NLO Electroweak Corrections to Higgs-Strahlung Processes at the LHC within THDM

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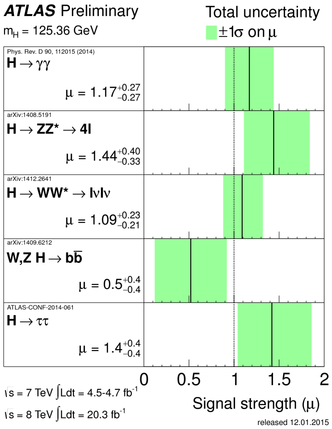
Intro.

$pp \to Vh + X$ @ LHC in THDM

Numerical Results

Summary

HIGGS@LHC



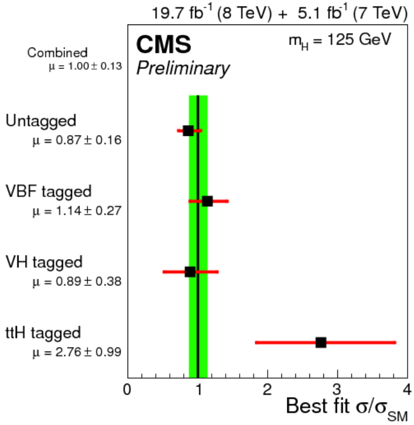
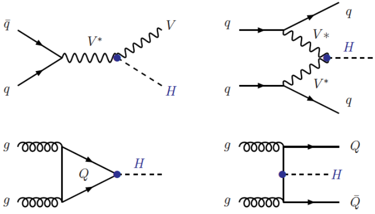


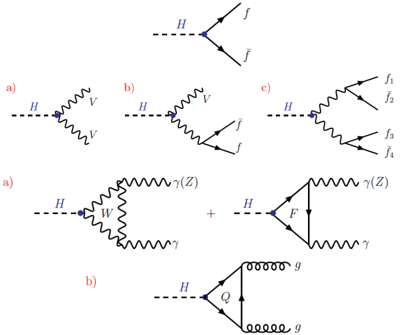
Figure: Signal strengths of the 125 GeV Higgs from ATLAS and CMS.

Higgs@LHC

Production



Decay



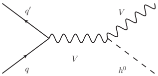
Theory $\to \sigma * BR \sim N_{sig} \leftarrow$ Exp.

Why Higher Order Matters - New Physics in Loops

- Direct:
  Higher experimental precision needs more accurate theoretical calculation to match.
- Indirect:
  - Heavy particles are not necessarily decoupled, especially when the couplings are related with particle's mass.
  - Electroweak Precision Tests; Flavor-Changing Neutral Current(FCNC)...

STATE OF THE ART

For the considered process: $pp \to Vh$ $(V = Z, W)$ at the LHC-14 TeV:



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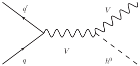

SM:

- In next-to-leading order (NLO) QCD, $\delta \sim 30\%$, scale dependence $\sim 5\%$
  [M. Spira, arXiv:hep-ph/9705337]
- In next-to-next-to-leading order (NNLO) QCD, $\delta \sim 1\%$, scale dependence $\sim 2\%$
  [O. Brein, A. Djouadi and R. Harlander,arXiv:hep-ph/0307206]
- In NLO electroweak (EW), $\delta \sim -5\%$ in G_μ-scheme, and very close to 0 $(\sim \pm 0.7\%)$ in $\alpha(0)$-scheme
  [M. L. Ciccolini, S. Dittmaier and M. Kramer, arXiv:hep-ph/0306234]

MSSM:
NLO SUSY-QCD corrections would be small and generally SM-like
[A. Djouadi and M. Spira, arXiv:hep-ph/9912476, 2000]

THDM:
NNLO QCD [Harlander, Liebler and Zirke, arXiv:1307.8122]

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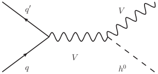

