Measurements of Higgs boson production and decay rates and their interpretation with the ATLAS experiment

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On behalf of ATLAS collaboration

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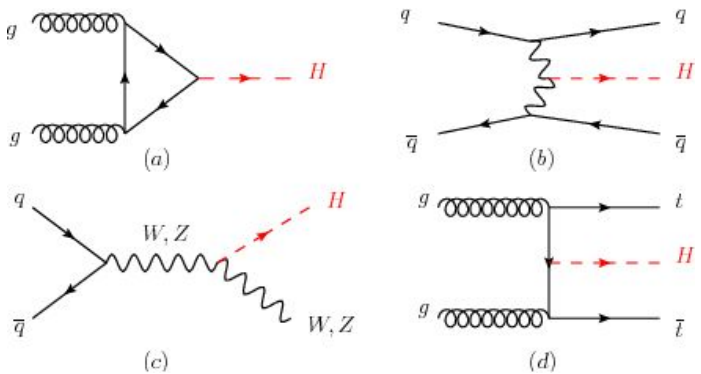
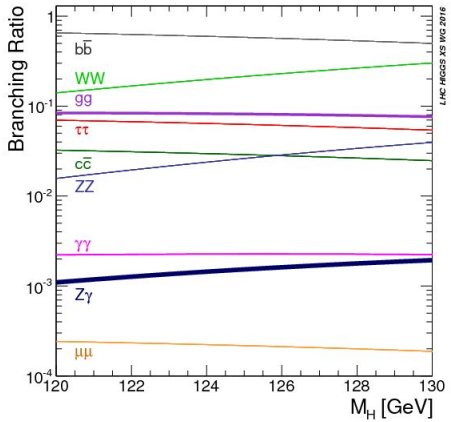
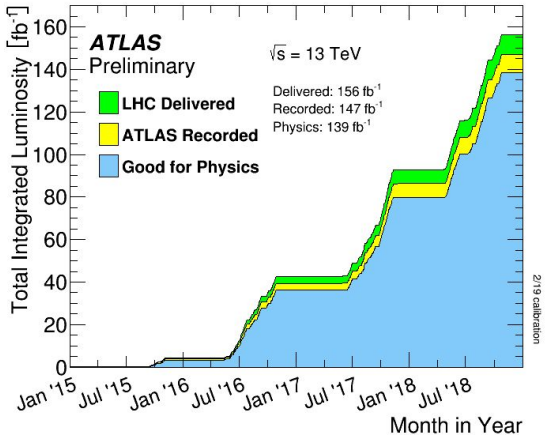
Introduction

- The measurement of Higgs properties, including its production and decay rates, is one of the most important tasks after Higgs discovery
- ATLAS recorded 139 fb^{-1} of good pp collision data at 13 TeV with LHC Run 2
- This talk mainly summarizes the latest publications of Higgs boson production and decay rates with ATLAS Run2 dataset







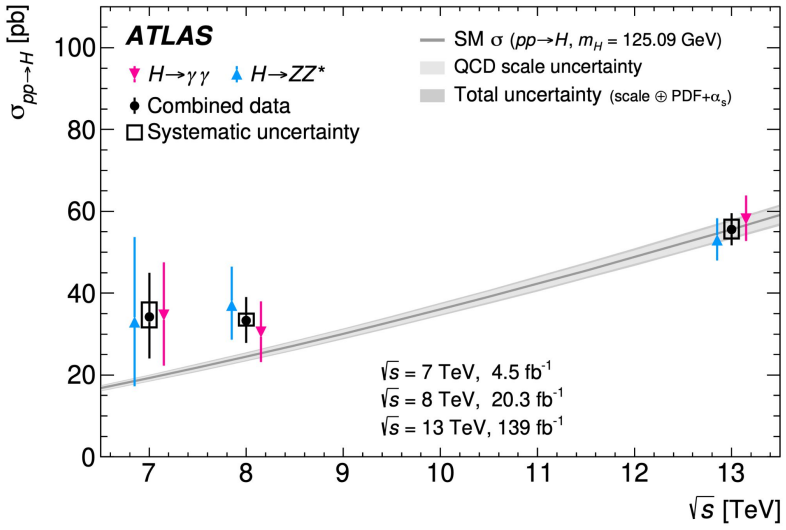
Outline

- Total and differential cross-sections:
  - Higgs to $\gamma\gamma$, Higgs to ZZ*: CERN-EP-2022-143 ($\gamma\gamma$ + ZZ), ATLAS-CONF-2023-003 ($\gamma\gamma$ Run 3)
  - Higgs to WW*: CERN-EP-2022-228 (ggF), CERN-EP-2023-025 (VBF), ATLAS-CONF-2022-067 (VH)
- Higgs rare decay searches
  - Higgs to invisible searches: CERN-EP-2022-289
  - (Higgs to $\gamma\gamma$) + X model-independent searches: CERN-EP-2022-232
- Combination and interpretation results
  - Higgs coupling strengths (κ modifiers): Nature 607 (2022) 52-59
  - SM effective field theory (SMEFT): ATL-PHYS-PUB-2022-037

- Note:
  - This talk focus on the publications < 1 year, so it doesn't cover various of simplified template cross-section publications, and ongoing studies

Higgs to γγ, Higgs to ZZ*

- The most sensitive channels to measure Higgs production and decay rates
  - γγ channel: selects **two isolated photons**. An unbinned simultaneous S+B fit is performed on **m(γγ)**. Backgrounds: non-resonant γγ, γ-jet, dijet, Vγγ, ttγγ
  - ZZ channel: selecting **4 leptons**, with a leading lepton pair in the Z mass window. A binned S+B fit is performed on the m(4l). Background: non-resonant ZZ*, ttbar, Z+jets
- Single channel full Run2 results (JHEP 08 (2022) 027, EPJC 80 (2020) 941) are combined as a new JHEP paper (CERN-EP-2022-143)



