Higgs Boson Measurements in Couplings to Quarks and Leptons with the ATLAS Experiment

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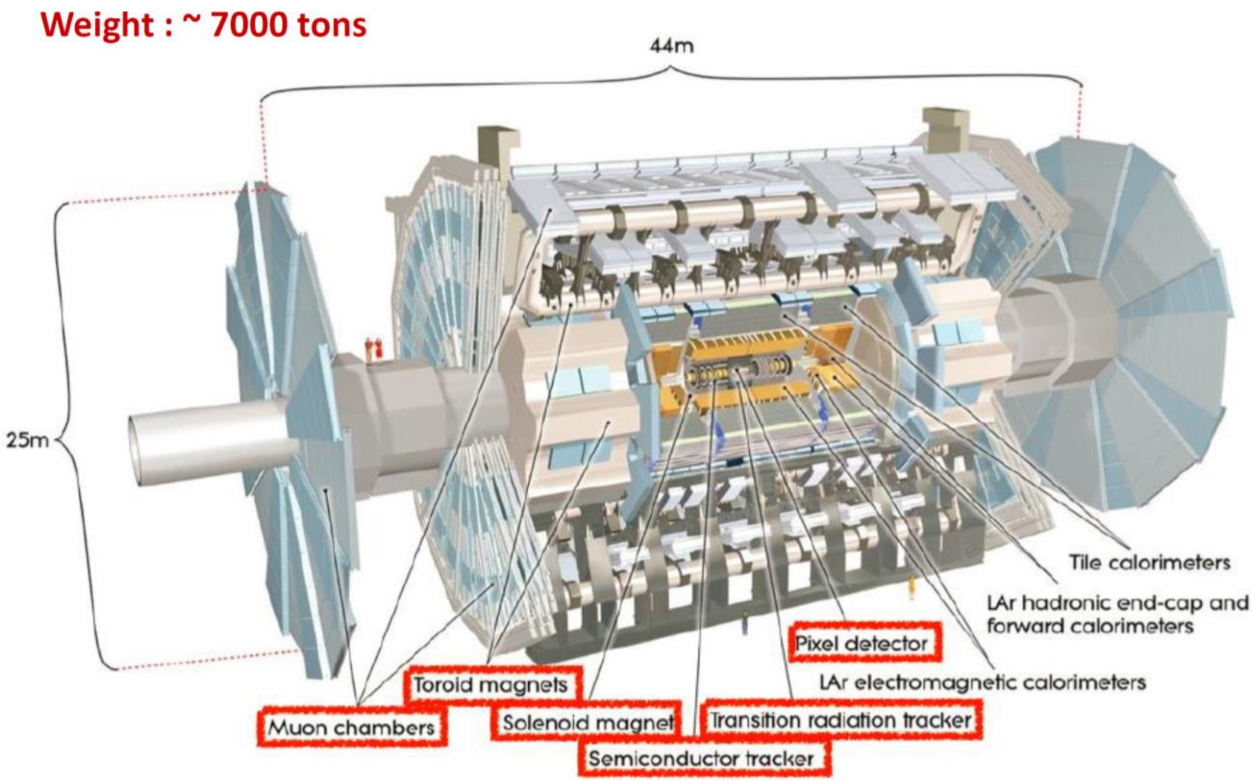
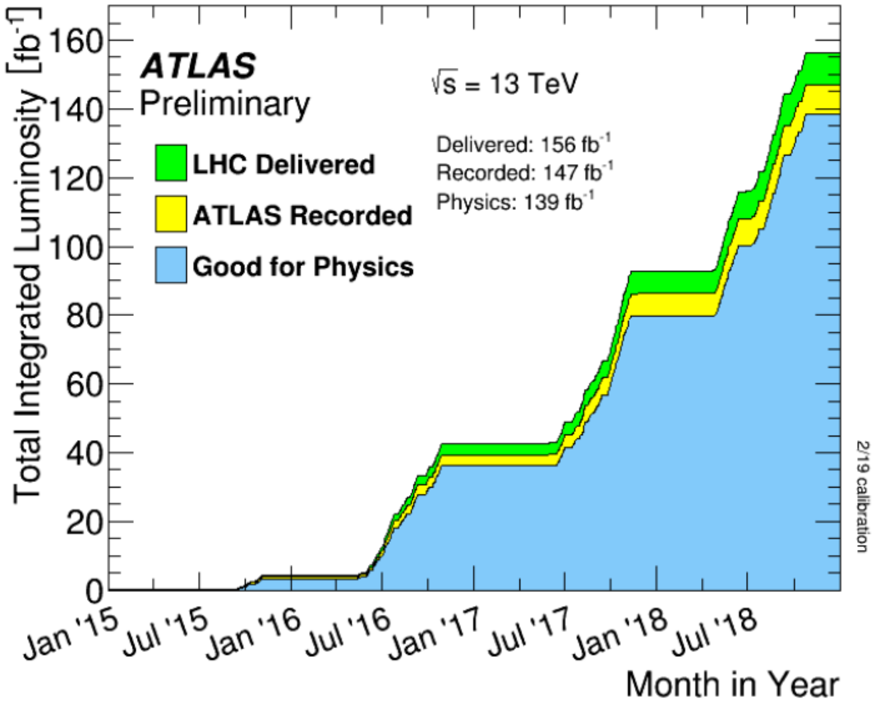
on behalf of the ATLAS Collaboration

ICNFP 2021, Greece

ATLAS Detector and Run-2 Data-taking





21.0×10^{33} cm^{-2} s^{-1}

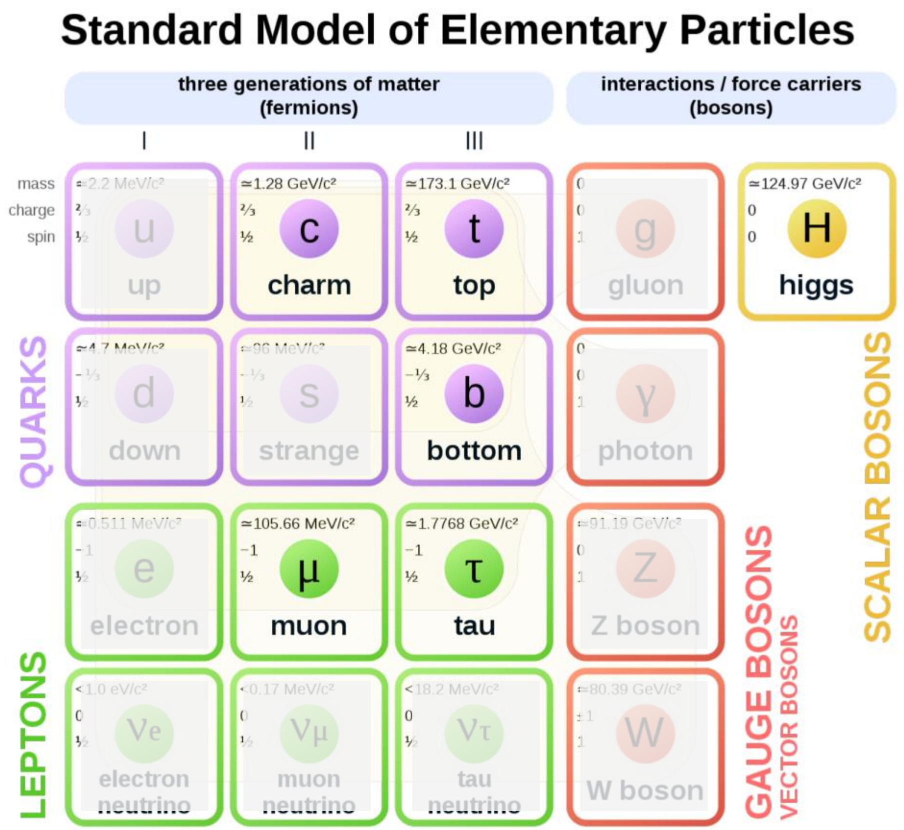
$139fb^{-1}$ usable for analyses

Introduction

- Higgs boson has a central role in SM
  - electroweak symmetry breaking
  - masses of the bosons and fermions

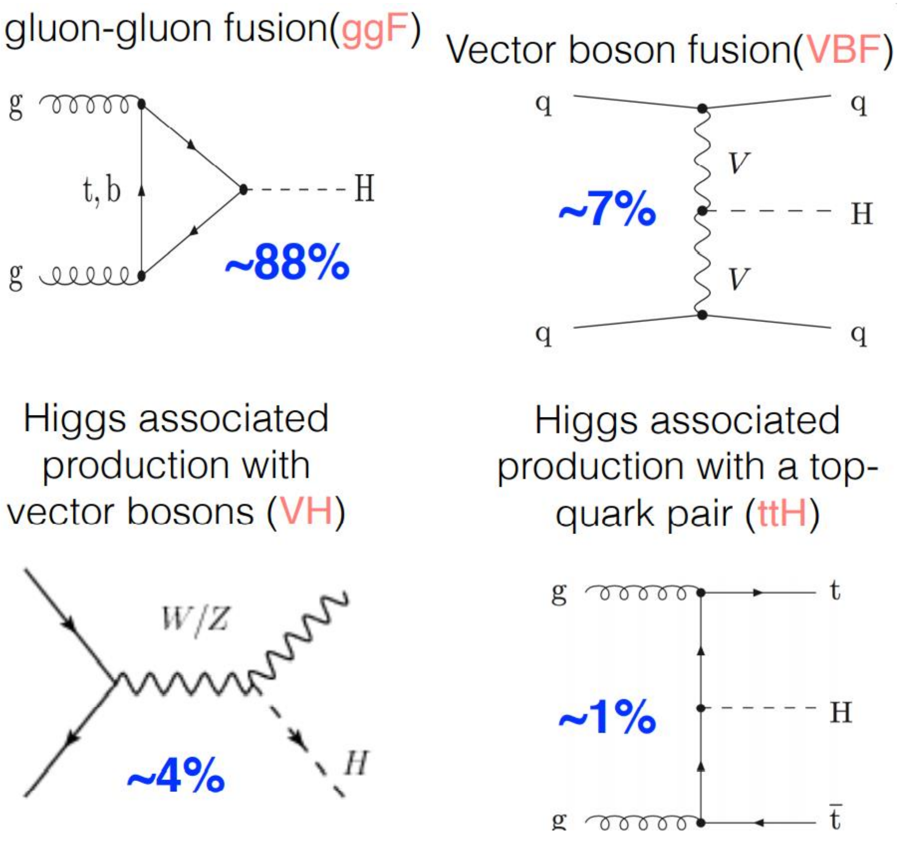
- ATLAS Run-2 Dataset allows us to probe even more subtle Higgs boson interactions
  - entering the "precision era” for couplings to 3rd gen fermions
  - hunting the first observation for 2nd gen fermions

