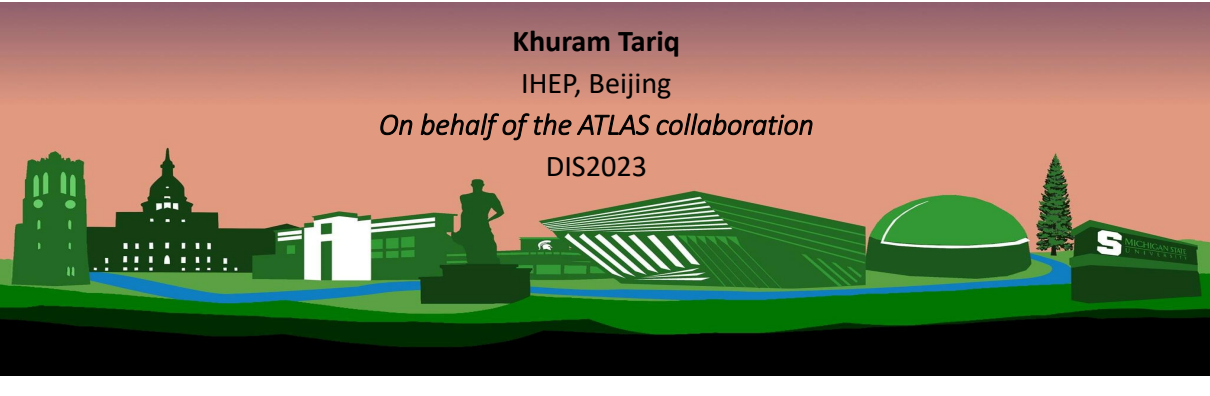
Institute of High Energy Physics
Chinese Academy of Sciences

ATLAS EXPERIMENT

Measurements of the Higgs boson coupling properties to fermions with the ATLAS detector



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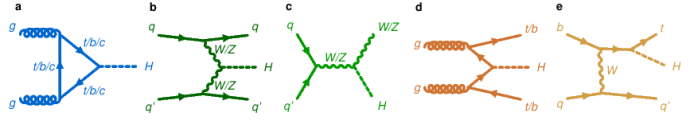
IHEP, Beijing
On behalf of the ATLAS collaboration
DIS2023

Introduction

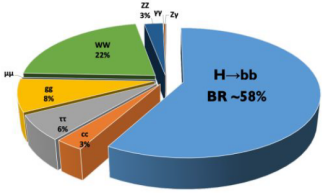
- The **strength of the interaction, or 'coupling'**, between the Higgs boson and a given particle
  - defined by the **particle's mass and type**

- The experimental determination of the **couplings of the Higgs boson to fermions**
  - provides important and **independent tests of the standard model**
  - provides stringent **constraints on theories beyond the standard model**

