

Measurements of the Higgs boson couplings and their interpretations at the ATLAS experiment

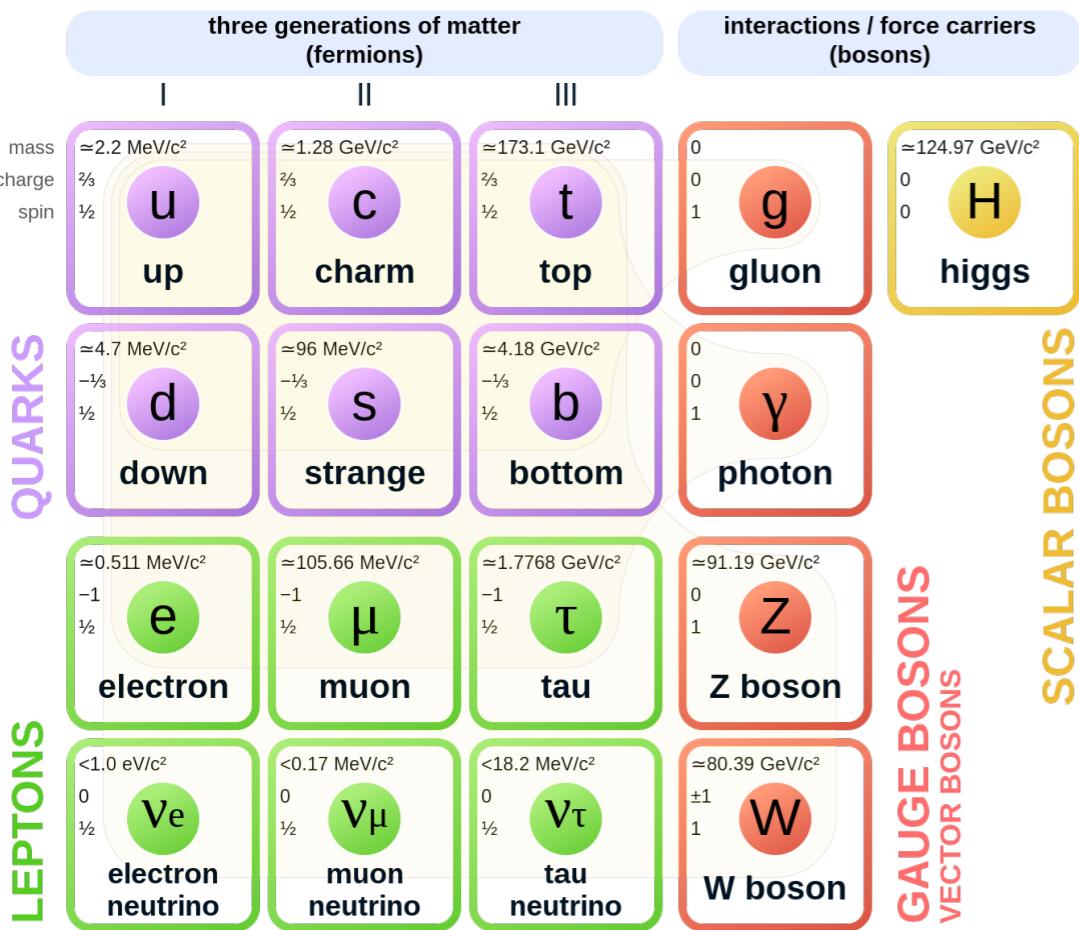
F. A. Di Bello for the ATLAS collaboration

Ioannina, SUSY2022



SM Higgs couplings

- Very rich physics content associated with Higgs couplings



Yukawa interactions

Third and second generation fermions

Higgs-boson
Higgs discovery
BHE EW symmetry breaking

Additional interactions?
Higgs to invisible

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

$$+ i \bar{\psi} \not{D} \psi + h.c.$$

$$+ \bar{\psi}_i \gamma_j \psi_i \phi + h.c.$$

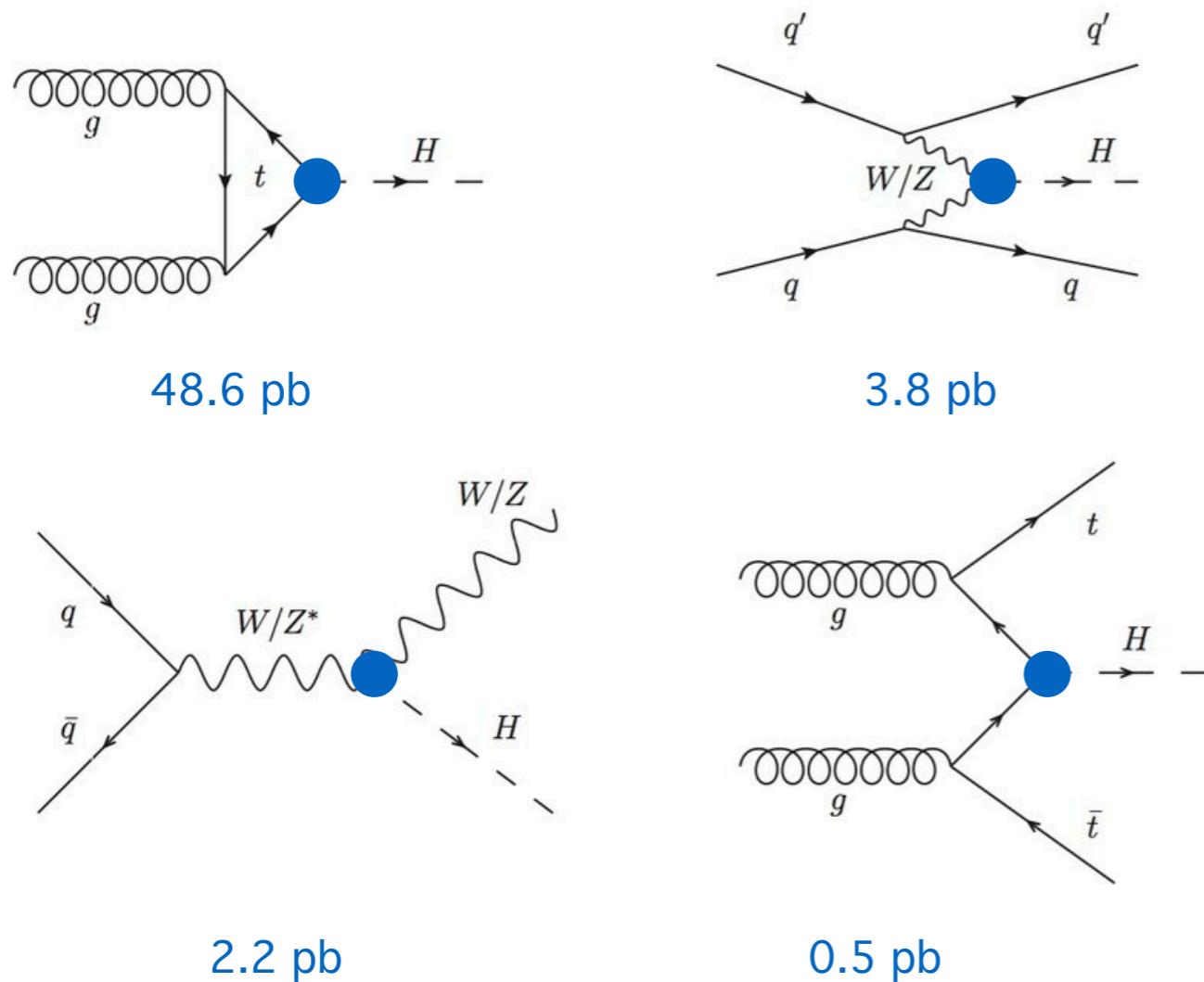
$$+ |\partial_\mu \phi|^2 - V(\phi)$$

Self-coupling
Not covered in this talk

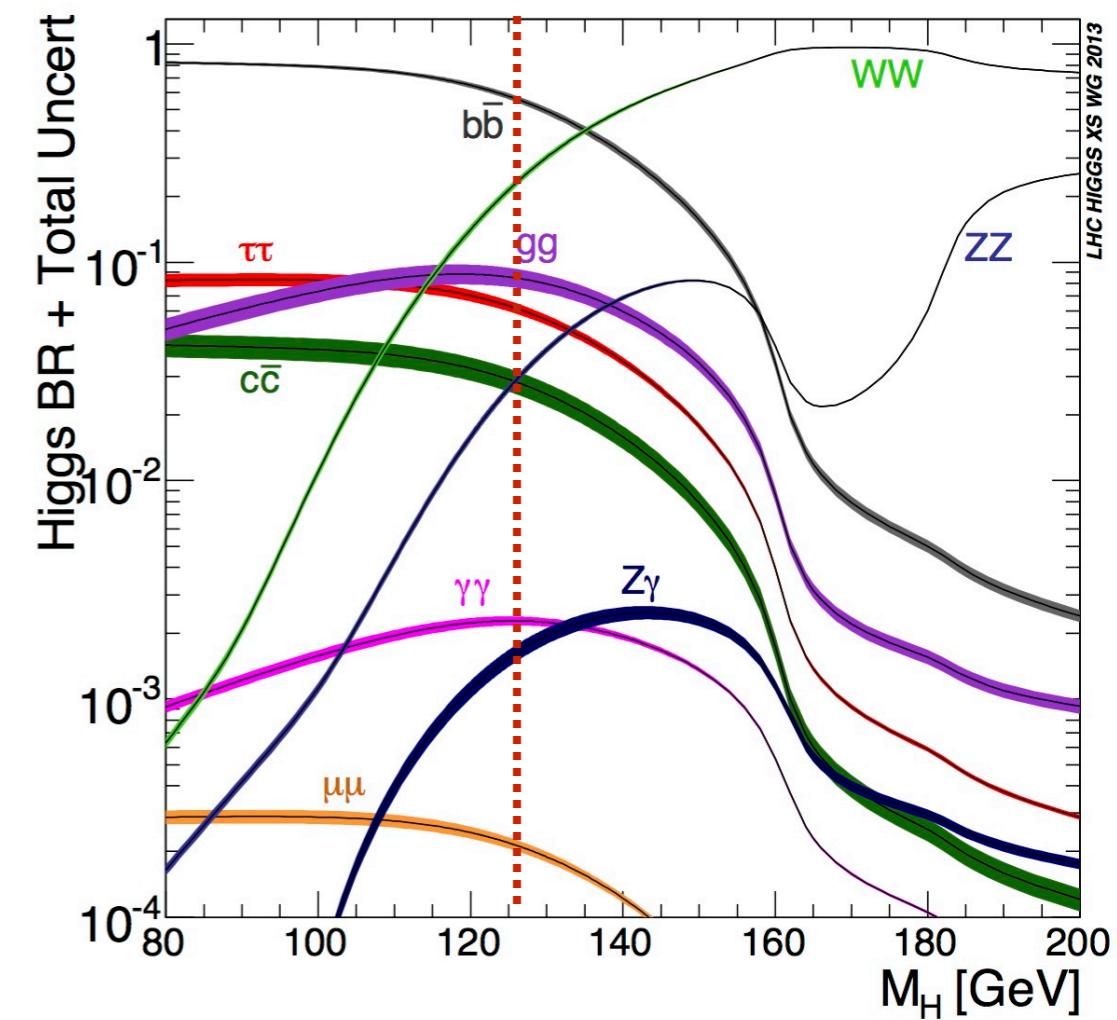
SM Higgs couplings 2

- Large experimental effort. Summary of ATLAS analysis available at: [ATLAS Higgs public results](#)
- Couplings exploits a large variety of decays and production modes

Main production modes



Decays



Measurements overview

- 140 ifb collected at the LHC. This opens up several analysis strategies: precision, rare decays, differential measurements

