Theory precision for CEPC Higgs measurements

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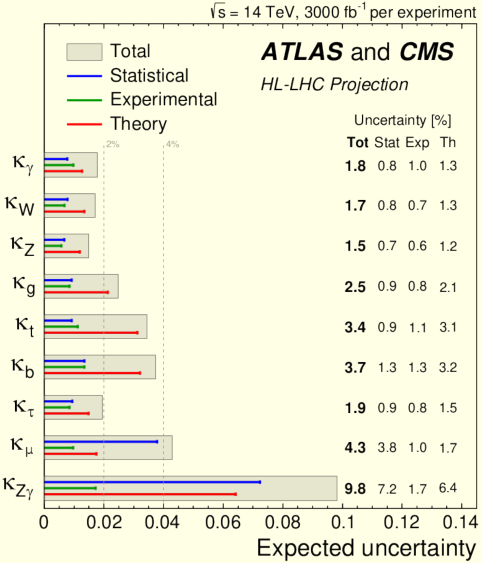
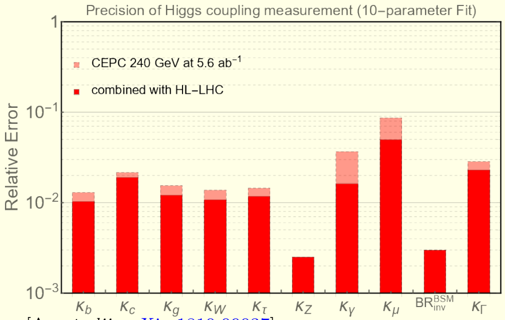
Contents

HL-LHC projection



[Working Group 2, arXiv:1902.00134]

- hadron collider
  $\Rightarrow$ QCD has predominant role
- compound initial state, no precise knowledge of partonic momenta
- κ-framework: $\kappa_X = \frac{g_{HXX}}{g_{HXX}^{\mathrm{SM}}}$
  relative uncertainty at %-level reachable
- some coupling modifiers limited by theory precision (PDF, signal, background)



[An *et alii*, arXiv:1810.09037]

- lepton collider
  $\Rightarrow$ electroweak physics predominant
- elementary particles in initial state, precise knowledge of momenta
- tune energy to set up 'Higgs factory'
- relative uncertainty at ‰-level reachable
- small background

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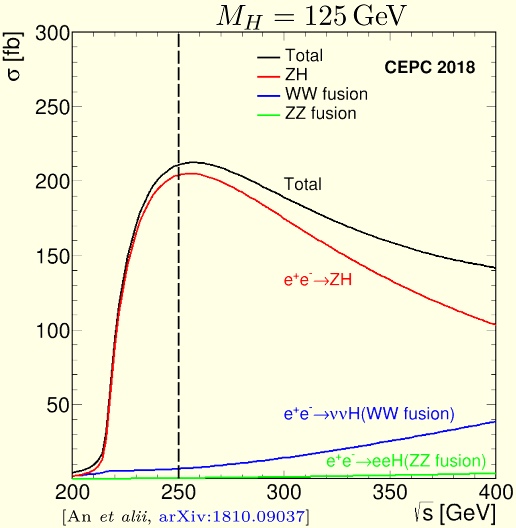
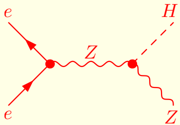
Higgs production at e^+e^- colliders



[An *et alii*, arXiv:1810.09037]

- cross-sections at $\sqrt{s} = 250\,\mathrm{GeV}$:

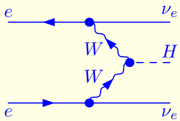
Higgs strahlung



$ee \to ZH$

$\sigma = 204.7\,\mathrm{fb}$

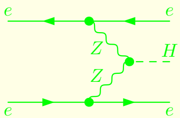
W fusion



$ee \to \nu_e \nu_e H$

$\sigma = 6.9\,\mathrm{fb}$

Z fusion



$ee \to eeH$

$\sigma = 0.6\,\mathrm{fb}$

employing `WHIZARD` [Kilian, Ohl, Reuter, arXiv:0708.4233] [Moretti, Ohl, Reuter, arXiv:0102195]

