Probing the nature of electroweak symmetry breaking with Higgs boson pair-production at ATLAS

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On behalf of ***ATLAS*** collaboration

NANJING UNIVERSITY

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- Overview of searches for Higgs boson pair production (HH)
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  - HH→bbbb
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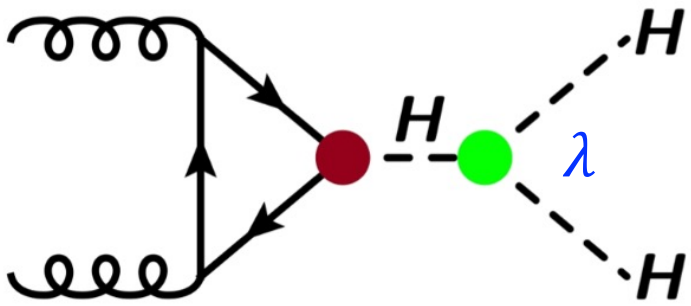
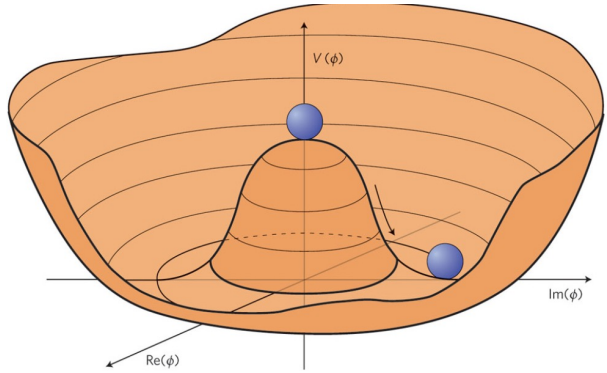
- Summary

Electroweak Symmetry Breaking

- In the electroweak sector of SM, fermions and Higgs fields respect the SU(2)xU(1) symmetry.
- However, the ground state of Higgs field does not. This leads to spontaneous electroweak symmetry breaking (**EWSB**). At the same time, W/Z bosons and fermions acquire non-zero masses.
- EWSB is directly driven by the special shape of Higgs potential. With the discovery of Higgs boson, we know the key parameter $\lambda = \frac{1}{2}\left(\frac{m_H}{v}\right)^2 \approx \frac{1}{8}$. It describes the Higgs self-interactions, i.e. hhh and hhhh couplings, in the SM.
- Di-Higgs production is a crucial mean to probe Higgs potential directly.

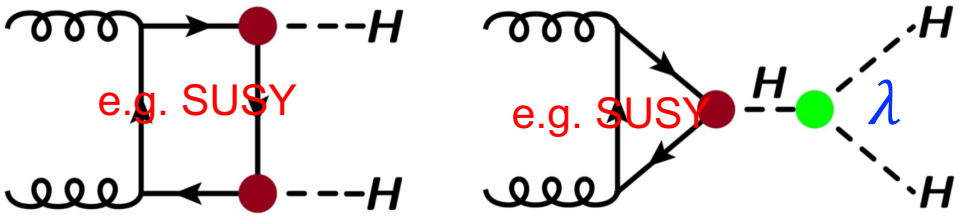
$$V(\phi) = -m^2|\phi|^2 + \lambda|\phi|^4$$



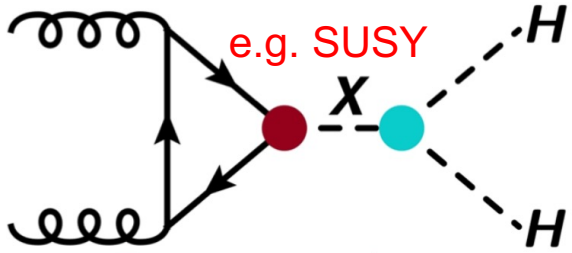


Overview of Higgs boson pair researches in ATLAS

- In SM, Higgs pairs are mainly produced in the gluon-gluon fusion process (Non-Resonant production, NR). Vector-boson fusion is also included.
- **New Physics,** e.g. **SUSY,** may appear as new loop-contribution in non-resonant HH productions or predict new scalar resonances decaying to two Higgs bosons.
- For Non-Resonant production, SUSY may enhance the rate or modify the kinematic properties (e.g. m_{HH}) and measured in the kappa formalism/EFT paradigm.
- All main decay modes are used in the searches.
  - ✓High branching fraction
  - ✓Precise Higgs reconstruction
  - ✓High background suppression



Non-resonant production



Resonant production

	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%

Overview of Higgs boson pair researches in ATLAS

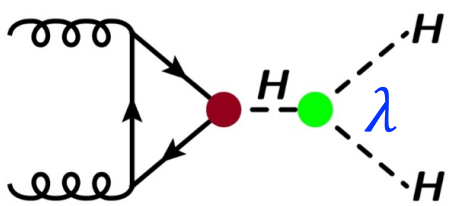
- ✓ We will cover the following researches in this talk.
- ✓ We'll present latest results based on full Run2 data in ATLAS (139 fb^{-1}).

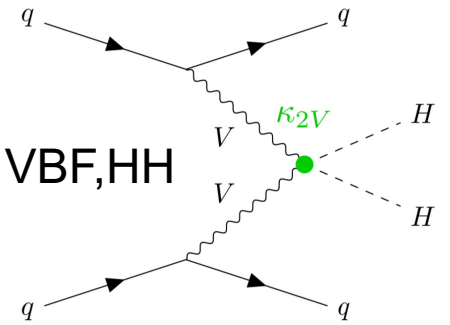
Process	Final state	Reference
HH→bbbb	>=4 jets (>=2 b-jets)	Arxiv:2301.03212
HH→bbbb	>=4 small-R jets or 2 large-R jets	PRD105,092002(2022)
HH→bb$\tau\tau$	2b+>1 had. tau	Arxiv:2209.10910
HH→bb$\gamma\gamma$	2b+2γ	PRD106,052001(2022)
HH combination	HH→bbbb/bb$\tau\tau$/bb$\gamma\gamma$	CONF-HDBS-2019-30
HH+H combination	HH→bbbb/bb$\tau\tau$/bb$\gamma\gamma$, H→WW/ZZ/$\tau\tau$/$\gamma\gamma$	PLB843(2023)137745
HEFT interpretation	HH→bb$\tau\tau$/bb$\gamma\gamma$	PUB-HDBS-2021-31
HL-LHC prospects	HH→bbbb/bb$\tau\tau$/bb$\gamma\gamma$	PUB-HDBS-2022-11 (bbbb, comb.) ATL-PHYS-PUB-2021-044 (bb$\tau\tau$) ATL-PHYS-PUB-2022-001 (bb$\gamma\gamma$)

❖ Many more results will be published soon!

Search for nonresonant pair production of Higgs bosons in the $b\bar{b}b\bar{b}$ final state in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

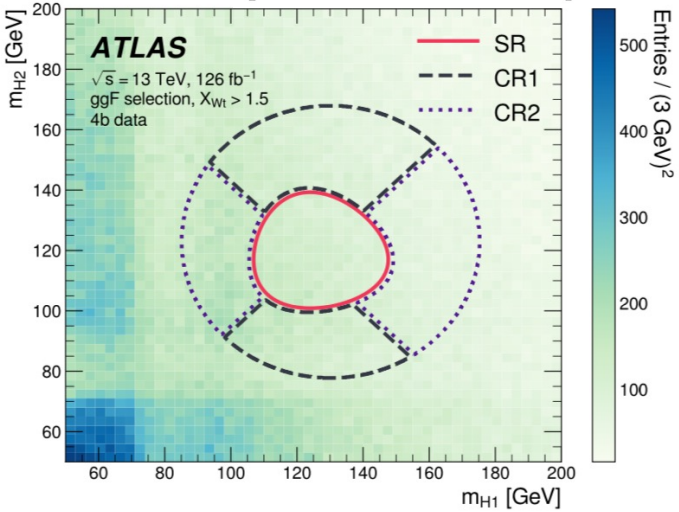
Arxiv:2301.03212



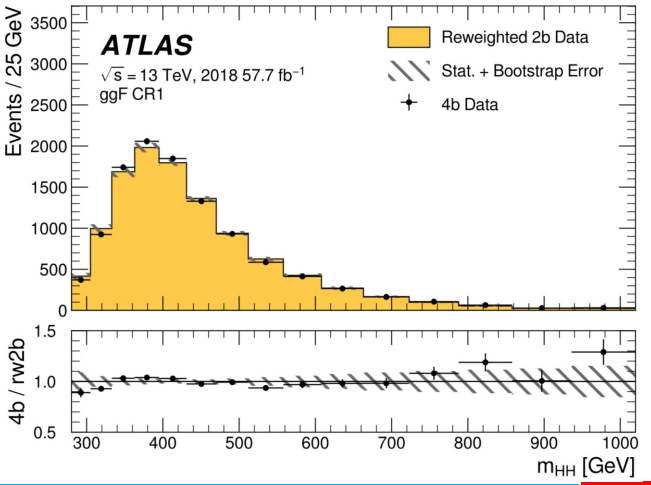


- Consider both ggF and VBF productions modes.
- Select events with at least 4 central b-tagged jets (“*4b*”). For VBF, 2 additional jets are required with m_{jj}>1TeV and $\Delta\eta_{jj}$>3.
- They are paired to form 2 Higgs candidates. Use the one with smallest ΔR for the higher-pT jet pair.
- Further require X_{HH}<1.6 and sub categories are defined based on X_{HH} and $\Delta\eta_{HH}$ to improve the sensitivity.

$$X_{HH} = \sqrt{\left(\frac{m_{H1} - 124\,\text{GeV}}{0.1\,m_{H1}}\right)^2 + \left(\frac{m_{H2} - 117\,\text{GeV}}{0.1\,m_{H2}}\right)^2}$$



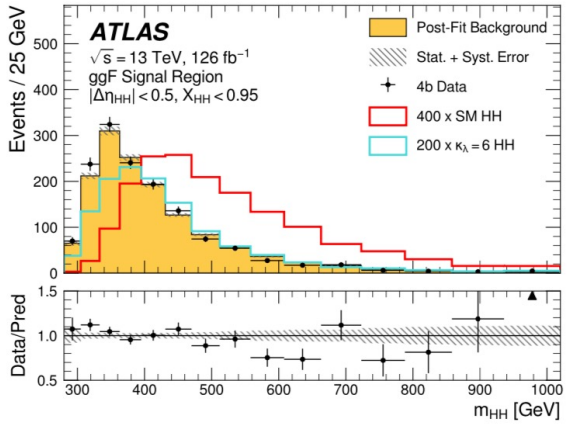
- Multijet bkg is dominant and estimated in a data-driven way.
  - Events selected as SR except requiring =2 b-tagged jets (*“2b”*) and reweight them to the *4b* SR.
  - Reweighting functions are obtained via a Neural Network in CR.

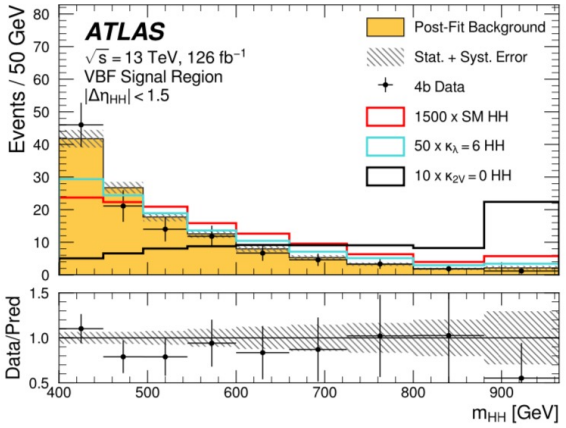


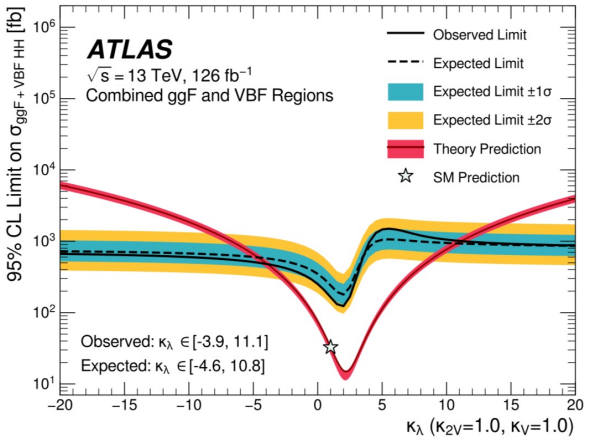
Search for nonresonant pair production of Higgs bosons in the $b\bar{b}b\bar{b}$ final state in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

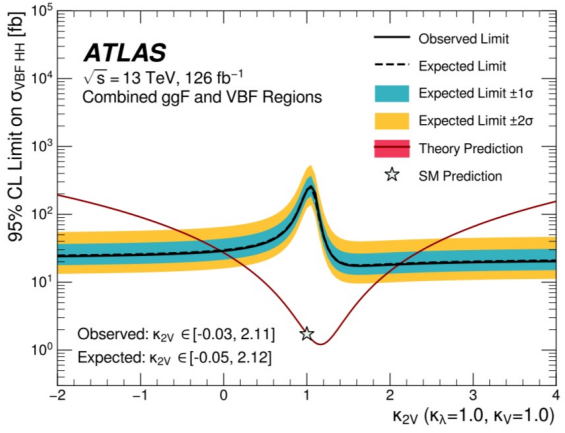
Arxiv:2301.03212

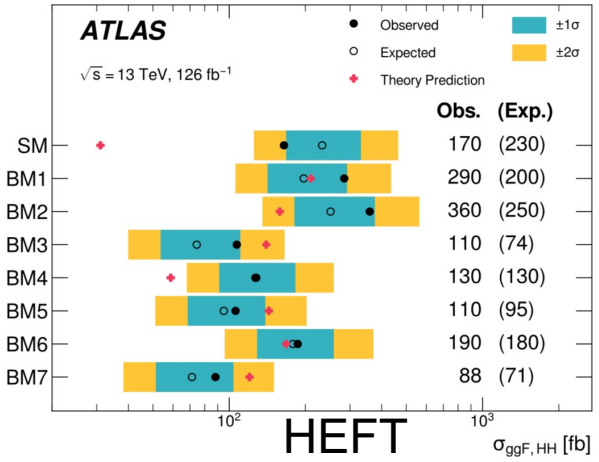
- m_{HH} is used to obtain signal sensitivity.
- Greatest syst. unc. is from bkg. estimation. and ggF HH signal theory uncertainty
- Main results:
  - κ_λ in [-3.9, 11.1] (exp. [-4.8, 10.8])
  - κ_{2V} in [-0.03, 2.11] (exp. [-0.05, 2.12])
  - Constraints on HEFT benchmark models and SMEFT parameters are also provided!











