Electroweak corrections to Higgs production through gluon fusion in the 2HDM

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I. Generalities & Context
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IV. Summary & Conclusion

based on JHEP 1609 (2016) 115
in collaboration with: A. Denner, L. Jenniches & J. Lang
+ work in preparation
in collaboration with: L. Jenniches & S. 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 processes for such BSMs
  CMS: 1603.02991, CMS: 1511.03610, ATLAS: 1509.00672, CMS: 1410.2751, ATLAS: 1310.0515, ATLAS-CONF-2013-027,...
  $\hookrightarrow$ 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

Introduction

Context, Motivation & Model

- EW corrections to SM Higgs production $gg \to H$ ✓
  $\hookrightarrow$ 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 $\to$ can be large!
  $\hookrightarrow$ example: Higgs production in 4th generation model ✓ (excluded)
  G. Passarino, C.S., S. Uccirati; A. Djouadi, P. Gambino, B. Kniehl
- The 2HDM potential:

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

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

Introduction

Model

- 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:

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

Introduction

Model, Experiment

- Higgs basis

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

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

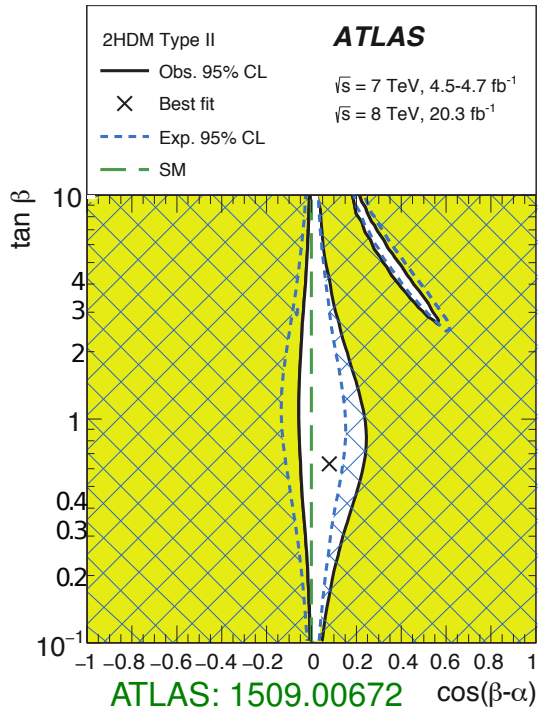
$$v = \sqrt{v_1^2 + v_2^2}$$

- 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
- Constraints on parameters $\hookrightarrow$ LHC experiments
- Decoupling limit: Alignment limit + new mass scales heavy

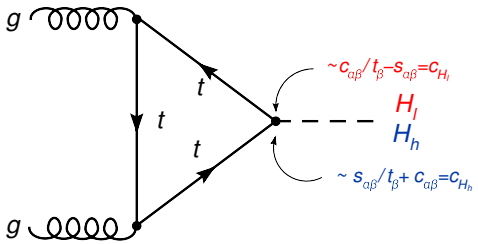


ATLAS: 1509.00672

Introduction

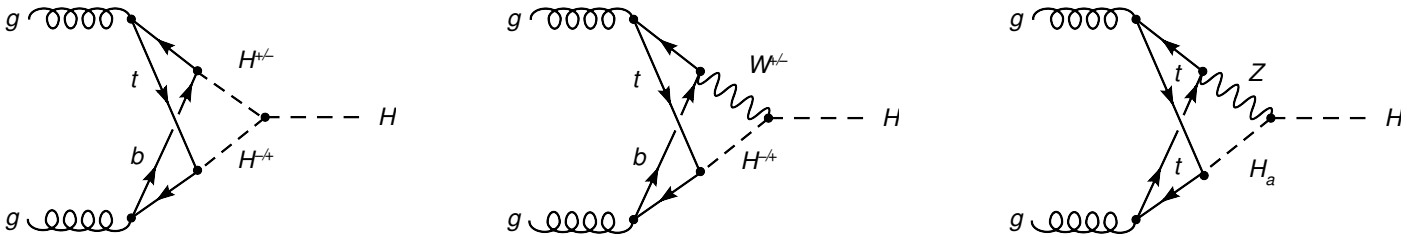
Process

- The process $gg \to H_l, H_h$ at LO



2HDM: multiplicative factor compared to SM

- Compared to QCD computation of EW corrections in 2HDM more involved
  $\hookrightarrow$ new diagrams



