



Electroweak corrections to $gg \rightarrow H$ and $H \rightarrow \gamma\gamma$ in the singlet extended Standard Model

Benjamin Summ

in collaboration with Christian Sturm and Sandro Uccirati

DIS2022

Julius-Maximilians-Universität Würzburg

03.05.2022

1 Introduction

2 Calculation and technical details

3 Results

4 Summary and conclusions

1 Introduction

2 Calculation and technical details

3 Results

4 Summary and conclusions

- Discovery of the Higgs boson formally completes the SM
- SM potential is **one possible parameterization** of EW symmetry breaking → is it the one realized in Nature?
- Simple extension of the SM: add a scalar singlet (HSESM)
V. Silveira, A. Zee; J. McDonald, T. Binoth, J. J. van der Bij;...
- The HSESM is being studied at the LHC
ATLAS: 1509.00672, 1906.02025,...
CMS: 1504.00936,...
⇒ **need for precise theory predictions**
- NLO EW corrections to Higgs strahlung, VBF,
 $H_{l,h} \rightarrow WW/ZZ \rightarrow 4f$ and $H_h \rightarrow H_l + H_l$ are known
A. Denner, J. N. Lang, S. Uccirati; L. Altenkamp, M. Boggia, S. Dittmaier;
A. Denner, S. Dittmaier, J. N. Lang; F. Bojarski, G. Chalons, D. Lopez-Val, T. Robens

The Model

- Singlet S only couples to doublet Φ
 \implies only potential is modified

$$V_{\text{HSESM}} = m_1^2 \Phi^\dagger \Phi + m_2^2 S^2 + \frac{\lambda_1}{2} (\Phi^\dagger \Phi)^2 + \frac{\lambda_2}{2} S^4 + \lambda_3 \Phi^\dagger \Phi S^2$$

- Assume S and all potential parameters to be real (CP-conserving)
- Spontaneous symmetry breaking:

$$\Phi = \begin{pmatrix} \phi^+ \\ \frac{1}{\sqrt{2}}(\nu + \rho_1 + i\eta) \end{pmatrix}, \quad S = \frac{\nu_S + \rho_2}{\sqrt{2}},$$

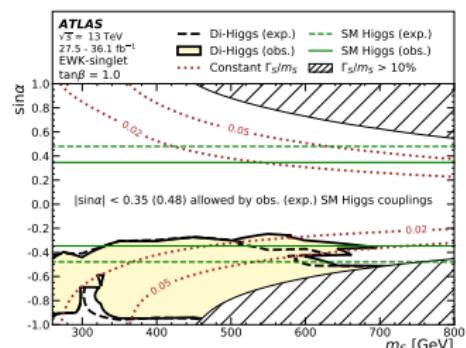
ν and ν_S are vacuum expectation values

The Model

- Diagonalization of the mass matrix by mixing angle α

$$\begin{pmatrix} \rho_1 \\ \rho_2 \end{pmatrix} = \begin{pmatrix} \cos \alpha & -\sin \alpha \\ \sin \alpha & \cos \alpha \end{pmatrix} \begin{pmatrix} H_l \\ H_h \end{pmatrix}$$

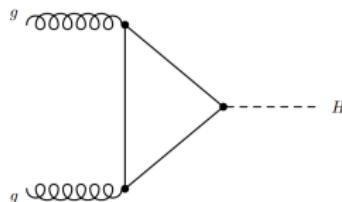
- Assume $125.25 \text{ GeV} = M_{H_l} < M_{H_h}$
- Free parameters:
 α , $\tan \beta = v_S/v$ and M_{H_h}
- SM-limit: $\sin \alpha \rightarrow 0$, $\tan \beta \rightarrow \pm\infty$
(for $\sin \alpha = 0$ H_h only couples to itself)



