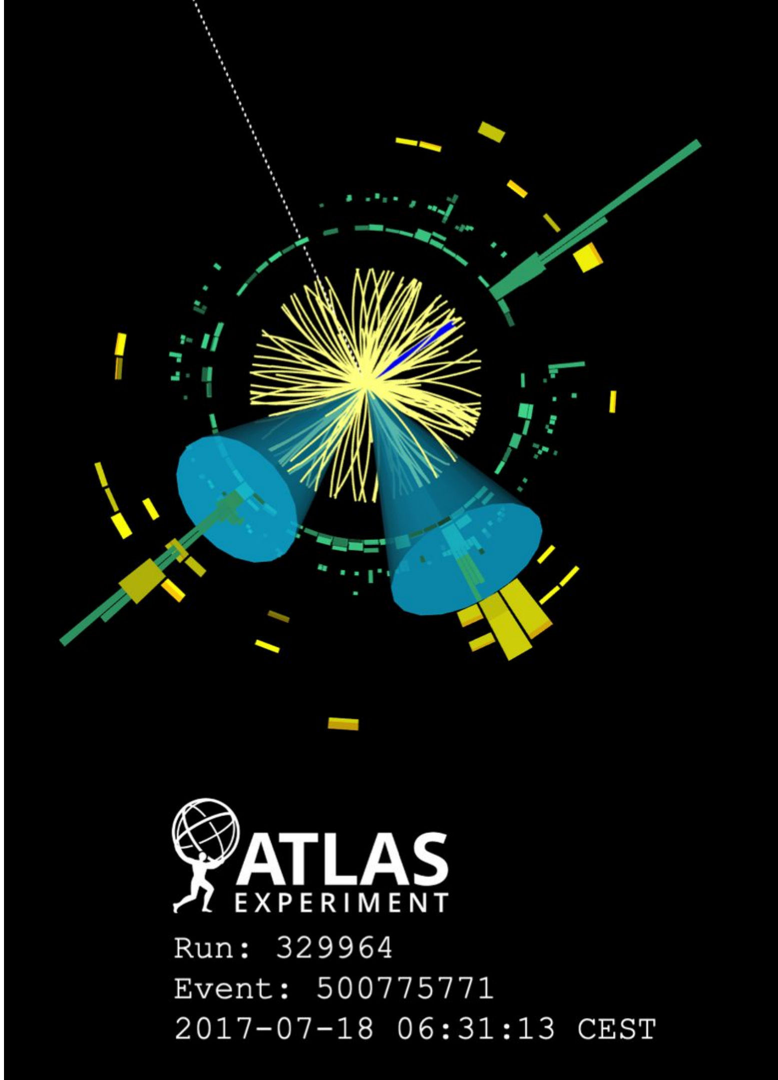
Measurements of the Higgs boson properties using *bb* and *cc* decays with the ATLAS detector

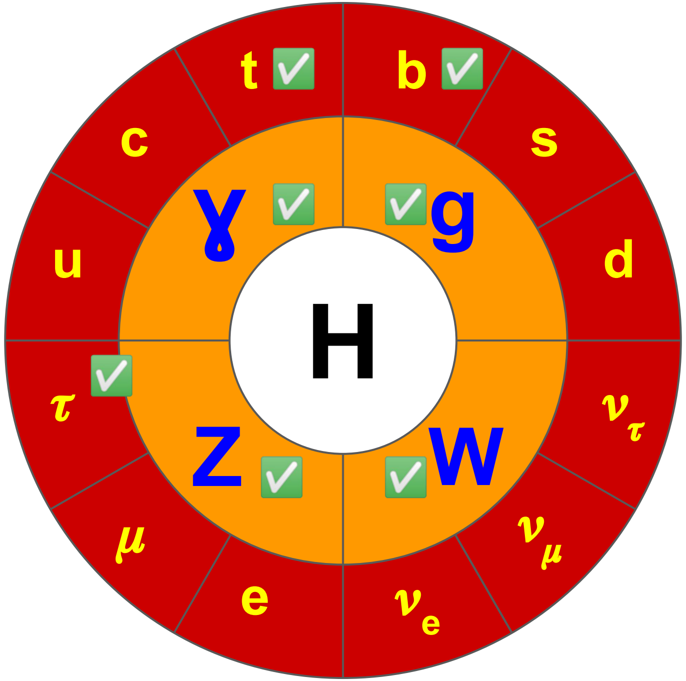
Martino Tanasini,

on behalf of the ATLAS Collaboration

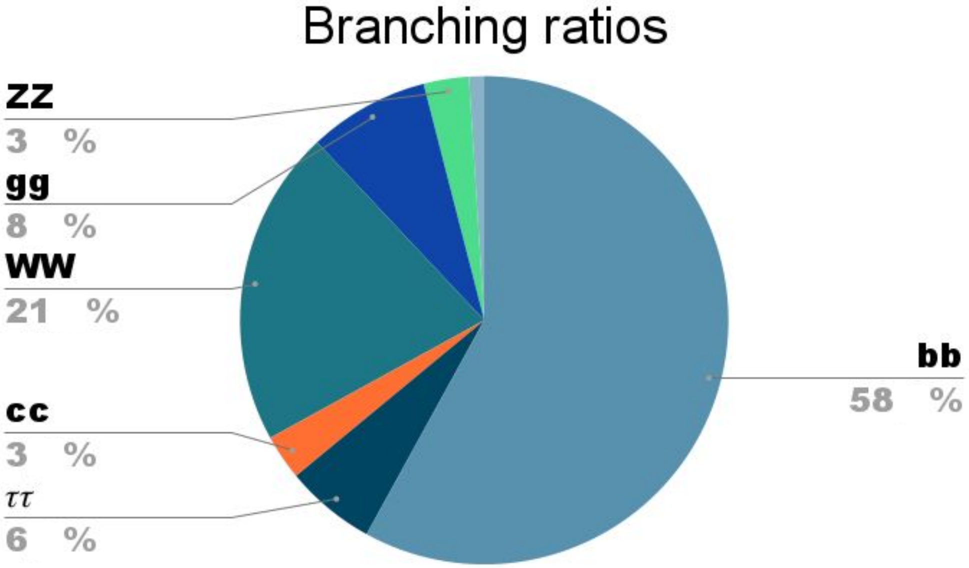
Higgs2023 - 28/11/2023 - Beijing



H→bb and H→cc

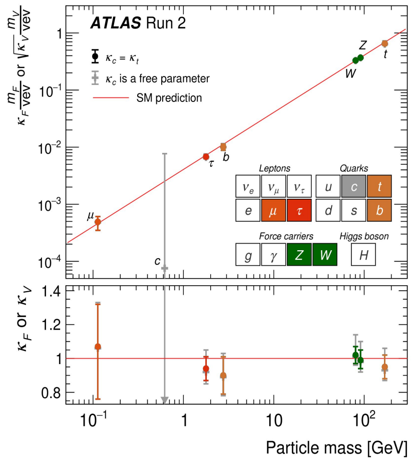


✅: *Observed direct and indirect couplings of the Higgs Boson with the other particles of the SM*



Predicted BRs for the SM 125 Gev Higgs Boson.

Properties



Magnitude of b-Higgs and c-Higgs Yukawa Couplings

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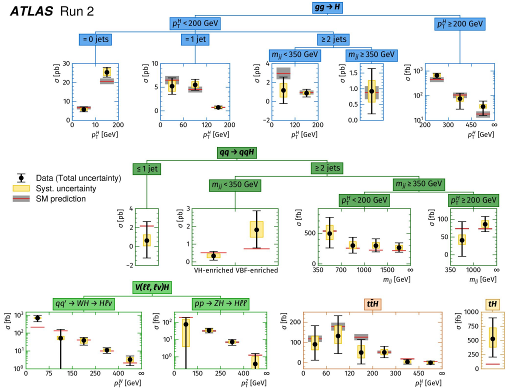
epjc/s10052-022-10588-3



qq→qqH and V(ll,lν)H production cross sections

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cds.cern.ch/record/2782535/
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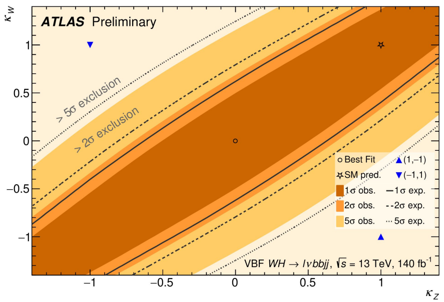
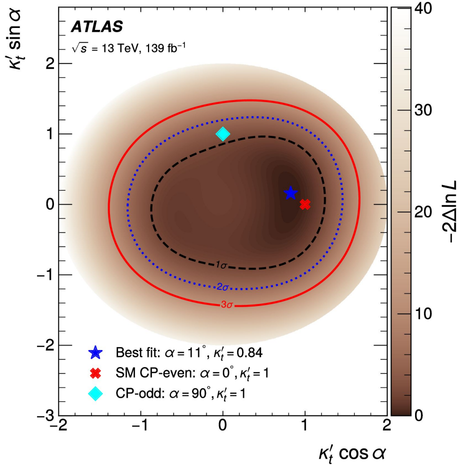
+
ATLAS-CONF-2023-067
epjc/s10052-021-09192-8
JHEP03(2021)268



