Combined measurements of Higgs boson production and decay using pp collisions at 13 TeV with the ATLAS experiment

CLHCP 2018

Zirui Wang (Shanghai Jiao Tong Univ./ Univ. of Michigan)

On behalf of the ATLAS Collaboration

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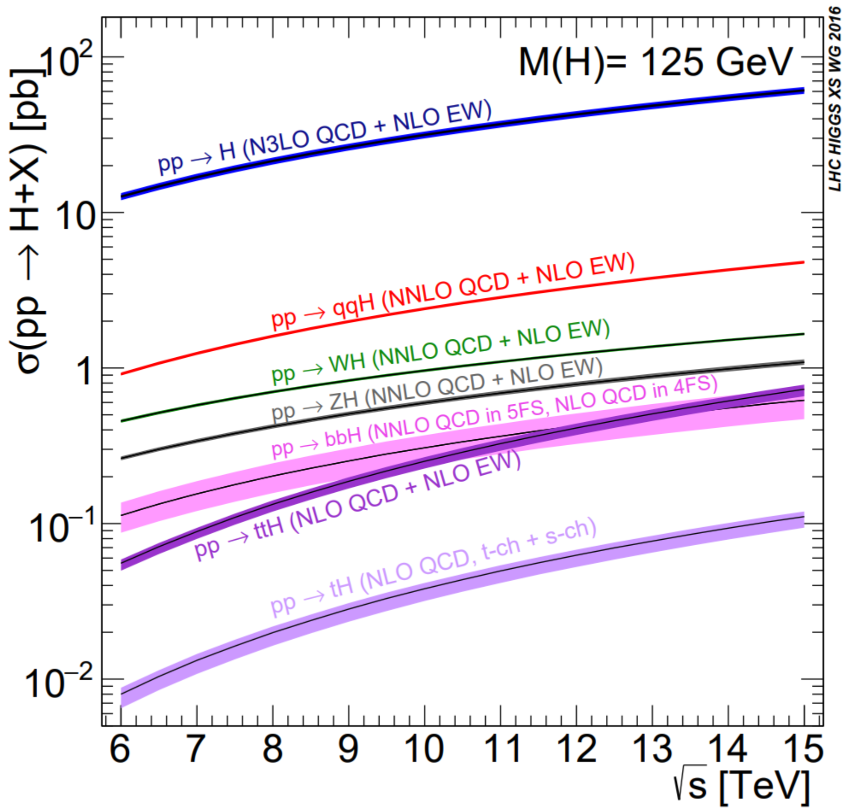
Outline

- Introduction
- Higgs combined property measurement results:
  - Global signal strength measurement
  - Production cross-section measurement
  - Measurement of coupling parameters in the “kappa” framework
- Summary

SM Higgs Production at LHC

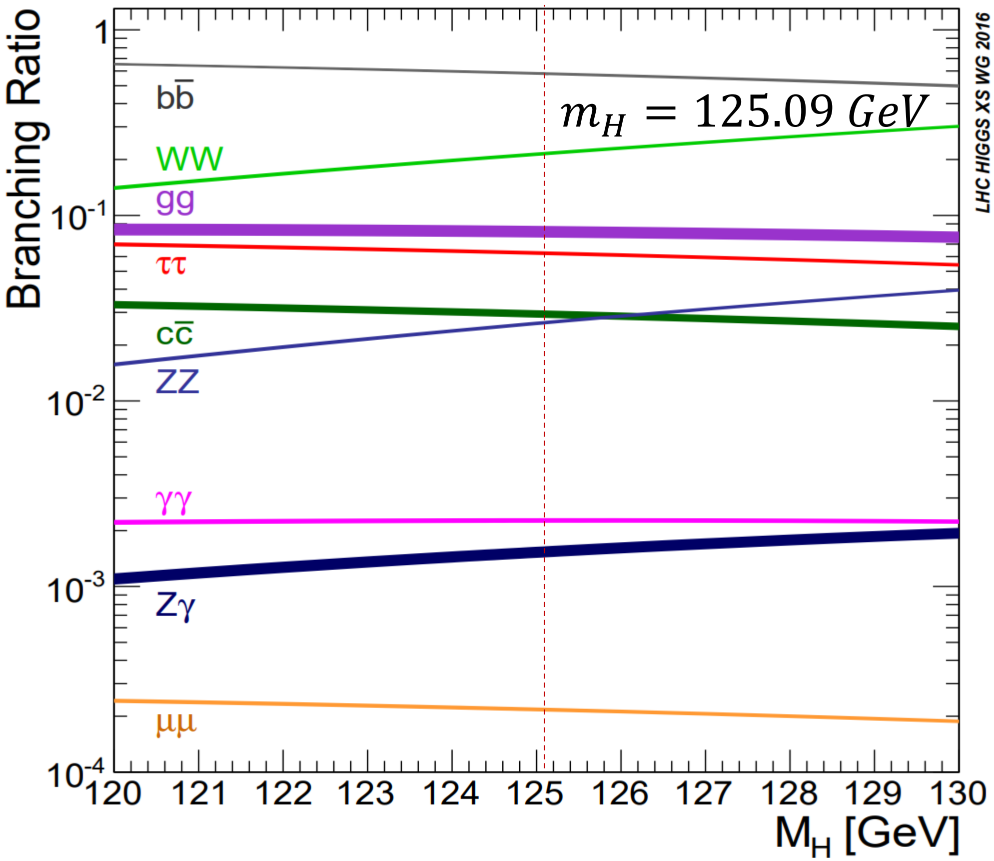
- Following the Higgs Boson with **mass ~ 125 GeV** discovered in 2012, more data (full run 2 **~140 /fb**) pushes Higgs physics from searching to precisely measuring properties.



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 by a factor of 2-4** in production cross sections.

