Constraints on Higgs self-coupling at the LHC with $\sqrt{s} = 13$ TeV

Yulei Zhang[1], Gregorio Bernardi[2], Liang Li[1]

[1] Shanghai Jiao Tong University

[2] APC, Université Paris Cité

Nov 7th , 2023

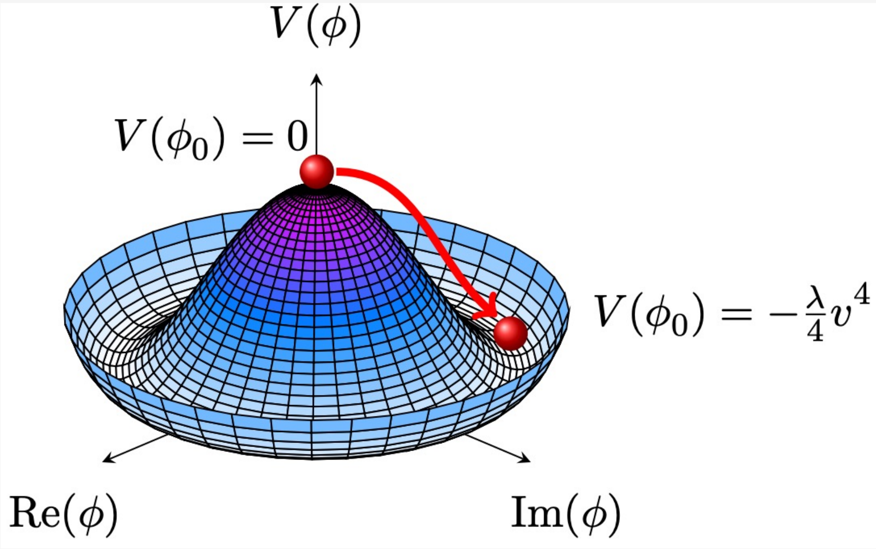
The Higgs Mechanism

- Higgs boson (H): prediction of Brout-Englert-Higgs mechanism (1964, Nobel 2013) of electroweak symmetry breaking for mass generation of SM particles.
- Discovered in 2012 the $H \to \gamma\gamma$ channel *[ATLAS: 1207.7214, CMS:1207.7235]*
- Present data compatible with **a scalar particle with spin 0 and even parity** (as predicted by the SM) of mass $m_H \approx 125\ \mathrm{GeV/c^2}$
- Coupling to fermions, EW gauge bosons, and Higgs itself.

$$V_H = \mu^2 + \frac{\mu^2}{v}H^3 + \frac{\mu^2}{4v}H^4 - \frac{1}{4}\mu^2 v^2$$
$$= \frac{1}{2}m_H^2 + \lambda_{HHH} v H^3 + \lambda_{HHHH} H^4 - \frac{1}{8}m_H^2 v^2$$

$$\lambda_{HHH} = 4\lambda_{HHHH} = \frac{m_H^2}{v^2}$$

only parameter regulating field's shape
+
predicted by the SM once m_H is measured

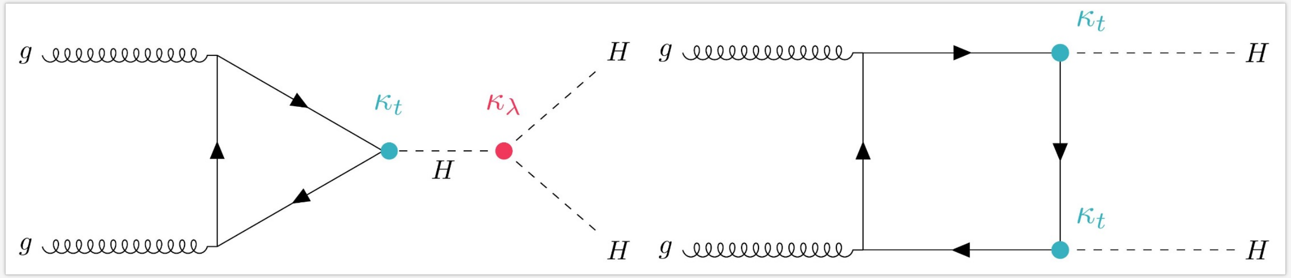


Refer to Jona's Talk

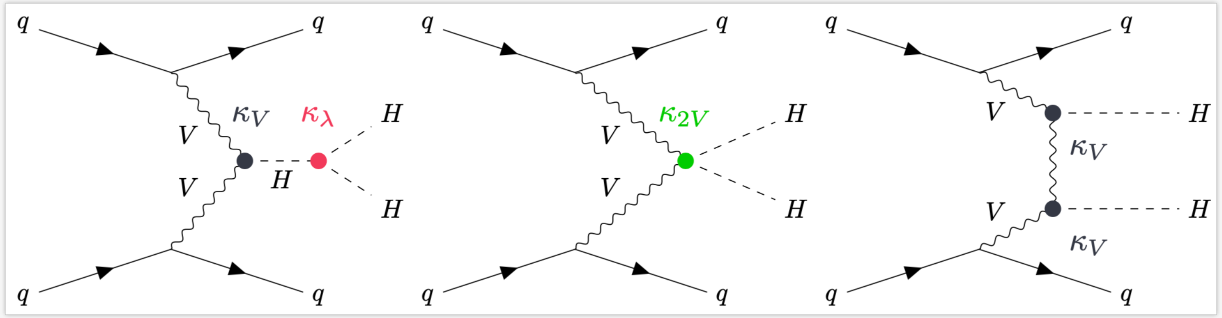
Higgs Self-Coupling

- Higgs boson discovered 10 years ago (**no deviations from SM observed so far)**
- Higgs can couple to Higgs itself (λ_{HHH}, λ_{HHHH}). (The only particle in SM with self-coupling)
- λ_{HHH} is **not a free parameter** → closure test of SM
- λ_{HHH} is **the only parameter** regulating **Higgs potential shape** → EWSB and vacuum stability test
- Deviation of λ_{HHH} from SM can allow *first order EW transition* → 3rd Sakharov condition for matter-antimatter asymmetry
- *Measuring λ_{HHH} through di-Higgs production is the focus of research interest.*

Non-resonant HH Production



Gluon-gluon Fusion (ggF): $\sigma_{HH}^{SM} = \mathbf{31.05} \pm 3\%\ (\mathrm{PDF} + \alpha_s)^{+6\%}_{-23\%}\ (\mathrm{Scale} + m_{\mathrm{top}})$ fb



Vector Boson Fusion (VBF): $\sigma_{HH}^{SM} = \mathbf{1.726} \pm 2.1\%\ (\mathrm{PDF} + \alpha_s)^{+0.03\%}_{-0.04\%}\ (\mathrm{Scale})$ fb

- The coupling modifier κ is used for **measuring deviation from SM**, where $\kappa_\lambda = \lambda_{HHH}/\lambda_{HHH}^{SM}$
- Test BSM effective models with anomalous couplings: κ_λ, κ_t, κ_V, and κ_{2V}

Direct HH Searches (ATLAS)

bbbb
γγbb
bbττ
bbℓℓ
bbVV
multi-
lepton

Ideally, we would like to investigate ***all the possible decay modes of HH*** *but given the current luminosity and the harsh experimental conditions, to achieve good sensitivity, we need:*

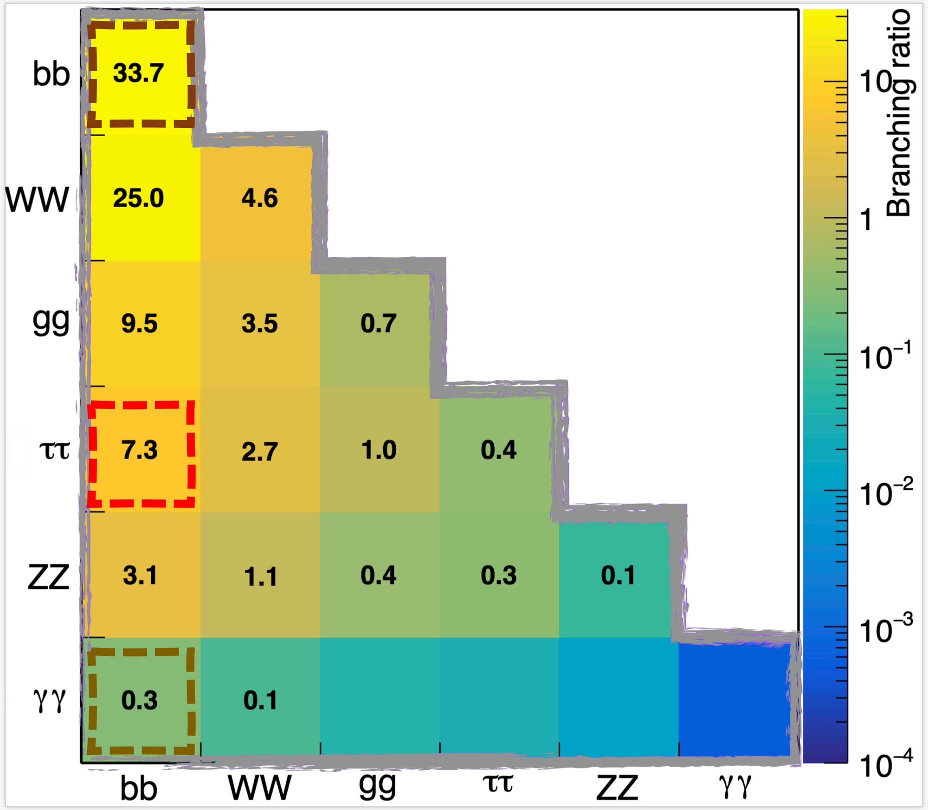
- 😄 Either large branching ratio
- 😄 Or very good selection purity
- 😍 Having both would be the best option

- Historic three HH channels: $bbbb$, $bb\gamma\gamma$, $\boldsymbol{bb\tau\tau}$ **New result**

Thanks to continuously advancing reconstruction techniques and identification algorithms, we are gradually escaping these two constraints to include:

- Other HH channels: $bbVV(0/1\ell)$, $bb\ell\ell$, and **multilepton**

First result



Refer to Jona's Talk

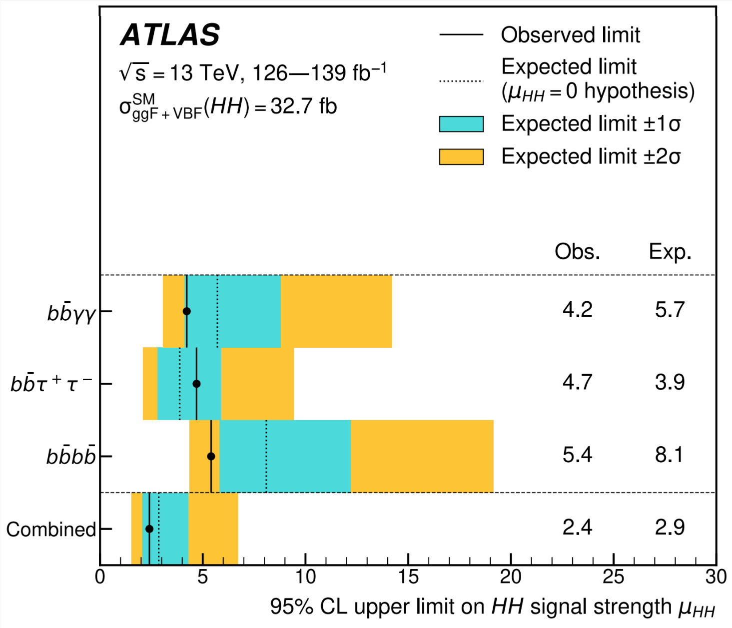
Latest ATLAS Combination Results

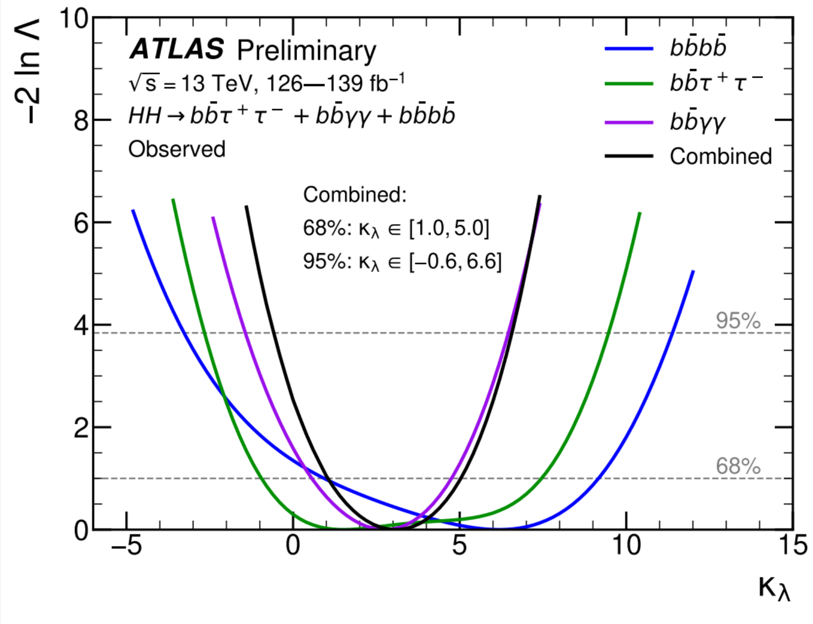
Phys. Lett. B 843 (2023) 137745

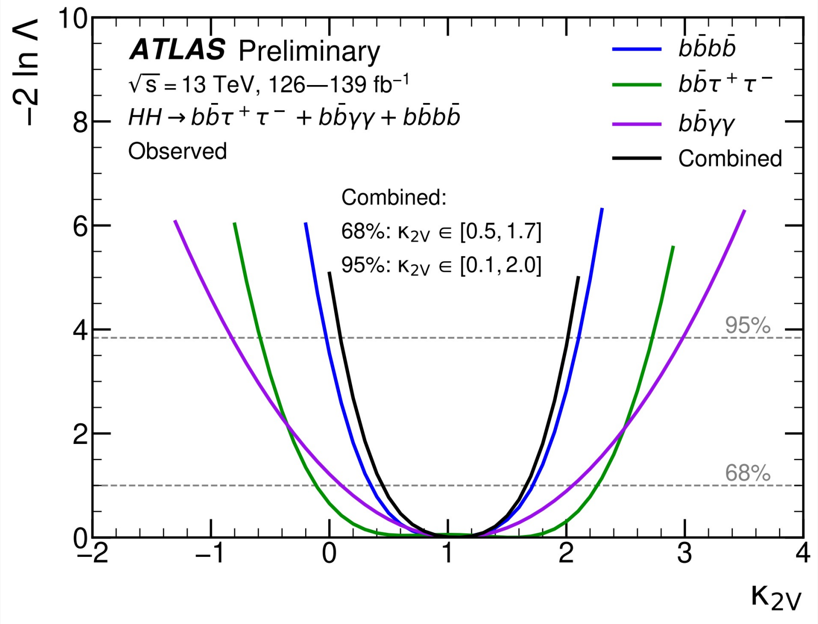
Combination - HH

- Combine $b\bar{b}b\bar{b}$ (Phys. Rev. D 108, 052003), $b\bar{b}\tau\tau$ (JHEP 07 (2023) 040) and $b\bar{b}\gamma\gamma$ (Phys. Rev. D, 106 (2022), 052001)
- Observed (expected) 95% CL upper limit on μ_{HH}: 2.4 (2.9)
- 95% CL on $\kappa_\lambda \in [-0.6, 6.6]$ $([-2.1, 7.8])$
- 95% CL on $\kappa_{2V} \in [0.1, 2.0]$ $([0.0, 2.1])$

Phys. Lett. B 843 (2023) 137745

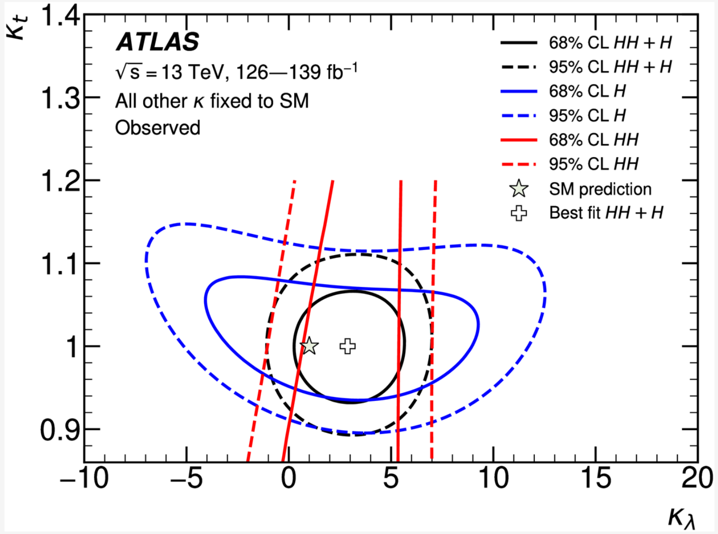


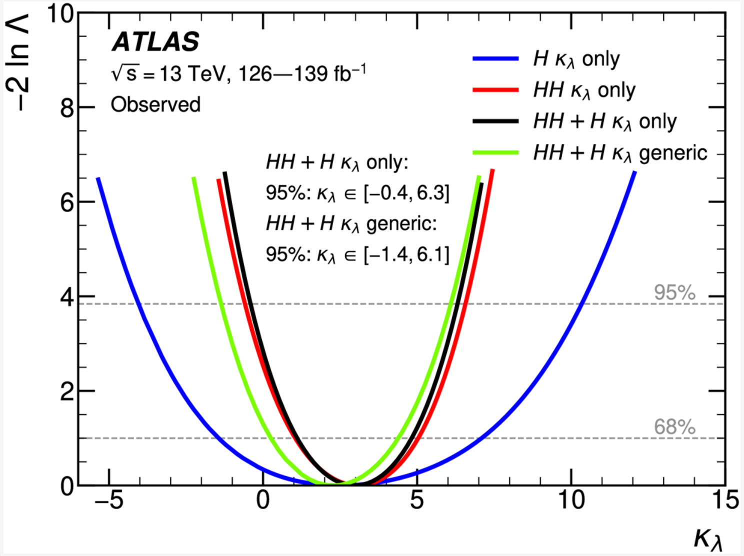




Combination – HH+H

- Single Higgs production does not depend on κ_λ at LO, but it contributes to the calculation @NLO(EW)
  - an indirect constraint on can be extracted.
- Two scenarios considered:
  - **κ_λ only**: Fit with κ_λ floating and all other coupling modifiers fixed to unity.
  - **κ_λ generic**: Fit with all coupling modifiers floating except for κ_{2V} fixed to unity (no available parameterization of single-Higgs NLO EW correction as a function of κ_{2V})
- κ_λ only: $[-0.4, 6.3]$ $([-1.9, 7.6])$
- κ_λ generic: $[-1.4, 6.1]$ $([-2.2, 7.7])$