Relative Sign of the W-Higgs and Z-Higgs Couplings

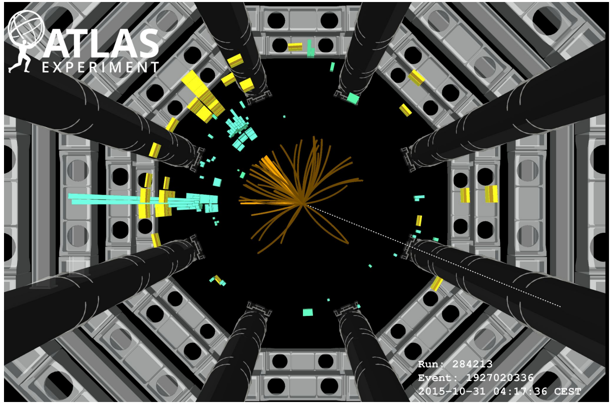
ATLAS-CONF-2023-057



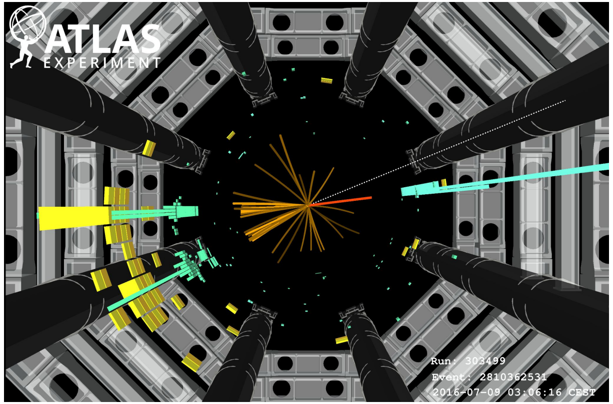
CP properties of the top-Higgs Yukawa Coupling

arxiv.org/abs/2303.05974

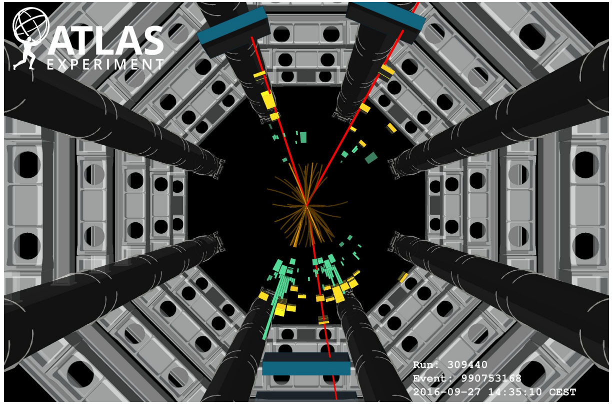
Resolved and Boosted Semileptonic WH/ZH, H→bb



A run-2 13 TeV Z(νν)H(bb) candidate event.



A Run-2 13 TeV W(eν)H(bb) candidate event.



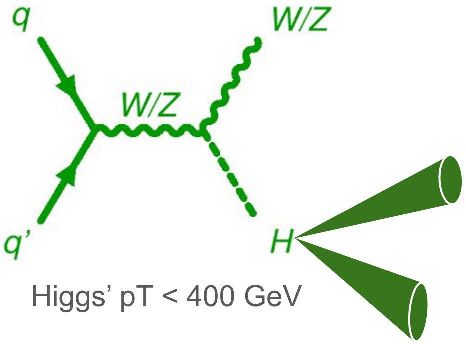
A run-2 13 TeV Z(μμ)H(bb) candidate event.

Analyses targeting the H→bb decay, based on three main channels targeting WH and ZH production, based on the W or Z decays both in the resolved and boosted regimes:

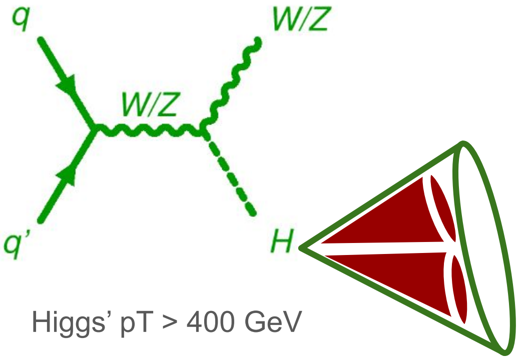
→ 0 leptons (for Z→νν)

→ 1-lepton (W→eν and W→μν)

→ 2-leptons (Z→ e^-e^+ and Z→ $\mu^-\mu^+$)

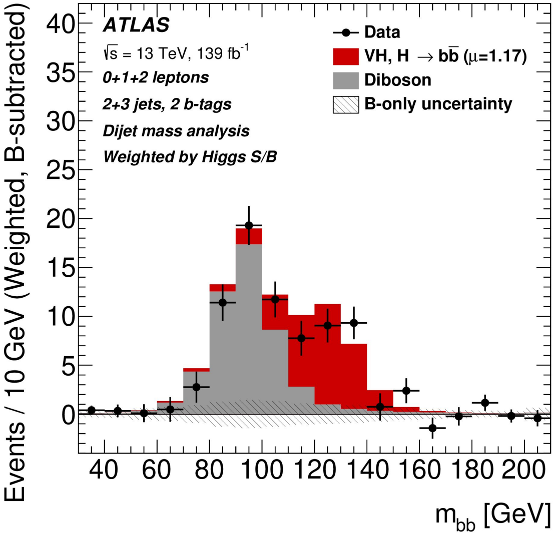


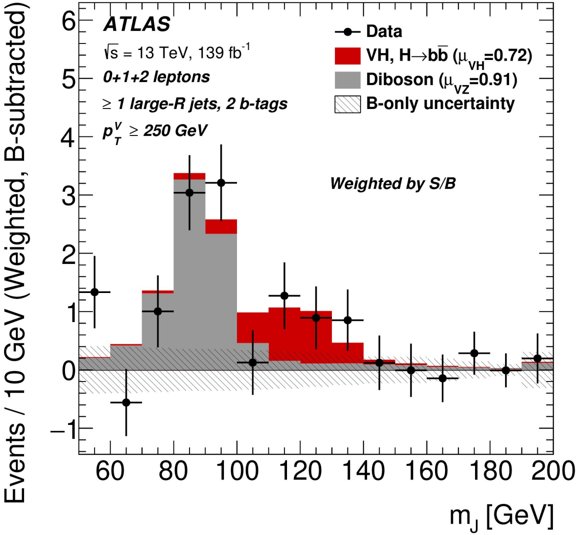
Higgs' pT < 400 GeV

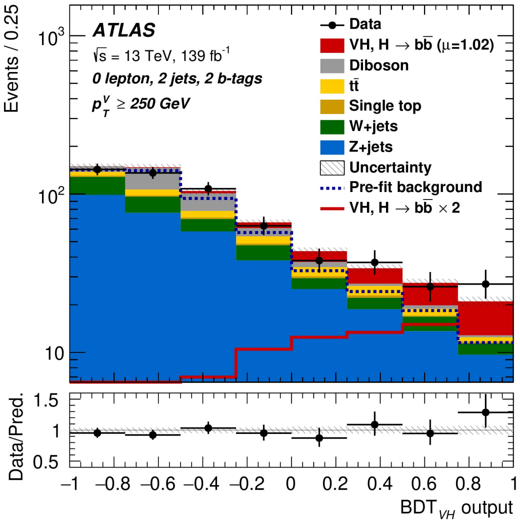


Higgs' pT > 400 GeV

Resolved and Boosted Semileptonic WH/ZH, H→bb

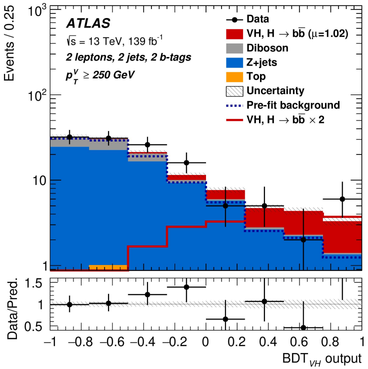


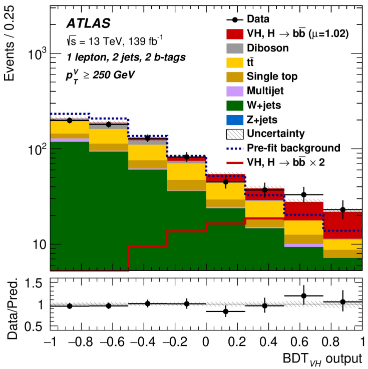




Main backgrounds → V+jets (in particular b-jets) and top production.
Modelling → simulation and auxiliary measurements. Controlled in the mass side-bands.

