Higgs boson production and decay rate measurements with the ATLAS experiment

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PASCOS 2026, Sheffield

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The Higgs Sector

➔ **Gauge symmetry requires massless mediators**, yet the W/Z bosons are massive!
- Spontaneous symmetry breaking generates their masses dynamically via a field with a non-zero minimum
- **Preserves Gauge invariance**
- Introduces a new fundamental particle

$$\boxed{V(\phi) = -\mu^2(\phi^\dagger\phi) + \lambda(\phi^\dagger\phi)^2}$$

$$\phi = \frac{1}{\sqrt{2}}\begin{bmatrix}0\\ \nu\end{bmatrix} \qquad \nu = \sqrt{\frac{\mu^2}{\lambda}}$$

$$\lambda > 0; \mu^2 > 0$$

$$\boxed{V(\nu + h) = V_0 + \underline{\lambda\nu^2h^2} + \underline{\lambda\nu h^3} + \frac{\lambda}{4}h^4}$$

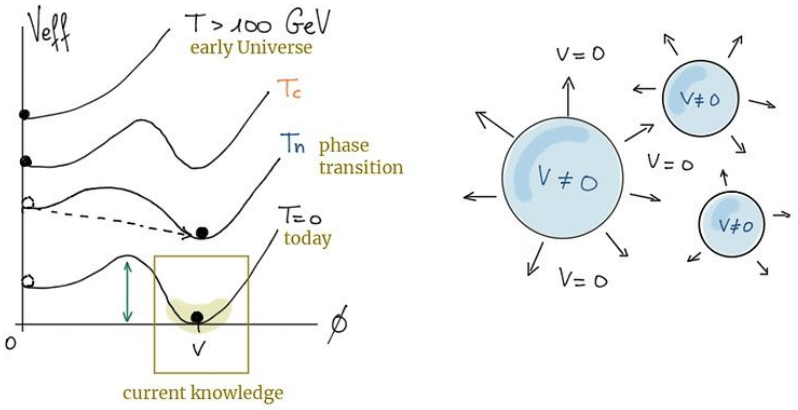
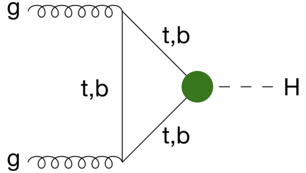


Photo: Kateryna Radchenko Serdula

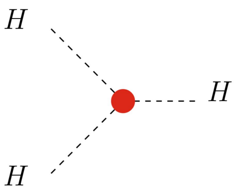
➔ Higgs properties can be determined once m(H) is known:
- Branching ratios
- Decay width
- Higgs self coupling

➔ Fermions get their mass through Yukawa coupling and Higgs vev value

Single Higgs

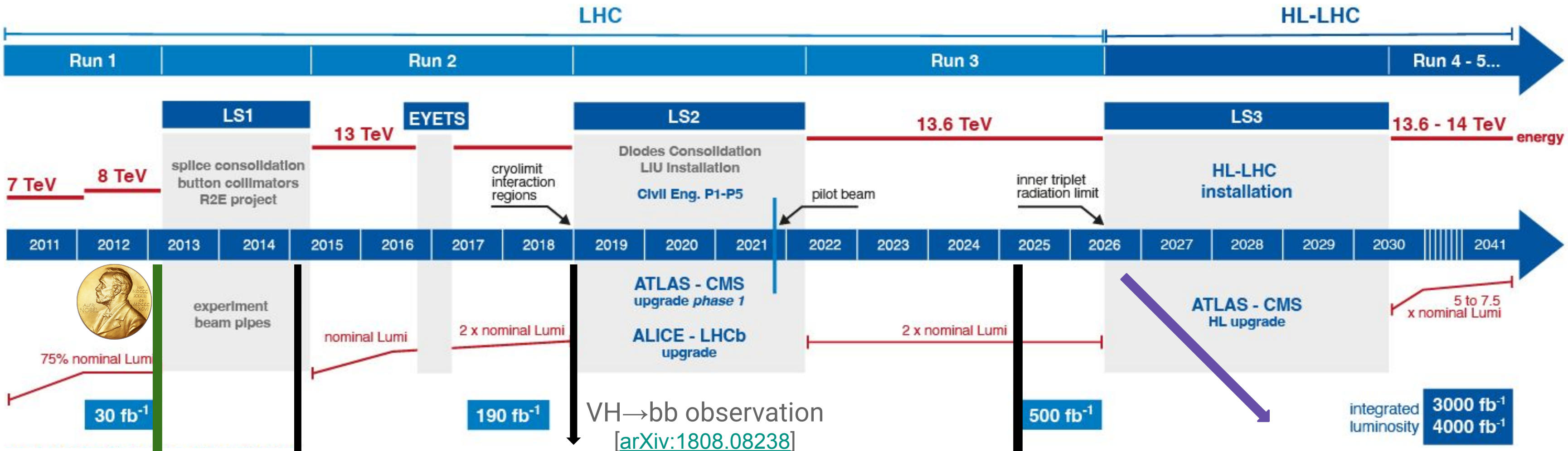


Trilinear Coupling



[Nature volume 607, pages 41–47 (2022)]

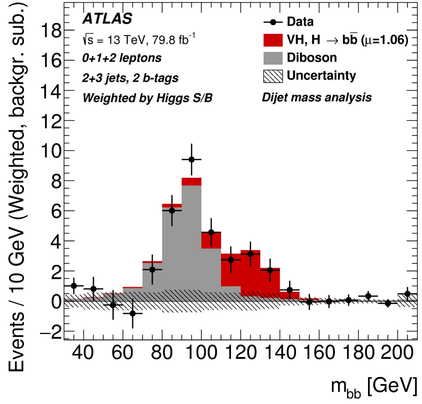
Higgs Physics at ATLAS



Higgs discovery

Higgs spin and parity
[Eur. Phys. J. C 75 (2015) 476]

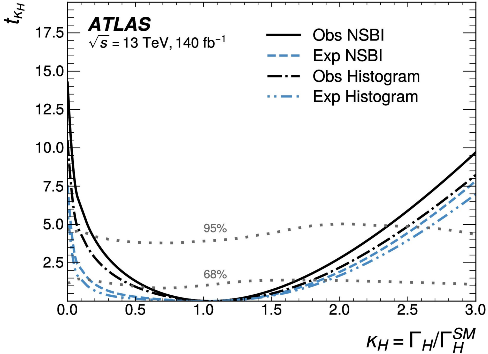
VH→bb observation
[arXiv:1808.08238]



Evidence for Off-Shell H→ZZ
[arXiv:2412.01548]

