Measurement of the Higgs boson couplings and their interpretations in fermionic final states at the ATLAS experiment

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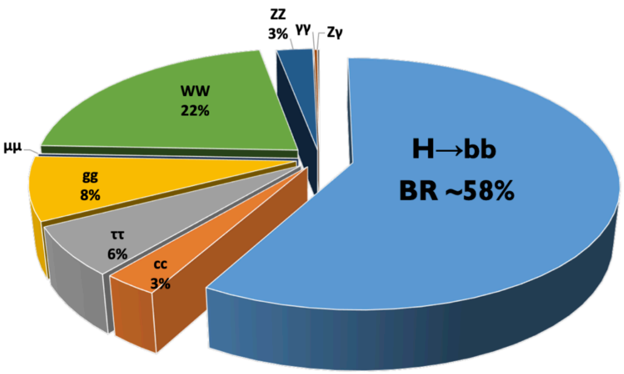
on behalf of the ATLAS Collaboration

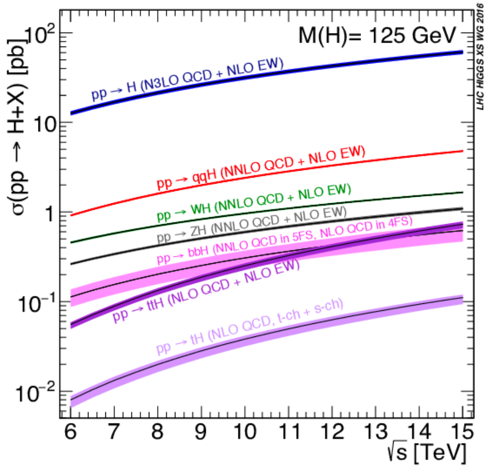
ICHEP 2022

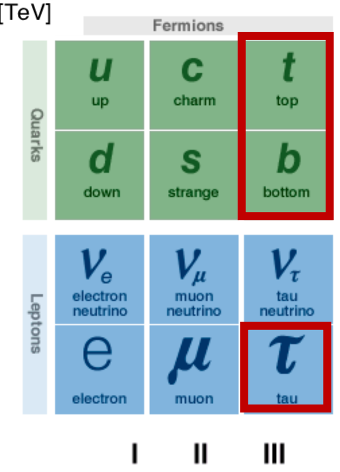
7th July 2022

Introduction



- **Higgs to fermionic final states** represent ~ **70%** of the Higgs decays.
- Measurement of the **Higgs coupling to fermions** can provide **stringent tests** of validity of **SM**.
- **All Higgs to third generation fermion couplings** have been **observed**
- Higgs to fermionic final states **studied** looking to **different production modes**
- Outline - only latest results using full Run 2 dataset:
  - **Coupling to third generation fermions**:
    - $H \to b\bar{b}$
    - $t\bar{t}H$
    - $H \to \tau\bar{\tau}$
  - **Simplified template cross-section** (STXS) and coupling **interpretations**
- More info on Higgs to second generation fermions in Robert's talk



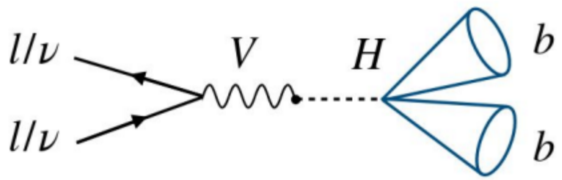


$VH(b\bar{b})$ combination

- **Best sensitivity** for dominant $H \to b\bar{b}$ **decay** in **VH production** due to high trigger efficiency and background suppression when targeting **V → lepton decays**.
- $VH(b\bar{b})$ final states studied by two analyses and significant **overlap** between the two analyses

Resolved analysis

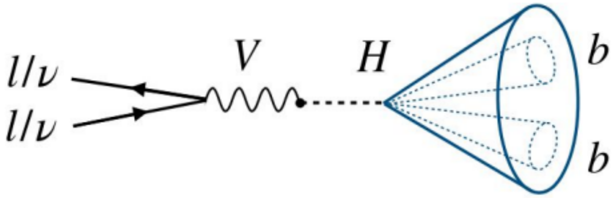
Eur. Phys. J. C 81 (2021) 178



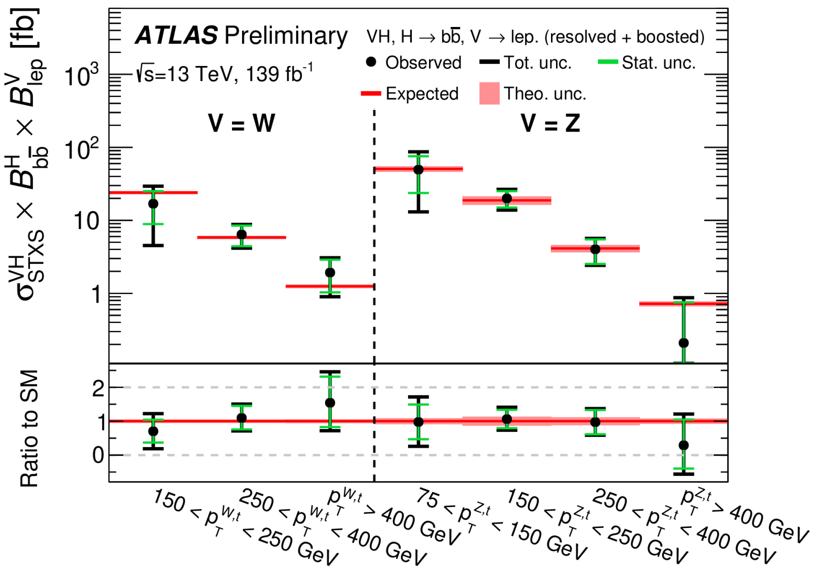
High precision (~30%) measurement

Boosted analysis

Phys. Lett. B 816 (2021) 13204



Probes high-p_T^V regime



- In the combination **drop resolved events with p_T^V>400 GeV** and **use boosted only in p_T^V > 400GeV**
- STXS measurements in 7 STXS bins
  - **Good agreement with SM predictions**.
  - **Most precise measurement of the VH production**

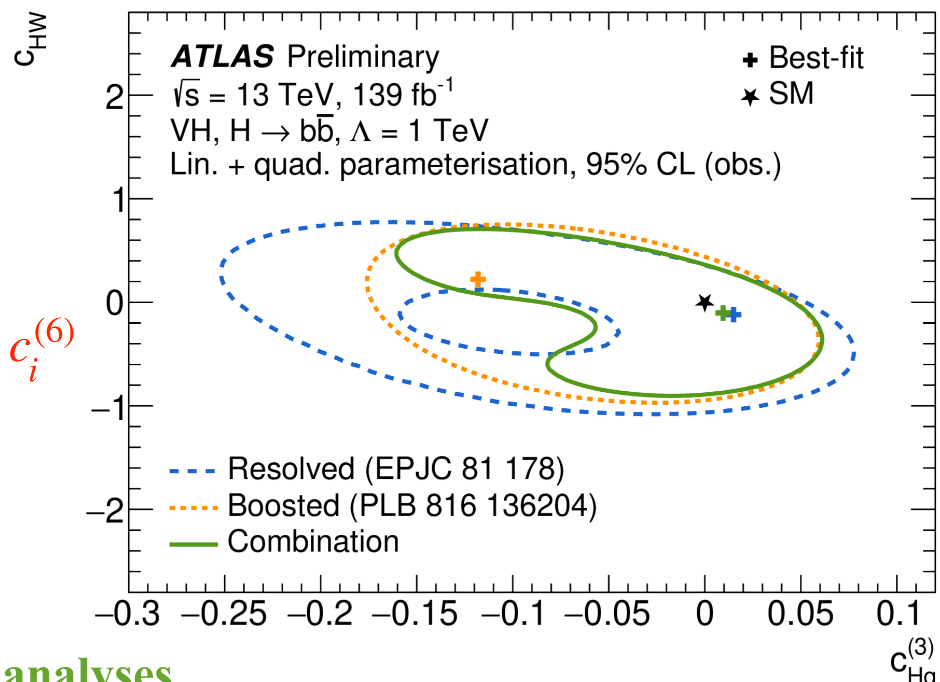
$VH(b\bar{b})$ combination: EFT interpretation