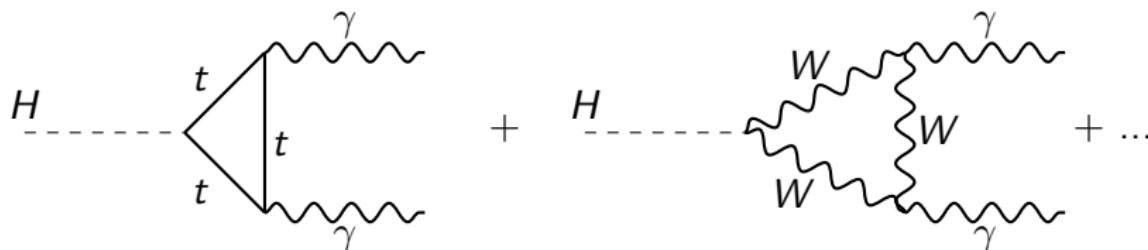
ATLAS: 1906.02025

Gluon fusion

- Dominant production mechanism at hadron colliders



- LO for $gg \rightarrow H_l, H_h$ is rescaled by $c_H = \cos \alpha, -\sin \alpha$
- QCD corrections obtainable from known SM QCD corrections (N³LO: C. Anastasiou, C. Duhr, F. Dulat, F. Herzog, B. Mistlberger) by rescaling
- NLO EW corrections depend non-trivially on $\alpha, \tan \beta$ and M_{H_h}
⇒ dedicated computation necessary

$H \rightarrow \gamma + \gamma$ 

- Doublet component ρ_1 couples like in the SM
- $H_{l,h} - t - t$ and $H_{l,h} - W^+ - W^-$ arise from mixing
 \Rightarrow all LO contributions rescaled by the same factor
- Hence the situation is similar to $g + g \rightarrow H_{l,h}$

1 Introduction

2 Calculation and technical details

3 Results

4 Summary and conclusions

Setup

FeynRules: Generation of Feynman rules

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

QGRAF: Generation of Feynman diagrams

P. Nogueira

QGS: Build amplitude and perform algebraic manipulations

Extension of GraphShot

S. Actis, A. Ferroglio, L. Jenniches, G. Passarino, M. Passera, C. Sturm, S. Uccirati, B.S.

Fortran: Numerical integration

General procedure

- Decompose amplitude into tensor structures

$$A^{\mu\nu} = \frac{g^3 s_\theta^2}{16\pi^2} \left[F_D g^{\mu\nu} + \sum_{i,j=1}^2 F_P^{(ij)} p_i^\mu p_j^\nu + F_\epsilon \epsilon(\mu, \nu, p_1, p_2) \right]$$

- $F_P^{(11)}$, $F_P^{(22)}$ and $F_P^{(12)}$ do not contribute after contraction with $\epsilon_{1,\mu} \epsilon_{2,\mu}$
- $F_\epsilon = 0$ at LO \implies only need F_D and $F_P \equiv F_P^{(21)}$ at NLO
- Ward identity $p_1^\mu p_2^\nu A_{\mu\nu} = 0$
 \implies only need one form factor for evaluation

Renormalization of mixing angle α

- $\tan \beta$ not present at LO
 \implies no renormalization needed
- Different schemes for α possible: A. Denner, S. Dittmaier, J.-N. Lang
 - ZZ scheme ✓
 - Further schemes will be studied:
 - Rigid symmetry scheme (work in progress)
 - ...

ZZ scheme

- Amplitude at LO

$$A_{\text{LO}}^{\mu\nu}(H_{l,h} \rightarrow ZZ) = A_{\text{LO}}^{(1)}(H_{l,h} \rightarrow ZZ)g^{\mu\nu}$$

$$\text{with } \frac{A_{\text{LO}}^{(1)}(H_l \rightarrow ZZ)}{A_{\text{LO}}^{(1)}(H_h \rightarrow ZZ)} = -\frac{\cos \alpha}{\sin \alpha}$$

- Amplitude at NLO

$$A_{\text{NLO}}^{\mu\nu}(H_{l,h} \rightarrow ZZ) = A_{\text{NLO}}^{(1)}(H_{l,h} \rightarrow ZZ)g^{\mu\nu} + A_{\text{NLO}}^{(2)}(H_{l,h} \rightarrow ZZ)p_1^\mu p_2^\nu$$

