Higgs boson couplings to quarks at the ATLAS experiment

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FPCP 2019, Victoria, Canada

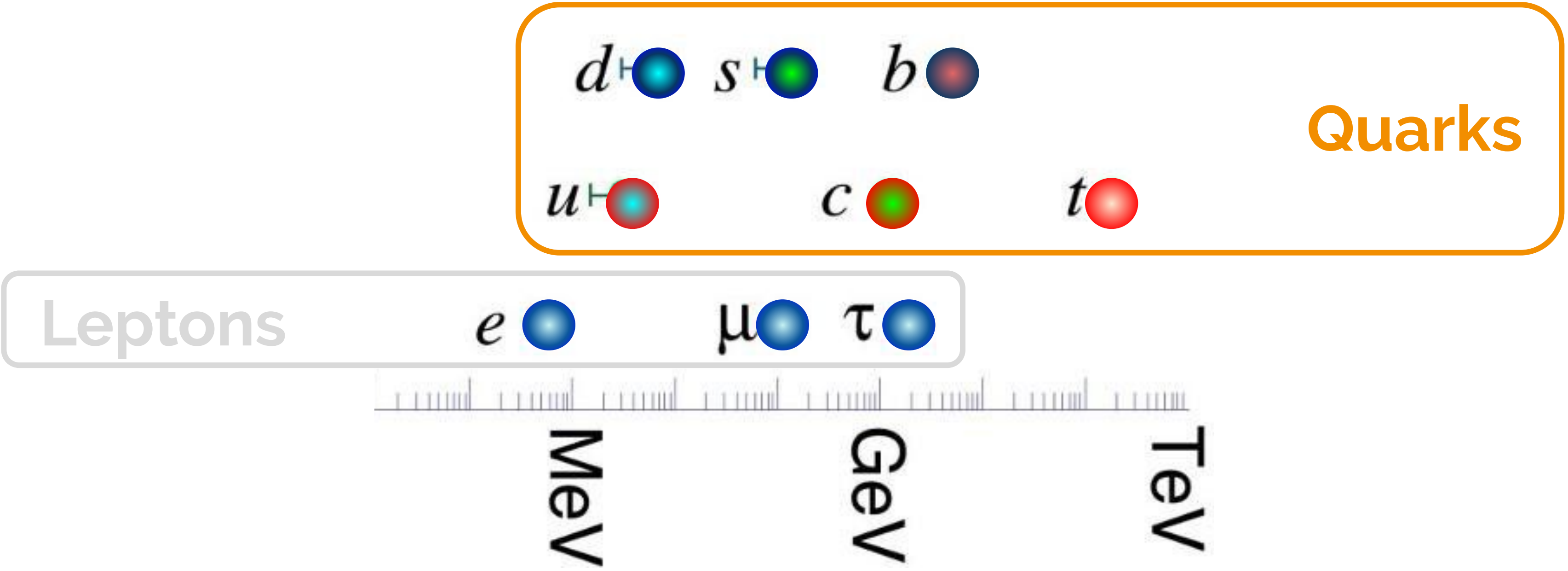
HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

DESY.

ATLAS EXPERIMENT

Outline

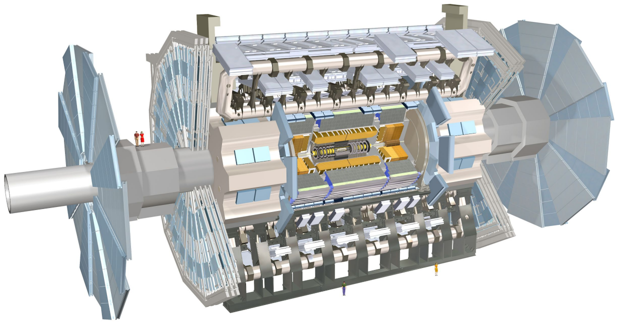
- Probing Higgs boson couplings with **quarks** at LHC proton-proton collider



Outline

- With the **ATLAS** experiment, first results on Higgs boson couplings:

  = heavriest quarks **top**, **bottom**, **charm**



Higgs boson couplings to:

this talk

Outline

- With the **ATLAS** experiment, first results on Higgs boson couplings:

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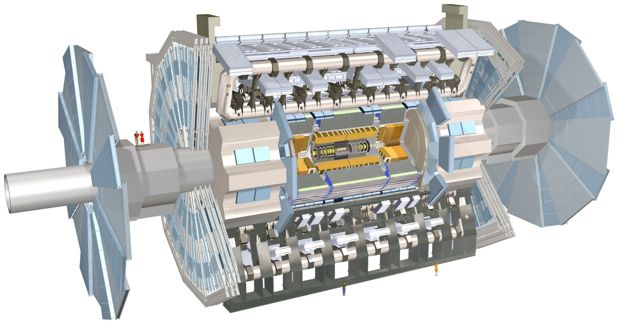
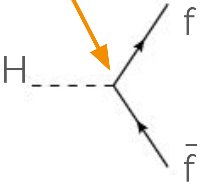


Higgs boson couplings to: *b* *c* *t*

this talk

- Yukawa couplings proportional to fermion masses: $y_{ij} \sim \sqrt{2}\,\frac{m_f}{v}$

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}D\!\!\!/\,\psi + |D_\mu\phi|^2 - V(\phi) + \boxed{\bar{\psi}_i\, y_{ij}\, \psi_j\, \phi} + h.c.$$



Fermion couplings unconstrained (added ad-hoc)

Higgs boson coupling with the top quark

Top Yukawa coupling

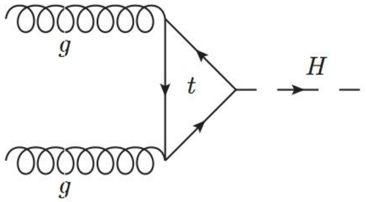
- **Measured at Run 1** (7 & 8 TeV) by ATLAS & CMS
  arXiv: [1606.02266](1606.02266)

$$y_t = 0.87^{+0.15}_{-0.13}$$ **× SM prediction**

- but results depends on **top quark contributions to loops** in:
  - gluon fusion (main Higgs production mode at LHC) →
  - di-photon decay

Gluon-gluon fusion

87%



- Direct access at tree-level (test of physics beyond Standard Model) through:

"ttH production mode"

ttH observation, 80 fb^{-1}

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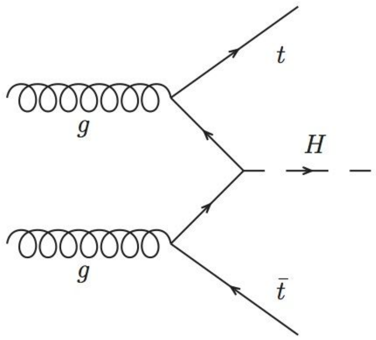
- ttH production mode → direct access to top Yukawa coupling at tree-level

How? Combination of the **big five** decay channels

→ most sensitive with ATLAS, not necessarily on branching ratios



ttH production

Rare: < 2%

γγ	→ reconstruction Higgs candidate to high resolution (detailed later)	0.23 %
ZZ → 4 leptons	reconstruction Higgs candidate to high resolution (detailed later)	2.64 % ← all ZZ; ZZ→ 4l: 1.185 × 10^{-4}
ττ	from "ttH multilepton" search 1712.08891	6.26 %
WW	from "ttH multilepton" search 1712.08891	21.5 %
bb	→ dedicated search "ttH , H → bb" 1712.08895	58.1 %

