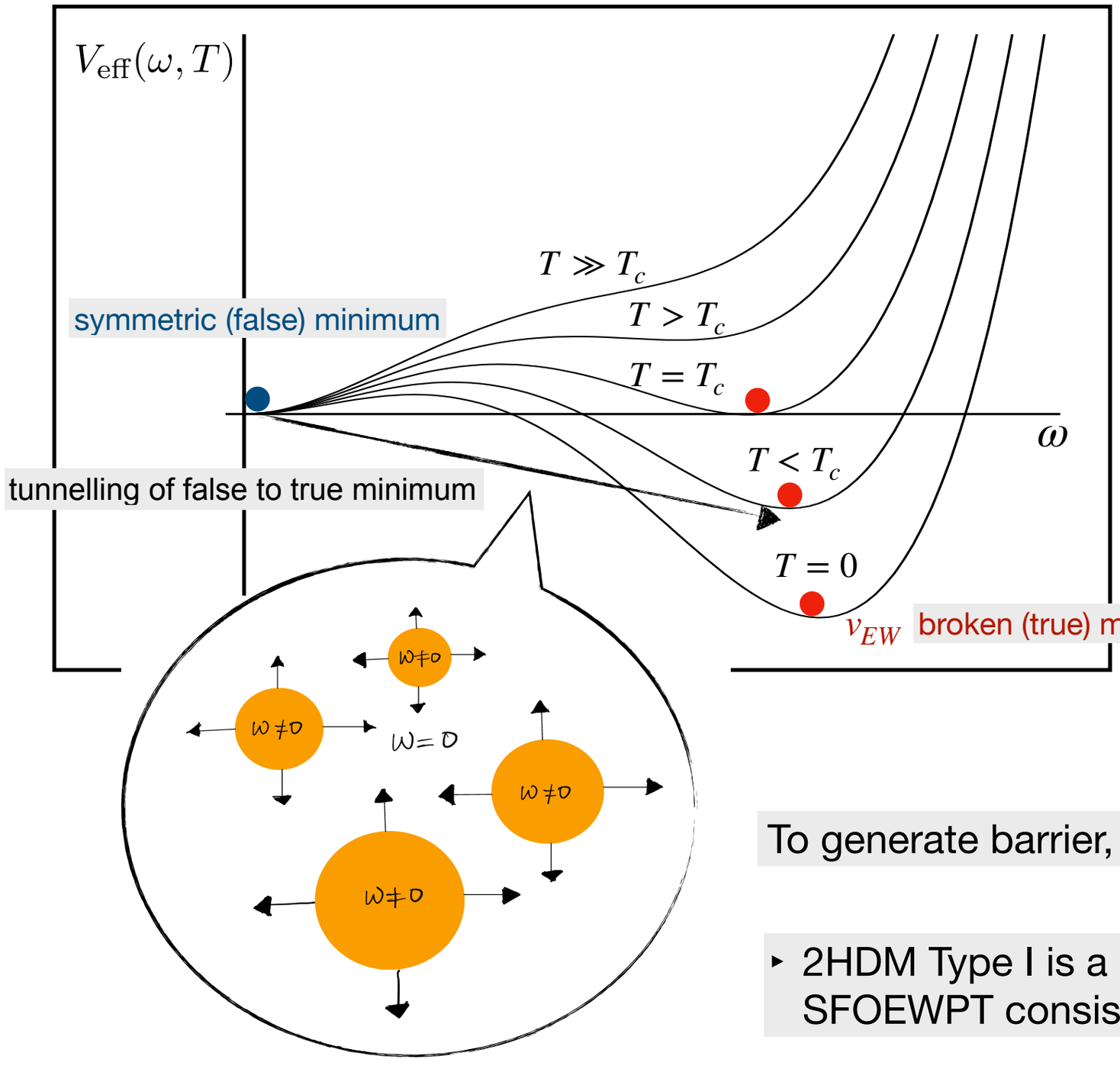
  - EWPT is a smooth crossover for observed Higgs mass

    Kajantie et al '96, Csikor et al '99

  - Strong first-order EW phase transitions



Strong *First-order* EWPT



Morrissey, Ramsey-Musolf 1206.2942

For a *first-order* phase transitions

- existence of barrier between unbroken and broken phase.
- For strong FOEWPT

  at percolation stage

  $$\xi_p = v_p(T_p)/T_p > 1$$

  *29% of the false phase has tunnelled.

To generate barrier, extended SM potential is required.

- 2HDM Type I is a promising candidate to generate SFOEWPT consistent with current experimental data.

2HDM Type I: Model Info

T.D. Lee `73, Gunion Haber `03
Branco et al 1106.0034

CP conserving

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{1}{\sqrt{2}}(v_1 + \zeta_1 + i\psi_1) \end{pmatrix} \qquad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{1}{\sqrt{2}}(v_2 + \zeta_2 + i\psi_2) \end{pmatrix}$$

softly broken $\mathbb{Z}_2$ symmetry: $\Phi_1 \to \Phi_1, \ \Phi_2 \to -\Phi_2$

five physical Higgs bosons: $h\,, \quad H\,, \quad A\,, \quad H^\pm$

Coupling modifiers

For Type I

ζ_f^h	ζ_f^H	ζ_u^A	$\zeta_{d,l}^A$
$\sin(\beta-\alpha) + \cos(\beta-\alpha)\ \cot\beta$	$\sin(\beta-\alpha) - \cos(\beta-\alpha)\ \cot\beta$	$\cot\beta$	$-\cot\beta$

Input Parameters

$$v = 246\,\text{GeV}\,, \quad m_h\,, \quad m_H\,, \quad m_A\,, \quad m_{H^\pm}\,, \quad \tan\beta\,, \quad \cos(\beta-\alpha)\,, \quad \bar{m}$$

lighter scalar h is SM-like

$$\bar{m}^2 = \frac{m_{12}^2}{\sin\beta\cos\beta}$$

Alignment without decoupling (alignment limit)

$\cos(\beta-\alpha) \to 0$ → BSM scalars can be light; tree-level SM-like couplings for h with gauge bosons and fermions

Alignment with decoupling (decoupling limit)

$$\cos(\beta-\alpha) \to 0, \qquad \bar{m} \sim m_H,\, m_A,\, m_{H^\pm} \gg v$$

Effective potential at finite temperature

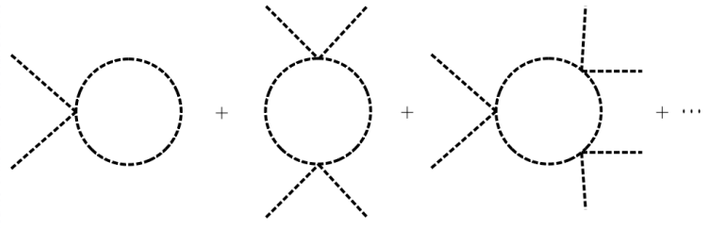
1-loop effective potential

$$V_{\text{eff}}(\omega, T) = V(\omega) + V_T(\omega, T)$$
$$= \boxed{V_{\text{dim-4}}(\omega)} + \boxed{V_{\text{CW}}(\omega)} + \boxed{V_{\text{CT}}(\omega)} + \boxed{V_T(\omega, T)}$$

ω is classical field configuration

Tree level | Coleman-Weinberg | Counter term | Temperature-dependent thermal part

- one-loop contributions at zero temperature.

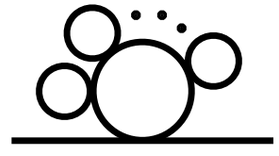


Coleman Weinberg '73

- fixes the 1- loop masses and mixing angles to tree level values.

Basler et al 1612.04086

- one-loop thermal corrections at high T $\propto T^2, T^4$
- resummation of n-loop daisy diagrams via Arnold-Espinosa method



Dolan Jackiw `74 Carrington `92 Quiros `99
Arnold, Espinosa `92

Implementation in BSMPTv3

Basler Mühlleitner 1803.02846
Basler et al 2007.01725, 2404.19037

SFOEWPT in 2HDM

- SFOEWPT arises from thermal barrier generated by radiative corrections.
  - BSM scalars need not be very heavy and sizeable scalar quartic couplings.