Brief summary of analyses

Interpretability

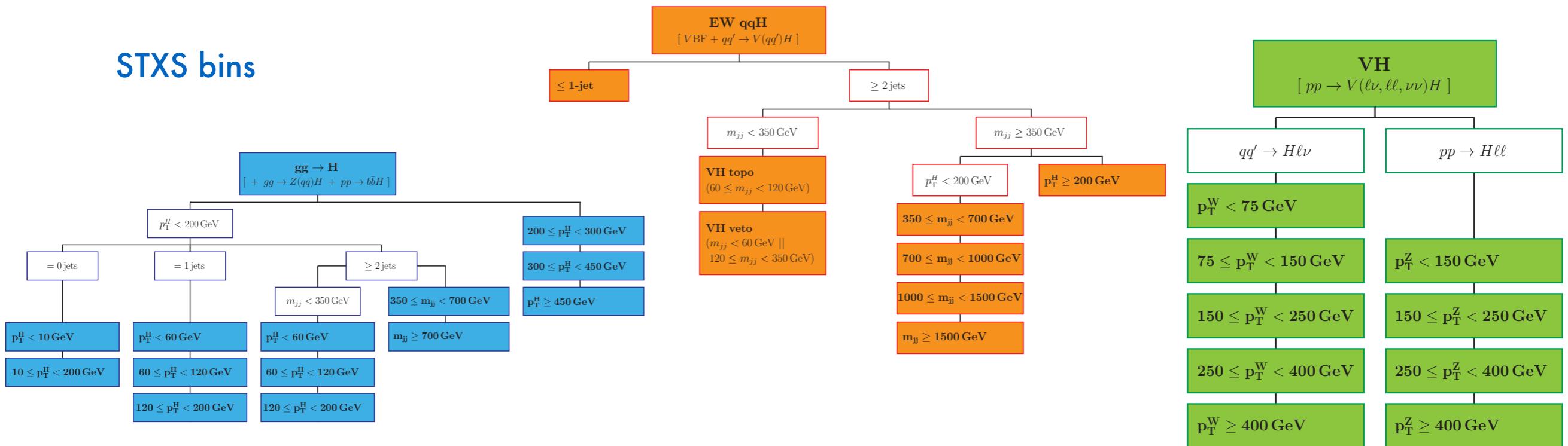
- Precision (e.g. gammagamma, ZZ*, WW)
- Entering precision (e.g. bb, tautau)
- Searches (e.g. cc, mumu, Zgamma, ee)

- Inclusive measurement:
 - x-sections
 - signal strength
 - coupling strength

- Differential fiducial measurements

- Semi-fiducial: STXS

STXS bins



k-framework and EFT

- Two main frameworks to study and summarise the Higgs coupling measurements

k-framework

$$\sigma \cdot \mathcal{B}(i \rightarrow H \rightarrow f) = \kappa_i^2 \cdot \kappa_f^2 \cdot \sigma_i^{\text{SM}} \cdot \frac{\Gamma_f^{\text{SM}}}{\Gamma_H(\kappa_i^2, \kappa_f^2)}$$
$$\kappa_i^2 = \frac{\sigma_i}{\sigma_i^{\text{SM}}} \quad \text{and} \quad \kappa_f^2 = \frac{\Gamma_f}{\Gamma_f^{\text{SM}}}$$

- Assumption on the parameters yet to be measured
- Nice framework to produce synthetic summaries of many different results.

EFT interpretation

- Wilson coefficients parametrise new couplings:

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i^{(5)}}{\Lambda_i} \mathcal{O}_i^{(5)} + \boxed{\sum_i \frac{c_i^{(6)}}{\Lambda_i^2} \mathcal{O}_i^{(6)}} + \dots$$

- Variety of initial and final state sensible to same operator
- can capture additional BSM effects:
e.g. CP odd/even operators

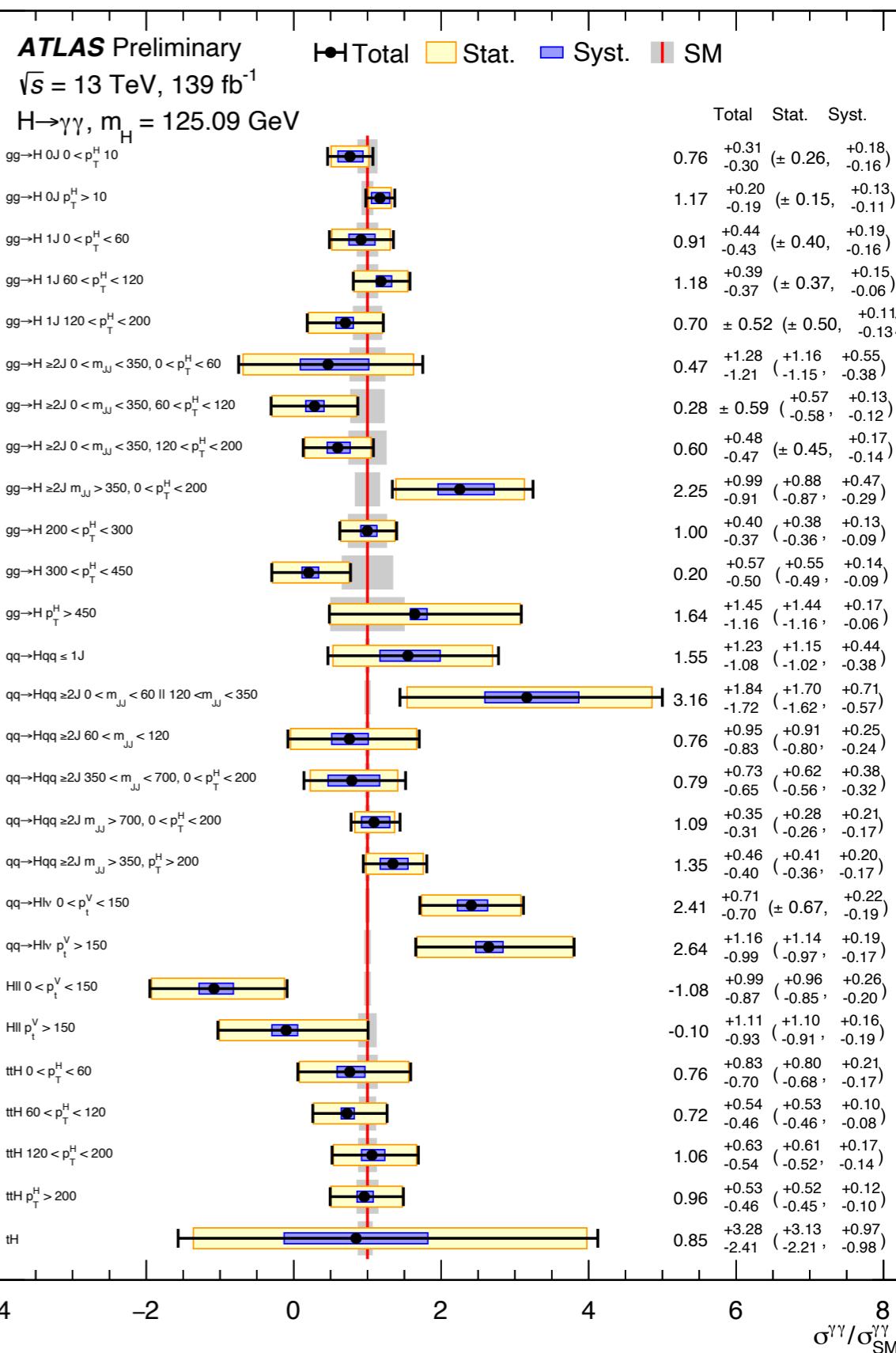
- Analysis strategy:

- High statistics and good mass resolution
- 27 STXS measurements
- Allow to also bin in ttH and tH categories
- Overall good compatibility with the SM

- Main uncertainty:

- Theory: PS and UE events
- Experimental: photon energy and ID (ggF); background modelling; jets and MET (VBF, ttH and tH)

Process ($ y_H < 2.5$)	Value [fb]	Uncertainty [fb]			SM pred. [fb]
		Total	Stat.	Syst.	
ggF + $b\bar{b}H$	104	+11 -11	+8 -8	+7 -6	102 ± 5
VBF	10.7	+2.1 -1.9	± 1.4	+1.4 -1.3	8.0 ± 0.2
WH	6.4	+1.5 -1.4	+1.5 -1.3	+0.4 -0.3	2.7 ± 0.1
ZH	-1.2	+1.1 -1.0	+1.1 -1.0	± 0.1	1.8 ± 0.1
$t\bar{t}H + tH$	1.2	+0.4 -0.3	± 0.3	± 0.1	1.3 ± 0.1



$H \rightarrow ZZ^* \rightarrow 4l$

- Analysis strategy:

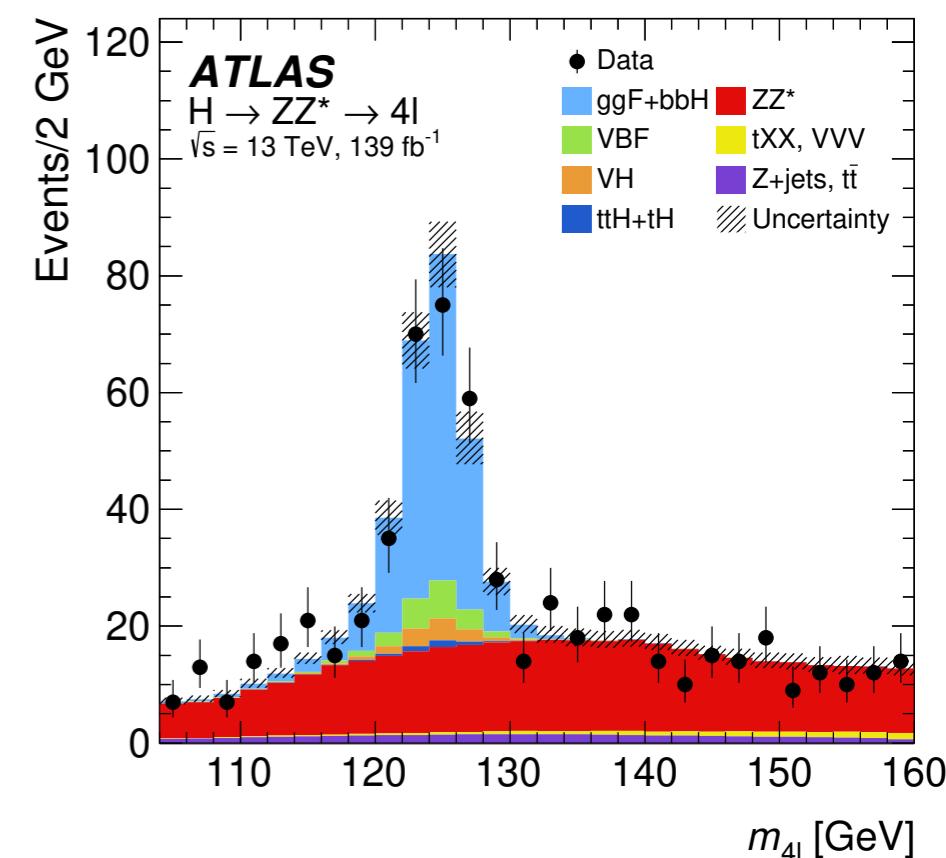
- Low stat. but clean and reach signatures
- DNN to define STXS categories.

- Main uncertainty:

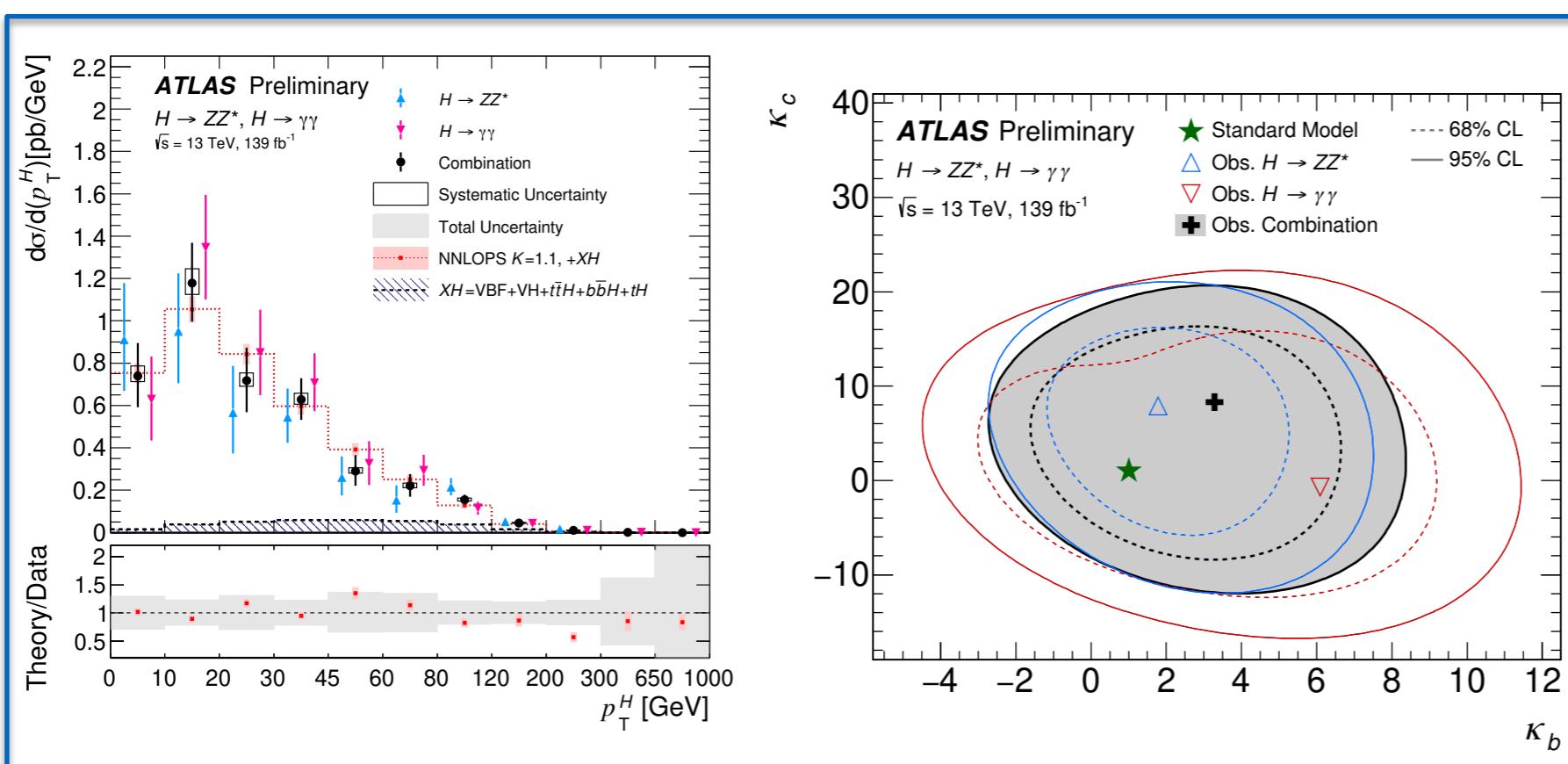
- Exp: lepton ID, luminosity, signal modelling