$\to$ NLO EW corrections in THDM at the LHC-14

INTRO. TO THDM

- Two Y=1 $SU(2)_L$ Higgs Doublets $\Phi_1 = \begin{pmatrix} \Phi_1^+ \\ \Phi_1^0 \end{pmatrix}$, $\Phi_2 = \begin{pmatrix} \Phi_2^+ \\ \Phi_2^0 \end{pmatrix}$
- $\mathcal{CP}$-conserving Higgs potential with Z_2 symmetry :

$$
\begin{aligned}
V(\Phi_1, \Phi_2) = \quad & \lambda_1 \left(\Phi_1^\dagger \Phi_1 - \frac{v_1^2}{2}\right)^2 + \lambda_2 \left(\Phi_2^\dagger \Phi_2 - \frac{v_2^2}{2}\right)^2 \\
& + \lambda_3 \left[\left(\Phi_1^\dagger \Phi_1 - \frac{v_1^2}{2}\right) + \left(\Phi_2^\dagger \Phi_2 - \frac{v_2^2}{2}\right)\right]^2 \\
& + \lambda_4 \left[(\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) - (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1)\right] \\
& + \lambda_5 \left[\mathrm{Re}\,(\Phi_1^\dagger \Phi_2) - \frac{v_1 v_2}{2}\right]^2 \\
& + \lambda_6 \left[\mathrm{Im}\,(\Phi_1^\dagger \Phi_2)\right]^2
\end{aligned}
$$

- λ_{1-6} (real) and $v_{1,2}$ ($\langle \Phi_i^0 \rangle = v_i/\sqrt{2}$) are free parameters, which differs from the case in MSSM.

Intro. to THDM

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{v_1+\phi_1^0+i\chi_1^0}{\sqrt{2}} \end{pmatrix} \qquad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{v_2+\phi_2^0+i\chi_2^0}{\sqrt{2}} \end{pmatrix}$$

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Particle contents: (8-3=5) Higgs Bosons

$\mathcal{CP}$-even states: h^0, H^0; $\mathcal{CP}$-odd state: A^0; charged states: $H^\pm$

$$\begin{pmatrix} H^0 \\ h^0 \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \phi_1^0 \\ \phi_2^0 \end{pmatrix}$$

$$\begin{pmatrix} G^0 \\ A^0 \end{pmatrix} = \begin{pmatrix} \cos\beta & \sin\beta \\ -\sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} \chi_1^0 \\ \chi_2^0 \end{pmatrix}$$

$$\begin{pmatrix} G^\pm \\ H^\pm \end{pmatrix} = \begin{pmatrix} \cos\beta & \sin\beta \\ -\sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} \phi_1^\pm \\ \phi_2^\pm \end{pmatrix}$$

Free parameters λ_{1-6} and $v_{1,2}$ can be translated into:

$$(M_{h^0}, M_{H^0}, M_{A^0}, M_{H^\pm}, \tan\beta, \alpha, \lambda_5) \text{ and } M_W$$

INTRO. TO THDM

$H = h^0, H^0, A^0, H^\pm$

Modified couplings(VVH)

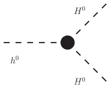
$$h^0 Z_\mu Z_\nu \quad : \quad \frac{ie\sin(\beta-\alpha)M_Z}{s_W c_W} g^{\mu\nu} \xrightarrow{\sin(\beta-\alpha)=1} \frac{ieM_Z}{s_W c_W} g^{\mu\nu}(SM)$$

$$H^0 Z_\mu Z_\nu \quad : \quad \frac{ie\cos(\beta-\alpha)M_Z}{s_W c_W} g^{\mu\nu} \xrightarrow{\sin(\beta-\alpha)=1} 0$$

New couplings(3H, 4H)

HIGGS SELF-COUPLINGS IN THDM

Take $\lambda_{h^0H^0H^0}$ as an instance



$$\lambda_{h^0H^0H^0} = \frac{ie\sin(\beta-\alpha)}{2M_W\sin 2\beta s_W}\left[(M_{h^0}^2 + 2M_{H^0})\sin 2\alpha - (3\sin 2\alpha + \sin 2\beta)s_W^2\frac{2\lambda_5 M_W^2}{e^2}\right]$$

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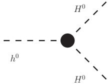

$$\lambda_{h^0 H^0 H^0} = \frac{ie \sin(\beta-\alpha)}{2M_W \sin 2\beta s_W} \left[(M_{h^0}^2 + 2M_{H^0}) \sin 2\alpha - (3 \sin 2\alpha + \sin 2\beta) s_W^2 \frac{2\lambda_5 M_W^2}{e^2} \right]$$

$$\downarrow \sin(\beta - \alpha) = 1$$

$$\lambda_{h^0 H^0 H^0} = -\frac{i}{v} \left[M_{h^0}^2 + 2M_{H^0}^2 - \lambda_5 v^2 \right] ,$$

