Probing the nature of electroweak symmetry breaking with Higgs boson pairs in ATLAS

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On behalf of the ATLAS collaboration

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@BrookhavenLab

Outline

- Introduction
- $HH \to b\bar{b}\gamma\gamma$
- $HH \to b\bar{b}\tau^{+}\tau^{-}$
- $HH \to b\bar{b}b\bar{b}$
- $HH \to 2b + 2\ell + E_{T}^{miss}$
- $HH \to Multilepton$
- Combination
- High-Luminosity LHC projection
- Summary

di-Higgs Physics Introduction

Higgs potential

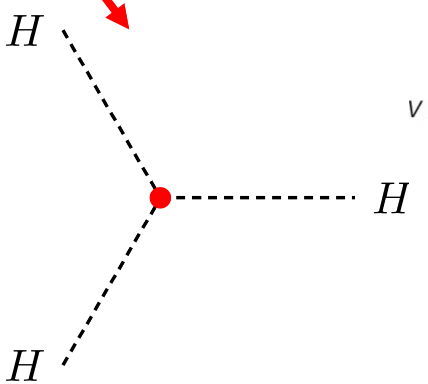
$$\mathcal{L}_H = \frac{1}{2} m_H^2 h^2 + \lambda_3 h^3 + \lambda_4 h^4$$

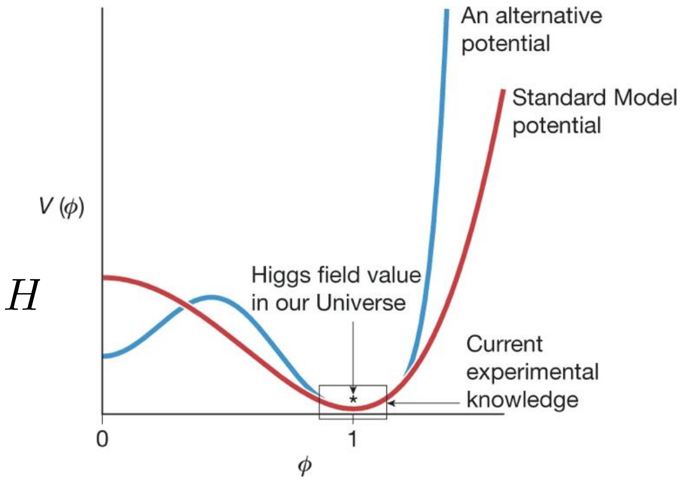
SM prediction:

Higgs mass

$$\lambda_3^{SM} = \frac{m_H^2}{2v}$$

Vacuum Expectation Value





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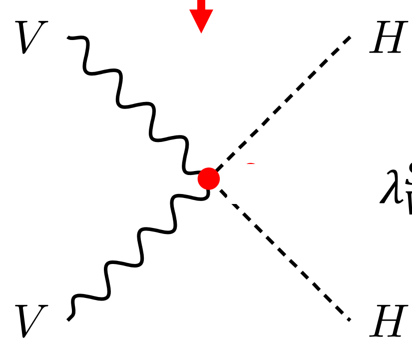
Higgs couplings to Electroweak

$$\mathcal{L}_{\text{Higgs}} = (D^\mu \phi)^\dagger (D_\mu \phi) - V(\phi)$$



$$\lambda_{VVHH}^{SM} = \frac{2m_V^2}{v^2}$$

Kappa framework: parametrize the Higgs boson couplings as the ratio to the SM prediction

$$\kappa_\lambda = \frac{\lambda_3}{\lambda_3^{SM}} \qquad \kappa_{2V} = \frac{\lambda_{VVHH}}{\lambda_{VVHH}^{SM}}$$

Measured Value

SM Prediction

$$\mu_{HH} = \frac{\sigma_{HH}}{\sigma_{HH}^{SM}}$$

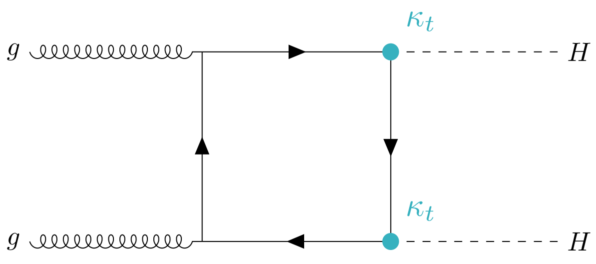
➢ **HHH and VVHH coupling accessible via HH production**

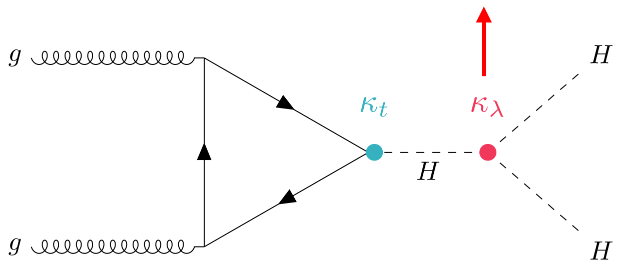
di-Higgs Production and Decay

HH Production mode:

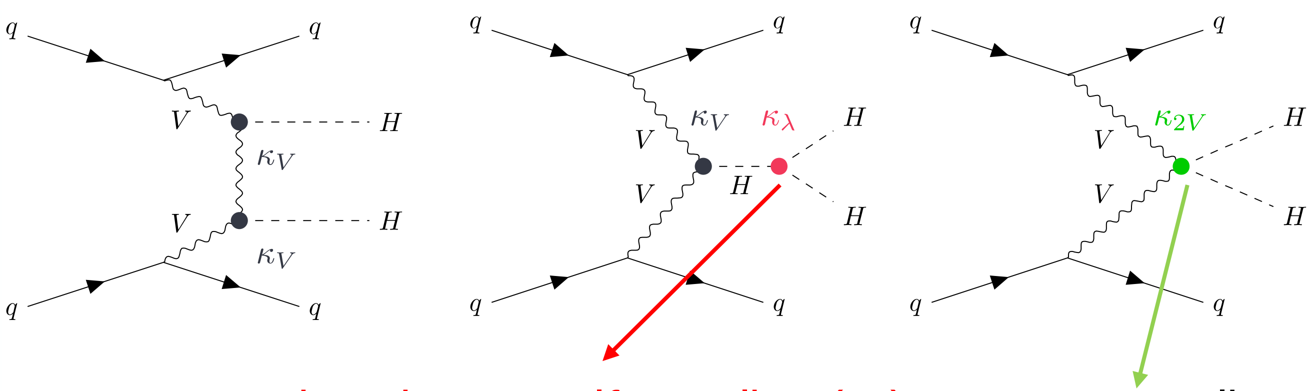
gluon-gluon Fusion (ggF) $\sigma_{ggF} = 31\ fb$ (SM)

Higgs boson self-coupling (κ_λ)





Vector Boson Fusion (VBF) $\sigma_{VBF} = 1.7\ fb$ (SM)



Higgs boson self-coupling (κ_λ) $VVHH$ coupling (κ_{2V})

HH decay Mode

	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

$b\bar{b}b\bar{b}$(34%) – largest branching ratio, but challenging multijet background

$b\bar{b}\gamma\gamma$ (0.26%) – low branching ratio, but clean final state, excellent $m_{\gamma\gamma}$ resolution

$b\bar{b}\tau^+\tau^-$ (7.3%) – in between in terms of signal vs background trade-off

$b\bar{b}\ell^+\ell^-$ + missing E_T (2.9%) – targeting events where one $H \to b\bar{b}$, one $H \to \ell^+\ell^-\nu\bar{\nu}$

Multilepton (6.5%) – Combination of 9 channels, Higgs boson decay to leptons

ATLAS Full Run 2 dataset

$\sqrt{s} = 13\ \text{TeV}, \mathcal{L} = 126 - 140\ fb^{-1}$

ATLAS has probed more than half of the decay modes

$HH \rightarrow b\bar{b}\gamma\gamma$

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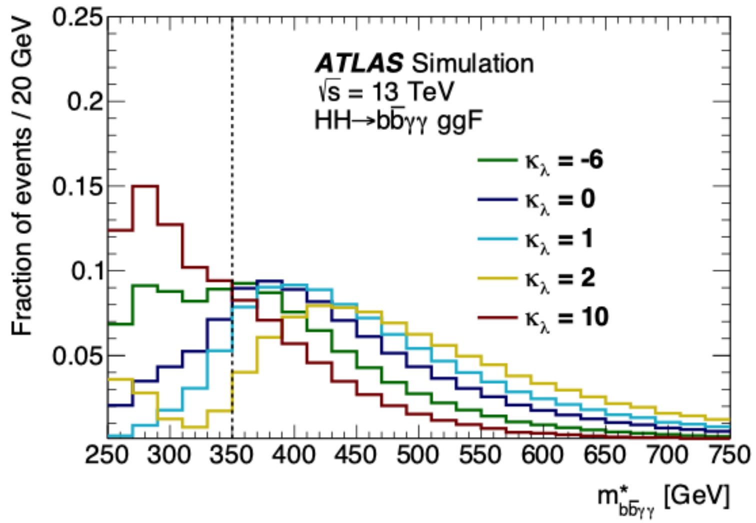
- **Tiny branching ratio but very clean signature:**
  - excellent $m_{\gamma\gamma}$ resolution
  - small backgrounds