- background: $\sigma < 1\,\mathrm{fb}$
- full one loop [Belanger *et alii*, arXiv:0212261] [Denner, Dittmaier, Roth, Weber, arXiv:0301189]
- two loop $\mathcal{O}(\alpha\,\alpha_s)$ [Gong, Li, Xu, Yang, Zhao, arXiv:1609.03955]
- remaining uncertainty of $\mathcal{O}(1\%)$ [Freitas *et alii*, arXiv:1906.05379]

channel	BR for $M_H = 125\,\text{GeV}$	relative uncertainty
$H \to b\bar{b}$	5.82×10^{-1}	${}^{+2.2}_{-2.2}\%$
$H \to W^+W^-$	2.14×10^{-1}	$\pm 2.6\%$
$H \to gg$	8.19×10^{-2}	$\pm 8.2\%$
$H \to \tau^+\tau^-$	6.27×10^{-2}	$\pm 2.8\%$
$H \to c\bar{c}$	2.89×10^{-2}	${}^{+7.7}_{-3.4}\%$
$H \to ZZ$	2.62×10^{-2}	$\pm 2.6\%$
$H \to \gamma\gamma$	2.27×10^{-3}	$\pm 3.3\%$
$H \to Z\gamma$	1.53×10^{-3}	${}^{+7.3}_{-7.4}\%$
$H \to \mu^+\mu^-$	2.18×10^{-4}	${}^{+2.8}_{-2.9}\%$

[Heinemeyer *et al.*, arXiv:1307.1347]
[de Florian *et al.*, arXiv:1610.07922]

- total width $= \sum$ partial widths

$$\Gamma_H^{\text{tot}} = \sum_i \Gamma\left[H \to f_1^i \cdots f_{n_i}^i\right] = 4.1\,\text{MeV}$$

[de Florian *et al.*, arXiv:1610.07922]

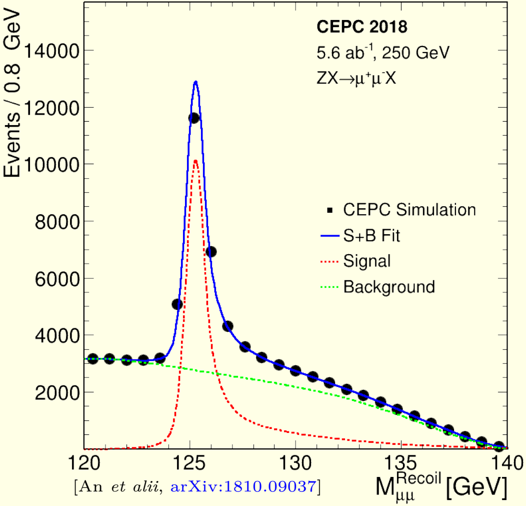
- branching ratios:

$$\text{BR}\left[H \to f_1^i \cdots f_{n_i}^i\right] = \frac{\Gamma\left[H \to f_1^i \cdots f_{n_i}^i\right]}{\Gamma_H^{\text{tot}}}$$

- LHC-like analysis of $\sigma_{\text{prod}} \times \text{BR}$
- problem:
  uncertainty in leading channels affects Γ_H^{tot} and therefore all BR-s
- NLO electroweak + up to four-loop QCD