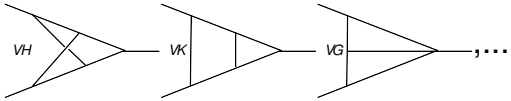
L. Jenniches, C.S., S. Uccirati $\to$ in preparation

First results: in context of renormalization

A. Denner, L. Jenniches, J. Lang, C.S.$\hookleftarrow$ ($gg \to H_l$ + alignment limit only!)

Computation

Setup

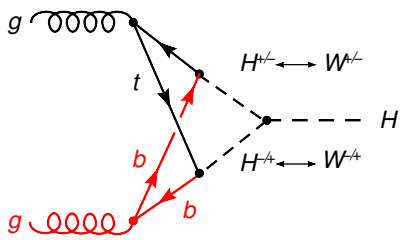
- 2HDM Feynman rules generated with `FeynRules`
  ⇓ A. Alloul, N. Christensen, C. Degrande, C. Duhr, B. Fuks
- Diagram generation with `QGRAF` P. Nogueira
  ⇓
  Build amplitude with in-house code `QGS`
  `QGS`: extension of `GraphShot(GS)`
  S. Actis, A. Ferroglia, L. Jenniches, G. Passarino, M. Passera, 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, reduction, counter terms, extracts pole-part of loop diagrams, renormalization↑,...
- UV-finite amplitude
  integrals classified into different topologies: 

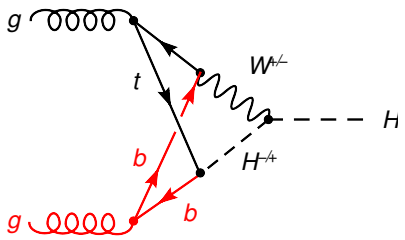
  subdivided in scalar, vector and tensor type integrals
  ↳ mapped on Form factors
- ↳ Form factors are evaluated numerically in Feynman parametric space (Fortran)

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:
  1st+2nd generation: $\log^2$, $\log^1$ $\to$ analytically ✓
  3^d generation: $\log^2$ $\to$ analytically ✓
  3^d generation: $\log^1$ coeff. $\to$ numerically ✓
  ($gg \to H_l$, alignment limit: completely analytically) ✓

Computation

2HDM renormalization

Higgs masses: on-shell

Mixing angles: α, β $\rightarrow$ different schemes:

- $\overline{\text{MS}}$ A. Denner, L. Jenniches, J. Lang, C.S.
  - ct's $\delta\alpha$, $\delta\beta$ fixed: $H_l \rightarrow \tau^+\tau^-$, $H_a \rightarrow \tau^+\tau^-$ UV finite

    $$\delta\bar{\alpha} = \frac{\delta\overline{Z}_{H_hH_l} - \delta\overline{Z}_{H_lH_h}}{4} = \frac{\Sigma^{\text{pp}}_{H_hH_l}(M^2_{H_h}) + \Sigma^{\text{pp}}_{H_hH_l}(M^2_{H_l}) + 2t_{H_lH_h}}{2(M^2_{H_h} - M^2_{H_l})}, \quad \delta\bar{\beta} = \frac{\delta\overline{Z}_{G_0H_a} - \delta\overline{Z}_{H_aG_0}}{4}$$

