

Combined measurements of Higgs production and decays with the ATLAS detector

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on behalf of the ATLAS Collaboration

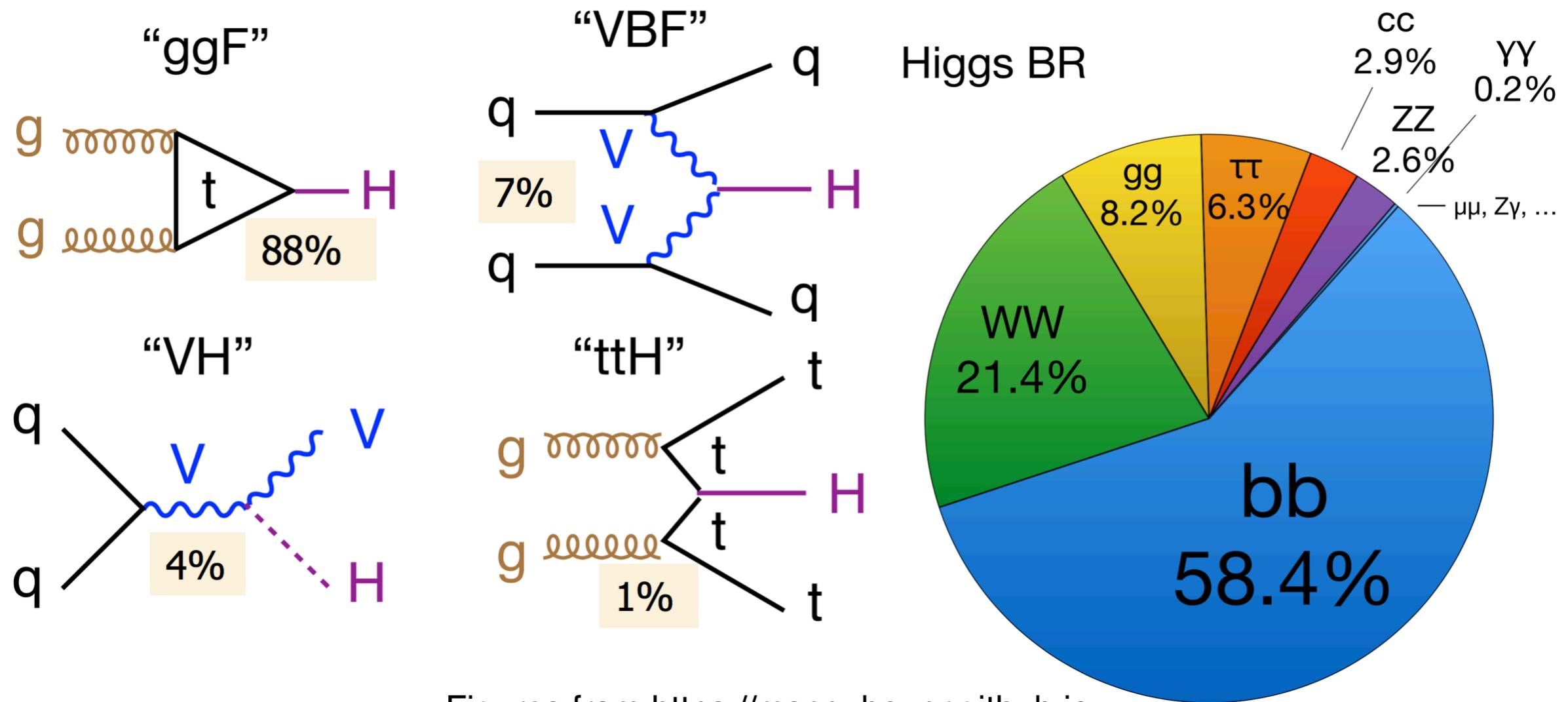


*July 10-17, 2019 - Ghent Belgium
European Physics Society Conference
on High Energy Physics*



Introduction

- Since the Higgs discovery by ATLAS and CMS in 2012, many **Higgs property studies** (mass, spin, parity, couplings, cross sections, etc.) have been performed
- Today: combined measurements of Higgs boson production and decays using **13 TeV data** collected with the ATLAS detector



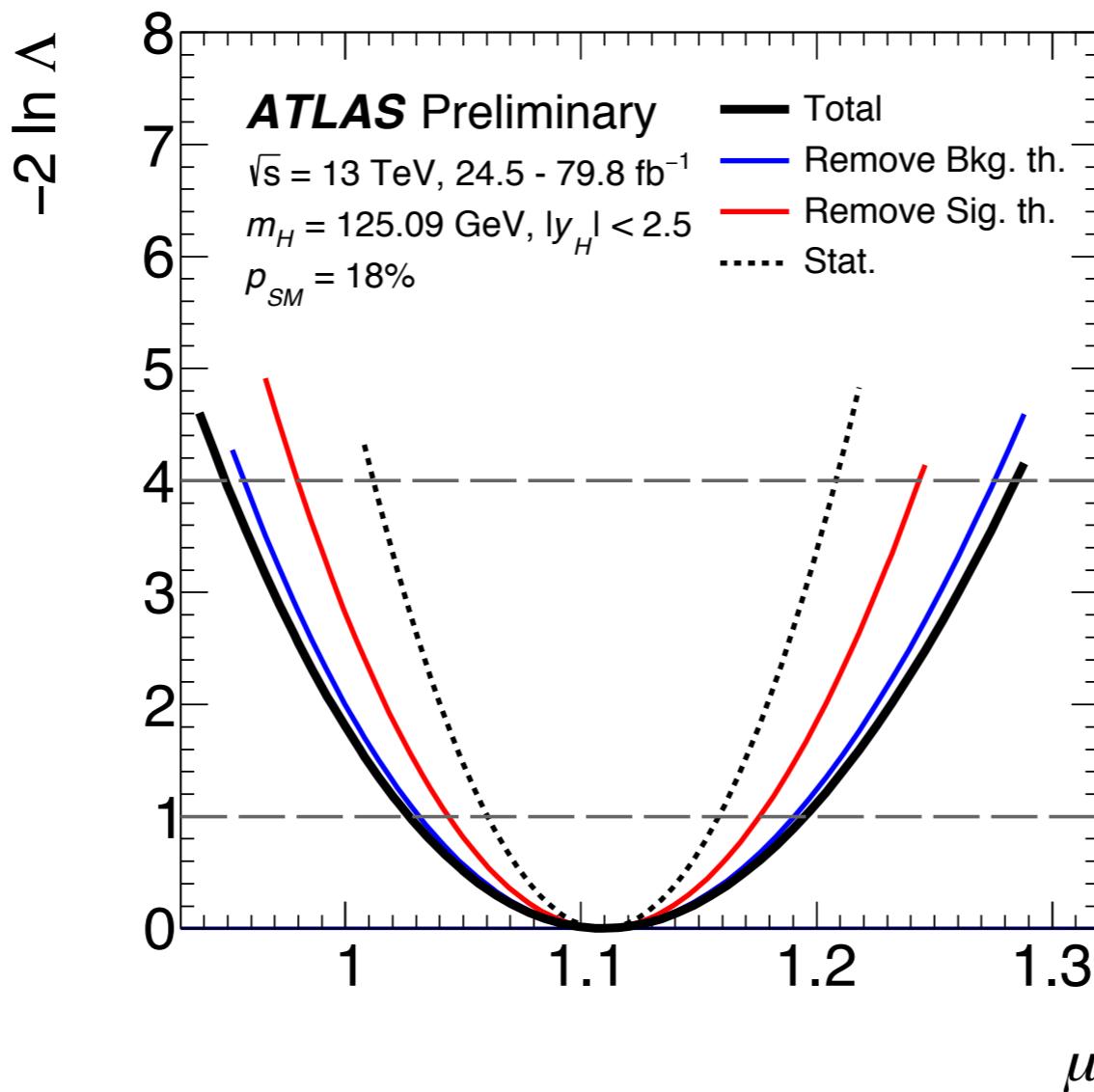
Figures from <https://msneubauer.github.io>

Signal strength & production cross-section measurements

	ggF	VBF	VH	ttH+tH
H \rightarrow γγ	✓ (80 fb $^{-1}$)	✓ (80 fb $^{-1}$)	✓ (80 fb $^{-1}$)	✓ (80 fb $^{-1}$)
H \rightarrow ZZ	✓ (80 fb $^{-1}$)	✓ (80 fb $^{-1}$)	✓ (80 fb $^{-1}$)	
H \rightarrow WW	✓ (36 fb $^{-1}$)	✓ (36 fb $^{-1}$)		✓ (36-80 fb $^{-1}$)
H \rightarrow ττ	✓ (36 fb $^{-1}$)	✓ (36 fb $^{-1}$)		
H \rightarrow bb		✓ (25-31 fb $^{-1}$)	✓ (80 fb $^{-1}$)	✓ (36 fb $^{-1}$)

✓: channel included in the combination

Inclusive signal strength

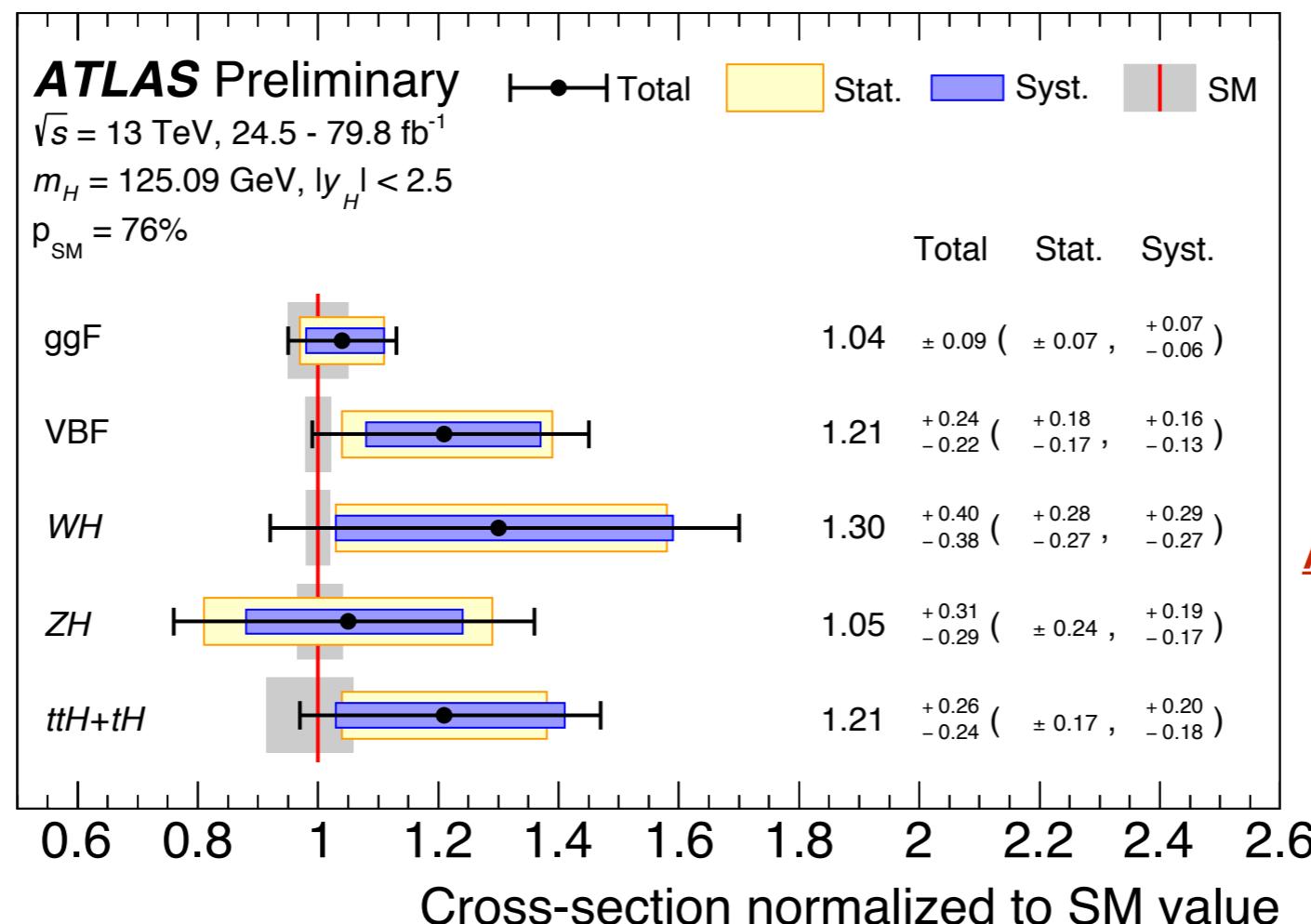


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$$\mu = 1.11^{+0.09}_{-0.08} = 1.11 \pm 0.05(\text{stat.})^{+0.05}_{-0.04}(\text{exp.})^{+0.05}_{-0.04}(\text{sig. th.}) \pm 0.03(\text{bkg. th.})$$

- This measurement is systematic limited with similar impacts from the experimental and theoretical uncertainty components

Production mode cross sections (assuming the SM decays)



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- ggF cross section is now measured with **9%** precision
 - Precision of N3LO cross section prediction: 5%
- All major production modes (ggF, VBF, VH, ttH) are observed!
 - VBF: **6.5σ** (first single experiment observation), VH: **5.3σ** , ttH: **5.8σ**

