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Projected sensitivity of Higgs boson pair production combining the $b\bar{b}\gamma\gamma$ and $b\bar{b}\tau^+\tau^-$ decay channels at the HL-LHC with the ATLAS detector

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A combination of projection studies of non-resonant Higgs boson pair production is performed in the $b\bar{b}\gamma\gamma$ and $b\bar{b}\tau^+\tau^-$ decay channels with the ATLAS detector, assuming 3000 fb^{-1} of proton-proton collision data at a center-of-mass energy of $\sqrt{s}$ = 14 TeV at the HL-LHC. The projected results are based on extrapolations of the Run 2 analyses conducted with 139^{-1} data at $\sqrt{s}$ = 13 TeV. In addition to the increased luminosity and center-of-mass energy at the HL-LHC, both experimental and theoretical systematic uncertainties are expected to be reduced relative to their Run 2 values. The projected results are expressed in terms of the significance of the observation of the Standard Model (SM) Higgs boson pair production, and the constraint on the Higgs boson trilinear self-coupling modifier κ_λ.

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1. Introduction

Following the discovery of the Higgs boson at the CERN Large Hadron Collider (LHC) in 2012 [2, 6], major efforts have been dedicated to studying its properties. In particular, the Higgs boson self-couplings play a crucial role in understanding the shape of the Higgs potential which carries important physics implications such as the stability of the Universe [7]. These couplings are still largely unconstrained experimentally due to the small cross-sections of the processes they are associated with. The quartic coupling λ_4 is out of reach for the LHC [8], but access to the trilinear coupling λ_3 is still possible. Specifically, λ_3 can be directly probed through the Higgs boson pair production (HH) process. A deviation of the coupling strength from the SM (measured by the coupling modifier $\kappa_\lambda = \lambda_3/\lambda_3^{\mathrm{SM}}$) may indicate new physics.

The two dominant HH production modes are gluon-gluon fusion (ggF) and vector boson fusion (VBF) which contribute to over 95% of the total production cross-section in the SM.

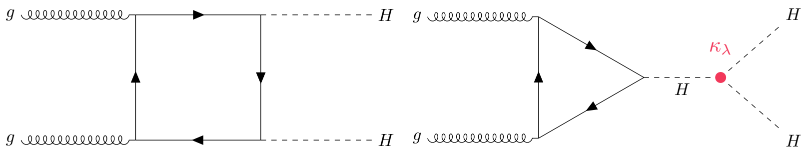


Figure 1: Leading order Feynman diagrams for HH production in the ggF production mode. The SM cross-section is $\sigma^{\mathrm{SM}}_{\mathrm{ggF}} = 36.69$ fb evaluated at NNLO, for a Higgs boson mass of $m_H = 125$ GeV at $\sqrt{s} = 14$ TeV.

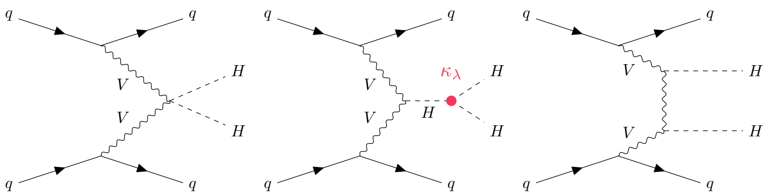


Figure 2: Leading order Feynman diagrams for HH production in the VBF production mode. The SM cross-section is $\sigma^{\mathrm{SM}}_{\mathrm{VBF}} = 2.1$ fb evaluated at N3LO, for a Higgs boson mass of $m_H = 125$ GeV at $\sqrt{s} = 14$ TeV.

The SM HH production is an extremely rare process, with only around 4000 events expected in the entire Run-2 operation (with an integrated luminosity of 139 fb^{-1} at $\sqrt{s} = 13$ TeV) of the LHC. In comparison, it is estimated over 8 million single Higgs bosons have been produced over the same period. The prospect of observing HH production as well as constraining the Higgs boson self-coupling will be greatly improved at the High Luminosity LHC (HL-LHC) which plans to increase the peak luminosity of pp collisions by a factor of five relative to the Run-2 operation, and ultimately deliver 3000 fb^{-1} of integrated luminosity at $\sqrt{s}$ =14 TeV.

2. Combination input analyses

In early 2022, the $b\bar{b}\gamma\gamma$ [5] and $b\bar{b}\tau^+\tau^-$ [4] analyses have released new HL-LHC projection results, assessed through extrapolations of the full LHC Run-2 data set with an integrated luminosity of 139 fb^{-1} at $\sqrt{s} = 13$ TeV.

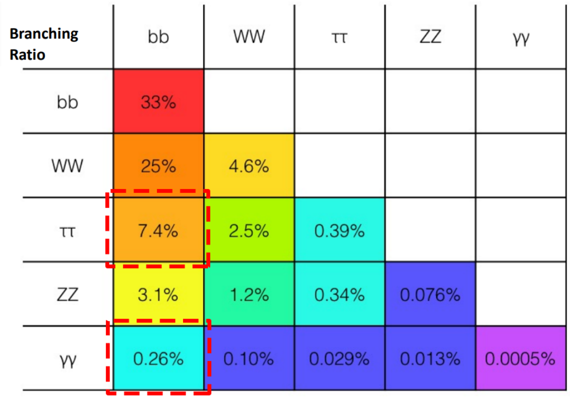


Figure 3: Branching ratios of various HH decay channels. The $b\bar{b}\gamma\gamma$ and $b\bar{b}\tau^+\tau^-$ decay channels are indicated by dotted red lines.