- Parameterization of BSM effects using **effective Lagrangian** with **dimension-6 operators** in the Warsaw basis: $\mathscr{L}_{\text{SMEFT}} = \mathscr{L}_{\text{SM}} + \sum_i c_i^{(6)} \cdot \mathcal{O}_i^{(6)}/\Lambda^2$
  - $c_i^{(6)}$ = Wilson coefficient
  - $\mathcal{O}_i^{(6)}$ = dimension-6 operator
  - Λ = BSM scale
- **EFT cross-section parametrisation**

$$\sigma_{EFT} = \sigma_{SM} + \sigma_{int} + \sigma_{BSM}$$

Linear dependence on $c_i^{(6)}$ (for σ_{int})

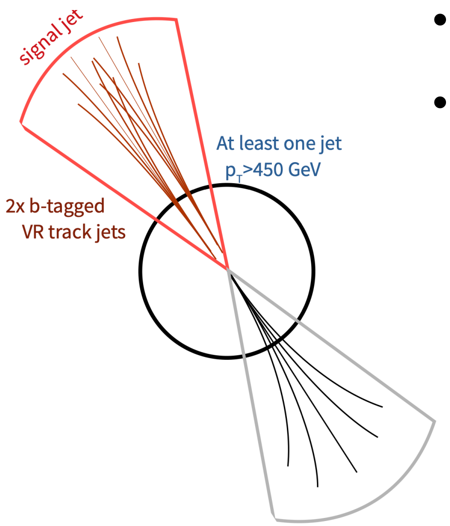
Quadratic dependence on $c_i^{(6)}$ (for σ_{BSM})



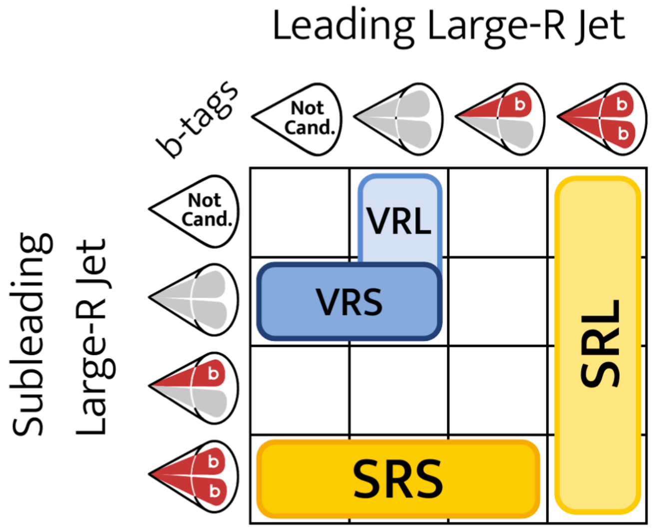
- **More stringent limits combining the two analyses**

[Phys.Rev.D105(2022)092003]

All-had H→$b\bar{b}$ analysis



- Analysis targeting boosted Higgs recoiling against a jet
- Final state with **two large-R jets**:
  - Higgs candidate:
    - p_T **> 450 GeV**, m_J>60 GeV;
    - **2 b-tagged VR track jets**



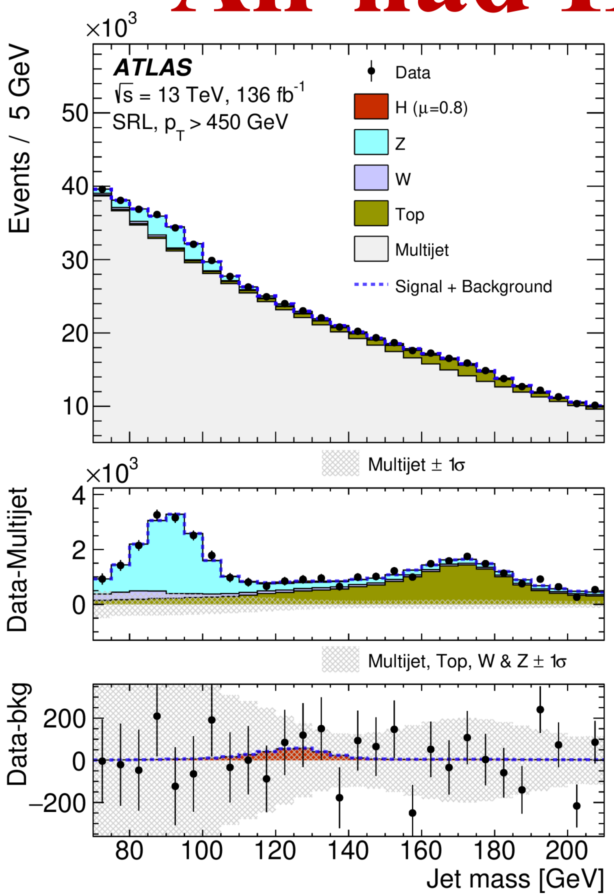
Fractional contribution for each signal production mode

Process	Jet p_T range [GeV] 250–450	450–650	650–1000	> 1000
		SRL		
ggF	–	0.56	0.50	0.39
VBF	–	0.17	0.16	0.17
VH	–	0.14	0.18	0.25
$t\bar{t}H$	–	0.13	0.16	0.19
		SRS		
ggF	0.28	0.46	0.43	–
VBF	0.07	0.19	0.21	–
VH	0.26	0.24	0.26	–
$t\bar{t}H$	0.39	0.11	0.10	–

- **Event categorization**
  - **SR**: SRL(SRS) in which the (sub-) lead. large-R jet is double b-tagged
  - **VR**: to study multi-jet and V+jet model
    - Multi-jet production modelled using parametric function
  - **CR**$_{t\bar{t}}$: to study top events;
    - Requiring one hadronic top decay and one muonic top decay

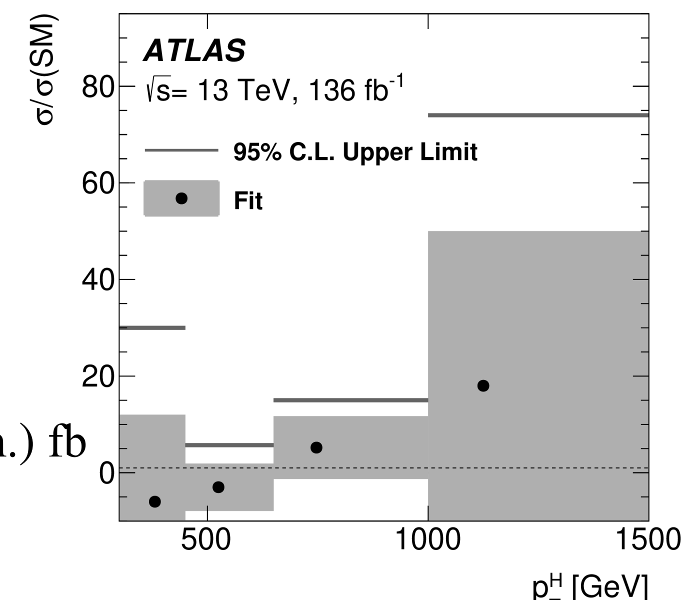
Phys.Rev.D105(2022)092003

All-had H→$b\bar{b}$ analysis- results



- Higgs candidate jet mass m_J is the **final discriminant**
  - $Z(b\bar{b})$+ jets production process used to **validate the analysis method**
- **Profile likelihood fit** to extract signal strength μ_H