Phys. Lett. B 843 (2023) 137745

Direct HH Searches: Sub-channels

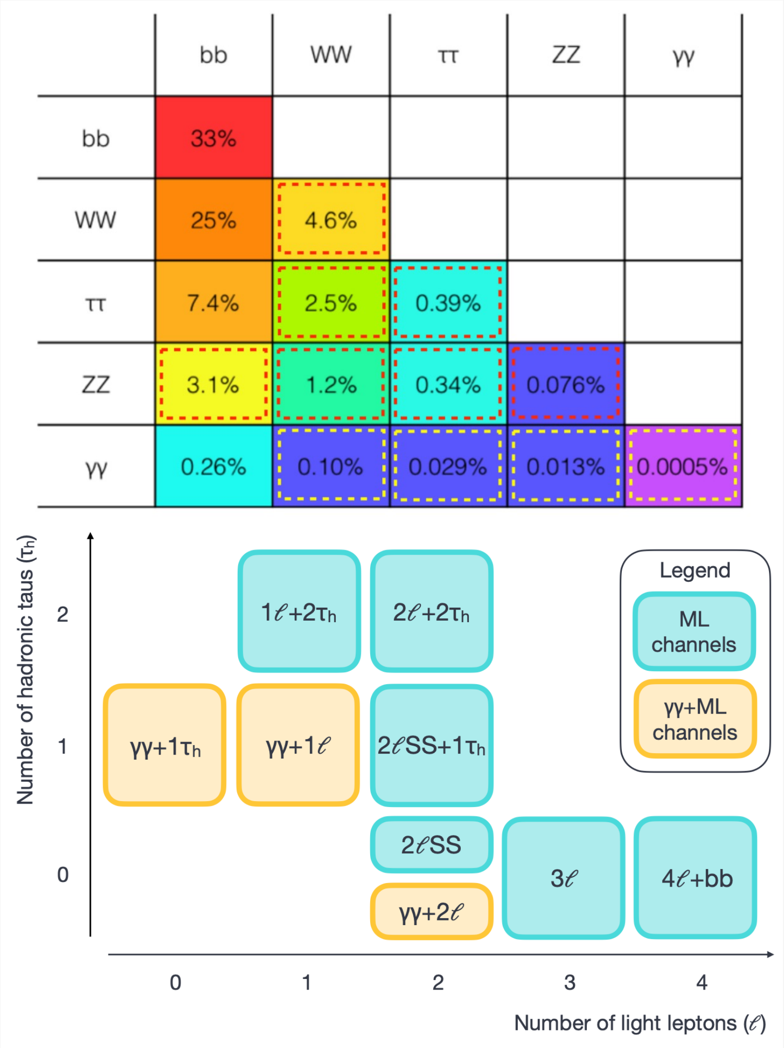
- HH $\rightarrow$ multilepton
- HH $\rightarrow b\bar{b}\tau^{+}\tau^{-}$
- HH $\rightarrow b\bar{b} + WW/ZZ/\tau\tau \rightarrow b\bar{b}\ell\bar{\ell} + \mathrm{MET}$
- HH $\rightarrow b\bar{b}\gamma\gamma$

NEW: multilepton decay channel

- Several HH decay modes with small branching ratios are included: $VVVV, VV\gamma\gamma, VV\tau\tau, \tau\tau\tau\tau, bbZZ \approx 12\,\%$
- Many of these are not covered by dedicated analyses.
- Use *a common analysis strategy* for the same final states
- Categorize final states by number of e, μ, τ_h, named by $\boldsymbol{\gamma\gamma + ML}$ **channel** (3) and **Multilepton channel** (6), **9 orthogonal channels in total**

- Two same-sign light leptons w/wo τ_h: $2\ell SS0\tau_h$ and $2\ell SS + 1\tau_h$
- Three light leptons: 3ℓ
- One/Two light leptons and two τ_h: $1/2\ell + 2\tau$
- 4 light leptons originated from $H \to ZZ$ and 2 b-jet: $b\bar{b}4\ell$

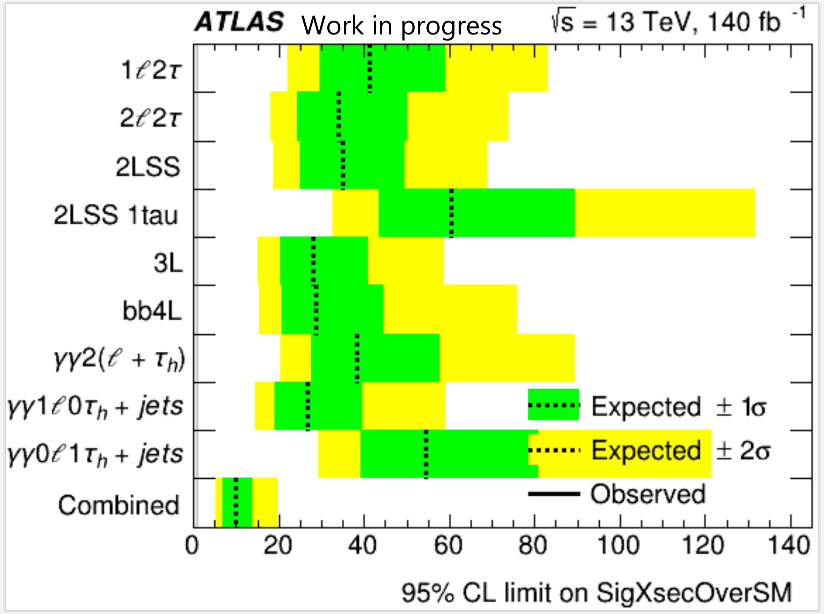
- Two photons with light leptons and τ_h: $\gamma\gamma + 1\ell0\tau, \gamma\gamma + 0\ell1\tau, \gamma\gamma + 2\ell$



FIRST Result for multilepton

Channels	Stats. Only	Stats.+ full syst.
$2\ell SS$	31.62	34.81
3ℓ	25.58	28.13
$bb4\ell$	27.62	28.71
$1\ell + 2\tau_h$	38.31	41.21
$2\ell + 2\tau_h$	33.46	33.99
$2\ell SS + 1\tau_h$	59.00	60.55
$\gamma\gamma + 1\ell 0\tau_h$	25.43	26.68
$\gamma\gamma + 0\ell 1\tau_h$	52.50	54.50
$\gamma\gamma + 2\ell$	37.05	38.21
Combined	**9.25**	**9.74**

ATLAS Glance [link]



- 95% C.L. combined expected upper limit reaches $9.74^{+13.91}_{-7.02}$ (full systematics) on the HH cross-section over SM for $HH \rightarrow$ multilepton final states with the full RUN2 data with 140^{-1} fb luminosity.
- *Machine learning techniques are introduced in multilepton for the first time, achieved an order of magnitude increasement in expected sensitivity.*
- κ_λ and κ_{2V} scan is ongoing. (Samples are ready)

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

Previous Run 2 analysis: JHEP 07 (2023) 040

ATLAS Glance for this study [link]

3 channels per di-τ decays

Optimize trigger strategy

$\otimes$

3 signal regions per production mode and m_{HH} split

Improve κ_{2V} constraint

$\oplus$

1 control region

Improve bkg modelling

LepHad

HadHad

$\tau_{\mathrm{had}}\tau_{\mathrm{had}}$ | $\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$ SLT | $\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$ LTT

$\otimes$

ggF $m_{HH} < 350$ GeV | ggF $m_{HH} \geq 350$ GeV | VBF

Dedicated MVA study with hyper-param and input var optimization

$\oplus$

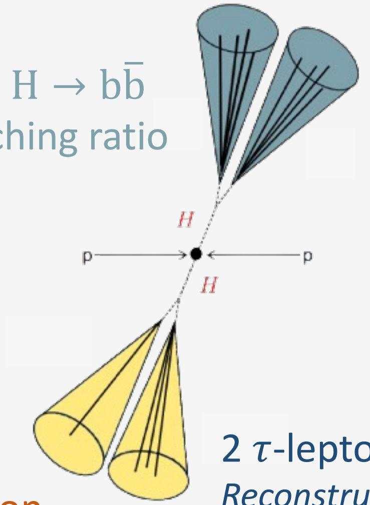
$m_{\ell\ell}$ CR

Sizeable Br = 7.3%

2 b-jets

77% efficiency per jet

Large $\mathrm{H} \rightarrow \mathrm{b}\bar{\mathrm{b}}$ branching ratio

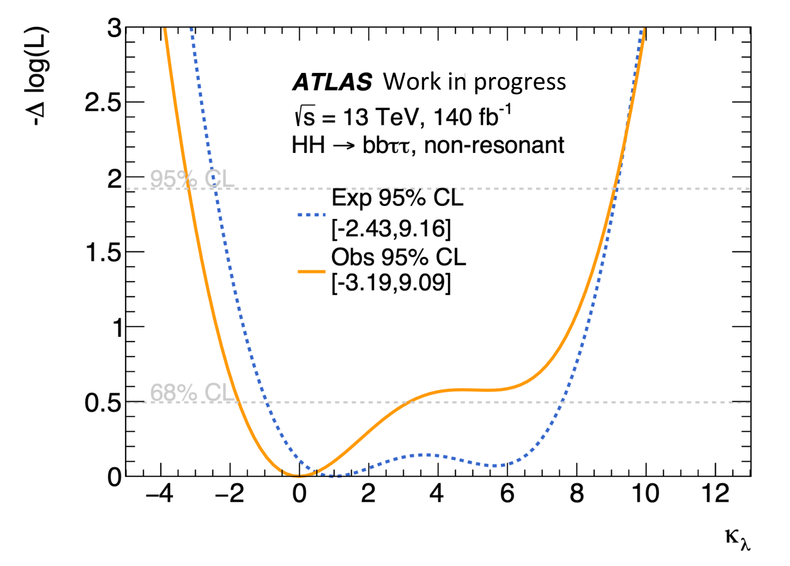


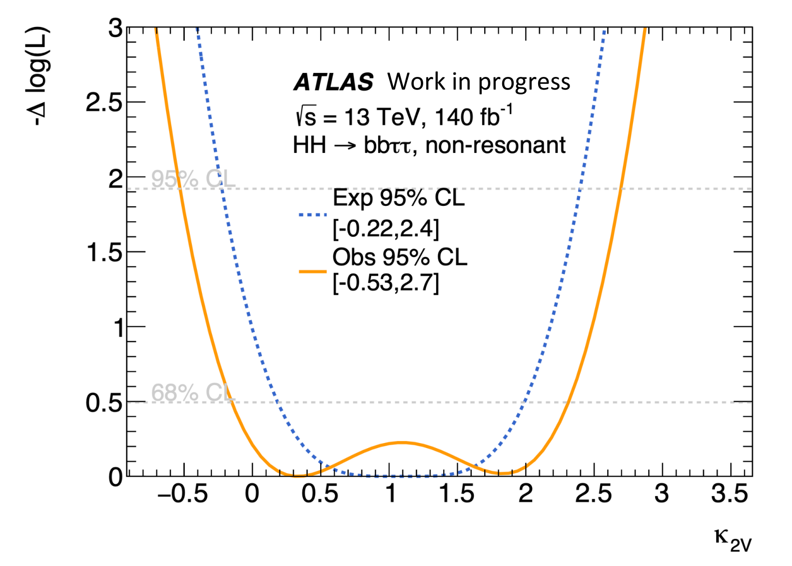
2 τ-leptons

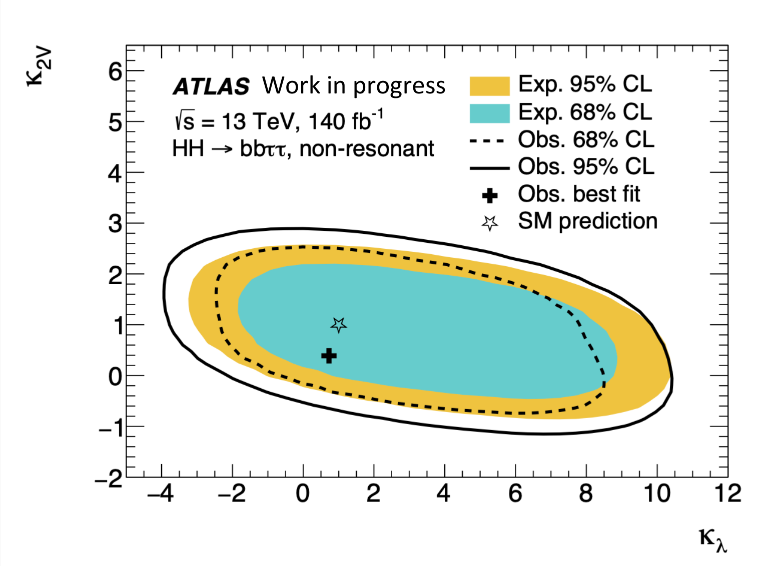
Reconstruct hadronic and leptonic decay

Multi-jet rejection from di-τ

κ likelihood scan







95% CI	κ_λ
Obs	[- 3.2, 9.1]
exp	[- 2.4, 9.2]