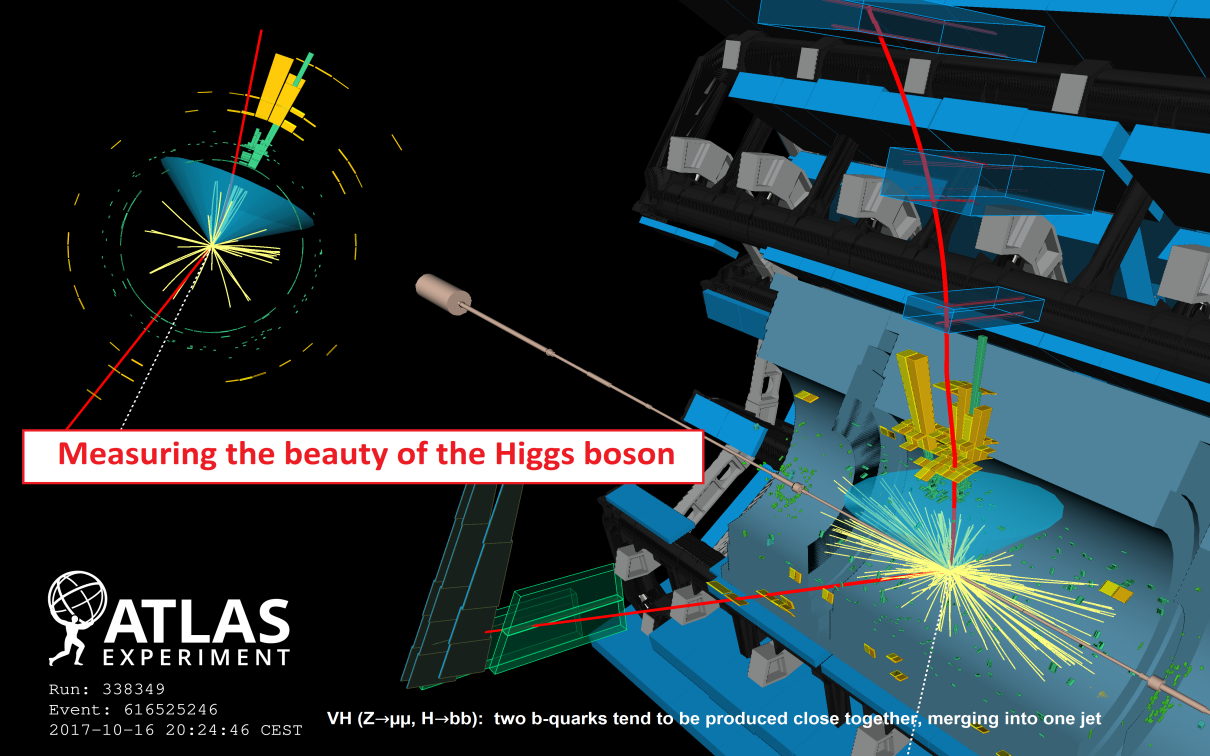
- Interactions with three **third-generation matter particles** (bottom (b) and top(t) quarks, and tau leptons (τ)) measured in **Run-2 "precision era"!**
- Indications of interactions with **second-generation particle** (muons(μ) and charm quark (c)) are emerging!



Higgs boson production modes



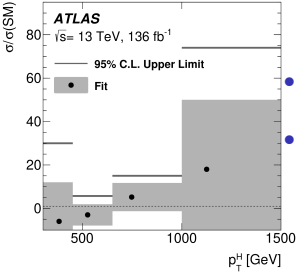
Higgs boson decay branching fraction


Measuring the beauty of the Higgs boson
ATLAS
EXPERIMENT
Run: 338349
Event: 616525246
2017-10-16 20:24:46 CEST
VH (Z→μμ, H→bb): two b-quarks tend to be produced close together, merging into one jet

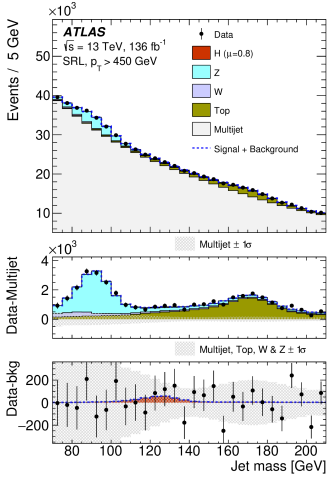
H→bb boosted all hadronic

Measuring H→bb decay inclusively (= all production modes, mostly dominated by ggF).

- Main Backgrounds:
  - Multijet: 200 times of the signal
  - Z+jets, W+jets, top: 20 times of signal
- Higgs candidate is a large-R jet
- **Higgs boson signal strength inclusive measurement:** μ_H **= 0.8±3.2**
- 95% CL limit on the Higgs boson production cross section w/o assumptions on pT(H) spectrum: σ_H (pT(H)>450GeV)<115 fb



- Differential measurement is also done in pT(H)
- Higgs boson production cross section for pT(H) > 1 TeV: 2.3±3.9(stat.)±1.3(syst.) ±0.5(theory) fb



doi.org/10.1103/PhysRevD.105.092003

VH(bb): the golden channel for H→bb and VH studies

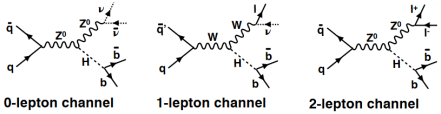
- **Three channels:**
- 3 lepton channels x 2, 3(+) jets x pT(V) bin x SR/CRs = 42 regions

