Combination of searches for resonant and non-resonant Higgs boson pair production in the $b\bar{b}\gamma\gamma$, $b\bar{b}\tau^+\tau^-$, and $b\bar{b}b\bar{b}$ decay channels with the ATLAS detectors

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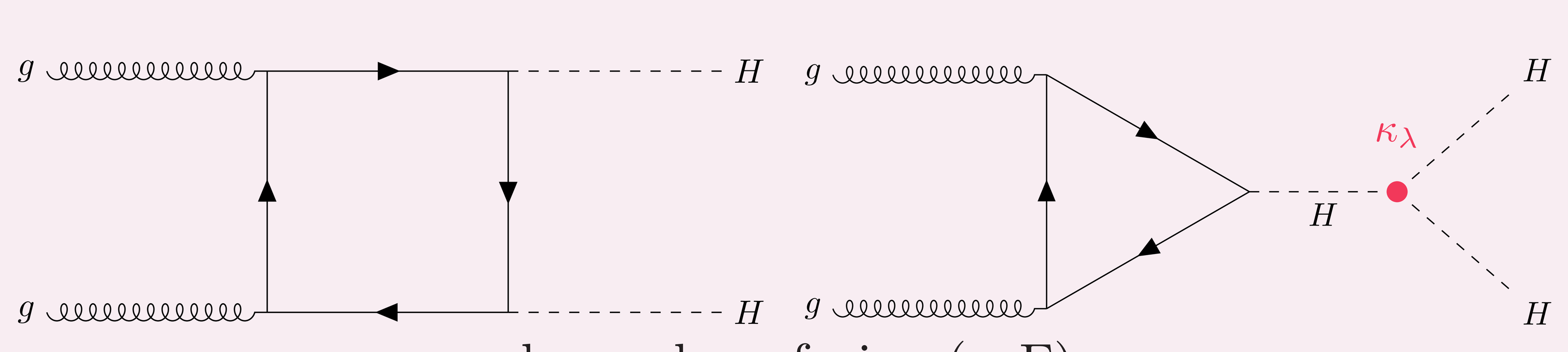
Introduction

What are we looking for?

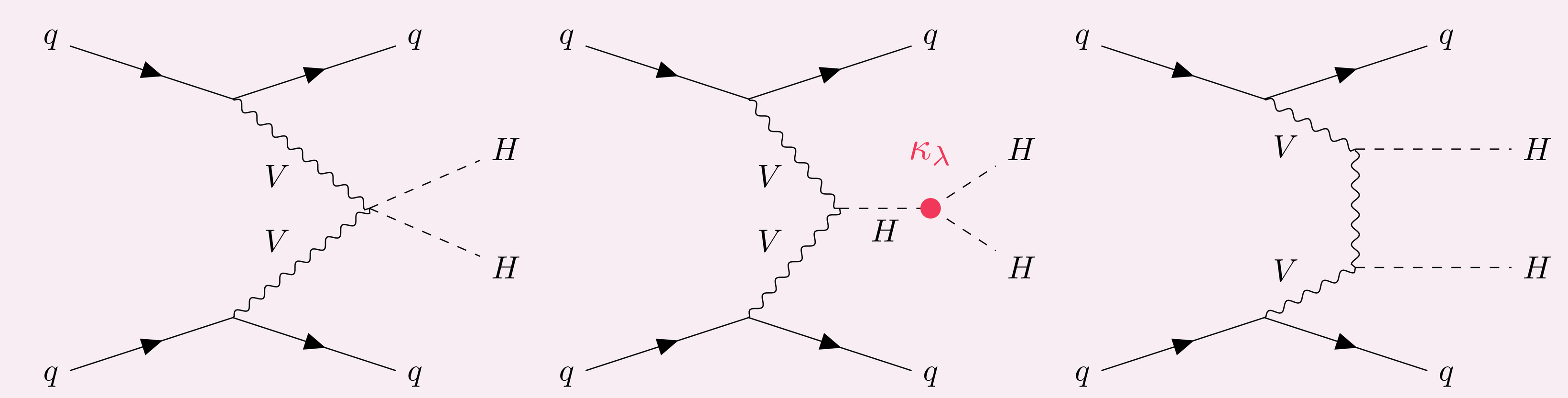
- In the Standard Model (SM), the Higgs boson (H) can self-interact and results in the simultaneous production of two Higgs bosons (HH). The HH production is a very rare process with a SM predicted cross–section three orders of magnitude smaller than the single Higgs production.

