

# HH, HHH searches, Higgs potential at the LHC

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*On behalf of the ATLAS*  
*collaboration*

*Phenomenology 2026 Symposium*  
*Pittsburgh, 11-23 May 2026*

# The Higgs potential

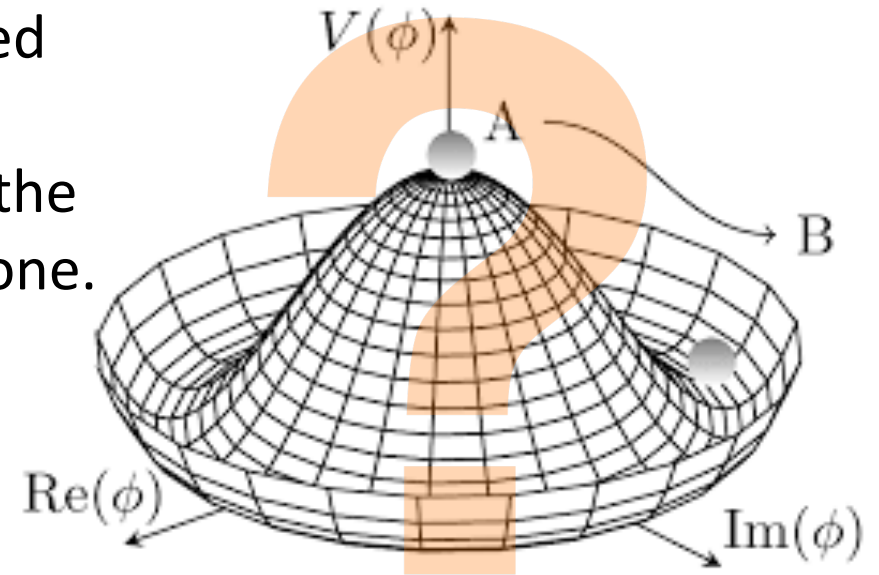
Many Standard Model (SM) predictions have been confirmed by the LHC experiments!

Among all, the **existence of the higgs field**, responsible for the generation of the particle masses, sets an incredible milestone.

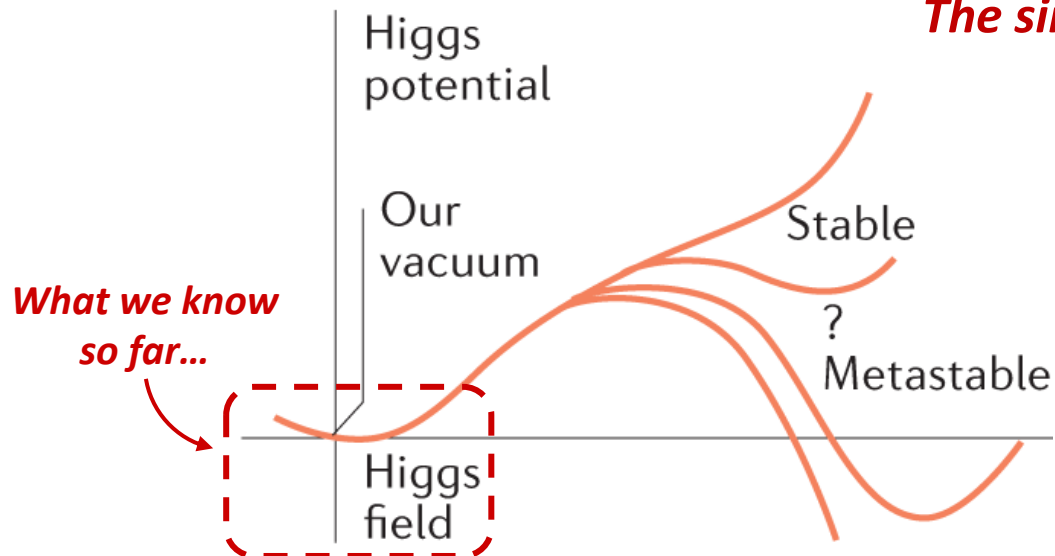
## **HOWEVER:**

The actual shape of the **higgs field potential** is still largely unconstrained!

$$V(\phi) = -\mu^2\phi^2 + \lambda\phi^4$$



*The simplest potential that works...but why stop there...*



## **A “thrilling” subject**

Without new physics our universe could be in a **metastable phase**!!

*...very high stakes!*

# Higgs self-coupling

## Electro-Weak Symmetry Breaking mechanism

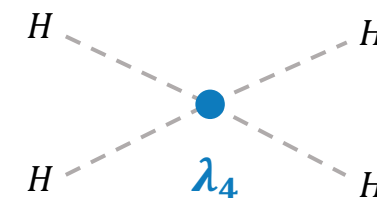
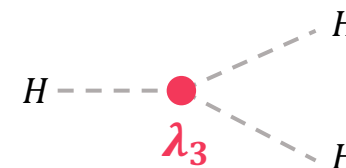
$$V(\phi) = -\mu^2\phi^2 + \lambda\phi^4 \xrightarrow[\phi \rightarrow \frac{1}{\sqrt{2}}(v+h)]{EWSB} V(H) = -\frac{1}{2}m_H^2 H^2 + \lambda v H^3 + \frac{1}{4}\lambda H^4$$

Higgs mass

Tri-linear coupling

Quartic coupling

The observation of **multi-higgs final states** in particle interactions grants direct access to the self-coupling constants  $\lambda_3$  and  $\lambda_4$ .



### HOWEVER:

**These processes are extremely rare!!**

- Pair production:  $\sim 38 \text{ fb}^{-1} \rightarrow (\sim 1000 \text{ times less than single-Higgs})$
- Triple production:  $\sim 0.1 \text{ fb}^{-1}$

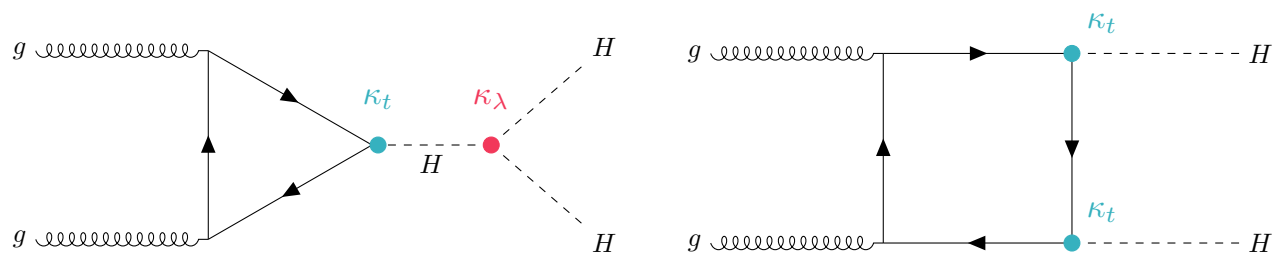
@ 13.6 TeV

Investigated in the  $\kappa$ -framework  
Switch the focus to the coupling variation w.r.t. the SM:  $\kappa_\lambda = \lambda_3/\lambda$

*We need very sensitive analyses just to put broad constraints on the shape of the potential...*

# Main HH production at the LHC

## Gluon-gluon fusion (ggF)

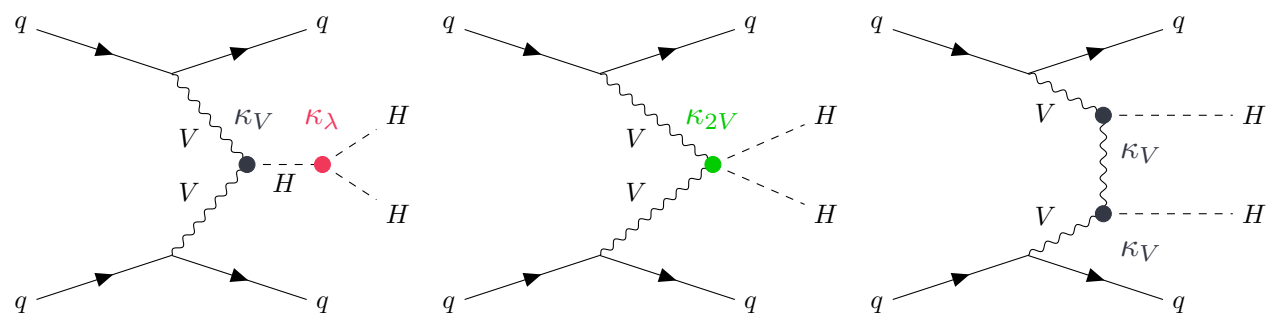


$$M(\kappa_t, \kappa_\lambda) = \kappa_t \kappa_\lambda M_T + \kappa_t^2 M_B$$

- Sensitive to  $\kappa_\lambda$  and  $\kappa_t$
- $\sigma_{ggF}^{SM}(HH) = 30.8_{-7.1}^{+2.0} \text{ fb @13 TeV}$
- $\sigma_{ggF}^{SM}(HH) = 34.1_{-7.9}^{+2.2} \text{ fb @13.6 TeV}$

Small  $\sigma_{ggF}^{SM}$  due to **destructive interference!**

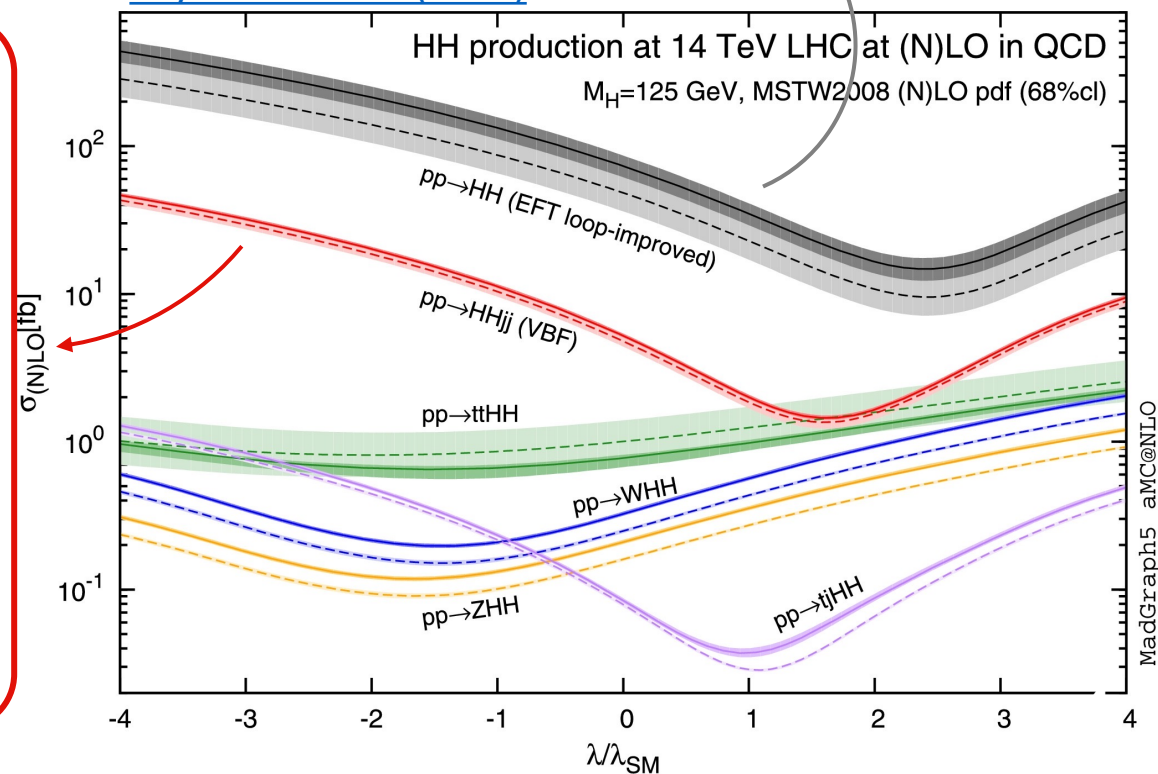
## Vector boson fusion (VBF)



$$M(\kappa_{2V}, \kappa_V, \kappa_\lambda) = \kappa_V \kappa_\lambda M_1 + \kappa_{2V} M_2 + \kappa_V^2 M_3$$

- Access to  $\kappa_\lambda$  and  $\kappa_{2V}$
- $\sigma_{ggF}^{SM}(HH) = 1.96 \pm 0.05 \text{ fb @13 TeV}$
- $\sigma_{ggF}^{SM}(HH) = 1.87 \pm 0.05 \text{ fb @13.6 TeV}$

Phys. Lett. B732 (2014)



# The HH decays network

The ATLAS experiment deploys a vast net of **different channels** analyses to boost its sensitivity!

