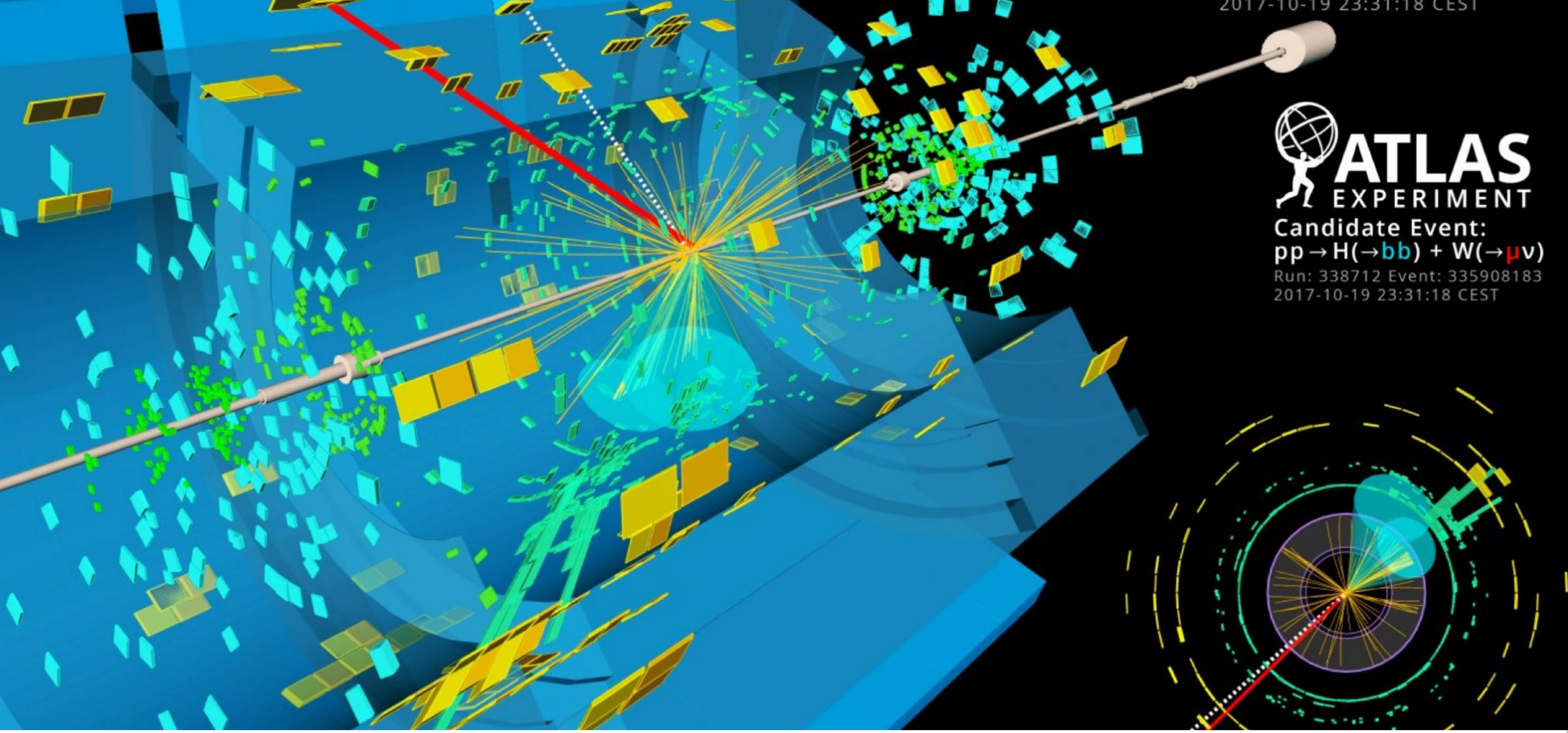


Higgs boson couplings to top, bottom and charm quarks with the ATLAS detector

Yan Ke

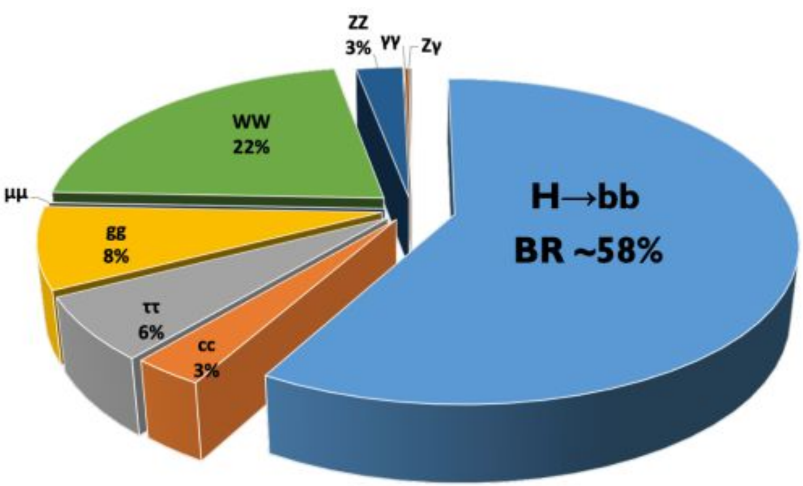
Stony Brook University

On behalf of the ATLAS collaboration

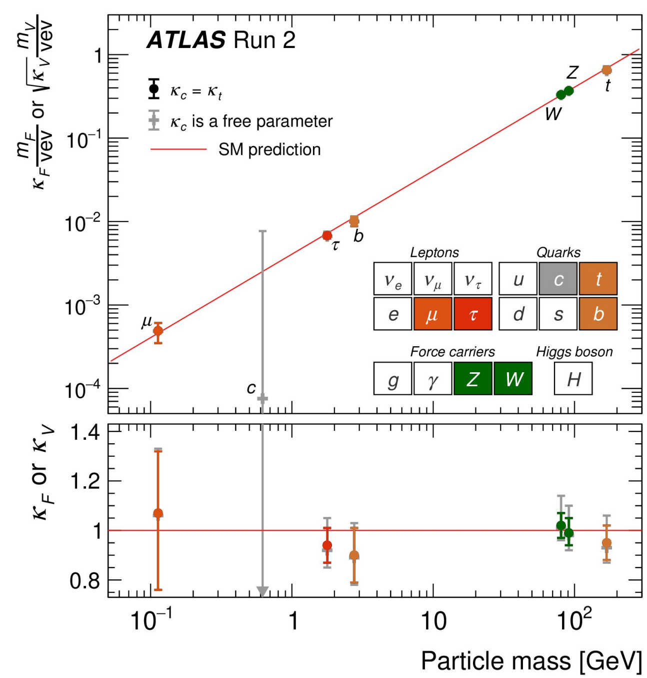
Higgs 2022, November 9th 2022

Introduction

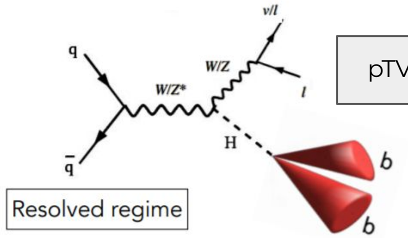
- **Higgs couplings to top, bottom: strongest couplings to fermions.**
  - Higgs decay to a pair of bottom quarks ~58% of the time → largest BR.
  - Tree level coupling to top accessible only through ttH production.
- **Higgs coupling to third generation quarks observed in Run-2 → "precision era"!**
- **Next challenge: measure Higgs to charm coupling (BR H→cc ~ 3%)**
  - Constrained from direct and indirect measurements.
- H→bb and H→cc sensitivity driven by VH production.