- **2 b-jets and 2 photons with 105 < $m_{\gamma\gamma}$ < 160 GeV**
- **7 event categories based on:**
  - High mass ($m^*_{bb\gamma\gamma} > 350$ GeV) vs low mass ($m^*_{bb\gamma\gamma} \leq 350$ GeV)

    $$m^*_{b\bar{b}\gamma\gamma} = m_{b\bar{b}\gamma\gamma} + (125\text{ GeV} - m_{b\bar{b}}) + (125\text{ GeV} - m_{\gamma\gamma})$$
  - classification BDT output
- **No dedicated VBF category but the mass and $\Delta\eta$ of VBF-tagged jets are inputs to the BDTs**



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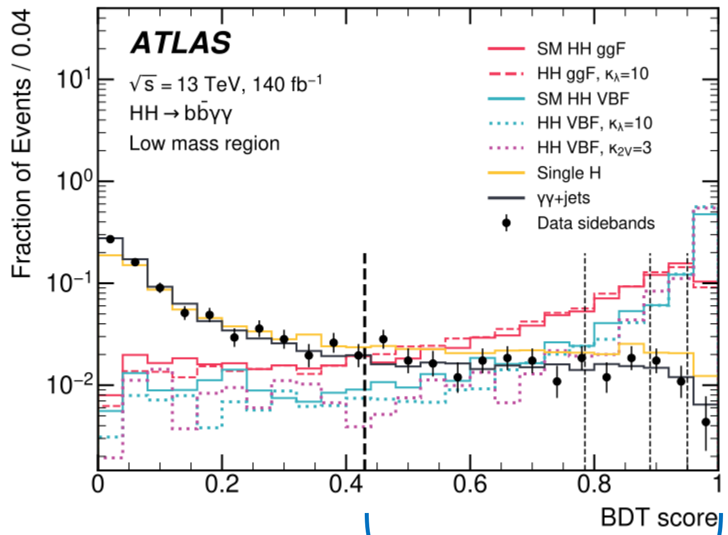
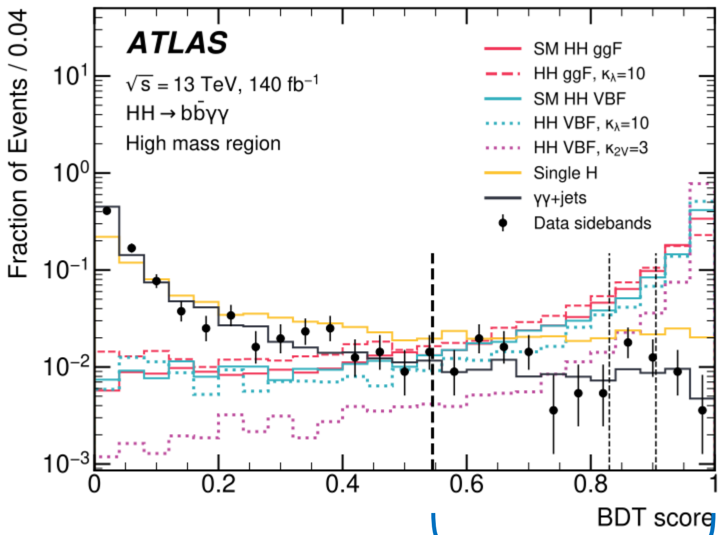


4 Categories at low mass



3 Categories at high mass

$HH \rightarrow b\bar{b}\gamma\gamma$

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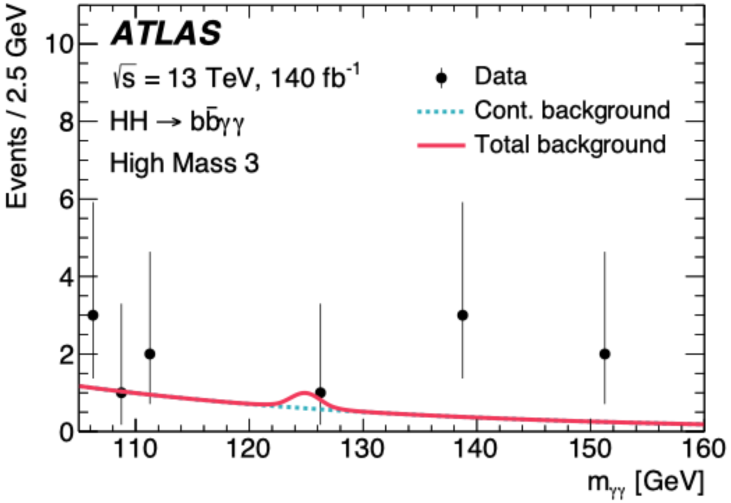
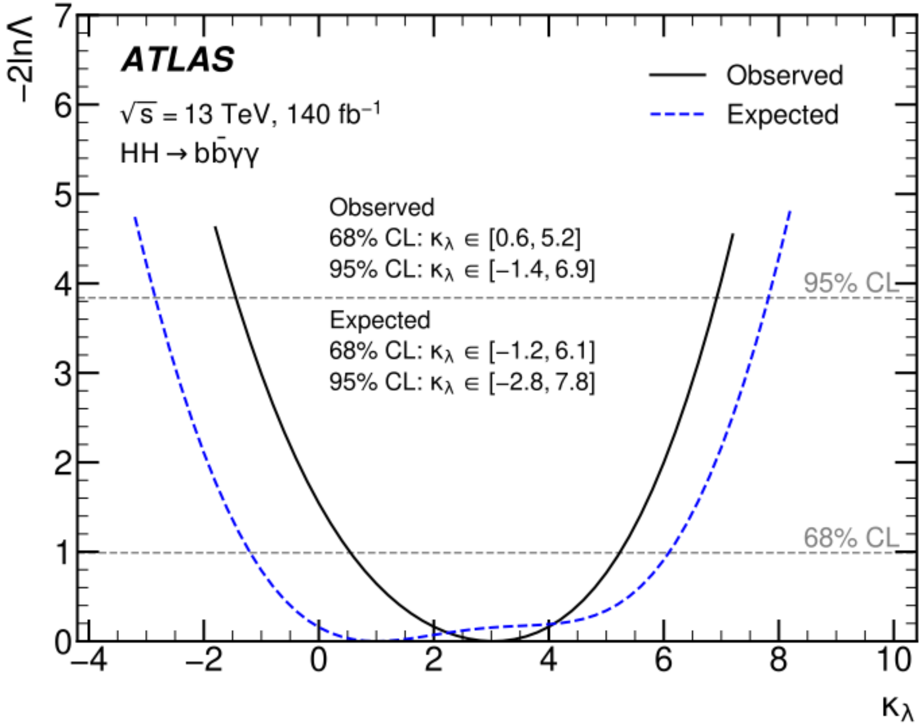
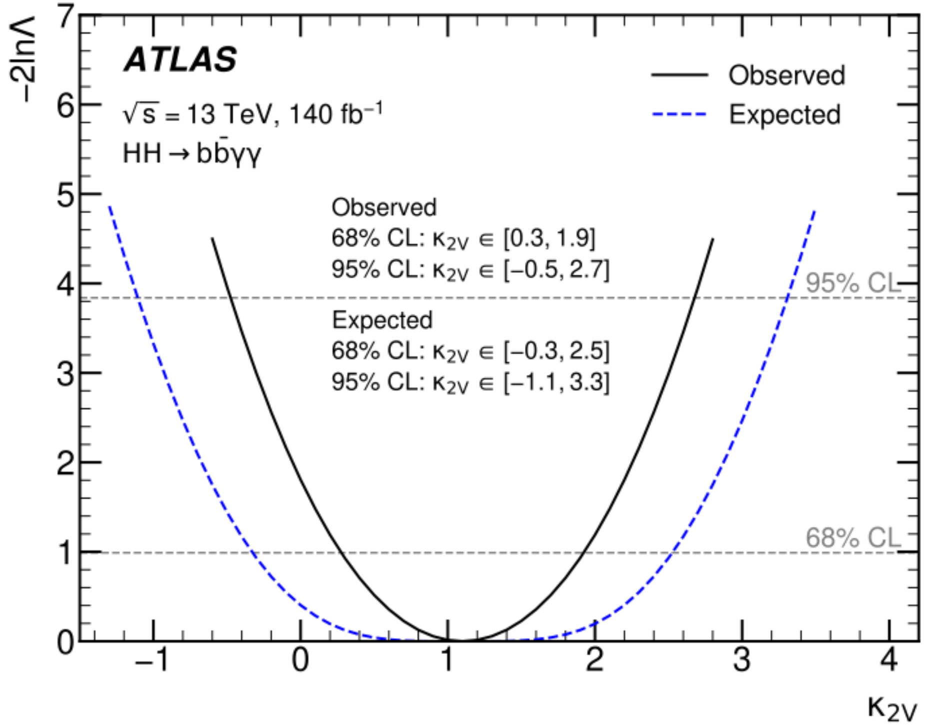
- **Fit $m_{\gamma\gamma}$ in each of 7 categories**
  - $\gamma\gamma$-continuum background modelled by exponential fit in sidebands
  - Signal and single-Higgs background modelled by Double-sided Crystal Ball



