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ATLAS EXPERIMENT

Constraints on Higgs boson width from Higgs and Top

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On behalf of the ATLAS collaboration

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Why the Higgs width?

- Important Higgs boson property
- Sensitive to the potential presence of beyond SM Higgs boson decays that are **not covered by direct searches**
- However in the SM, Higgs width is **4.1 MeV**, which is inaccessible via most of the direct measurement at ATLAS/CMS due to limited detector resolution

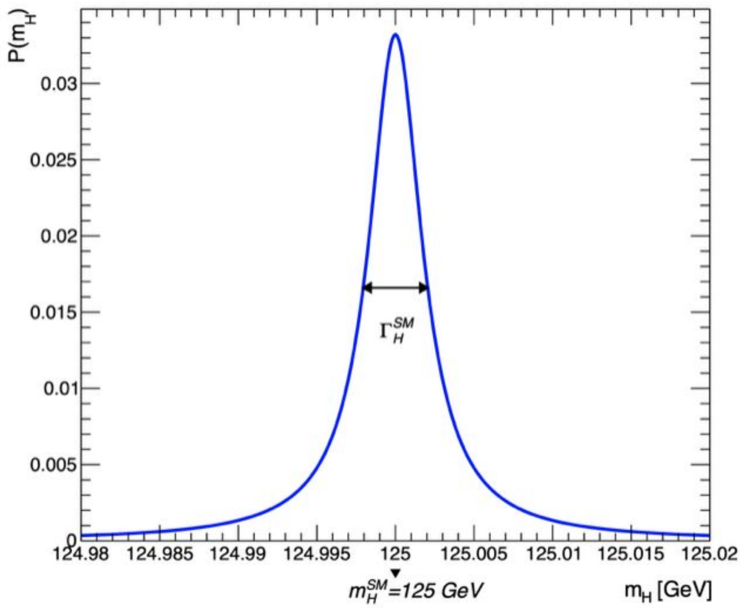


Figure 1: The relativistic Breit-Wigner distribution of the Higgs boson resonance with a width (Γ_H) of 4.1 MeV. For comparison, the width of the Z boson is more than 600 times larger (2.495 GeV), allowing us to measure it directly from the Breit-Wigner line shape. (Image: M. Javurkova/ATLAS Collaboration)

How to measure the Higgs width

$$\frac{d\sigma}{dm^2} = \frac{g_i^2 g_f^2}{(m^2 - m_H^2)^2 + m_H^2 \Gamma_H^2}$$

Higgs boson lineshape

$$\sigma \propto \frac{g_i^2 g_f^2}{m_H \Gamma}$$

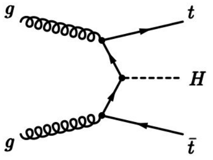
On-shell Higgs: coupling and width correlated

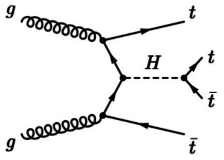
$$\frac{d\sigma}{dm^2} \propto \frac{g_i^2 g_f^2}{(m^2 - m_H^2)^2}$$

Off-shell Higgs: coupling and width uncorrelated

Combined measurement of on-shell and off-shell Higgs boson : $R_\Gamma = \frac{\Gamma_H}{\Gamma_{H,SM}} = \frac{\mu_{\text{off-shell}}}{\mu_{\text{on-shell}}}$

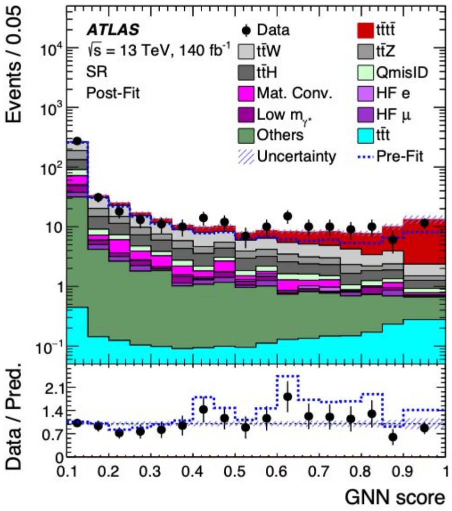
- Higgs width with off-shell HZZ:
  - ATLAS: PLB 846 (2023) 138223 (95% CL limit of Γ_H < 10.2 MeV)
  - CMS: Nature Phys. 18 (2022) 1329 (limit of Γ_H < 8.5 MeV)
- However, the loop-induced effective Higgs-gluon coupling could vary differently between on-shell and off-shell production processes
- **Today's talk: new paper for Higgs width from Higgs and top (off-shell Htt within Standard Model four-top process)** arxiv:2407.10631, https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/TOPQ-2023-22/