The total cross-section in the combined measurement (55.5 + 4 - 3.8 pb) is compatible with the SM (55.6 ± 2.5 pb)

Compatibility between 2 channels: 49%
Compatibility between obs. and SM: 98%

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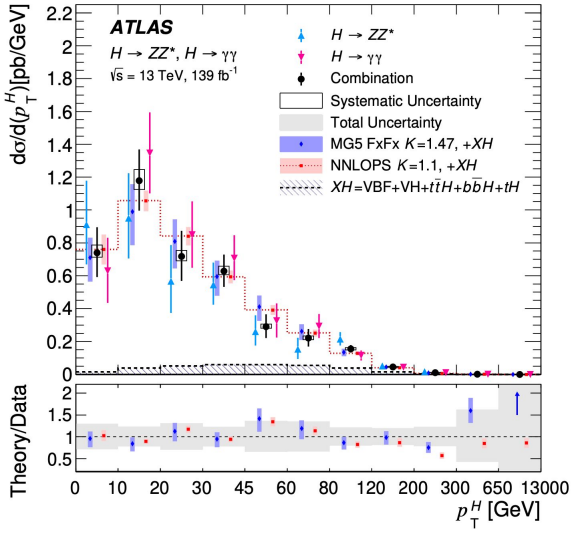
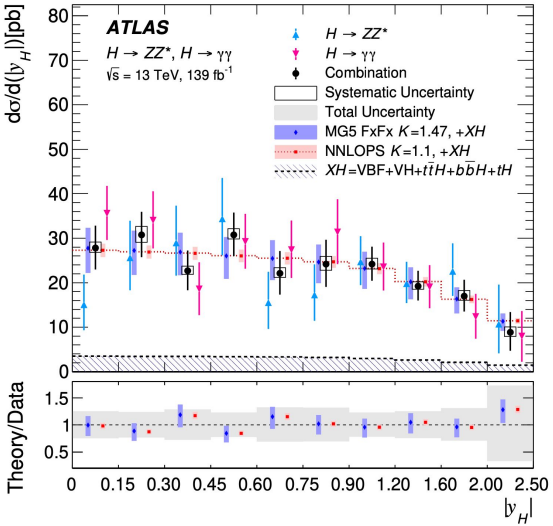
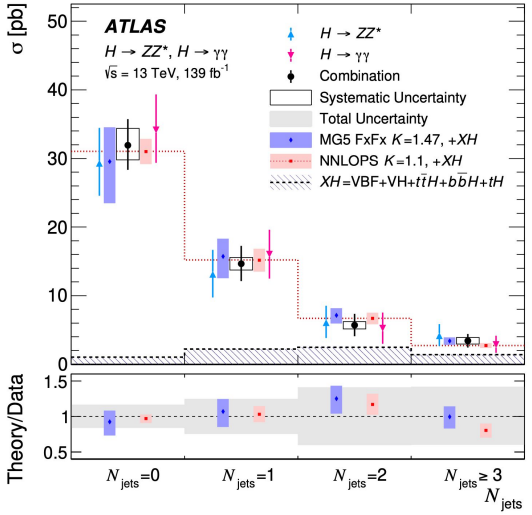
γγ + ZZ* : differential cross-section

- Model-independent measurement of Higgs production cross-section in various differential regions
  - Variables: kinematic of Higgs boson, number of jets, leading jet pT
- Results are compatible with SM, compatibility 20-80%, most bins are driven by stat. uncertainties