- this talk covers Yukawa coupling to
  - quark: t, b, c
  - lepton: tau, muon

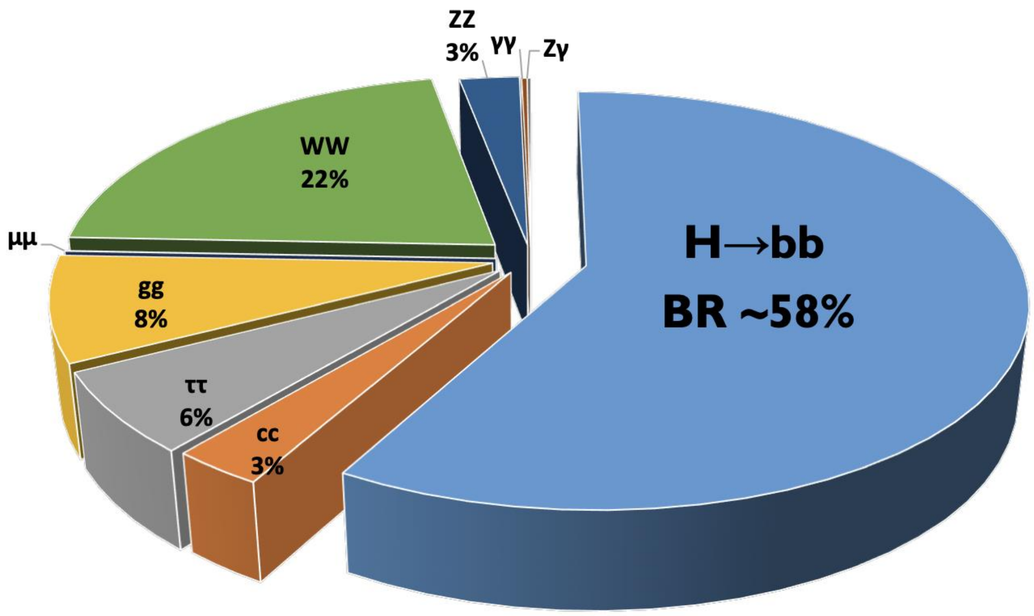


SM Higgs Boson Production and Decay

LHC, 13TeV centre-of-mass energy



SM Higgs Decay



m(Higgs) ~125 GeV from ATLAS and CMS

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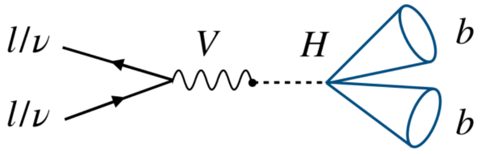
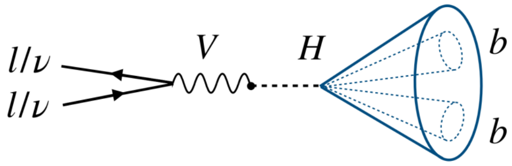
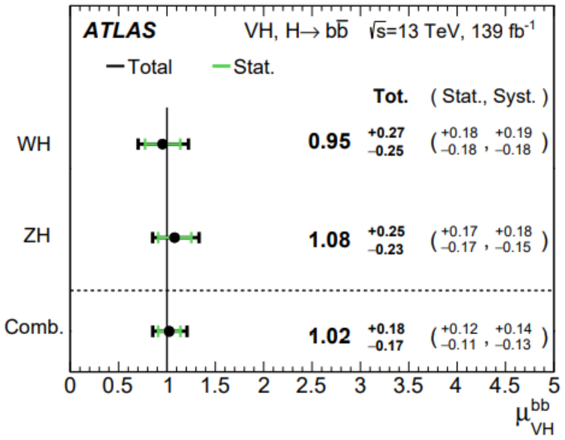
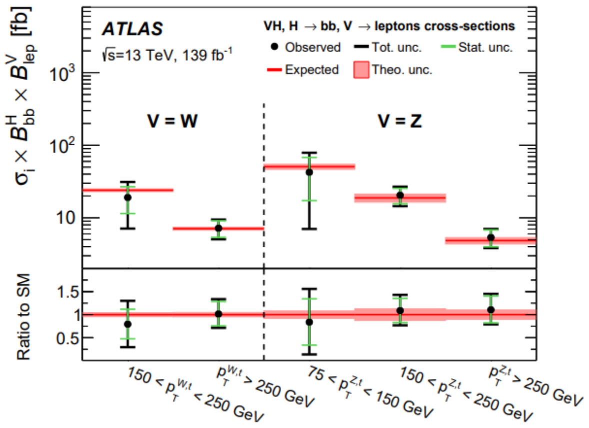
VH, Higgs→bb

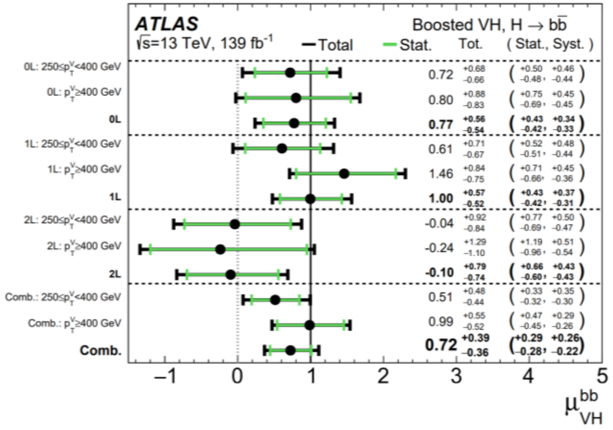


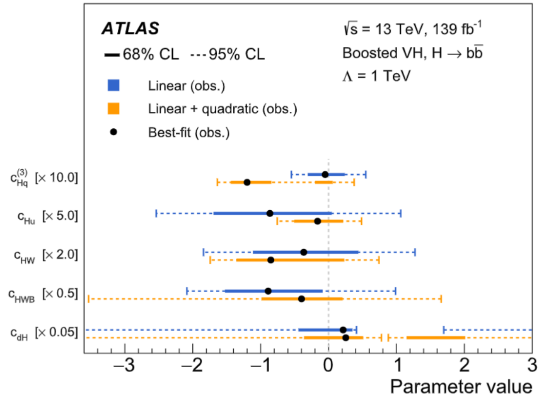


- leptonic decay of W/Z enables efficient triggering and a large reduction of QCD background
  - 0, 1, 2 lepton channels for Z→vv, W→lv, and Z→ll
  - main bkgs: ttbar, W+jets, Z+jets
  - 2 b-tagged jets for resolved H→bb topo
  - large-R jet to reconstruct high pT Higgs→bb (above 250 GeV), track-jet for b-tagging
- Signal strength, branching fraction in STXS scheme, and Wilson coefficient from measurements







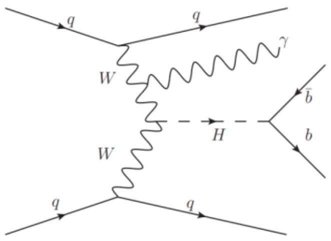


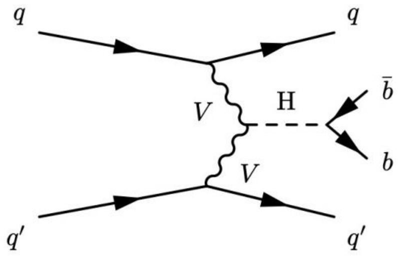
resolved
VH obs(exp) significance : **6.7(6.7) σ**
- WH: 4.0(4.1) σ
- ZH: 5.3(5.1) σ

boosted
significance obs(exp): **2.1(2.7) σ**

JHEP 03 (2021) 268
EPJC 81 (2021) 537

VBF, Higgs→bb

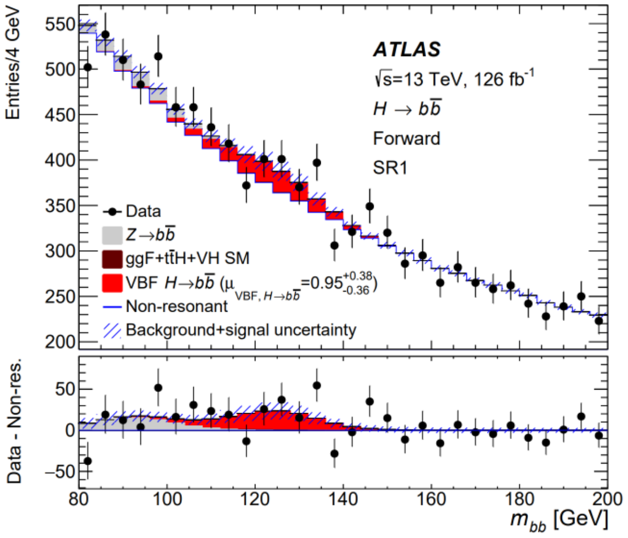


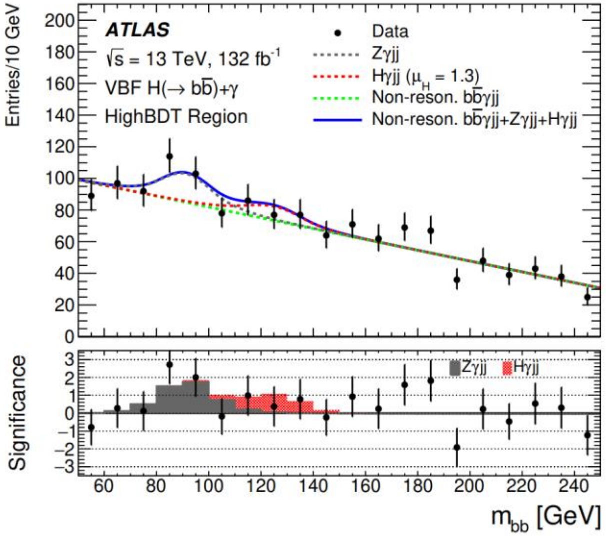


- VBF production used to reduce the backgrounds: 2 forward jets
- two orthogonal analyses feature different techniques to identify this signal
  1. inclusive VBF Hbb (high E photon is vetoed): two b-tagged jets and two jets from the VBF
  2. additional initial state radiation photon to provide a trigger and reduce the multi-jet background

inclusive

sig: **2.6(2.8) σ**





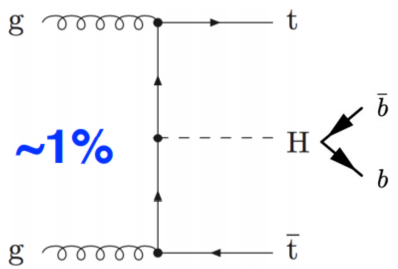
photon-tagged

μ=1.3+/- 1.0

The combined signal strength is $\mu_{VBF} = 0.99^{+0.30}_{-0.30}(Stat.)^{+0.18}_{-0.16}(Syst.)$