SM Higgs Decay BR

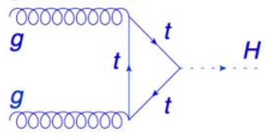
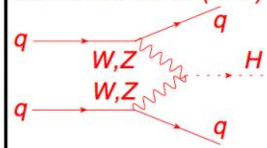
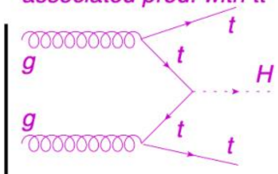
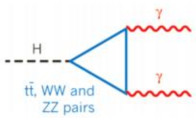
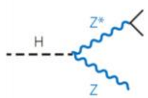
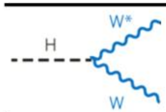
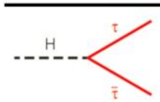
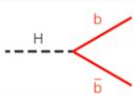
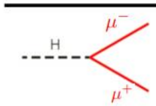


Decay channel	Branching Ratio[%]
H→bb	58.1
*H→WW**	21.5
H→gg	8.2
H→ττ	6.3
H→cc	2.9
*H→ZZ**	2.6
H→γγ	0.23
H→Zγ	0.15
H→μμ	0.02

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

Input channels/analysis

ATLAS-CONF-2018-031

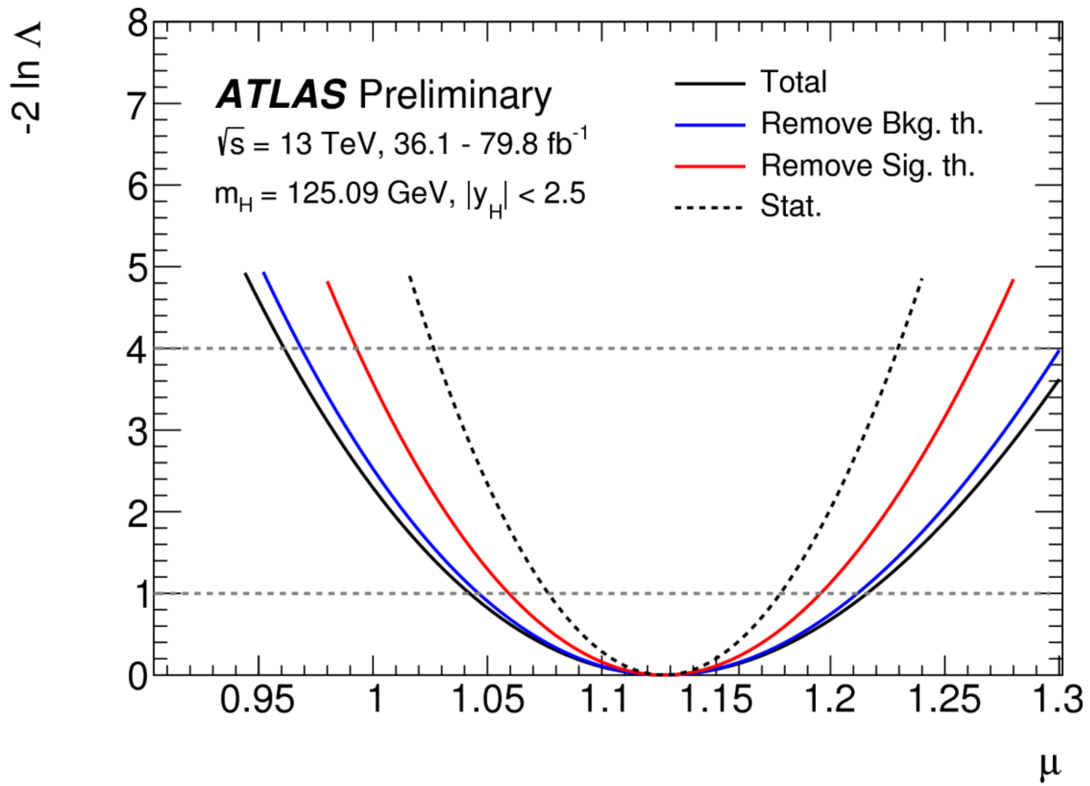
Production	gluon fusion 	vector boson fusion (VBF) 	associated prod. with W/Z 	associated prod. with tt 
Decay 	80/fb	80/fb	80/fb	80/fb
	80/fb	80/fb	80/fb	80/fb
	36.1/fb	36.1/fb		36.1/fb
	36.1/fb	36.1/fb		36.1/fb
			36.1 /fb	36.1/fb
	80/fb	80/fb		

- Measurement is based on combining
  - 79.8/fb: H → ZZ, H → γγ, and H → μμ
  - 36.1/fb: H → WW, H → ττ and H → bb (ttH, H→WW, ττ come from the same input analysis, see Zhi's talk)

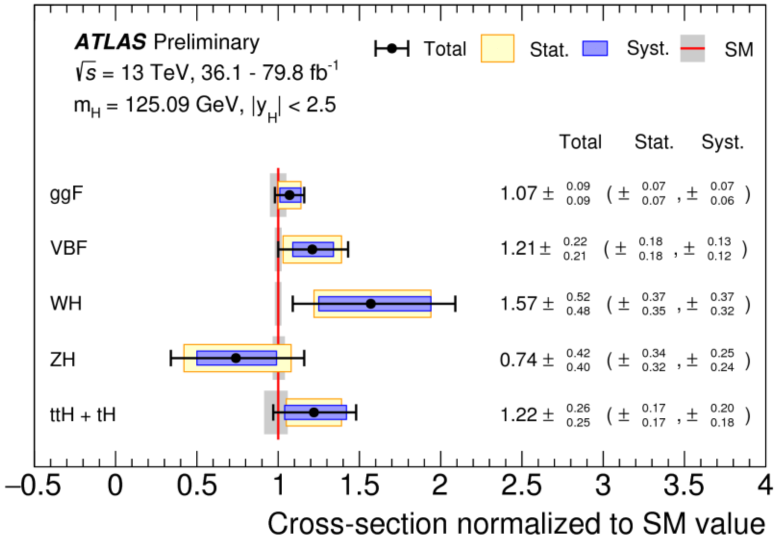
Global signal strength

Inclusive signal strength μ : $$\mu = \frac{\sigma \times \mathrm{B}}{(\sigma \times \mathrm{B})_{\mathrm{SM}}}$$

$$\mu = 1.13^{+0.09}_{-0.08} = 1.13^{+0.05}_{-0.05}(\mathrm{stat.})^{+0.05}_{-0.05}(\mathrm{exp.})^{+0.05}_{-0.04}(\mathrm{sig.\,th.})^{+0.03}_{-0.03}(\mathrm{bkg.\,th.})$$