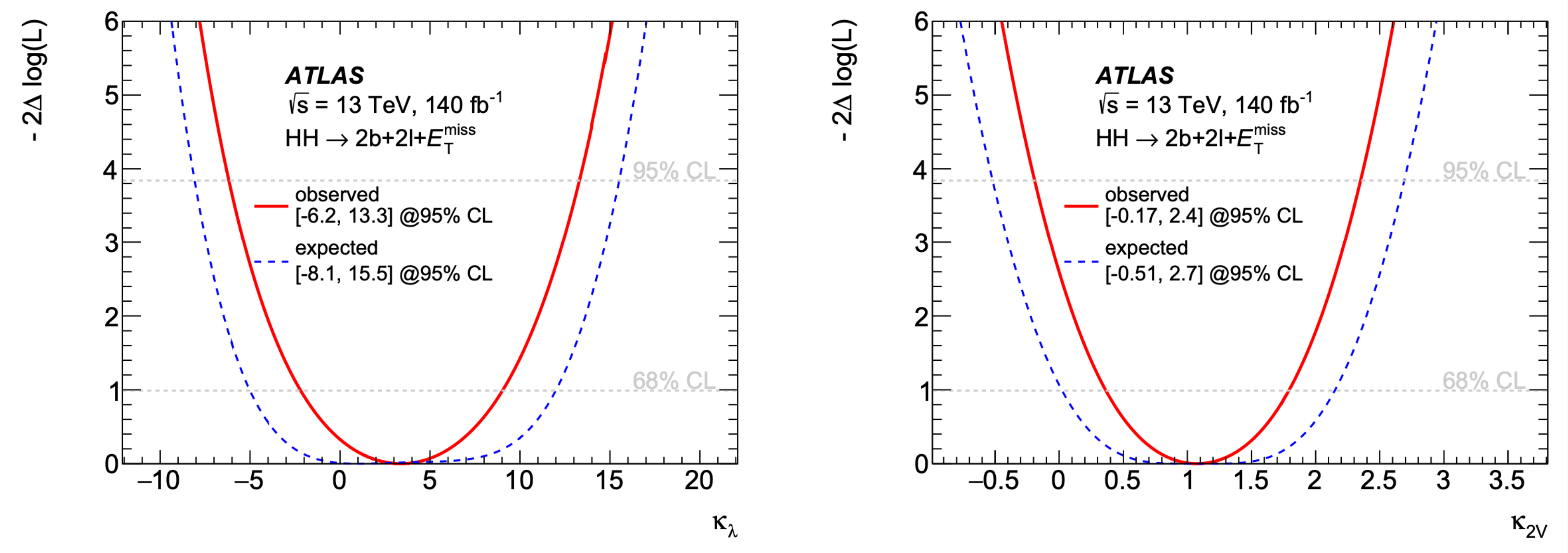
95% CI	κ_{2V}
Obs	[- 0.53, 2.7]
exp	[- 0.22, 2.4]

95% CI	κ_λ	κ_{2V}
Obs	0.73	0.39

NEW: $\mathrm{HH} \to b\bar{b} + WW/ZZ/\tau\tau \to b\bar{b}\ell\bar{\ell} + \mathrm{MET}$

- Dominant background from top quark processes and Z+HF – estimated from simulation
- MVA used to separate signal and background events and set limits
- Observed (expected) upper limit on
  - μ_{HH}: 9.6 (16.2)
  - $\kappa_\lambda \in [-6.2, 13.3]([-8.1, 15.5])$
  - $\kappa_{2V} \in [-0.2, 2.4]([-0.5, 2.7])$

arXiv:2310.11286

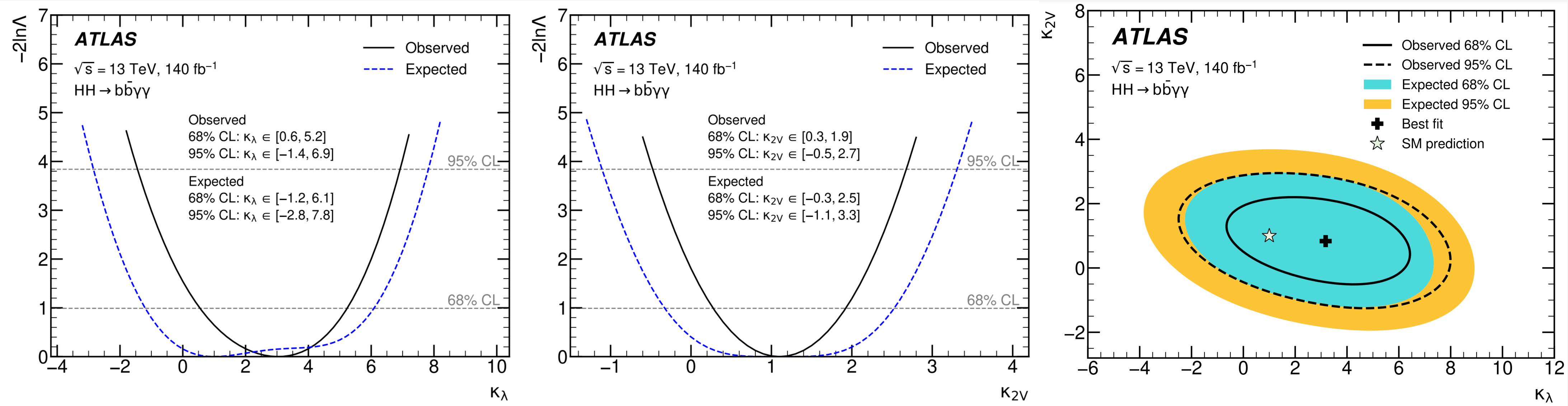


NEW: HH → $b\bar{b}\gamma\gamma$

More details in Qiuping's Talk [link]

- Tiny BR (≈ 0.3%), with very good purity
- Reoptimized analysis to probe anomalous values of the κ_λ and the κ_{2V}
- Observed (expected) upper limit on
  - μ_{HH}: 4.0 (5.0)
  - $\kappa_\lambda \in [-1.4, 6.9]([-2.8, 7.8])$
  - $\kappa_{2V} \in [-0.5, 2.7]([-1.1, 3.3])$

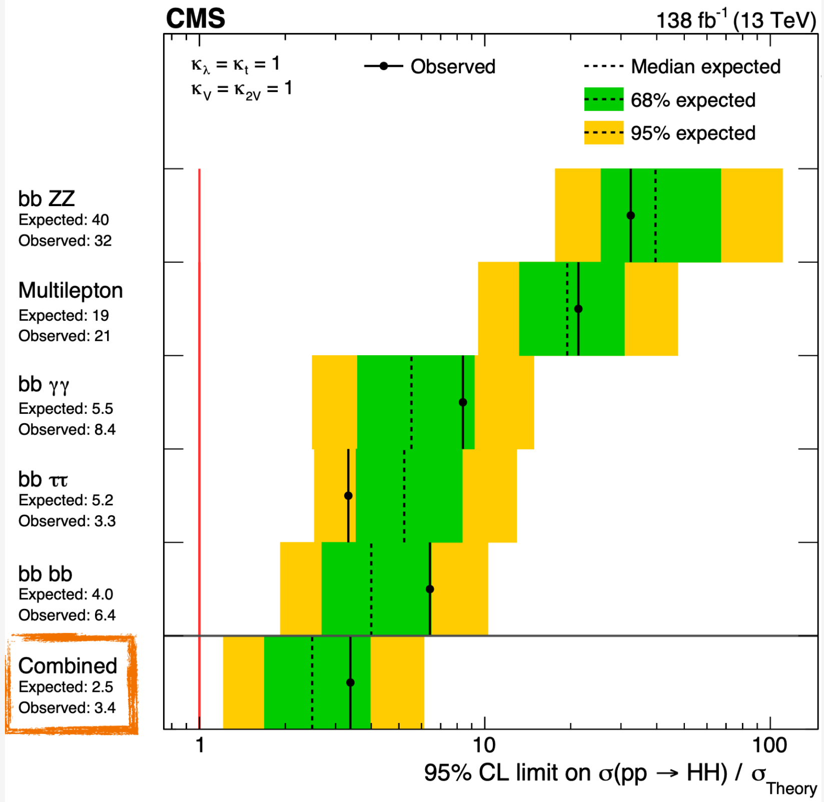
arXiv:2310.12301



HH results from CMS

$\mathbf{HH \to bbbb}$ *	Non-resonant, resolved topology Phys. Rev. Lett. 129.081802
	Non-resonant, boosted topology Phys. Rev. Lett. 131.041803
	Non-resonant, VHH production CMS-PAS-HIG-22-006
	Resonant $X \to YH$ Phys. Lett. B 842.137392
$\mathbf{HH \to bb\tau\tau}$ *	Non-resonant Phys. Lett. B 842.137531
	Resonant $X \to YH$ JHEP 11 (2021) 057
$\mathbf{HH \to bb\gamma\gamma}$ *	Non-resonant JHEP 03 (2021) 257
	Resonant $X \to YH$ CMS-PAS-HIG-21-011
$\mathbf{HH \to bbZZ}$ *	Non-resonant JHEP 06 (2023) 130
	Resonant Phys. Rev. D. 102.032003
$\mathbf{HH \to bbWW}$	Non-resonant + Resonant CMS-PAS-HIG-21-005
	Resonant JHEP 05 (2022) 005
$\mathbf{HH \to WW\gamma\gamma}$	Non-resonant CMS-PAS-HIG-21-014
$\mathbf{HH \to WWWW + WW\tau\tau + \tau\tau\tau\tau}$ *	Non-resonant + Resonant JHEP 07 (2023) 095
HH combination	Nature 607 (2022) 60 (uses only starred * final states)

