Combined Higgs boson measurements at the ATLAS experiment

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On behalf of the ATLAS Collaboration

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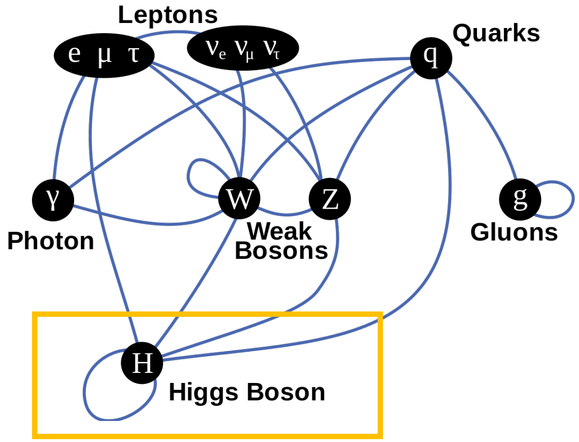
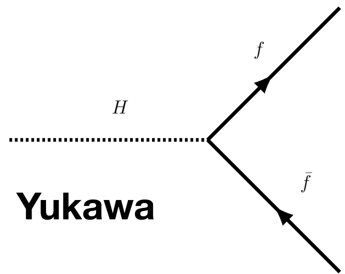
Introduction

- Following the discovery of the **Higgs** by the ATLAS and CMS, its coupling properties to other SM particles can be precisely probed, therefore providing stringent tests of the SM validity

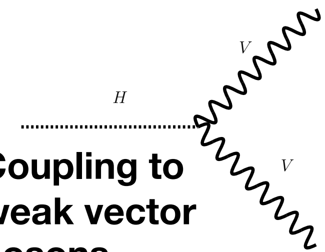


- $\mathcal{L}_H = -g_{Hff} f\bar{f}H + \delta_V V_\mu V^\mu \left(g_{HVV} H + \frac{g_{HHVV}}{2} H^2 \right) + \frac{g_{HHH}}{6} H^3 + \frac{g_{HHHH}}{6} H^4$

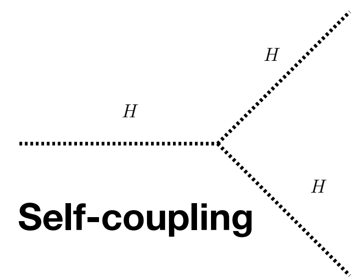
Yukawa



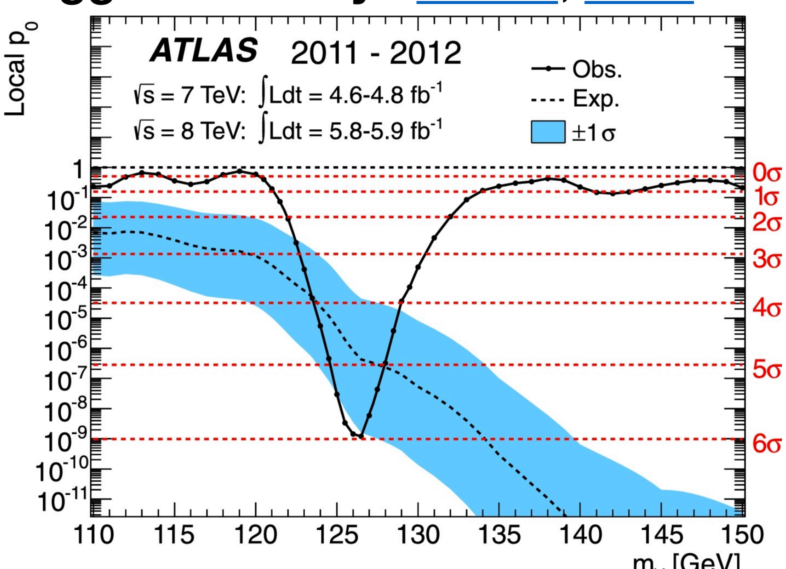
Coupling to weak vector bosons

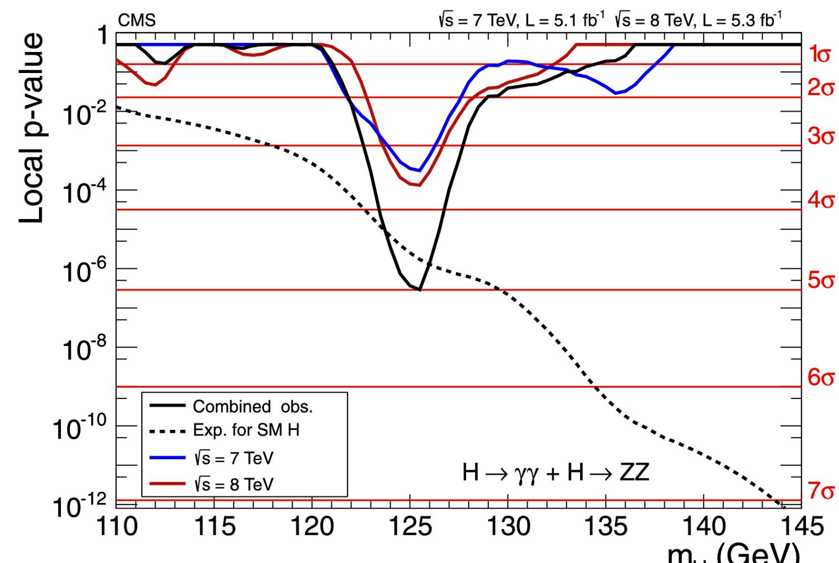


Self-coupling



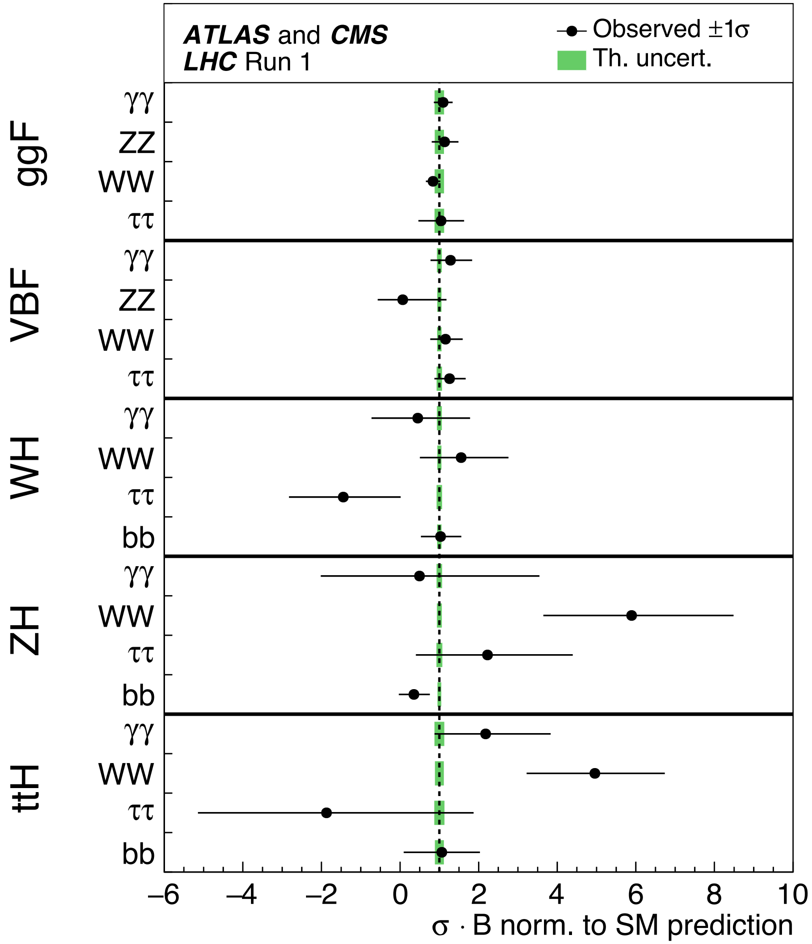
- **Higgs discovery:** ATLAS, CMS

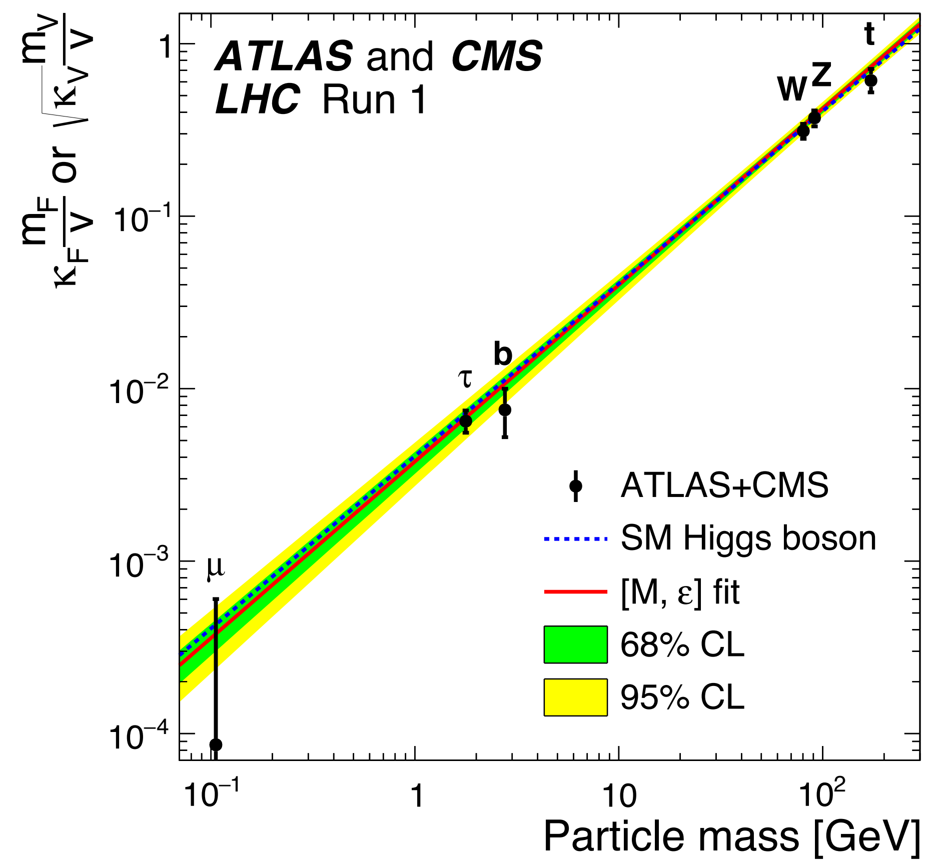




Run1 combination

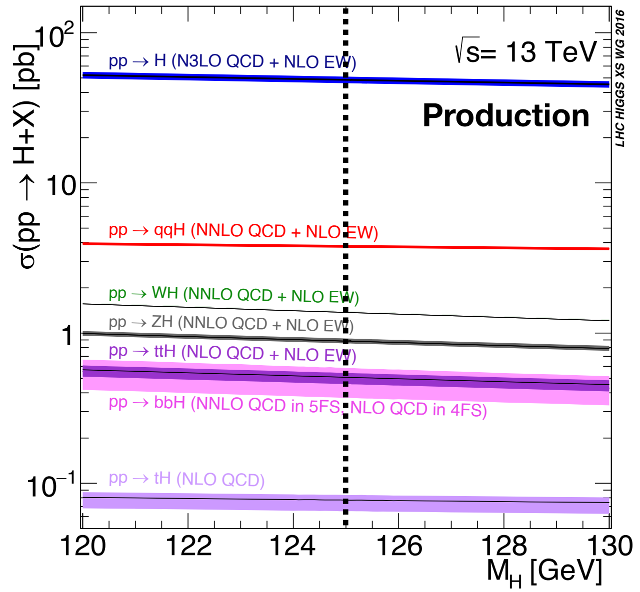
- Run 1 **combination of ATLAS and CMS** [JHEP 08 (2016) 045]

