Electroweak corrections in the 2HDM for Higgs-boson production through gluon fusion

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I. Generalities & Context
II. Computation
III. Results
IV. Summary & Conclusion

based on JHEP 09 (2018) 017
in collaboration with:
Laura Jenniches and Sandro Uccirati

Introduction

Generalities & Background, Motivation

- Higgs boson (H) discovered at the LHC experiments
  $\hookrightarrow$ Determine properties of Higgs boson (theory+experiment)
- Higgs boson could be part of extended, more general Higgs sector
  $\hookrightarrow$ Contribute to solve open problems of particle phys., e.g.
  question of origin of matter–anti-matter asymmetry
  question of nature of dark matter, ...
- Extension of H sector: Two-Higgs-Doublet Model (2HDM)
- LHC studies 2HDM extension
  ATLAS: 1712.06386, 1509.00672, 1507.05930, 1506.00285, 1502.04478, 1310.0515, ATLAS-CONF-2013-027,...
  CMS: CMS-PAS-HIG-17-031, 1603.02991, 1511.03610, 1510.01181, 1506.02301, 1504.04710, 1410.2751,...
  $\hookrightarrow$ precise theory predictions necessary
- Important Higgs boson production: gluon fusion
  $\hookrightarrow$ $gg \to H \qquad H = H_l, H_h$
- Study effect of extension on Higgs production
  $\hookrightarrow$ EW corrections

- EW corrections to SM Higgs production $gg \to H$ ✓
  ↪ 5.1% S. Actis, G. Passarino, C.S., S. Uccirati; G. Degrassi, F. Maltoni; U. Aglietti, R. Bonciani, G. Degrassi, A. Vicini; A. Djouadi, P. Gambino, B. Kniehl
- EW corrections in SM extensions → can be large!
  ↪ example: Higgs production in 4th generation model ✓ (excluded)
  G. Passarino, C.S., S. Uccirati; A. Djouadi, P. Gambino, B. Kniehl
- The 2HDM potential:

$$\Phi_i = \begin{pmatrix} \phi_i^+ \\ \frac{1}{\sqrt{2}}(v_i + \rho_i + \mathrm{i}\eta_i) \end{pmatrix}, i = 1, 2 \text{ Higgs doublets}, \quad v_i : vevs$$

$$\begin{aligned} V(\Phi_1, \Phi_2) &= m_1^2 \Phi_1^\dagger \Phi_1 + m_2^2 \Phi_2^\dagger \Phi_2 - m_{12}^2 \left(\Phi_1^\dagger \Phi_2 + \Phi_2^\dagger \Phi_1\right) \\ &+ \frac{\lambda_1}{2} \left(\Phi_1^\dagger \Phi_1\right)^2 + \frac{\lambda_2}{2} \left(\Phi_2^\dagger \Phi_2\right)^2 + \lambda_3 \left(\Phi_1^\dagger \Phi_1\right) \left(\Phi_2^\dagger \Phi_2\right) \\ &+ \lambda_4 \left(\Phi_1^\dagger \Phi_2\right) \left(\Phi_2^\dagger \Phi_1\right) + \frac{\lambda_5}{2} \left[\left(\Phi_1^\dagger \Phi_2\right)^2 + \left(\Phi_2^\dagger \Phi_1\right)^2\right] \end{aligned}$$

- Here: all parameters real, CP-conserving version

- Diagonalize scalar sector $\rightarrow$ mass eigenstates, physical basis

$$\begin{pmatrix}\rho_1\\ \rho_2\end{pmatrix} = R(\alpha)\begin{pmatrix}H_h\\ H_l\end{pmatrix}, \quad \begin{pmatrix}\phi_1^\pm\\ \phi_2^\pm\end{pmatrix} = R(\beta)\begin{pmatrix}G^\pm\\ H^\pm\end{pmatrix}, \quad \begin{pmatrix}\eta_1\\ \eta_2\end{pmatrix} = R(\beta)\begin{pmatrix}G_0\\ H_a\end{pmatrix}$$