I. Non-resonant HH production

- The dominant SM HH production mode is the gluon–gluon fusion (ggF) process with a cross–section of 31.05 fb at 13 TeV with m_H=125 GeV. The next leading production mode proceeds with the vector boson fusion (VBF) with a cross–scetion of 1.726 fb.



gluon–gluon fusion (ggF)

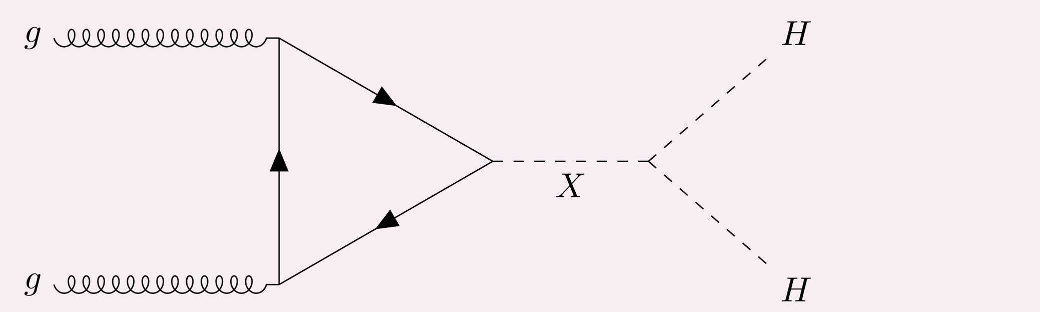


vector boson fusion (VBF)

- The SM ggF and VBF productions are referred to as the **non-resonant HH production**. They provide a **direct probe of the Higgs trilinear self–coupling** ($\kappa_\lambda = \lambda_{HHH}/\lambda_{SM}$), which affects the HH production cross–section. A deviation from the SM predicted self-coupling value may point to physics **Beyond the Standard Model (BSM)**.

II. Resonant HH production

- HH production can be mediated by a **heavy scalar (spin-0) resonance X** as predicted by several BSM models (e.g. hMSSM).
- For the resonant production, only the dominant ggF production mode is considered.

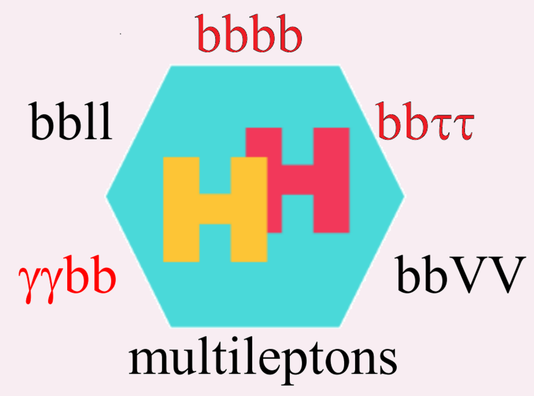


Combination input analyses

- ATLAS has released the HH combination result using the **full Run 2 (139 fb^{-1}) dataset** of pp collisions at $\sqrt{s}$=13 TeV.
- Statistically independent decay channels are combined to maximize sensitivity:

  Non–resonant production: $b\bar{b}\tau^+\tau^-$, $b\bar{b}\gamma\gamma$

  Resonant production: $b\bar{b}b\bar{b}$, $b\bar{b}\tau^+\tau^-$, $b\bar{b}\gamma\gamma$



- $b\bar{b}b\bar{b}$: Largest branching ratio, but also largest SM background with tricky multi–jet background.
  (Reference: ATLAS-CONF-2021-035)
- $b\bar{b}\gamma\gamma$: Small branching ratio, but clean diphoton signature for triggering. (Reference: ATLAS-CONF-2021-016)
- $b\bar{b}\tau^+\tau^-$: Higher production rate than $b\bar{b}\gamma\gamma$ and lower background rates than $b\bar{b}b\bar{b}$. However, tau leptons can decay in many ways, making them sometimes tricky to identify. (Reference: ATLAS-CONF-2021-030)

Branching Ratio	bb	WW	ττ	ZZ	γγ
bb	33%				
WW	25%	4.6%			
ττ	7.4%	2.5%	0.39%		
ZZ	3.1%	1.2%	0.34%	0.076%	
γγ	0.26%	0.10%	0.029%	0.013%	0.0005%

Systematic Uncertainties

In the combination, common systematic sources are correlated across channels.