- Corresponds to an observed (expected) significance of $2.9(2.9)\sigma$

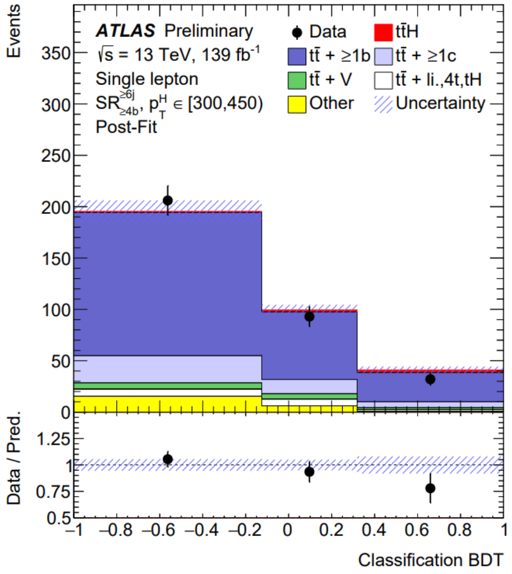
ttH, H→bb

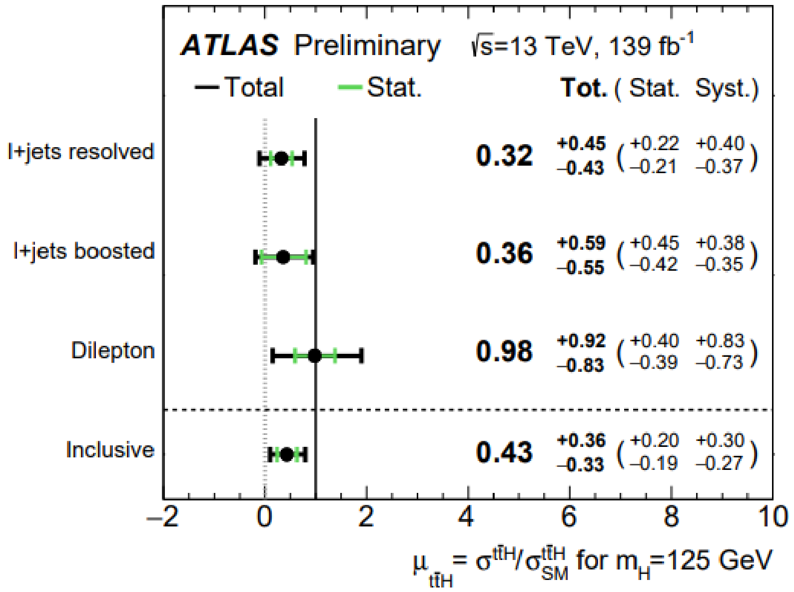


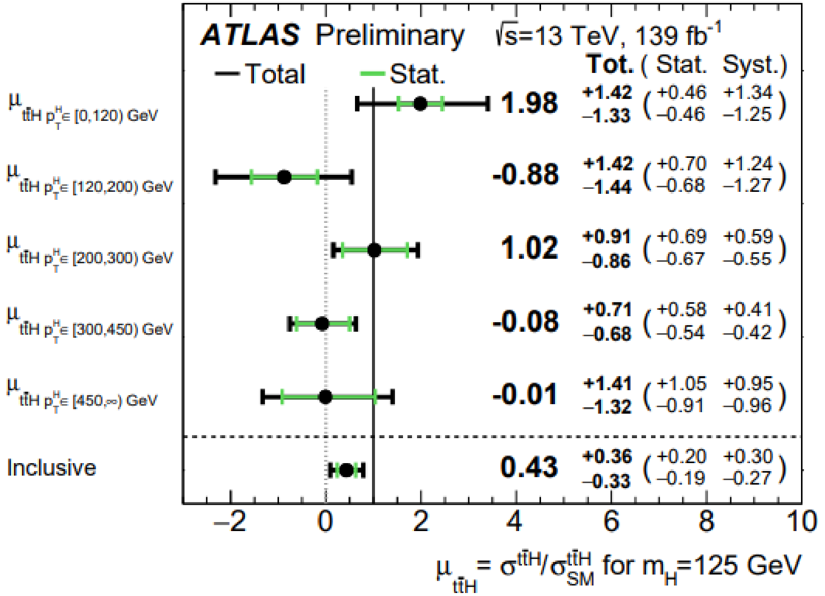
- Yukawa coupling to heaviest fermion
  - 6.3σ observation via ttH, H→γγ (PLB 784(2018) 173)
- Event selection and categories depends on
  - Single or Di-lepton; Number jets, and b-jets; pT(Higgs); BDT
- Systematical uncertainty dominant

Uncertainty source	$\Delta\mu$	
$t\bar{t} + \geq 1b$ modelling	+0.25	−0.24
$t\bar{t}H$ modelling	+0.14	−0.06
tW modelling	+0.08	−0.08

significance **1.3(3.0) σ**







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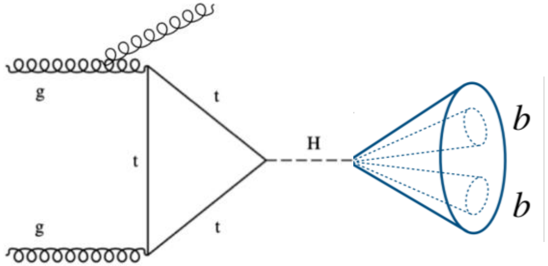
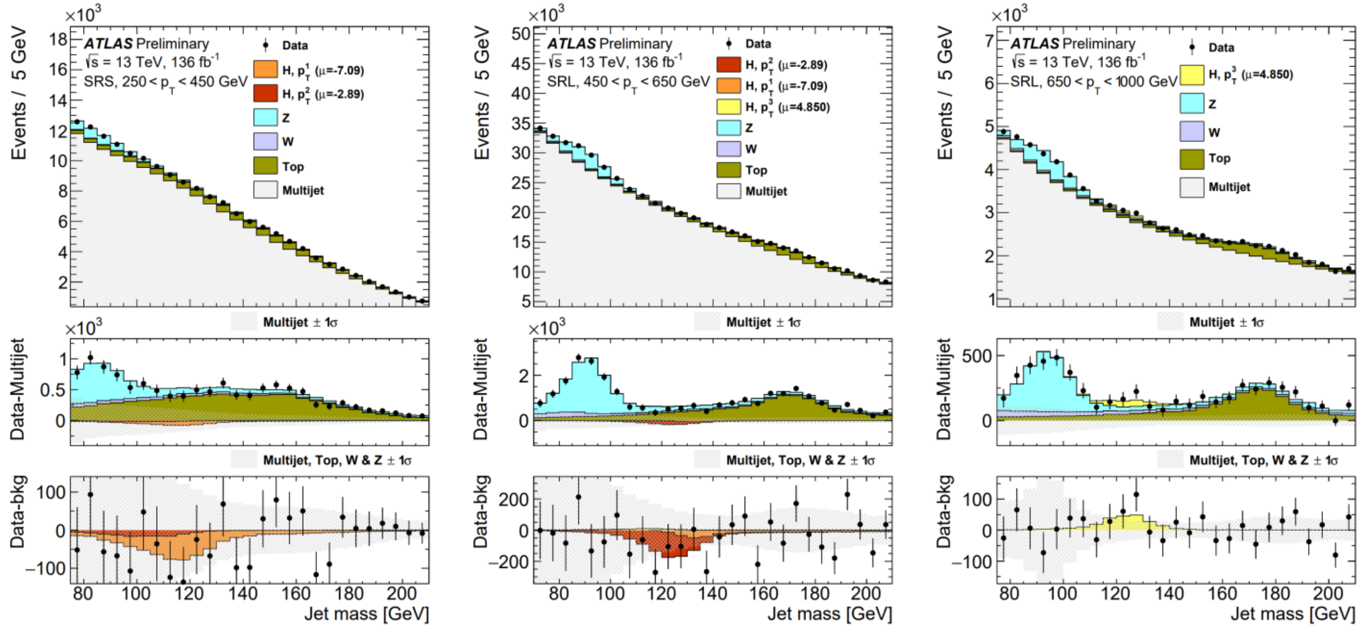
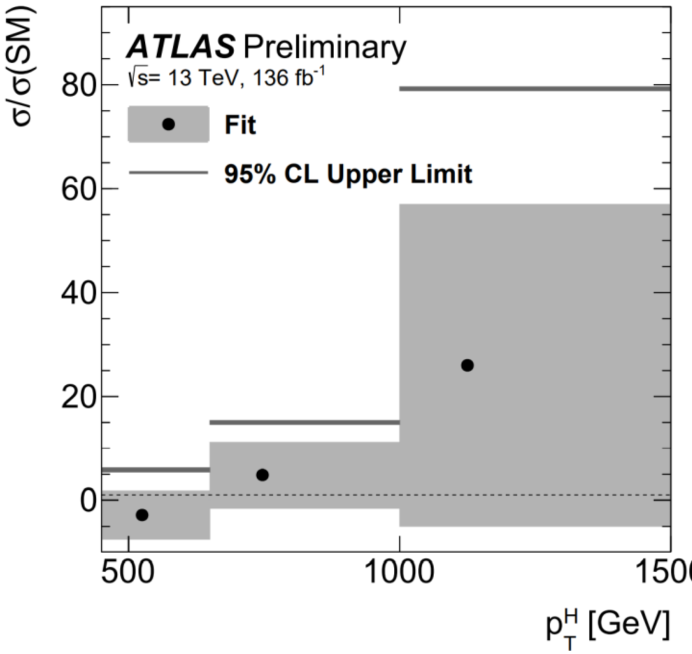
boosted Higgs→ bb