(typically requiring *b*-quarks to boost BR)

Not a single “golden” channel, but 3 “*silver candidates*” (+additional complementary channels)

## Silver channels

$HH \rightarrow b\bar{b}b\bar{b}$  (34%)  
Highest decay fraction but messy multi-jet bacground

$HH \rightarrow b\bar{b}\tau\tau$  (7.3%)  
The “compromise”, medium abundance but cleaner final state

$HH \rightarrow b\bar{b}\gamma\gamma$  (0.26%)  
Low branching ratio but excellent  $m_{\gamma\gamma}$  resolution

|                | bb    | WW    | $\tau\tau$ | ZZ     | $\gamma\gamma$ |
|----------------|-------|-------|------------|--------|----------------|
| bb             | 34%   |       |            |        |                |
| WW             | 25%   | 4.6%  |            |        |                |
| $\tau\tau$     | 7.3%  | 2.7%  | 0.39%      |        |                |
| ZZ             | 3.1%  | 1.1%  | 0.33%      | 0.069% |                |
| $\gamma\gamma$ | 0.26% | 0.10% | 0.028%     | 0.012% | 0.0005%        |

$HH \rightarrow b\bar{b}\ell\ell + E_T^{miss}$  (2.9%)  
Targeting simultaneously  $bbWW$ ,  $bb\tau\tau$  and  $bbZZ$  di-lepton decays

**Multi-lepton** final states (6.4%)  
Scanning the remaining final states orthogonal to the main channels

**Photon** final states  
Targeting the remaining photon (no *b*-quarks) decays

# Run 2+(partial)3 $HH \rightarrow b\bar{b}\gamma\gamma$

## Analysis strategy

- **Categorisation:** Definition of 7 categories for both Run 2 and Run 3 (independently) based on a BDT score
- **Signal Extraction:** Simultaneous  $m_{\gamma\gamma}$  fit on all categories
- Relying on a di-photon trigger  
→ selecting events with at least 2  $\gamma$  and 2  $b$ -jets
- New event based **Kinematic Fit** used to increase resolution of the  $m_{bb}$  peak
- Continuum background normalised on data sidebands
- First ATLAS HH result using  $308 fb^{-1}$  data!  
140  $fb^{-1}$  Run 2 data (2015-2018,  $\sqrt{s} = 13 TeV$ )  
168  $fb^{-1}$  Run 3 data (2022-2024,  $\sqrt{s} = 13.6 TeV$ )

## Results

Best fit  $\mu_{HH} = 0.9_{-1.0}^{+1.3}(\text{stat}) \pm 0.5(\text{syst.})$

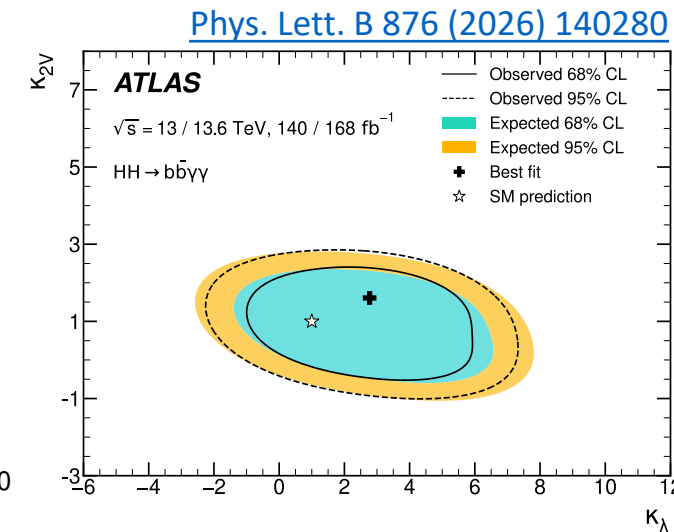
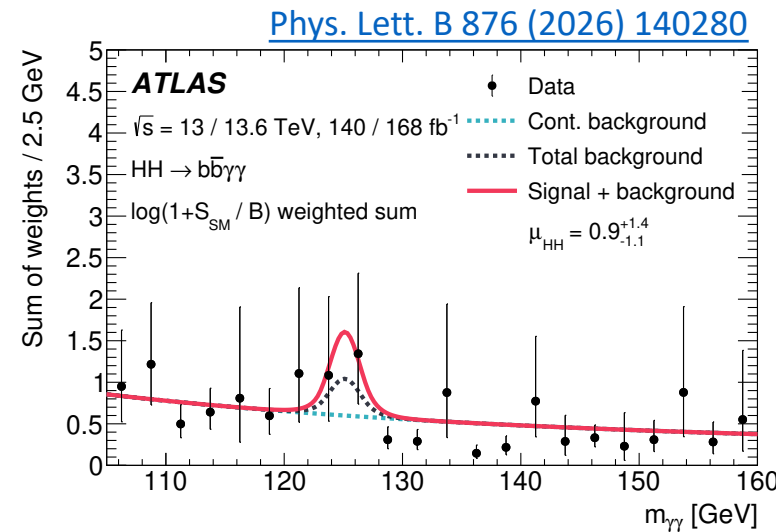
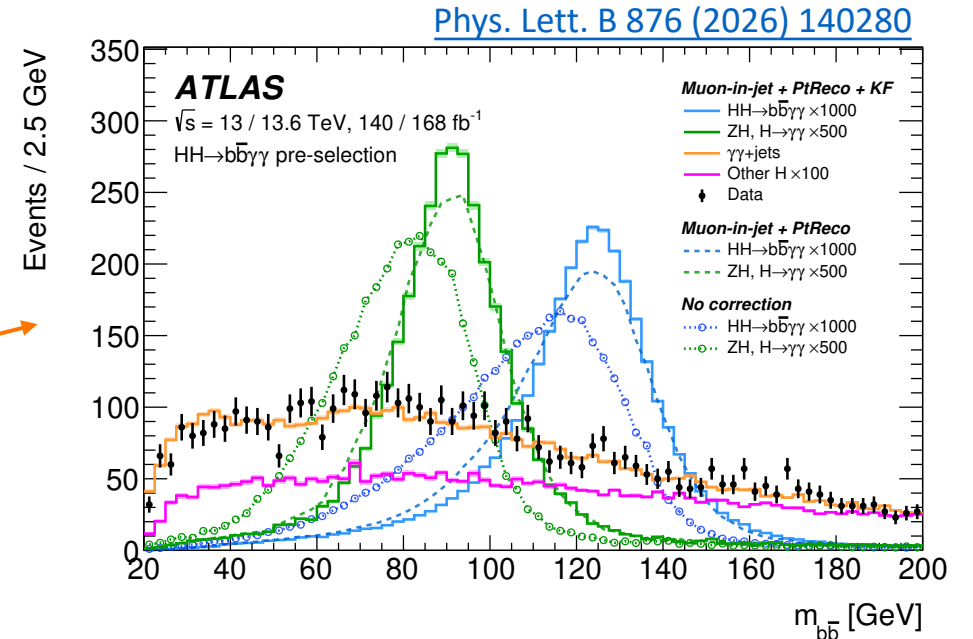
Obs. (Exp.)  $\mu_{HH}$  upper limit: **3.7(2.6)xSM**

Obs. (Exp.)  $\kappa_\lambda$  constraints:

$$-1.6(-1.8) < \kappa_\lambda < 6.6(6.9)$$

*Most sensitive channel to  $\kappa_\lambda$ !*

Published on Physics Letter B (April 2026)



# Run 2 $HH$ (main) analyses

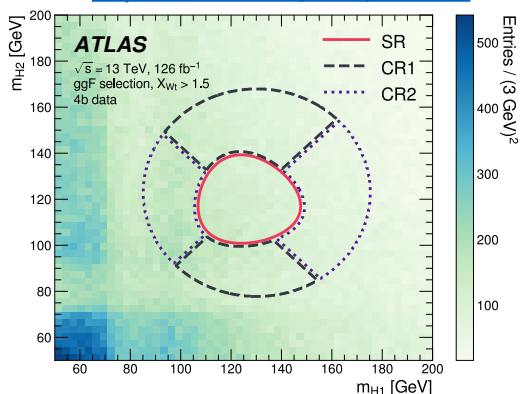
## Run 2 $HH \rightarrow b\bar{b}b\bar{b}$

Resolved (+ Boosted)

$ggF+VBF$

$VBF$

Phys. Lett. B 108 (2024) 052003



- 2  $b$ -jets trigger (+ Large-R jets trigger)

$$E_T > 450 \text{ GeV}$$

- $b$ -jets pairing based on  $\Delta R$
- Full data-driven background estimation (relying on a NN to reweight 2 $b$  events to 4 $b$ )
- BDT used to select signal
- Combined  $m_{HH}$  fit in all SRs

Resolved

### Results

Obs. (Exp.)  $\mu_{HH}$  upper limit: **5.4(8.1)xSM**

Obs. (Exp.)  $\kappa_{2V}$  constraints:  
 **$-0.0(-0.1) < \kappa_{2V} < 2.1(2.1)$**

**Strongest constraint on  $\kappa_{2V}$ !**

$\kappa_{2V}=0$  scenario excluded with  $3.8\sigma$

Boosted

## Run 2 $HH \rightarrow b\bar{b}\tau\tau$

Considering both final states:

- Had-had  $b\bar{b}\tau_h\tau_h$
  - Lep-had  $b\bar{b}\tau_h\tau_\ell$
- Further divided into:
- SLT (Single Lepton Trigger)
  - LTT (Lepton + Tau visible Trigger)
- Two BDTs used:
    - ggF vs VBF
    - Signal vs background
  - Fake tau background derived from data
  - Fit of BDT score in the 9 SRs

