Higgs boson property measurements at the ATLAS experiment

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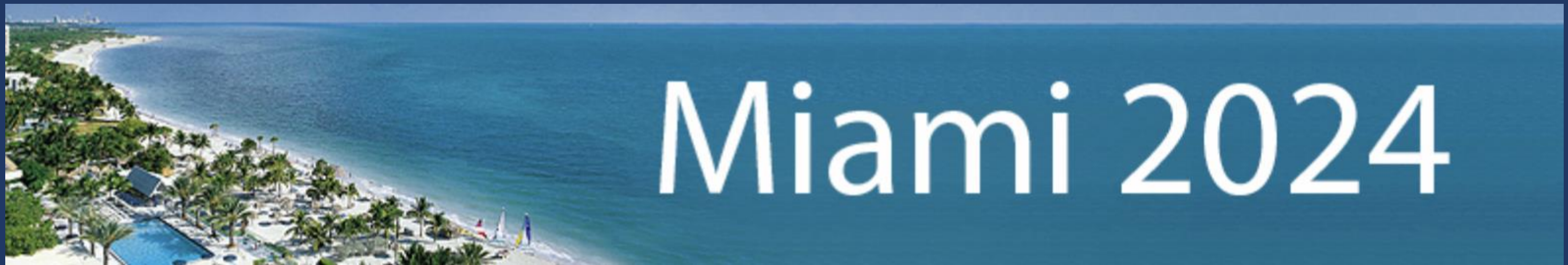
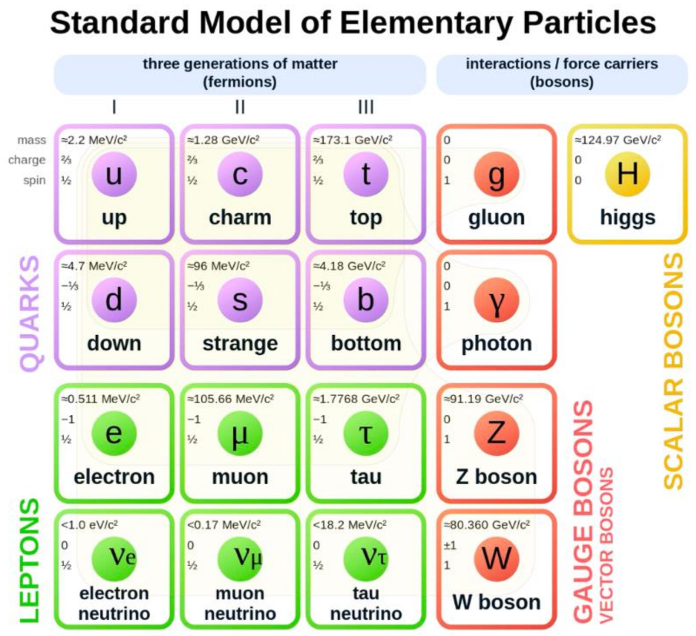
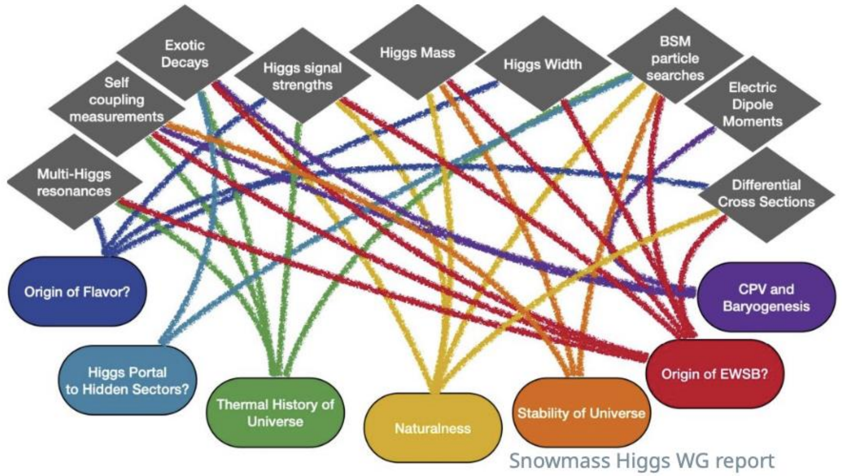
on behalf of the ATLAS collaboration



Introduction

- The Standard Model (SM) is a well-established theory defining the elementary particle content and their interaction
  - Extremely successful! Predicts vast majority of observed phenomena
- The Higgs boson is at the heart of SM
  - linked to many fundamental open questions of the nature
- The Higgs boson has a rich set of properties that can be verified experimentally → powerful test of SM and constraint of BSM physics
  - BSM can alter the Higgs boson production and decay



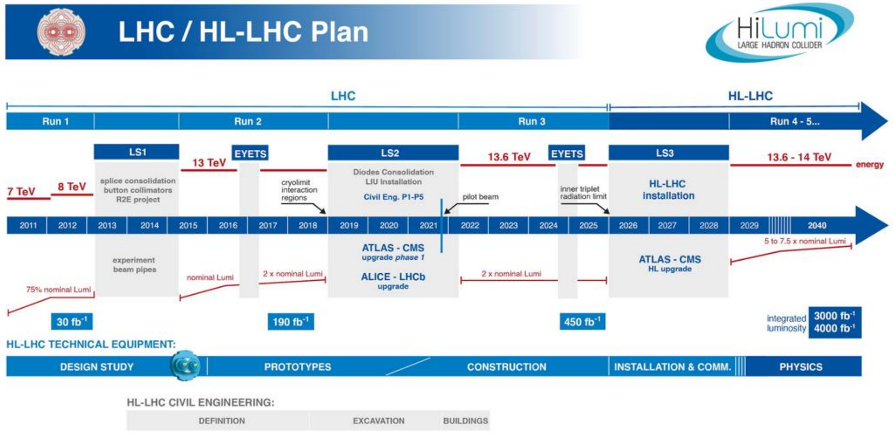


Snowmass Higgs WG report

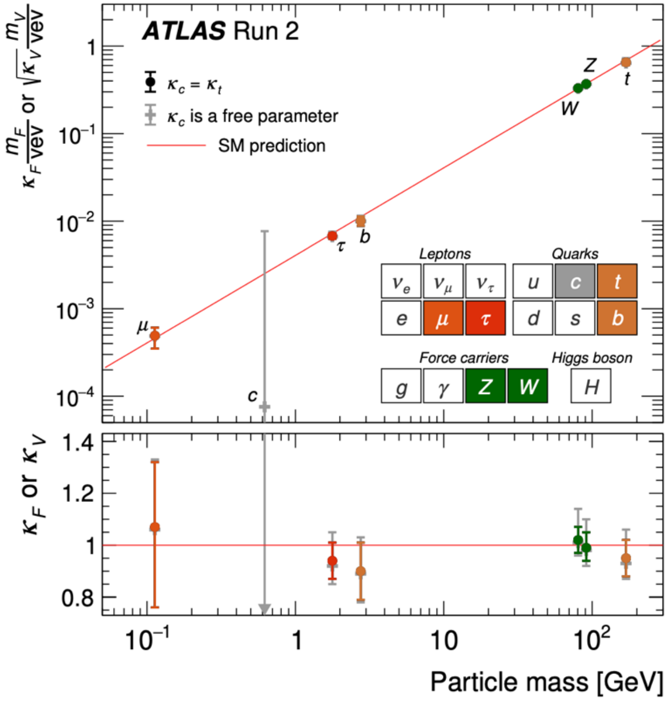
Run 2 Measurements

- Collected pp data corresponding to an integrated luminosity of 140 fb^{-1}
- Start of the precision measurements era and BSM searches!

- Major achievements in last years:
  - Observation of $H \rightarrow \tau\tau$ decay in 2016
  - Observation of $H \rightarrow bb$ decay using 2018 data
  - Observation of ttH production with different decay modes
  - Evidence for of $H \rightarrow \mu\mu$ decay
- this talk will present the recent results beyond them

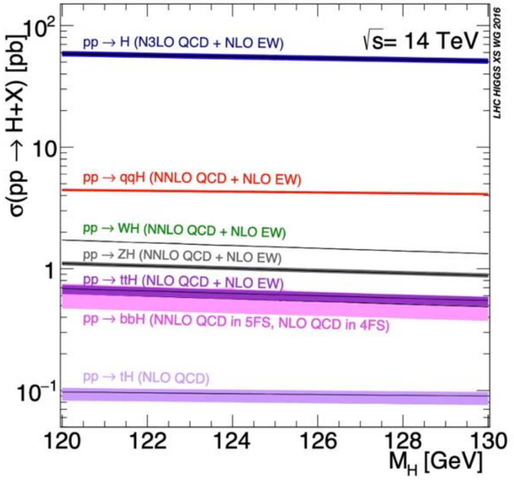


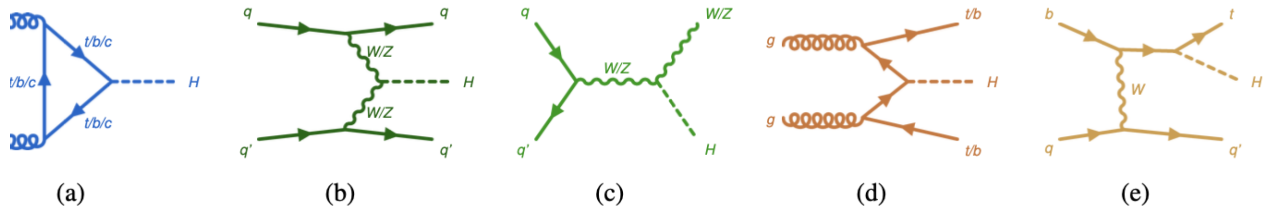
Nature 607 52 (2022)



Higgs boson production and decay

Production





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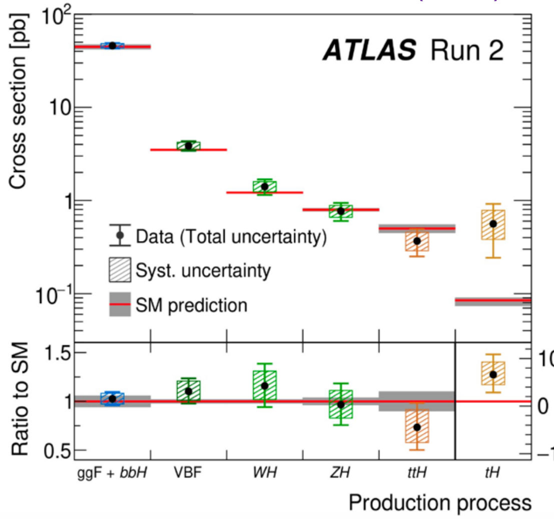
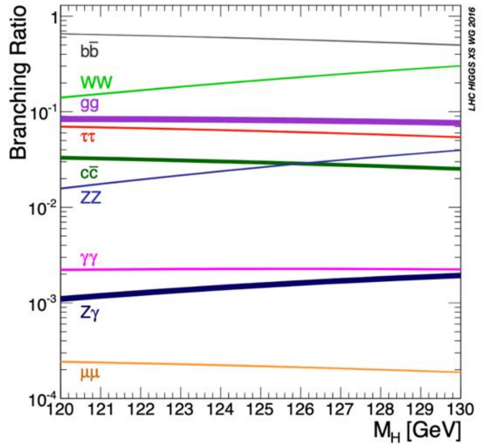
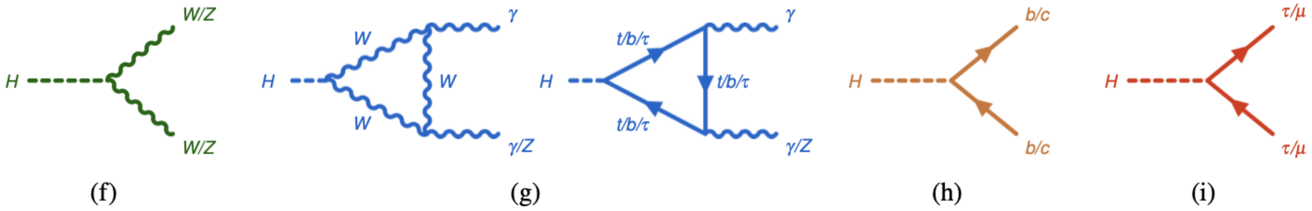