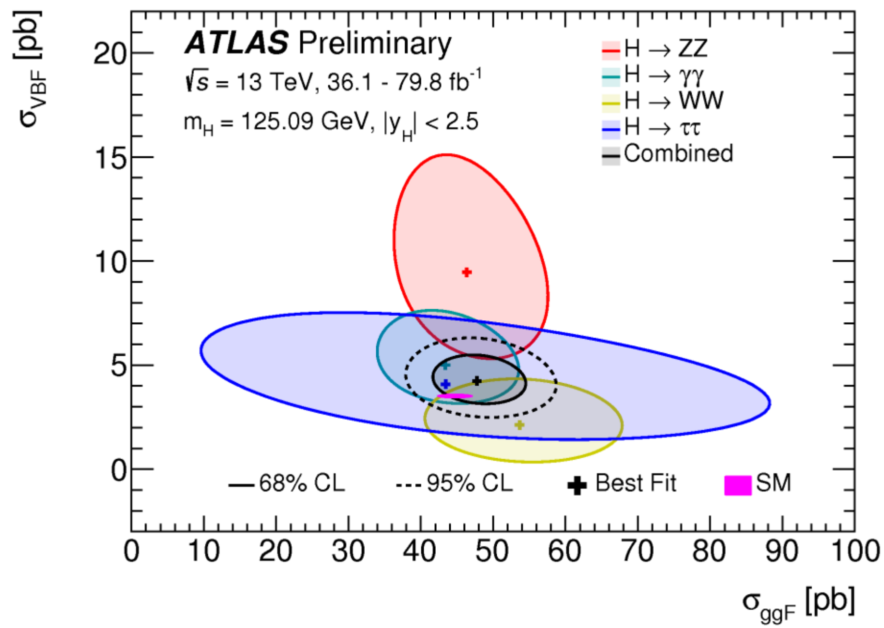
compatibility with SM: 13%



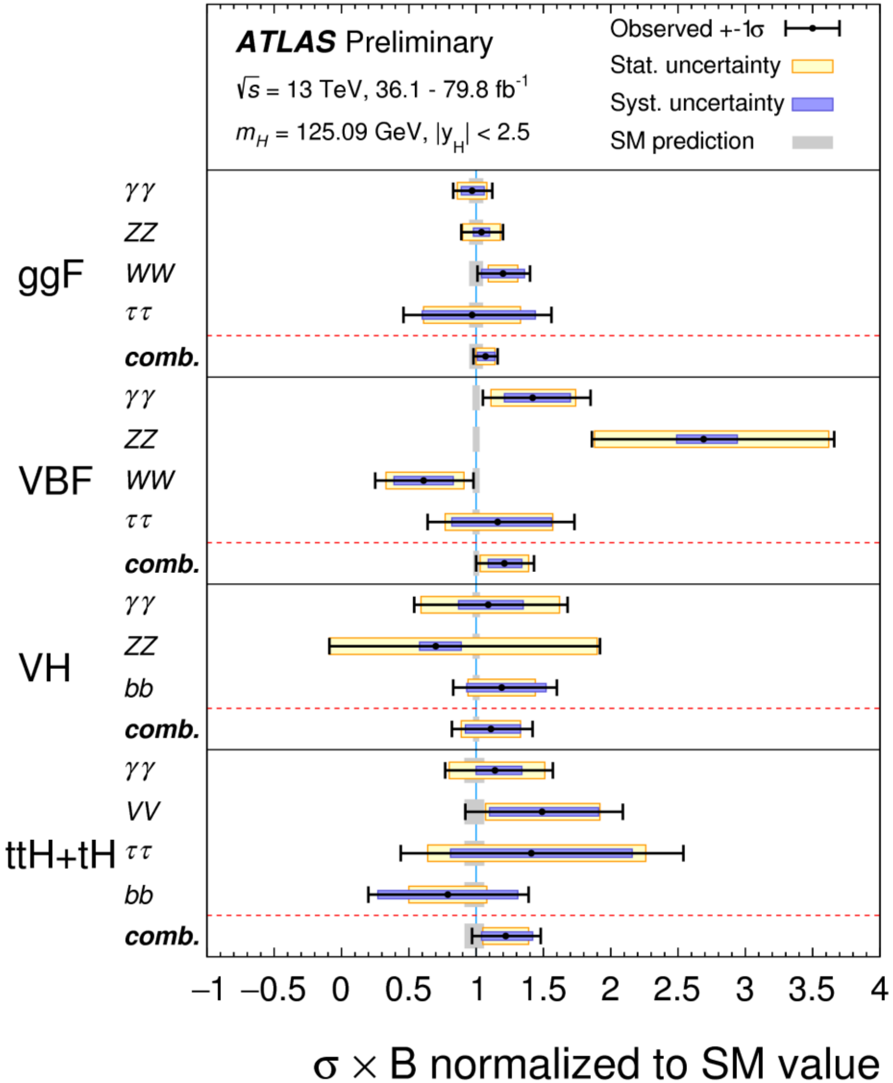
- ATLAS has observed VBF production mode independently (6.5σ). (see Yaquan's talk)

Significance obs. (exp.)	ATLAS+CMS Run-1	ATLAS(36.1 – 79.8 /fb)
VBF	5.4(4.6)	6.5(5.3)
VH	3.5(4.2)	5.3(4.8)
ttH	4.4(2.0)	5.8(5.3)

- 5-D compatibility with SM: 51%.