Measurement of VZ process with Z to *b* quarks to validate the strategy.

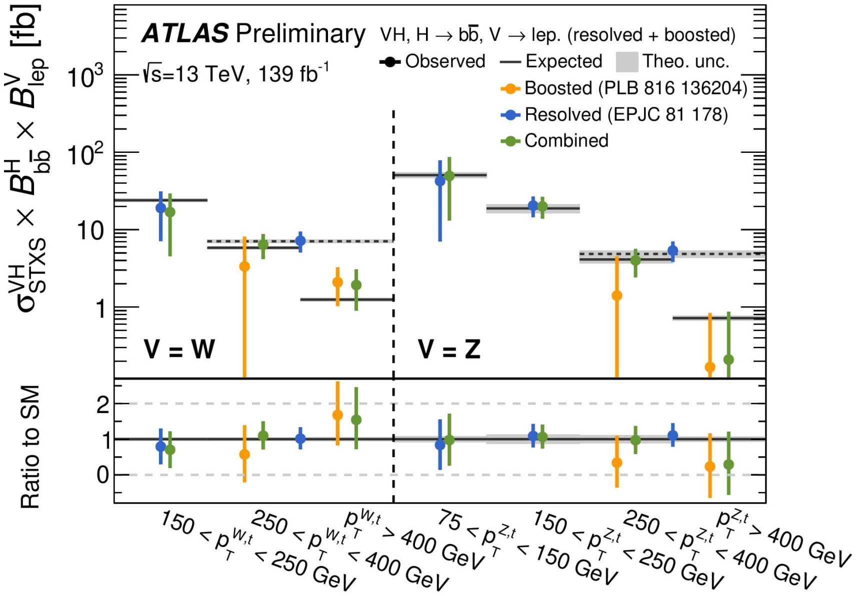




Resolved and Boosted Semileptonic WH/ZH, H→bb

	Process	Signal Strength μ	Obs (Exp) Sig. σ
Resolved	(Z/W)H,Hbb	$1.02^{+0.18}_{-0.17}$	6.7 (6.7)
	ZH, Hbb	$1.08^{+0.25}_{-0.23}$	4.0 (4.1)
	WH, Hbb	$0.95^{+0.27}_{-0.25}$	5.3 (5.1)
Boosted	(Z/W)H,Hbb	$0.72^{+0.39}_{-0.36}$	2.1 (2.7)
Combined	(Z/W)H,Hbb	$1.00^{+0.18}_{-0.17}$	6.4 (6.3)
	ZH, Hbb	$0.97^{+0.25}_{-023}$	4.6 (5.0)
	WH,Hbb	$1.03^{+0.28}_{-0.27}$	4.1 (3.9)

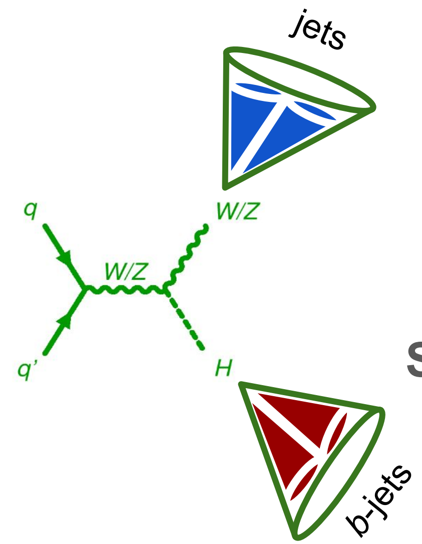
Precision on μ driven by Resolved Analysis.



Combination for reduced STXS1.2 cross-section measures in bins of $p_T^{W/Z}$.

Boosted All-Hadronic WH/ZH, H→bb

NEW! (2023)

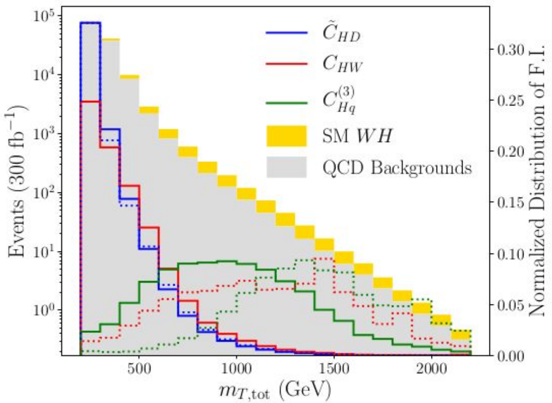


ATLAS-CONF-2023-067

Higher hadronic W/Z branching fractions (~ **x2** signal events) → Extend reach to $p_T^H \sim 1$ TeV.

Sensitivity to BSM affecting VH production.

Challenged by **dominant multijet** background → Enabled by improvement in multijet rejection (V-tagger and DNN-based **Hbb** tagger) and modelling (two data-driven estimations).



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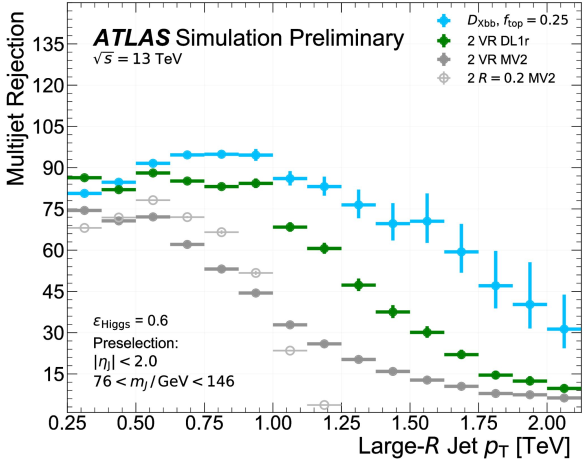

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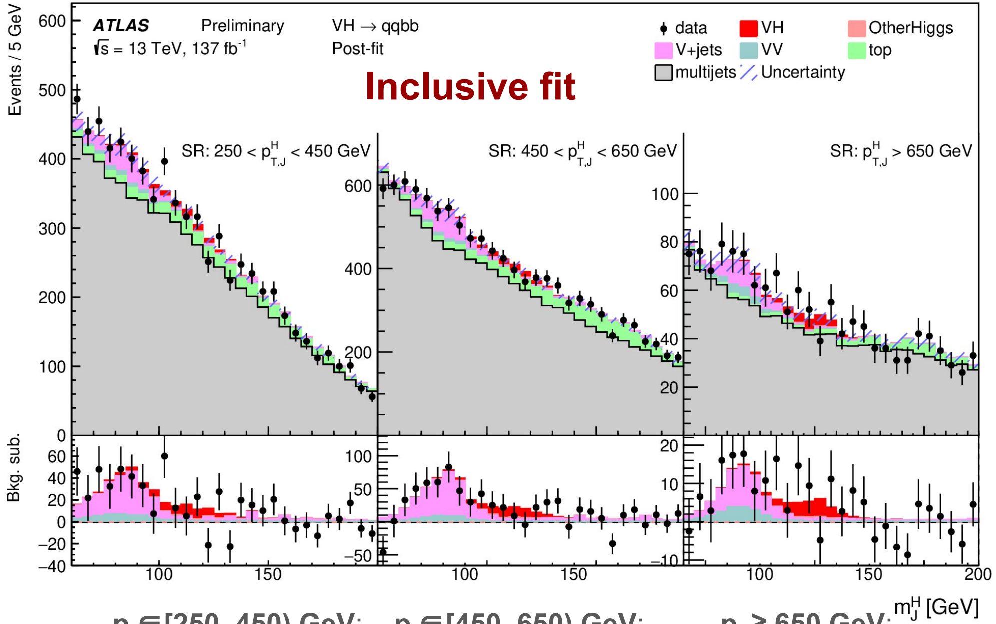
Boosted All-Hadronic WH/ZH, H→bb