Simultaneous fit to signal & control regions of individual analyses

ttH observation, 80 fb^{-1}, results

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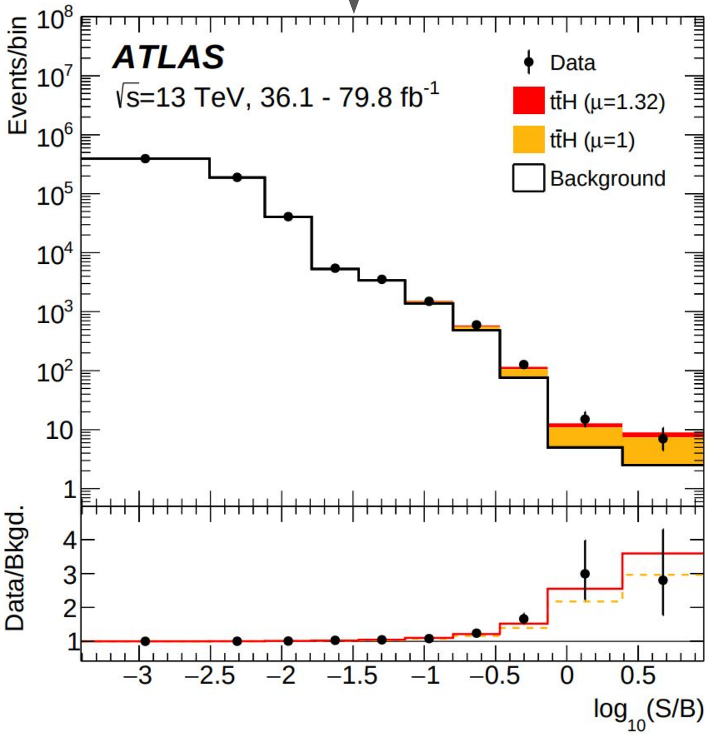
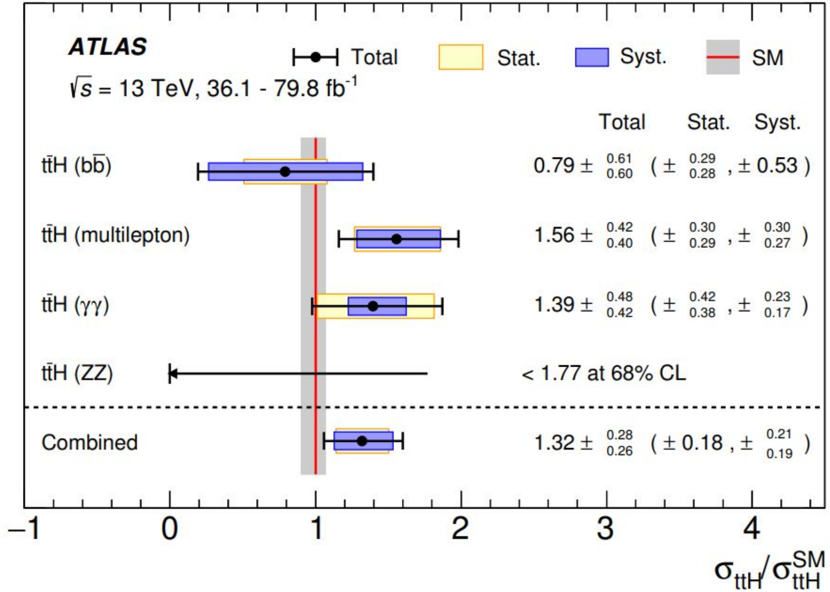
Combined event yields in all analysis categories. Background extracted from fit, with freely floating signal



Observed

SM



- Main uncertainties: tt + bb (cc) & ttH modelling
- **Observed ttH significance of 6.3 σ** (5.1 σ expected)
- consistent with SM expectations

ttH measurement: H → γγ , 140 fb^{-1}

ATLAS-CONF-2019-004

- First **full Run 2 data** Higgs result, enough luminosity in **H → γγ channel alone** for a ttH measurement

- Events split in:
  - **Hadronic** events: ≥ 1 b-jet, ≥ 3 jets, 0 lepton → BDT Hadronic
  - **Leptonic** events: ≥ 1 b-jet, ≥ 1 lepton → BDT Leptonic

7 BDT slices = signal-enriched regions

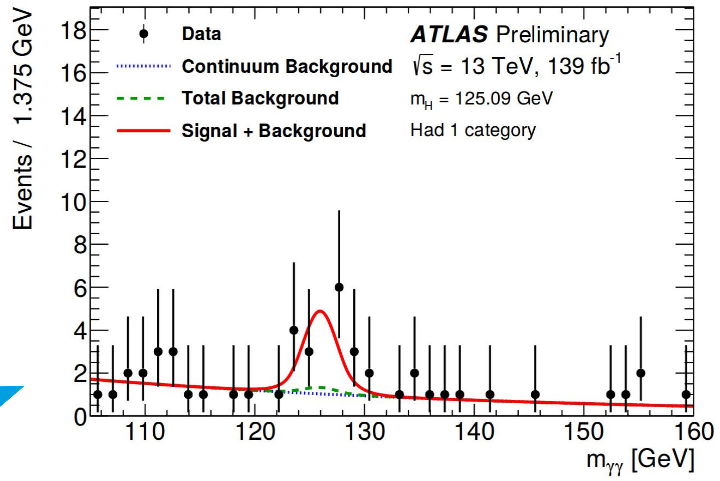
Had 1	Had 2	Had 3	Had 4

Lep 1	Lep 2	Lep 3

- Backgrounds:
  - non-resonant diphoton (ttbar + γγ)
  - non-ttH Higgs production modes (100% uncertainty)

- Simultaneous **fit of $m_{\gamma\gamma}$ in each BDT slice**:
  - Unbinned fit 105 < $m_{\gamma\gamma}$ < 160 GeV
  - Shapes S & B → modelled by analytical functions

Fit example in BDT bin Had 1 (most sensitive)



ttH measurement: H → γγ , 140 fb^{-1}

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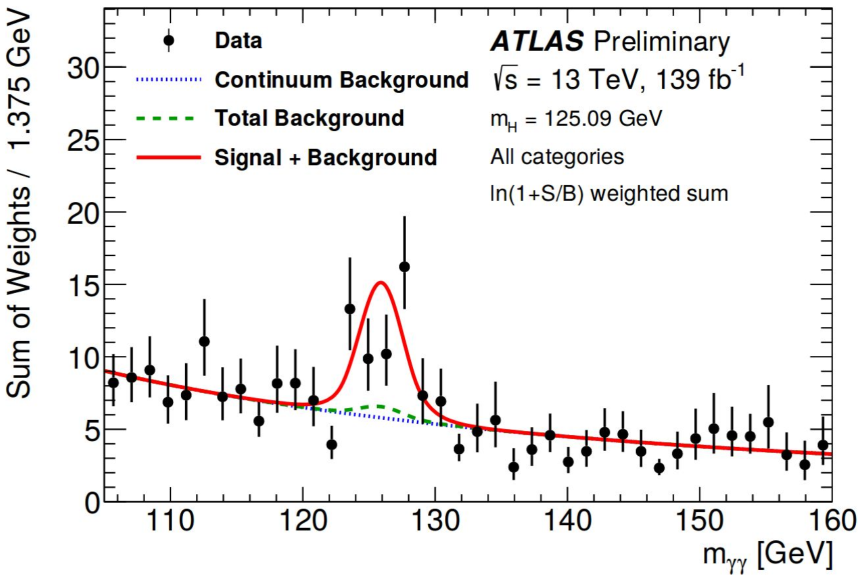
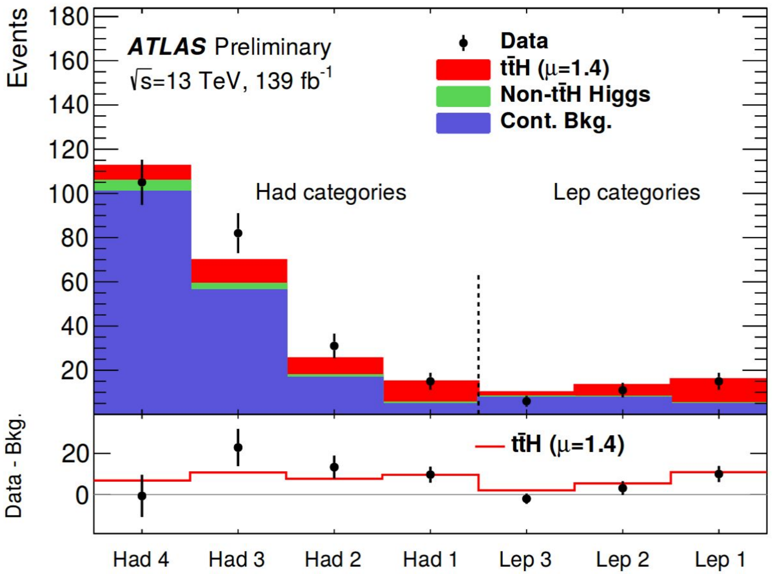
Weighted yields by ln(1 + S/B) in all BDT bins



