Measurement of the Higgs boson cross section and Width with the ATLAS detector

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The 10th China LHC Physics Conference
November 14, 2024

Introduction

- **Early Run3 H→γγ fiducial cross-section**
  - First look at Higgs Boson at 13.6TeV with ATLAS experiment.
  - Quick analysis with data taken during 2022 → 31.4 fb^{-1}.
  - Combined with H → ZZ*→4l channel to measure σ(pp→H).

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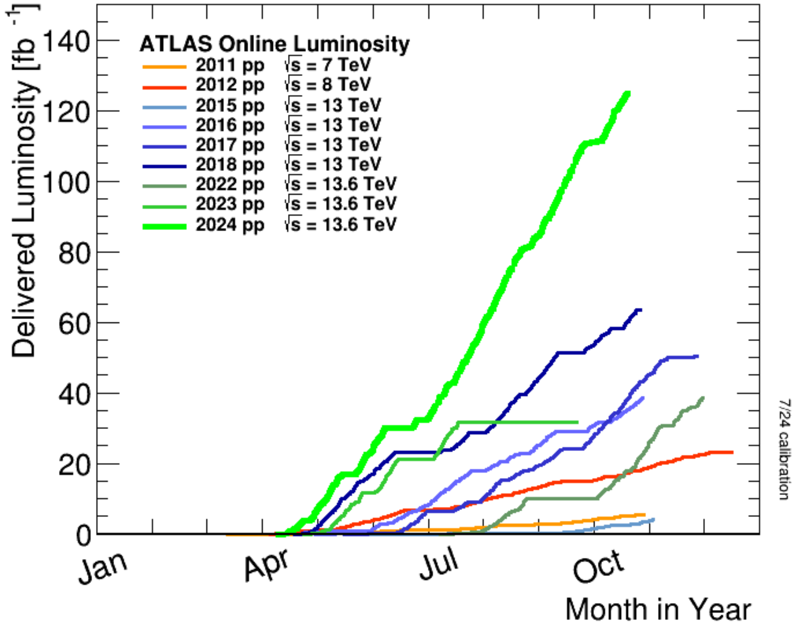
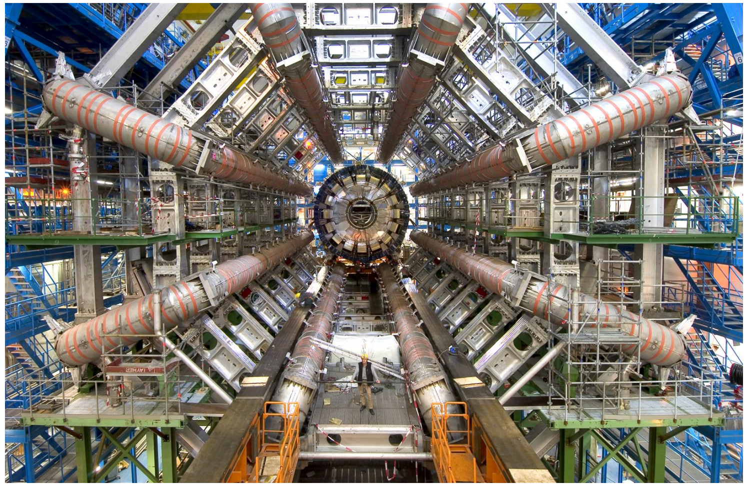
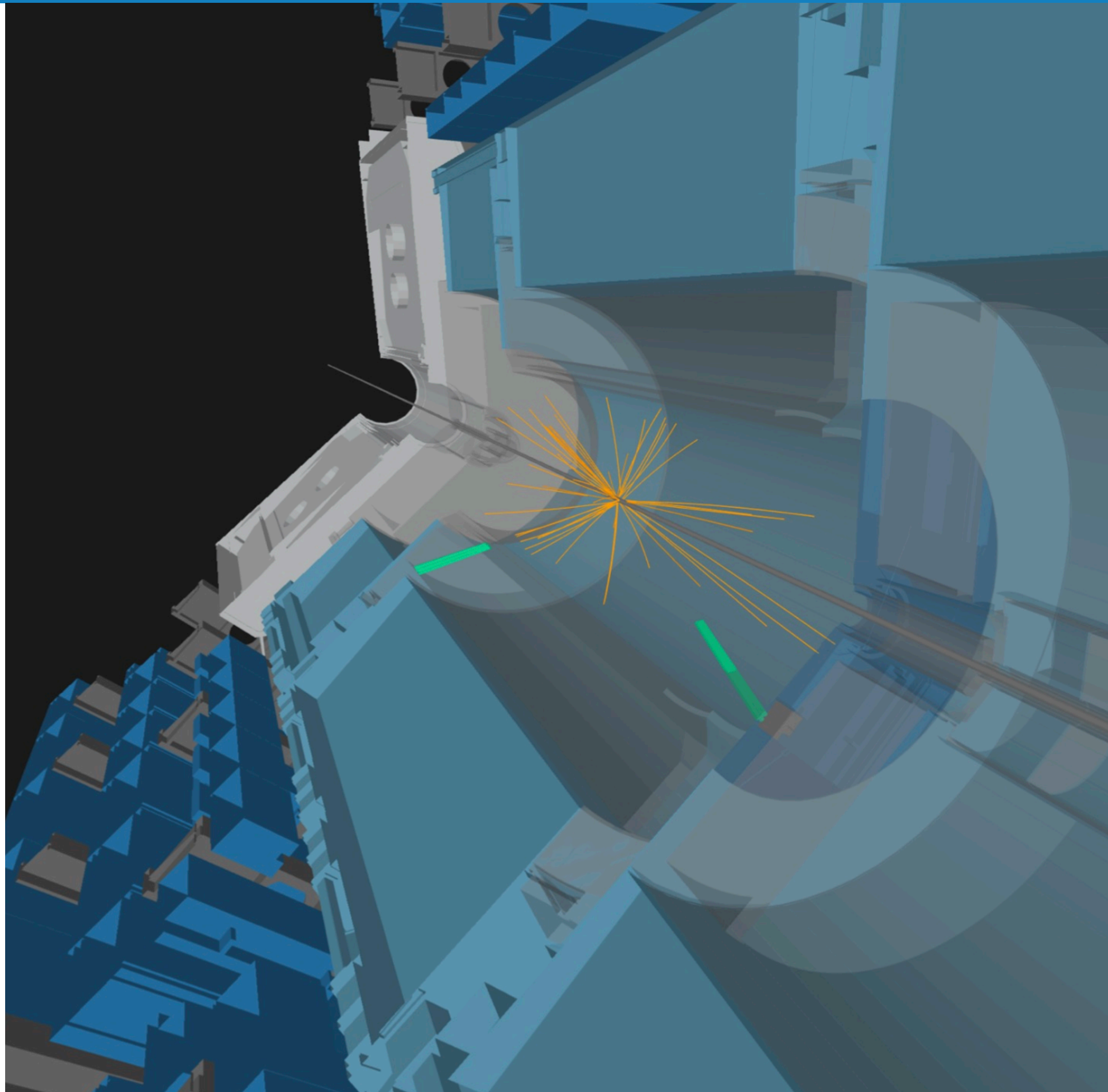


- **Higgs width measurement**
  - First to constraint Higgs boson width based on Higgs-Top Yukawa coupling.
  - Using the Run2 data set → up to 140 fb^{-1}.

  arXiv:2407.10631 Submitted to PLB

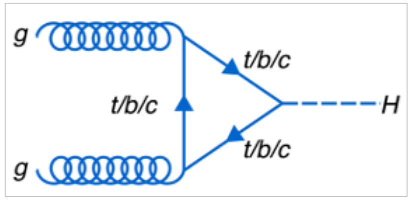


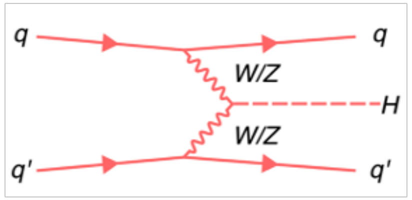
Early Run-3 $H\rightarrow\gamma\gamma$ fiducial cross-session