- pTH spectrum from combination of 4l and gamma gamma allows to set limits on k_c/k_b

[ATLAS-CONF-2022-002](#)



[Eur. Phys. J. C 80 \(2020\) 957](#)



- Analysis strategy:

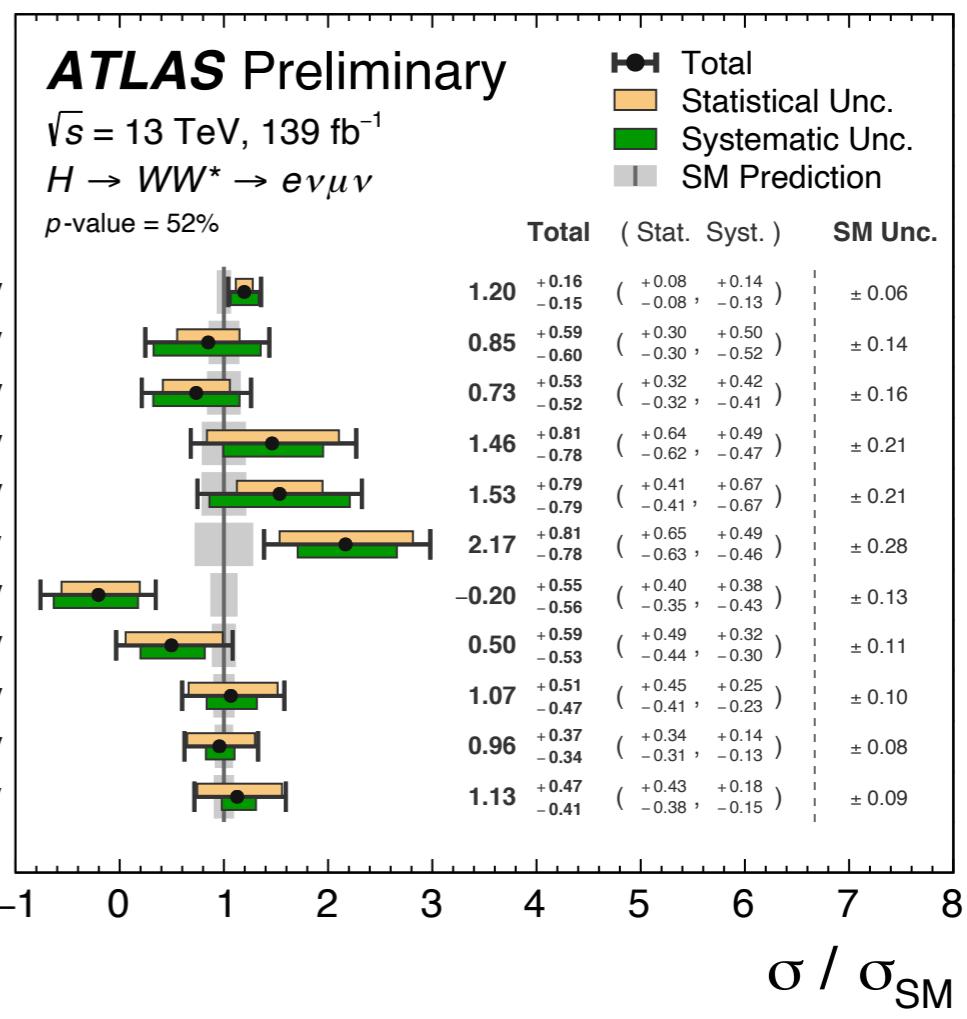
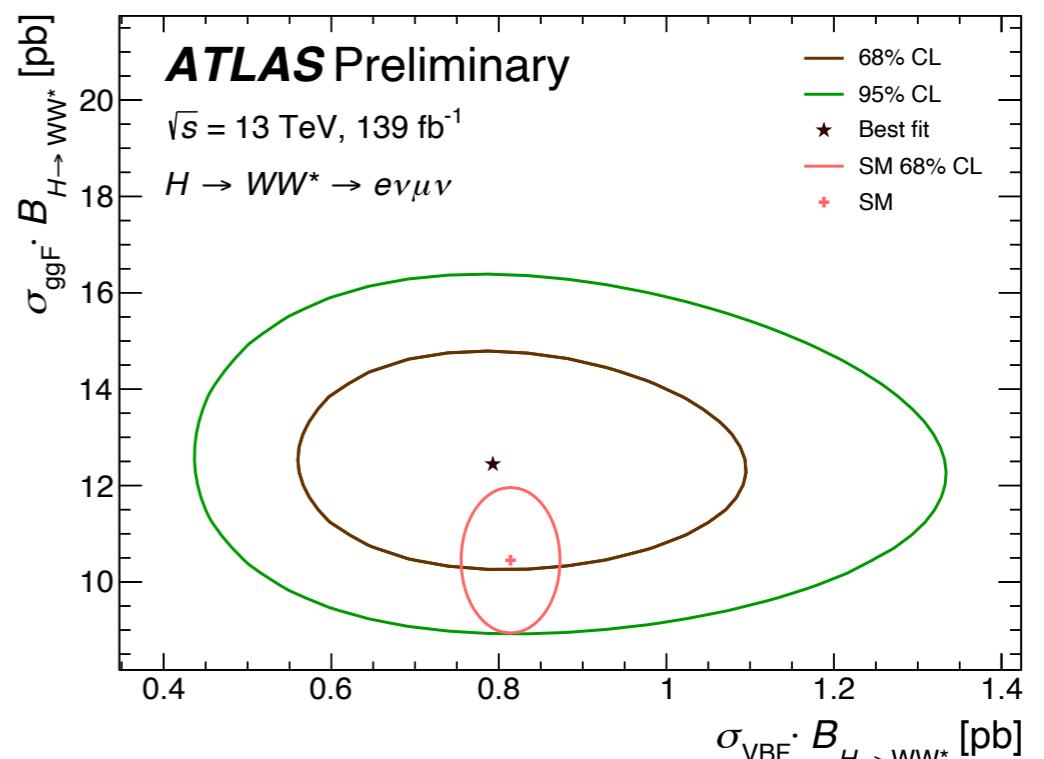
- Targeting ggF and VBF in emu final state
- Complex backgrounds (top, WW, mis-ID, Z->tautau)

- Main uncertainty:

- Exp and theory similar in ggF

- Signal unc. Largest in VBF

Source	$\frac{\Delta\sigma_{\text{ggF}} \cdot \mathcal{B}_{H \rightarrow WW^*}}{\sigma_{\text{ggF}} \cdot \mathcal{B}_{H \rightarrow WW^*}} [\%]$	$\frac{\Delta\sigma_{\text{VBF}} \cdot \mathcal{B}_{H \rightarrow WW^*}}{\sigma_{\text{VBF}} \cdot \mathcal{B}_{H \rightarrow WW^*}} [\%]$
Data statistical uncertainties	5	13
Total systematic uncertainties	11	18
MC statistical uncertainties	4	3.2
Experimental uncertainties	6	7
Flavour Tagging	2.4	0.9
Jet energy scale	1.4	3.3
Jet energy resolution	2.3	1.9
E_T^{miss}	1.9	5
Muons	2.1	0.7
Electrons	1.5	0.3
Fake factors	2.4	1.0
Pile-up	2.4	1.3
Luminosity	2.0	2.1
Theoretical uncertainties	8	16
ggF	5	4
VBF	0.7	13
Top	4	5
$Z\tau\tau$	2.0	2.1
WW	4	5
Other VV	3	1.2
Background normalisations	5	5
WW	3.1	0.5
Top	2.4	2.2
$Z\tau\tau$	3.1	4
TOTAL	12	22



- Direct measurement of coupling to the third gen. leptons

- Analysis strategy:

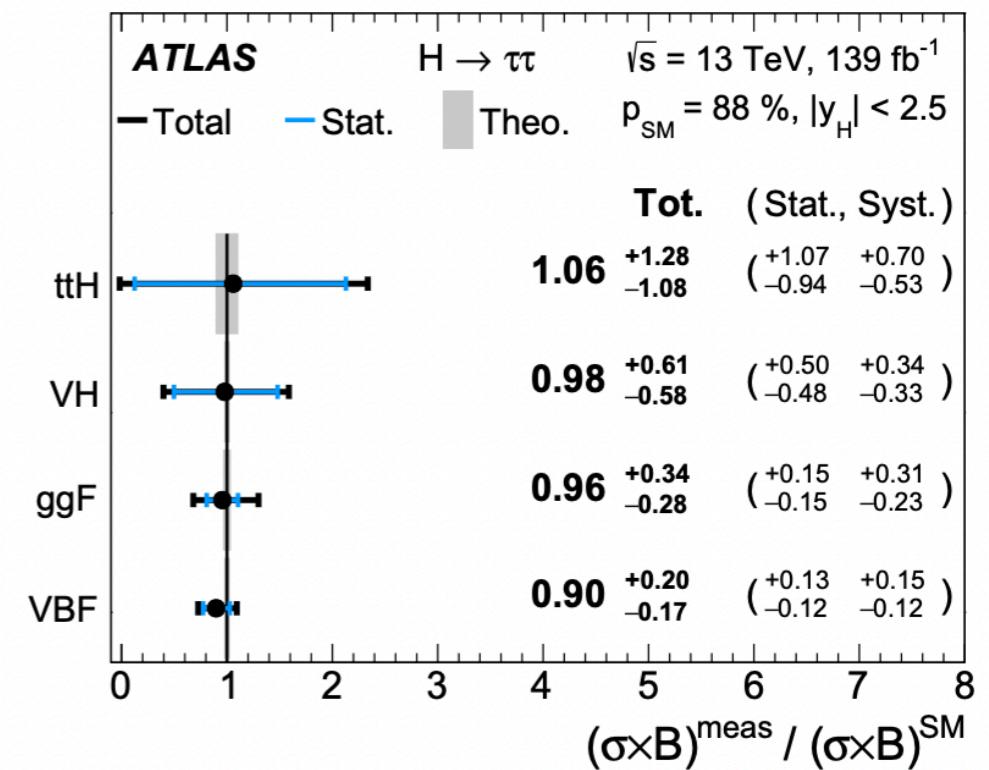
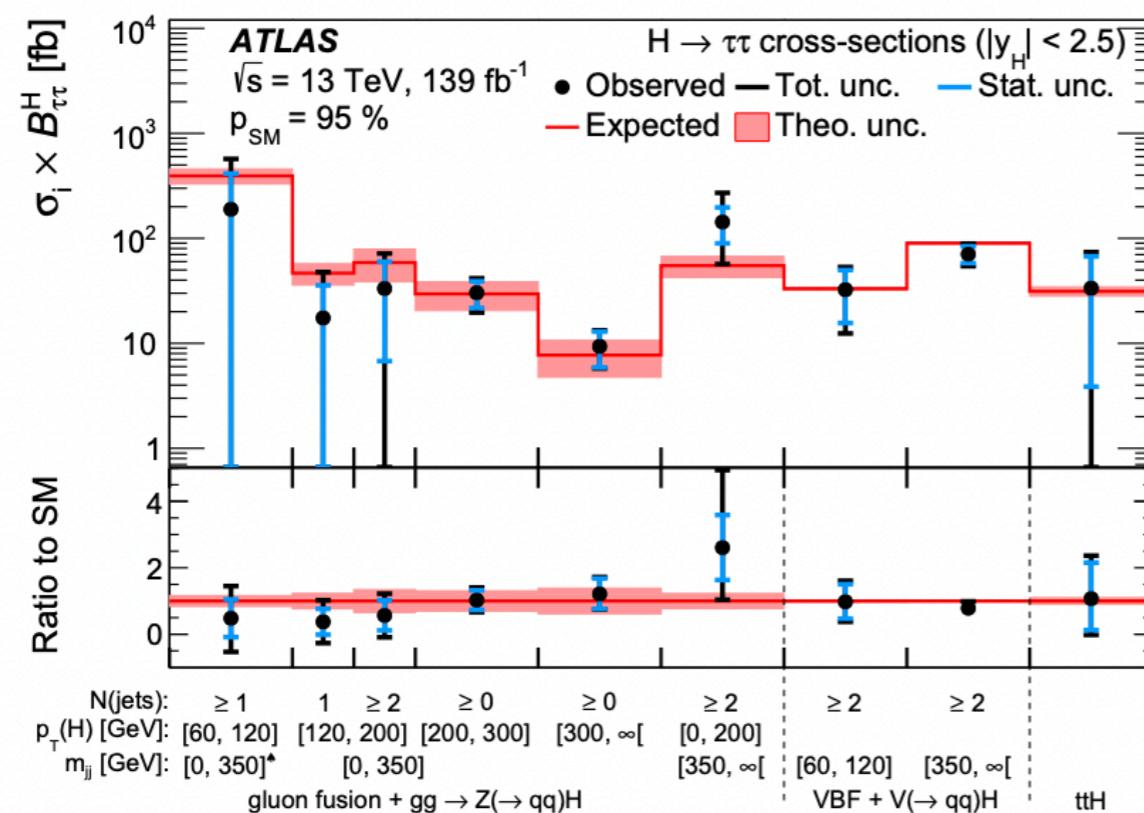
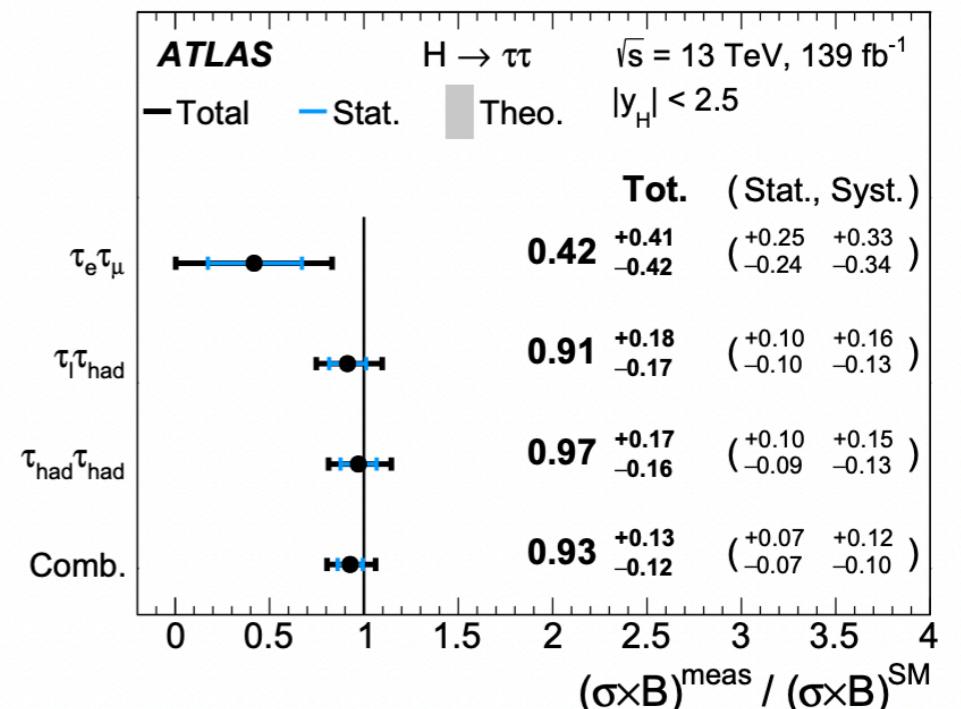
- Targets several production modes, good sensitivity to VBF in high mass region and ggF

- MVA discriminants employed

- Test CP properties: [Shigeki's contribution](#)

- Main uncertainty:

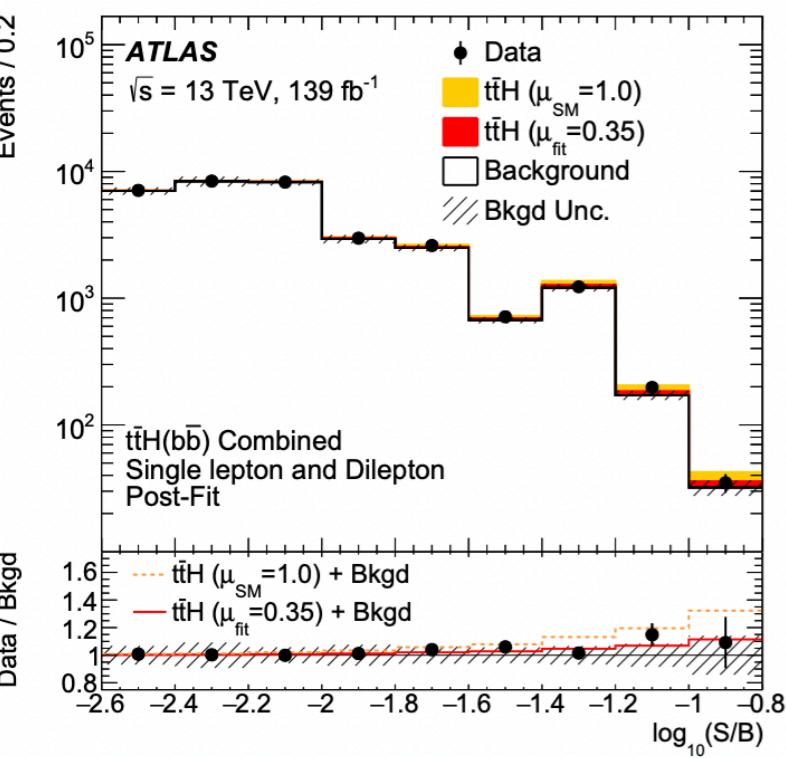
- Signal theory, jets and MET



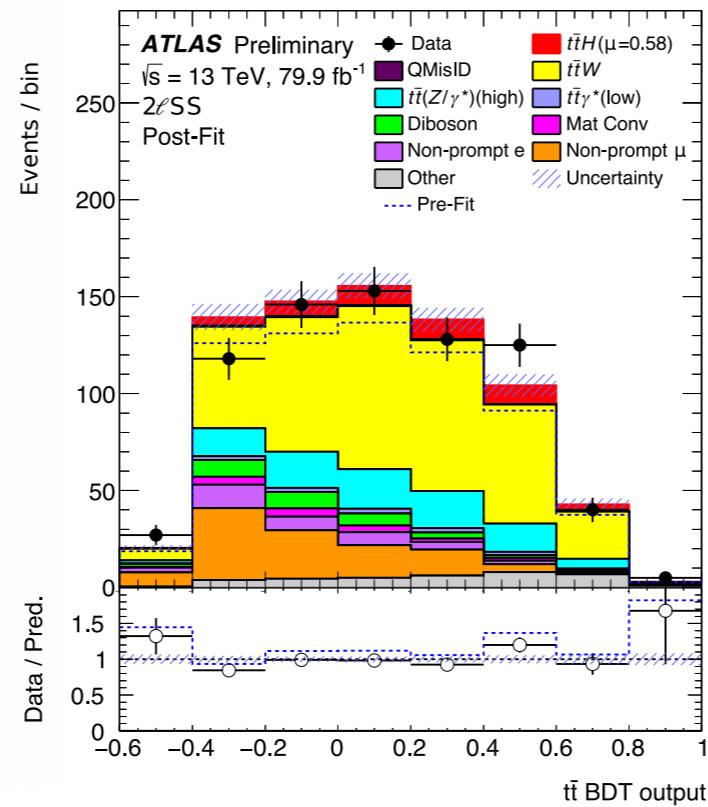
$t\bar{t}H$

- Accessing of coupling to the third gen. up-type. quark
- Complex and rich final state
- CP studies in $H \rightarrow \gamma\gamma$ gamma and bb (previous talk)
- Analysis example: $t\bar{t}Hbb$

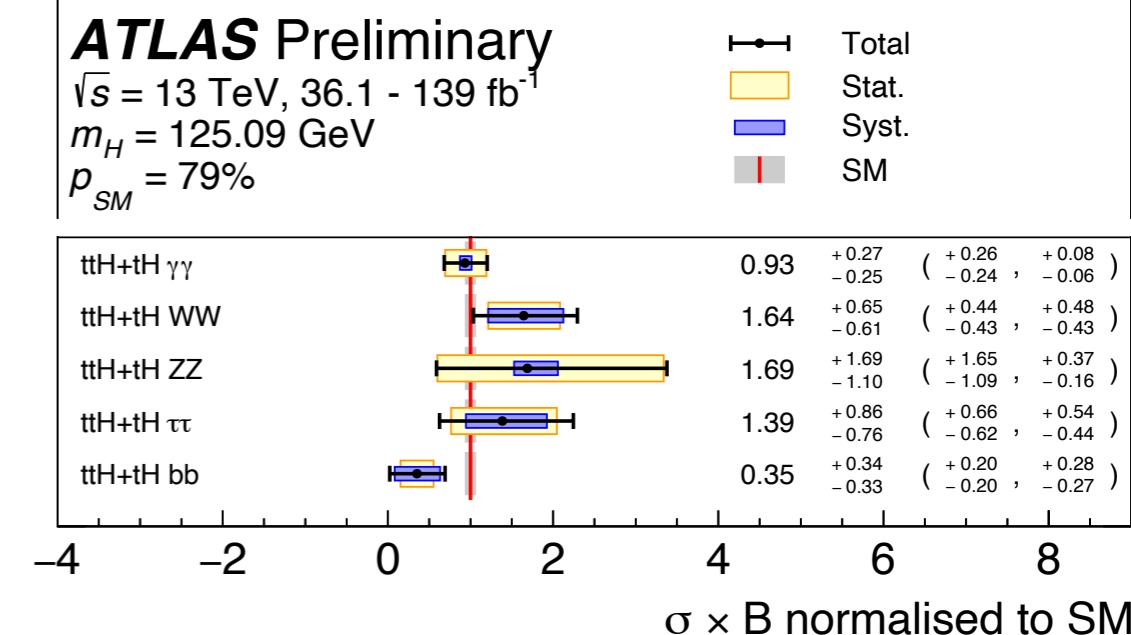
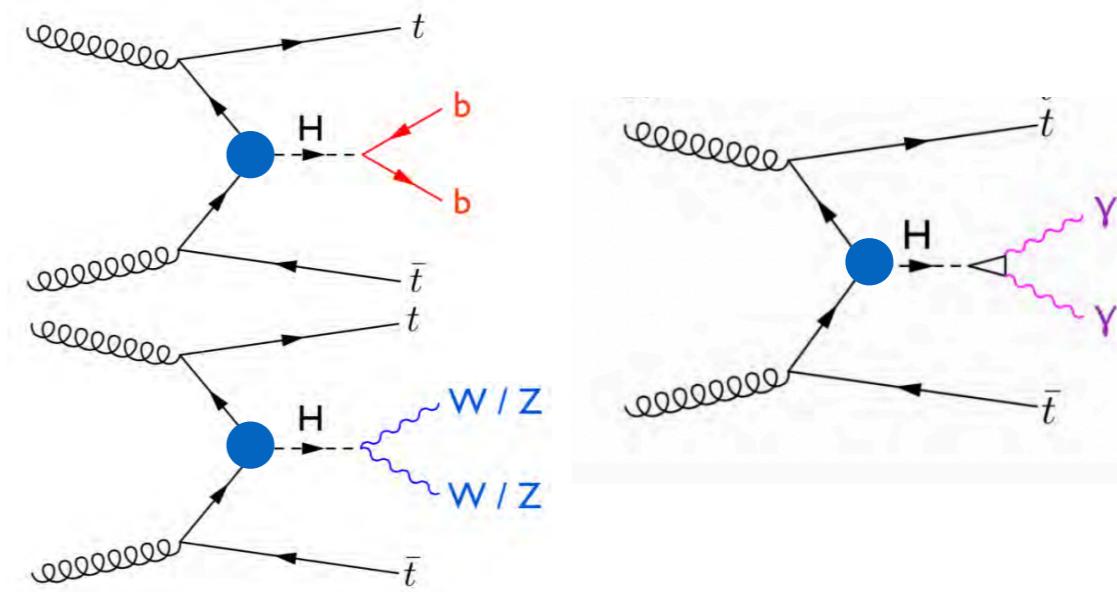
[arxiv 2111.06712](https://arxiv.org/abs/2111.06712)



[ATLAS-CONF-2019-045](https://atlas.cern.ch/CONF-PAPERS/ATLAS-CONF-2019-045.pdf)