Post-fit data yields in each BDT bin (= category)

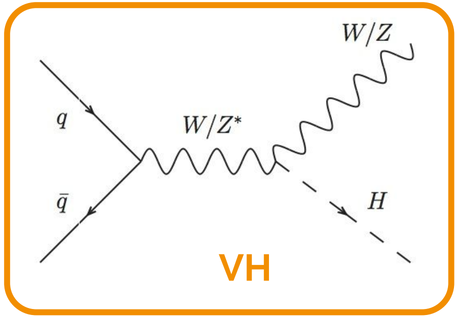


- **Observed ttH significance: 4.9 σ** (4.2 σ expected)
- Before with 80 fb^{-1} : **4.1 σ** (3.7σ)
- Consistent with SM expectations:

$$\mu_{ttH} = 1.38 \,^{+0.33}_{-0.31}\,(\text{stat.})\,^{+0.13}_{-0.11}\,(\text{exp.})\,^{+0.22}_{-0.14}\,(\text{th.})$$

Higgs boson coupling with the bottom quark

VH, H → bb , 80 fb^{-1}



Large multijet background!

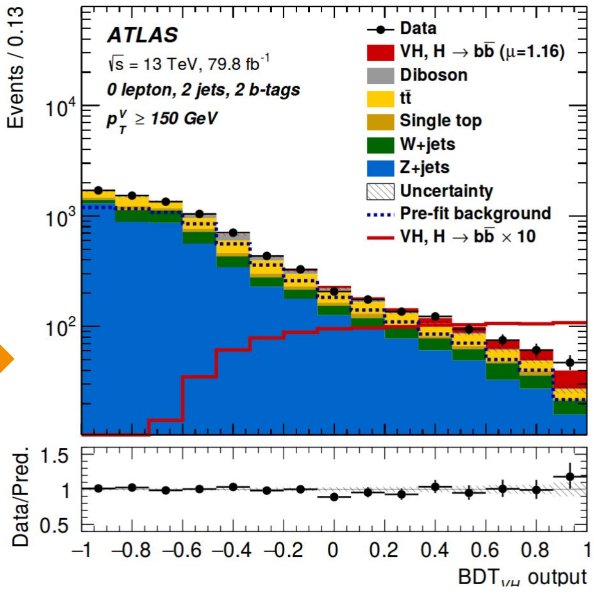
Reduced:

- Events split by W/Z boson **leptonic decays**
- Large **boost** of the Higgs boson

ZH → ννbb	0 lepton
WH → ℓνbb	1 lepton
ZH → ℓℓ bb	2 leptons

- **b-jet tagger** + correction methods to improve m_{bb} resolution
- Main **backgrounds**: **W+jets , $t\bar{t}$** , single top
- Boosted Decision Trees (**BDT**) to reduce background

  trained separately in each region example 0 lepton →



- Simultaneous **profile likelihood fit** performed in **8 SR + 6 CR**

  to extract signal strength μ

VH, H → bb , 80 fb^{-1}

arXiv 1808.08238 Phys. Lett. B 786 (2018) 59

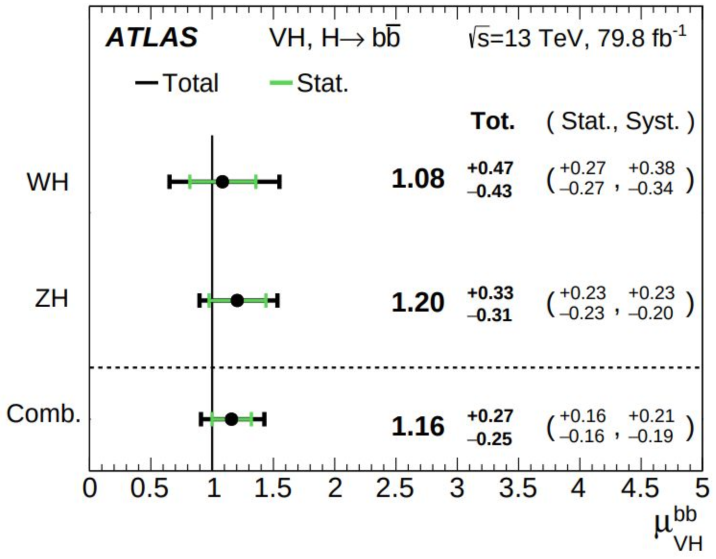
- Run 2 results at √s = 13 TeV:

$$\mu_{VH}^{bb} = 1.16^{+0.27}_{-0.25} = 1.16 \pm 0.16(\text{stat.})^{+0.21}_{-0.19}(\text{syst.})$$

Main uncertainties:
Experimental: b-tagging
Theory modeling: W/Z + jets
$t\bar{t}$

details in backups

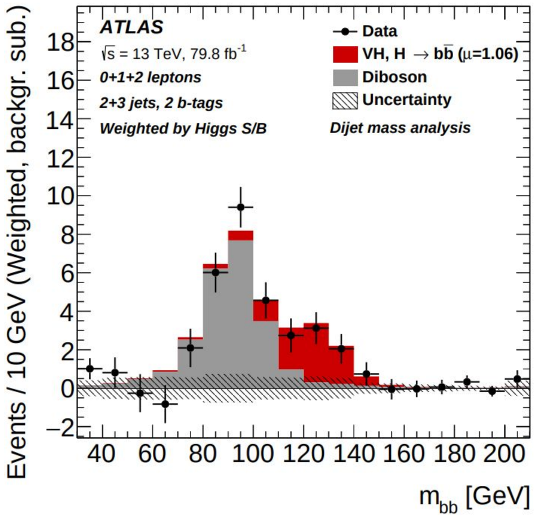
- Combined fit with separate floating signal strengths μ_{WH} and μ_{ZH}



Significances

Observed	Expected
2.5 σ	2.3 σ
Linear correl. -1%	
4.0 σ	3.5 σ
4.9 σ	**4.3 σ**

Di-jet mass distribution in all regions (all backgrounds except WZ and ZZ)

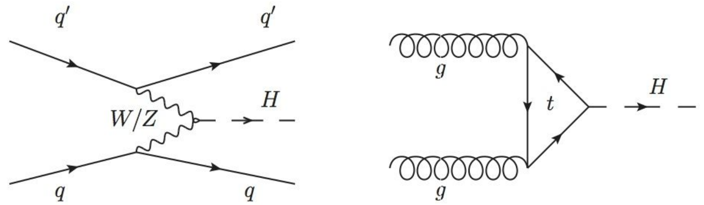


Observation of H → bb decays

[arXiv 1808.08238](https://arxiv.org/abs/1808.08238) Phys. Lett. B 786 (2018) 59

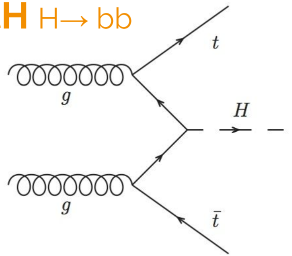
- Combination of analyses targeting H → bb from different Higgs production modes:

VBF + ggF



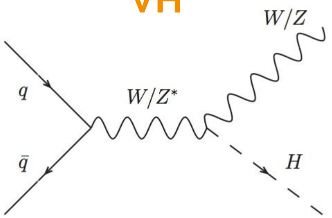
Run 1 & 2, Phys. Rev. D 98 (2018) 052003

ttH H→ bb



Phys. Rev. D 97 (2018) 072016

VH



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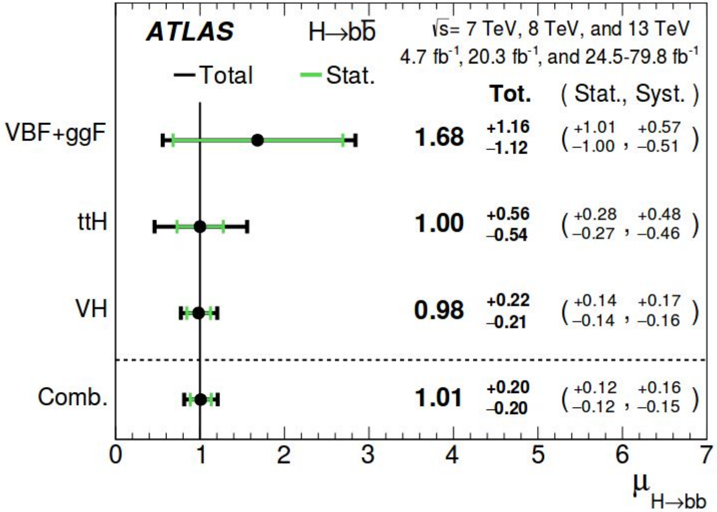
- Simultaneous fit: all signal strength μ floating independently

