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

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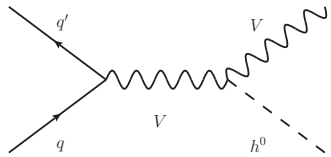
State of the Art

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



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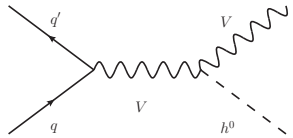

SM:

- 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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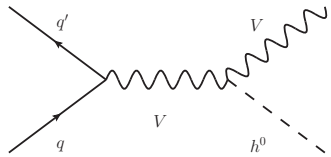

$\to$ NLO EW corrections in THDM at the LHC-14

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

INTRO. TO THDM

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

Intro. to THDM

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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: $H^\pm$

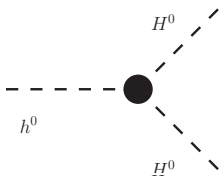
$$\begin{pmatrix} H^0 \\ h^0 \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \phi_1^0 \\ \phi_2^0 \end{pmatrix}$$
$$\begin{pmatrix} G^0 \\ A^0 \end{pmatrix} = \begin{pmatrix} \cos\beta & \sin\beta \\ -\sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} \chi_1^0 \\ \chi_2^0 \end{pmatrix}$$
$$\begin{pmatrix} G^\pm \\ H^\pm \end{pmatrix} = \begin{pmatrix} \cos\beta & \sin\beta \\ -\sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} \phi_1^\pm \\ \phi_2^\pm \end{pmatrix}$$

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

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

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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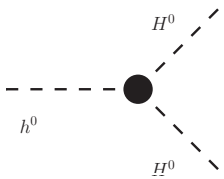

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$$\downarrow \sin(\beta-\alpha) = 1$$

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

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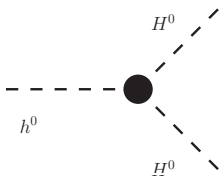

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$$\downarrow \sin(\beta-\alpha) = 1$$

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

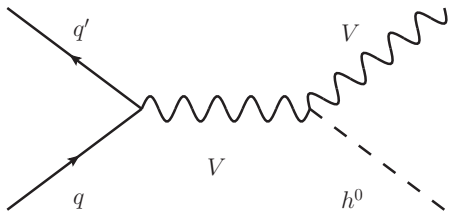
- Effects from scalar masses and λ_5 can get canceled:

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

- 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

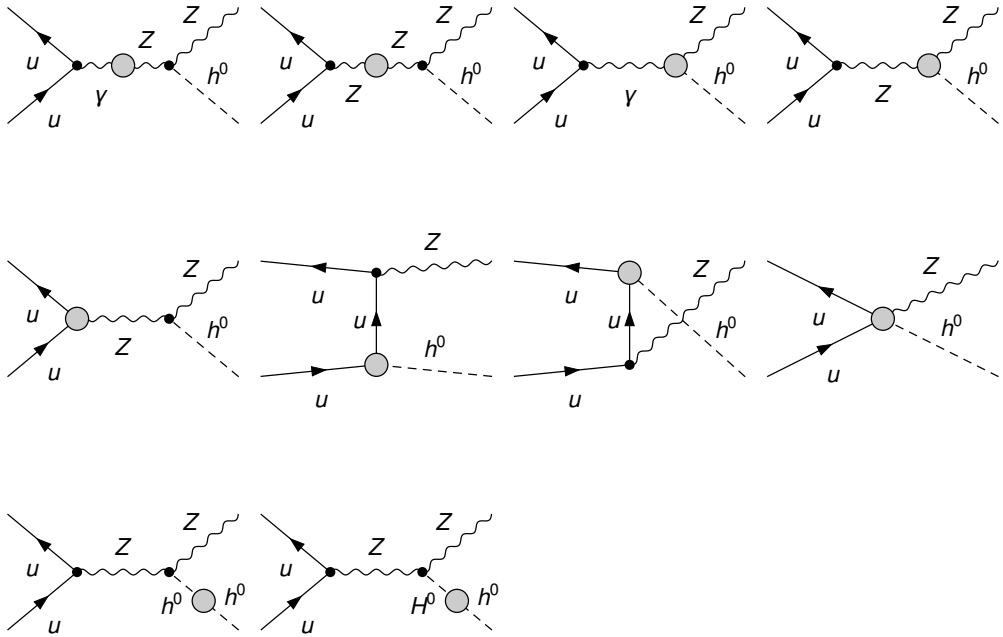


V: Z, $W^{\pm}$
h^0: the observed SM-like Higgs boson($M_{h^0} = 125$ GeV)

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

EW CORRECTIONS TO $pp \to Zh^0$

One loop electroweak corrections:

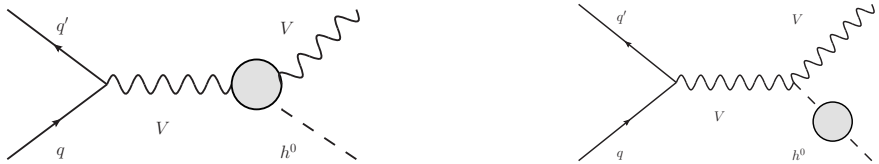


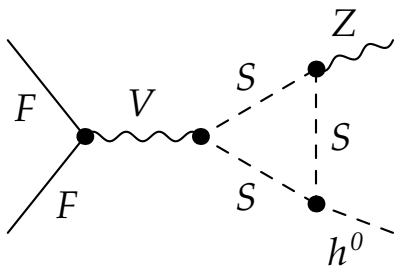
Real photon radiations:

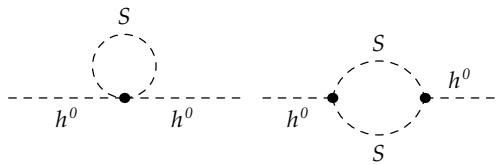
as the same as in SM

EW CORRECTIONS TO $pp \to Zh^0$

Main THDM contributions:







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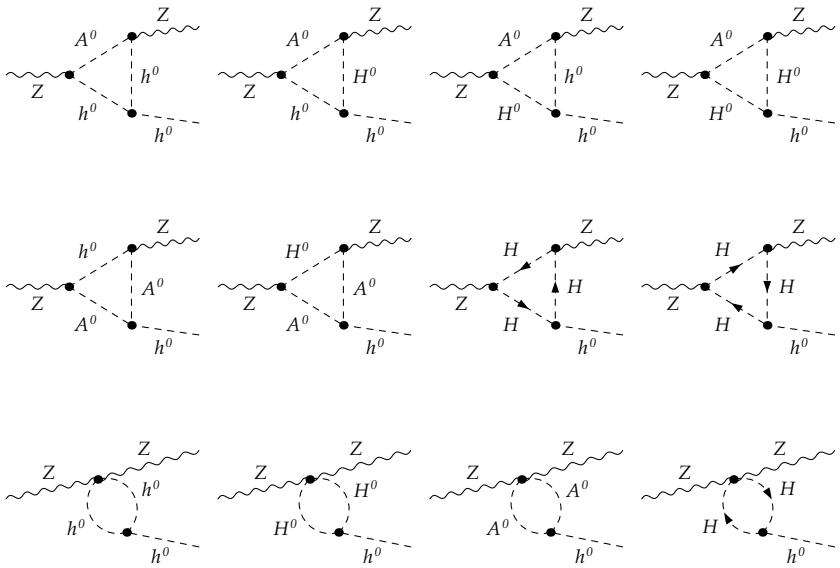

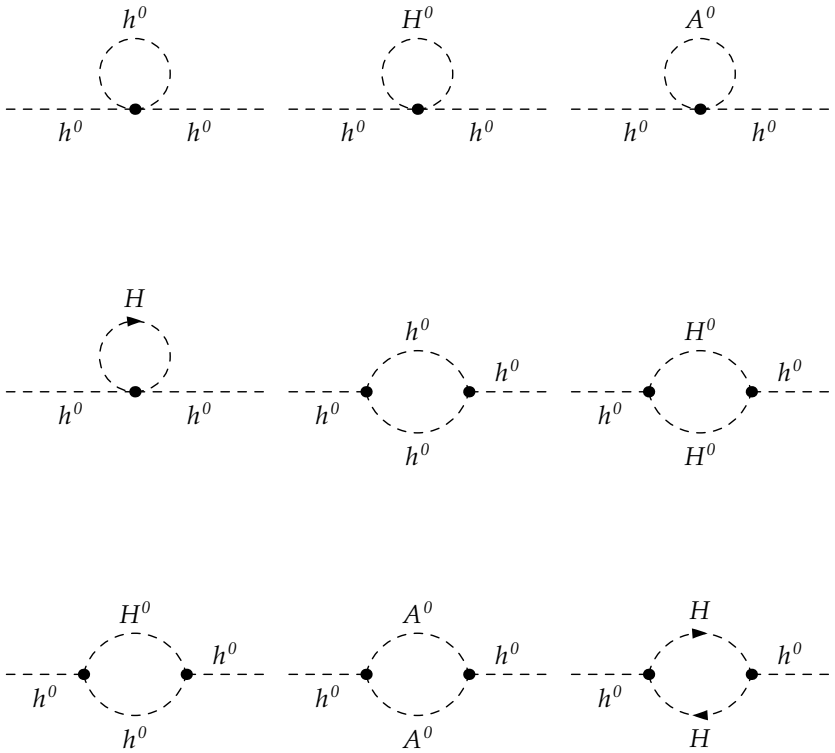

Numerical Results for $pp \to Zh^0 + X$: Parton Level

Free parameters: (M_{h^0}, M_{H^0}, M_{A^0}, $M_{H^\pm}$, $\tan\beta$, α, λ_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)
- $\tan\beta = 1$ (no $\tan\beta$ dependence under condition $\alpha = \beta - \frac{\pi}{2}$)