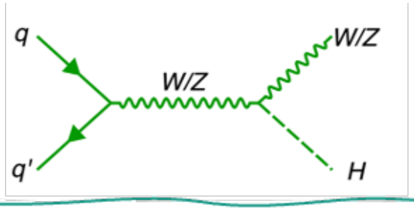


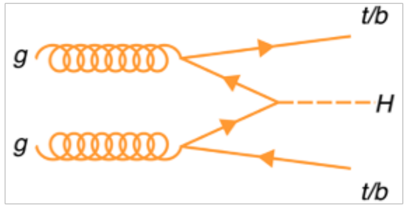
Early Run-3 H→γγ fiducial XS

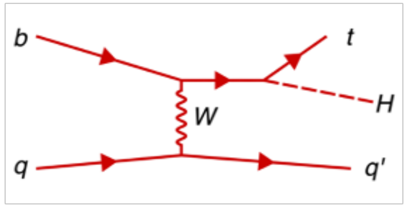
- **SM predicted Total cross-section of Higgs boson at 13.6 TeV**
  - **$\sigma(pp \rightarrow H)_{SM}$ = 59.9 ± 2.6 pb**

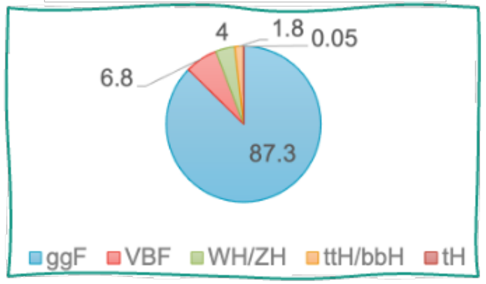


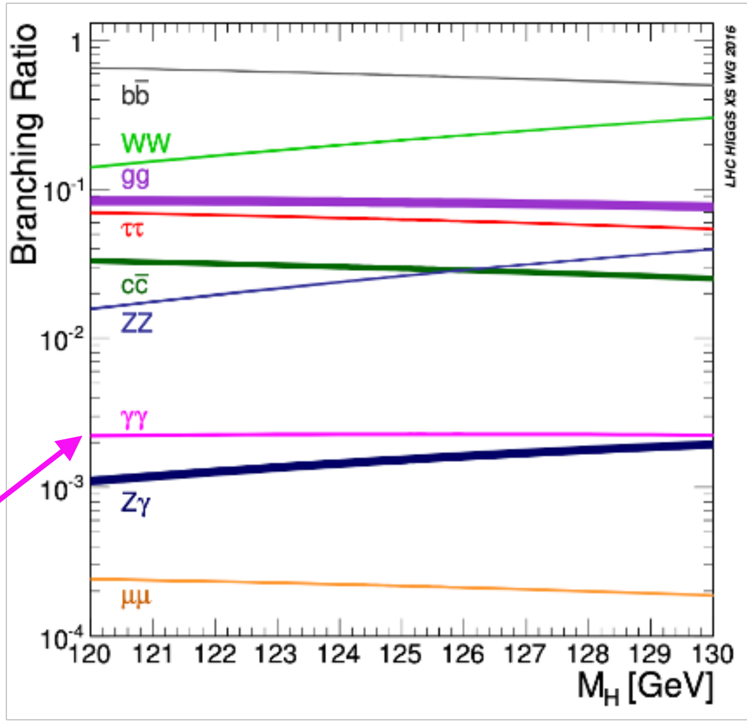




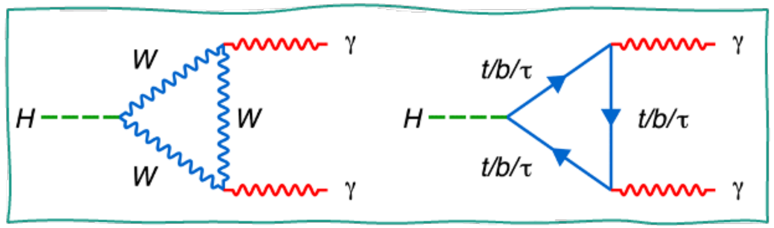








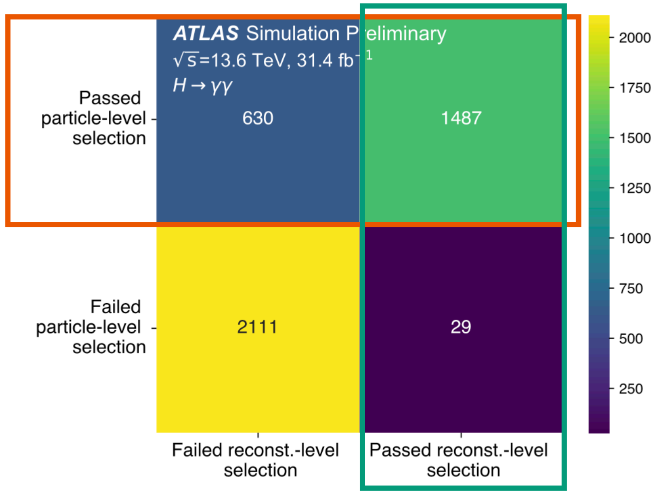
- **Di-photon final state:**
  - Small branching ratios of Higgs boson decays into two photons.
  - Excellent mass reconstruction and photon identification efficiencies of the ATLAS detector.
  - Loop induced decay mode



Analysis strategy

- **Fiducial region definition**
  - Two highest E_T candidates are used to build a di-photon system.
  - Fiducial region defined closely to the detector acceptance.
  - Correction Factor ($C_{\mathcal{F}}$): 71.6%
  - Acceptance ($\mathcal{A}$): 49.7%

Total phase space

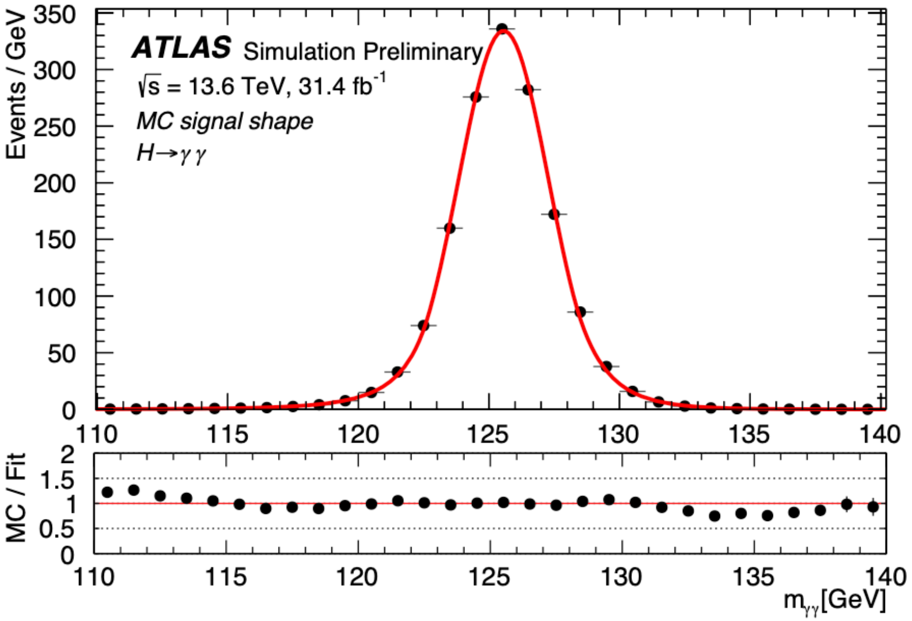


$$N_S = \sigma_{\text{fid}} \times \mathcal{L} \times C_{\mathcal{F}}$$

$$\sigma_{\text{fid}} = \sigma_{\text{tot}} \times \mathcal{B}_{\gamma\gamma} \times \mathcal{A}$$

- **Fit procedure**
  - The cross-section is measured via an analytic fit to the di-photon mass spectrum

$$\mathcal{L}\left(m_{\gamma\gamma}; \nu^{\text{sig}}, \nu^{\text{bkg}}\right) = \frac{e^{-\nu}}{n!} \prod_{j}^{n} \frac{1}{\nu}\left[\nu^{\text{sig}} \mathcal{S}\left(m_{\gamma\gamma}^{j}; \theta_k\right) + \nu^{\text{bkg}} \mathcal{B}\left(m_{\gamma\gamma}^{j}\right)\right]$$