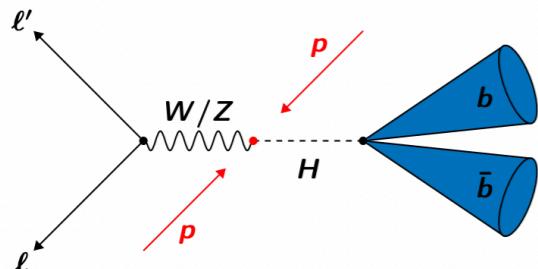
[ATLAS-CONF-2021-053](https://atlas.cern.ch/CONF-PAPERS/ATLAS-CONF-2021-053.pdf)



H->bb

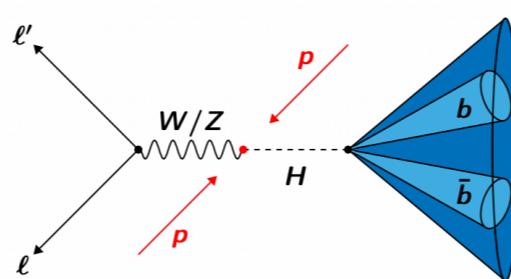
- Measuring the coupling to the third gen. down-type. quark
- Mostly constrained from VH channels, followed by VBF
- Dominated by b-tagging and jets unc, as well as signal and V+j modelling

VH->bb



[EPJC 81 \(2021\)](#)

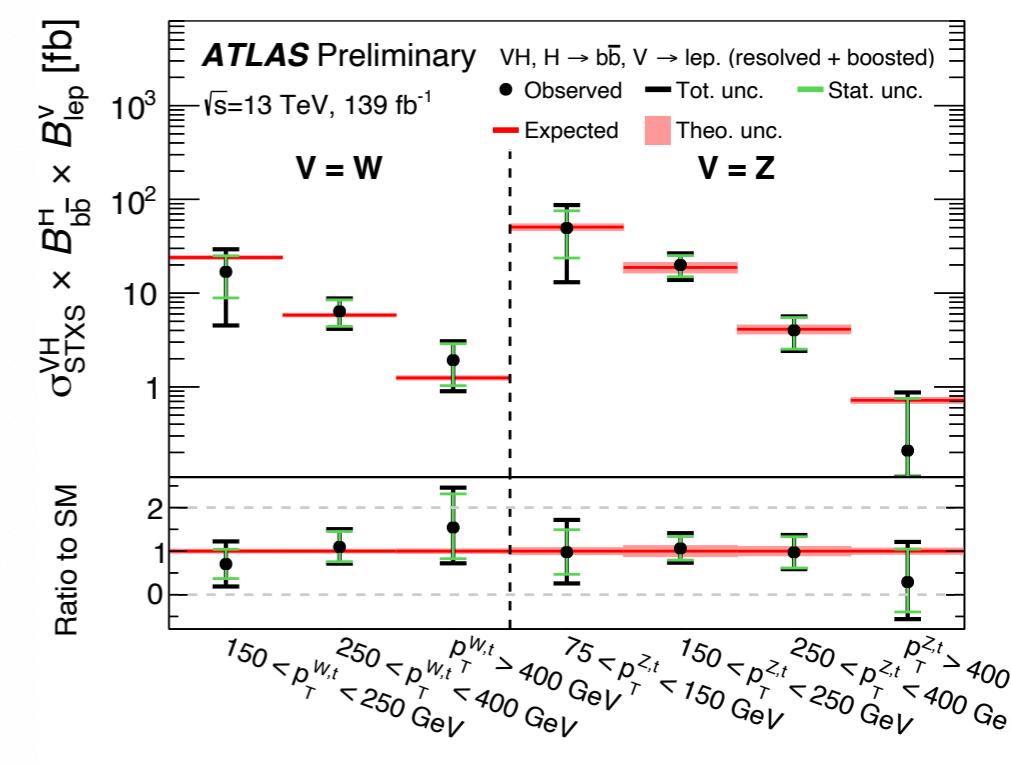
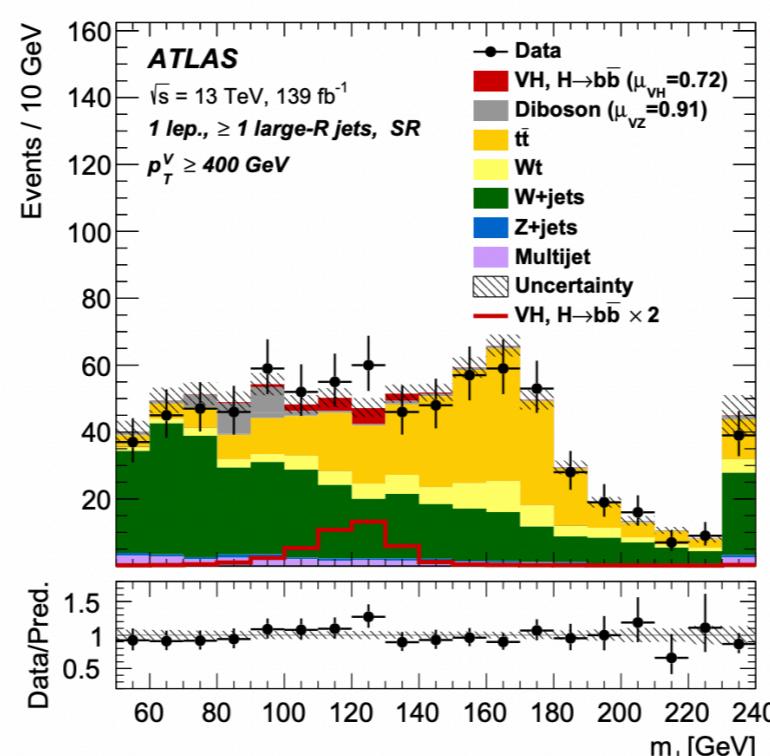
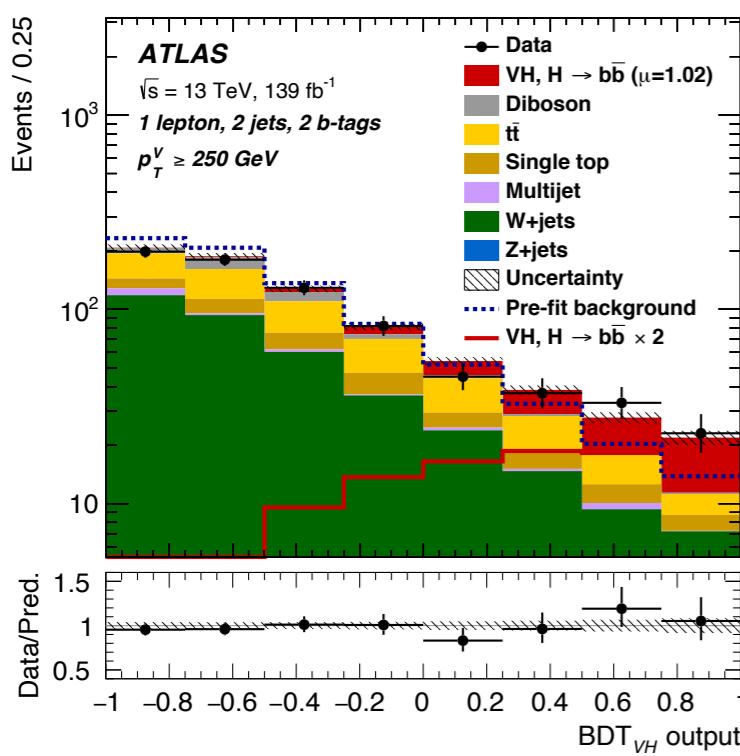
VH->bb boosted



[Phys.Lett.B 816 \(2021\)](#)

Combination of the two analyses:

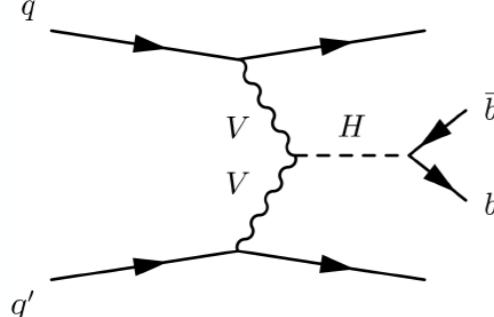
[ATLAS-CONF-2021-051](#)



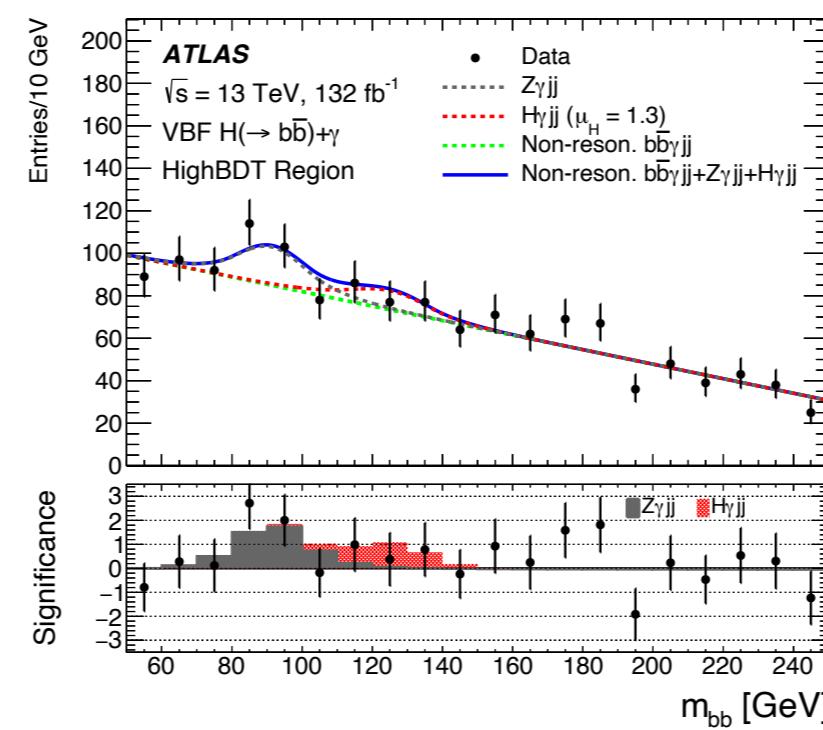
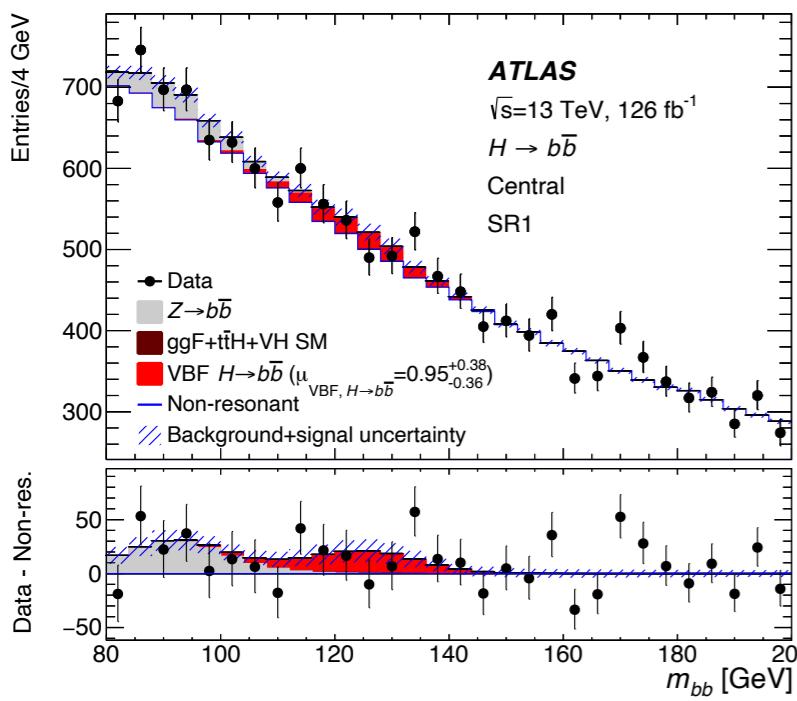
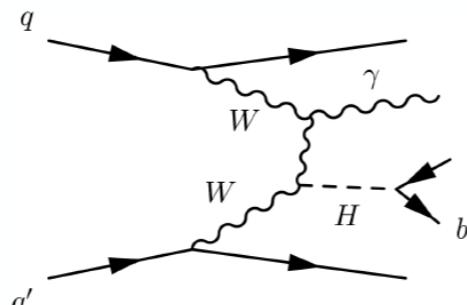
- Additional searches for Hbb: VBF (+gamma) and full hadronic
- Mostly stat dominated followed by background modelling

