Combined Higgs boson measurements at the ATLAS experiment

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On behalf of the ATLAS Collaboration

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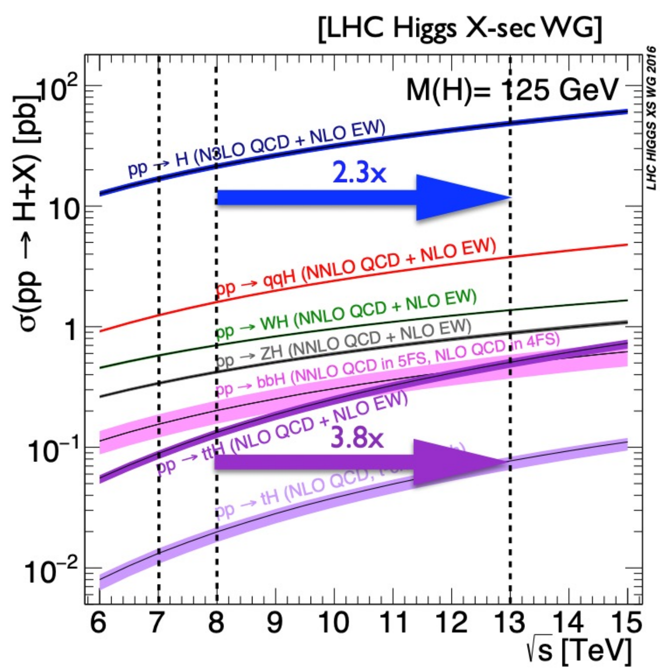
Introduction

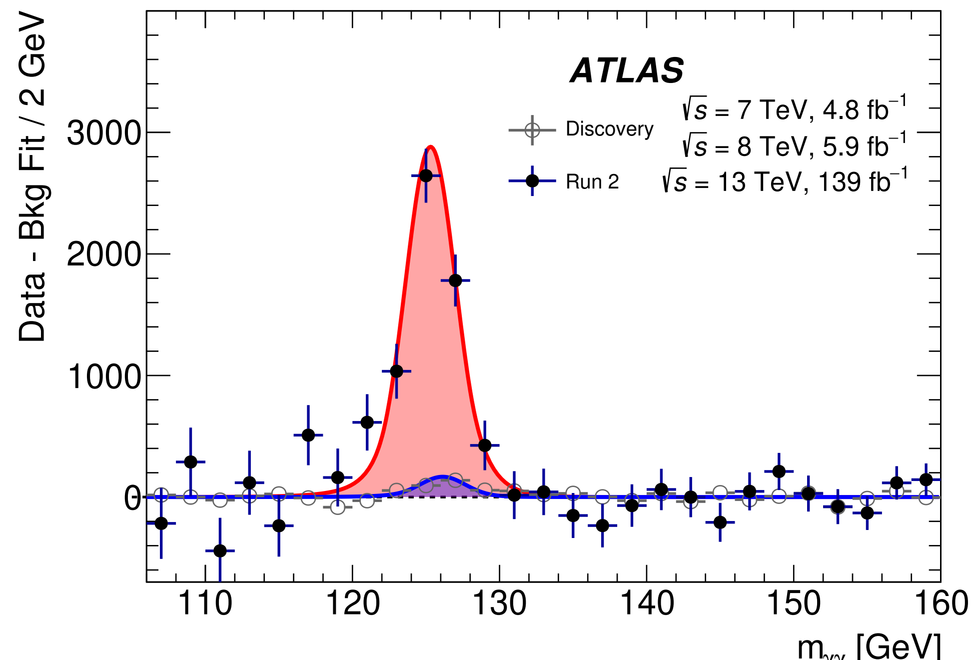
- Higgs plays a key role in SM, discovered in Run 1 by ATLAS and CMS [PLB paper].

  2022 is the **10th anniversary** of the Higgs boson discovery!

- In LHC Run-2, 30x more Higgs recorded by the ATLAS detector, allows for **precise measurements** of cross-sections, couplings and properties, **search** for rare decay modes, and test phase space hasn't been probed before.



Significant increase in production date from Run-1 to Run-2



Comparison of $m_{\gamma\gamma}$ spectrum between discovery and full Run-2 datasets

Input analyses

Decay channel	Branching Ratio[%]
$H \to bb$	58.1
$H \to WW^*$	21.5
$H \to gg$	8.2
$H \to \tau\tau$	6.3
$H \to cc$	2.9
$H \to ZZ^*$	2.6
$H \to \gamma\gamma$	0.23
$H \to Z\gamma$	0.15
$H \to \mu\mu$	0.02

Decay BR at m_H= 125.09 GeV

Decay mode	Targeted production processes	$\mathcal{L}$ [fb^{-1}]	Fits deployed in
$H \to \gamma\gamma$	ggF, VBF, $WH, ZH, t\bar{t}H, tH$	139	All
$H \to ZZ$	ggF, VBF, $WH + ZH, t\bar{t}H + tH$	139	All
	$t\bar{t}H + tH$ (multilepton)	36.1	All but fit of kinematics
$H \to WW$	ggF, VBF	139	All
	WH, ZH	36.1	All but fit of kinematics
	$t\bar{t}H + tH$ (multilepton)	36.1	All but fit of kinematics
$H \to Z\gamma$	inclusive	139	All but fit of kinematics
$H \to b\bar{b}$	WH, ZH	139	All
	VBF	126	All
	$t\bar{t}H + tH$	139	All
	inclusive	139	Only for fit of kinematics
$H \to \tau\tau$	ggF, VBF, $WH + ZH, t\bar{t}H + tH$	139	All
	$t\bar{t}H + tH$ (multilepton)	36.1	All but fit of kinematics
$H \to \mu\mu$	ggF + $t\bar{t}H + tH$, VBF + $WH + ZH$	139	All but fit of kinematics
$H \to c\bar{c}$	$WH + ZH$	139	Only for free-floating κ_c
$H \to$ invisible	VBF	139	κ models with $B_{\text{u.}}$ & $B_{\text{inv.}}$
	ZH	139	κ models with $B_{\text{u.}}$ & $B_{\text{inv.}}$

A measurement based on **a combined likelihood** constructed from **all major ATLAS Higgs analyses**, to get **more sensitive** and **less model-dependent** results on Higgs interactions:

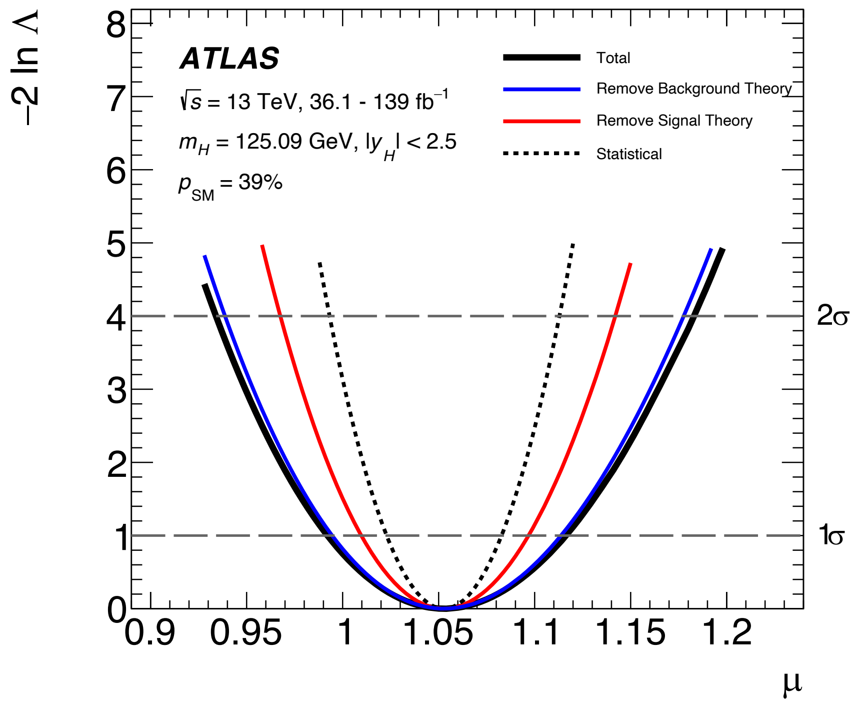
- Nature 607, 52–59 (2022), HEPdata
- Almost all measurements updated with the **LHC full Run-2** dataset

Global signal strength

- **Considering all production and decay modes together:** $\mu = \frac{\sigma \times B}{(\sigma \times B)_{SM}}$

$$\mu = 1.05 \pm 0.06 = 1.05 \pm 0.03\,(\text{stat.}) \pm 0.03\,(\text{exp.}) \pm 0.04\,(\text{sig. th.}) \pm 0.02\,(\text{bkg. th.}).$$

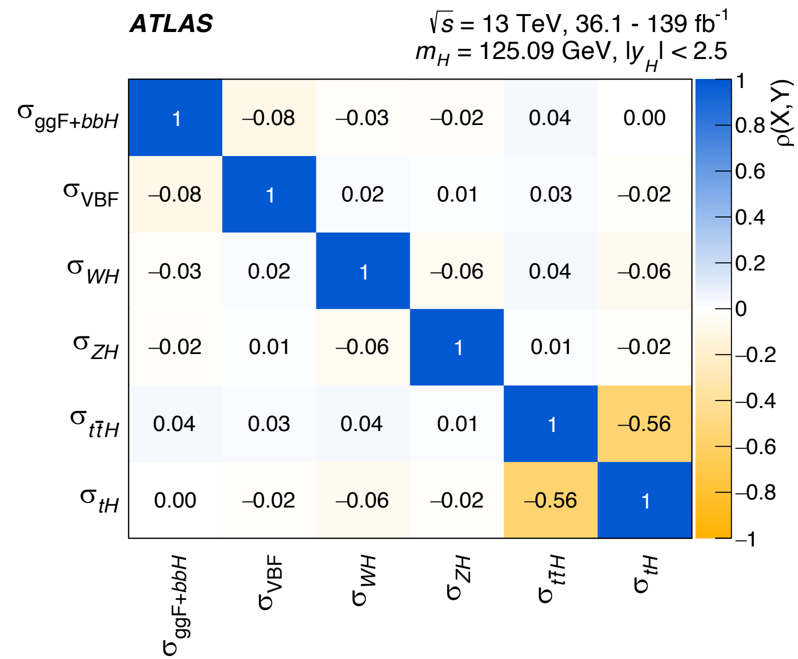
  - Experimental and theory uncertainties reduced by a factor of 2 wrt Run 1 result
  - SM compatibility (p-value): 39%