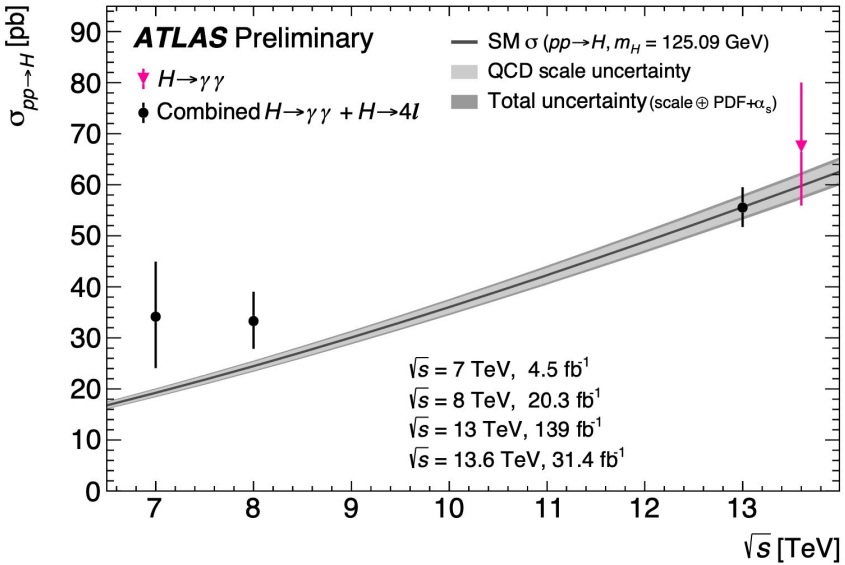




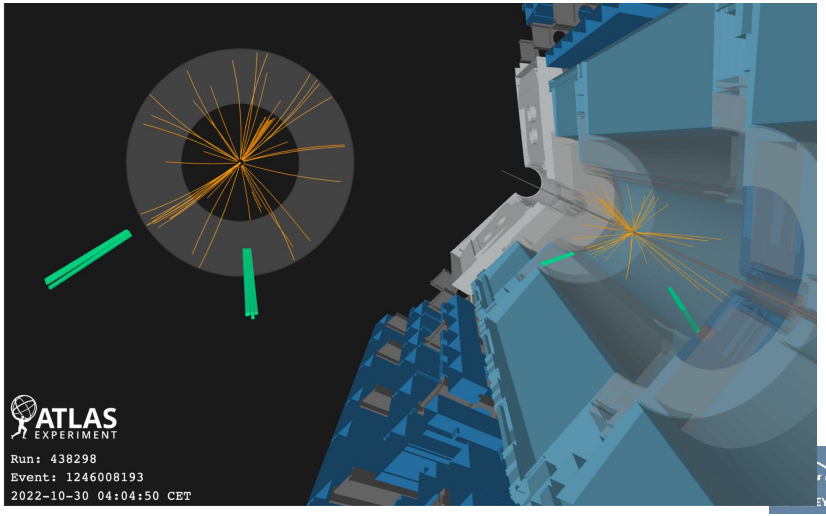


Higgs to γγ, Run3

- The Higgs total cross-section with γγ is also measured with 2022 Run3 data (lumi = 31.4 /fb)
  - ATLAS-CONF-2023-003
  - The center-of-mass energy of Run3 is 13.6 TeV.
- The result is compatible with SM, many uncertainties conservatively extrapolated from Run-2 values. More precious calibration studies are ongoing.

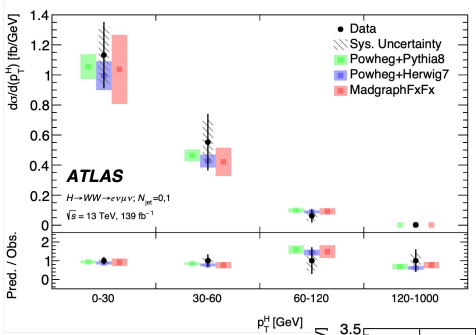


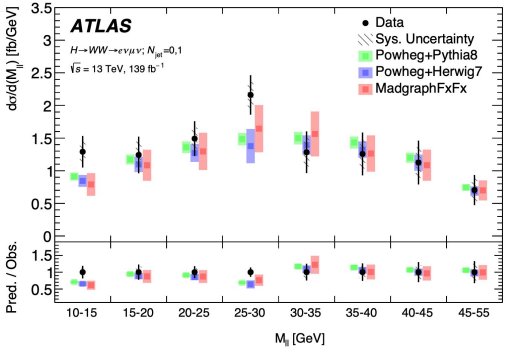
The total cross-section with Run3 data and Higgs to γγ (67 + 12 - 11 pb) is compatible with the SM (59.8 ± 2.6 pb)

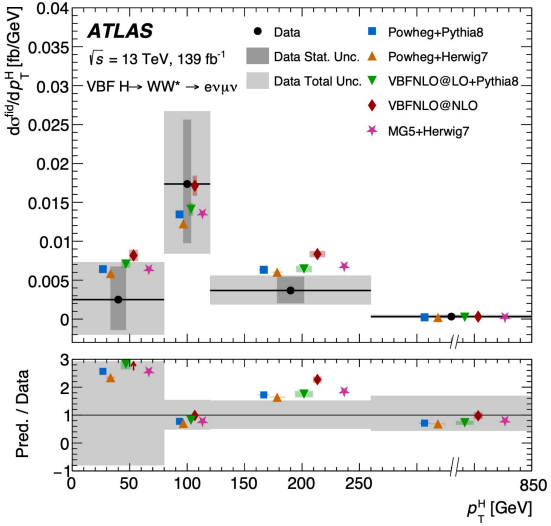


Higgs to WW* ($e\nu\mu\nu$ for VBF/ggF)

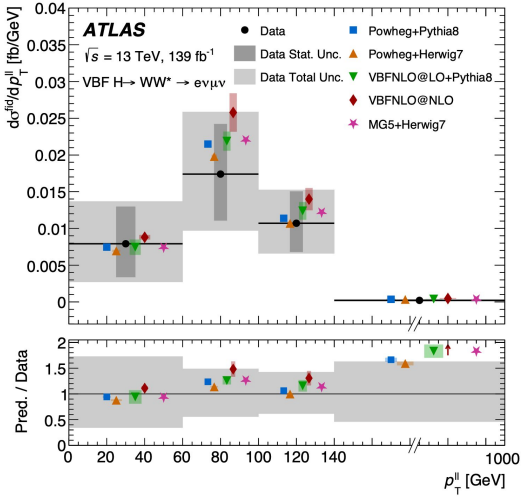
- Selecting events with **2 different-flavour, opposite-sign leptons** and missing transverse energy (MET). **ggF events**: 0, 1 jets; **VBF events**: 2 forward jets with large invariant mass.
- Main background: SM WW*, ttbar/tW, $Z\tau\tau$ + jets, W+jets, VV. A binned S+B fit is performed on **mT** for ggF, and on **BDT scores** for VBF.
- Differential cross-sections (CERN-EP-2022-228, CERN-EP-2023-025) and compatible with SM.







$$m_{\mathrm{T}} = \sqrt{\left(E_{\mathrm{T}}^{\ell\ell} + E_{\mathrm{T}}^{\mathrm{miss}}\right)^2 - \left|\vec{p}_{\mathrm{T}}^{\,\ell\ell} + \vec{E}_{\mathrm{T}}^{\mathrm{miss}}\right|^2}$$