Decay





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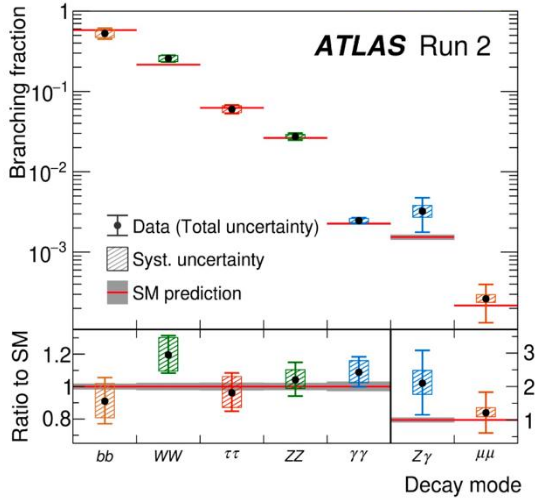
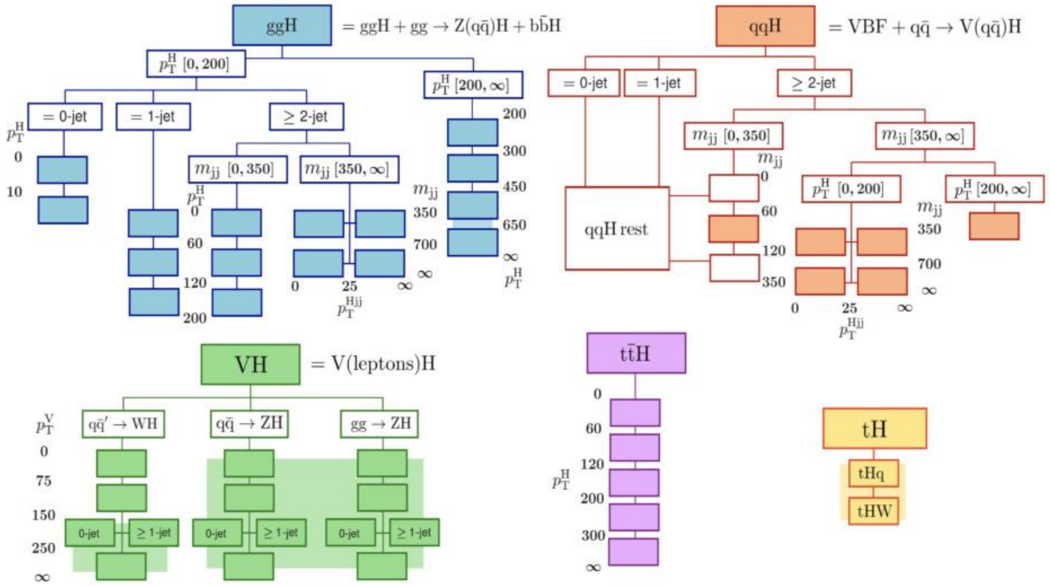


Higgs Boson Measurements

- Simplified Template Cross Sections (STXS) :
  - split production phase space in multiple regions (bins) and measure the cross-section in each
    - optimized for SM and BSM sensitivity while reducing theory dependence
    - facilitate combinations in different decay channels
  - bins can be chosen/merged depending on statistics



- K framework:
  - event rates for Higgs production and decay processes can be expressed in terms of coupling modifiers (κ) multiplying the SM Higgs coupling strengths to other particles.
  - kinematic distributions not altered

$$\sigma \cdot \mathcal{B}(i \to H \to f) = \kappa_i^2 \cdot \kappa_f^2 \cdot \sigma_i^{SM} \cdot \frac{\Gamma_f^{SM}}{\Gamma_H(\kappa_i^2, \kappa_f^2)}$$

$$\kappa_i^2 = \frac{\sigma_i}{\sigma_i^{SM}} \quad \text{and} \quad \kappa_f^2 = \frac{\Gamma_f}{\Gamma_f^{SM}}$$

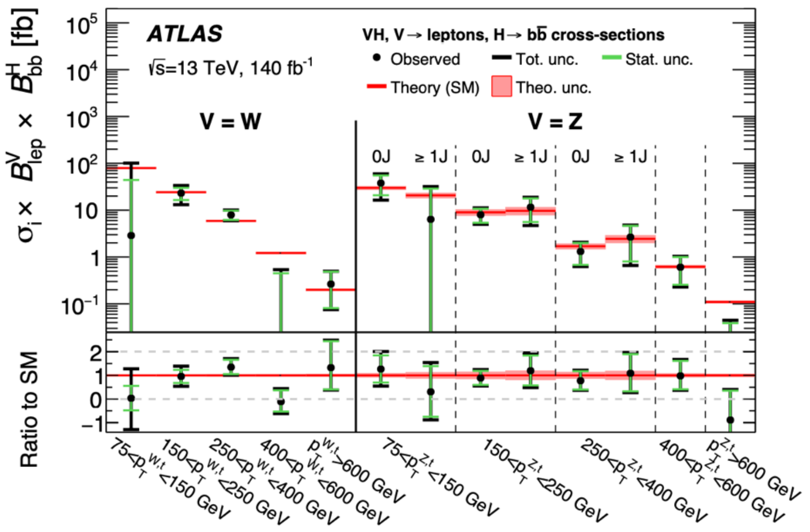
- In addition to :
  - inclusive measurements (cross sections, signal strenghts)
  - unfolded/fiducial/differential measurements

VH production, H→bb and H→cc decay

The individual production of WH and ZH with $H \to b\bar{b}$ is established with observed (expected) significances of **5.3** (5.5) and **4.9** (5.6) respectively

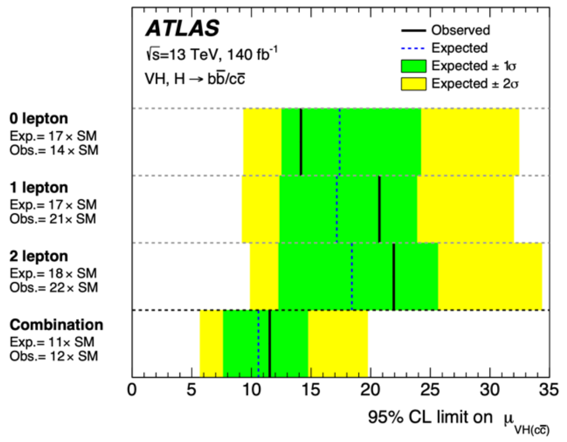
H→bb differential measurements (STXS) in 13 kinematical fiducial region!

arXiv:2410.19611



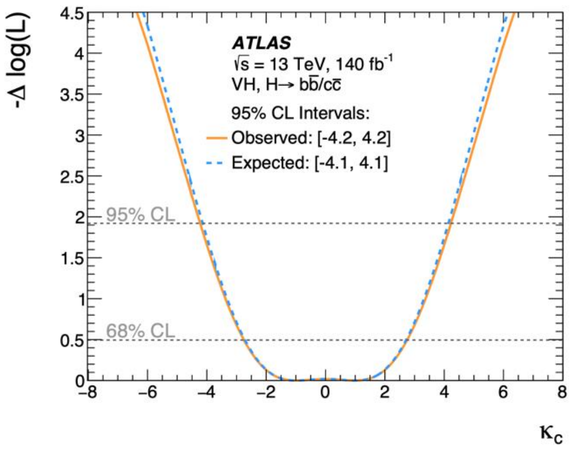
The search for the $H \to c\bar{c}$ decay yields an observed (expected) upper limit of **11.5** (10.6) times the SM prediction at 95% CL

arXiv:2410.19611



$\mu^{cc} < 11.5$ at 95% CL

arXiv:2410.19611



$|\kappa_c| < 4.2$ at 95% CL

Improved RUN2 measurement : uncertainties improved by 15% for $H \to b\bar{b}$ and ~3 for $H \to c\bar{c}$ compared with the previous ATLAS results.

BONUS: $VZ, Z \to c\bar{c}$ process observed with a significance > 5σ

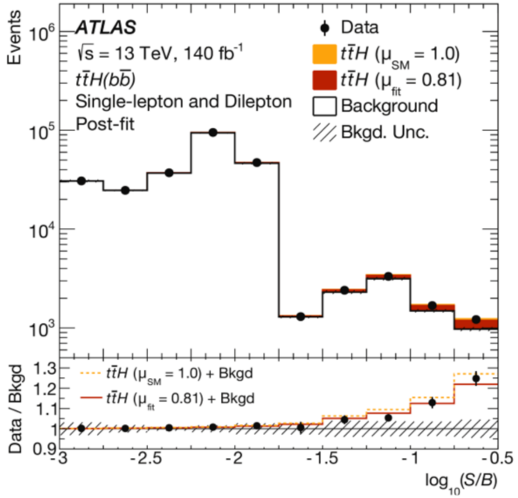
ttH production, H→bb decay

- Test of the top Yukawa coupling

- 1 or 2 lepton final states
- Improved Run2 measurement of a factor ~2 on the expected ttH significance compared to the previous result
- improved b-jet identification → 3X signal acceptance on the same dataset
- better modelling of tt+jets background and use of signal/bkg control regions based on multiclass neural network

- observed (expected) significance of 4.6 (5.4)
- cross secton 411 ± 54(stat.) $^{+85}_{-75}$ fb in agreement with SM
  - dominated by the systematic uncertainties from the ttH signal modelling and from tt+ jets background modelling.
  - Overall uncertainty improved by factor 1.8