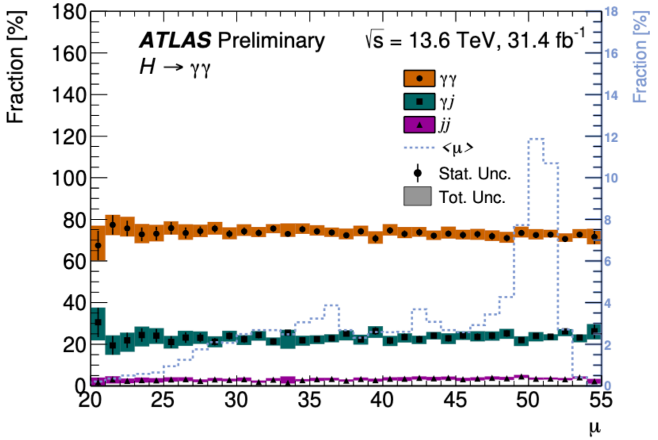


  - Parameters of the signal model derived from simulation

Background estimation

- **The main sources of background are the non-resonant production of prompt and isolated di-photons ($\gamma\gamma$) and the γ + jet and jet+jet processes.**

  - γj and jj
    → derived from data control samples.

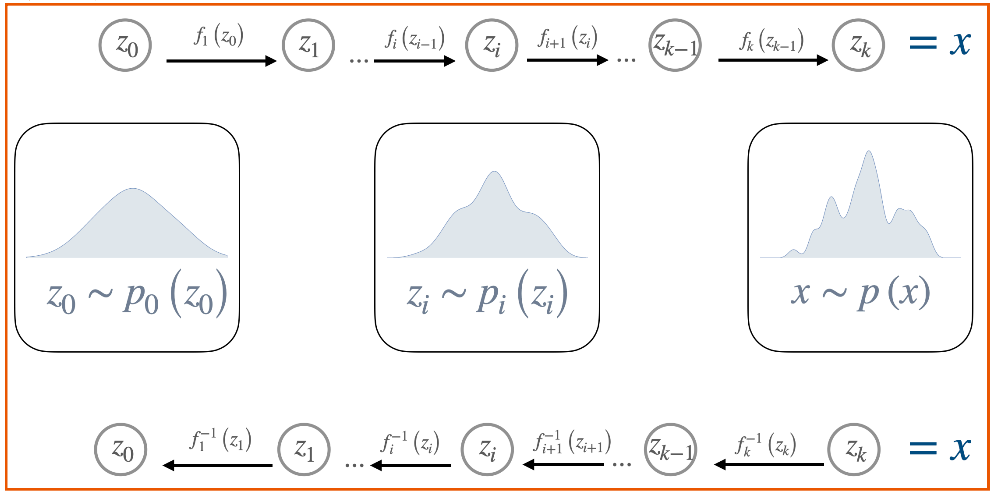


  - $\gamma\gamma$
    → directly derived from the bkg MC after applying the event selection.

    A. Full simulated template by Geant4.

    B. Template introduced the detector response by Normalizing Flow (NF) method
    → A generative machine-learning model.

    - S/B is ~ 1% level, background modeling is important.
    - Rely on the large stats simulated sample.
    - Detector simulation is computationally expensive.
    - Benefit from fast machine-learning.

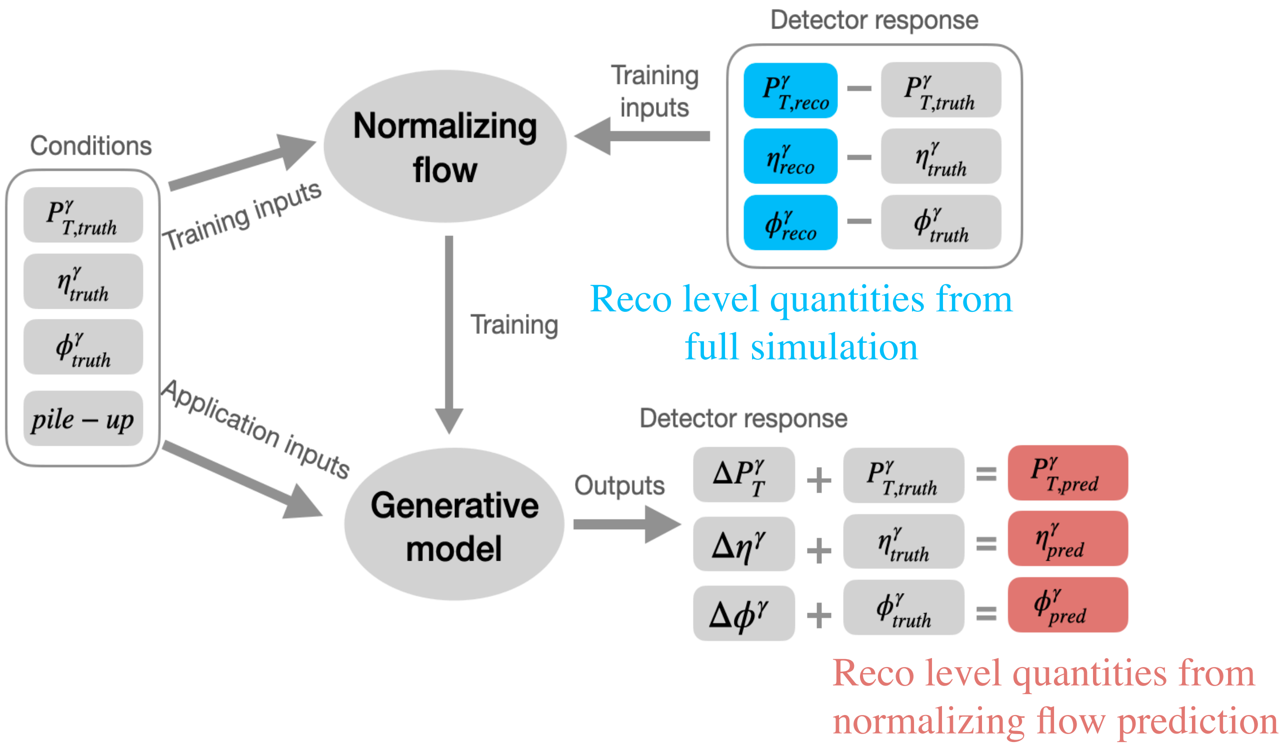


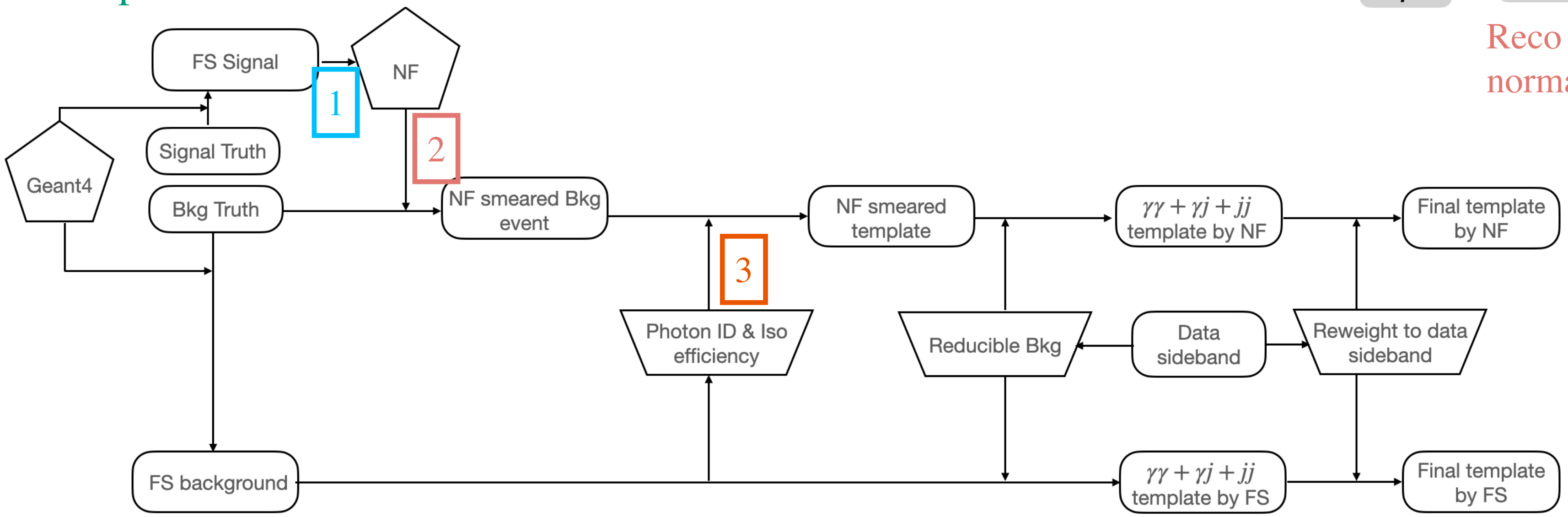
Background estimation

- **Normalizing flow (NF) Method** → To achieve large statistics to satisfy the requirement of Bkg modeling.