    For consistency with LHC data

    favours close to the alignment $\cos(\beta-\alpha)\approx 0$

    $$m_H, m_A, m_{H^\pm} < 1\ \text{TeV}$$

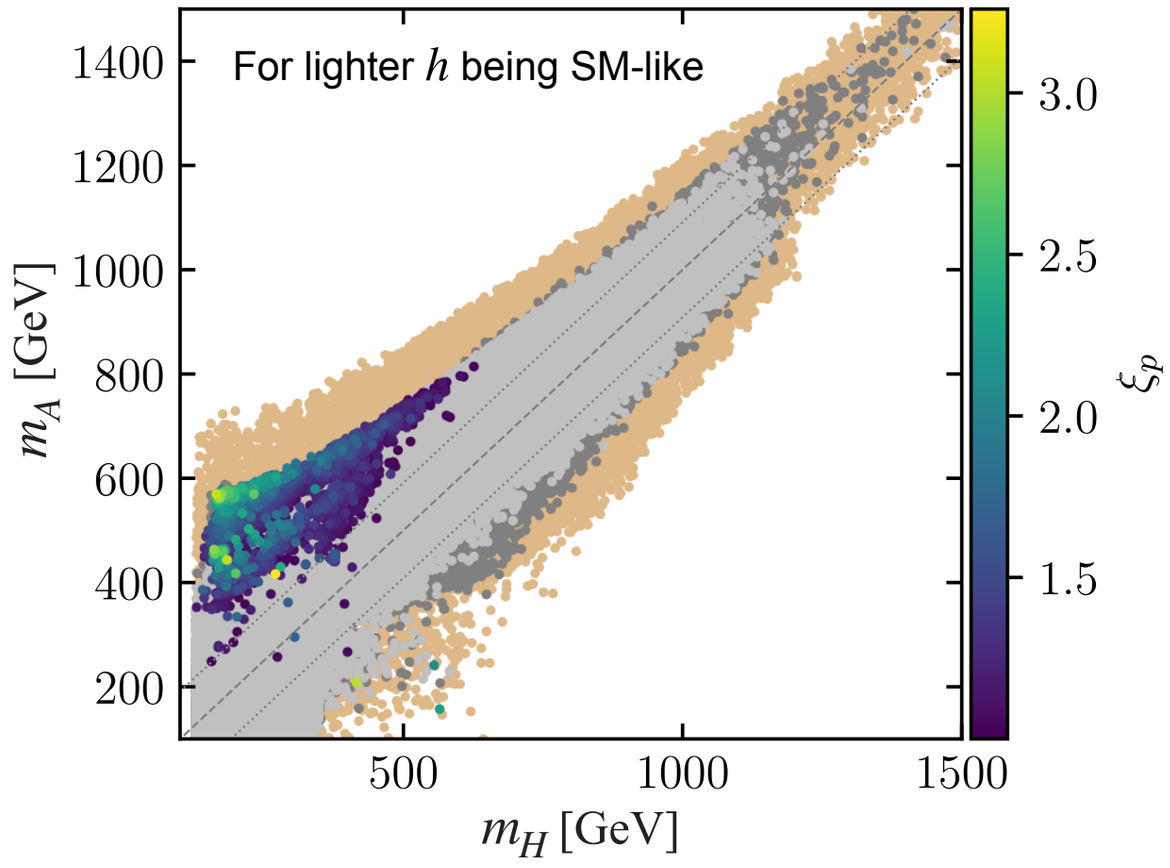
  - Mass splittings between BSM scalars.

    SFOEWPT favour spectrum with non-decoupling regime

    T-parameter

    $$m_A \sim m_{H^\pm}$$
    $$m_A > m_H$$
    $$m_h$$

    $\Longrightarrow$ alignment without decoupling



Biermann, Borschensky, Boto, Mühlleitner, Santos, Viana 2608.25636

For literature on collider phenomenology favoured by SFOEWPT

Dorsch et al 1405.5537, 1705.09186, Basler et al 1612.04086, 1711.04097, Andersen et al 1711.09849, Bernon et al 1712.08430, Su et al 2011.04540, Gonçalves et al 2108.05356, Biekötter et al 2208.14466, 2309.17431, Bitter et al 2504.02024

Scan methodology

Scan ranges of the 2HDM input parameters

m_h [GeV]	m_H [GeV]	m_A [GeV]	$m_{H^\pm}$ [GeV]	$\tan\beta$	$\cos(\beta-\alpha)$	$\overline{m}$ [GeV]
125.25	150...1500	20...1500	20...1500	0.5...50	-0.35...0.35	0...1500

lighter scalar h is SM-like



ScannerS

Coimbra et al 1301.2599
Mühlleitner et al 2007.02985



BSMPTv3

Basler Mühlleitner 1803.02846
Basler et al 2007.01725, 2404.19037



- Parameter points generated are checked for the consistency with the theoretical and experimental constraints.

  tree-level unitarity
  vacuum stability
  boundedness from below

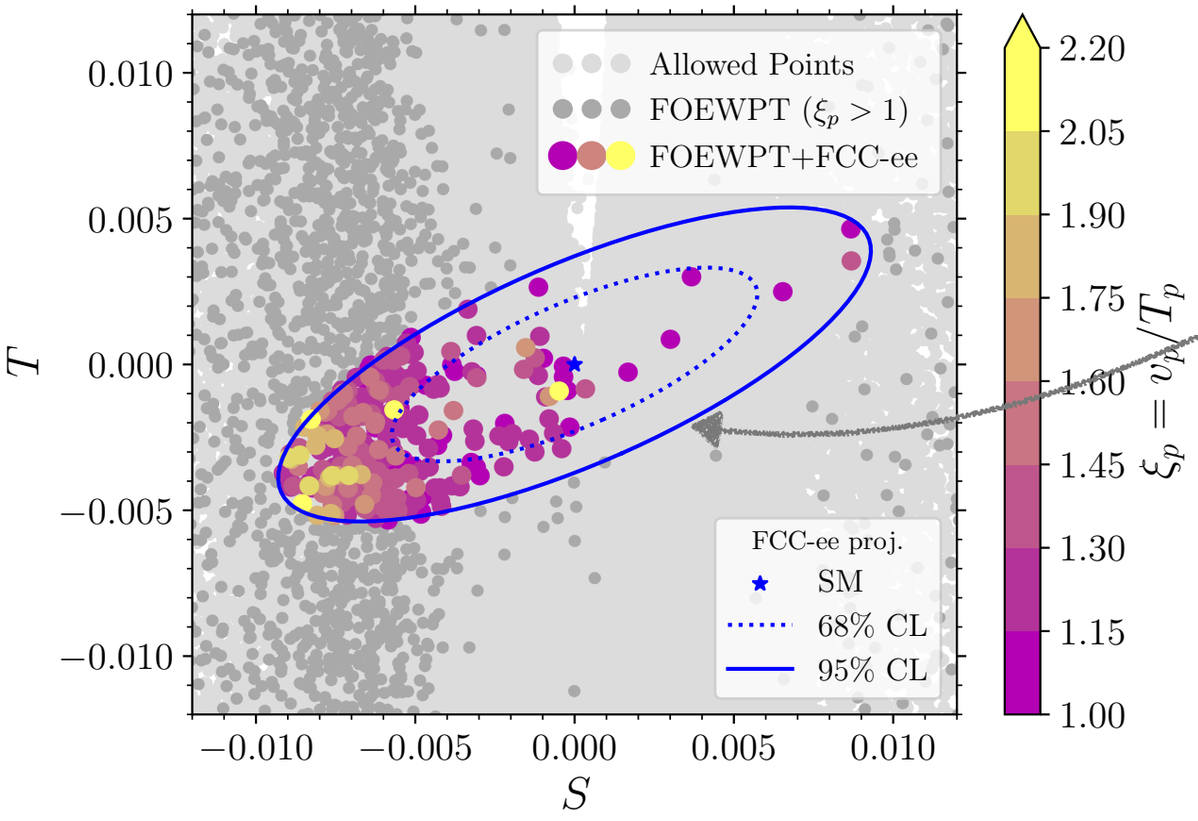
  EWPO constraints via S, T, U 2σ limits at one-loop
  `HiggsTools` — collider BSM searches
  Flavour constraints

- Implementation of loop-corrected resummed effective potential
- Minimisation of loop-corrected potential to explore the vacuum structure
  $\longrightarrow$ $v(T)$ at a given temperature T
- Calculation of the strength of PT : $\xi_p = v_p/T_p$

Collider implications on the parameter space favoured by SFOEWPT

- Precision Electroweak and Higgs measurements at future e^-e^+ colliders.