- Target very high-pT Higgs production, ~ 1TeV
    - Choose at least one large-R jet with two b-tagged subjets
- fully hadronic final states, using initial state radiation
    - Multijet bkg dominants
- Jet mass reconstruction is validated using W, Z and top resonances

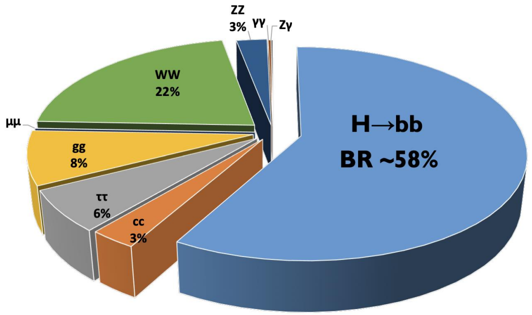
$$\sigma_H(p_T^H > 450\ \text{GeV}) = 13 \pm 57\ (\text{stat.}) \pm 22\ (\text{syst.}) \pm 3\ (\text{theory})\ \text{fb},$$
$$\sigma_H(p_T^H > 650\ \text{GeV}) = 13 \pm 16\ (\text{stat.}) \pm 7\ (\text{syst.}) \pm 3\ (\text{theory})\ \text{fb},$$
$$\sigma_H(p_T^H > 1\ \text{TeV}) = 3.4 \pm 3.9\ (\text{stat.}) \pm 1.0\ (\text{syst.}) \pm 0.8\ (\text{theory})\ \text{fb}.$$





[ATLAS-CONF-2021-044](#) **New**

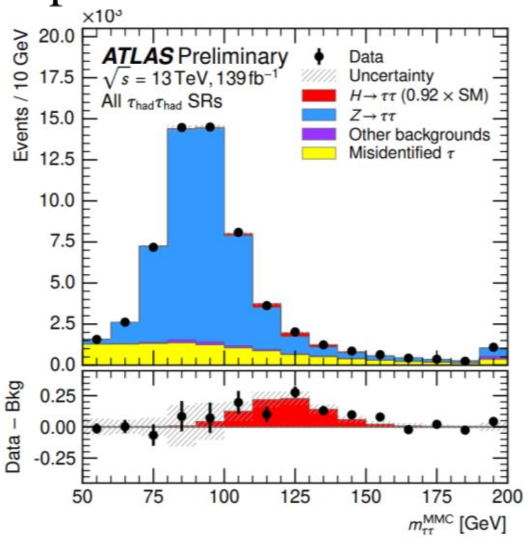
Higgs→tau tau

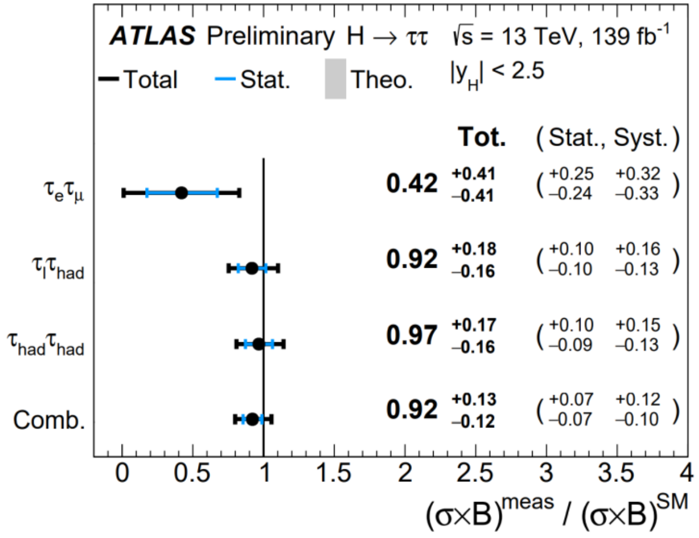


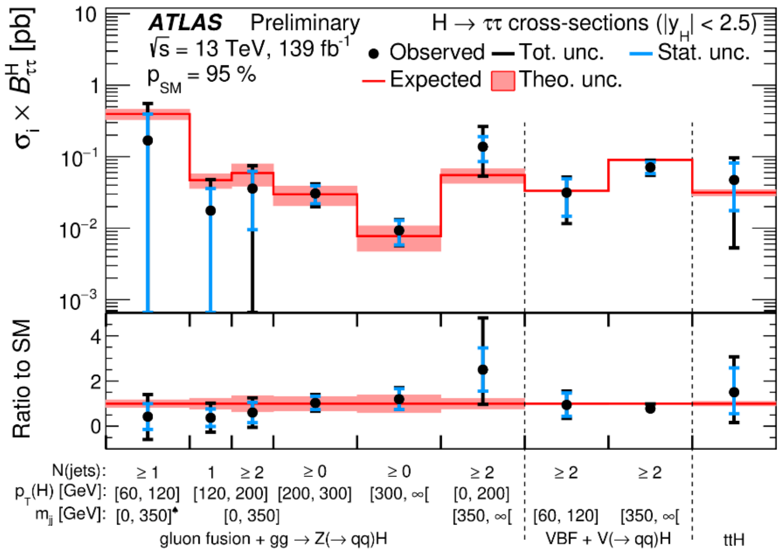
- Yukawa coupling to heaviest lepton
- 3 di-tau decay combinations (lep-had, had-had, eμ) are included
  - same flavour lep-lep are not included because of bkg from leptonic Z decay
- VBF, boosted, V(had)H, tt(0lep)H Higgs boson production modes
- Simplified embedding technique to model the dominant bkg Z→tautau with Z→leplep data

Run2 36fb^{-1}
$3.77\ ^{+1.06}_{-0.95}\ \left(^{+0.60}_{-0.59},\ ^{+0.87}_{-0.74}\right)$

production cross-section of the $pp \to H \to \tau\tau$ process is measured to be $2.90 \pm 0.21\,(\text{stat})\ ^{+0.37}_{-0.32}(\text{syst})$ pb

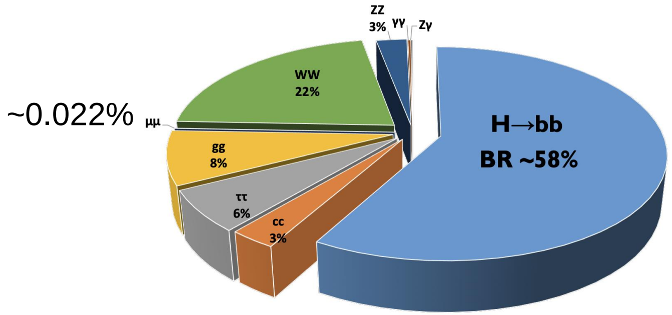






*MMC: missing mass calculator
arXiv 1012.4686

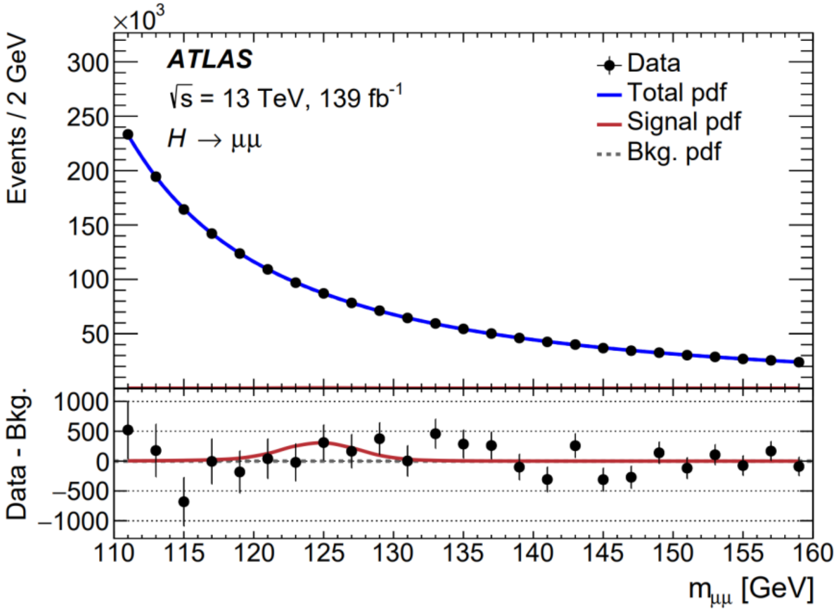
PLB 812 (2021) 135980

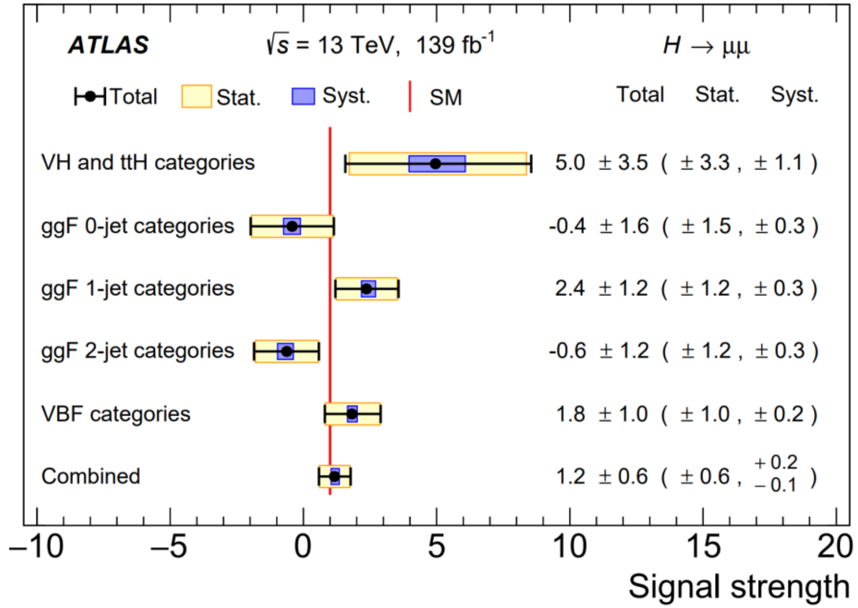


Higgs→ mu mu

- direct probe Yukawa coupling to the **2nd gen Lepton**
- Clean final state, but need to handle overwhelming background from Z/γ∗→ μμ
  - signal production mode includes ggF, VBF, VH, and ttH
  - Improve m(μμ) with recovering an FSR γ from μ
  - *stat uncertainty dominant