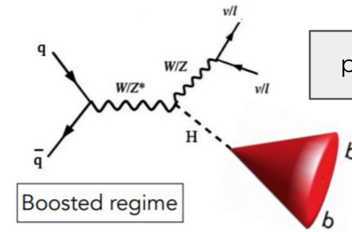
Higgs combination paper



VH(bb) resolved/boosted combination



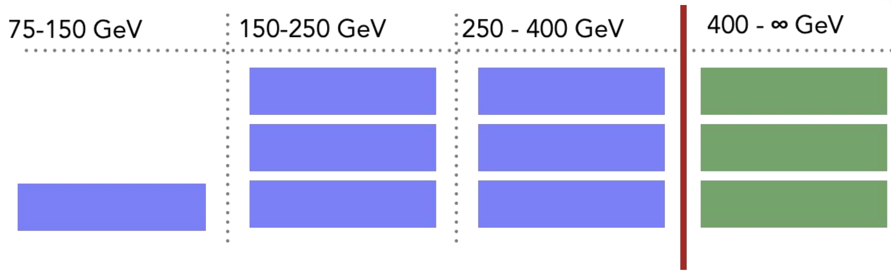
pTV < 400GeV



pTV > 400GeV

3 channels:
number of leptons in the V (Z/W) decay.
Lepton: e/μ

$Z\to\nu\nu$	0 Lepton
$W\to e\nu/\mu\nu$	1 Lepton
$Z\to ee/\mu\mu$	2 Lepton



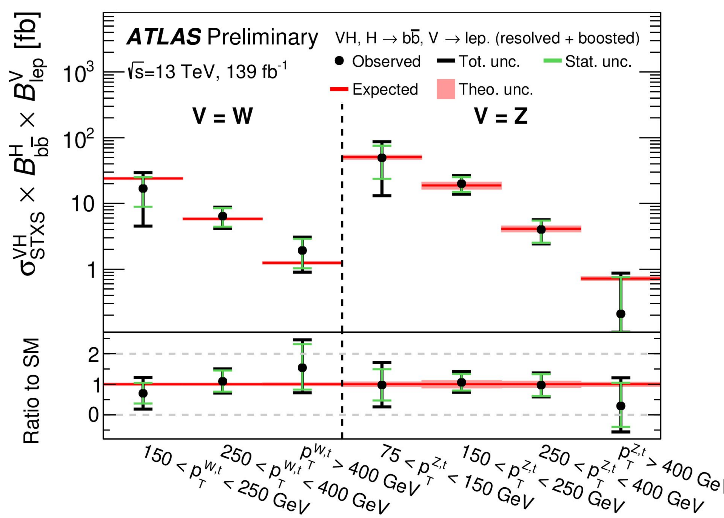
VHbb combination: 19 SRs and 30 CRs.

CONF-HIGG-2021-10(inspire)

Higgs combination paper

- Orthogonality through p_T^V cut at 400 GeV
- Main backgrounds: ttbar, W+jets and Z+jets.
- Higgs candidate:
  - Resolved regime → two small radius jets
  - Boosted → leading large-R jet (R=1.0)

STXS measurement with 7 POI



Inclusive signal strength:

$$\mu_{VH}^{bb} = 1.00^{+0.18}_{-0.17} = 1.00^{+0.12}_{-0.11}\ (\text{stat.})^{+0.14}_{-0.13}\ (\text{syst.})$$

EFT interpretation

[Higgs combination paper](#)

[CONF-HIGG-2021-10(inspire)](#)

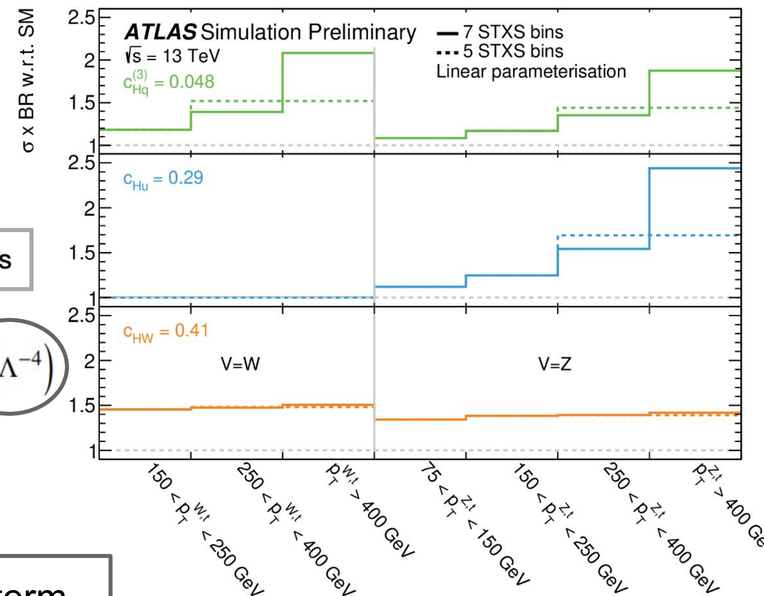
Effective lagrangian from SM lagrangian for BSM physics:

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{i}^{N_{d6}} \frac{c_i}{\Lambda^2} O_i^{(6)} + \sum_{j}^{N_{d8}} \frac{b_i}{\Lambda^4} O_i^{(8)} + \dots,$$

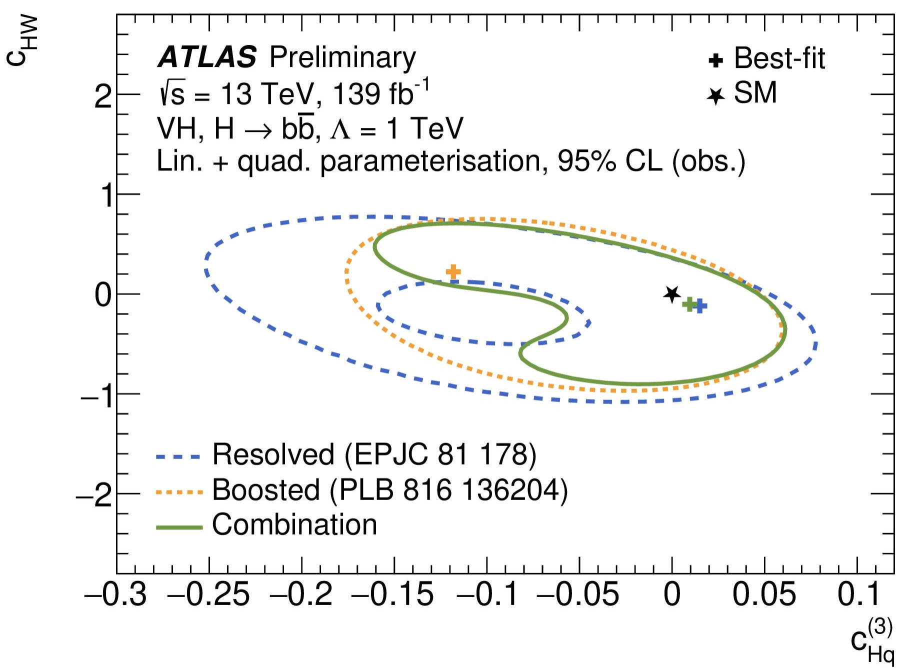
Wilson coefficients

Scale of new physics (1 TeV)

Dimension-6 operators describing new physics



$$\sigma = |\mathcal{M}_{\text{SMEFT}}|^2 = |\mathcal{M}_{\text{SM}} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} \mathcal{M}_i^{(6)}|^2 + \mathcal{O}\left(\Lambda^{-4}\right) = |\mathcal{M}_{\text{SM}}|^2 + \sum_i \frac{c_i^{(6)}}{\Lambda^2} 2\text{Re}\left(\mathcal{M}_i^{(6)} \mathcal{M}_{\text{SM}}^*\right) + \mathcal{O}\left(\Lambda^{-4}\right)$$

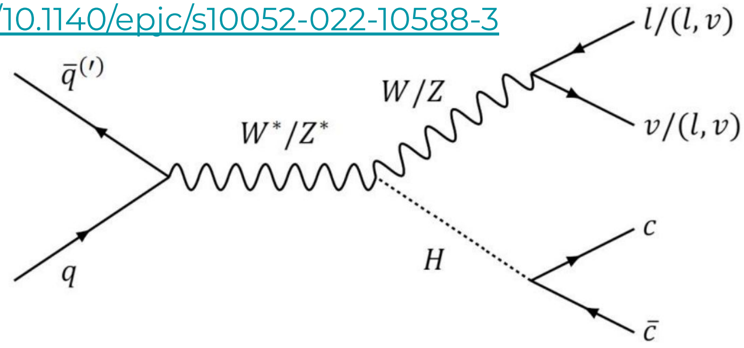


Quadratic term inside

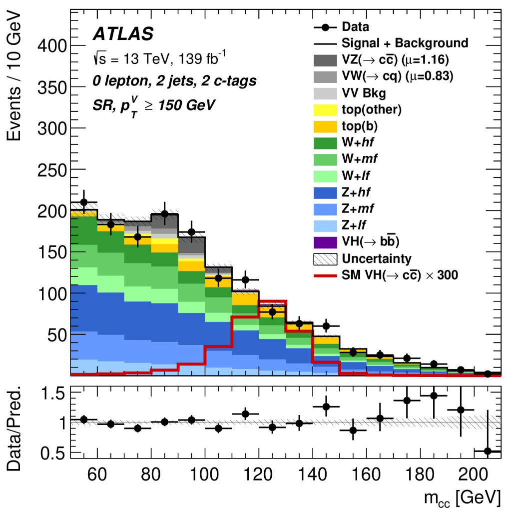
- **The resolved+boosted combination improves EFT limits** especially for higher dimensional scans
- Measured wilson coefficient consistent with SM.