[Kniehl, Spira, arXiv:9501392, arXiv:9505225]
[Baikov, Chetyrkin, Kühn, arXiv:0511063]
[Baikov, Chetyrkin, arXiv:0604194]
[Bredenstein, Denner, Dittmaier, Weber, arXiv:0604011, arXiv:0611234]
[Passarino, Sturm, Uccirati, arXiv:0707.1401]
[Moch, Vogt, arXiv:0709.3899]
[Actis, Passarino, Sturm, Uccirati, arXiv:0809.3667]
[Maierhöfer, Marquard, arXiv:1212.6233]
[Mihaila, Schmidt, Steinhauser, arXiv:1509.02294]

Higgs tagging from recoil against Z



[An *et alii*, arXiv:1810.09037]

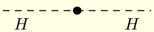
- initial-state momenta known
  $\Rightarrow$ apply conservation laws
- select Higgs-strahlung events with visible Z decays
- recoil mass computed as
  $M_{\text{rec}}^2 = (\sqrt{s} - E_{\text{vis}})^2 - p_{\text{vis}}^2 = s - 2\,E_{\text{vis}}\,\sqrt{s} + m_{\text{vis}}^2$
- resonance expected at $M_{\text{rec}} = M_H = 125\,\text{GeV}$
  - $\Rightarrow$ extract Higgs mass from position of resonance ($\Delta M_H = 5.9\,\text{MeV}$)
  - $\Rightarrow$ extract $\sigma(ZH)$ from height of resonance ($\Delta\sigma(ZH)/\sigma(ZH) = 0.5\%$)
  - — width of resonance dominated by beam uncertainties
- independent of Higgs decay
- full two-loop Z observables known
  [Dubovyk, Freitas, Gluza, Riemann, Usovitsch, arXiv:1804.10236]

Higgs potential

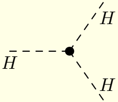
$$V = -\mu^2\,|\phi|^2 + \lambda\,|\phi|^4$$

minimization for

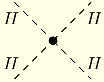
$$\phi = \begin{pmatrix} G^+ \\ v + \frac{1}{\sqrt{2}}\,(H + i\,G^0) \end{pmatrix} \quad \Rightarrow \quad \mu^2 = 2\,\lambda\,v^2$$

$\Rightarrow$ 

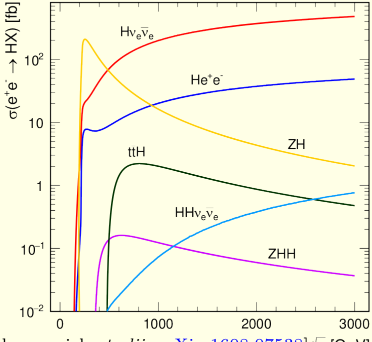
$\widehat{=}\ M_H^2 = 4\,\lambda\,v^2$



$\widehat{=}\ g_{HHH} = 6\,\sqrt{2}\,\lambda\,v = \frac{3}{\sqrt{2}}\,\frac{M_H^2}{v}$

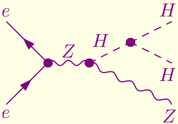


$\widehat{=}\ g_{HHHH} = 6\,\lambda = \frac{3}{2}\,\frac{M_H^2}{v^2}$

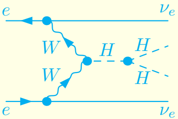


[Abramovich *et alii*, arXiv:1608.07538]

$ee \to ZHH$



$ee \to \nu_e \nu_e HH$



- test predictions of SM Higgs potential
- but: need $\sqrt{s} \gtrsim 500\,\text{GeV}$
- indirect effect in loops: low sensitivity

BSM deviations	
Model	$\Delta g_{HHH}/g_{HHH}$
mixed-in singlet	-18%
composite Higgs	tens of %
minimal SUSY	$-2\%\ (t_\beta > 10)$ $-15\%\ (t_\beta \simeq 5)$
NMSSM	-25%

[Gupta, Rzehak, Wells, arXiv:1305.6397]

Contents

Extended Higgs sectors

motivation:

- Higgs-boson properties are/become precision observables
- high-precision theory predictions necessary
- ample scope for BSM theories with extended Higgs sector

extended Higgs sector:

- multiple scalar fields ϕ_i (after EWSB) with same quantum numbers
- gauge eigenstates ϕ_i mix into mass eigenstates $h_i \equiv$ physical states
- compute high-precision predictions for masses, production and decays of physical states
- due to Higgs mixing, in general amplitude $\mathcal{A}^{\text{BSM}} \neq \mathcal{A}^{\text{SM}} + \mathcal{A}^{\text{non-SM}}$
  $\Rightarrow$ new calculations required for each model
- typically achieved precision:
  full one loop, leading two-loop QCD for popular models, but often less ...

Models

non-exhaustive list of models with extended Higgs sector:

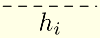
- real or complex singlet (SSM)
- two doublets (THDM)
- singlet and two doublets (NTHDM)
- triplets (Georgi–Machacek)
- minimal SUSY (MSSM)
- singlet and minimal SUSY (NMSSM)
- neutrino superfields ($\mu\nu$SSM)
- singlet, triplet, octet gauge superfields (MDGSSM)
- R-symmetric (MRSSM)
- exceptional groups (E_6SSM)

⋮

- your favourite model

Higgs-mass prediction

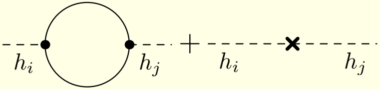
- tree level: $\mathcal{L} \ni m_{ij}^2\, \phi_i\, \phi_j \overset{!}{=} m_{h_i}^2\, h_i^2$
  eigenvalues $m_{h_i}^2$ of matrix m_{ij}^2 are poles of propagators



$\equiv \dfrac{i}{p^2 - m_{h_i}^2}$

- loop order: matrix of propagators $i\left[p^2\,\mathbb{1} - \operatorname{diag} m_{h_i}^2 + \hat{\Sigma}_{h_i h_j}(p^2)\right]^{-1}$ via renormalized self-energies

$\hat{\Sigma}_{h_i h_j}(p^2) \equiv$

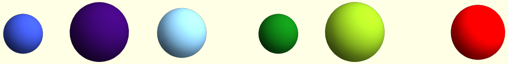


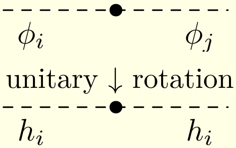
- if on-shell scheme (possible in SM, THDM, ...): $\hat{\Sigma}_{h_i h_j}(m_{h_i}^2) = 0$
  $\Rightarrow$ tree-level fields and masses preserved at all orders
- otherwise: new physical (loop-corrected) fields H_i induced,
  formally, mass $M_{H_i}^2 = \Re\mathfrak{e}\left[\mathcal{M}_{H_i}^2\right]$ of H_i via solution of
  $\det\left[\mathcal{M}_{H_i}^2 - \operatorname{diag}(m_{h_i}^2) + \hat{\Sigma}_{h_i h_j}(\mathcal{M}_{H_i}^2)\right] = 0$ but how exactly?

example: CP-conserving NMSSM

- tree-level mass eigenstates = mixed gauge eigenstates:

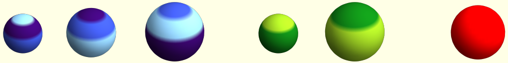
	CP-even			CP-odd		charged
h_i:	h	H	S	a	A	$H^\pm$

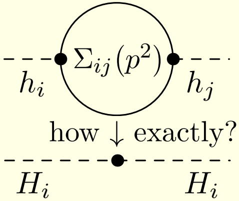




- off-diagonal entries in $\hat{\Sigma}_{ij}(p^2)$ induce loop-mixing

	CP-even			CP-odd		charged
H_i:	H_1	H_2	H_3	H_4	H_5	$H^\pm$





- with CP-mixing: H_1  , etc.