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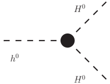

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$$\lambda_{h^0 H^0 H^0} = -\frac{i}{v} \left[M_{h^0}^2 + 2M_{H^0}^2 - \lambda_5 v^2 \right] \; ,$$

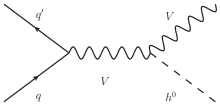
- Effects from scalar masses and λ_5 can get canceled:

$$\lambda_5^0 = \frac{M_{h^0}^2 + 2M_{H^0}^2}{v^2} \to \lambda_{h^0 H^0 H^0} = 0$$

- When M_{H^0} goes large(↑) and λ_5 becomes negatively large(- ↑), we get the largest triple-Higgs coupling.

EW CORRECTIONS TO $pp \to Zh^0$

Tree-level

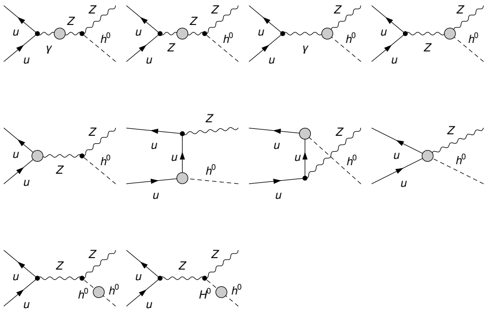


V: Z, $W^{\pm}$
h^0: the observed SM-like Higgs boson
($M_{h^0} = 125$ GeV, $\sin(\beta - \alpha) = 1$)

$pp \to Zh^0$: q = q′ = u, d, c, s, b
$pp \to W^+h^0$: q= u, c and q′ = d, s

EW CORRECTIONS TO $pp \to Zh^0$

One loop electroweak corrections:

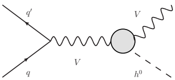


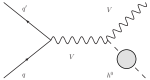
Real photon radiations:

as the same as in SM

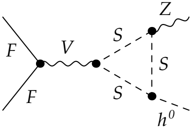
EW CORRECTIONS TO $pp \to Zh^0$

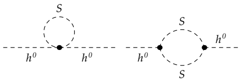
Main THDM contributions:





$\downarrow$





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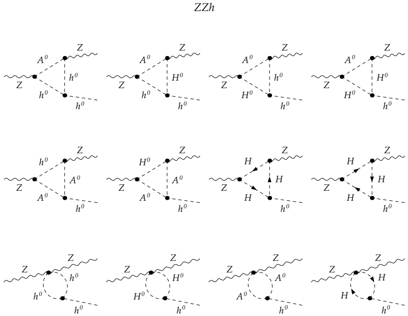

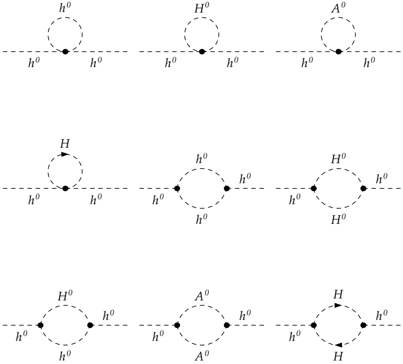

Renormalization in THDM

- On-shell conditions for all the Higgs masses

$$Re\hat{\Sigma}_H(M_H^2) = 0 \; (H = h^0, H^0, A^0, H^\pm)$$

- Tadpole cancellation conditions

$$T_{h^0/H^0} + \delta t_{h^0/H^0} = 0$$

- For $\tan\beta = \frac{v_2}{v_1}$, we follow the condition

$$\frac{\delta v_1}{v_1} = \frac{\delta v_2}{v_2}$$

- No mixing between CP-even scalars at one-loop level

$$Re\hat{\Sigma}_{h^0 H^0}(M_{h^0}^2) = 0$$

- Field renormalization

$$\begin{aligned} \delta Z_{\Phi_1}^{\overline{\text{MS}}} &= -\text{Re}\Sigma'^{\text{div}}_{\Phi_1}, \\ \delta Z_{\Phi_2}^{\overline{\text{MS}}} &= -\text{Re}\Sigma'^{\text{div}}_{\Phi_2}. \end{aligned}$$