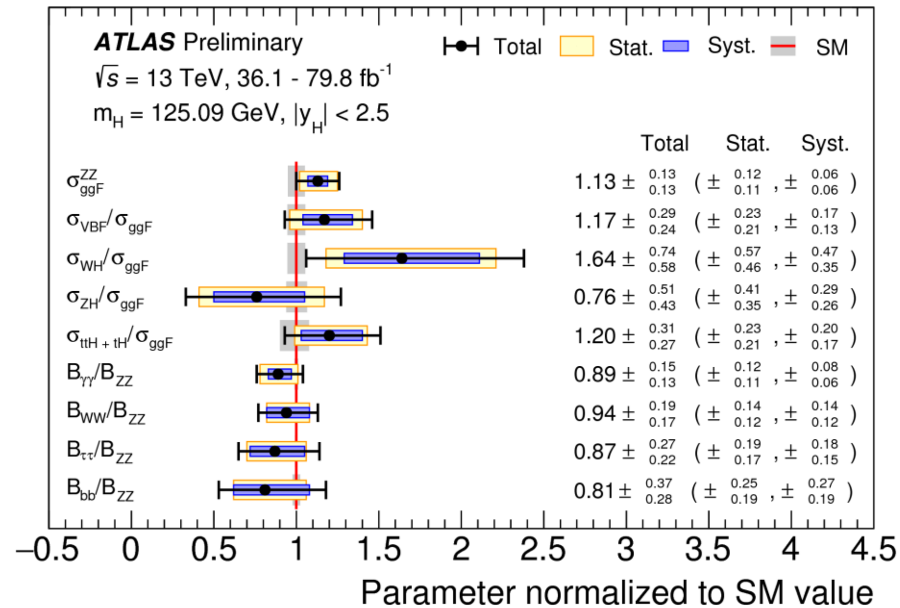
- The ggF and VBF are anticorrelated at 14% level.
- The ggF-VBF contour shows the measurement is consistent with SM within 68% CL.



Cross-sections times branching fraction for production in each relevant decay modes

Ratios of cross sections and of branching fractions are measured using as reference the rate of the gg → H → ZZ →4l process:

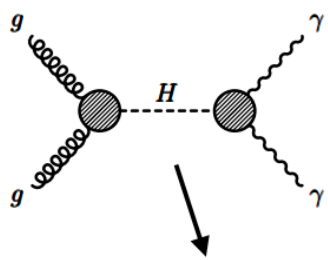
$$\sigma_i \cdot \mathrm{B}_f = \sigma_{\mathrm{ggF}} \cdot \mathrm{B}_{4\ell} \cdot \left(\frac{\sigma_i}{\sigma_{\mathrm{ggF}}}\right) \cdot \left(\frac{\mathrm{B}_f}{\mathrm{B}_{4\ell}}\right)$$



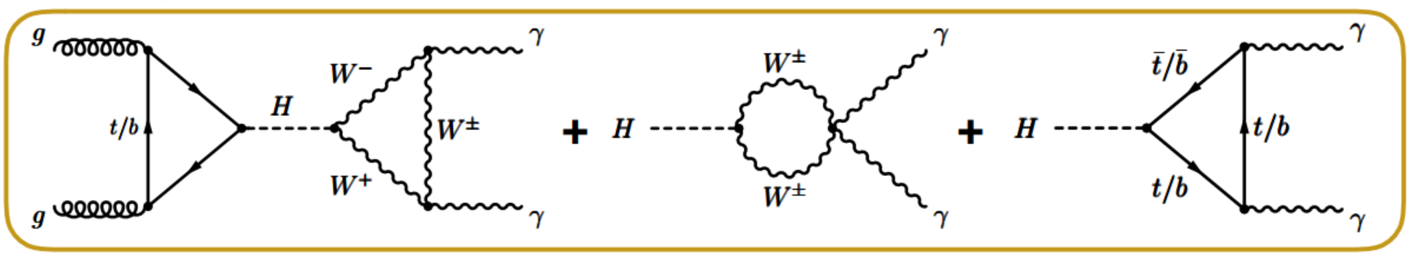
- 9-D compatibility with SM: 83%.

“kappa” framework

- With known Higgs boson mass, the SM Higgs sector is fixed.
- Use the LO coupling modifier to probe for deviations from the SM.
- Introduce one scale factor κ per SM particle with observable “Higgs coupling” at the LHC: κW, κZ, κt, κb, κτ, κμ, κγ, κg, κH
- Eg:



$$(\sigma \times \mathbf{BR})(\mathbf{gg} \rightarrow \mathbf{H} \rightarrow \gamma\gamma) \sim \frac{\kappa_{\mathbf{g}}^{\mathbf{2}}(\kappa_{\mathbf{t}}, \kappa_{\mathbf{b}}, \ldots)\kappa_{\gamma}^{\mathbf{2}}(\kappa_{\mathbf{W}}, \kappa_{\mathbf{t}}, \ldots)}{\kappa_{\mathbf{H}}^{\mathbf{2}}(\kappa_{\mathbf{b}}, \kappa_{\mathbf{W}}, \kappa_{\mathbf{Z}}, \kappa_{\tau}, \kappa_{\mathbf{t}}, \ldots)}$$



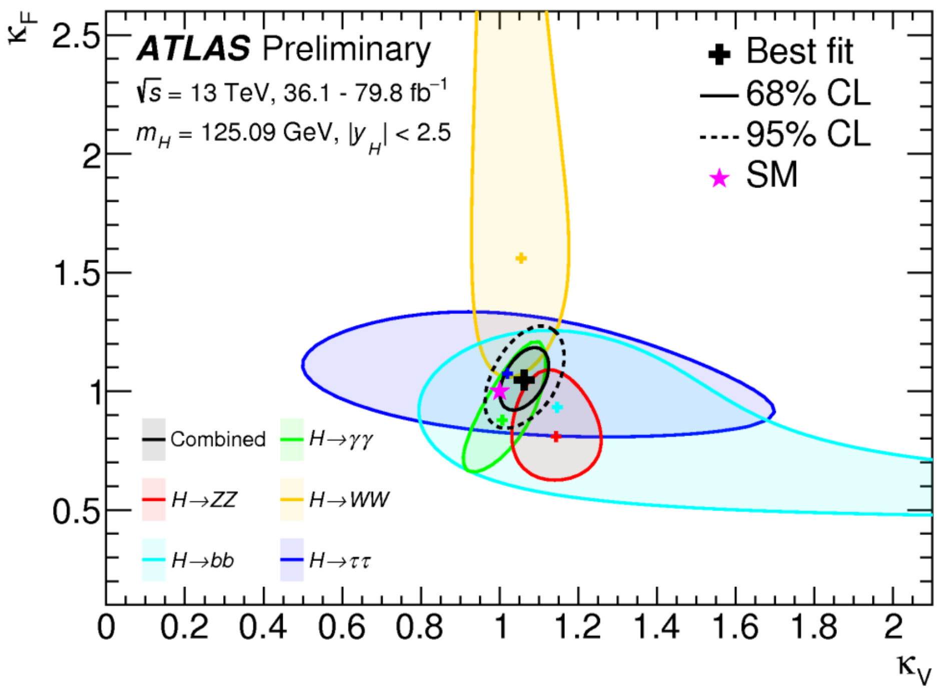
- Can handle other production and decay vertices in a similar way (much simpler in most cases)