SFOEWPT favoured FCC-ee Z pole constraints



Blas et al 1905.03764, ESPPU 2020

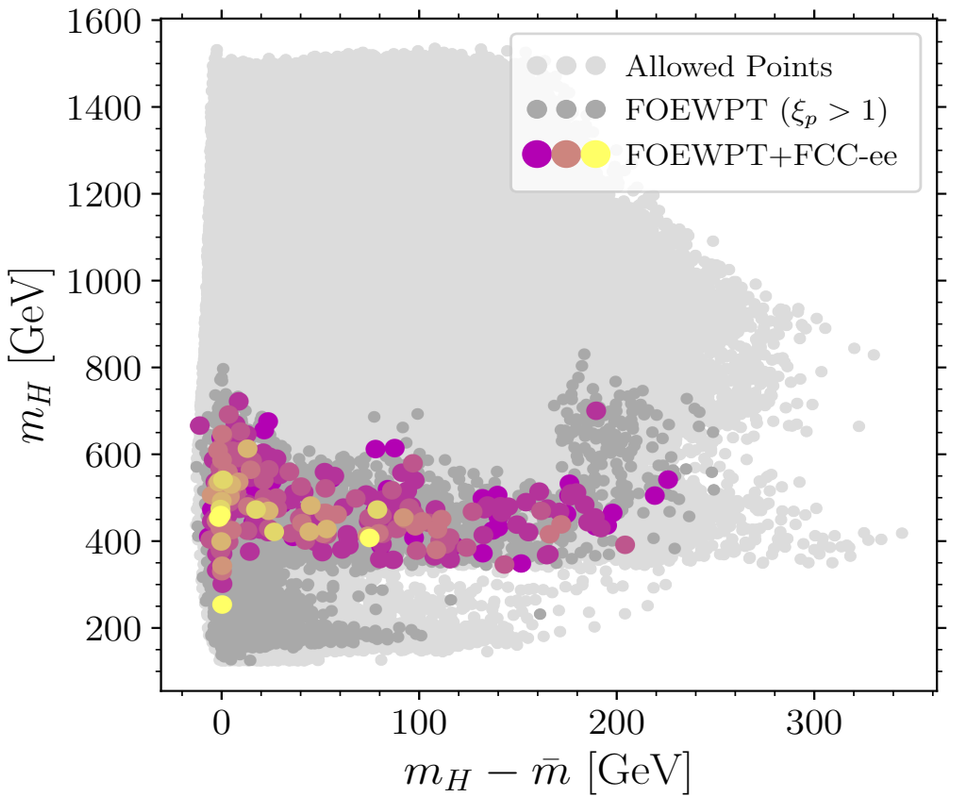
FCC-ee Z-pole 1σ sensitivity

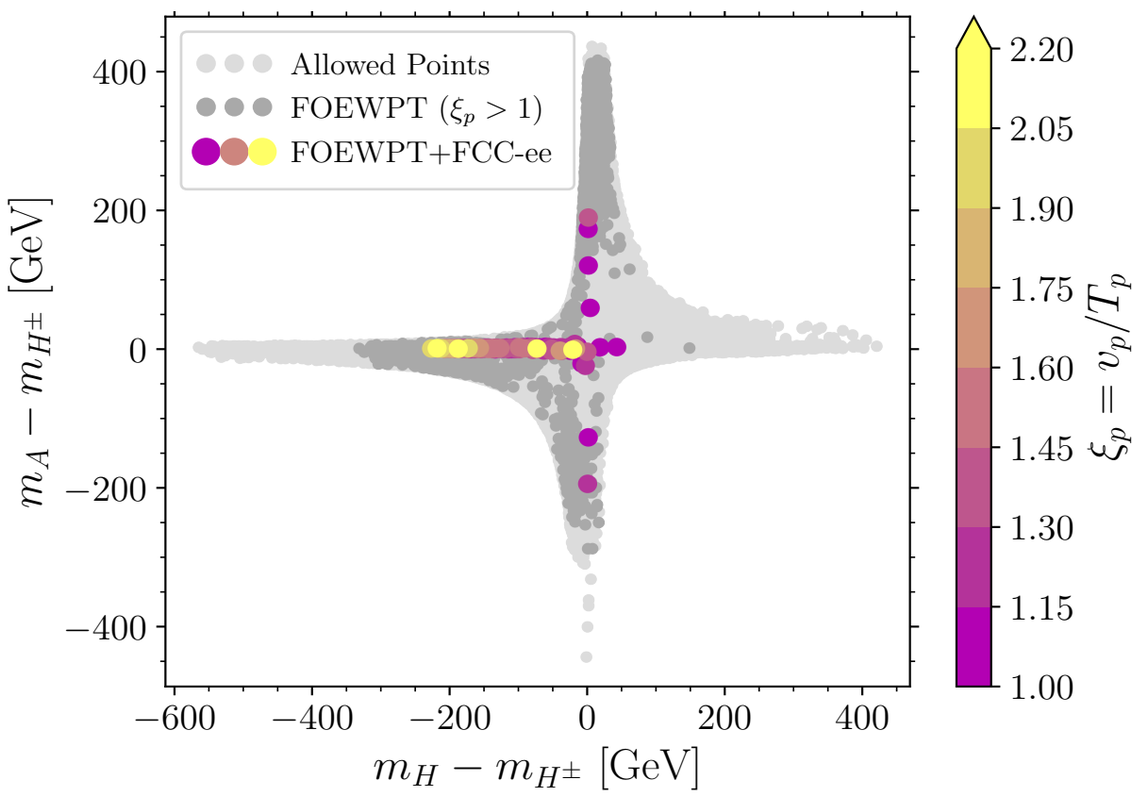
$\sigma_S = 0.0038\,,\ \sigma_T = 0.0022\,,\ \rho_{ST} = 0.724$

No theory uncertainties!

- Z pole constraints probe
  - region specifically *away* from alignment limit.
- Disfavours the large mass splittings for SFOEWPT
  - shifts the allowed points towards alignment with lower mass scales.

- Similar allowed regions with CEPC precision.