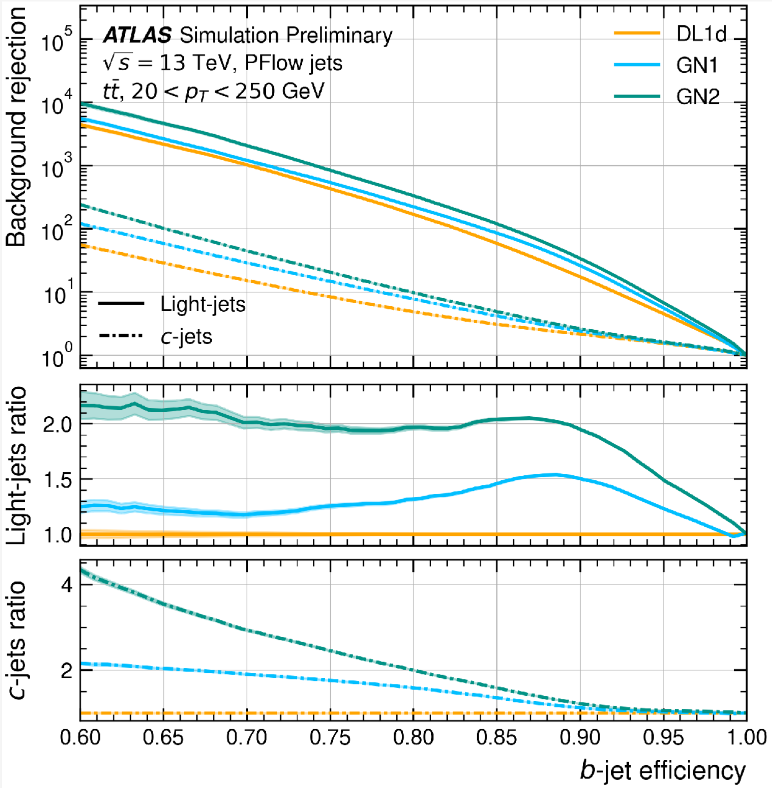
- Observed (expected) 95% CL upper limit on μ_{HH}: 3.4 (2.5)
- $\kappa_\lambda \in [-1.24, 6.49]$
- $\kappa_{2V} \in [-0.67, 1.38]$



Refer to Jona's Talk

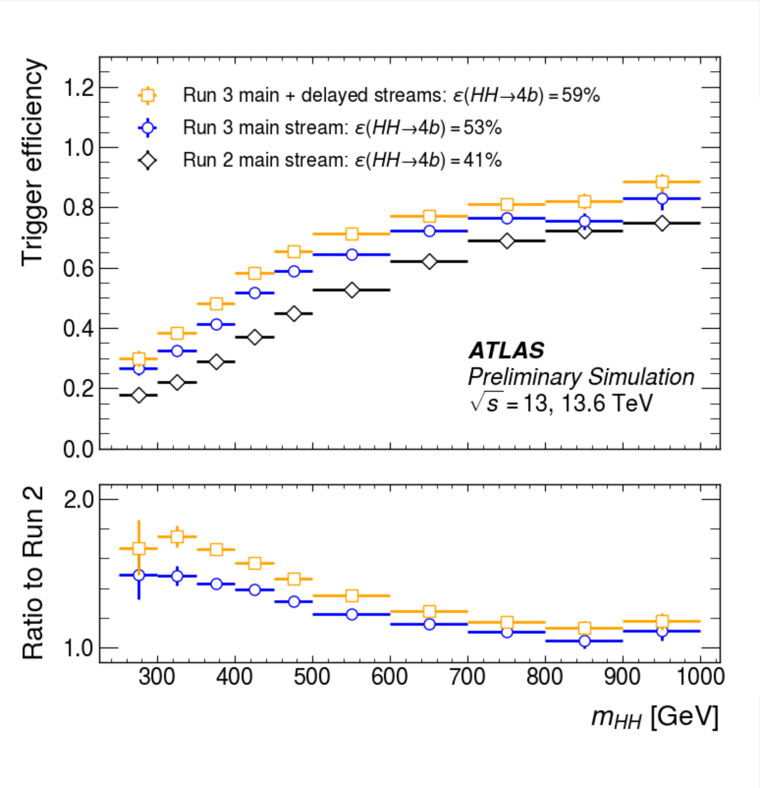
Outlook: LHC Run 3

Better b-tagging

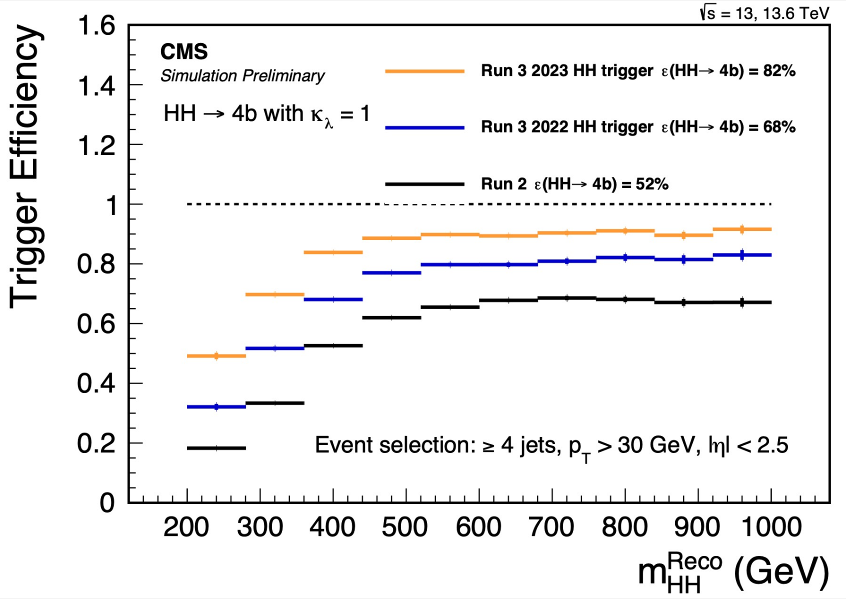


FTAG-2023-01

Better triggering



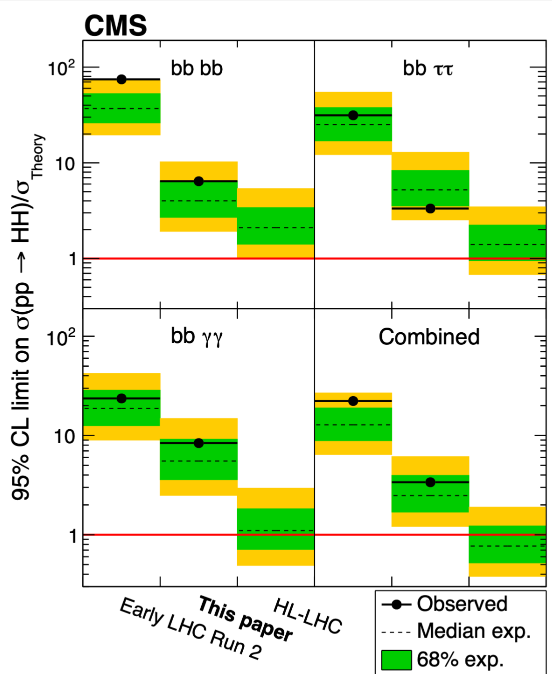
b-jet trigger Public results



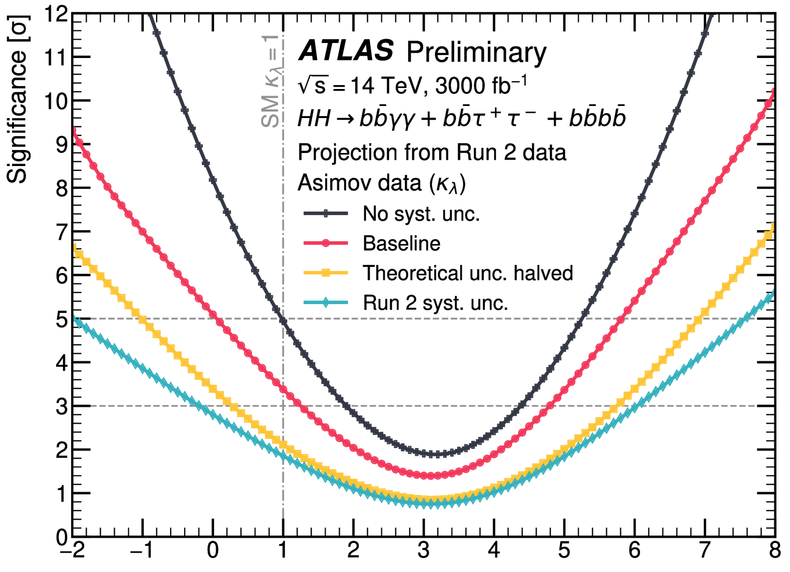
CERN-CMS-DP-2023-050

Conclusion

- Probing λ_{HHH} is one of the main goals we have for the coming years
- Full Run 2 analyses shown an impressive result for observed(expected) constraints in terms of the coupling modifier κ_λ (only):
  - **ATLAS:** $[-0.6, 6.6]$ ($[-2.1, 7.8]$)
  - **CMS:** $[-1.24, 6.49]$ ($[-1.23, 7.2]$)
- Important trigger and b-jet ID improvements have already been introduced for HH searches in Run-3
- Run-3 serves as a crucial proving ground for innovative concepts that will be implemented in the HL-LHC phase.