- Fix $\delta\alpha$ by **requiring** that

$$\frac{A_{\text{NLO}}^{(1)}(H_l \rightarrow ZZ)}{A_{\text{NLO}}^{(1)}(H_h \rightarrow ZZ)} \stackrel{!}{=} \frac{A_{\text{LO}}^{(1)}(H_l \rightarrow ZZ)}{A_{\text{LO}}^{(1)}(H_h \rightarrow ZZ)} = -\frac{\cos \alpha}{\sin \alpha}$$

Checks

- Comparison of $H_{l,h} \rightarrow ZZ$ and $H_h \rightarrow H_l H_l$ to Recola 2 ✓
- UV renormalization yields finite amplitude ✓
- Collinear logarithms are cancelled analytically ✓
- Ward identity is satisfied ✓
- Agreement with SM in the SM-limit ✓

A. Denner, J. N. Lang, S. Uccirati

1 Introduction

2 Calculation and technical details

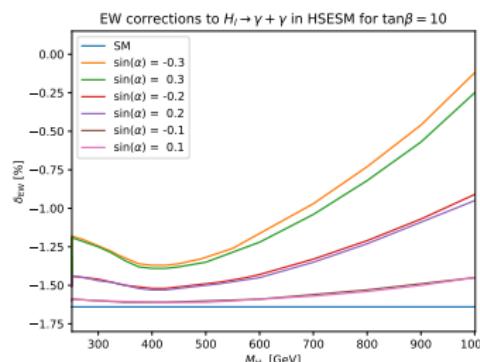
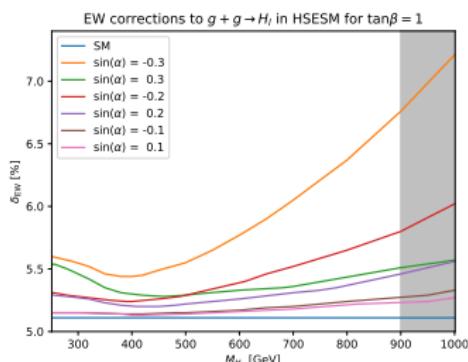
3 Results

4 Summary and conclusions

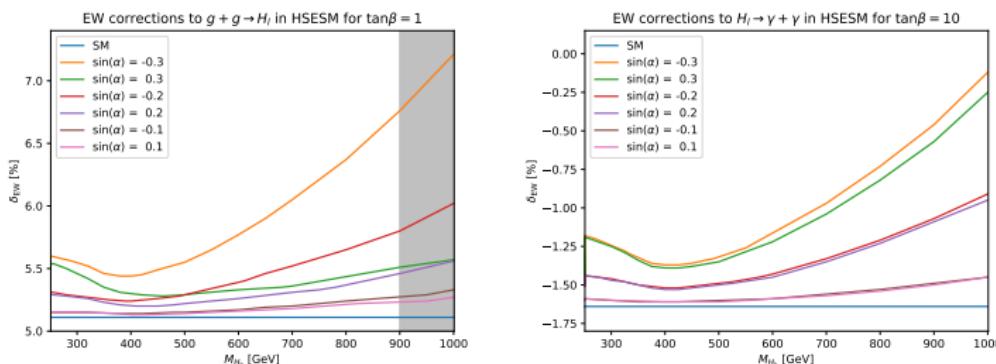
$g + g \rightarrow H_l$ and $H_l \rightarrow \gamma + \gamma$

- Always plot δ_{EW} against M_{H_h} , with

$$|A|^2 = |A_{LO}|^2 (1 + \delta_{EW}) \text{ with } \delta_{EW} = \frac{2 \operatorname{Re}[A_{NLO,EW} \cdot A_{LO}^*]}{|A_{LO}|^2}$$