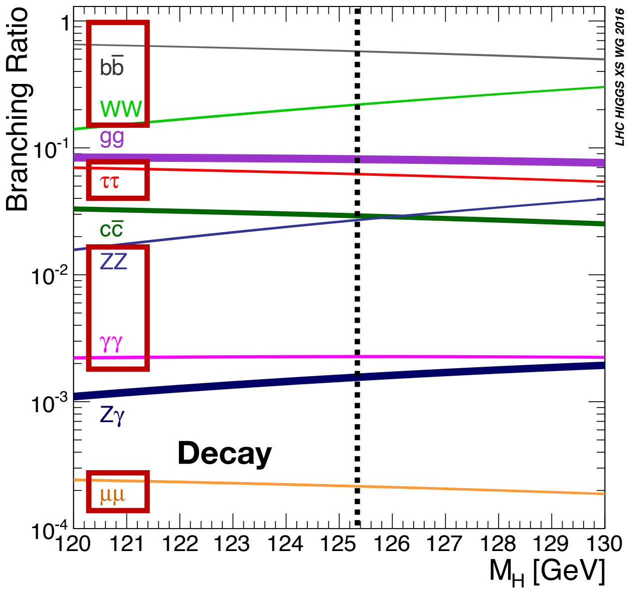




- The data are consistent with the SM within Run1 precision
- The measurements are extended in **ATLAS** using the **Run 2 dataset up to 80 fb^{-1},** to probe Higgs properties more precisely [Phys. Rev. D 101 (2020) 012002]

Combined production modes/decays





Analysis	Dataset	$\mathcal{L}$ [fb^{-1}]
$H \to \gamma\gamma$ (including $t\bar{t}H$, $H \to \gamma\gamma$)	2015–2017	79.8
$H \to ZZ^* \to 4\ell$ (including $t\bar{t}H$, $H \to ZZ^* \to 4\ell$)		79.8
VH, $H \to b\bar{b}$		79.8
$H \to \mu\mu$		79.8
$H \to WW^* \to e\nu\mu\nu$	2015–2016	36.1
$H \to \tau\tau$		36.1
VBF, $H \to b\bar{b}$		24.5 – 30.6
$t\bar{t}H$, $H \to b\bar{b}$ and $t\bar{t}H$ multilepton		36.1
$H \to$ invisible		36.1
Off-shell $H \to ZZ^* \to 4\ell$ and $H \to ZZ^* \to 2\ell 2\nu$		36.1

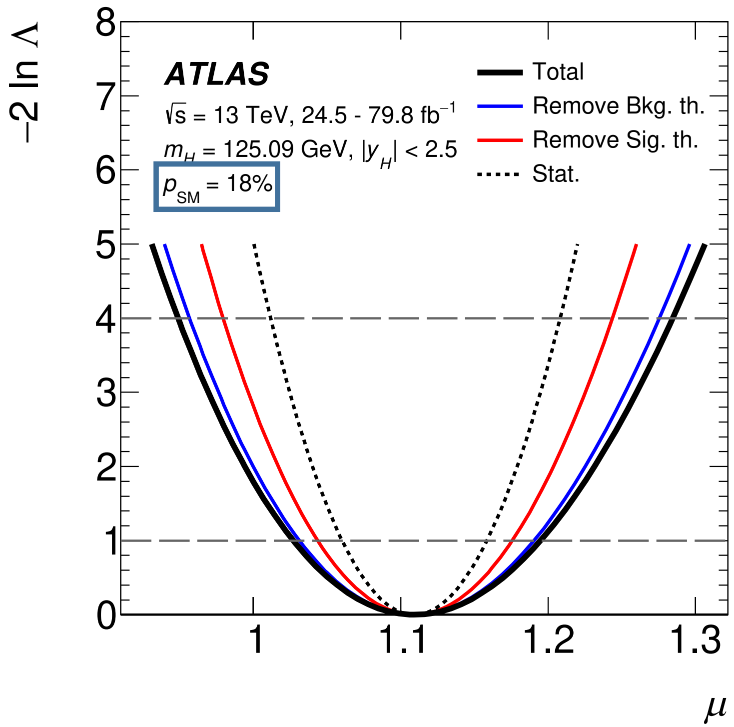
- $H \to b\bar{b}$, $H \to WW$, $H \to \tau\tau$
  - **Large BR**
  - low mass resolution
- $H \to ZZ^* \to 4l$, $H \to \gamma\gamma$
  - Low BR
  - **Excellent mass resolution**
  - High precision channels

Global signal strength

- **Global signal strength μ:** a common scaling of the expected Higgs boson yield, showing the overall sensitivity

$$\mu = \frac{(\sigma \times B)_H}{(\sigma \times B)_H^{SM}}$$

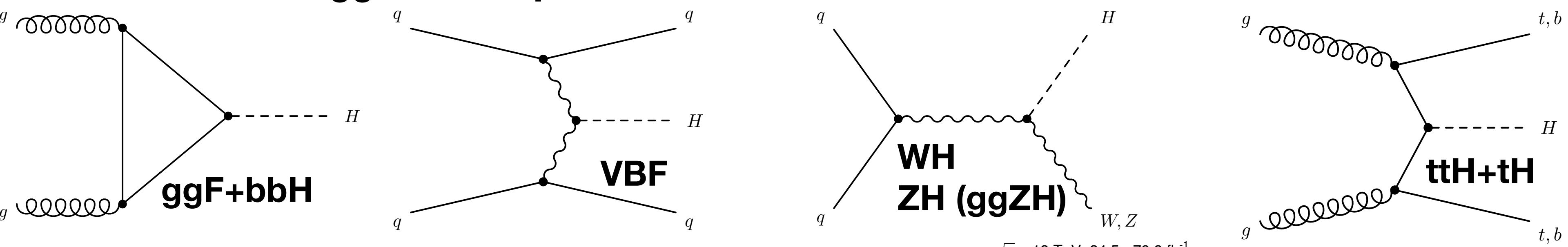
- $\mu = 1.11^{+0.09}_{-0.08} = 1.11 \pm 0.05(stat.)^{+0.05}_{-0.04}(exp.)^{+0.05}_{-0.04}(sig.th.) \pm 0.03(bkg.th.)$

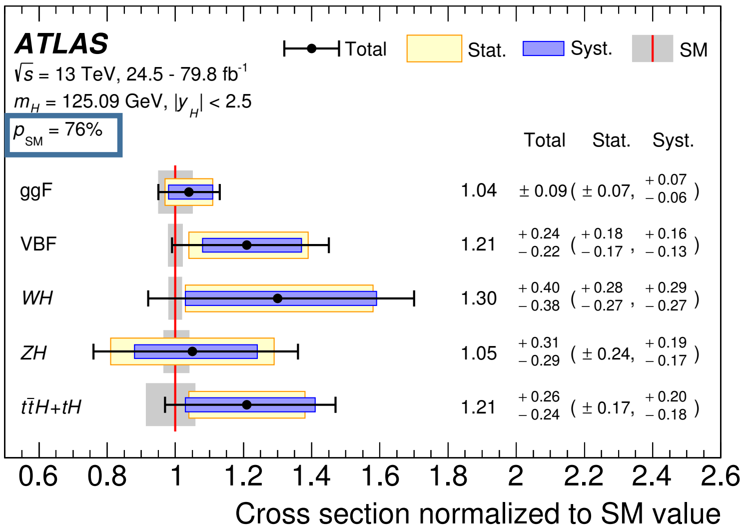


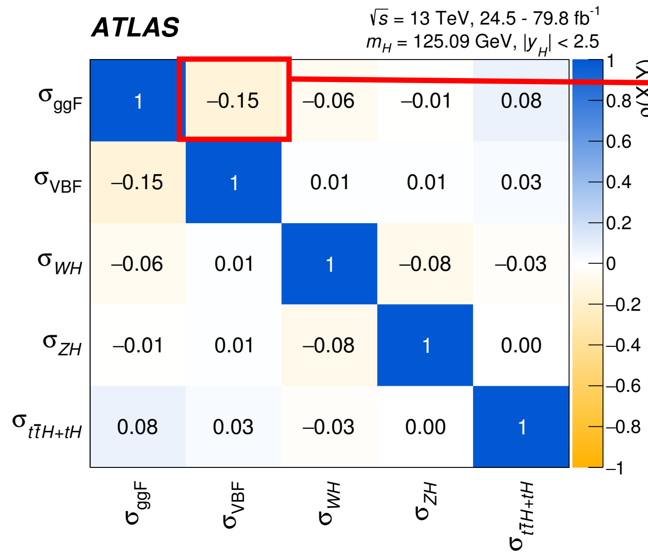
Uncertainty source	$\Delta\mu/\mu$ [%]
Statistical uncertainty	4.4
Systematic uncertainties	6.2
Theory uncertainties	4.8
Signal	4.2
Background	2.6
Experimental uncertainties (excl. MC stat.)	4.1
Luminosity	2.0
Background modeling	1.6
Jets, E_T^{miss}	1.4
Flavor tagging	1.1
Electrons, photons	2.2
Muons	0.2
τ-lepton	0.4
Other	1.6
MC statistical uncertainty	1.7
Total uncertainty	7.6