Despite its small branching ratio, the $b\bar{b}\gamma\gamma$ decay channel benefits from the clean diphoton signature for triggering and signal extraction. On the other hand, the $b\bar{b}\tau^+\tau^-$ decay channel has a larger production rate but suffers from the production of hadronically decaying tau leptons that are hard to disentangle from QCD jets.

In order to maximize sensitivity to HH searches, a statistical combination of the $b\bar{b}\gamma\gamma$ and $b\bar{b}\tau^+\tau^-$ HL-LHC projection studies was performed [1]. This proceeding presents a brief summary of the extrapolation procedure and a discussion of the combined projection results.

3. Extrapolation Procedure

To extrapolate results from Run-2 to the HL-LHC, scale factors are applied to the signal and background distributions in each final state to account for two main changes. The first one is due to an increase in integrated luminosity from 139 fb^{-1} in Run-2 to 3000 fb^{-1} in the HL-LHC. This results in a global scale factor of around 20. The second one comes from changes in cross-sections due to an increase of center-of-mass energy from $\sqrt{s}$ = 13 TeV to 14 TeV. Depending on the processes involved, this results in scale factors that range from 1.18 to 1.21.

Systematic uncertainties are also scaled to reflect improvements expected at the HL-LHC. In particular, detector performance is expected to remain similar but uncertainties on heavy jet tagging are expected to decrease while theory uncertainties are expected to be halved. To perform a statistical combination, uncertainties from common systematic sources are correlated across channels.

4. Results

In the combination, four main uncertainty scenarios are considered. They include 1. No systematic uncertainties, 2. Baseline with experimental uncertainties scaled, and theory uncertainties halved, 3. Theory uncertainties halved, but with Run-2 experimental uncertainties, and 4. Run-2 systematic uncertainties. Statistical results based on these systematic scenarios are presented in the following sections.

4.1 Significance and Signal Strength Measurement

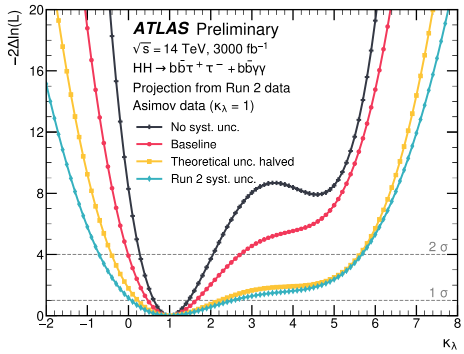
The expected HH signal significance and precision on the measured signal strength ($\sigma_{HH}/\sigma_{HH}^{SM}$) is shown in Table 1. In the baseline scenario, major sources of uncertainties include the theoretical uncertainties on the ggF, VBF, and W-associated single Higgs production and on the HH cross-section. Compared to the previous combination in 2018 [3] which also includes the contribution from the $b\bar{b}b\bar{b}$ channel, a small improvement in the combination significance of around 0.3 is obtained. A major gain comes from the $b\bar{b}\tau^+\tau^-$ channel due to improved objection identification.

	Significance [σ]			Measured combined
Uncertainty scenario	$b\bar{b}\gamma\gamma$	$b\bar{b}\tau^+\tau^-$	Comb.	signal strength
No systematic uncertainties	2.3	4.0	4.6	1 ± 0.23
Baseline	2.2	2.8	3.2	1 ± 0.32
Theory uncertainties halved	1.1	1.7	2.0	1 ± 0.50
Run 2 systematic uncertainties	1.1	1.5	1.7	1 ± 0.59
Previous combination (2018)	2.0	2.0	2.9	1 ± 0.40

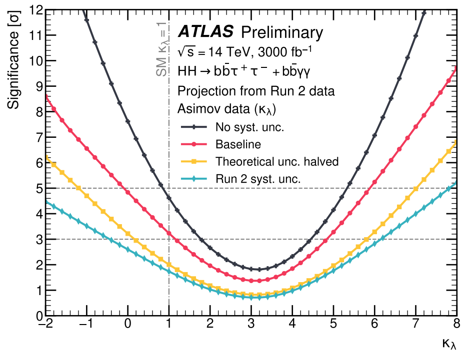
Table 1: Projected significance and signal strength precision of the SM HH signals for the four uncertainty scenarios and for the 2018 combination. The significances for $b\bar{b}\gamma\gamma$ and $b\bar{b}\tau^+\tau^-$ are also summarized.

4.2 Likelihood and Significance in terms of the Higgs self-coupling

To obtain a constraint on the Higgs boson trilinear self-coupling, a scan of the negative log-profile-likelihood ratio as a function of κ_λ under the SM hypothesis is performed as shown in figure 4a. In the baseline scenario, κ_λ is constrained to within [0.5, 1.5] ([0.0, 2.7]) at 1σ (2σ) confidence interval. In addition, the expected significance as a function of κ_λ is given in figure 4b. Evidence for HH production (3σ) is expected if κ_λ< 1.1 or κ_λ >4.8, while observation (5σ) is expected if $\kappa_\lambda < 0.1$ or $\kappa_\lambda > 5.9$.



(a)



(b)

Figure 4: (a) Projected negative log-profile-likelihood ratio as a function of κ_λ evaluated on an Asimov data set constructed under the SM hypothesis. Dashed horizontal lines correspond to $1\,\sigma$ and $2\,\sigma$ confidence intervals. (b) Projected HH significance for different κ_λ hypotheses evaluated on Asimov data sets produced under the signal plus background hypothesis, where the signal is generated with the κ_λ value under test. Dashed horizontal lines correspond to $3\,\sigma$ and $5\,\sigma$. The dashed vertical line indicates the SM hypothesis.

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