### Results

Obs. (Exp.)  $\mu_{HH}$  upper limit:

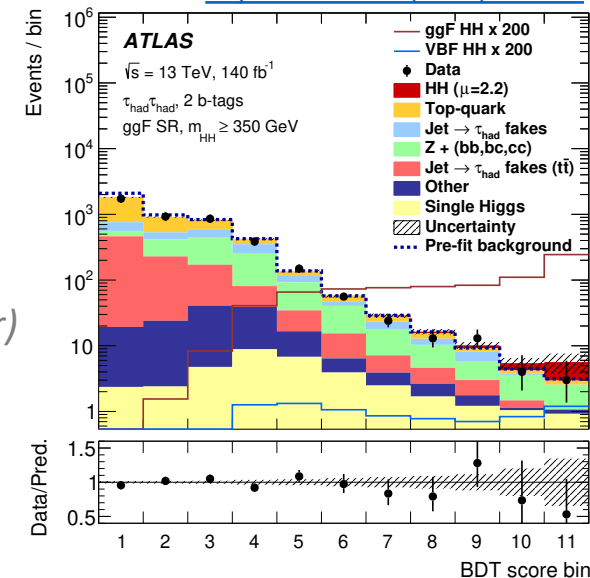
**5.9(3.3)xSM**

Obs. (Exp.)  $\kappa_\lambda$  constraints:

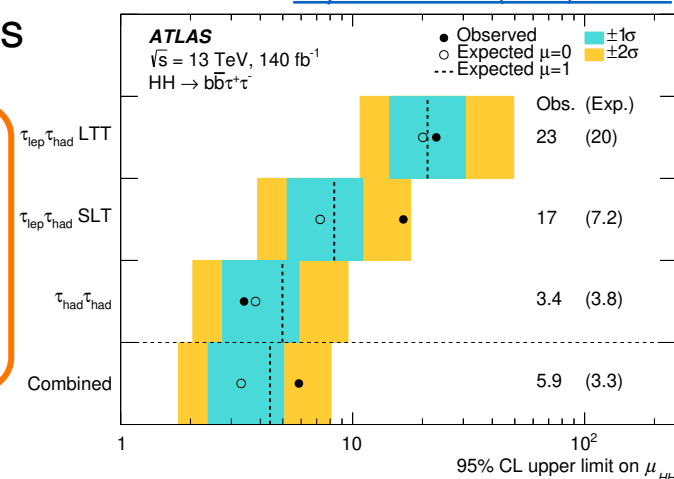
**$-3.1(-2.5) < \kappa_\lambda < 9.0(9.3)$**

**Best upper limit on  $\sigma_{HH}$ !**

Phys. Rev. D 110 (2024) 032012



Phys. Rev. D 110 (2024) 032012



# ATLAS $HH$ combination

The strongest asset of the ATLAS  $HH$  search is the channels **combination!**

*(fundamental in rare processes to boost sensitivity)*

## ATLAS Run 2 legacy combination

- ATLAS  $HH$  analyses are **orthogonal** by design
- Analyses are optimised for their strengths ( $\mu_{HH}$ ,  $\kappa_\lambda$ ,  $\kappa_{2V}$ )
- Each analysis uses specialised triggers

Phys. Lett. 133 (2024) 101801

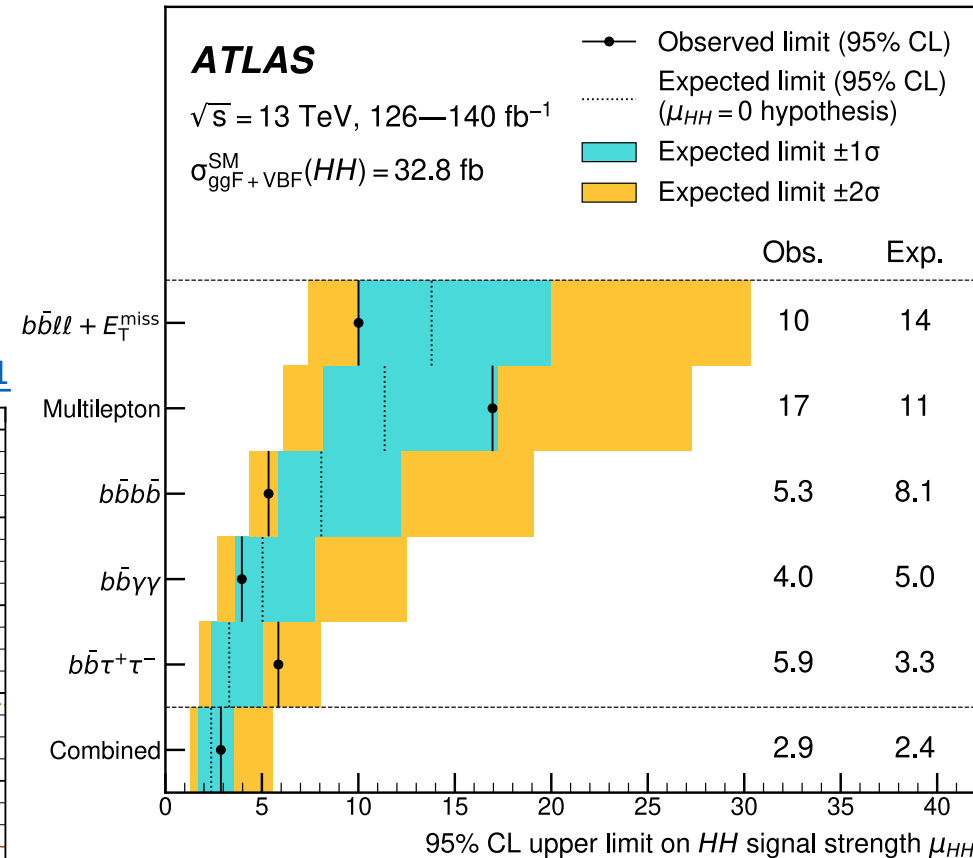
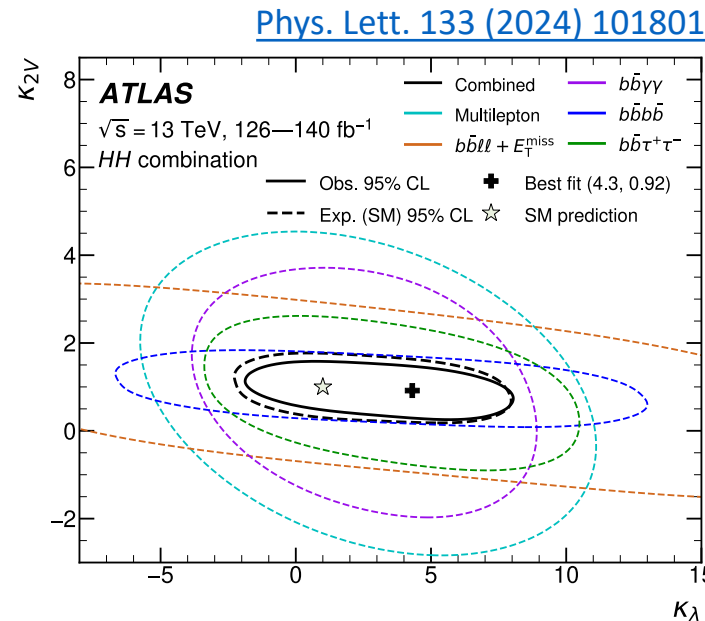
### Results

Combined upper limit: **2.9 (2.5)  $\times$  SM**

Obs. (Exp.) significance: **0.4 $\sigma$  (1.0 $\sigma$ )**

Obs. (Exp.)  $\kappa_\lambda$  constraints:  
**-1.2(-1.6)  $< \kappa_\lambda <$  7.2(7.2)**

Obs. (Exp.)  $\kappa_{2V}$  constraints:  
**0.6(0.4)  $< \kappa_{2V} <$  1.5(1.6)**

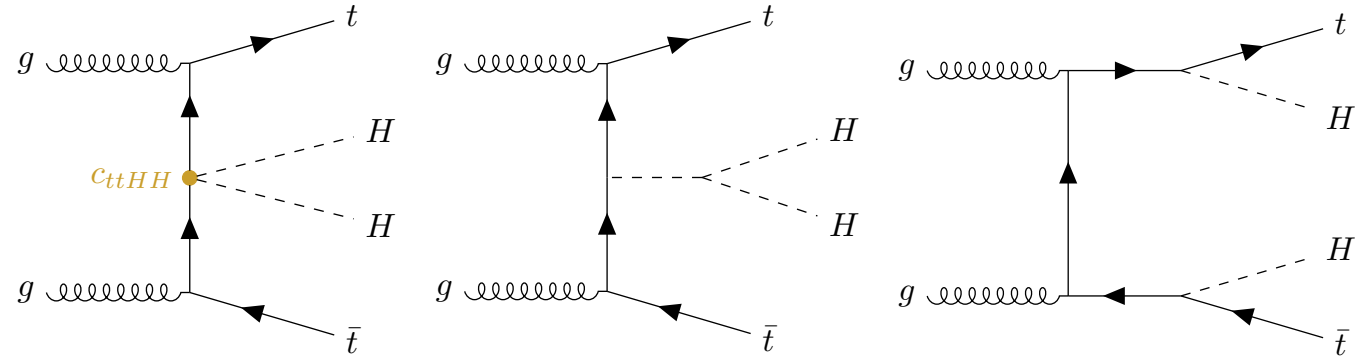


# The first $ttHH$ search

New HH analysis aiming at investigating BSM scenarios through the  $c_{ttHH}$  EFT coupling.