κ_F vs. κ_V and κ_g vs. κ_γ model

- Model 1. Assume uniform coupling modifiers for all weak vector bosons (κ_V) and all fermions (κ_F).

$$\kappa_F = 1.05^{+0.09}_{-0.09}$$
$$\kappa_V = 1.06^{+0.04}_{-0.04}$$

2D compatibility with SM: 31%



- Model 2. Assign coupling modifier to gg→H/ H→gg (κ_g) and H→γγ (κ_γ). All the other couplings are fixed to SM.
- 2D compatibility with SM: 70%

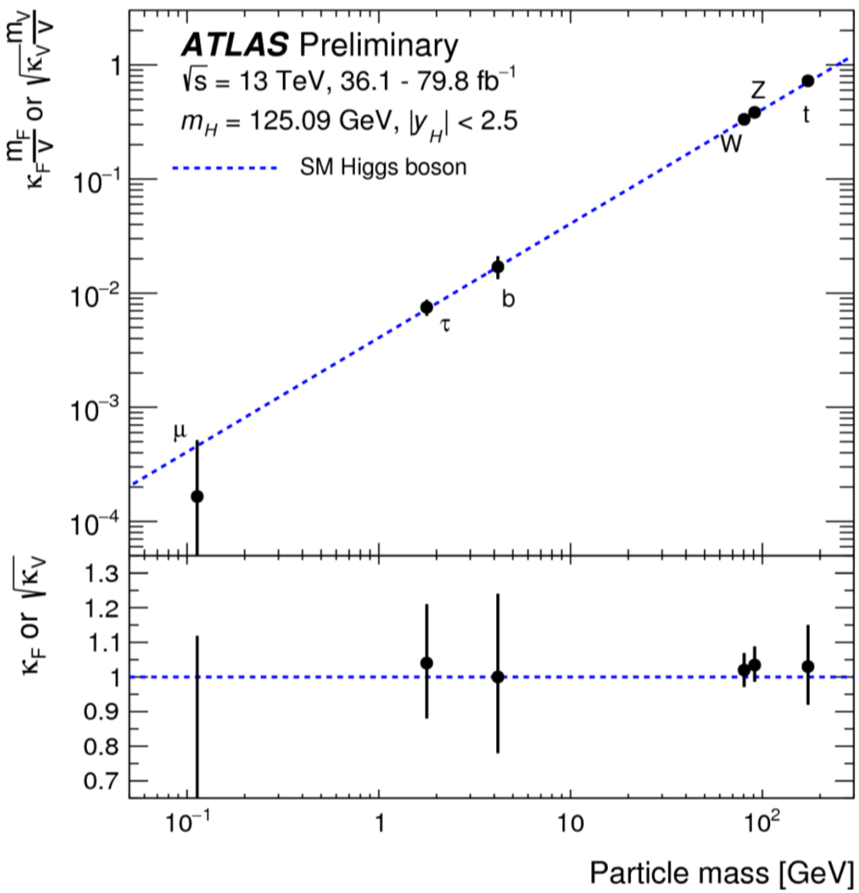
$$\kappa_g = 1.05^{+0.06}_{-0.06}$$
$$\kappa_\gamma = 1.00^{+0.06}_{-0.06}$$

- Model 3. Assuming BSM contribution in the total width, then:

$$\kappa_g = 1.05^{+0.06}_{-0.06}$$
$$\kappa_\gamma = 1.00^{+0.07}_{-0.06}$$

B_{BSM} <0.13 @ 95% CL

Parameterization assuming SM structure

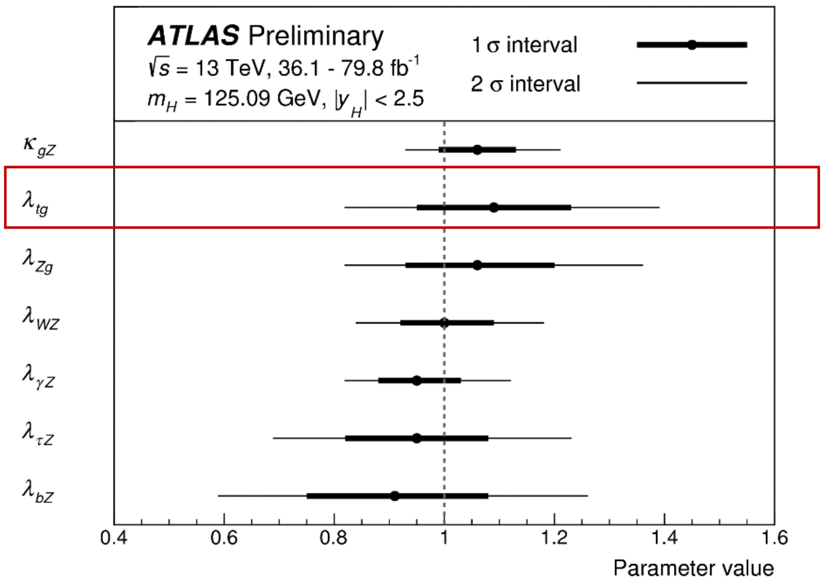


Parameter	Result
κ_Z	$1.07^{+0.11}_{-0.10}$
κ_W	1.04 ± 0.10
κ_b	$1.00^{+0.24}_{-0.22}$
κ_t	$1.03^{+0.12}_{-0.11}$
κ_τ	$1.04^{+0.17}_{-0.16}$
κ_μ	< 1.63 at 95% CL.