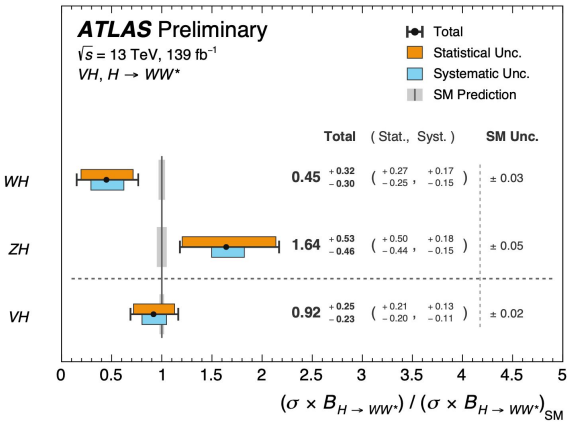


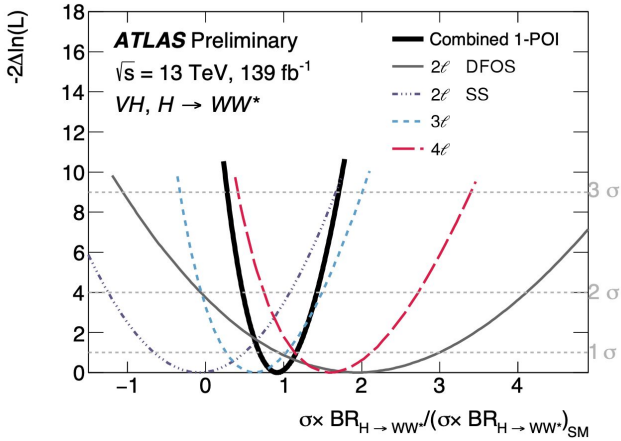
Variables: kinematic of Higgs and di-lepton system

Higgs to WW* (lνlν + lνjj for VH)

- VH: lνlν + lνjj, consider for signatures targeting different decay modes of the W and V boson. performing S+B fits on discriminant variables (based on ANN, RNN, BDT scores)
- WH and ZH cross-sections are measured and combined using the four channels, the results are compatible with SM (ATLAS-CONF-2022-067)

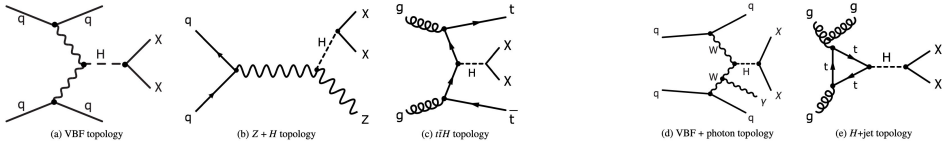
Channel	Background	Normalisation factor
Opposite-sign 2ℓ →V(qq)WW(lνlν)	Top	$0.99^{+0.31}_{-0.22}$
	Z+jets	$0.87^{+0.15}_{-0.14}$
	WW	$0.89^{+0.27}_{-0.24}$
Same-sign 2ℓ →W(lν)WW(lνqq)	$W(Z/\gamma^*)$	$0.91^{+0.18}_{-0.16}$
	$W(Z/\gamma^*)$ 0-jet	1.03 ± 0.06
3ℓ →W(lν)WW(lνlν)	$W(Z/\gamma^*)$ ≥1-jets	$0.88^{+0.16}_{-0.15}$
	WWW	$2.18^{+0.73}_{-0.61}$
4ℓ →Z(ll)WW(lνlν)	ZZ	$0.99^{+0.08}_{-0.07}$

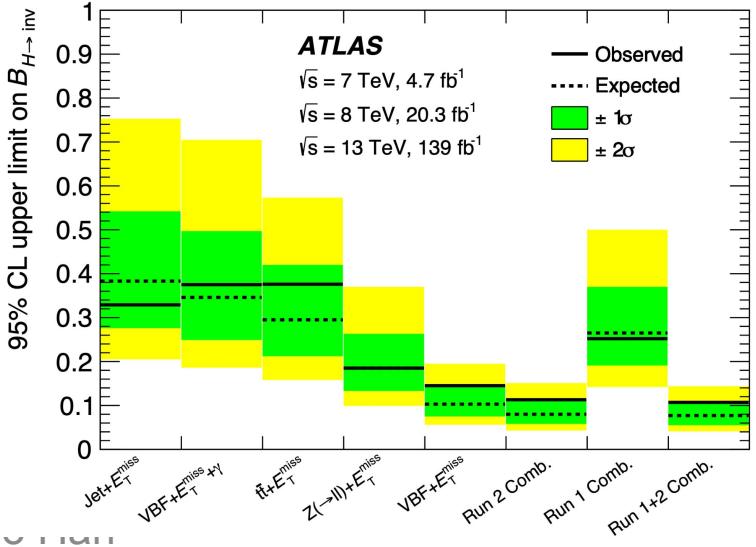




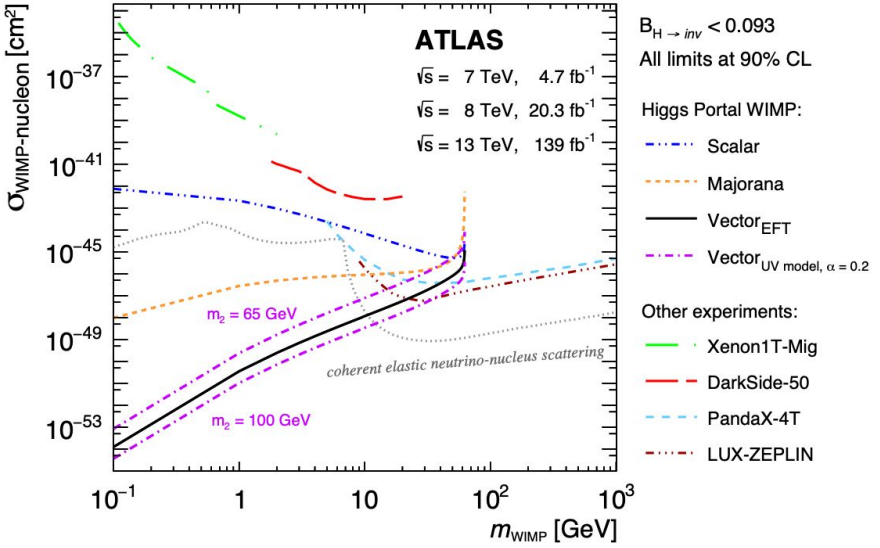
Higgs → invisible searches

- Higgs to invisible searches were combined in various high MET channels. (CERN-EP-2022-289)
- No excess is observed, the limits are set on the H → inv branching ratio. The 95% CL upper limit on Br(H→inv), combining the Run1 and Run2 results is Br(H→inv) = 0.107.