Guiding principle

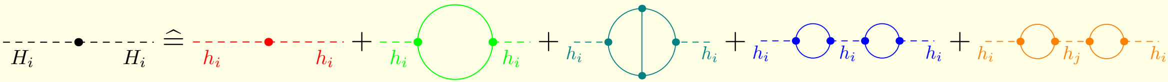
- observables are measurable quantities
- theoretical predictions of observables should
  not depend on unphysical parameters
  (more strictly: results that depend on theory regulators are wrong,
  but maybe: impact on observables numerically negligible)
- examples for unphysical parameters in higher-order corrections:
  - UV-, IR-regulators → standard treatment
  - gauge-fixing parameters ξ
  - field renormalization δZ

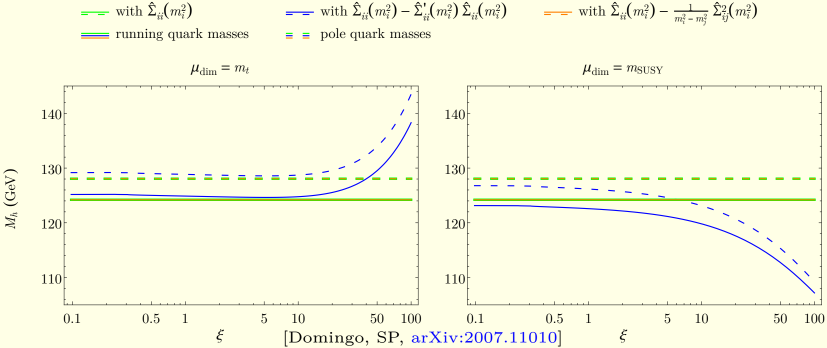
some contributions for treatment of latter two topics:
[Williams, Rzehak, Weiglein, arXiv:1103.1335], [Goodsell, Liebler, Staub, arXiv:1703.09237],
[Domingo, Heinemeyer, SP, Weiglein, arXiv:1807.06322], [Bahl, arXiv:1812.06452],
[Baglio, Dao, Mühlleitner, arXiv:1907.12060],
[Dao, Fritz, Krause, Mühlleitner, Patel, arXiv:1911.07197] [Domingo, SP, arXiv:2007.11010, arXiv:2105.01139]

Consistent mass prediction

perturbative expansion: (for degenerate scenarios, see [Domingo, SP, arXiv:2007.11010, arXiv:2105.01139])

$$\mathcal{M}^2_{h_i} = \underbrace{m^2_{h_i}}_{\text{tree}} \underbrace{- \hat{\Sigma}^{1L}_{h_ih_i}(m^2_{h_i})}_{\text{one loop}} \underbrace{- \hat{\Sigma}^{2L}_{h_ih_i}(m^2_{h_i}) + \hat{\Sigma}^{1L}_{h_ih_i}(m^2_{h_i}) \frac{d\hat{\Sigma}^{1L}_{h_ih_i}}{dp^2}(m^2_{h_i}) + \sum_{j \neq i} \frac{\hat{\Sigma}^{1L}_{h_ih_j}(m^2_{h_i})\, \hat{\Sigma}^{1L}_{h_jh_i}(m^2_{h_i})}{m^2_{h_i} - m^2_{h_j}}}_{\text{two loop}} + \mathcal{O}(3L)$$





[Domingo, SP, arXiv:2007.11010]