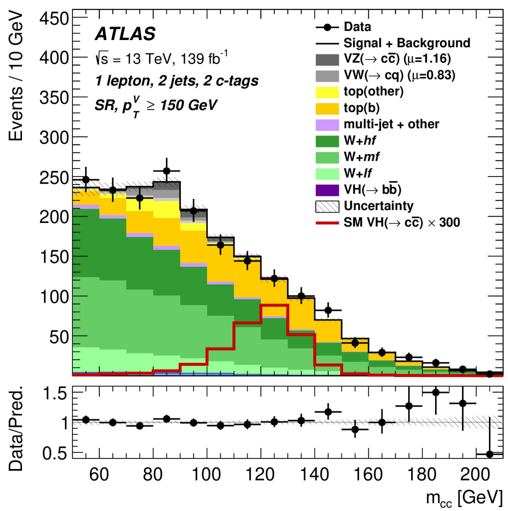
VH(cc) analysis

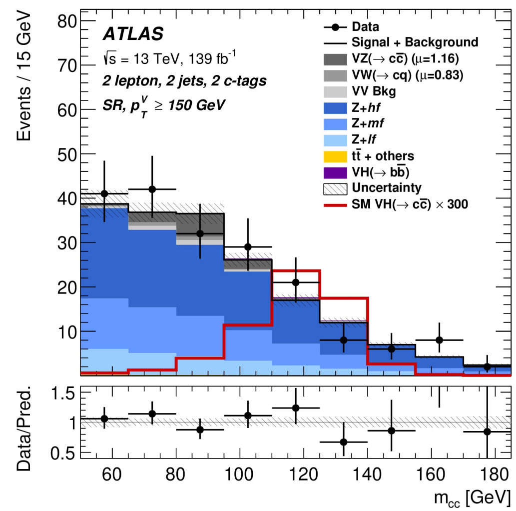
[doi: https://doi.org/10.1140/epjc/s10052-022-10588-3](https://doi.org/10.1140/epjc/s10052-022-10588-3)



- **H→cc branching fraction: 2.89%**
  H→bb branching fraction: ~58%
- 3 channels as in VH(bb) analysis: 0/1/2 lepton.
- **Use m_{cc} as discriminating variable.**







- C-tagged jet selected with a c-tag + b-veto tagger (c-jet efficiency 20%).
  - Orthogonality w.r.t VH(bb) analysis.
  - Dedicated top CR to control top background based on one c-tag amongest two leading jets & b-tagged third jet.
- VW(cq) and VZ(cc) are simultaneously measured as a cross-check.

VH(cc) analysis: results

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

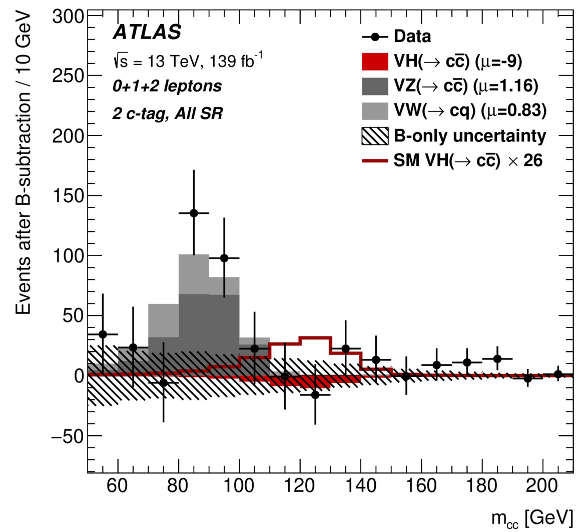
Inclusive signal strengths:

$\mu_{VH(cc)}$ = -9 ± 10(stat) ± 12(syst)

$\mu_{VW(cq)}$ = 0.83 ± 0.11(stat) ± 0.21(syst), significance: 3.8σ

$\mu_{VZ(cc)}$ = 1.16 ± 0.32(stat) ± 0.36(syst), significance: 2.6σ

The 3 measured signal strengths are compatible at 84% with the SM.



Constraints on EFT coupling modifiers *(kappa framework)*

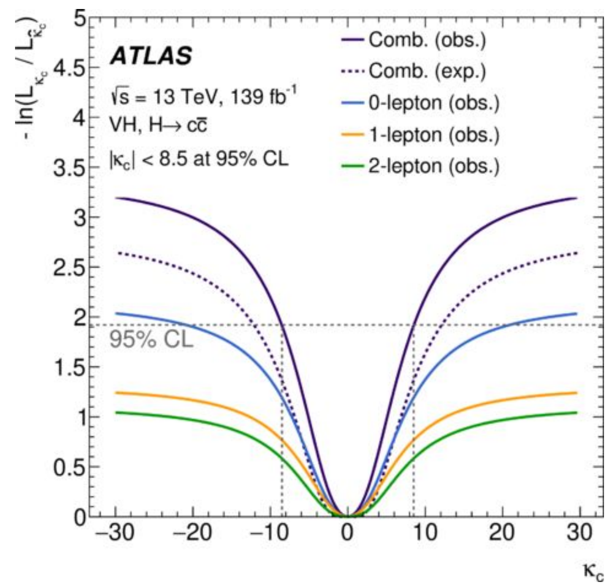
- Parametrize the signal strength in the likelihood as:

$$\mu_{VH(c\bar{c})}(\kappa_c) = \frac{\kappa_c^2}{1 + B^{SM}_{H\to c\bar{c}}(\kappa_c^2 - 1)},$$

Coupling modifier

Results:

- Constraint: $|K_c|$ < 8.5(12.4) at 95% CL

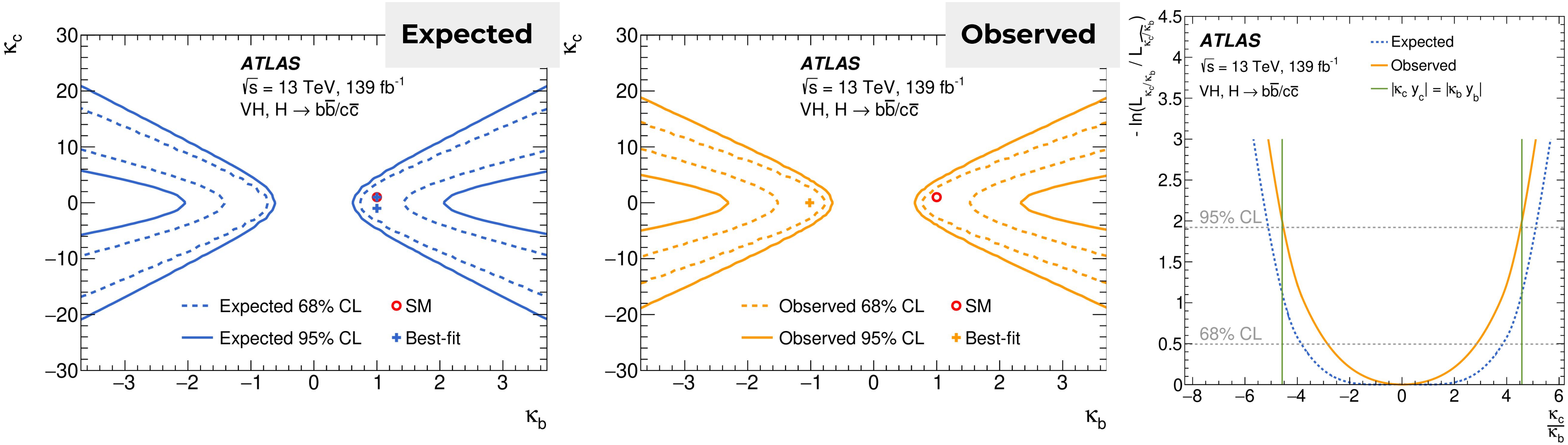


VH(bb/cc) combination

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

VH(bb) and VH(cc) analyses are orthogonal → **combination**

- Common experimental systematic uncertainties: correlated
- Background normalisations and modeling uncertainties: uncorrelated.
- ***Fitted signal strengths consistent with individual analyses.***