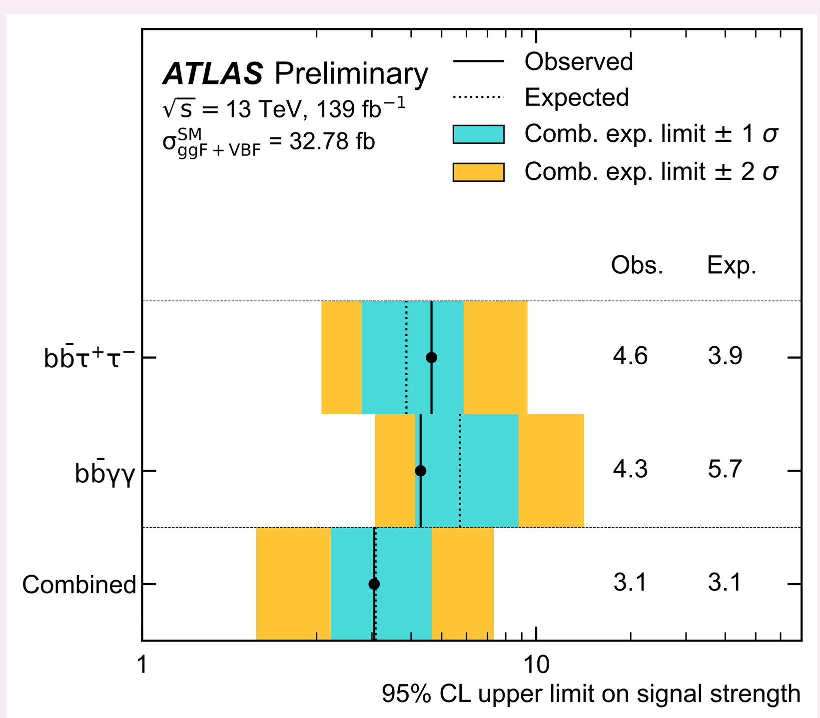
Source	Channels	Correlation
Luminosity	$b\bar{b}\tau\tau + b\bar{b}\gamma\gamma + b\bar{b}b\bar{b}$	Correlated
Pile-up	$b\bar{b}\tau\tau + b\bar{b}\gamma\gamma + b\bar{b}b\bar{b}$	Correlated
Electron	$b\bar{b}\tau\tau$	–
Muon	$b\bar{b}\tau\tau$	–
Tau	$b\bar{b}\tau\tau$	–
Photon	$b\bar{b}\gamma\gamma$	–
JES	$b\bar{b}\tau\tau + b\bar{b}\gamma\gamma + b\bar{b}b\bar{b}$	Correlated
JER	$b\bar{b}\tau\tau + b\bar{b}\gamma\gamma + b\bar{b}b\bar{b}$	Correlated
Boosted JES	$b\bar{b}b\bar{b}$	–
FTAG	$b\bar{b}\tau\tau + b\bar{b}\gamma\gamma + b\bar{b}b\bar{b}$	Partly Correlated*
Boosted FTAG	$b\bar{b}b\bar{b}$	–
EGamma	$b\bar{b}\tau\tau + b\bar{b}\gamma\gamma$	Partly Correlated*
MET	$b\bar{b}\tau\tau$	–
Parton shower	$b\bar{b}\tau\tau + b\bar{b}\gamma\gamma + b\bar{b}b\bar{b}$	Partly Correlated*
PDF_α	$b\bar{b}\tau\tau + b\bar{b}\gamma\gamma + b\bar{b}b\bar{b}$	Correlated
QCD scale	$b\bar{b}\tau\tau + b\bar{b}\gamma\gamma + b\bar{b}b\bar{b}$	Correlated
Branching ratio	$b\bar{b}\tau\tau + b\bar{b}\gamma\gamma + b\bar{b}b\bar{b}$	Correlated