Simplified template cross section (STXS) measurements

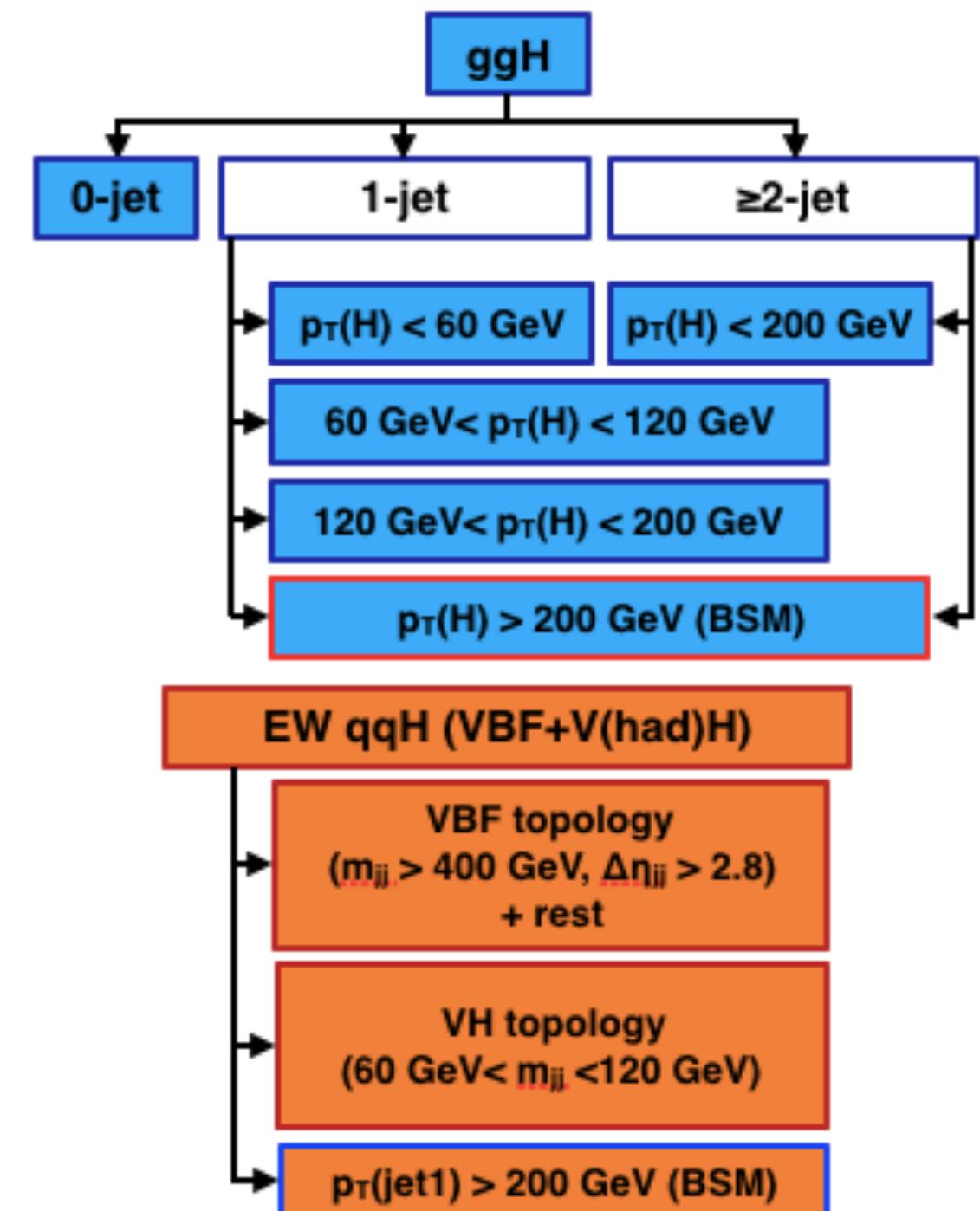
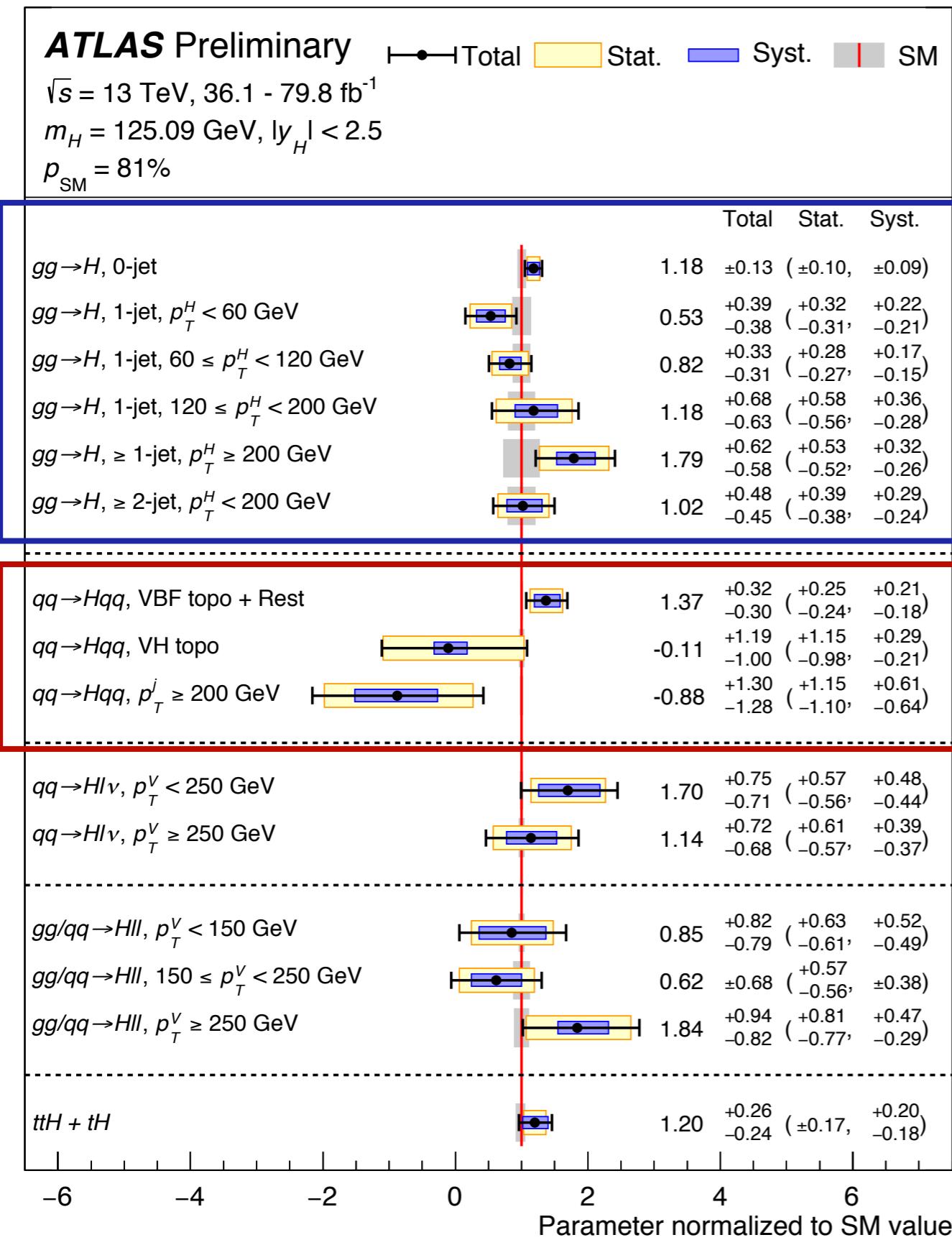
	ggF	VBF	VH	ttH+tH
H→γγ	✓ (80 fb ⁻¹)			
H→ZZ	✓ (80 fb ⁻¹)	✓ (80 fb ⁻¹)	✓ (80 fb ⁻¹)	
H→WW	✓ (36 fb ⁻¹)	✓ (36 fb ⁻¹)		✓ (36-80 fb ⁻¹)
H→ττ	✓ (36 fb ⁻¹)	✓ (36 fb ⁻¹)		
H→bb			✓ (80 fb ⁻¹)	✓ (36 fb ⁻¹)

✓: channel included in the combination

Simplified template cross sections

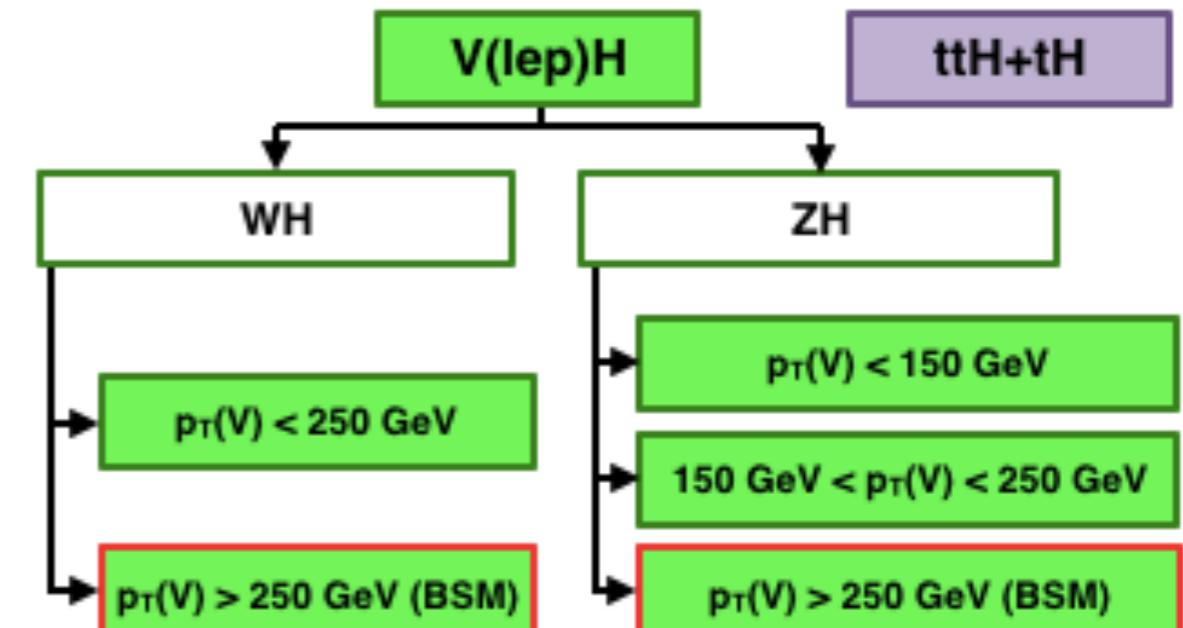
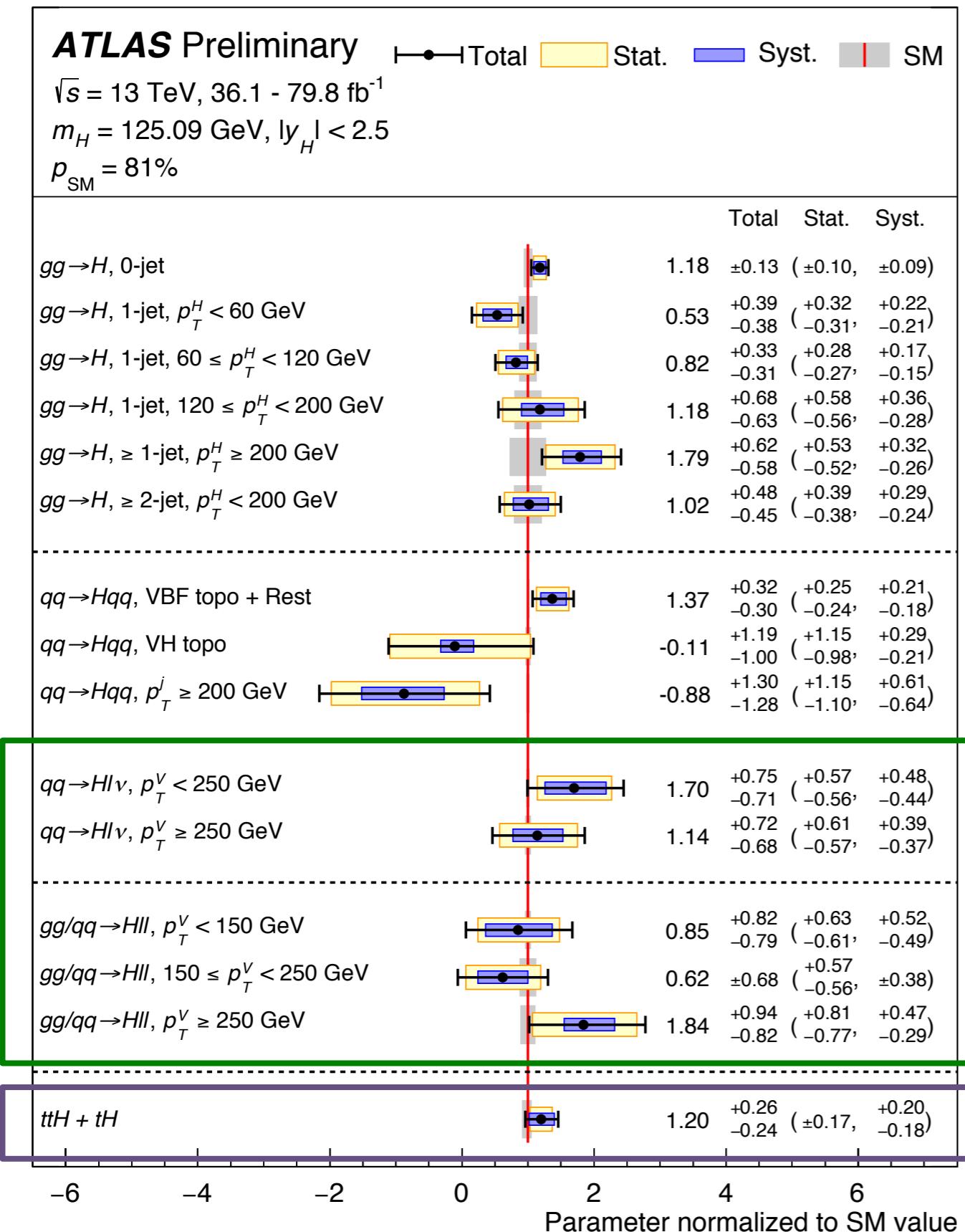
- Measure production mode cross-sections in **various phase-space regions**, which are chosen according to
 - sensitivity to BSM effects
 - avoidance of large theory uncertainties
 - matching to experimental selections
- Within each region, use the **SM predicted signal templates** to fit data
 - Can still exploit powerful analysis techniques (e.g. MVA)
- **STXS are measured granularly in the combination**
 - with and without assuming the SM decays of Higgs boson