- Results compatible with Standard Model



Significances

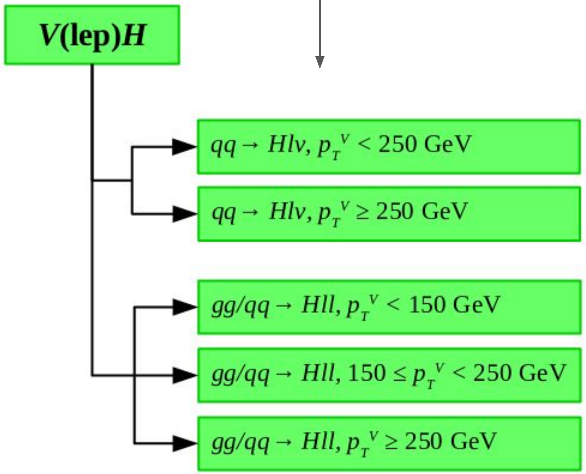
	Observed	Expected
VBF+ggF	1.5 σ	0.9 σ
ttH	1.9 σ	1.9 σ
VH	4.9 σ	5.1 σ
Comb.	**5.4 σ**	**5.5 σ**

Measurement VH, H → bb 80 fb^{-1}

arXiv 1903.04618

- using **simplified template cross-sections (STXS)** framework to measure cross-section:
  - Split in Higgs production modes & further splitting in fiducial regions based on Higgs kinematics
  - Split-stages: **increasing granularity** with the increased integrated luminosity (enough stat)

- STXS truth categories split in **reconstructed vector boson p_T bins**



Event selected using BDTs trained in each category

⇒ exploiting correlations

Pros of STXS framework

✓ enhanced sensitivity
✓ smaller theor. uncertainties
✓ less model dependance
✓ easier to interpret (EFT)
✓ access BSM (high p_T bin)
✓ allows BDT, ML techniques

Systematic uncertainties assessed in ATL-PHYS-PUB-2018-035

Measurement VH, H → bb, 80 fb^{-1}

arXiv 1903.04618

- 5 measurements of **WH and ZH cross-section** in **p_T^V regions** → optimized sensitivity for each BDT
- Largest **uncertainties: statistical**
- **good agreement with SM**

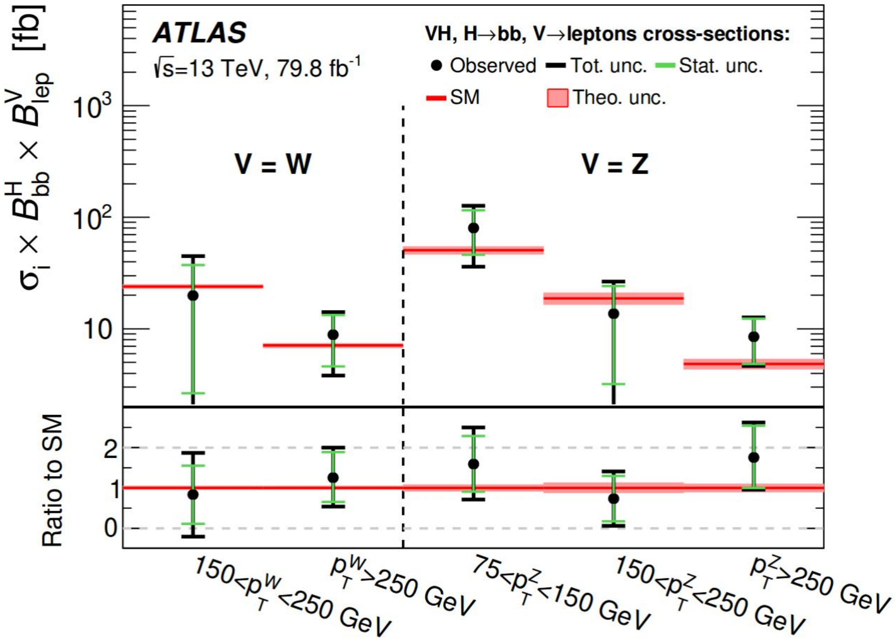
- Limits used to constrain Effective Lagrangian:

$$\mathcal{L} = \mathcal{L}_{SM} + \sum c_i \mathcal{O}_{6i} / \Lambda_{NP}^2$$

focus on coefficients of operators of "Strongly Interacting Higgs" formulation (paper)