*Uncertainties with inconsistent definitions among channels are decorrelated

Results

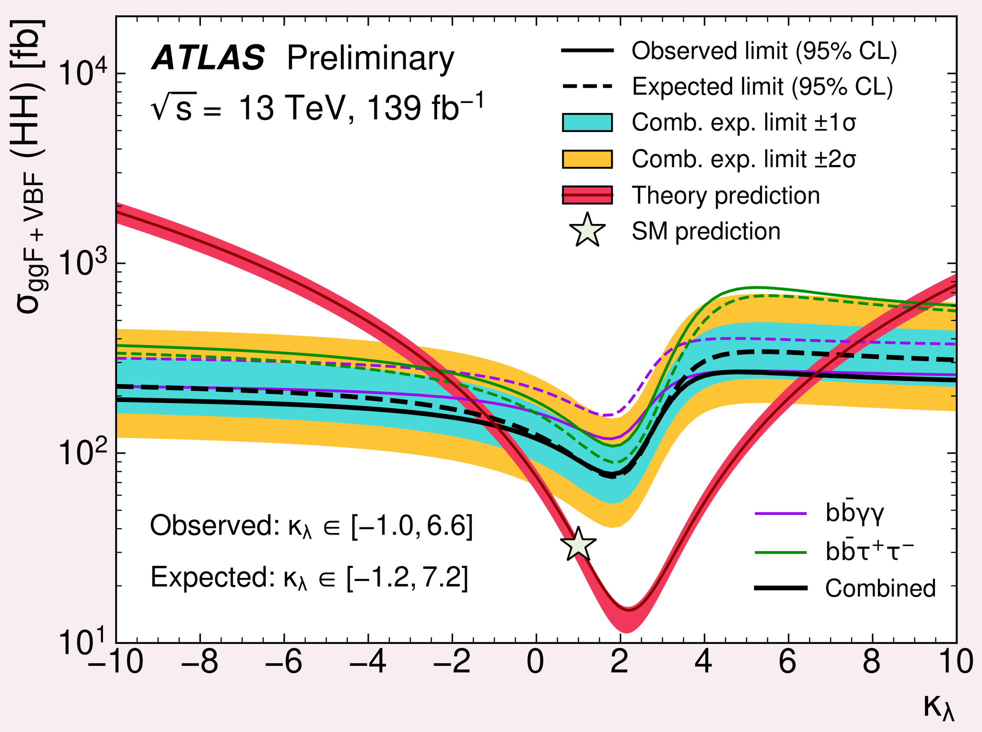
Limit on non–resonant HH production

- The observed (expected) exclusion upper limits on the signal strength from $b\bar{b}\gamma\gamma$ and $b\bar{b}\tau^+\tau^-$ lie at 4.3 (3.9) and 4.6 (5.7) times the SM prediction individually, and goes down to 3.1 (3.1) when combined.
- Improved by a factor of three with respect to the previous ATLAS results using partial Run 2 dataset.



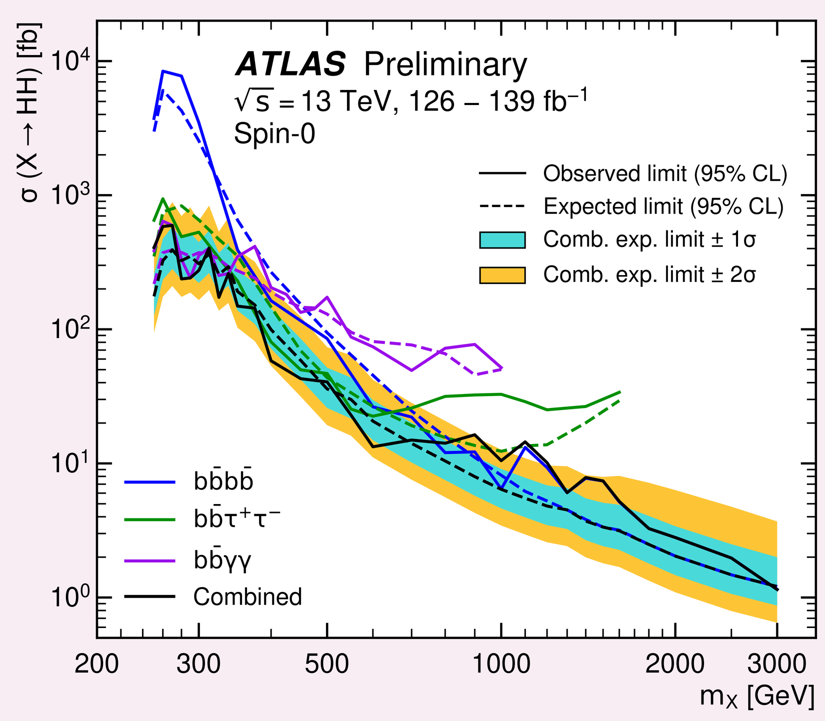
Constraints on κ_λ

- The cross–section upper limits on the non–resonant production are set as a function of the Higgs self–coupling modifier (κ_λ). Exclusion on κ_λ is derived from the intersections with the theory prediction.
- The value of κ_λ has been excluded outside the range $-1.0 \le \kappa_\lambda \le 6.6$ ($-1.2 \le \kappa_\lambda \le 7.2$) in observation (expectation).



Limit on resonant HH production

- Upper limits are set on the production rates of the heavy scalar X decaying into Higgs boson pairs as a function of its mass m_X.
- The $b\bar{b}\gamma\gamma$ search is most sensitive at low m_X, the $b\bar{b}\tau^+\tau^-$ search is most sensitive in the 400–800 GeV range and the $b\bar{b}b\bar{b}$ search dominates for high m_X, demonstrating the complementary of these searches.



Reference: ATLAS-CONF-2021-052