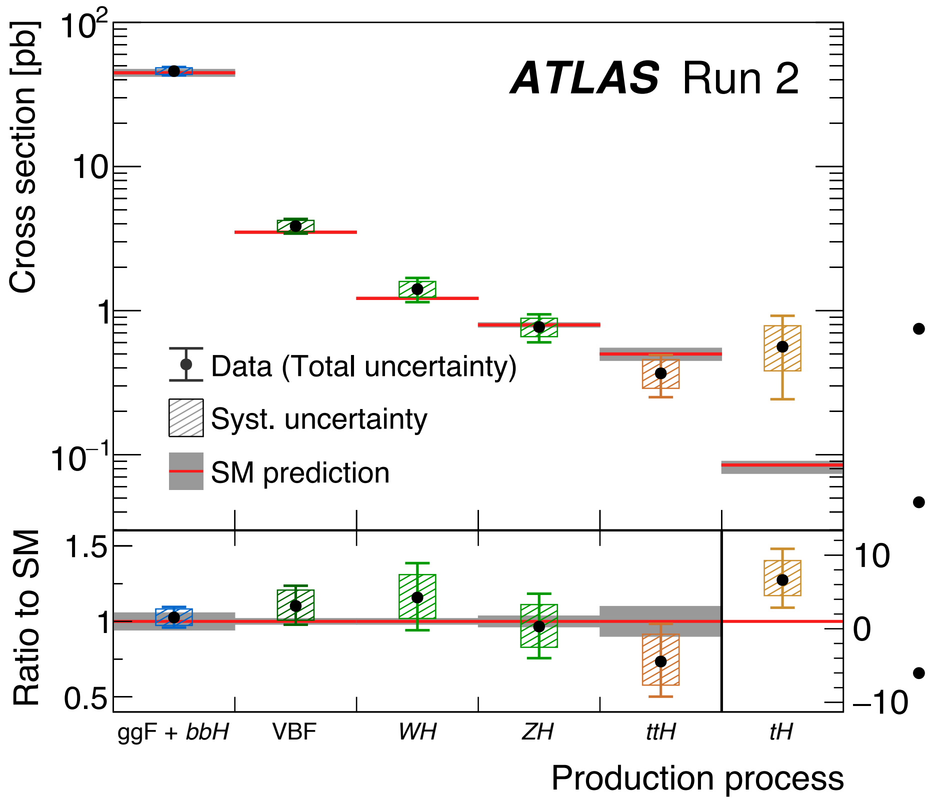
Previous results:

ATLAS+CMS (Run 1 combination): $1.09^{+0.11}_{-0.10} = 1.09^{+0.07}_{-0.07}(\text{stat.})^{+0.04}_{-0.04}(\text{exp.})^{+0.07}_{-0.06}(\text{sig. th.})^{+0.03}_{-0.03}(\text{bkg. th.})$

Production cross-sections



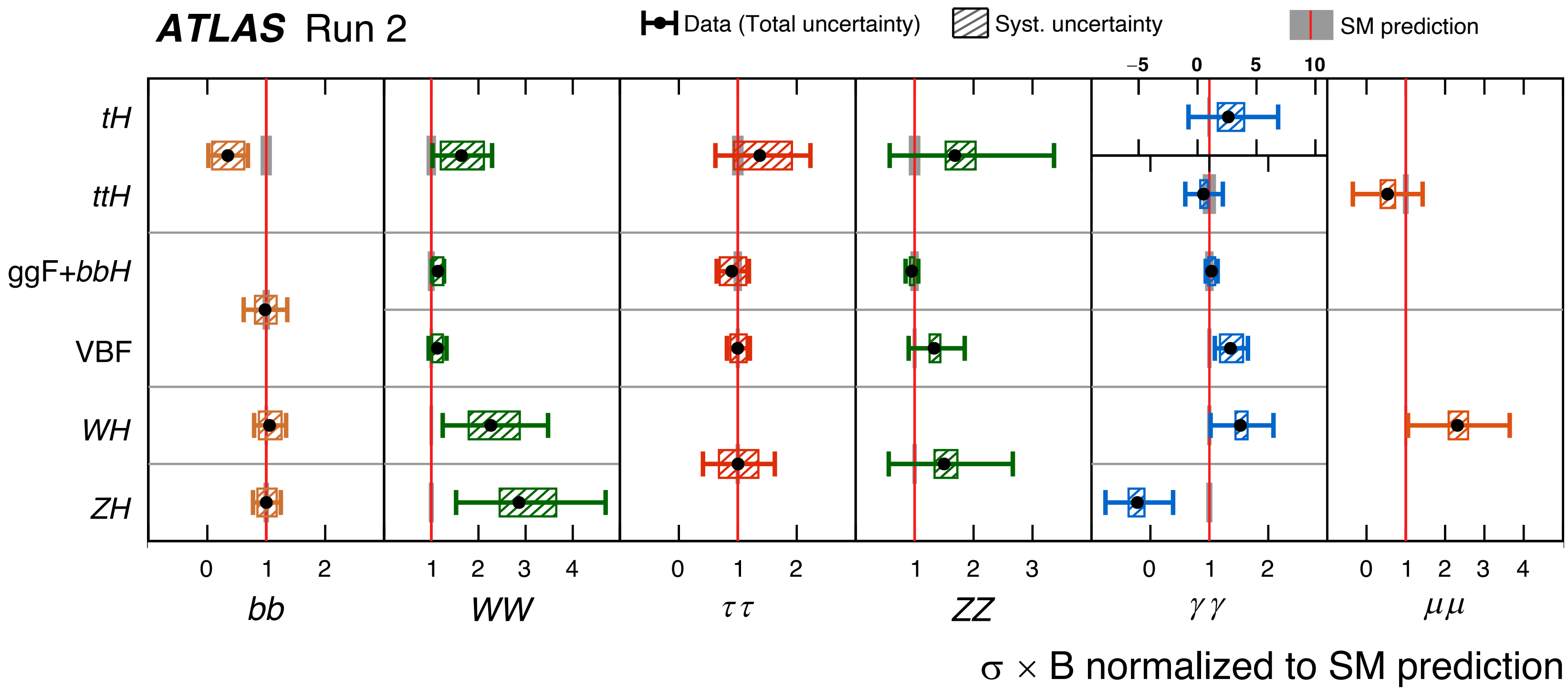
- **Branching ratios are assumed to be SM-like** when combining processes and measurements
- SM compatibility (p-value): 65%



- **Better precision**:
  - ggF now at precision of 7%
  - VBF now at precision of 12%
- **All major production have been observed**:
  - *WH* is observed with 5.8σ (5.1σ), *ZH* with 5.0σ (5.5σ) and *ttH+tH* with 6.4σ (6.6σ)
- **Evidence of rare production mode**:
  - Upper limit on *tH* of 15(7) x SM at 95% C.L.
    - Strong correlation with *ttH*

Production and Decay

- Cross sections times branching ratios:
  - Measurements for all available cross sections and branching ratios
  - **Assumptions on SM-BR relaxed**
  - SM compatibility (p-value): 72%
- **For decay BR:**
  - *H→WW, ττ, ZZ, γγ* now all at precisions between 10% and 12%
  - *H→bb* observed with 7.0σ (7.7σ)
  - *H→ μμ* with significances of 2.0σ (1.7σ) and *Zγ* with 2.3σ (1.1σ)

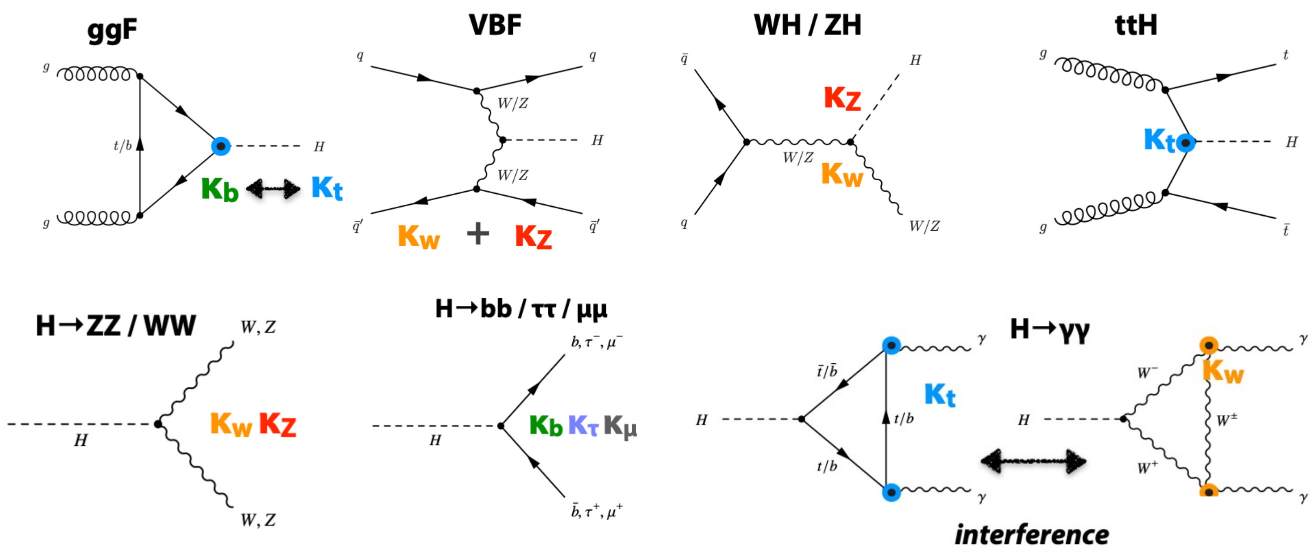


“kappa” framework

- With known Higgs boson mass, the SM Higgs sector is fixed.
- Use the **LO** coupling modifier to probe for rate deviations from the SM.
- Introduce one scale factor κ per SM particle with observable "Higgs coupling” at the LHC: κ_W, κ_Z, κ_t, κ_b, κ_τ, κ_μ, κ_γ, κ_g, etc.

$$(\sigma \cdot BR)(i \to H \to f) \sim \frac{\sigma_i \cdot \Gamma_f}{\Gamma_H} = \frac{\sigma_i^{SM} \cdot \Gamma_f^{SM}}{\Gamma_H^{SM}} \cdot \left(\frac{\boldsymbol{\kappa}_i^2 \cdot \boldsymbol{\kappa}_f^2}{\boldsymbol{\kappa}_H^2}\right)$$

- E.g.:



- Can handle other rare production and decay vertices in a similar way.