STXS results (assuming the SM decays)



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STXS results (assuming the SM decays)



- Good compatibility with the SM
- Some regions are quite statistically limited

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Coupling modifier (“kappa”) interpretation

	ggF	VBF	VH	ttH+tH
H→γγ	✓ (80 fb ⁻¹)	✓ (80 fb ⁻¹)	✓ (80 fb ⁻¹)	✓ (80 fb ⁻¹)
H→ZZ	✓ (80 fb ⁻¹)	✓ (80 fb ⁻¹)	✓ (80 fb ⁻¹)	
H→WW	✓ (36 fb ⁻¹)	✓ (36 fb ⁻¹)		✓ (36-80 fb ⁻¹)
H→ττ	✓ (36 fb ⁻¹)	✓ (36 fb ⁻¹)		
H→bb		✓ (25-31 fb ⁻¹)	✓ (80 fb ⁻¹)	✓ (36 fb ⁻¹)

✓: channel included in the combination

Analyses of H→μμ (80 fb⁻¹), H→invisible (36 fb⁻¹), and off-shell Higgs (36 fb⁻¹) are also included in relevant studies

Coupling modifier (“kappa”)

- Leading order motivated framework: assign **coupling modifier** to each (effective) **interaction vertex** (e.g. κ_w , κ_t ...)
- In this framework, **production cross section** times **decay branch fraction** of $i \rightarrow H \rightarrow f$ can be parameterized as

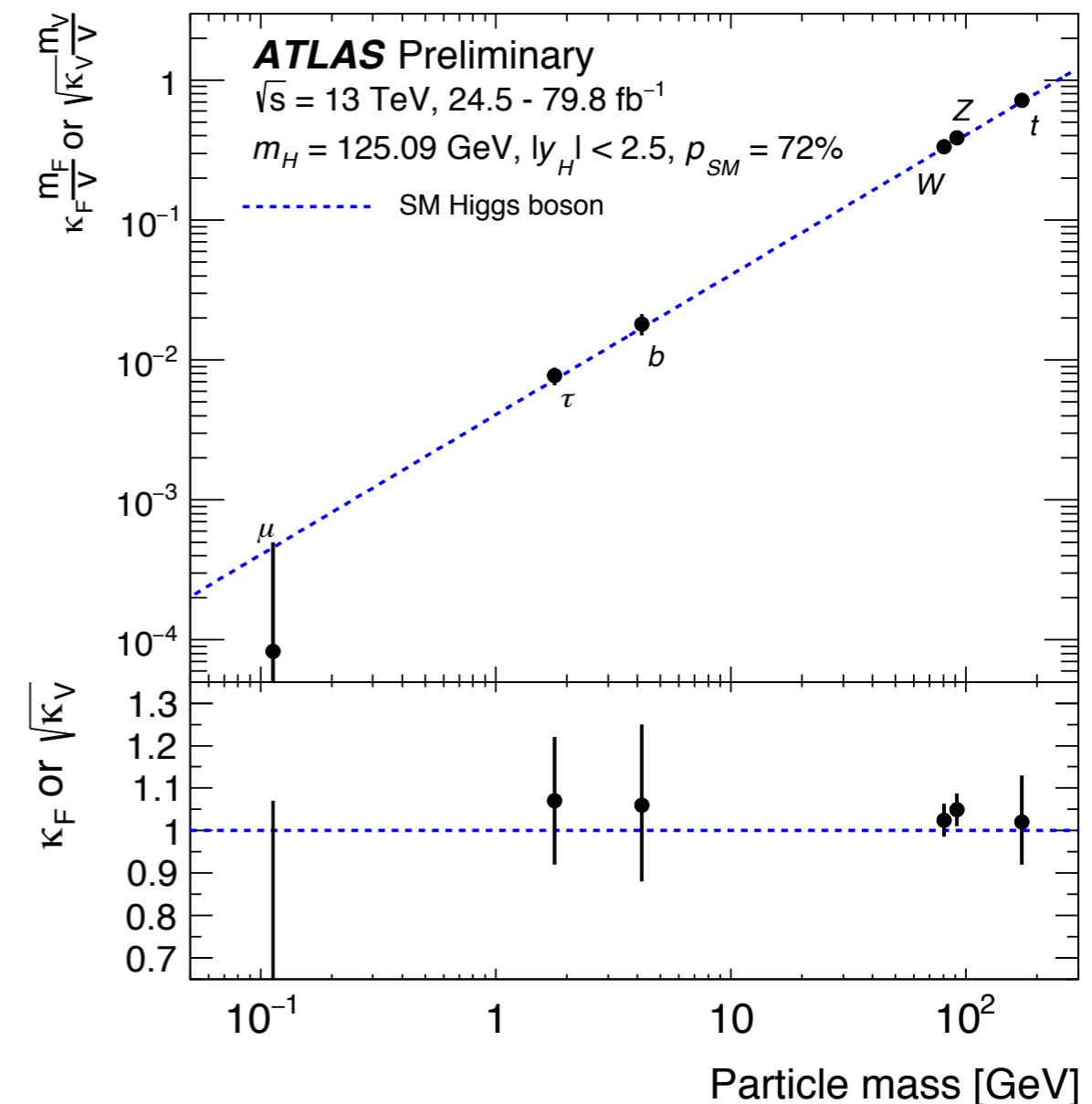
$$\sigma_i \times B_f = \frac{\sigma_i(\kappa) \times \Gamma_f(\kappa)}{\Gamma_H}, \quad \kappa_j^2 = \frac{\sigma_j}{\sigma_j^{\text{SM}}} \quad \text{or} \quad \kappa_j^2 = \frac{\Gamma_j}{\Gamma_j^{\text{SM}}}$$

- (this allows for a consistent treatment of production and decay)
- **Total width of Higgs boson** can be expressed as

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

Coupling modifier vs. particle mass

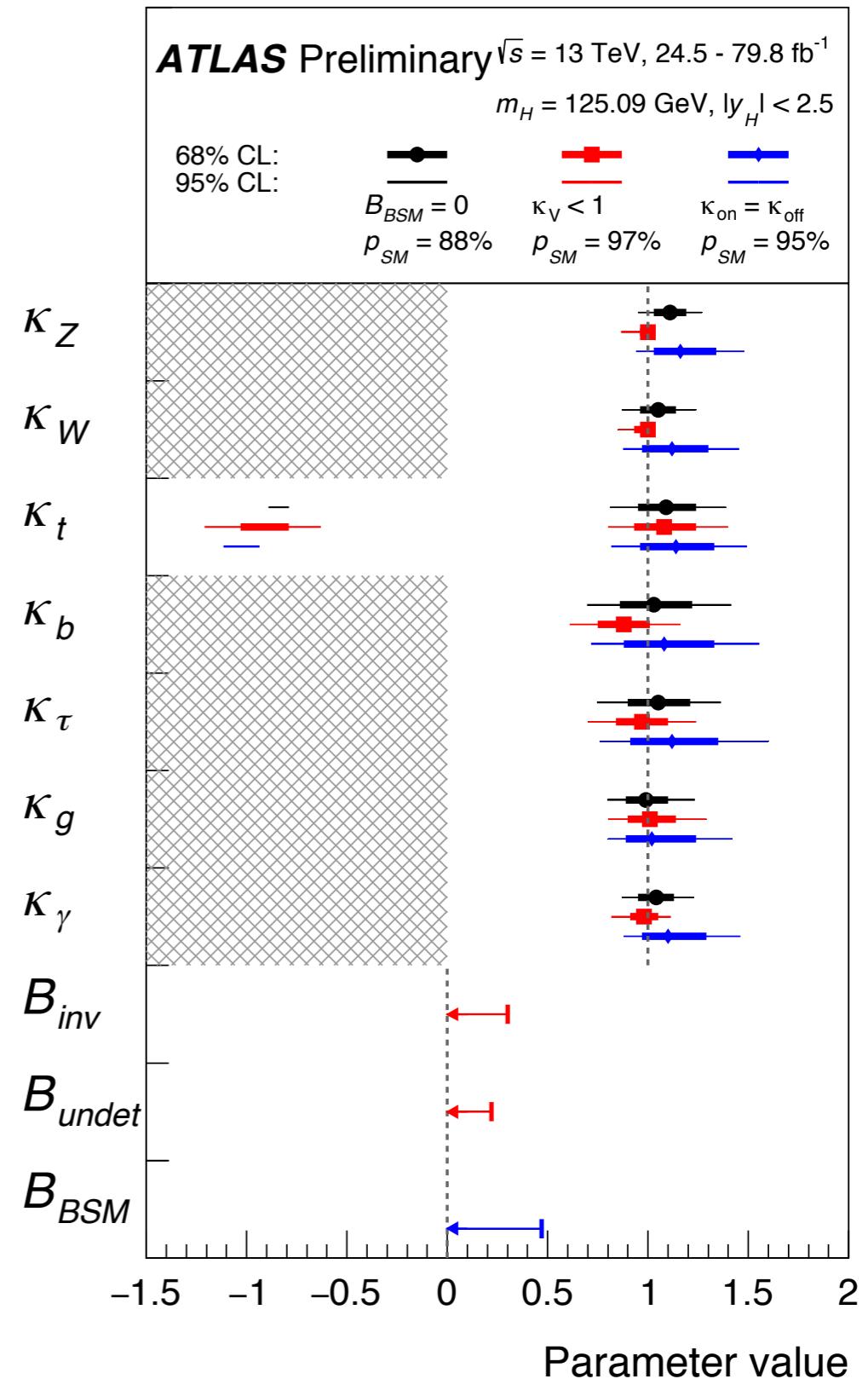
- Assume no BSM contribution in loop-induced processes (ggF, $H \rightarrow \gamma\gamma$ etc.) or total width. Resolve ggF and $H\gamma\gamma$ effective vertices
- Good agreement with the SM across 3 orders of magnitude of particle mass!



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Coupling modifier: different scenarios

- Not resolving ggF and H $\gamma\gamma$ effective vertices, explore three different scenarios for total width:
 - Black:** assume $B_{inv}=B_{undet}=0$
 - Red:** constrain B_{inv} and B_{undet} using $H \rightarrow$ invisible analysis and $\kappa_V < 1$
 - Blue:** constrain $B_{BSM} = B_{inv} + B_{undet}$ using off-shell analysis and $\kappa_{on-shell} = \kappa_{off-shell}$
- All coupling modifiers are measured to be compatible with the SM



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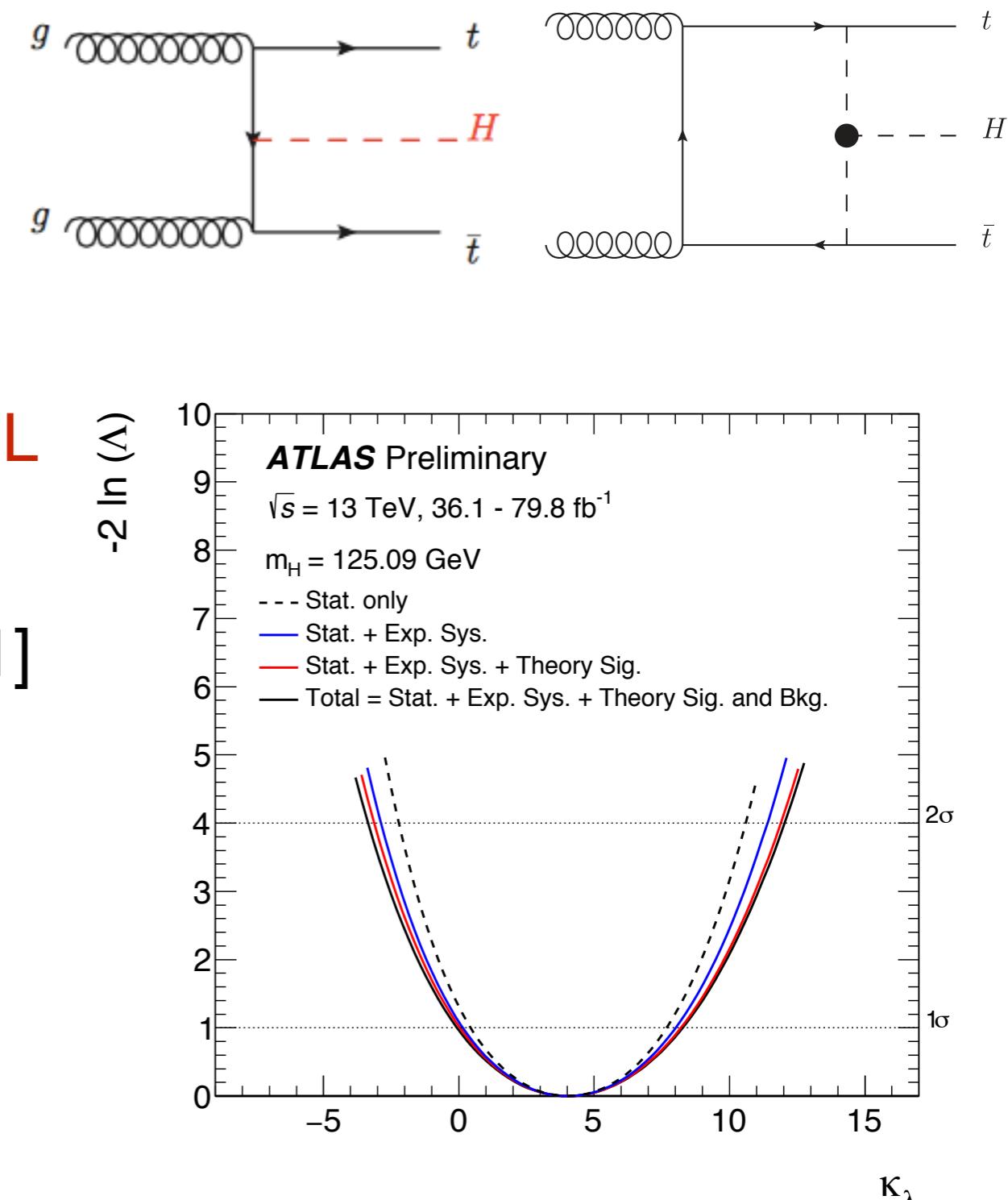
Probe Higgs boson self-coupling using single-Higgs production

	ggF	VBF	VH	ttH+tH
H→γγ	✓ (80 fb ⁻¹)			
H→ZZ	✓ (80 fb ⁻¹)	✓ (80 fb ⁻¹)	✓ (80 fb ⁻¹)	
H→WW	✓ (36 fb ⁻¹)	✓ (36 fb ⁻¹)		✓ (36-80 fb ⁻¹)
H→ττ	✓ (36 fb ⁻¹)	✓ (36 fb ⁻¹)		
H→bb			✓ (80 fb ⁻¹)	✓ (36 fb ⁻¹)

