NLO CORRECTIONS TO HIGGS TO HIGGS DECAY IN THE SINGLET-EXTENDED SM

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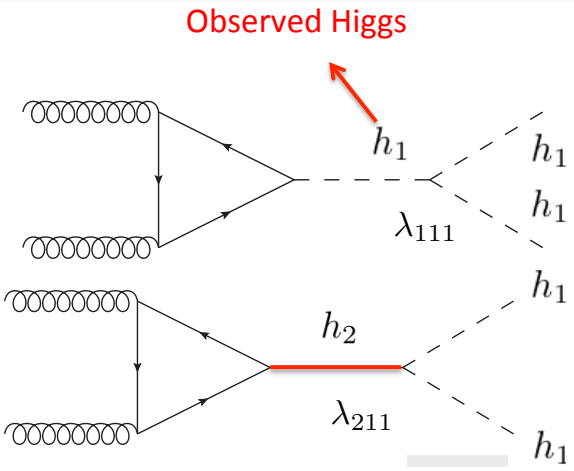
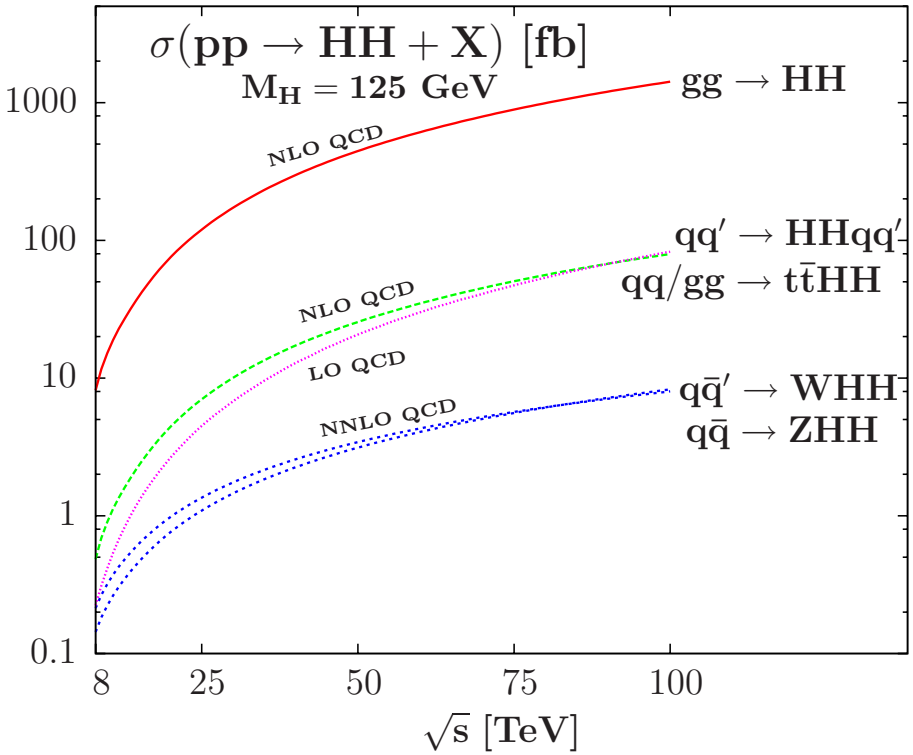
based on F. Bojarski, G.C, D. Lopez-Val, T. Robens, ArXiv: 1511.08120 [hep-ph]
recommended for publication in JHEP

WHY SINGLET EXTENSIONS OF THE SM (HIGGS PORTAL) ?