⇒ constrain down-type quark ~ unity

more details in talk at Higgs coupling conference



⇒ measurements can be combined with other decay channels of STXS framework

Combining Higgs boson production and decay

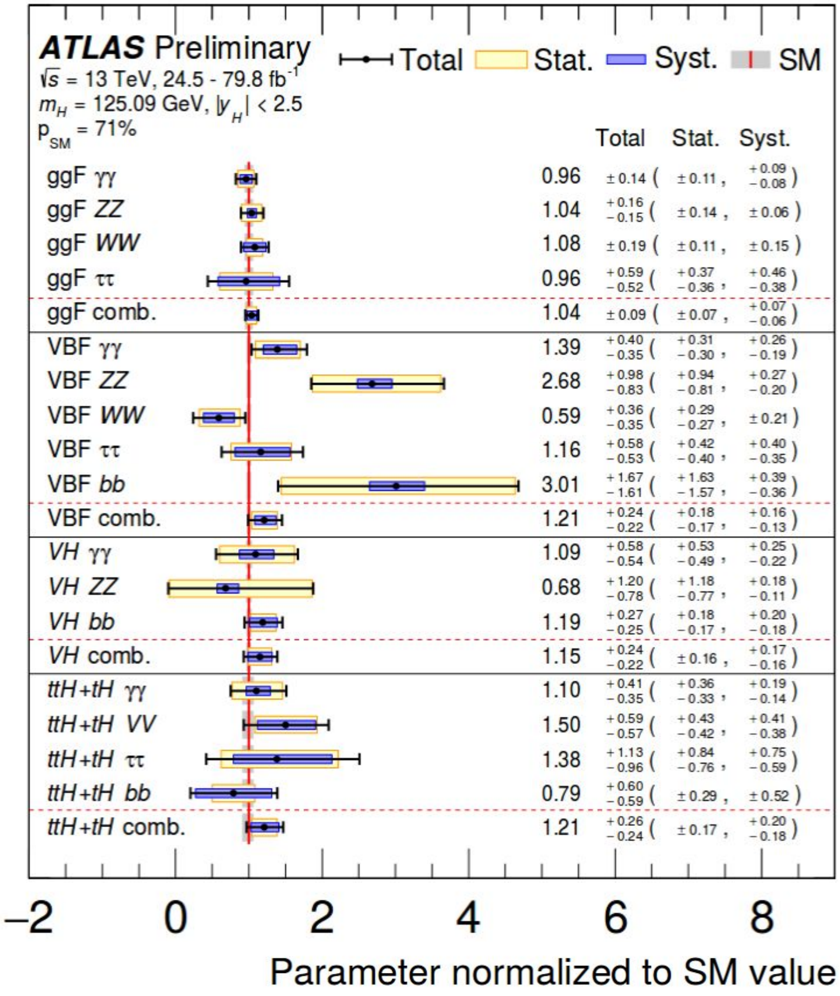
Best precision to date

Combined Higgs measurements 80 fb^{-1}

Production cross-sections in each decay channel

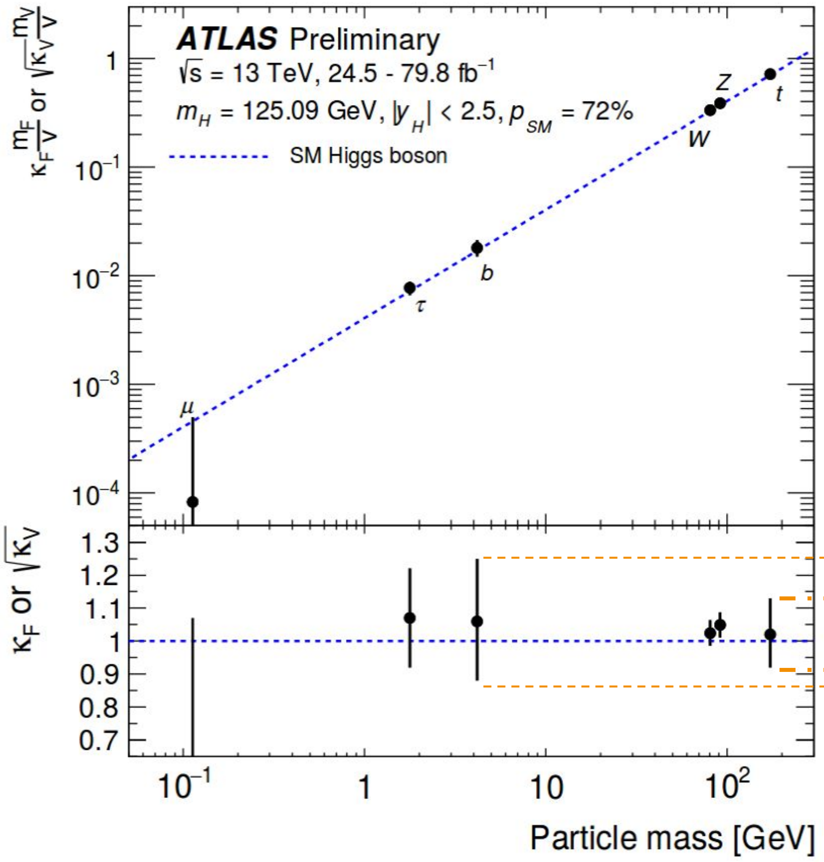
- Now **all production modes** assessed (ttH observed)
- Good **compatibility** among decay channels
- **Consistent with SM**

ATLAS-CONF-2019-005



Couplings vs quark masses

ATLAS-CONF-2019-005



- Kappa framework ⟶ assigning coefficient κ_F and κ_V = coupling modifiers for each interaction vertex

  Standard Model ⟷ $\kappa_F = \kappa_V = 1$

- Here:
  - all coupling scale factors treated **independently**
  - **only SM particles** contribute to Higgs width

$\kappa_t = 1.02^{+0.11}_{-0.10}$ **±10%**

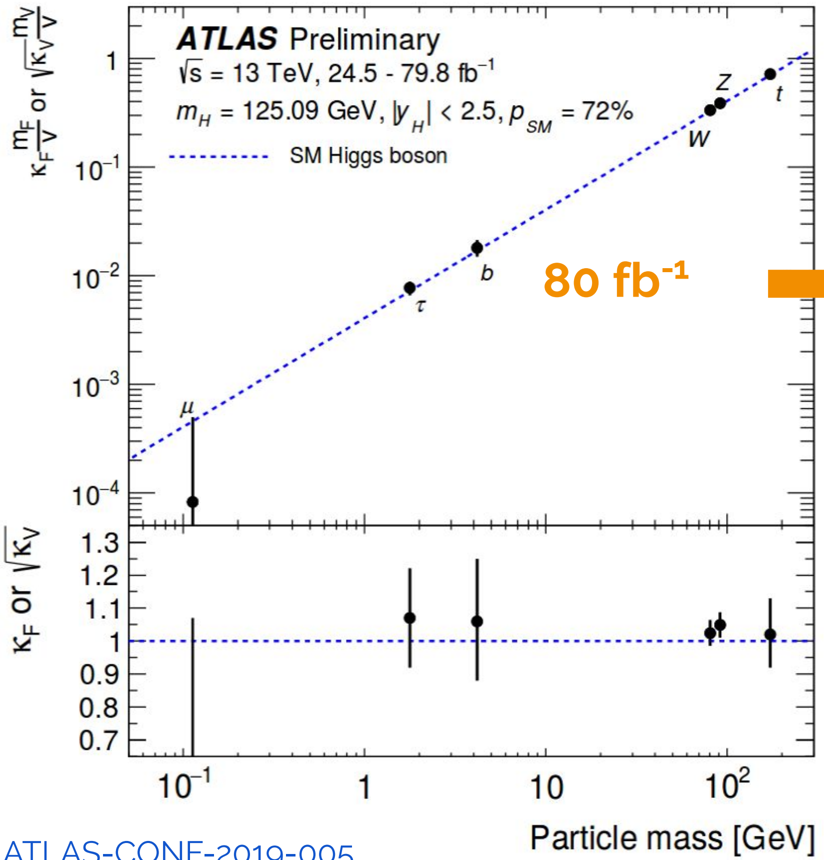
$\kappa_b = 1.06^{+0.19}_{-0.18}$ **±20%**

Couplings compatible with SM expectations

And with more data?

80 fb^{-1} → 3000 fb^{-1}

Projections with 3000 fb^{-1}, end of High-Luminosity LHC



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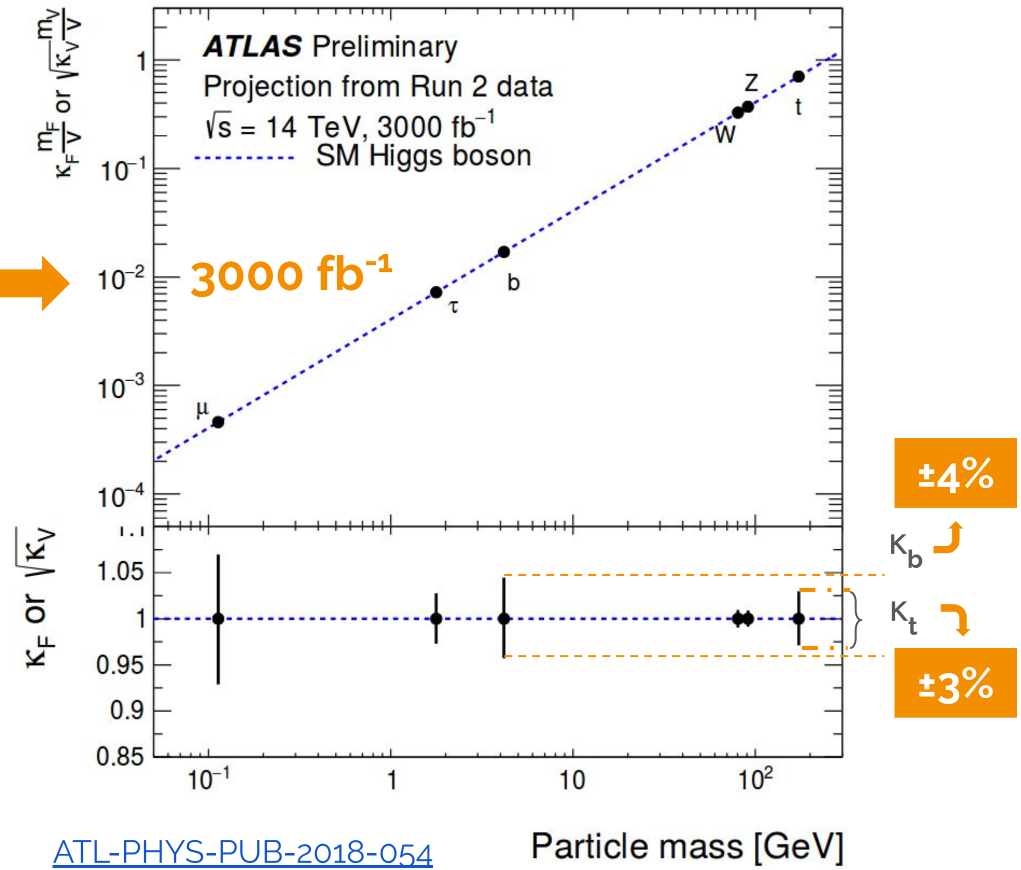

ATL-PHYS-PUB-2018-054

Summary

ATLAS **Run 2 at 13 TeV: fruitful** past two years, **2 observations papers** and 2 measurements follow-up

Measurements on couplings with top, bottom and quark **compatible with SM**.

t

Observation of ttH — 80 fb^{-1}

https://arxiv.org/abs/1806.00425

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Measurement of ttH — 140 fb^{-1}

ATLAS-CONF-2019-004

(channel $H \rightarrow \gamma\gamma$ only)

Full Run 2

b

Observation of VH → bb — 80 fb^{-1}

https://arxiv.org/abs/1808.08238

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Measurement of VH → bb — 80 fb^{-1}

https://arxiv.org/abs/1903.04618

Submitted to Phys. Lett. B.

c

Search for VH → cc — 36 fb^{-1}

https://arxiv.org/abs/1802.04329

Phys. Rev. Lett. 120 (2018) 211802

Combination Higgs boson production & decay — 80 fb^{-1}

ATLAS-CONF-2019-005

NEW!