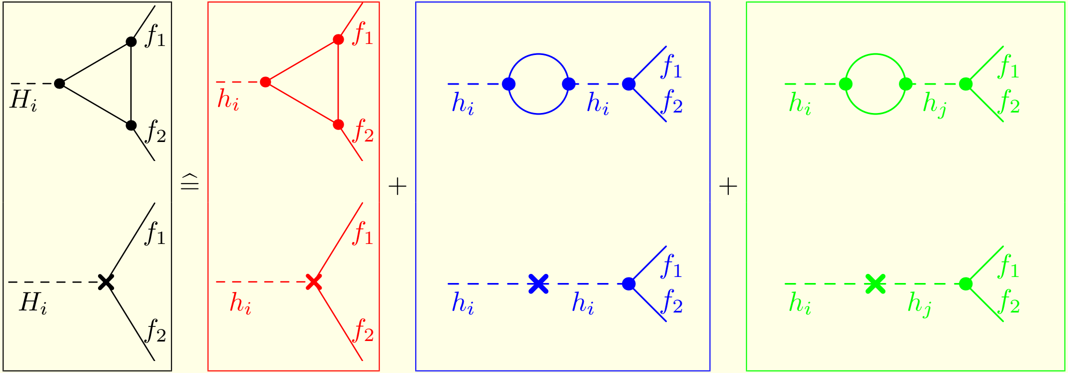
numerical impact on M_h in MSSM when including partial higher-order terms:

- $\mathcal{O}(1\,\text{GeV})$ uncertainty due to ξ-dependence [Domingo, SP, arXiv:2007.11010]
- $\mathcal{O}(1\,\text{GeV})$ uncertainty due to δZ-dependence [Domingo, SP, arXiv:2105.01139]

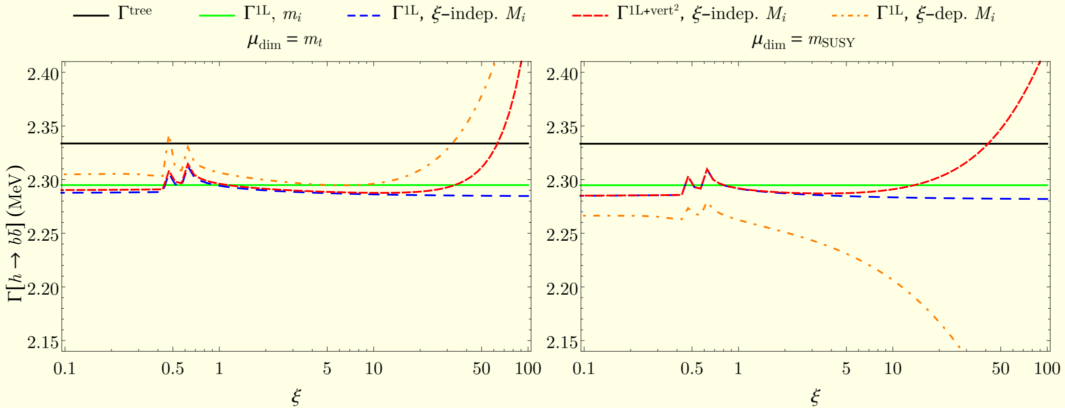
perturbative expansion of amplitudes $\mathcal{A}$ involving loop-corrected fields (Higgs, Z boson) in agreement with LSZ reduction formula:

$$\mathcal{A}^{1\text{L}}\left[H_i\, f_1\, f_2\right] = \mathcal{A}^{\text{vert}}\left[h_i\, f_1\, f_2\right] + \mathcal{A}^{\text{mix}}\left[h_i\, f_1\, f_2\right]$$