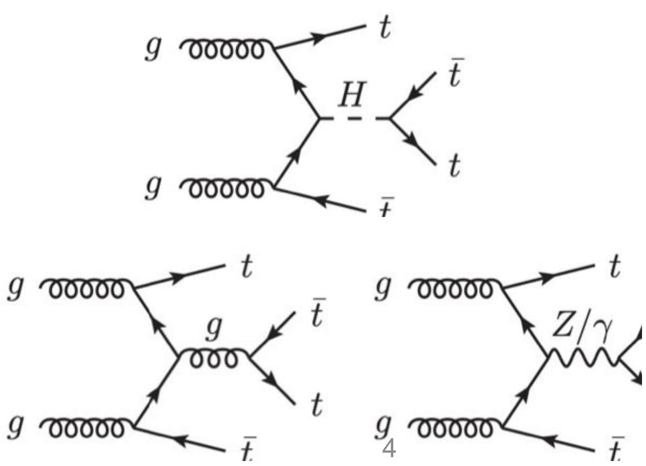


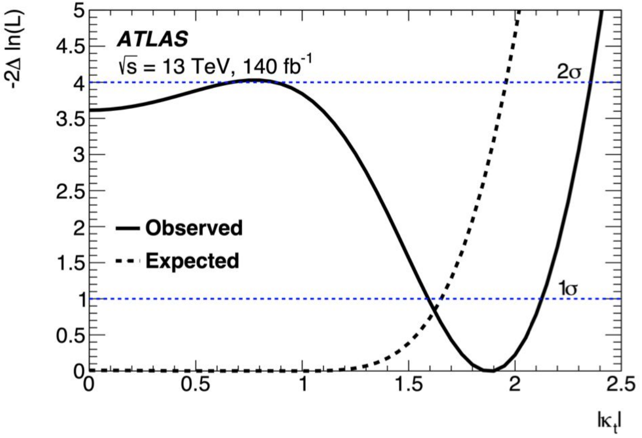
Off-shell input: four-top measurement

- The observation of SM four-top process: EPJC 83 (2023) 496
  - Multi-lepton channel contains events with 2 same-sign leptons or at least 3 leptons.
  - Binned S+B fit on the Graph Neural Network (GNN) scores
- Observed four-top process at **6.1σ (4.3σ expected)**
  - **95% CL limit was set on top-Higgs Yukawa coupling modifier $|\kappa_t| < 2.3$ (1.9 expected)**



$$\sigma_{t\bar{t}t\bar{t}} = A + B\kappa_t^2 + C\kappa_t^4$$

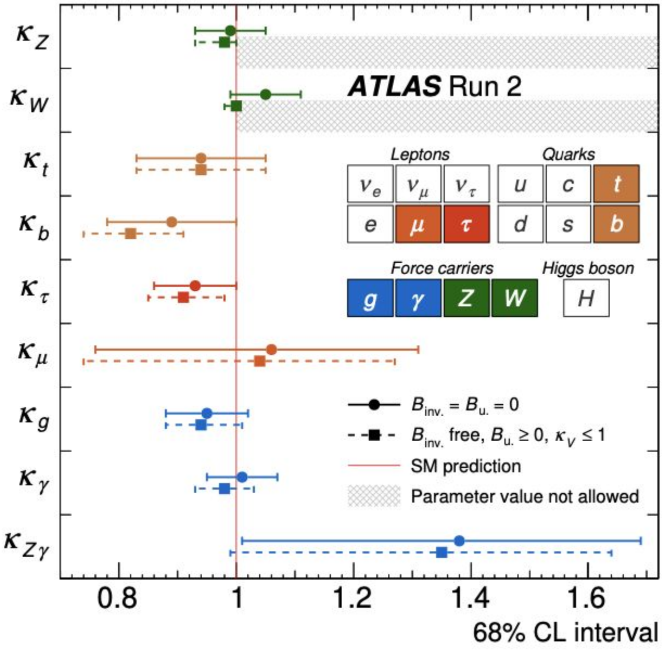




On-shell input: the Higgs couplings

- Higgs coupling measurements: [Nature 607 (2022) 52-59]
  - $t\bar{t}H$ (multi-lepton) channel is removed in the combined measurement due to non-trivial overlap with the $t\bar{t}t\bar{t}$ measurement: the measured κ_t is modified from 0.94±0.11 to 0.86±0.13