We are **HERE**

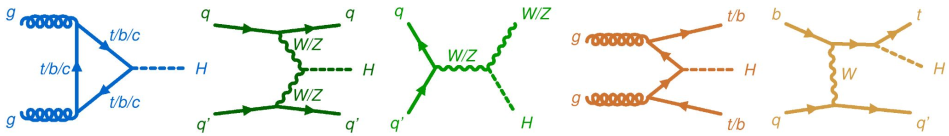
→ **~25M Higgs** bosons produced



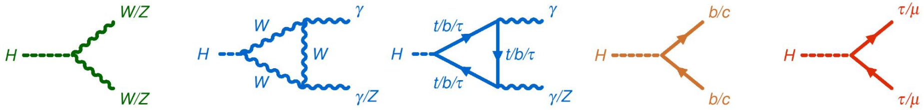
Run 2 & Run 3: Single Higgs

Run 2: Higgs Combined Measurement

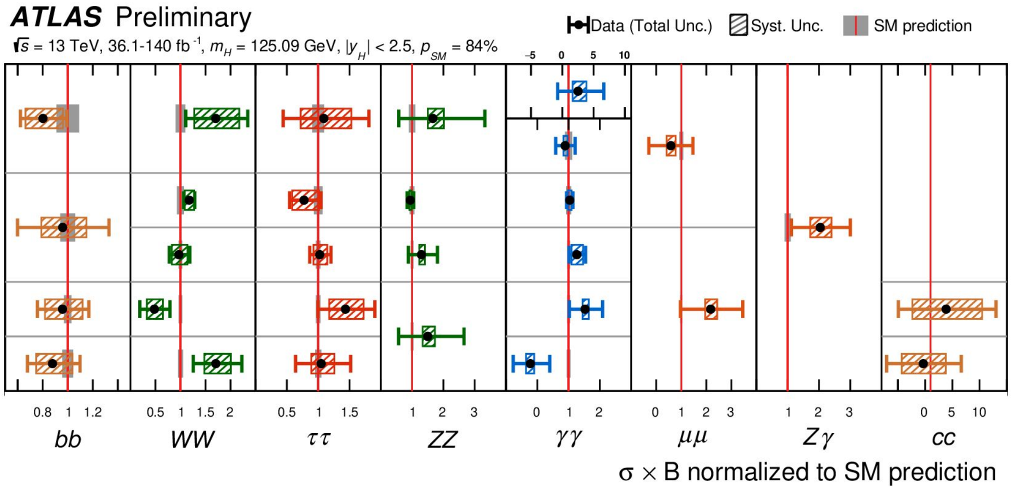
Production modes:



Decay modes:



Analysis	Prod. modes	$\mathcal{L}$ (fb^{-1})	Reference
$H \to \gamma\gamma$	All	139	JHEP 07 (2023)
$H \to ZZ^* \to 4\ell$	All	139	Eur. Phys. J. C 80 (2020)
$H \to \tau\tau$	All	140	JHEP 03 (2025)
$H \to WW$	ggF,VBF	140	Eur. Phys. J. C 85 (2025)
$H \to WW$	VH	140	JHEP 08 (2025)
$H \to b\bar{b}$	VBF	126	Eur. Phys. J. C 81 (2021)
$H \to b\bar{b}, c\bar{c}$	VH	140	JHEP 04 (2025)
$H \to$ multileptons	$t\bar{t}H$	36.1	Phys. Rev. D 97 (2018)
$H \to b\bar{b}$	$t\bar{t}H$	140	Eur. Phys. J. C 85 (2025)
$H \to \tau\tau$	VH	140	Phys. Lett. B 855 (2024)
$H \to Z\gamma$	All	139	Phys. Lett. B 809 (2020)
$H \to \mu\mu$	All	139	Phys. Lett. B 855 (2024)



Signal strength: $$\mu = \frac{\sigma_i \times B_f}{\sigma_f^{SM} \times B_f^{SM}}$$

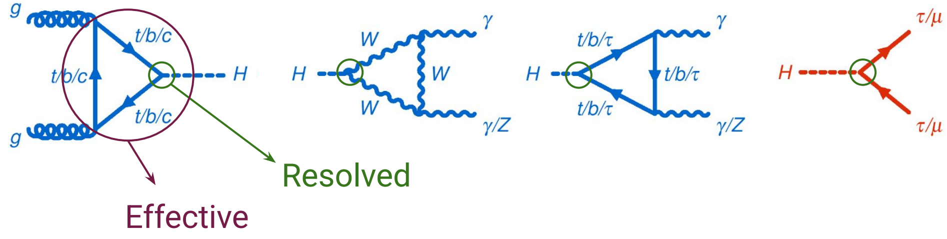
Total Higgs signal strength: $$\mu = 1.023^{+0.056}_{-0.053}$$

[ATLAS-CONF-2025-006]

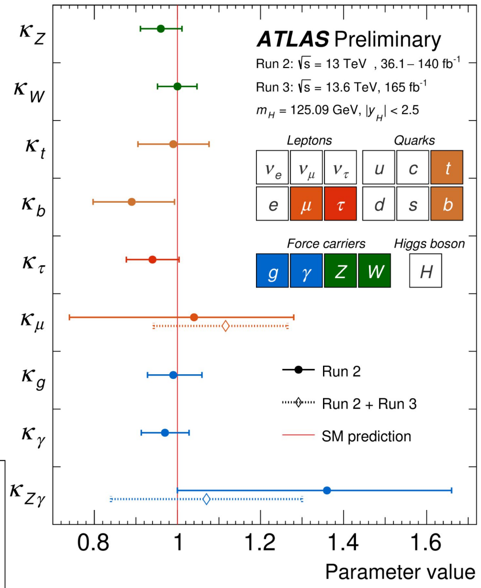
Run 2: Higgs Combined Measurement

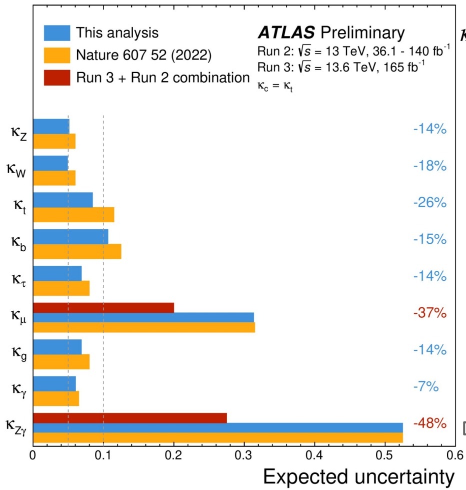
Coupling interpretation (Kappa):

$$\sigma_i \times B(H \to f) = \frac{\sigma_i \times \Gamma_f}{\Gamma_H} = \frac{\kappa_i^2 \kappa_f^2}{\kappa_H^2} \sigma_i^{SM} \times B^{SM}(H \to f)$$



Improvement from Run 3 analyses





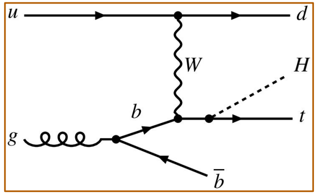
- ➔ Various Higgs properties and phenomena are studied:
  - ◆ CP violations (Álvaro's talk)
  - ◆ Effective Field Theory (Oleksii's talk)
  - ◆ Coupling interpretations
- ➔ First Run 3 results have been considered

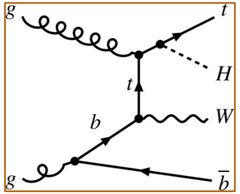
⟹ More in Xingchen's talk

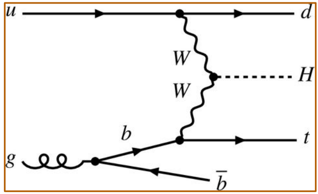
Run 2: tH Combined Measurement

pp→tH Combination [ATLAS-CONF-2026-002]:

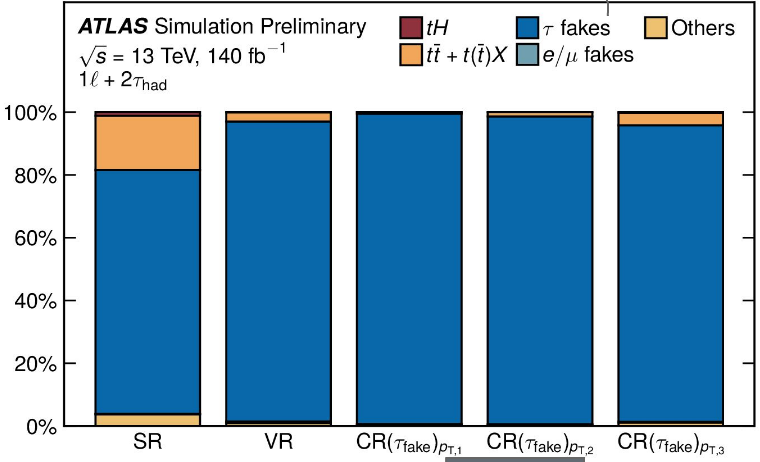
- ➔ Two folds study:
  - ◆ tH→$\tau\tau$ measurement
    - ● With at least 1 hadronic τ → In two regions 2l+τ & 1l+2τ
  - ◆ tH combination with:
    - ● H→bb/ZZ/WW/$\tau\tau$ [JHEP10 (2025) 093]
    - ● H→$\gamma\gamma$ [JHEP 07 (2023) 088]
- ➔ Combined inverted top coupling (κ_t=-1): >5-σ exclusion