  1. Learn the detector response to photons from full simulated sample.
  2. Applied to particle-level simulated $\gamma\gamma$ events.
  3. Photon efficiency derived from the full simulated sample is applied to the NF simulated events.

  - Introduce detector response to ~ billion level events in several hours.





Background modeling

- **Background model**
  - $M_{\gamma\gamma}$ bkg is a smoothly falling spectrum.
  - Parameterized by an empirical function selected using the bkg MC templates.

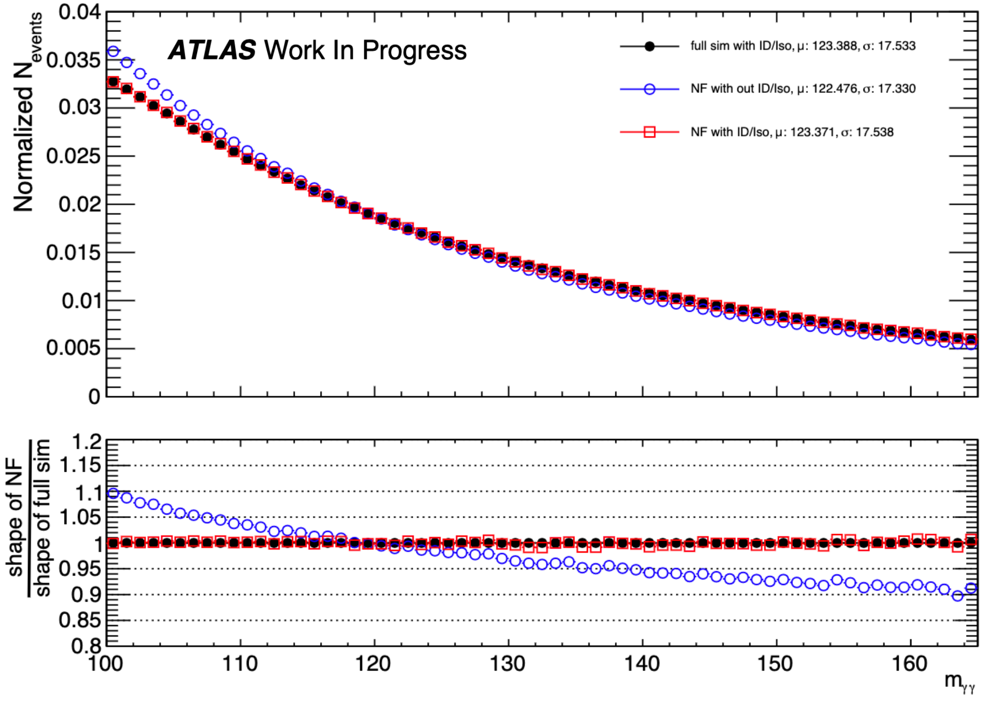
◉ Spurious signal study
→ S + B fit on the Bkg only template.

➡ Select the a background function from candidates.

- $exp(-\frac{m_{\gamma\gamma}}{\alpha_1} - \frac{m_{\gamma\gamma}^2}{\alpha_1})$ is selected.

➡ Determine the associated systematic uncertainty.

- 6.2% of the expected SM signal yield.



$H\rightarrow\gamma\gamma$ Fiducial XS result and combination

- **The cross-section of the SM prediction at 13.6 TeV**
  - $\sigma(pp \rightarrow H \rightarrow \gamma\gamma)_{\text{fid},SM} = 67.6 \pm 3.7$ fb
  - $\sigma(pp \rightarrow H)_{SM} = 59.9 \pm 2.6$ pb
- **Results**
  - $\sigma_{fid} = 76 \pm 11(stat.)^{+9}_{-7}(syst.)$ fb

Source	Uncertainty [%]
Statistical uncertainty	14.0
Systematic uncertainty	10.3
Background modelling (spurious signal)	6.0
Photon trigger and selection efficiency	5.8
Photon energy scale & resolution	5.5
Luminosity	2.2
Pile-up modelling	1.2
Higgs boson mass	0.1
Theoretical (signal) modelling	<0.1
Total	17.4