Feb 2018 — Jun 2018 — Aug 2018 — Mar 2019

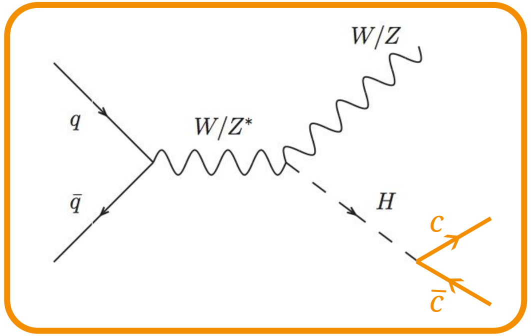
Extra

Higgs boson coupling with the charm quark

Using a charm tagger

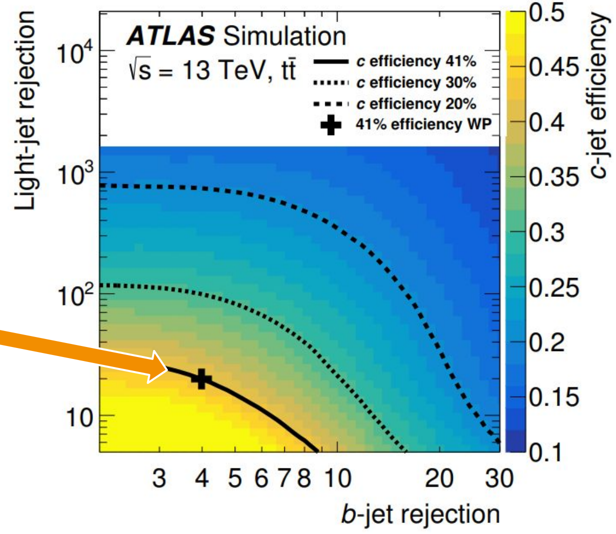
VH, H → cc , 36.1 fb^{-1}

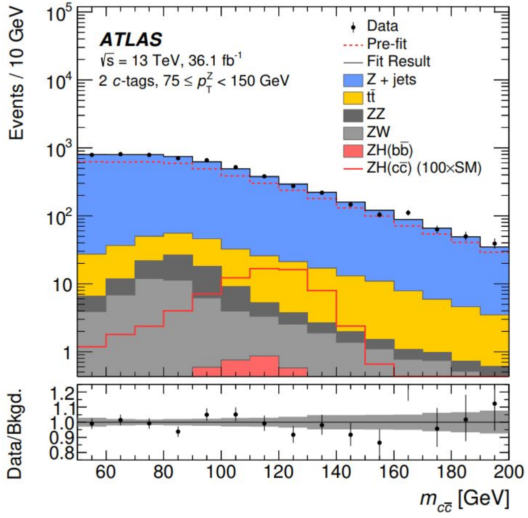
[Phys. Rev. Lett. 120 (2018) 211802]

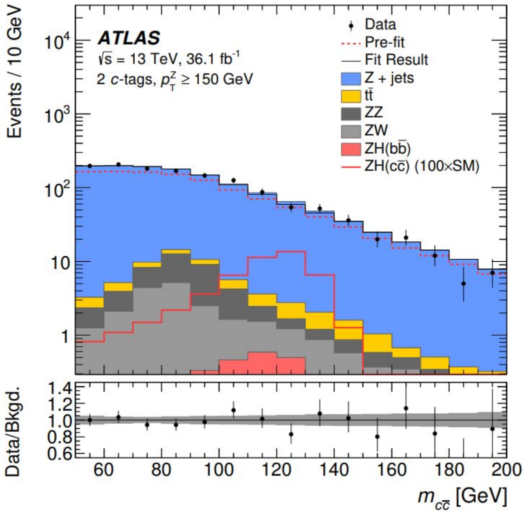


- Process: ZH → cc ℓℓ
- Dedicated **charm tagger** identifying jets from c quark

Working point: 41% efficiency from ttbar simulated events







- categories defined with **reco Z p_T**
- 4 regions of different signal purities
- Final discriminant = $\mathbf{m_{cc}}$

VH, H → cc , 36.1 fb^{-1}

Phys. Rev. Lett. 120 (2018) 211802

- Dominant uncertainties:

Source	σ/σ_{tot}
Statistical	**49%**
Floating Z + jets normalization	31%
Systematic	**87%**
Flavor tagging	73%
Background modeling	47%
Lepton, jet and luminosity	28%
Signal modeling	28%
MC statistical	6%

Procedure validated measuring diboson production

Fraction ZW, W → cs, sd = 65%

Fraction ZZ, Z → cc = 55%

in 2 c-tags region

Diboson μ_{ZV} = **$0.6^{+0.5}_{-0.4}$** significance **1.4 σ** observed

2.2 σ expected

- **First limit on Higgs coupling to 2nd generation quarks**

- Upper limit σ (pp → ZH) × BR(H → cc) = **2.7 pb** observed at 95% CL

$3.9^{+2.1}_{-1.1}$ pb expected

σ_{SM} = 0.026 pb

Challenging to measure even at High-Lumi LHC

[Numbers] VH, H → cc , 36.1 fb^{-1}

Phys. Rev. Lett. 120 (2018) 211802

- Dedicated **charm tagger** identifying jets from c quark

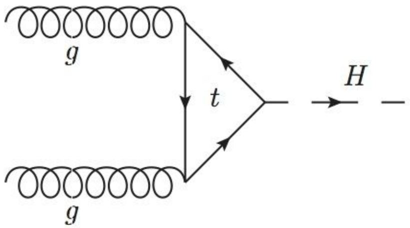
Efficiencies & uncertainties →

Working point	c	b	l
Efficiency c	41%	-	-
Rejection b/l	-	4	20
Uncertainty	25%	5%	20%

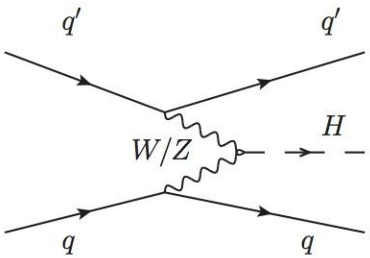
Sample	Yield, 50 $GeV < m_{c\bar{c}} < 200$ GeV			
	1 c-tag		2 c-tags	
	$75 \le p_T^Z < 150\,GeV$	$p_T^Z \ge 150\,GeV$	$75 \le p_T^Z < 150\,GeV$	$p_T^Z \ge 150\,GeV$
$Z+$jets	69400 ± 500	15650 ± 180	5320 ± 100	1280 ± 40
ZW	750 ± 130	290 ± 50	53 ± 13	20 ± 5
ZZ	490 ± 70	180 ± 28	55 ± 18	26 ± 8
$t\bar{t}$	2020 ± 280	130 ± 50	240 ± 40	13 ± 6
$ZH(b\bar{b})$	32 ± 2	19.5 ± 1.5	4.1 ± 0.4	2.7 ± 0.2
$ZH(c\bar{c})$ (SM)	-143 ± 170 (2.4)	-84 ± 100 (1.4)	-30 ± 40 (0.7)	-20 ± 29 (0.5)
Total	72500 ± 320	16180 ± 140	5650 ± 80	1320 ± 40
Data	72504	16181	5648	1320