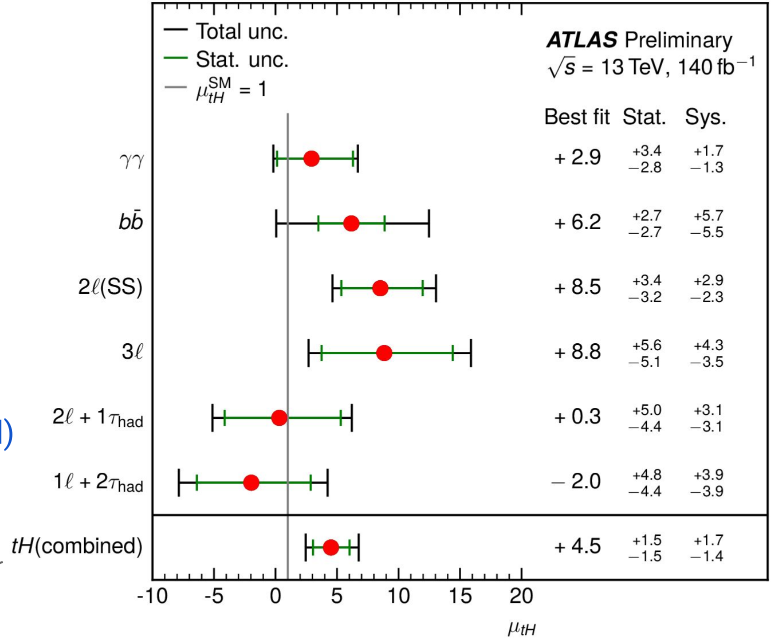


Estimated using MC templates with dedicated Normalizations



1-Tight lepton + Loose but !Tight tau(had) with progressive τ-had window of [20,30), [30,60), and >60 GeV

95%CL of 8.6 (9.6) on observed (expected)



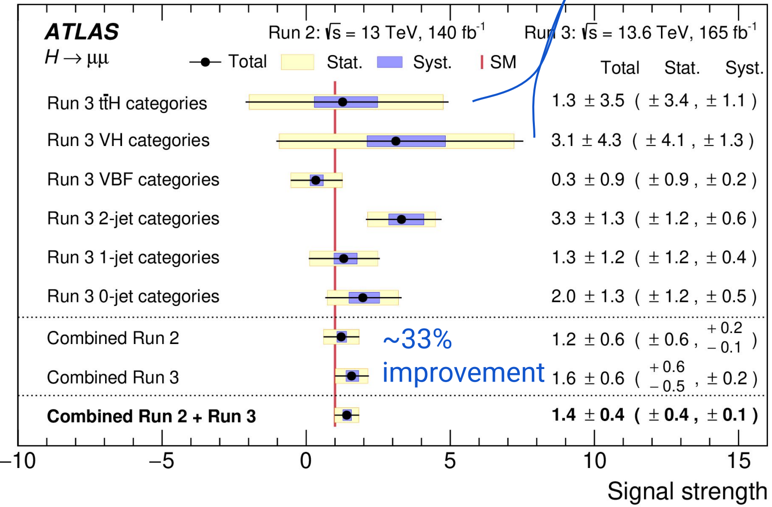
Run 2+3: H→$\mu\mu$

H→$\mu\mu$:

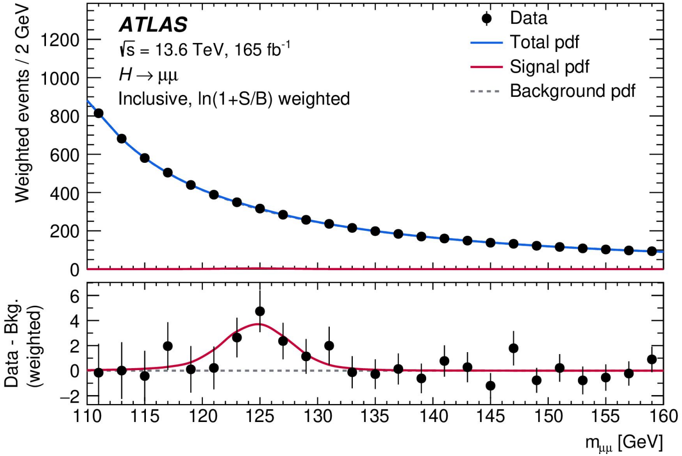
- ➔ Run 2: 140ifb, Run-3: 165ifb
- ➔ Targeting ggF, VBF, VH, and ttH productions
- ➔ Utilize the reconstructed mass of each signature
- ➔ **Evidence** of Yukawa second generation coupling:
  - ◆ Observed significance: 3.0σ
  - ◆ Expected significance: 2.5σ

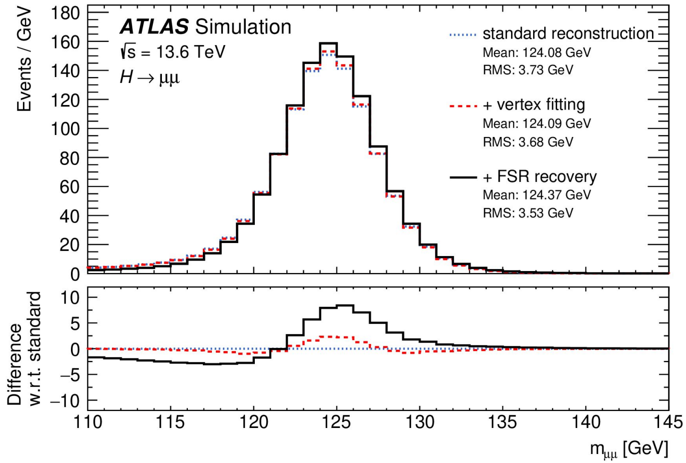
New channels to the categories:
→ 2-Lepton VH
→ All hadronic ttH

[Physics Letters B 876 (2026) 140313]



Improved resolution through vertex refitting





Run 3: H→4l

H→4l [arXiv:2605.19016]:

- ➔ Run 3: 164ifb
- ➔ Major precision channel
- ➔ Two measurements:
  - ◆ **In Fiducial phase space**
    - Detector level selection
    - Minimal extrapolation and theory dependence

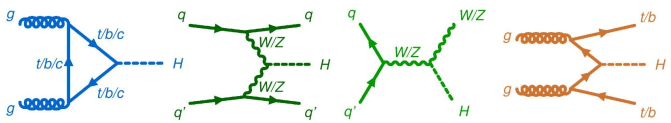
Fid. Bin (i)

$$N_i\,(m_{4\ell}) = \sum_j \sigma_j^{\mathrm{fid}} \cdot \mathcal{P}_i\,(m_{4\ell}) \cdot r_{ij} \cdot \left(1 + f_i^{\mathrm{nonfid}}\right) \cdot \mathcal{L} + N_i^{\mathrm{bkg}}\,(m_{4\ell})$$