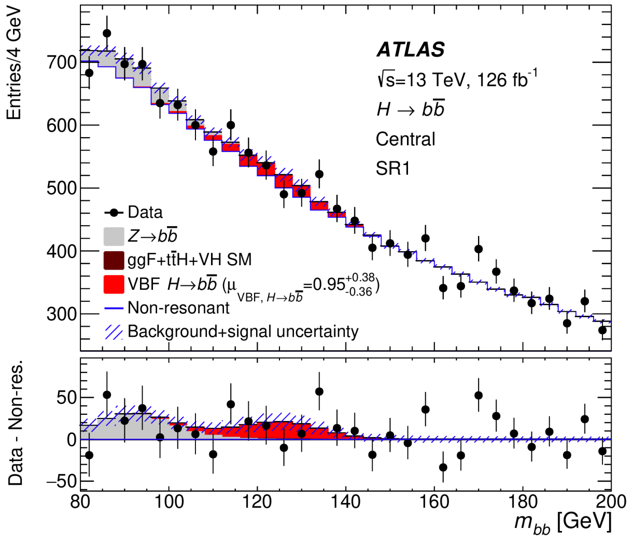
Result	μ_H	μ_Z	$\mu_{t\bar{t}}$
Expected	1.0 ± 3.2	1.00 ± 0.17	1.00 ± 0.07
Observed	0.8 ± 3.2	1.29 ± 0.22	0.80 ± 0.06

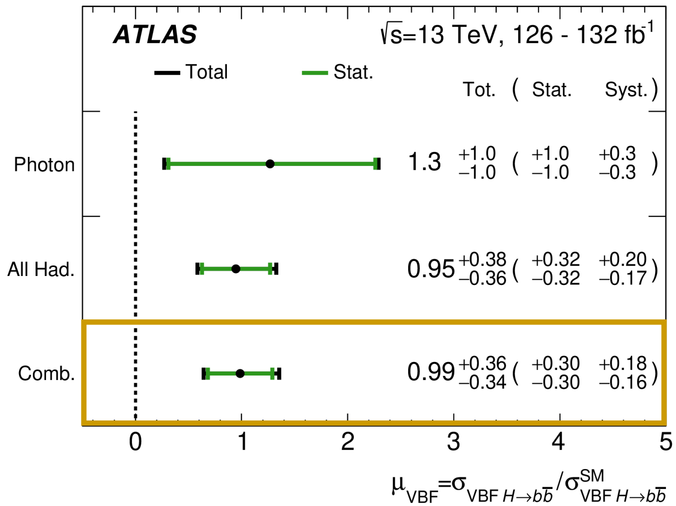


- **Cross-section measurement** performed in **4 STXS bins**
  - **First cross-section measurement in high p_T^H region**
    $\sigma_H\ (p_T^H > 1\text{TeV}) = 2.3 \pm 3.9(\text{stat}) \pm 1.3(\text{syst}) \pm 0.5(\text{th.})$ fb
  - 95% CL limits are set on the cross-sections

VBF, H→$b\bar{b}$ analysis

- **VBF, H→ $b\bar{b}$ all-had** - [Eur. Phys. J. C 81 (2021) 537]
  - Select events with 2 central b-tagged and 2 VBF-like jets
- **VBF, H→ $b\bar{b}$ + photon** - [JHEP 03 (2021) 268]
  - Similar to the inclusive analysis but with an additional photon
    - Multi-jet bkg is suppressed and VBF purity is enriched
- Main bkgs: QCD multi-jet and **Z($b\bar{b}$)+jets**
  - Z($b\bar{b}$)+jets constrained directly from data
- **Machine learning** (BDTs and ANNs) used to **distinguish signal from bkg** and to **define analysis categories**.



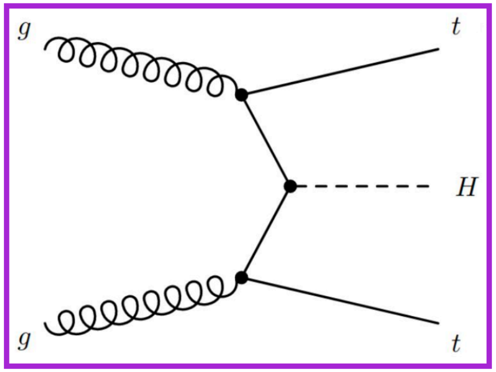


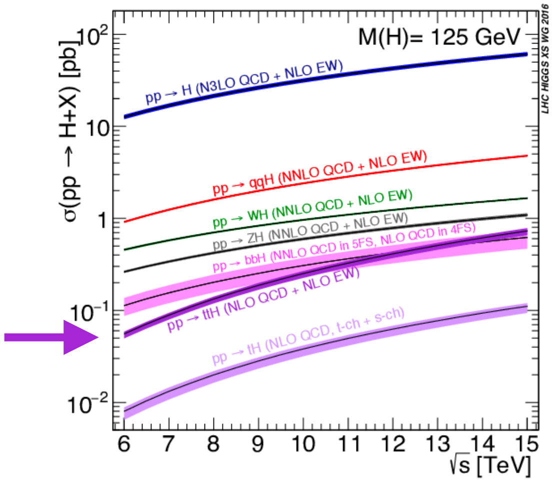
Obs. (exp) significance = 2.9 (2.9) σ

JHEP 06 (2022) 097

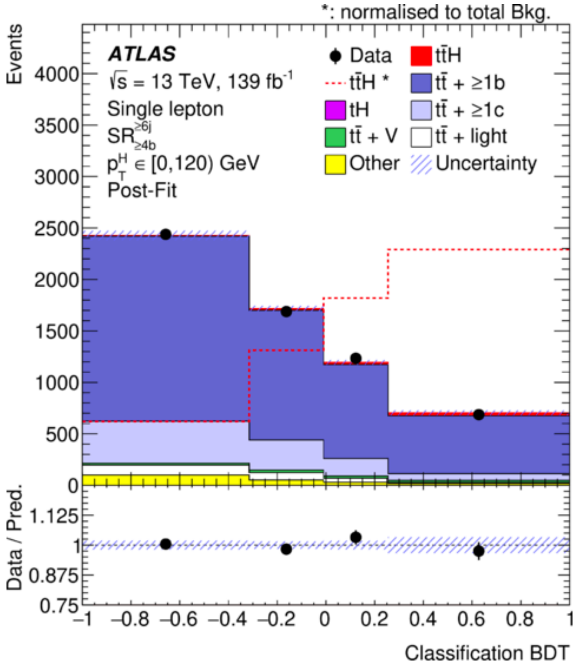
$t\bar{t}H(b\bar{b})$ analysis

- **Top-Yukawa coupling** can be probed **directly** with the $t\bar{t}H$ production
  - Strongest Yukawa coupling





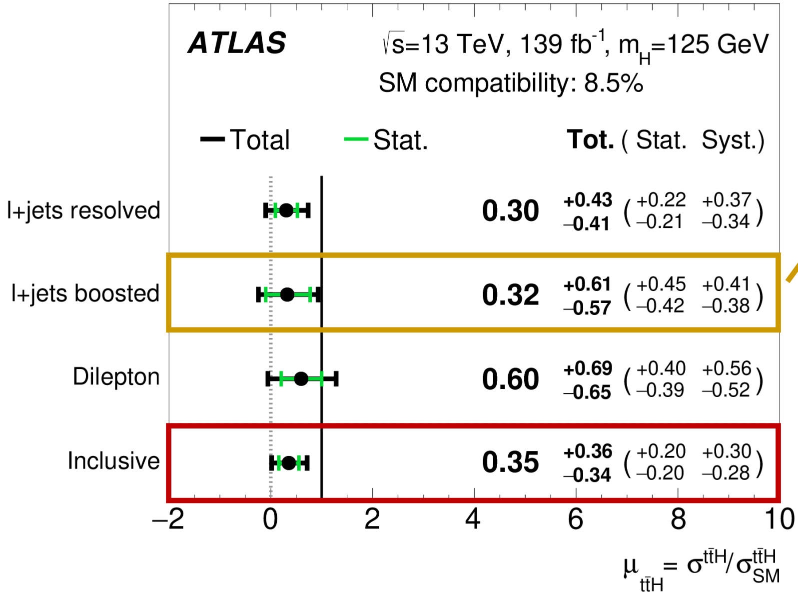
- Target **events with one** (single-lep) or **two** (dilepton) **leptonically decaying tops**
- Events classified according to the number of leptons*, number of jets and number of b-jets
- Machine learning techniques used to classify the events and distinguish $t\bar{t}H$ and bkgs
  - $t\bar{t}$ **+jets** is the **dominant bkg** →constrained using CRs