HEFT

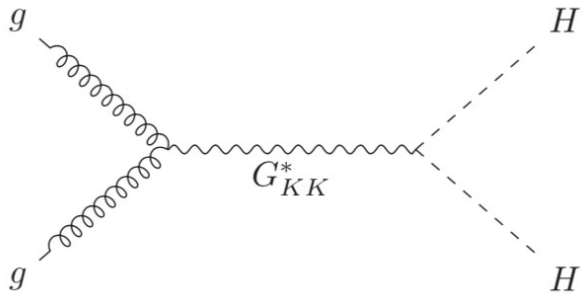
Parameter	Expected Constraint		Observed Constraint	
	Lower	Upper	Lower	Upper
c_H	−20	11	−22	11
c_{HG}	−0.056	0.049	−0.067	0.060
$c_{H\Box}$	−9.3	13.9	−8.9	14.5
c_{tH}	−10.0	6.4	−10.7	6.2
c_{tG}	−0.97	0.94	−1.12	1.15

SMEFT

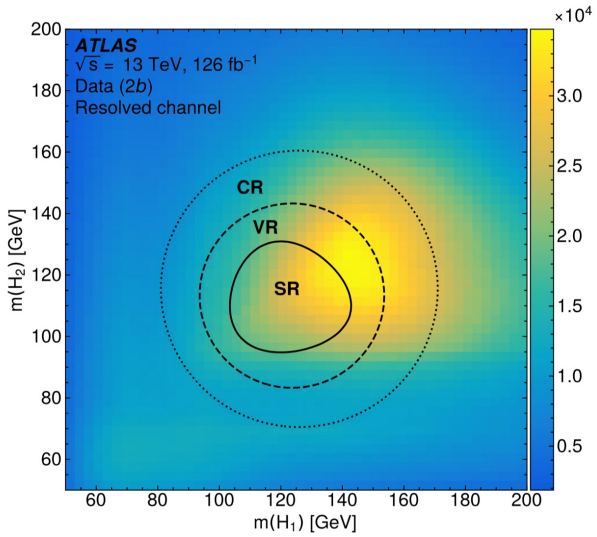
Search for resonant pair production of Higgs bosons in the $b\bar{b}b\bar{b}$ final state using pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

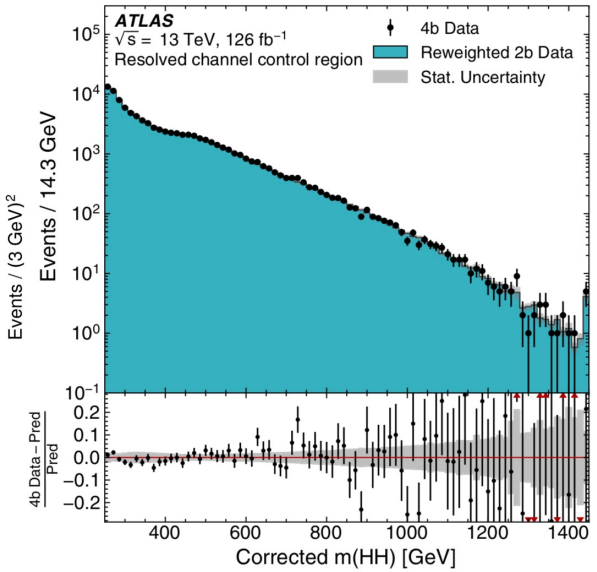
PRD105,092002(2022)

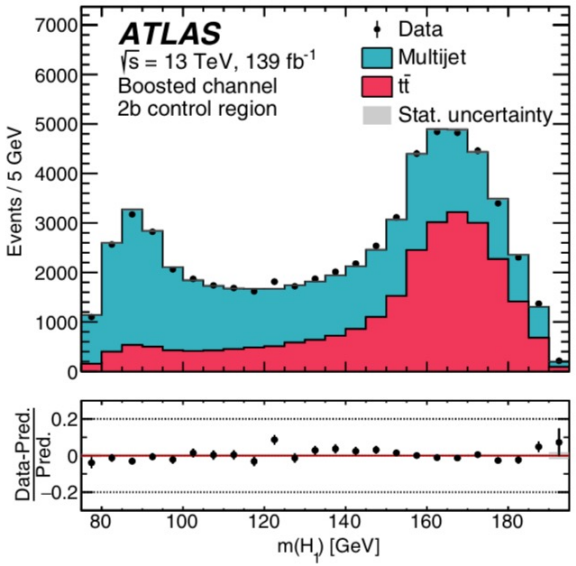
- Two complementary channels:
  - ***Resolved***: *b*-quarks ➔ individual small-R jets, targeting low-mass X up to 1.5 TeV
    - At least 4 b-tagged jets
    - b-jets are paired to form 2 Higgs candidates via a BDT training
  - ***Boosted***: H→bb ➔ single large-R jet, targeting high-mass X up to 5 TeV
    - At least 2 large-R jets with pT>450, 250 GeV
    - 3 SRs defined based on b-tagging status of the associated track jets



- Multi-jet bkg. is dominant and estimated with the same method as the non-resonant HH→bbbb (previous slide).



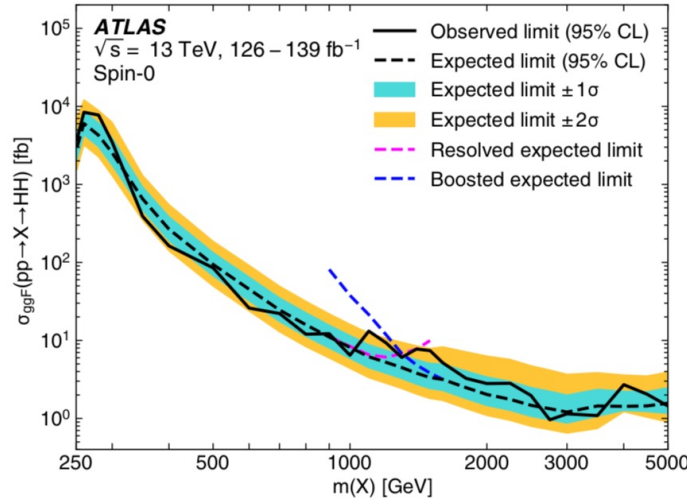


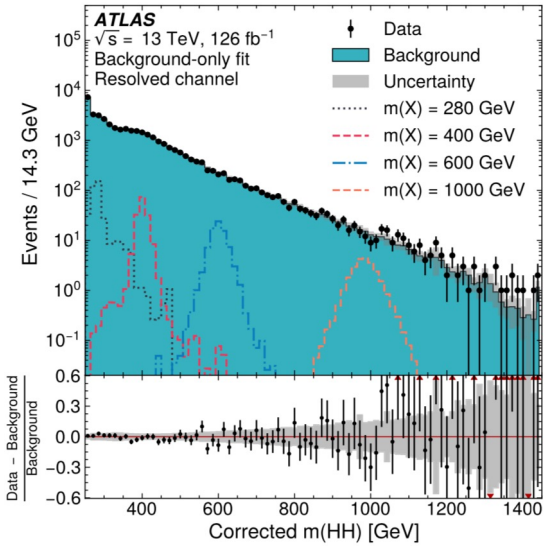


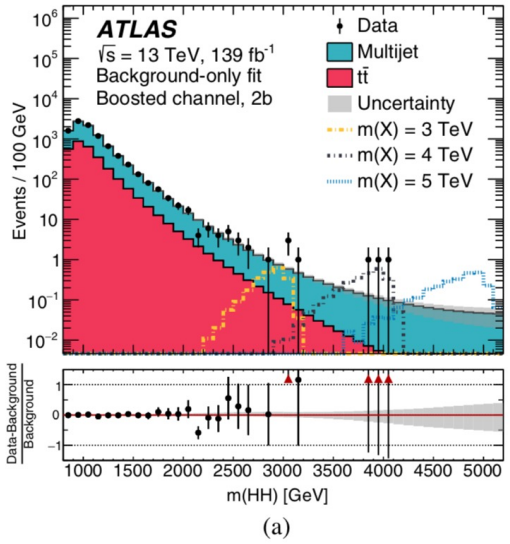
Search for resonant pair production of Higgs bosons in the $b\bar{b}b\bar{b}$ final state using pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

PRD105,092002(2022)

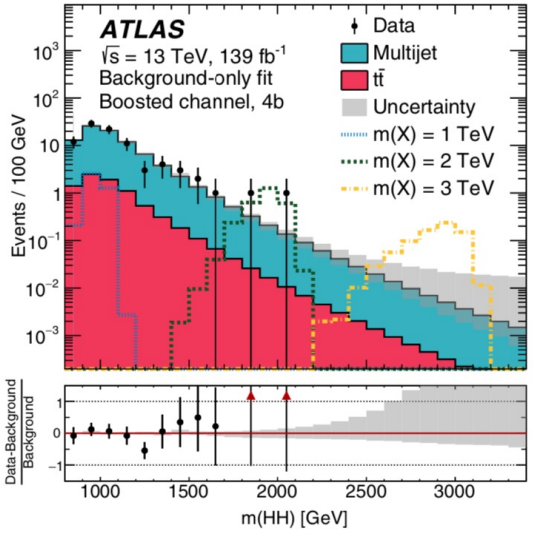
- m_{HH} is used to obtain signal sensitivity.
- ***Resolved*** channel is limited by background estimation.
- ***Boosted*** channel is limited by statistical uncertainties.
- Main results:
  - No significant evidence of a signal m_X = 251~5000 GeV!
  - Upper limits on the production XS in two models are provided.
  - Exclude the bulk Randall-Sundrum model with m_G = 298~1460 GeV



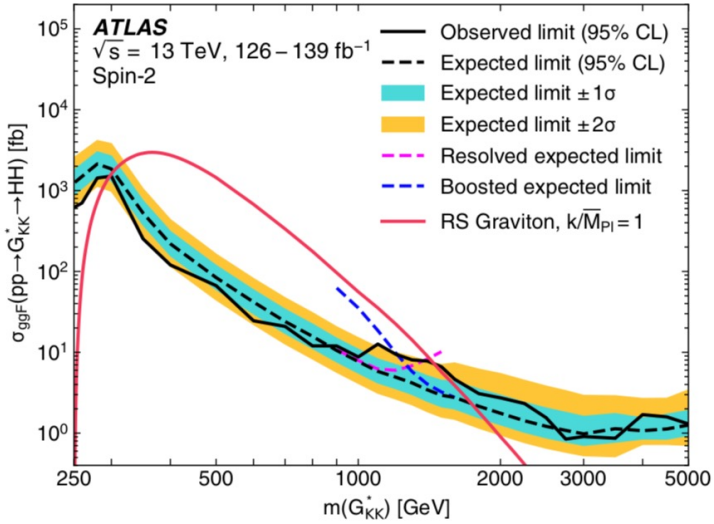




(a)



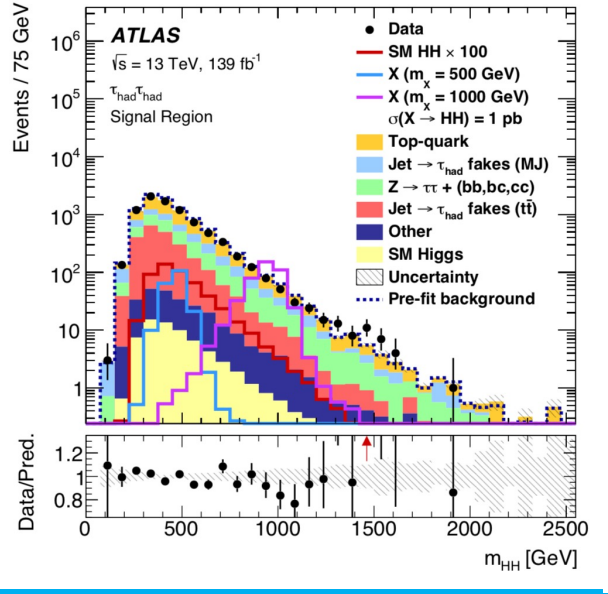
(c)