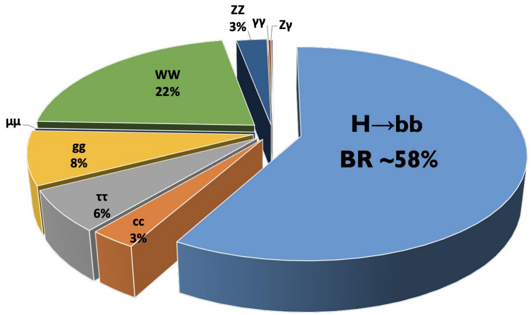
obs(exp) significance **2.0(1.7)σ**



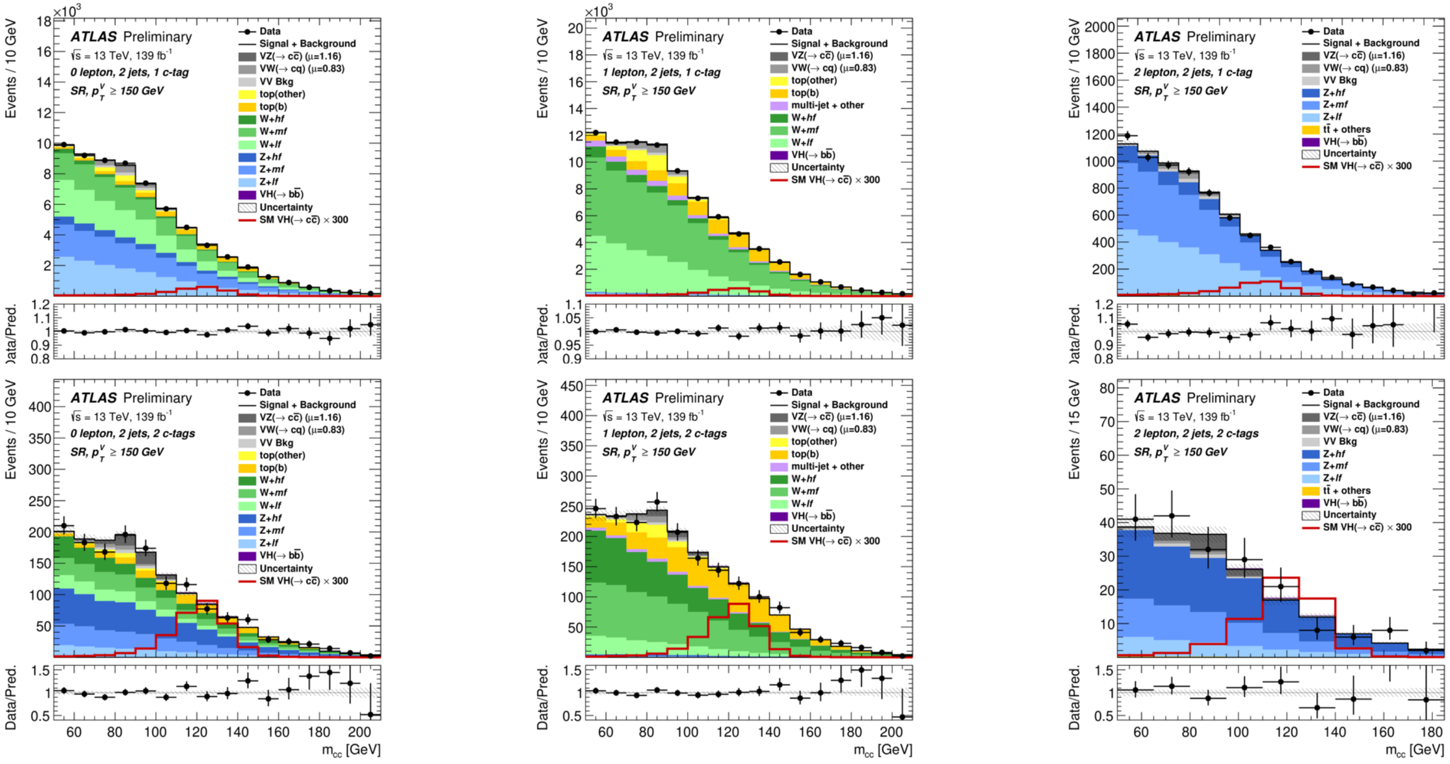


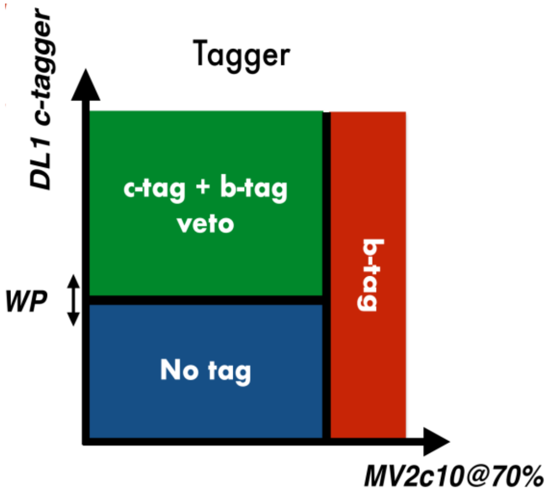
ATLAS-CONF-2021-021 **New**

VH, H→cc



- probing the Higgs mechanism for the **2nd gen quark**
- analysis strategy is like VHbb search. Most differences:
  - B-tag veto to remove potential VHbb events
  - signal: 1c-tag & 2c-tag
  - discriminant: m(cc)



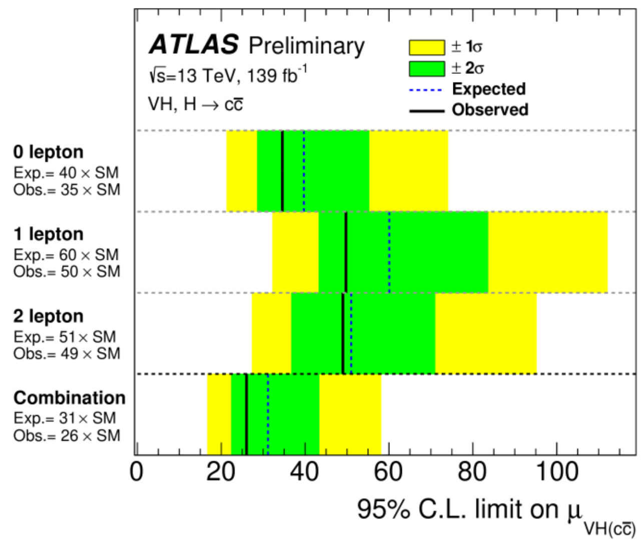


Performance

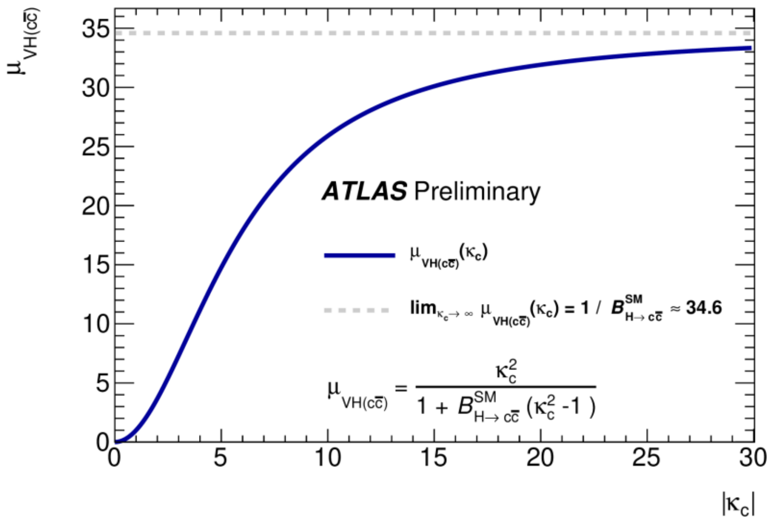
	c-tagging efficiency
c-jets	27%
b-jets	8%
light-jets	1.6%

VH, H→cc

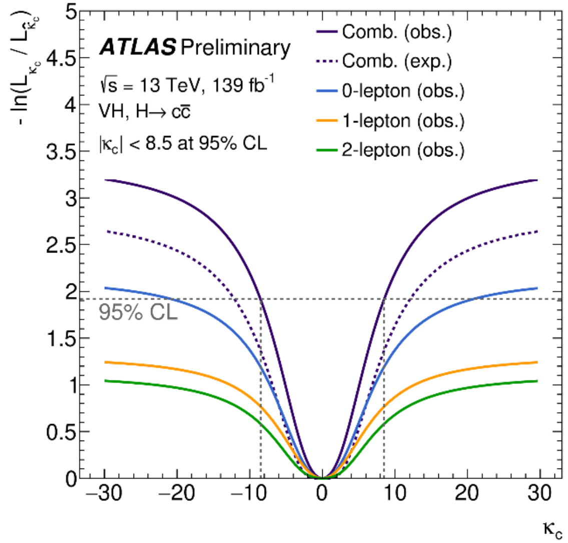
- **world's tightest direct constraint on H→cc**
  - VH(cc) obs(exp) < **26** **(31)** xSM



- κc: quantify possible deviations from the SM
  - signal strength as a function of coupling enhancement Kc
  - Assuming κ=1 for other fermions and bosons and no BSM contributions to Higgs width