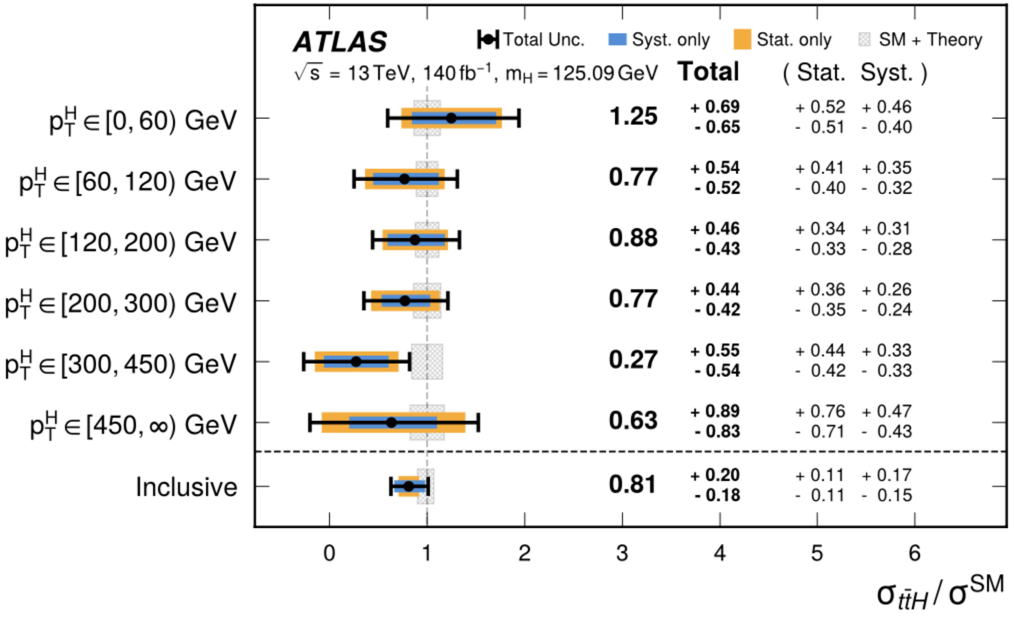
- up to date, most precise ttH cross-section measurement in a single decay channel, inclusively and in STXS



arXiv:2407.10904

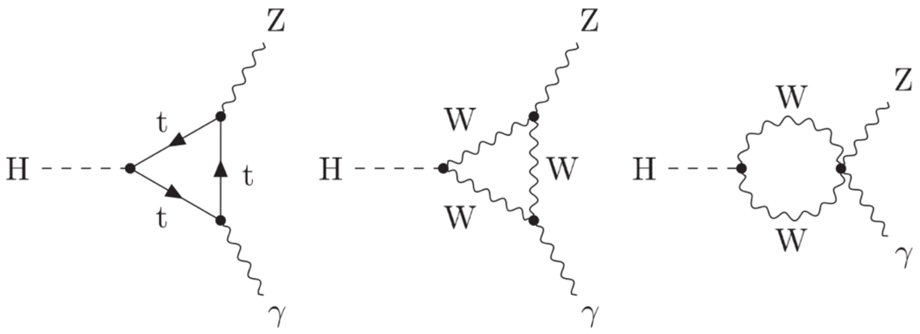
cross-section is also measured differentially in bins of the Higgs boson transverse momentum within STXS

arXiv:2407.10904

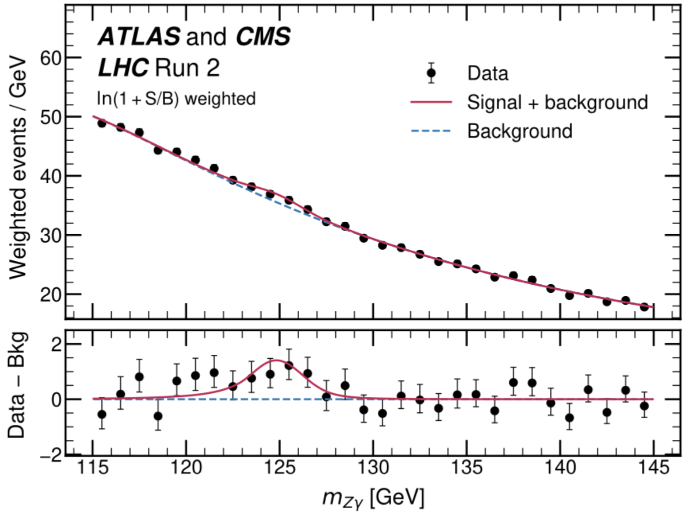


Evidence of H→ $Z\gamma$ Rare Decay (ATLAS+CMS)

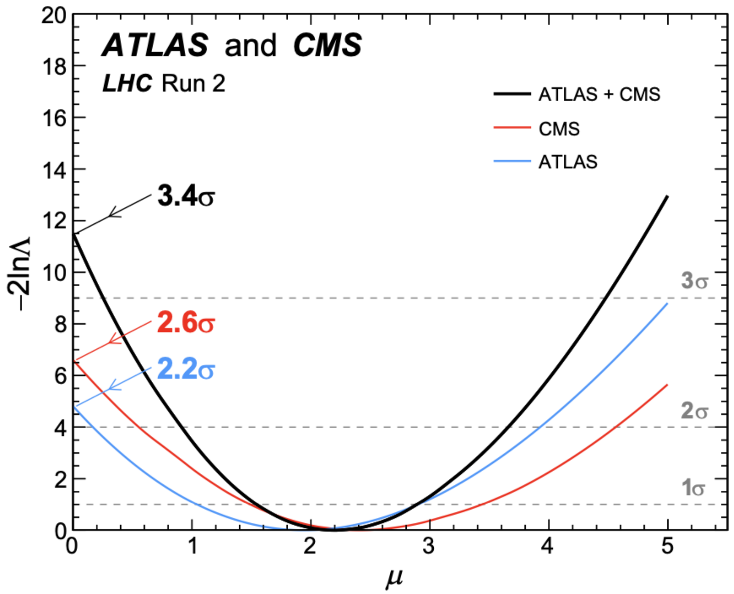
- SM branching ratio ~ 1.5×10^{-3}
- occurs via loop diagrams→sensitive to BSM physics
- ATLAS+CMS combination gives 3.4σ evidence
- $\mu = 2.0^{+1.0}_{-0.9}$ (ATLAS) $\mu = 2.4^{+1.0}_{-0.9}$ (CMS),
- Combined $\mu = 2.2 \pm 0.6(stat)^{+0.3}_{-0.2}(sys)$
  - expected: $1.0 \pm 0.6(stat) \pm 0.2(sys)$
- measured H → Zγ BR $(3.4 \pm 1.1) \times 10^{-3}$



Phys. Rev. Lett. 132 (2024) 021803



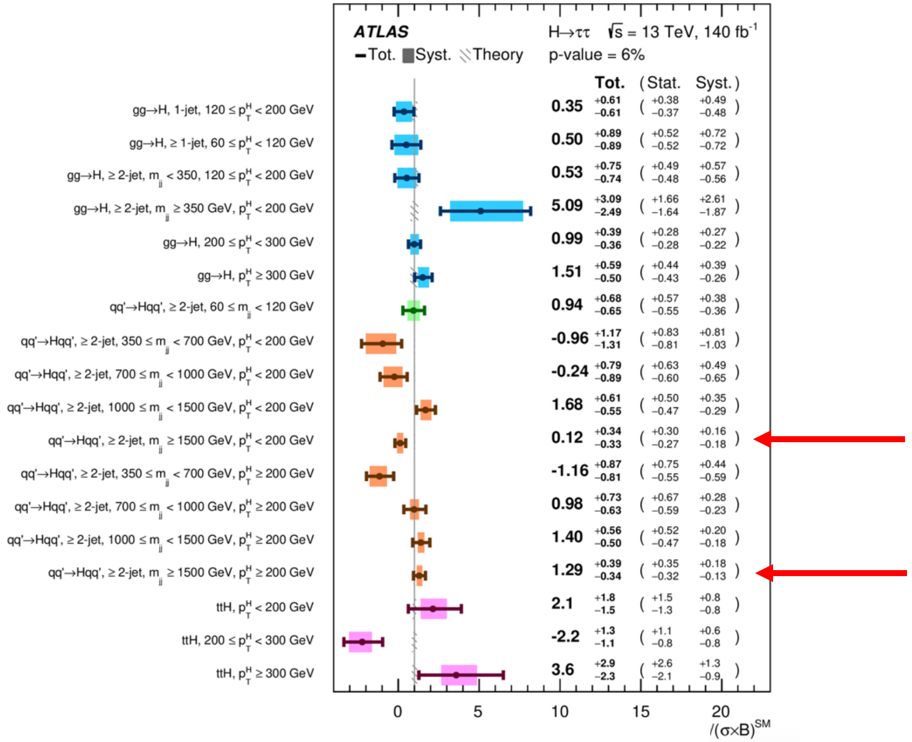
Phys. Rev. Lett. 132 (2024) 021803



H→ττ Differential Measurements

- STXS and VBF fiducial unfolded differential measurement
  - first VBF measurement for the higher-pT criteria, and the most precise for the lower-pT criteria
  - VBF enhanced differential fiducial measurements precision 25%–50%, in agreement with SM, and interpretation in the SMEFT framework
  - CP: strongest constraints to date on the CP-odd Wilson coefficient $c_{WH\sim}$

arXiv:2407.16320



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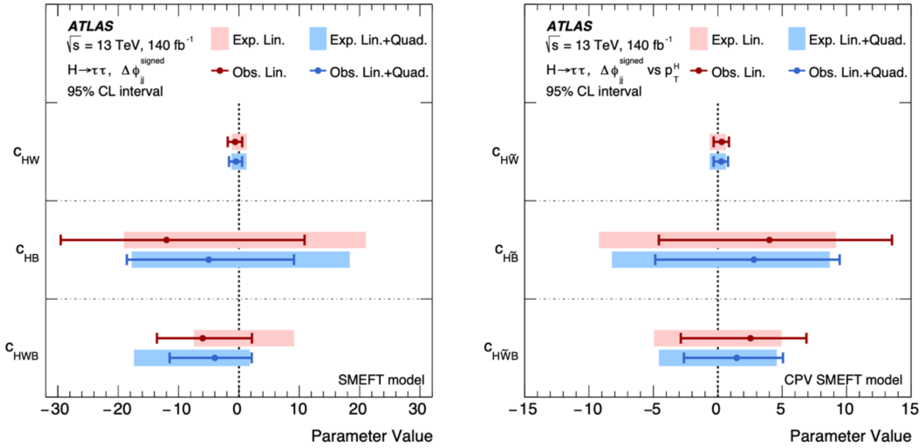
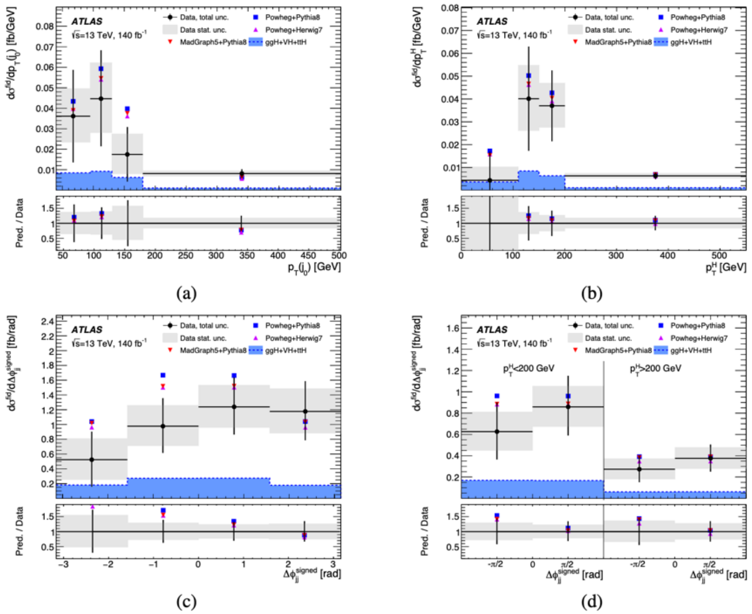