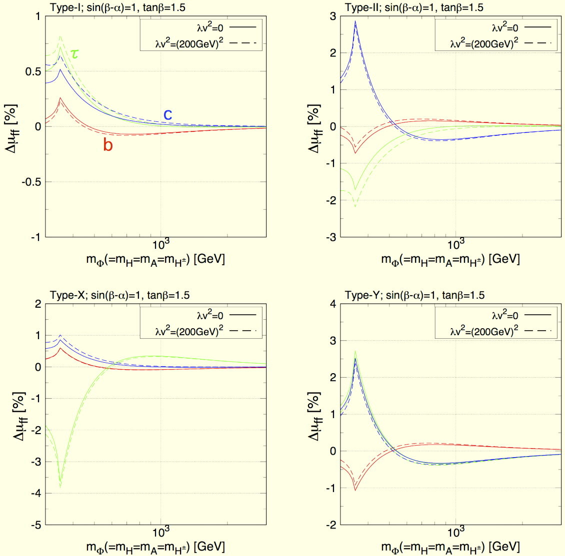
$$= \mathcal{A}^{\text{vert}}\left[h_i\, f_1\, f_2\right] - \frac{d\hat{\Sigma}_{h_i h_i}}{dp^2}\left(m^2_{h_i}\right)\mathcal{A}^{\text{tree}}\left[h_i\, f_1\, f_2\right] - \sum_{j\neq i}\frac{\hat{\Sigma}_{h_i h_j}\left(m^2_{h_i}\right)}{m^2_{h_i}-m^2_{h_j}}\mathcal{A}^{\text{tree}}\left[h_j\, f_1\, f_2\right]$$



same principle applies to all loop-corrected external legs

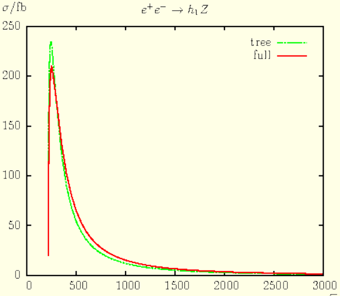


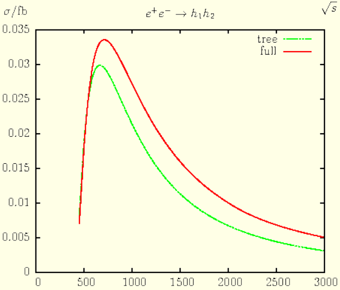
- QCD-corrected tree-level width (all further lines show electroweak corrections)
- strict 1L expansion, $p^2 = m_h^2$ (tree-level mass)
- strict 1L expansion, $p^2 = M_h^2$ (loop-corrected mass, no ξ-dependence)
- include $1L^2$ vertex correction, $p^2 = M_h^2$ (loop-corrected mass, no ξ-dependence)
- Z-matrix formalism, $p^2 = M_h^{2\,(\xi)}$ (loop-corrected mass, ξ-dependent)



[Kanemura, Kikuchi, Mawatari, Sakurai, Yagyu, arXiv:1906.10070]

- BSM effect in fermionic decays:
  $\mu_{ff} = \frac{\mathrm{BR}\left(h\to ff\right)_{\mathrm{THDM}}}{\mathrm{BR}\left(H\to ff\right)_{\mathrm{SM}}} - 1$
  $\lambda\, v^2 = m_\phi^2 - \frac{m_3^2}{s_\beta\, c_\beta}$
- unitarity, vacuum stability preserved
- deviations of about 0.5% for $m_\phi \simeq 1$ TeV
- decoupling for heavy Higgs





[Heinemeyer, Schappacher, arXiv:1511.06002]

- Higgs strahlung at lepton colliders for MSSM Higgs bosons
- additional production channel $ee \to h_1 h_2$ including CP-odd Higgs $h_2 = A$, here: $M_{h_2} \simeq 300\,\text{GeV}$ $\Rightarrow$ no contribution at $\sqrt{s} = 250\,\text{GeV}$
- current project: $ee \to Zh_i, h_i h_j$ in NMSSM [Heinemeyer, SP, Schappacher] possibility: additional light Higgs $ee \to Zh_s$ to find CP-even Higgs $ee \to ha_s$ to find CP-odd Higgs (or complex parameters)

Summary

- complementary physics at hadron and lepton colliders
- well-defined initial state, low background
  $\Rightarrow$ unprecedented precision possible
- precise study of single-Higgs observables
- in extended Higgs sectors:
  careful treatment of radiative corrections necessary,
  strict perturbative expansion to avoid erroneous contributions to masses, production and decay
- electroweak radiative corrections necessary for sub-percent precision