✓: channel included in the combination

Probe Higgs boson self-coupling

- Parameterize single Higgs boson production and decays with self coupling modifier $\kappa_\lambda = \lambda_3 / \lambda_{\text{SM}}^{\text{SM}} \lambda_3$
- Excluding $\kappa_\lambda \notin [-3.2, 11.9]$ @ 95% CL
 - Comparable to limits from ATLAS 36 fb⁻¹ di-Higgs search: [-5.0, 12.1]
- Assume the SM single Higgs couplings to fermions and bosons. Without this assumption, the sensitivity to self-coupling will be significantly weaker



[ATL-PHYS-PUB-2019-009](#)

Combined measurements of the total and differential cross sections of Higgs boson production

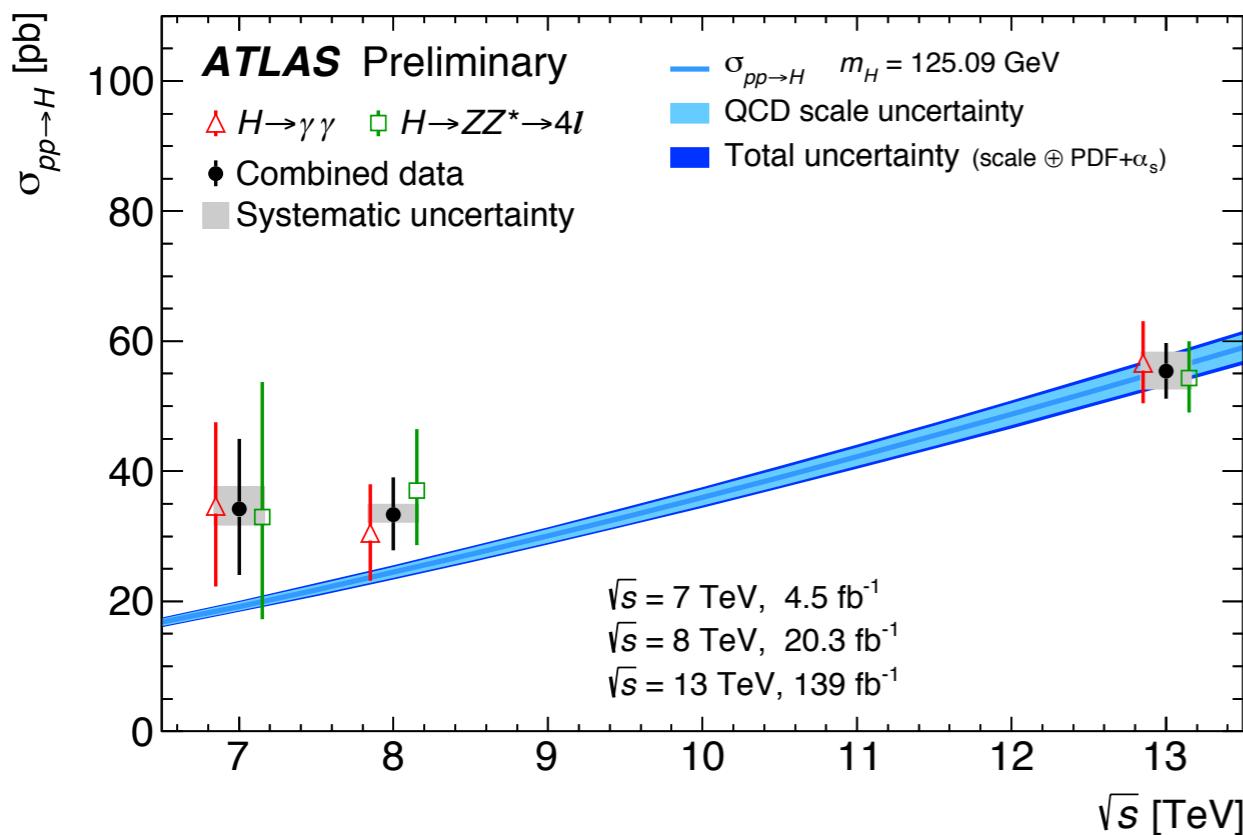
NEW

Including the $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^ \rightarrow 4\text{-lepton}$
decay channels*

*Using the **full Run-2 dataset** recorded by ATLAS,
correspond to 139 fb^{-1}*

Total and differential cross sections

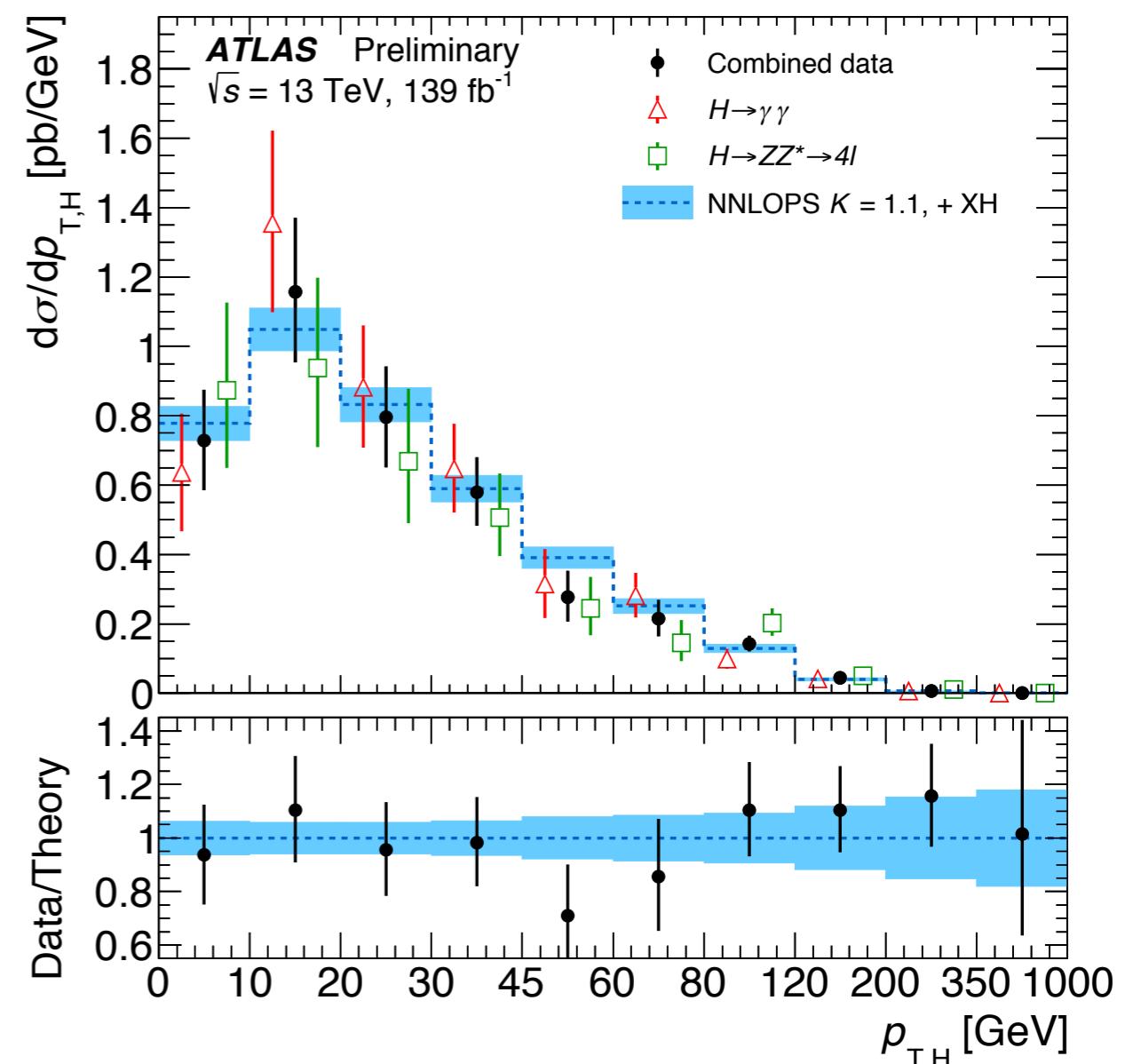
NEW



For total cross section at 13 TeV,
combined measurement : $55.4^{+4.3}_{-4.2} \text{ pb}$
 (~8% precision)

SM prediction : $55.6 \pm 2.5 \text{ pb}$

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(~20% precision in 9 bins)

- The results from the two decay channels are found to be compatible with each other, and their combination agrees with the Standard Model prediction

Summary

- Based on up to **80 fb⁻¹** of Run 2 data, ATLAS performed combined measurements of Higgs boson production and decays:
 - inclusive signal strength
 - production cross sections
 - simplified template cross sections
 - coupling modifiers (“kappa”)
- Based on **139 fb⁻¹** of full Run 2 data, ATLAS performed combined measurements of total and differential Higgs boson cross sections
- All major production modes (ggF, VBF, VH, ttH) are observed
- All measurements are in agreement with the SM within (the improved) uncertainties
- Results can be used to probe Higgs self-couplings and BSM effects

Backup slides

Summary of signal regions entering combined measurements

	$H \rightarrow \gamma\gamma$	$H \rightarrow ZZ^*$	$H \rightarrow WW^*$	$H \rightarrow \tau\tau$	$H \rightarrow bb$	
$t\bar{t}H$	$t\bar{t}H$ leptonic (3 categories) $t\bar{t}H$ hadronic (4 categories)	$t\bar{t}H$ multilepton 1 $\ell + 2 \tau_{\text{had}}$ $t\bar{t}H$ multilepton 2 opposite-sign $\ell + 1 \tau_{\text{had}}$ $t\bar{t}H$ multilepton 2 same-sign ℓ (categories for 0 or 1 τ_{had}) $t\bar{t}H$ multilepton 3 ℓ (categories for 0 or 1 τ_{had}) $t\bar{t}H$ multilepton 4 ℓ (except $H \rightarrow ZZ^* \rightarrow 4\ell$) $t\bar{t}H$ leptonic, $H \rightarrow ZZ^* \rightarrow 4\ell$ $t\bar{t}H$ hadronic, $H \rightarrow ZZ^* \rightarrow 4\ell$				$t\bar{t}H$ 1 ℓ , boosted $t\bar{t}H$ 1 ℓ , resolved (11 categories) $t\bar{t}H$ 2 ℓ (7 categories)
VH	VH 2 ℓ VH 1 ℓ , $p_T^{\ell+E_T^{\text{miss}}} \geq 150$ GeV VH 1 ℓ , $p_T^{\ell+E_T^{\text{miss}}} < 150$ GeV VH $E_T^{\text{miss}}, E_T^{\text{miss}} \geq 150$ GeV VH $E_T^{\text{miss}}, E_T^{\text{miss}} < 150$ GeV $VH + \text{VBF}$ $p_T^{j1} \geq 200$ GeV VH hadronic (2 categories)	VH leptonic 0-jet, $p_T^{4\ell} \geq 100$ GeV 2-jet, $m_{jj} < 120$ GeV			$2 \ell, 75 \leq p_T^V < 150$ GeV, $N_{\text{jets}} = 2$ $2 \ell, 75 \leq p_T^V < 150$ GeV, $N_{\text{jets}} \geq 3$ $2 \ell, p_T^V \geq 150$ GeV, $N_{\text{jets}} = 2$ $2 \ell, p_T^V \geq 150$ GeV, $N_{\text{jets}} \geq 3$ $1 \ell p_T^V \geq 150$ GeV, $N_{\text{jets}} = 2$ $1 \ell p_T^V \geq 150$ GeV, $N_{\text{jets}} = 3$ $0 \ell, p_T^V \geq 150$ GeV, $N_{\text{jets}} = 2$ $0 \ell, p_T^V \geq 150$ GeV, $N_{\text{jets}} = 3$	
VBF	$\text{VBF}, p_T^{\gamma\gamma jj} \geq 25$ GeV (2 categories) $\text{VBF}, p_T^{\gamma\gamma jj} < 25$ GeV (2 categories)	2-jet VBF, $p_T^{j1} \geq 200$ GeV 2-jet VBF, $p_T^{j1} < 200$ GeV	2-jet VBF	$\text{VBF } p_T^{\tau\tau} > 140$ GeV ($\tau_{\text{had}}\tau_{\text{had}}$ only) $\text{VBF high-}m_{jj}$ $\text{VBF low-}m_{jj}$	$\text{VBF, two central jets}$ $\text{VBF, four central jets}$ $\text{VBF} + \gamma$	
ggF	2-jet, $p_T^{\gamma\gamma} \geq 200$ GeV 2-jet, 120 GeV $\leq p_T^{\gamma\gamma} < 200$ GeV 2-jet, 60 GeV $\leq p_T^{\gamma\gamma} < 120$ GeV 2-jet, $p_T^{\gamma\gamma} < 60$ GeV 1-jet, $p_T^{\gamma\gamma} \geq 200$ GeV 1-jet, 120 GeV $\leq p_T^{\gamma\gamma} < 200$ GeV 1-jet, 60 GeV $\leq p_T^{\gamma\gamma} < 120$ GeV 1-jet, $p_T^{\gamma\gamma} < 60$ GeV 0-jet (2 categories)	1-jet, $p_T^{4\ell} \geq 120$ GeV 1-jet, 60 GeV $\leq p_T^{4\ell} < 120$ GeV 1-jet, $p_T^{4\ell} < 60$ GeV 0-jet, $p_T^{4\ell} < 100$ GeV	1-jet, $m_{\ell\ell} < 30$ GeV, $p_T^{\ell_2} < 20$ GeV 1-jet, $m_{\ell\ell} < 30$ GeV, $p_T^{\ell_2} \geq 20$ GeV 1-jet, $m_{\ell\ell} \geq 30$ GeV, $p_T^{\ell_2} < 20$ GeV 1-jet, $m_{\ell\ell} \geq 30$ GeV, $p_T^{\ell_2} \geq 20$ GeV 0-jet, $m_{\ell\ell} < 30$ GeV, $p_T^{\ell_2} < 20$ GeV 0-jet, $m_{\ell\ell} < 30$ GeV, $p_T^{\ell_2} \geq 20$ GeV 0-jet, $m_{\ell\ell} \geq 30$ GeV, $p_T^{\ell_2} < 20$ GeV 0-jet, $m_{\ell\ell} \geq 30$ GeV, $p_T^{\ell_2} \geq 20$ GeV	Boosted, $p_T^{\tau\tau} > 140$ GeV Boosted, $p_T^{\tau\tau} \leq 140$ GeV		