Coupling modifiers:

- Best fit (K_b ,K_c) = (-1.02, 0), only 0.02 away from (1.02, 0) in terms of likelihood.
- Likelihood parameterised as a function of $\mathbf{K_c/K_b}$
- **Constraint: $|K_c/K_b|$ < 4.5 at 95% confidence level.**

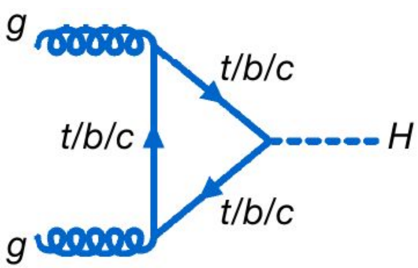
Higgs coupling to charm must be weaker than coupling to bottom!

Constraint κ_b κ_c by combining $H \to ZZ^* \to 4l$ and $H \to \gamma\gamma$ with VH(bb/cc)

Stony Brook University

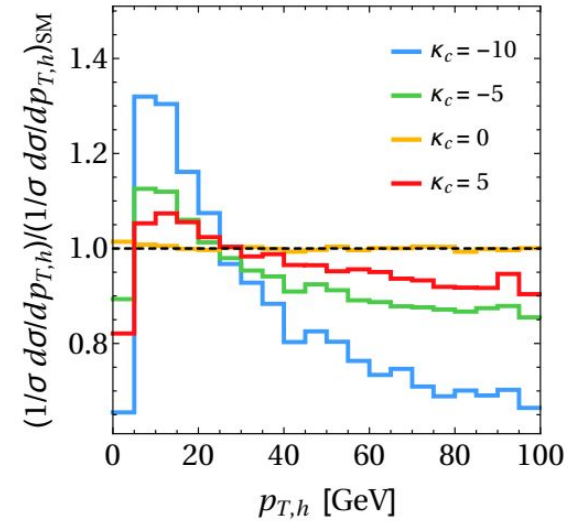
ATLAS EXPERIMENT

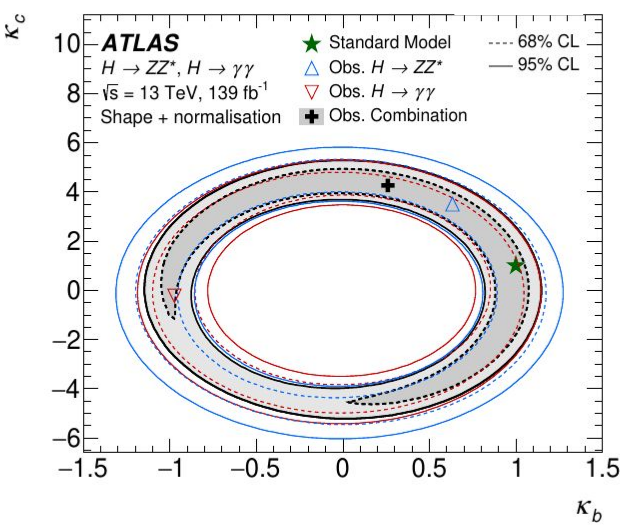
κ_b κ_c can be constrained by p^T_H measured from $H \to ZZ^* \to 4l$ and $H \to \gamma\gamma$ analyses.



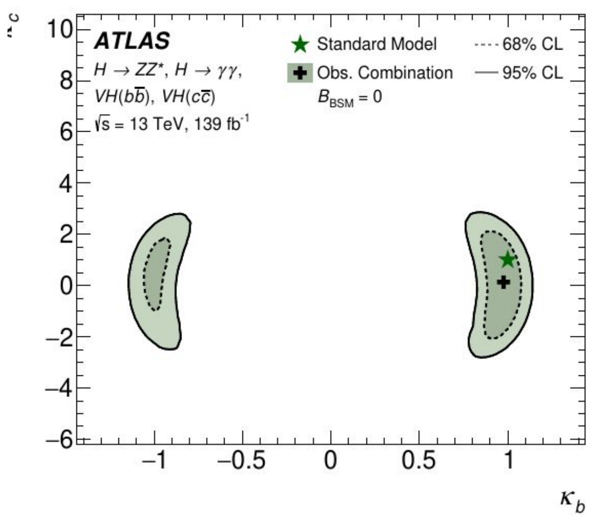
arxiv:2207.08615

arxiv:1606.09253





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



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

Best fit results, 95% CL:

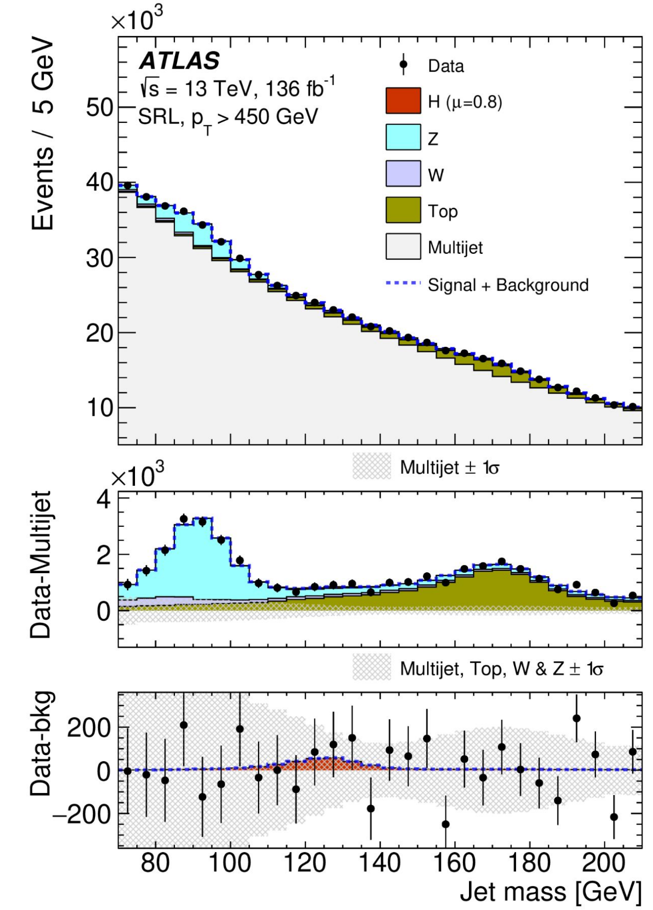
H4l & $H\gamma\gamma$, shape & normalisation:
K_b: [−1.09, −0.86] ∪ [0.81, 1.09]
K_c [−2.27, 2.27]