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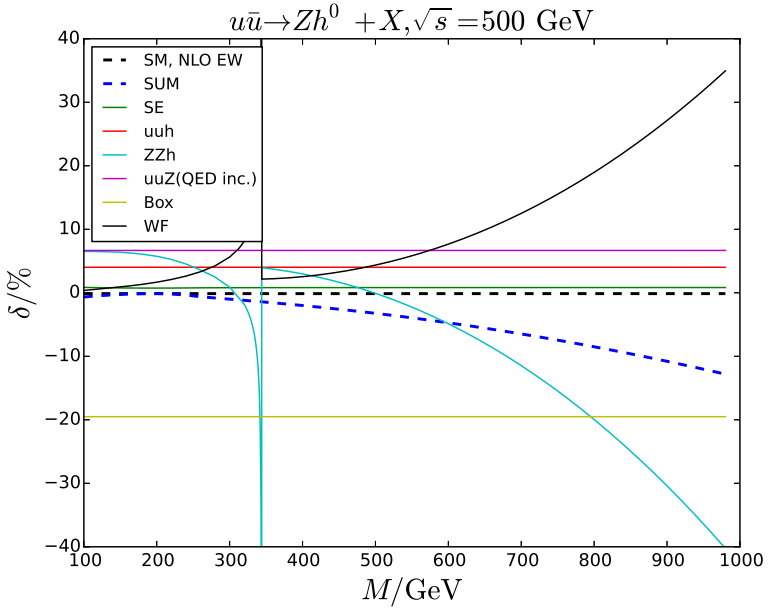
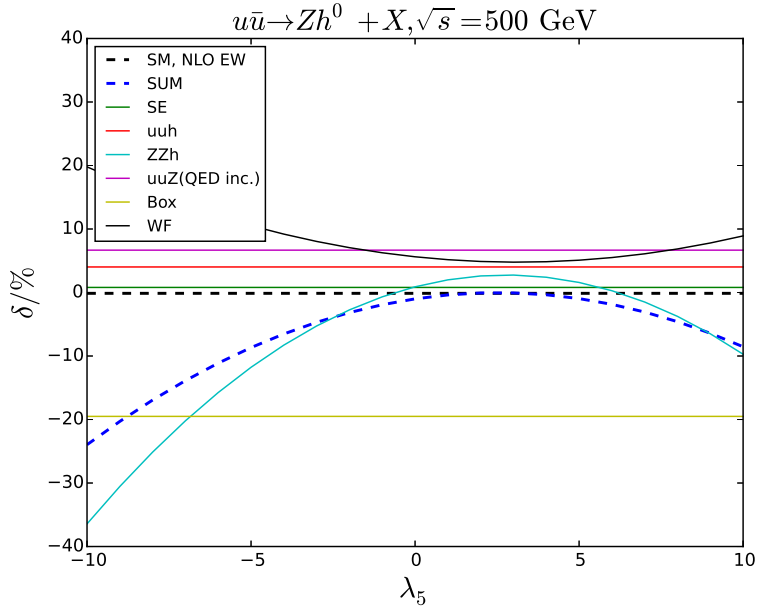


$\lambda_5 = 0$



$M = 300$ 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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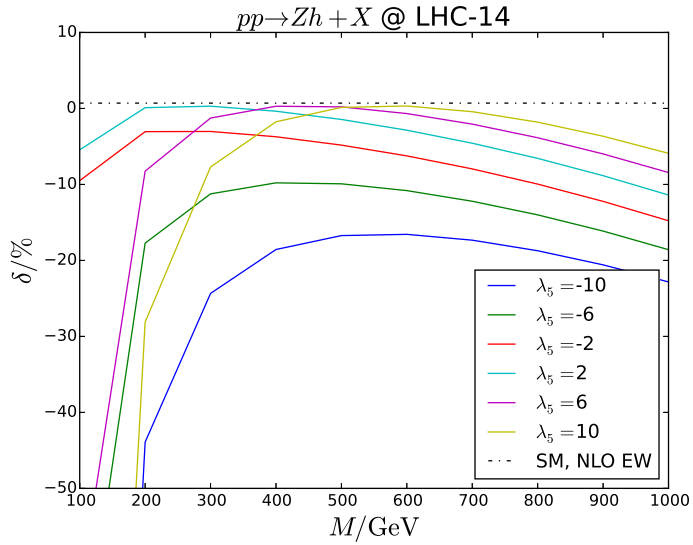