- **VH(bb) MVA**
  - Multivariate analysis to discriminate between signal and background
  - Separate trainings for 2jet and 3jet and for pT(V)<150 GeV and pT(V)>150 GeV in 2-lep (inclusive in SR+CR)
  - Good compatibility: Between production modes (71%), With the SM prediction (89%)

- Cross checks: VH(bb) di-jet mass analysis and VZ(bb) MVA

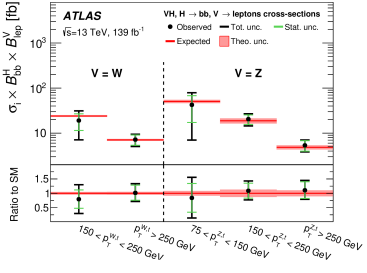
$$\mu_{VH}^{bb} = 1.17^{+0.25}_{-0.23} = 1.17 \pm 0.16(\text{stat.})^{+0.19}_{-0.16}(\text{syst.})$$

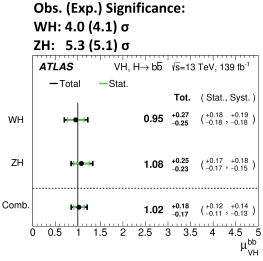
$$\mu_{VZ}^{bb} = 0.93^{+0.16}_{-0.13} = 0.93^{+0.07}_{-0.06}(\text{stat.})^{+0.14}_{-0.12}(\text{syst.})$$

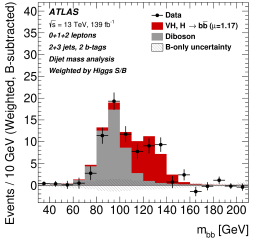


STXS measurement:

- STXS framework to maximize the sensitivity of the cross section measurement while minimizing the theory dependency
- Stage 1.2 merged down to 5 STXS bins

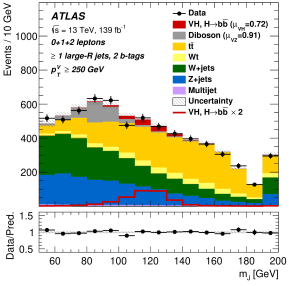


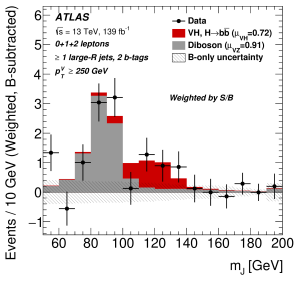




Boosted VH(bb): pushing to high pT

- Push towards higher pT(V) → **focus on pT(V) > 250 GeV**:
- Final discriminant: large-R jet mass m_J
- **Search for deviations from the SM (EFT approach):**
  → some operators are pT dependent
- Binned profile likelihood fit in m_J in 14 regions:
  → simultaneously extracting VH(→bb) and VZ(→bb) signal strengths



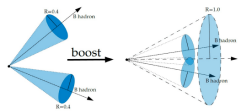


$$\mu_{VH}^{bb} = 0.72^{+0.39}_{-0.36} = 0.72^{+0.29}_{-0.28}(\text{stat.})^{+0.26}_{-0.22}(\text{syst.}) \qquad \sigma_{VH}^{bb} = 2.1\,(2.7)\ obs.\,(exp.)$$

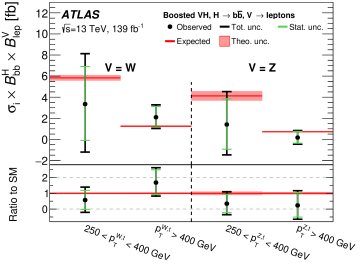
$$\mu_{VZ}^{bb} = 0.91^{+0.29}_{-0.23} = 0.91 \pm 0.15(\text{stat.})^{+0.25}_{-0.17}(\text{syst.}) \qquad \sigma_{VZ}^{bb} = 5.4\,(5.7)\ obs.\,(exp.)$$

doi.org/10.1016/j.physletb.2021.136204

$$\Delta R(b_1, b_2) \approx \frac{2 \cdot m_H}{p_T^H} \qquad \Delta R(b_1, b_2) \leq 1,\ p_T^H \geq 250\,GeV$$