arXiv:2407.16320

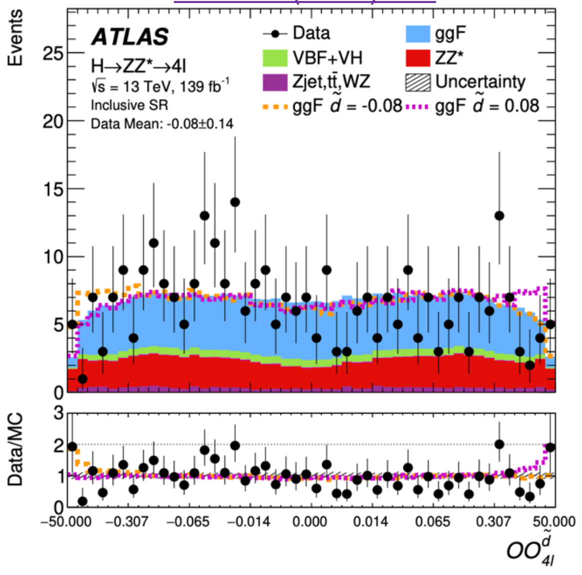
CP: $H \to ZZ^* \to 4\ell$

- Goal is to probe the coupling strength of CP-odd operators(CP-violation) in VBF production and 4l decay
    - 4 VBF signal regions based on output score of a NN discriminant

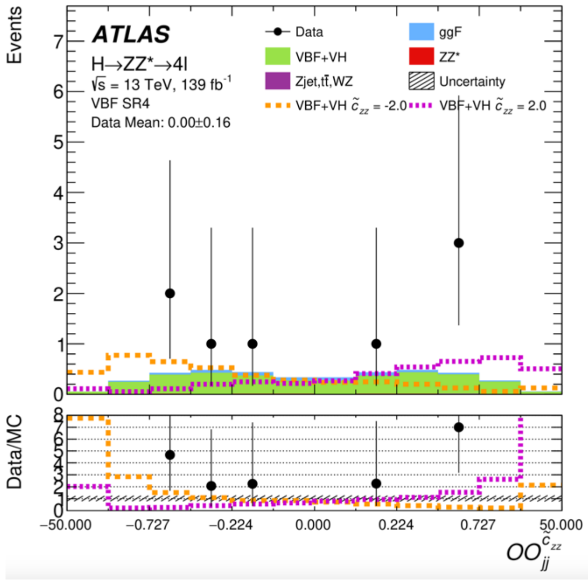
- SMEFT framework
- Build optimal observables (OO)
    - differential cross-section measurements

- Good agreement between data and SM expectation

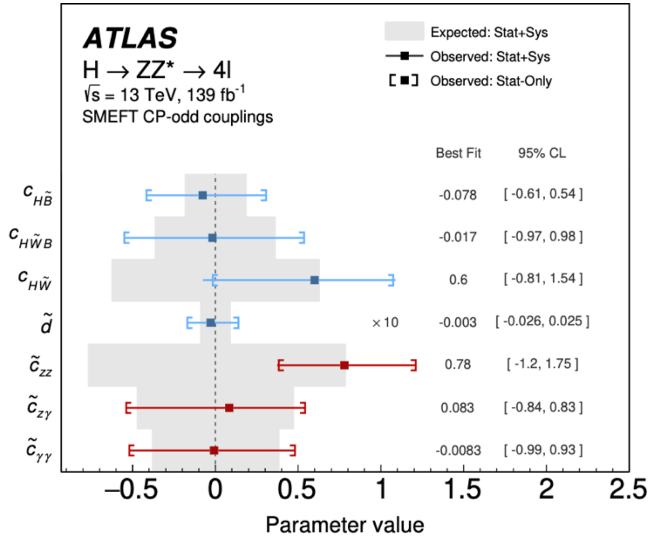
JHEP 05 (2024) 105



JHEP 05 (2024) 105



JHEP 05 (2024) 105



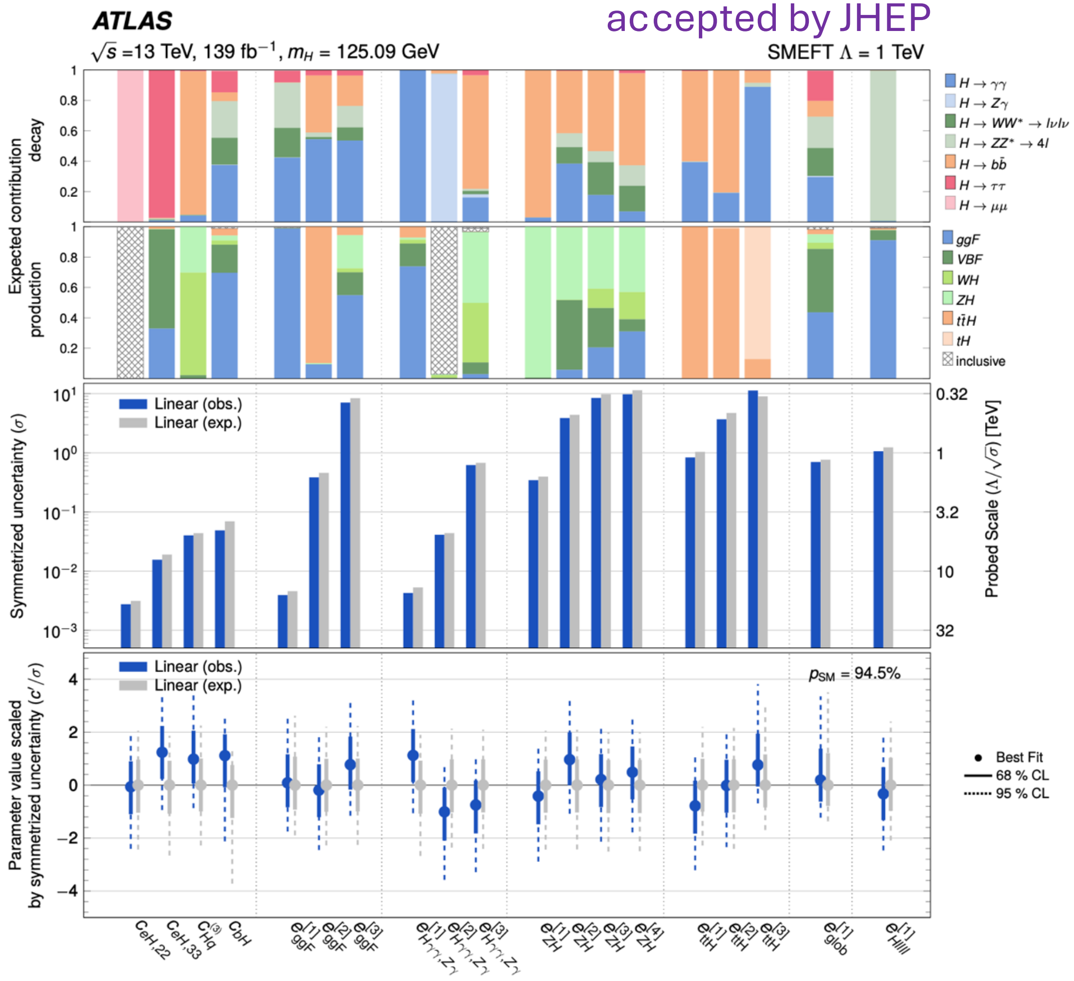
Combined Interpretation in SMEFT

- Production, STXS and fiducial differential cross-sections in different decay channels re-parameterised in SMEFT operators
- constraints on linear combinations of dim-6 Wilson coefficients in the Warsaw basis
- no significant deviations from SM

arXiv:2402.05742v1
accepted by JHEP

Decay channel	Analysis Production mode	$\mathcal{L}$ [fb^{-1}]	Reference	Binning	SMEFT	2HDM and (h)MSSM
$H \to \gamma\gamma$	$(ggF, VBF, WH, ZH, ttH, tH)$	139	[25] [21]	STXS-1.2 differential	✓ ✓(subset)	✓
$H \to ZZ^*$	$(ZZ^* \to 4\ell$: ggF, VBF, $WH+ZH$, $ttH+tH)$	139	[24] [20]	STXS-1.2 differential	✓ ✓(subset)	✓
	$(ZZ^* \to \ell\ell\nu\bar{\nu}/\ell\ell q\bar{q}$: ttH multileptons)	36.1	[36]	STXS-0*		✓
$H \to \tau\tau$	(ggF, VBF, $WH+ZH$, $ttH+tH$)	139	[31]	STXS-1.2	✓	✓
	(ttH multileptons)	36.1	[36]	STXS-0*		✓
$H \to WW^*$	(ggF, VBF)	139	[32]	STXS-1.2	✓	✓
	(WH, ZH)	36.1	[48]	STXS-0*		✓
	(ttH multileptons)	36.1	[36]	STXS-0*		✓
$H \to bb$	(WH, ZH)	139	[26, 27]	STXS-1.2	✓	✓
	(VBF)	126	[28]	STXS-1.2	✓	✓
	($ttH+tH$)	139	[30]	STXS-1.2	✓	✓
	(boosted Higgs bosons: inclusive production)	139	[29]	STXS-1.2	✓	✓
$H \to Z\gamma$	(inclusive production)	139	[33]	STXS-0*	✓	✓
$H \to \mu\mu$	(ggF + $ttH+tH$, VBF + $WH+ZH$)	139	[34]	STXS-0*	✓	✓