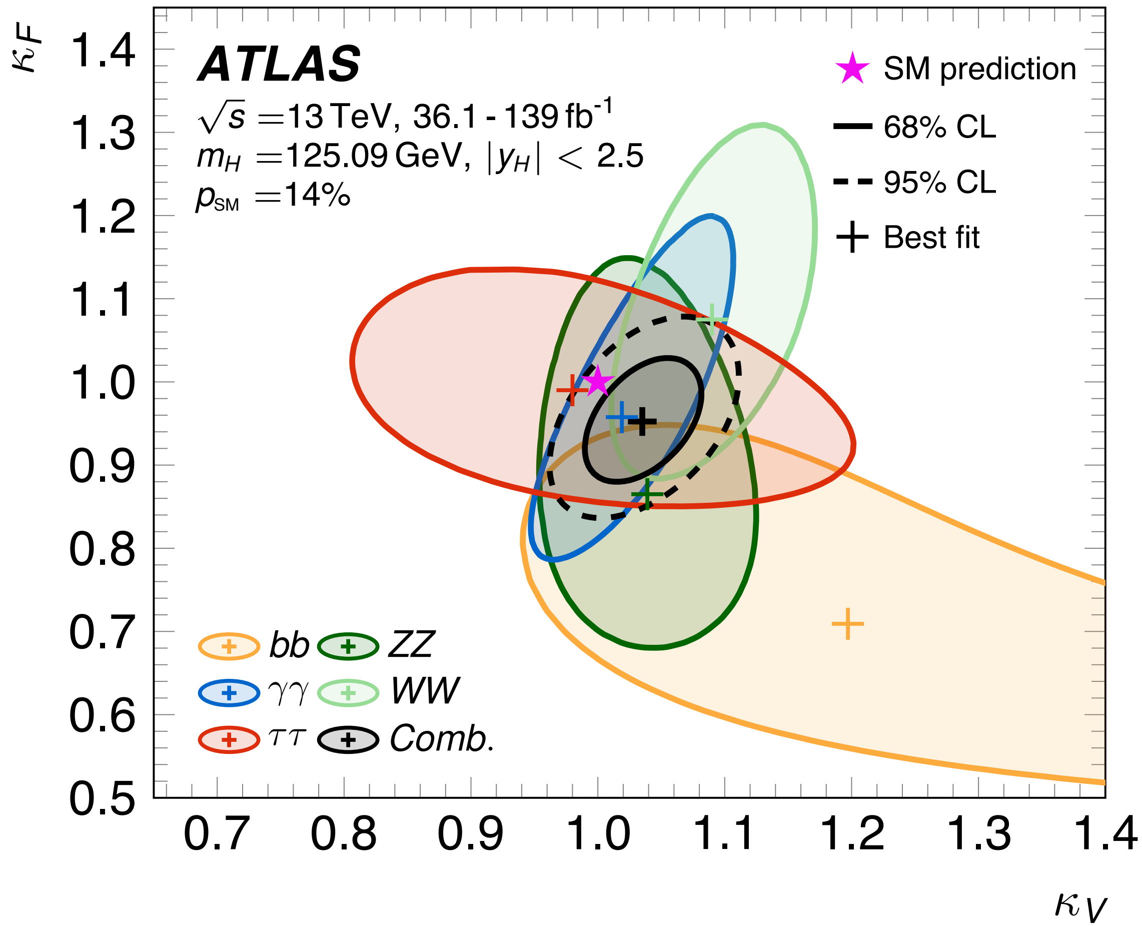
Fermion vs Vector boson coupling

κ_V vs κ_F : one coupling modifier for **vector boson coupling** and another for **fermions**

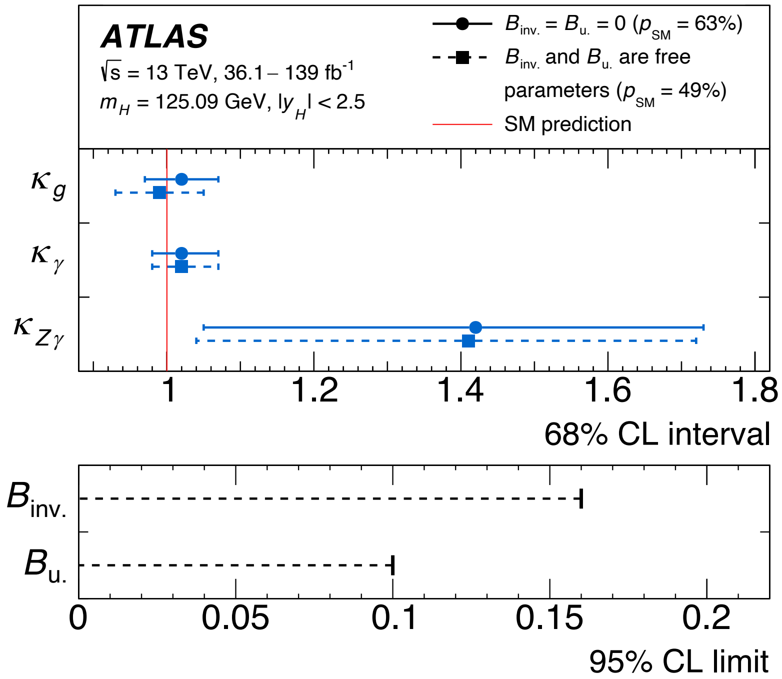
- Loop processes resolved according to the SM particles that contribute to them
- SM compatibility (p-value): 14%

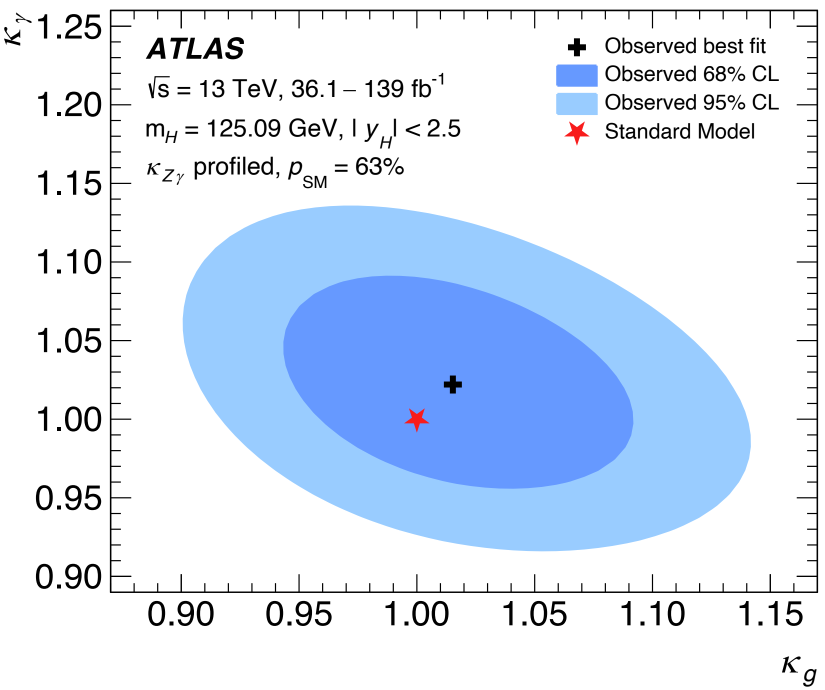
$$\kappa_V = 1.035^{+0.031}_{-0.031}$$
$$\kappa_F = 0.95^{+0.05}_{-0.05}$$

Vector-boson vs. fermion coupling in each decay channels



Effective coupling of loop contributions

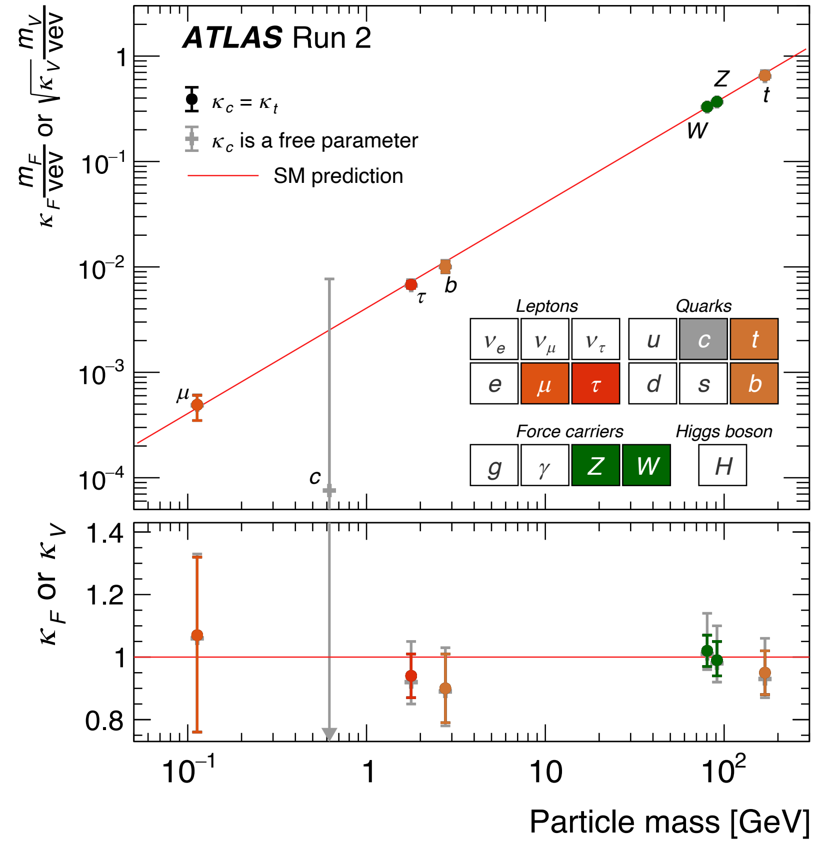




- Assign coupling modifiers of **ggF**, ***H→gg*** (κ_g), ***H→γγ*** (κ_γ) and ***H→Zγ*** ($\kappa_{Z\gamma}$)
  - capture all loop contributions to the Higgs interaction with gluons and photons
- Two scenarios: with and without invisible and undetected non-SM Higgs decays.
- SM compatibility (p-value): 63% ($B_{inv} = B_u = 0$)
- Upper limits on B_{inv} of 0.16 (0.09) and B_u of 0.10 (0.18) at 95% CL