NEW! (2023)



$p_t \in$[250, 450) GeV: $\mu = 0.6^{+1.8}_{-1.7}$

$p_t \in$[450, 650) GeV: $\mu = 0.6^{+1.3}_{-1.2}$

$p_t \geq$ 650 GeV: $\mu = 4.5^{+8.8}_{-2.7}$

Uncertainty source	$\delta\mu$
Signal modeling	$^{+0.10}_{-0.02}$
MC statistical uncertainty	$^{+0.13}_{-0.13}$
Instrumental (pileup, luminosity)	$^{+0.012}_{-0.004}$
Large-R jet	$^{+0.13}_{-0.14}$
Top-quark modeling	$^{+0.14}_{-0.15}$
Other theory modeling	$^{+0.050}_{-0.031}$
$H \to b\bar{b}$ tagging	$^{+0.52}_{-0.23}$
Multijet estimate (TF uncertainty)	$^{+0.52}_{-0.41}$
Multijet modeling (TF vs. BDT)	$^{+0.14}_{-0.18}$
Total systematic uncertainty	$^{+0.80}_{-0.61}$
Signal statistical uncertainty	$^{+0.60}_{-0.60}$
Z+jets normalization	$^{+0.42}_{-0.20}$
Total statistical uncertainty	$^{+0.63}_{-0.63}$
Total uncertainty	$^{+1.02}_{-0.88}$

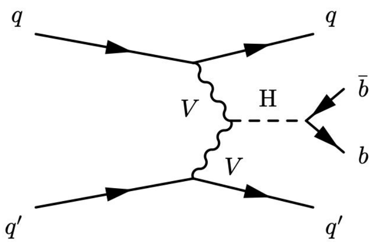
Inclusive fit: $\boldsymbol{\mu = 1.4^{+1.0}_{-0.9}}$ → obs.(exp.) **1.7 (1.2)** σ.

Cross Sec. = 3.3 +- 1.5 (stat)$^{+1.9}_{-1.5}$(syst) pb.

Systematic uncertainty dominated by multijet estimation and Hbb tagger calibration.

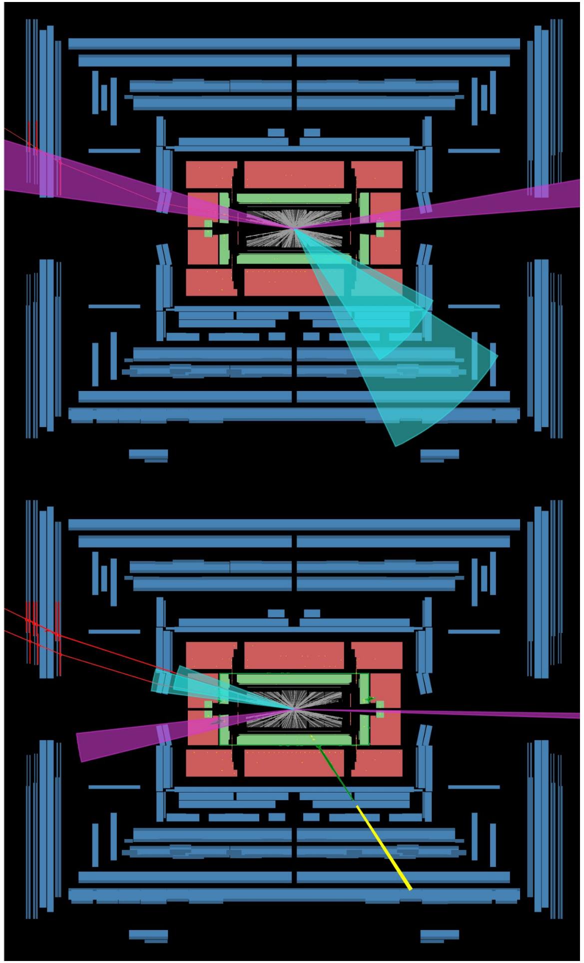
Vector Boson Fusion and VBF-photon H→bb

EPJC 81 (2021)



Difficult trigger against multijet background.

t-channel → forward jets.
Hbb → *b*-tagged jets.



Additional photon for topological advantages.

→ Useful for trigger.
→ Reduces multijet background, which has destructive interference.

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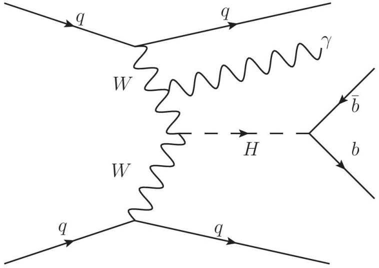
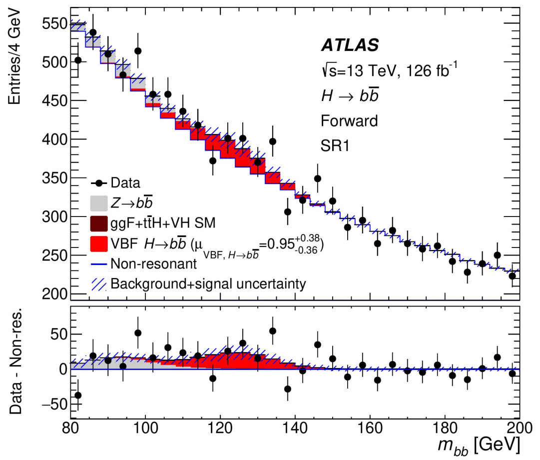
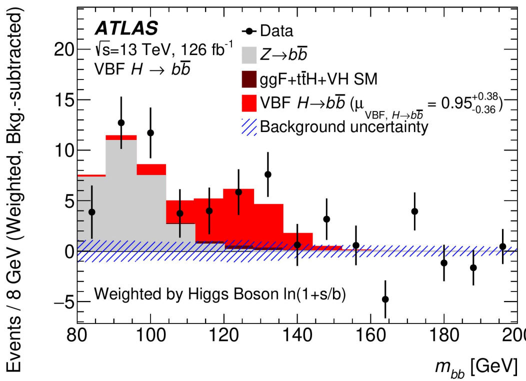
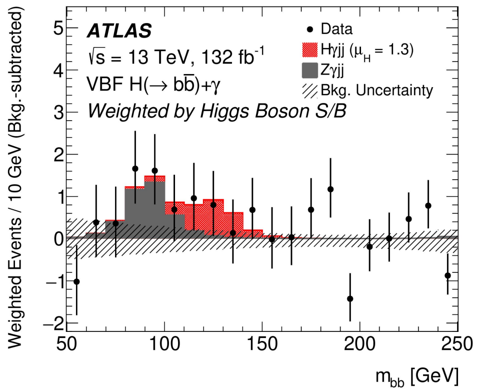


VBF and VBF-photon H→bb





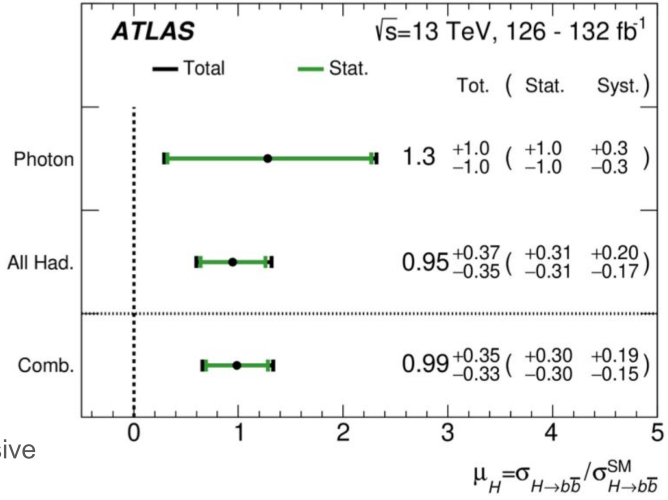


***VBF:** Multijet from low NN score regions. Zbb from embedding (Z$\mu\mu$ from data, substitute μ with simulated b-quarks).*
***VBF-photon:** Fit of Signal on smoothly falling background.*

1.3σ (1.0 exp) ←

2.7σ (2.9 exp) ←

3.0σ (3.0 exp)* ←



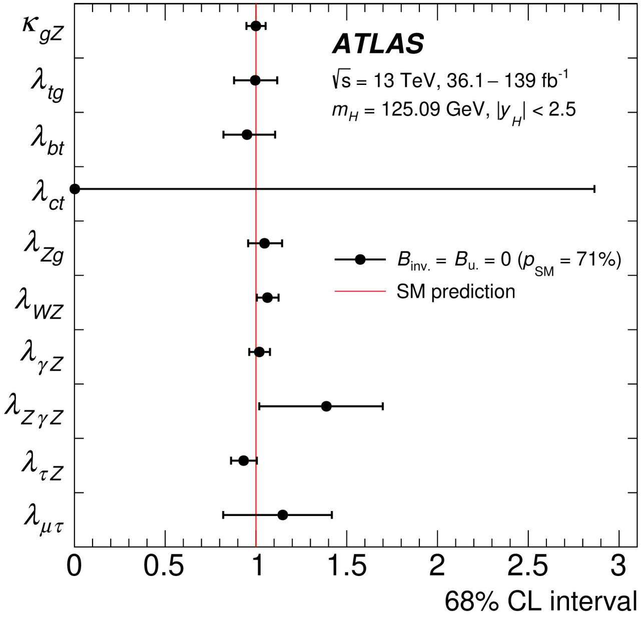
*This evidence is obtained when fitting the inclusive *H* production in the combination.