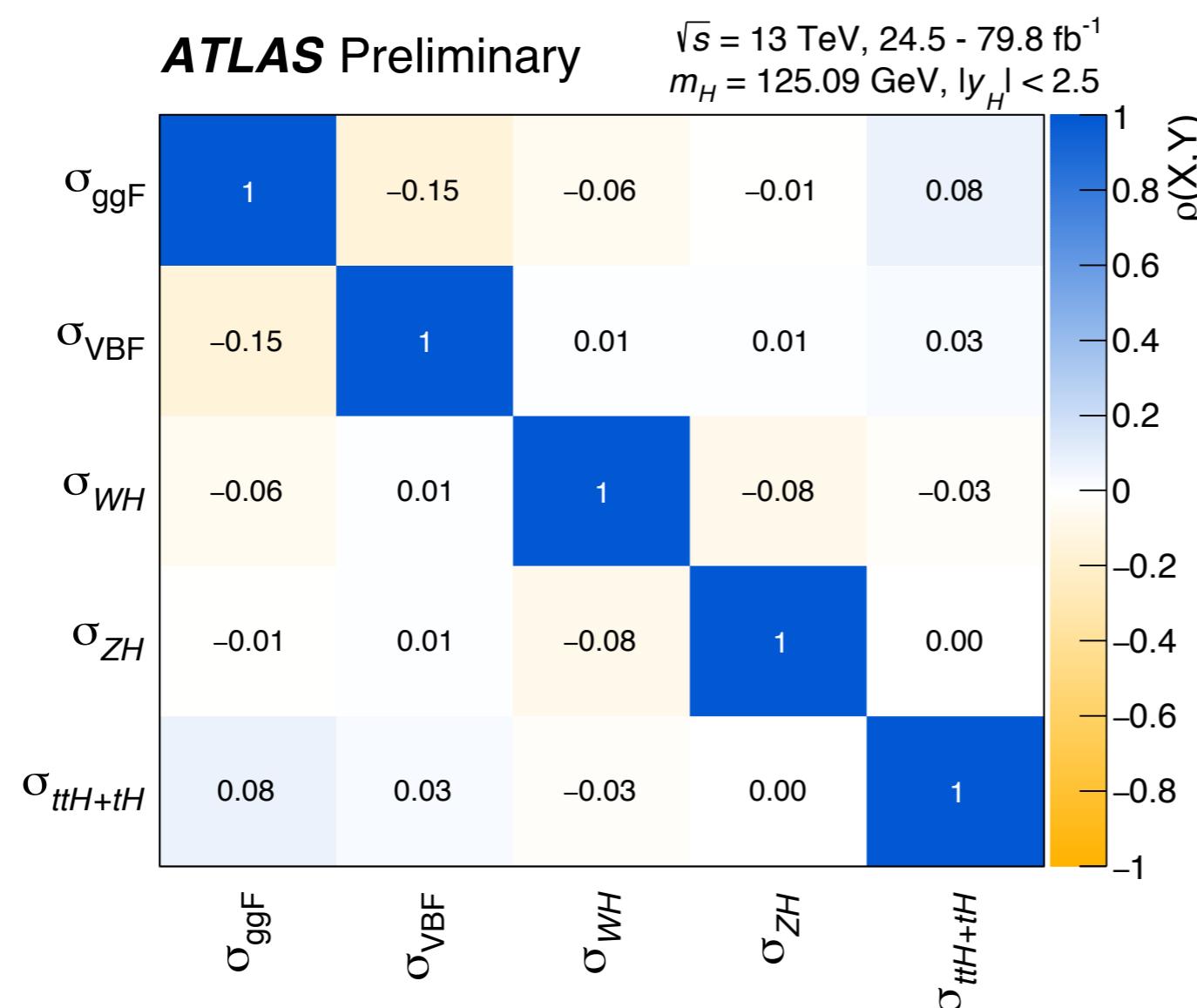
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Inclusive signal strength

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
Flavour 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

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Production mode cross sections (assuming the SM decays)



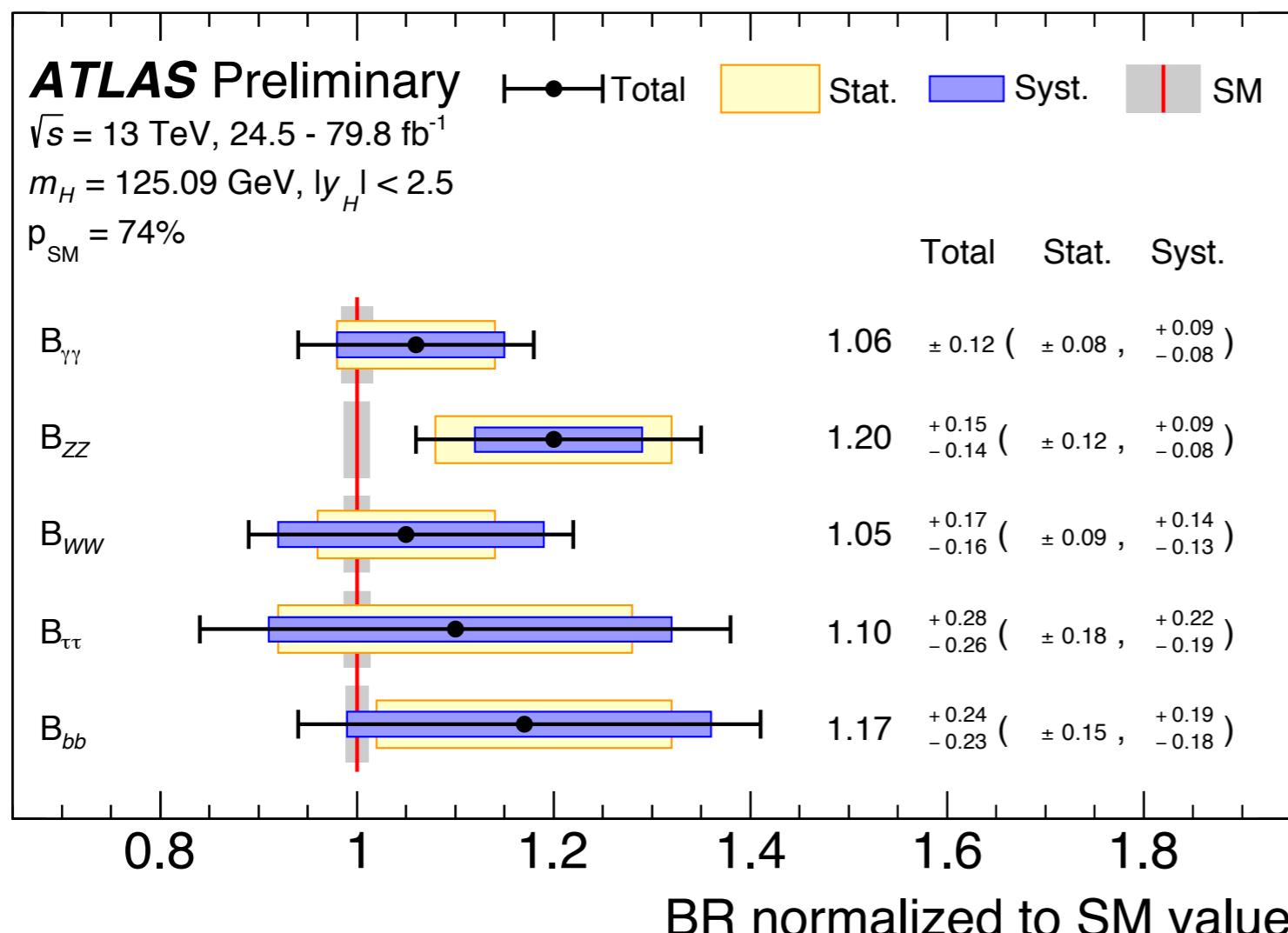
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Production mode cross sections (assuming the SM decays)

Uncertainty source	$\frac{\Delta\sigma_{ggF}}{\sigma_{ggF}} [\%]$	$\frac{\Delta\sigma_{VBF}}{\sigma_{VBF}} [\%]$	$\frac{\Delta\sigma_{WH}}{\sigma_{WH}} [\%]$	$\frac{\Delta\sigma_{ZH}}{\sigma_{ZH}} [\%]$	$\frac{\Delta\sigma_{t\bar{t}H+tH}}{\sigma_{t\bar{t}H+tH}} [\%]$
Statistical uncertainties	6.4	15	21	23	14
Systematic uncertainties	6.2	12	22	17	15
Theory uncertainties	3.4	9.2	14	14	12
Signal	2.0	8.7	5.8	6.7	6.3
Background	2.7	3.0	13	12	10
Experimental uncertainties (excl. MC stat.)	5.0	6.5	9.9	9.6	9.2
Luminosity	2.1	1.8	1.8	1.8	3.1
Background modeling	2.5	2.2	4.7	2.9	5.7
Jets, E_T^{miss}	0.9	5.4	3.0	3.3	4.0
Flavour tagging	0.9	1.3	7.9	8.0	1.8
Electrons, photons	2.5	1.7	1.8	1.5	3.8
Muons	0.4	0.3	0.1	0.2	0.5
τ -lepton	0.2	1.3	0.3	0.1	2.4
Other	2.5	1.2	0.3	1.1	0.8
MC statistical uncertainties	1.6	4.8	8.8	7.9	4.4
Total uncertainties	8.9	19	30	29	21

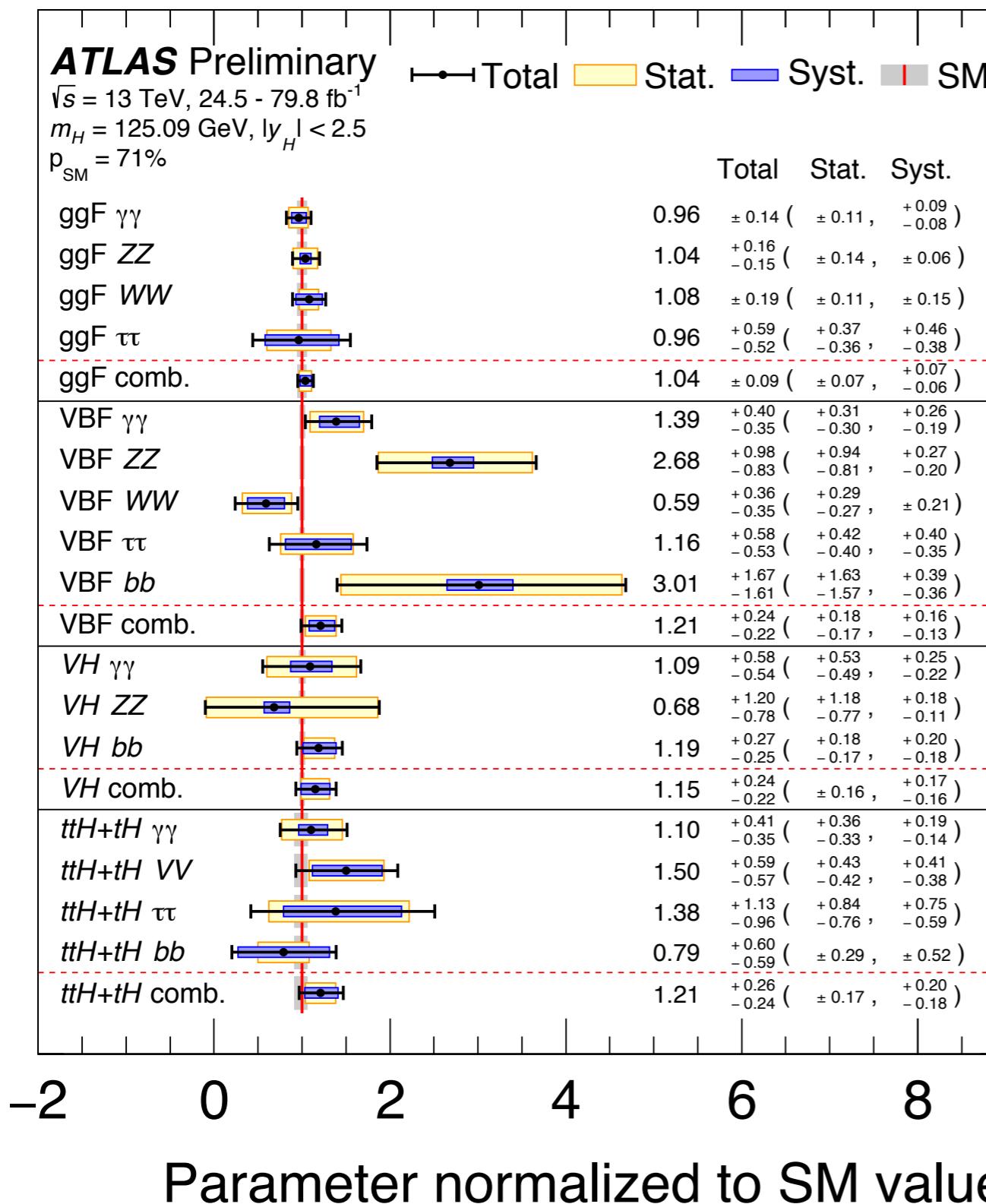
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Decay branch ratios (assuming the SM production rates)