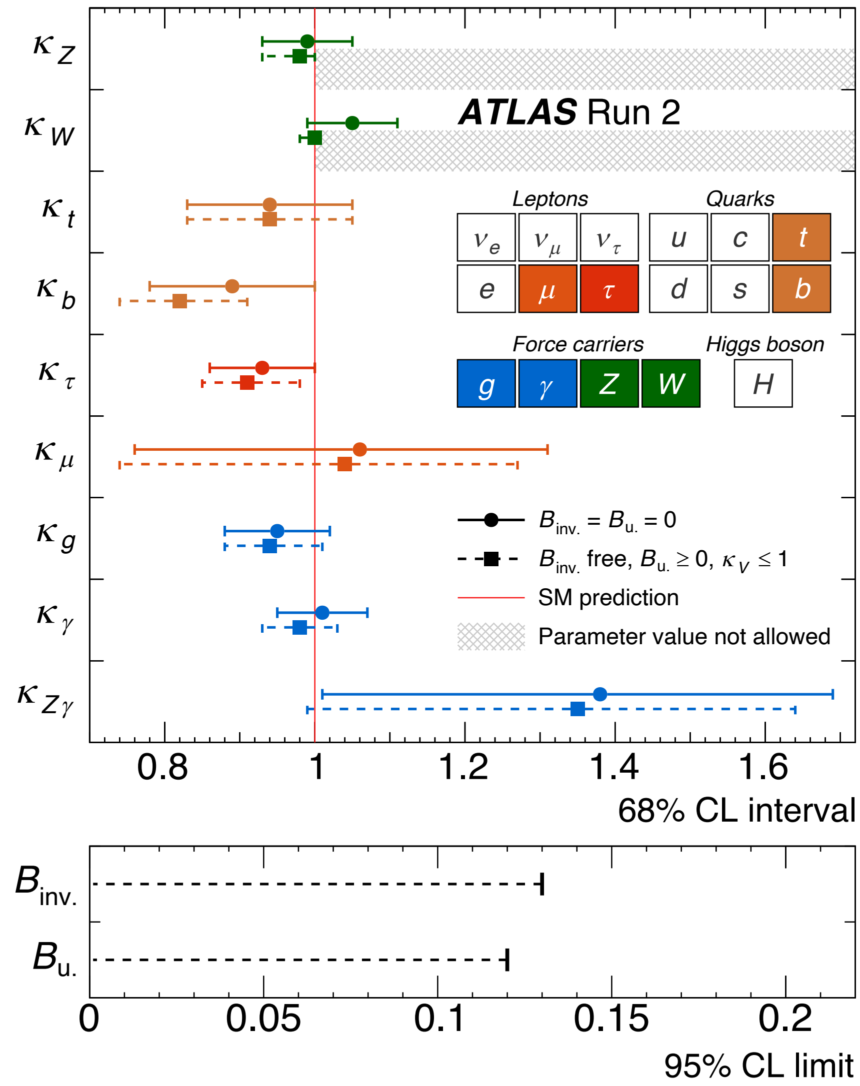
Coupling to each particle

- **All modifiers assumed to be positive**
- **Only SM particles in loop processes**
- **No invisible or undetected non-SM Higgs decays**
- Two setups: with and without κ_c to cope with low sensitivity
  - Upper limit on κ_c of 5.7 (7.6) x SM at 95% CL
- Coupling measurements:
  - Fermions (*t, b, τ*): precision between 7% and 12%
  - Vector bosons (W, Z): precision of 5%
  - SM compatibility (p-value): 56% (κ_c=κ_t) and 65% (κ_c free-floating)



Generic coupling

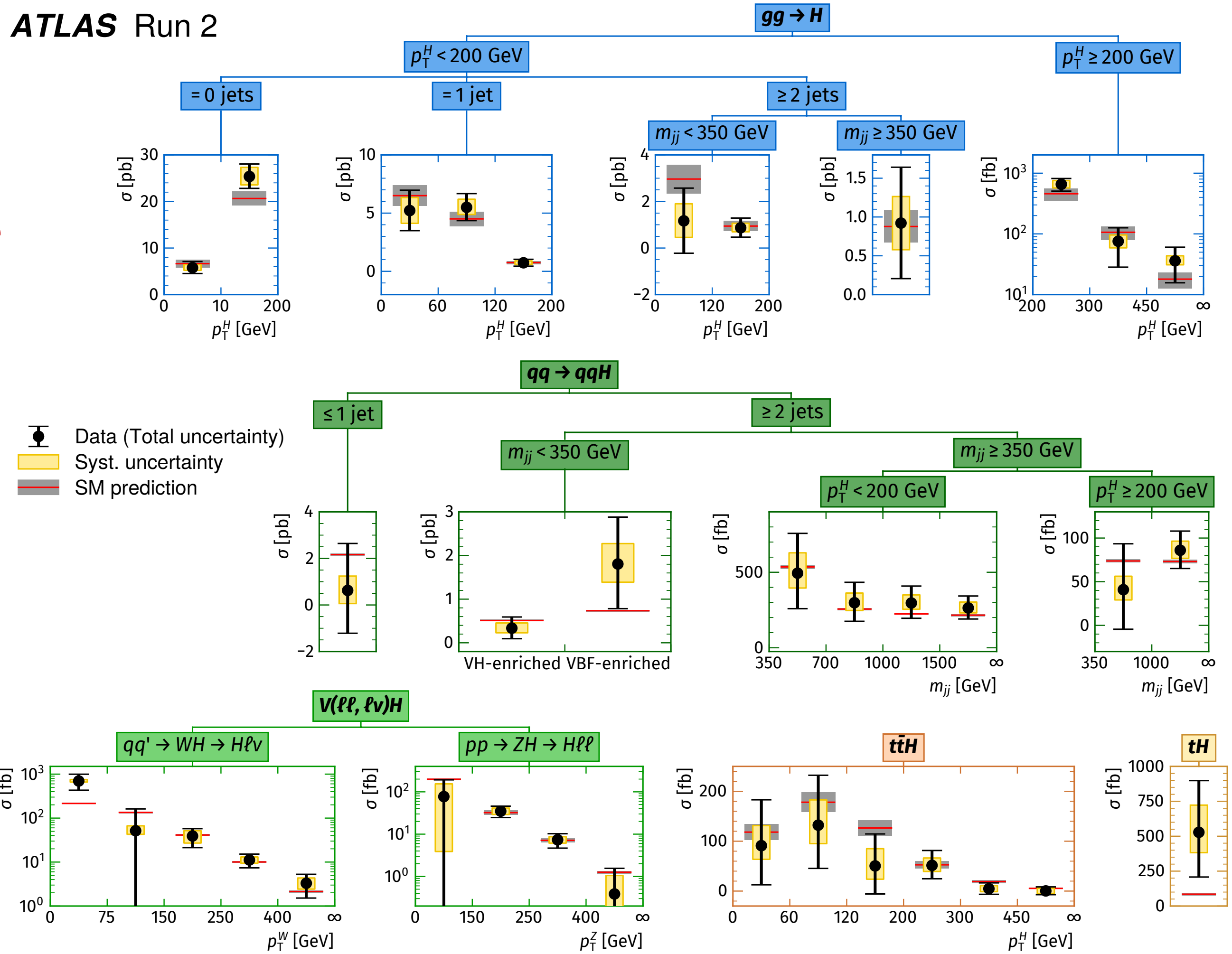
- **Similar to previous setup with this time allowing for non-SM particles in loop processes, with effective coupling strengths.**
- **κ_t allowed to be negative.**
- Two scenarios: with and without invisible and undetected non-SM Higgs decays.
- SM compatibility (p-value):
  61% ($B_{inv} = B_u = 0$)
- Upper limits on B_{inv} of 0.13 (0.08) and B_u of 0.12 (0.21) at 95% CL



STXS framework

- STXS (Simplified Template Cross Sections)
- Split phase space of Higgs production processes into **36 kinematic regions**
  - Defined by kinematics of Higgs Boson and of associated jets, W, Z bosons where relevant

- **Goal:** provide sensitivity to BSM effects, avoid large theory uncertainties in predictions and minimise model-dependence from acceptance extrapolations
- Branching ratios and kinematics of Higgs Boson decays are assumed to be SM-like
- SM compatibility (p-value): 92%

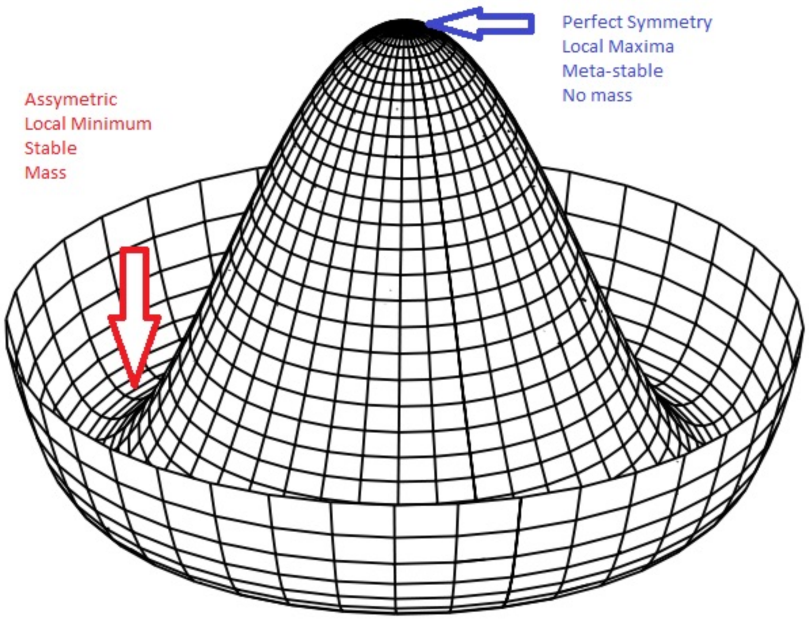


Summary

- In the **10 years** since the Higgs discovery, many measurements have been performed by the ATLAS collaboration, with confirmation that the properties of this Higgs Boson show **good agreement with the SM**.
- A combined measurement of Higgs interactions has been presented
  - All main production and decay modes have been observed
  - Hints of rare Higgs decays have been seen
  - Kinematic dependence of production cross sections has been studied across a wide range of phase space
  - Unprecedented precision reached on coupling measurements
- Stay tuned for even better results from LHC Run 3!