Target processes	
Off-shell measurement	
$pp \to t\bar{t}t\bar{t}$	
On-shell measurement	
Production	Decay
ggF, VBF, WH, ZH, $t\bar{t}H$, tH	$H \to \gamma\gamma$
$t\bar{t}H + tH$	$H \to b\bar{b}$
WH, ZH	$H \to b\bar{b}$
VBF	$H \to b\bar{b}$
ggF, VBF, $WH + ZH$, $t\bar{t}H + tH$	$H \to ZZ$
ggF, VBF	$H \to WW$
WH, ZH	$H \to WW$
ggF, VBF, $WH + ZH$, $t\bar{t}H + tH$	$H \to \tau\tau$
ggF+ $t\bar{t}H + tH$, VBF+ $WH + ZH$	$H \to \mu\mu$
Inclusive	$H \to Z\gamma$



Combined analysis strategy

- Likelihood combination of the two input analysis results
- Parameter Of Interest:
  - top-Higgs coupling modifier κ_t and Higgs width modifier R_Γ

Four-top	κ_t
Higgs combination	$R_\Gamma, \kappa_t, \kappa_Z, \kappa_W, \kappa_b, \kappa_\tau, \kappa_\mu, \kappa_g, \kappa_\gamma, \kappa_{Z\gamma}$
Combined	$R_\Gamma, \kappa_t, \kappa_Z, \kappa_W, \kappa_b, \kappa_\tau, \kappa_\mu, \kappa_g, \kappa_\gamma, \kappa_{Z\gamma}$

- The $t\bar{t}H$ events in $t\bar{t}t\bar{t}$ analysis, and the $t\bar{t}t\bar{t}$ events in $t\bar{t}H$-bb analysis are not parameterized as a function of κ_t, its impact on limits is checked to be < 2%

Systematic uncertainties

- The high impact systematic uncertainties are correlated, because the input analyses consider the same set of uncertainty sources. The uncorrelated uncertainties have negligible impacts.
- The largest impacts are from the theoretical uncertainties of the four-top analysis

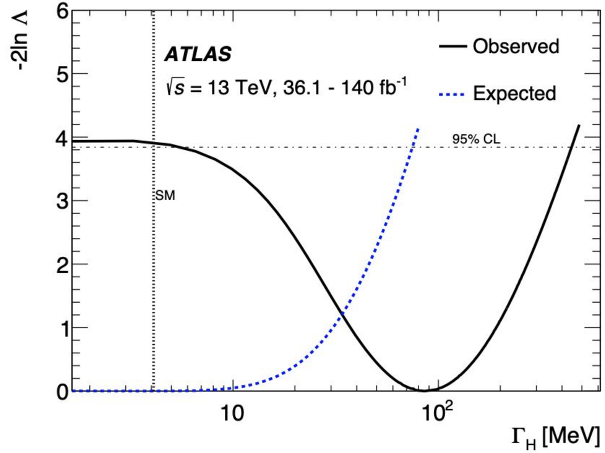
Systematic uncertainty	Impact on 95% CL upper limit on Γ_H	
	Expected [%]	Observed [%]
Theory	37	33
$t\bar{t}t\bar{t}$ production	25	13
Higgs boson production/decay	5	6
Other processes	10	16
Experimental	2	2
Jet flavour tagging	2	1
Jet and missing transverse energy	< 1	< 1
Leptons and photons	< 1	< 1
All other systematic uncertainties	< 1	< 1

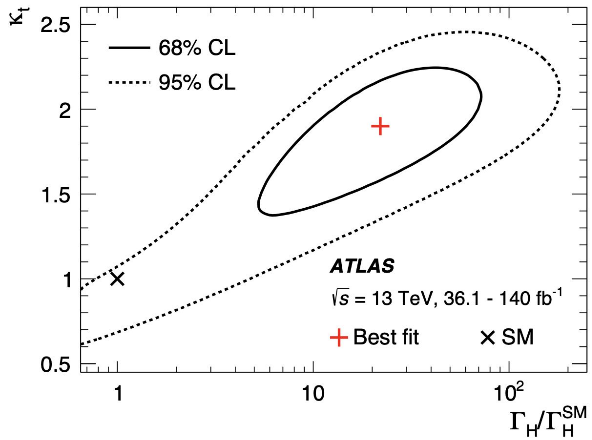
Result

- Observed (expected) limit: 450 (75) MeV
  - 110 (18) times the SM
  - Stat-only: 280 (44) MeV

    $\Gamma_H = 86^{+110}_{-49}$ MeV
- Deviation from SM: 2.0 σ, mainly from the 1.8 σ deviation in the measurement of $t\bar{t}t\bar{t}$ cross-section