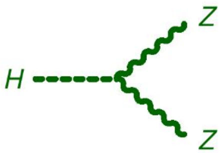
Signal Reconstructed template

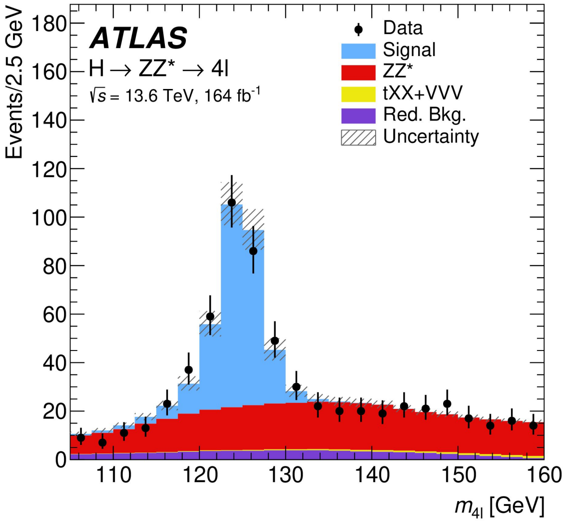
Response element: Probability bin i→j

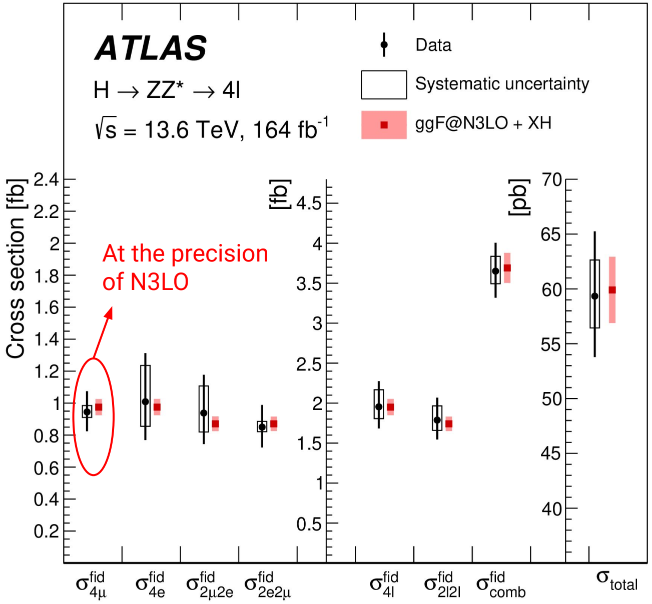
Fraction of outside fid. phase-space → inside phase-space



&





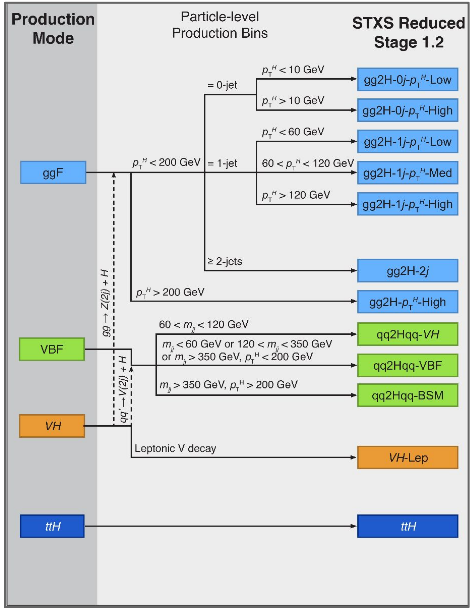


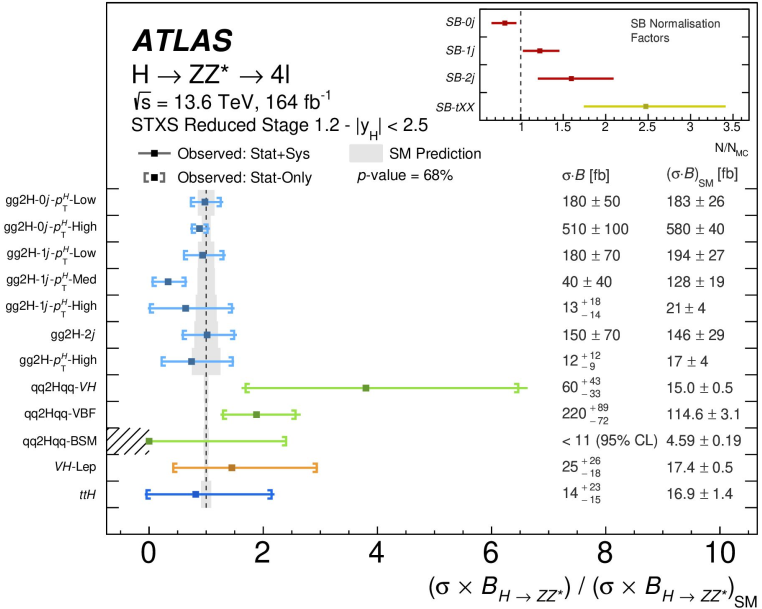
$\sigma_{\mathrm{fid.}} = 3.65^{+0.35}_{-0.33}$ fb; $\sigma_{\mathrm{total}} = 59.3 \pm 5.7$ pb

Run 3: H→4l

H→4l [arXiv:2605.19016]:

- ➔ Run 3: 164ifb
- ➔ Major precision channel
- ➔ Two measurements:
  - ◆ **STXS/Production cross-section**
    - Dissects phase-space into different regions
    - Aims to distinguish SM & possible BSM phenomena
    - Harmonized between analyses of various decays





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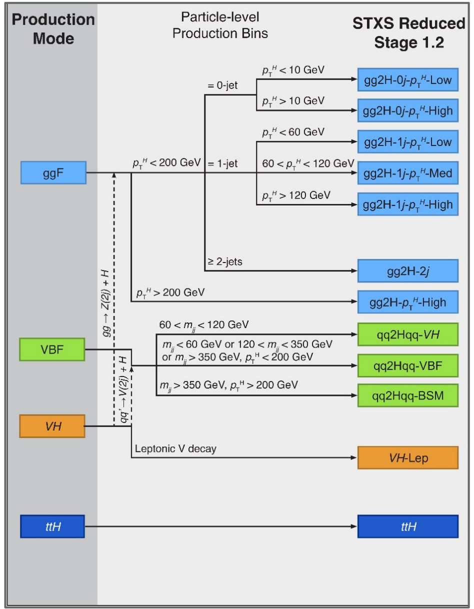
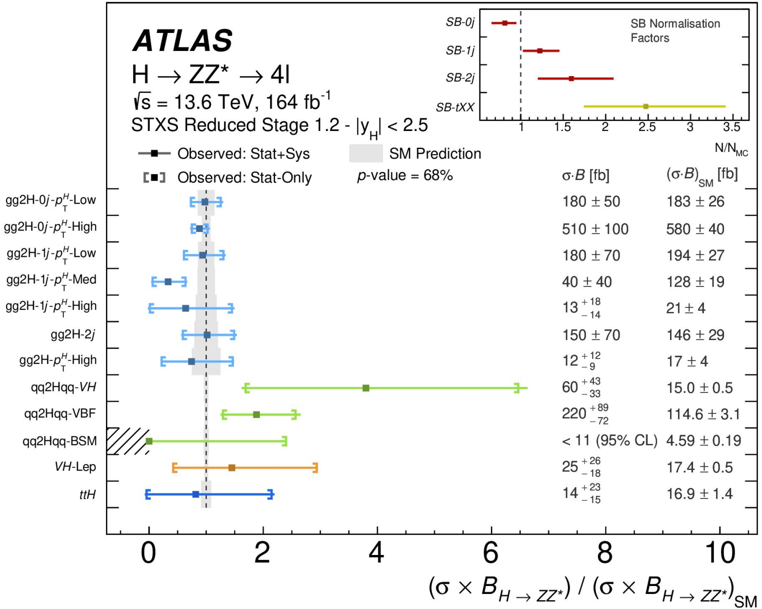
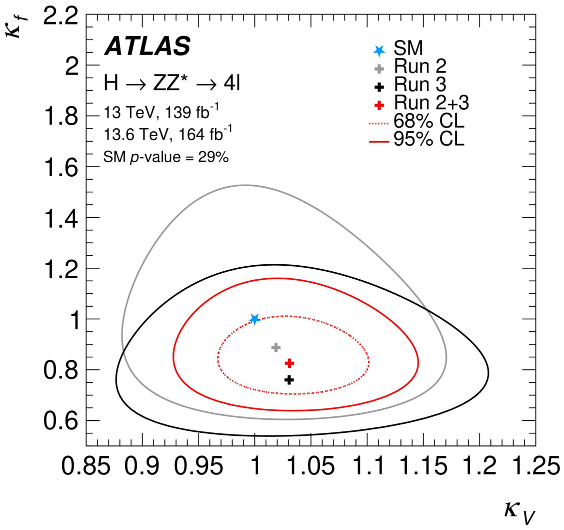
    - Harmonized between analyses of various decays