PROCESS $pp \to Zh$ IN THDM

Examine the dominant contributions:
For WF corrections:

$$M^{WF} = (\sqrt{\hat{Z}_{h^0}} - 1)M^{(0)} = -\frac{1}{2}Re\hat{\Sigma}'_{h^0}(M_{h^0})M^{(0)}$$

$$Re\hat{\Sigma}'_{h^0}(M_{h^0}) = Re\Sigma'_{h^0}(M_{h^0}) + \delta Z_{h^0}$$

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Effects in δZ_{h^0} is canceled between vertex ZZh and WF.

$$\delta = \frac{\sigma^{(0+1)} - \sigma^{(0)}}{\sigma^{(0)}} = \frac{\langle 2M^{(0)}M^{(1)} \rangle}{\langle |M^{(0)}|^2 \rangle} \simeq -\frac{|\lambda_{3H}|^2}{16\pi^2 M^2} f(M_{h^0}^2, M^2, M^2)$$

Loop suppression of M_H v.s. Enhancement from λ_{3H}

Rough estimation: for $M = 300$ GeV, $f \sim \mathcal{O}(1)$, $\delta \to -90\%$

Numerical Results for $pp \to Zh^0 + X$: Parton Level

Free parameters: $(M_{h^0}, M_{H^0}, M_{A^0}, M_{H^\pm}, \tan\beta, \alpha, \lambda_5)$
Basic Setup:

- h^0 is SM-like $\to M_{h^0} = 125$ GeV and decoupling limit: $\alpha = \beta - \frac{\pi}{2}$
- Degenerate mass: $M_{H^0} = M_{A^0} = M_{H^\pm} = M$ (EWPT restricts ΔM)
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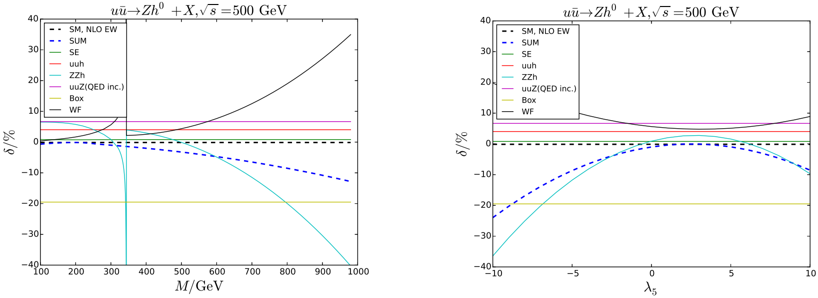

$\lambda_5 = 0$ $M = 300$ GeV

NUMERICAL RESULTS FOR $pp \to Zh^0 + X$: HADRON LEVEL

Input parameter scheme: $\alpha(0)$-scheme
PDF: NNPDF2.3QED
Mass factorization: DIS-scheme
$\mu_R = \mu_F = (M_{h^0} + M_V)$

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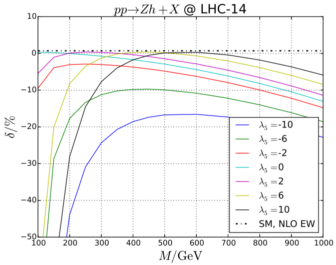
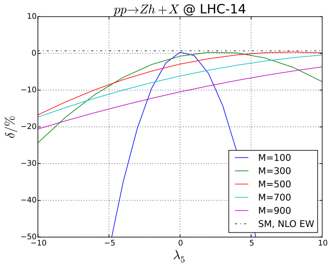
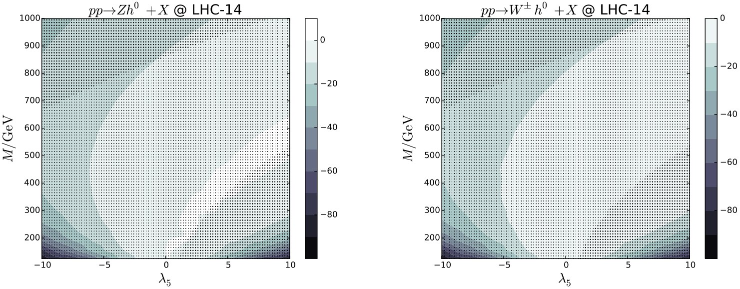