Production cross sections

- Measure the Higgs 5 main **production cross sections**







Contributions from **ggF production** in the **VBF-enriched selections**

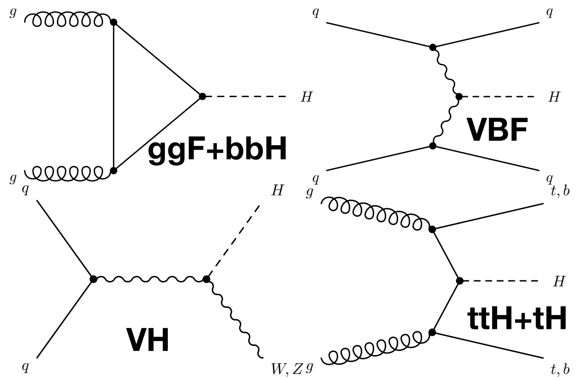
Correlations are small
- Various powerful analyses contribute to different production modes
- Analysis strategies optimized

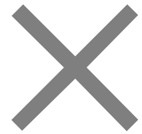
Process	Value	Uncertainty [pb]					SM pred.	Significance	
($\lvert y_H \rvert$ < 2.5)	[pb]	Total	Stat.	Exp.	Sig. th.	Bkg. th.	[pb]	obs. (exp.)	
ggF	46.5	± 4.0	± 3.1	± 2.2	± 0.9	± 1.3	44.7 ± 2.2	-	
VBF	4.25	$^{+0.84}_{-0.77}$	$^{+0.63}_{-0.60}$	$^{+0.35}_{-0.32}$	$^{+0.42}_{-0.32}$	$^{+0.14}_{-0.11}$	3.515 ± 0.075	6.5 (5.3)	
WH	1.57	$^{+0.48}_{-0.46}$	$^{+0.34}_{-0.33}$	$^{+0.25}_{-0.24}$	$^{+0.11}_{-0.07}$	± 0.20	1.204 ± 0.024	3.5 (2.7)	5.3 (4.7)
ZH	0.84	$^{+0.25}_{-0.23}$	± 0.19	± 0.09	$^{+0.07}_{-0.04}$	± 0.10	0.797 $^{+0.033}_{-0.026}$	3.6 (3.6)	
$t\bar{t}H+tH$	0.71	$^{+0.15}_{-0.14}$	± 0.10	$^{+0.07}_{-0.06}$	$^{+0.05}_{-0.04}$	$^{+0.08}_{-0.07}$	0.586 $^{+0.034}_{-0.049}$	5.8 (5.4)	

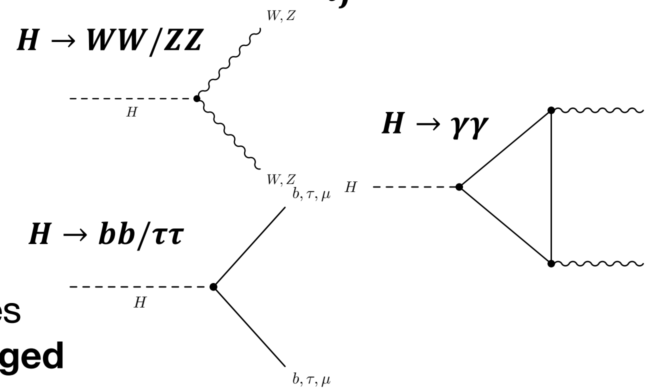
Single experiment observation

Production cross sections × BR

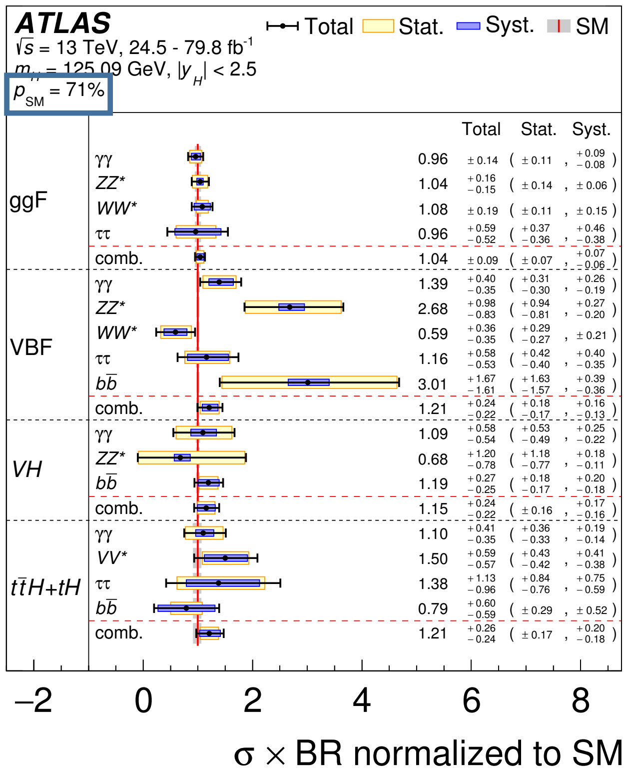
- Prob Higgs property in each **production and Higgs decay:** $(\sigma \times B)_{if}$