- **At 95% confidence level:**
  - $\mu_{HH} < 4.0$ (5.0 expected)
  - Observed: $-1.4 < \kappa_\lambda < 6.9$ Expected: $-2.8 < \kappa_\lambda < 7.8$
  - Observed: $-0.5 < \kappa_{2V} < 2.7$ Expected: $-1.1 < \kappa_{2V} < 3.3$

The best expected constrain on κ_λ





$HH \rightarrow b\bar{b}\tau^+\tau^-$

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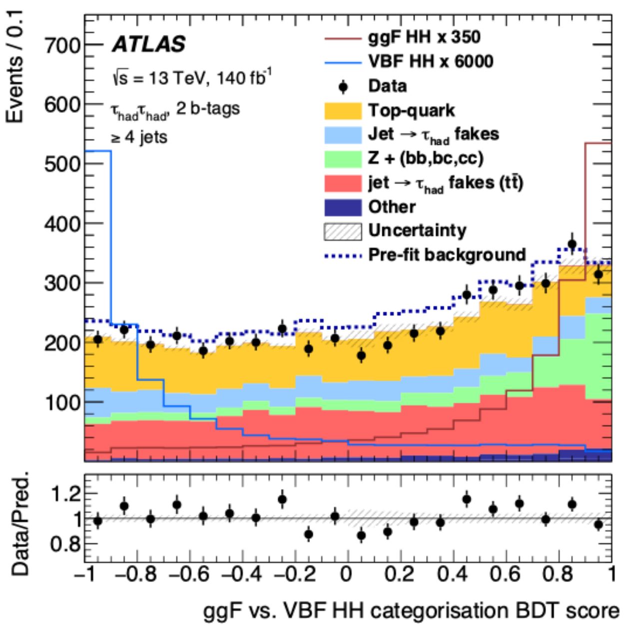
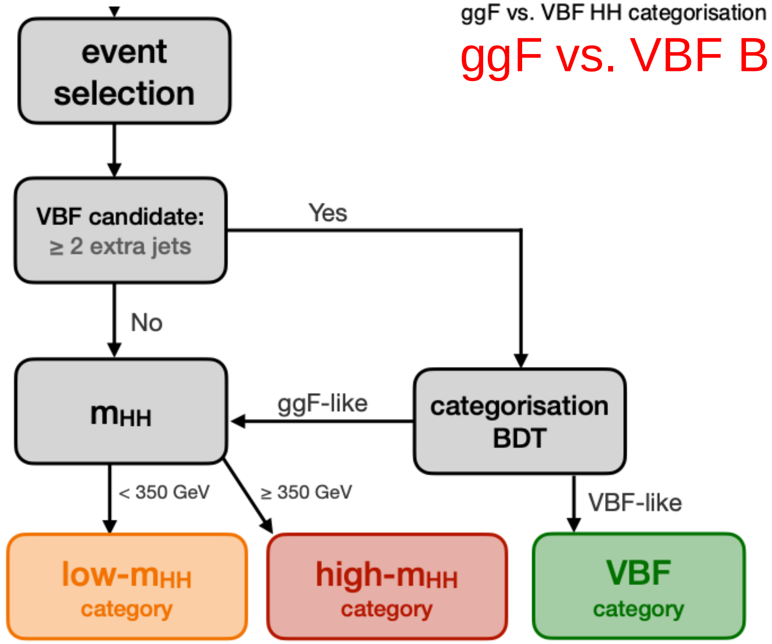
- **$\tau_{had}\tau_{had}$ and $\tau_{lep}\tau_{had}$ (Single lepton trigger and lepton + $\tau_{had-vis}$ triggers) final states:**
  - 3 Final state categories
  - BDT to separate ggF and VBF
  - ggF low mass ($m_{HH} < 350$ GeV), ggF High mass ($m_{HH} > 350$ GeV), VBF
  - 1 Control Region depends on $m_{\ell\ell}$
  - In total, 9 Signal region + 1 Control Region

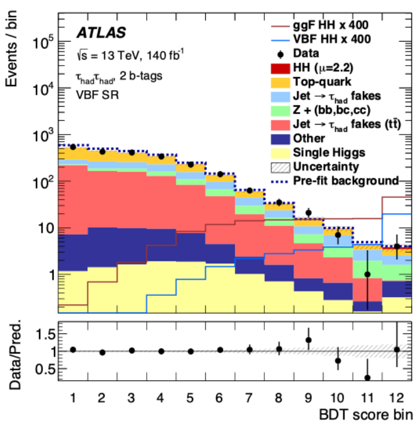


ggF vs. VBF BDT

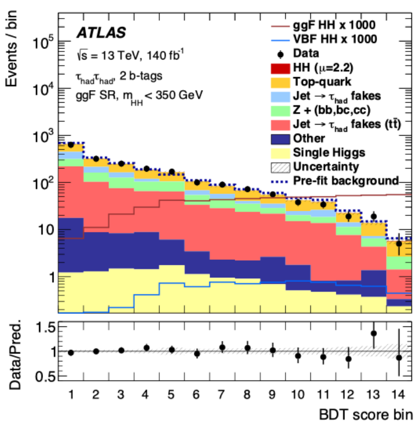
- **BDT trained in each Signal Region to discriminate Signal vs. Background**

- **Backgrounds:**
  - Fake τ from $t\bar{t}$ or multi-jets – estimated using data driven methods, deriving fake factors or scale factors from control regions

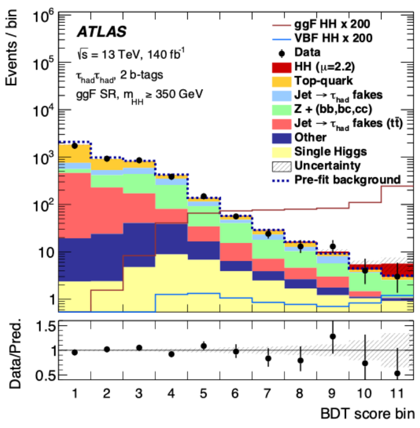




VBF



ggF low mass



ggF high mass

$HH \rightarrow b\bar{b}\tau^{+}\tau^{-}$

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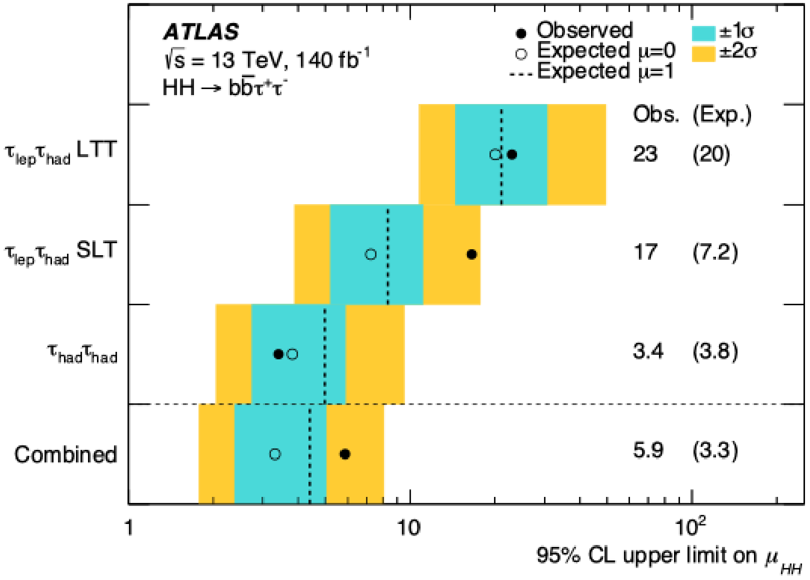
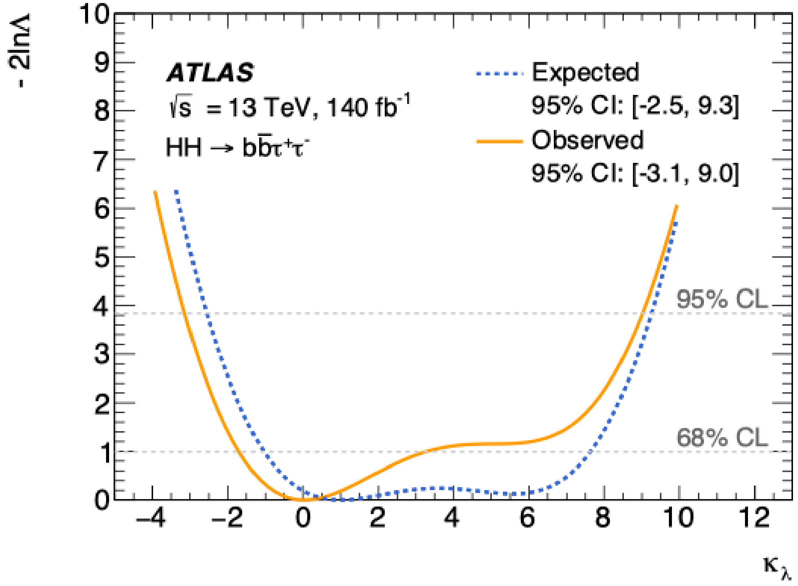
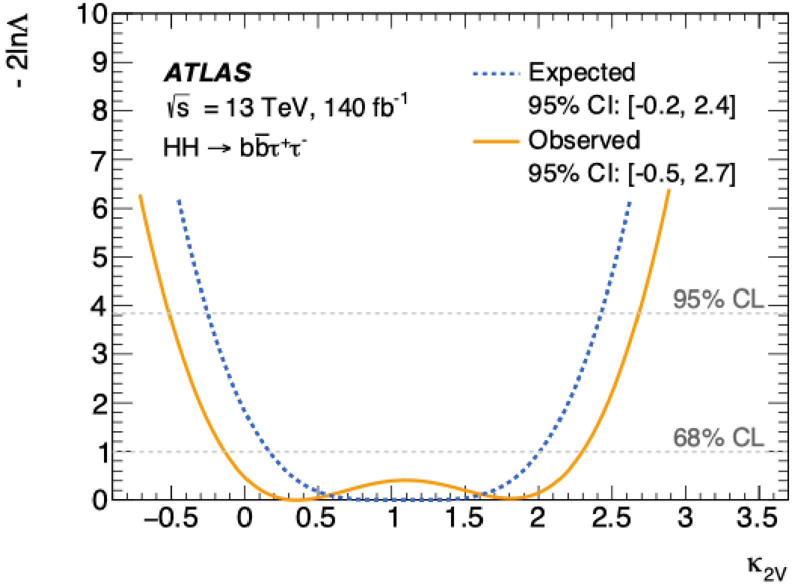