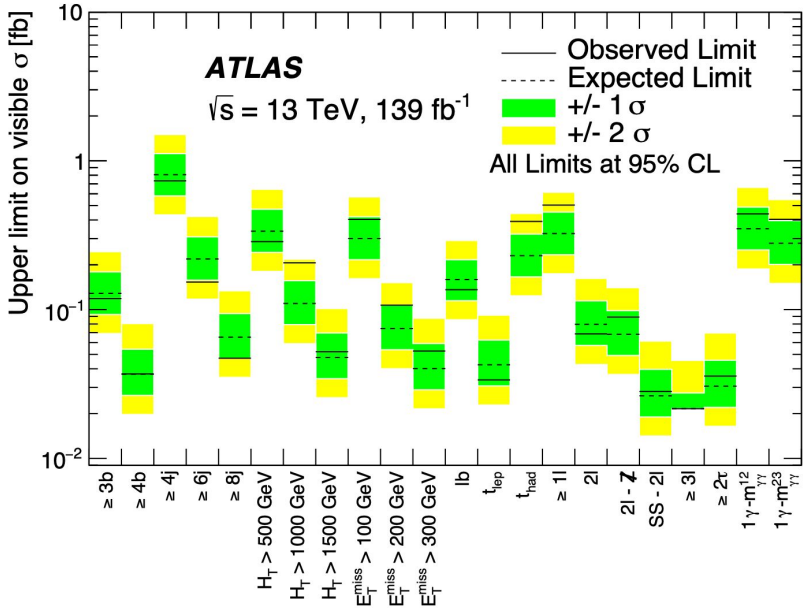
Limits are also set on dark-matter - nucleon scattering cross-section in Higgs portal models



Higgs→γγ, model-independent searches

- Model-independent searches are performed with 22 regions targeting (Higgs → γγ) + X
- No excess beyond the SM expectation (largest deviation 1.9 standard deviation), results are reported as limits on the visible cross-sections of Higgs+X, but efficiency ranges (for several benchmark BSM models) are also quoted for reinterpretation in terms of constraints on particle-level cross-sections and BSM models (CERN-EP-2022-232)

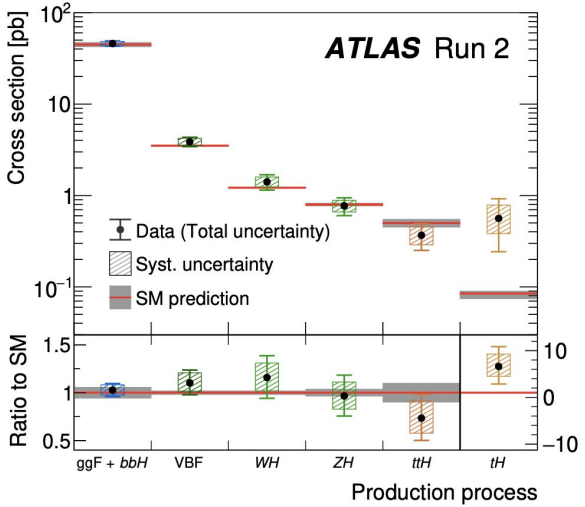
Target	Region	Detector level	Particle level
Heavy flavour	$\geq 3b$	$n_{b\text{-jet}} \geq 3$, 85% WP	$n_{b\text{-jet}} \geq 3$
	$\geq 4b$	$n_{b\text{-jet}} \geq 4$, 85% WP	$n_{b\text{-jet}} \geq 4$
High jet activity	≥ 4j	$n_{\text{jet}} \geq 4$, $\lvert\eta_{\text{jet}}\rvert < 2.5$	$n_{\text{jet}} \geq 4$, $\lvert\eta_{\text{jet}}\rvert < 2.5$
	≥ 6j	$n_{\text{jet}} \geq 6$, $\lvert\eta_{\text{jet}}\rvert < 2.5$	$n_{\text{jet}} \geq 6$, $\lvert\eta_{\text{jet}}\rvert < 2.5$
	≥ 8j	$n_{\text{jet}} \geq 8$, $\lvert\eta_{\text{jet}}\rvert < 2.5$	$n_{\text{jet}} \geq 8$, $\lvert\eta_{\text{jet}}\rvert < 2.5$
	$H_{\text{T}} > 500$ GeV	$H_{\text{T}} > 500$ GeV	$H_{\text{T}} > 500$ GeV
	$H_{\text{T}} > 1000$ GeV	$H_{\text{T}} > 1000$ GeV	$H_{\text{T}} > 1000$ GeV
	$H_{\text{T}} > 1500$ GeV	$H_{\text{T}} > 1500$ GeV	$H_{\text{T}} > 1500$ GeV
$E_{\text{T}}^{\text{miss}}$	$E_{\text{T}}^{\text{miss}} > 100$ GeV	$E_{\text{T}}^{\text{miss}} > 100$ GeV	$E_{\text{T}}^{\text{miss,tru}} > 100$ GeV
	$E_{\text{T}}^{\text{miss}} > 200$ GeV	$E_{\text{T}}^{\text{miss}} > 200$ GeV	$E_{\text{T}}^{\text{miss,tru}} > 200$ GeV
	$E_{\text{T}}^{\text{miss}} > 300$ GeV	$E_{\text{T}}^{\text{miss}} > 300$ GeV	$E_{\text{T}}^{\text{miss,tru}} > 300$ GeV
Top	ℓb	$n_{\ell=e,\mu} \geq 1$, $n_{b\text{-jet}} \geq 1$, 70% WP	$n_{\ell=e,\mu} \geq 1$, $n_{b\text{-jet}} \geq 1$
	t_{lep}	$n_{\ell=e,\mu} = 1$, $n_{\text{jet}} = n_{b\text{-jet}} = 1$, 70% WP	$n_{\ell=e,\mu} = 1$, $n_{\text{jet}} = n_{b\text{-jet}} = 1$
	t_{had}	$n_{\ell=e,\mu} = 0$, $n_{\text{jet}} = 3$, $n_{b\text{-jet}} = 1$, 70% WP, $\text{BDT}_{\text{top}} > 0.9$	$n_{\ell=e,\mu} = 0$, $n_{\text{jet}} = 3$, $n_{b\text{-jet}} = 1$
Lepton	$\geq 1\ell$	$n_{\ell=e,\mu} \geq 1$	$n_{\ell=e,\mu} \geq 1$
	2ℓ	$ee, \mu\mu$, or $e\mu$	$ee, \mu\mu$, or $e\mu$
	2ℓ–$\not{Z}$	$ee, \mu\mu, e\mu$; $\lvert m_{\ell\ell} - m_Z\rvert > 10$ GeV for same-flavour leptons	$ee, \mu\mu, e\mu$; $\lvert m_{\ell\ell} - m_Z\rvert > 10$ GeV for same-flavour leptons
	SS-2ℓ	$ee, \mu\mu$, or $e\mu$ with same charge	$ee, \mu\mu$, or $e\mu$ with same charge
	$\geq 3\ell$	$n_{\ell=e,\mu} \geq 3$	$n_{\ell=e,\mu} \geq 3$
	$\geq 2\tau$	$n_{\tau,\text{had}} \geq 2$	$n_{\tau} \geq 2$
Photon	1γ–$m_{\gamma\gamma}^{12}$	$n_{\gamma} \geq 3$, $m_{\gamma\gamma}$ defined with γ_1,γ_2	$n_{\gamma} \geq 3$, $m_{\gamma\gamma}$ defined with γ_1,γ_2
	1γ–$m_{\gamma\gamma}^{23}$	$n_{\gamma} \geq 3$, $m_{\gamma\gamma}$ defined with γ_2,γ_3	$n_{\gamma} \geq 3$, $m_{\gamma\gamma}$ defined with γ_2,γ_3