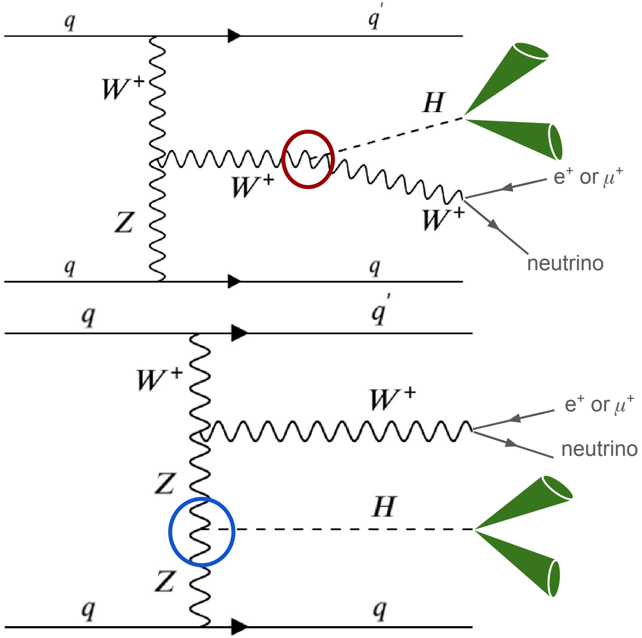
VBF WH, H→bb

NEW! (2023)

Same final state through either **W-Higgs** or **Z-Higgs** coupling → **Information on relative sign of the couplings through amplitudes interference!**

[A detailed map of Higgs interactions by ATLAS]





Uses *H* to *b*-quarks and *W* to electron or muon.

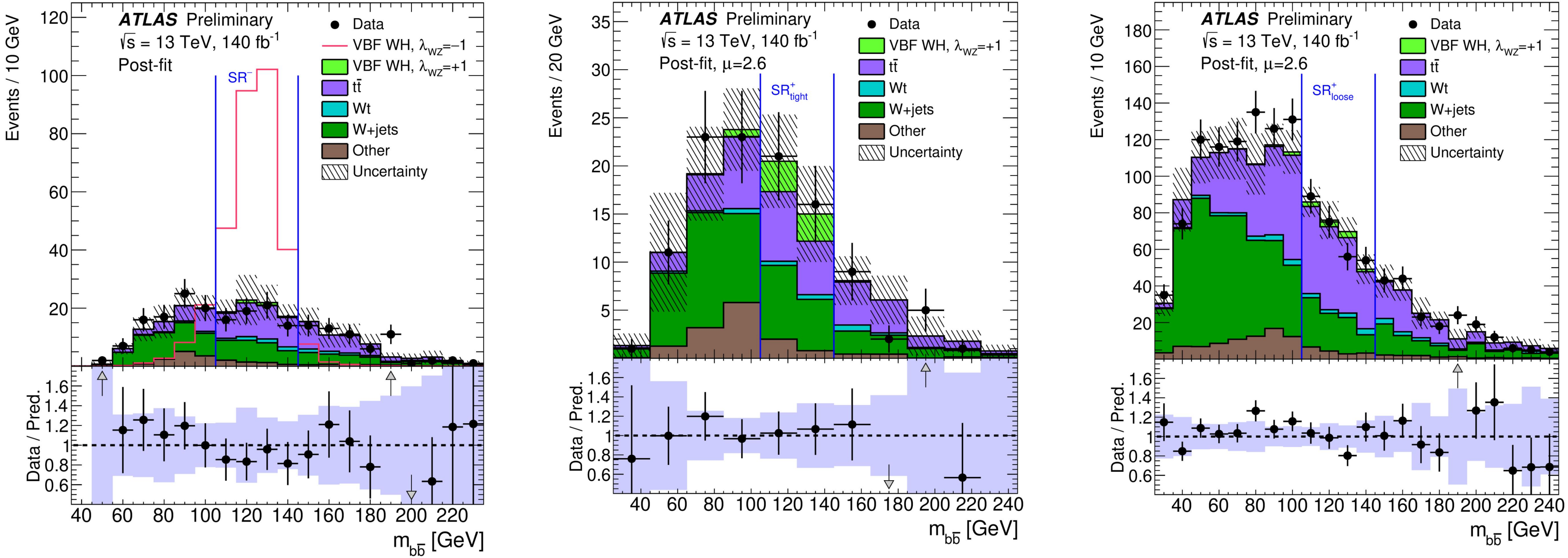
Couplings parameterized through *k*-modifiers ($k_{particle}$ is 1 if coupling is SM) or their ratios λ.

Best ATLAS estimate from combination:
λ_{WZ}= 1.06 +- 0.06 → Involves analyses not sensitive to relative W-Higgs/Z-Higgs sign.

VBF WH, H→bb: if sign(λ_{WZ}) = -1, constructive interference, enhanced process rate, violation of the SM.

VBF WH, H→bb

NEW! (2023)



Event kinematics affected by sign($\boldsymbol{\lambda}_{\mathbf{WZ}}$). Two “cut-and-count” analyses:

→ “Negative $\boldsymbol{\lambda}_{\mathbf{WZ}}$”: aim to observe or exclude BSM scenarios with $\boldsymbol{\lambda}_{\mathbf{WZ}}$ < 0.

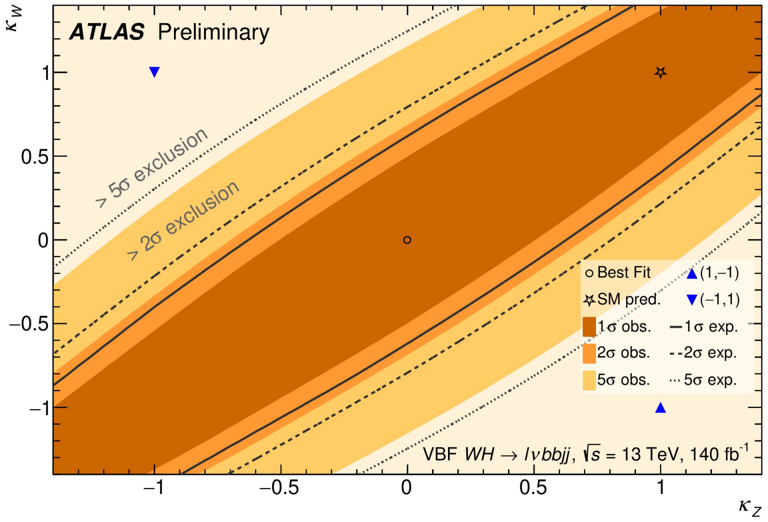
→ “Positive $\boldsymbol{\lambda}_{\mathbf{WZ}}$”: Set the best possible limits on SM-like VBF WH production (two orthogonal *tight* and *loose* SRs)

Main backgrounds are tt and W+Jets
→ Dedicated CRs.