$\Longrightarrow$ Simplest extensions of the $\mathcal{SM}$ $\Longleftarrow$

- Improve SM stability ($\mu_{RG} \gtrsim 10^{11}$ GeV)
- Help account for the baryon asymmetry of the Universe
- Provide Dark Matter candidate
- Rich phenomenology with **Higgs to Higgs decays**





[Baglio et al, 1212.5581]

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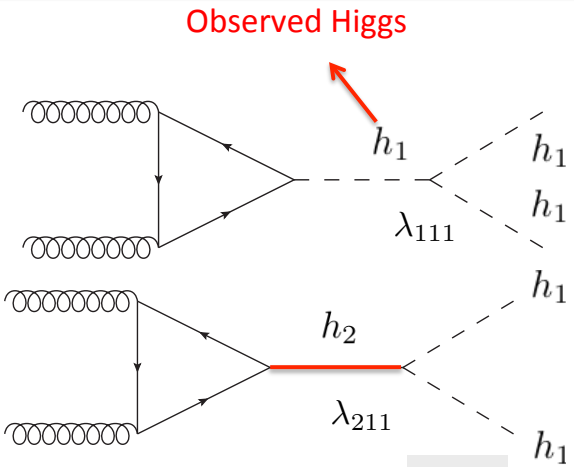

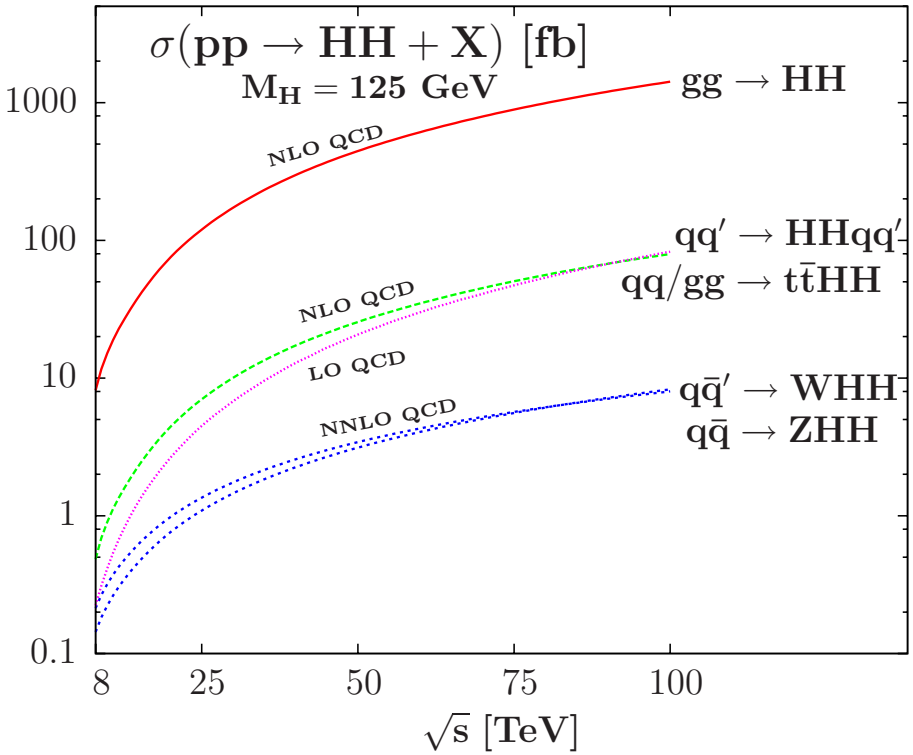

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LHC run 2 $\rightarrow$ start probing Higgs self-couplings
Di-Higgs production can be enhanced due to decay of heavy resonances
$\Rightarrow$ opportunity to probe extended Higgs sectors also

THE REAL SINGLET EXTENSION OF THE SM (xSM)

- Add a $\mathbb{R}$ scalar field S, singlet under $G_{\mathcal{SM}}$
- Only scalar potential V is modified
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$$\Phi = \left(G^+, \frac{v + \phi_h + iG^0}{\sqrt{2}} \right)^T, S = \frac{v_s + \phi_s}{\sqrt{2}}$$

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5 free parameters:

- ☞ Potential : $\lambda_1, \lambda_2, \lambda_3, v, v_s$
- ☞ Physical : $m_h, m_H, \sin\alpha, v, \tan\beta$
- ☞ Each SM-like coupling rescaled by $\cos\alpha(\mathrm{h})/\sin\alpha(H)$