$$R(x) = \begin{pmatrix}\cos x & -\sin x\\ \sin x & \cos x\end{pmatrix}$$

Mass eigenstates, new particle spectrum: H_l, H_h, H_a, $H^\pm$

α: diagonalizes neutral Higgs mass matrix

β: diagonalizes other scalar mass matrices, $t_\beta = \tan\beta = v_2/v_1$

- Physical parameters:

$$\lambda_1,\ \lambda_2,\ \lambda_3,\ \lambda_4,\ \lambda_5,\ m_1,\ m_2,\ m_{12}$$
$$\Downarrow$$
$$M_{H_l},\ M_{H_h},\ M_{H_a},\ M_{H^\pm},\ M_{sb},\ \alpha,\ \beta,\ v(g, M_W)$$

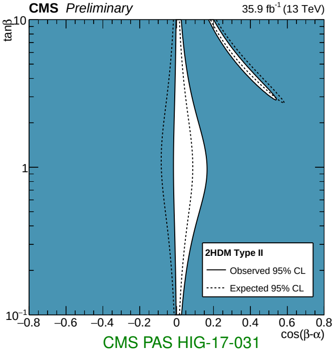
- Higgs basis

$$\Phi_a = \phi_1 \cos\beta + \phi_2 \sin\beta$$
$$\Phi_b = -\phi_1 \sin\beta + \phi_2 \cos\beta$$

$$\Phi_a = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v - H_l s_{\alpha\beta} + H_h c_{\alpha\beta} + \mathrm{i}G_0) \end{pmatrix} \quad \Phi_b = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(H_l c_{\alpha\beta} + H_h s_{\alpha\beta} + \mathrm{i}H_a) \end{pmatrix}$$

$$v = \sqrt{v_1^2 + v_2^2}$$

- Alignment limit:
  $c_{\alpha\beta} = \cos(\alpha - \beta) \to 0,$
  $s_{\alpha\beta} = \sin(\alpha - \beta) \to -1$
- H_l has SM-like couplings to fermions and gauge bosons
- Decoupling limit: Alignment limit + new mass scales heavy
- Constraints on parameters
  $\hookrightarrow$ LHC experiments



CMS PAS HIG-17-031

- Higggs basis

$$\Phi_a = \phi_1 \cos\beta + \phi_2 \sin\beta$$
$$\Phi_b = -\phi_1 \sin\beta + \phi_2 \cos\beta$$

$$\Phi_a = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v - H_l s_{\alpha\beta} + H_h c_{\alpha\beta} + \mathrm{i}G_0) \end{pmatrix} \quad \Phi_b = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(H_l c_{\alpha\beta} + H_h s_{\alpha\beta} + \mathrm{i}H_a) \end{pmatrix}$$

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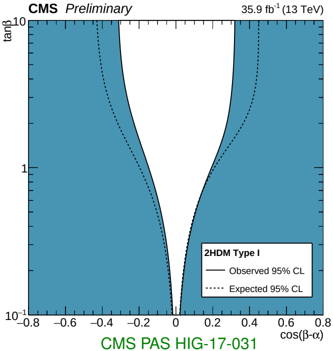
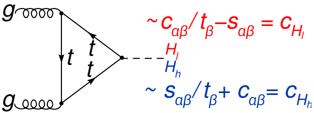


CMS PAS HIG-17-031

Introduction

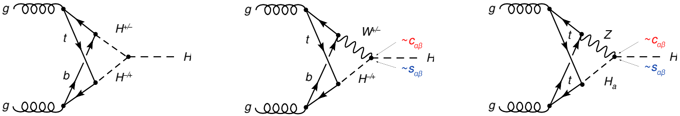
Process

- Here: only top-quark massive fermion
- The process $g + g \to H_l, H_h$ at LO



2HDM: multiplicative factor compared to SM

- Factor c_H can be large/small
  $\hookrightarrow$ choice of parameters α, $\beta \rightsquigarrow$ LO suppressed
  $\hookrightarrow$ NLO EW amp. not $\propto$ same factor $\rightsquigarrow$ pot. big NLO corr.
- Compared to QCD computation of EW corrections in 2HDM more involved
  $\hookrightarrow$ new diagrams