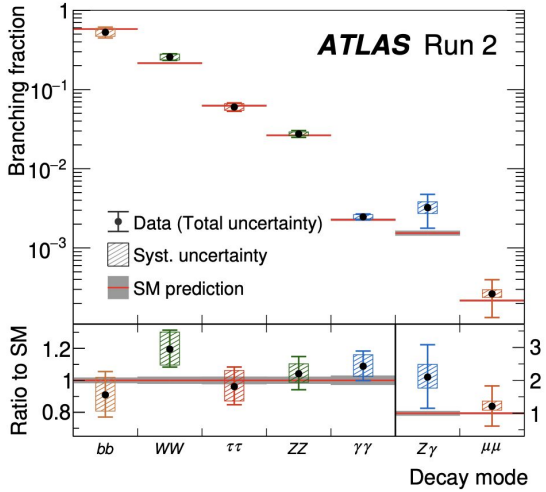


Combination and interpretation

- A combined measurement on the Higgs cross-sections was published for the 10 year anniversary of the Higgs boson discovery (Nature 607 (2022) 52-59)
- The result includes the input measurements from **γγ, ZZ*, WW*, bb and ττ channels**, as well as the **searches for the μμ, Zγ, cc and invisible decays**.
- The combined results are in good agreement with the SM predictions..

$$\mu = 1.05 \pm 0.06 = 1.05 \pm 0.03\,(\text{stat.}) \pm 0.03\,(\text{exp.}) \pm 0.04\,(\text{sig. th.}) \pm 0.02\,(\text{bkg. th.}).$$