Just submitted to JHEP (March 2026)

Even smaller cross section:  $\sigma_{ttHH} \sim 0.87 \text{ fb}$



Relies on 3 different decay modes:

- $b\bar{b}\gamma\gamma$
- Same Sign Multi Lepton (SSML)  
( $HH \rightarrow b\bar{b} + [ZZ, \tau\tau, WW]$ )
- 1 Lepton (1L)  
( $HH \rightarrow b\bar{b}b\bar{b}$ )

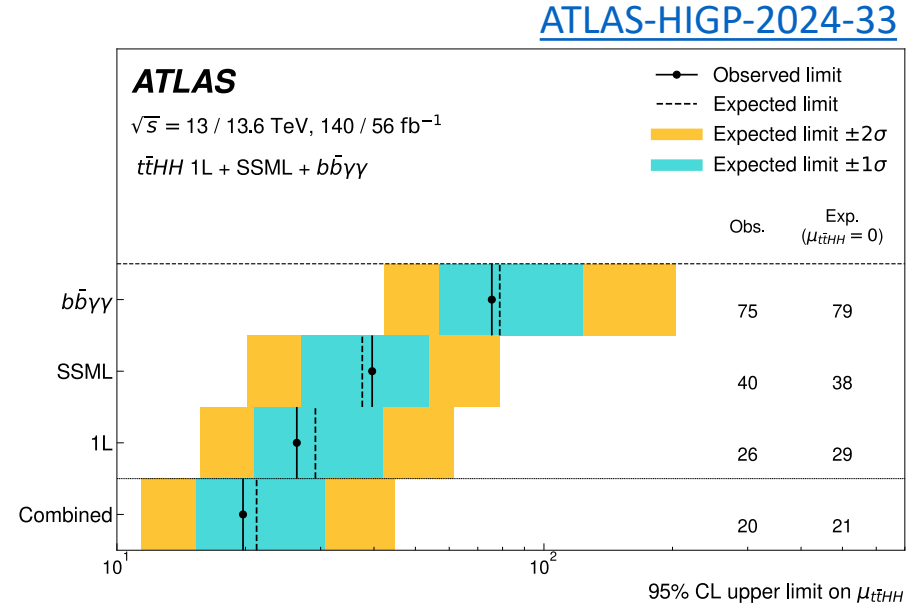
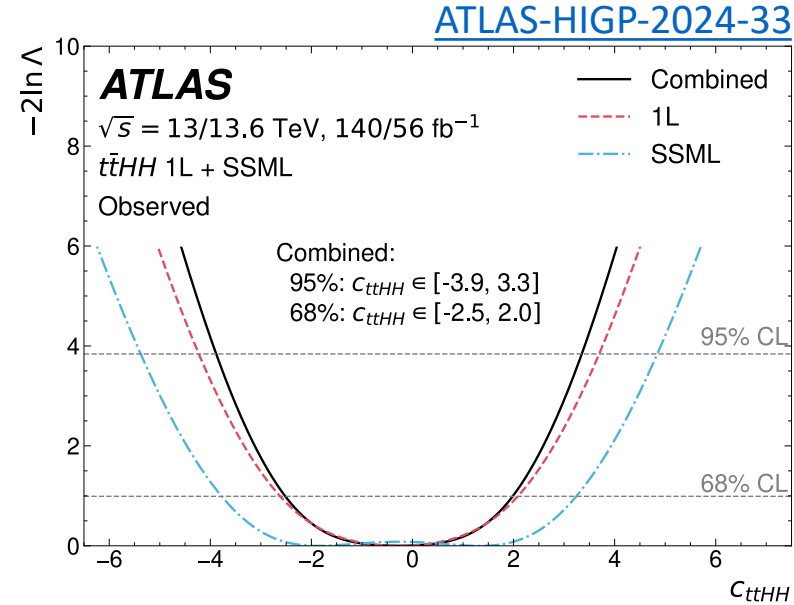
- Using both Run 2 ( $140 \text{ fb}^{-1}$ ) and Run 3 ( $56 \text{ fb}^{-1}$ )

**Results**

Best fit  $\mu_{HH} = -3_{-12}^{+11}$

Obs. (Exp.)  $c_{ttHH}$  constraint:  
 $-3.9(-4.0) < c_{ttHH} < 3.3(3.5)$

Obs. (Exp.)  $\mu_{HH}$  upper limit:  
 $20(21)xSM$



# High-luminosity LHC

## Run 2

- $\sim 140 \text{ fb}^{-1}$  for analyses
- 13 TeV center of mass energy

## Run 3

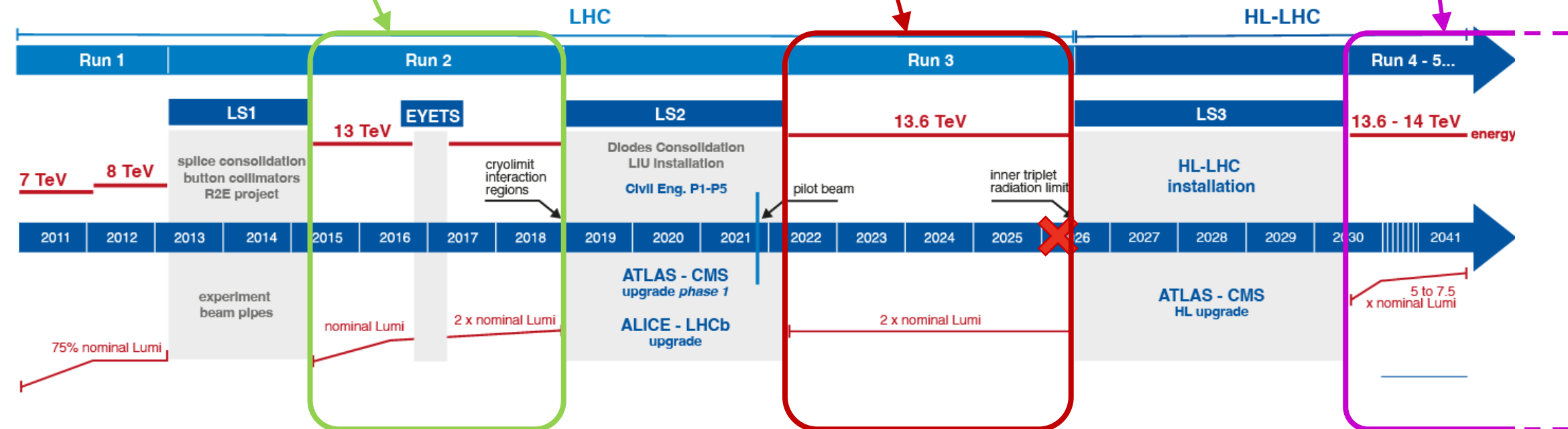
- $\sim 300 \text{ fb}^{-1}$  for analyses
- 13.6 TeV center of mass energy
- $\sigma_{HH}$  increased by 11%

## Run 4-5

- $\sim 3000 \text{ fb}^{-1}$  for analyses
- 14 TeV center of mass energy
- $\sigma_{HH}$  increased by 18%



## LHC / HL-LHC Plan

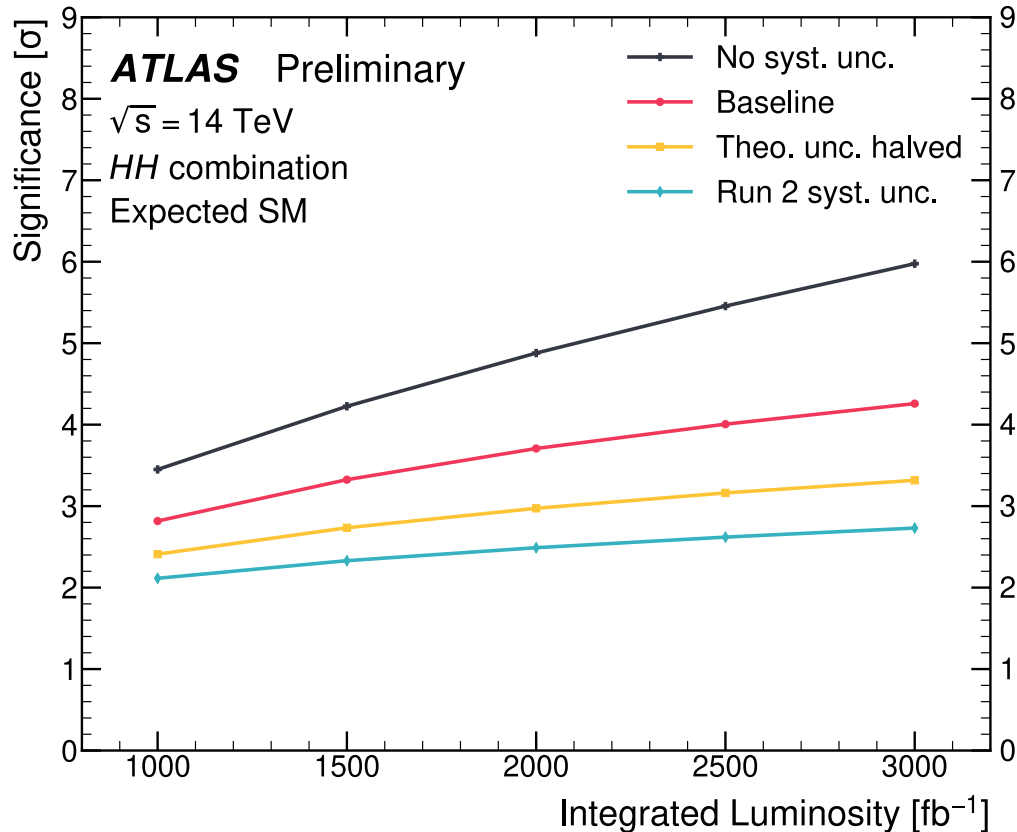


# HH projections for Hi-Lumi

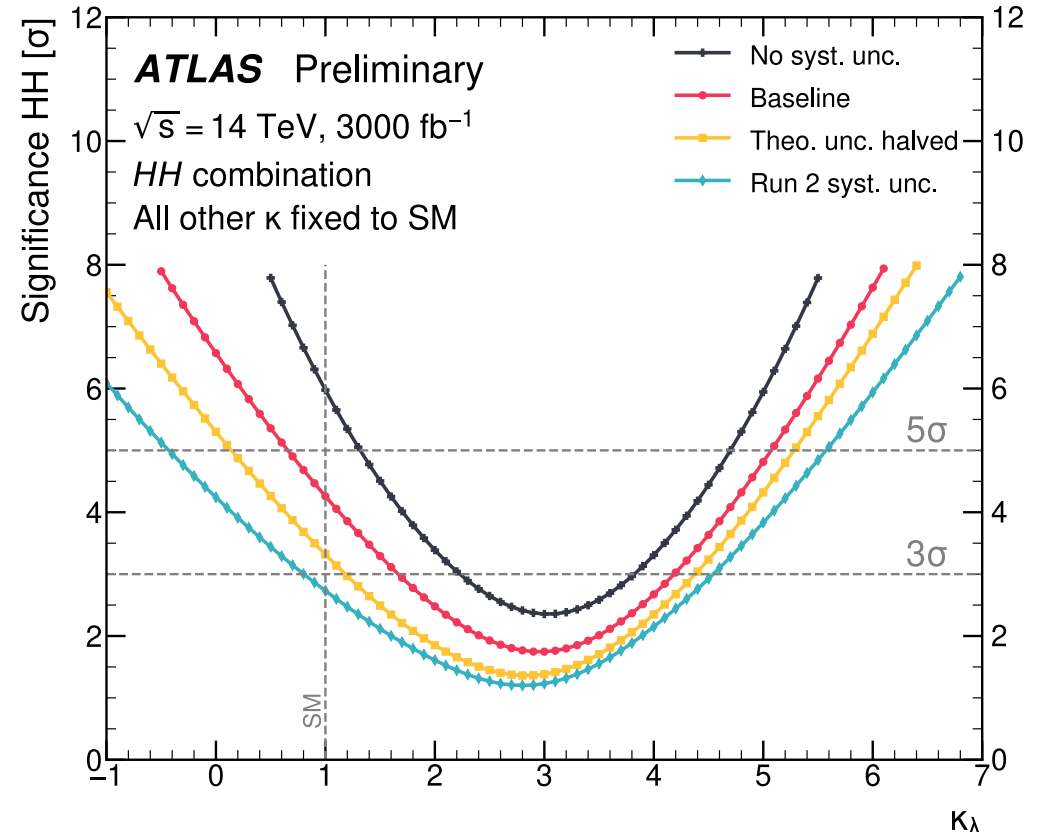
- Expected discovery significance with 3000  $fb^{-1}$  data at  $\sqrt{s} = 14 TeV$ : **4.26 $\sigma$**
- Precision on  $\mu_{HH}$ :  **$\sim 25\%$**
- Precision on  $\kappa_\lambda$  (SM): **+48%/−42%**
- Precision on  $\kappa_{2V}$  (SM): **+18%/−15%**