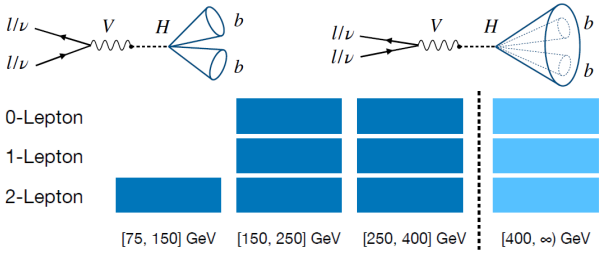
Large-Rjets: at least one large-Rjet, pT>250 GeV, $|\eta|$ <2.0
Track-jets: at least two track-jets, pT>10GeV, $|\eta|$ <2.5, matched to the leading large-Rjet

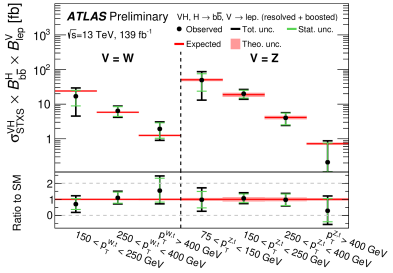


STXS measurement in 2 pT(V) analysis
bins:[250,400], [400,∞]

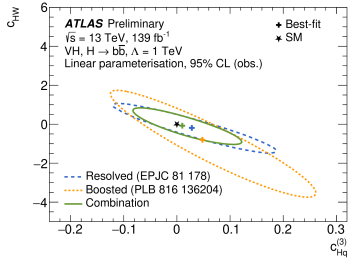
VH(bb) resolved/boosted combination

ATLAS-CONF-2021-051

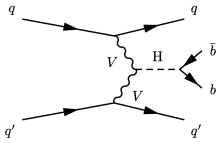




- **Taken together: more complete picture of the VH process**
- Orthogonality through pT(V) cut at 400 GeV
- **Higgs candidate:**
  - Resolved regime → two small radius jets
  - Boosted → leading large-R jet (R=1.0)
- More granular STXS measurement
- Stronger SMEFT constraints for scale-dependent modifications
- Results well-understood: compatible with individual analyses



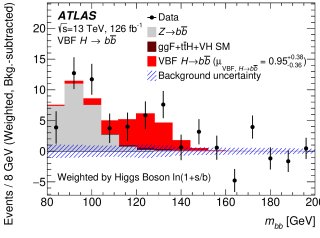
VBF



Higgs Boson decaying to b-quark pairs in the vector boson fusion (VBF) production mode

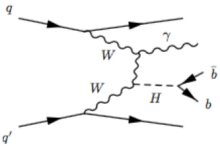
- All-hadronic final state:
  - Signature: 2 b-jets, 2 VBF jets
  - Backgrounds: Non-resonant (NR) bbjj, Zjj
  - VBF topology allows for discrimination against QCD background

doi.org/10.1140/epjc/s10052-021-09192-8



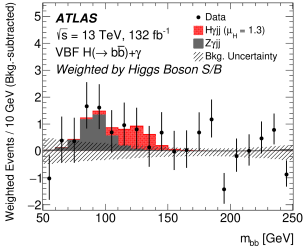
$\mu_{VBF,H\to bb} = 0.95^{+0.32}_{-0.32}(stat.)^{+0.20}_{-0.17}(syst.)$ significance: 2.6σ (2.8σ expected)

Add extra photon to VBF production

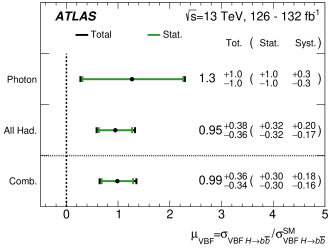


- Heavily reduce QCD multi-jet contribution
- Extra EM object help to explore low pT phase space