→ Vector boson and Fermionic coupling
→ Analysis provides +40%/+25% improvement for **κ**(V)/**κ**(F)







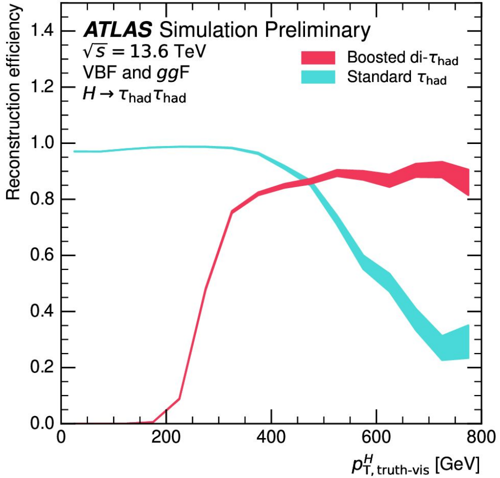
Run 2+3: Boosted Higgs H→$\tau\tau$

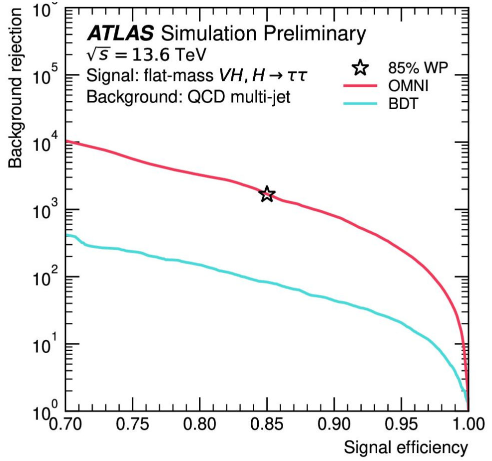
Investigating boosted Higgs:

- ➔ Better "resolution" of difficult yet abundant Higgs decays: H→bb, H→$\tau\tau$
- ➔ Exploitation of b-tagging, large-radius jets
- ➔ Outlook at high energy BSM: composite Higgs, heavy vector bosons

H→$\tau\tau$ [ATLAS-CONF-2026-005]**:**

- Run 2+Run 3: 140ifb+162ifb
- First boosted H→$\tau\tau$ study
- Dedicated di-τ identification [OMNI tagger]:
  - Point-edge transformer
  - Utilizes low-level track information





Run 2+3: Boosted Higgs H→ττ

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H→ττ [ATLAS-CONF-2026-005]:

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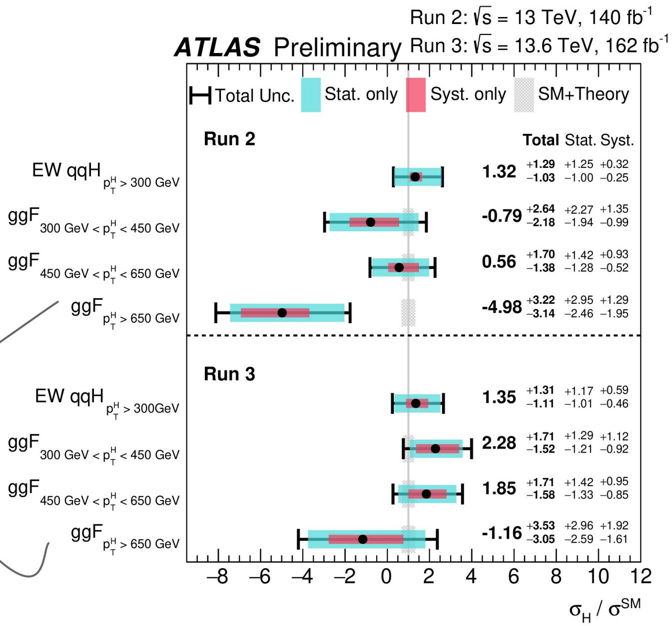
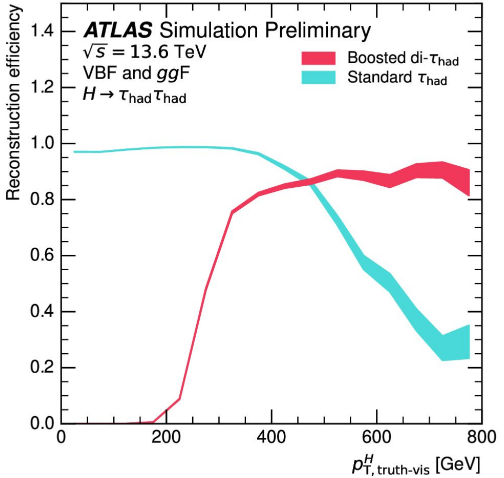
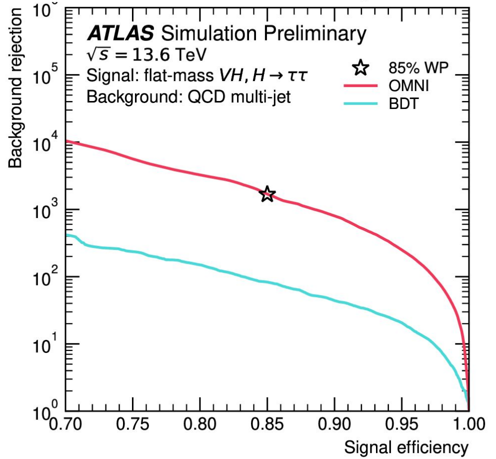


Extremely high-pT regions





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H→bb [arXiv:2603.19369]**:**

- Run 2+Run 3: 140ifb+161ifb
- Utilize GN2X tagger
- First large-R b-jet pT and mass regression algorithm

- The jet mass peak is fitted with an **exponentiated polynomial (*fN*) multiplicative transfer function(*tM*)**