  - Proper treatment of Higgs tadpoles: *FJ* tadpole scheme
    gauge independent physical ct's J. Fleischer, F. Jegerlehner
    Higgs tadpole ct's are shift vev's: $v_i \rightarrow v_i + \Delta v_i$
  - $\bar{\alpha}$, $\bar{\beta}$ scale dependent
  - May lead to large corrections
- 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)
  - pinch technique (pt) (BFM talk: J. Lang ↑)

    $$\delta\alpha^{\text{pt}} = \frac{\Sigma_{H_hH_l}(M^2_{H_h}) + \Sigma_{H_hH_l}(M^2_{H_l}) + \Sigma^{\text{add}}_{H_hH_l}(M^2_{H_h}) + \Sigma^{\text{add}}_{H_hH_l}(M^2_{H_l}) + 2t_{H_lH_h}}{2(M^2_{H_h} - M^2_{H_l})}, \quad \delta\beta^{\text{pt}} = \ldots \text{ analog}$$

  - p^* scheme:

    $$\delta\alpha^* = \frac{\Sigma_{H_hH_l}(p^{*2}) + t_{H_lH_h}}{M^2_{H_h} - M^2_{H_l}}, \quad \delta\beta^{\text{pt}} = \ldots \text{ analog} \quad \text{with } p^{*2} = (M^2_{H_h} + M^2_{H_l})/2$$

Computation

2HDM renormalization

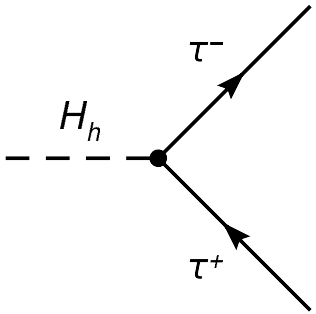
Mixing angles: α, β $\rightarrow$ different schemes:

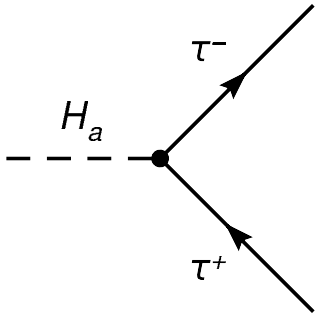
- process dependent (proc)

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

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

  - Unnatural large corrections to some other processes/config.
  - Processes phenomenologically accessible