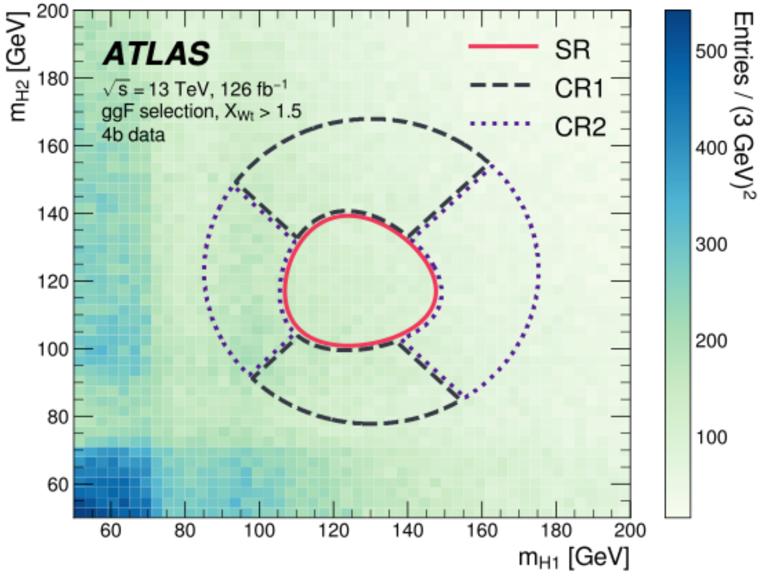
- **At 95% confidence level:**
  - $\mu_{HH} < 5.9$ (3.3 expected)
  - Observed: $-3.1 < \kappa_{\lambda} < 9.0$ Expected: $-2.5 < \kappa_{\lambda} < 9.3$
  - Observed: $-0.5 < \kappa_{2V} < 2.7$ Expected: $-0.2 < \kappa_{2V} < 2.4$

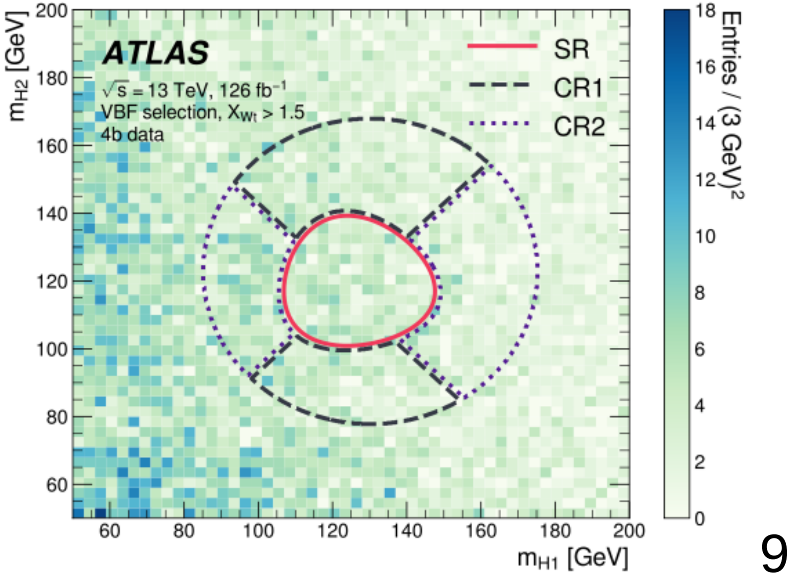
- **$\tau_{had}\tau_{had}$ is the most sensitive channel**
- **$HH \rightarrow b\bar{b}\tau^{+}\tau^{-}$ is expected to be the most sensitive channel to SM HH**

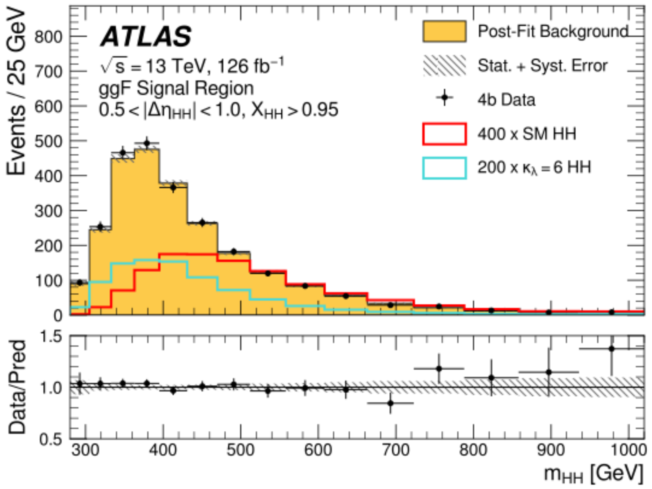
$HH \rightarrow b\bar{b}b\bar{b}$

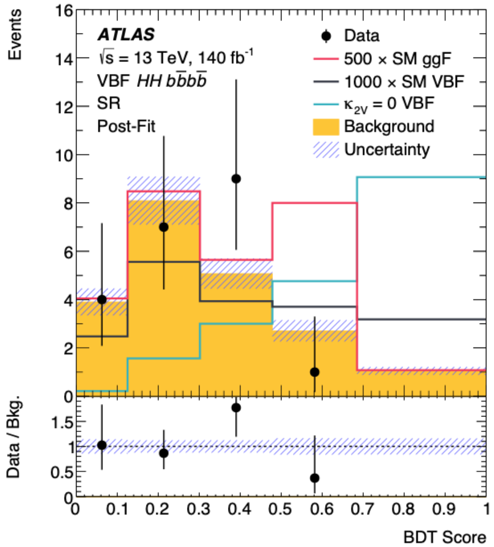
Phys. Rev. D 108 (2023) 052003 resolved
Phys. Lett. B 858 (2024) 139007 boosted

- **Resolved**
  - 4 b-tagged jets, Pair “Closest jets” to form Higgs candidates
  - ggF and VBF categories
- **Boosted:**
  - 2 $X \rightarrow bb$ jets and two VBF jets
  - VBF topology only
- **Signal centered in m_{H1} and m_{H2} plane**
- **Main background from QCD multijet**
  - Data driven normalisation from signal region sidebands
  - Simple scale factor (Neutral Network) in Resolved (Boosted)
- **Fit to m_{HH} (BDT) in Resolved (Boosted)**