6D compatibility with SM: 79%

- Model 4. All couplings are assumed to positive. B_{BSM} is assumed to be zero. $H \rightarrow \mu\mu$ is included in this parameterization.
- Couplings are in an excellent agreement with the Standard Model prediction over a range covering 3 orders of magnitude in particle mass.

Coupling strength and Ratio of modifiers

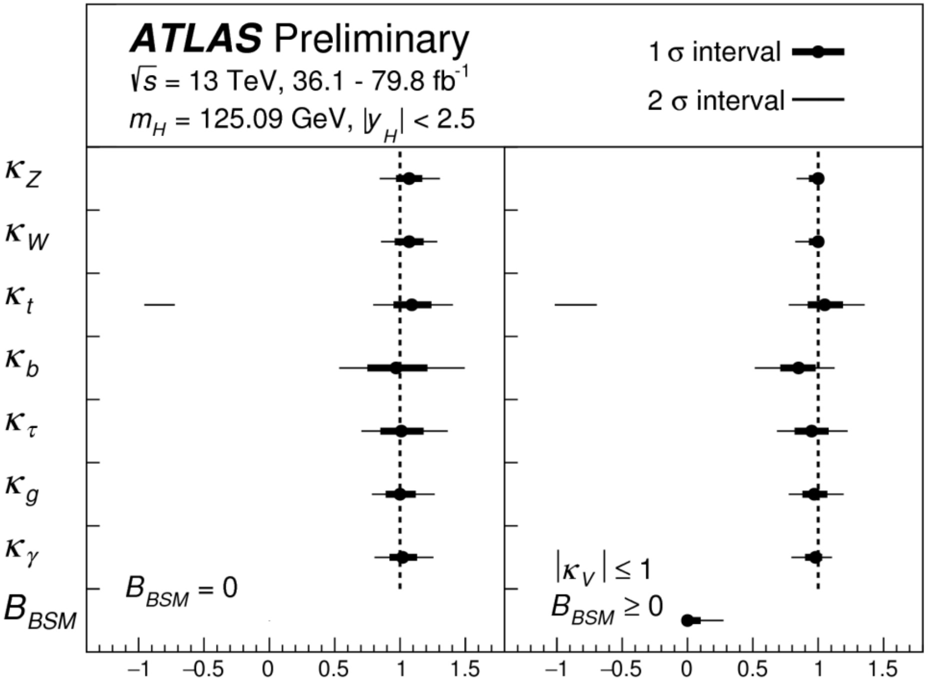


Parameter	Definition in terms of κ modifiers	Result
κ_{gZ}	$\kappa_g \kappa_Z / \kappa_H$	1.06 ± 0.07
λ_{tg}	κ_t / κ_g	$1.09^{+0.14}_{-0.14}$
λ_{Zg}	κ_Z / κ_g	$1.06^{+0.14}_{-0.13}$
λ_{WZ}	κ_W / κ_Z	$0.99^{+0.09}_{-0.08}$
$\lambda_{\gamma Z}$	κ_γ / κ_Z	$0.95^{+0.08}_{-0.07}$
$\lambda_{\tau Z}$	κ_τ / κ_Z	0.95 ± 0.13
λ_{bZ}	κ_b / κ_Z	$0.91^{+0.17}_{-0.16}$

7D compatibility with SM: 86%

- Model 5. The parameterization requires no assumption on the total width of the Higgs boson. All parameters are assumed to be positive.
- Unprecedented precision reached for all modifiers comparing to the previous results.
- The gluon-gluon fusion and Higgs boson production in association with top quarks is sensitive to test for new physics in the ggF loop.

Generic “kappa” model



Parameter	(a) no BSM	(b) with BSM
κ_Z	1.07 ± 0.10	restricted to $\kappa_Z \leq 1$
κ_W	1.07 ± 0.11	restricted to $\kappa_W \leq 1$
κ_b	$0.97^{+0.24}_{-0.22}$	$0.85^{+0.13}_{-0.14}$
κ_t	$1.09^{+0.15}_{-0.14}$	$1.05^{+0.14}_{-0.13}$
κ_τ	$1.02^{+0.17}_{-0.16}$	0.95 ± 0.13
κ_γ	$1.02^{+0.09}_{-0.12}$	$0.98^{+0.05}_{-0.08}$
κ_g	$1.00^{+0.12}_{-0.11}$	$0.97^{+0.10}_{-0.09}$
$\mathrm{B_{BSM}}$	-	< 0.26 at 95% CL

- Model 6. No BSM contributions to the total width are considered. 7D compatibility with SM: 87%.

- Model 7. BSM contributions to the total width are included, constrained by assuming $\mathrm{B}_{BSM} \geq 0$ and $\kappa_{Z,W} \leq 1$.
- B_{BSM} <0.26 @ 95% CL

Summary

- Measurement of Higgs boson production and decay performed based on
  - 79.8/fb $H \rightarrow ZZ$, $H \rightarrow \gamma\gamma$, and $H \rightarrow \mu\mu$
  - 36.1/fb $H \rightarrow WW$, $H \rightarrow \tau\tau$ and $H \rightarrow bb$
- Combined signal strength:

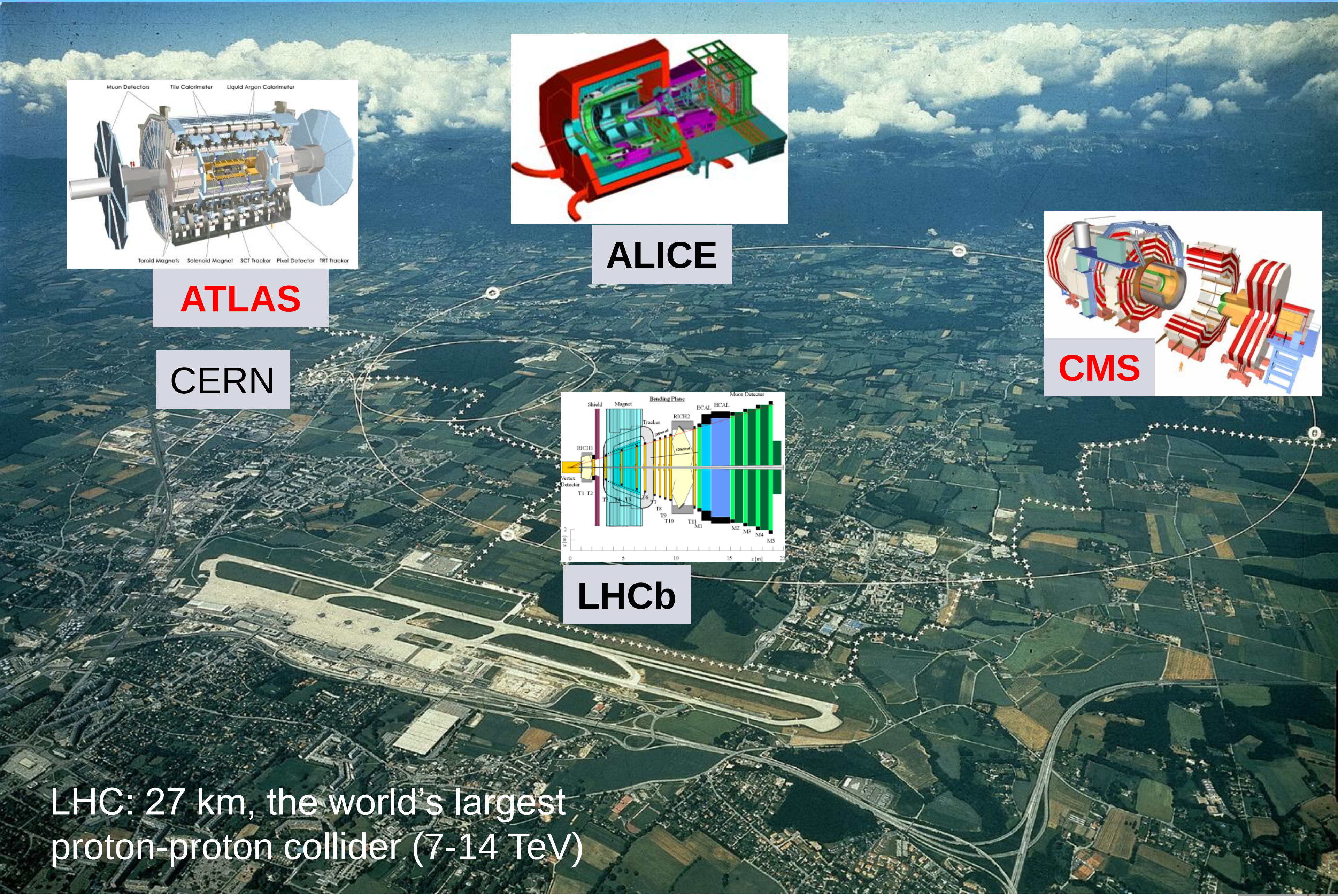
$$\boldsymbol{\mu} = \mathbf{1.13^{+0.09}_{-0.08} = 1.13^{+0.05}_{-0.05}(stat.)^{+0.05}_{-0.05}(exp.)^{+0.05}_{-0.04}(sig.\,th.)^{+0.03}_{-0.03}(bkg.\,th.)}$$

- Production mode cross sections, ratios of production mode cross sections measurements are performed. **The significance of VBF, VH and ttH production mode are measured to be 6.5σ, 5.3σ and 5.8σ, respectively.**
- Data also interpreted using κ framework. **Unprecedented precision reached for many of the parameterizations.**
- In all cases, **compatibility between data and SM is within 2 standard deviation.** No deviation from SM captured.
- More channels and more integrated luminosity will be added in the following combination analysis.

Thanks

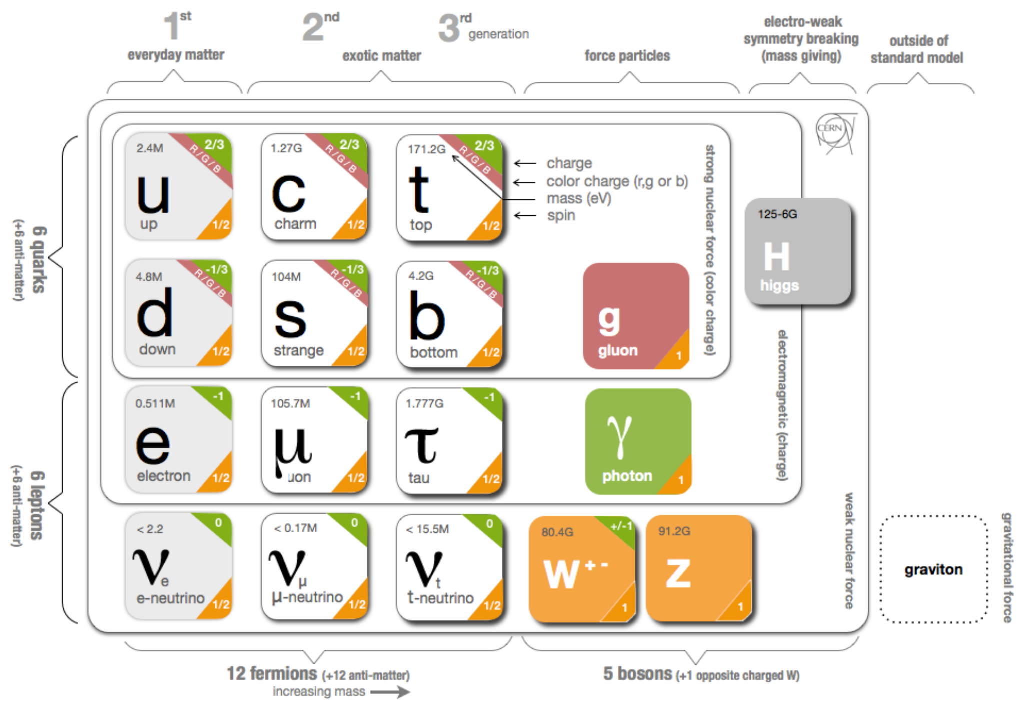
Backup

Large Hadron Collider at CERN

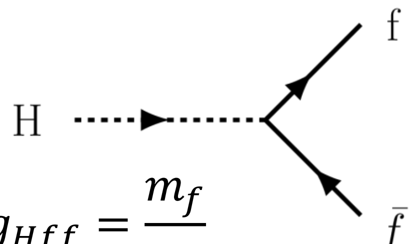


LHC: 27 km, the world's largest proton-proton collider (7-14 TeV)