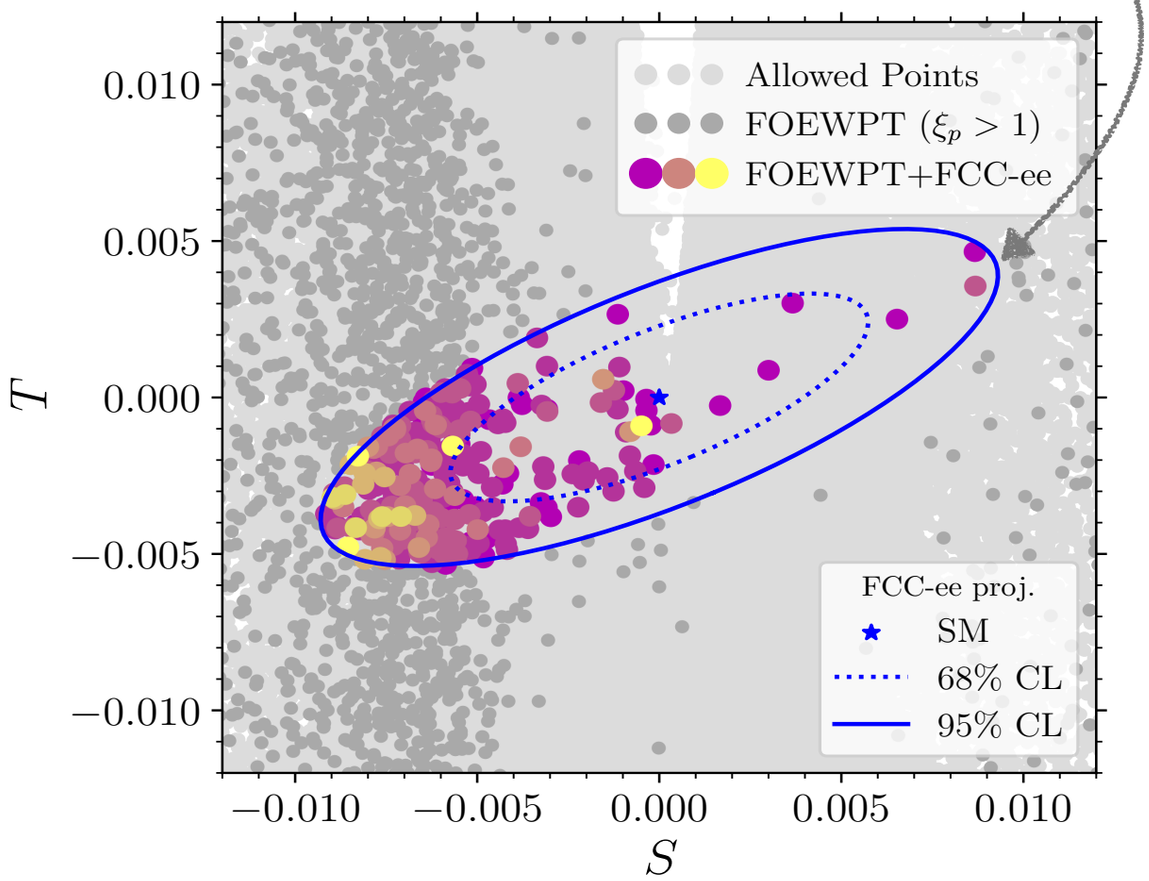


HL-LHC constraints with SFOWEPT

Blas et al 1905.03764, ESPPU 2020

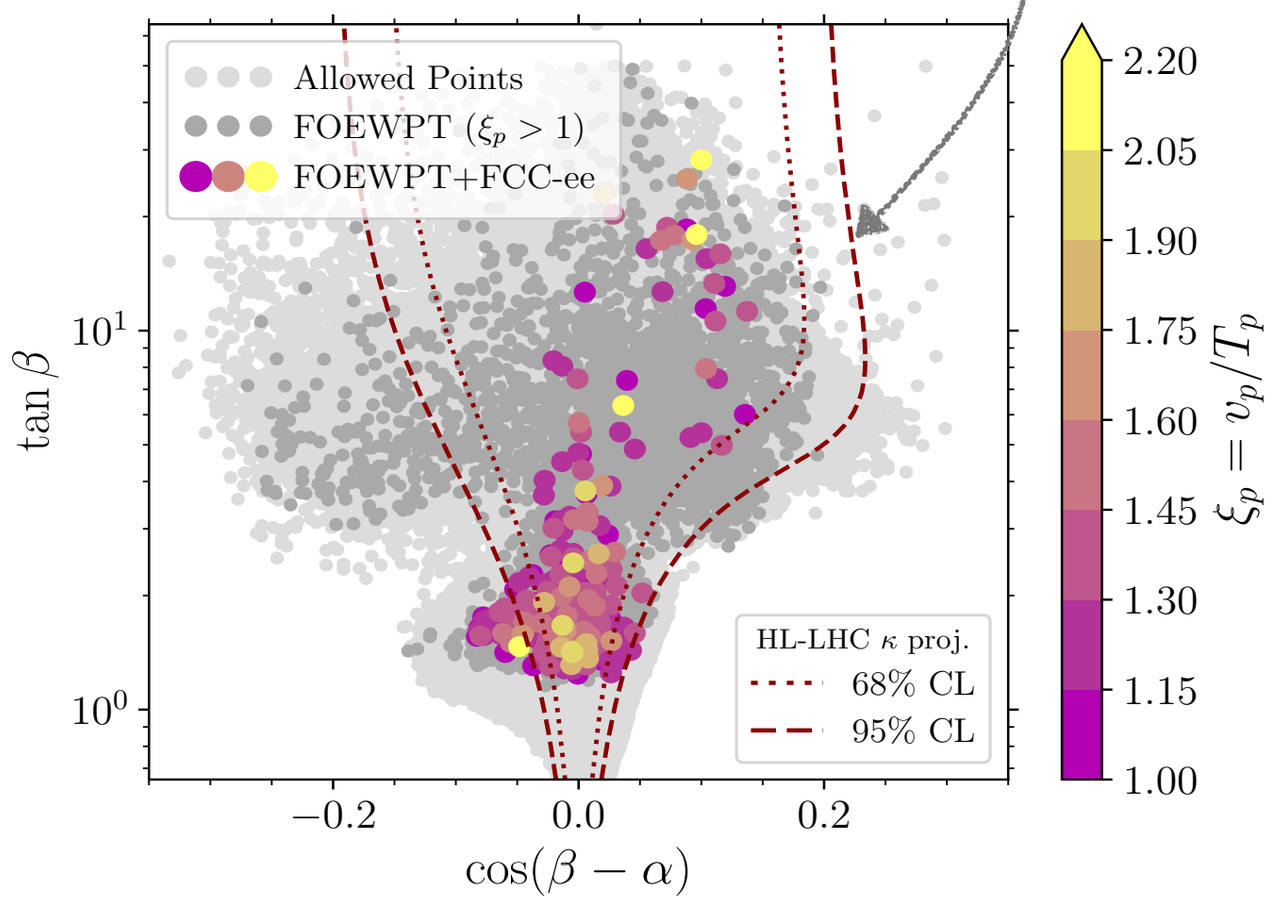
FCC-ee Z-pole 1σ sensitivity

$\sigma_S = 0.0038\,,\ \sigma_T = 0.0022\,,\ \rho_{ST} = 0.724$



ATLAS, CMS 2504.00672

HL-LHC projected κ modifiers



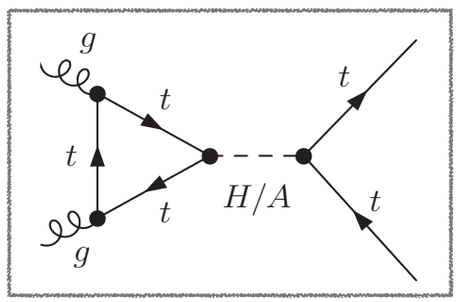
$\Longrightarrow$ HL-LHC constrained region is weaker as compared to FCC-ee.

- BSM scalars are within the reach of LHC as $m_H/m_A > t\bar{t}$ threshold.
  - top-philic exotic scalar searches are viable candidates for 2HDM constraints.