doi.org/10.1007/JHEP03(2021)268

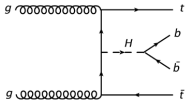


$\mu_H = 1.3 \pm 1.0$ observed significance of 1.3σ, Expected $1.0\ \sigma$



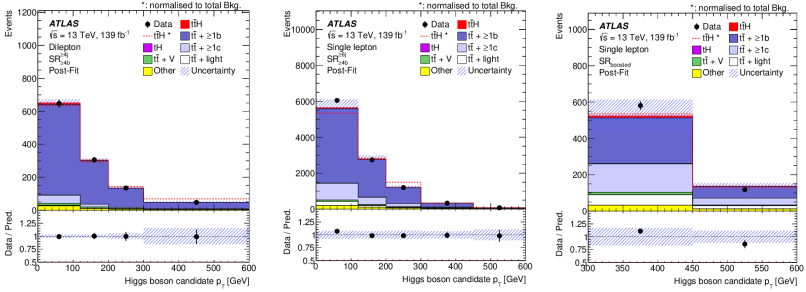
The combined measured signal strength: corresponding to a significance of 2.9σ (2.9σ expected)

Higgs-Top coupling (ttH)



- **The strongest coupling**: top-quark Yukawa coupling (y_t)
- top quark couples directly to the Higgs boson at tree level: **direct measurement of y_t**
- Event selection targets tt events decaying to final states containing one or two leptons

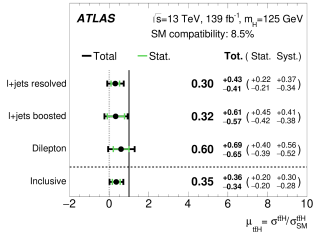
- Analysis done in both **resolved and boosted regime**
- Separate between **single-lepton** and **di-lepton** regions.
- Dominant background is **tt+$\geq$1b**

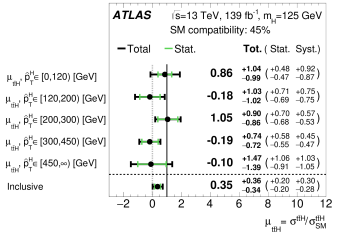


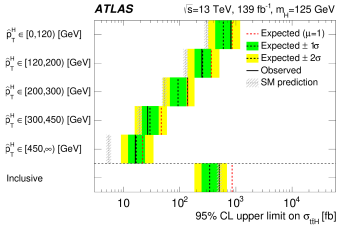
doi.org/10.1007/JHEP06(2022)097

Higgs-Top coupling (ttH): Results

- **Best-fit inclusive signal strength:**
  $\mu = 0.35 \pm 0.20(stat.)^{+0.30}_{-0.28}(syst.) = 0.35^{+0.36}_{-0.34}$
- observed (expected) significance of 1.0 (2.7) standard deviations





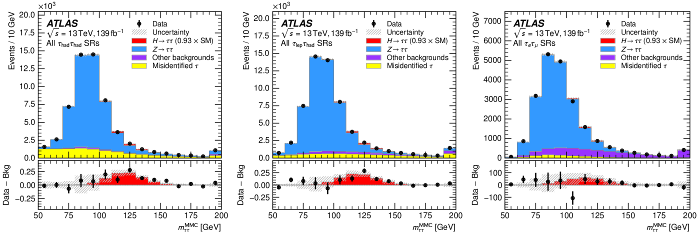


- Signal strength measurement also performed in Higgs pT bins in **STXS framework**
- First STXS measurement in the ttH(H→bb) channel and STXS measurement in the pT(H)>450 GeV bin
- Allows to probe higher Higgs pT => specially selected boosted Higgs bosons with pT above 300 GeV
- Measured 95% confidence level (CL) cross-section upper limits in each STXS bin

$H \to \tau\tau$

Test of Yukawa coupling in SM: Measure cross section of $H \to \tau\tau$

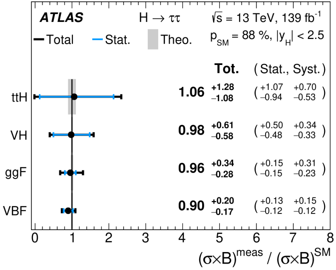
- Target four main Higgs boson production modes
- Three analysis channels: $\tau_{had}\tau_{had}$, $\tau_{lep}\tau_{had}$, $\tau_e\tau_\mu$
- Dominant backgrounds
  - $Z \to \tau\tau$: MC simulation, Dedicated/Embedded CRs
  - Misidentified τ: Data-driven estimation
  - Top: MC simulation, Dedicated CRs