*lepton = electron or muon

JHEP 06 (2022) 097

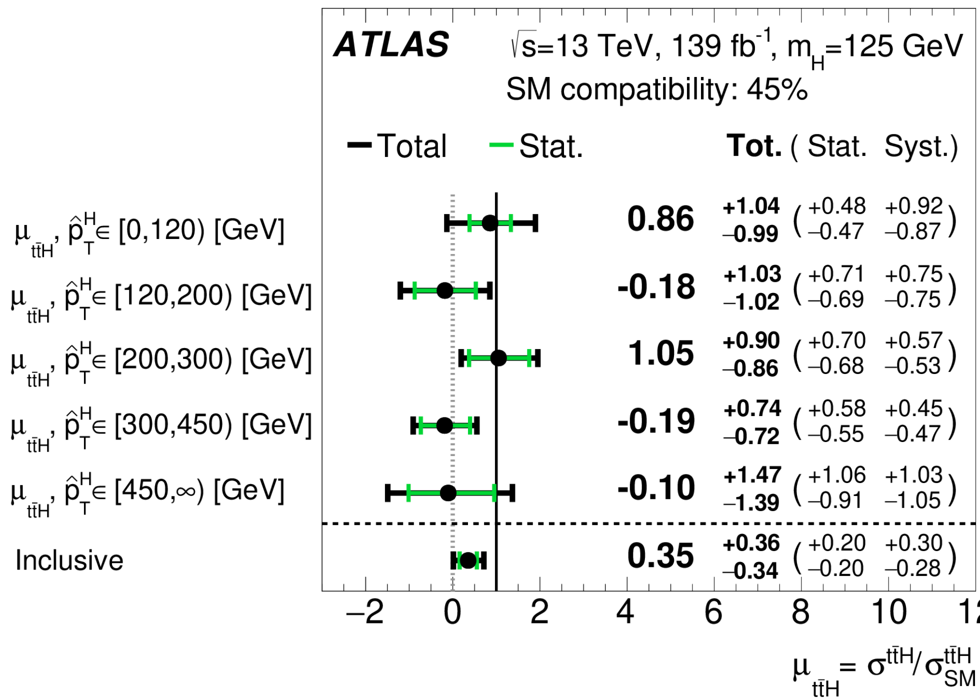
$t\bar{t}H(b\bar{b})$ analysis: results



Boosted category in $p_T^H > 300$ GeV single-lep chan.

- **Profile likelihood fit** to extract μ_{ttH}
- Measurement **dominated by syst unc**.
  - $t\bar{t}$ modelling is the dominant contribution

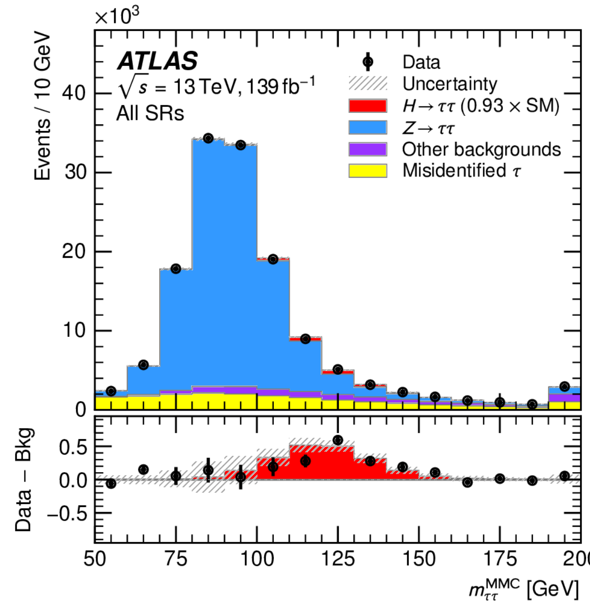
- **Cross-section** measurement in **5 STXS bins**
  - STXS bins defined on **transverse momentum of the Higgs p_T^H**
- **First $t\bar{t}H(b\bar{b})$ STXS cross-section measurements**
- **First cross-section measurement in p_T^H > 300 GeV**

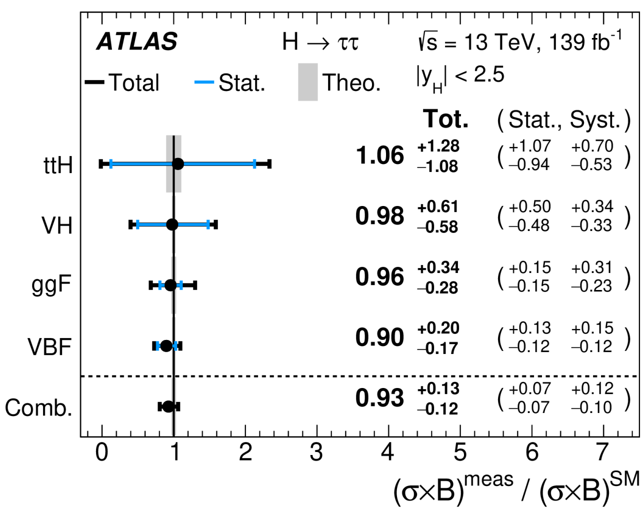


$H \rightarrow \tau\tau$ analysis

- **Most sensitive probe of Higgs boson coupling to leptons**
  - Second most copious fermionic decay (BR ~ 6.3%)
- Analysis **targets** all dominant production modes
- Events classified by τ decay channels.
- **Binned maximum-likelihood fit to $m_{\tau\tau}$**

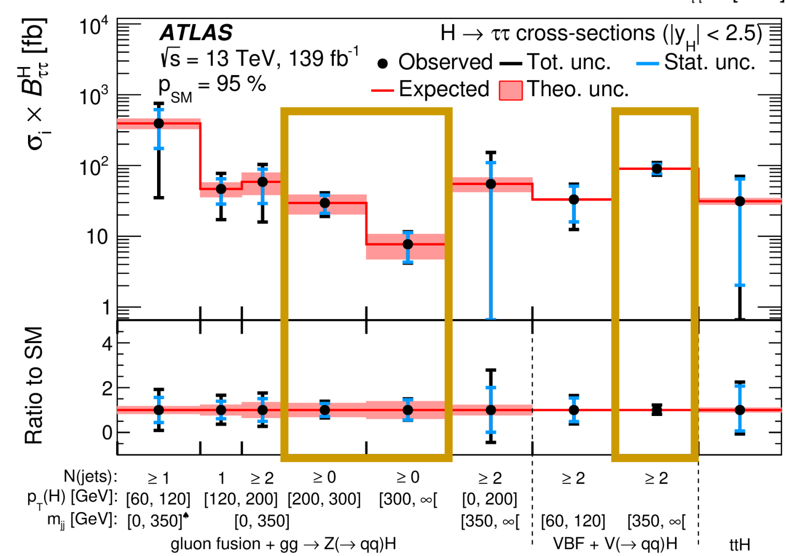
$Z \rightarrow \tau\tau$ is dominant **irreducible bkg**
$\Rightarrow$ $Z \rightarrow \tau\tau$ **CRs** used to extract the normalisation