← Post-fit yields

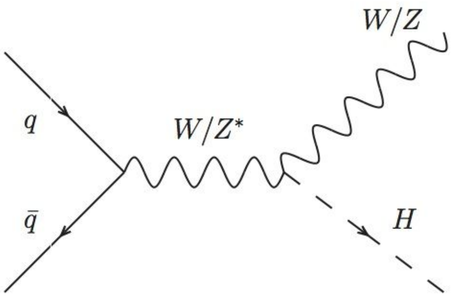
Higgs boson production modes at the LHC



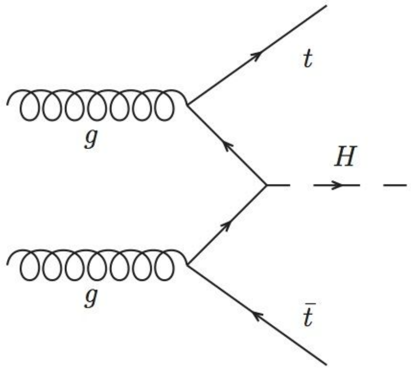
ggF
gluon-gluon Fusion
87%



VBF
Vector Boson Fusion
7%



VH
Associated with W or Z
4%



ttH
Associated with ttbar
2%

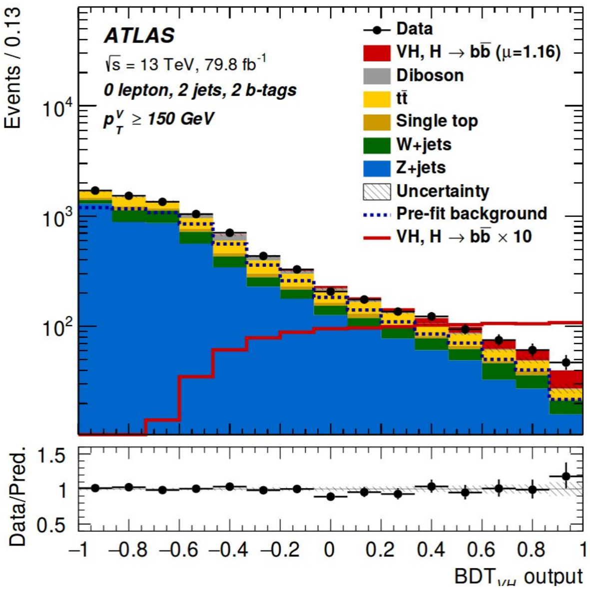
- Direct access (tree level) to top Yukawa coupling through **ttH production mode** — but rare
- Top quark = heaviest fermion ➡ most strongly-coupled to Higgs boson ➡ window to physics beyond SM

VH, H → bb , 80 fb^{-1}

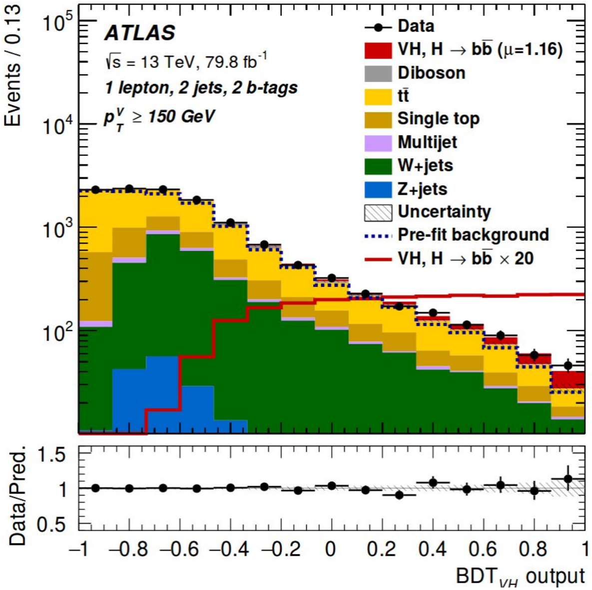
arXiv 1808.08238 Phys. Lett. B 786 (2018) 59

- Boosted Decision Trees (BDT) to further discriminate the background (trained separately for each region)

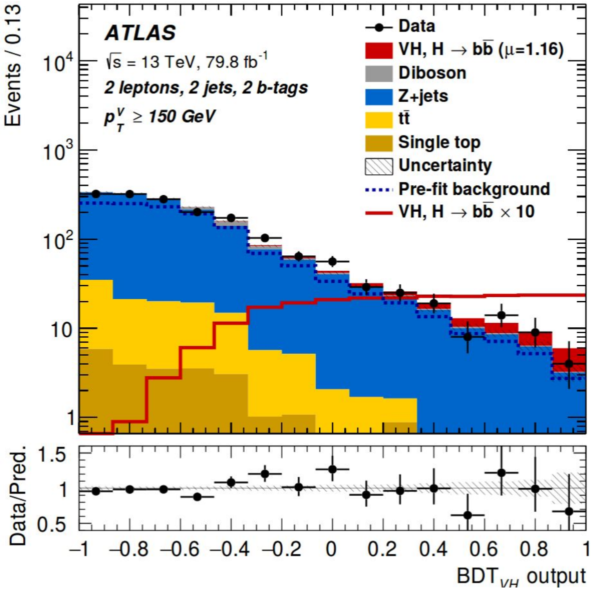
0 lepton



1 lepton



2 leptons



- Simultaneous **profile likelihood fit** performed in **8 SR + 6 CR** ⇒ extracting signal strength μ

VH, H → bb 80 fb^{-1}

arXiv 1808.08238 Phys. Lett. B 786 (2018) 59

- Run 2 results at √s = 13 TeV

Source of uncertainty	σ_μ
Total	0.259
Statistical	0.161
Systematic	0.203

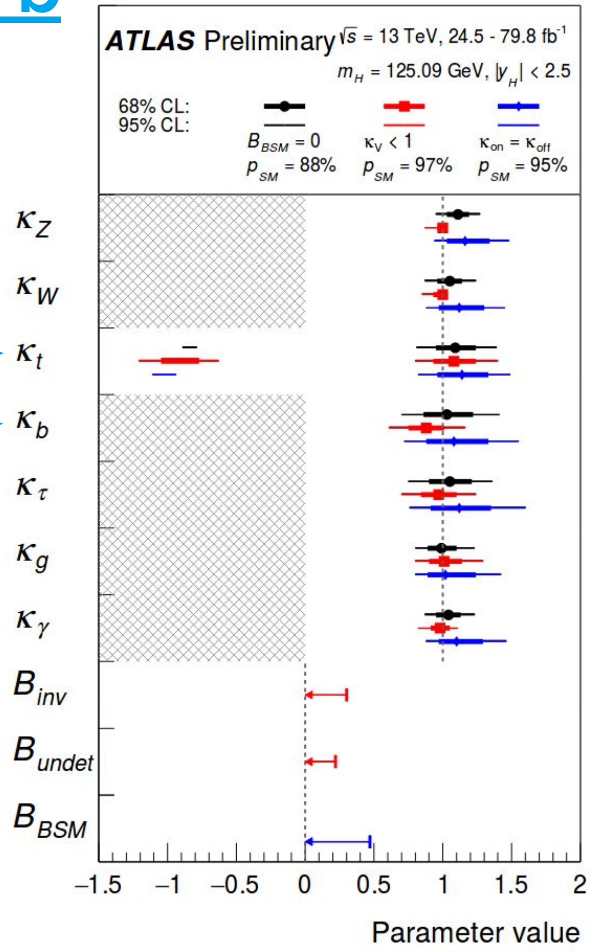
Theoretical and modelling uncertainties	
Signal	0.094
Floating normalisations	0.035
Z + jets	0.055
W + jets	0.060
$t\bar{t}$	0.050
Single top quark	0.028
Diboson	0.054
Multi-jet	0.005
MC statistical	0.070

Experimental uncertainties		
Jets		0.035
E_T^{miss}		0.014
Leptons		0.009
b-tagging	b-jets	0.061
	c-jets	0.042
	light-flavour jets	0.009
	extrapolation	0.008
Pile-up		0.007
Luminosity		0.023