$HH \rightarrow b\bar{b}b\bar{b}$

Phys. Rev. D 108 (2023) 052003 resolved
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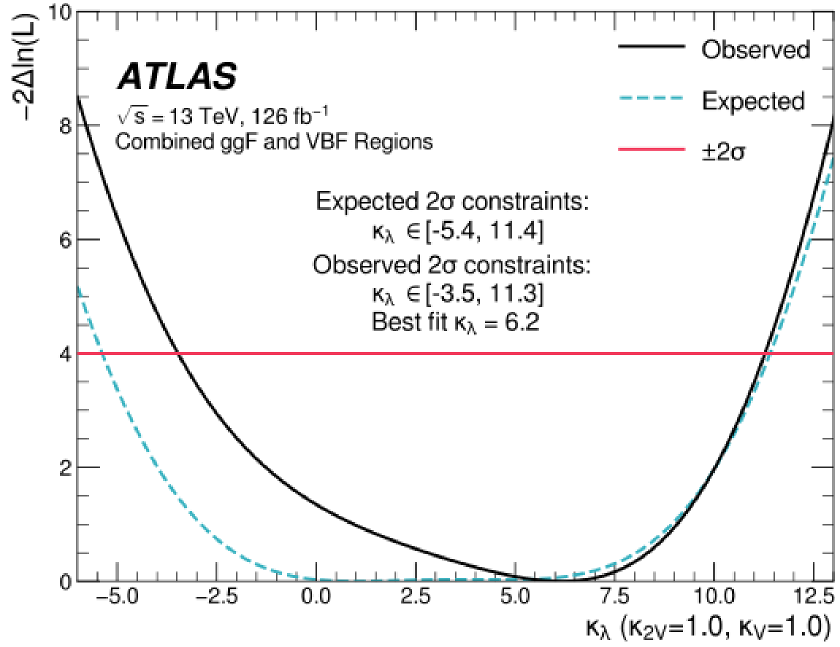
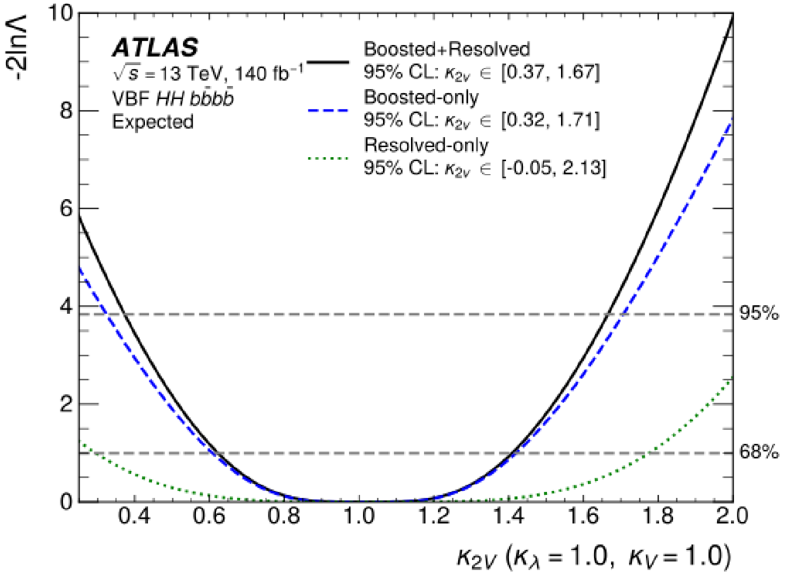
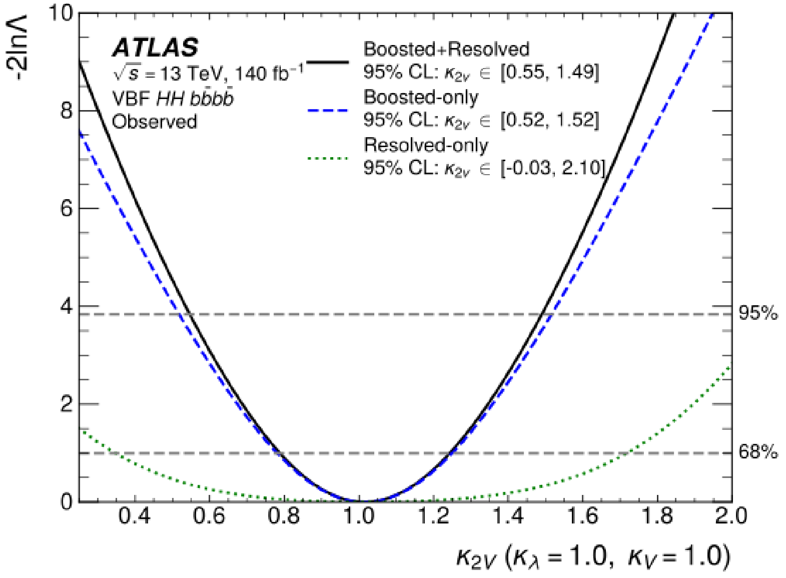






κ_λ from Resolved

κ_{2V} from Boosted + Resolved

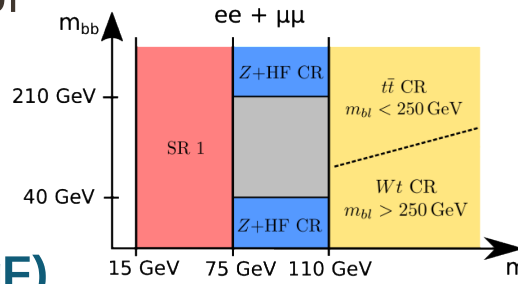
❖ At 95% confidence level:

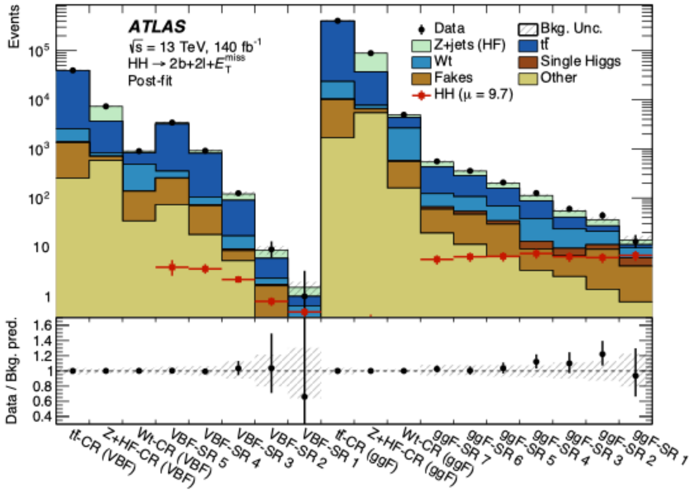
- ➢ $\mu_{HH} < 5.4$ (8.1 expected), from Resolved
- ➢ Observed: $-3.5 < \kappa_\lambda < 11.3$ Expected: $-5.4 < \kappa_\lambda < 11.4$ **Resolved**
- ➢ Observed: $0.55 < \kappa_{2V} < 1.49$ Expected: $0.37 < \kappa_{2V} < 1.67$ **Resolved + Boosted**

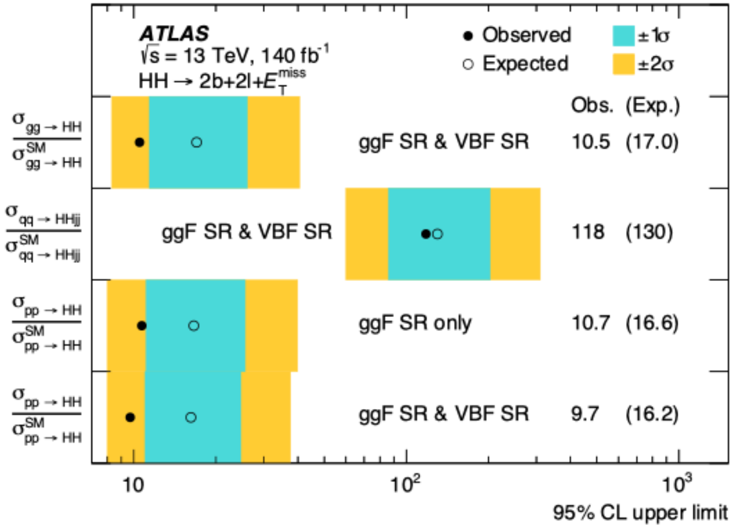
$HH \rightarrow 2b + 2\ell + E_T^{miss}$