→ **3.9σ**

→ **5.3σ First VBF $H \rightarrow \tau\tau$ observation**

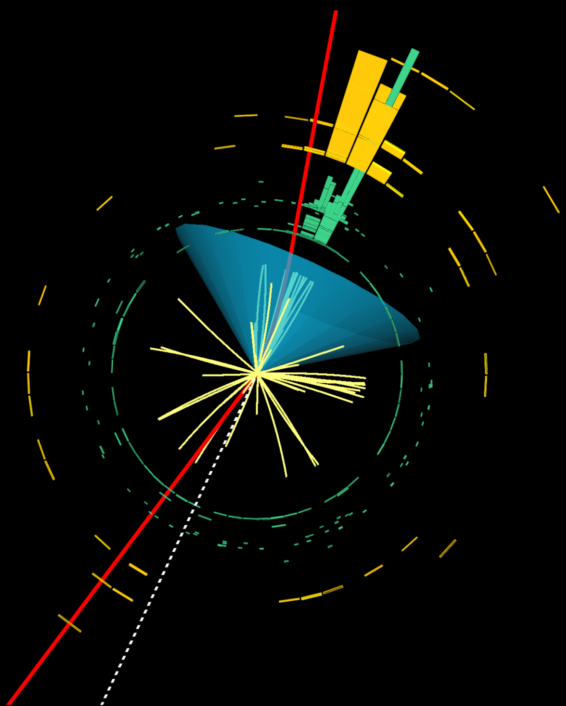


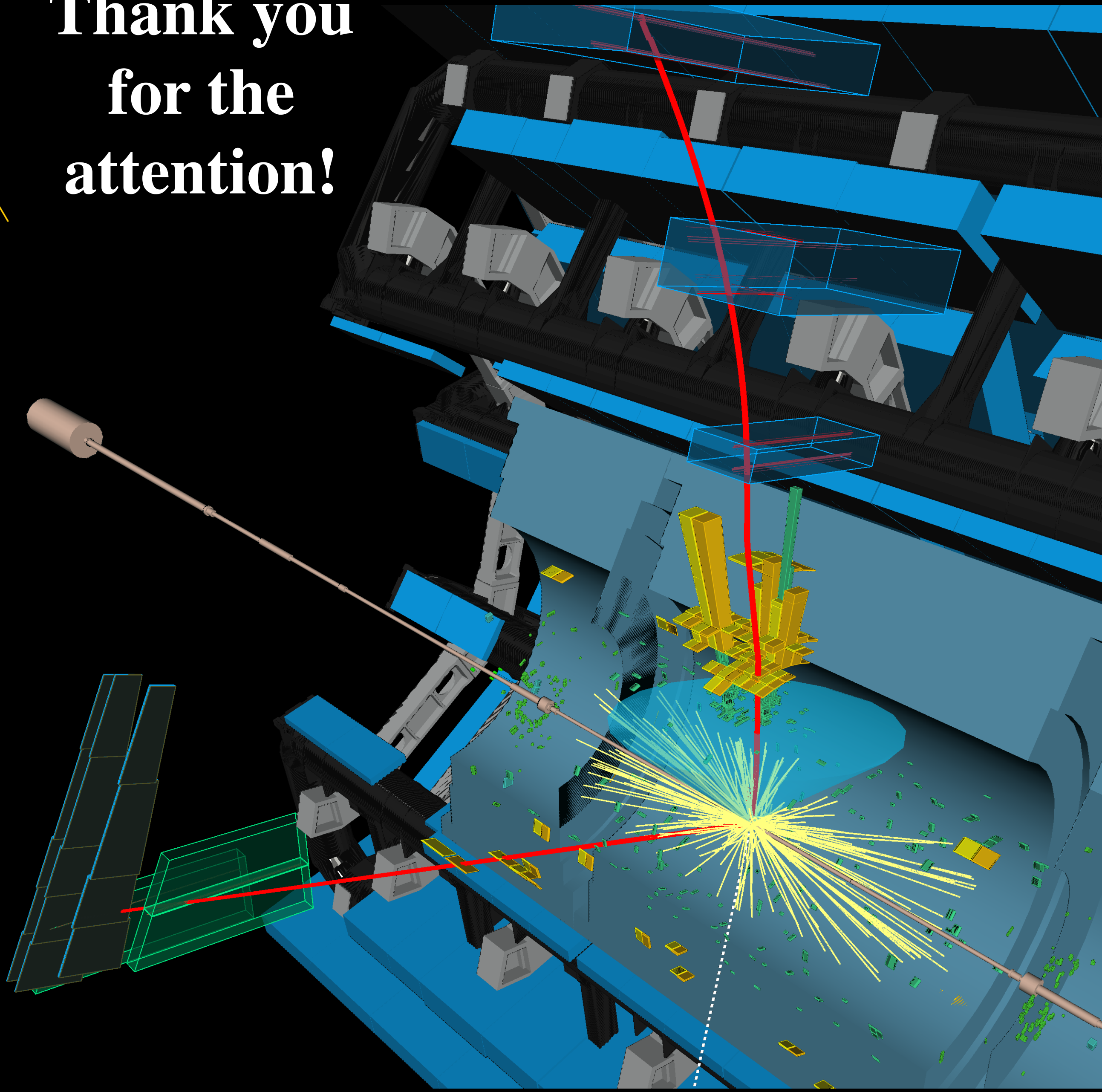
- <u>STXS measurement in 9 STXS bins</u>:
  - **Good agreement with SM prediction**;
  - O(40%) accuracy in some **ggF** and **VBF bins**

Conclusion

- **Higgs decays into fermions** extensively studied using Run 2 analyses
  - Higgs decay into **third generation fermions** offers a **unique opportunity** to study the **Yukawa coupling with fermions**
    - **Couplings to third generation fermions** are very **well established**
  - **Good agreement with the SM predictions**
- **Cross-section measurements** using the Simplified Template Cross-Section framework.
- **Run 3** will offer **exciting opportunity** to further study **fermion couplings** → **stay tuned!**

Thank you for the attention!





ATLAS EXPERIMENT

Run: 338349
Event: 616525246
2017-10-16 20:24:46 CEST

Back-up slides

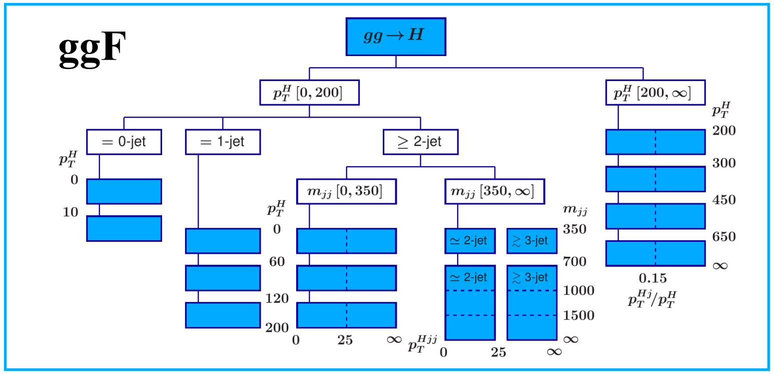
STXS framework

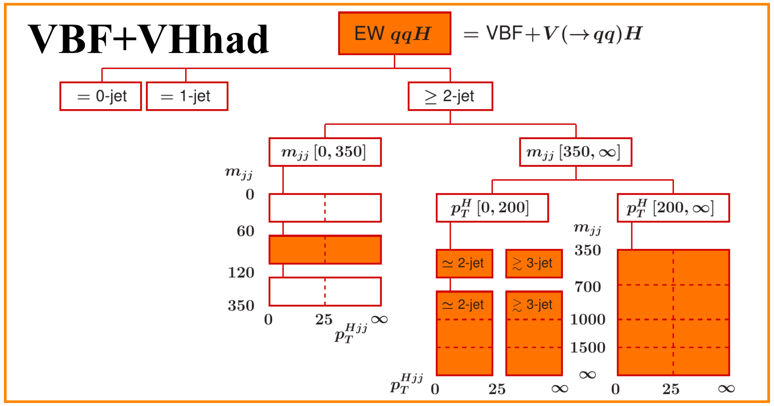
- Framework for **subdividing Higgs Boson measurements into orthogonal regions** - *STXS bins* [defined using generator level information]
  - **($\sigma \times B$) measurement** for each bin