Generic parametrization   kappas t & b

ATLAS-CONF-2019-005

- Current LHC data **insensitive** to κ_c and κ_s
  - ⇒ for now assumed to **vary like** κ_t and κ_b
- ggH vertex and H→γγ loop processes
  - ⇒ treated as **effective coupling strength** modifiers κ_g and κ_γ
- All $\kappa_i > 0$ κ_t either + or −
  - ⇒ constrained using tH and gg → ZH processes



3 scenarios for Higgs total width

- no BSM contribution: $\mathbf{BR_{invisible} = BR_{undetected} = 0}$
- $\mathbf{BR_{invisible}}$ **and** $\mathbf{BR_{undetected}}$ **free parameters** + set $\kappa_V < 1$ to remove extra d.o.f.
- **single free parameter** $\mathbf{BR_{BSM}} = BR_{invisible} = BR_{undetected}$

Fermions and gauge boson couplings

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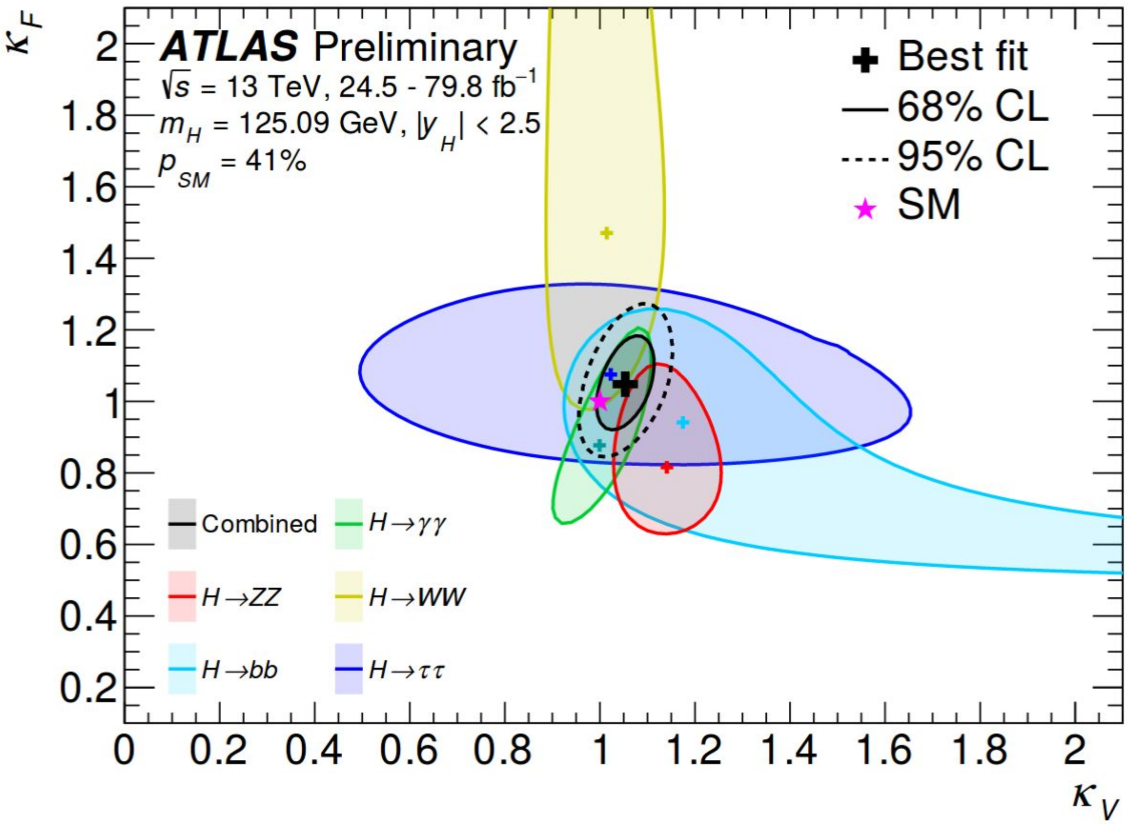

Probing Higgs boson

universal coupling strength scale factors

for all bosons and all fermions.

Assuming:

- All bosons $\kappa_V = \kappa_W = \kappa_Z$
- All fermions $\kappa_F = \kappa_t = \kappa_b = \kappa_\tau = \kappa_\mu$
- No invisible Higgs decays
- No undetected Higgs decays

κ_V and κ_F compatible with SM with

p-value = 41%

Parametrization of Higgs boson production cross sections & decay widths as function of coupling strength modifiers κ

$$\sigma_i \times \mathrm{B}_f = \frac{\sigma_i(\boldsymbol{\kappa}) \times \Gamma_f(\boldsymbol{\kappa})}{\Gamma_H},$$

$$\kappa_j^2 = \frac{\sigma_j}{\sigma_j^{\mathrm{SM}}} \quad \text{or} \quad \kappa_j^2 = \frac{\Gamma_j}{\Gamma_j^{\mathrm{SM}}}.$$

$$\Gamma_H(\boldsymbol{\kappa}, \mathrm{B_{inv}}, \mathrm{B_{undet}}) = \frac{\kappa_H^2(\boldsymbol{\kappa})}{(1 - \mathrm{B_{inv}} - \mathrm{B_{undet}})} \Gamma_H^{\mathrm{SM}}.$$

Production	Loops	Interference	Effective modifier	Resolved modifier
$\sigma(\text{ggF})$	✓	$t-b$	κ_g^2	$1.04\,\kappa_t^2 + 0.002\,\kappa_b^2 - 0.04\,\kappa_t\kappa_b$
$\sigma(\text{VBF})$	-	-	-	$0.73\,\kappa_W^2 + 0.27\,\kappa_Z^2$
$\sigma(qq/qg \to ZH)$	-	-	-	κ_Z^2
$\sigma(gg \to ZH)$	✓	$t-Z$	$\kappa_{(ggZH)}$	$2.46\,\kappa_Z^2 + 0.46\,\kappa_t^2 - 1.90\,\kappa_Z\kappa_t$
$\sigma(WH)$	-	-	-	κ_W^2
$\sigma(t\bar{t}H)$	-	-	-	κ_t^2
$\sigma(tHW)$	-	$t-W$	-	$2.91\,\kappa_t^2 + 2.31\,\kappa_W^2 - 4.22\,\kappa_t\kappa_W$
$\sigma(tHq)$	-	$t-W$	-	$2.63\,\kappa_t^2 + 3.58\,\kappa_W^2 - 5.21\,\kappa_t\kappa_W$
$\sigma(b\bar{b}H)$	-	-	-	κ_b^2
Partial decay width				
Γ^{bb}	-	-	-	κ_b^2
Γ^{WW}	-	-	-	κ_W^2
Γ^{gg}	✓	$t-b$	κ_g^2	$1.11\,\kappa_t^2 + 0.01\,\kappa_b^2 - 0.12\,\kappa_t\kappa_b$
$\Gamma^{\tau\tau}$	-	-	-	κ_τ^2
Γ^{ZZ}	-	-	-	κ_Z^2
Γ^{cc}	-	-	-	$\kappa_c^2\ (= \kappa_t^2)$
$\Gamma^{\gamma\gamma}$	✓	$t-W$	κ_γ^2	$1.59\,\kappa_W^2 + 0.07\,\kappa_t^2 - 0.67\,\kappa_W\kappa_t$
$\Gamma^{Z\gamma}$	✓	$t-W$	$\kappa_{(Z\gamma)}^2$	$1.12\,\kappa_W^2 - 0.12\,\kappa_W\kappa_t$
Γ^{ss}	-	-	-	$\kappa_s^2\ (= \kappa_b^2)$
$\Gamma^{\mu\mu}$	-	-	-	κ_μ^2
Total width ($\mathrm{B_{inv}} = \mathrm{B_{undet}} = 0$)				
Γ_H	✓	-	κ_H^2	$0.58\,\kappa_b^2 + 0.22\,\kappa_W^2$ $+0.08\,\kappa_g^2 + 0.06\,\kappa_\tau^2$ $+0.03\,\kappa_Z^2 + 0.03\,\kappa_c^2$ $+0.0023\,\kappa_\gamma^2 + 0.0015\,\kappa_{(Z\gamma)}^2$ $+0.0004\,\kappa_s^2 + 0.00022\,\kappa_\mu^2$