# Extracting trilinear Higgs boson self-coupling events from HH production at the FCC-hh

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## 1 Introduction

Precision measurements of the Higgs boson self-couplings, which determine the shape of the Higgs potential at the heart of the electroweak symmetry breaking mechanism, have been deemed of utmost priority in the current particle physics strategies [1–3].

The trilinear Higgs boson self-coupling, hereafter denoted $\lambda_{hhh}$, can be directly measured in high-energy physics experiments through the production rate of Higgs boson pairs (HH). HH production at the hadron-hadron Future Circular Collider, FCC-hh, is dominated by the interaction of two gluons mediated by a loop of heavy quarks [4]. This *gluon-gluon fusion* (ggF) HH production mode further decomposes into two contributions, whose highly destructive interference significantly lowers the resulting cross section $\sigma_{gg\to hh}$. One involves both the trilinear Higgs boson self-coupling $\lambda_{hhh}$ and the Yukawa coupling $y_q$ of the Higgs boson to the mediating quark $q = t, b, ...$ in a *triangle*-shaped loop, the other contribution depends solely on the Yukawa coupling in a *box*-like quark loop (Fig. 1).

In this preliminary note, we first investigate the kinematic differences between these two processes at the loop-induced leading order (LO) and generator level in section 2. We then study the separation of the triangle and box contributions using a boosted decision tree (BDT) or deep neural network (DNN) trained on their kinematics in section 3. We show that we can effectively enhance the purity of the triangle process involving the trilinear Higgs boson self-coupling $\lambda_{hhh}$, considering the box contribution as a background to discard.

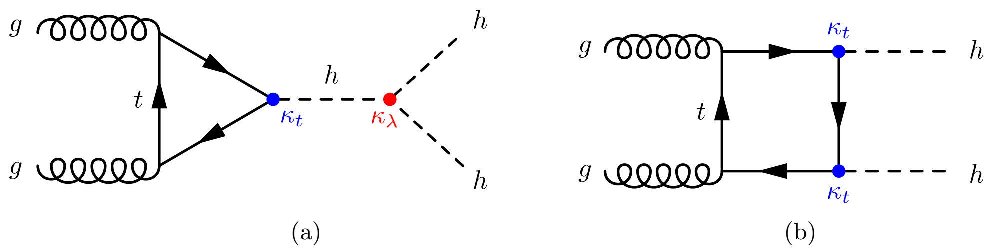



**Fig. 1**: Feynman diagrams of the leading-order (LO), loop-induced, *triangle* (a) and *box* (b) contributions to gluon-gluon fusion HH production, the dominant HH production mode for high-energy hadron colliders like the FCC-hh; adapted from Ref. [5]. The corresponding probability amplitudes are proportional to $\kappa_t \equiv y_t/y_t^{\mathrm{SM}}$ and $\kappa_\lambda \equiv \lambda_{hhh}/\lambda_{hhh}^{\mathrm{SM}}$, respectively the Higgs-top Yukawa coupling and trilinear Higgs self-coupling modifiers.

## 2 Generator-level kinematics of Higgs boson pair production at LO

We use `MadGraph_aMC@NLO` to generate triangle, box, and undifferentiated $gg \to hh$ events at the loop-induced LO. Fig. 2 shows the normalised distributions of kinematic variables of the two final state Higgs bosons for the triangle, box, and interference contributions, the latter being deduced by subtracting the unnormalised triangle and box distributions from the unnormalised total.

The $m_{hh}$ and $p_{\mathrm{T},h}$ distributions for the box process, corresponding to the total HH production for $\kappa_\lambda = 0$, closely match Fig. 14 from Ref. [6]. The $\min \eta_h$ and $\max \eta_h$ distributions further confirm that both Higgs bosons are more forward, i.e. have a higher pseudorapidity $\eta_h$ corresponding to a lower transverse momentum $p_{\mathrm{T},h}$, when produced through the trilinear Higgs boson self-coupling.