Nature 607 (2022) 60



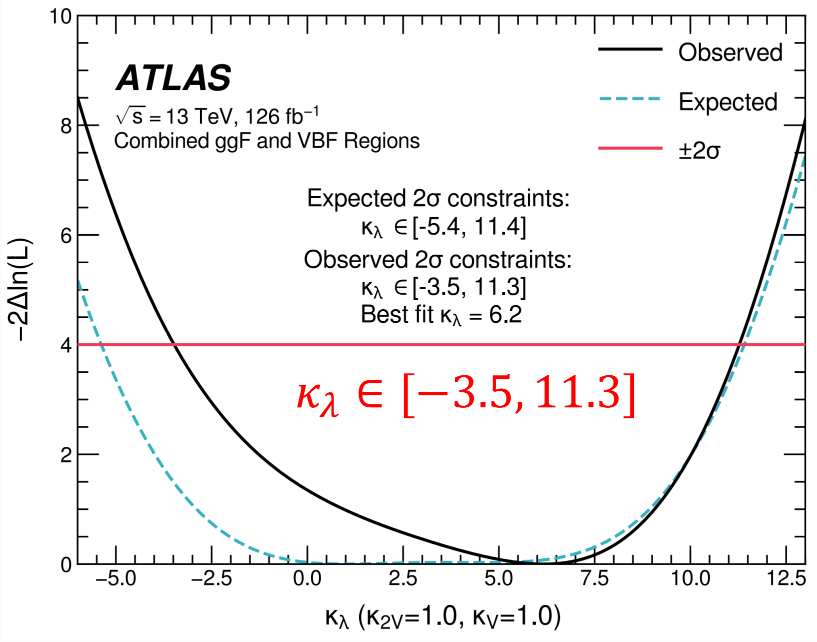
HDBS Public Results

Thank you!

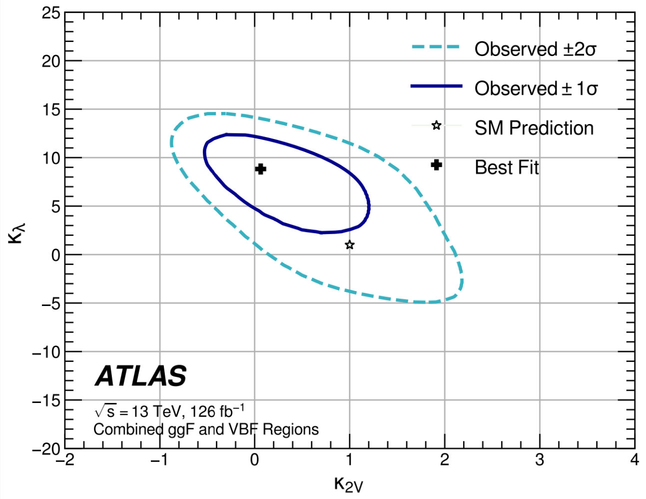
Backup

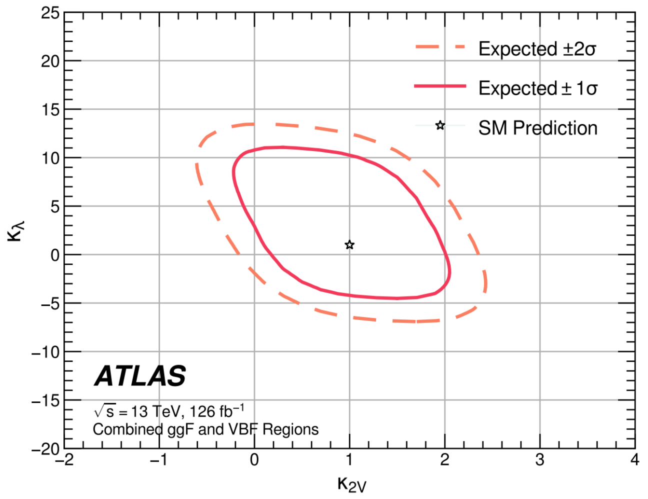
HH → $b\bar{b}b\bar{b}$

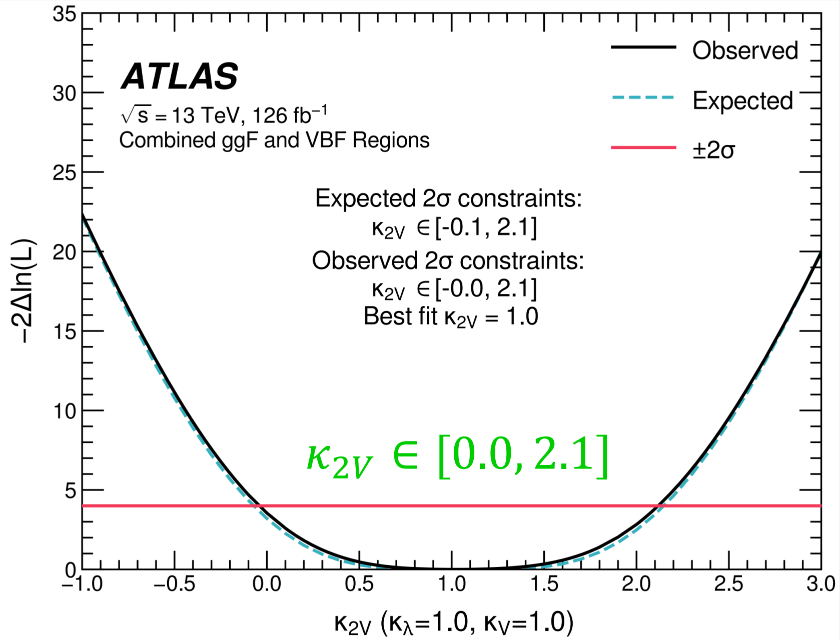
- Highest BR (≈ 34%), but also large background
  - 4 central jets fulfilling b-jet tagging (DL1r)
  - b-jets used in trigger as well (MV2c10)
  - To separate VBF production - 2 forward jets
- Background estimation - 90% of the background events come from multi-jet processes