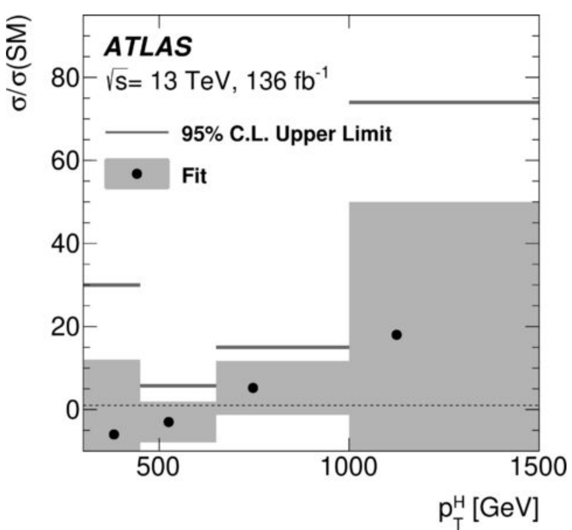
H4l & $H\gamma\gamma$ & VH(bb) & VH(cc)
BSM decays not allowed:
K_c:[−2.47, 2.53]
BSM decays allowed:
K_c :[−4.46, 4.81]

H→bb boosted all hadronic

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

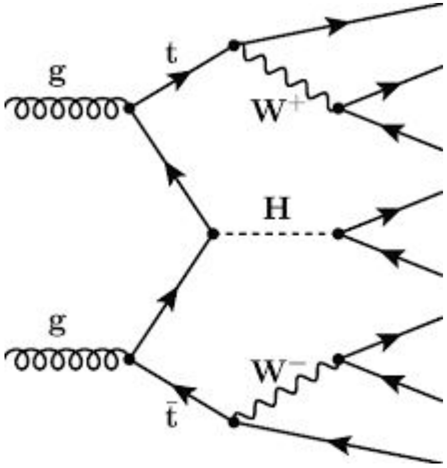
- **Measuring H→bb decay inclusively** (= all production modes, mostly dominated by ggF).
- Main Backgrounds:
  - Multijet: 200 times of the signal
  - Z+jets, W+jets, top: 20 times of signal
- Higgs candidate is a large-R jet,events are categorized into signal region, validation region and ttbar control region.
- Higgs boson signal strength inclusive measurement: $\mu_H = 0.8 \pm 3.2$
- Differential measurement is also done in p_T^H
- All Higgs boson results consistent with SM.





- **Constraints on Higgs boson inclusive production with transverse momentum above 1 TeV.**

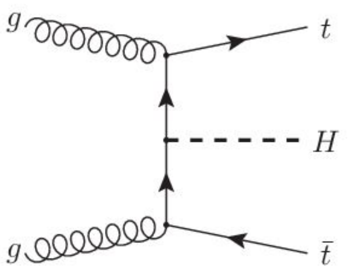
Higgs-Top coupling measurements



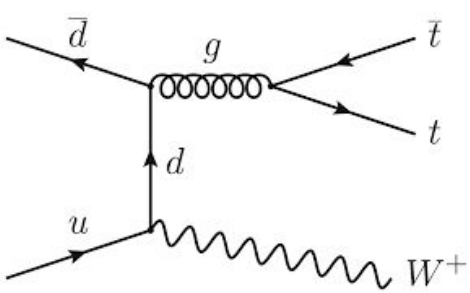
Measuring Higgs Top coupling by ttH

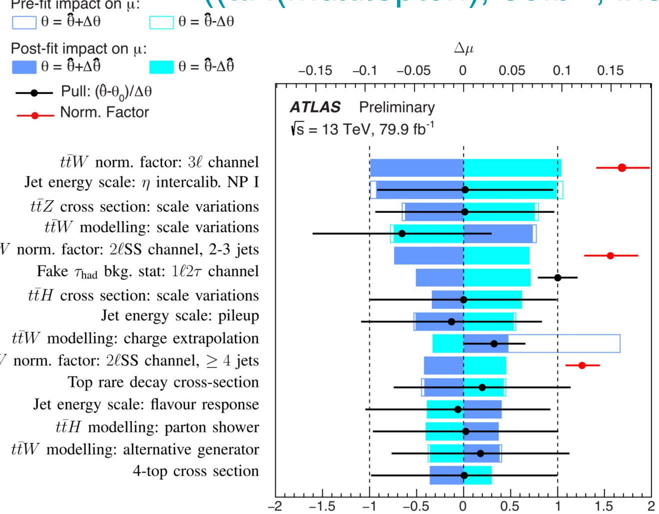
- **ttH** is a good production mode for measuring Higgs Top coupling

- **Outline**
  - ttH(bb) signal strength measurement
  - Higgs top coupling CP measurement in mainly ttH(bb) (more recent)
  - Higgs top coupling CP measurement in mainly ttH($\gamma\gamma$) (older)
  - Study on ttH(ML) background: ttW charge asymmetry



ATLAS-CONF-2019-045
((ttH(multilepton), 80fb^{-1}, inspire)





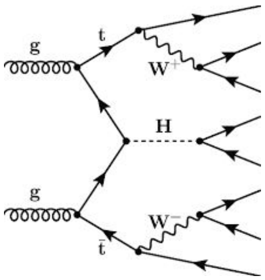
ttH(bb) analysis

doi.org/10.1007/JHEP06(2022)097

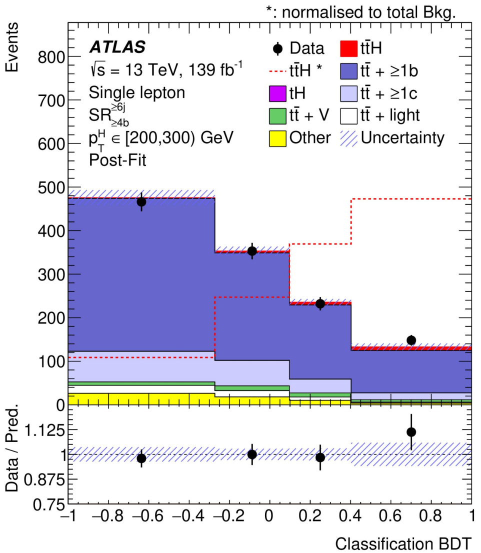
- Higgs has the **strongest coupling to top quark**
  - ttH(bb) analysis → best direct probe of top coupling

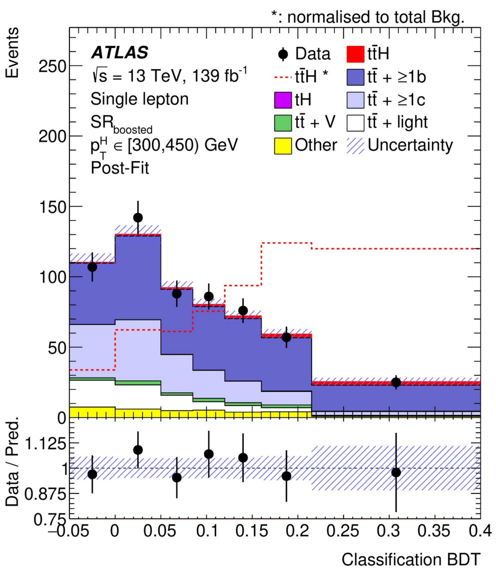
- Analysis done in both **resolved and boosted regime**.
- Separate between single-lepton and di-lepton regions.

- **ttH(bb) challenges**:
  - Match jets with Higgs and top.
  - Large background of ttbar + jets



- **Multivariate analysis used in two parts of ttH(bb):**
  - Reconstruction: Trained BDT(resolved)/DNN(boosted) used to associate final state particle with Top, Higgs, W.
  - Classification: Trained BDT used to separate signal from background.