Mass spectrum:

$$\begin{pmatrix} h \\ H \end{pmatrix} = \underbrace{\begin{pmatrix} c_\alpha & -s_\alpha \\ s_\alpha & c_\alpha \end{pmatrix}}_{U(\alpha)} \begin{pmatrix} \phi_h \\ \phi_s \end{pmatrix}$$

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$\rightarrow$ Decay rates $\simeq$ as in $\mathcal{SM}$, unless $H \to hh$ open

RENORMALISATION OF THE XSM

- xSM will be used as a template model to probe extended Higgs sectors at run II (see LHCXSWG YR4)
- Reach the same accuracy for Higgs lineshapes as in the $\mathcal{SM}$: Full NLO EW corrections missing

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$$\mathcal{L}^0 = \mathcal{L}(\lambda_i, M_{ij}, \phi_i) + \delta\mathcal{L}(\lambda_i, M_{ij}, \phi_i, \delta\lambda_i, \delta M_{ij}, \delta Z_{ij}), \quad i = h, H$$

SHIFTS

- $\Phi_i^0 \longrightarrow (\delta_{ij} + \frac{1}{2}\delta Z_{ij})\Phi_j$
- $\lambda_i^0 \longrightarrow \lambda_i + \delta\lambda_i,\ v_i^0 \longrightarrow v_i + \delta v_i$
- $M_{ij}^{0\,2} \longrightarrow M_{ij}^2 + \delta M_{ij}^2$
- $T_i^0 \longrightarrow T_i + \delta T_i$

ON-SHELL SCHEME

- $\widetilde{\mathcal{R}e}\hat{\Sigma}_{ii}(M_i^2) = 0 \longrightarrow \delta M^2$
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- Higgs $\longrightarrow$ definition for $\Rightarrow$ $\boxed{\delta v_s, \delta m^2_{hH}}$ $\Leftarrow$

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$$\boxed{\phi_s + v_s \to Z_S^{1/2}(\phi_s + v_s + \delta\bar{v}_s)}, \quad \delta\bar{v}_s = \delta\bar{v}_s|^{\infty} + \delta\bar{v}_s|^{\text{fin}}$$

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- ☞ $\delta Z_S|^{\infty} = 0$ **at 1L** (S prop. corr. given by $\mathcal{L} \supset \lambda_3\, \Phi^\dagger \Phi\, S^2 \Rightarrow$ **no momentum dep.**)

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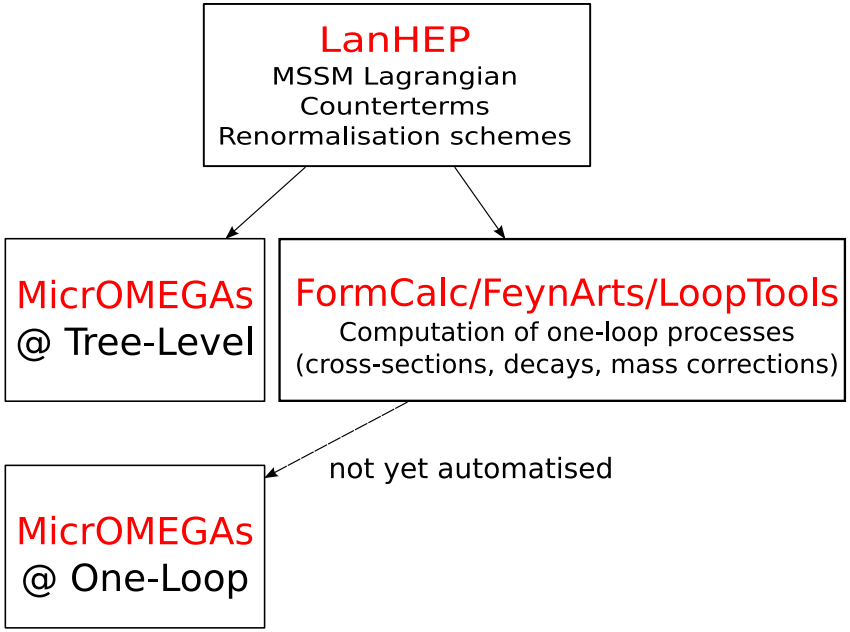
AUTOMATIC TOOL FOR ONE-LOOP CALCULATIONS: SLOOPS



SLOOPS

An automatic code for calculation of loops diagrams for $\mathcal{SM}$ and $\mathcal{BSM}$ processes with application to colliders, astrophysics and cosmology.