Full-hadronic H->bb

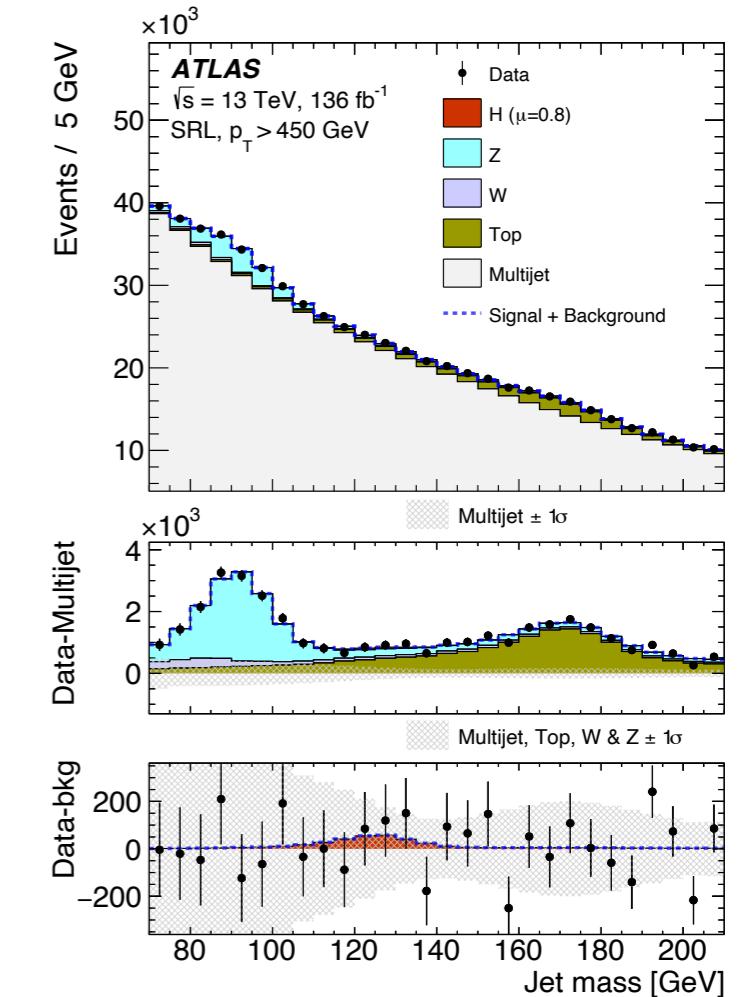
[Eur.Phys.J.C 81 \(2021\)](#)



[JHEP 03 \(2021\) 268](#)



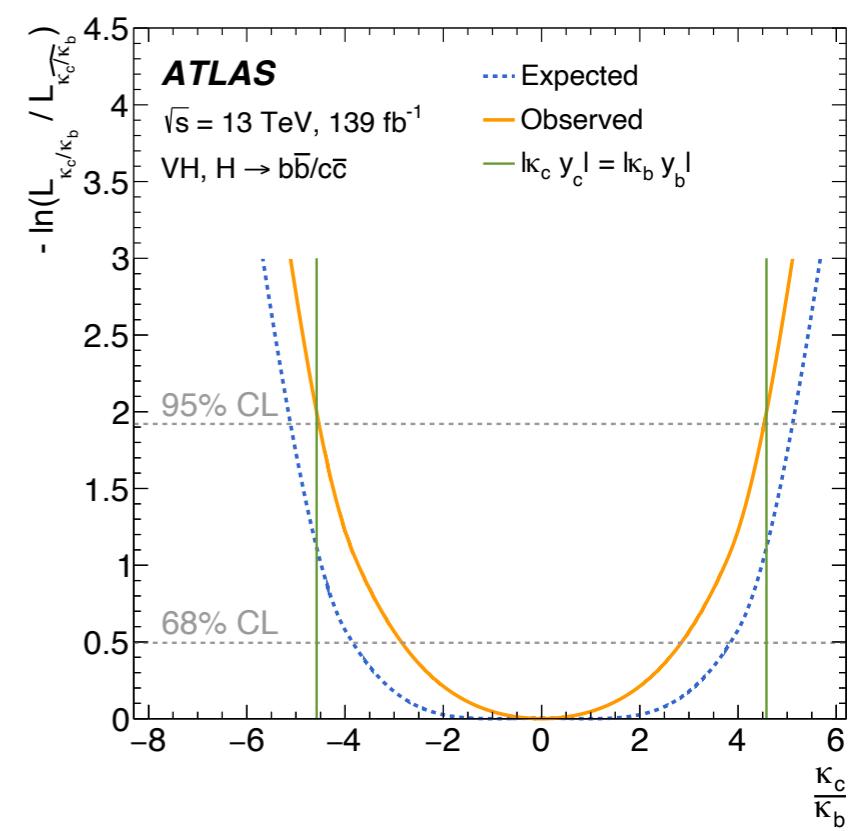
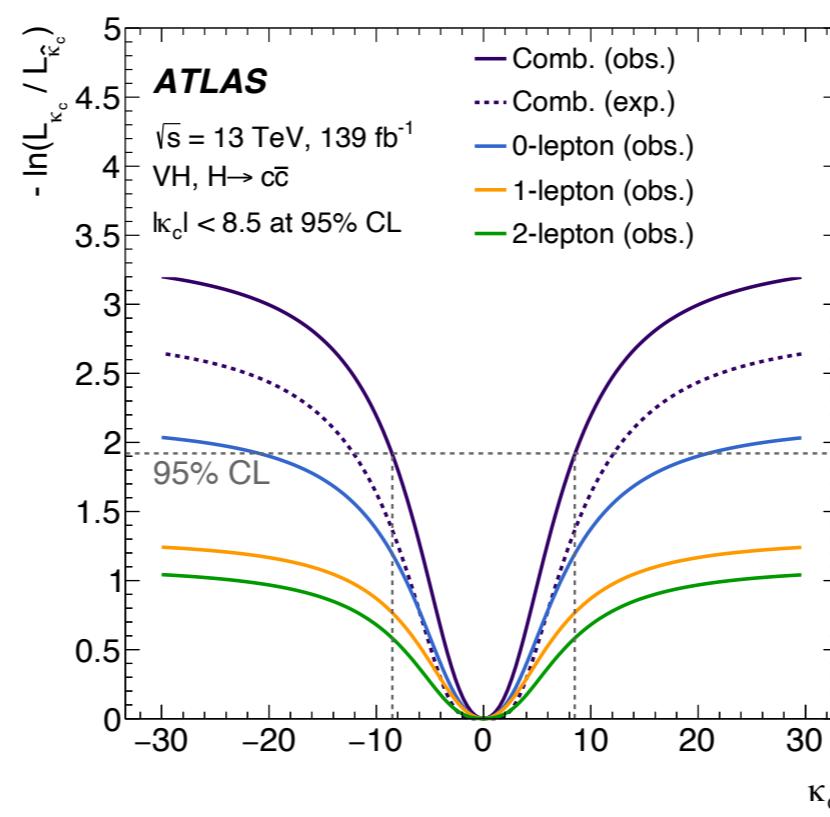
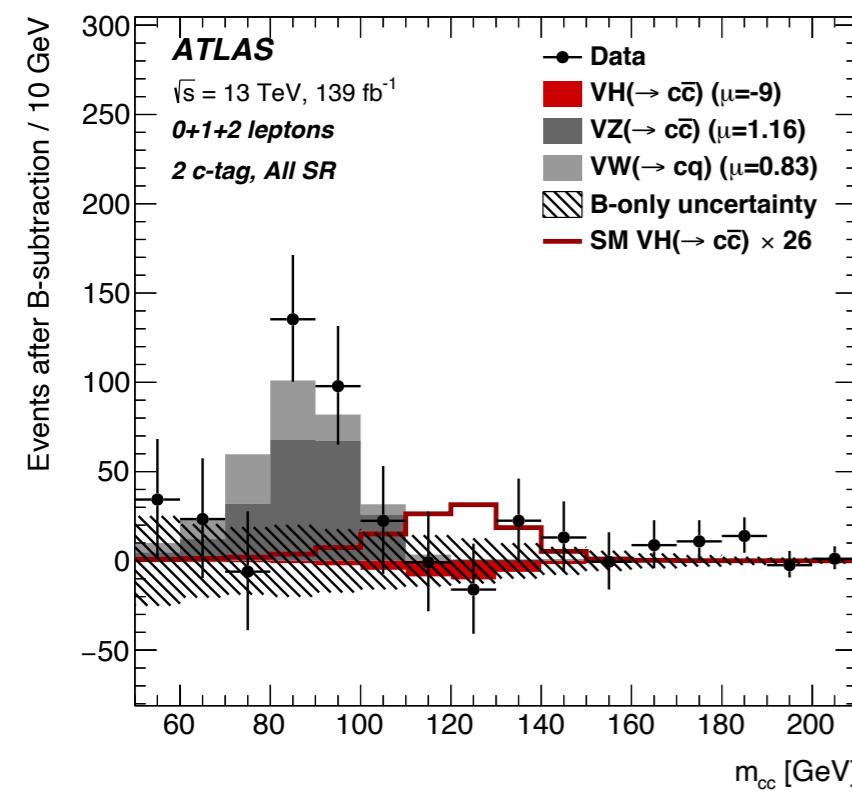
p_T^H [GeV]	Exp.	μ_H	Obs.
300–450	1	± 18	-6 ± 18
450–650	1.0 ± 3.3		-3 ± 5
650–1000	1	± 6	5 ± 7
>1000	1	± 30	18 ± 32



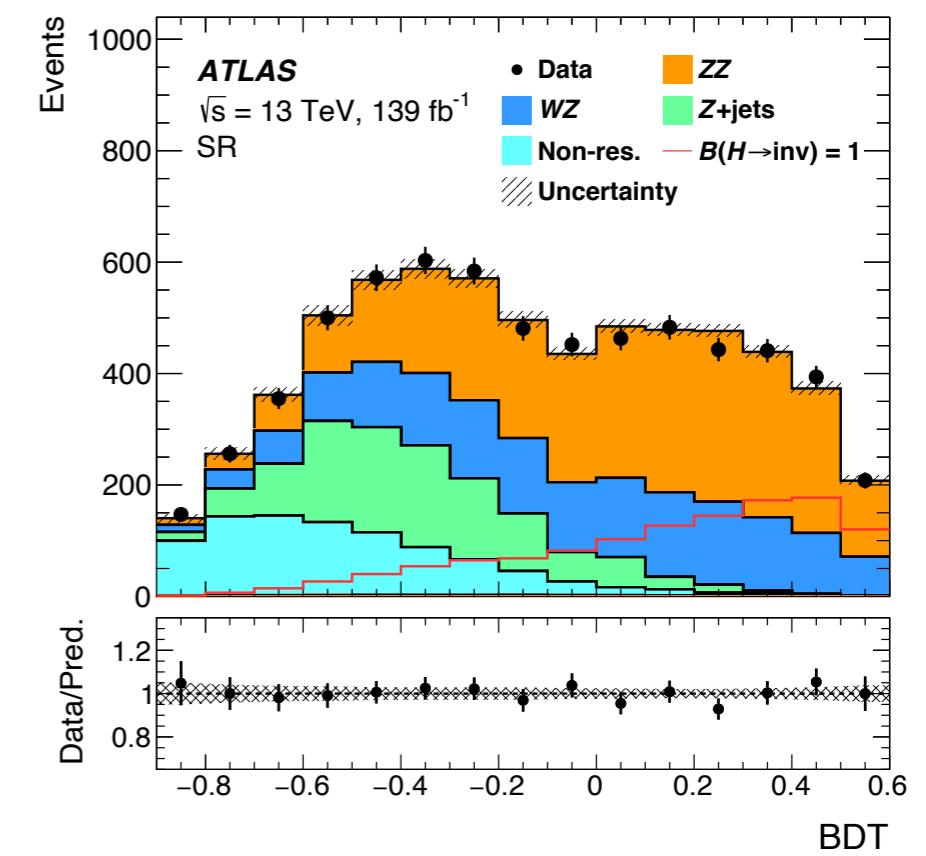
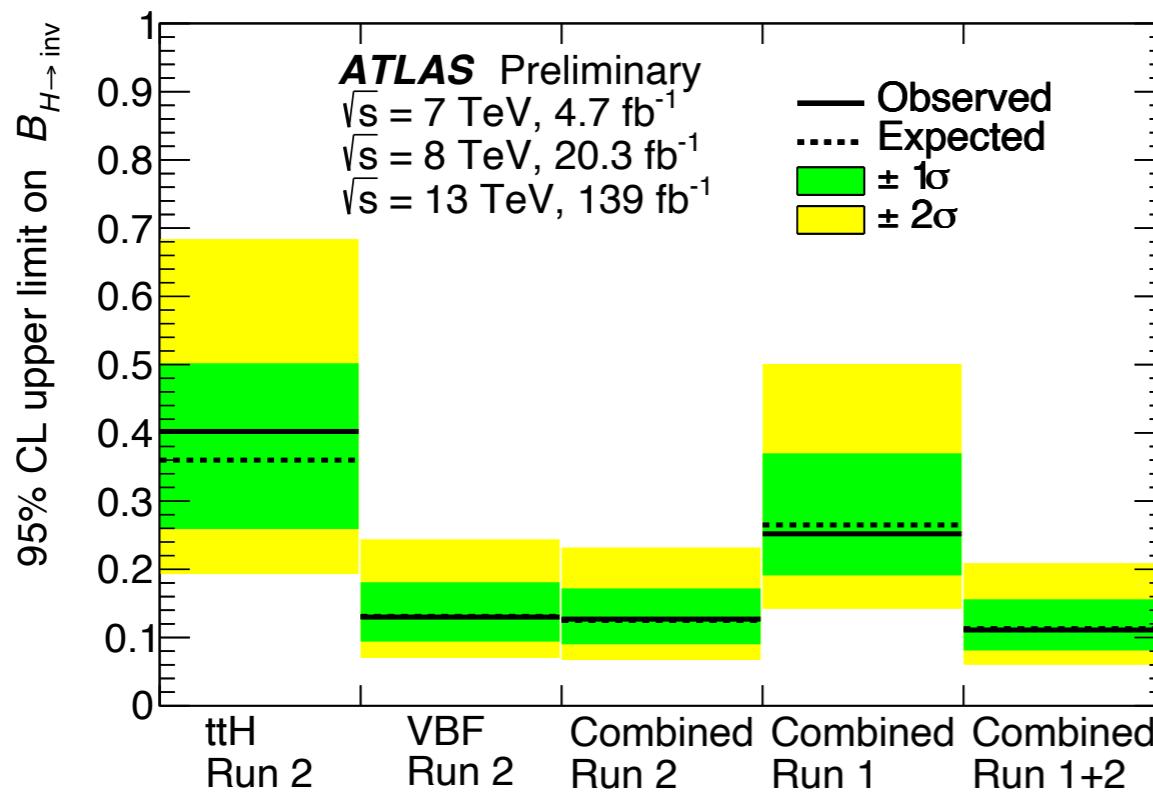
- Probing the coupling to second generation quark!
- Challenging at the LHC, several approaches: indirect and **direct** measurements
- VH; H->cc is the most promising channel. Ability to tag c-jets is the key component
- Several control regions to constraint ttbar and W/Z+jets backgrounds