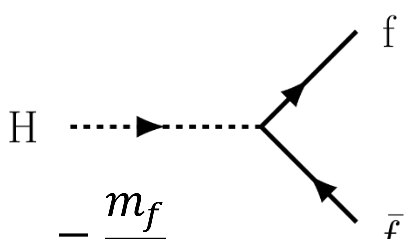
Backup

Higgs boson in the SM

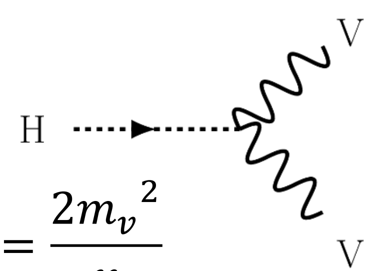


- Vector bosons masses → **spontaneous symmetry breaking**
- Fermions masses → **Yukawa couplings**
- The Higgs Boson couplings to other particles are set by their masses →determine all Higgs Boson production and decay.

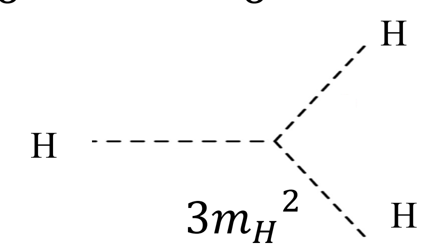
$$\mathcal{L} = -g_{Hff} f\bar{f}H + \delta_V V_\mu V^\mu \left(g_{HVV}H + \frac{g_{HHVV}}{2}H^2\right) + \frac{g_{HHH}}{6}H^3 + \frac{g_{HHHH}}{6}H^4$$



$$g_{Hff} = \frac{m_f}{v}$$



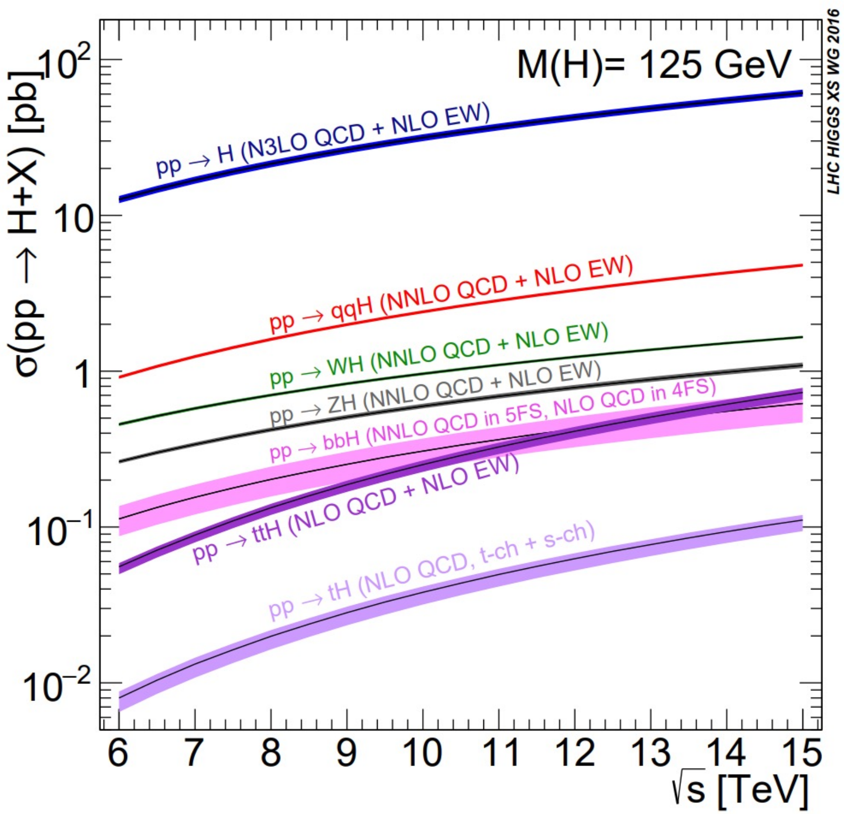
$$g_{HVV} = \frac{2{m_v}^2}{v}$$



$$g_{HHH} = \frac{3{m_H}^2}{v}$$

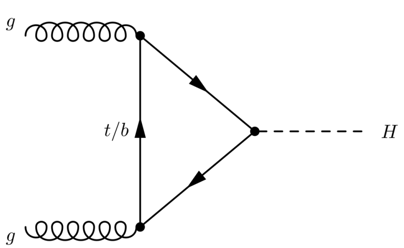
v = vacuum expectation value of the Higgs field

SM Higgs Production at LHC

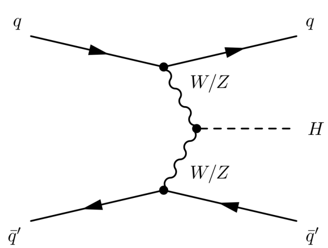


XS in pb	13 TeV	8 TeV	σ13/σ8
ggF	48.5	21.4	**2.3**
VBF	3.78	1.60	2.4
WH	1.37	0.70	2.0
ZH	0.88	0.42	2.1
bbH	0.49	0.20	**2.4**
ttH	0.51	0.13	**3.8**
tH	0.09	0.02	**3.9**

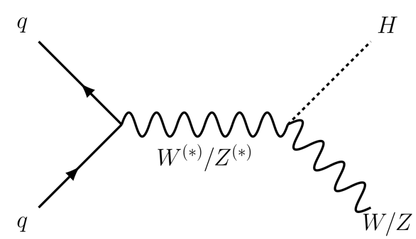
- There is **an increase** in production cross sections from increased center-of-mass energy.



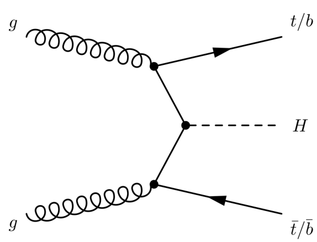
ggF



VBF

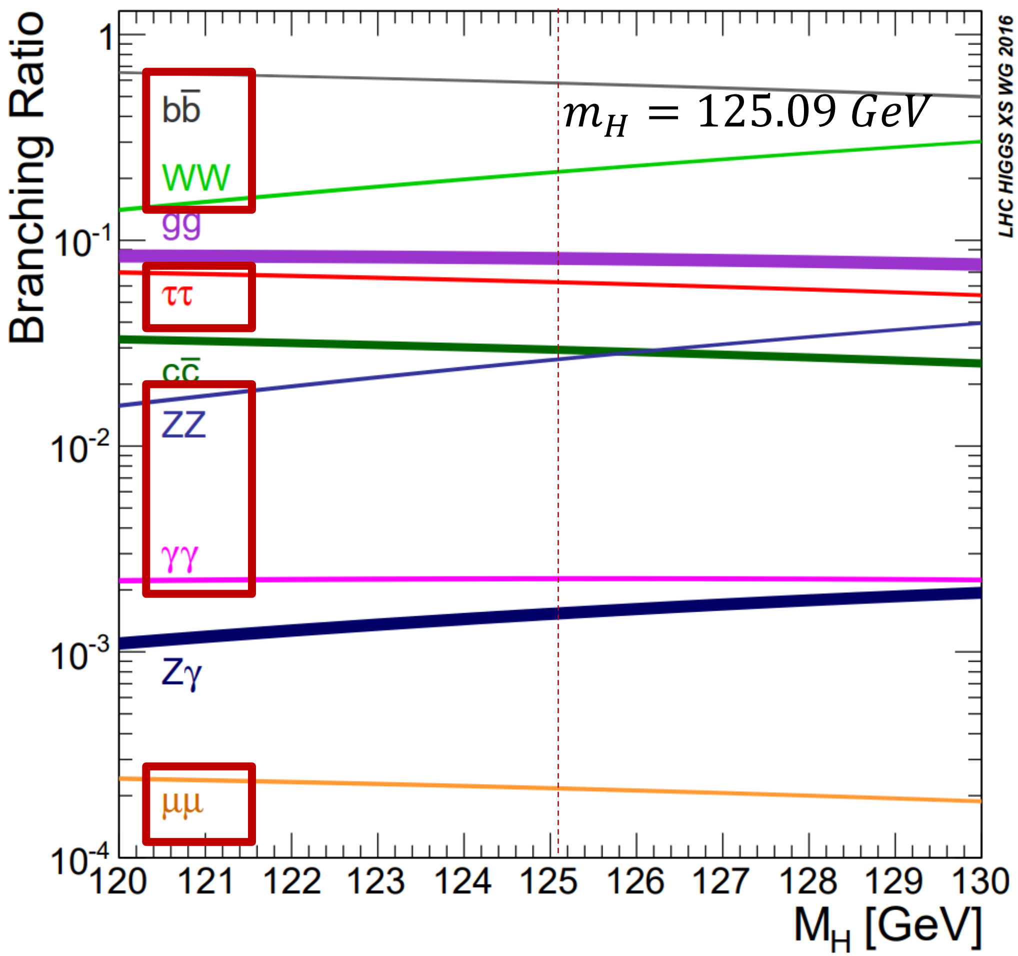


VH



ttH

SM Higgs Decay BR

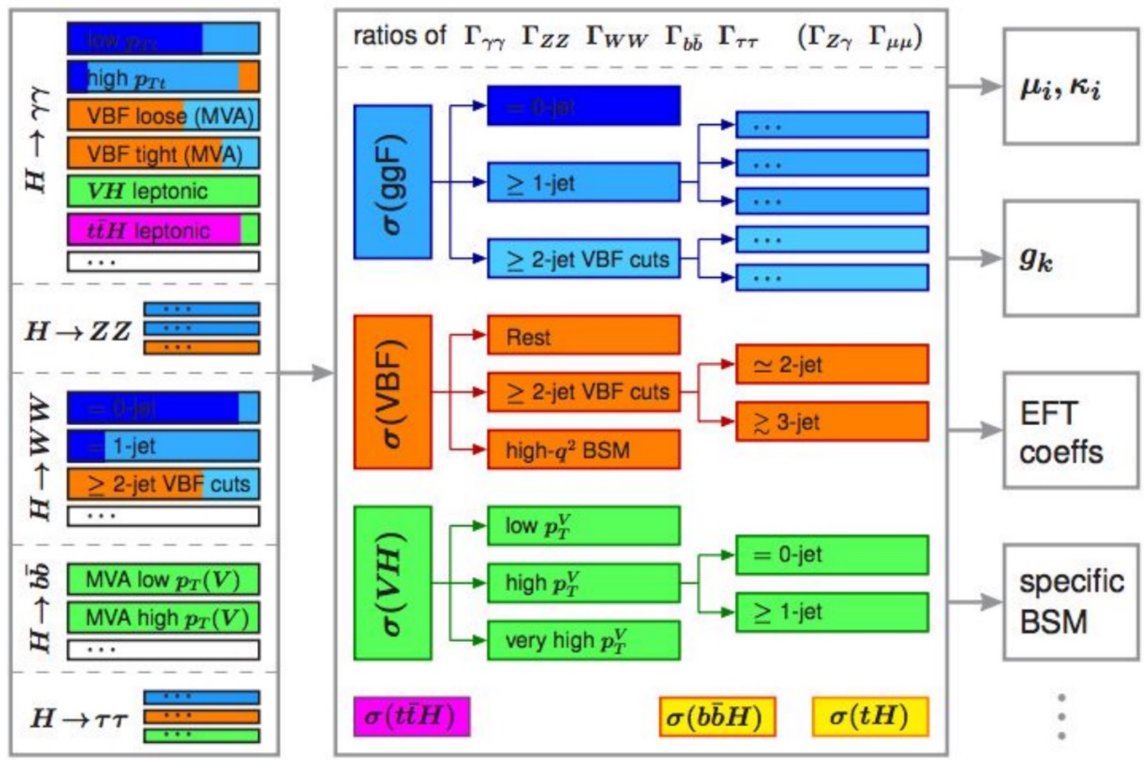


Decay channel	Branching Ratio[%]
H→bb	**58**
H→WW*	**22**
H→gg	8.2
H→ττ	**6.3**
H→cc	2.9
H→ZZ*	**2.6**
H→γγ	**0.23**
H→Zγ	0.15
H→μμ	**0.02**