At the leading order, the ggF HH production cross section is a quadratic function of the trilinear Higgs boson self-coupling modifier $\kappa_\lambda \equiv \lambda_{hhh}/\lambda_{hhh}^{\mathrm{SM}}$ parametrising the discrepency of $\lambda_{hhh}$ from its expected value $\lambda_{hhh}^{\mathrm{SM}}$ in the Standard Model (SM):

$$\sigma_{gg\to hh}^{\mathrm{LO}} = \kappa_\lambda^2 \kappa_t^2 \sigma_{\triangle}^{\mathrm{LO,SM}} + \kappa_\lambda \kappa_t^3 \sigma_{\mathrm{inter}}^{\mathrm{LO,SM}} + \kappa_t^4 \sigma_{\square}^{\mathrm{LO,SM}}.$$

The cross section of the interference contribution is related to the triangle and box contributions through an interference angle $\theta$ such that

$$\sigma_{\mathrm{inter}}^{\mathrm{LO,SM}} = 2\cos\theta \sqrt{\sigma_{\triangle}^{\mathrm{LO,SM}} \sigma_{\square}^{\mathrm{LO,SM}}}.$$

This equality allows us to compute $\cos\theta$ for various center-of-mass energies, and find that it varies only slightly from $\cos\theta = -0.896$ at 14 TeV to $\cos\theta = -0.886$ at 100 TeV.