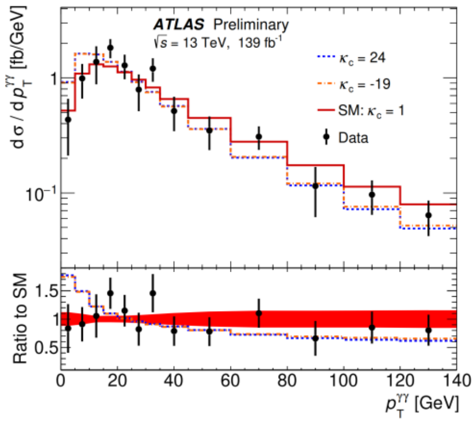
➔ $|K_C| < 8.5$ @ 95% CL



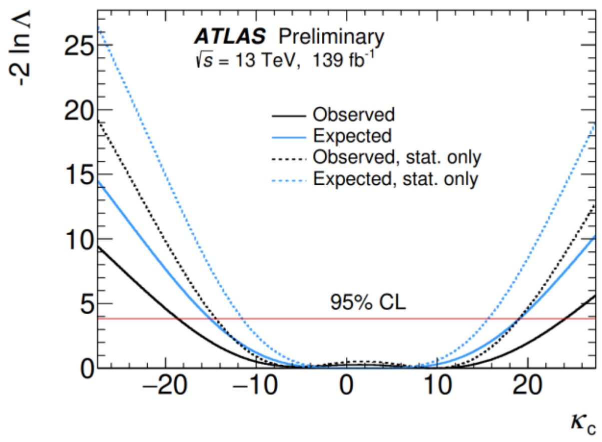
κ_c Indirect constraint from H→γγ and ZZ*

- modification the coupling strength would impact the Higgs production and affect both the normalization and shapes of the Higgs pT spectrum

H→γγ

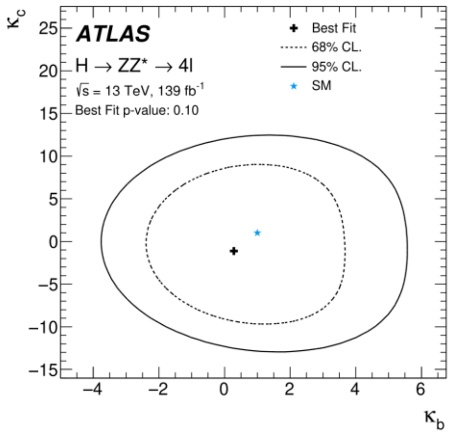


*pT shape only

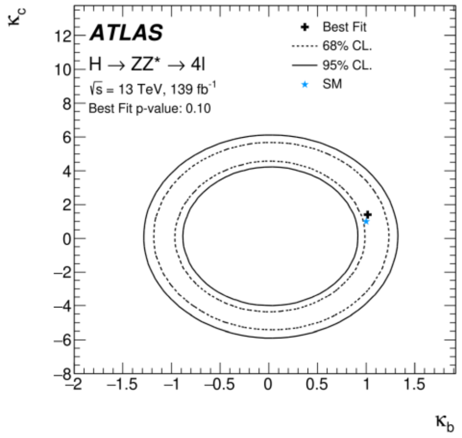


Coefficient	Observed 95% CL limit	Expected 95% CL limit
κ_c	$[-19, 24]$	$[-15, 19]$

H→ZZ*→4l



*pT shape only



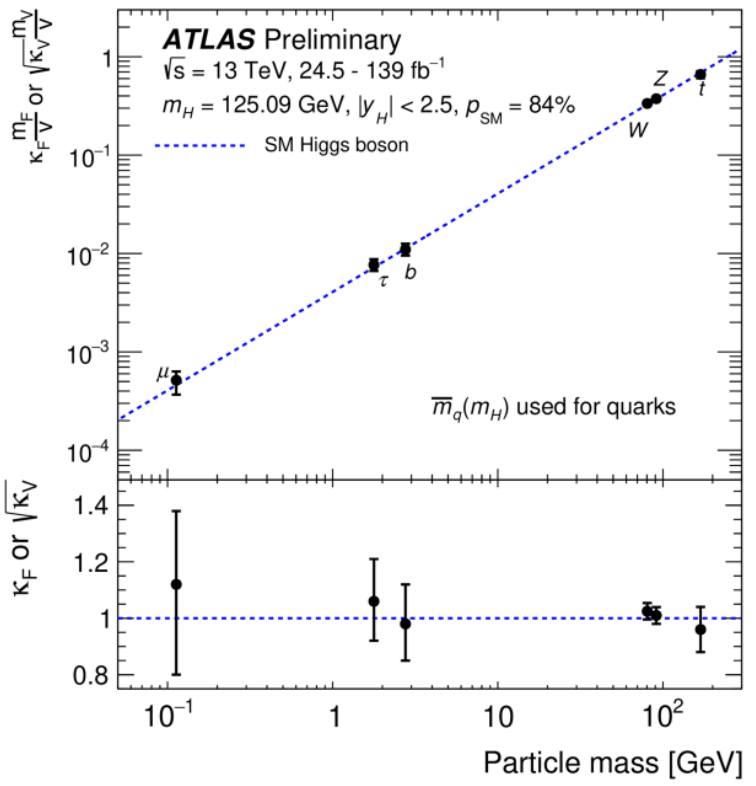
*both the prediction of the pT(4l) diff. x-sec and the modification to the branching ratio due to the κc and κb

Parameter best-fit value	95% confidence interval
$\kappa_c = -1.1$	$[-11.7,\ 10.5]$
$\kappa_b = 0.28$	$[-3.21,\ 4.50]$

Conclusion

- Standard Model Higgs boson discovered in 2012!
- measurements at LHC have established Higgs Yukawa couplings to Fermions are close to the Standard Model(SM) expectation
  - H→bb, H→ττ, ttH
  - Improved combinations using the latest sets of results shown in this talk are currently in progress
- search of H→μμ and H→cc decay is crucial for probing the Higgs mechanism for the 2nd gen of fermions
- LHC Run-3 operation will start in 2022
  - The data size will be **Twice** as large as what we have now
  - Good opportunity to more precisely understand Higgs properties

https://atlas.cern/updates/briefing/higgs-boson-finds-strength-unity



* recent H→tautau H→cc are not updated/included

Backup

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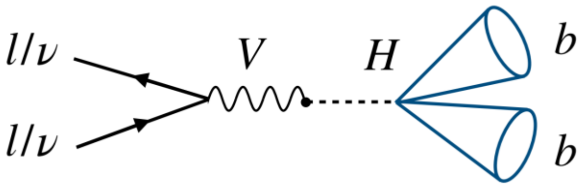
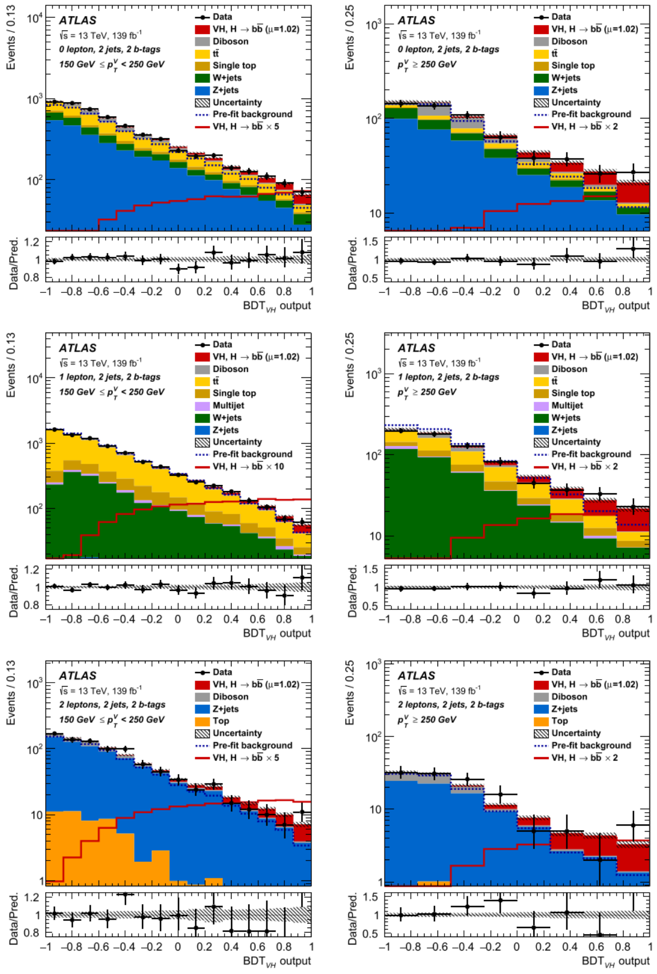
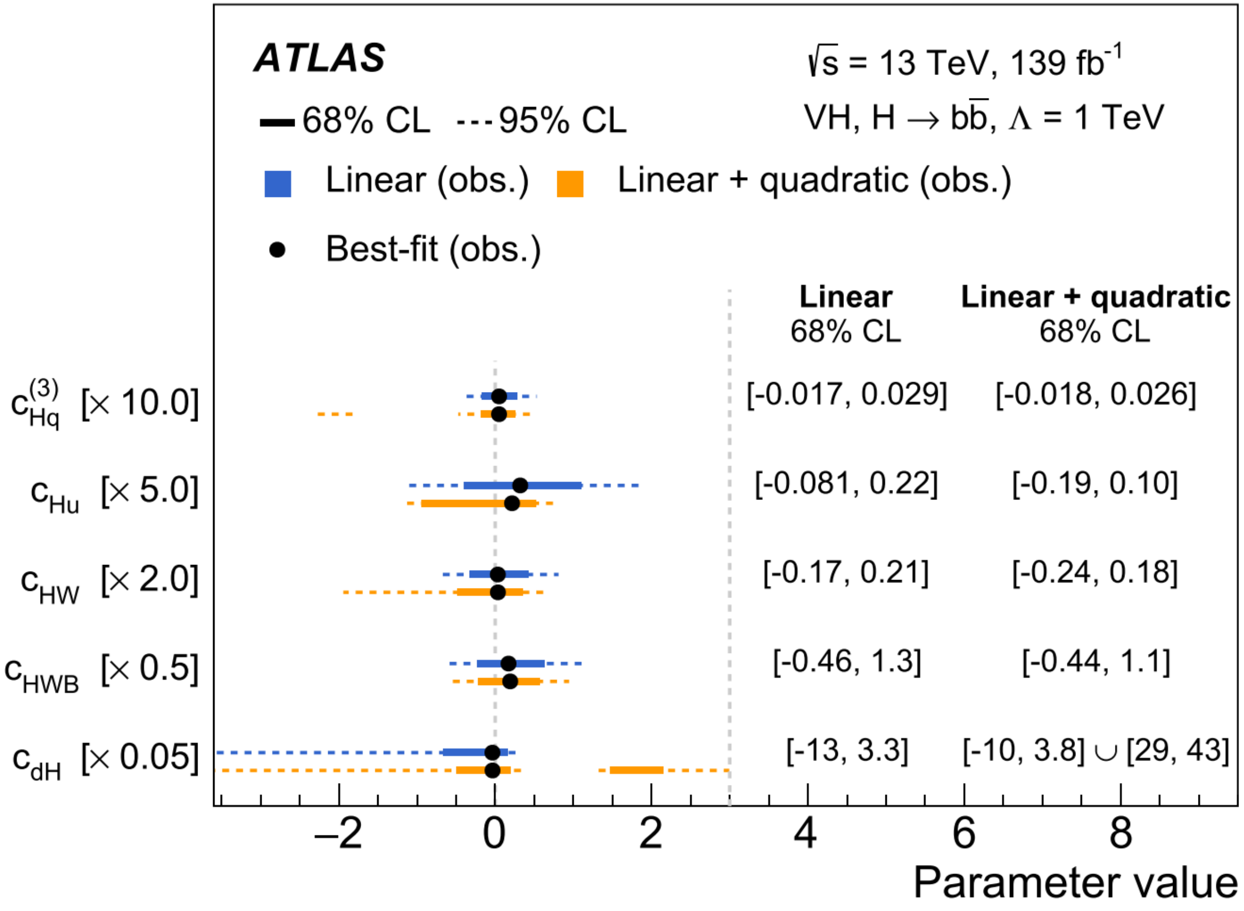
VH, Higgs→bb, resolved