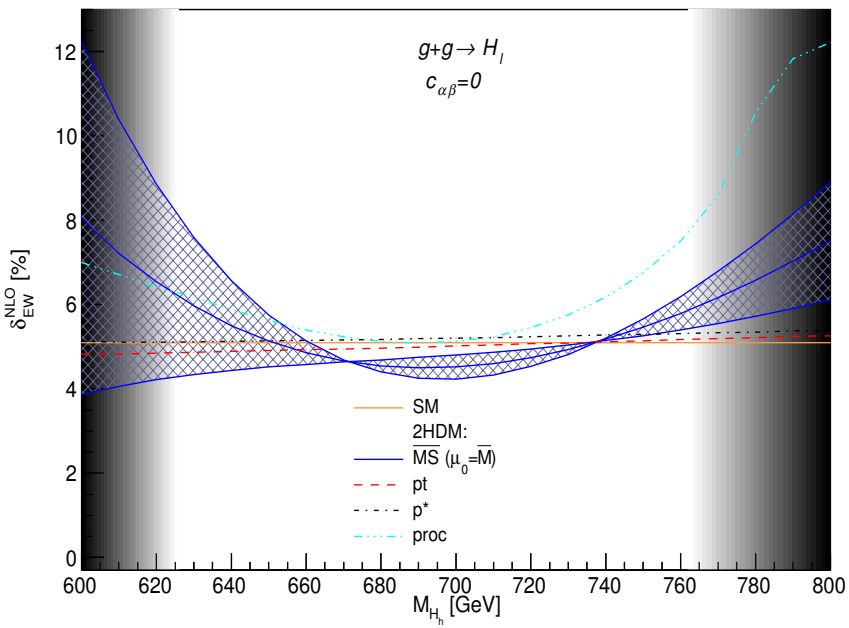


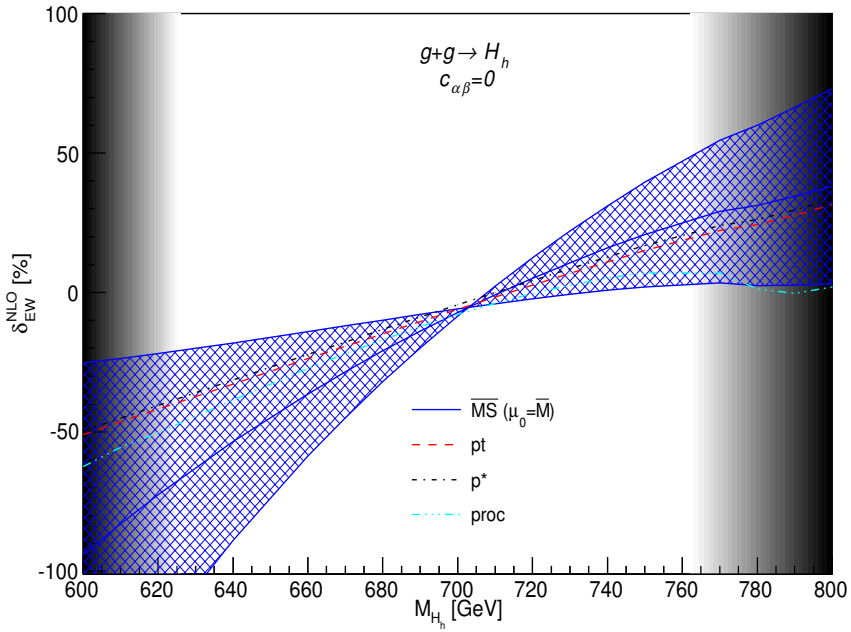


Results

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

- EW % corr. for $gg \to H_l$ and $gg \to H_h$ as fct. of M_{H_h}, $M^* = 700$ GeV (example)