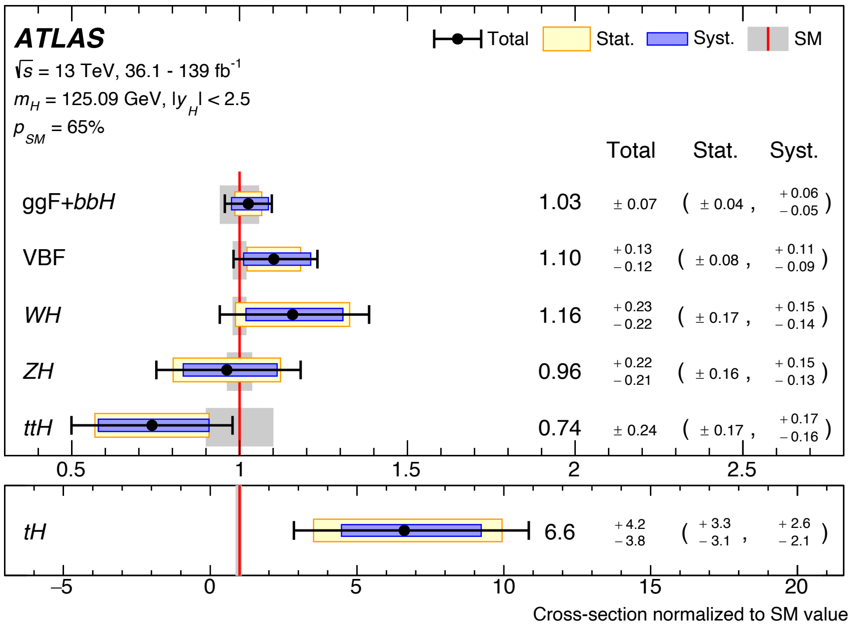
- *H→ZZ*→4l* (l=e,μ) and *H→γγ*: **low BR but clean signature, excellent mass resolution** → crucial for the Higgs boson mass measurement.
- *H→WW** : high BR but low mass resolution.
- *H→bb* and *H→ττ* : high BR, low S/B and low mass resolution at LHC.

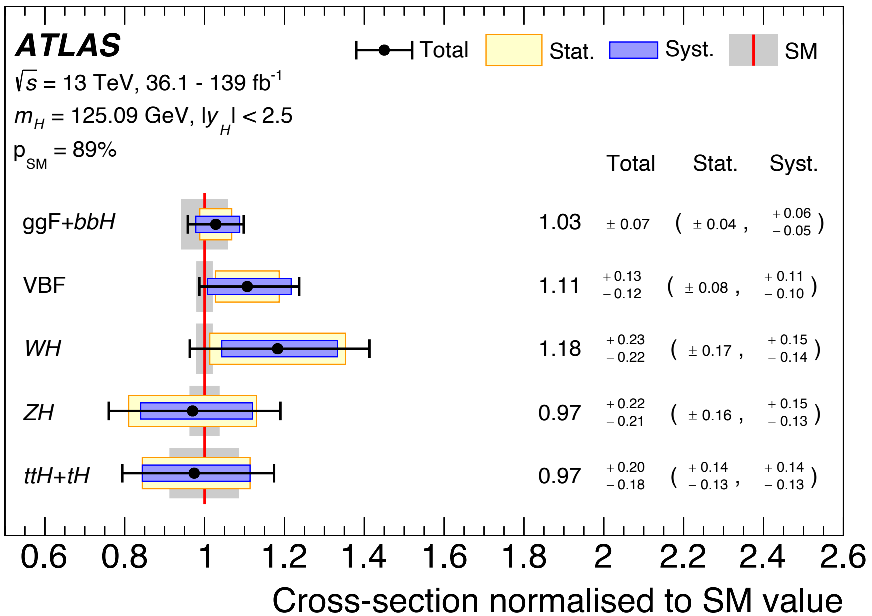
STXS can make Higgs measurements less model dependent than measurements during Run 1

- STXS (Simplified Template Cross Sections) splits Higgs productions into exclusive kinematic regions (Described in YellowReport4 (Section III.2).
- Instead of performing differential measurement in clean channels only, intend for **combination of all decay channels**.
- Minimize the dependence on theoretical uncertainties.



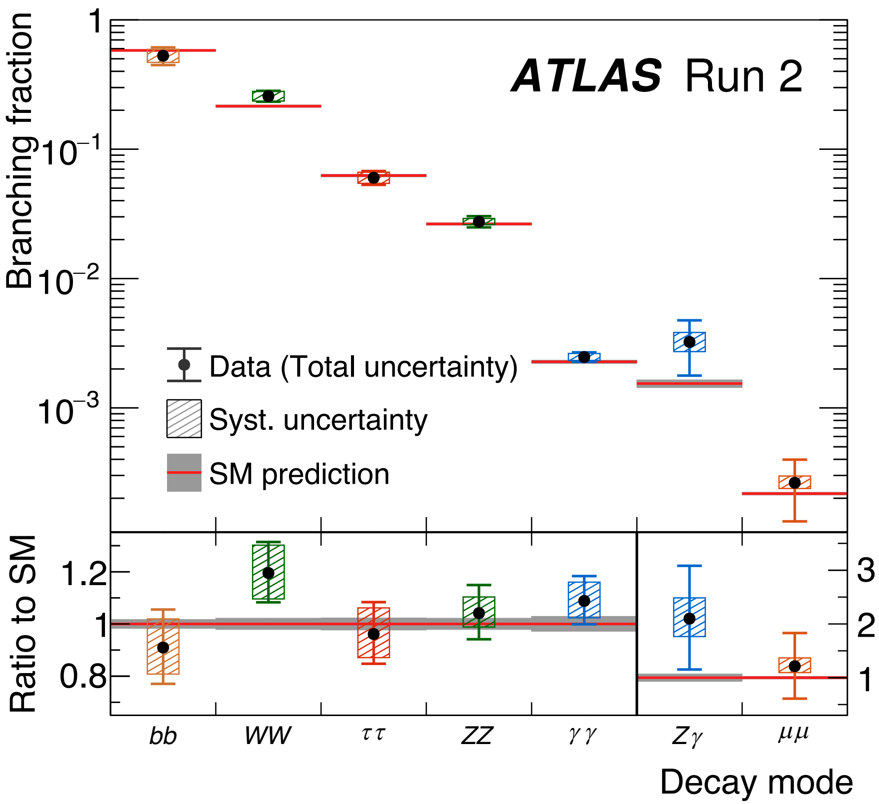
Cross section

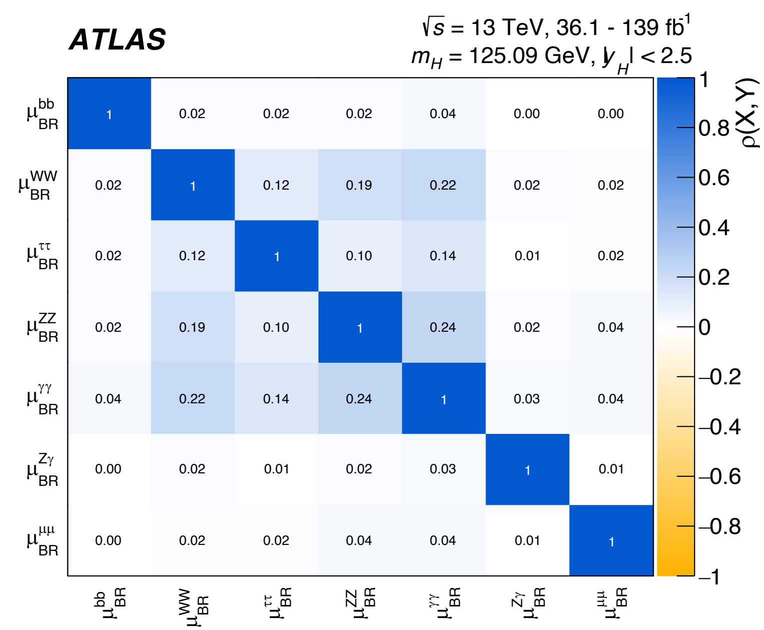




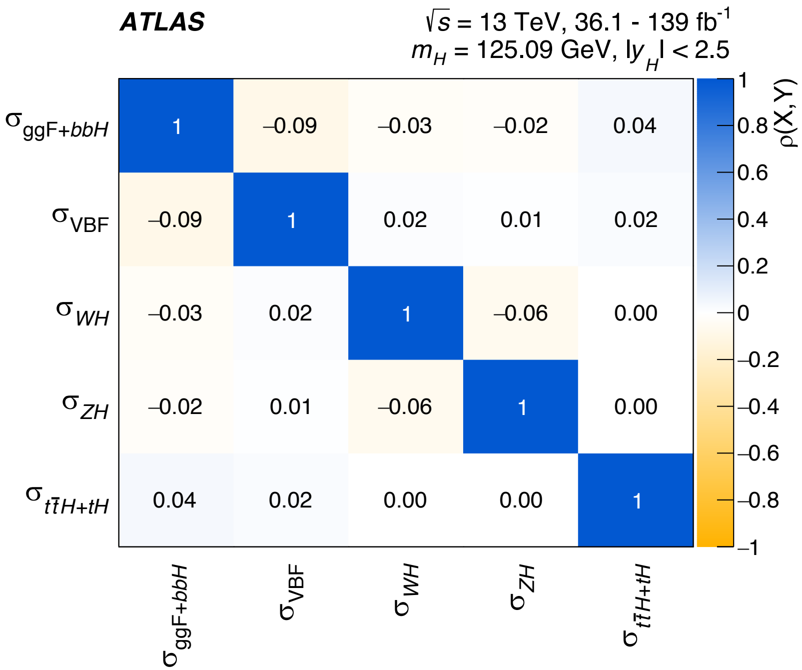
Decay branching-ratios

- Branching ratios:
  - **Production cross sections are assumed to be SM-like** when combining processes/measurements
  - SM compatibility (p-value): 56%