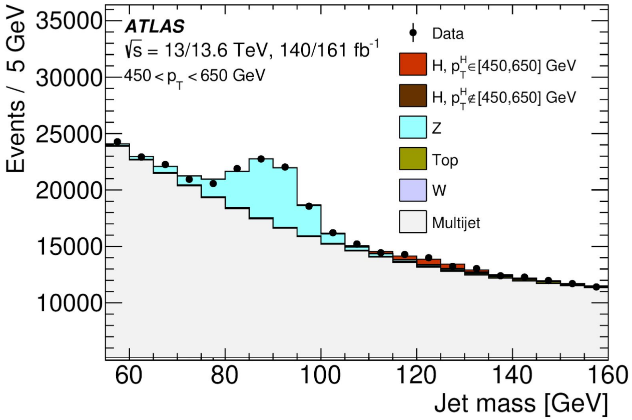
[SR/CR] [CR]

$$f_N(x|\vec{\phi}) = \phi_0 \exp\left(\sum_{i=1}^{N} \phi_i x^i\right), \quad t_M(x|\vec{\psi}) = 1 + \sum_{j=1}^{M} \psi_j x^j$$

$$x = (m_J - 140\ \text{GeV})/70\ \text{GeV}$$

ϕ_0: SR/CR indep. normalizations

ϕ_i/ψ_i: Free parameters per pT/category



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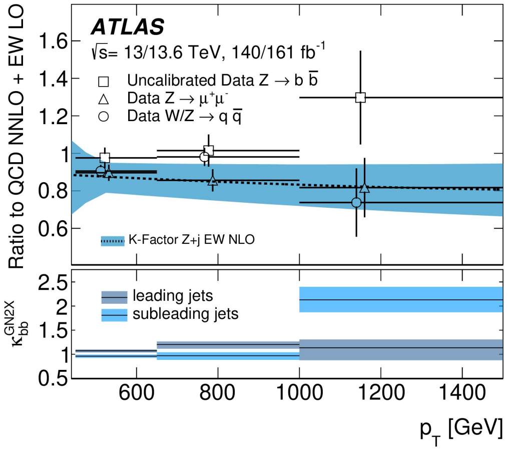
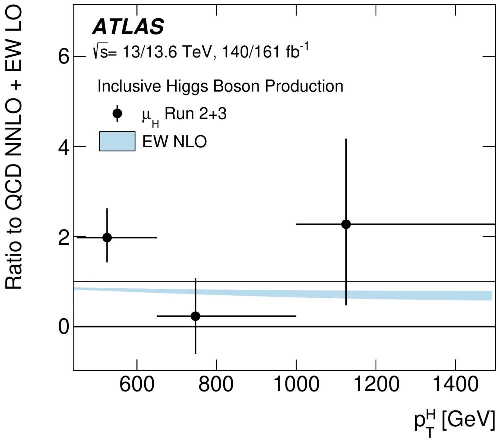
H→bb [arXiv:2603.19369]:

- Run 2+Run 3: 140ifb+161ifb
- Utilize GN2X tagger
- First large-R b-jet pT and mass regression algorithm
- Inclusive signal strength:

$$\mu_{>450\mathrm{GeV}} = 1.53 \pm 0.27(\mathrm{stat.})^{+0.33}_{-0.27}(\mathrm{sys.}) \pm 0.17(\mathrm{theo.})$$





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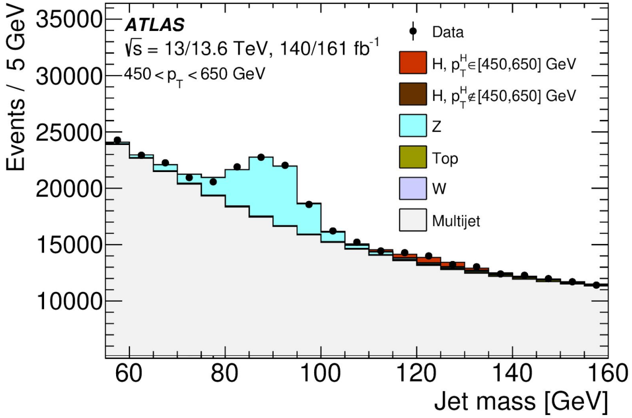

Run 3: Di-Higgs

Run 2+3: HH→bb$\gamma\gamma$

HH→bb$\gamma\gamma$ [Phys. Lett. B 876 (2026) 140280]:

- Good compromise between cross-section and signature purity
- **Requirements:**
  - 2-photons in EM Calorimeter
  - 2-bjets passing GN2 85%
- Relies on BDTs to enhance signal:
  - m(bb$\gamma\gamma$) Regions split at 350 GeV
  - Low: 4 regions, High: 3 regions
- $\kappa(\lambda,2V,V)$ → 6 samples for VBF, $\kappa(\lambda)$ → 3 samples for ggF

Largest BR(H)

	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%

Distinct signature

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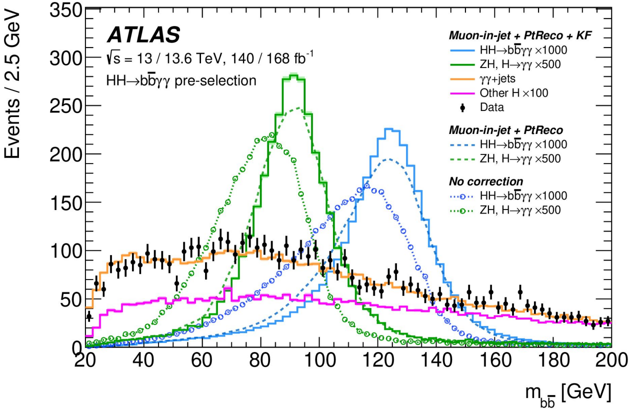

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  - m(bb$\gamma\gamma$) Regions split at 350 GeV
  - Low: 4 regions, High: 3 regions
- $\boldsymbol{\kappa}(\lambda$,2V,V) → 6 samples for VBF, $\boldsymbol{\kappa}(\lambda)$ → 3 samples for ggF
- **Results:**
  - $\mu_{HH} < 3.7$ at 95%CL
  - $-1.6 < \kappa_\lambda < 6.6$ at 95%CL

Largest BR(H) ←

Distinct signature ←

	bb	WW	ττ	ZZ	γγ
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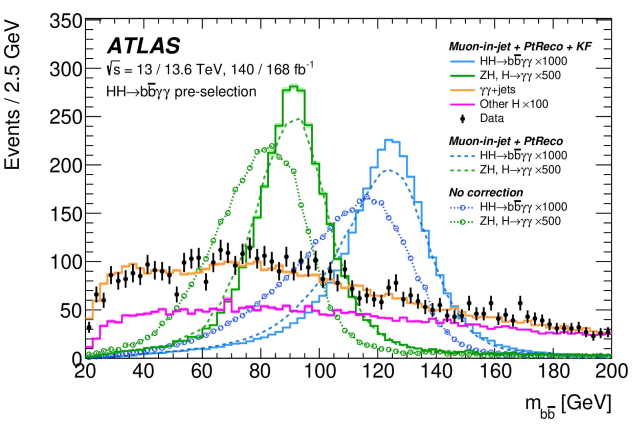
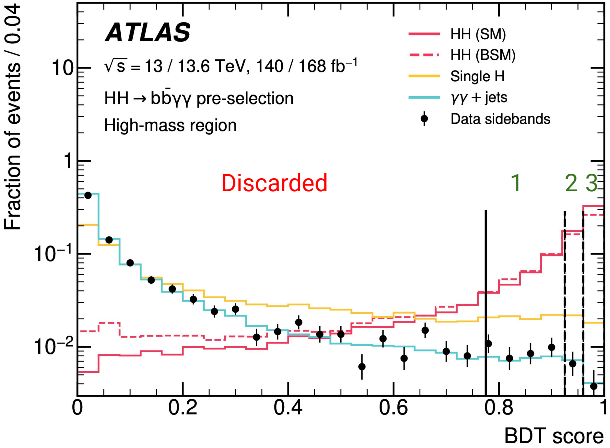
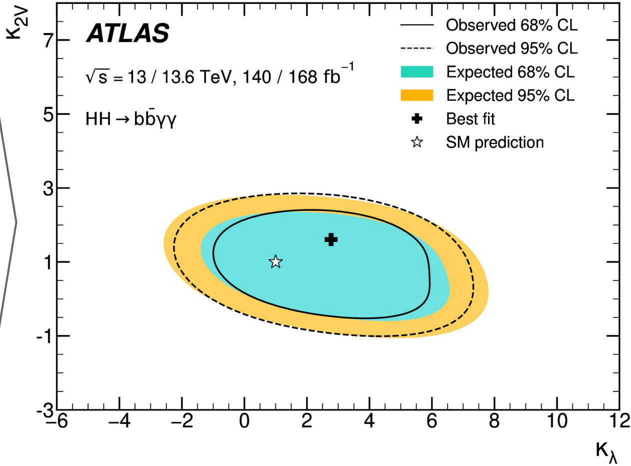
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%