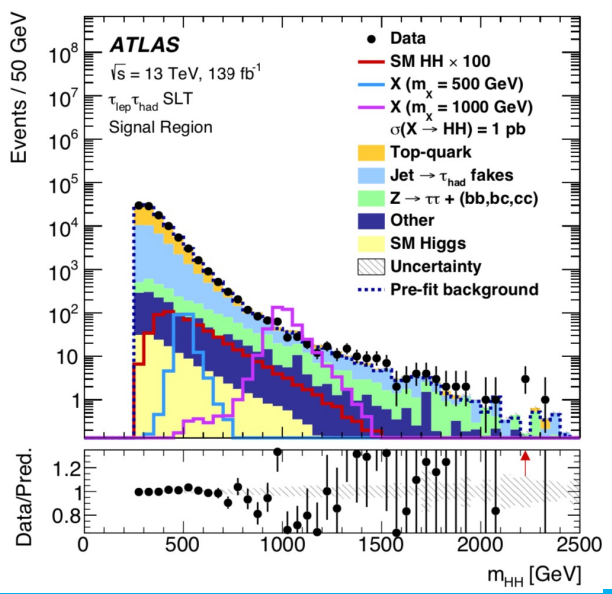


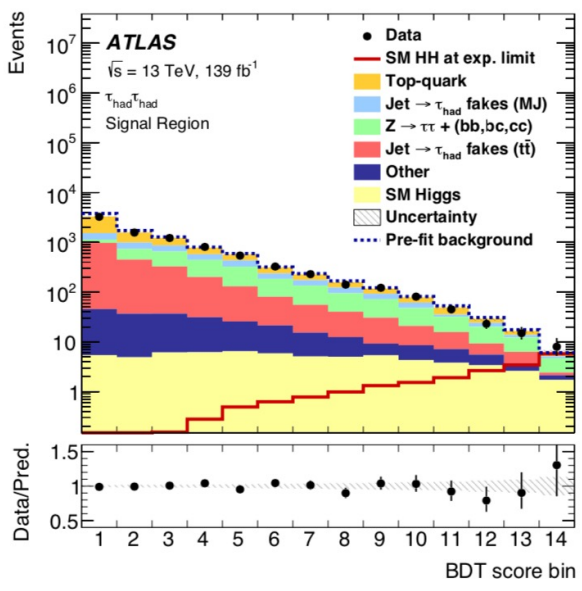
Search for resonant and non-resonant Higgs boson pair production in the $b\bar{b}\tau^+\tau^-$ decay channel using 13 TeV pp collision data from the ATLAS detector

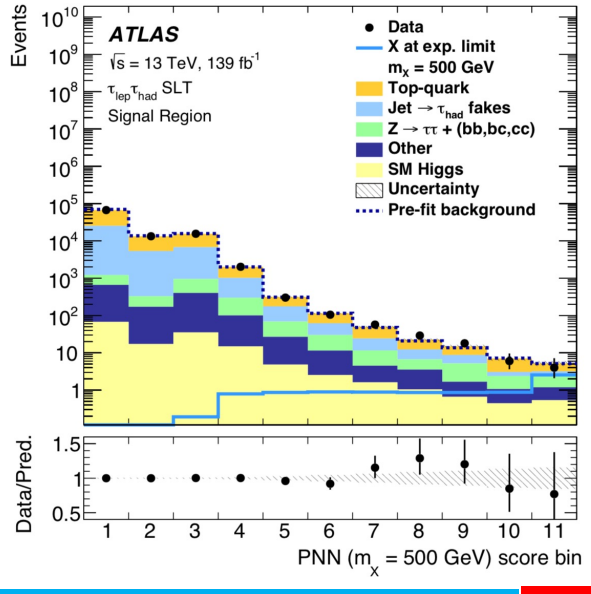
Arxiv:2209.10910

- Select events with 2 b-tagged jets and 2 tau candidates
  - $\tau_{had}\tau_{had}$: two oppositely charged τ_{had} : single tau triggers (STT), di-tauhad triggers (DTT)
  - $\tau_{lep}\tau_{had}$: an electron/muon and an oppositely charged τ_{had} : single lepton triggers (SLT), lepton-plus-tauhad triggers (LTT)
  - Further conditions: MMC $m\tau\tau$>60 GeV (to suppress Drell-Yan), m_{bb}<150 GeV (to reject tt bkg.)
  - Fake τ_{had} background (tt/Multi-jet) estimated with semi-data-driven methods
- Machine Learning methods (BDT,NN,PNN) are used to extract signals.





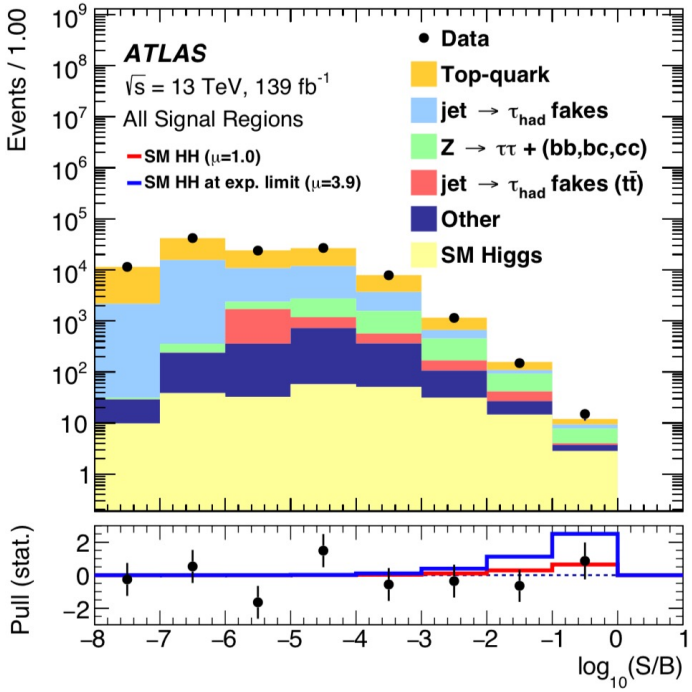


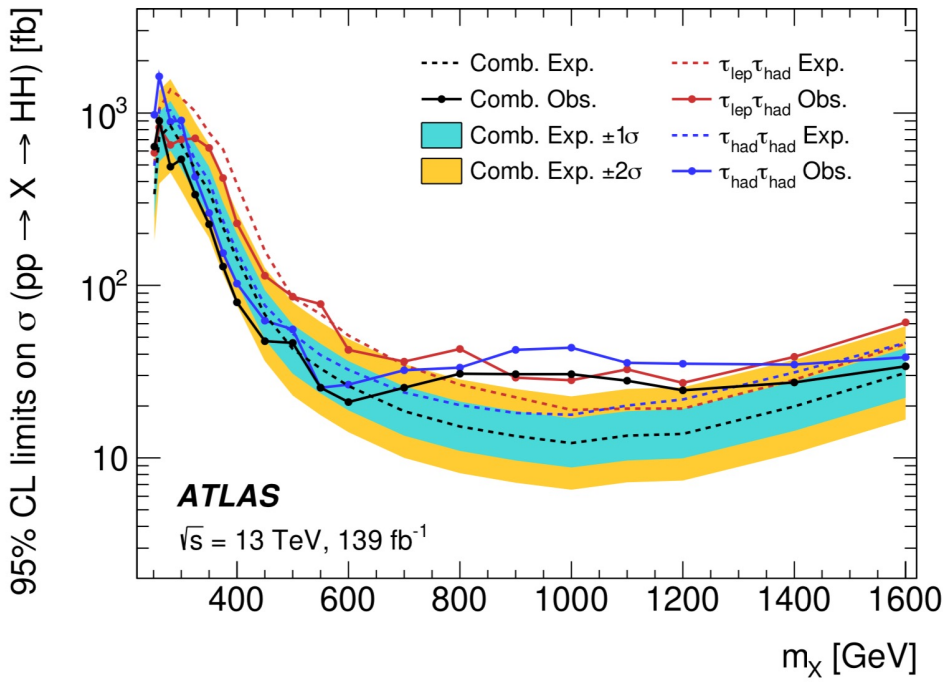


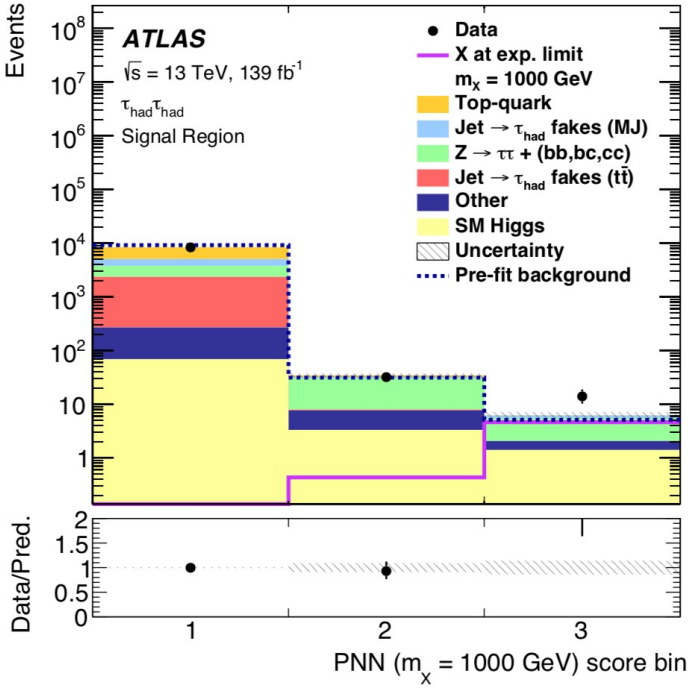
Search for resonant and non-resonant Higgs boson pair production in the $b\bar{b}\tau^+\tau^-$ decay channel using 13 TeV pp collision data from the ATLAS detector

Arxiv:2209.10910

- Obs. upper limit of HH production XS to SM value is 4.7 (3.9).
- HH resonance is searched from 251 GeV to 1600 GeV.
- A broad excess observed between 0.7 to 1.2 TeV with a local significance 3.1σ (globally 2.0σ).







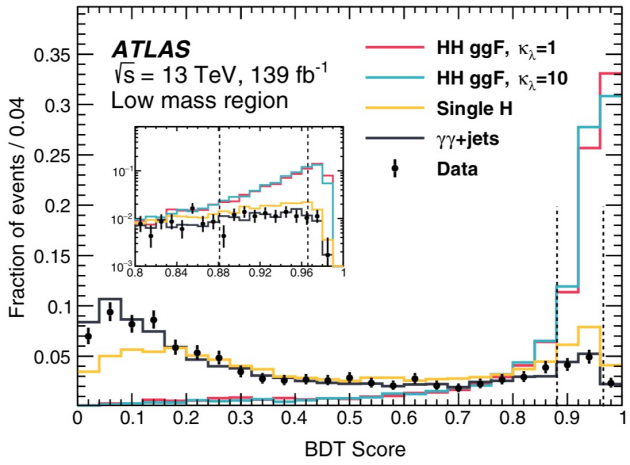
Search for Higgs boson pair production in the two bottom quarks plus two photons final state in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

PRD106,052001(2022)

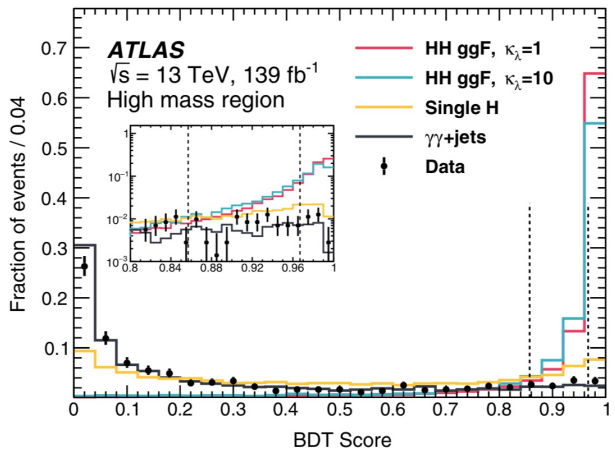
- Select events with 2 b-tagged jets and >=2 photons
- Non-Resonant selection:

$$m^*_{b\bar{b}\gamma\gamma} = m_{b\bar{b}\gamma\gamma} - m_{b\bar{b}} - m_{\gamma\gamma} + 250 \text{ GeV}$$

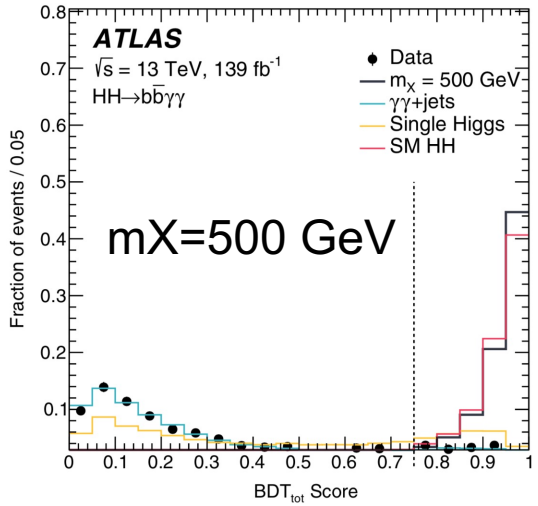
  - 2 regions: $m_{bb\gamma\gamma}^*$>350 (SM signal), $m_{bb\gamma\gamma}^*$<350 (BSM signal e.g. κ_λ=10)
  - Dedicated BDT trained between benchmark HH signal and a combined background
  - For each mass region, two categories defined based on BDT score.
- Resonant selection:
  - Joint BDT for all resonance masses (reweighted to the same mHH as bkg.) and background.
  - Two BDTs trained against 1) continuum bkg. ($\gamma\gamma$) and 2) peaking bkg. (ZH,ttH) and combined.
  - Events must pass a minimum BDT score value and be in m_X window +/-2 σ.