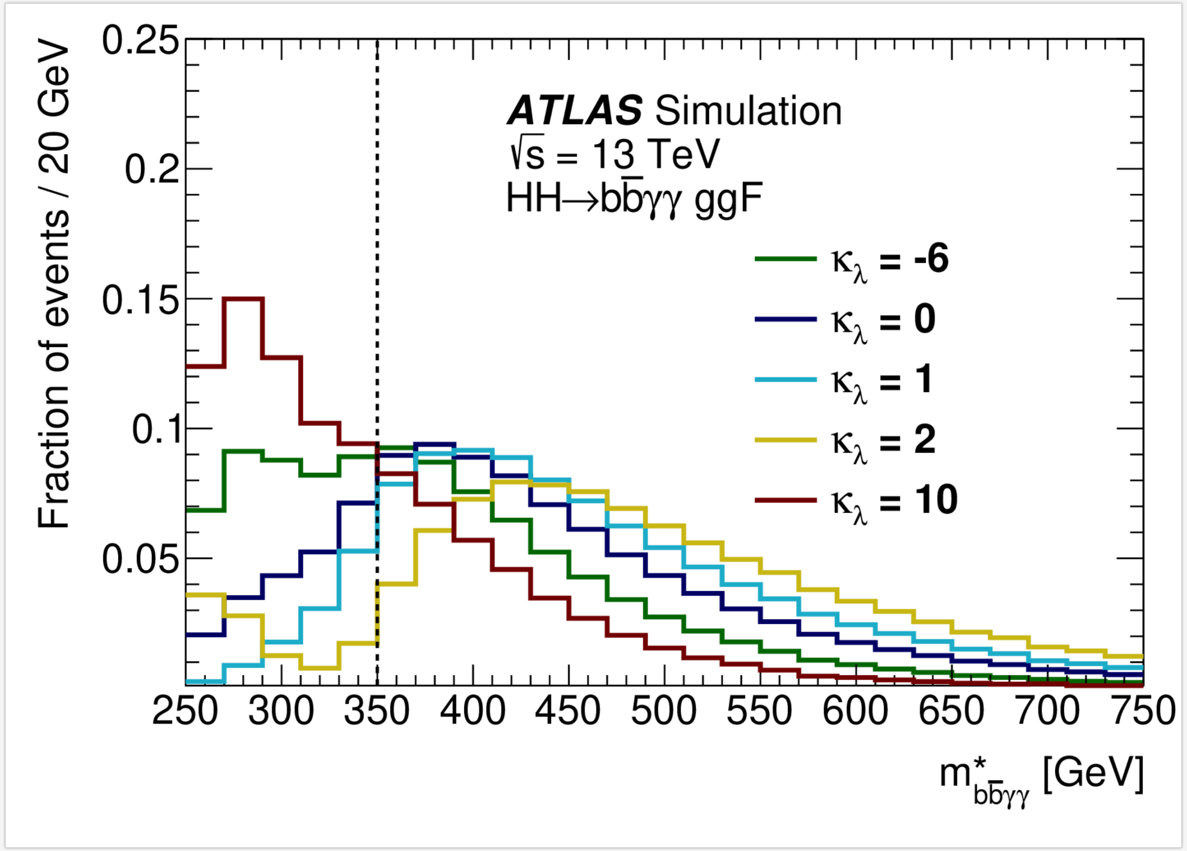


Phys. Rev. D **108**, 052003

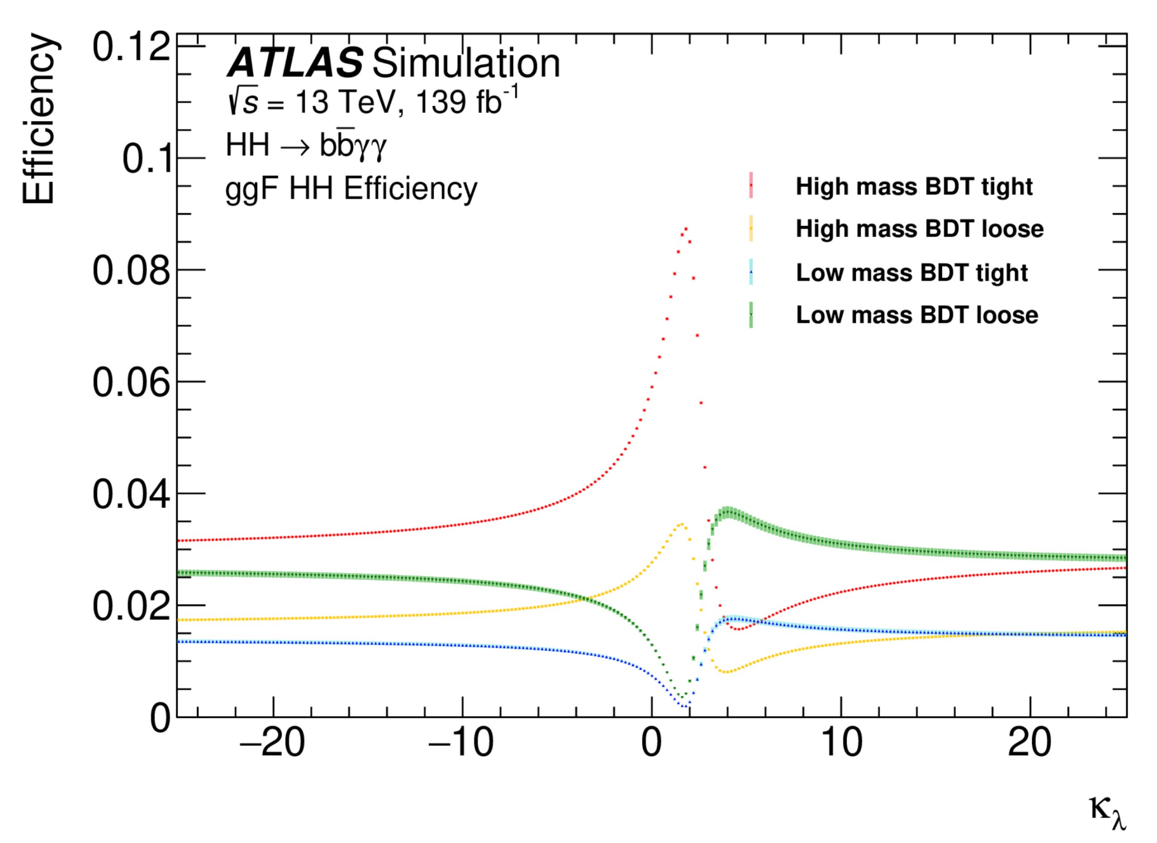








ATLAS Simulation
√s = 13 TeV
HH→bb̄γγ ggF
κλ = -6
κλ = 0
κλ = 1
κλ = 2
κλ = 10
Fraction of events / 20 GeV
m*bb̄γγ [GeV]



ATLAS Simulation
√s = 13 TeV, 139 fb-1
HH → bb̄γγ
ggF HH Efficiency
High mass BDT tight
High mass BDT loose
Low mass BDT tight
Low mass BDT loose
Efficiency
κλ

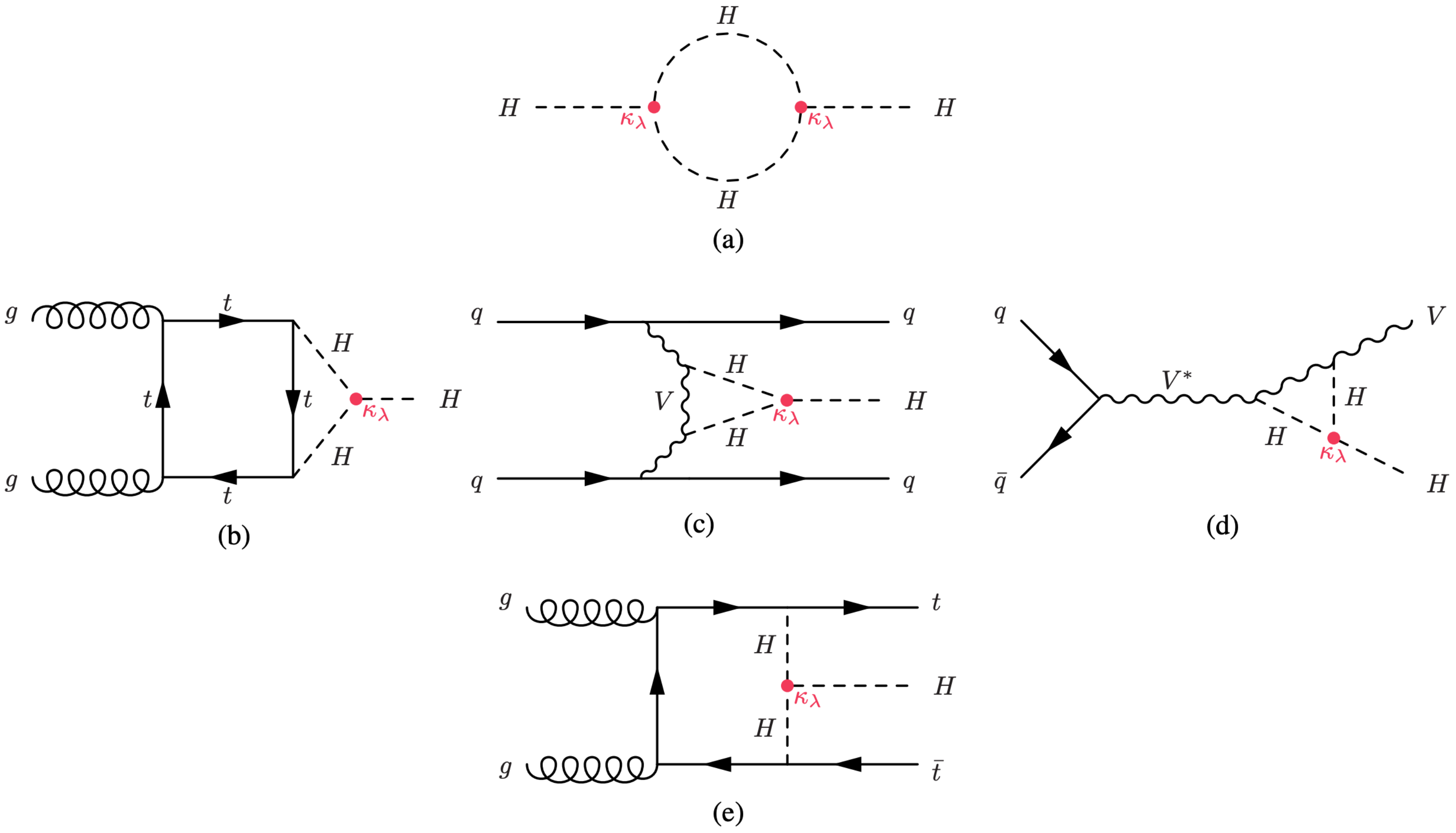
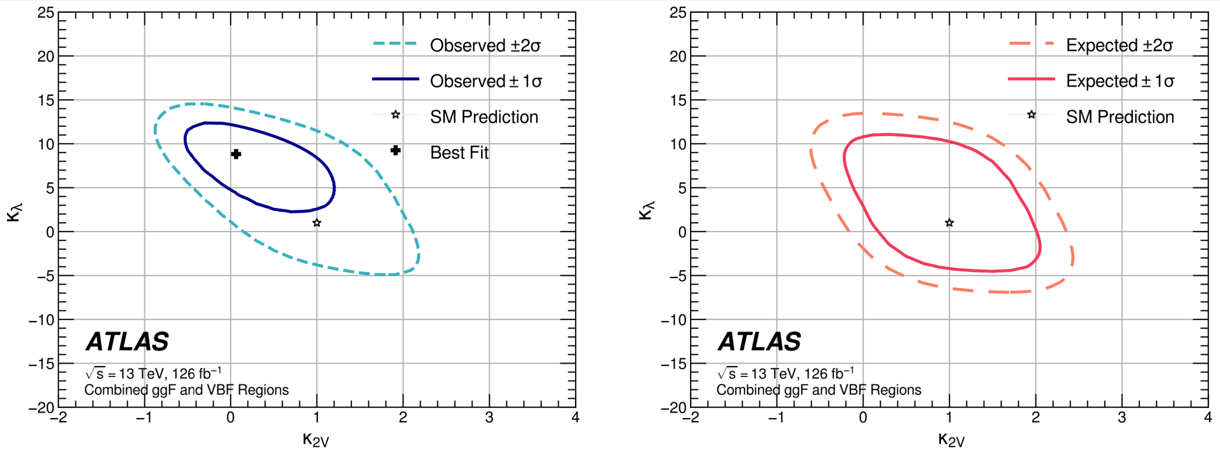


Figure 2: Examples of one loop λ_{HHH}-dependent diagrams for the Higgs boson self-energy (a) and the single-Higgs production in the ggF (b), VBF (c), VH (d), and $t\bar{t}H$ (e) modes. The self-coupling vertex is indicated by the filled circle.