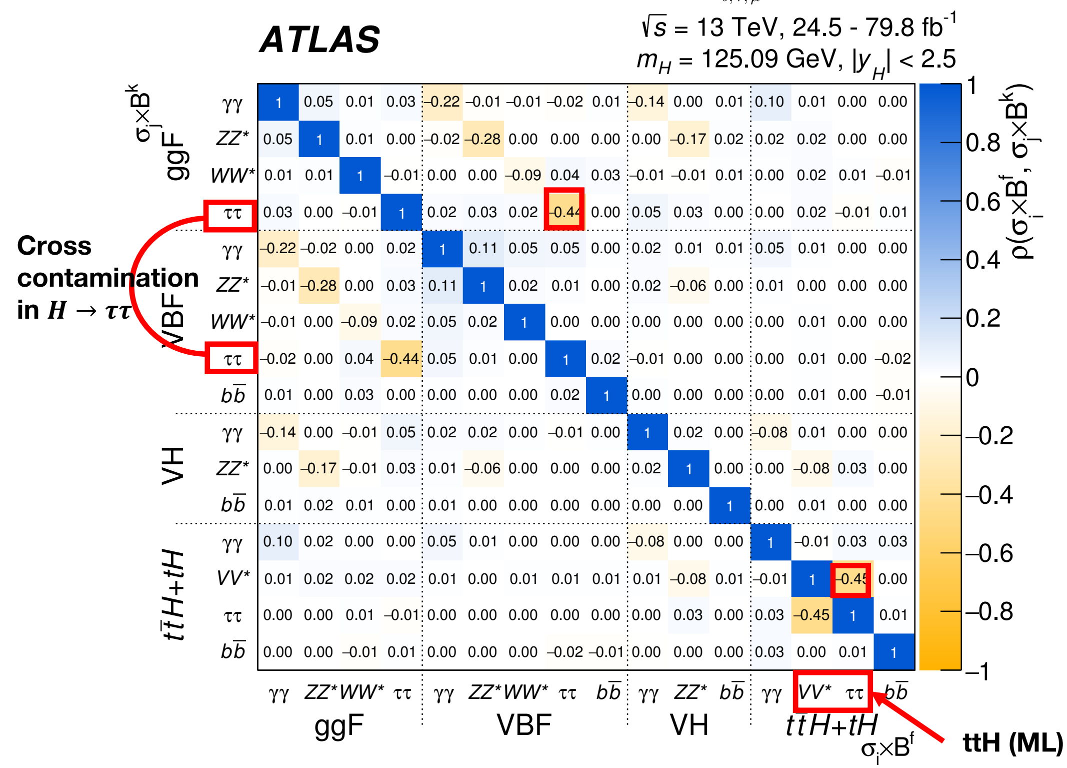






Bins with limited sensitivities are **fixed to the SM** or **merged**

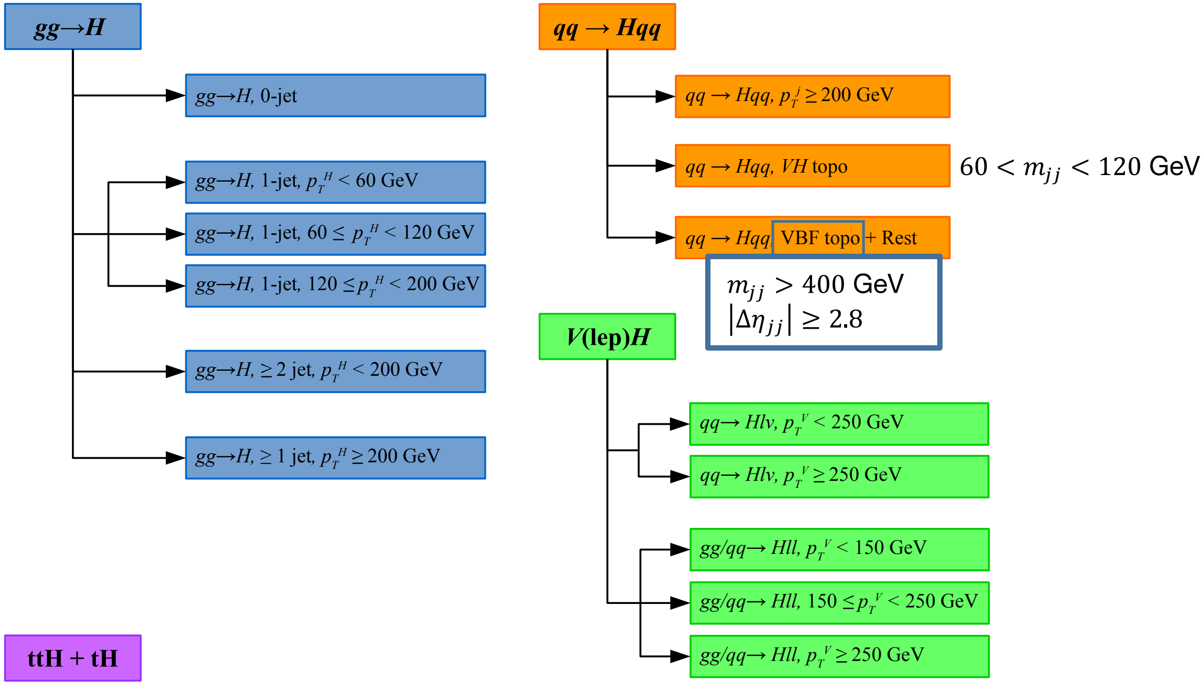




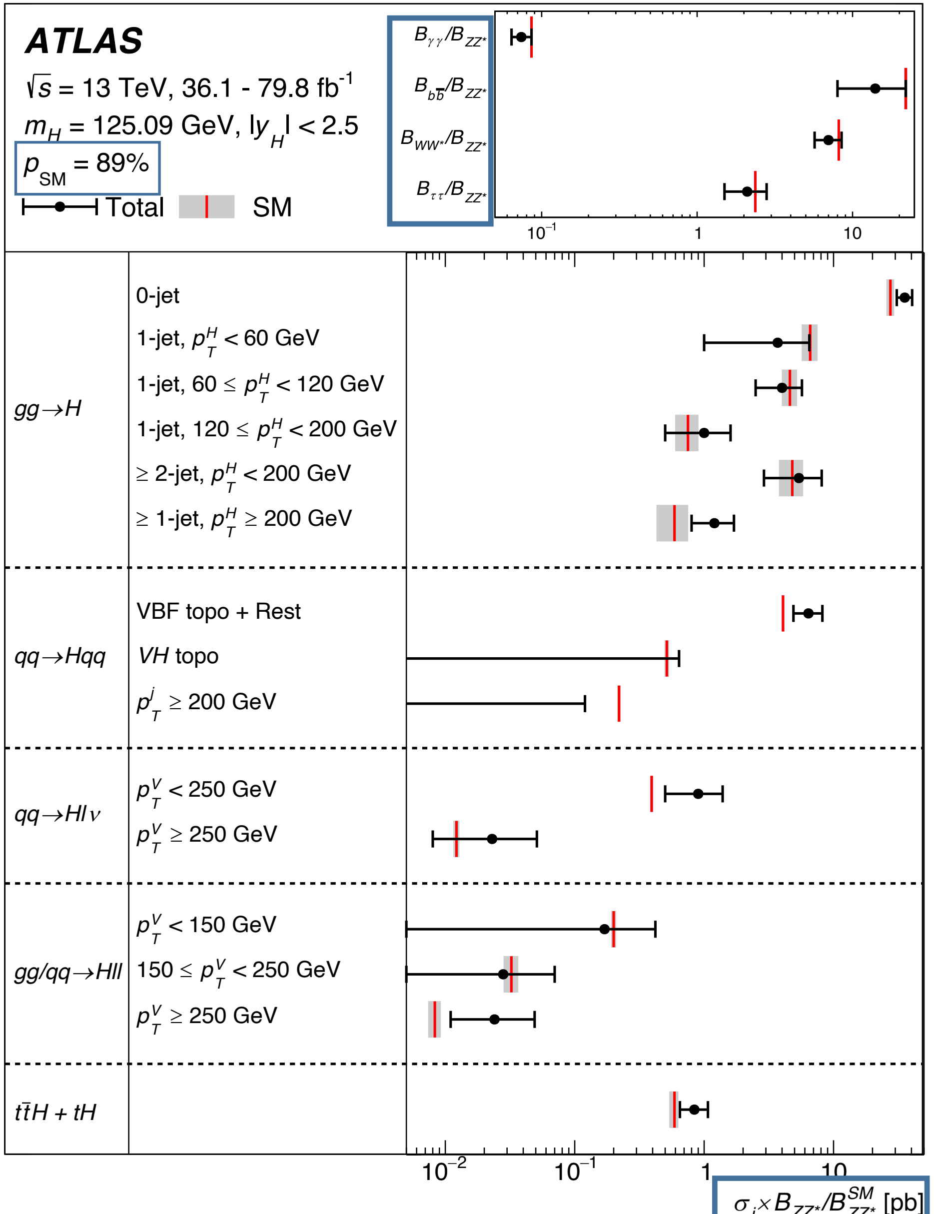
Simplified template cross section

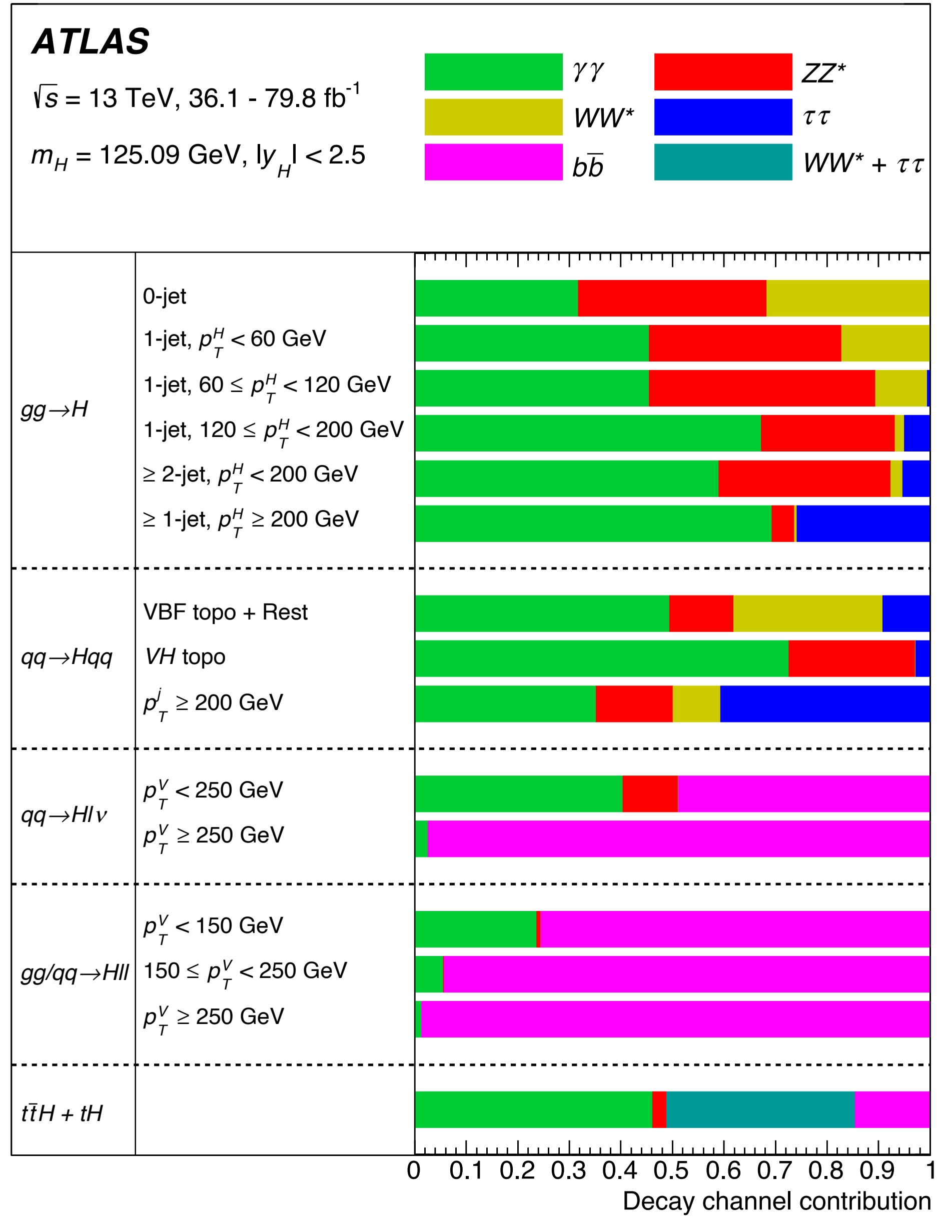
- A **new scheme** in Run2, defined trough a partition of the phase space of the **Higgs production process,** independently of the **Higgs decay process,** aim to
  - Have good **sensitivity**
  - Avoid **large theory uncertainties**
  - Approximately match experimental selections, to **minimize model-dependent** extrapolations

- **Merged Stage 1**



STXS measurements

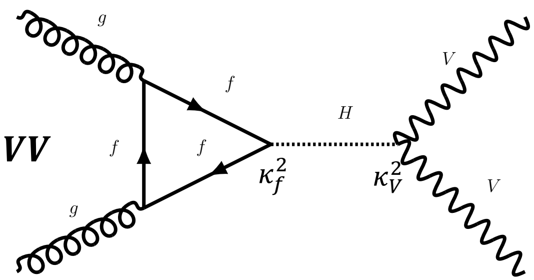




κ framework

- To measure **Higgs coupling strengths directly,** and to test deviations from SM

ggF, $H \to VV$

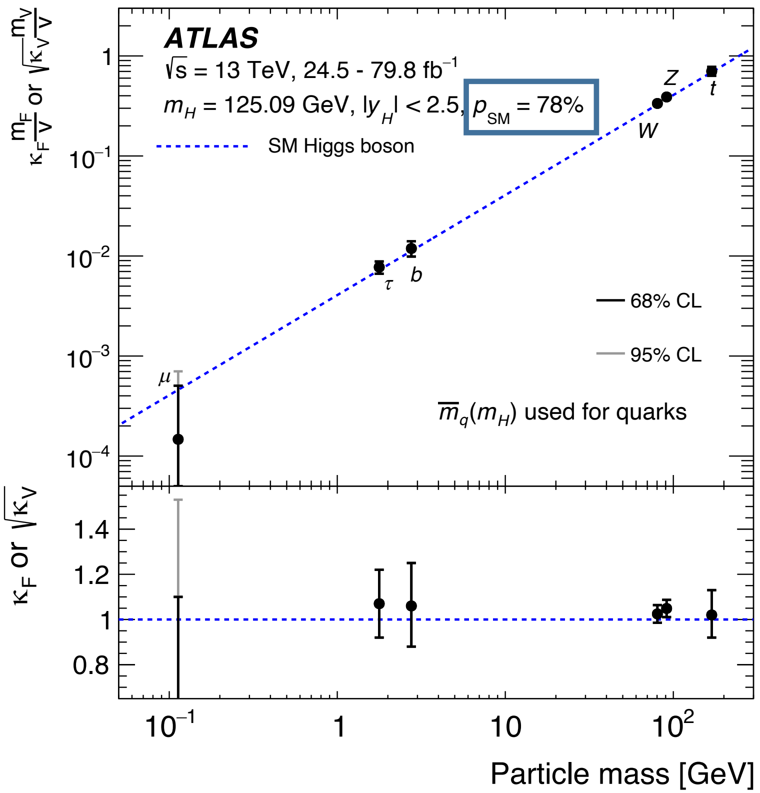


- ***κ* framework**
  - Coupling modifiers to **productions** and **decays**
- $\sigma_i \times B_f = \frac{\boldsymbol{\sigma_i(\kappa) \times \Gamma_f(\kappa)}}{\boldsymbol{\Gamma_H}}$, $\kappa_i^2 = \frac{\sigma_i}{\sigma_i^{SM}}$, $\kappa_f^2 = \frac{\Gamma_f}{\Gamma_f^{SM}}$
- $\kappa_H^2(\kappa, B_{inv}, B_{undet}) = \frac{\sum_j B_f^{SM} \kappa_j^2}{(1 - B_{inv} - B_{undet})}$
  - $\boldsymbol{B_{inv}}$: ~0.1% from $H \to ZZ^* \to 4\nu$
  - $\boldsymbol{B_{undet}}$: no sensitive analyses: H → light quarks, H → BSM particles, etc.