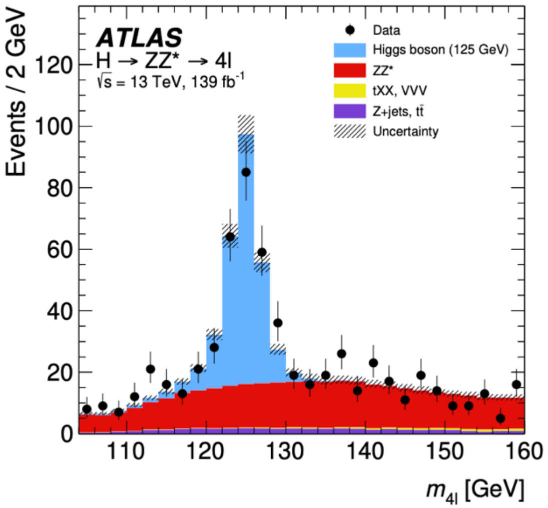
arXiv:2402.05742
accepted by JHEP



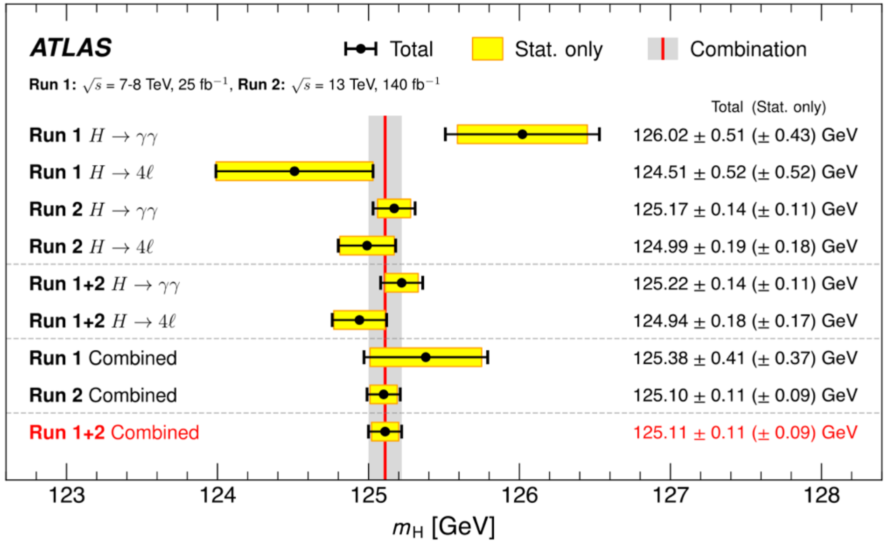
Higgs Boson Mass

- Processes for mass measurements :
  - $H \rightarrow ZZ \rightarrow 4l$, dominated from statistical uncertainties, clean final state
  - $H \rightarrow \gamma\gamma$, high statistics, uncertainty from photon energy calibration, reduced by a factor ~4
- precision on $m_H < 0.1\%$!

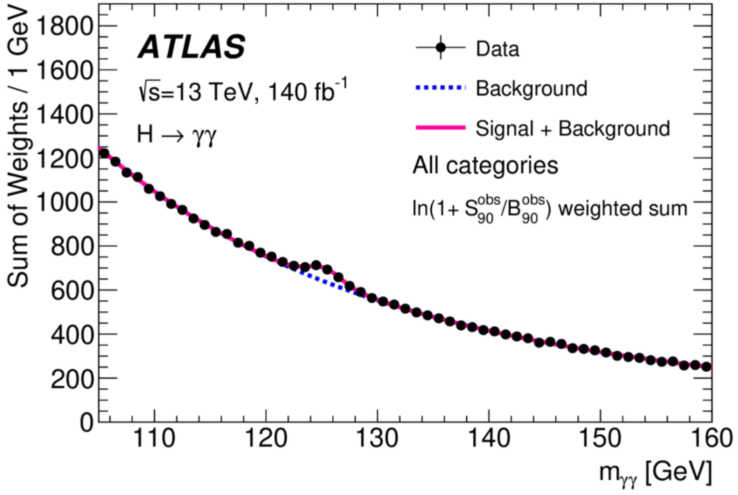
Phys Lett. B 843 (2023) 137880



Phys. Rev. Lett. 131 (2023) 251802

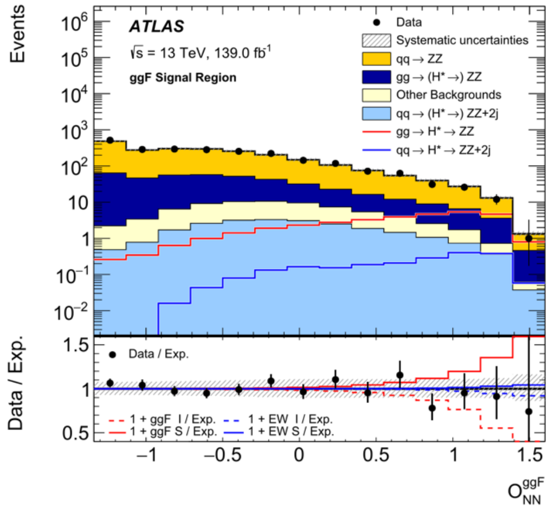


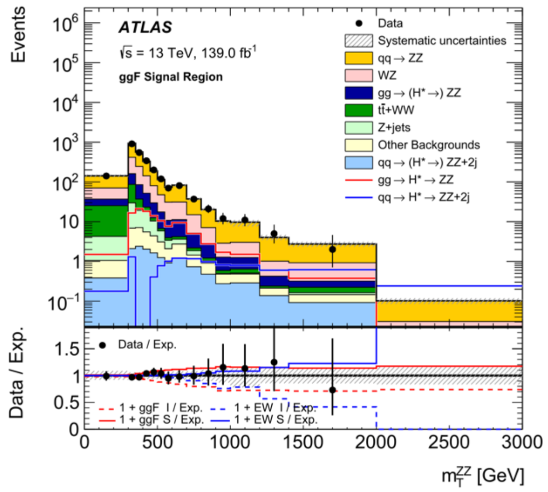
Phys. Lett. B 847 (2023) 138315



Higgs Boson Width

Phys. Lett. B 846 (2023) 138223



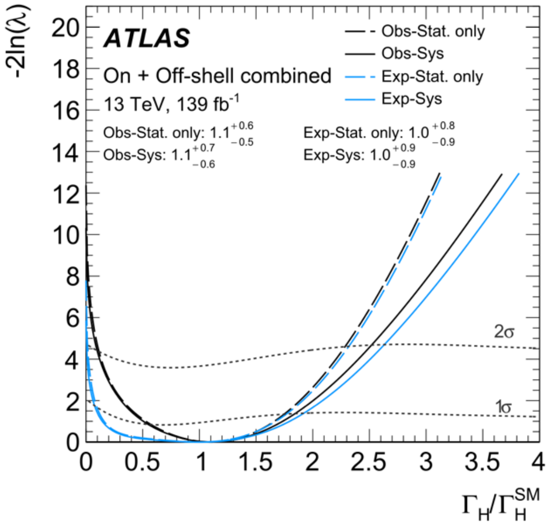


Phys. Lett. B 846 (2023) 138223

- SM prediction Γ_H = 4.1 MeV too small to be measured directly
- Measured from H→ZZ→4l on-shell/off-shell comparison
  - relies on on-shell/off-shell couplings being the same
- Off-shell analysis performed in 4l and 2l2v channels
  - use of Neural Network to enhance the analysis sensitivity in 4l channel

$$\sigma^{\text{off-shell}}_{gg\to H\to ZZ} \sim \frac{g^2_{\text{ggF}} g^2_{\text{HZZ}}}{m^2_{ZZ}} \qquad \sigma^{\text{on-shell}}_{gg\to H\to ZZ} \sim \frac{g^2_{\text{ggF}} g^2_{\text{HZZ}}}{m_H \Gamma_H}$$

$$\Gamma_H \propto \frac{\sigma_{gg\to H^*\to ZZ}}{\sigma_{gg\to H\to ZZ^*}}$$

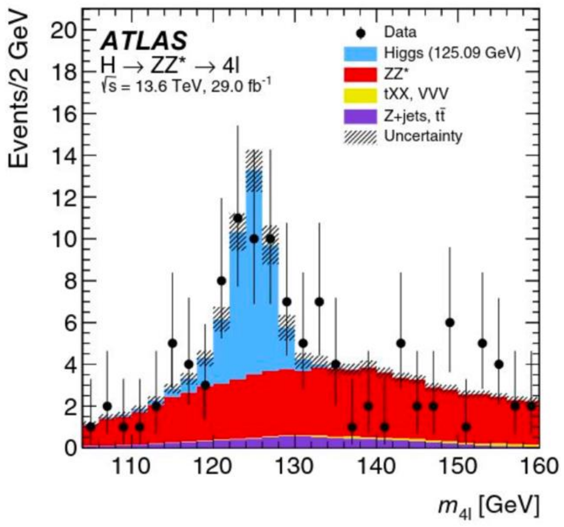


- $\Gamma_H = 4.5^{+3.3}_{-2.5}$ MeV
  - Uncertainty from theoretical modelling of signal and backgrounds is the dominant systematic
- 3.3σ evidence of Higgs off-shell production

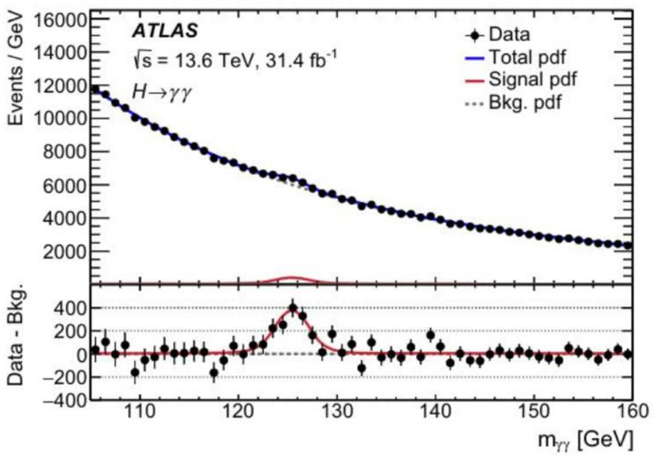
Run3 Measurements at 13.6 TeV

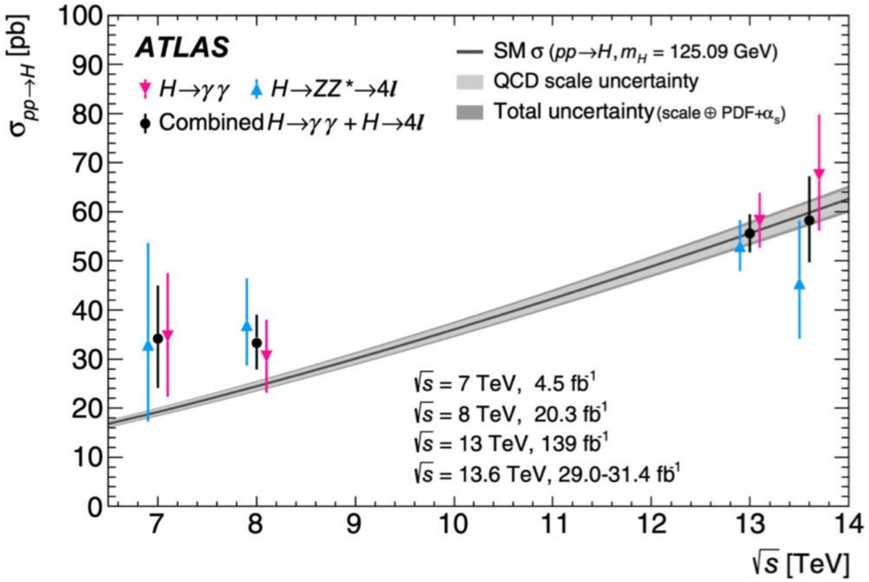
- H→ γγ and H→ 4l channels
- can add to Run 1, Run 2 and show cross-section as a function of center of mass energy
- Good agreement with SM predictions!