Computation
Setup

- 2HDM Feynman rules generated with FeynRules

  ⇓ A. Alloul, N. Christensen, C. Degrande, C. Duhr, B. Fuks

- Diagram generation with QGRAF P. Nogueira

  ⇓

  Build amplitude with in-house code QGS

  QGS: extension of GraphShot (GS)

  S. Actis, A. Ferroglia, L. Jenniches, G. Passarino, M. Passera, C. S., S. Uccirati

  performs algebraic manipulations, FORM based

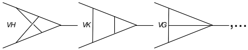
  J. Kuipers, T. Ueda, J. Vermaseren, J. Vollinga

- perform traces, remove reducible scalar products, symmetrize integrals, tadpole reduction, counter terms, extracts pole-part of loop diagrams, renormalization↑,...

  ↲

- UV-finite amplitude

  integrals classified into different topologies:



  subdivided in scalar, vector and tensor type integrals

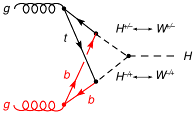
  ↳ mapped on Form factors

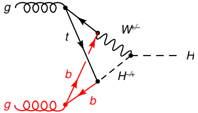
- ↳ Form factors are evaluated numerically in Feynman parametric space (Fortran)

Computation

Collinear singularities

- No real corrections to $gg \to H$ (considering EW corrections)
  $\Rightarrow$ collinear singularities cancel in pure virtual amplitude
  $\Rightarrow$ Check of calculation
- Collinear singularities are regularized by small fermion mass m; singularities become manifest as $\log^1(m)$,$\log^2(m)$





- Collinear logarithms of:

1^{st}+2^{nd} generation:	3^{d} generation:
$\log^2 \to$ analytically ✓	$\log^2 \to$ analytically ✓
$\log^1 \to$ analytically ✓	$\log^1 \to$ special case analytically
	$gg \to H_l$, alignment limit ✓
	otherwise coeff numerically ✓

Computation
2HDM renormalization

- Higgs masses: on-shell
- Mixing angles: α, β $\quad\rightarrow$ different schemes
  $\overline{\text{MS}}$ ct's $\delta\bar{\alpha}$, $\delta\bar{\beta}$ fixed: $H_l \rightarrow \tau^+\tau^-$, $H_a \rightarrow \tau^+\tau^-$ UV finite

A. Denner, L. Jenniches, J. Lang, C.S.

$$\delta\bar{\alpha} = \frac{\delta\overline{Z}_{H_h H_l} - \delta\overline{Z}_{H_l H_h}}{4} = \frac{\Sigma^{\text{pp}}_{H_h H_l}(M^2_{H_h}) + \Sigma^{\text{pp}}_{H_h H_l}(M^2_{H_l}) + 2t_{H_l H_h}}{2(M^2_{H_h} - M^2_{H_l})}, \quad \delta\bar{\beta} = \frac{\delta\overline{Z}_{G_0 H_a} - \delta\overline{Z}_{H_a G_0}}{4}$$

  - Proper treatment of Higgs tadpoles: *FJ* tadpole scheme
    gauge independent physical ct's