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 ($B_{\text{inv}} = B_{\text{undet}} = 0$)				
Γ_H	✓	-	κ_H^2	$0.58\,\kappa_b^2 + 0.22\,\kappa_W^2$ $+0.08\,\kappa_g^2 + 0.06\,\kappa_\tau^2$ $+0.03\,\kappa_Z^2 + 0.03\,\kappa_c^2$ $+0.0023\,\kappa_\gamma^2 + 0.0015\,\kappa_{(Z\gamma)}^2$ $+0.0004\,\kappa_s^2 + 0.00022\,\kappa_\mu^2$

Generic model assuming no new particles

- κ_W, κ_Z, $\kappa_t(\kappa_c)$, $\kappa_b(\kappa_s)$, κ_τ, κ_μ
- **Assumption**
  - All $\kappa \geq 0$
  - Only SM particle contribute to Higgs vertices
  - $B_{inv} = B_{undet} = 0$



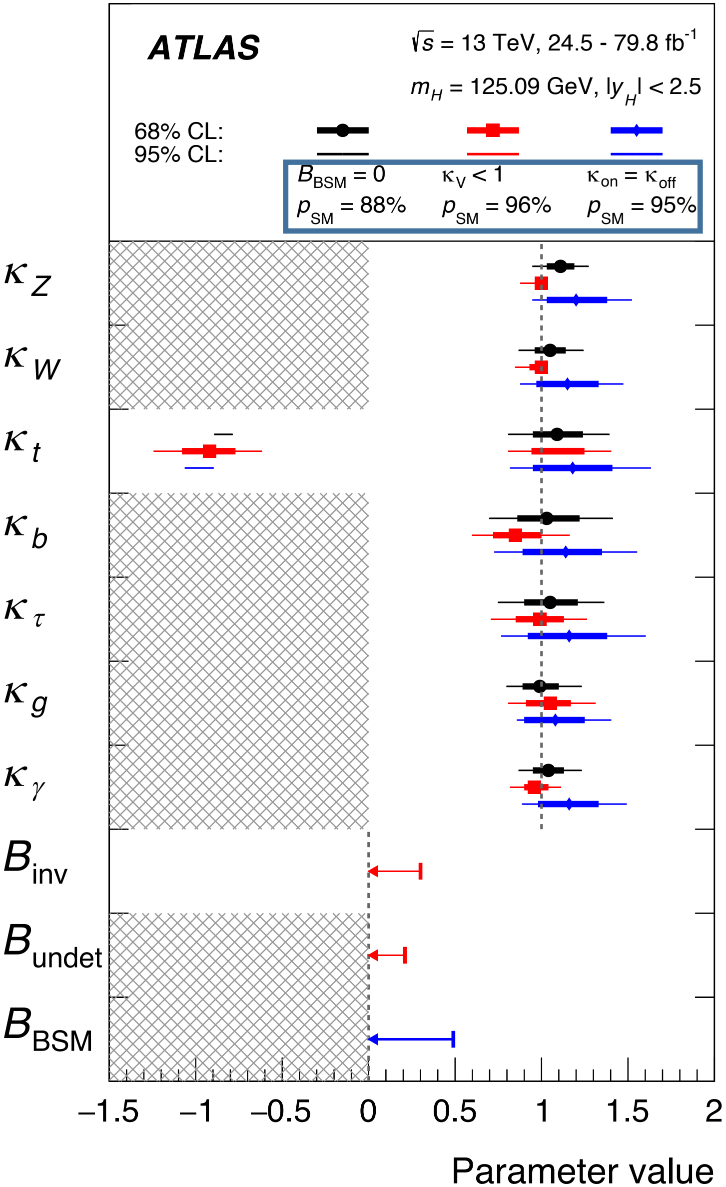
Parameter	Result
κ_Z	1.10 ± 0.08
κ_W	1.05 ± 0.08
κ_b	$1.06\ ^{+\,0.19}_{-\,0.18}$
κ_t	$1.02\ ^{+\,0.11}_{-\,0.10}$
κ_τ	1.07 ± 0.15
κ_μ	< 1.53 at 95% CL

Generic model with/without BSM contributions

- κ_W, κ_Z, $\kappa_t(\kappa_c)$, $\kappa_b(\kappa_s)$, κ_τ, $\boldsymbol{\kappa_\gamma}$, $\boldsymbol{\kappa_g}$
  - $\boldsymbol{\kappa_g}$: ggF, $H \to gg$; $\boldsymbol{\kappa_\gamma}$: $H \to \gamma\gamma$
- All $\kappa \geq 0$ except $\boldsymbol{\kappa_t}$ **without loss of generality**

Assumption

Parameter	(a) $B_{\text{inv}} = B_{\text{undet}} = 0$	(b) B_{inv} free, $B_{\text{undet}} \geq 0$, $\kappa_{W,Z} \leq 1$	(c) $B_{\text{BSM}} \geq 0$, $\kappa_{\text{off}} = \kappa_{\text{on}}$
κ_Z	1.11 ± 0.08	> 0.88 at 95% CL	$1.20\ ^{+0.18}_{-0.17}$
κ_W	1.05 ± 0.09	> 0.85 at 95% CL	1.15 ± 0.18
κ_b	$1.03\ ^{+0.19}_{-0.17}$	$0.85\ ^{+0.15}_{-0.13}$	$1.14\ ^{+0.21}_{-0.25}$
κ_t	$1.09\ ^{+0.15}_{-0.14}$	$[-1.08, -0.77] \cup [0.96, 1.23]$ at 68% CL	1.18 ± 0.23
κ_τ	$1.05\ ^{+0.16}_{-0.15}$	0.99 ± 0.14	$1.16\ ^{+0.22}_{-0.24}$
κ_γ	1.05 ± 0.09	$0.96\ ^{+0.08}_{-0.06}$	$1.16\ ^{+0.17}_{-0.18}$
κ_g	$0.99\ ^{+0.11}_{-0.10}$	$1.05\ ^{+0.12}_{-0.14}$	$1.08\ ^{+0.17}_{-0.18}$
B_{inv}	-	< 0.30 at 95% CL	-
B_{undet}	-	< 0.21 at 95% CL	-
B_{BSM}	-	-	< 0.49 at 95% CL

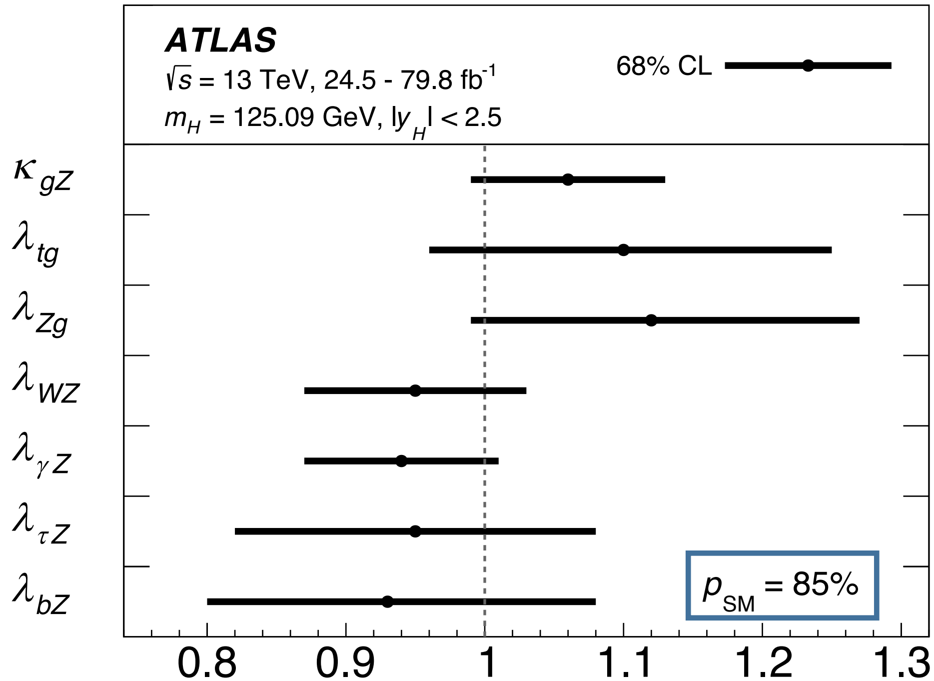


Generic ratio model

- Ratio model is the most **model-independent**
  - **Independent** of any assumptions about $\boldsymbol{\kappa_H}$
  - Common **systematics** cancel out

Parameter	Definition in terms of κ modifiers	Result
κ_{gZ}	$\kappa_g \kappa_Z / \kappa_H$	1.06 ± 0.07
λ_{tg}	κ_t / κ_g	$1.10^{+0.15}_{-0.14}$
λ_{Zg}	κ_Z / κ_g	$1.12^{+0.15}_{-0.13}$
λ_{WZ}	κ_W / κ_Z	0.95 ± 0.08
$\lambda_{\gamma Z}$	κ_γ / κ_Z	0.94 ± 0.07
$\lambda_{\tau Z}$	κ_τ / κ_Z	0.95 ± 0.13
λ_{bZ}	κ_b / κ_Z	$0.93^{+0.15}_{-0.13}$

All assume positive



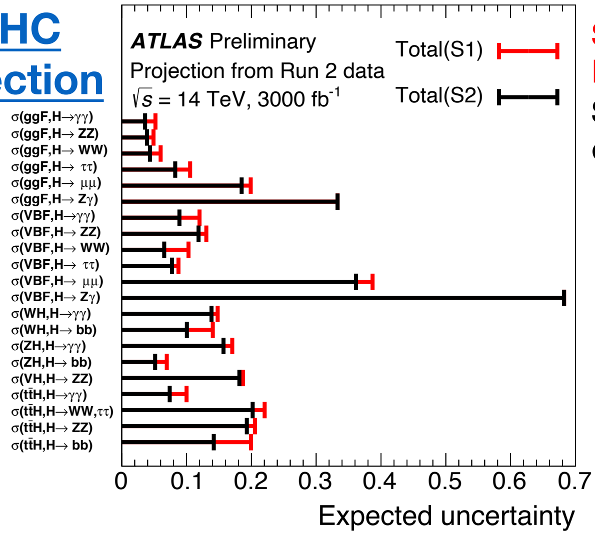
- $\boldsymbol{\lambda_{\gamma Z}}$: Sensitive to **new charged particles** contributing to $\boldsymbol{H \to \gamma\gamma}$ unlike in $H \to ZZ^*$
- $\boldsymbol{\lambda_{tg}}$: Sensitive to **new colored particles** through **ggF loop** unlike in ttH events