Eur. Phys. J. C 84, 78 (2024)



Eur. Phys. J. C 84, 78 (2024)

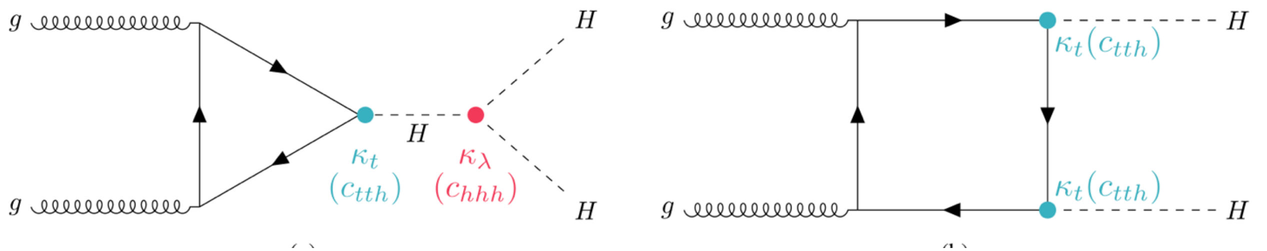




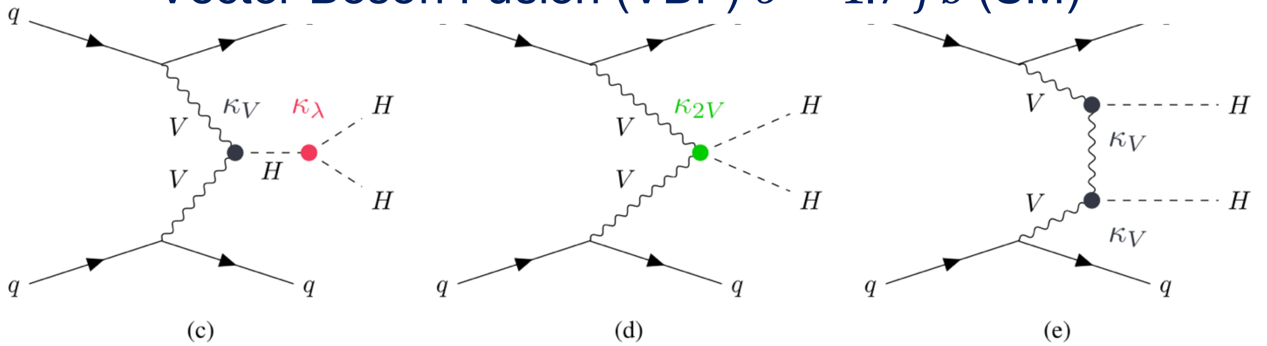
HH production & decay

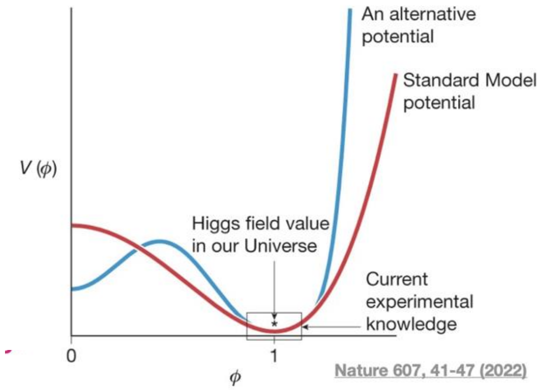
- HH production not yet observed experimentally
- measurement of the H boson self couplings
  - provides information on the shape of the Higgs potential
- HHH (k_λ) and VVHH (K_{2V}) couplings accessible via HH production
  - Kappa framework: parametrize the Higgs boson couplings as the ratio to the SM prediction

gluon-gluon Fusion (ggF) $\sigma = 31\ fb$ (SM)



Vector Boson Fusion (VBF) $\sigma = 1.7\ fb$ (SM)



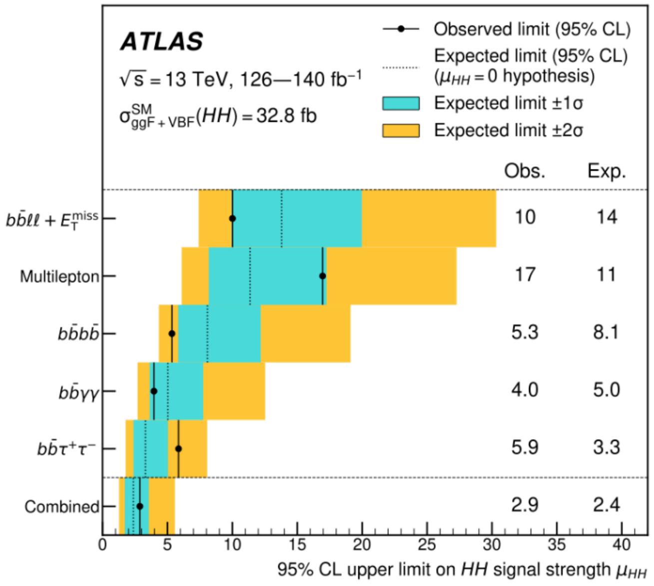


HH decay Mode

	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%

HH Combination

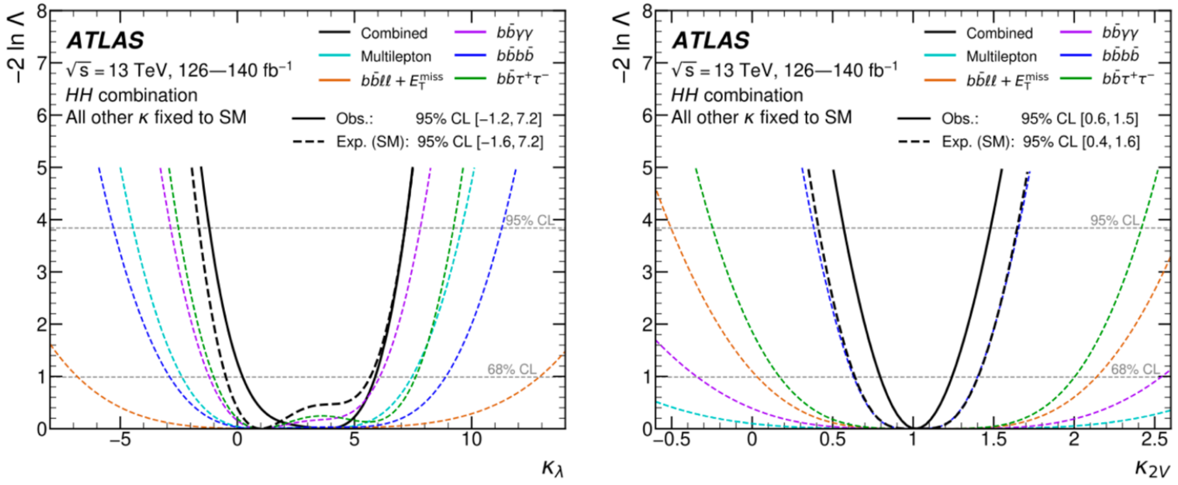
Phys. Rev. Lett. 133 (2024) 101801



- Channels:
  - $HH \to bb\gamma\gamma$,
  - $HH \to bb\tau+\tau-$,
  - $HH \to bbbb$,
  - $HH \to 2b + 2\ell + ETmiss$,
  - $HH \to Multilepton$

- μ_{HH} < 2.9 at 95% CL (2.4 expected assuming no Higgs boson pair production)
- $-1.2 < \kappa_\lambda < 7.2$ @ 95% CL
  - Expected: $-1.6 < \kappa_\lambda < 7.2$
- $0.6 < \kappa_{2V} < 1.5$ @ 95% CL
  - Expected: $0.4 < \kappa_{2V} < 1.6$

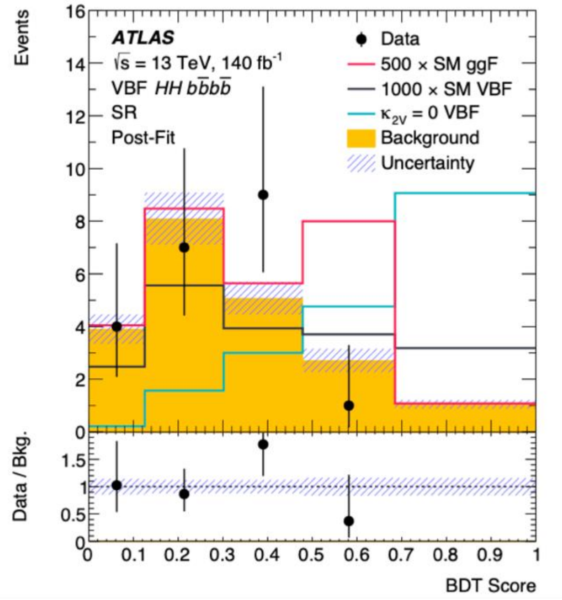
Phys. Rev. Lett. 133 (2024) 101801



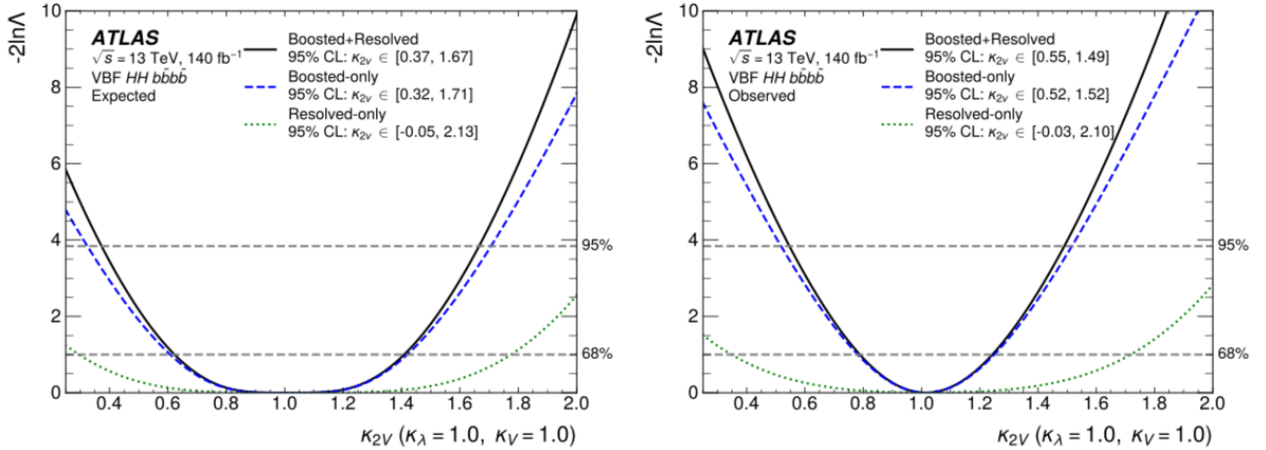
HH→bbbb via VBF (boosted)