    J. Fleischer, F. Jegerlehner

  - Scale dependent amplitude
  - $\bar{\alpha}$, $\bar{\beta}$ scale dependent
  - Running parameters $\bar{\alpha}$, $\bar{\beta}$, $\overline{M}_{sb}$ $\qquad$ RGEs

$$\frac{\partial\bar{\alpha}}{\partial \ln \mu^2} = B_\alpha(\bar{\alpha}(\mu), \bar{\beta}(\mu), \overline{M}_{sb}(\mu)), \quad \frac{\partial\bar{\beta}}{\partial \ln \mu^2} = B_\beta(\bar{\alpha}(\mu), \bar{\beta}(\mu), \overline{M}_{sb}(\mu))$$

$$\frac{\partial\overline{M}_{sb}}{\partial \ln \mu^2} = B_{M_{sb}}(\bar{\alpha}(\mu), \bar{\beta}(\mu), \overline{M}_{sb}(\mu))$$

coupled system of DEQs

Scale dependence

Example

Logarithmic scale dependence, example $g+g\to H_l$: $c_{\alpha\beta}=0$

$$\delta_{\text{EW}}^{\text{NLO},\mu-\text{dep.}} = \frac{G_f\sqrt{2}}{8\pi^2 t_\beta^2 M_{H_h}^2 (M_{H_h}^2 - M_{H_l}^2)} \ln\frac{\mu^2}{M_{H_l}^2} \times \Big[(1-t_\beta^2)(M_{H_h}^2 - M_{sb}^2)\big[3M_{H_h}^2 M_{H_l}^2 + M_{sb}^2(M_{H_a}^2 + 2M_{H^\pm}^2 - 3M_{H_h}^2)\big] + 6m_t^2 M_{H_l}^2 (M_{H_h}^2 - 4M_{sb}^2 m_t^2/M_{H_l}^2) \Big]$$

$\hookrightarrow$ Coefficient depends on the "choice" of M_{H_h}, t_β,...
e.g. $t_\beta = 1$, $M_{H_h} \approx 2M_{sb}m_t/M_{H_l}$ $\to$ coeff. small, small scale dependence
e.g. $M_{H_h} \approx M_{H_l}$ $\to$ enhancement, large scale dependence

$\hookrightarrow$ scale dependence can be quite different for different scenarios but same process

$c_{\alpha\beta} \neq 0$: expression lengthy, but similar features

Computation
Renormalization

- **Scale independent schemes**
  J. Espinosa, I. Navarro, Y. Yamada, 2HDM: Kanemura, Kikuchi, Yagyu;
  M. Krause, R. Lorenz, M. Mühlleitner, R. Santos, H. Ziesche (pt); A. Denner, J. Lang, S. Uccirati (BFM)
  - on-shell

$$\delta\alpha^{\text{os}} = \frac{\Sigma_{H_h H_l}(M_{H_h}^2)+\Sigma_{H_h H_l}(M_{H_l}^2)+\Sigma^{\text{add}}_{H_h H_l}(M_{H_h}^2)+\Sigma^{\text{add}}_{H_h H_l}(M_{H_l}^2)+2t_{H_l H_h}}{2(M_{H_h}^2 - M_{H_l}^2)}, \qquad \delta\beta^{\text{os}} = \ldots \text{ analog}$$

(equivalent to self-energy in BFM)

  - p^* scheme

$$\delta\alpha^{*} = \frac{\Sigma_{H_h H_l}(p^{*2})+t_{H_l H_h}}{M_{H_h}^2 - M_{H_l}^2}, \qquad \delta\beta^{*} = \ldots \text{ analog} \qquad \text{with } p^{*2} = (M_{H_h}^2 + M_{H_l}^2)/2$$

- **Process dependent (proc)**

$$\Gamma^{\text{NLO}}_{\text{weak}}(H_h \to \tau^+\tau^-) = \Gamma^{\text{LO}}(H_h \to \tau^+\tau^-), \; \Gamma^{\text{NLO}}_{\text{weak}}(H_a \to \tau^+\tau^-) = \Gamma^{\text{LO}}(H_a \to \tau^+\tau^-)$$