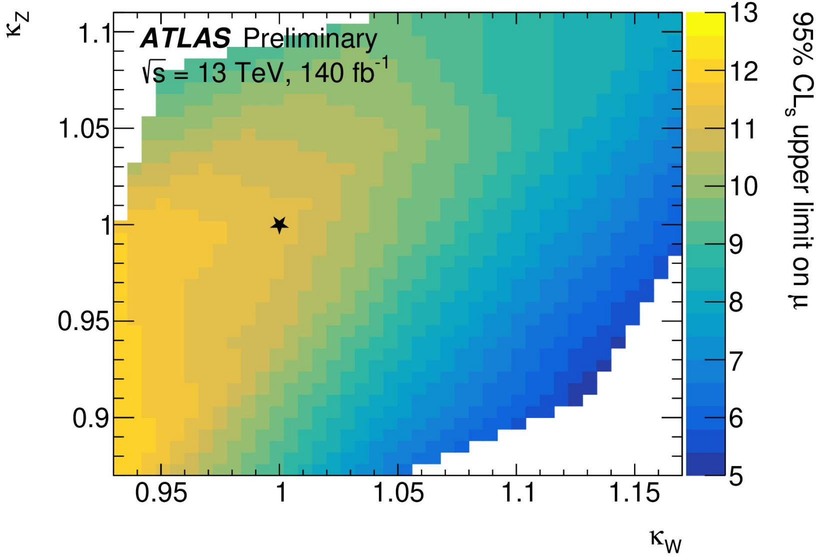
VBF WH, H→bb

k_W, k_Z values with opposite sign are excluded with significance > 8σ.

Higgs-boson couplings to W and Z bosons have the same sign.



NEW! (2023)



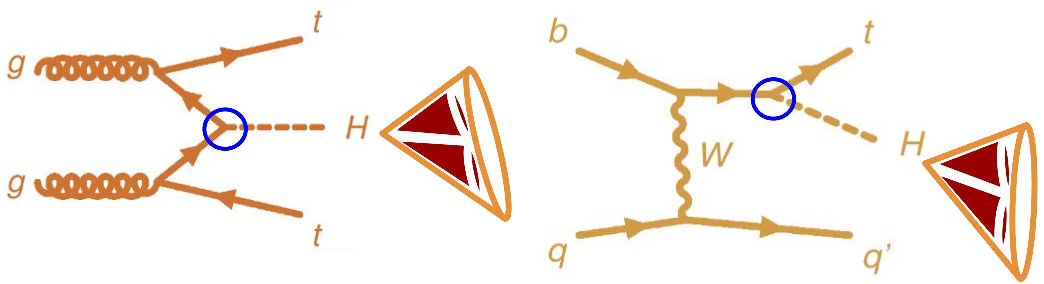
"Positive λ_{WZ}" analysis obs. (exp.) limit → $\mu_{\text{VBF WH, Hbb}} < 11.2\ (9.4)$.

First limit on VBF, WH production.

top-Higgs CP in ttH and tH, H→bb

arXiv:2303.05974

NEW! (2023)



Very complex final state with at least 3 *b*-jets (H→ bb and t→Wb). 1 and 2-lepton regions, boosted and resolved *bb*-pairs.

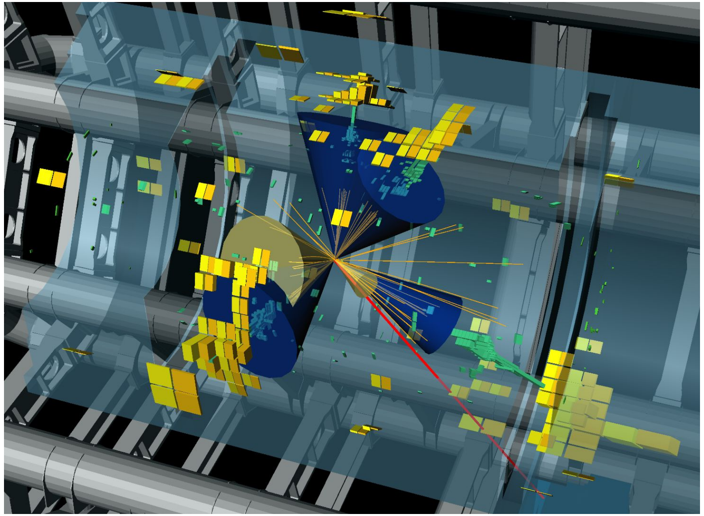
Dominated by uncertainties on background modelling.

ttH and tH → Tree-level probe of top-Higgs Yukawa coupling.

$$\mathcal{L}_{t\bar{t}H} = -\kappa_t' y_t \phi \bar{\psi}_t (\cos\alpha + i\gamma_5 \sin\alpha)\psi_t$$

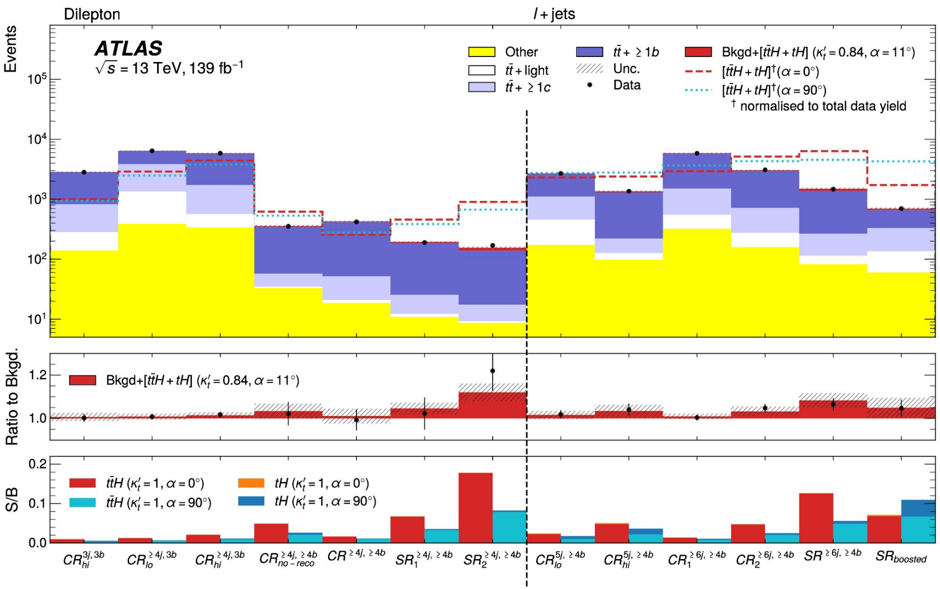
BSM models allow CP-odd component of top-Higgs. Pure CP-odd excluded by H→$\gamma\gamma$, but **mixtures with angle α still allowed.**

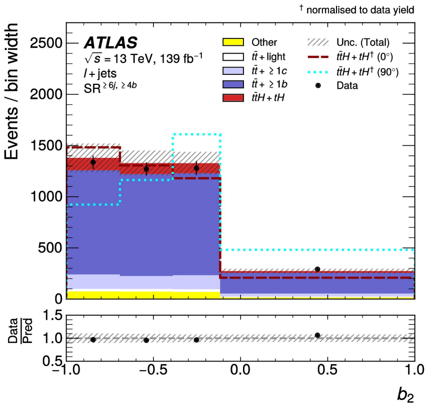
tH production suppressed in SM due to interference with other diagrams → **Modified top-Higgs would enhance tH production.**

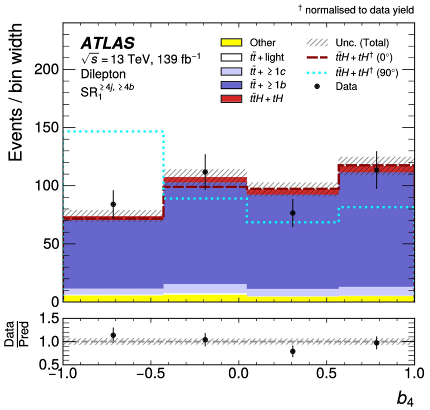


top-Higgs CP in ttH and tH, H→bb

NEW! (2023)







$$b_2 = \frac{(\vec{p}_1 \times \hat{z}) \cdot (\vec{p}_2 \times \hat{z})}{|\vec{p}_1||\vec{p}_2|} \qquad b_4 = \frac{(\vec{p}_1 \cdot \hat{z})(\vec{p}_2 \cdot \hat{z})}{|\vec{p}_1||\vec{p}_2|}$$

Simultaneous fit of the CP sensitive observables in the many regions of the analyses.

Expected yields from pure CP-odd and CP-even are overlaid.