LHC exotic scalar searches

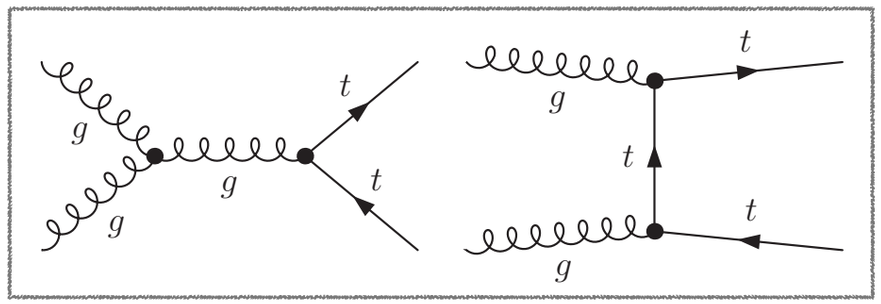
ATLAS 2404.18986
CMS 1908.01115, 2507.05119

Signal: resonant production
$gg \to H/A \to t\bar{t}$



$$\mathrm{d}\sigma^{\mathrm{LO}} \sim |\mathcal{M}_S|^2$$

dominant background is QCD induced
$gg \to t\bar{t}$



$$\mathrm{d}\sigma^{\mathrm{LO,I}} \sim 2\mathrm{Re}\left(\mathcal{M}_S^* \mathcal{M}_{\mathrm{rest}}\right)$$

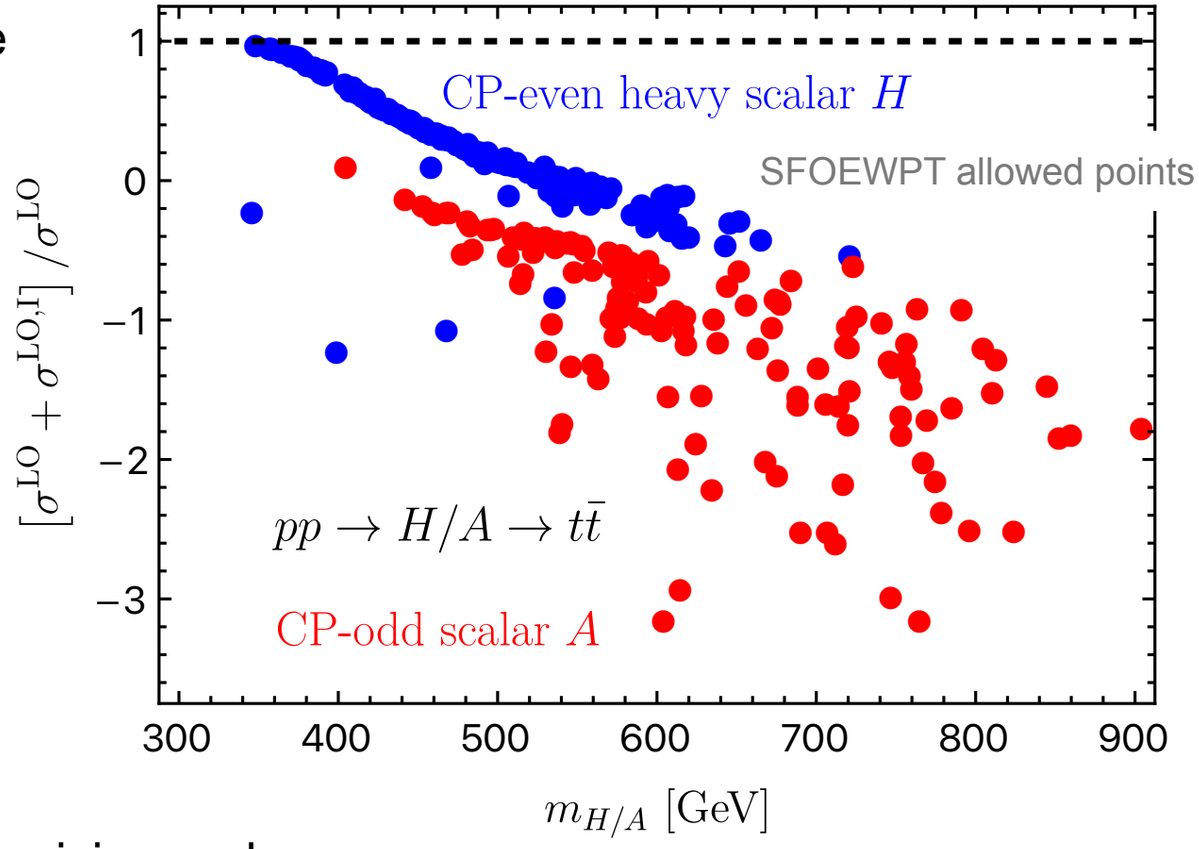
+ other scalars

- Large signal-background destructive interference distorts the resonant signal.

Gaemers, Hoogeveen `84, Basler et al 1909.09987, Bahl et al 2503.02705

- Reduced sensitivity to observe new scalars at LHC.

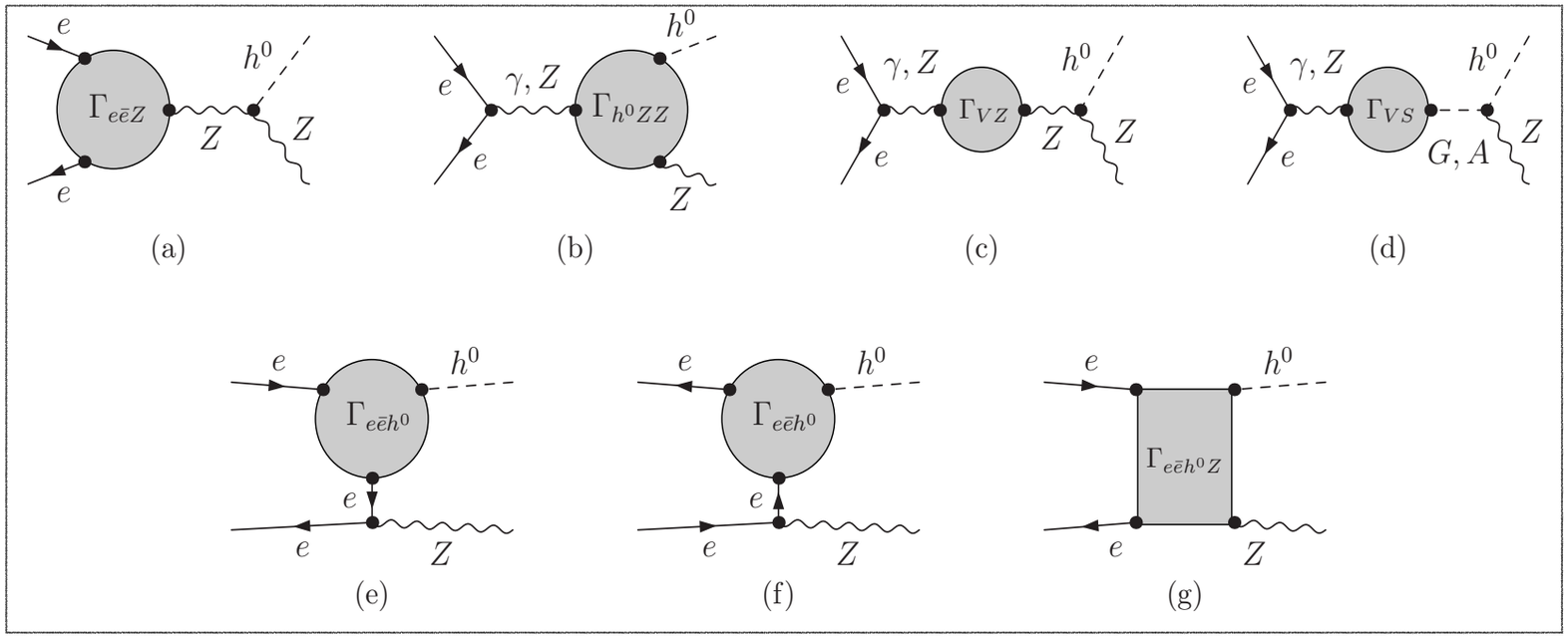
- Current LHC $t\bar{t}$ expected suppressed sensitivity may not be sufficient to fully probe the 2HDM parameter space.



$\Longrightarrow$ To look for BSM, FCC-ee via hZ can be a promising probe.

Higgs-strahlung hZ production

- EW-NLO corrections to $e^-e^+ \to hZ$



- For the renormalisation to handle the UV divergences: Krause et al 1605.04853
  - ***alternative tadpole scheme*** for the renormalisation of the fields and masses. Fleischer,Jegerlehner `81, Denner et al 0709.1075
  - ***on-shell pinched technique*** for the renormalisation of α, β. Binosi Papavassiliou 0909.2536
  - cross-checks done with 2HDECAY. Krause et al 1810.00768
- For IR divergences in QED, soft energy cut off $\Delta E = 30$ GeV. Bloch,Nordsieck `37, Kinoshita '62, Lee,Nauenberg `64
- Numerical integration in the decoupling limit compared with MadGraph5_aMC@NLO for SM.