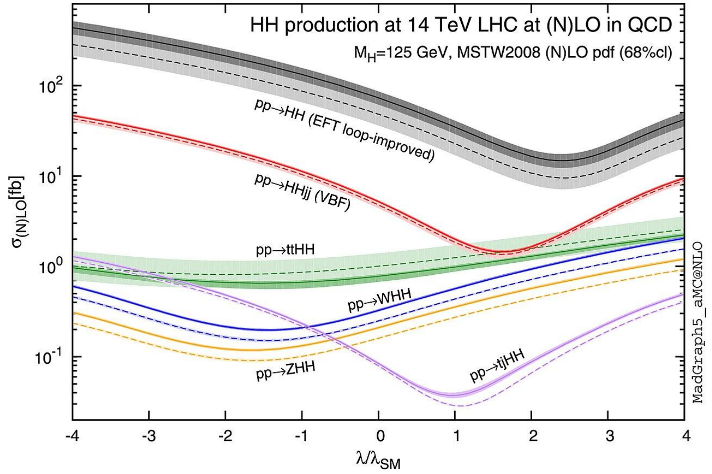


Run 2+3: ttHH

ttHH [arXiv:2603.13113]:

- Relies on three selections
  - **1-Lepton (1L):** ≥ 6 jets & ≥ 4 b-jets
    - HH→bbbb & leptonic W decay (Large yield)
    - Binary transformer discriminator
  - **Same Sign Multi-Leptons (SSML):** ≥ 2 leptons & ≥ 2 b-jets
    - H→ WW/bb/$\tau\tau$ (excl. bbbb) – Small BR, better S/B
    - Three class transformer
  - **bb$\gamma\gamma$:** 2-photons & ≥ 2 b-jets
    - Clear resonance peak H→$\gamma\gamma$
    - BDT based discriminator
- Helps resolve κ_λ ambiguities as the cross-section trend differs from ggF & VBF

[Phy.Let.B 732 (2014) 142–149]



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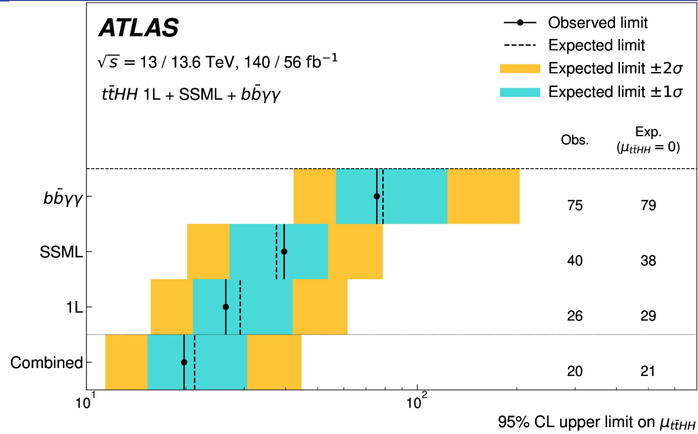
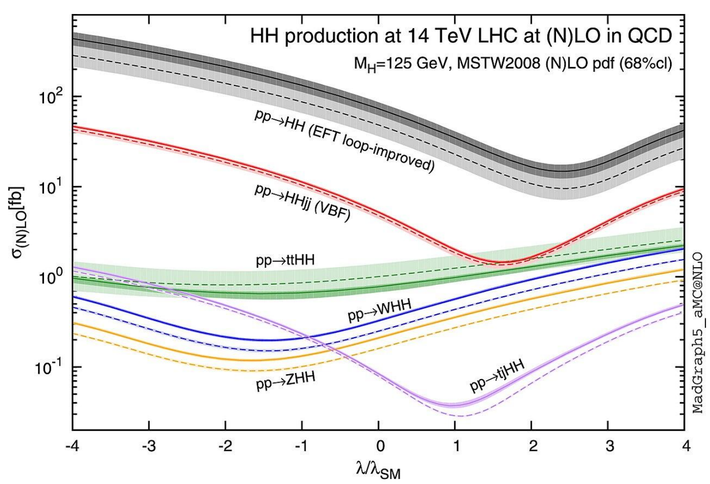
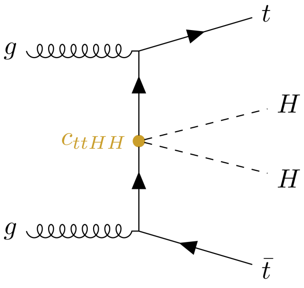


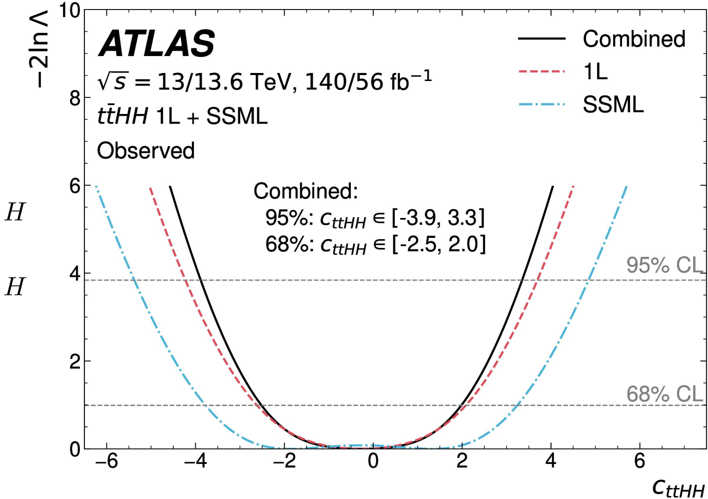
[Phy.Let.B 732 (2014) 142−149]



EFT modifier



$$\mathrm{SM}(c_{ttHH}) = 0$$



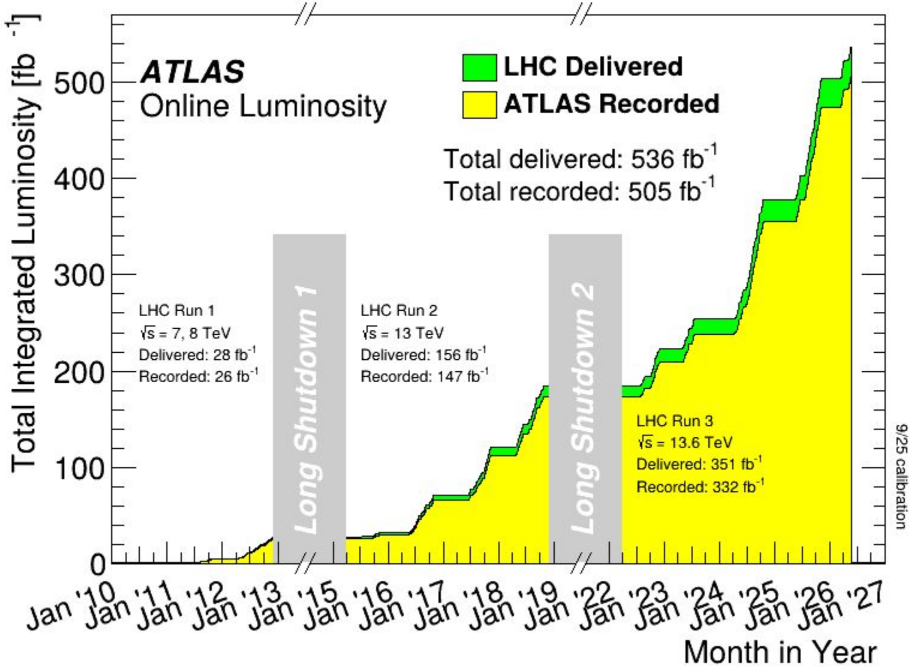
Outlook

Outlook:

➔ Run 3 is now providing ATLAS with:

- Precise measurements of the Higgs cross-sections
- And better interpretations
- Increase in statistics for better di-Higgs searches

➔ Exciting full Run 3 papers are yet to come!