ttH(bb) analysis result

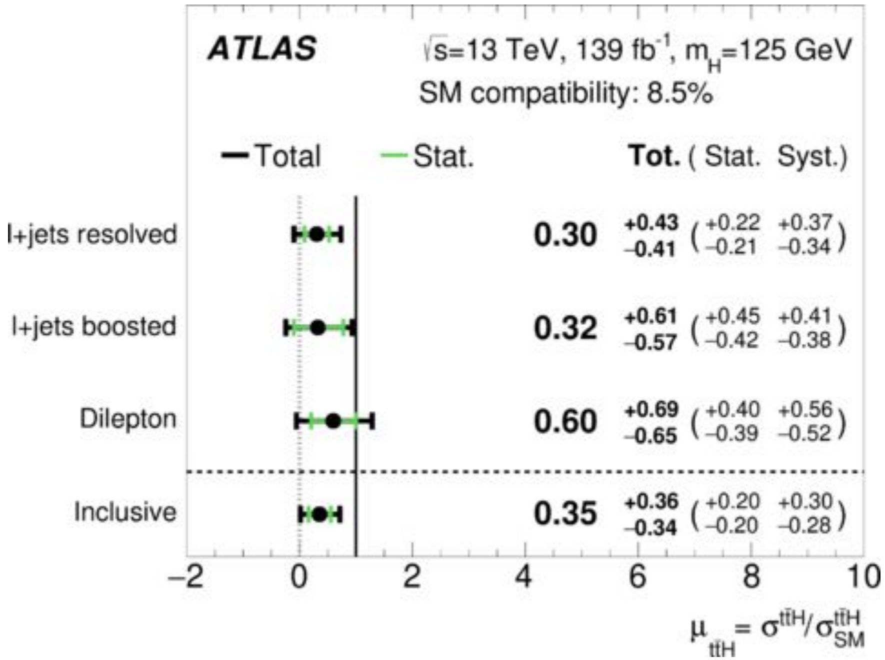
doi.org/10.1007/JHEP06(2022)097

- **Best-fit inclusive signal strength**:

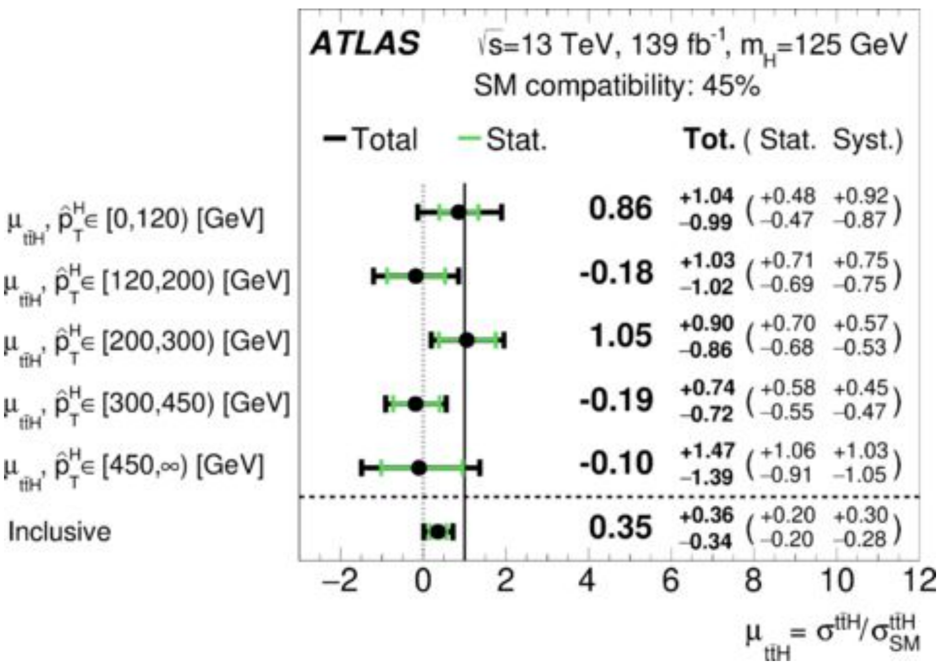
$$\mu = 0.35 \pm 0.20\,(\text{stat.})\,^{+0.30}_{-0.28}\,(\text{syst.}) = 0.35^{+0.36}_{-0.34}$$

- Observed significance: 1.0 (expected significance 2.7)
- STXS computed in a 5 POI fit as a function of p_T^H

Single channel



STXS - 5 POI



Higgs coupling to Top: CP measurement

ATLAS-CONF-2022-016(inspire)

- Yukawa coupling between Higgs and top:

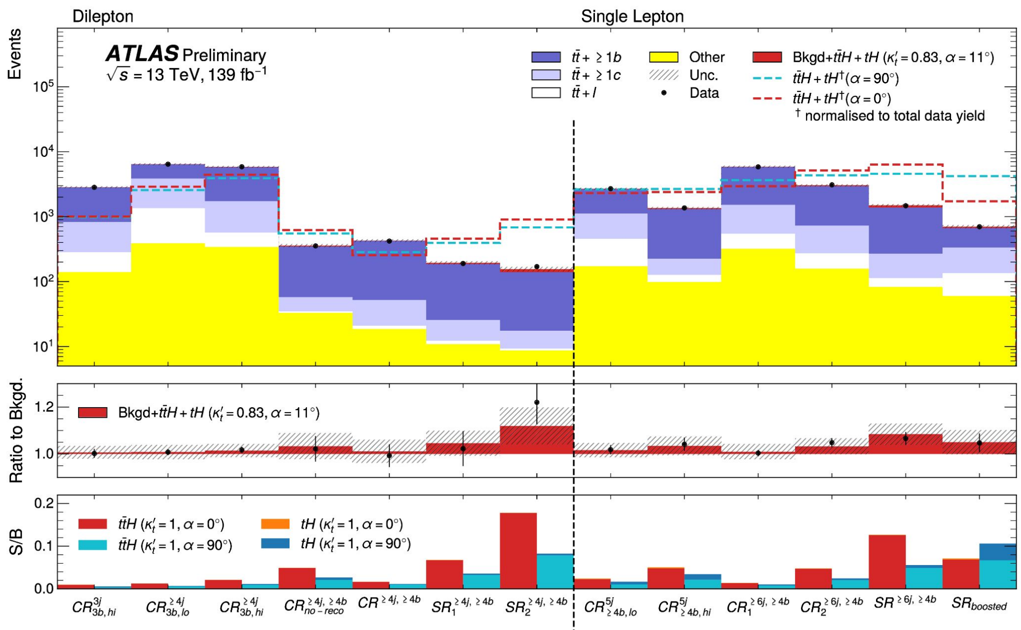
$$\mathcal{L} = -\frac{m_t}{v}\{\bar{\psi}_t \kappa_t [\cos(\alpha) + i\sin(\alpha)\gamma_5]\psi_t\}H$$

- Standard model predicts $k_t = 1$, $\alpha = 0$ (CP even)
- The measurement is performed using: **ttH + tH, H→bb**.
  - The prediction on cross section and kinematics distribution is **expected to be different for CP even and CP odd**.
- **Use "b_2" and "b_4" as CP discriminating variables,** defined as:

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

$$b_4 = \frac{p_1^z p_2^z}{|\vec{p}_1||\vec{p}_2|}$$

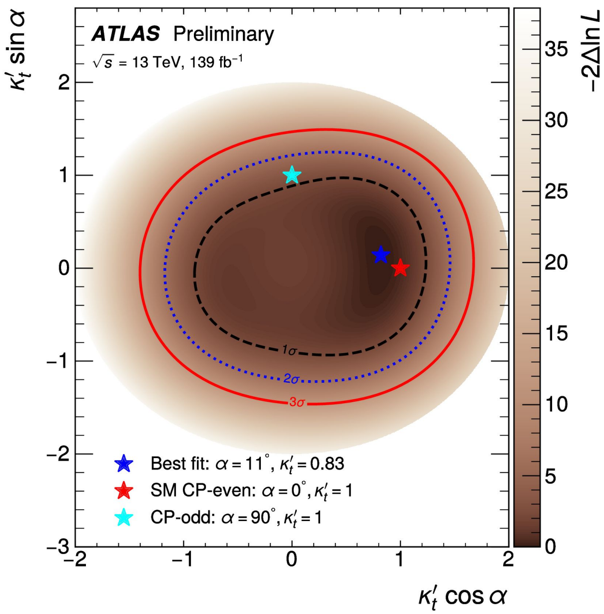
Where $\hat{\mathbf{n}}$ is unit vector in z axis. p is momentum of two top quarks.