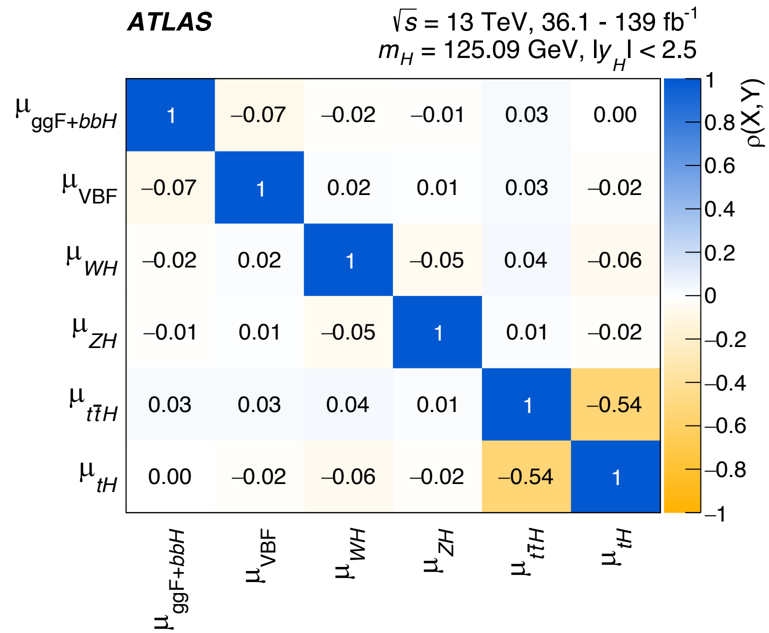




Cross section

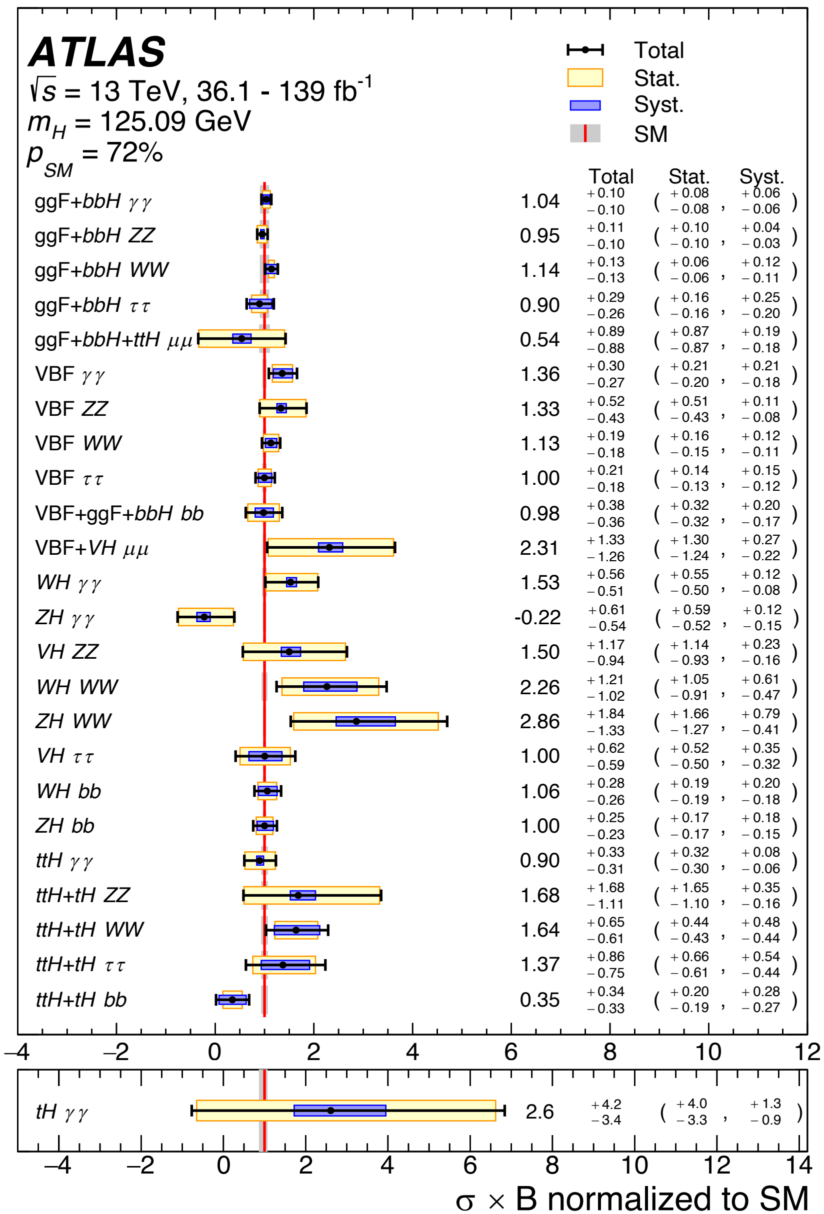


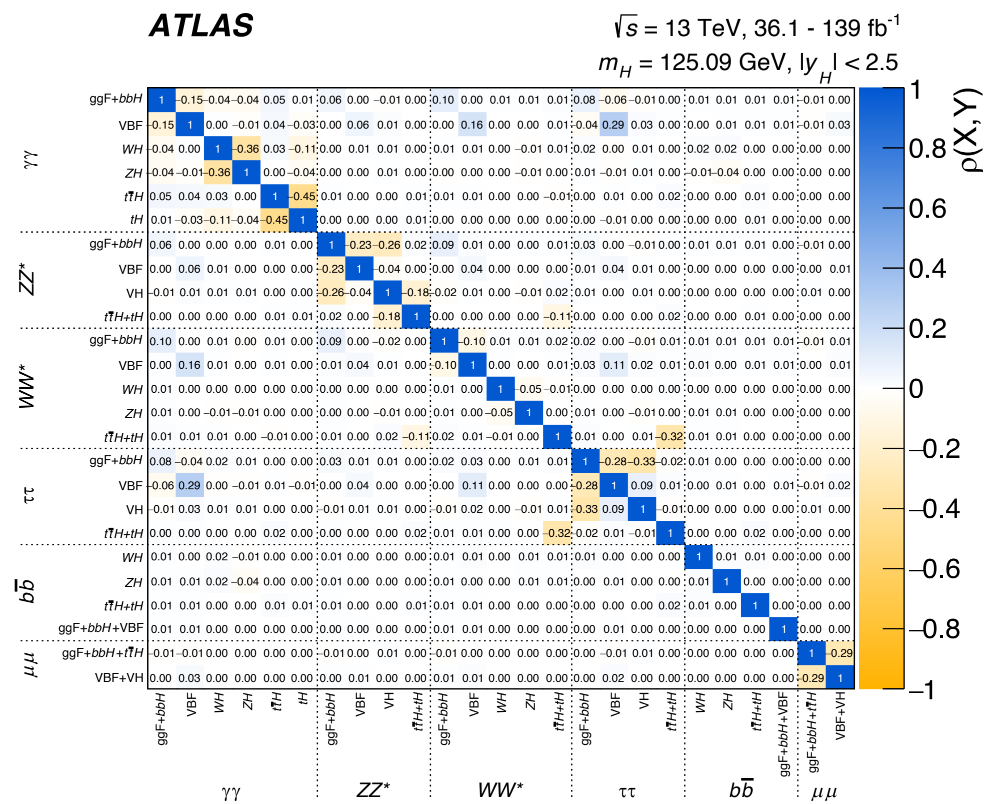
	$\sigma_{ggF+bbH}$	σ_{VBF}	σ_{WH}	σ_{ZH}	$\sigma_{t\bar{t}H+tH}$
$\sigma_{ggF+bbH}$	1	−0.09	−0.03	−0.02	0.04
σ_{VBF}	−0.09	1	0.02	0.01	0.02
σ_{WH}	−0.03	0.02	1	−0.06	0.00
σ_{ZH}	−0.02	0.01	−0.06	1	0.00
$\sigma_{t\bar{t}H+tH}$	0.04	0.02	0.00	0.00	1