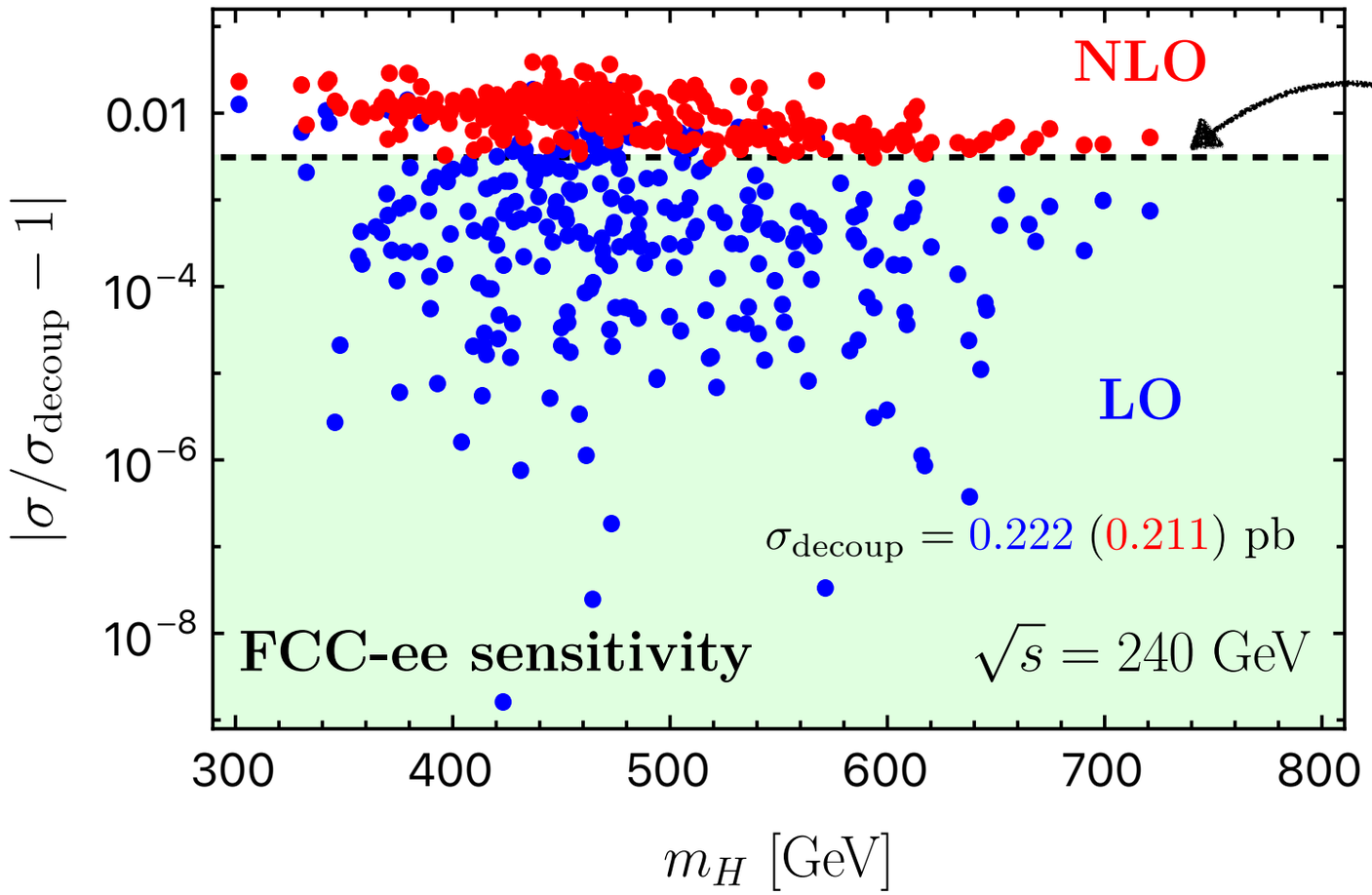
For literature on renormalisation in 2HDM

Krause et al 1605.04853, 1609.04185, 1708.01578, 1810.00768, Denner et al 1607.07352, 1808.03466 Altenkamp et al 1704.02645, 1710.07598, Kanemura et al 0408364, 2408.08033

For literature on radiative corrections to Higgs-strahlung in 2HDM

Lopez-Val et al 1003.4312, Xie et al 1812.02597, Abouabid et al 2009.03250, Aiko et al 2109.02884

Effect of NLO corrections



Projected FCC-ee precision

$$\frac{\Delta\sigma(e^+e^- \to hZ)}{\sigma(e^+e^- \to hZ)} = 0.31\%$$

ESPPU Higgs, EW, Top update

Similar CEPC precision of 0.26%

CEPC Snowmass 2205.08553

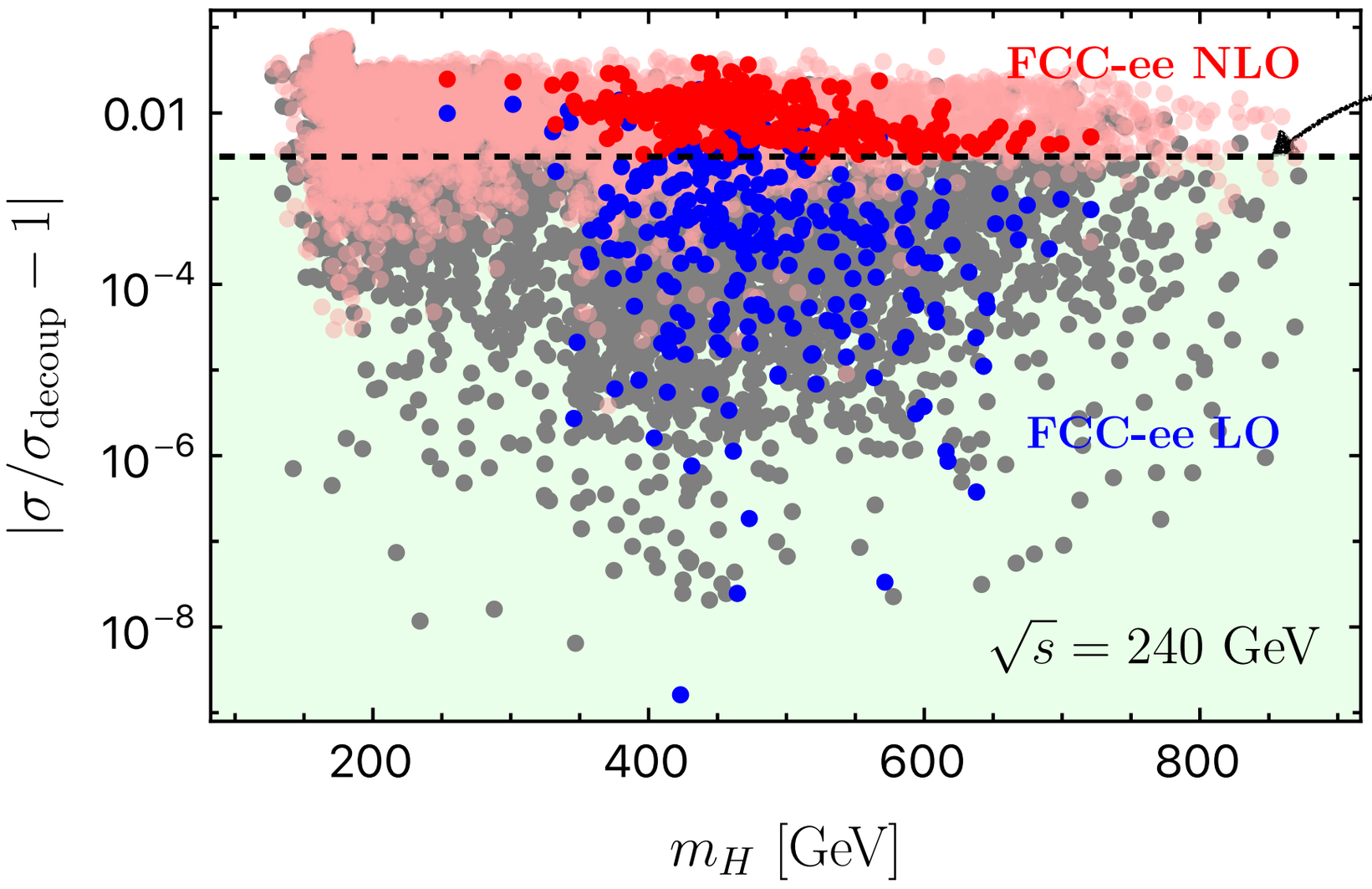
Deviations detectable at FCC-ee/CEPC!