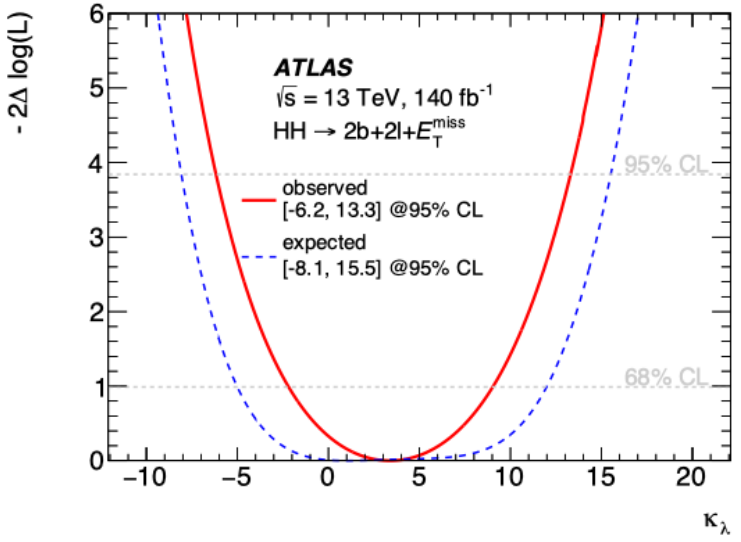
JHEP 02 (2024) 037

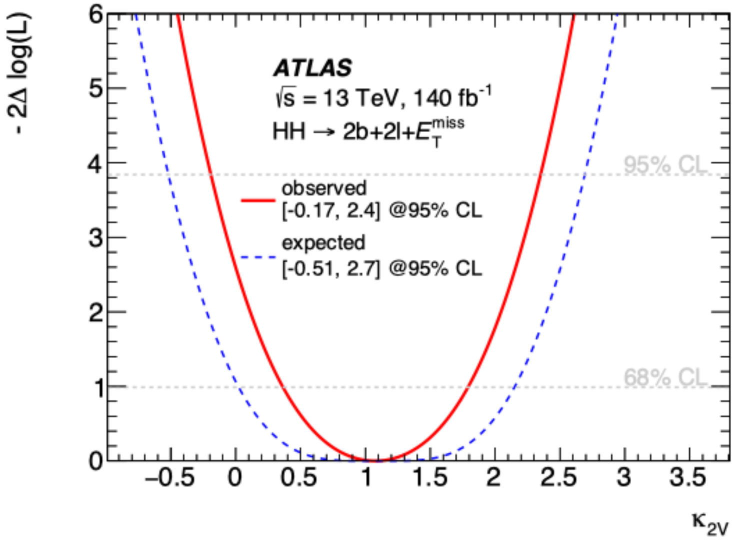
- ❖ One H $\rightarrow b\bar{b}$, one H $\rightarrow (W^+W^-, \tau^+\tau^-, ZZ) \rightarrow \ell^+\ell^- +$ neutrinos ($\ell = e, \mu$)
  - ➢ Lepton has opposite charge, can be different flavor
- ❖ Signal Region and Control Region based on $m_{\ell\ell}$ and m_{bb}
- ❖ Fit of the 5 (7) highest BDT (DNN) bins on VBF (ggF)







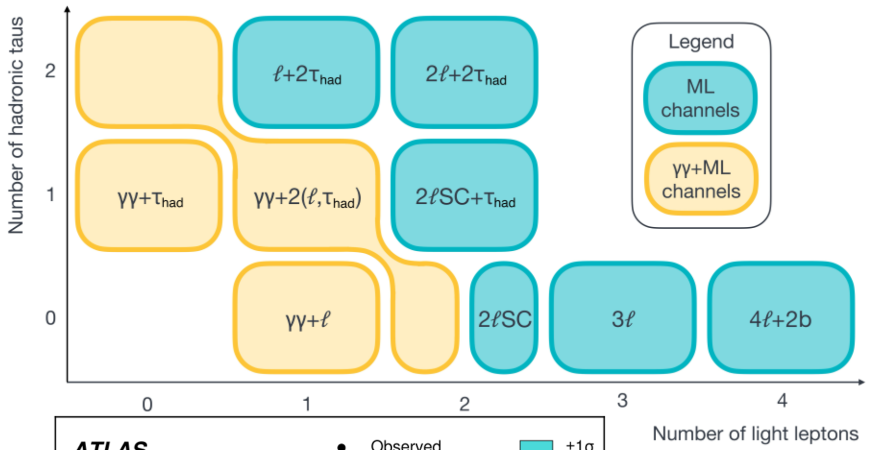


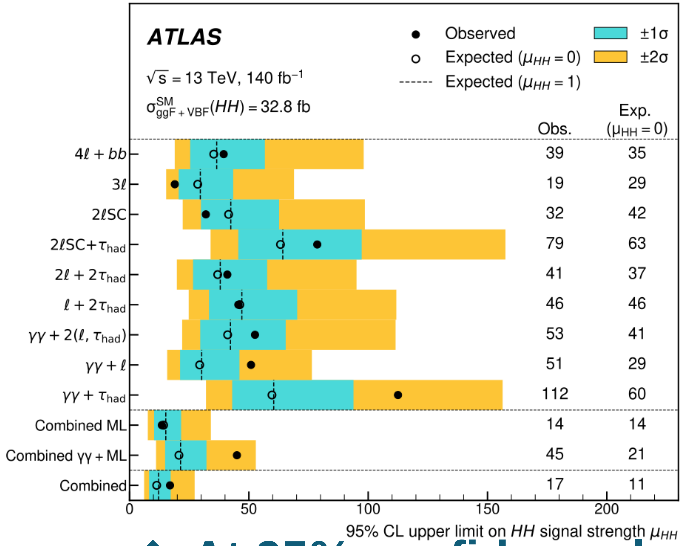


- ❖ **At 95% confidence level:**
  - ➢ $\mu_{HH} < 9.7$ (16.3 expected)
  - ➢ Observed: $-6.2 < \kappa_\lambda < 13.3$ Expected: $-8.1 < \kappa_\lambda < 15.5$
  - ➢ Observed: $-0.17 < \kappa_{2V} < 2.4$ Expected: $-0.51 < \kappa_{2V} < 2.7$

$HH \rightarrow MultiLeptons$

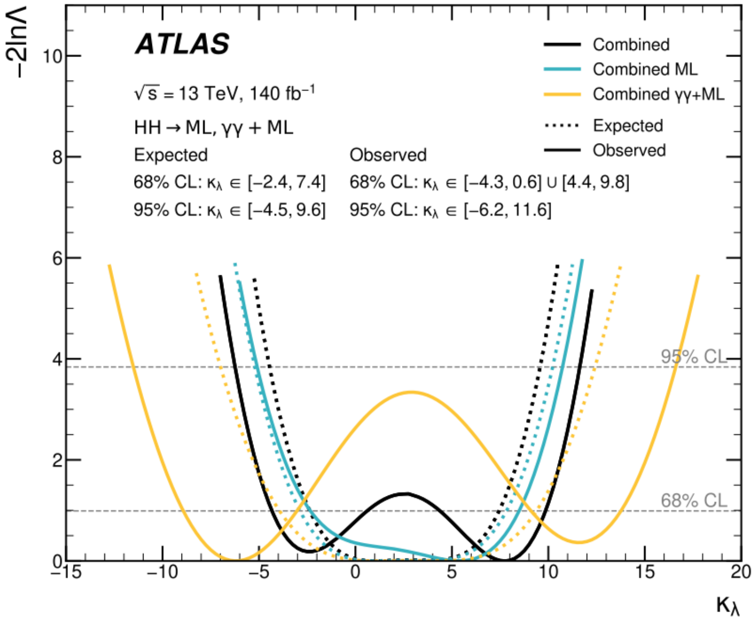
❖ **9 different di-Higgs decay final states are considered in this analysis**

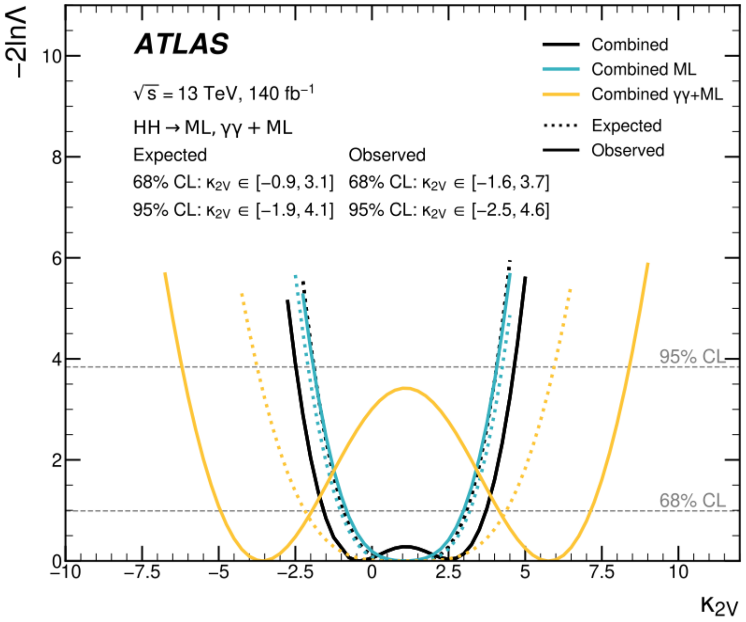




❖ **BDT trained in each sub-channel**

- ➢ Discriminant in Multilepton channels
- ➢ Define categories, $m_{\gamma\gamma}$ used for fit in $\gamma\gamma$ + Multilepton channels





❖ **At 95% confidence level:**

- ➢ $\mu_{HH} < 17$ (11 expected)
- ➢ Observed: $-6.2 < \kappa_\lambda < 1.6$ Expected: $-4.5 < \kappa_\lambda < 9.6$
- ➢ Observed: $-2.5 < \kappa_{2V} < 4.6$ Expected: $-1.9 < \kappa_{2V} < 4.1$