Summary

- **Higgs coupling properties** have been measured in ATLAS by combining Run2 data up to 80 fb^{-1} [Phys. Rev. D 101 (2020) 012002]
- **Global signal strength** $\mu = 1.11^{+0.09}_{-0.08}$
  - 21% higher precision w.r.t Run1: $1.09^{+0.11}_{-0.10}$
- Higgs **production cross sections** and **decay BR** are measured as well
  - The precision is 9% - 30% with various production modes respectively
- Measured merged **Stage 1 STXS** (new results)
- Higgs couplings are measured within $\boldsymbol{\kappa}$ **frameworks** with/without **BSM** $(\boldsymbol{B_{inv}}, \boldsymbol{B_{undet}})$ contributions to the $\boldsymbol{\Gamma_H}$

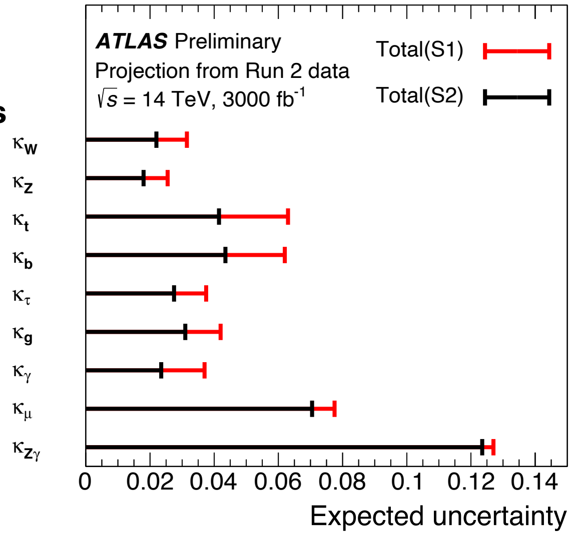
- **No significant deviation from the SM is observed in any models**

HL-LHC projection



S1: Same systematics at Run2

S2: Reduced systematics expected at HL-LHC



Backup

Run1 combination significances

Production process	Measured significance (σ)	Expected significance (σ)
VBF	5.4	4.6
WH	2.4	2.7
ZH	2.3	2.9
VH	3.5	4.2
ttH	4.4	2.0
Decay channel		
$H \to \tau\tau$	5.5	5.0
$H \to bb$	2.6	3.7

Combined production modes/decays

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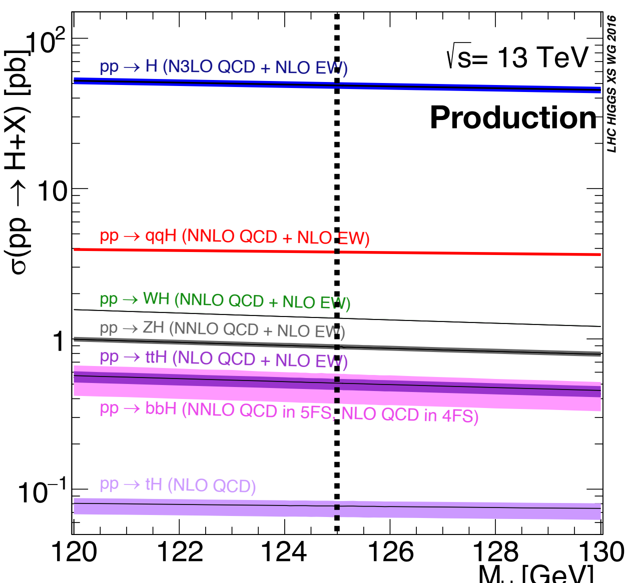
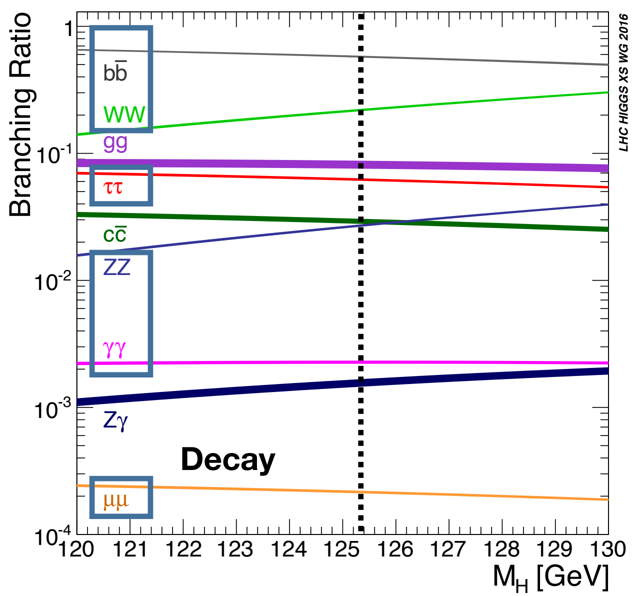
VBF, $H \to b\bar{b}$ Not used in **STXS**		24.5 – 30.6
$t\bar{t}H$, $H \to b\bar{b}$ and $t\bar{t}H$ multilepton		36.1
$H \to$ invisible Only for $\boldsymbol{B_{inv}}$		36.1
Off-shell $H \to ZZ^* \to 4\ell$ and $H \to ZZ^* \to 2\ell 2\nu$	Only for $\boldsymbol{\kappa_{off}}$	36.1

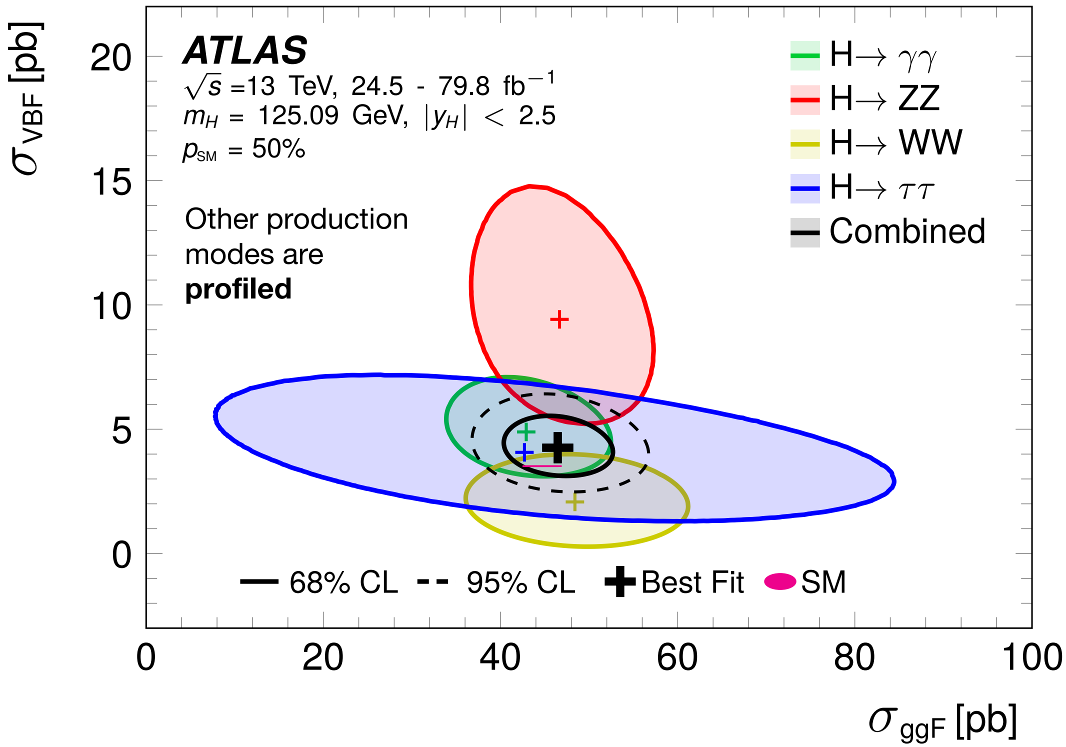




- $H \to b\bar{b}$, $H \to WW$, $H \to \tau\tau$
  - **Large BR**
  - low mass resolution
- $H \to ZZ^* \to 4l$, $H \to \gamma\gamma$
  - Low BR
  - **high S/B, excellent mass resolution**
  - Gold channels