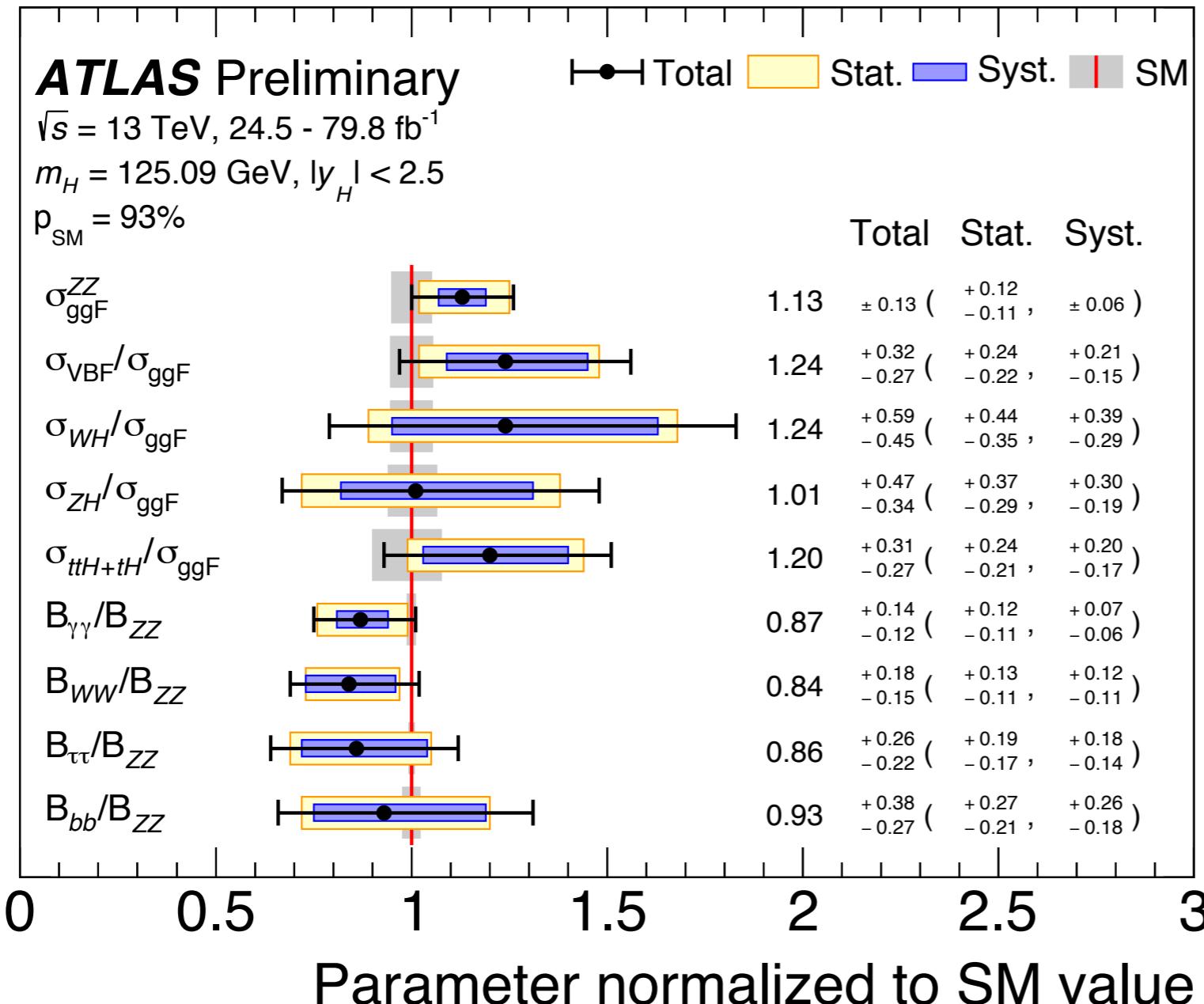
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Production mode cross sections in each decay channel



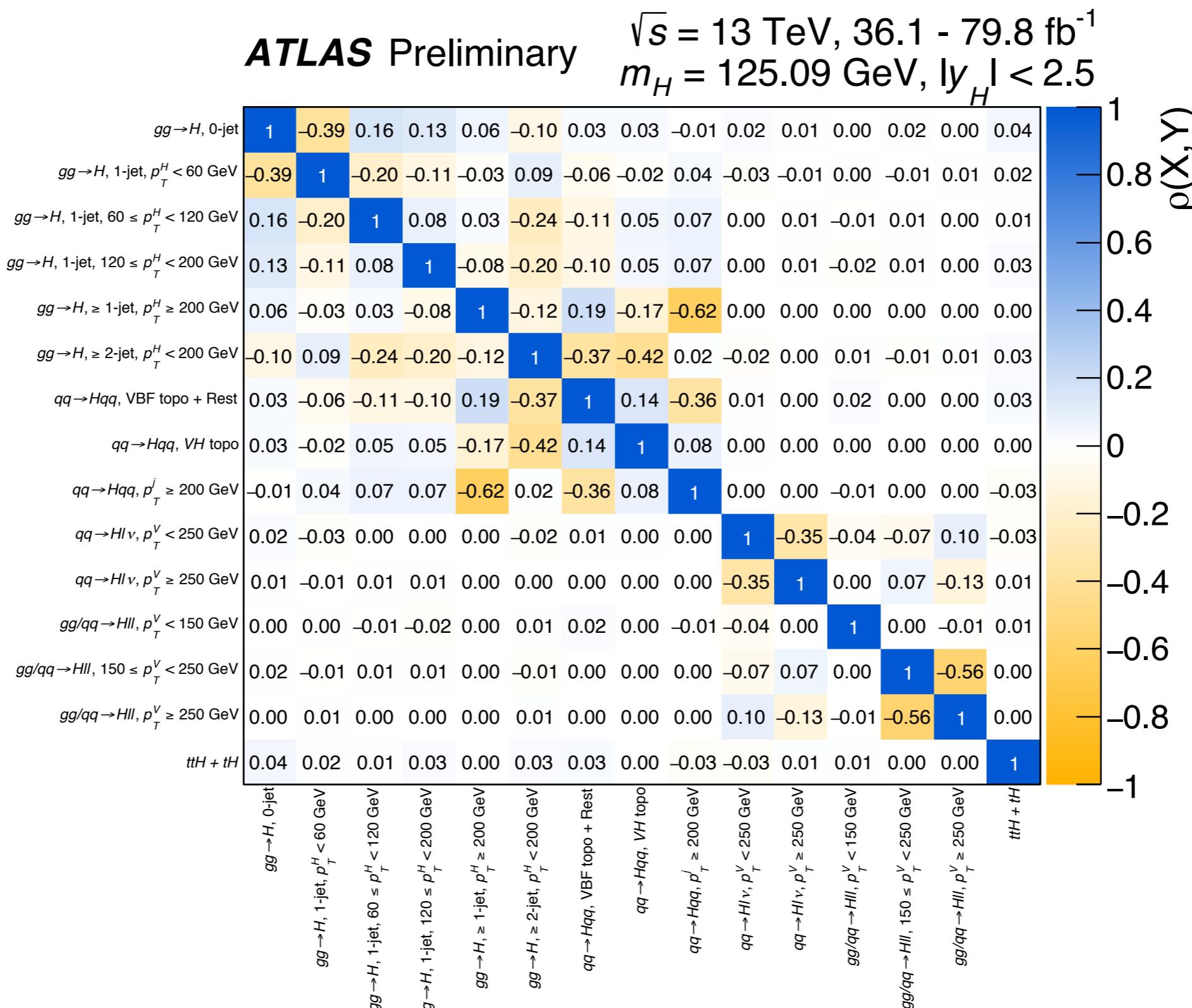
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Ratios of cross-sections and BRs



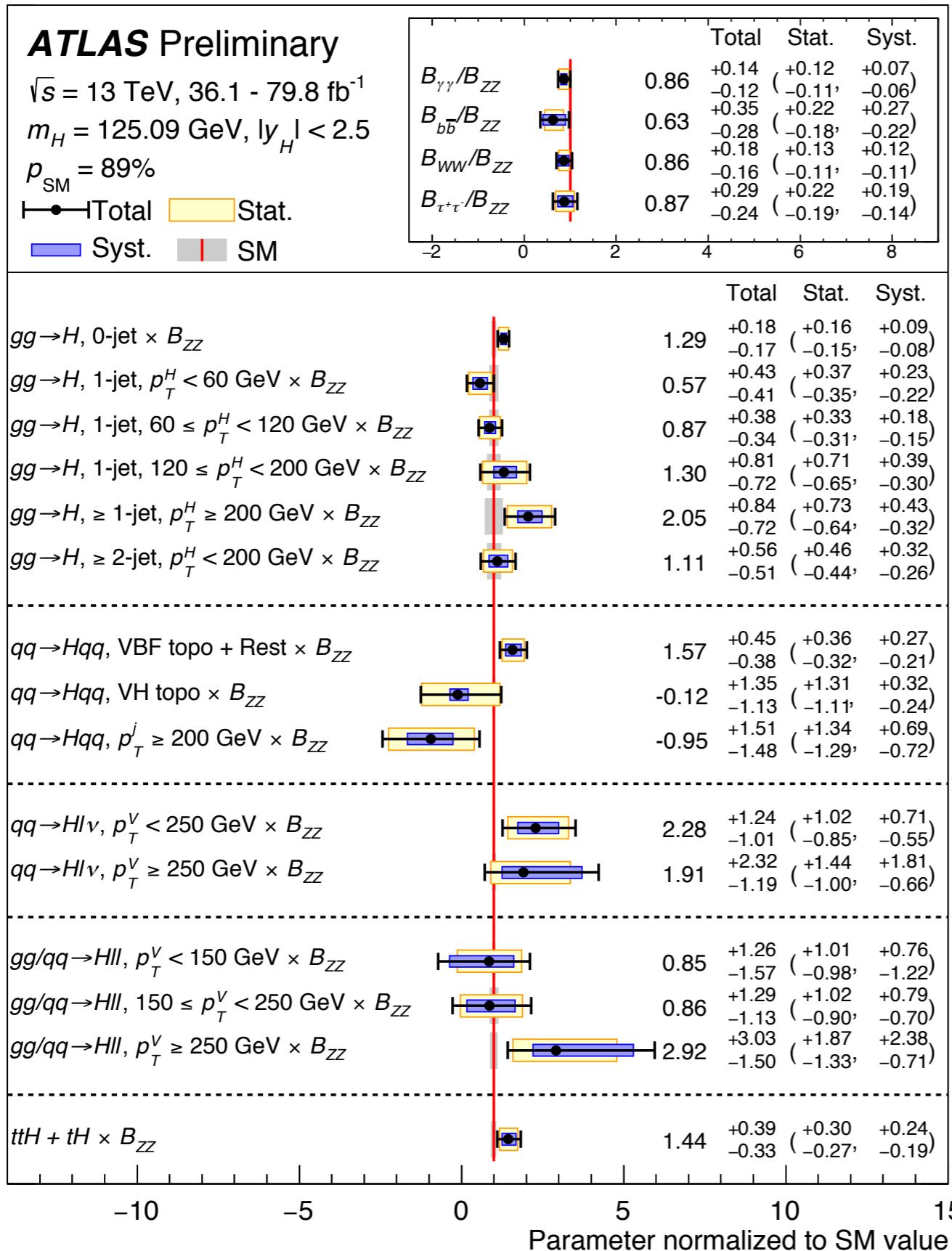
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STXS results (assuming the SM decays)



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STXS results (not assuming the SM decays)



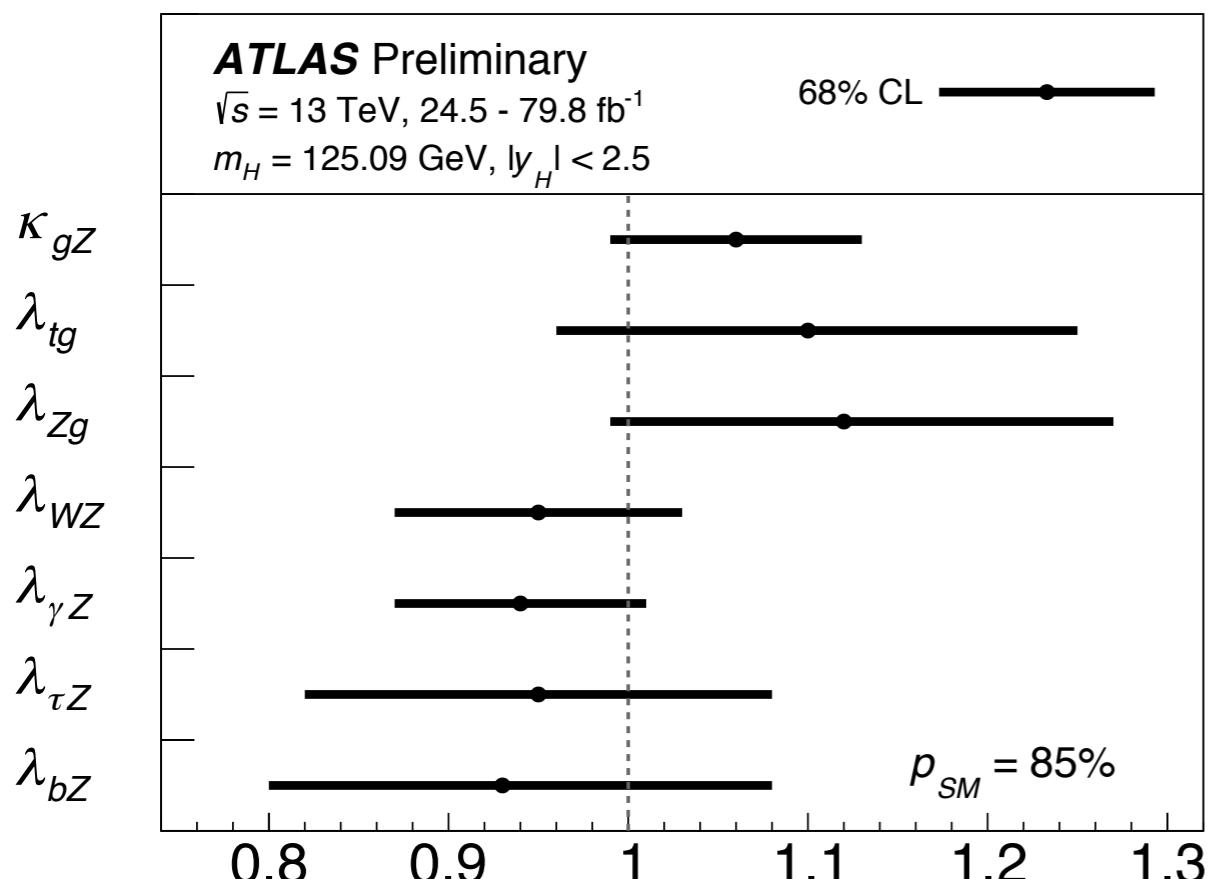
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Parametrizations using coupling modifier (“kappa”)