VH, Higgs→bb, resolved

Table 4 The simplified template cross-section regions used for measurements and the corresponding reconstructed analysis regions that are most sensitive. The current analysis is not sensitive to the regions WH, $p_T^{W,t} < 150$ GeV and ZH, $p_T^{Z,t} < 75$ GeV, and their cross-sections are fixed to the SM prediction within their theoretical uncertainties. All leptonic decays of the weak gauge bosons (including $Z \to \tau\tau$ and $W \to \tau\nu$, which are extrapolated from the electron and muon channel measurements) are considered for the STXS definition

STXS region		Corresponding reconstructed analysis regions		
Process	$p_T^{V,t}$ interval (GeV)	Number of leptons	p_T^V interval (GeV)	Number of jets
WH	150–250	1	150–250	2, 3
WH	> 250	1	> 250	2, 3
ZH	75–150	2	75–150	2, ≥ 3
ZH	150–250	0	150–250	2, 3
		2	150–250	2, ≥3
ZH	> 250	0	> 250	2, 3
		2	> 250	2, ≥3

Table 14 Wilson coefficients c_i and corresponding dimension-6 SMEFT operators $\mathcal{Q}_i$, to which this analysis is sensitive, in the Warsaw formulation [126]

Wilson coefficient	Operator	Impacted vertex	
		Production	Decay
c_{HWB}	$\mathcal{Q}_{HWB} = H^\dagger \tau^I H W^I_{\mu\nu} B^{\mu\nu}$	HZZ	
c_{HW}	$\mathcal{Q}_{HW} = H^\dagger H W^I_{\mu\nu} W^{\mu\nu}_I$	HZZ, HWW	
$c^{(3)}_{Hq}$	$\mathcal{Q}^{(3)}_{Hq} = (H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{q}_p \tau^I \gamma^\mu q_r)$	$qqZH, qq'WH$	
$c^{(1)}_{Hq}$	$\mathcal{Q}^{(1)}_{Hq} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$	$qqZH$	
c_{Hu}	$\mathcal{Q}_{Hu} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$	$qqZH$	
c_{Hd}	$\mathcal{Q}_{Hd} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$	$qqZH$	
c_{dH}	$\mathcal{Q}_{dH} = (H^\dagger H)(\bar{q} d H)$		Hbb

Table 15 The composition and eigenvalues of the eigenvectors, which are composed of a linear combination of the Wilson coefficients of the Warsaw-basis operators [126]. All modifications that alter the branching ratio are absorbed into an additional independent term ($\Delta\mathrm{BR}/\mathrm{BR}_{\mathrm{SM}}$), which linearly alters the branching ratio and all contributions with a coefficient below 0.2 are omitted. The full composition of the eigenvectors is available in the HEPData repository [123]

Wilson coefficient	Eigenvalue	Eigenvector
c_{E0}	2000	$0.98 \cdot c^{(3)}_{Hq}$
c_{E1}	38	$0.85 \cdot c_{Hu} - 0.39 \cdot c^{(1)}_{Hq} - 0.27 \cdot c_{Hd}$
c_{E2}	8.3	$0.70 \cdot \Delta\mathrm{BR}/\mathrm{BR}_{\mathrm{SM}} + 0.62 \cdot c_{HW}$
c_{E3}	0.2	$0.74 \cdot c_{HWB} + 0.53 \cdot c^{(1)}_{Hq} - 0.32 \cdot c_{HW}$
c_{E4}	6.4×10^{-3}	$0.65 \cdot c_{HW} - 0.60 \cdot \Delta\mathrm{BR}/\mathrm{BR}_{\mathrm{SM}} + 0.35 \cdot c^{(1)}_{Hq}$

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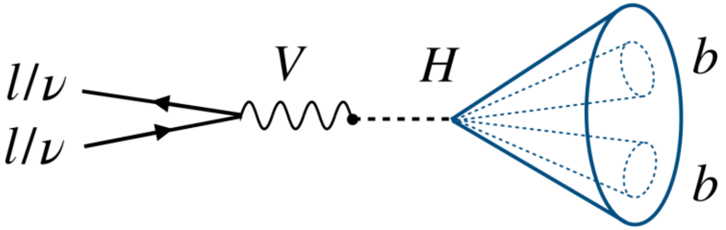
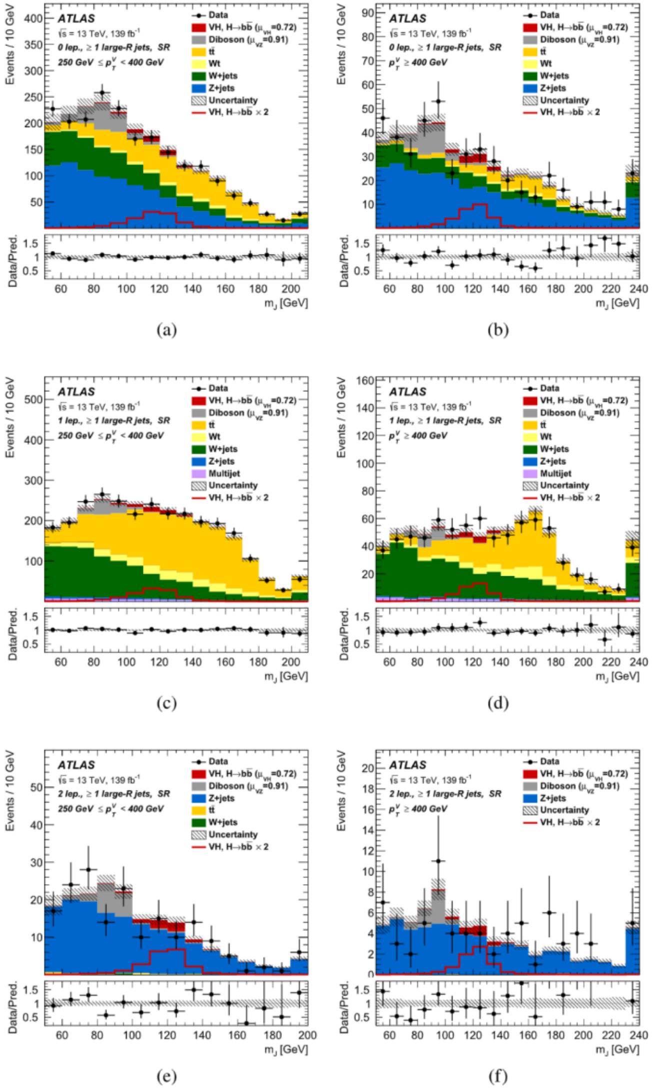
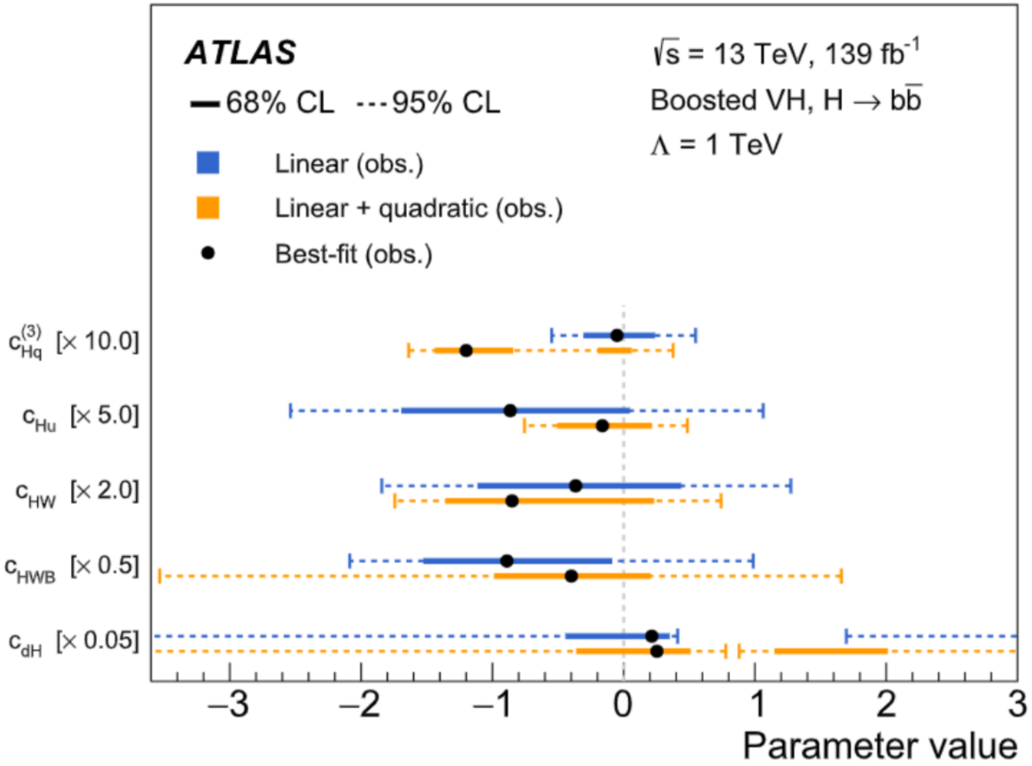
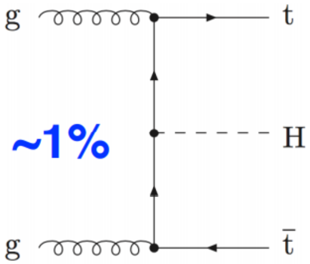
VH, Higgs→ bb, boosted