$$\mu_{VH(c\bar{c})} = \frac{\kappa_c^2}{1 + B_{H \rightarrow c\bar{c}}^{\text{SM}} (\kappa_c^2 - 1)}$$

$|\kappa_c/\kappa_b| < 4.5$ @ 95% CL



- Challenging at the LHC, several approaches: indirect and **direct** measurements
- Analysis strategy:
 - Targets VBF + MET and ttH + MET processes. Dedicated interpretation with dark matter models possible
 - Uncertainties dominated by statistics
- ZH->llvv analysis reports a limit of 19% on BR(H->inv). [2111.08372](#)



Main H rare decays

$H \rightarrow \mu\mu$

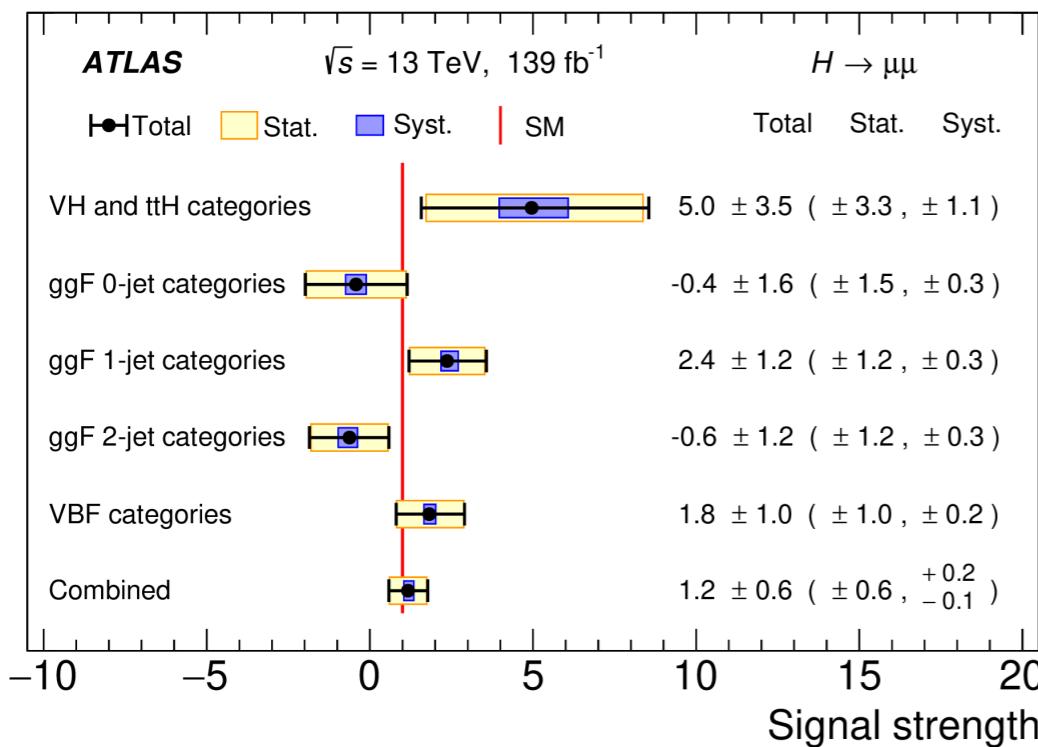
Second generation leptons

$\text{BR} \sim 2\text{e-}4$

Need to exploit several production modes

Muon resolutions crucial aspect

[2007.07830](#) Obs (exp) ~ 2.0 (1.7) sigma



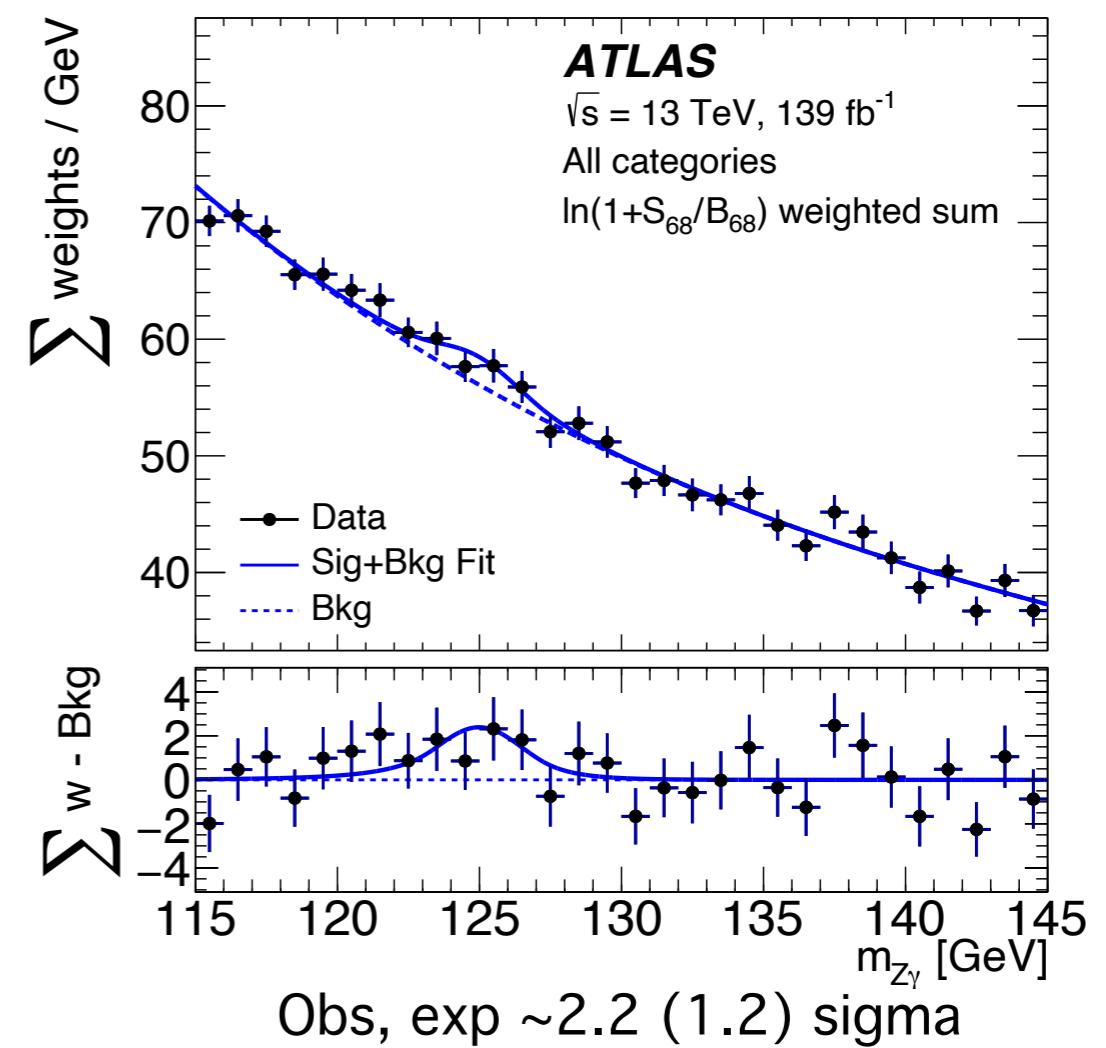
$H \rightarrow Z\gamma$

Z \rightarrow leptonically decaying in e or mu pairs

$\text{BR} \sim 1.5\text{e-}3$

Limits on $\text{BR}(H \rightarrow Z\gamma) < 0.55\% @ 95 \text{ CL}$

[Phys.Lett.B 809 \(2020\) 135754](#)