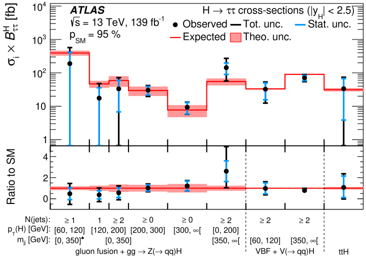


Total measured $H \to \tau\tau$ cross section:
2.94 ± 0.21 (stat)$^{+0.37}_{-0.32}$(syst) pb
in agreement with the SM prediction of **3.17 ± 0.09 pb**

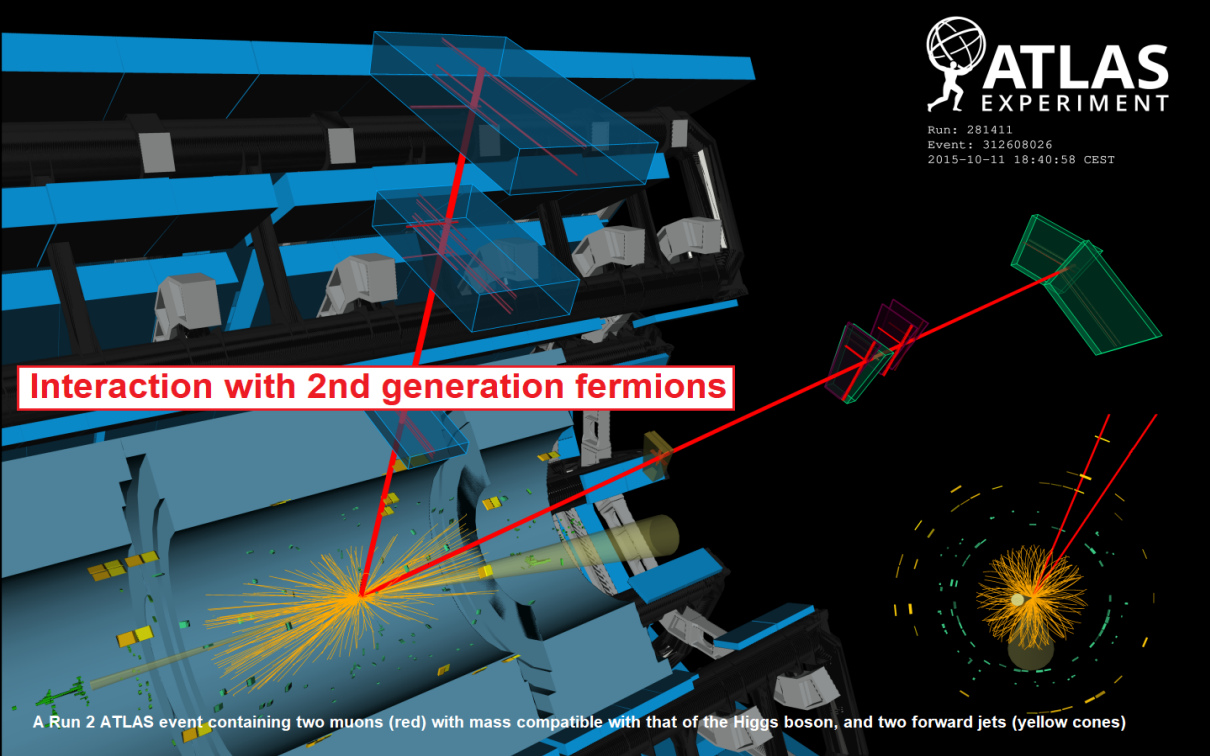
doi.org/10.1007/JHEP08(2022)175

4 POIs: Cross-sections per production mode





9 POIs crossponding to STXS measurements



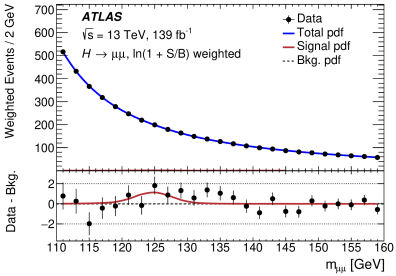
A Run 2 ATLAS event containing two muons (red) with mass compatible with that of the Higgs boson, and two forward jets (yellow cones)