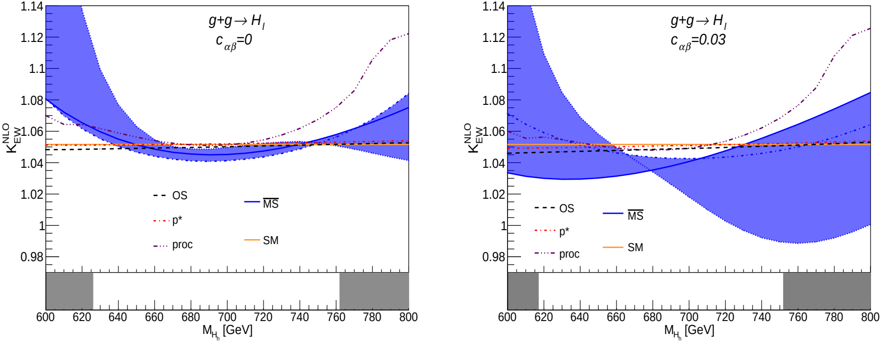
2HDM: M. Krause, R. Lorenz, M. Mühlleitner, R. Santos, H. Ziesche

- **Further schemes** L. Altenkamp, S. Dittmaier, H. Rzehak; A. Denner, S. Dittmaier, J.-N. Lang
  see also talk J.-N. Lang ↑
  currently not implemented yet

Results

$gg \to H_l$

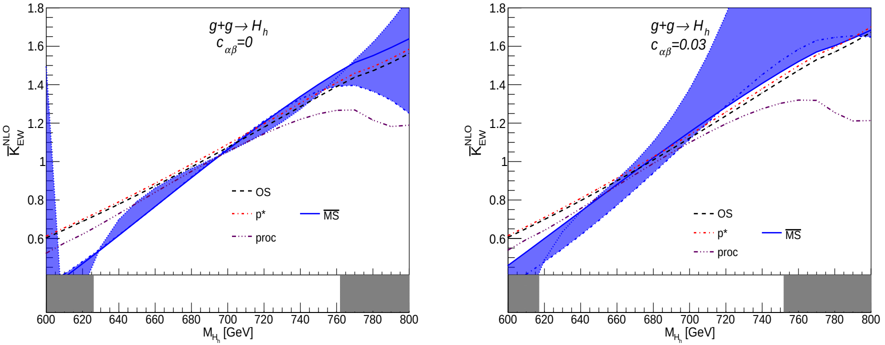
- EW corr. $\sigma^{\text{NLO}}_{\text{EW}} = K^{\text{NLO}}_{\text{EW}} \sigma^{\text{LO}}$ as fct. of M_{H_h}
- Example scenario: $t_\beta = 2$, $M^* = 700$ GeV except M_{H_h}



- $gg \to H_l$: comparison to SM: orange line: 5.1%
- Blue band: $\overline{\text{MS}}$ $(\mu_0/2, \mu_0, 2\mu_0)$, other lines: other schemes
- Grey bands: $\frac{\lambda}{4\pi} \geq 0.5$

Results $gg \to H_h$, same scenario

- LO: $c^2_{H_h} = 0.2 \ldots 0.25$ ($c^2_{H_l} = 1.0 \ldots 1.02$), LO suppressed
- Large corrections
- $$|A^{(1)} + A^{(2)}|^2 = \underbrace{|A^{(1)}|^2}_{\text{LO}} + \underbrace{2\mathrm{Re}(A^{(1)}A^{(2)*})}_{\text{NLO}} + \underbrace{|A^{(2)}|^2}_{\subset\text{NNLO}} \equiv |A^{(1)}|^2 \overline{K}^{\text{NLO}}_{\text{EW}}$$



- $M_{H_h} = 700$ GeV:
  $c_{\alpha\beta} = 0$: $\delta^{\text{OS}}_{\text{EW}} = 7\%$ $\qquad$ $c_{\alpha\beta} = 0.03$: $\delta^{\text{OS}}_{\text{EW}} = 12\%$
- Going away from M_{H_h}=700 GeV ... unstable

Benchmark points (BPs)

- Example BPs
  - alignment limit, $c_{\alpha\beta} = 0$:

BP	M_{H_h}	M_{H_a}	$M_{H^\pm}$	M_{sb}	t_β	$c^2_{H_l}$	$c^2_{H_h}$
$BP2_{1A}$	200 GeV	500 GeV	200 GeV	198.7 GeV	1.5	1	0.4
$BP2_{1B}$	200 GeV	500 GeV	500 GeV	198.7 GeV	1.5	1	0.4
$BP2_{1C}$	400 GeV	225 GeV	225 GeV	0 GeV	1.5	1	0.4
$BP2_{1D}$	400 GeV	100 GeV	400 GeV	0 GeV	1.5	1	0.4
$BP3_{A1}$	180 GeV	420 GeV	420 GeV	129.1 GeV	3	1	0.1

BPX_{XX}: 1610.07922

  - general case, $c_{\alpha\beta} \neq 0$:

BP	M_{H_h}	M_{H_a}	$M_{H^\pm}$	M_{sb}	t_β	$c_{\alpha\beta}$	$c^2_{H_l}$	$c^2_{H_h}$
a-1	700 GeV	700 GeV	670 GeV	624.5 GeV	1.5	-0.0910	0.9	0.6
b-1	200 GeV	383 GeV	383 GeV	204.2 GeV	2.52	-0.0346	1.0	0.2
$BP2_{2A}$	500 GeV	500 GeV	500 GeV	500 GeV	7	0.28	1.0	0.02
$BP4_3$	263.7 GeV	6.3 GeV	308.3 GeV	81.5 GeV	1.9	0.14107	1.1	0.1
$BP4_4$	227.1 GeV	24.7 GeV	226.8 GeV	89.6 GeV	1.8	0.14107	1.1	0.2

a-1, *b*-1: 1403.1264, BPX_{XX}: 1610.07922

- Essentially any other scenario can be computed too!

Results

Corrections to $gg \to H_l$

- Corrections:
  $\sim$ order several percent
- Corrections mainly of comparable size with SM correction ($\sim$ 5.1%)
- Corrections sensitive to BPs
- Similar corrections in different schemes with few exceptions, $\overline{\text{MS}}$ different, large/small scale dependence

$c_{\alpha\beta} = 0$:

BP	$K_{\text{EW}}^{\text{OS}}$	$K_{\text{EW}}^{p^*}$	$K_{\text{EW}}^{\text{proc}}$	$K_{\text{EW}}^{\overline{\text{MS}}}$
2_{1A}	1.053	1.063	1.101	$0.994\,^{-0.030}_{+0.342}$
2_{1B}	1.038	1.048	1.044	$0.930\,^{+0.066}_{+2.389}$
2_{1C}	1.043	1.044	1.099	$1.126\,^{-0.001}_{-0.007}$
2_{1D}	1.029	1.035	1.042	$1.145\,^{-0.012}_{-0.015}$
3_{A1}	1.041	1.040	1.045	$1.118\,^{-0.042}_{-0.010}$

$c_{\alpha\beta} \neq 0$:

BP	$K_{\text{EW}}^{\text{OS}}$	$K_{\text{EW}}^{p^*}$	$K_{\text{EW}}^{\text{proc}}$	$K_{\text{EW}}^{\overline{\text{MS}}}$
a-1	1.043	1.047	1.048	$0.962\,^{+0.042}_{+2.634}$
b-1	1.048	1.045	1.054	$0.995\,^{+0.002}_{+0.175}$
2_{2A}	1.017	1.018	1.015	$1.006\,^{-0.871}_{-}$
4_3	1.042	1.043	1.038	$1.126\,^{-0.022}_{+0.030}$
4_4	1.043	1.044	1.038	$1.103\,^{+0.002}_{+0.002}$

Results

Corrections to $gg \to H_h$

$c_{\alpha\beta} = 0$:

BP	$\overline{K}^{\text{OS}}_{\text{EW}}$	$\overline{K}^{p^*}_{\text{EW}}$	$\overline{K}^{\text{proc}}_{\text{EW}}$	$\overline{K}^{\overline{\text{MS}}}_{\text{EW}}$
2_{1A}	0.486	0.492	0.426	$0.655^{+0.197}_{-0.451}$
2_{1B}	0.177	0.178	0.166	$0.257^{-0.033}_{-0.060}$
2_{1C}	0.958	0.950	0.822	$0.822^{+0.176}_{-0.088}$
2_{1D}	0.854	0.840	0.803	$0.693^{+0.244}_{-0.095}$
3_{A1}	0.581	0.580	0.486	$0.336^{+0.667}_{-0.100}$

$c_{\alpha\beta} \neq 0$:

BP	$\overline{K}^{\text{OS}}_{\text{EW}}$	$\overline{K}^{p^*}_{\text{EW}}$	$\overline{K}^{\text{proc}}_{\text{EW}}$	$\overline{K}^{\overline{\text{MS}}}_{\text{EW}}$
a-1	1.145	1.161	1.121	$1.401^{+0.253}_{-1.385}$
b-1	0.696	0.693	0.628	$0.981^{+0.154}_{-0.574}$
2_{2A}	7.504	7.456	7.517	$4.030^{+0.758}_{-}$
4_3	0.945	0.941	0.979	$0.580^{+0.531}_{-0.171}$
4_4	1.028	1.024	1.067	$0.807^{+0.322}_{-0.190}$

- $\underbrace{|A^{(1)}|^2}_{\text{LO}} + \underbrace{2\text{Re}(A^{(1)}A^{(2)*})}_{\text{NLO}} + \underbrace{|A^{(2)}|^2}_{\subset\text{NNLO}} \equiv |A^{(1)}|^2 \overline{K}^{\text{NLO}}_{\text{EW}}$
- Large corrections
- Strong sensitivity to BPs
- $\overline{\text{MS}}$ strong scale dependence

Summary & Conclusion

- Discussed production of light/heavy, scalar, neutral Higgs

$$g\,g \rightarrow H_l \qquad\qquad g\,g \rightarrow H_h$$

within 2HDM

- Extended code for computation of 2-loop EW corrections in 2HDM in several schemes
- Can determine the EW corrections for essentially any scenario (masses, angles)
- EW corrections for various scenarios presented

  Corrections sensitive to details of scenario

- For light Higgs corrections mostly comparable with SM
- For heavy Higgs corrections can be very large

  $\rightsquigarrow$ as important as QCD corrections

- Results applicable to decay widths

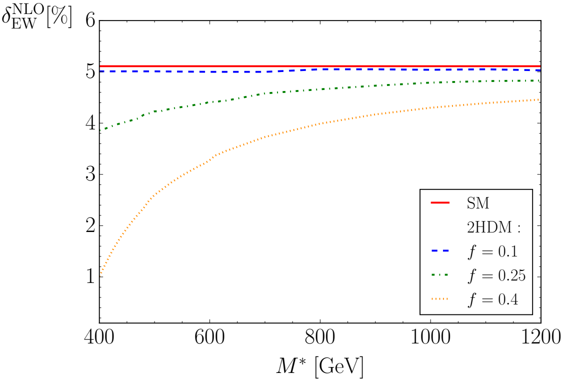
$$H_l \rightarrow g\,g \qquad\qquad H_h \rightarrow g\,g$$

same δ_{EW}

$gg \to H_l$

Alignment / decoupling limit

$$M_{H_h} = M^* - f\frac{v^2}{M^*}, \quad M_{H_c} = M^* + f\frac{v^2}{M^*}, \quad M_{sb} = M^*, \quad M_{H_a} = M^*, \quad c_{\alpha\beta} = f\frac{v^2}{{M^*}^2}$$



2HDM results approach SM result for
$f \to 0$ (alignment limit) and $M^* \to \infty$ (decoupling limit)