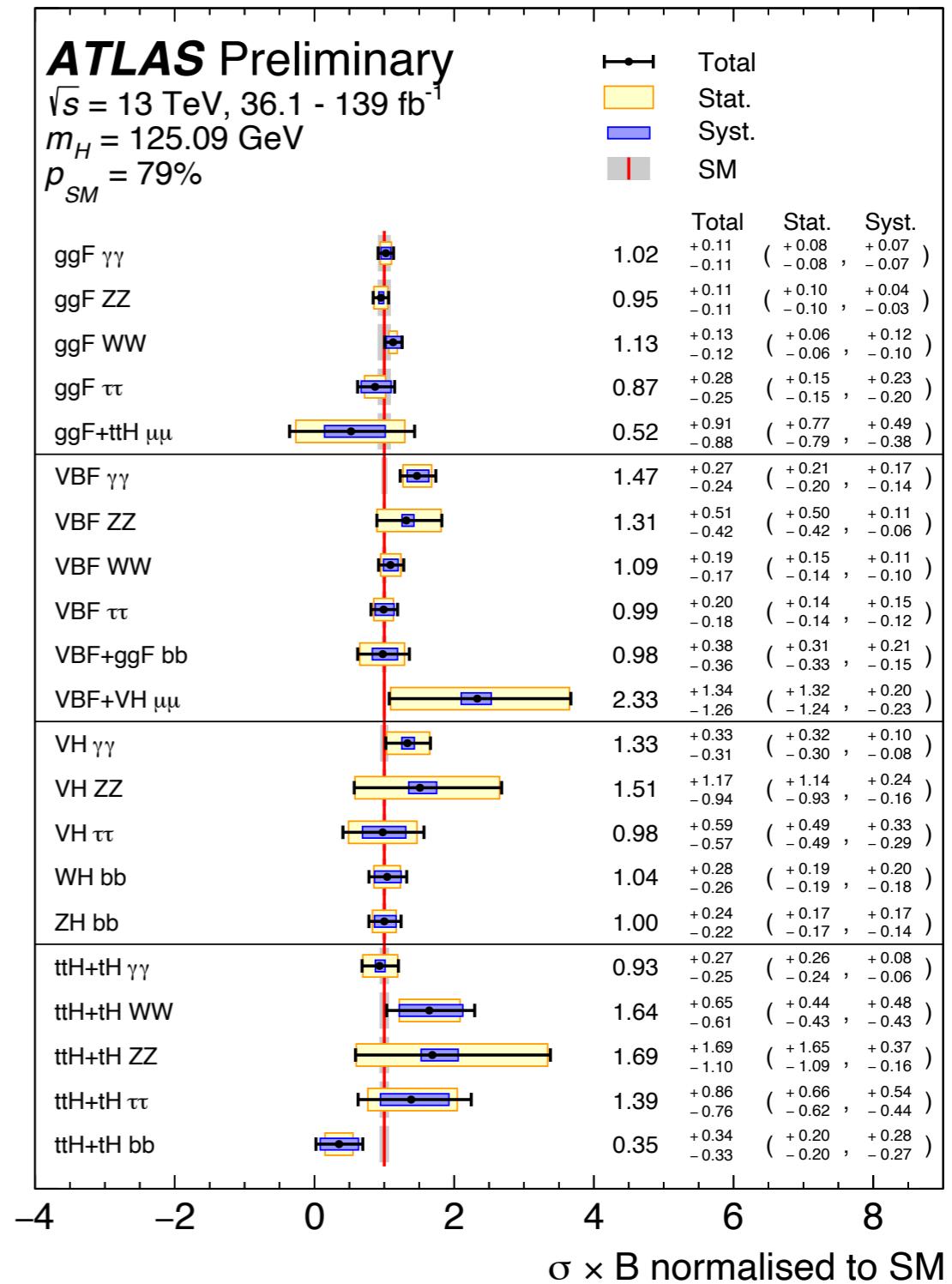
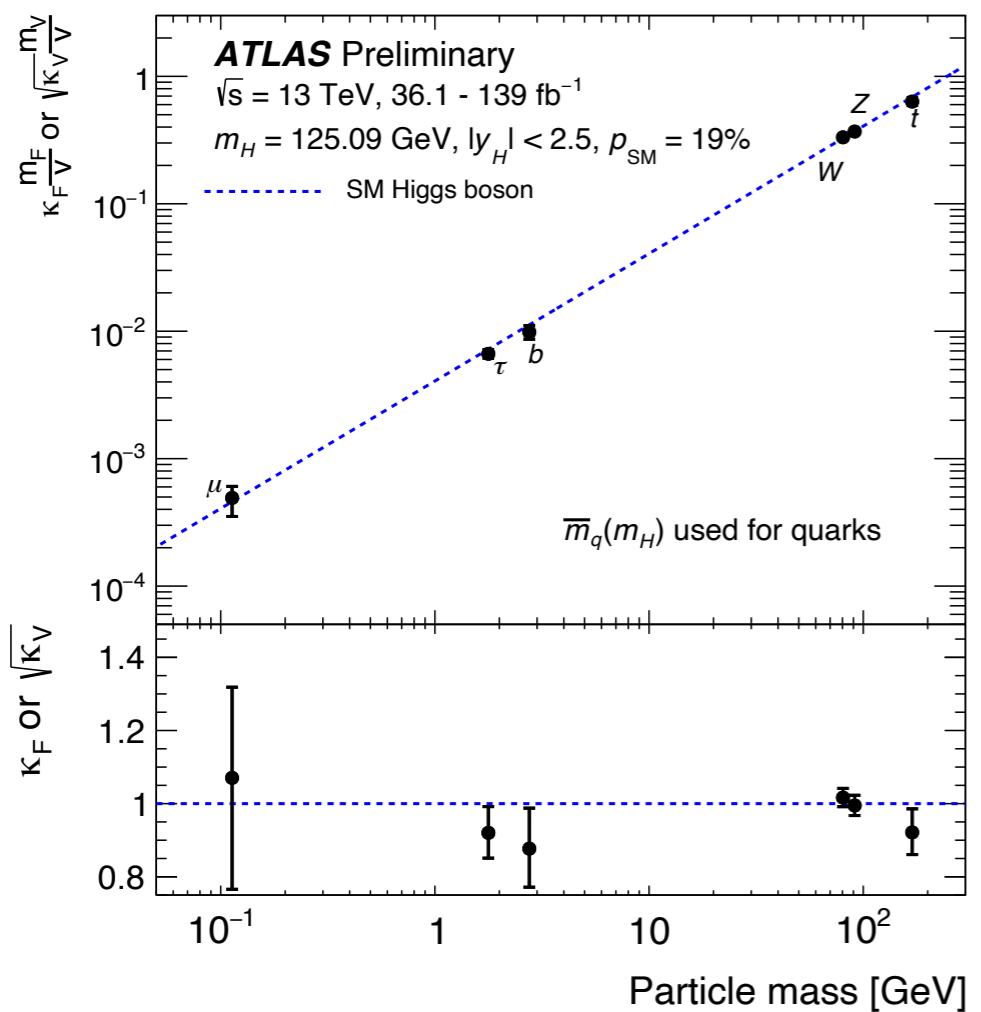
Putting everything together - combination

[ATLAS-CONF-2021-053](#)

- Combination of XS measurement in various productions (ggF, VBF, VH, ttH+tH) and decays (gamma gamma, bb, ZZ, WW, ttautau, mumu, Zgamma)

$$\mu = 1.06 \pm 0.03 \text{ (stat.)} \pm 0.03 \text{ (exp.)} \pm 0.04 \text{ (th.)}$$

- No deviation from SM predictions observed



EFT

- Dimension 6 operators considered using the Warsaw basis

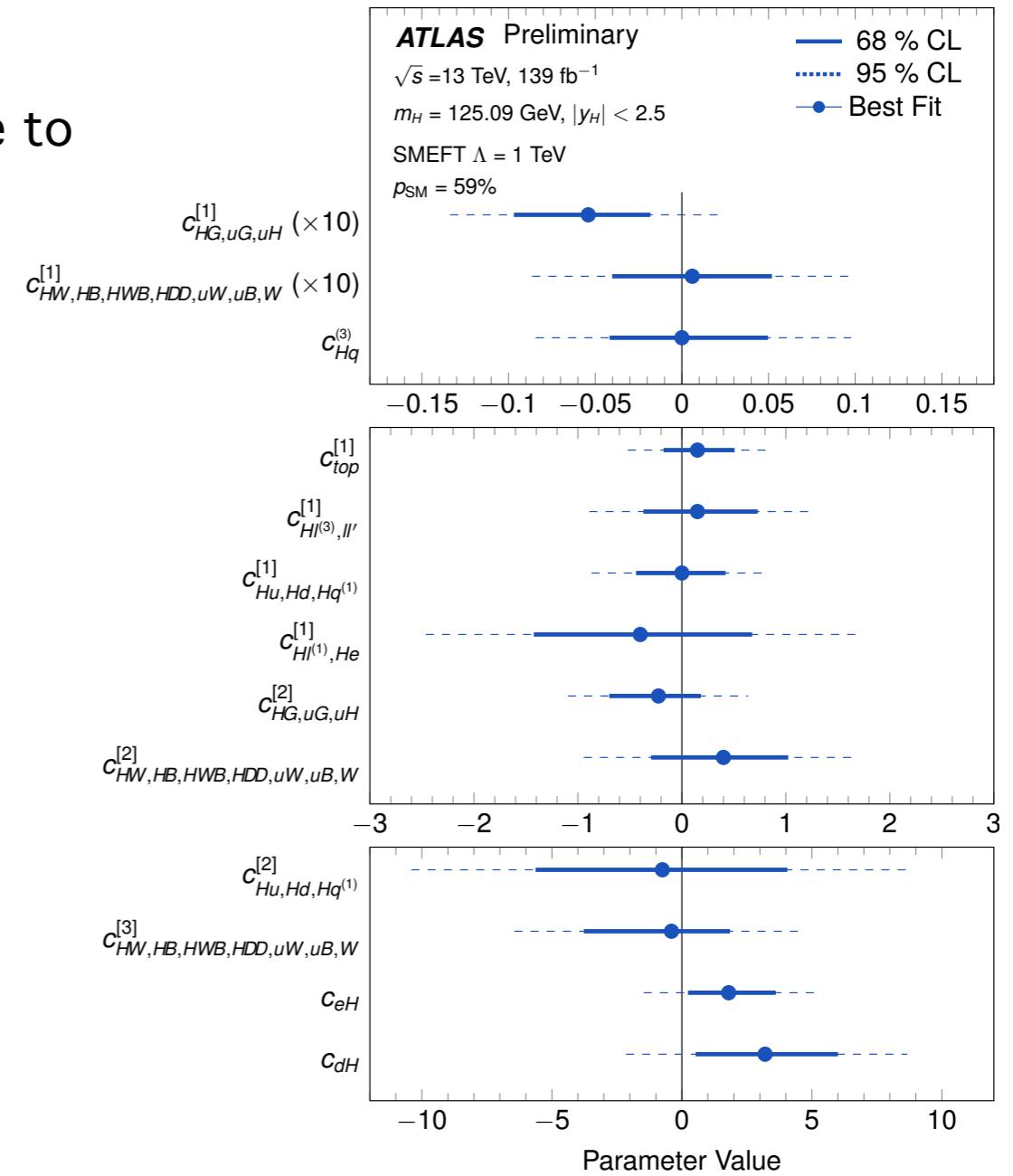
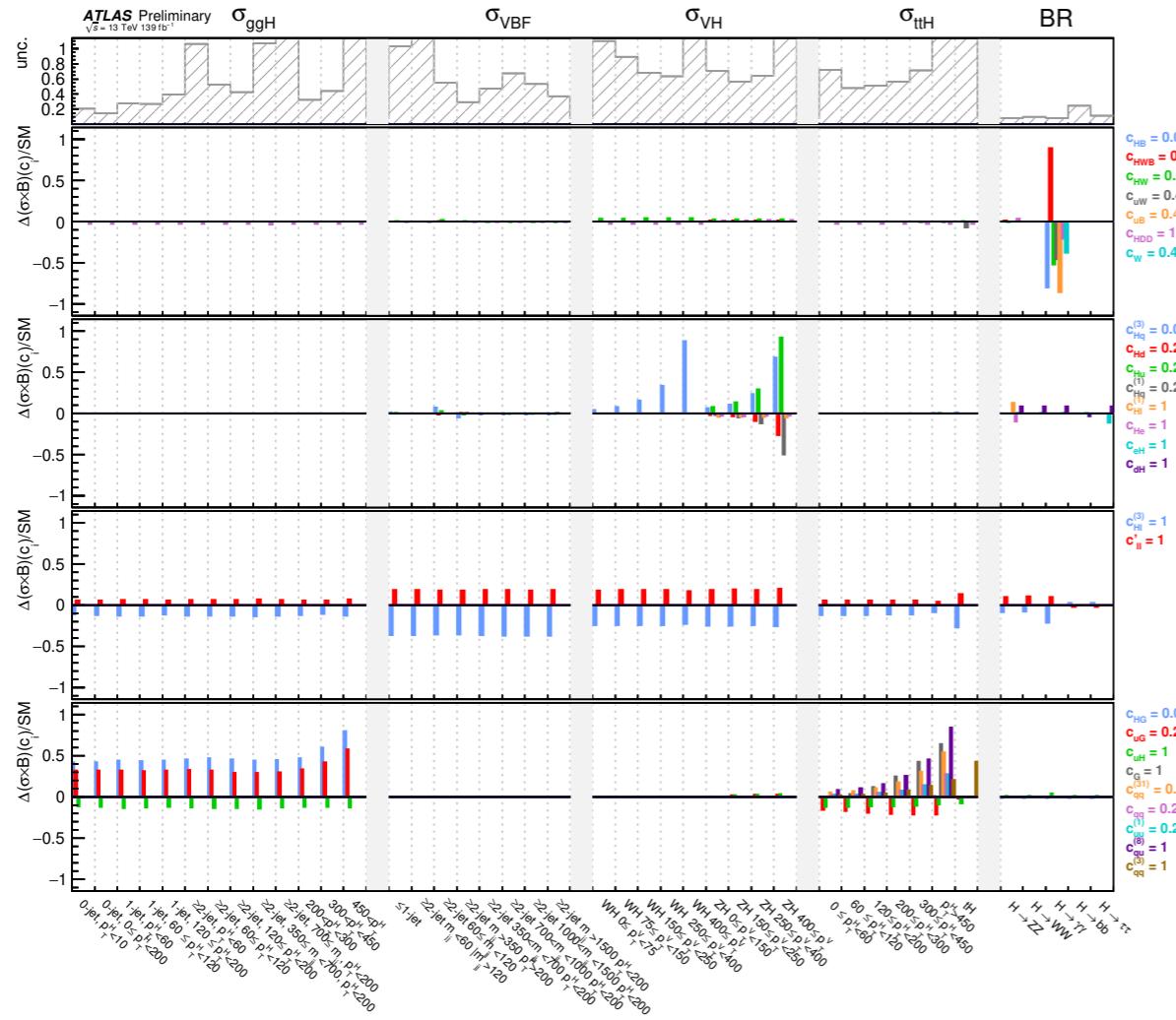
[ATLAS-CONF-2021-053](#)

- Lamda = 1 TeV

- Only look at a sub-set of operators that we are sensitive to

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

Effect of Wilson coefficients



No significant deviations are found

Conclusions

- Many new results since Higgs discovery. Expanded phase, space, rare decays, etc...
- Interpretations with k-framework and SMEFT. No significant deviation is found.
- More analyses and combination in progress (will be available soon)
- Many improvements can still be expected in the next years from experiment and theoretical improvements

Thank you!