Production cross sections

σ_{ggF} VS σ_{VBF}

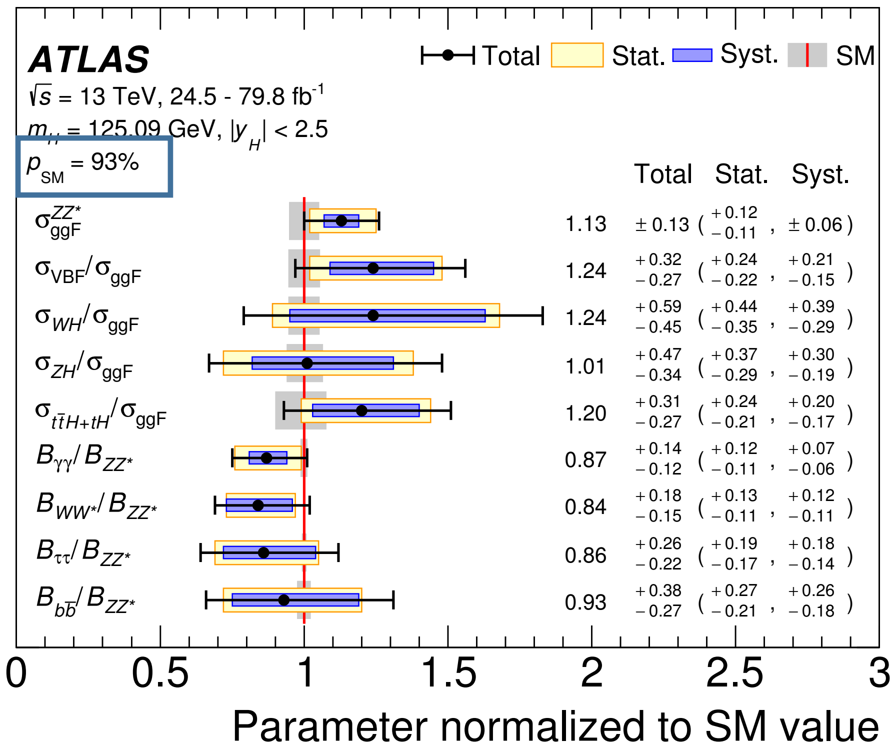


Ratios of cross sections and branching fractions

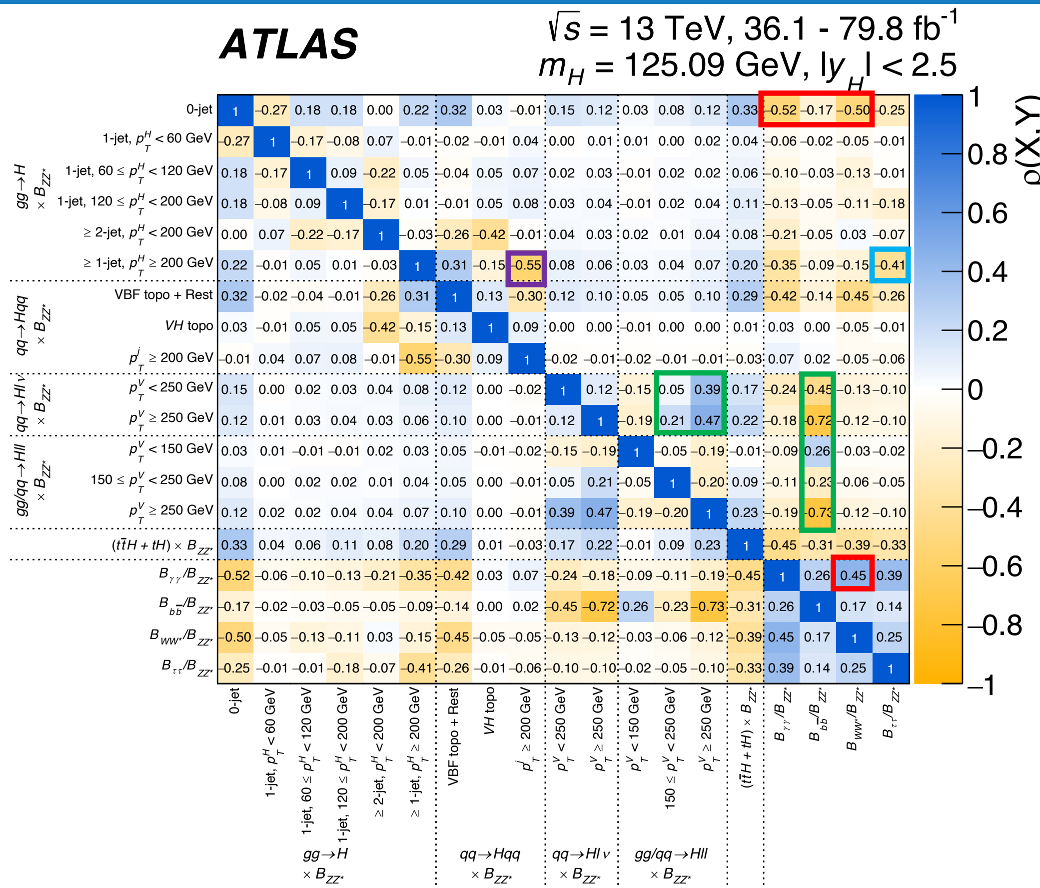
- Measurement on the **ratios of cross sections and BR** can
  - Cancel the **SM assumption of the relative fractions** between Higgs production cross sections and BR
  - Reduce the **common systematics** through the ratios

$$(\sigma \times B)_{if} = \sigma_{ggF}^{ZZ} \cdot \left(\frac{\sigma_i}{\sigma_{ggF}}\right) \cdot \left(\frac{B_f}{B_{ZZ}}\right)$$

Precisely measured
Small systematics



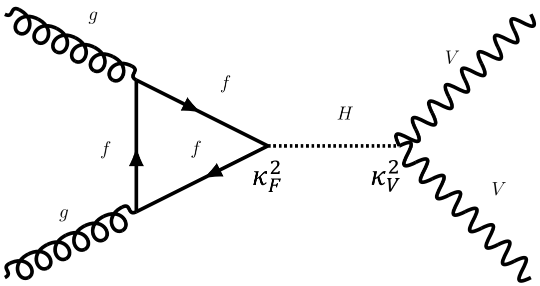
Correlations between STXS bins



- VHlep VS B_{bb}/B_{ZZ}, WHlep VS Zhlep
  - Only **VHbb** is sensitive
- gg2H 0j VS $B_{\gamma\gamma}/B_{ZZ}$, gg2H 0j VS B_{WW}/B_{ZZ}, $B_{\gamma\gamma}/B_{ZZ}$ VS B_{WW}/B_{ZZ}
  - $\boldsymbol{H \to \gamma\gamma, H \to WW, H \to ZZ}$ are the most sensitive
- $p_T^H \ge 200$ GeV VS $B_{\tau\tau}/B_{ZZ}$
  - $\boldsymbol{H \to \tau\tau}$ is sensitive in high pTH
- gg2H, ≥1j, $p_T^H \ge 200$ GeV VS qq2Hqq, $p_T^j \ge 200$ GeV
  - **cross-contamination** in experimental selections

Fermions and gauge boson couplings

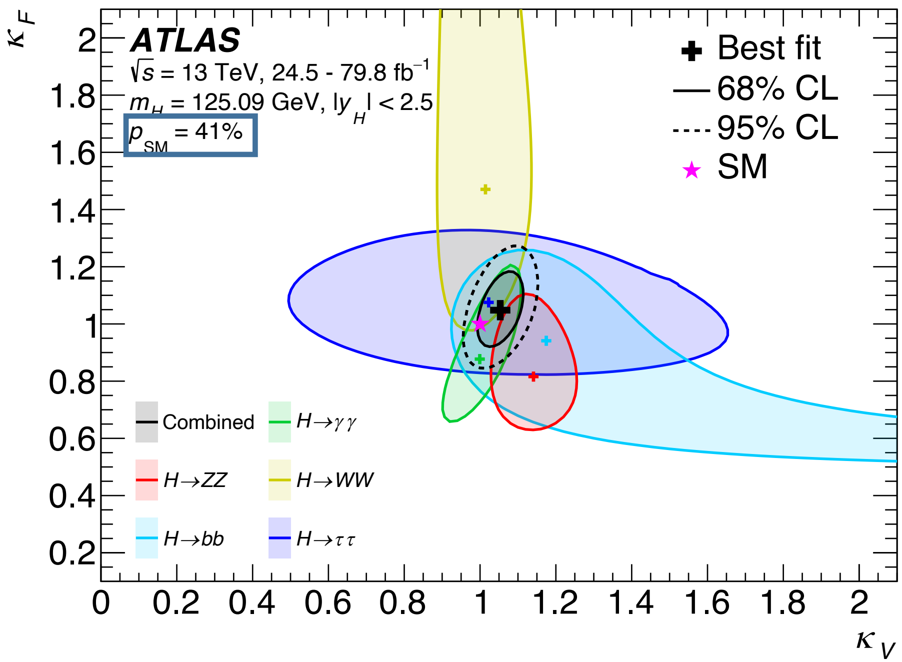
- Universal coupling-strength
  - $\boldsymbol{\kappa_V} = \kappa_W = \kappa_Z$
  - $\boldsymbol{\kappa_F} = \kappa_t = \kappa_b = \kappa_\tau = \kappa_\mu$



- **Assumption**
  - $B_{inv} = B_{undet} = 0$
  - $\boldsymbol{\kappa_V \geq 0, \kappa_F \geq 0}$ **(negative** relative sign is already excluded[JHEP 08 (2016) 045])

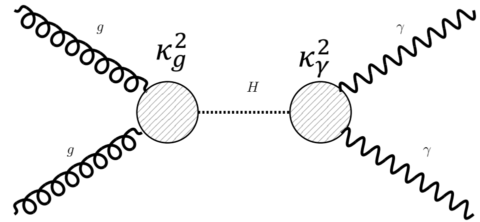
- $\kappa_V = 1.05 \pm 0.04$
- $\kappa_F = 1.05 \pm 0.09$

- **Correlation:** κ_V VS κ_F: 44%

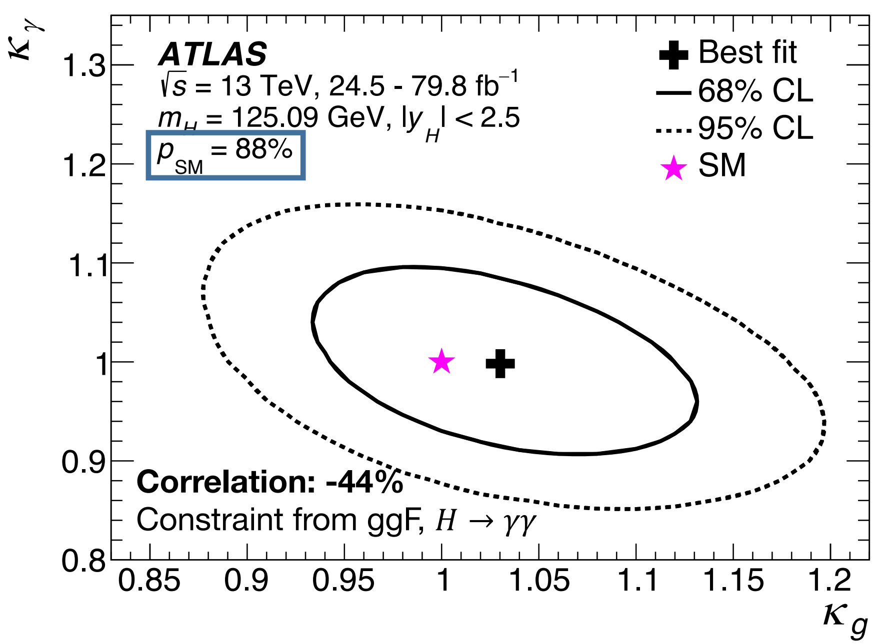


Prob BSM contributions in loops and decays

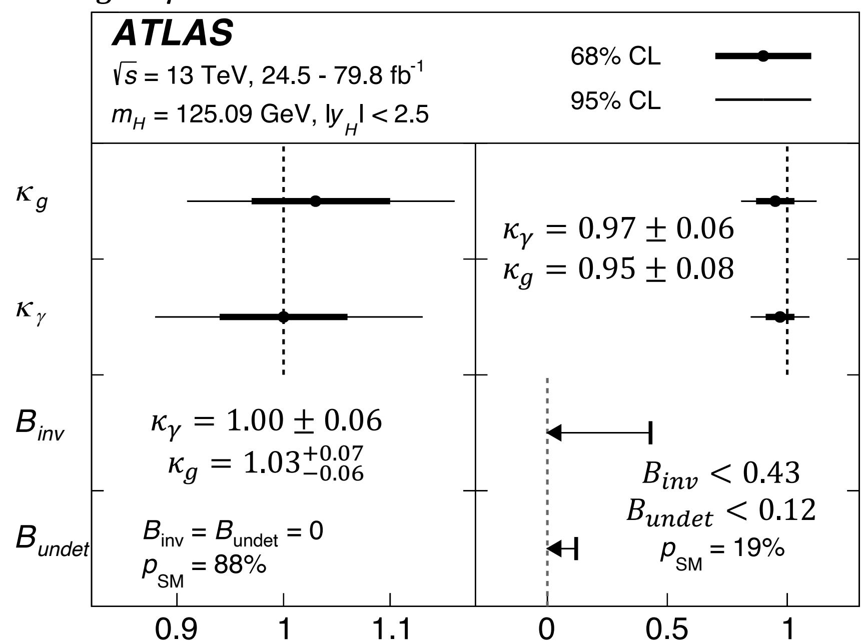
- $\boldsymbol{\kappa_\gamma}$ VS $\boldsymbol{\kappa_g}$
  - To probe **new particles** contributions through **loops** or **new final states**
  - $\boldsymbol{\kappa_\gamma \geq 0, \kappa_g \geq 0}$ (No sensitivity to measure relative sign)
  - Other $\boldsymbol{\kappa}$ are fixed to the **SM**