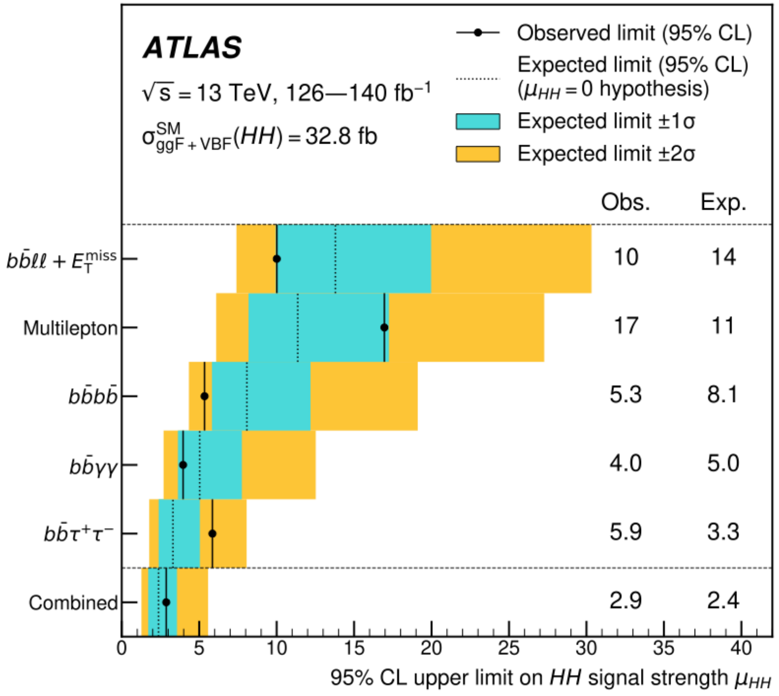
❖ **No channel driving the sensitivity, we need all to achieve this expected limit**

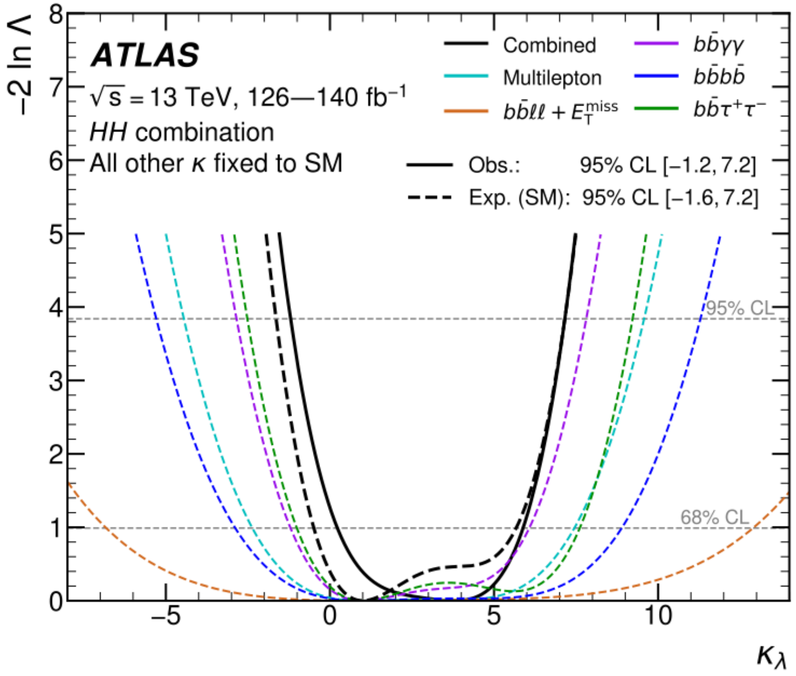
HH Combination

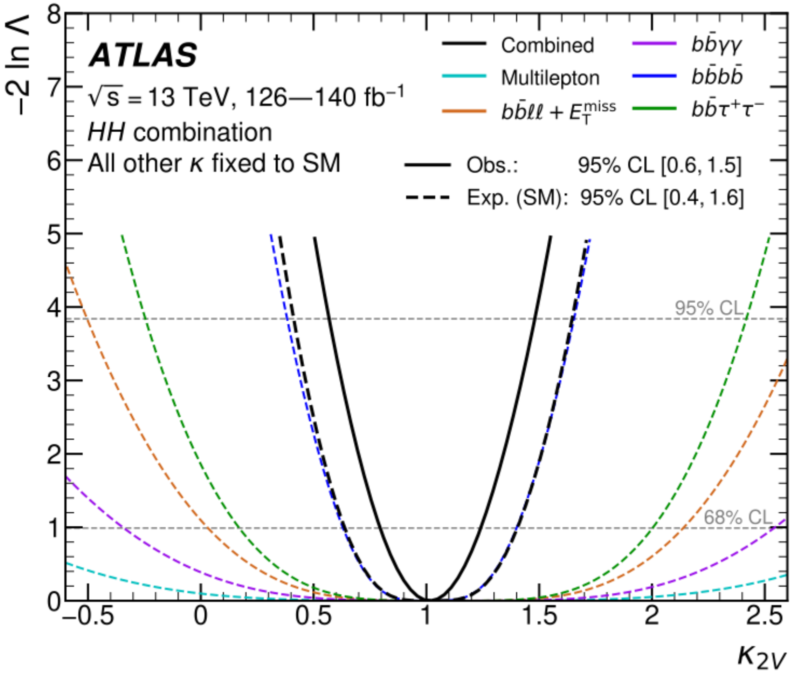
Phys. Rev. Lett. 133 (2024) 101801

❖ Combining:

➢ $HH \rightarrow b\bar{b}\gamma\gamma, HH \rightarrow b\bar{b}\tau^+\tau^-, HH \rightarrow b\bar{b}b\bar{b}, HH \rightarrow 2b + 2\ell + E_T^{miss}, HH \rightarrow Multilepton$







❖ At 95% confidence level:

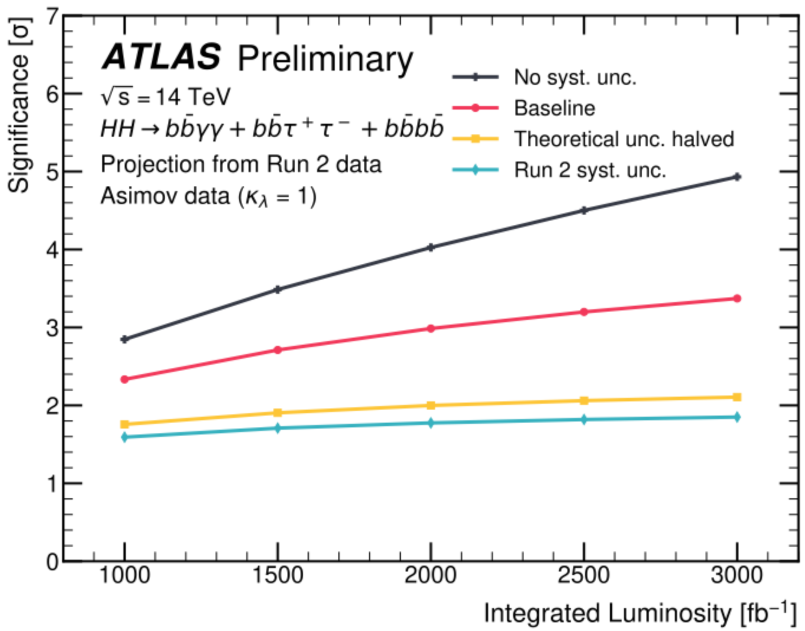
➢ $\mu_{HH} < 2.9$ (2.4 expected assuming no HH)

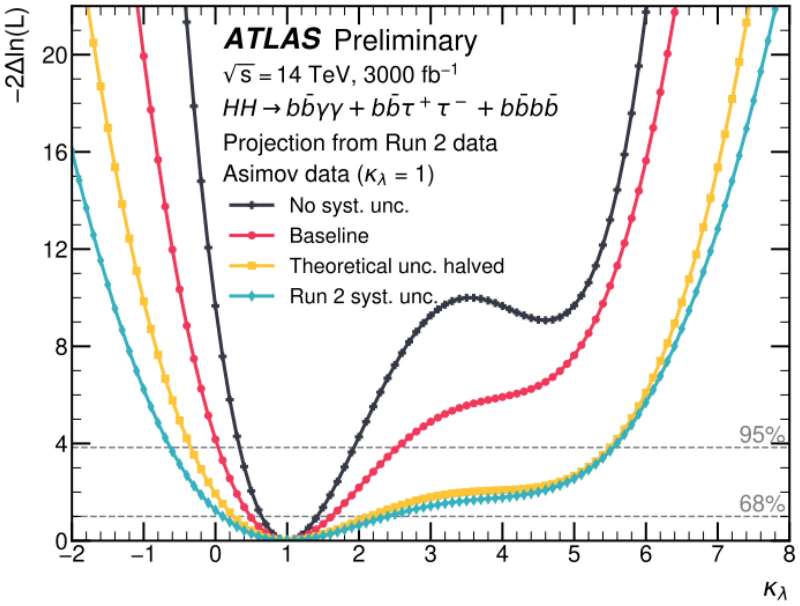
➢ Observed: $-1.2 < \kappa_\lambda < 7.2$ Expected: $-1.6 < \kappa_\lambda < 7.2$