$\boldsymbol{p_1}$ and $\boldsymbol{p_2}$ are the 3-momenta of the top quarks, $\boldsymbol{z}$ is the beam axis.

top-Higgs CP in ttH and tH, H→bb

NEW! (2023)

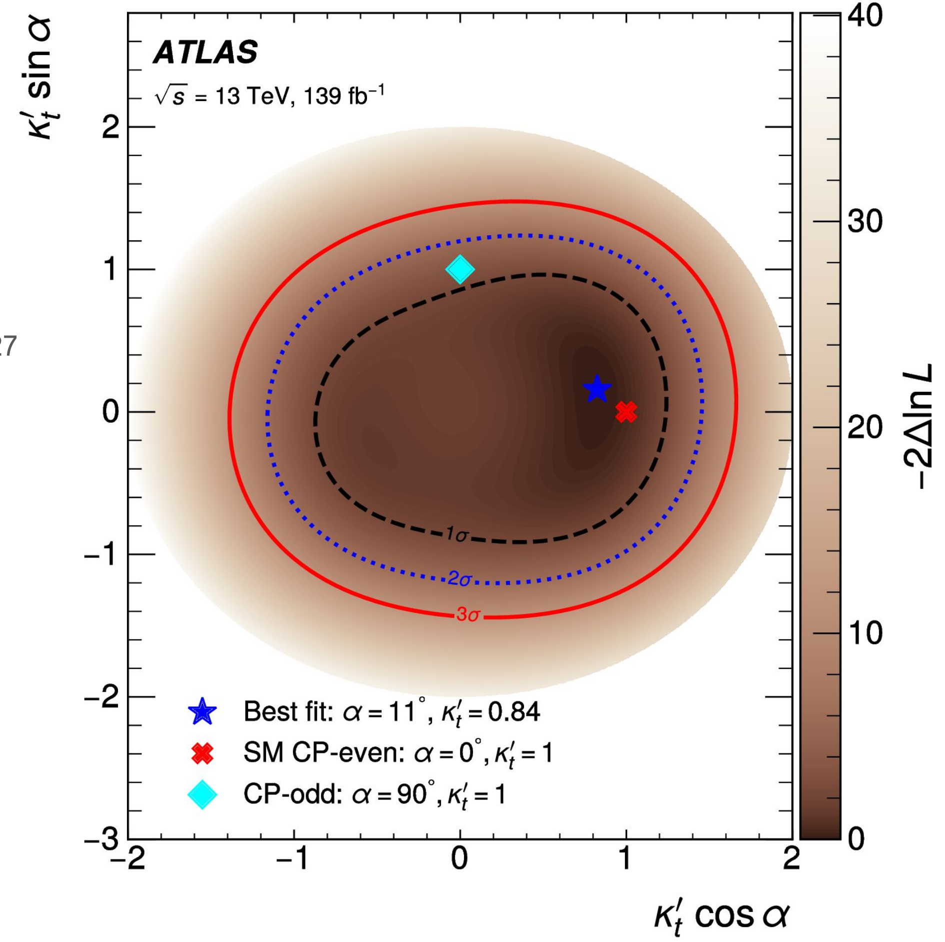
H→bb rate is assumed to be SM.

Best fit result:

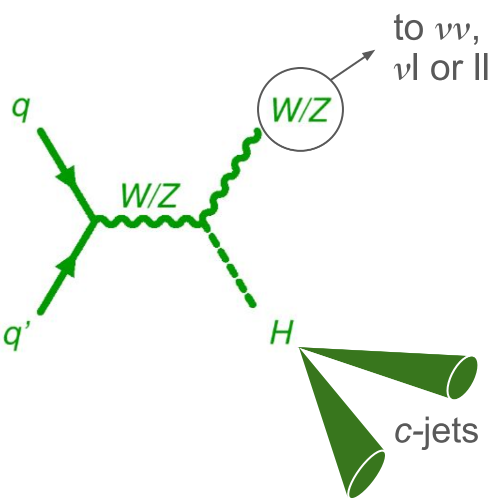
→ obs. (exp.) $\mu_{\mathrm{ttH}} = 0.84^{+0.30}_{-0.46} (1.0^{+0.25}_{-0.27})$

→ $\alpha = 11^{+52}_{-73}$ and $k_t' = 0.84^{+0.30}_{-0.46}$

Pure CP-odd coupling disfavoured at 1.2σ



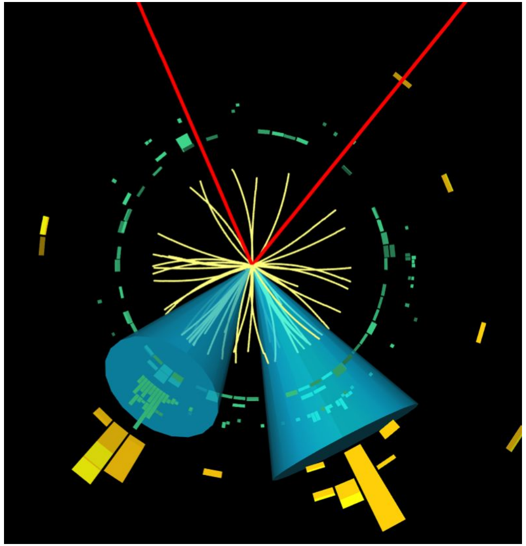
Search for Semileptonic WH/ZH, H→cc



Higgs couplings to 3rd generation fermions (ttH, H→$\tau\tau$, H→bb) observed. Probing couplings to lighter 2nd generation fermions could **open windows to new physics**.

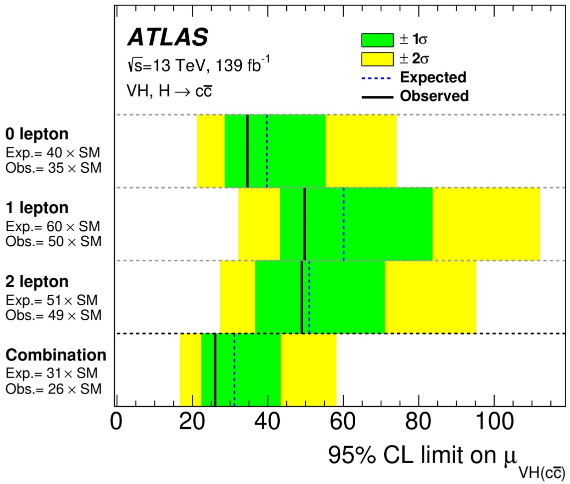
H→cc: one of the **most common** yet unobserved decay modes.

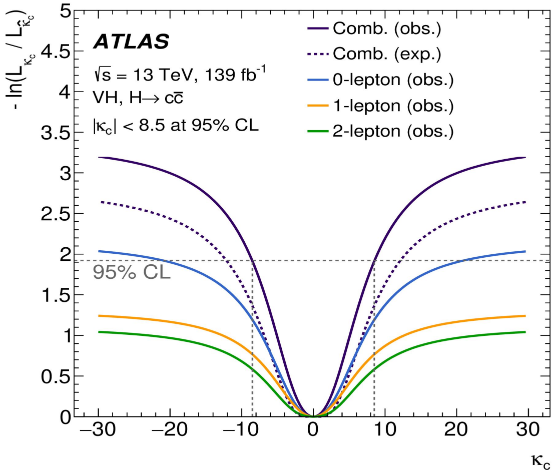
Deep learning based dedicated *c*-tagger with 27% c-jet efficiency, 8.3% b-jet efficiency, and 1.7% light jet efficiency (on a ttbar sample).

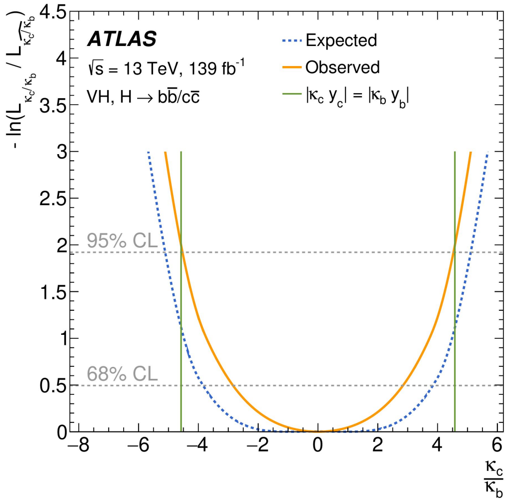


10.1140/epjc/s10052-022-10588-3

Search for Semileptonic WH/ZH, H→cc







Obs. (exp.) $\mu_{VH,Hcc}$< 26 (31) times the SM @ 95% Confidence Level.