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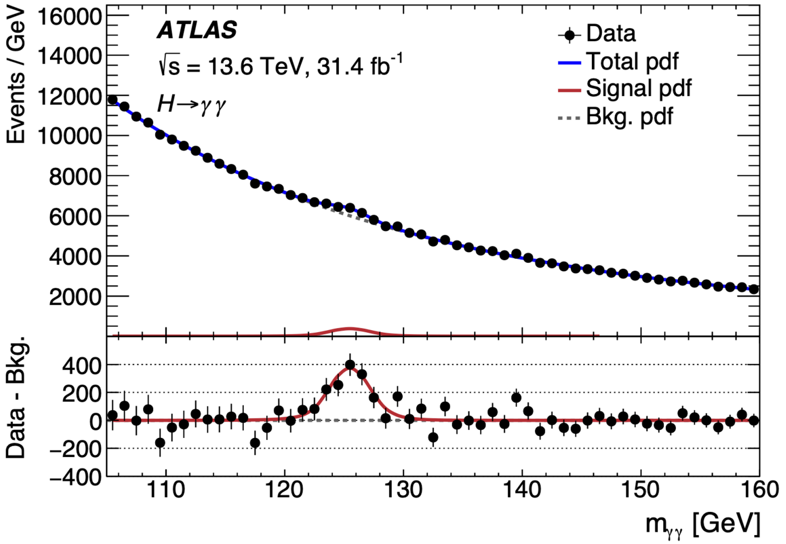
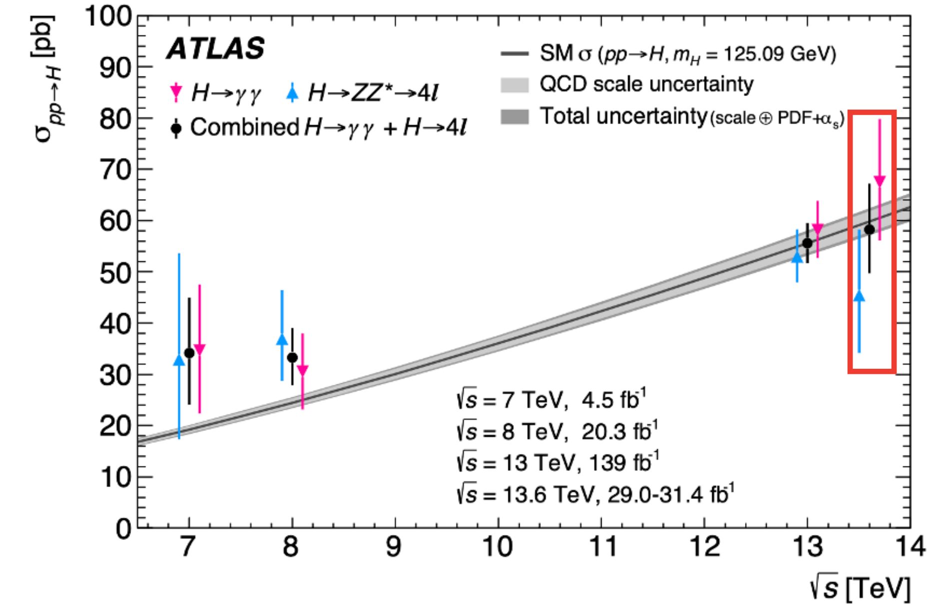
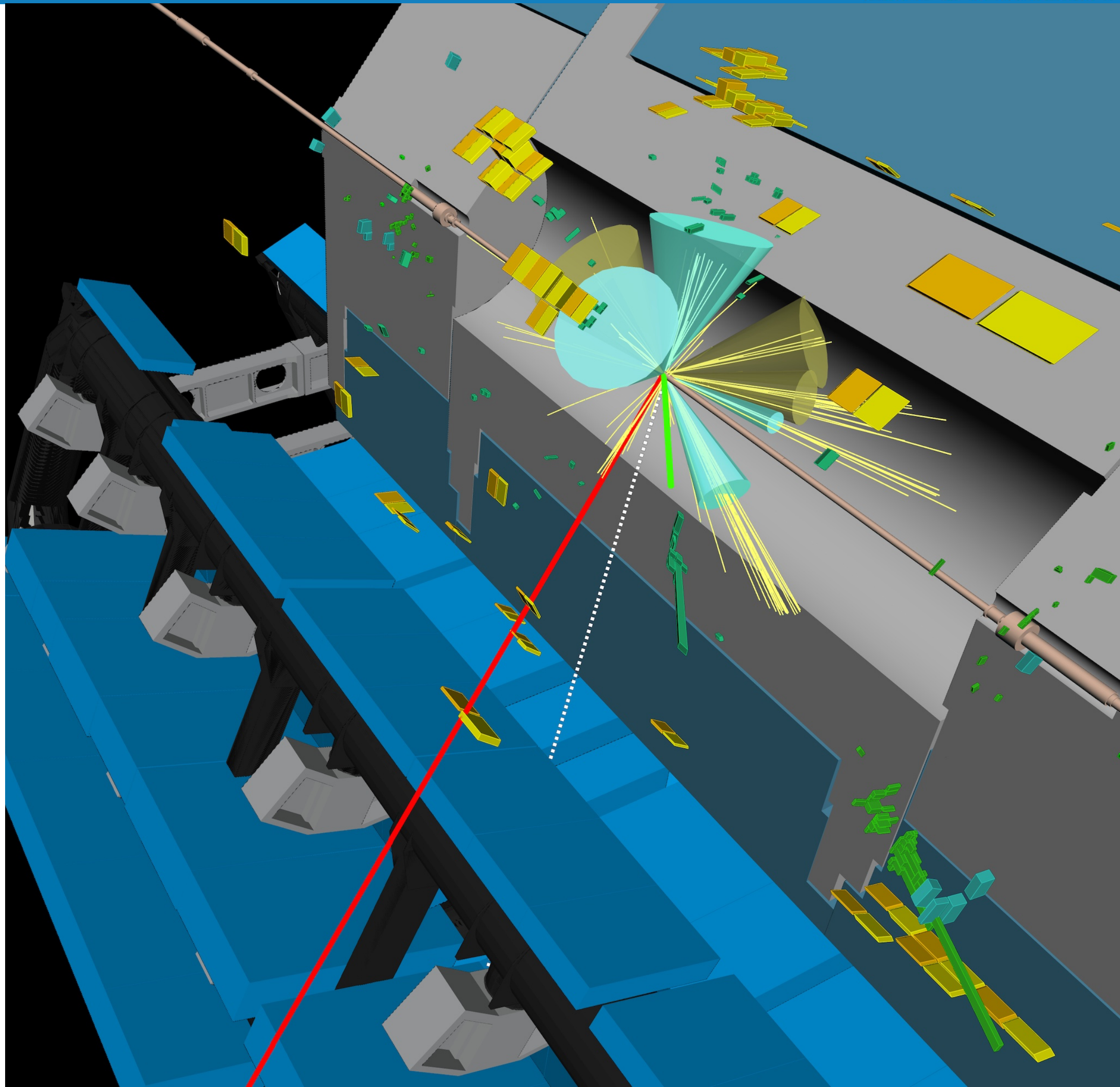


- **Combination**
  - $\sigma_{tot} = 67^{+12}_{-11}$ $(H\rightarrow\gamma\gamma)$
  - $\sigma_{tot} = 46 \pm 12$ $(H \rightarrow ZZ^{*} \rightarrow 4l)$

$\sigma(pp \rightarrow H) = 58.2 \pm 8.7 = 58.2 \pm 7.5(stat.) \pm 4.5(syst.)$ pb



Higgs width measurement



Higgs width measurement

- **Higgs width measurements from the line shape and lifetime are not precise enough to approach SM value** → For $m_H = 125$ GeV → Γ_H^{SM} **= 4.1 MeV**

- **Combined on- and off-shell measurements translate into a constraint on the Higgs width.**
  - Kappa modifier → $\kappa_i = \frac{g_i}{g_{i,SM}}$ → $\frac{d\sigma}{dm^2} = \frac{g_{i,SM}^2 g_{f,SM}^2 \kappa_i^2 \kappa_f^2}{(m^2 - m_H^2)^2 + m_H^2 \Gamma^2}$

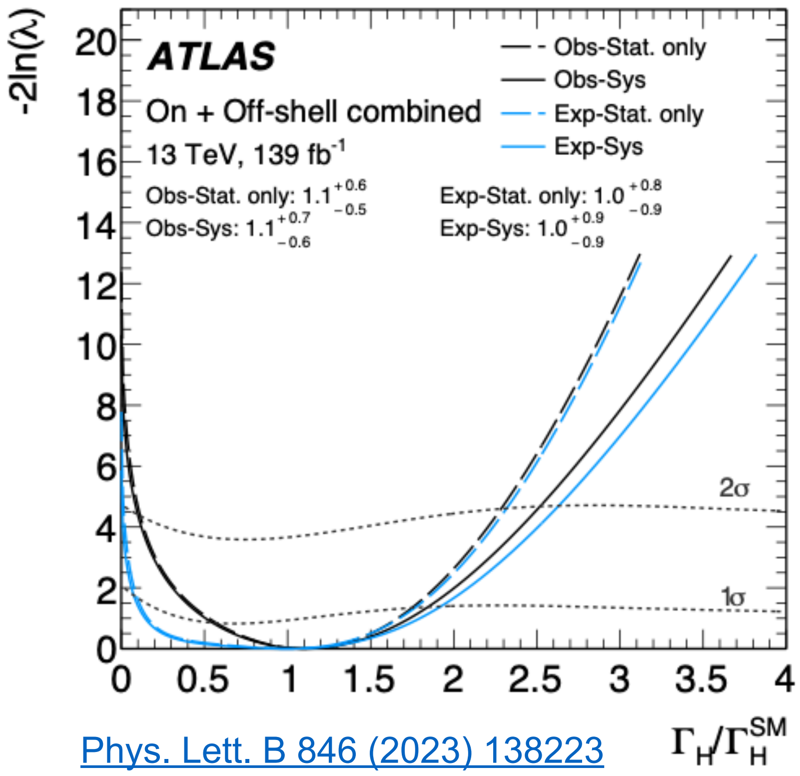
$$\mu_{i \to H \to f} = \frac{\sigma_i \times B(H \to f)}{\sigma_i^{SM} \times B^{SM}(H \to f)}$$

➡ On-shell → $= \frac{\kappa_i^2 \kappa_f^2}{R_\Gamma}$ $\quad R_\Gamma = \frac{\Gamma_H}{\Gamma_{H,SM}}$

➡ Off-shell → $= \kappa_i^2 \kappa_f^2$

Allows us to measure κ and Γ_H simultaneously

- **Most recent result by ATLAS with H→ZZ* and H*→ZZ**
  - 95% CL upper limit: 9.8 MeV