- Automatic derivation of the CT Feynman rules and computation of the CT's
- Models renormalized: SM, MSSM, NMSSM, **xSM** (w/ & w/o singlet vev)
- Modularity between different renormalisation schemes.
- Non-linear gauge fixing.
- Checks: results UV,IR finite and gauge independent.

http://code.sloops.free.fr/

Non-Linear gauge fixing

$$
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\mathcal{L}_{GF} \quad = \quad & -\frac{1}{\xi_W}|(\partial_\mu - ie\tilde{\alpha}A_\mu - igc_w\tilde{\beta}Z_\mu)W^{\mu +} \\
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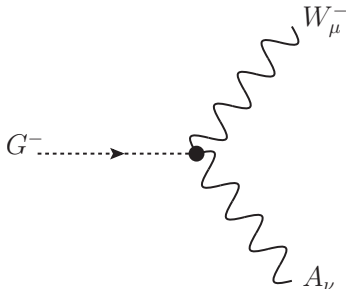

$$eM_W(1 + \tilde{\alpha}g_{\mu\nu})$$

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$\longrightarrow$ Gauge parameter dependence in gauge/Goldstone/ghost vertices.
$\longrightarrow$ No "unphysical" threshold, no higher rank tensor.

INVESTIGATING GAUGE INVARIANCE: SCHEME CHOICE

- Random point, numerically vary $\Delta \propto 1/\epsilon = 0 \ldots 10^7$ and nlgs $= \alpha, \beta, \tilde{\kappa}, \tilde{\delta}_i, \tilde{\epsilon}_i = 0 \ldots 10$

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Gauge independent definition:[Espinosa, Yamada '03, Baro, Boudjema '09]

$$\boxed{\delta m^2_{hH} = \widetilde{\mathcal{R}e}\,\Sigma_{hH}(p^2_*)\big|_{\xi_W=\xi_Z=1,\tilde{\delta}_i=0} \quad \text{with} \quad p^2_* = \frac{m_h^2 + m_H^2}{2}}$$: "Improved OS"

INVESTIGATING GAUGE INVARIANCE: SCHEME CHOICE

- Random point, numerically vary $\Delta \propto 1/\epsilon = 0 \ldots 10^7$ and nlgs $= \alpha, \beta, \tilde{\kappa}, \tilde{\delta}_i, \tilde{\epsilon}_i = 0 \ldots 10$

	$\delta\Gamma^{\text{1-loop}}(H \to hh)$ [MeV]		
Scheme	$\Delta = 0, \{\text{nlgs}\} = 0$	$\Delta = 10^7, \{\text{nlgs}\} = 0$	$\Delta = 10^7, \{\text{nlgs}\} = 10$
OS	$+4.26334888$	$+4.26334886$	-5.27015844×10^6
Improved	$+3.9393569$	$+3.9393568$	$+3.9393556$

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NUMERICAL SCAN: CONSTRAINTS

- ☞ $m_{H_{SM}} = 125.09$ GeV
- ☞ Set of constraints as in [Robens, Stefaniak '15]

Theoretical constraints:

- ✓ Vac. stability/potential minimization up to $\mu_{\rm RG} \sim 4 \times 10^{10}$ GeV (iff. $h \simeq H_{SM}$)
- ✓ Perturbative unitarity (at LO)
- ✓ Perturbativity of couplings, $|\lambda_i| \leq 4\pi$, up to $\mu_{\rm RG}$ (only for $m_H > m_{h \simeq H_{SM}}$)

Experimental constraints:

- ✓ EW oblique parameters S, T, U
- ✓ NLO calculation W mass [Lopez-Val, Robens '14]
- ✓ 95% C.L limits from Higgs searches at LEP and LHC (`HiggsBounds`)
- ✓ Consistency with Higgs signal strength (`HiggsSignals`)

Two regions:

- ☞ High mass region: $m_H > 2m_{h \simeq H_{SM}}$
- ☞ Low mass region: $m_{H \simeq H_{SM}} < 2m_h$

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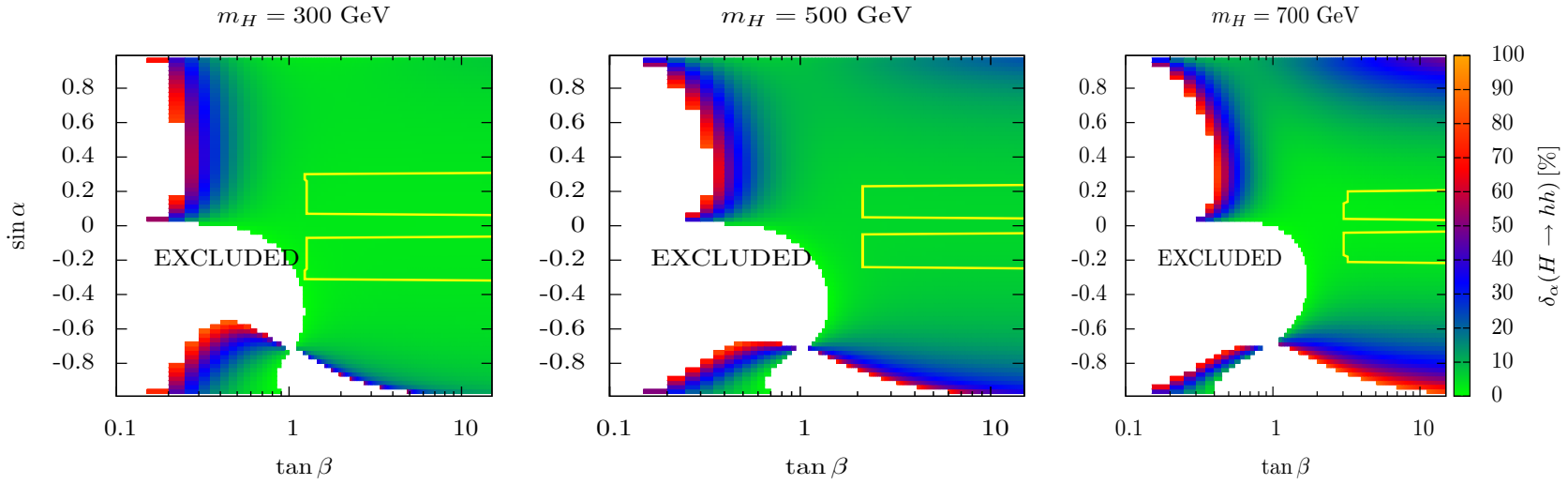
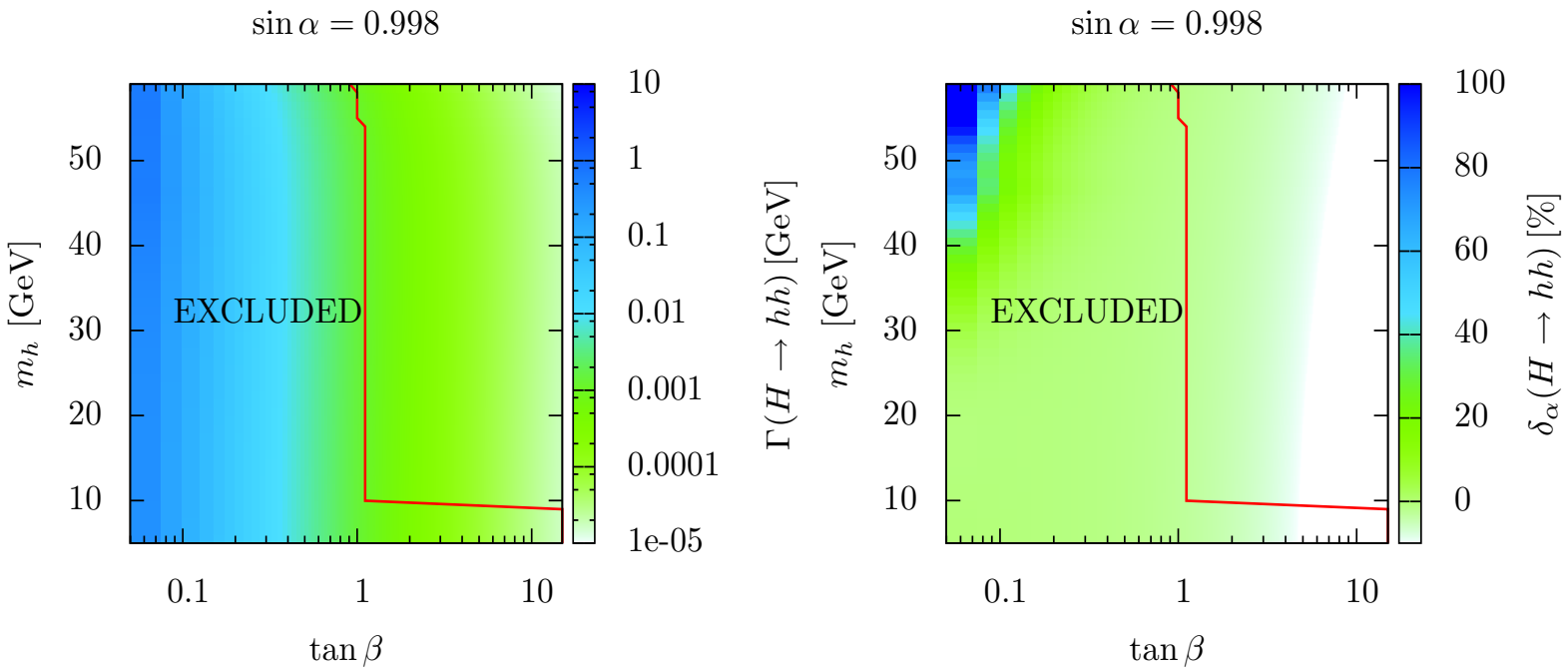
RESULTS: HIGH MASS REGION $m_H > 2m_{h_{SM}}$