(a) Low mass region



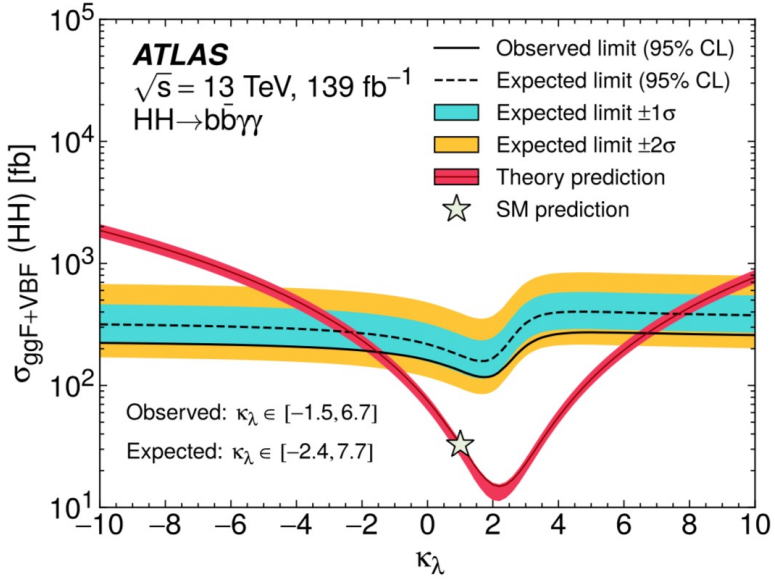
(b) High mass region

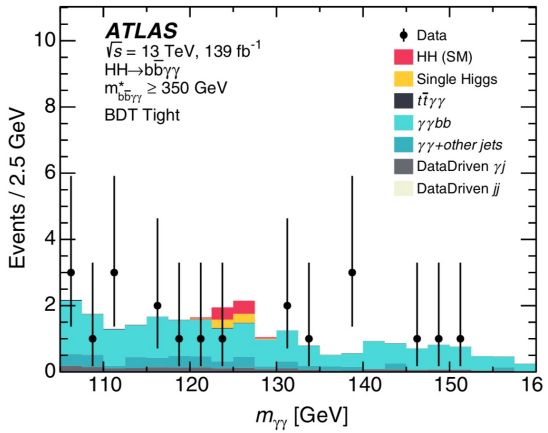


Search for Higgs boson pair production in the two bottom quarks plus two photons final state in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

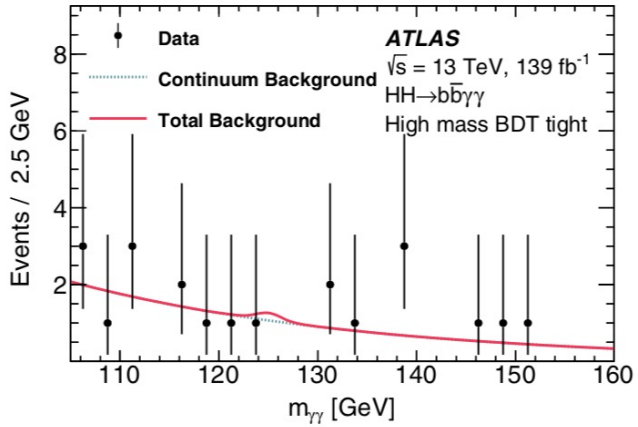
PRD106,052001(2022)

- Signal sensitivity obtained from a simultaneuous fit to the $m\gamma\gamma$ distributions.
- Dominant systematic uncertainty due to functional from for the continuum background (spurious signal).
- Main results:
  - Constraint on κ_λ in [-1.5, 6.7] (exp. [-2.4, 7.7])
  - No significant evidence for HH resonances
  - X→HH cross section upper limits: 640-44 fb for m_X=251-1000 GeV.

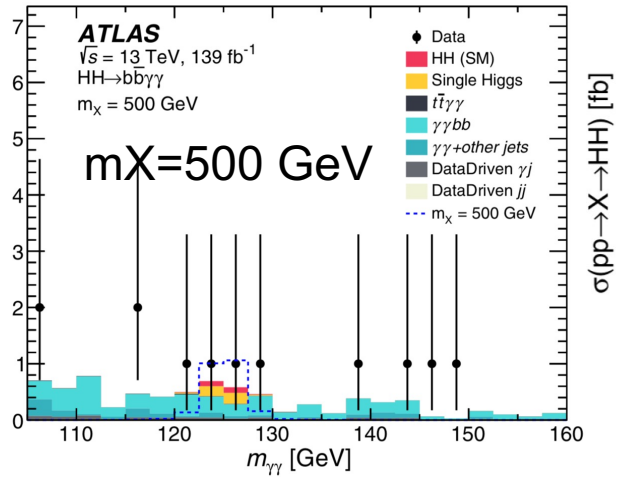


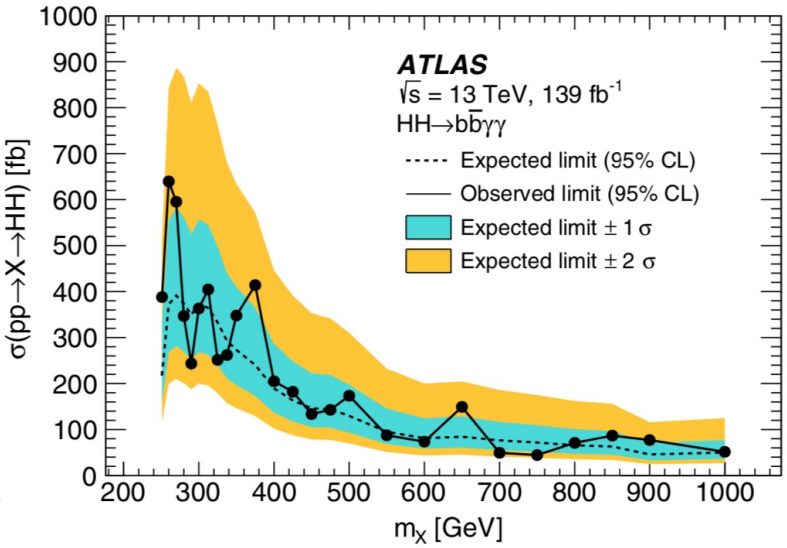


(a) High mass BDT tight selection



(a) High mass BDT tight

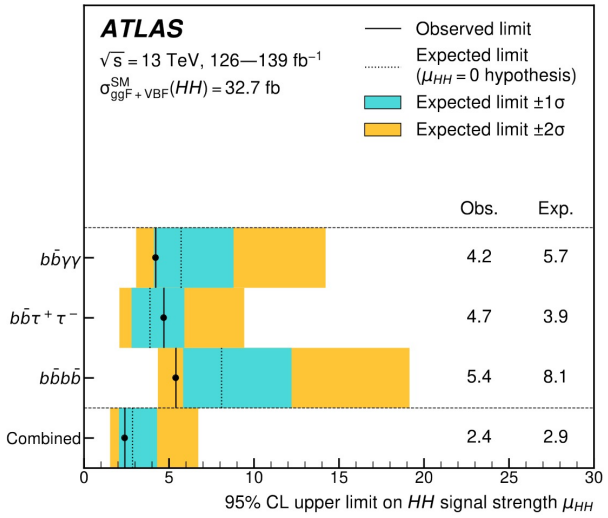


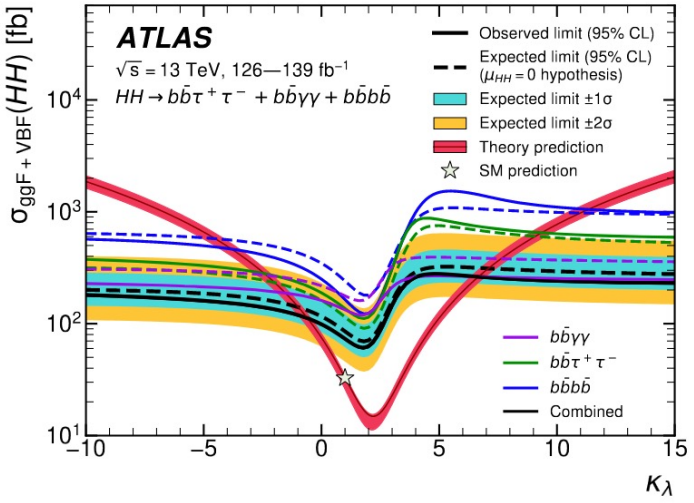


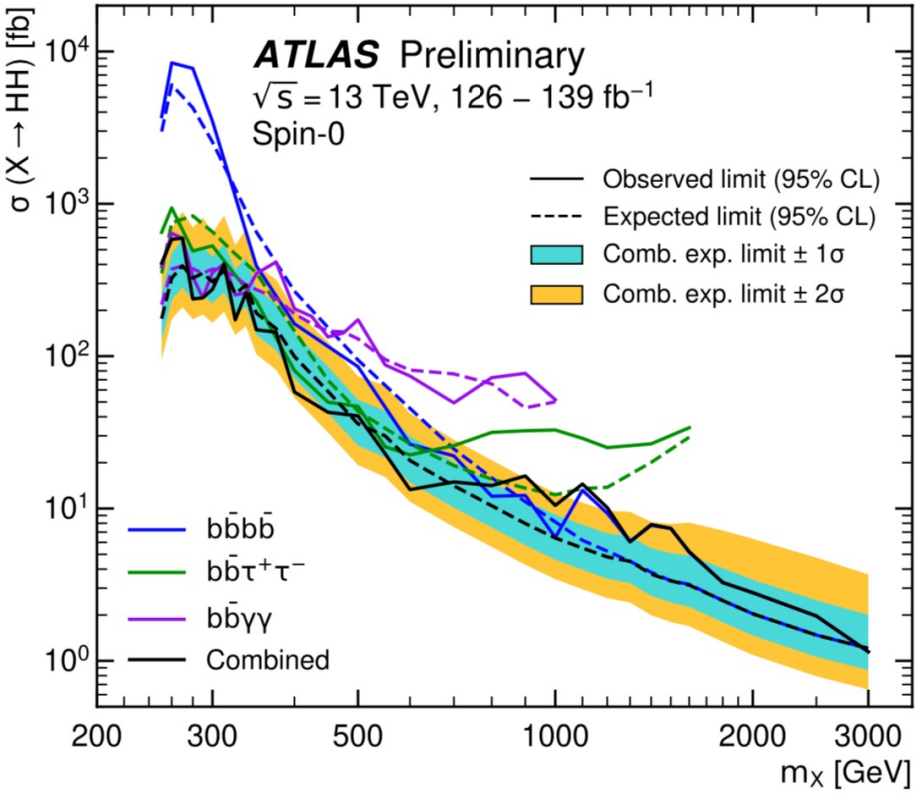
Combination of searches for non-resonant and resonant Higgs boson pair production in the $b\bar{b}\gamma\gamma$, $b\bar{b}\tau^+\tau^-$ and $b\bar{b}b\bar{b}$ decay channels using pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector

CONF-HDBS-2019-30
PLB843(2023)137745

- All signal regions are orthogonal!
- Simultaneous fit to data with uncertainties from common source fully correlated when possible
- Main results:
  - Obs. (exp.) U.L. on HH signal strength is 2.4 (2.9).
  - Exclude κ_λ outside [-0.6, 6.6] ([-2.1, 7.8])
  - HH resonances with mass = 251GeV~3TeV are searched.
    - No significance evidence, cross section U.L. provided

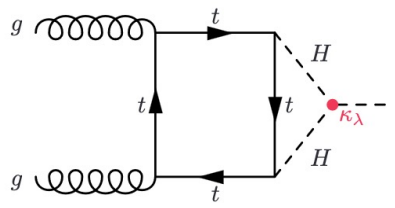






Constraints on the Higgs boson self-coupling from single- and double-Higgs production with the ATLAS detector using pp collisions at $\sqrt{s} = 13$ TeV

PLB843(2023)137745

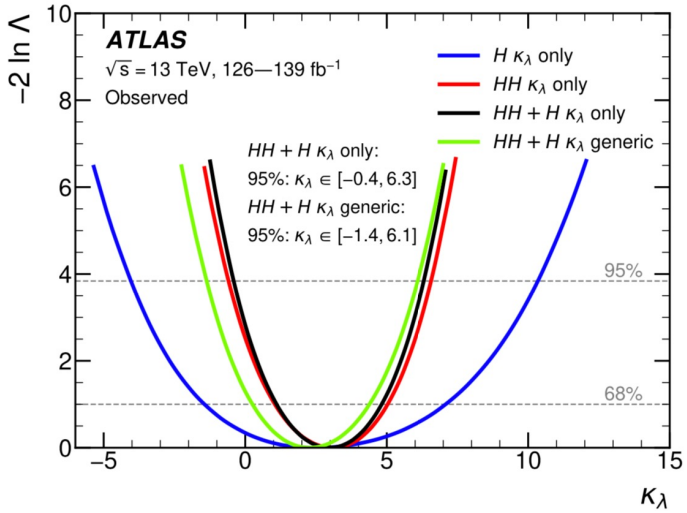


- Higgs self-coupling λ_{HHH} can be directly accessed in HH productions.
- It also contributes to single Higgs production XS and BR via NLO electroweak corrections.