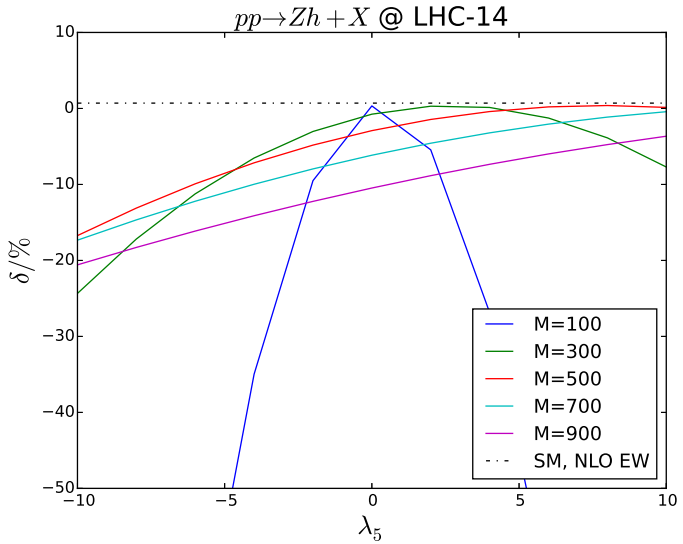

BENCHMARK POINTS

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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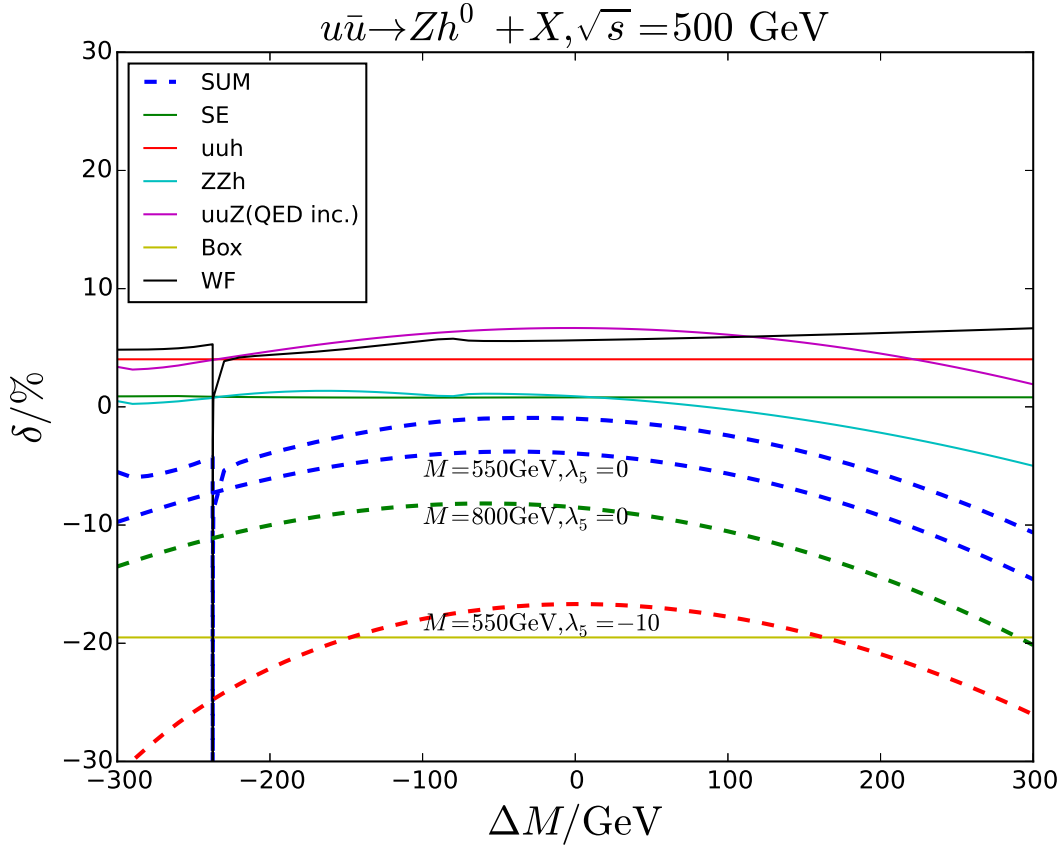
  - Heavy non-standard Higgs bosons don't decouple, they manifest themselves through self-couplings in the loop corrections: $\delta(M = 900\text{GeV}, \lambda_5 = -10) \sim -20\%$
  - Combination between non-standard Higgs boson masses and λ_5 give intriguing patterns in relative corrections
- We only presented the results for $pp \to Zh^0 + X$. However, the case for $pp \to W^{\pm}h^0 + X$ is similar in principle.

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 $\Delta g_{VVh}/g_{VVh} \sim 5.7 - 2.7\%$