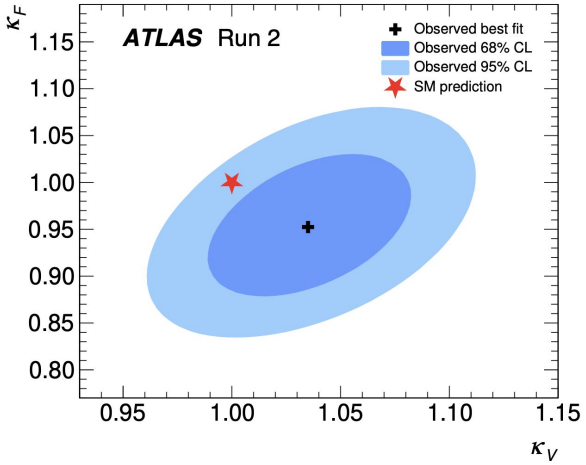


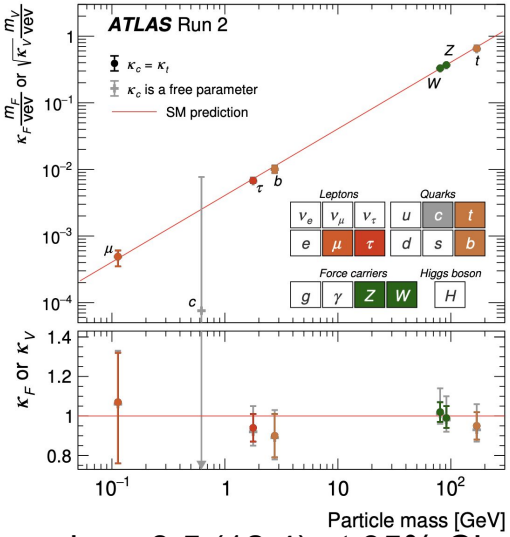


Interpretation: κ-framework

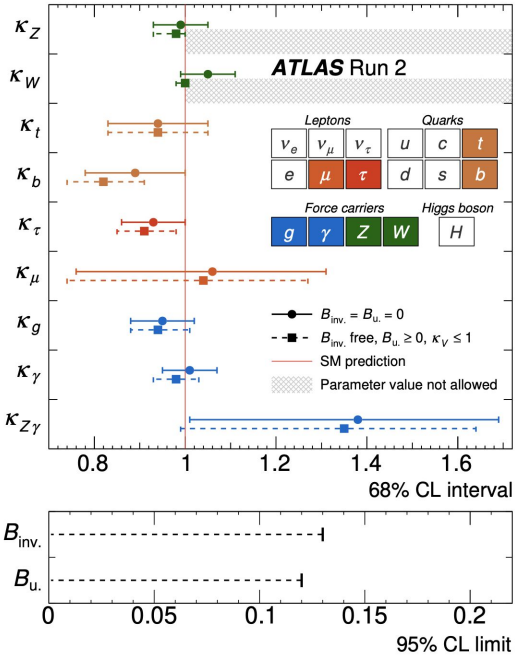
- Event rates for Higgs production and decay processes are interpreted in terms of coupling modifiers (k) multiplying the SM Higgs boson coupling strengths to other particles..
- Results are compatible with SM.
  - kc < 8.5 (12.4) at 95% CL, which is improved wrt the H→cc analysis with constraint power from the Higgs total width
  - Br of undetected Higgs decays (Bu) is also constrained

$$\kappa_p^2 = \sigma_p / \sigma_p^{\mathrm{SM}}$$





kc < 8.5 (12.4) at 95% CL



Interpretation: effective field theory

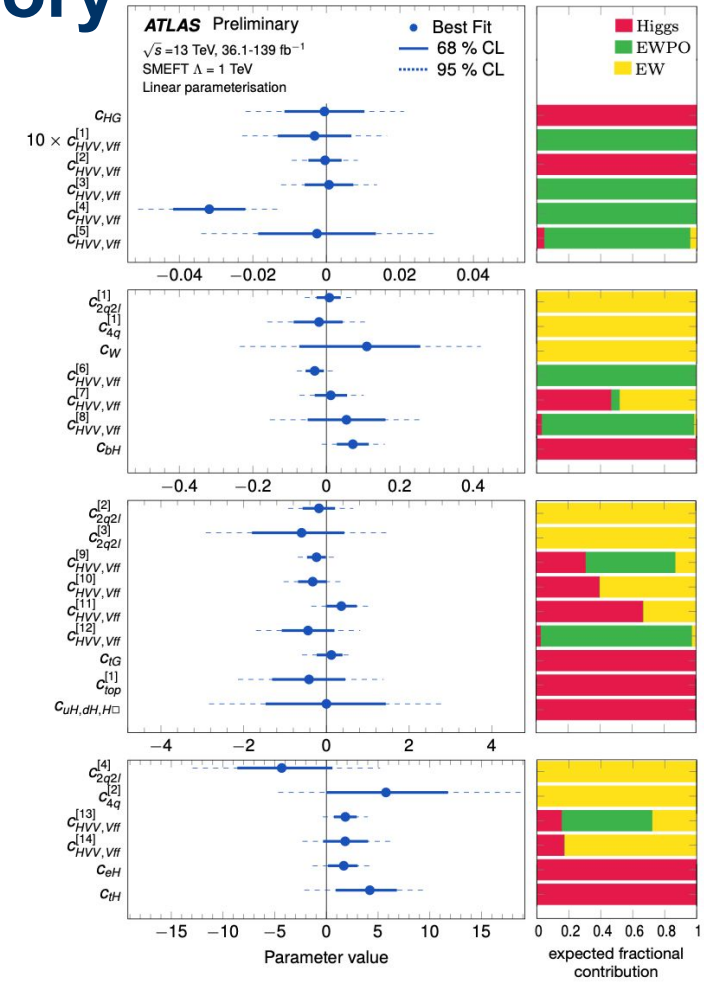
- Standard Model Effective Field Theory (SMEFT, ref) describes the deviations from SM predictions in terms of new effective interactions caused by new physics at very large energy scales.
- New interactions are scaled by Wilson coefficients which are free parameters of the theory.
- Limits are set on the selected linear combinations of Wilson coefficients (eigenvectors) in a simultaneous fit of all relevant coefficients. (ATL-PHYS-PUB-2022-037)

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \mathcal{L}^{(5)} + \mathcal{L}^{(6)} + \mathcal{L}^{(7)} + \ldots,$$

$$\mathcal{L}^{(\text{d})} = \sum_i \frac{C_i^{(\text{d})}}{\Lambda^{\text{d}-4}} \mathcal{Q}_i^{(\text{d})} \text{ for } \text{d} > 4.$$

Decay channel	Target Production Modes	$\mathcal{L}$ [fb^{-1}]
$H \to \gamma\gamma$	ggF, VBF, $WH, ZH, t\bar{t}H, tH$	139
$H \to ZZ^*$	ggF, VBF, $WH, ZH, t\bar{t}H(4\ell)$	139
$H \to WW^*$	ggF, VBF	139
$H \to \tau\tau$	ggF, VBF, $WH, ZH, t\bar{t}H(\tau_{\text{had}}\tau_{\text{had}})$	139
	WH, ZH	139
$H \to b\bar{b}$	VBF	126
	$t\bar{t}H$	139