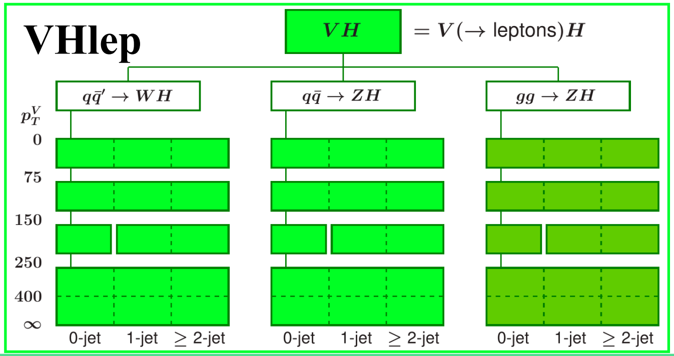
tH

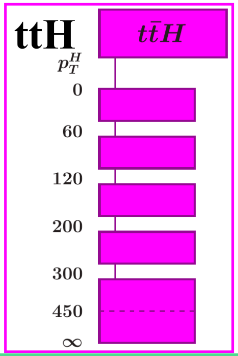
- STXS bins chosen such that they:
  - are **defined by Higgs production modes**;
  - **reduce theory uncertainties**
  - **isolate regions** potentially **sensitive to BSM**;

- STXS stage 1.2 Higgs boson signal split according to
  - production modes,
  - number of jets
  - p_T^H/p_T^V;
  - invariant mass of the leading jets m_{jj}.
- **Advantage**: easy to combine different analyses.





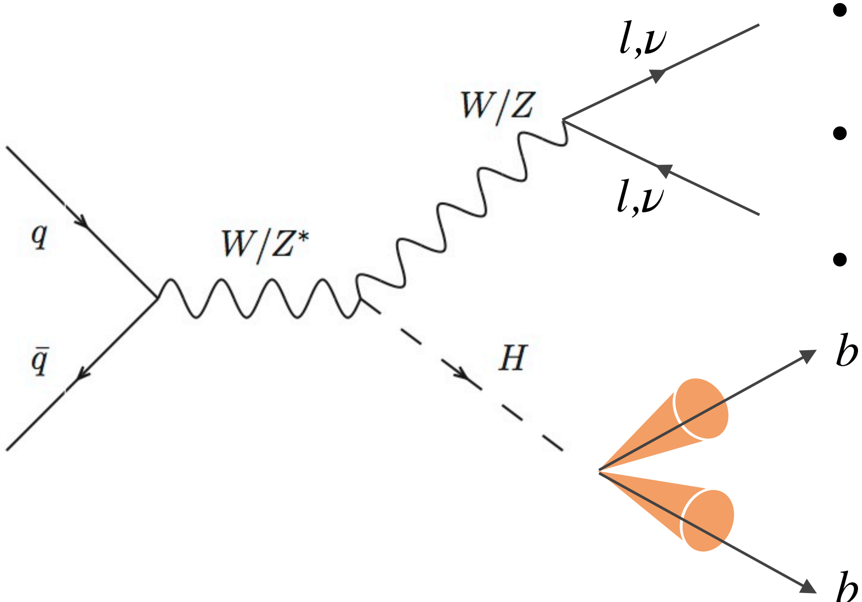




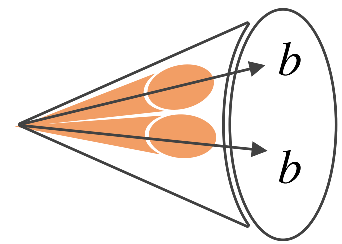
VH($b\bar{b}$) channel

<u>Vector boson candidate reconstruction</u>

- Z $\rightarrow \nu\bar{\nu}$: Missing transverse momentum E_T^{miss}
  ↪ **0-lepton channel (0L)**
- W $\rightarrow l\nu$: 1 charged lepton (e, μ)
  ↪ **1-lepton channel (1L)**
- Z $\rightarrow l\bar{l}$: 2 charged leptons $(ee, \mu\mu)$
  ↪ **2-lepton channel (2L)**



Increase p_T^H



<u>Higgs candidate reconstruction:</u>

<u>Resolved analysis</u>

- Exactly **2 small-R jets** (R=0.4) ***b*-tagged** [70% efficiency for *b*-jets]

<u>Boosted analysis</u>

- **1 large-R jet** (R=1)
- **2 leading track jets *b*-tagged** [70% efficiency for *b*-jets]

EFT cross-section parametrization

- Parameterization of BSM effects using **effective Lagrangian** with **dimension-6 operators** in the Warsaw basis: $\mathscr{L}_{\mathrm{SMEFT}} = \mathscr{L}_{\mathrm{SM}} + \sum_i c_i^{(6)} \cdot \mathcal{O}_i^{(6)} / \Lambda^2$
  - $c_i^{(6)}$ = Wilson coefficient
  - $\mathcal{O}_i^{(6)}$ = dimension-6 operator
  - Λ = BSM scale
- **EFT cross-section parametrisation**

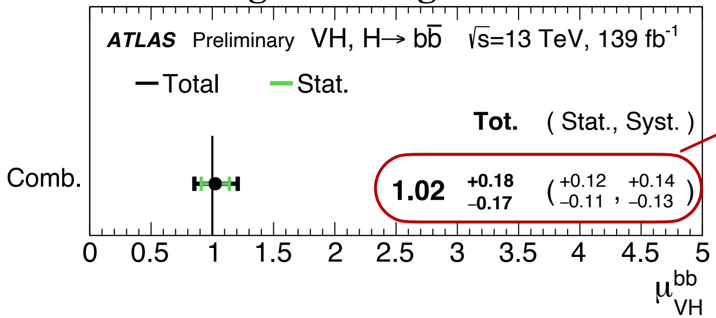
$$\sigma_{EFT} = \sigma_{SM} + \sigma_{int} + \sigma_{BSM}$$

$$\frac{\sigma_{EFT}}{\sigma_{SM}} = 1 + \sum_i A_i c_i + \sum_{ij} B_{ij} c_i c_j$$

Linear term **Quadratic term**

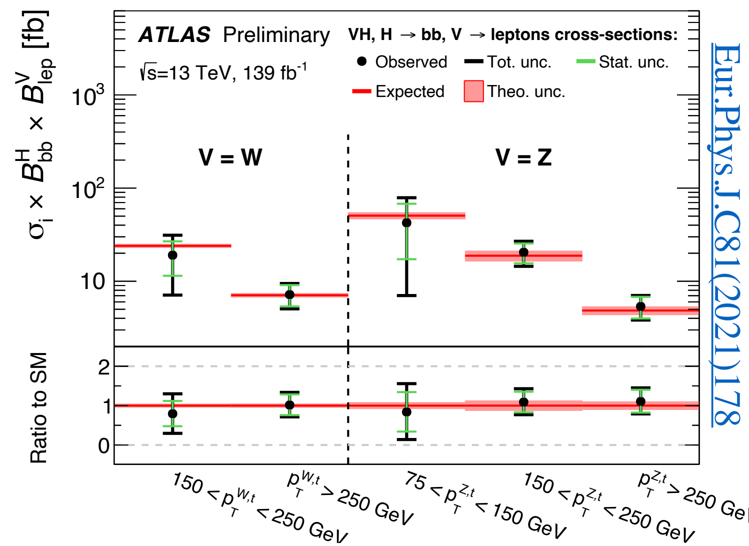
VH($b\bar{b}$) results

Resolved signal strength measurement



Good agreement with SM prediction

Resolved VH(bb) differential XS measurement

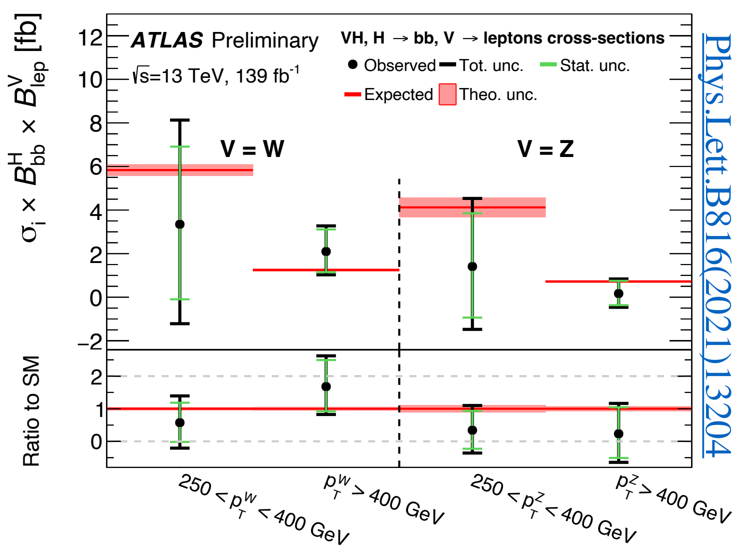


Eur.Phys.J.C81(2021)178

Observed (expected) significance:

- **VH:** 6.7 (6.7) σ
- **WH**: 4.0 (4.1) σ → **strong evidence of WH($b\bar{b}$) production**
- **ZH**: 5.3 (5.1) σ → **observation of ZH($b\bar{b}$) production**

Boosted VH(bb) differential XS measurement



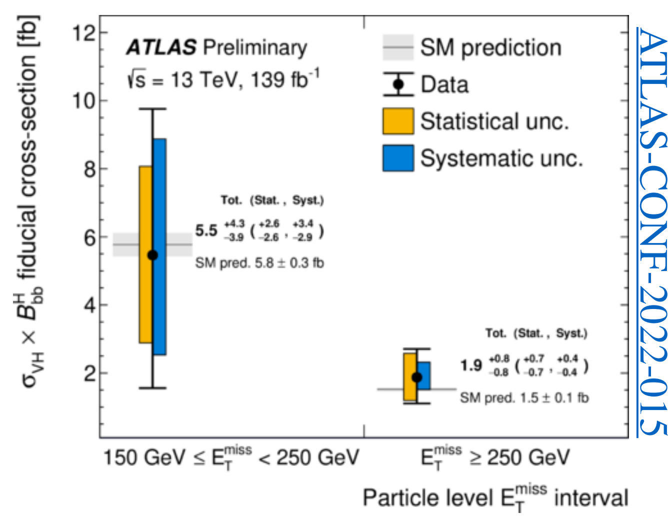
Phys.Lett.B816(2021)13204

Simultaneous extraction of the **VZ($b\bar{b}$) and VH($b\bar{b}$) signal strengths:**

$$\mu_{VZ} = 0.91^{+0.29}_{-0.23}$$

$$\mu_{VH} = 0.72^{+0.39}_{-0.36}$$

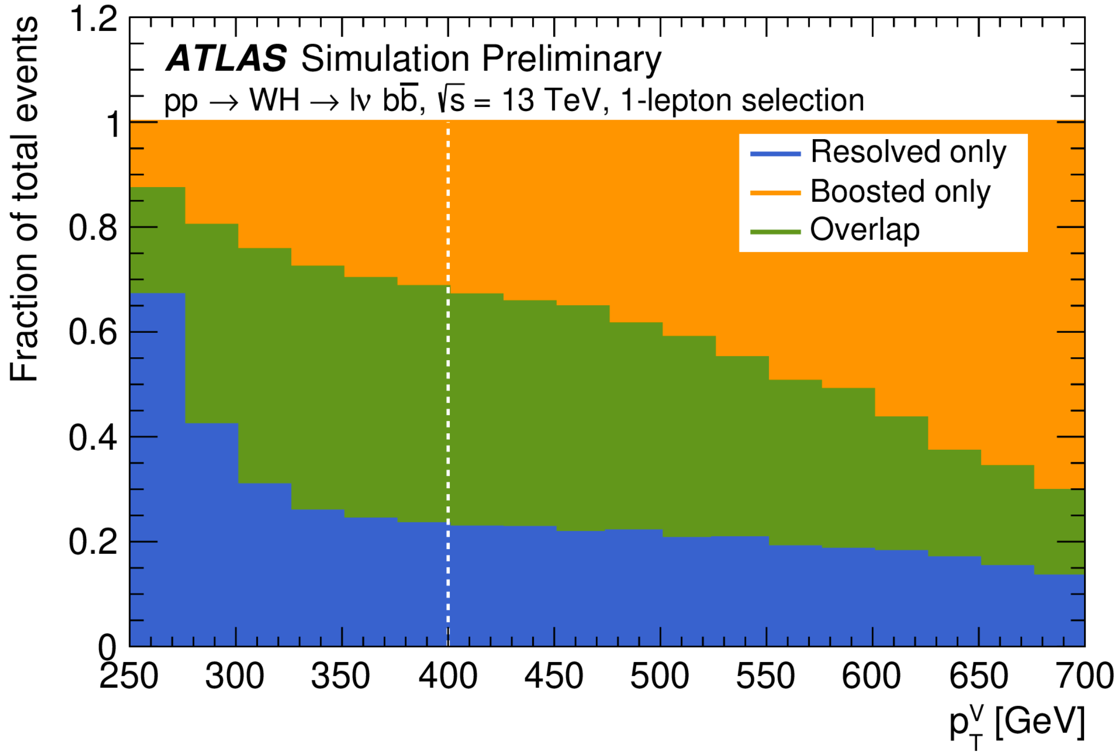
Resolved VH(bb) fiducial XS measurement



ATLAS-CONF-2022-015

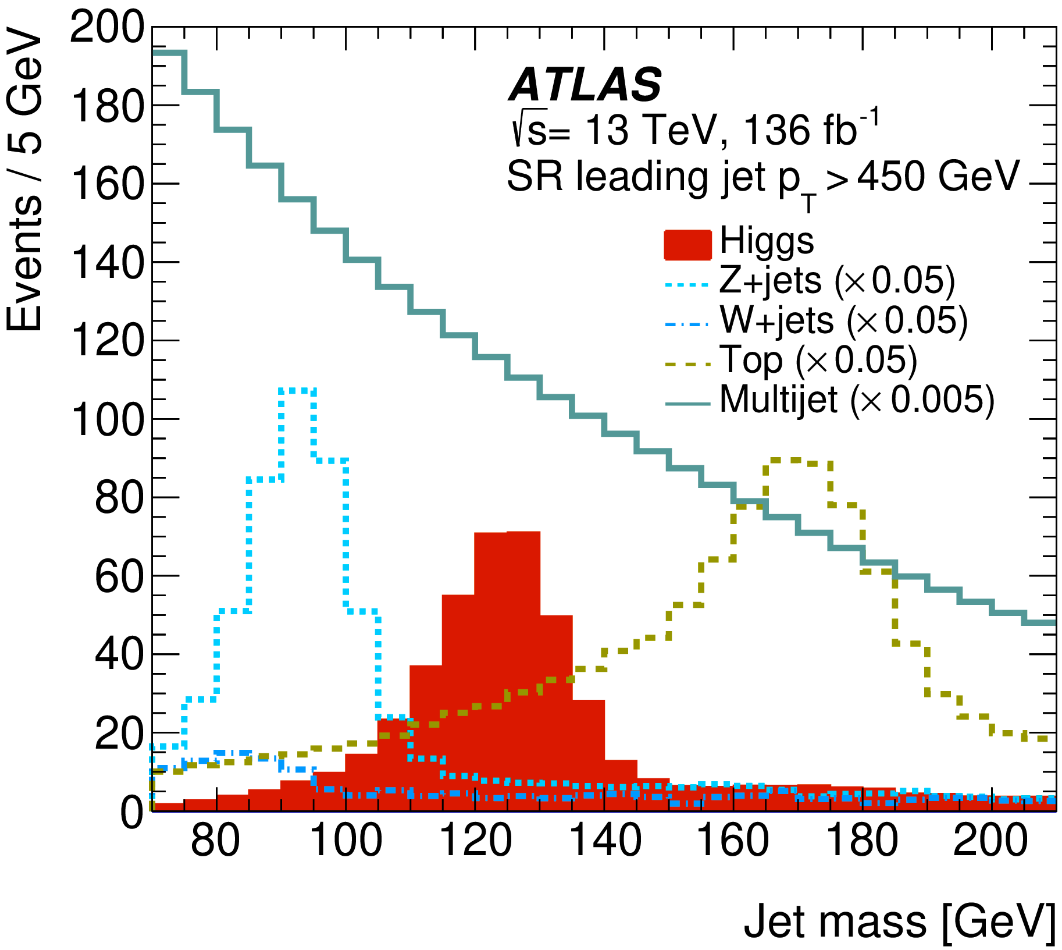
$VH, H \rightarrow b\bar{b}$ combination