$|k_c|$ < 8.5 (12.4) @ 95%CL

$|k_c/k_b|$< 4.5 (5.1) @ 95%CL*

*$|k_c/k_b|$ obtained through a combination with the Semileptonic (W/Z)H, H→bb analysis (slide 4). The observation $|k_c/k_b| < m_b/m_c$ (= 4.578+-0.008) **implies *c*-Higgs < *b*-Higgs Yukawa.**

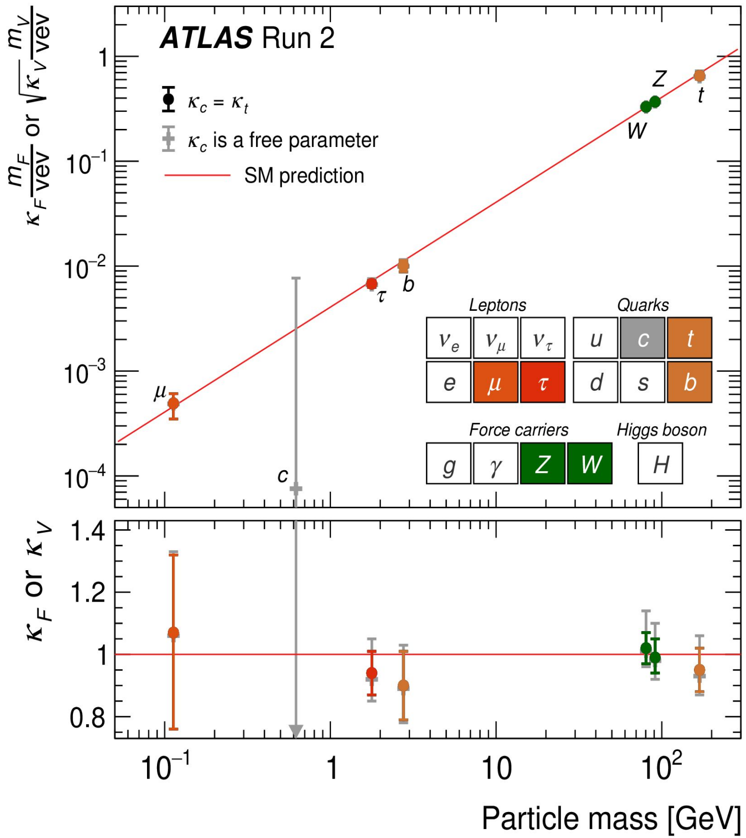
Conclusion

H→bb and H→cc decay channels are **essential tools** to probe various properties of the Higgs boson.

Combining with all the other decay modes → a detailed map of the Higgs boson properties (**>** 10 years after the discovery!).

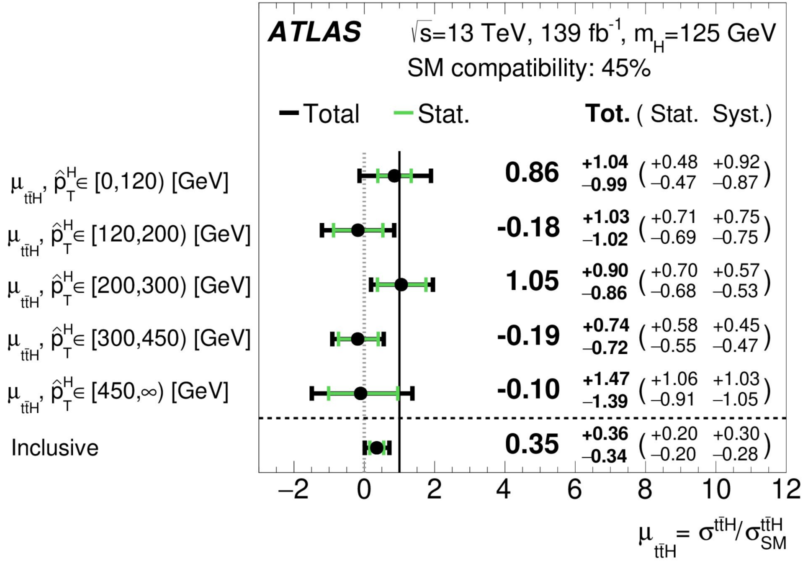
H→bb and H→cc open windows on Higgs physics well beyond the *b*-Higgs and *c*-Higgs Yukawa couplings.

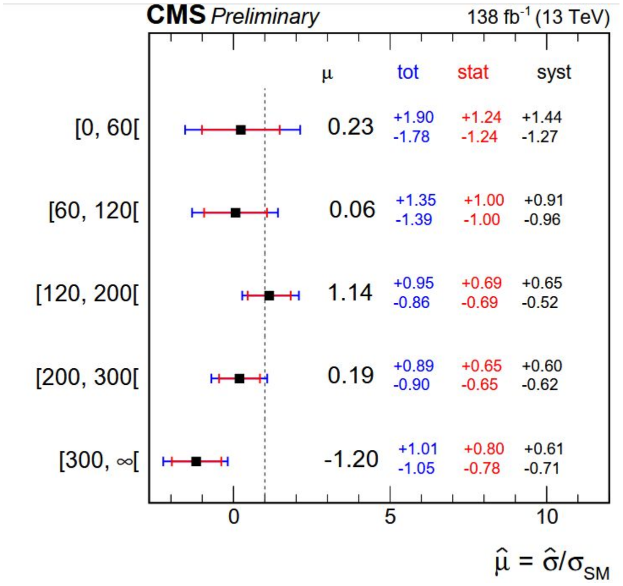
A detailed map of Higgs interactions by ATLAS



Backup

ttH, H→bb - ATLAS and CMS comparison

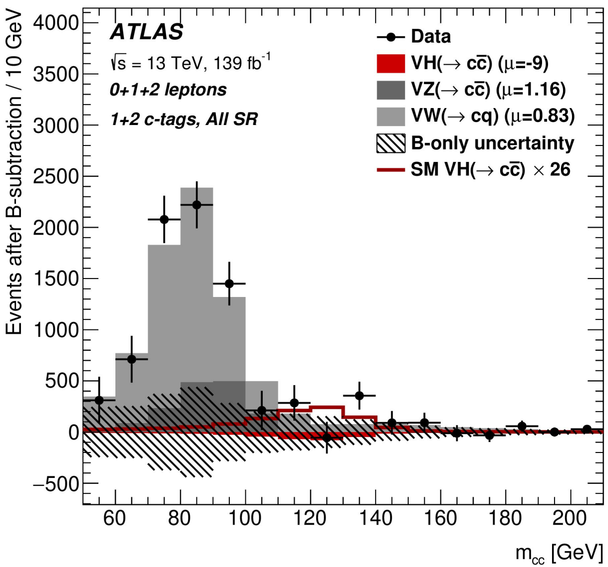


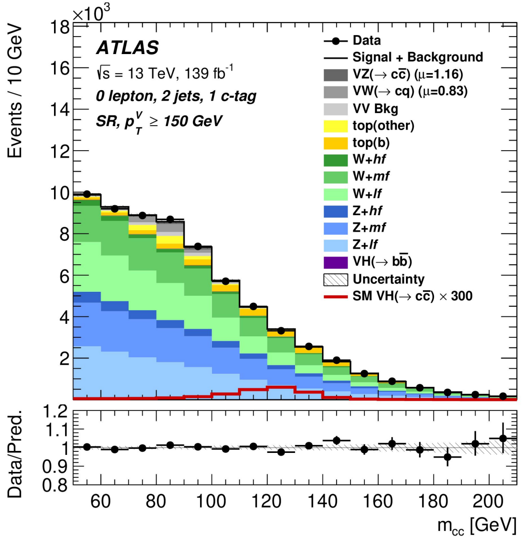


ATLAS → Results compatible with SM predictions within 1-2 σ, but several negative fit values.

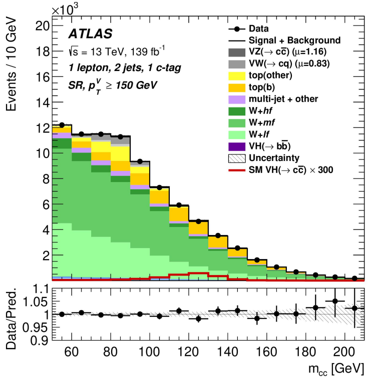
CMS → Results compatible with SM (≤2.4σ), but fairly significant deficits, similar to ATLAS.

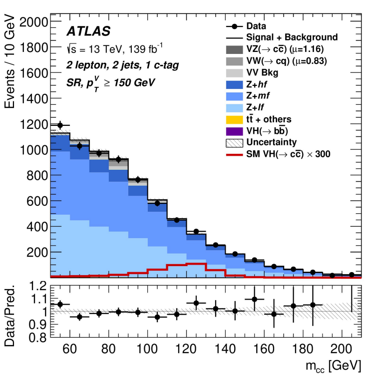
Search for Semileptonic (W/Z)H, H→cc





Complex composition of backgrounds: V+jets and top quark → backgrounds constrained in dedicated control regions.





Measurement of VZ process with Z to *c* quarks to validate the strategy.

(Z/W)H, (Z/W)→ $\nu\nu$/lν/ll H→bb