- **Assumption 1**
  - $B_{inv} = B_{undet} = 0$
- $\kappa_\gamma = 1.00 \pm 0.06,\ \kappa_g = 1.03^{+0.07}_{-0.06}$



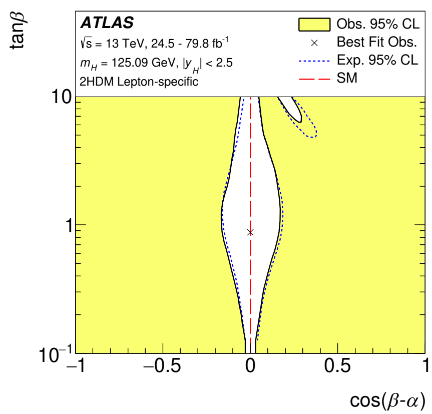
- **Assumption 2**
  - B_{inv}, B_{undet} as free
- B_{undet} is constraint by processes other than κ_g, κ_γ

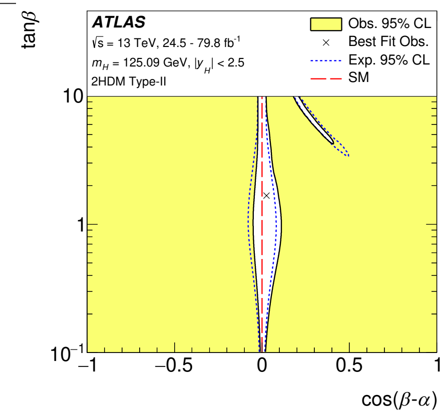


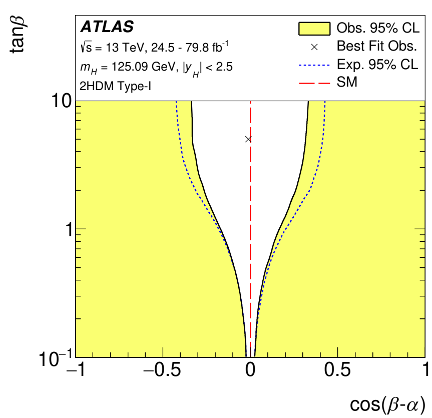
2HDM

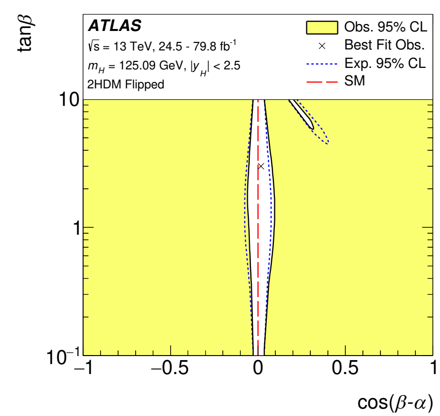
- SM Higgs sector is extended by an additional **doublet** of the complex field
- Neutral CP even: ***h* (lighter, SM-like),** H (heavier); Neutral CP odd: A; Charged: $H^{\pm}$
- **Vacuum expectation**: $v_1^2 + v_2^2 = v^2 \approx (246\ GeV)^2$; $\tan\boldsymbol{\beta} \equiv \frac{v_2}{v_1}$
- **Mixing angle** $\boldsymbol{\alpha}$ of h and H
- $\kappa_{hVV} = \sin(\beta - \alpha)$, $\boldsymbol{\kappa_{HVV} = \cos(\beta - \alpha)}$

Coupling scale factor	Type I	Type II	Lepton-specific	Flipped
κ_V	$\sin(\beta - \alpha)$			
κ_u	$\cos(\alpha)/\sin(\beta)$			
κ_d	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$
κ_ℓ	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$



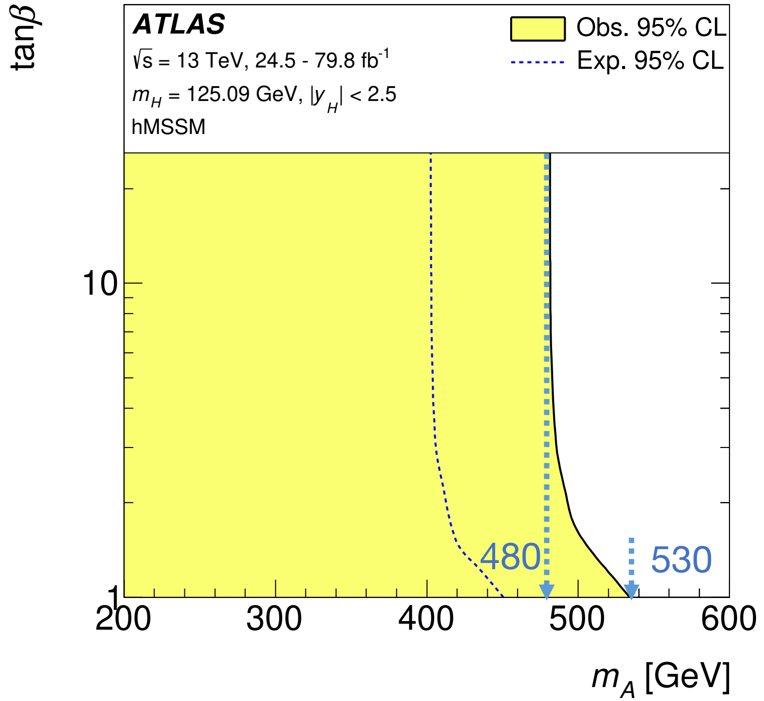






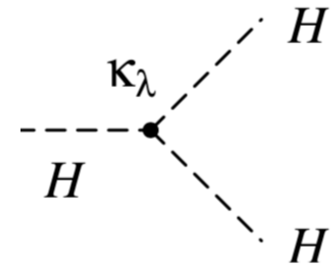
hMSSM

- Realization of a type II 2HDM
- $\kappa_V = \frac{s_d(m_A, \tan\beta) + \tan\beta\, s_u(m_A, \tan\beta)}{\sqrt{1+\tan^2\beta}}$, $\boldsymbol{\tan\beta \equiv \frac{v_2}{v_1}}$
- $\kappa_u = s_u(m_A, \tan\beta)\frac{\sqrt{1+\tan^2\beta}}{\tan\beta}$, $\kappa_d = s_d(m_A, \tan\beta)\sqrt{1+\tan^2\beta}$
- $s_u = \frac{1}{\sqrt{1+\frac{(m_A^2+m_Z^2)^2\tan^2\beta}{\left(m_Z^2+m_A^2\tan^2\beta - m_h^2(1+\tan^2\beta)\right)^2}}}$, $s_d = \frac{(m_A^2+m_Z^2)\tan\beta}{m_Z^2+m_A^2\tan^2\beta - m_h^2(1+\tan^2\beta)} s_u$



Higgs self-coupling

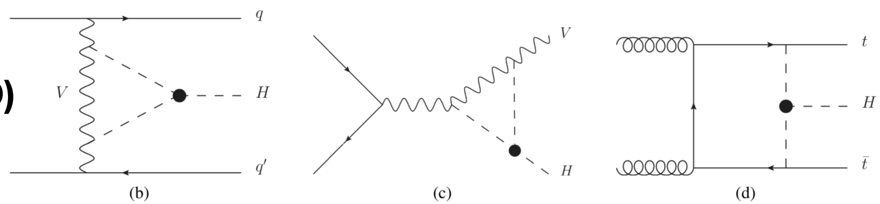
- In Run2, **Higgs couplings to other SM particles** are measured with an increasing precision
- The properties of **Higgs boson self-coupling** are still unconstrained



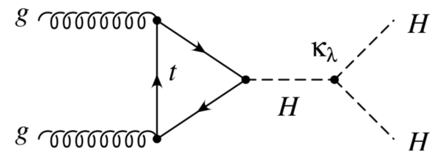
- Constrain $\boldsymbol{\kappa_\lambda} = \frac{\lambda_{HHH}}{\lambda_{HHH}^{SM}}$ by single/double-Higgs and combination

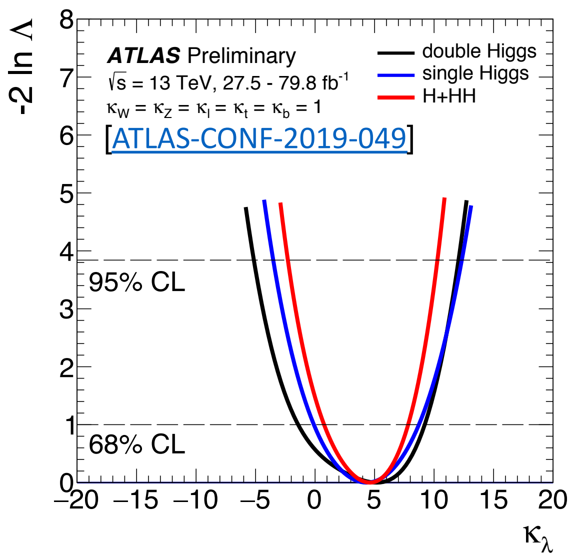
Analysis	Integrated luminosity (fb^{-1})
$H \to \gamma\gamma$	79.8
$H \to ZZ^* \to 4\ell$ (including $t\bar{t}H$, $H \to ZZ^* \to 4\ell$)	79.8
$H \to WW^* \to e\nu\mu\nu$	36.1
$H \to \tau\tau$	36.1
VH, $H \to b\bar{b}$	79.8
$t\bar{t}H$, $H \to b\bar{b}$ and $t\bar{t}H$ multilepton	36.1
$HH \to b\bar{b}b\bar{b}$	27.5
$HH \to b\bar{b}\tau^+\tau^-$	36.1
$HH \to b\bar{b}\gamma\gamma$	36.1

H (NLO)



HH (LO)





95% CL	Obs.	Exp.
H [ATL-PHYS-PUB-2019-009]	[-3.2, 11.9]	[-6.2, 14.4]
HH [arXiv:1906.02025]	[-5.0, 12.0]	[-5.8, 12.0]
H+HH [ATLAS-CONF-2019-049]	[-2.3, 10.3]	[-5.1, 11.2]