- FCC-ee Z-pole → Pushes 2HDM towards SM *alignment limit.*
  - LO cross-section mostly consistent with SM.
- Requirement of strong first-order phase transitions → Needs deviation from SM
  - non-decoupled BSM scalars and modified Higgs couplings

- Loop effects modify NLO cross-section away from the decoupling limit.
  - Higgs mixing, Higgs self-coupling and effects of BSM scalars via inter-Higgs couplings.

Understanding the NLO effects

- Importance of Z-pole run $\sqrt{s} = m_Z$



Projected FCC-ee sensitivity

$$\frac{\Delta\sigma(e^+e^- \to hZ)}{\sigma(e^+e^- \to hZ)} = 0.31\%$$

ESPPU Higgs, EW, Top update

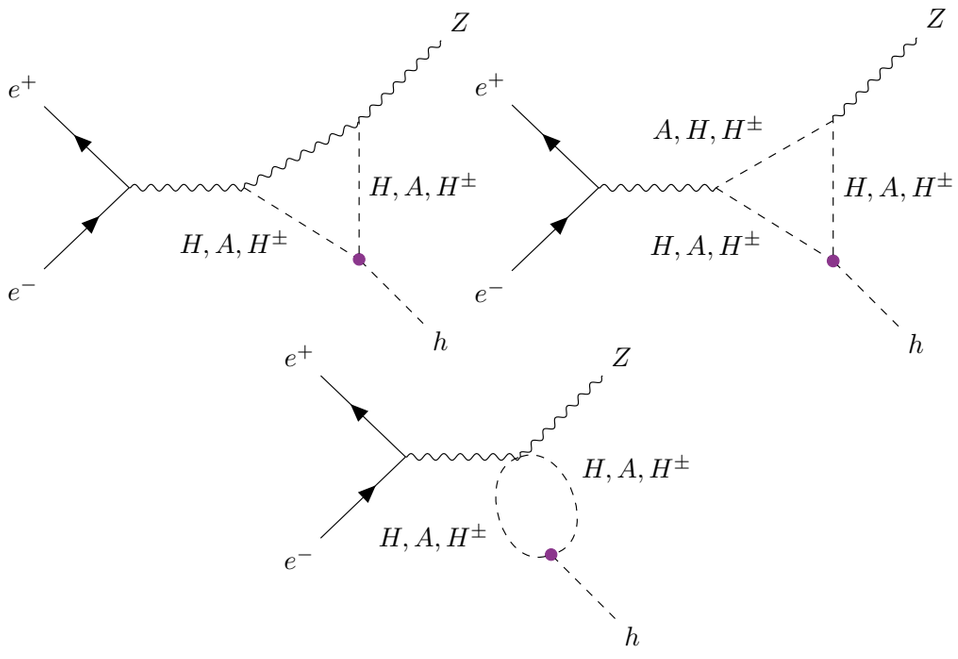
Z-pole constraints enhance NLO vs LO discrimination.

→ via reduced EW-input theory uncertainties.

Disentangling the NLO effects

- Impact of the BSM scalars

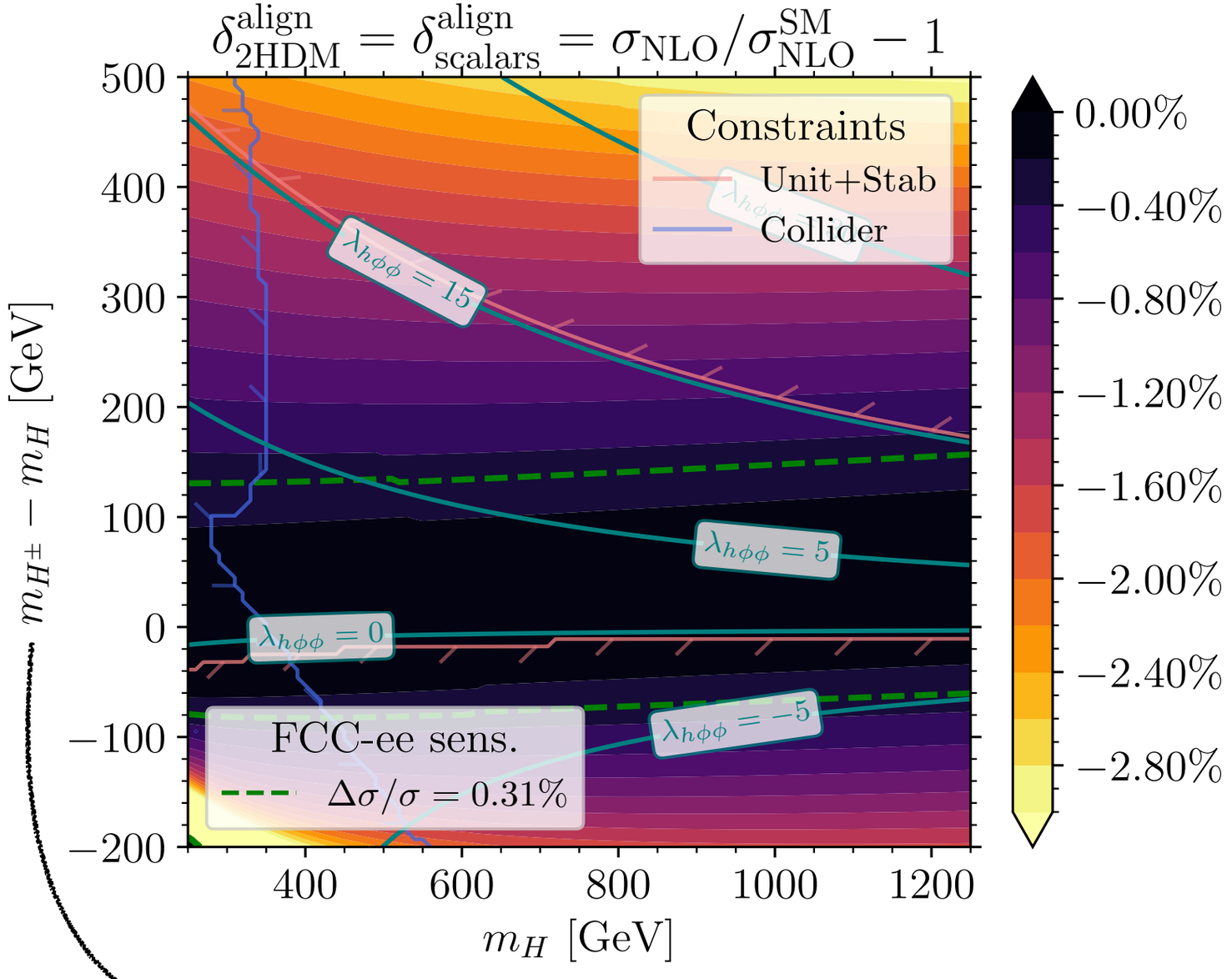
$\Longrightarrow$ In alignment, NLO effects are BSM scalar loops.