- VBF signature is an handle for bkg suppression
- Higgs candidates reconstructed as a single large-radius jet
- sensitive to the quartic coupling between two vector bosons and two Higgs → strong sensitivity to k_{2V}
  - large boost when k_{2V} deviates from SM
- combined with the resolved analysis [Phys. Rev. D 108 (2023) 052003]
  - b-quarks are reconstructed as small-R jets
- 0.55 < κ_{2V} < 1.49 at the 95% CL
  - (expected: 0.37 < κ_{2V} < 1.67)
- NULL value excluded with a significance of 3.8σ

Phys. Lett. B 858 (2024) 139007



Phys. Lett. B 858 (2024) 139007

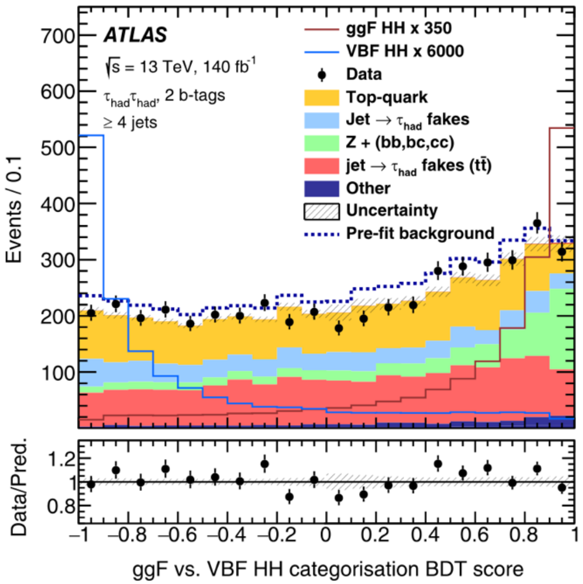


HH→bbττ

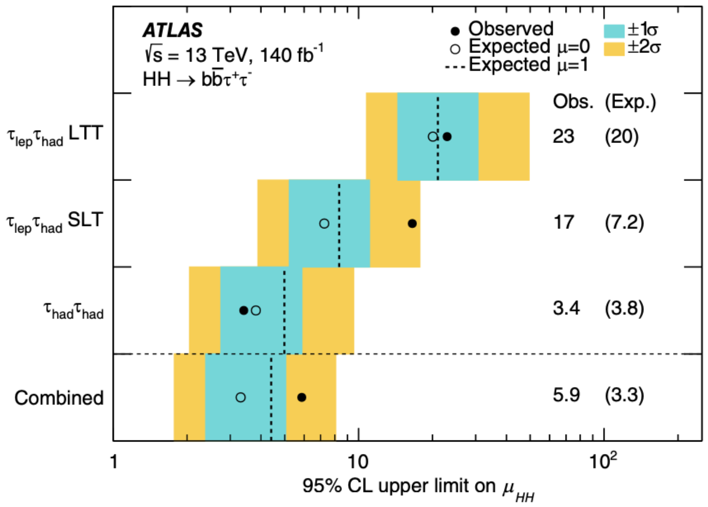
- combines fully hadronic (dominant) and semi-leptonic decay channels
- BDT discriminant in each SR to discriminate ggF/VBF productions and background
    - optimized to enhance the sensitivity to κ_λ and to VBF
    - improvement ~15% wrt previous analysis

- $\mu_{HH} < 5.9$ (3.3 expected) at 95% CL
- $-3.1 < \kappa_\lambda < 9.0$,
  $-0.5 < \kappa_{2V} < 2.7$ at 95% CL
    - expected : $-2.5 < \kappa_\lambda < 9.3$, $-0.2 < \kappa_{2V} < 2.4$

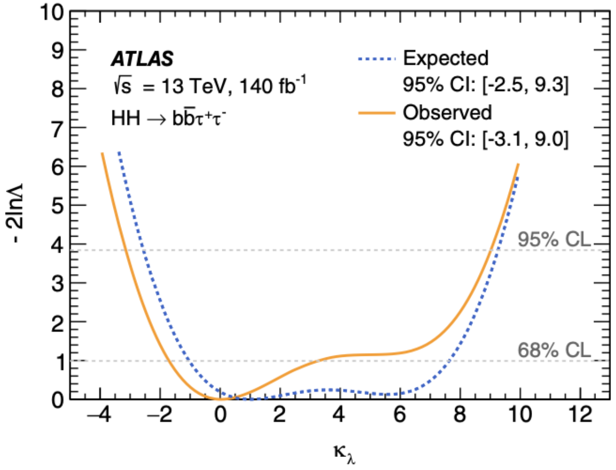
Phys. Rev. D 110 (2024) 032012



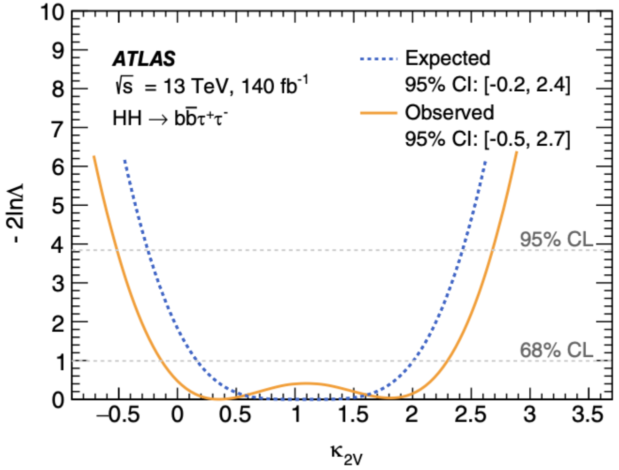
Phys. Rev. D 110 (2024) 032012



Phys. Rev. D 110 (2024) 032012



Phys. Rev. D 110 (2024) 032012

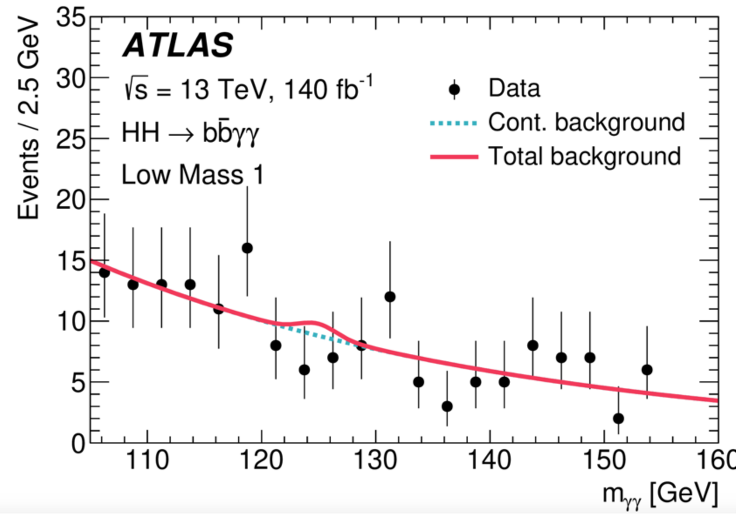


HH→ bbγγ

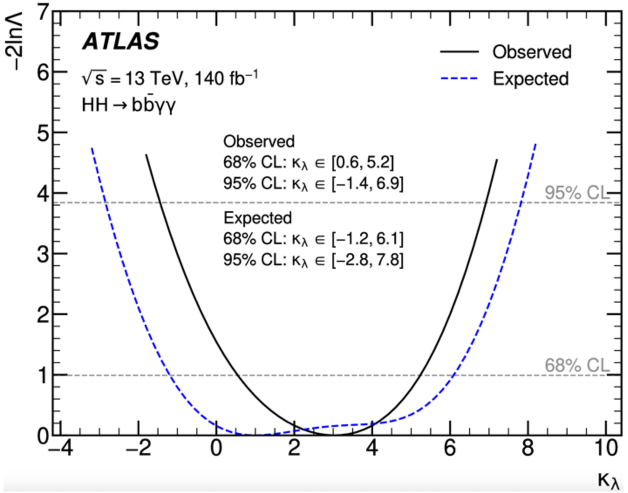
- Tiny branching ratio but very clean signature:
  - excellent $m_{\gamma\gamma}$ resolution
  - small backgrounds
- 7 event categories based on $m_{bb\gamma\gamma}$ and BDT classification
  - sensitivity increased by 6% (κ_λ) –17% (κ_{2V}) wrt previous analysis
- Fit $\boldsymbol{m_{\gamma\gamma}}$ in each category

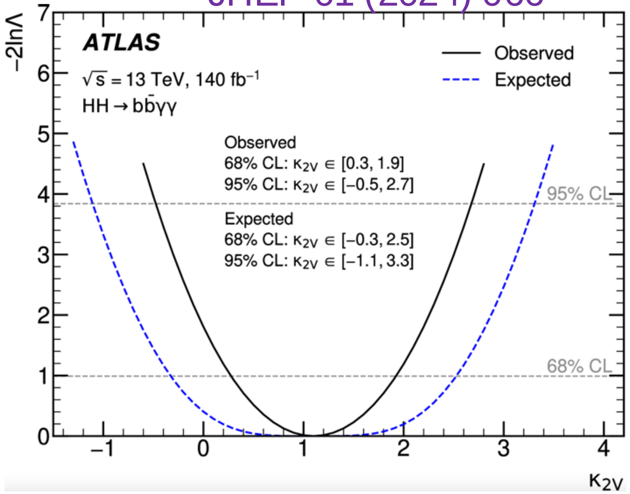
- μ_{HH} < 4.0 (5.0 expected) @ 95% CL
- observed: −1.4 < κ_λ < 6.9 @ 95% CL
  - expected: −2.8 < κ_λ < 7.8
- observed: −0.5 < κ_{2V} < 2.7 @ 95% CL
  - expected: −1.1 < κ_{2V} < 3.3

JHEP 01 (2024) 066

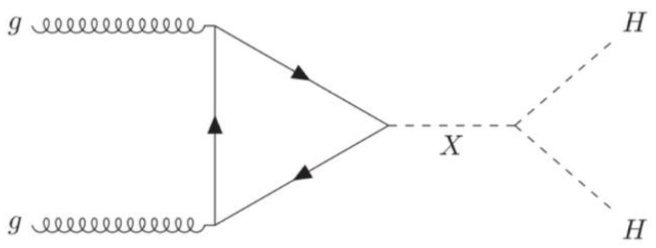


JHEP 01 (2024) 066





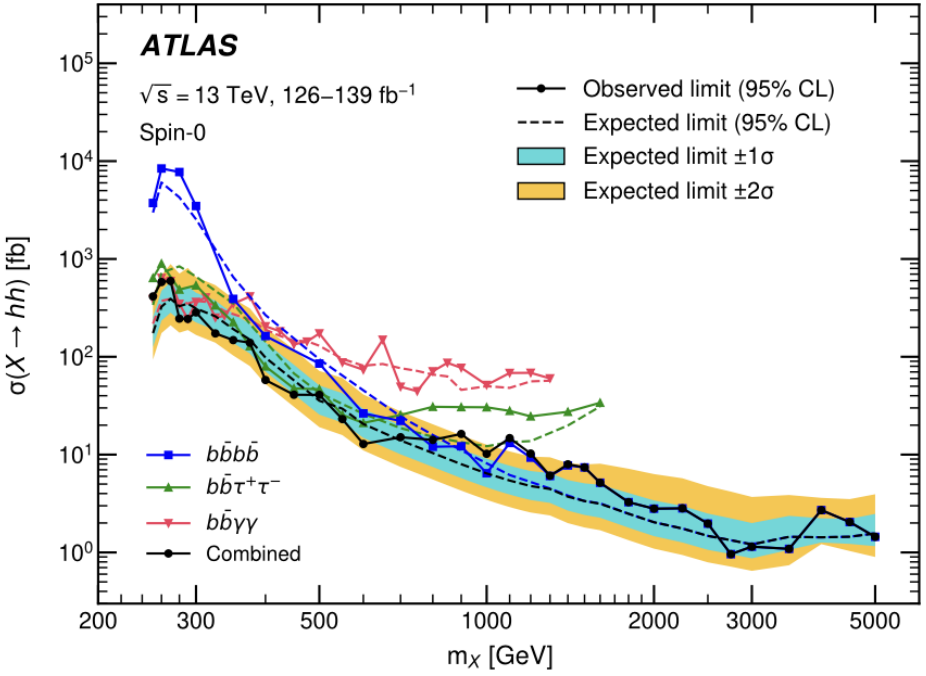
Resonant X → HH (Combination)