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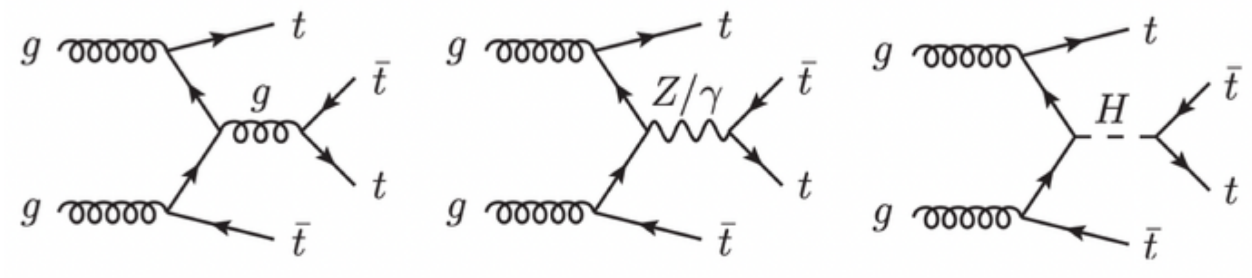
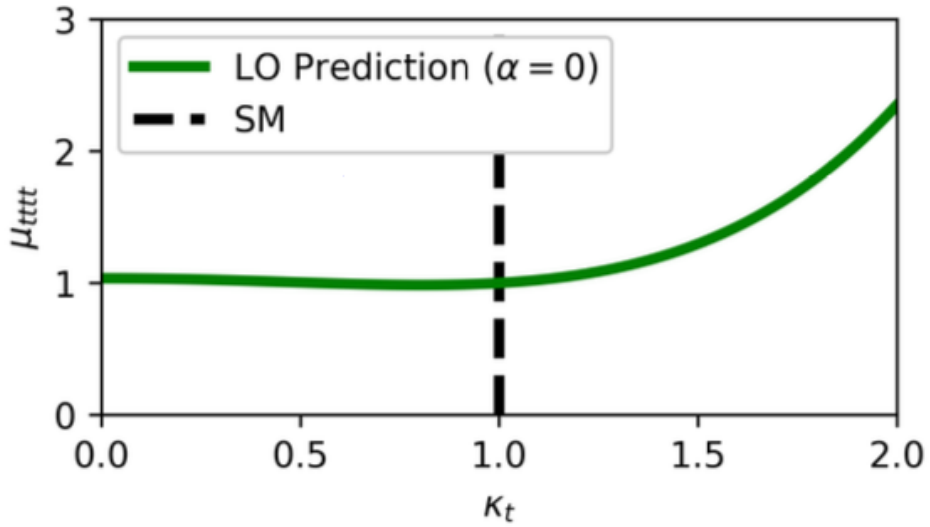
Higgs width with $t\bar{t}t\bar{t}$ and On-shell Higgs

- **Rely on tree-level Higgs-Top Yukawa coupling**
  - Unlike the current analysis based on κ_V, κ_t not affected by the presence of unknown colored particles.

- **Off-shell Higgs in four-tops process gives dependence on κ_t.**





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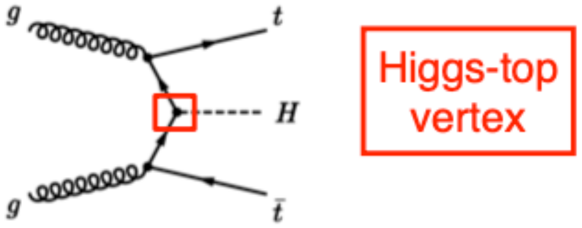
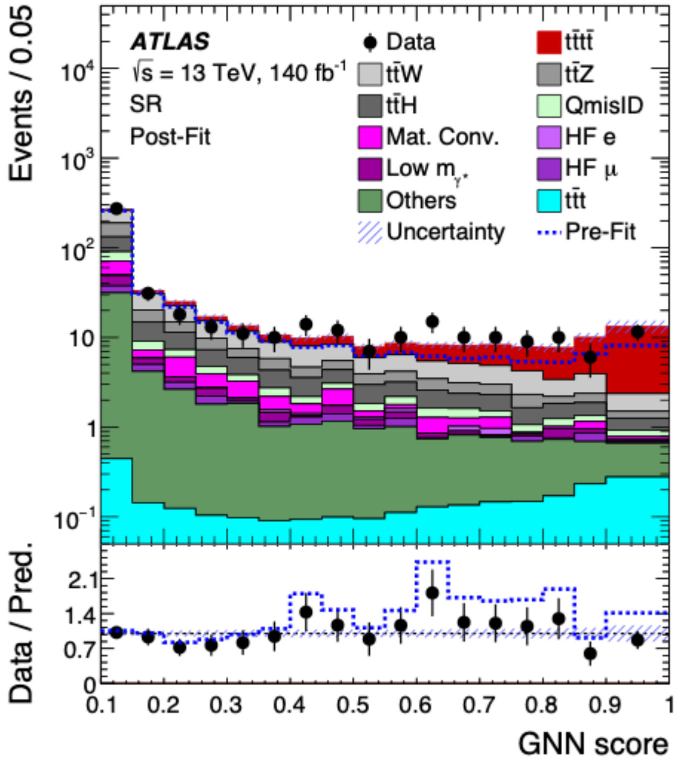
- **On-shell measurement has constraint from $t\bar{t}H$.**



- **Assumes κ_t remains the same between the on-shell and off-shell regimes.**

Off-shell part : $t\bar{t}t\bar{t}$ process

- **Target at Multi-lepton final state**
  - Template based fit with Signal Region + different Control Regions.
  - GNN used to separate signal/background processes.
  - 6.1(4.3)σ significance
  - $\mu = 1.9^{+0.8}_{-0.5}$
  - Interpreted into κ_t measurement→ 95% CL upper limit: 2.3



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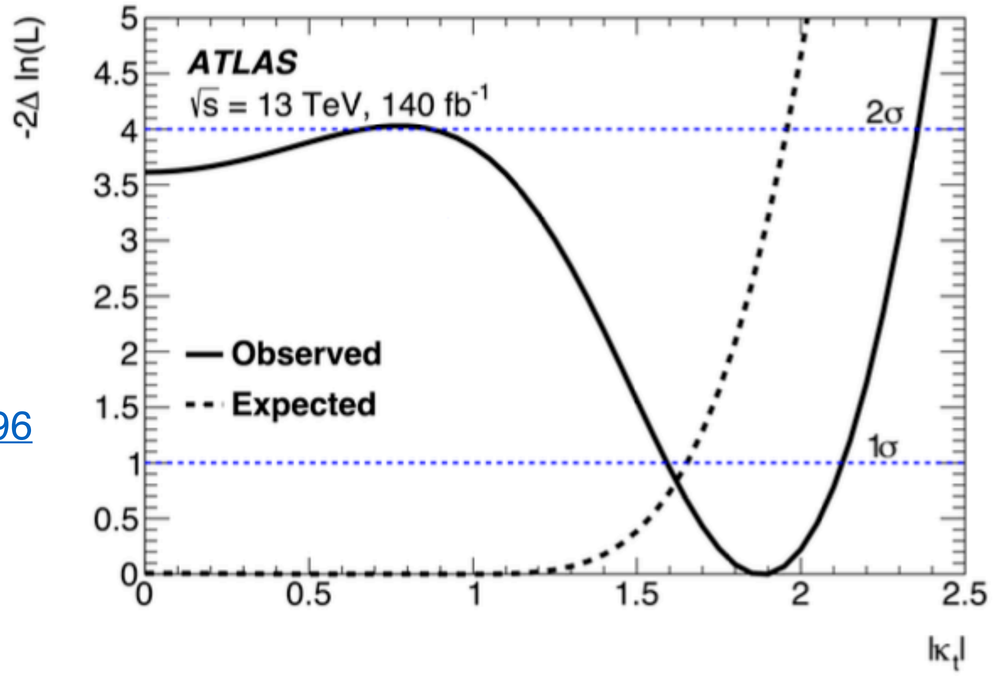
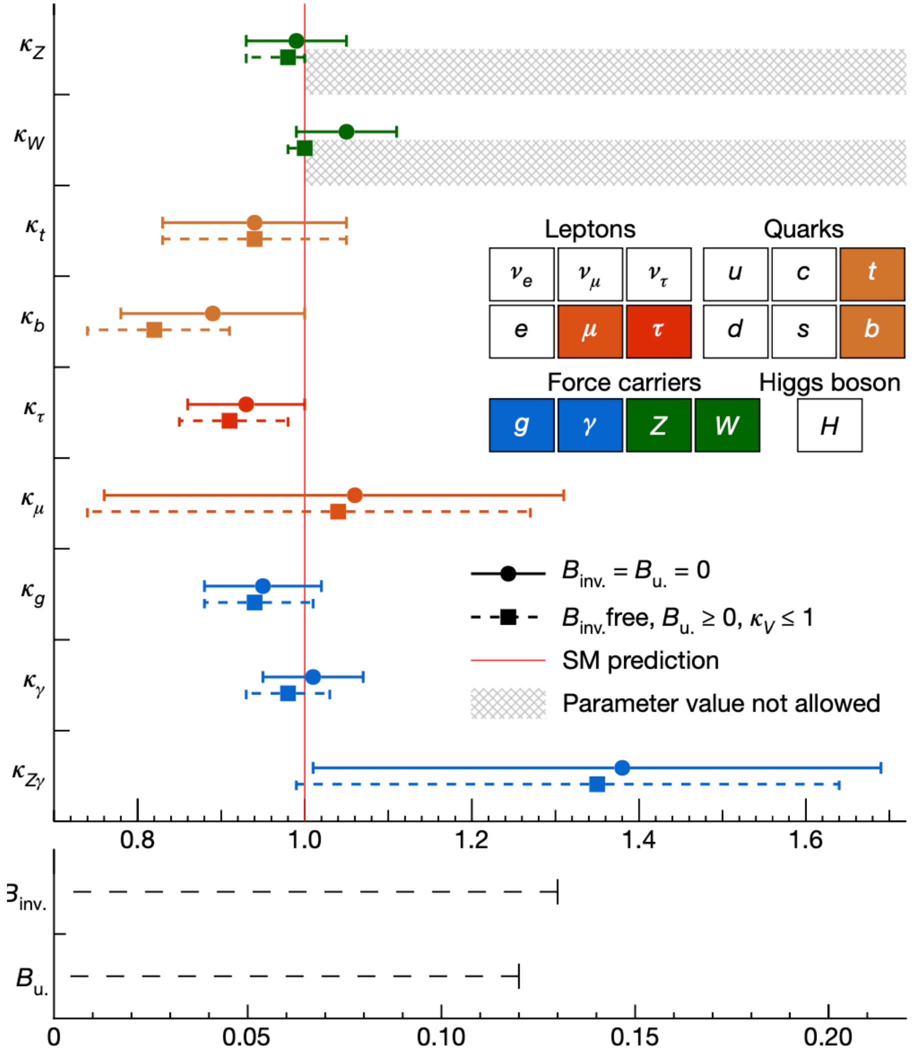