Beside Higgs production and decay rate, the interpretation also includes electroweak cross-section measurements by ATLAS and EWPO measurements by LEP



Summary

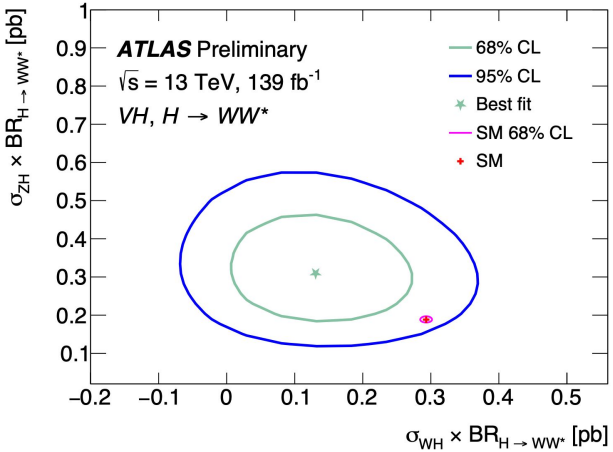
- Measurement of the Higgs boson production and decay rates is one of the most important tasks for the high energy physics
- The analysis with full Run2 ATLAS data are well established, most of the sensitive channels to measure Higgs properties are published
  - The analysis with Run3 data has started.
  - The measurements are interpreted in the k-framework and within an effective field theory framework
  - All measurements are in a good agreement with the predictions of the Standard Model

Backup

Higgs to WW* (lνlν + lνjj for VH)

- VH: lνlν + lνjj, combining 2LOS, 2LSS, 3L and 4L selections, performing S+B fits on discriminant variables (based on ANN, RNN, BDT scores)
- WH and ZH cross-sections are measured and combined across the four channels, the results are compatible with SM

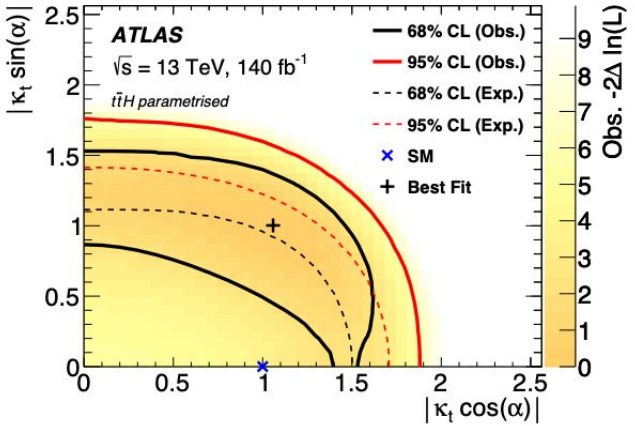
Channel	POI / Z_0	Expected	Observed
Opposite-sign 2ℓ	μ_{VH}	$1.00^{+1.02}_{-0.98}$	$1.94^{+1.07}_{-1.02}$
	Z_0	1.0	1.9
Same-sign 2ℓ	μ_{WH}	$1.00^{+0.61}_{-0.60}$	-0.08 ± 0.58
	Z_0	1.6	0.0
3ℓ	μ_{WH}	$1.00^{+0.44}_{-0.40}$	$0.64^{+0.42}_{-0.37}$
	Z_0	2.8	1.8
4ℓ	μ_{ZH}	$1.00^{+0.47}_{-0.39}$	$1.59^{+0.54}_{-0.47}$
	Z_0	3.1	4.5
Combined 1-POI	μ_{VH}	$1.00^{+0.27}_{-0.25}$	$0.92^{+0.25}_{-0.23}$
	Z_0	4.7	4.6
Combined 2-POI	μ_{WH}	$1.00^{+0.35}_{-0.33}$	$0.45^{+0.32}_{-0.30}$
	μ_{ZH}	$1.00^{+0.47}_{-0.39}$	$1.64^{+0.55}_{-0.47}$
	Z_0^{WH}	3.3	1.5
	Z_0^{ZH}	3.1	4.6



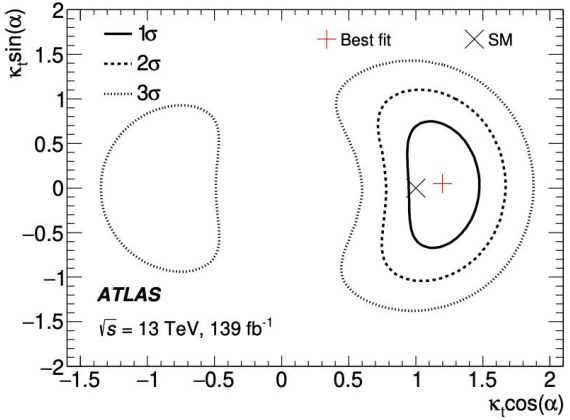
Top-Higgs Yukawa coupling and Higgs CP

- Top-Higgs Yukawa coupling (κt) and CP properties can be measured in particular channels
  - Recent result - ttH, Higgs - bb: CERN-EP-2022-208
  - Reference 1 - ttH, Higgs to γγ: PRL 125 (2020) 061802
  - Reference 2 - Four top observation (with ttH, Higgs to WW and tt): CERN-EP-2023-055
- The measurements are all compatible with the SM

$$\mathcal{L} = -\frac{1}{\sqrt{2}} y_t \bar{t} \left(a_t + i b_t \gamma_5\right) t h,$$



H→γγ



H→bb