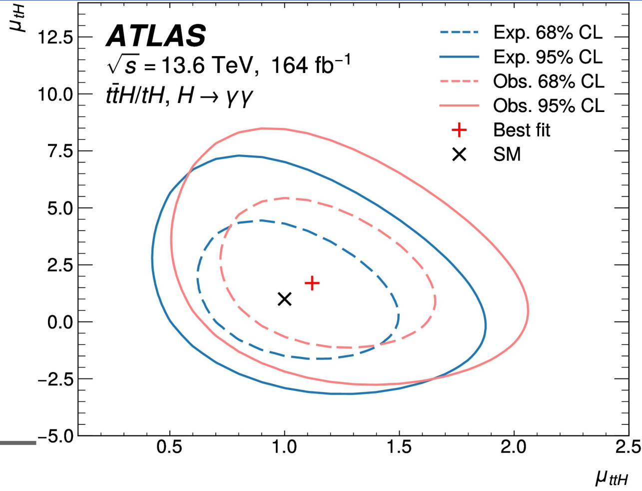
Appendix

Run 3: CP in Higgs–Top Yukawa Interactions

ttH+tH→γγ [arXiv:2606.04855]:

- CP-even in SM: $J^{CP} = 0^{++}$
- Search for CP-odd component:
  - Two Higgs doublet
  - SUSY

$$\mu_{\mathrm{ttH}} = 1.13^{+0.33}_{-0.28}$$
$$\sigma_{\mathrm{ttH}} \times B_{\gamma\gamma} = 1.46^{+0.40}_{-0.35}\ \mathrm{fb}$$



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$$\mathcal{L} = -\frac{m_t}{v}\left\{\bar{\psi}_t \underline{\kappa_t}\left[\cos(\underline{\alpha}) + i\sin(\underline{\alpha})\gamma_5\right]\psi_t\right\} H$$

Top coupling CP mixing angle

→ α=0 → CP-even, α≠0 → CP-odd component

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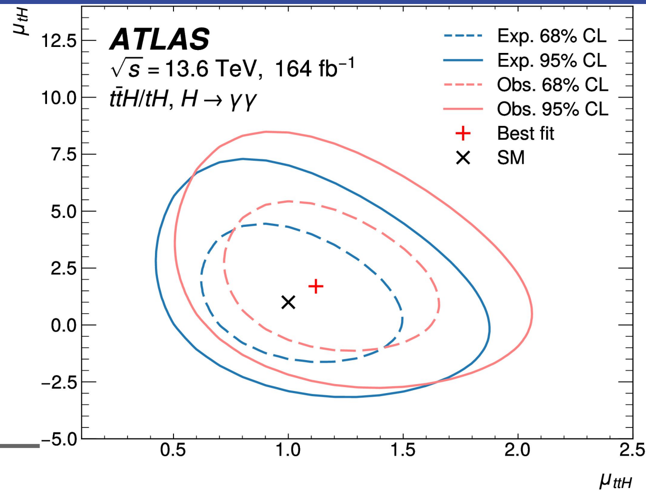

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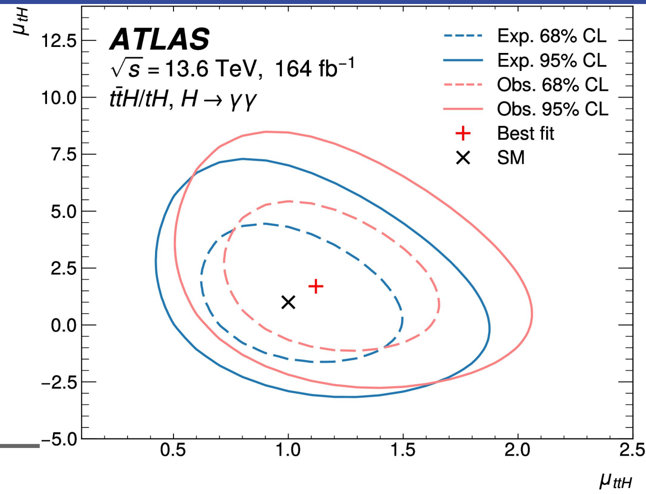

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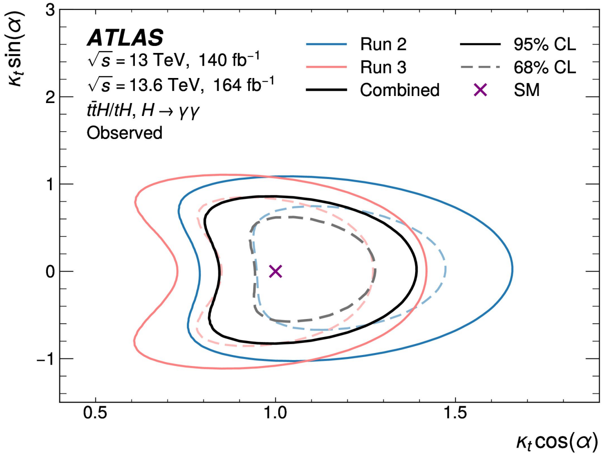
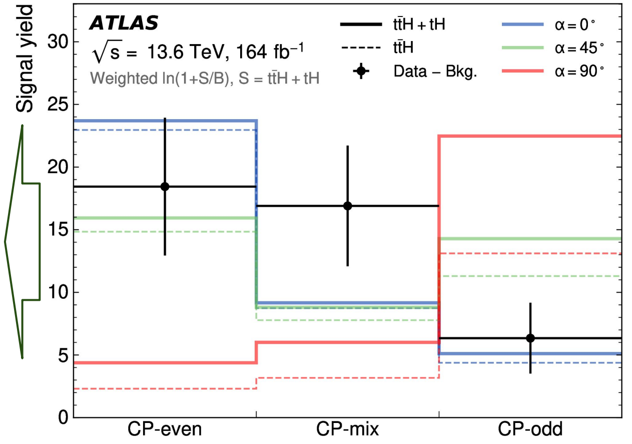


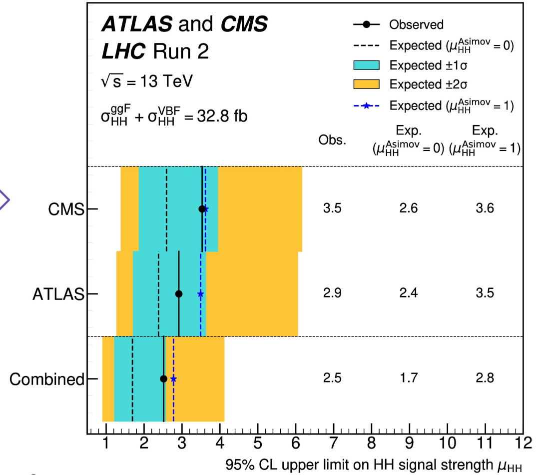
→ **CP-odd:** Excluded at 5.8σ (previously 3.9)
→ **CP-mix:** |α|>38° at 95CL (previously 43°)
→ $\kappa_t = 1.11 \pm 0.11$ Assuming CP-even



Di-Higgs Combinations & High Lumi LHC

- ➔ Even with Run 2+3, Di-Higgs falls short on statistics:
  - ◆ **~17k** inclusive Di-Higgs
  - ◆ 2000 times less than single Higgs!
- ➔ Combining with CMS doubles the dataset

ATLAS+CMS Di-Higgs Run 2 Combination
[arXiv:2602.23991]



- ➔ High Lumi LHC will deliver an unprecedented luminosity of **3000ifb**

[ATL-PHYS-PUB-2025-001]