On-shell part : Higgs Coupling Combination

- **The full Higgs combination published in Nature**
  - A simultaneous fit of many individual production times branching fraction measurements.
  - Covering all major Higgs production and decay modes at LHC.
- **ttH Multi-lepton channel is removed from the on-shell part due to overlap with $t\bar{t}t\bar{t}$ measurement.**

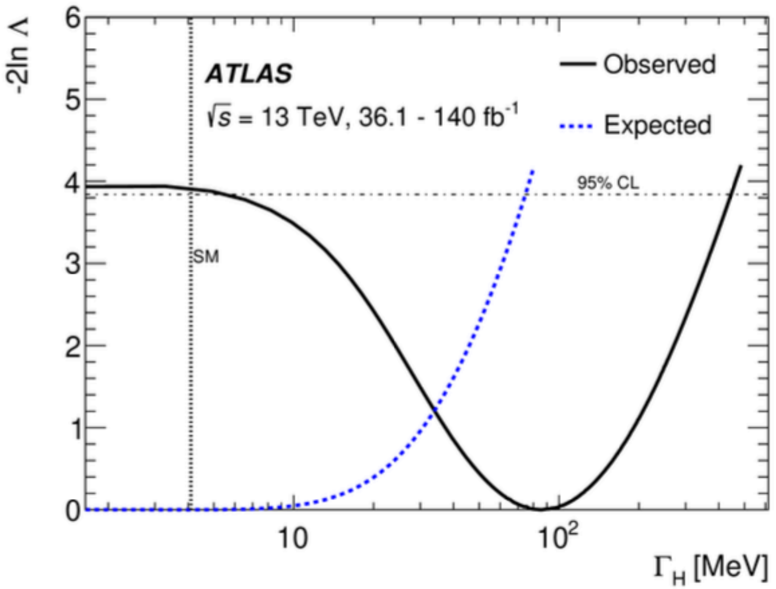
Nature 607(2022)52



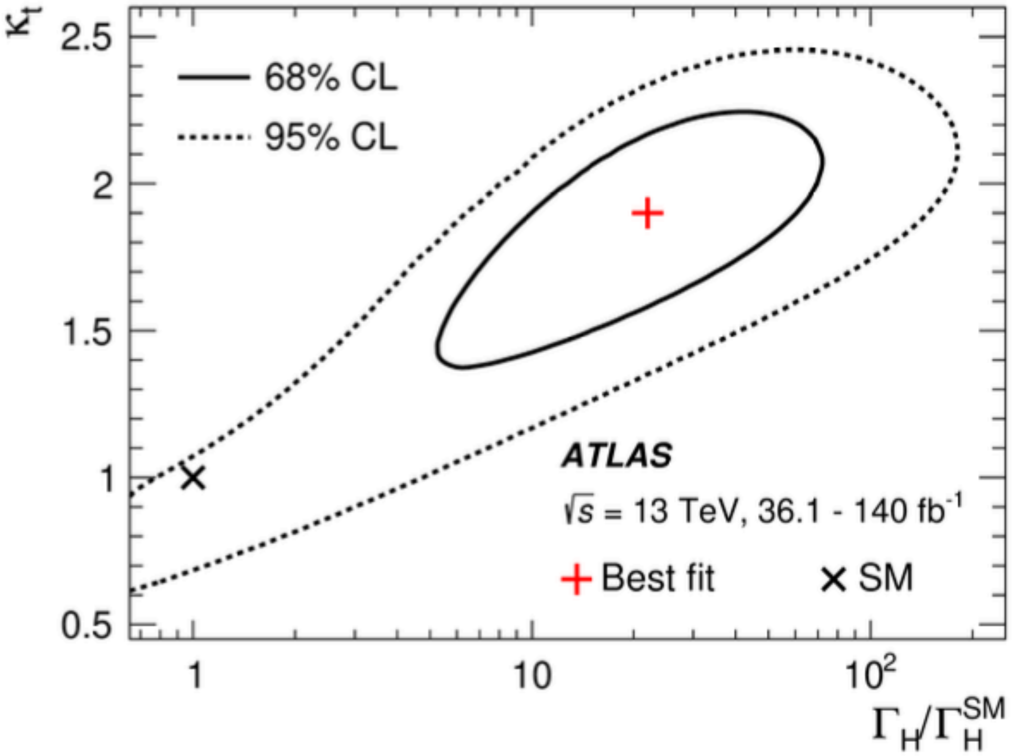
Combination result

- **Perform a full likelihood combination of the two input workspaces**

[arXiv:2407.10631](https://arxiv.org/abs/2407.10631) Submitted to PLB



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



- **95% CL upper limit [MeV]: 445(75)**
  - Strong correlation between R_Γ and κ_t

Summary

- **First measurement of the $H \rightarrow \gamma\gamma$ fiducial cross-section with ATLAS at 13.6 TeV!**
  - Extrapolated to total phase space to measure $\sigma_{tot}(pp \rightarrow H)$
  - Combined with $H \rightarrow ZZ^* \rightarrow 4l$ measurement
  - SM prediction: $\sigma(pp \rightarrow H)_{SM} = 59.9 \pm 2.6$ pb
  - Combination: $\sigma(pp \rightarrow H) = 58.2 \pm 8.7 = 58.2 \pm 7.5(stat.) \pm 4.5(syst.)$ pb

- **First constraint on Higgs boson width based on both on-shell and off-shell production processes involving the Higgs-top Yukawa coupling.**
  - The observed (expected) 95% CL upper limit for Higgs Boson total width is 445 (75) MeV.
  - Could benefit from the more precise top-Higgs coupling measurement during Run3 and HL-LHC.

Thanks!