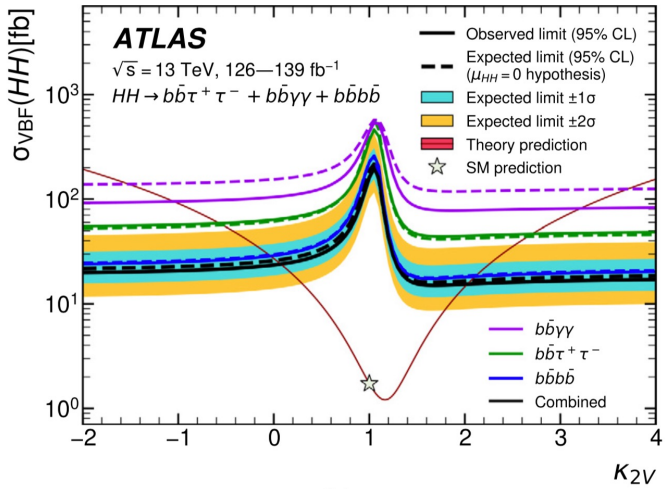
Analysis channel
$HH \to b\bar{b}\gamma\gamma$
$HH \to b\bar{b}\tau^+\tau^-$
$HH \to b\bar{b}b\bar{b}$
$H \to \gamma\gamma$
$H \to ZZ^* \to 4\ell$
$H \to \tau^+\tau^-$
$H \to WW^* \to e\nu\mu\nu$ (ggF,VBF)
$H \to b\bar{b}$ (VH)
$H \to b\bar{b}$ (VBF)
$H \to b\bar{b}$ $(t\bar{t}H)$

- 3 HH channels and 7 single H channels are considered.
- Negligible overlapping among the signal regions

- Exclude κ_λ outside [-0.6, 6.6] (HH only)
  outside [-0.4, 6.3] (HH+H)



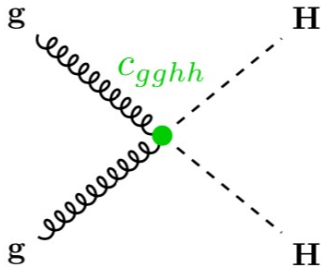
- Exclude κ_{2V} outside [0.1, 2.0] (HH)

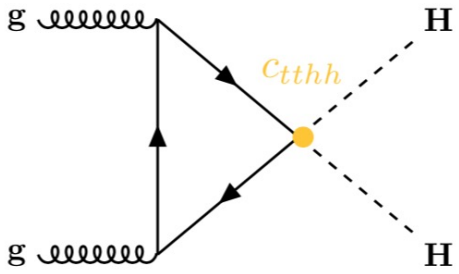


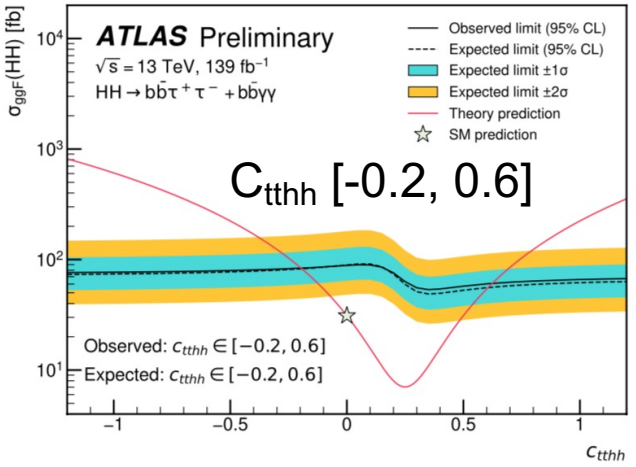
HEFT interpretations of Higgs boson pair searches in $b\bar{b}\gamma\gamma$ and $b\bar{b}\tau\tau$ final states and of their combination in ATLAS

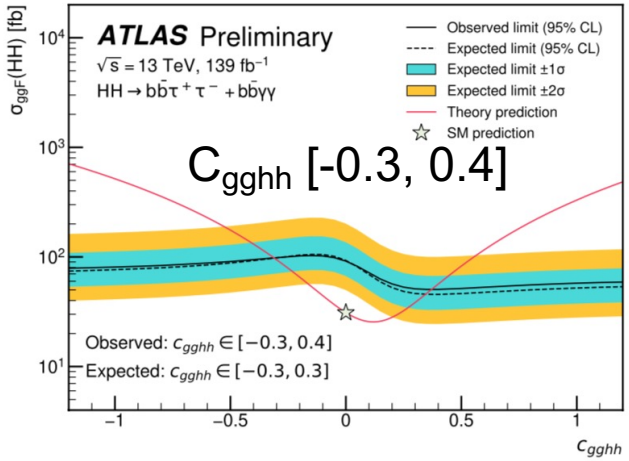
CONF-HDBS-2019-30

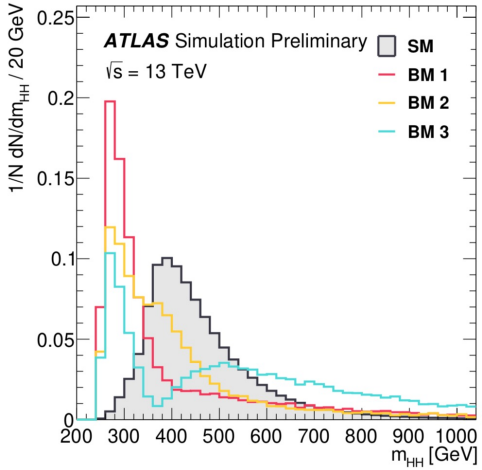
- **E**ffective **F**ield **T**heories: describe the effects of New physics in terms of effective couplings at low-energy scale
- 5 Wilson Coefficients and 7 HEFT benchmark models are considered! c_{hhh} c_{tth} c_{ggh} c_{gghh} c_{tthh}

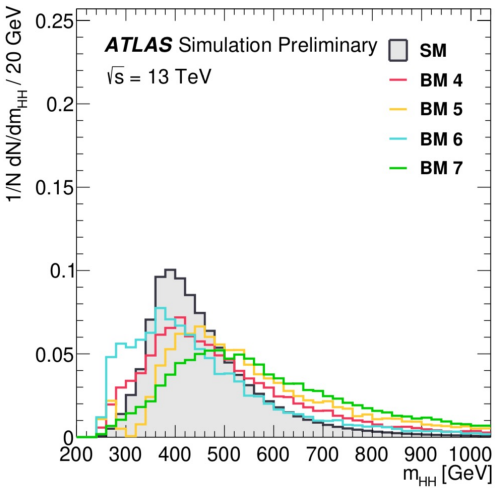


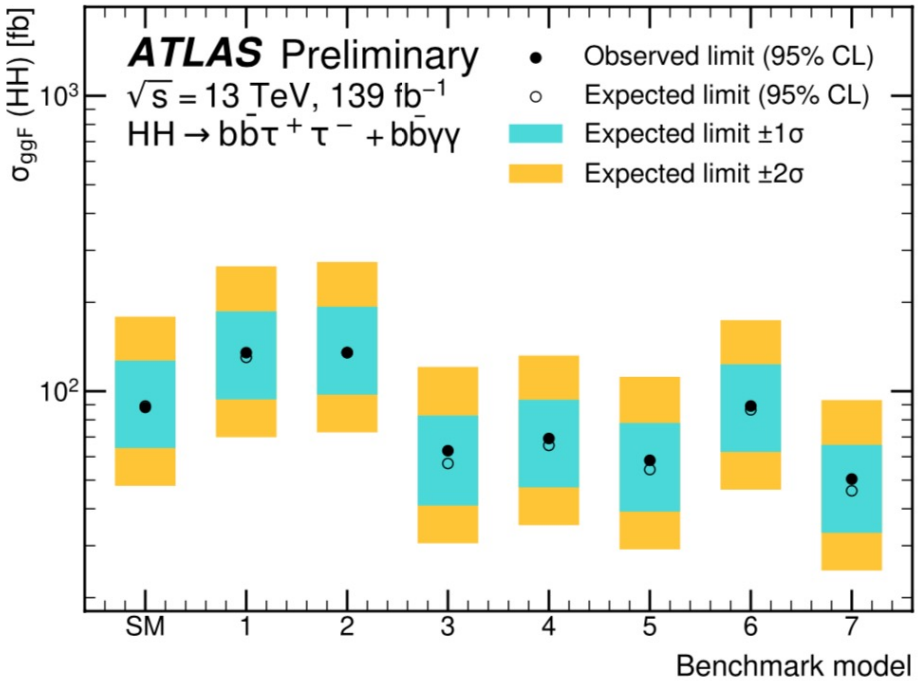








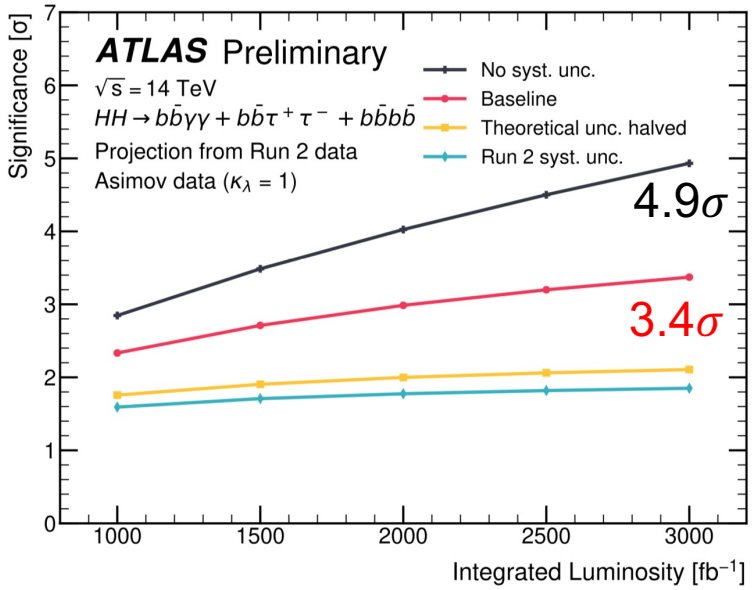




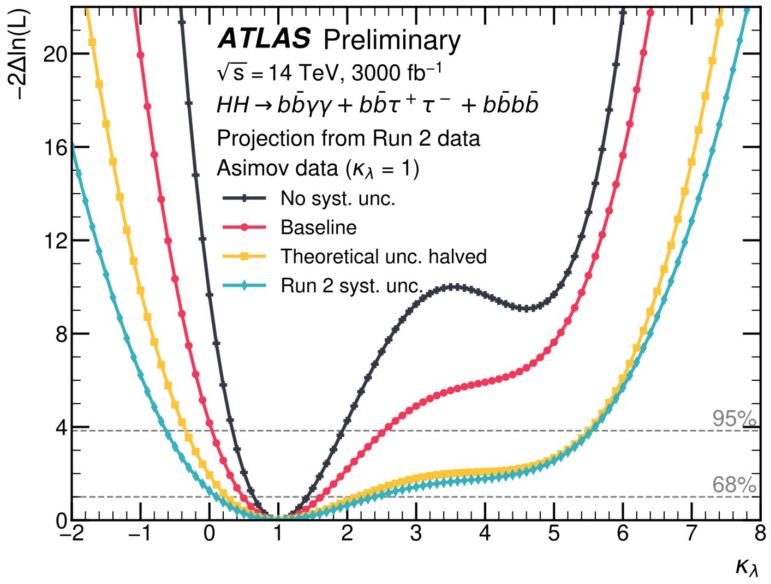
HL-LHC prospects for measurements of HH production

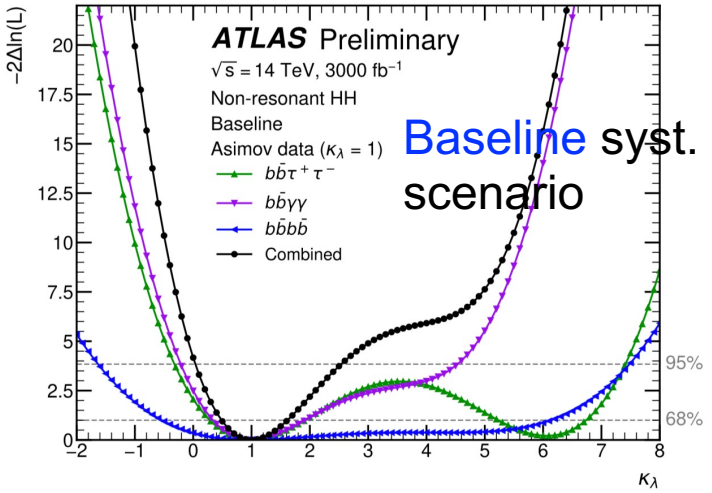
- **H**igh **L**uminosity **LHC** project:
  - C.m. energy=14 TeV, Int. lumi.=3000 fb-1, Starts in 2029
- Extrapolate the latest Run2 results
  - Assume the same detector performance as in Run2
  - 13 TeV → 14 TeV, 140 fb-1 → 3000 fb-1, data-driven bkg. is also scaled properly.
  - Different systematic uncertainty scenarios are evaluated.