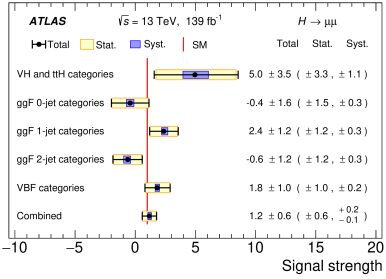
The elusive Higgs-boson decay to muon pairs

doi.org/10.1016/j.physletb.2020.135980

- **$H \to \mu\mu$** provides an unique opportunity to study Higgs coupling to 2nd generation fermions
  - SM BR: $(2.17 \pm 0.04) \times 10^{-4}$
  - Dominant background: Drell-Yan. Typical S/B at 0.1% level
- Split into 20 different regions for categorization
- Exclusively selected in the order of ttH $\to$ VH $\to$ VBF $\to$ ggF

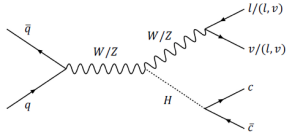
Data compatible with SM:
Obs. significance 2.0σ (exp. 1.7 σ), μ 1.2 $\pm$ 0.6
BR (H$\to\mu\mu$) $<$ 4.7 x 10^{-4} excluded at 95% CL





Higgs-charm coupling

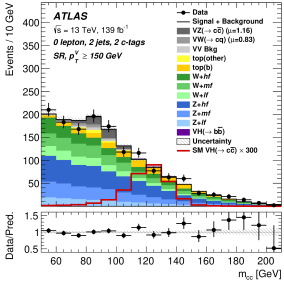
- **VH(cc) analysis:**
- Direct probe of Higgs boson coupling to 2nd generation of quarks.
- 3 channels as in VH(bb) analysis: 0/1/2 lepton.
- Use m_{cc} as discriminating variable

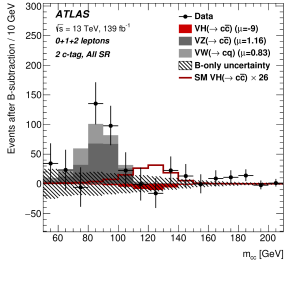


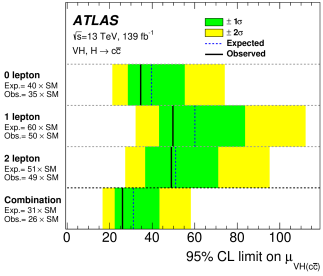
doi.org/10.1140/epjc/s10052-022-10588-3

Flavour tagging:

- Efficiencies: c-jets (27%), b-jets (8%), light-jets (1.6%)
- c-tag with b-tag veto on two leading jets
- 1 and 2 c-tag categories are considered for signal regions







VH (H → ccc)

Observed (expected) limit:26.0 x SM (31^{+12}_{-8} x SM)

VW(cq) and VZ(cc) are simultaneously measured as a cross-check

VW (W → cs/cd):

Observed (expected) significance: 3.8σ (4.6σ)

VZ (Z →cc):

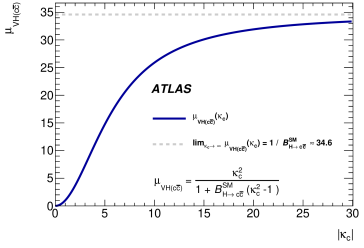
Observed (expected) significance: 2.6σ (2.2σ)

Constraints on EFT coupling modifiers

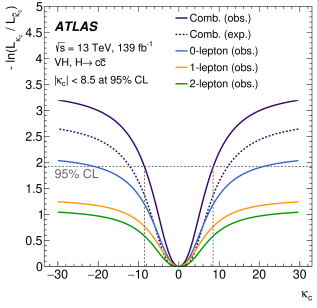
Definitions: $\sigma \times \mathrm{BR}(V \to H \to c\bar{c}) = \sigma_{SM} \times \mathrm{BR}(V \to H \to c\bar{c})_{SM} \times \frac{\kappa_V^2 \kappa_c^2}{\kappa_H^2}$, $\kappa_H^2 = \frac{\Sigma_j \Gamma_j^{SM} \times \kappa_j^2}{\Gamma_H^{SM}}$