Production	Loops	Interference	Effective modifier	Resolved modifier
$\sigma(\text{ggF})$	✓	$t - b$	κ_g^2	$1.04 \kappa_t^2 + 0.002 \kappa_b^2 - 0.04 \kappa_t \kappa_b$
$\sigma(\text{VBF})$	-	-	-	$0.73 \kappa_W^2 + 0.27 \kappa_Z^2$
$\sigma(qq/qg \rightarrow ZH)$	-	-	-	κ_Z^2
$\sigma(gg \rightarrow ZH)$	✓	$t - Z$	$\kappa_{(ggZH)}$	$2.46 \kappa_Z^2 + 0.46 \kappa_t^2 - 1.90 \kappa_Z \kappa_t$
$\sigma(WH)$	-	-	-	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	$0.58 \kappa_b^2 + 0.22 \kappa_W^2$
				$+ 0.08 \kappa_g^2 + 0.06 \kappa_\tau^2$
				$+ 0.03 \kappa_Z^2 + 0.03 \kappa_c^2$
				$+ 0.0023 \kappa_\gamma^2 + 0.0015 \kappa_{(Z\gamma)}^2$
				$+ 0.0004 \kappa_s^2 + 0.00022 \kappa_\mu^2$

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Coupling modifier interpretation: no assumption on total width



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	$0.93^{+0.15}_{-0.13}$

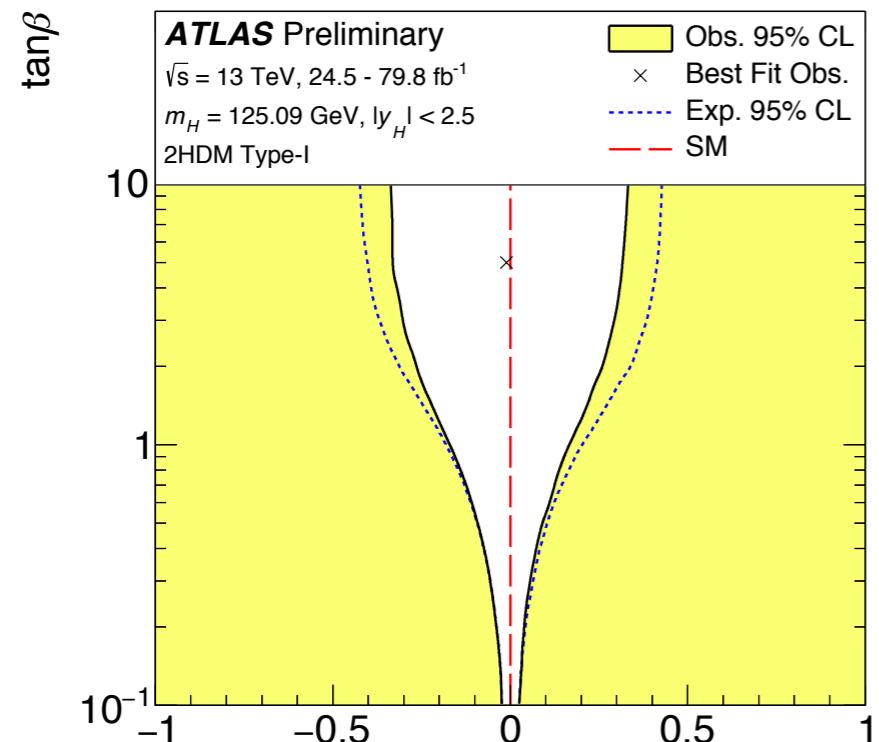
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Constraints on Two Higgs Doublet Model (2HDM)

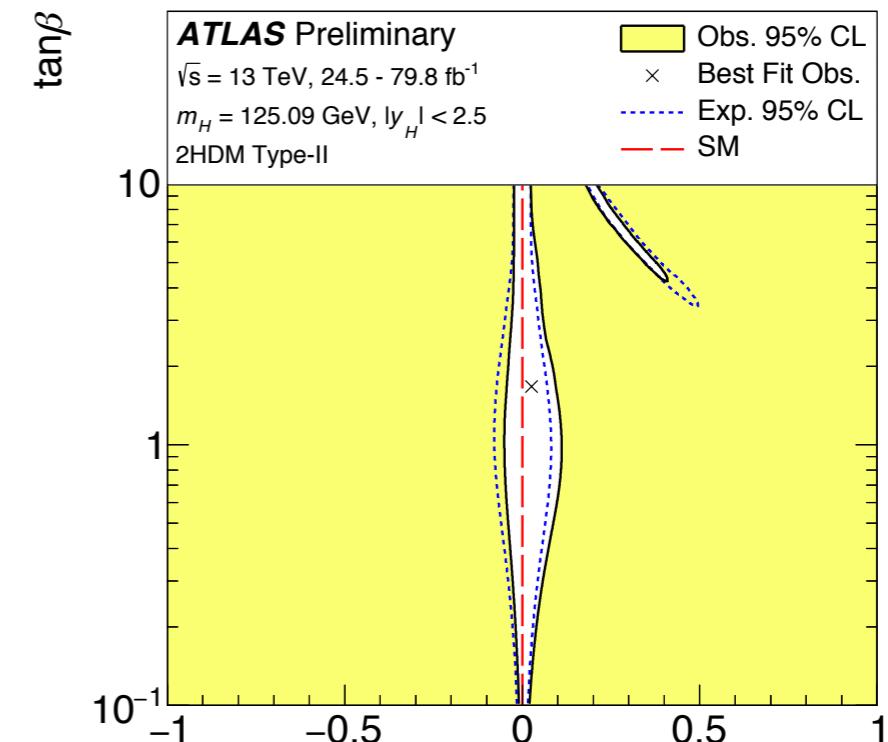
Coupling scale factor	Type I	Type II	Lepton-specific	Flipped
κ_V			$\sin(\beta - \alpha)$	
κ_u			$\cos(\alpha)/\sin(\beta)$	
κ_d	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$
κ_ℓ	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$-\sin(\alpha)/\cos(\beta)$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

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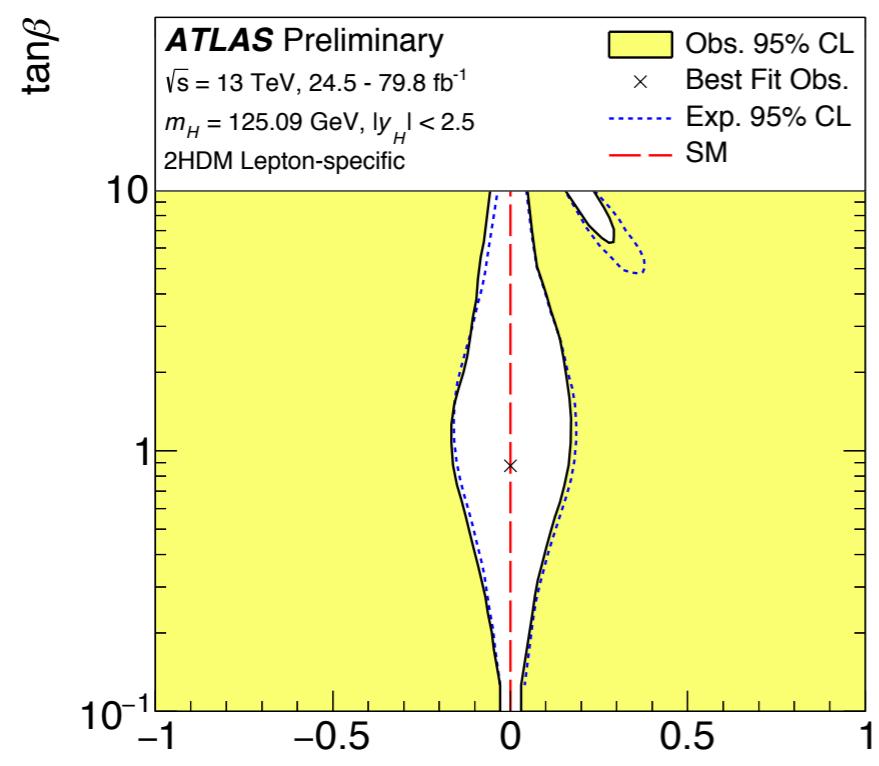
Constraints on Two Higgs Doublet Model (2HDM)



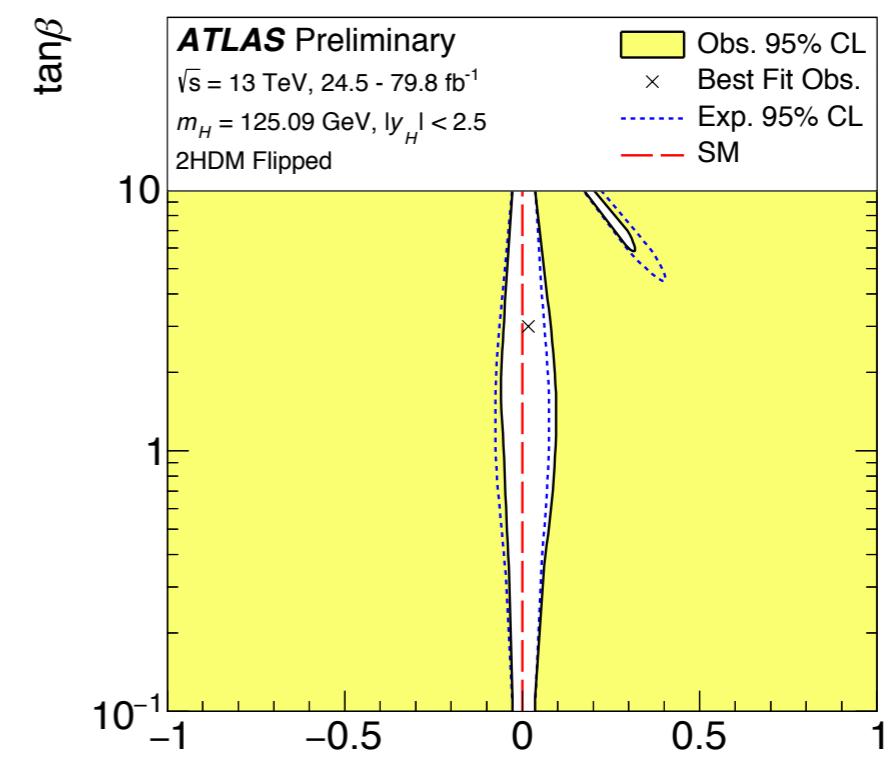
Type-I



Type-II



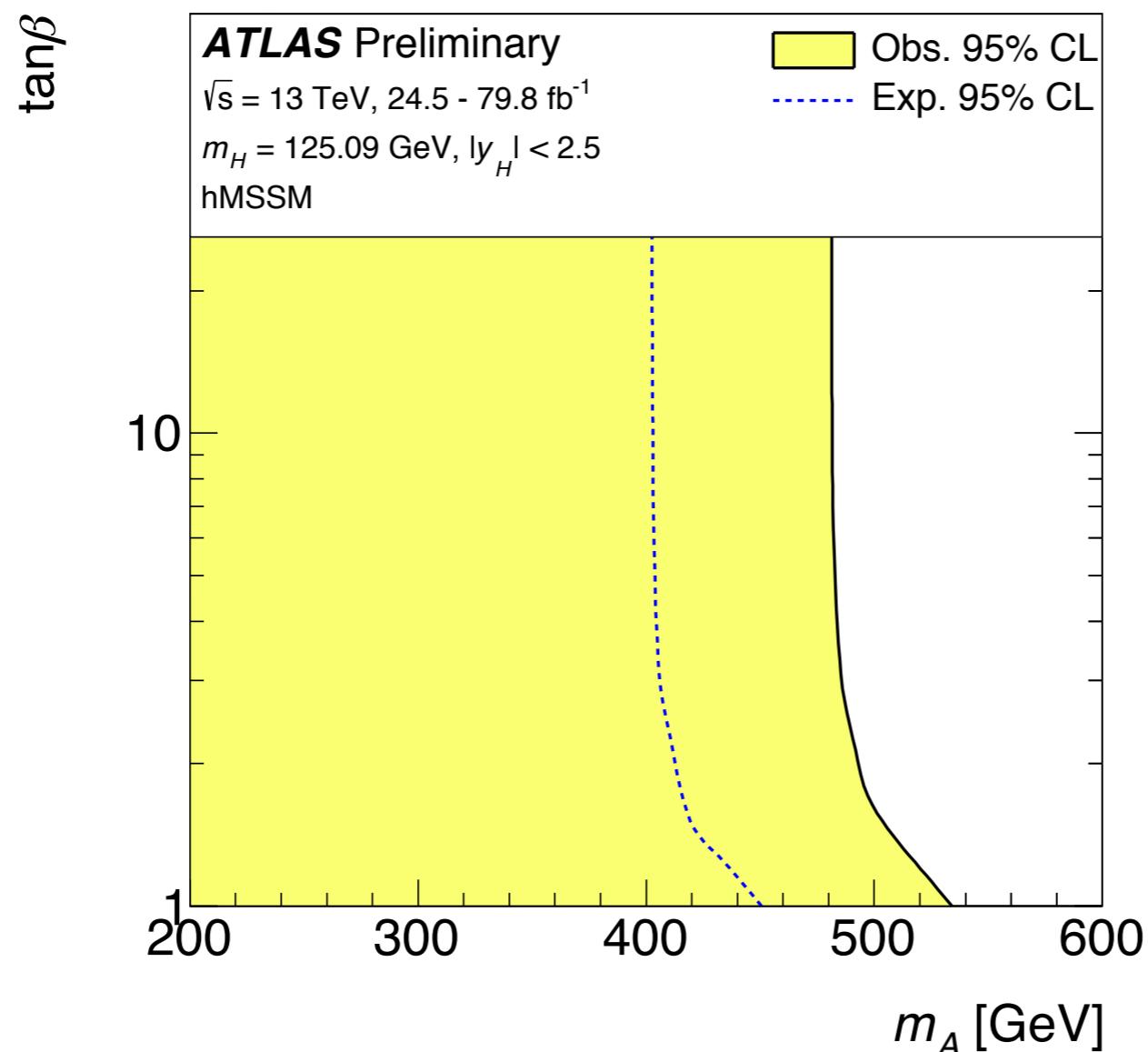
Lepton-specific



Flipped

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Constraints on Simplified Minimal Supersymmetric Standard Model (hMSSM)