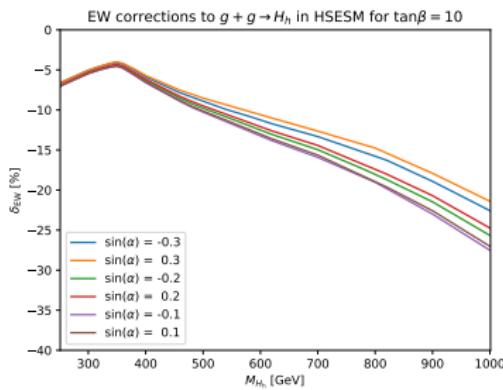
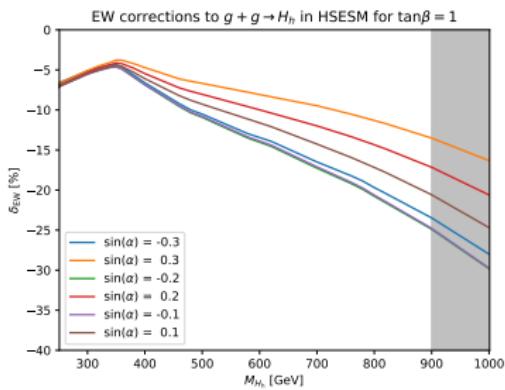
- Corrections close to SM unless $|\sin \alpha|$ far from zero and heavy Higgs mass M_{H_h} large

$g + g \rightarrow H_1$ and $H_1 \rightarrow \gamma + \gamma$ 

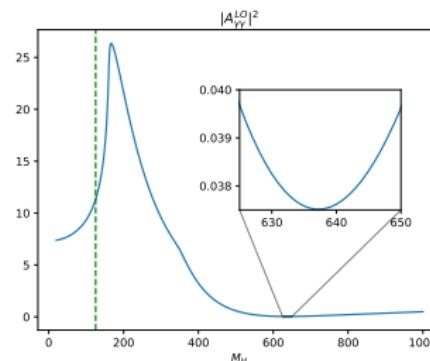
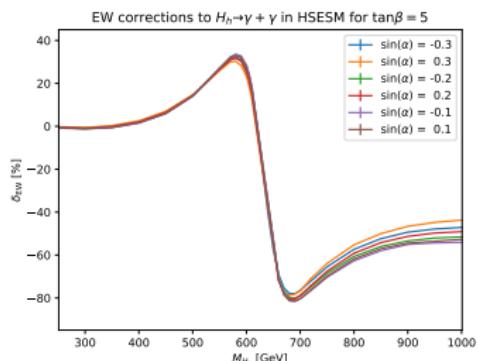
- For low $\tan\beta$ perturbativity is jeopardized (grey shaded area)

$$\lambda_2 = \frac{M_{H_1}^2}{v^2 \tan^2 \beta} \sin^2 \alpha + \frac{M_{H_h}^2}{v^2 \tan^2 \beta} \cos^2 \alpha$$

- For $\tan\beta = 1$, $\lambda_2/(4\pi) = 1$ when $M_{H_h} \approx 900$ GeV

$g + g \rightarrow H_h$ 

- Contributions that are sensitive to the sign of $\sin\alpha$ are $\tan\beta$ -suppressed \Leftarrow true for all 4 processes!
- Corrections of -25% even in the fully perturbative regime!

$H_h \rightarrow \gamma + \gamma$ 

- For $M_{H_h} > 500$ GeV the LO amplitude is very small
⇒ the relative correction δ_{EW} becomes large
- $|\text{Re}A_{\gamma\gamma}^{\text{LO}} \cdot \text{Re}A_{\gamma\gamma}^{\text{NLO}}|$ outgrows $|\text{Im}A_{\gamma\gamma}^{\text{LO}} \cdot \text{Im}A_{\gamma\gamma}^{\text{NLO}}|$
⇒ sign of NLO correction changes

1 Introduction

2 Calculation and technical details

3 Results

4 Summary and conclusions

Summary

- Presented NLO EW corrections to $g + g \rightarrow H_{l,h}$ and $H_{l,h} \rightarrow \gamma + \gamma$ in the HSESM
- For processes involving an external light Higgs boson the corrections are moderate and close to the SM
- For processes with a heavy external Higgs the corrections can become large and thus are important