WITH THEORETICAL CONSTRAINTS CONSIDERED

Theoretical Constraints:

- Tree-level Unitarity
- Vacuum Stability



BENCHMARK POINTS

Results for a few benchmark points:

$$M_{h^0} = 125\ \text{GeV}$$
$$\tan\beta = 1, \alpha = \beta - \frac{\pi}{2}$$
$$M_{H^0} = M_{A^0} = M_{H^\pm} = M$$

M	λ_5	$\delta(Zh^0)$	$\delta(W^\pm h^0)$
300	0	-0.77%	-2.44%
300	-10	-24.3%	-26.1%
500	0	-2.94%	-4.62%

SUMMARY

- In THDM, EW loop contributions can make a strong reduction of the cross section of Higgs-strahlung processes $pp \to Vh^0$, which essentially results from the non-standard Higgs self-couplings.

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  - Heavy non-standard Higgs bosons don't decouple, they manifest themselves through self-couplings in the loop corrections: $\delta(M = 900\text{GeV}, \lambda_5 = -10) \sim -20\%$
  - Combination between non-standard Higgs boson masses and λ_5 give intriguing patterns in relative corrections
- At ILC, the effects are very similar. [D. Lopez-Val, J. Sola, N. Bernal, arXiv: 1003.4312]

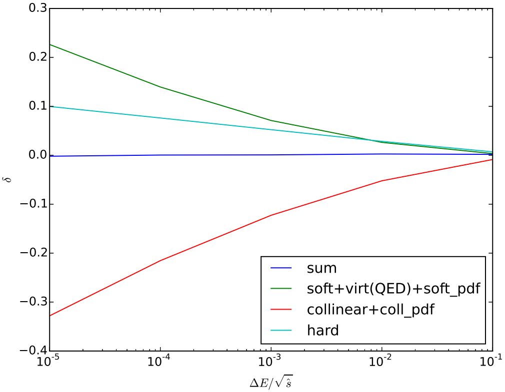
MSSM AS A THDM

In MSSM, the Higgs potential is determined by Supersymmetry. Thus only gauge couplings rule the potential. In MSSM, the higgs potential would reduce to:

$$
\begin{aligned}
\lambda_1 &= \lambda_2 \\
\lambda_3 &= \frac{\pi\alpha_{em}}{2s_W^2c_W^2} - \lambda_1 \\
\lambda_4 &= 2\lambda_1 - \frac{2\pi\alpha_{em}}{c_W^2} \\
\lambda_5 &= \lambda_6 = 2\lambda_1 - \frac{2\pi\alpha_{em}}{s_W^2c_W^2}
\end{aligned}
$$

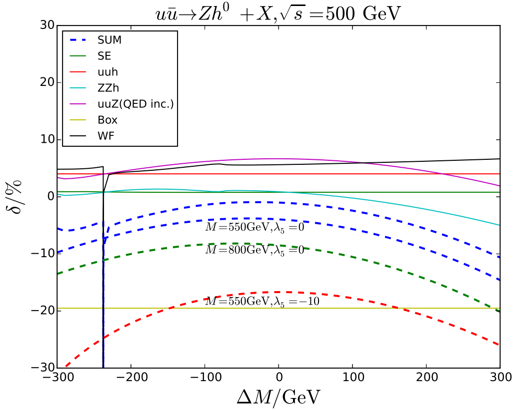
IR & Collinear Divergence

We use phase-space slicing method to deal with soft and collinear photon radiations. Scale independence has been checked:



ΔM EFFECTS

Investigate the $\Delta M = M_{H^\pm} - M_{H^0}$-effects
$M_{H^0} = M_{A^0} = 300$ GeV, $\tan\beta = 1$, $\lambda_5 = 0$



Full program within THDM

$$\sigma_{WH} = \sigma_{WH}^{VH@NNLO}(1+\delta_{WH,EW})$$
$$\sigma_{ZH} = \sigma_{ZH}^{VH@NNLO}(1+\delta_{ZH,EW}) + \sigma_{gg\to ZH}$$

@ LHC-14, 300 fb^{-1}, we have $\Delta g_{VVh}/g_{VVh} \sim 5.7 - 2.7\%$