PUB-HDBS-2022-11 (bbbb, comb.)
ATL-PHYS-PUB-2021-044 (bb$\tau\tau$)
ATL-PHYS-PUB-2022-001 (bb$\gamma\gamma$)

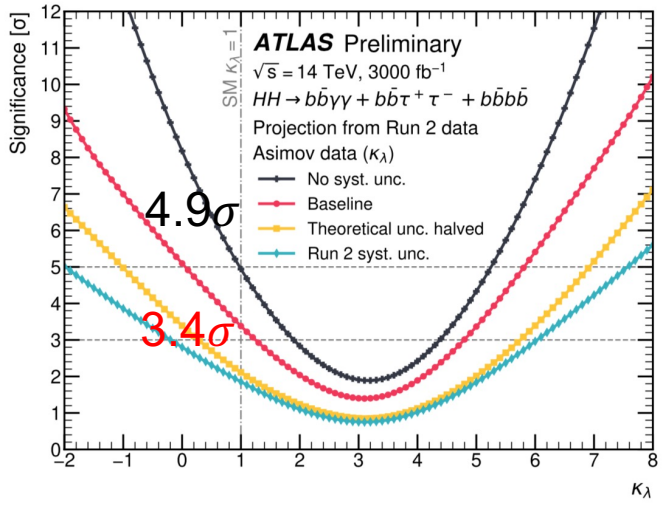


κ_λ in [0.5, 1.6] @68%CL





Baseline syst. scenario

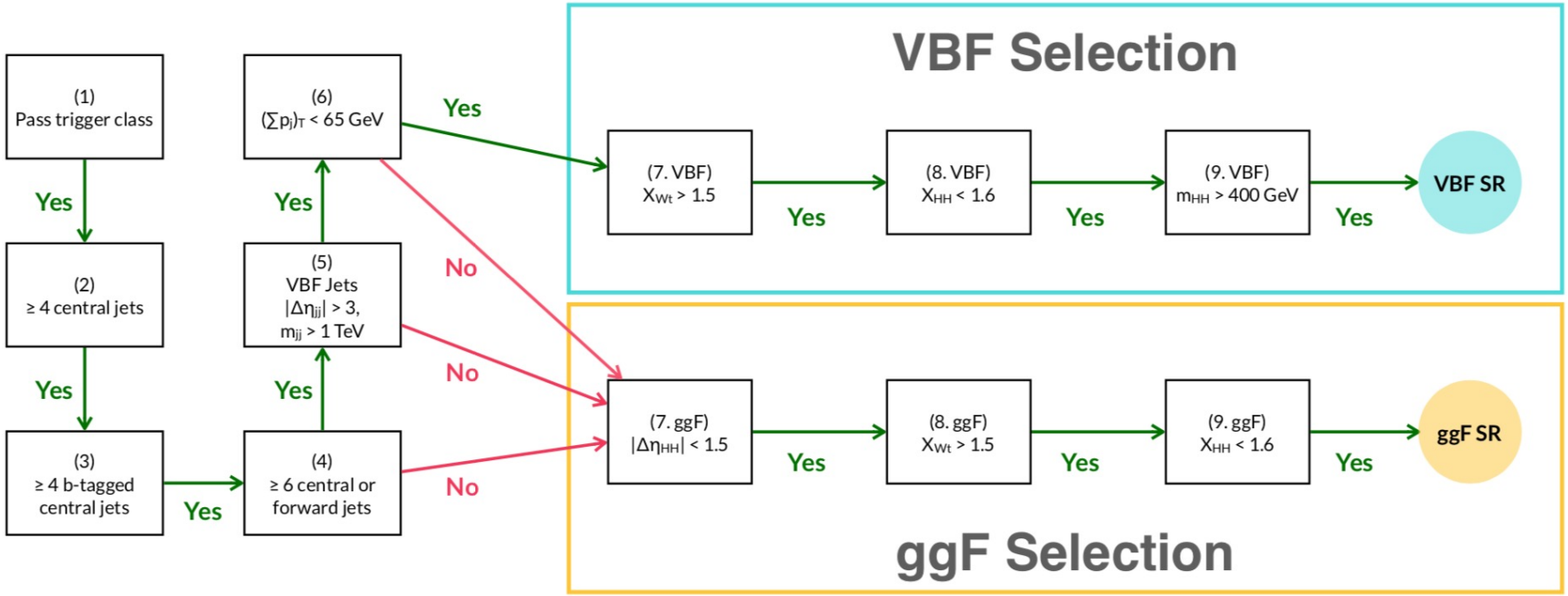


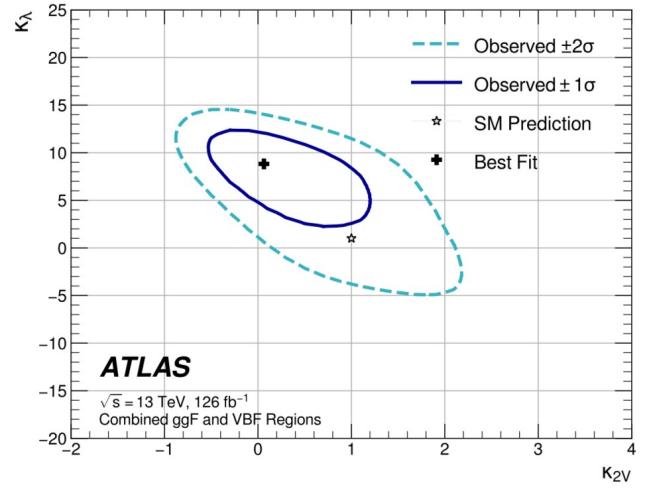
Summary

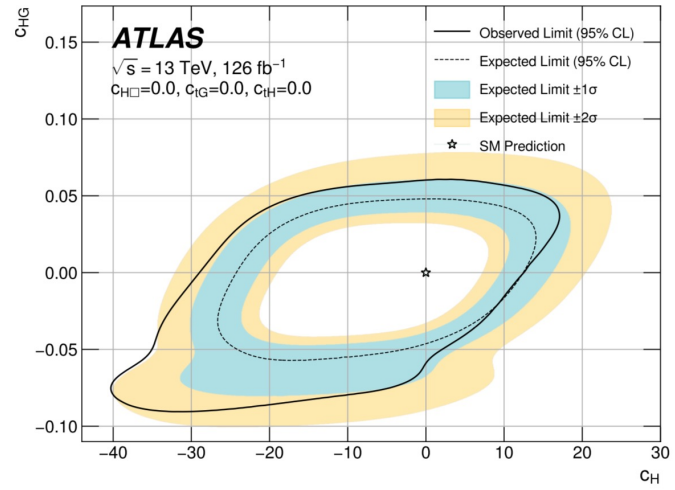
- Latest searches for Higgs boson pair production using full Run2 dataset are presented. No significant excess above SM prediction is observed.
- Stringent constraints are obtained on the Higgs self-coupling from individual measurements and also combined measurements (κ_λ in [-0.4, 6.3])
- Resonances decaying to Higgs pair are searched for mass from 251 GeV to 5 TeV. U.L. of production XS are provided.
- HL-LHC expects to see SM Higgs self-coupling with 3.4σ.
- More and more exciting experimental results will be public soon!

- BACK UP

BACK UP for bbbb (NR)





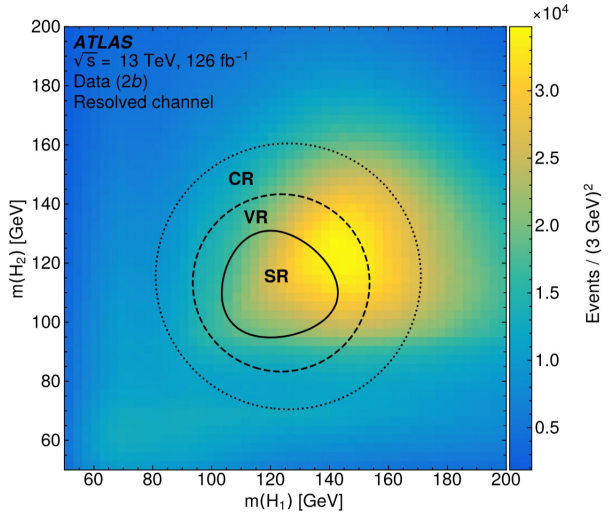


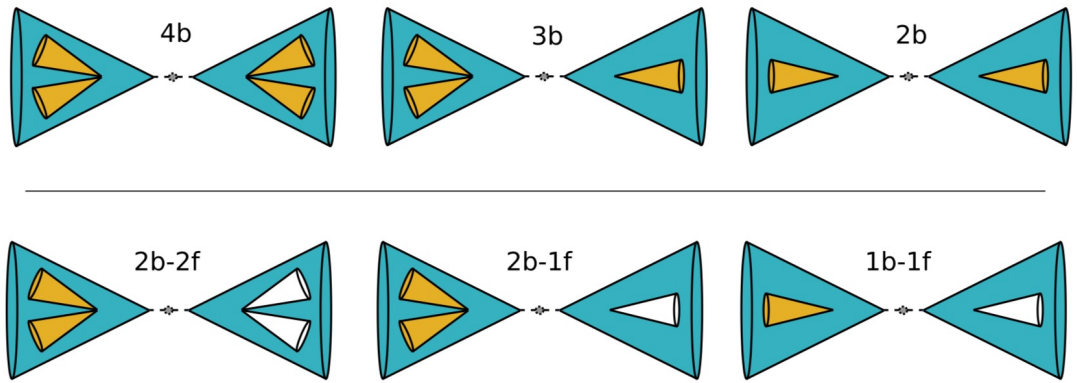
$$X_{Wt} = \min\left[\sqrt{\left(\frac{m_{jj} - m_W}{0.1 m_{jj}}\right)^2 + \left(\frac{m_{jjb} - m_t}{0.1 m_{jjb}}\right)^2}\right]$$

Further require X_{Wt}>1.5 to suppress tt bkg.

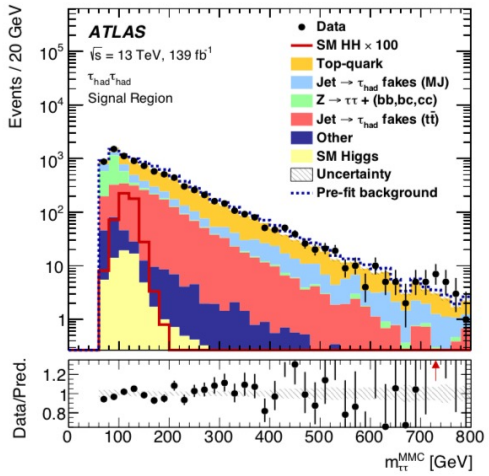
BACK UP for bbbb (R)

$$X_{HH} = \sqrt{\left(\frac{m(H_1) - 120\,\text{GeV}}{0.1 \times m(H_1)}\right)^2 + \left(\frac{m(H_2) - 110\,\text{GeV}}{0.1 \times m(H_2)}\right)^2}.$$

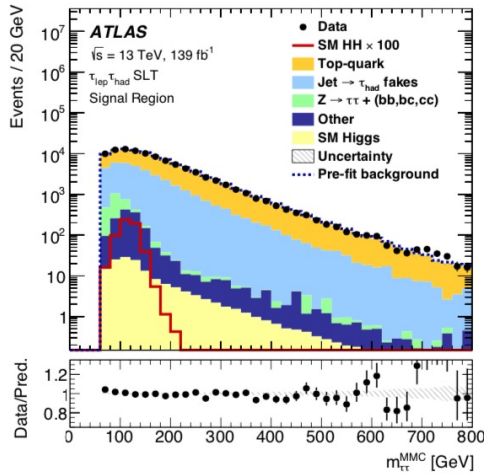




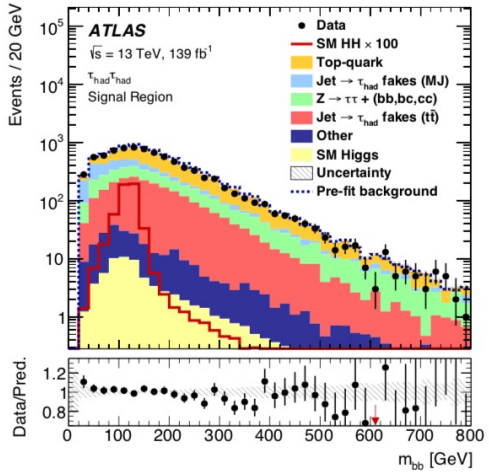
BACK UP for bbtata



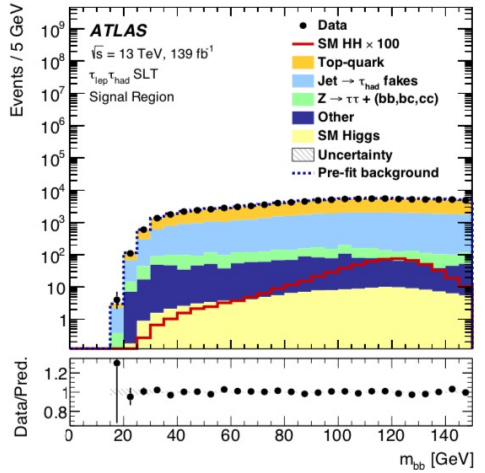
(d)