**“Baseline scenario”**  
scaling down statistical uncertainties and assuming improvements in analysis techniques ([HL-LHC projections](#))

ATL-PHYS-PUB-2025-006

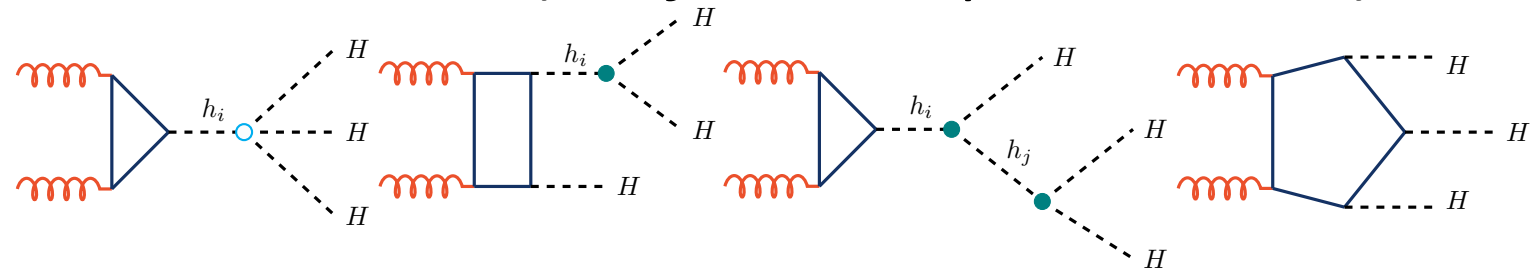


ATL-PHYS-PUB-2025-006

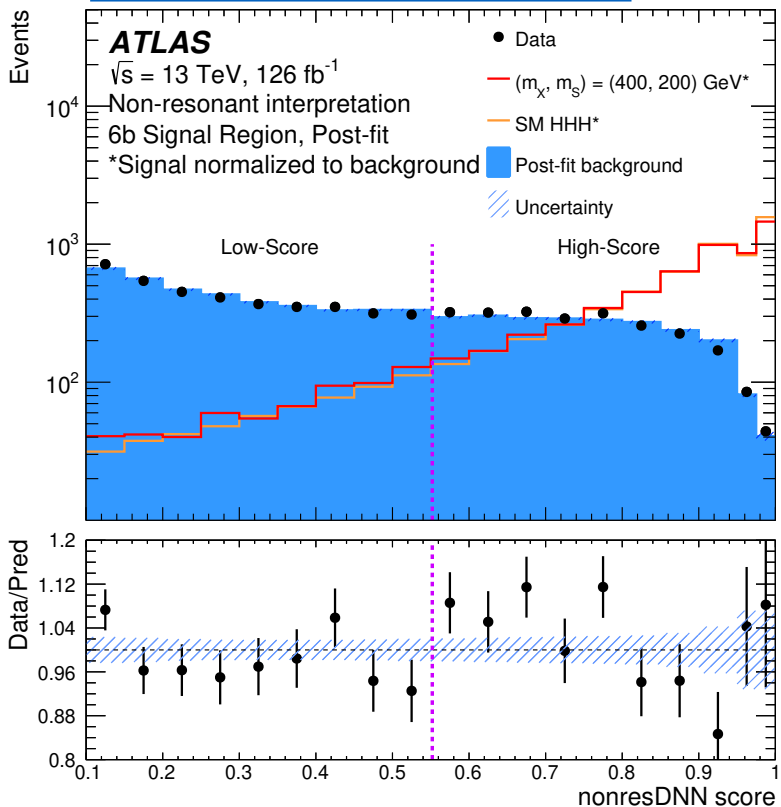


# The $HHH$ frontier

## Run2 $HHH \rightarrow 6b$ (the first $HHH$ public result!)

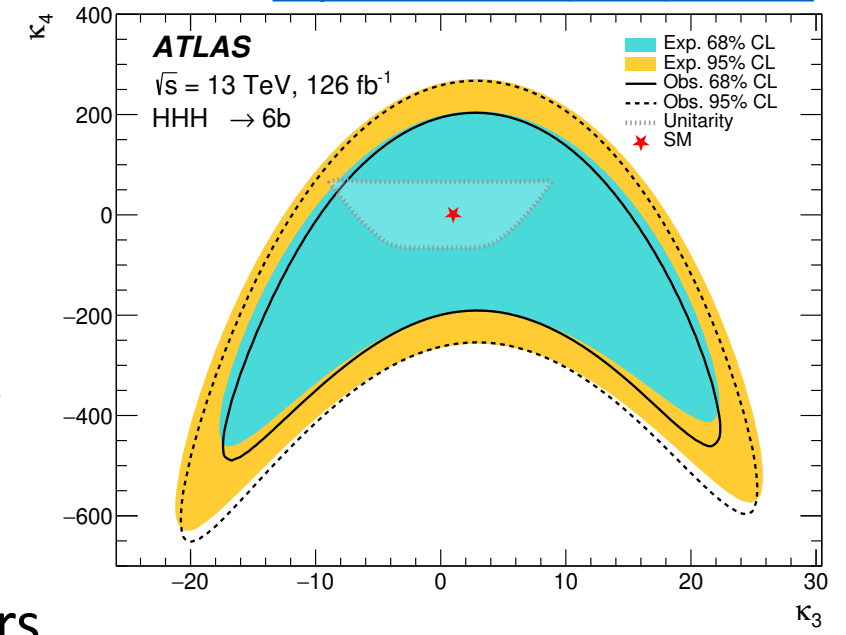


Phys. Rev. D 111 (2025) 032006



- Very small cross section due to interference with  $\lambda_3$ :  
 $\sigma_{HHH} \sim 0.08 \text{ fb}$
- Multi-jets & Multi b-jets triggers  
 $\geq 6 \text{ jets } (\geq 4 \text{ b-jets})$   
*(categorisation on b-jet multiplicity)*
- DNN to discriminate signal & define SR and CR
- Main QCD background extracted via data-driven methods

Phys. Rev. D 111 (2025) 032006



**Results**

No excess over the SM expectation

Upper limit of **59 fb** on the SM cross-section is set at 95% CL

**First constraints on the quartic coupling!**

# Conclusions

- The shape of the higgs boson potential is **fundamental**
- **HH** and **HHH** productions directly **probe the higgs potential** through the self interacting terms
- ATLAS **HH** searches are already steadily closing in on the **tri-linear coupling**
- ATLAS **HL-LHC projections** indicate a discovery **significance of  $\sim 4.2\sigma$**
- First **HHH** searches **just published!**

Determines the properties of the scalar sector & the evolution of the universe...

Look forward for the full Run 3 analyses!

ATLAS only!

Still far from probing the SM but it opens a very compelling new research field (to possibly even study BSM effects)

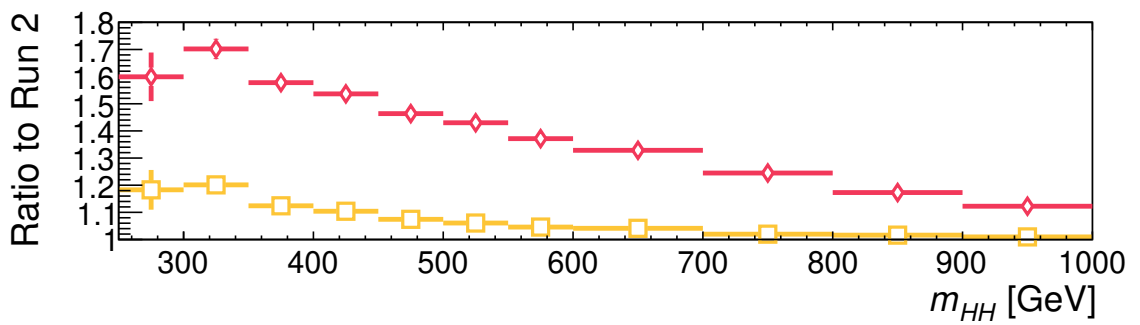
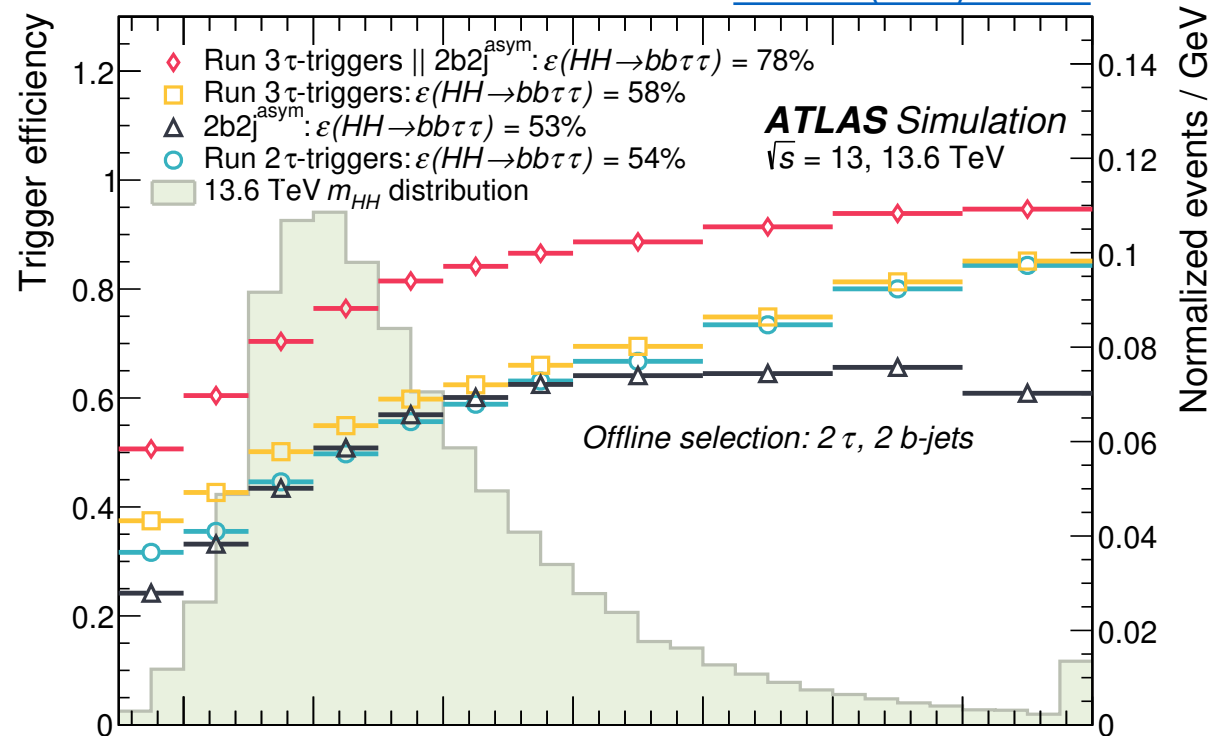
**Thank you for the  
attention**