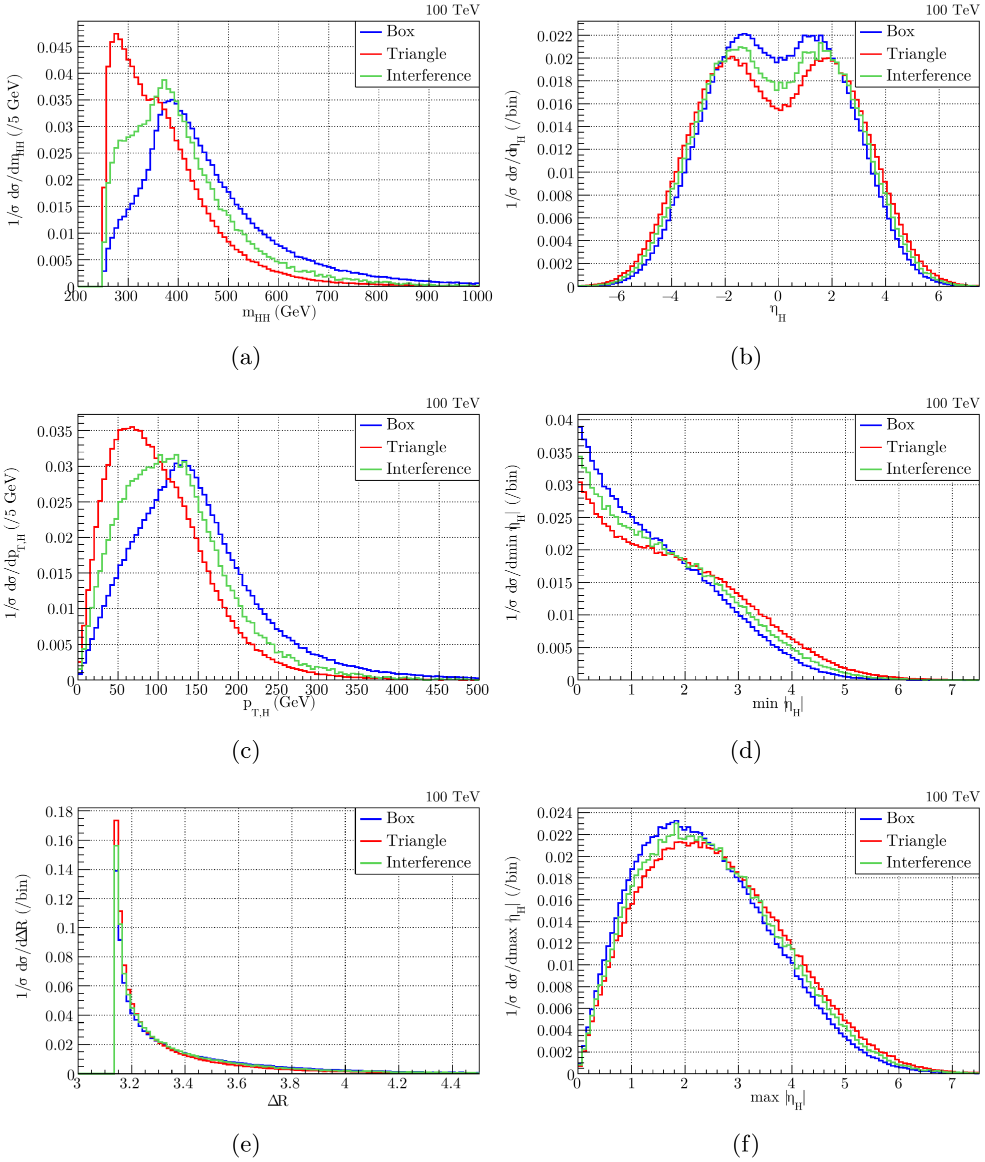



**Fig. 2**: Normalised distributions, i.e. binned differential cross sections divided by the integrated cross sections, of the generated Higgs boson pair for the triangle, box, and interference contributions: invariant mass $m_{hh}$ (a), transverse momenta $p_{\mathrm{T},h}$ (c), angular separation $\Delta R_{hh} \equiv \sqrt{(\Delta\eta_h)^2 + (\Delta\phi_h)^2}$ (e), pseudorapidities $\eta_h$ (b), minimum and maximum pseudorapidities $\min_{h=h_1,h_2} \eta_h$ (d) and $\max_{h=h_1,h_2} \eta_h$ (f).

We define the reduced LO $gg \to hh$ cross section

$$\hat{\sigma}^{\text{LO}}_{gg\to hh}(\kappa_\lambda, \kappa_t) \equiv \sigma^{\text{LO}}_{gg\to hh}(\kappa_\lambda, \kappa_t)/\sigma^{\text{LO,SM}}_{gg\to hh} = \frac{\kappa_\lambda^2 \kappa_t^2 \sigma^{\text{LO,SM}}_{\triangle} + 2\kappa_\lambda \kappa_t^3 \cos\theta \sqrt{\sigma^{\text{LO,SM}}_{\triangle} \sigma^{\text{LO,SM}}_{\square}} + \kappa_t^4 \sigma^{\text{LO,SM}}_{\square}}{\sigma^{\text{LO,SM}}_{\triangle} + 2\cos\theta \sqrt{\sigma^{\text{LO,SM}}_{\triangle} \sigma^{\text{LO,SM}}_{\square}} + \sigma^{\text{LO,SM}}_{\square}}$$

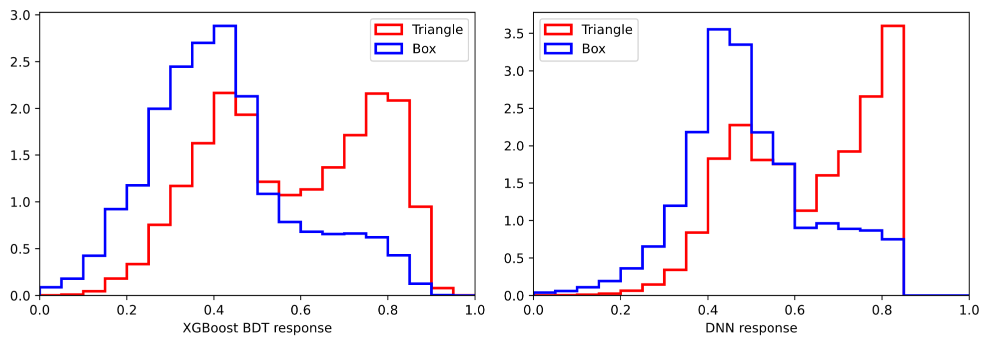
where $\sigma^{\text{LO,SM}}_{gg\to hh} = \sigma^{\text{LO}}_{gg\to hh}(\kappa_\lambda = 1, \kappa_t = 1)$ by definition of $\kappa_\lambda$ and $\kappa_t$. The sensitivity of $\hat{\sigma}^{\text{LO}}_{gg\to hh}$ to $\kappa_\lambda$, illustrated by the sharpness of the corresponding parabola, is given by the second-order factor

$$\sigma^{\text{LO,SM}}_{\triangle}/\sigma^{\text{LO,SM}}_{gg\to hh},$$

which is the signal-to-background ratio (assuming the SM value $\kappa_\lambda = 1$) when we only consider the *triangle* contribution as the signal, instead of the entire HH production as it is generally done. To improve the precision of the trilinear Higgs boson self-coupling measurement from an upper bound on the HH production rate, we will thus purify the triangle contribution using a classifier trained on our box and triangle event samples.