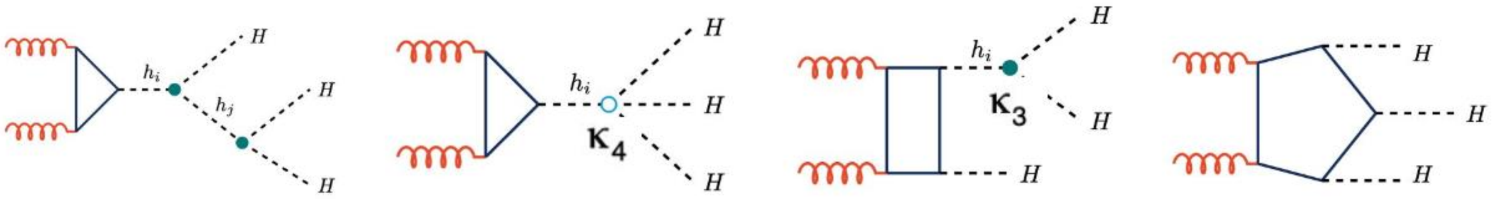
- Sensitive to BSM physics – effects parametrised by resonance mass m_X
- signal has a peak in m_{HH}
- Combination of bbbb, bbττ, bbγγ

- Obs. upper limits (0.96 – 600) fb
  - Improved by of a factor of 2-5 from partial Run-2 results (36 fb^{-1})

Phys. Rev. Lett. 132 (2024) 231801

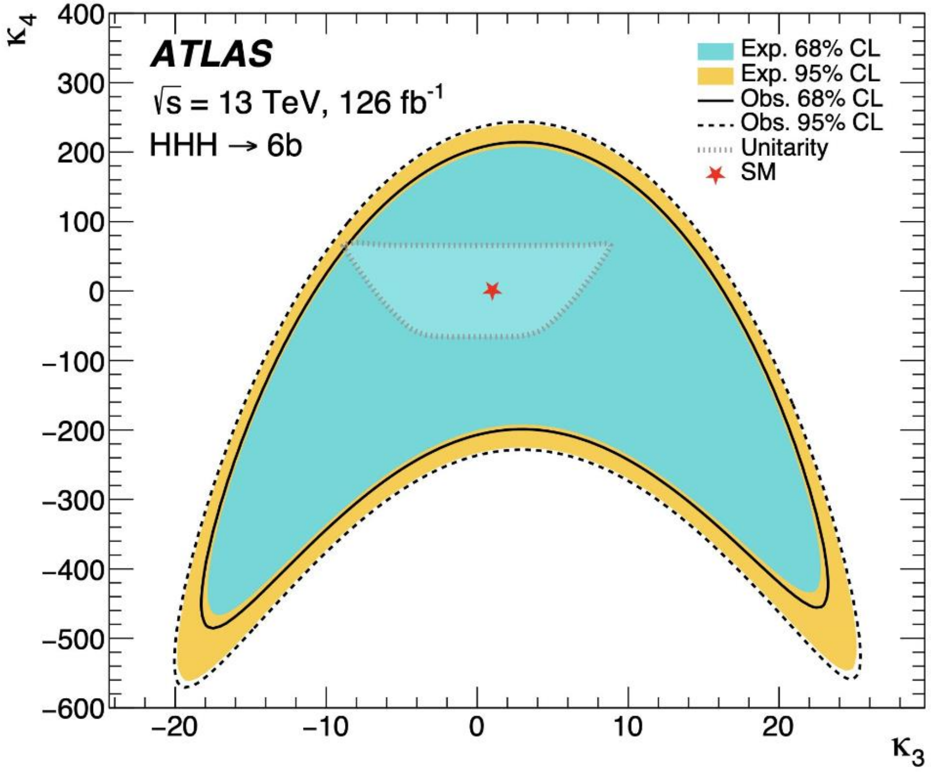


Search for HHH→6b

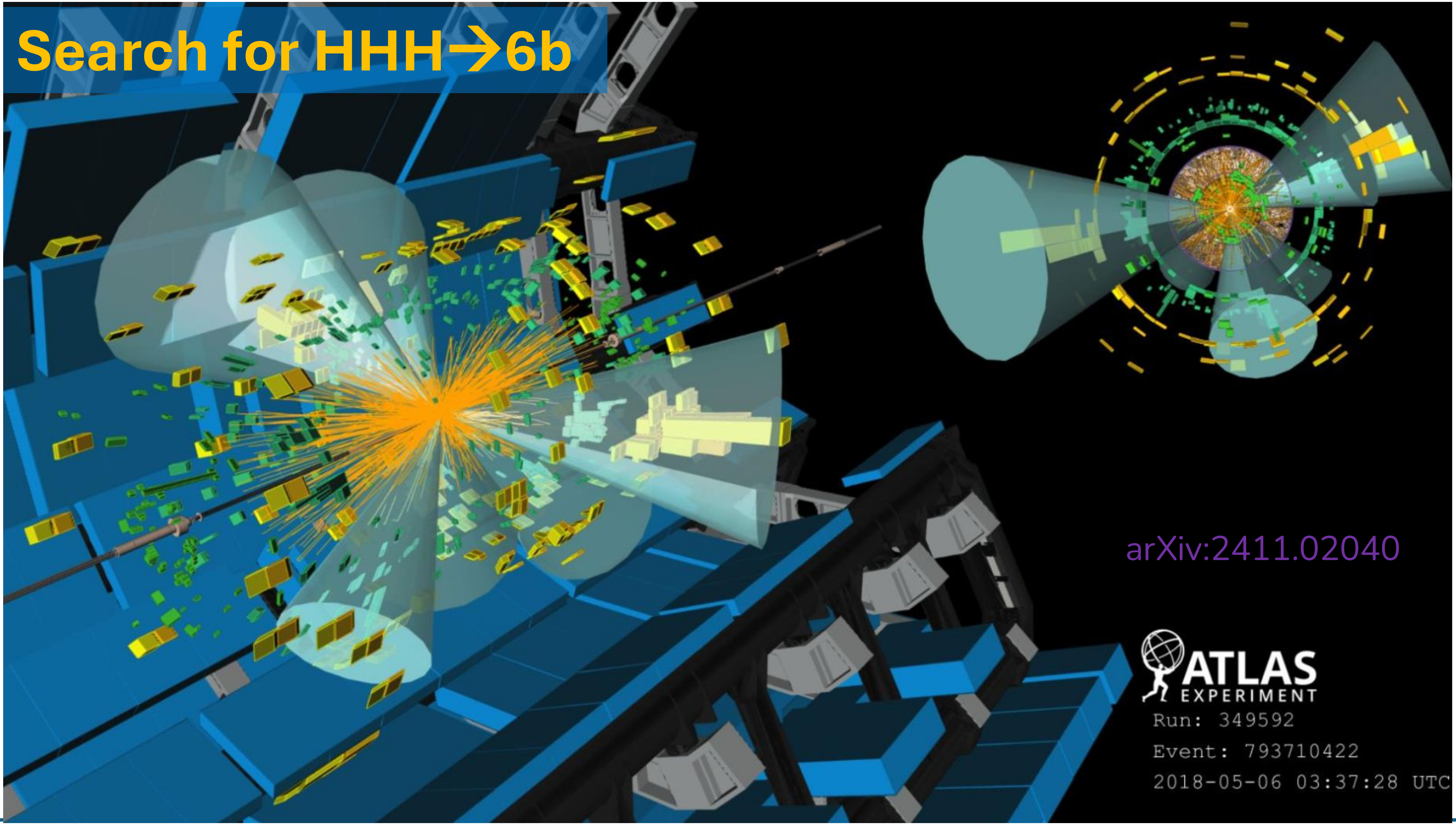


- First LHC search for HHH production with 6b-quark final state
  - Very rare process, suppressed by a factor of ~ 400 compared to SM HH production
- Both resonant and non-resonant production:
  - Resonant: extended scalar sectors can produce cascade decays and appear in this channel first
  - Non-resonant: probe Higgs quartic coupling as well as cross section / signal strength
- No evidence of tri-Higgs production observed ⇒ σ<59.4 fb at 95% CL (for SM kinematic shape)
  - SM prediction 0.08 fb
- Experimental constraints on quartic coupling κ_4 set for the first time

arXiv:2411.02040



Search for HHH→6b



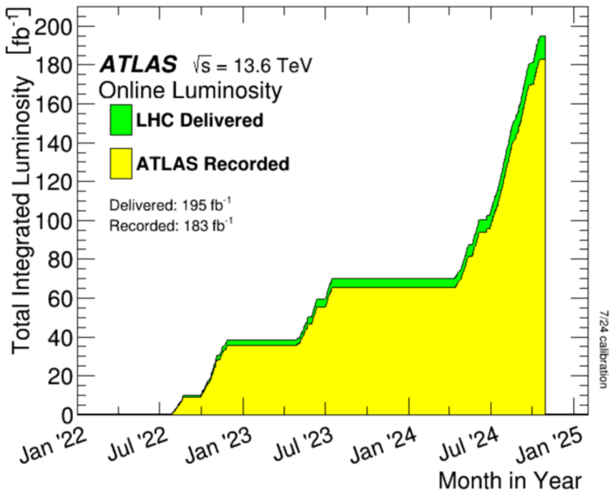
arXiv:2411.02040

Conclusions

- The Higgs boson is a unique probe for seeking answers to fundamental questions about the universe
- The Higgs is a tool in the search for new physics: direct and indirect way

- Large set of measurements from ATLAS : from precision to HHH

- So far good agreement with SM prediction given current accuracy
- LHC delivered more data during Run 3 → improvements in sensitivity for all measurements



https://twiki.cern.ch/twiki/bin/view/AtlasPublic/LuminosityPublicResultsRun3