# Back-up

# Improvements for Run 3 - Triggers

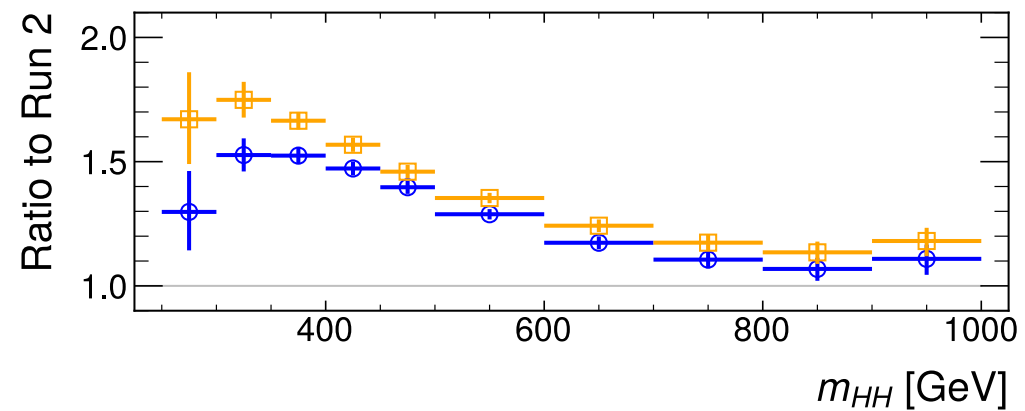
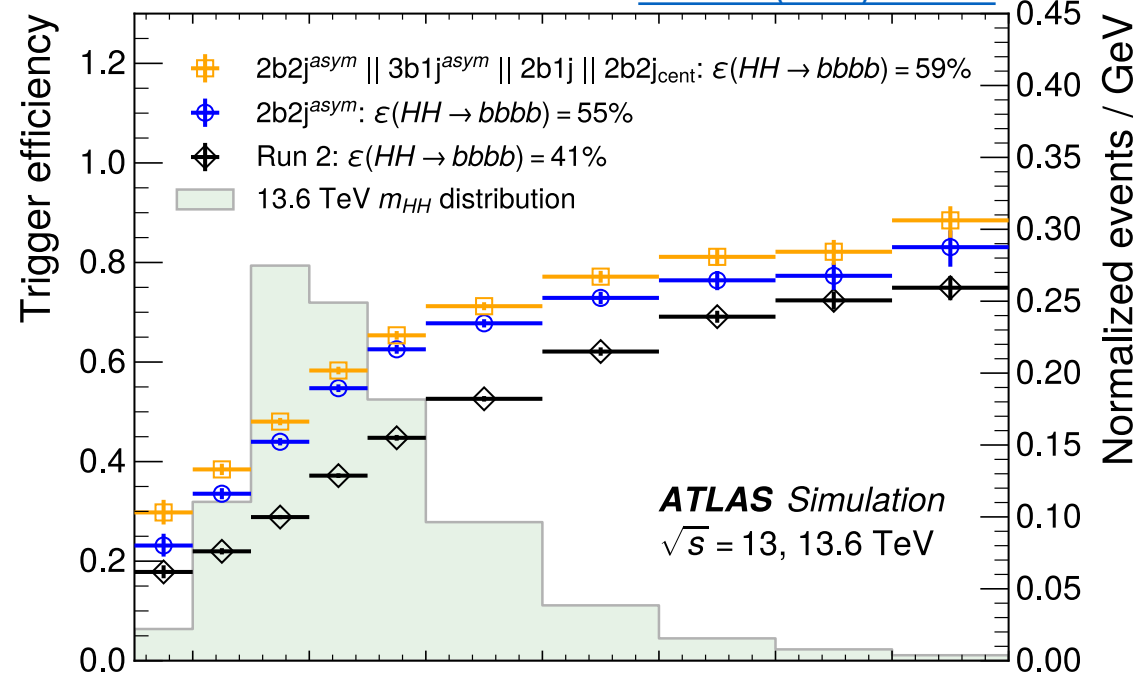
New specialised triggers for fully hadronic  $HH \rightarrow b\bar{b}\tau\tau$

[JINST 20 \(2025\) P03002](#)



New specialised triggers for  $HH \rightarrow b\bar{b}b\bar{b}$

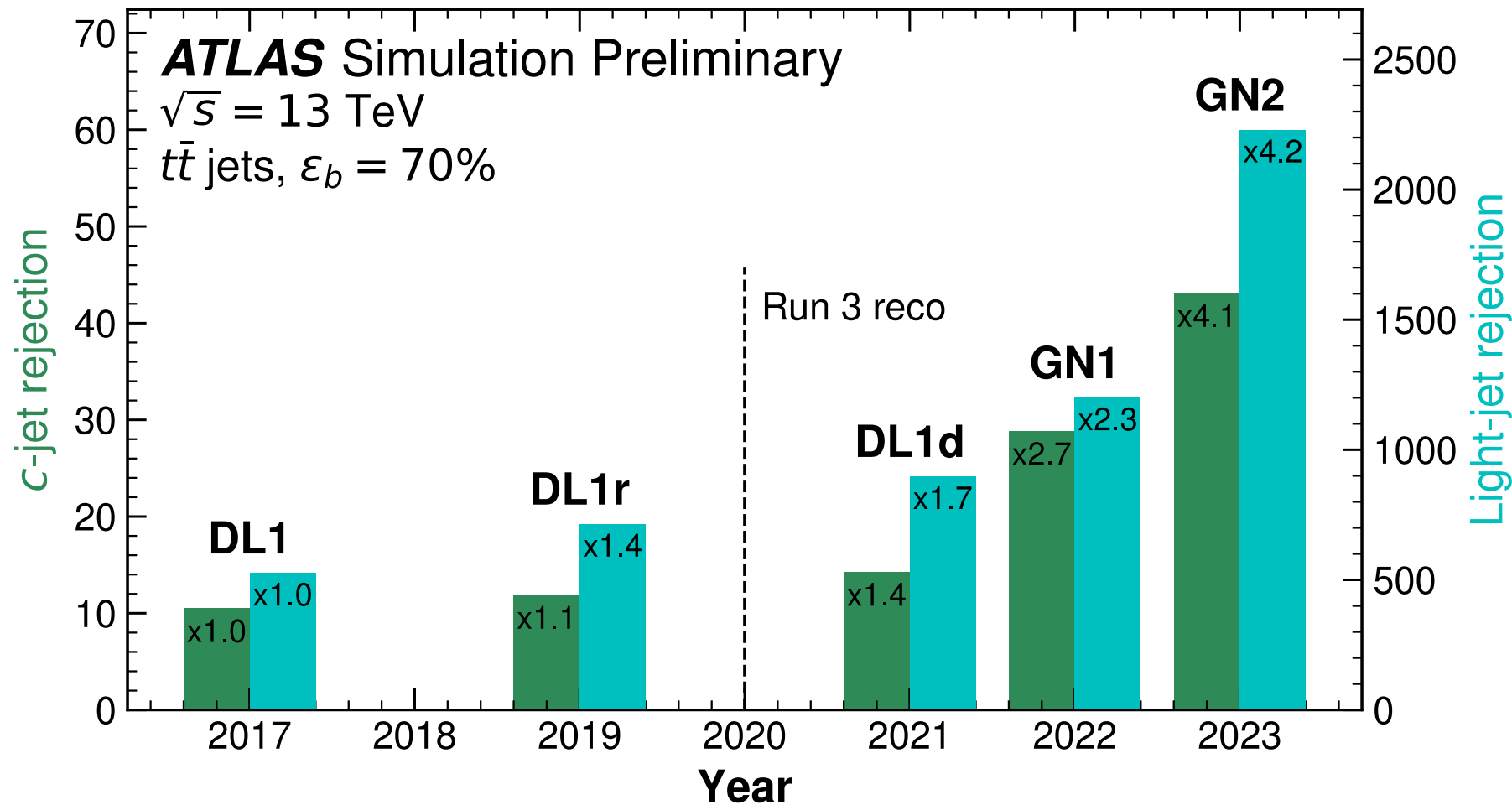
[JINST 20 \(2025\) P03002](#)



# Improvements for Run 3 - Triggers

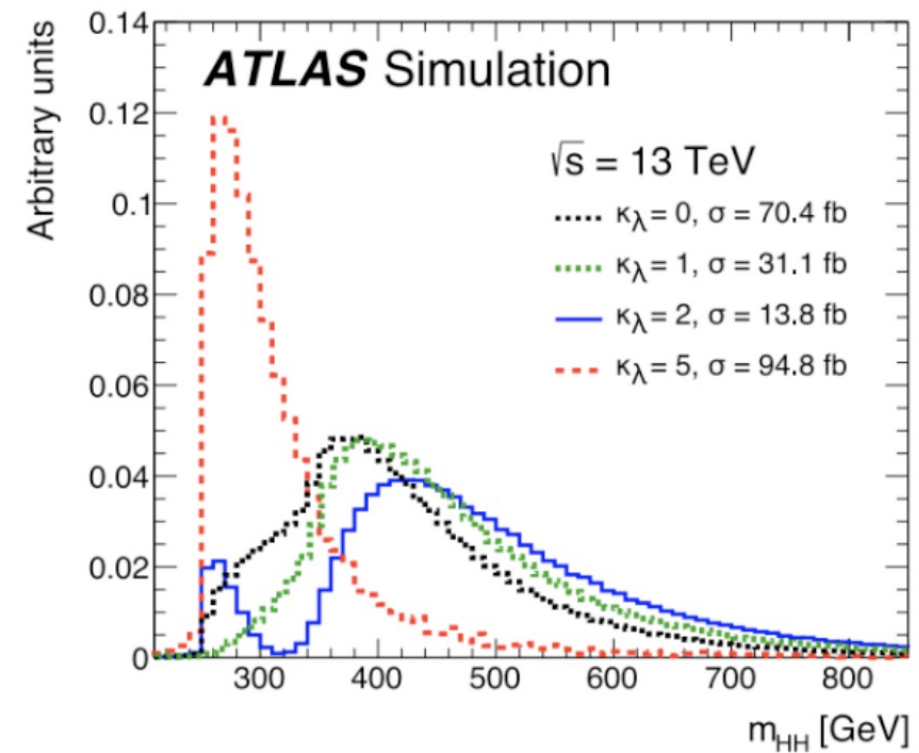
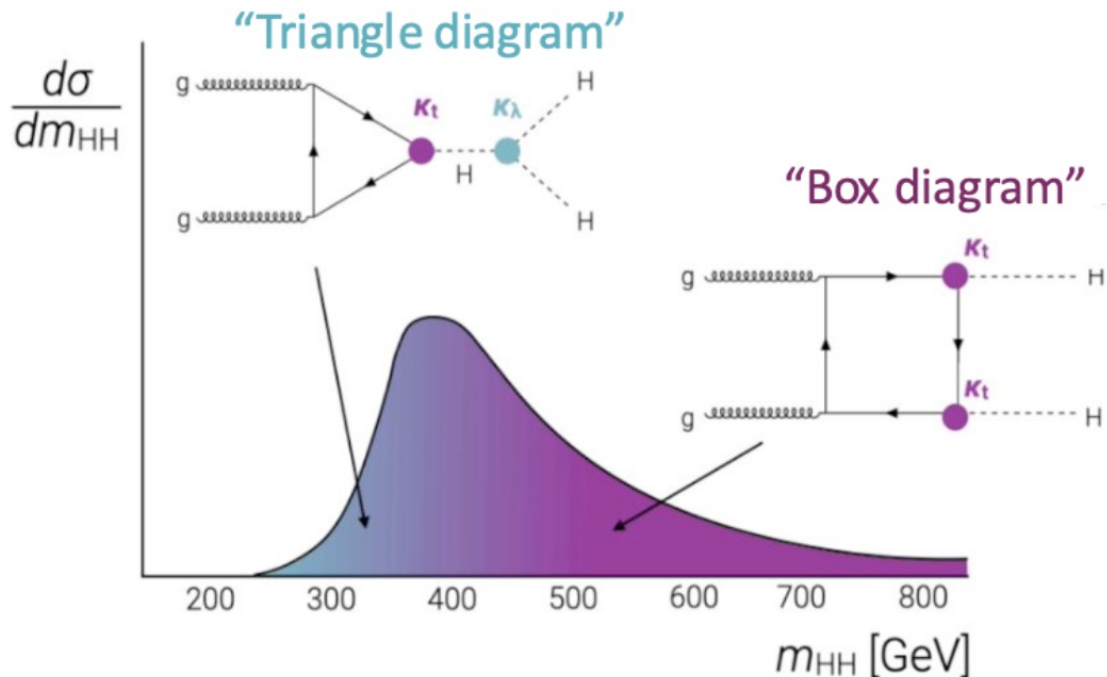
Major improvement in  $b$ -tagging algorithm  
(deployed in Run 3 analyses)