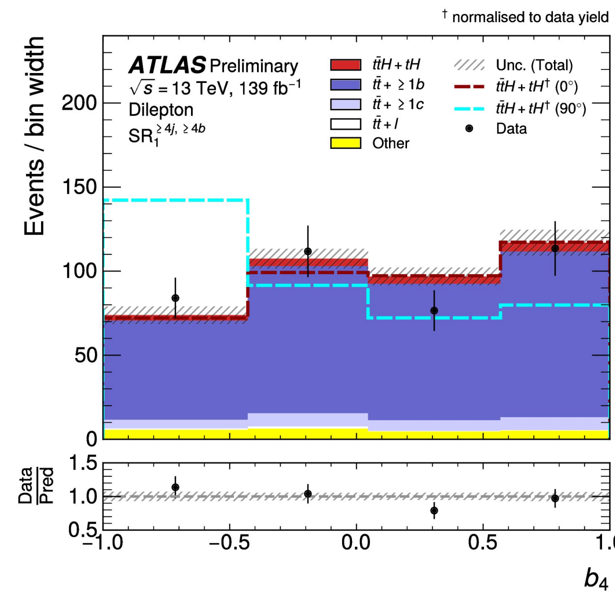


Higgs coupling to Top: CP measurement

[ATLAS-CONF-2022-016(inspire)](#)

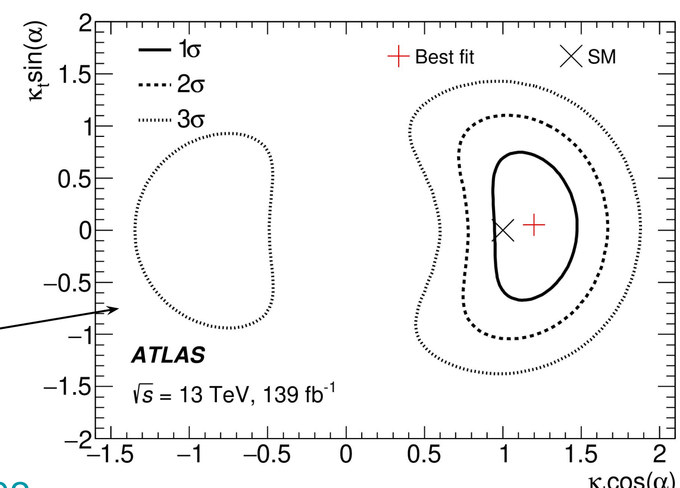
- Signal of ttH and tH signal over background prediction: 1.3 σ
- **Best fit for mixing angle α = 11° (err. +56°, -77°).**
- **Pure CP-odd hypothesis is disfavoured at 1.2σ.**





Note. **The Higgs coupling to Top has also been measured via ttH(γγ):**

- Pure CP-odd is excluded at 3.9σ.
- |α| > 43° is excluded at 95% CL.

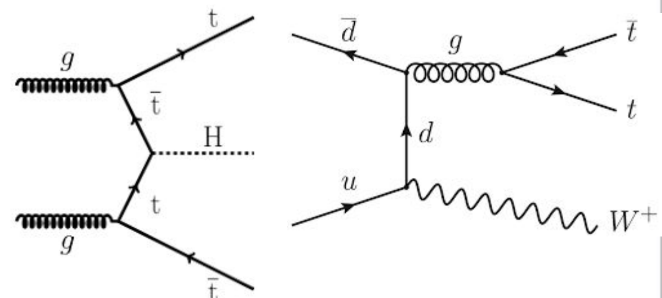


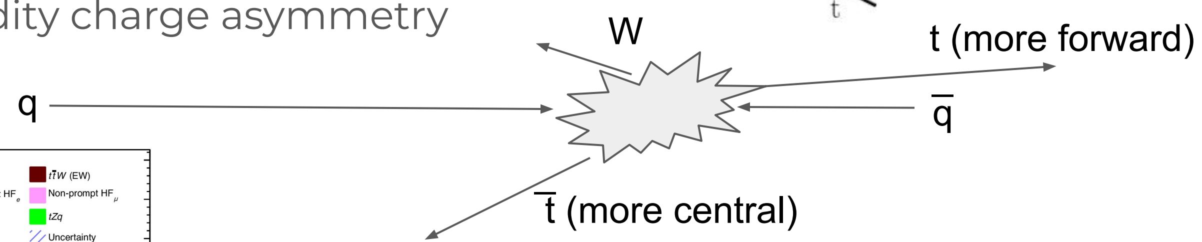
[doi.org/10.1103/PhysRevLett.125.061802](#)

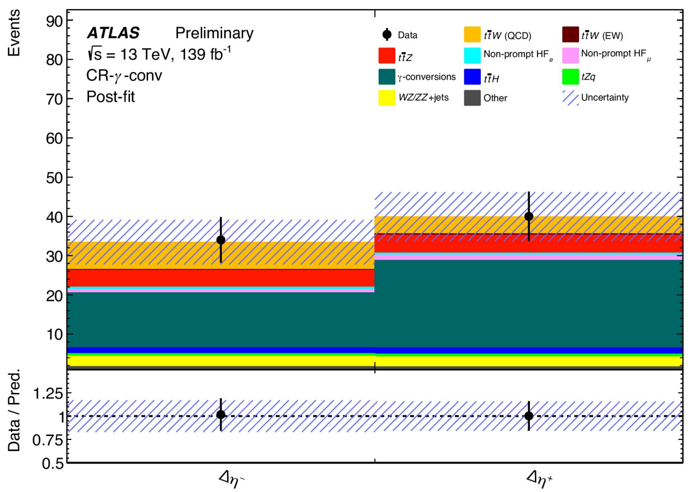
ttW charge asymmetry

[ATLAS-CONF-2022-062(inspire)](#)

- ttH multilepton analysis requires better understanding of the ttW since it is a major background.
- In the ttW process, the top quark (anti top) has a higher probability of being produced in the direction of the initial quark (anti quark).
  ⇒ central-forward rapidity charge asymmetry







- Analysis in done in 3L channel

Charge asymmetry defined as:

$$A_c^t = \frac{N(\Delta_y^t > 0) - N(\Delta_y^t < 0)}{N(\Delta_y^t > 0) + N(\Delta_y^t < 0)} \qquad \Delta_y^t = |y_t| - |y_{\bar{t}}|$$

Resconsruction level result:	**Unfolded result:**
Measured: $A_c^\ell(t\bar{t}W) = -0.123 \pm 0.136\,(\text{stat.}) \pm 0.051\,(\text{syst.})$	$A_c^\ell(t\bar{t}W)^{\text{PL}} = -0.112 \pm 0.170\,(\text{stat.}) \pm 0.055\,(\text{syst.})$
Predicted: $A_c^\ell(t\bar{t}W)_{\text{SM}} = -0.084\,^{+0.005}_{-0.003}\,(\text{scale}) \pm 0.006\,(\text{MC stat.})$	$A_c^\ell(t\bar{t}W)^{\text{PL}}_{\text{SM}} = -0.063\,^{+0.007}_{-0.004}\,(\text{scale}) \pm 0.004\,(\text{MC stat.})$

Conclusions

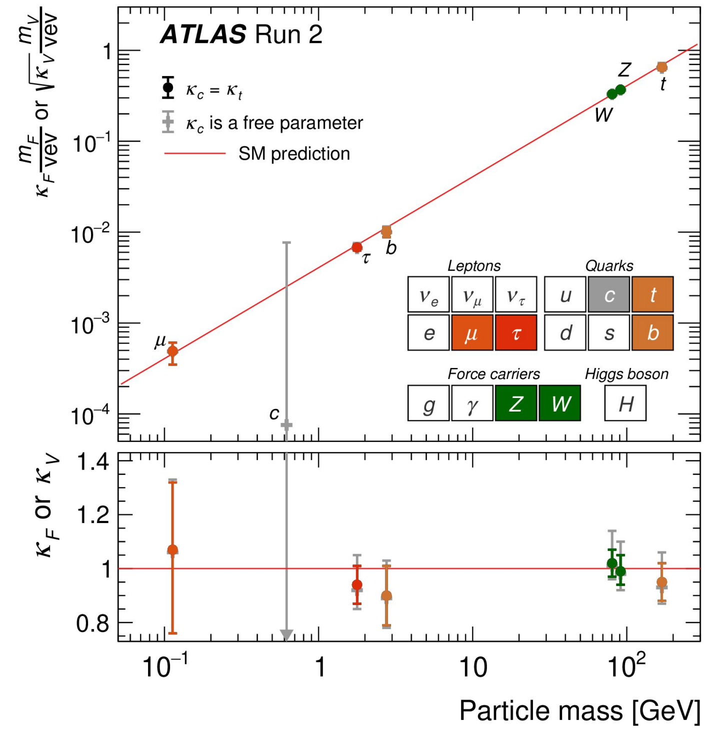
All analyses show an overall good agreement with the Standard Model predictions

- **"Precision era":** Moved from inclusive searches to differential x-section measurements

- Higgs coupling to top, bottom and charm **provides an important test for the SM.**

- The ATLAS analyses using full Run2 dataset all shows Higgs coupling to top, bottom and charm 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.