ATLAS-CONF-2021-051



- Significant **overlap** between the **VH($b\bar{b}$) resolved** and **VH($b\bar{b}$) boosted analyses**
- In the combination **drop resolved events with p_T^V>400 GeV** and **use boosted only in p_T^V > 400 GeV**

All-had H→$b\bar{b}$ analysis: bkg contributions



Ttbar

- Modelled by Powheg+Pythia8
- Normalization constrained from $CR_{t\bar{t}}$

Single-top

- Modelled using Powheg+Pythia 8

Q/Z+jets

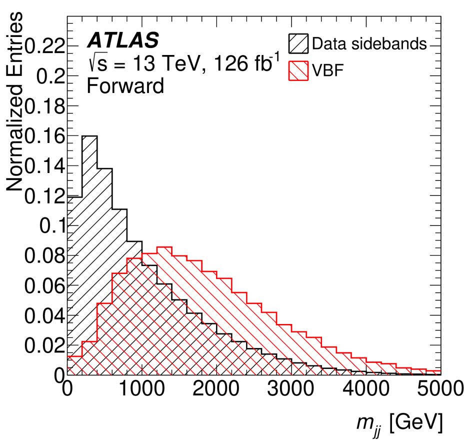
- Shape from Sherpa 2.2.8
- Fully floating during fit (standard candle)

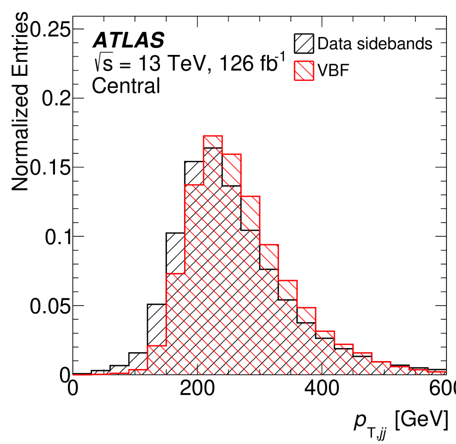
QCD

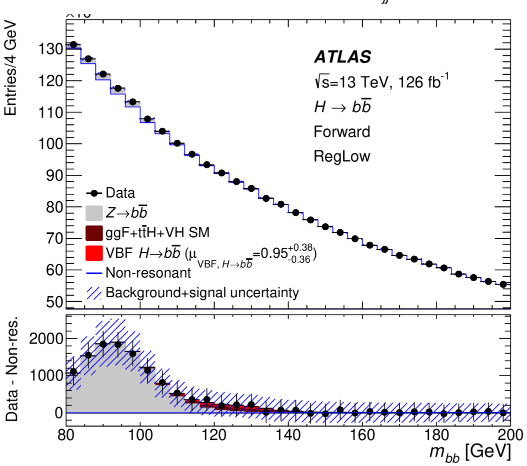
- Fit with a smooth function

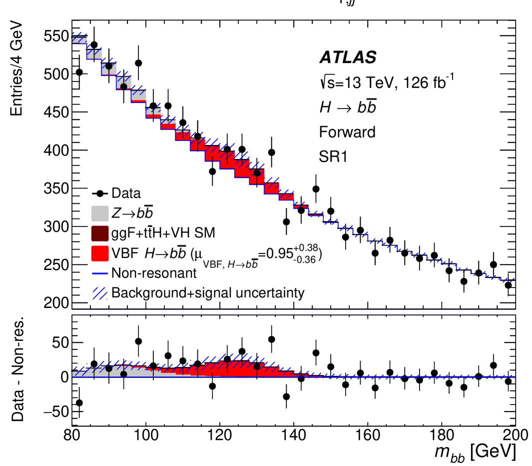
VBF, H→$b\bar{b}$ analysis: event categorisation

- Adversarial Neural Network (**ANN**) for **event categorization**
  - Training performed between MC signal and data sidebands*
  - **Loss function** to penalise m_{bb} and score correlation
  - Each channel is divided into **5 regions**









Input variables:

- m_{jj}
- $p_{T,jj}$
- $p_T^{balance}$
- $(p_T^{j_1} - p_T^{j_2})/(p_T^{j_1} + p_T^{j_2})$
- $\Delta\eta(bb, jj)$
- $\Delta\phi(bb, jj)$
- $\tan^{-1}(\tan(\Delta\phi(bb)/2) / \tanh(\Delta\eta(bb)/2))$
- n_{jets}
- $\min(\Delta R(j_{1(2)}))$
- $N_{trk}^{j_{1(2)}}$

*70 GeV < m_{bb} < 100 GeV and 140 GeV < m_{bb} < 200 GeV

$t\bar{t}H(b\bar{b})$ analysis: analysis regions

Region	Dilepton				Single-lepton			
	$SR^{\geq 4j}_{\geq 4b}$	$CR^{\geq 4j}_{3b\ hi}$	$CR^{\geq 4j}_{3b\ lo}$	$CR^{3j}_{3b\ hi}$	$SR^{\geq 6j}_{\geq 4b}$	$CR^{5j}_{\geq 4b\ hi}$	$CR^{5j}_{\geq 4b\ lo}$	$SR_{boosted}$
#leptons	$= 2$				$= 1$			
#jets	≥ 4			$= 3$	≥ 6	$= 5$		≥ 4
#b-tag @85%	–				≥ 4			
#b-tag @77%	–				–			$\geq 2^{\dagger}$
#b-tag @70%	≥ 4	$= 3$			≥ 4			–
#b-tag @60%	–	$= 3$	< 3	$= 3$	–	≥ 4	< 4	–
#boosted cand.	–				0			≥ 1
Fit input	BDT	Yield			BDT/Yield	ΔR^{avg}_{bb}		BDT

H → $\tau\tau$ analysis: STXS uncertainty

STXS bin				SM prediction	Result	Stat. unc.	Syst. unc. [fb]		
Process	m_{jj} [GeV]	$p_T(H)$ [GeV]	N_{jets}	[fb]	[fb]	[fb]	Th. sig.	Th. bkg.	Exp.
ggF + $gg \to Z(\to qq)H$	[0, 350]♠	[60, 120]	≥ 1	394 ± 60	189 ± 390	±220	±59	±152	±240
		[120, 200]	$= 1$	47 ± 11	17 ± 30	±18	±4	±4	±16
	[0, 350]	[120, 200]	≥ 2	59 ± 20	33 ± 39	±27	±10	±10	±23
		[200, 300]	≥ 0	30 ± 9	30.3 ± 11.0	±8.6	±2.9	±0.8	±5.6
		[300, ∞[	≥ 0	7.7 ± 3.0	9.35 ± 3.80	±3.50	±1.00	±0.22	±1.20
	[350, ∞[	[0, 200]	≥ 2	55 ± 13	143 ± 110	±54	±58	±6	±71
EW	[60, 120]		≥ 2	33.1 ± 1.1	32 ± 20	±17	±4	±2	±6
	[350, ∞[		≥ 2	90.1 ± 2.2	71 ± 17	±13	±10	±2	±4
$t\bar{t}H$				31.3 ± 3.2	34 ± 37	±32	±7	±10	±8