In exact alignment limit

$\cos(\beta-\alpha)=0,\ \tan\beta=2,\ \bar{m}=m_H,\ m_A=m_{H^\pm}$

$\delta^{\text{align}}_{\text{2HDM}}=\delta^{\text{align}}_{\text{scalars}}=\sigma_{\text{NLO}}/\sigma^{\text{SM}}_{\text{NLO}}-1$



$\propto$ inter-Higgs $\lambda_{h\phi\phi}$ couplings

Anisha, Arco, Di Noi, Englert, Mühlleitner, 2609.04039

Summary & Conclusions

- 2HDM Type I is a promising BSM candidate to realize an SFOEWPT.
  - Requires non-decoupled 2HDM scalars with sizeable mass splittings.

- Considering a pessimistic scenario: no BSM observed at the LHC or HL-LHC.
  - Interference effects hide the BSM scalars in $t\bar{t}$ searches.

- FCC-ee Z-pole measurements at the sub-percent level impose stringent constraints.
  - Push 2HDM closer towards the alignment limit.

- SFOEWPT favoured 2HDM parameter region predict NLO deviations discoverable in FCC-ee hZ production.

- Precision Z-pole + Higgs measurements at future e^+e^- colliders offer an indirect discovery potential for EW Baryogenesis motivated new physics.

Thank you for the attention !

2HDM Type I: Lagrangian

CP conserving

T.D. Lee `73, Branco et al 1106.0034

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{1}{\sqrt{2}}(v_1 + \zeta_1 + i\psi_1) \end{pmatrix} \qquad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{1}{\sqrt{2}}(v_2 + \zeta_2 + i\psi_2) \end{pmatrix}$$

$$V(\Phi_1,\Phi_2) = m_{11}^2(\Phi_1^\dagger\Phi_1) + m_{22}^2(\Phi_2^\dagger\Phi_2) - m_{12}^2(\Phi_1^\dagger\Phi_2 + \Phi_2^\dagger\Phi_1) + \lambda_1(\Phi_1^\dagger\Phi_1)^2 + \lambda_2(\Phi_2^\dagger\Phi_2)^2$$
$$+ \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{1}{2}\lambda_5[(\Phi_1^\dagger\Phi_2)^2 + (\Phi_2^\dagger\Phi_1)^2]$$
$$+ \left(\lambda_6(\Phi_1^\dagger\Phi_1) + \lambda_7(\Phi_2^\dagger\Phi_2)\right)\left(\Phi_1^\dagger\Phi_2 + \Phi_2^\dagger\Phi_1\right)$$

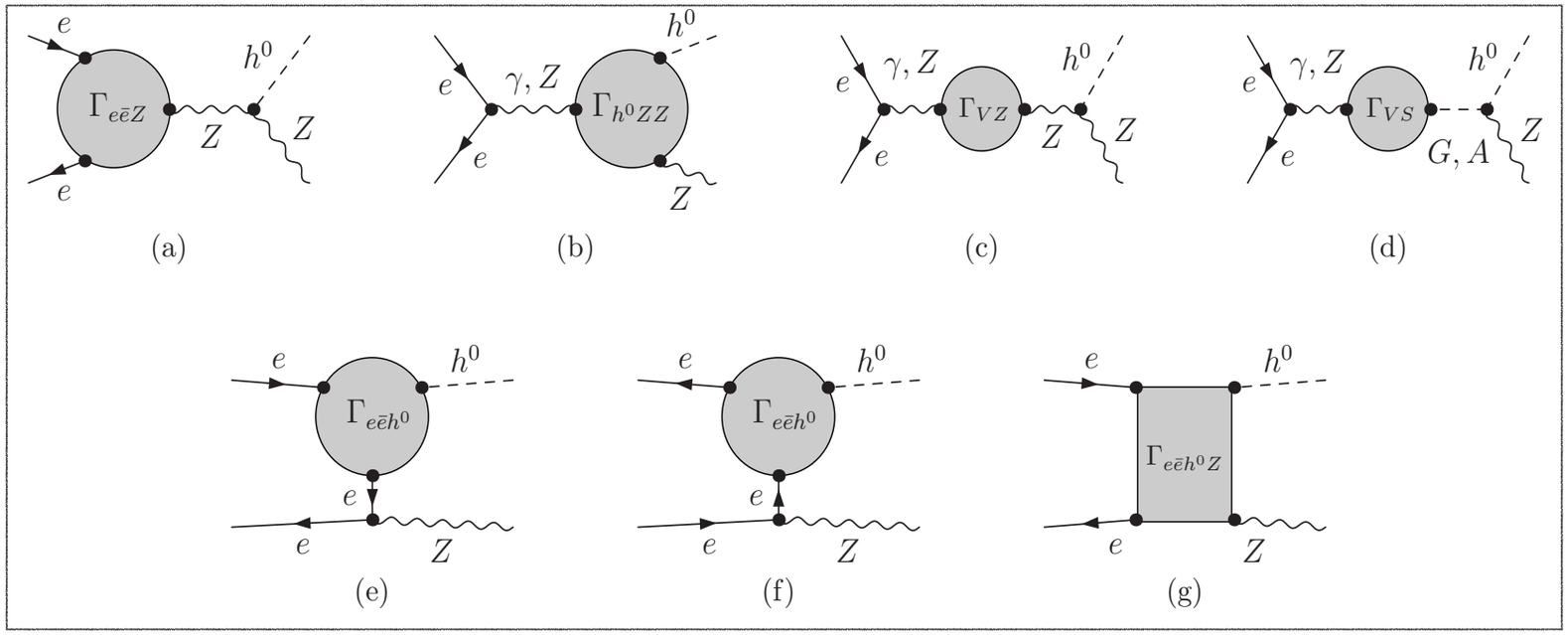
softly broken $\mathbb{Z}_2$ symmetry: $\Phi_1 \to -\Phi_1, \;\; \Phi_2 \to \Phi_2$

$$\mathcal{L}_{\rm Yuk} = -Y_1^e\bar{L}\Phi_1 e - Y_2^e\bar{L}\Phi_2 e - Y_1^d\bar{Q}\Phi_1 d - Y_2^d\bar{Q}\Phi_2 d - Y_1^u\bar{Q}\tilde{\Phi}_1 u - Y_2^u\bar{Q}\tilde{\Phi}_2 u + \text{h.c.}$$

For Type I $\mathcal{L}_{\rm Yuk} = -Y_2^e\bar{L}\Phi_2 e - Y_2^d\bar{Q}\Phi_2 d - Y_2^u\bar{Q}\tilde{\Phi}_2 u + \text{h.c.}$

Higgs-strahlung hZ production

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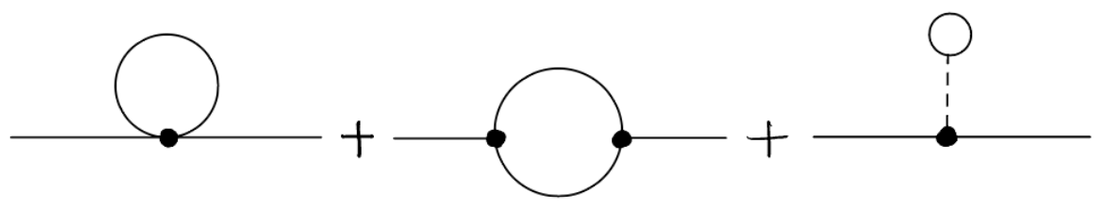


- For the renormalisation to handle the UV divergences:
  - ***alternative tadpole scheme*** for the renormalisation of the fields and masses.

Fleischer,Jegerlehner `81

Denner et al 0709.1075

$$i\Sigma^{\mathrm{tad}}(p^2) \equiv$$



  - ***on-shell pinched technique*** for the renormalisation of α, β.

Binosi Papavassiliou 0909.2536

Krause et al 1605.04853, 1810.00768

$$\alpha \to \alpha + \delta\alpha$$

$$\delta\alpha = \frac{\mathrm{Re}\left[\left[\Sigma^{\mathrm{tad}}_{Hh}(m_H^2) + \Sigma^{\mathrm{tad}}_{Hh}(m_h^2)\right]_{\xi=1} + \Sigma^{\mathrm{add}}_{Hh}(m_H^2) + \Sigma^{\mathrm{add}}_{Hh}(m_h^2)\right]}{2\left(m_H^2 - m_h^2\right)}$$