HH → $b\bar{b}b\bar{b}$

- Highest BR (≈ 34%), but also large background
- Observed (expected) upper limit on
  - μ_{HH}: 5.4 (8.1)
  - $\kappa_\lambda \in [-3.5, 11.3]([-5.4, 11.4])$
  - $\kappa_{2V} \in [0.0, 2.1]([-0.1, 2.1])$



*Phys. Rev. D **108**, 052003*

HH → $b\bar{b}\gamma\gamma$

- Tiny BR (≈ 0.3%), with very good purity
- Observed (expected) upper limit on
  - μ_{HH}: 4.0 (5.0)
  - $\kappa_\lambda \in [-1.4, 6.9]([-2.8, 7.8])$
  - $\kappa_{2V} \in [-0.5, 2.7]([-1.1, 3.3])$

arXiv:2310.12301

More details in Qiuping's Talk [link]

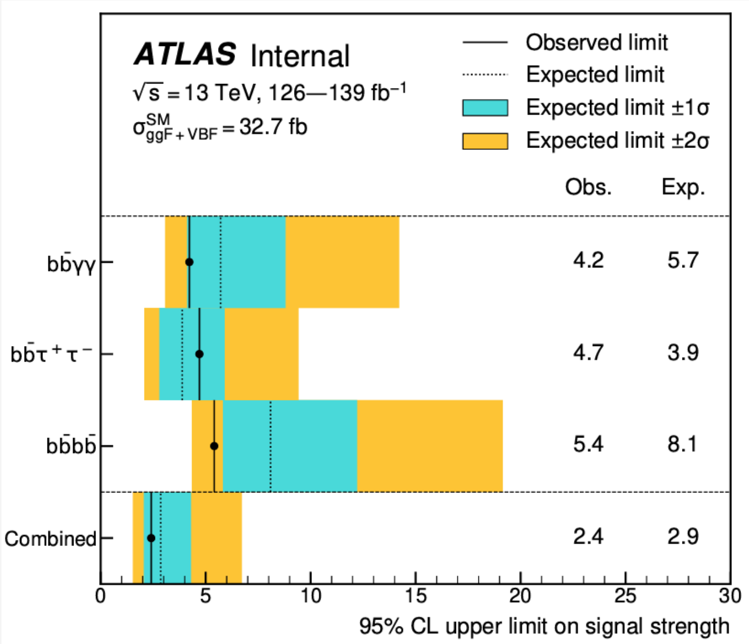
- Combination of H and HH productions using the full Run 2 data ($126\sim139$ [fb^{-1}]) of pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector. [CONF. Notes]

Channel	Integrated Luminosity [$\mathbf{fb}^{-1}$]	Reference
$HH \to b\bar{b}\gamma\gamma$ (ggF, VBF)	139	[1]
$HH \to b\bar{b}\tau\bar{\tau}$ (ggF, VBF)	139	[2]
$HH \to b\bar{b}b\bar{b}$ (ggF, VBF)	126	[3]
$H \to \gamma\gamma$ (all production modes)	139	[4]
$H \to ZZ^* \to 4\ell$ (all production modes)	139	[5]
$H \to \tau^+\tau^-$ (all production modes)	139	[6]
$H \to WW^* \to e\nu\mu\nu$ (ggF, VBF)	139	[7]
$H \to b\bar{b}$ (VH)	139	[8]
$H \to b\bar{b}$ (VBF)	126	[9]
$H \to b\bar{b}$ ($t\bar{t}H$)	139	[10]

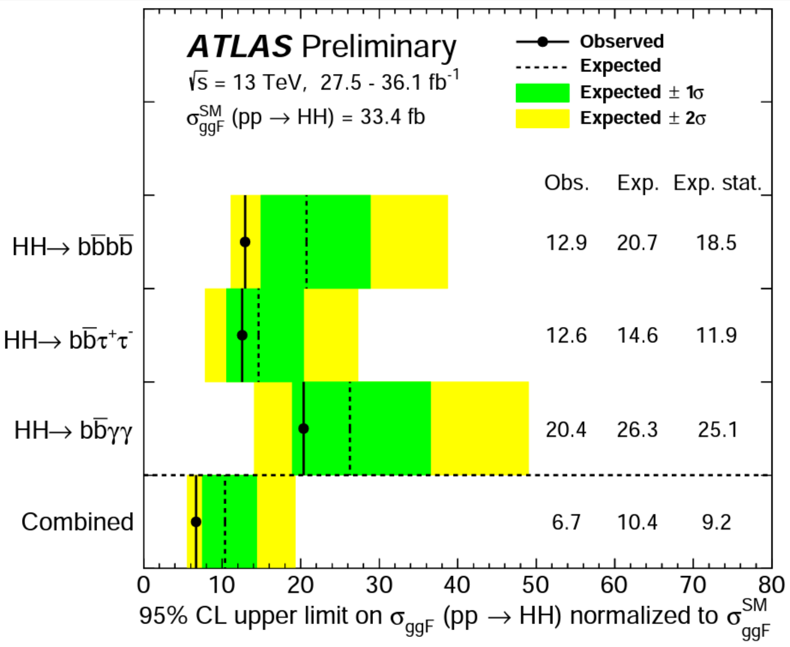
- For $H \to b\bar{b}$ (VBF) and $HH \to b\bar{b}b\bar{b}$, which use b-jet triggers, there exists an **inefficiency** in the online primary vertex reconstruction at the beginning of 2016 data taking. The 2015 dataset is excluded due to the **less performing online tagger**.
- The **overlap** between/within HH and H analyses is **negligible** or has a minor impact on the statistical results.
- Uncertainties across channels are **correlated** when relevant.

HH combination results: Limit on cross-section

- Upper limit on $\mu_{HH} = \sigma_{HH}/\sigma_{HH}^{SM}$ at 95% CL assuming no HH production, **improvement from 6.7 to 2.4**.
- The HH cross-section results include both ggF and VBF production modes.



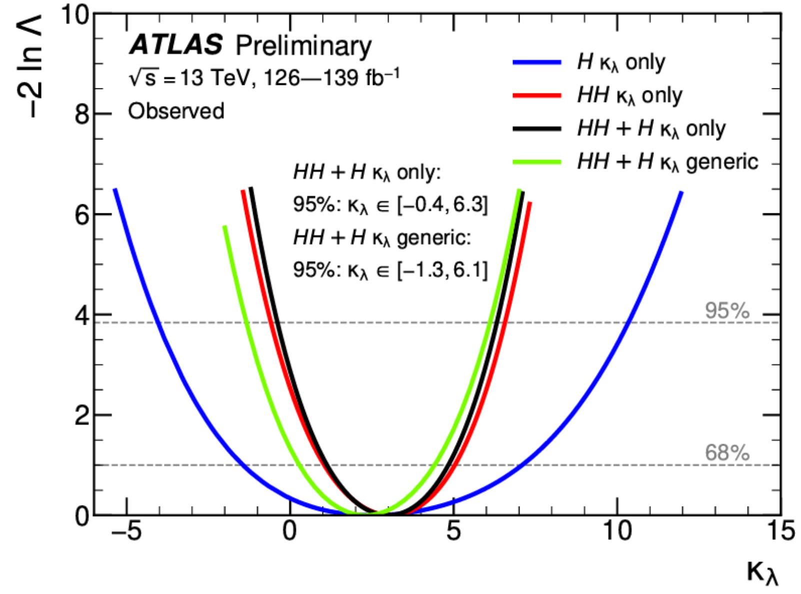
2022

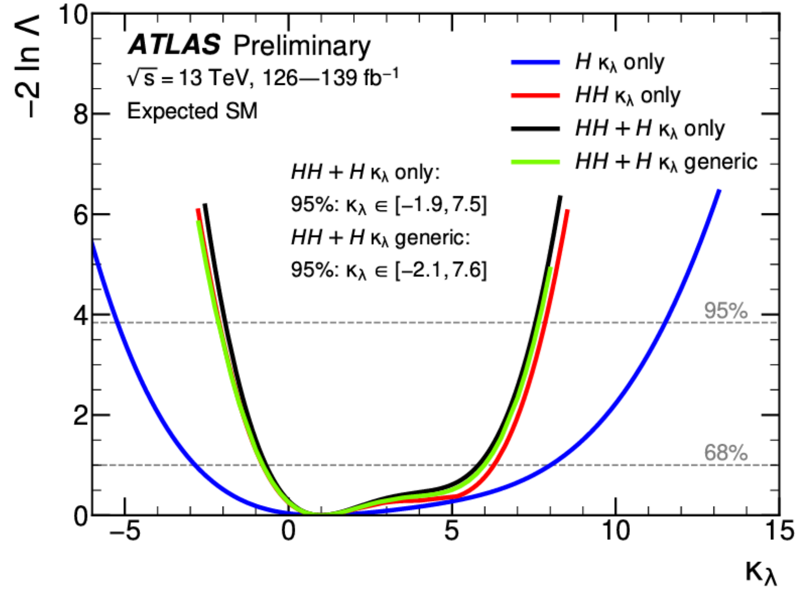


2018

H+HH combination Results: measurement of κ_λ

- Two scenarios considered:
  - **κ_λ only**: Fit with κ_λ floating and all other coupling modifiers fixed to unity.
  - **κ_λ generic**: Fit with all coupling modifiers floating except for κ_{2V} fixed to unity (no available parameterization of single-Higgs NLO EW correction as a function of κ_{2V})
- Expected result derived from the Asimov dataset generated under the SM assumption with all coupling modifiers at unity ($\kappa_\lambda, \kappa_t, \kappa_b, \kappa_\tau, \kappa_V, \kappa_{2V} = 1$).





- **Dominant** contribution from the HH channel.
- The constraints on κ_λ is still **substantial** even in the **generic scenario**.

Summary of κ_λ measurements

Channel	Obs. 95% CL	Exp. 95% CL	Obs. value $^{+1\sigma}_{-1\sigma}$
HH Combination	$-0.6 < \kappa_\lambda < 6.6$	$-2.1 < \kappa_\lambda < 7.8$	$\kappa_\lambda = 3.1^{+1.9}_{-2.0}$
Single-H Combination	$-4.0 < \kappa_\lambda < 10.3$	$-5.2 < \kappa_\lambda < 11.5$	$\kappa_\lambda = 2.5^{+4.6}_{-3.9}$
H+HH Combination	$-0.4 < \kappa_\lambda < 6.3$	$-1.9 < \kappa_\lambda < 7.6$	$\kappa_\lambda = 3.0^{+1.8}_{-1.9}$
H+HH Combination (2019)	$-2.3 < \kappa_\lambda < 10.3$	$-5.1 < \kappa_\lambda < 11.2$	$\kappa_\lambda = 4.6^{+3.2}_{-3.8}$
H+HH Combination, κ_t floating	$-0.4 < \kappa_\lambda < 6.3$	$-1.9 < \kappa_\lambda < 7.6$	$\kappa_\lambda = 3.0^{+1.8}_{-1.9}$
H+HH Combination, $\kappa_t, \kappa_V, \kappa_b, \kappa_\tau$ floating	$-1.4 < \kappa_\lambda < 6.1$	$-2.2 < \kappa_\lambda < 7.7$	$\kappa_\lambda = 2.3^{+2.1}_{-2.0}$
H+HH Combination (2019), $\kappa_t, \kappa_V, \kappa_b, \kappa_\tau$ floating	$-3.7 < \kappa_\lambda < 11.5$	$-6.2 < \kappa_\lambda < 11.6$	$\kappa_\lambda = 5.5^{+3.5}_{-5.2}$

- **Single Higgs** processes allow the constrain of κ_λ with fewer model-dependent assumptions by allowing other coupling modifiers to be free parameters.
- Improvement of around **50%** over the **2019 combination** [1].