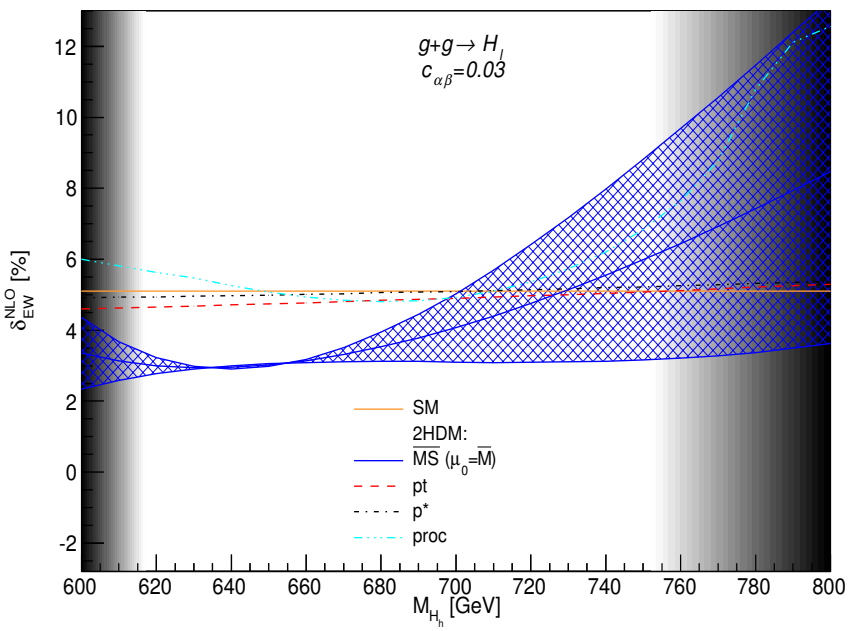


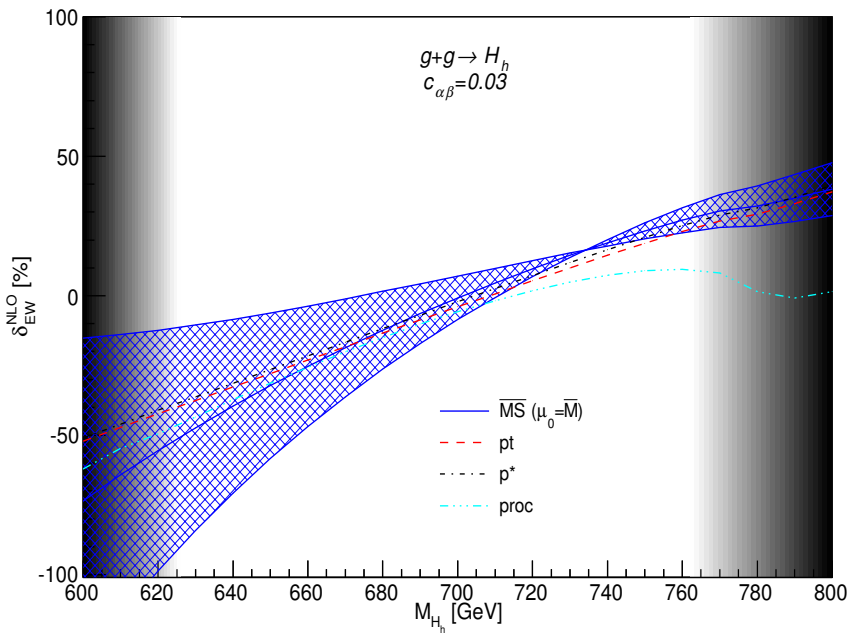
- $gg \to H_l$: comparison to SM: orange line: 5.1%
- Blue band: $\overline{\text{MS}}$ ($\mu_0/2$, μ_0, $2\mu_0$), other lines: other schemes
- Grey bands: $\frac{\lambda}{4\pi} \geq 0.5$
- $gg \to H_h$: large corrections
- $gg \to H_h$: $\overline{\text{MS}}$ unstable for M_{H_h} away from M^*

Results

Non-alignmemt Limit: $c_{\alpha\beta} = 0.03 \neq 0$

- EW % corr. for $gg \to H_l$ and $gg \to H_h$ as fct. of M_{H_h}, $M^* = 700$ GeV (example)