## 3 Triangle-enhancing event classifier

Using `Keras`, the high-level API of `TensorFlow`, we create and train an XGBoost boosted decision tree (BDT) and a deep neural network (DNN) to classify triangle and box events using $m_{hh}$, $p_{\text{T},h}$, $\min \eta_h$, $\max \eta_h$, $y_{hh}$, and $\Delta R_{hh}$. Fig. 3 shows the responses of the BDT and DNN for our triangle and box event samples. The area under the ROC curve is 0.72 in both cases. Fig. 4 shows how the $\sigma^{\text{LO}}_{gg\to hh}(\kappa_\lambda, \kappa_t = 1)$ parabola becomes sharper and sharper w.r.t. the threshold of the triangle-enhancing cut.




(a) (b)

**Fig. 3**: BDT (a) and DNN (b) classifier responses for triangle and box events.

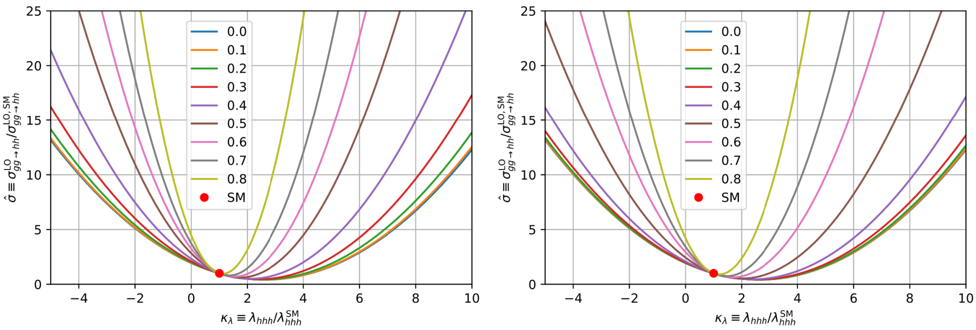



**Fig. 4**: Evolution of the reduced LO cross section $\hat{\sigma}(\kappa_\lambda, \kappa_t) \equiv \sigma^{\rm LO}_{gg\to hh}(\kappa_\lambda, \kappa_t)/\sigma^{\rm LO,SM}_{gg\to hh}$ w.r.t. the trilinear Higgs boson self-coupling modifier $\kappa_\lambda \equiv \lambda_{hhh}/\lambda^{\rm SM}_{hhh}$ for different values of the triangle-enhancing cut assuming the SM value of the Higgs-top coupling ($\kappa_t = 1$).

# 4 Conclusion

In this preliminary study, we showed that we could exploit the distinct kinematic signature of the ggF HH production contribution which is sensitive to the trilinear Higgs boson self-coupling $\lambda_{hhh}$ to improve the sensitivity of the $\lambda_{hhh}$ measurement. To properly assess this strategy, an application to a full $hh \to b\bar{b}\gamma\gamma$ analysis [7] is ongoing and other HH decay channels like $hh \to b\bar{b}\tau^+\tau^-$ will be also considered in the near future. The kinematics of ggF HH production should also be studied at the next-to-leading order (NLO). Lastly, focusing on the reduction of the highly-destructive *interference* contribution could enhance the purity of the triangle contribution whilst keeping sufficient statistics, as HH production is already $10^3$ times less frequent than single-Higgs production.

# Acknowledgements

The ongoing evaluation of our triangle-enhancing strategy on a $hh \to b\bar{b}\gamma\gamma$ analysis is made possible thanks to the collaboration and contribution of Angela Taliercio et al. [7] This work has been partly supported by the Future Circular Collider Innovation Study (FCCIS) project, that has received funding from the European Union's Horizon 2020 research and innovation programme under grant No 951754.

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