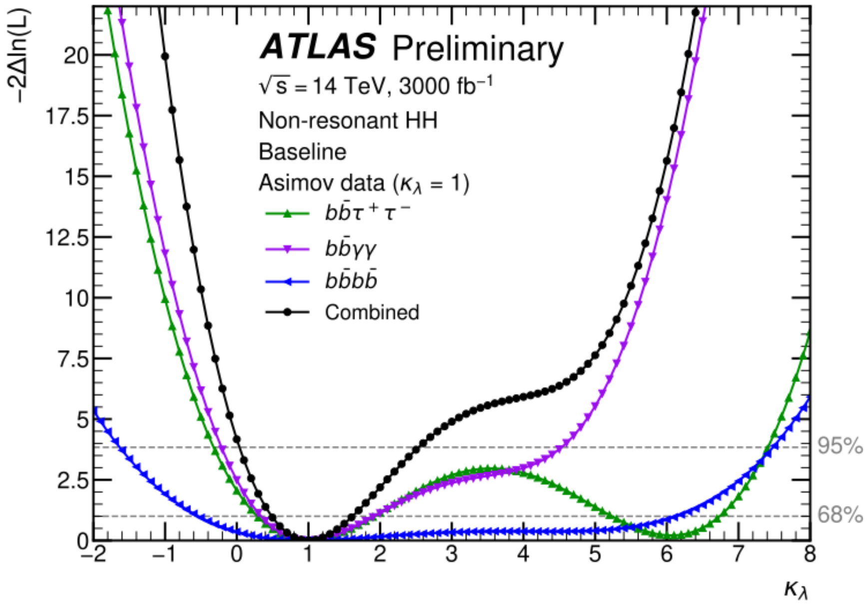
➢ Observed: $0.6 < \kappa_{2V} < 1.5$ Expected: $0.4 < \kappa_{2V} < 1.6$

HL-LHC projection:

- **HL-LHC: $\sqrt{s} = 13\ \text{TeV} \rightarrow 14\ \text{TeV}, \mathcal{L} = 140\ fb^{-1} \rightarrow 3000\ fb^{-1}$** **Will Start in 2030**
- **$HH \rightarrow b\bar{b}\gamma\gamma, HH \rightarrow b\bar{b}\tau^{+}\tau^{-}, HH \rightarrow b\bar{b}b\bar{b}$ based on previous round of full Run 2 analysis**
- **Baseline assuming 2 times reduction in theory modelling uncertainty and 2 times better b-tagging**



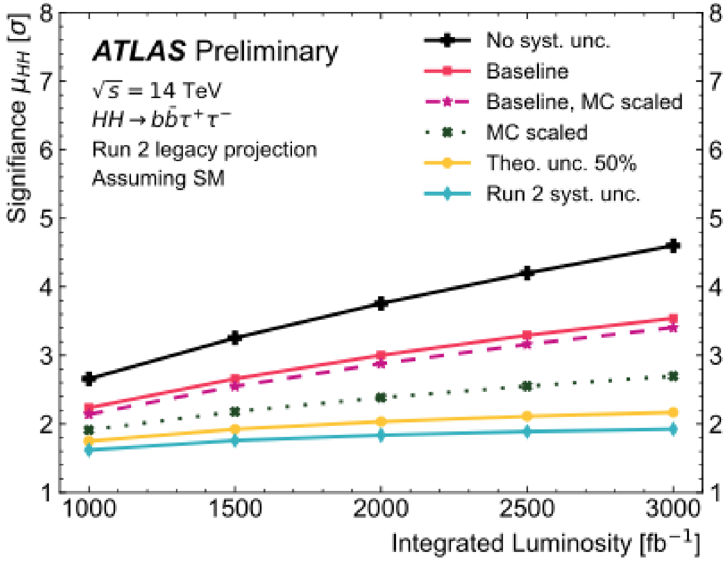


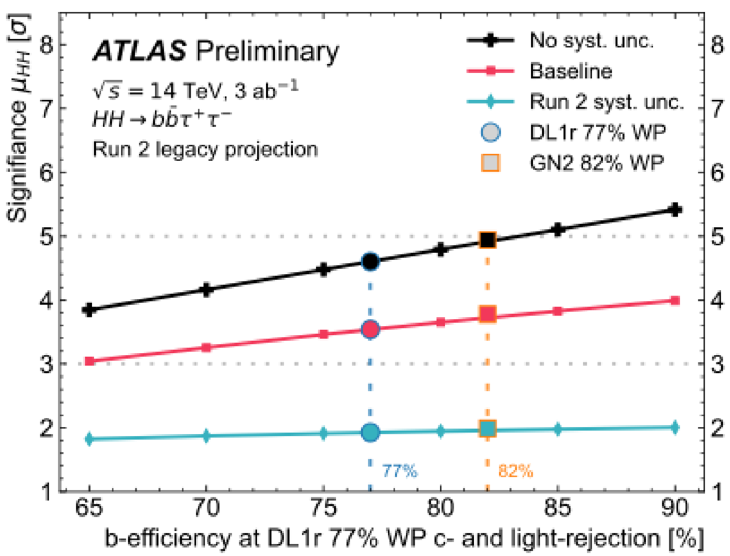


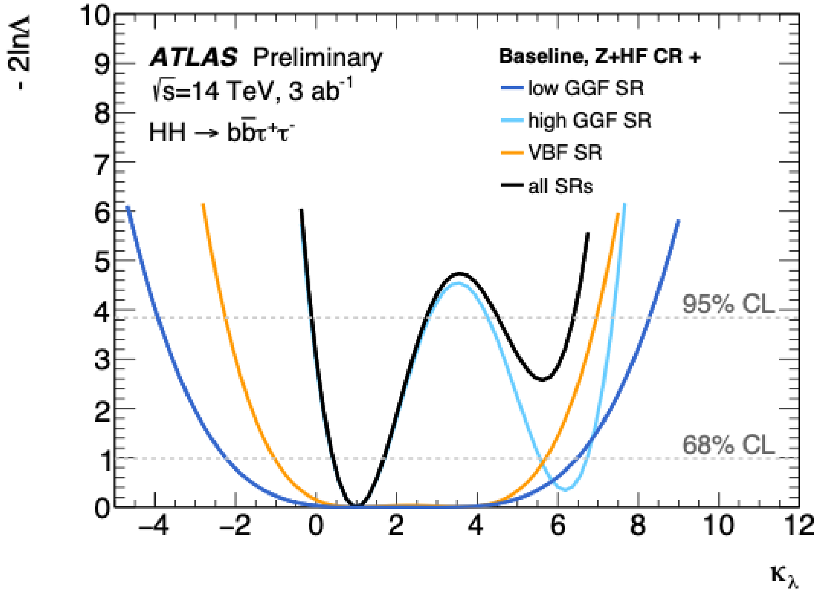
- **HH discovery significance 3.4σ**
- **95% confidence interval for κ_λ expected to be [0.0, 2.5]**

HL-LHC: $b\bar{b}\tau^+\tau^-$ update

- ❖ HL-LHC: $\sqrt{s} = 13$ TeV → 14 TeV, $\mathcal{L} = 140\ fb^{-1}$ → 3000 fb^{-1} **Will Start in 2030**
- ❖ Latest update base on Run 2 Legacy analysis (Latest, shown today) Phys. Rev. D 110 (2024) 032012







- ❖ Assuming SM HH production, a signal significance of 3.5σ (4.6σ) is expected in the baseline (statistical only)
- ❖ Improvements in b-tagging developed for Run 3 are expected to further increase the signal significance to 3.8σ (4.9σ statistical only)
- ❖ $\kappa_\lambda \in [-0.1, 2.7] \cup [4.5, 6.4]$ at 95% confidence level constraints ([0.2, 2.1] without systematic uncertainties)

Summary

- **HH events provides unique experimental reconstruction of Higgs Potential**
- **HH events are rare process**
- **Constraints on HH cross-section:**
  - $\mu_{HH} < 2.9$ Observed (2.4 Expected)
- **Constraints on Higgs self-coupling:**
  - Observed: $-1.2 < \kappa_\lambda < 7.2$ Expected: $-1.6 < \kappa_\lambda < 7.2$
- **Constraints on HHVV coupling:**
  - Observed: $0.6 < \kappa_{2V} < 1.5$ Expected: $0.4 < \kappa_{2V} < 1.6$
- **ATLAS has the best expected sensitivity on $\boldsymbol{\kappa_\lambda}$**
- **HL-LHC will help us for further constraint on HH**