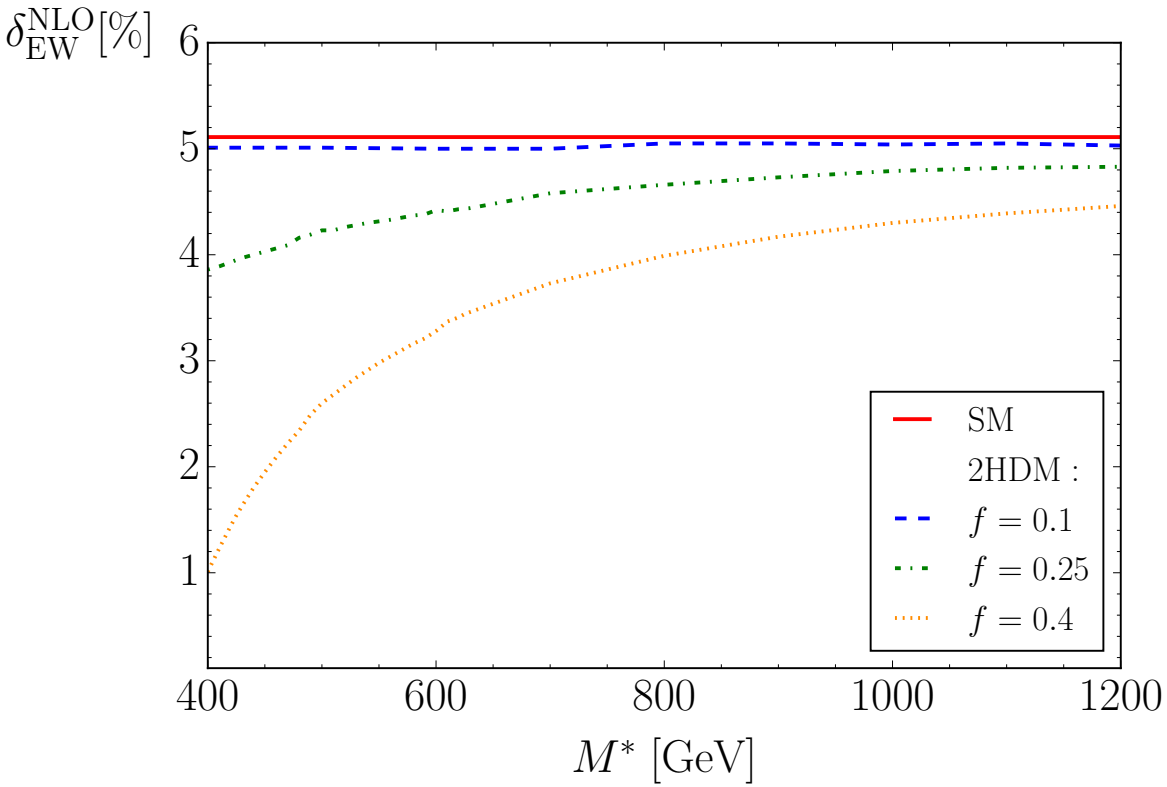


- Any other scenario can be computed too!

Results

$gg \to H_l$ decoupling limit: $M^* \to \infty$

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



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

Benchmark points (BPs)

- BPs collected by LHCHXSWG 1610.07922
  BPs fulfill conditions:

  perturbativity, vacuum stability, exp. constraints

- Alignment limit, $c_{\alpha\beta} = 0$:

BP	M_{H_h}	M_{H_a}	$M_{H^\pm}$	M_{sb}	t_β	$\frac{\lambda_i^{\max}}{4\pi}$	$c^2_{H_l}$	$c^2_{H_h}$
$BP2_{1A}$	200 GeV	500 GeV	200 GeV	198.7 GeV	1.5	0.28 (i=5)	1	0.4
$BP2_{1B}$	200 GeV	500 GeV	500 GeV	198.7 GeV	1.5	0.57 (i=3)	1	0.4
$BP2_{1C}$	400 GeV	225 GeV	225 GeV	0 GeV	1.5	0.49 (i=1)	1	0.4
$BP2_{1D}$	400 GeV	100 GeV	400 GeV	0 GeV	1.5	0.49 (i=1)	1	0.4
$BP3_{A1}$	180 GeV	420 GeV	420 GeV	129.1 GeV	3	0.42 (i=3)	1	0.1

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

BP	M_{H_h}	M_{H_a}	$M_{H^\pm}$	M_{sb}	t_β	$c_{\alpha\beta}$	$\frac{\lambda_i^{\max}}{4\pi}$	$c^2_{H_l}$	$c^2_{H_h}$
$BP2_{2A}$	500 GeV	500 GeV	500 GeV	500 GeV	7	0.28	0.64 (i=3)	1.0	0.02
$BP3_{B1}$	200 GeV	420 GeV	420 GeV	142.0 GeV	3	0.3	0.44 (i=3)	1.1	0.0003
$BP3_{B2}$	200 GeV	420 GeV	420 GeV	142.0 GeV	3	0.5	0.46 (i=3)	1.1	0.04
$BP4_3$	263.7 GeV	6.3 GeV	308.3 GeV	81.5 GeV	1.9	0.14107	0.35 (i=1)	1.1	0.1
$BP4_4$	227.1 GeV	24.7 GeV	226.8 GeV	89.6 GeV	1.8	0.14107	0.23 (i=1)	1.1	0.2
$BP4_5$	210.2 GeV	63.06 GeV	333.5 GeV	116.2 GeV	2.4	0.71414	0.31 (i=3)	1.0	0.2
a-1	700 GeV	700 GeV	670 GeV	624.5 GeV	1.5	-0.0910	0.16 (i=2)	0.9	0.6
b-1	200 GeV	383 GeV	383 GeV	204.2 GeV	2.52	-0.0346	0.30 (i=3)	1.0	0.2

a-1, b-1: 1403.1264

- Higgs self-coupling in the SM: $\frac{\lambda}{4\pi} \to \mathcal{O}(10^{-2})$

Results

BPs, correction 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 some exceptions, except $\overline{\text{MS}}$ for some BPs, scale choice