H→γγ fiducial region definition

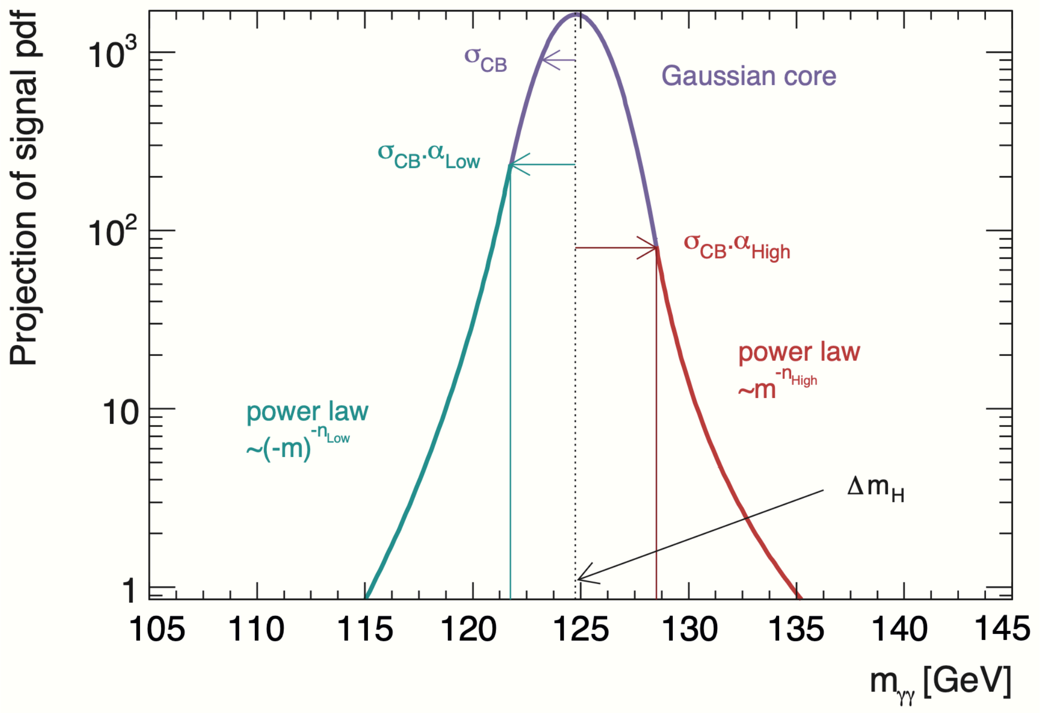
Photons	
Leading (sub-leading) p_T^γ	$p_T^\gamma / m_{\gamma\gamma} > 0.35(0.25)$
Pseudorapidity	$|\eta| < 2.37$ and outside $1.37 < |\eta| < 1.52$
Isolation ($\Delta R = 0.2$)	$E_T^{\text{iso}} / E_T^\gamma < 0.05$
Di-photon system	
Mass window	$105\,\text{GeV} < m_{\gamma\gamma} < 160\ \text{GeV}$

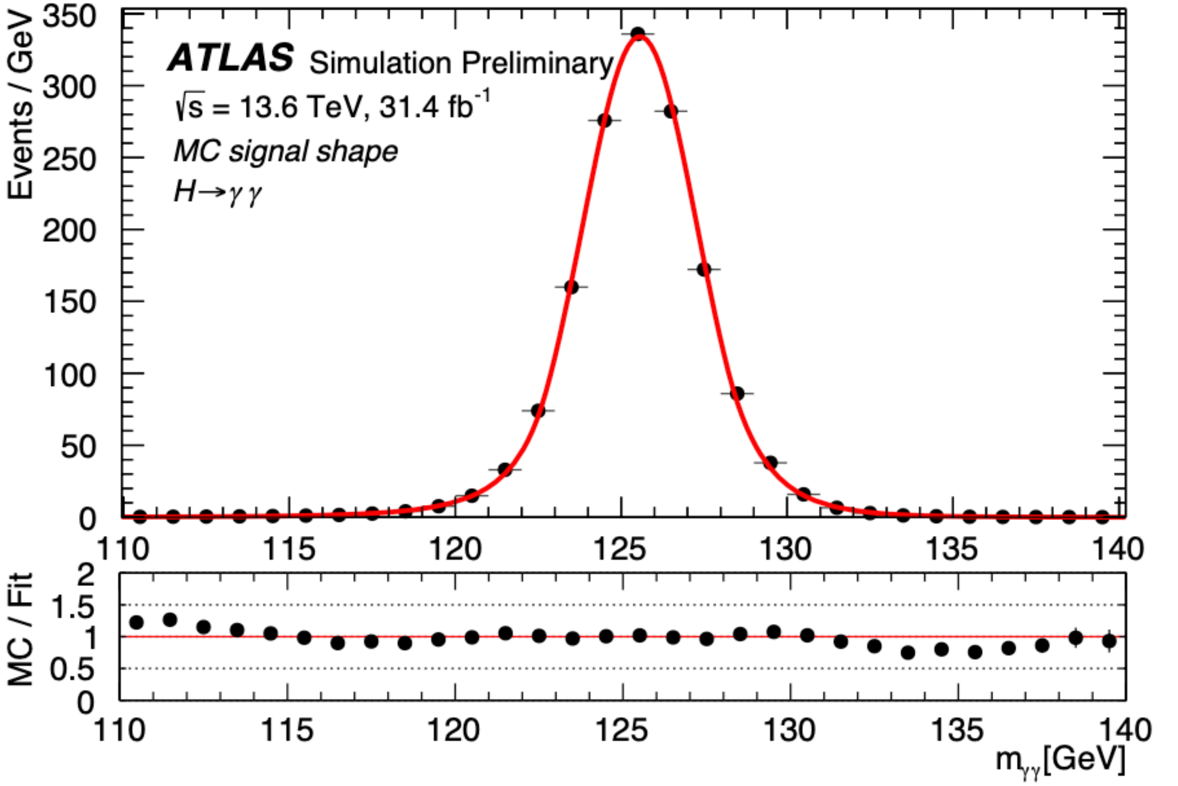
Event selection

- **Preselection**
  - $|\eta| < 2.37$, excluding $1.37 < |\eta| < 1.52$
  - Loose working point
  - Events with at least two photon candidates, each with $E_T > 25$ GeV
  - If more than 2, the two highest-E_T candidates are used
- **Primary vertex selection**
  - Selected using a neural-network algorithm
  - Selection efficiency of 71.4% for ggF
  - Direction of the two photon candidates is re-computed after primary vertex is selected
  - Improves the di-photon invariant mass resolution by ~8%
- **Event selection**
  - $E_T^{\gamma 1}/m_{\gamma\gamma} \geq 0.35$ and $E_T^{\gamma 2}/m_{\gamma\gamma} \geq 0.25$
  - Tight working point
  - Track and calorimeter isolation requirements in $\Delta R = 0.2$ cone
  - $M_{\gamma\gamma}$ should be in the range of 105–160 GeV
- **Selected events in the 2022 Run3 data sample is 307 996** → The selection efficiency: 36%

Signal modeling

- **Signal model**
  - Double-Sided Crystal Ball function





  - Shape parameters are determined from a fit to the signal MC samples and are kept fixed in the fit to the data.
  - Normalization parameter *N* is determined in the fit to the data.

Systematic uncertainties

- **Affected by several sources of uncertainty**
  - Shape of the $m_{\gamma\gamma}$ signal distribution
    - Photon-energy scale
    - Photon-energy resolution
    - Higgs boson mass
  - Background modeling
    - Quantified through the spurious signal yield described in the last page
  - Correction factor CF
    - Uncertainties related to photon trigger efficiency
    - Identification and isolation selections
    - Uncertainty in the pile-up modeling
    - Other theoretical uncertainties
  - Uncertainty in the luminosity measurement
  - Uncertainty in the $H \to \gamma\gamma$ branching ratio

Higgs width measurement

- **Higgs width Γ_H: predicted by theory once the Higgs mass is given**
  - For $m_H = 125$ GeV → $\Gamma_H^{SM} = 4.1$ MeV
  - Deviation from predicted value will indicate new physics.

- **Width measurements from the lineshape and lifetime are not precise enough to approach SM value. → Detector resolution**

Phys. Rev. D 89, 092007