(e)



(g)

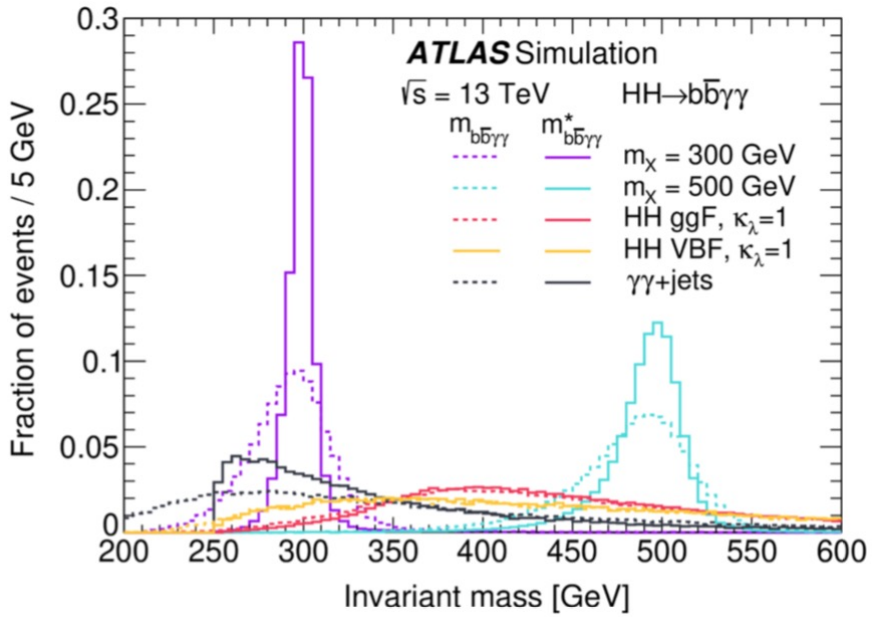


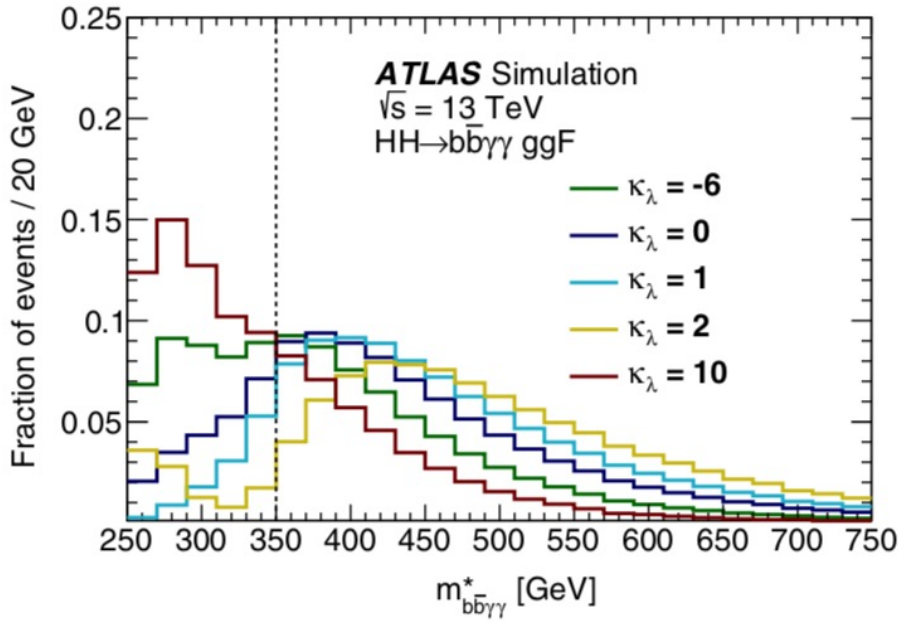
(h)

back up for bbyy

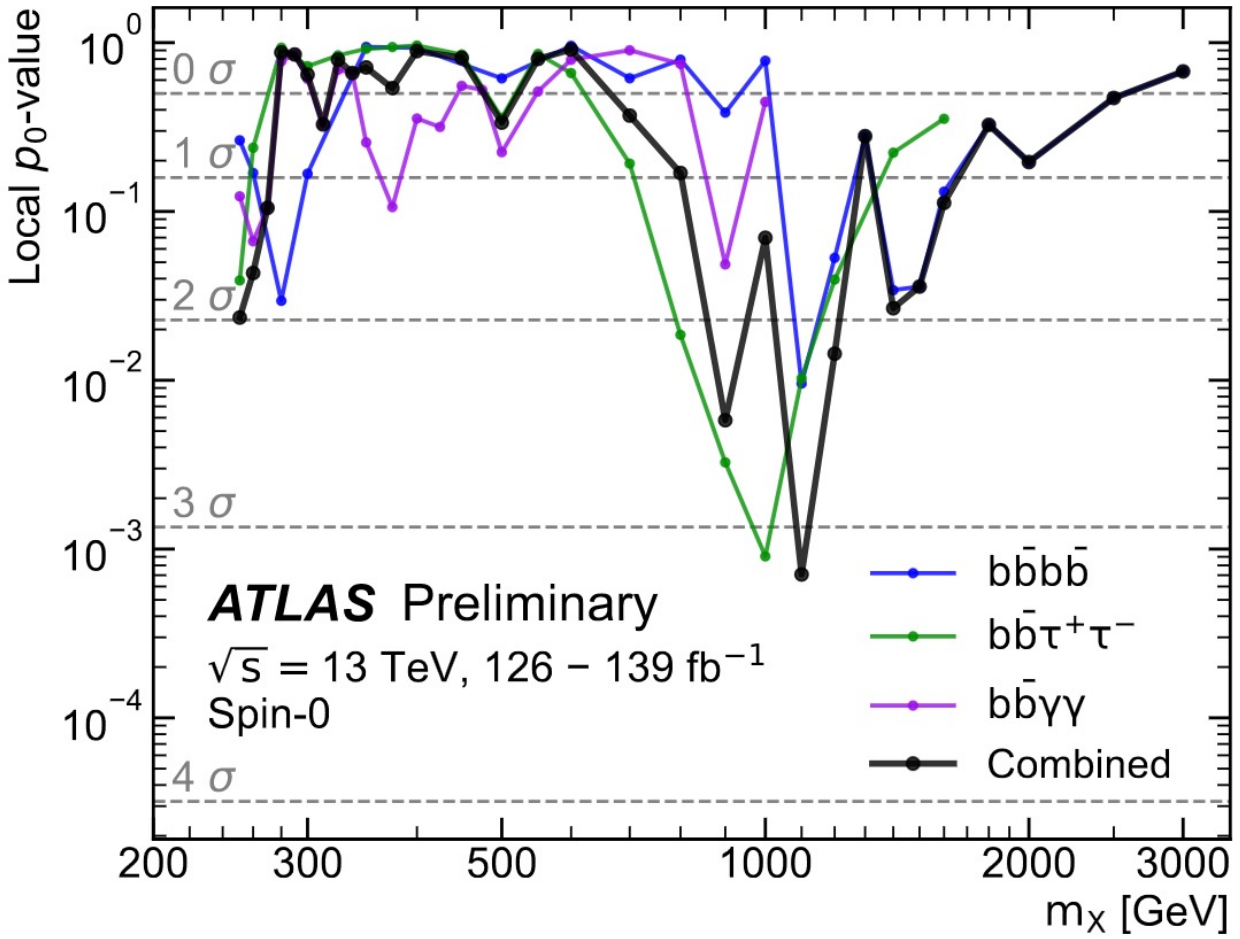
$$\mathrm{BDT_{tot}} = \frac{1}{\sqrt{C_1^2 + C_2^2}} \times \sqrt{C_1^2 \left(\frac{\mathrm{BDT}_{\gamma\gamma} + 1}{2}\right)^2 + C_2^2 \left(\frac{\mathrm{BDT}_{\mathrm{Single}H} + 1}{2}\right)^2}$$