[FTAG-2023-01](#)



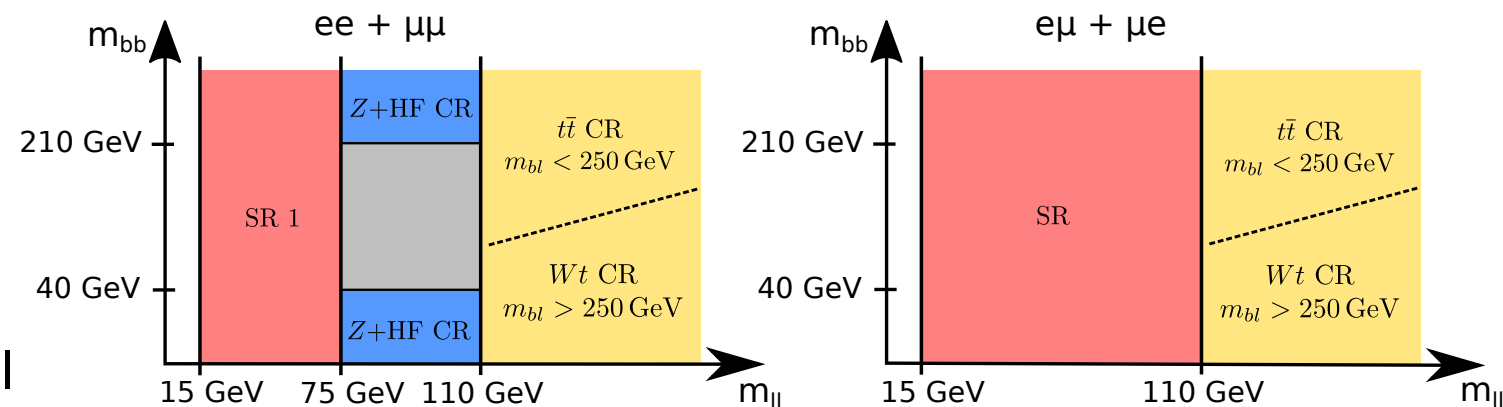
# $HH$ mass distribution

- Non linear dependence on  $\kappa_\lambda$  due to destructive interference between “triangle” and “box” diagrams
- The “triangle” diagram dominates at low  $m_{HH}$
- Higher values of  $\kappa_\lambda$  more difficult to probe experimentally due to low momentum objects in the final state

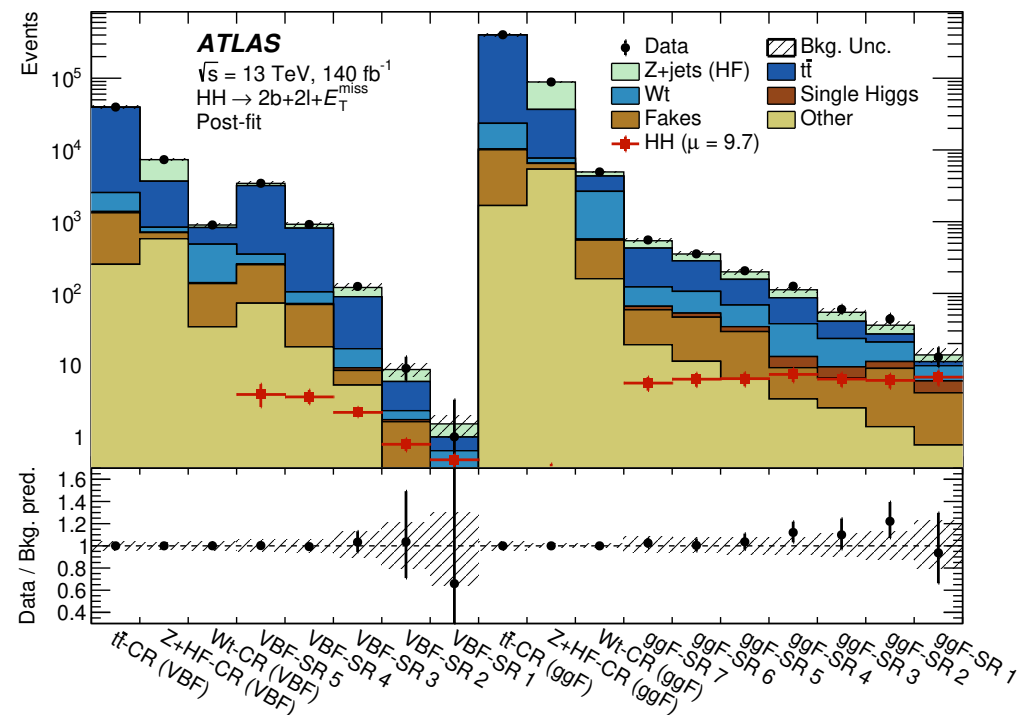


# Run 2 $HH \rightarrow b\bar{b}\ell\ell + E_T^{miss}$

- Single-lepton and di-lepton triggers
- Two light leptons (e/μ),  $p_T > 9 \text{ GeV}$
- Two b-tagged jets ( $\varepsilon=77\%$ )
- SRs and CRs based on  $m_{\ell\ell}$  and  $m_{bb}$
- VBF and ggF categories:
  - BDT trained with VBF HH as signal and ggF HH as background
  - Multi-class NN: ggF HH signal, top-quark background and other backgrounds
- Fit of highest-score BDT (DNN) bins and CR event yields in the VBF (ggF) categories.



JHEP 02 (2024) 037



## Results

Obs. (Exp.) 95% CL upper limit on

$$\sigma_{HH}^{ggF+VBF} = 9.7(16.2) \times SM$$

# Run2 $HH$ multilepton

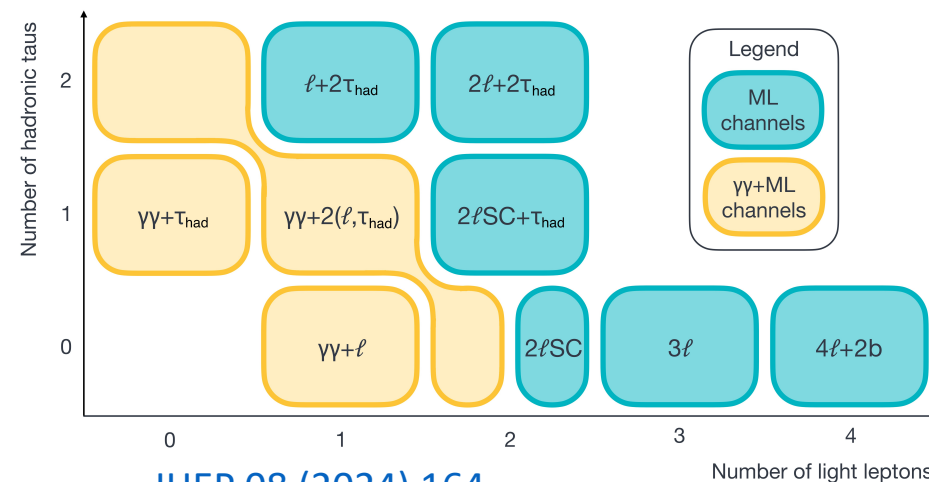
Events categorised based on number of light leptons, hadronic taus, and photons

ML channels:

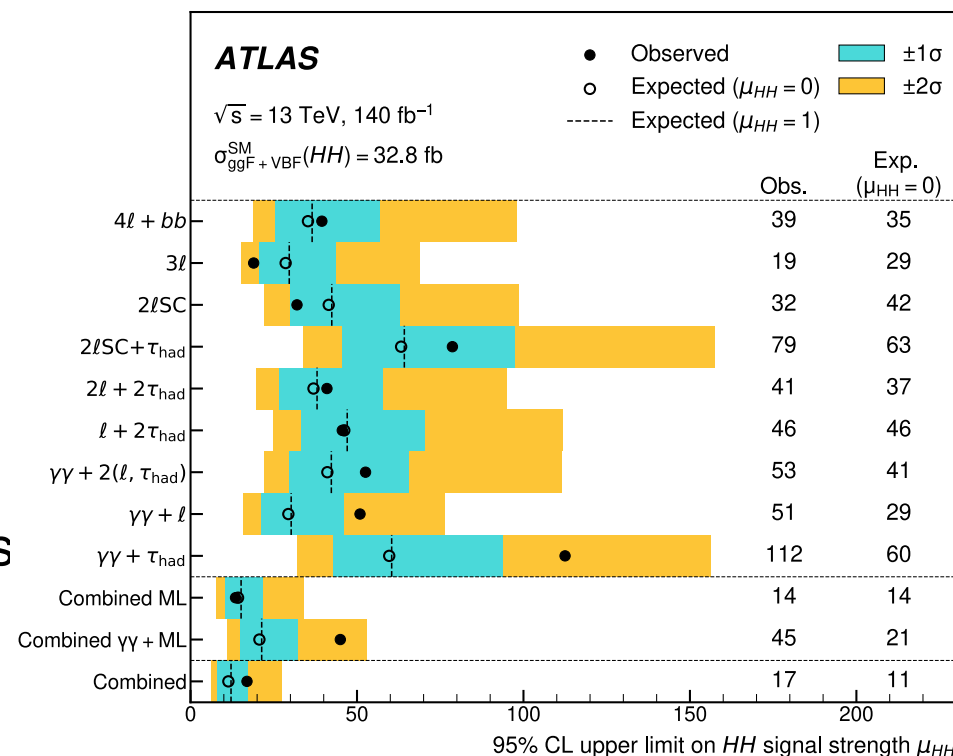
- Single and di-lepton triggers
- BDTs in all channels to separate signal from backgrounds
- Backgrounds with prompt leptons estimated from MC processes with non-prompt or charge mis-ID leptons estimated using data-driven methods