- Analysis sensitive to exclude some parts of κ_c parameter space (parametrisation below used)
- $\mu = \frac{\kappa_c^2}{[(1-BR_{Hcc})+BR_{Hcc}*\kappa_c^2]}$ (other coupling modifiers set to 1)

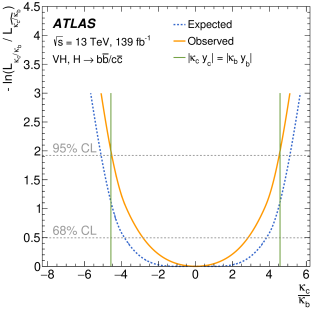
3POI combined fit provides **observed constraint of $|\kappa_c| \leq 8.5$ at 95% CL ← first direct constraint from H → cc̄ decays**



Parametrisation of $\mu(k_c)$ includes effects on the Higgs width



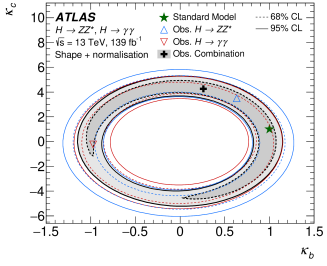
Likelihood scan on k_c



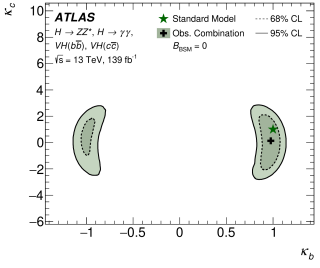
Constraint: $|K_c/K_b| < 4.5$ at 95% confidence level

Constraint k_b k_c by combining H→ZZ*→4l and H→$\gamma\gamma$ with VH(bb/cc)

k_b k_c can be constrained by pT(H) measured from H→ZZ*→4l and H→$\gamma\gamma$ analyses.

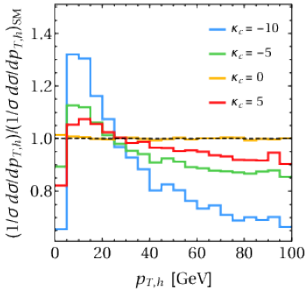


H→ZZ*→4l and H→$\gamma\gamma$ combination using shape & normalisation



VH(bb/cc), H→ZZ*→4l, H→$\gamma\gamma$ combination (BSM decays not allowed

arxiv:1606.09253



Best fit results, 95% CL:
H4l & H$\gamma\gamma$, shape & normalisation:
k_b: [-1.09, -0.86] U [0.81, 1.09]
k_c [-2.27, 2.27]
H4l & H$\gamma\gamma$ & VH(bb) & VH(cc)
BSM decays not allowed:
k_c::[-2.47, 2.53]
BSM decays allowed:
k_c :[-4.46, 4.81]

doi.org/10.48550/arXiv.2207.08615

Conclusion

All analyses show an overall good agreement with the Standard Model predictions

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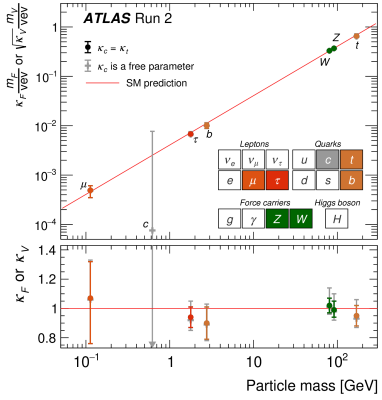
- **Precision era:** Moved from inclusive searches to differential x-section measurements
- Higgs coupling to fermions **provides an important test for the SM**.
- The ATLAS analyses using full Run2 dataset all show Higgs coupling to fermions consistent with SM.
- For analyses with adequate statistics and significance, STXS measurement with multiple POIs has been done and result is reinterpreted in EFT framework.



More data => more measurements, more differential, more complex interpretations

Thank You

For Your Attention