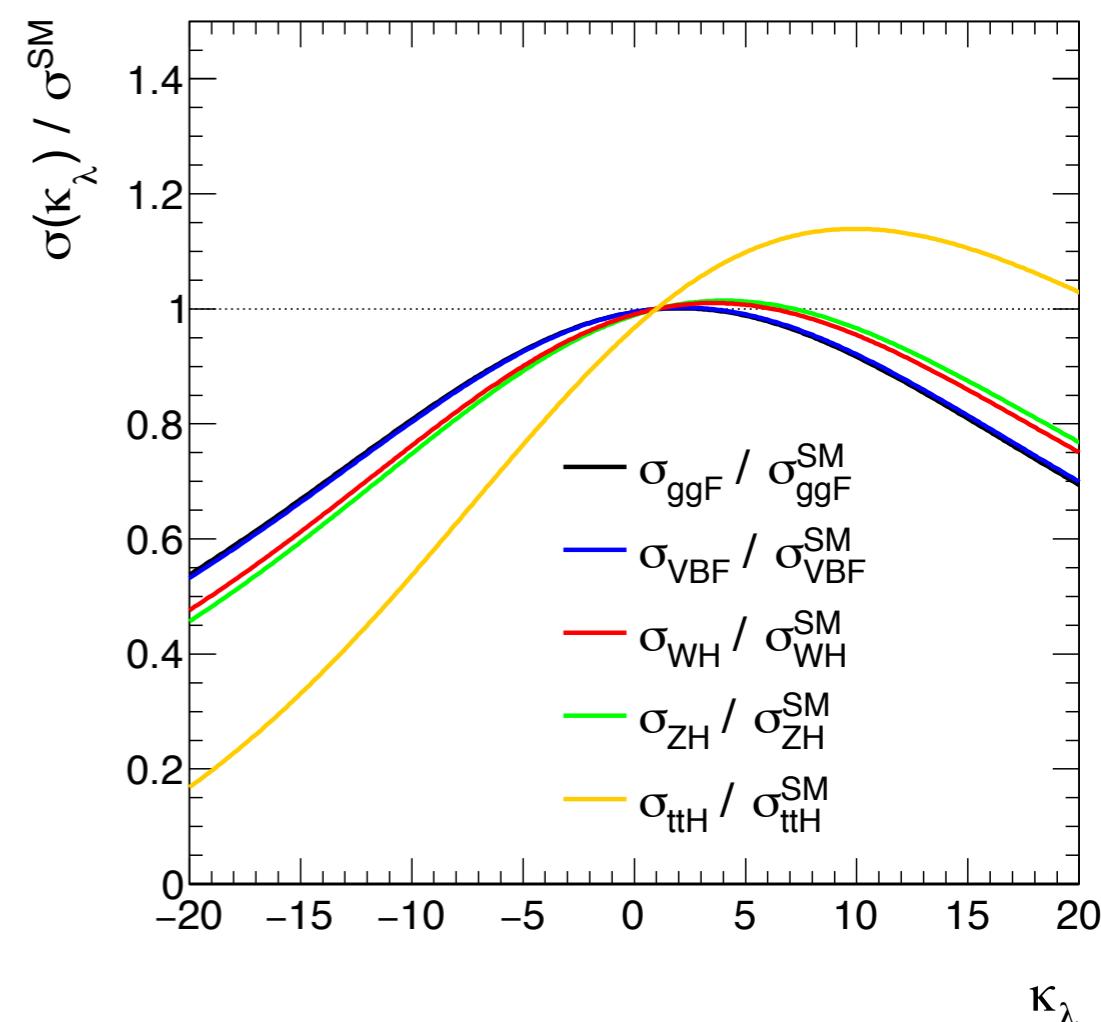
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Probe Higgs boson self-coupling: theory framework

- Higgs boson self-coupling is an important feature of the SM

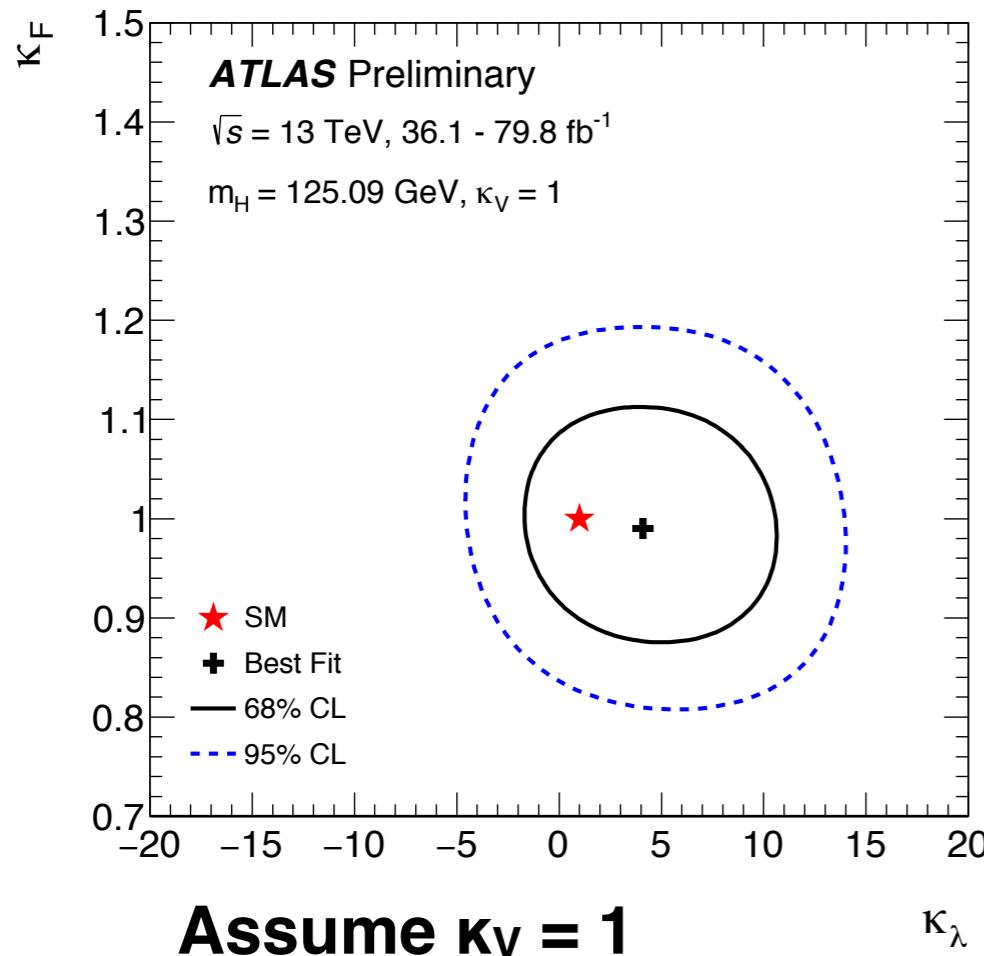
$$V(H) = \frac{1}{2}m_H^2H^2 + \lambda_3 vH^3 + \frac{1}{4}\lambda_4 H^4 + O(H^5)$$

- Traditionally studied by searching for double Higgs production
- However rates and kinematics of single Higgs boson production and decays can be altered by self-coupling through EW corrections

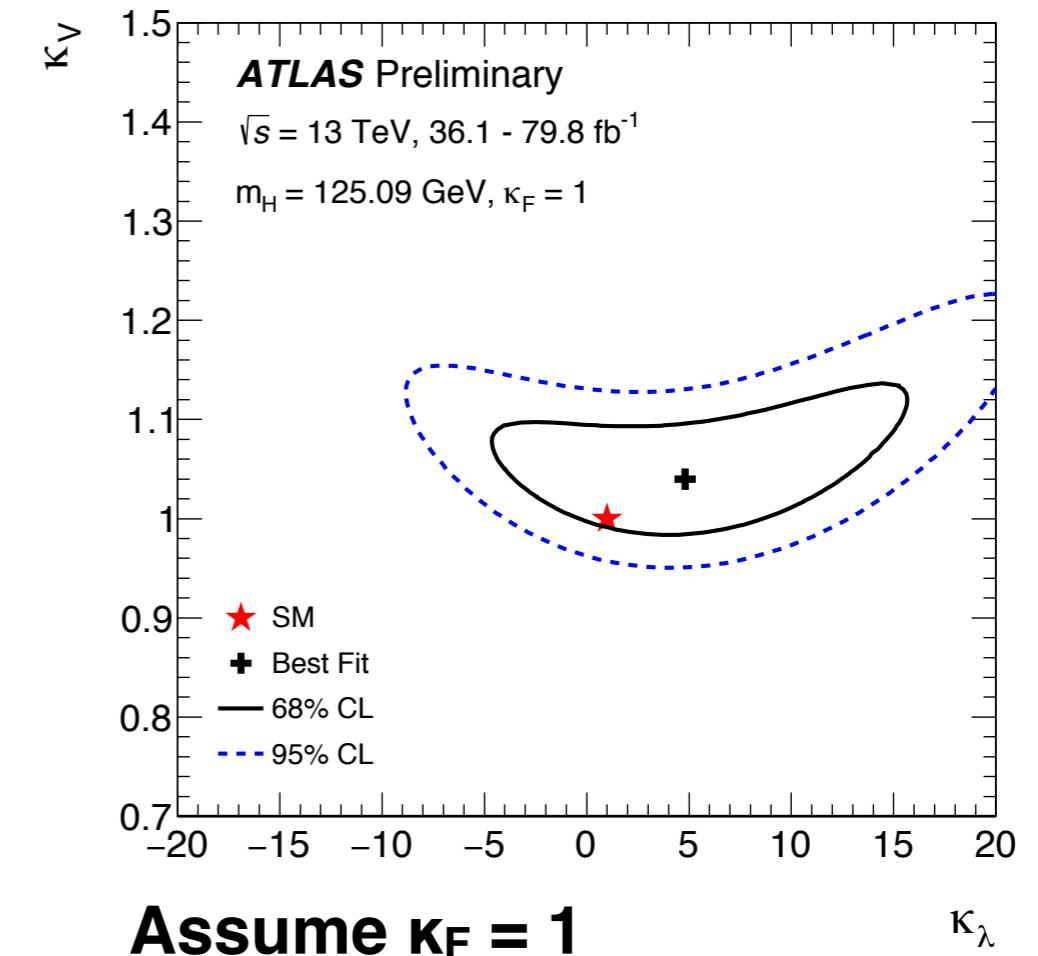


G. Degrassi et. al., [JHEP 12 \(2016\) 080](#),
F. Maltoni et. al., [EPJC 77 \(2017\) 887](#)

Probe Higgs boson self-coupling: results



Assume $\kappa_V = 1$



Assume $\kappa_F = 1$

POIs	Granularity	$\kappa_F^{+1\sigma}_{-1\sigma}$	$\kappa_V^{+1\sigma}_{-1\sigma}$	$\kappa_\lambda^{+1\sigma}_{-1\sigma}$	$\kappa_\lambda [95\% \text{ C.L.}]$
κ_λ	STXS	1	1	$4.0^{+4.3}_{-4.1}$ $1.0^{+8.8}_{-4.4}$	$[-3.2, 11.9]$ $[-6.2, 14.4]$
κ_λ	inclusive	1	1	$4.6^{+4.3}_{-4.2}$ $1.0^{+9.5}_{-4.3}$	$[-2.9, 12.5]$ $[-6.1, 15.0]$
κ_λ, κ_V	STXS	1	$1.04^{+0.05}_{-0.04}$ $1.00^{+0.05}_{-0.04}$	$4.8^{+7.4}_{-6.7}$ $1.0^{+9.9}_{-6.1}$	$[-6.7, 18.4]$ $[-9.4, 18.9]$
κ_λ, κ_F	STXS	$0.99^{+0.08}_{-0.08}$ $1.00^{+0.08}_{-0.08}$	1	$4.1^{+4.3}_{-4.1}$ $1.0^{+8.8}_{-4.4}$	$[-3.2, 11.9]$ $[-6.3, 14.4]$

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Total and differential cross sections

Process	Accuracy	Fraction [%]
ggF	N ³ LO in QCD, NLO in EW	87.2
VBF	(approximate) NNLO in QCD, NLO in EW	6.8
VH	qq/qg: NNLO in QCD, NLO in EW; gg: NLO+NLL in QCD	4.0
$t\bar{t}H + tH$	$t\bar{t}H$: NLO in QCD, NLO in EW, tH : NLO in QCD	1.1
$b\bar{b}H$	NNLO (NLO) in QCD for 5FS (4FS)	0.9

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