C_1=0.65, C_2=1-C_1

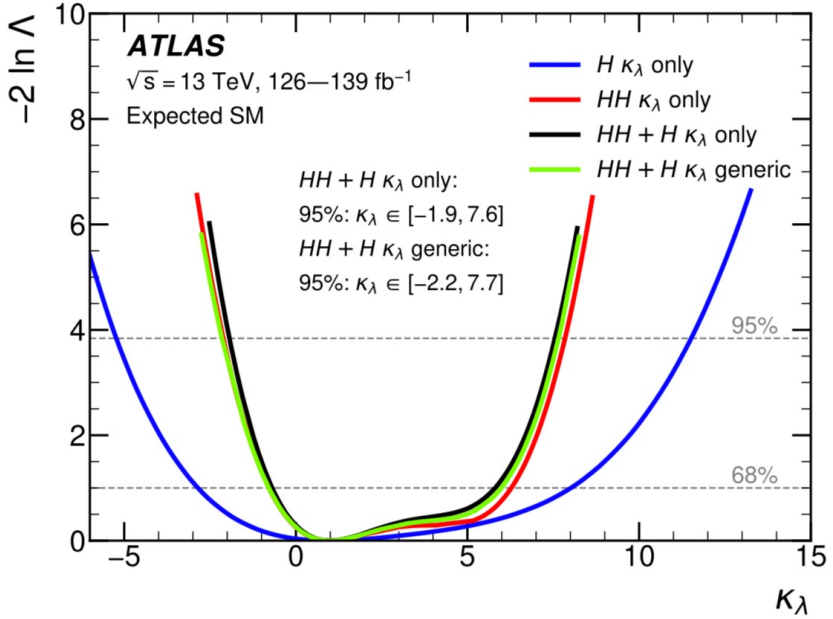


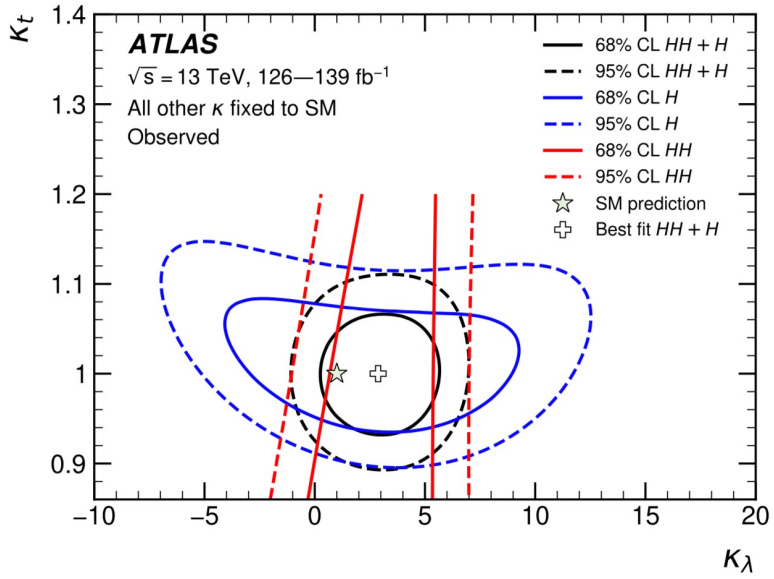


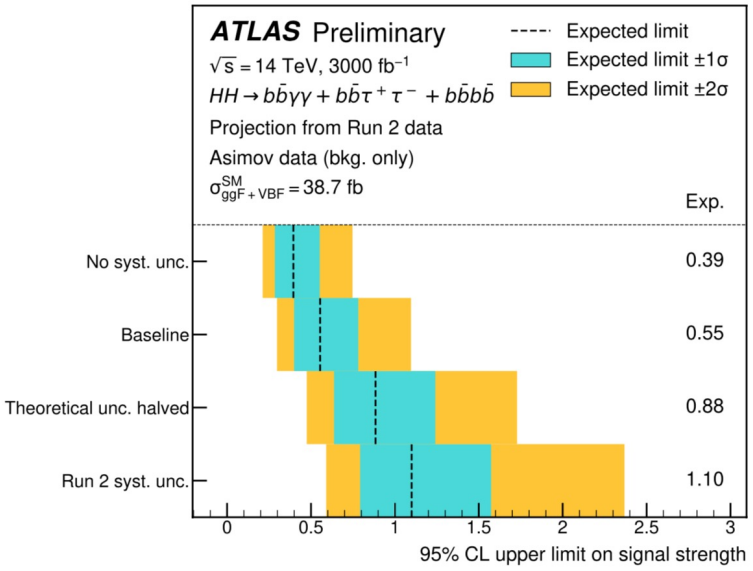
(a) ggF HH production mode

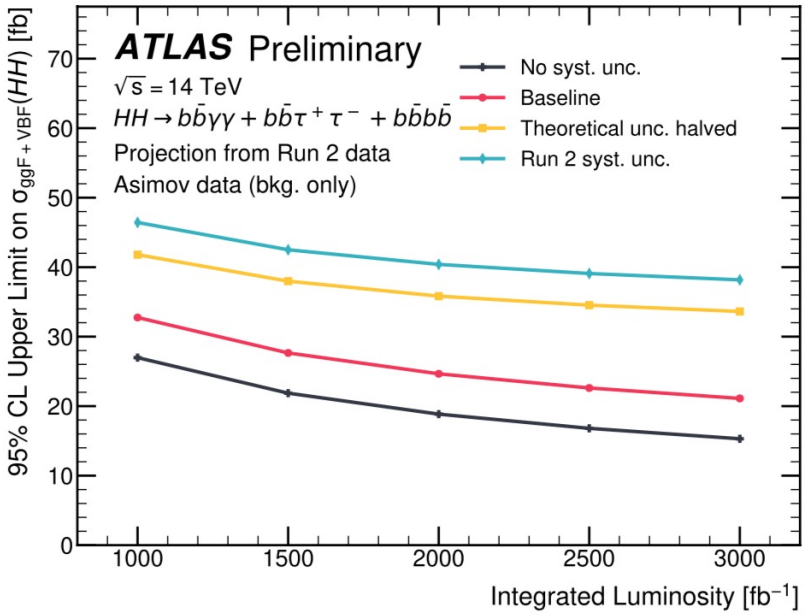


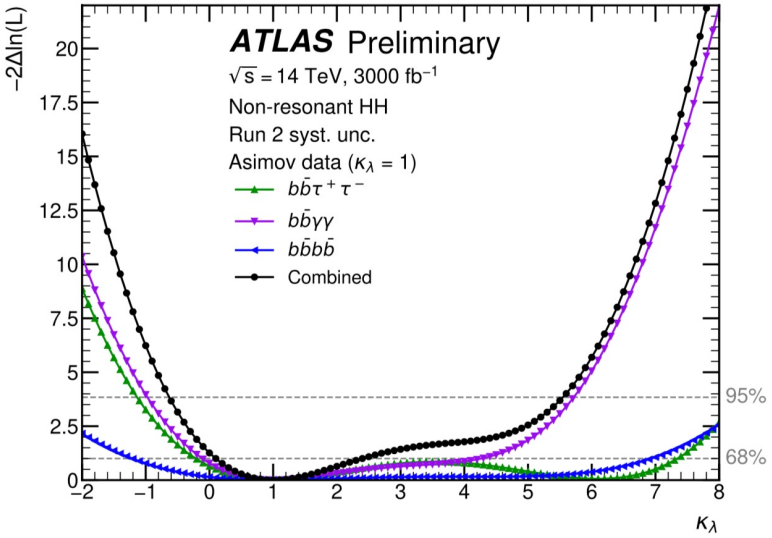
local significance: 3.2 sigma
global significance: 2.1 sigma





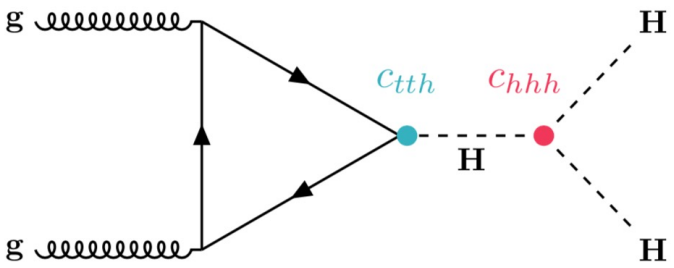


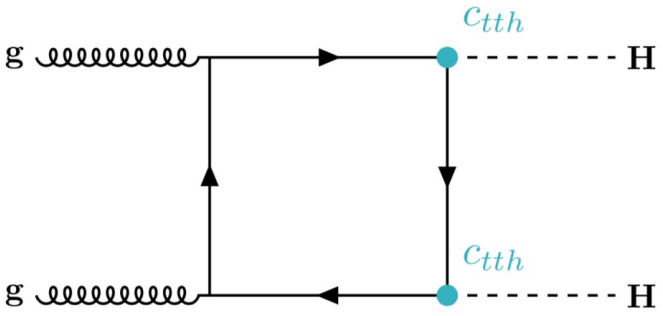


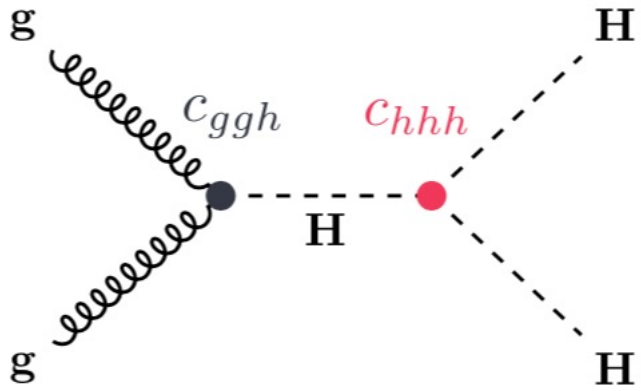


(d) Run 2 systematic uncertainties

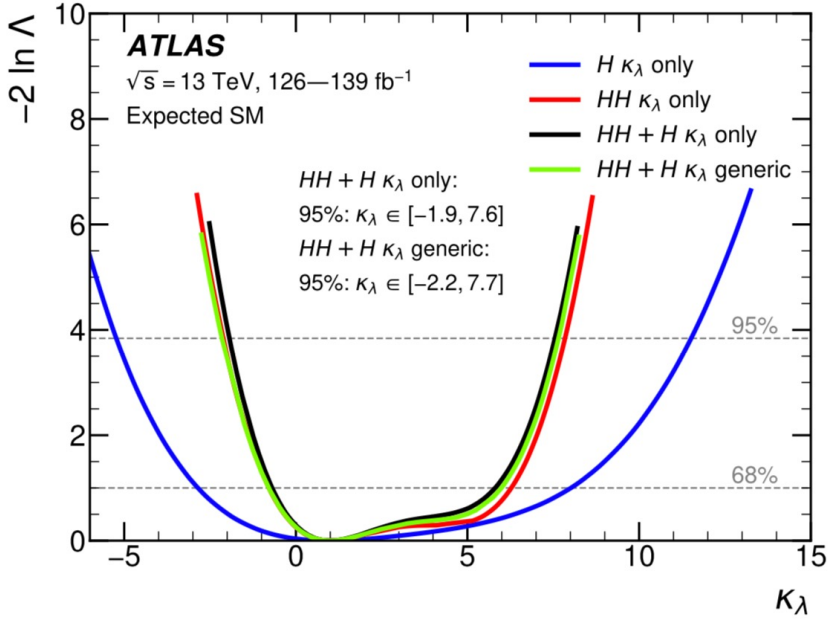
BACK UP for HEFT combination

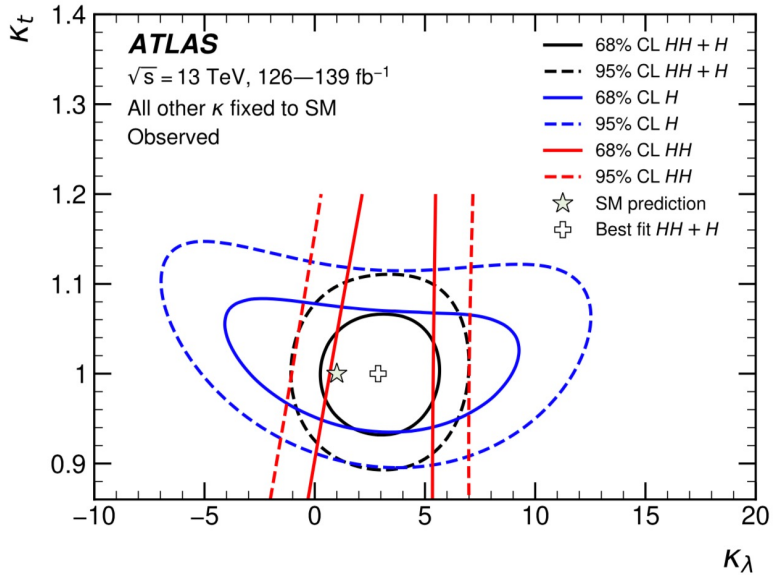


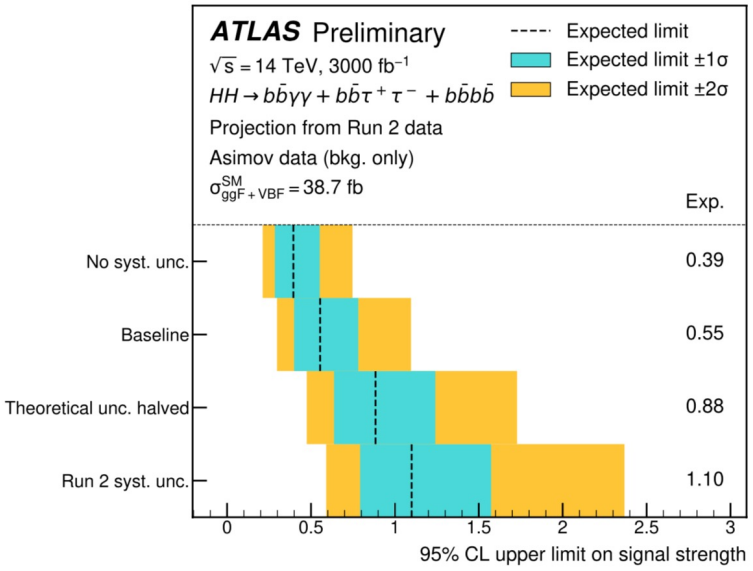


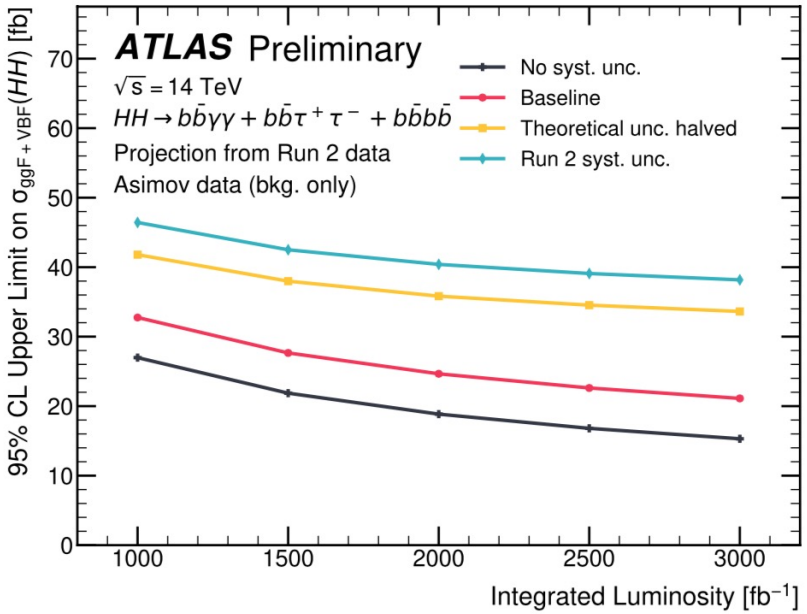


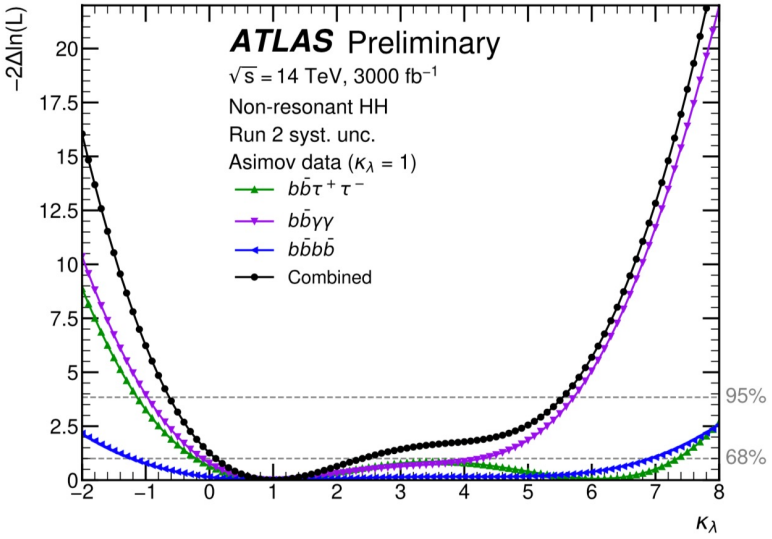
Benchmark model	c_{hhh}	c_{tth}	c_{ggh}	c_{gghh}	c_{tthh}
SM	1	1	0	0	0
BM 1	3.94	0.94	1/2	1/3	−1/3
BM 2	6.84	0.61	0.0	−1/3	1/3
BM 3	2.21	1.05	1/2	1/2	−1/3
BM 4	2.79	0.61	−1/2	1/6	1/3
BM 5	3.95	1.17	1/6	−1/2	−1/3
BM 6	5.68	0.83	−1/2	1/3	1/3
BM 7	−0.10	0.94	1/6	−1/6	1











(d) Run 2 systematic uncertainties

Overview of Higgs boson pair researches in ATLAS

	bb	WW	ττ	ZZ	$\gamma\gamma$
bb	33%				
WW	25%	4.6%			
ττ	7.4%	2.5%	0.39%		
ZZ	3.1%	1.2%	0.34%	0.076%	
$\gamma\gamma$	0.26%	0.10%	0.09%	0.013%	0.0005%