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

BP \ %	$\delta_{\text{EW}}^{\text{pt}}$	$\delta_{\text{EW}}^{p^*}$	$\delta_{\text{EW}}^{\text{proc}}$	$\delta_{\text{EW}}^{\overline{\text{MS}}}$
$BP2_{1A}$	5.3	6.3	10.1	-0.6 ± 9.8
$BP2_{1B}$	3.8	4.8	4.5	-7.0 ± 10.0
$BP2_{1C}$	4.3	4.4	9.9	12.7 ∓ 0.6
$BP2_{1D}$	2.9	3.5	4.1	14.5 ∓ 0.6
$BP3_{A1}$	4.1	4.0	4.5	11.8 ∓ 8.1

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

BP \ %	$\delta_{\text{EW}}^{\text{pt}}$	$\delta_{\text{EW}}^{p^*}$	$\delta_{\text{EW}}^{\text{proc}}$	$\delta_{\text{EW}}^{\overline{\text{MS}}}$
$BP2_{2A}$	1.7	1.8	1.5	0.57 ± 0.01
$BP3_{B1}$	3.9	3.8	3.9	7.2 ∓ 4.0
$BP3_{B2}$	3.7	3.7	3.5	-8.3 ± 0.4
$BP4_3$	4.3	4.3	3.8	12.6 ∓ 2.1
$BP4_4$	4.4	4.4	3.8	10.3 ± 0.45
$BP4_5$	3.6	3.6	2.6	4.5 ± 10.0
a-1	4.4	4.7	4.8	-3.8 ∓ 25.4
b-1	4.8	4.5	5.4	-0.5 ∓ 6.2

Results

BPs, corrections to $gg \to H_h$

- Large corrections, very sensitive to BPs
- Perturbative behaviour sometimes poor or lost ($BP2_{1A}$, $BP3_{A1}$, $BP2_{1B}$, $BP2_{2A}$)
- $BP3_{B1}$ has tiny c_{H_h}
- $\overline{\text{MS}}$ strong scale dependence

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

BP \ %	$\delta_{\rm EW}^{\rm pt}$	$\delta_{\rm EW}^{p^*}$	$\delta_{\rm EW}^{\rm proc}$	$\delta_{\rm EW}^{\overline{\rm MS}}$
$BP2_{1A}$	-65	-63	-72	-41 ∓ 30
$BP2_{1B}$	-177	-176	-183	-139 ∓ 30
$BP2_{1C}$	-6	-7	-22	-21 ± 17
$BP2_{1D}$	-16	-17	-22	-34 ± 22
$BP3_{A1}$	-70	-70	-79	-115 ± 120

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

BP \ %	$\delta_{\rm EW}^{\rm pt}$	$\delta_{\rm EW}^{p^*}$	$\delta_{\rm EW}^{\rm proc}$	$\delta_{\rm EW}^{\overline{\rm MS}}$
$BP2_{2A}$	179	177	181	-128 ∓ 786
$BP3_{B1}$	-328	-382	–	–
$BP3_{B2}$	-6	-5	-17	344 ∓ 209
$BP4_3$	-11	-23	-18	-55 ± 49
$BP4_4$	-2	-3	0.6	-26 ± 28
$BP4_5$	-21	-21	-16	9 ∓ 46
a-1	3	5	1	27 ± 78
b-1	-43	-44	-50	-10 ± 39

Summary & Conclusion

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

$$g\,g \to H_l \qquad\qquad g\,g \to H_h$$

within 2HDM

- Extended QGS for computation of 2-loop EW corrections in 2HDM in several schemes
- Can determine EW percentage corrections for essentially any scenario (masses, angles)
- Percentage corrections for BPs of LHCHXWG presented

Corrections sensitive to BPs

- 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

$$H_l \to g\,g \qquad\qquad H_h \to g\,g$$

same δ_{EW}!

Results

Scale dependence: $gg \to H_l$

- Logarithmic scale dependence in $\overline{\text{MS}}$ scheme:

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

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

$\hookrightarrow$ Coefficient depends on the "choice" of the Higgs masses, t_β
e.g. $M_{H_h} = 2M_{sb}m_t/M_{H_l}$, $t_\beta = 1 \to$ small $\Leftrightarrow$ enhance...
$\hookrightarrow$ scale dependence can be quite different
for different scenarios but same process

- $c_{\alpha\beta} \neq 0$: lengthy ...