$$\Gamma^{LO}(H \to hh) = \frac{\lambda_{Hhh}^2}{32\,\pi\, m_H}\sqrt{1-\frac{4m_h^2}{m_H^2}} \text{ where } \lambda_{Hhh} = -\frac{i s_{2\alpha}}{v}\left[m_h^2 + \frac{m_H^2}{2}\right](c_\alpha + s_\alpha\, t_\beta^{-1})$$



RESULTS: LOW MASS REGION $m_{H_{SM}} > 2m_h$

$$\Gamma^{LO}(H \to hh) = \frac{\lambda_{Hhh}^2}{32\,\pi\, m_H}\sqrt{1-\frac{4m_h^2}{m_H^2}} \text{ where } \lambda_{Hhh} = -\frac{is_{2\alpha}}{v}\left[m_h^2+\frac{m_H^2}{2}\right](c_\alpha + s_\alpha\, t_\beta^{-1})$$



CONCLUSIONS AND OUTLOOK

Summary:

- Full 1L renormalisation of the xSM
- "Best scheme": Improved OS (should also be commonly used for mixing 2×2 scalar field system rather than OS scheme)
- Full NLO corrections to $\Gamma(H \to hh)$
- Mild EW corrections when constraints applied
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Outlook:

- Full Higgs boson lineshapes at NLO EW
- Physical definition for v_s (*e.g* through $H \to hh$)
- Finite width and interference/off-shell effects in di-higgs production
- Relevant effects on EW baryogenesis ?