ttH, H→bb



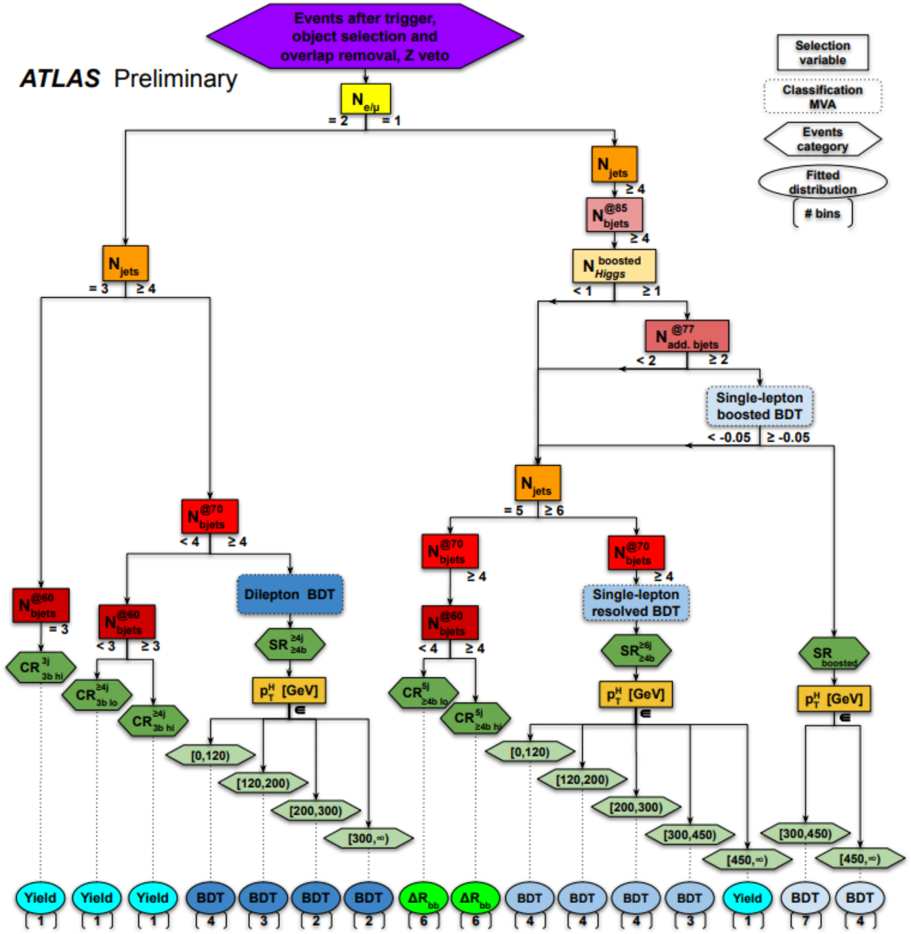
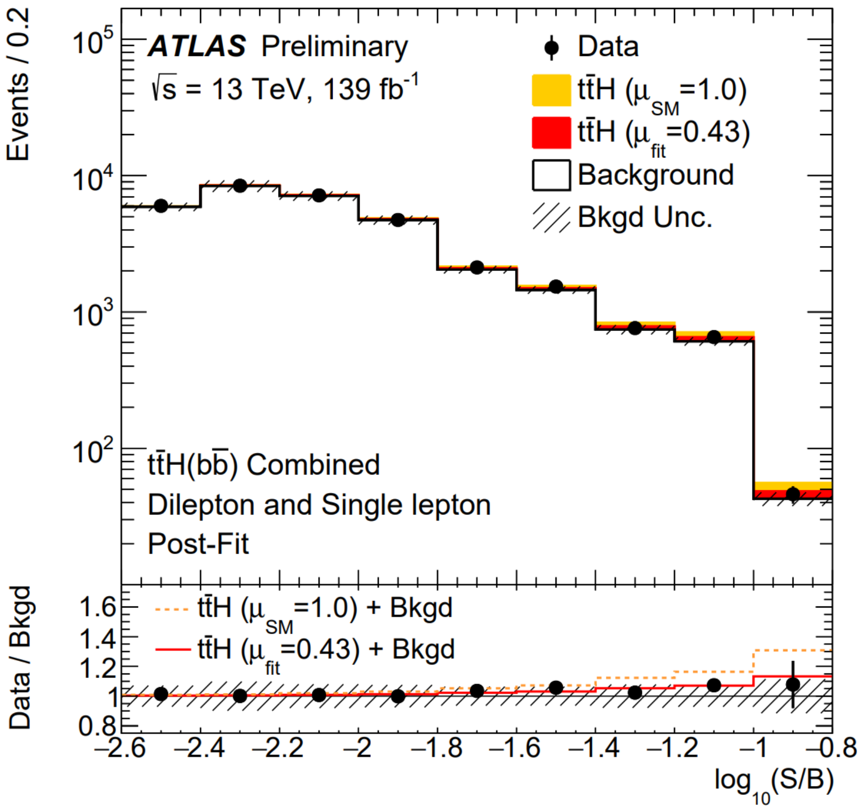


Figure 8: Flow chart summarising the analysis region selections.



Higgs→tau tau

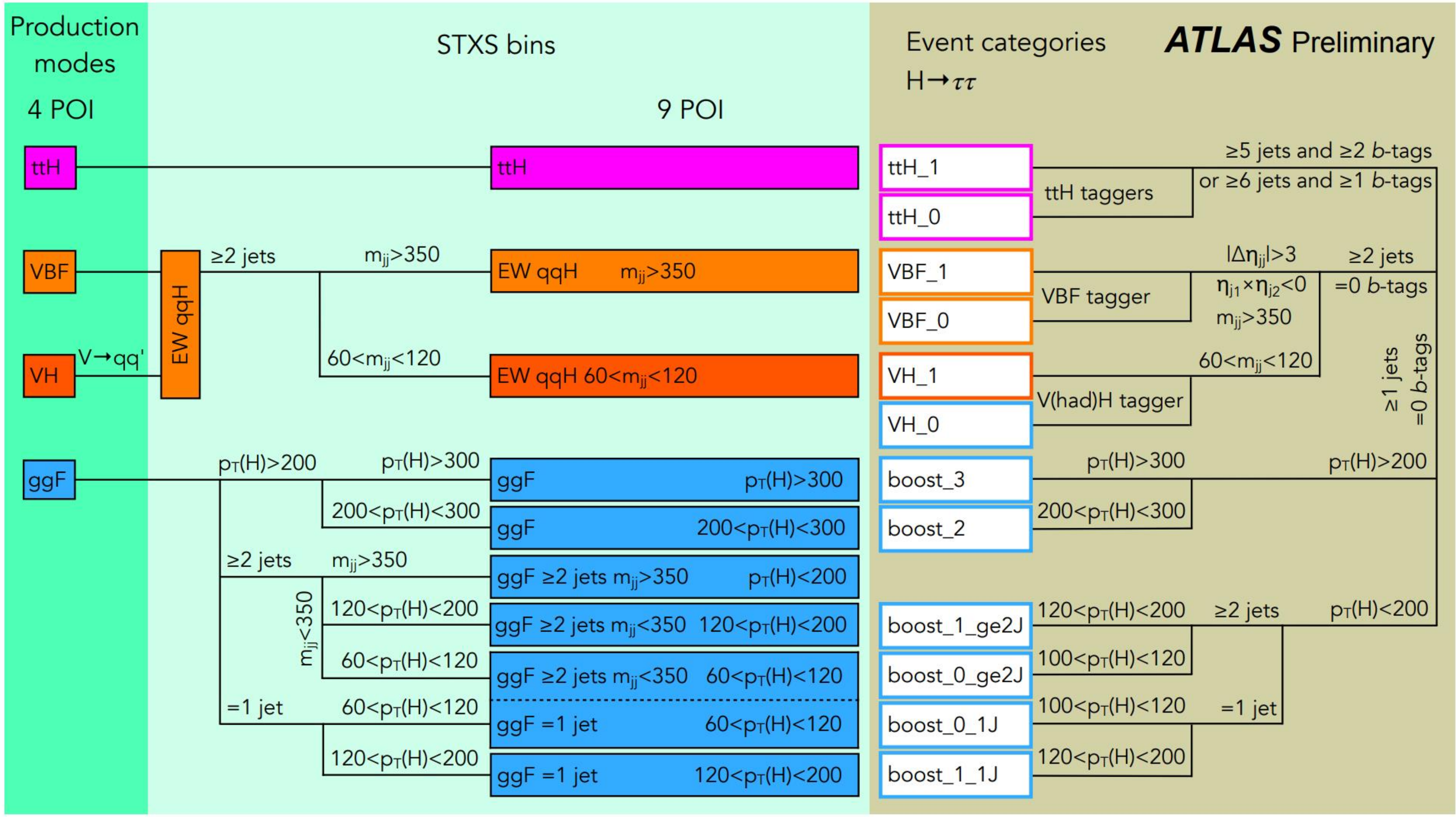


Figure 1: Sketch of the event categorisation and the STXS bins targeted. The dominant STXS bin contributing to each event category is indicated by the colour of the category box or the STXS bin adjacent to it. The background colours on the left side indicate which parameters of interest (POI) are estimated in the fit. The requirements on $p_T(H)$ and m_{jj} are given in units of GeV.