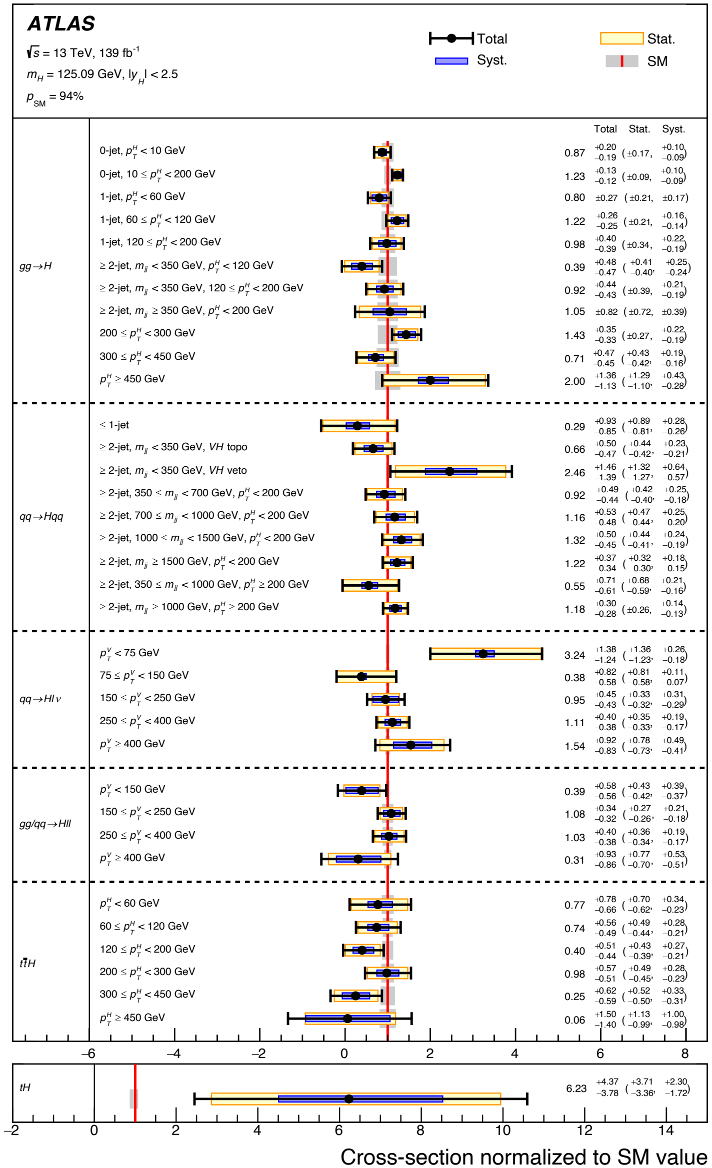


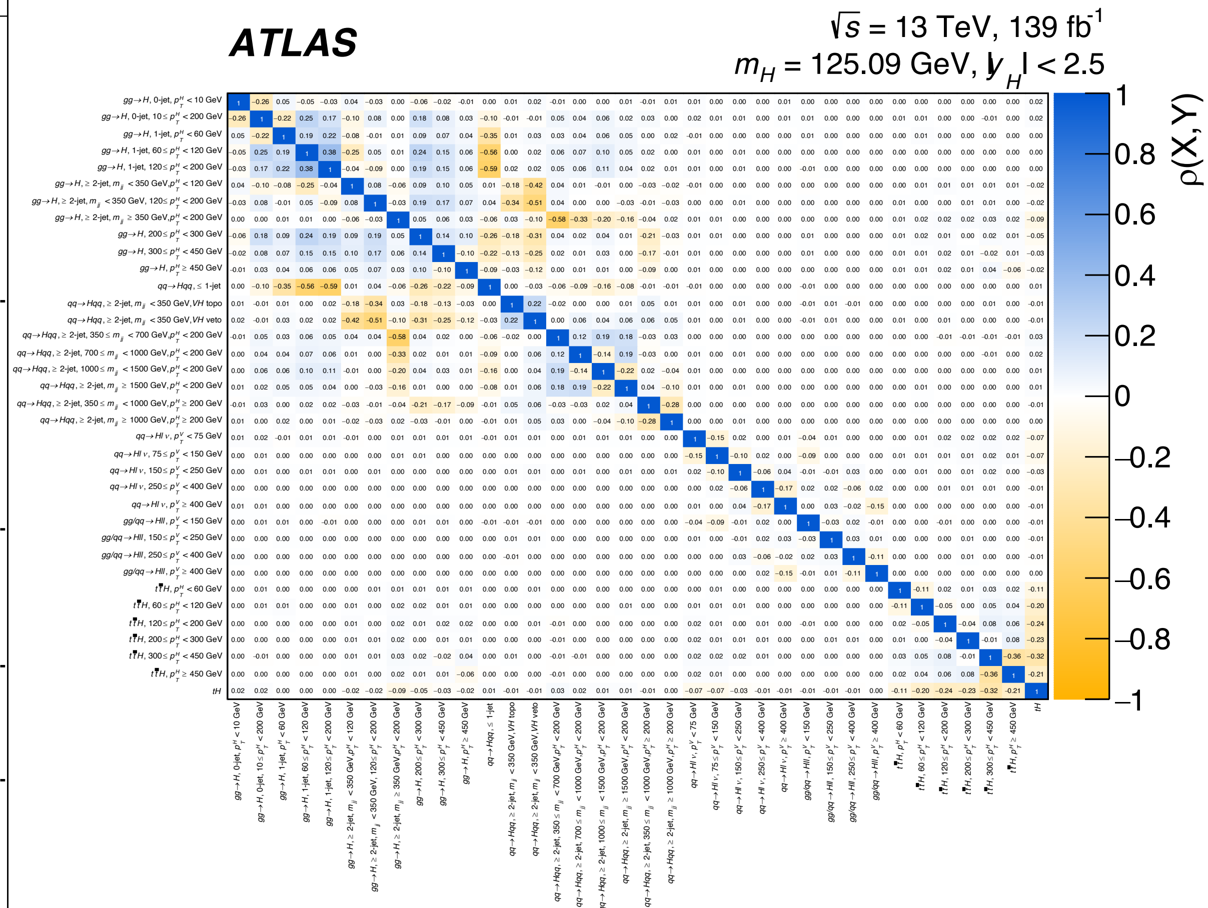
	$\mu_{ggF+bbH}$	μ_{VBF}	μ_{WH}	μ_{ZH}	$\mu_{t\bar{t}H}$	μ_{tH}
$\mu_{ggF+bbH}$	1	−0.07	−0.02	−0.01	0.03	0.00
μ_{VBF}	−0.07	1	0.02	0.01	0.03	−0.02
μ_{WH}	−0.02	0.02	1	−0.05	0.04	−0.06
μ_{ZH}	−0.01	0.01	−0.05	1	0.01	−0.02
$\mu_{t\bar{t}H}$	0.03	0.03	0.04	0.01	1	−0.54
μ_{tH}	0.00	−0.02	−0.06	−0.02	−0.54	1

Cross section tims BR



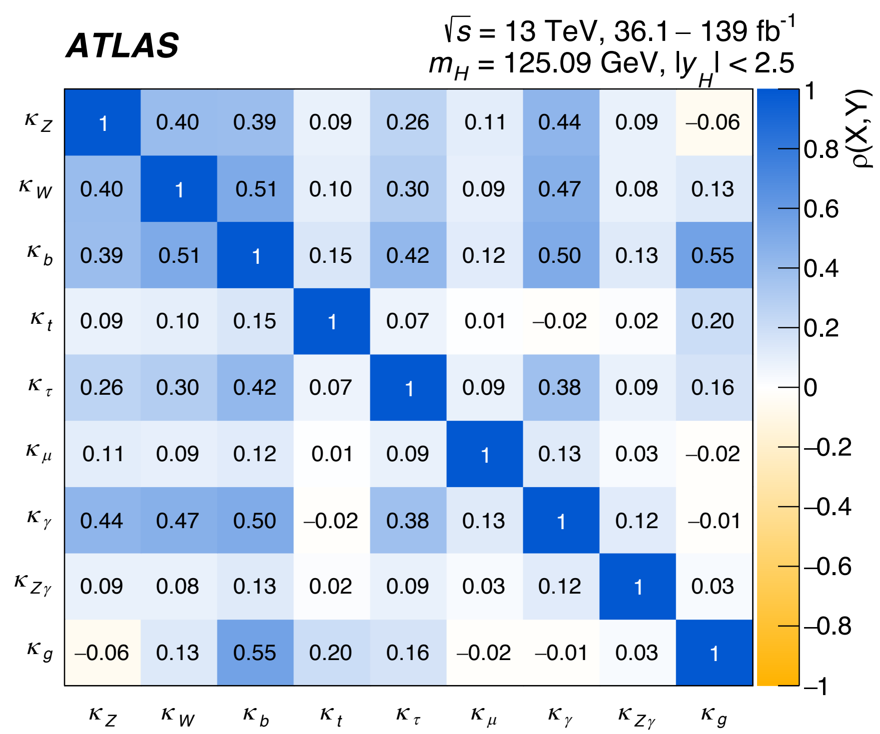



ATLAS
√s = 13 TeV, 139 fb⁻¹
m_H = 125.09 GeV, |y_H| < 2.5
p_SM = 94%
Total
Stat.
Syst.
SM
gg→H
qq→Hqq
qq→Hlν
gg/qq→Hll
ttH
tH
Cross-section normalized to SM value


ATLAS
√s = 13 TeV, 139 fb⁻¹
m_H = 125.09 GeV, |y_H| < 2.5
ρ(X,Y)

Generic kappa

	(a) $B_{inv.} = B_{u.} = 0$	(b) $B_{inv.}$ free, $B_{u.} \geq 0$, $\kappa_{W,Z} \leq 1$
κ_Z	$0.99^{+0.06}_{-0.06}$	$0.98^{+0.02}_{-0.05}$
κ_W	$1.05^{+0.06}_{-0.06}$	$1.00_{-0.02}$
κ_t	$0.94^{+0.11}_{-0.11}$	$0.94^{+0.11}_{-0.11}$
κ_b	$0.89^{+0.11}_{-0.11}$	$0.82^{+0.09}_{-0.08}$
κ_τ	$0.93^{+0.07}_{-0.07}$	$0.91^{+0.07}_{-0.06}$
κ_μ	$1.06^{+0.25}_{-0.30}$	$1.04^{+0.23}_{-0.30}$
κ_g	$0.95^{+0.07}_{-0.07}$	$0.94^{+0.07}_{-0.06}$
κ_γ	$1.01^{+0.06}_{-0.06}$	$0.98^{+0.05}_{-0.05}$
$\kappa_{Z\gamma}$	$1.38^{+0.31}_{-0.37}$	$1.35^{+0.29}_{-0.36}$
$B_{inv.}$	-	< 0.13
$B_{u.}$	-	< 0.12



Ratio kappa model

Parameter	Definition in terms of κ modifiers	Result
κ_{gZ}	$\kappa_g \kappa_Z / \kappa_H$	1.00 ± 0.05
λ_{tg}	κ_t / κ_g	1.00 ± 0.12
λ_{bt}	κ_b / κ_t	$0.95\,^{+\,0.15}_{-\,0.13}$
λ_{ct}	κ_c / κ_t	$0.00\,^{+\,2.86}$
λ_{Zg}	κ_Z / κ_g	$1.05\,^{+\,0.10}_{-\,0.09}$
λ_{WZ}	κ_W / κ_Z	1.06 ± 0.06
$\lambda_{\gamma Z}$	κ_γ / κ_Z	1.02 ± 0.06
$\lambda_{Z\gamma Z}$	$\kappa_{Z\gamma} / \kappa_Z$	$1.39\,^{+\,0.31}_{-\,0.37}$
$\lambda_{\tau Z}$	κ_τ / κ_Z	0.93 ± 0.07
$\lambda_{\mu\tau}$	κ_μ / κ_τ	$1.15\,^{+\,0.27}_{-\,0.33}$