$\gamma\gamma$ +ML channels:

- Di-photon triggers
- Dominant backgrounds normalised to data in CRs
- $\gamma\gamma$ -continuum background estimated in CR sidebands
- Fit to  $m_{\gamma\gamma}$  distribution

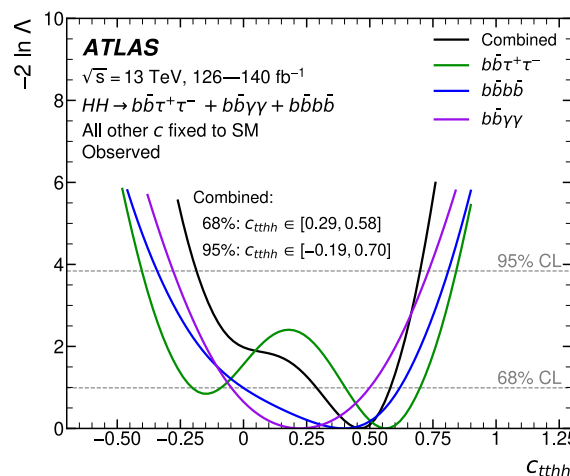
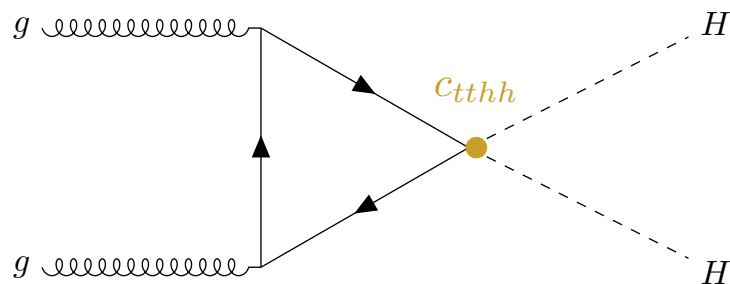
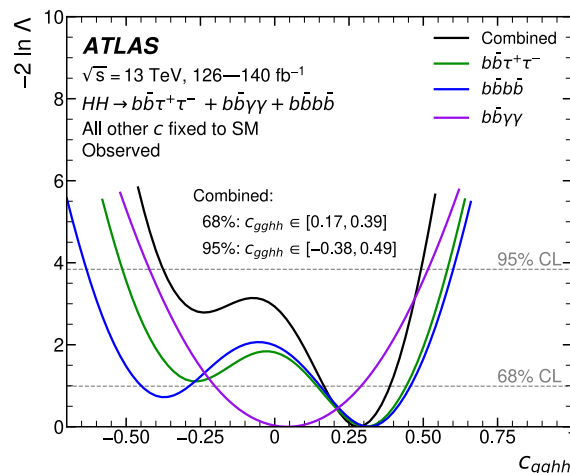
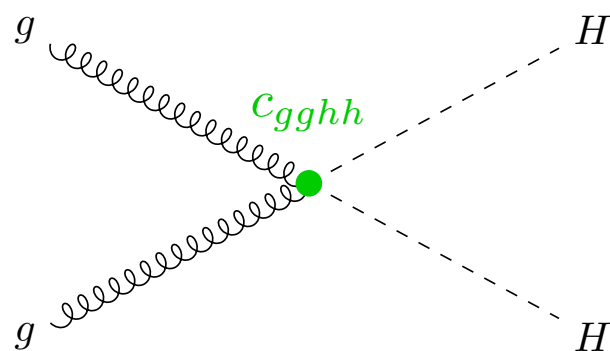


[JHEP 08 \(2024\) 164](#)

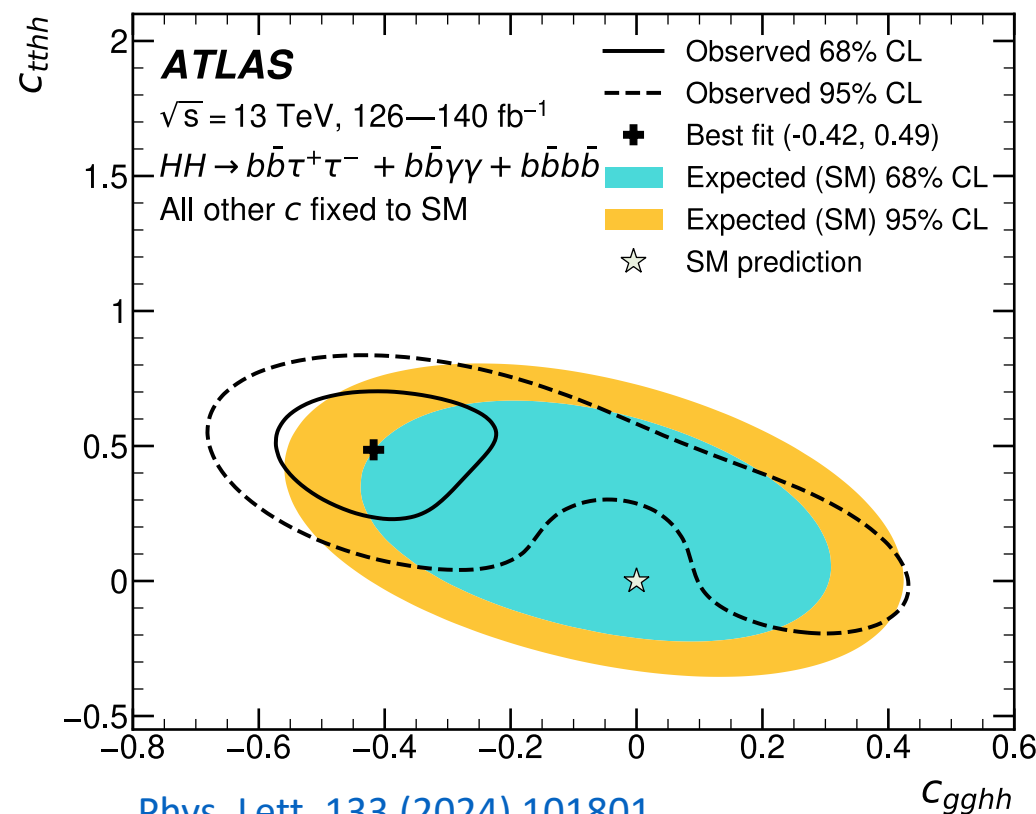


# Run 2 EFT interpretations

Effective Field Theories (EFTs) provide a model-independent framework to parametrise deviations from the SM, where higher-dimension operators modify the interactions of the SM particles

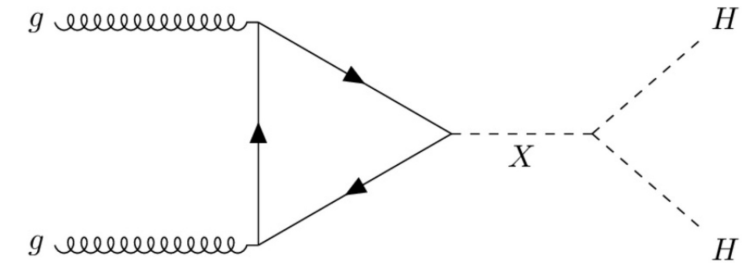


## Reinterpretation of legacy Run 2 $b\bar{b}\gamma\gamma$ , $b\bar{b}\tau\tau$ and $b\bar{b}b\bar{b}$ analyses

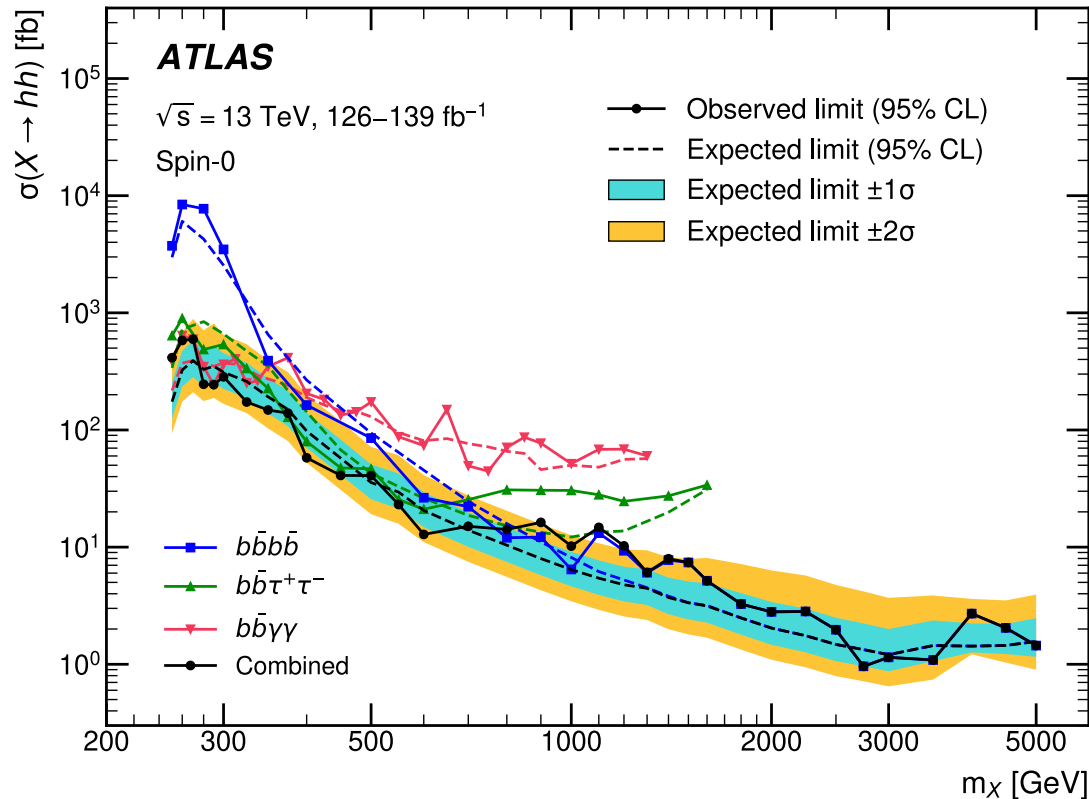


# Resonant $HH$ searches

- Higgs boson pairs can also be produced via the decay of a hypothetical heavy resonance ( $X$ ), and many BSM theories predict the existence of such heavy particles.
- Summary of individual and combined resonant HH limits ( $b\bar{b}\gamma\gamma$ ,  $b\bar{b}\tau\tau$ ,  $b\bar{b}b\bar{b}$ ):  
*The largest excess in the combined limit is found at 1.1 TeV and corresponds to a local (global) significance of  $3.2\sigma$  ( $2.1\sigma$ )*



[Phys. Rev. Lett. 132 \(2024\) 231801](#)



[Phys. Rev. Lett. 132 \(2024\) 231801](#)