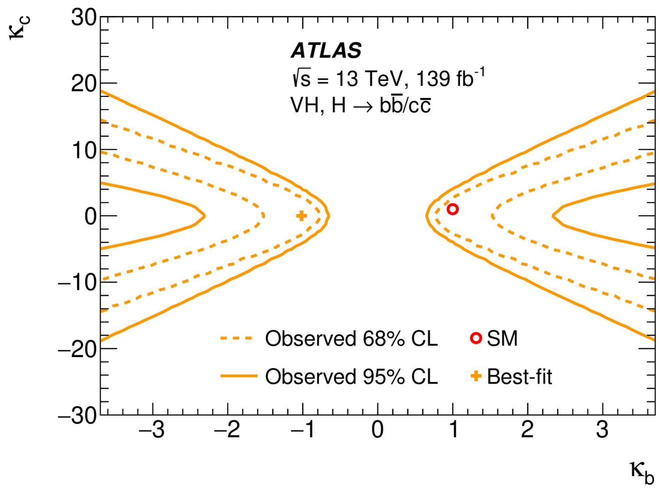


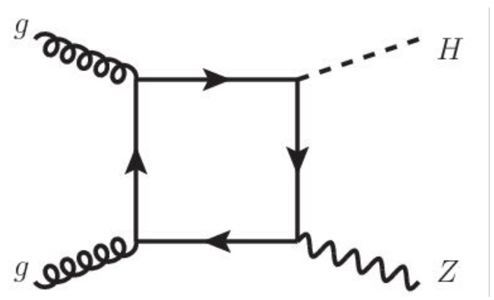
More data ⇒ more measurements, more differential, more complex interpretations

Back up

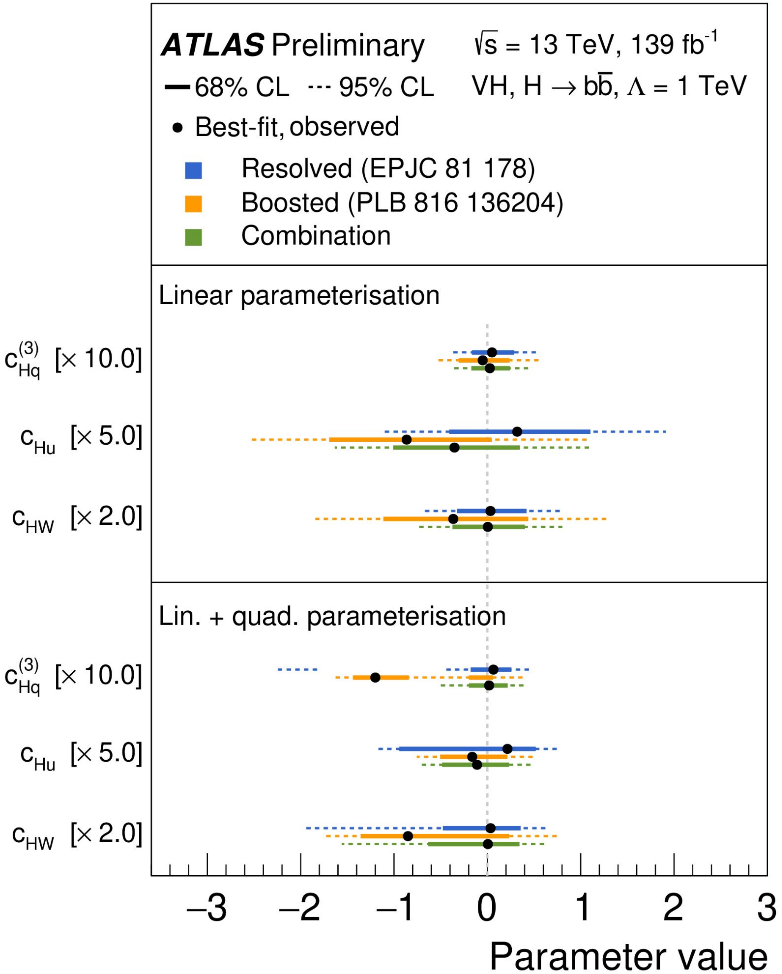
Negative κ_b value in VH(cc)

- Dependence on LH on sign comes from gg—>ZH

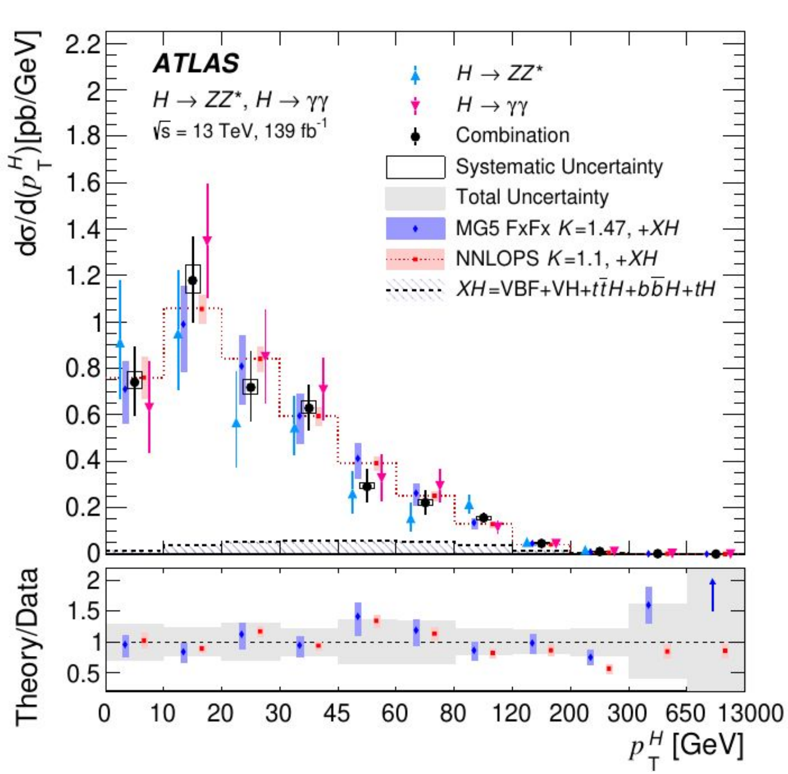




$\sigma(gg \to ZH)$	✓	$Z - t$	$\sim$	$2.27 \cdot \kappa_Z^2 + 0.37 \cdot \kappa_t^2 - 1.64 \cdot \kappa_Z \kappa_t$



ATLAS Preliminary
√s = 13 TeV, 139 fb^-1
68% CL --- 95% CL
VH, H → bb̄, Λ = 1 TeV
Best-fit, observed
Resolved (EPJC 81 178)
Boosted (PLB 816 136204)
Combination
Linear parameterisation
c(3)Hq [× 10.0]
cHu [× 5.0]
cHW [× 2.0]
Lin. + quad. parameterisation
c(3)Hq [× 10.0]
cHu [× 5.0]
cHW [× 2.0]
−3
−2
−1
0
1
2
3
Parameter value


ATLAS
H → ZZ*, H → γγ
√s = 13 TeV, 139 fb-1
H → ZZ*
H → γγ
Combination
Systematic Uncertainty
Total Uncertainty
MG5 FxFx K=1.47, +XH
NNLOPS K=1.1, +XH
XH=VBF+VH+tt̄H+bb̄H+tH
dσ/d(pTH)[pb/GeV]
Theory/Data
0 10 20 30 45 60 80 120 200 300 650 13000
pTH [GeV]