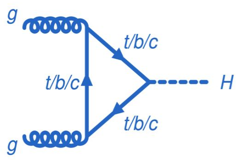
In the 2D limit plane, the κ_t best-fit value (κ_t=1.9) is mainly decided by the four-top observed result, and Higgs width is scaled together with other POI





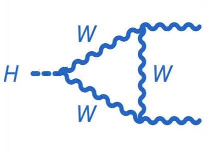
Result with top loops

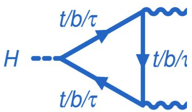
In the nominal result, the modification of the ggF cross-section and Hγγ/HZγ branching ratio are described by κ_g , κ_γ and $\kappa_{Z\gamma}$

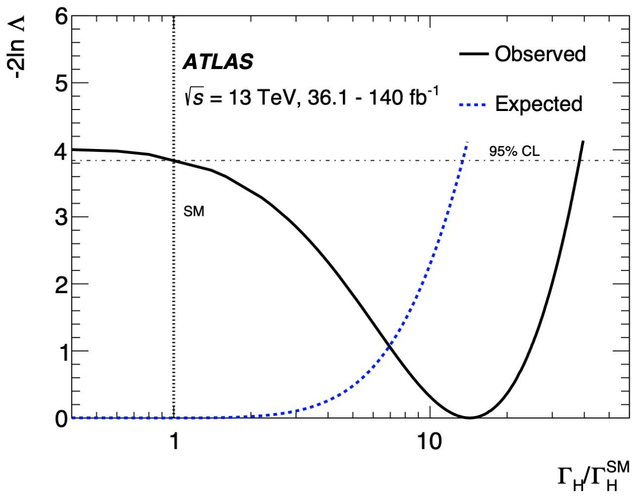


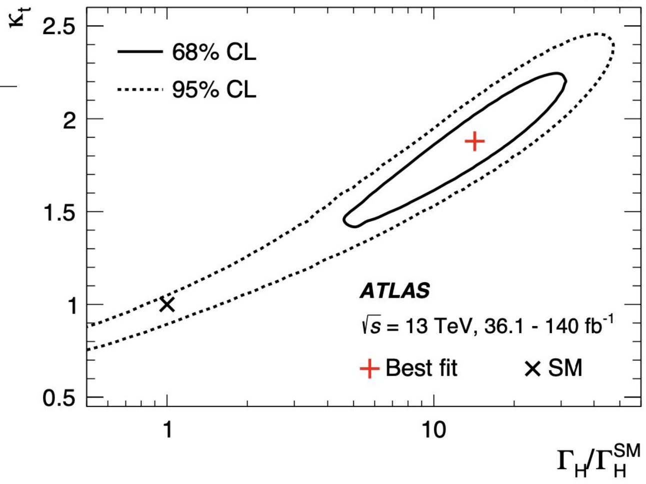
If the top loops in ggF and Hγγ/HZγ are parameterized as a function of κ_t:

- Limit: 160 (55) MeV
- Deviation from SM: 2.0σ









Production cross section	Effective coupling	Parametrization in terms of coupling strength modifiers
$\sigma(\text{ggF})$	κ_g^2	$1.040\,\kappa_t^2 + 0.002\,\kappa_b^2 - 0.038\,\kappa_t\kappa_b - 0.005\,\kappa_t\kappa_c$
Partial decay width		
$\Gamma^{\gamma\gamma}$	κ_γ^2	$1.589\,\kappa_W^2 + 0.072\,\kappa_t^2 - 0.674\,\kappa_W\kappa_t + 0.009\,\kappa_W\kappa_\tau + 0.008\,\kappa_W\kappa_b - 0.002\,\kappa_t\kappa_b - 0.002\,\kappa_t\kappa_\tau$
$\Gamma^{Z\gamma}$	$\kappa_{Z\gamma}^2$	$1.118\,\kappa_W^2 - 0.125\,\kappa_W\kappa_t + 0.004\,\kappa_t^2 + 0.003\,\kappa_W\kappa_b$

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HIGG-2021-23/

Conclusion

- A first measurement of the Higgs width based on top-Higgs coupling is performed
  - It explores model assumptions distinct from diboson final states, thereby testing the robustness the Higgs boson total width measurements

- The observed (expected) 95% CL upper limit for is 450 (75) MeV.
  - Theoretical uncertainties have large impact on the results
  - The tension with the SM is found to be 2.0 σ
  - If further resolving the loops of gluon fusion and Higgs to γγ and Zγ, the observed (expected) 95% CL upper limit for is 160 (55) MeV

- Further constraints can be achieved with the future four-top analyses and Higgs coupling results

Backup

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