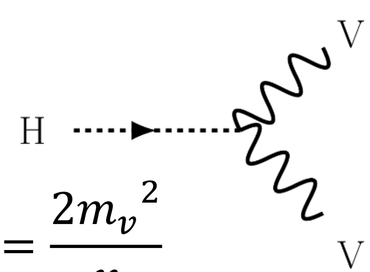
The Higgs boson in the SM



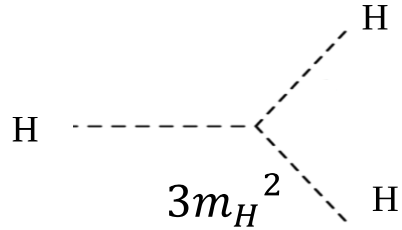
$$\mathcal{L} = -g_{Hff} f \bar{f} H + \delta_V V_\mu V^\mu \left(g_{HVV} H + \frac{g_{HHVV}}{2} H^2 \right) + \frac{g_{HHH}}{6} H^3 + \frac{g_{HHHH}}{6} H^4$$



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



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



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

“kappa” model

- Parametrisation:

	Loops	Interference	Effective scaling factor	Resolved scaling factor
Production				
$\sigma(\mathrm{ggH})$	✓	g-t	κ_g^2	$1.04\kappa_t^2 + 0.002\kappa_b^2 - 0.038\kappa_t\kappa_b$
$\sigma(\mathrm{VBF})$	—	—		$0.73\kappa_W^2 + 0.27\kappa_Z^2$
$\sigma(\mathrm{WH})$	—	—		κ_W^2
$\sigma(qq/qg \rightarrow \mathrm{ZH})$	—	—		κ_Z^2
$\sigma(gg \rightarrow \mathrm{ZH})$	✓	Z-t		$2.46\kappa_Z^2 + 0.47\kappa_t^2 - 1.94\kappa_Z\kappa_t$
$\sigma(\mathrm{ttH})$	—	—		κ_t^2
$\sigma(gb \rightarrow \mathrm{WtH})$	—	W-t		$2.91\kappa_t^2 + 2.31\kappa_W^2 - 4.22\kappa_t\kappa_W$
$\sigma(qb \rightarrow \mathrm{tHq})$	—	W-t		$2.63\kappa_t^2 + 3.58\kappa_W^2 - 5.21\kappa_t\kappa_W$
$\sigma(\mathrm{bbH})$	—	—		κ_b^2
Partial decay width				
Γ^{ZZ}	—	—		κ_Z^2
Γ^{WW}	—	—		κ_W^2
$\Gamma^{\gamma\gamma}$	✓	W-t	κ_γ^2	$1.59\kappa_W^2 + 0.07\kappa_t^2 - 0.67\kappa_W\kappa_t$
$\Gamma^{\tau\tau}$	—	—		κ_τ^2
Γ^{bb}	—	—		κ_b^2
$\Gamma^{\mu\mu}$	—	—		κ_μ^2
Total width for $\mathcal{B}_{BSM} = 0$				
Γ_H	✓	—	κ_H^2	$0.58\kappa_b^2 + 0.22\kappa_W^2 + 0.08\kappa_g^2 +$ $+ 0.06\kappa_\tau^2 + 0.026\kappa_Z^2 + 0.029\kappa_c^2 +$ $+ 0.0023\kappa_\gamma^2 + 0.0015\kappa_{Z\gamma}^2 +$ $+ 0.00025\kappa_s^2 + 0.00022\kappa_\mu^2$

“kappa” model performed

Models	POIs	comment
1. Modifications to fermion and gauge bosons couplings	κ_F, κ_V	No BSM contribution κ_F, $\kappa_V > 0$
2/3. Modifications to effective photons and gluon couplings w/ or w/o BSM decays	κ_g, κ_γ, (B_{BSM})	κ_g, $\kappa_\gamma > 0$ B_{BSM} within (0,0.5)
4. Parameterization assuming SM structure of the loops and no BSM decays	κ_μ, κ_W, κ_Z,κ_t, κ_τ, κ_b	No BSM contribution All POIs are positive $H \rightarrow \mu\mu$ included
5. Parameterization using ratios of coupling modifiers	κ_{gZ}, λ_{Zg}, λ_{tg}, λ_{WZ}, $\lambda_{\gamma Z}$, $\lambda_{\tau Z}$, λ_{bZ}	No BSM contribution No assumption on the total width All POIs are positive
6/7 Generic parameterization w/ or w/o BSM decays	κ_g, κ_γ, κ_W, κ_Z,κ_t, κ_τ, κ_b, (B_{BSM})	Only allow κ_t to go both positive and negative B_{BSM} within (0,0.5)

Uncertainty source	$\frac{\Delta\mu}{\mu}$ [%]
Statistical uncertainties	4.5
Systematic uncertainties (excl. MC stat.)	6.1
Theory uncertainties	4.8
Signal	4.3
Background	2.3
Experimental uncertainties	4.0
Luminosity	2.1
Fake leptons	1.2
Jets, $E_{\mathrm{T}}^{\mathrm{miss}}$	1.3
Flavour tagging	0.9
Background modeling	1.2
Electrons, photons	2.2
Muons	0.3
τ-lepton	0.4
Other	1.5
MC stat. uncertainties	1.5

Significance obs. (exp.)	ATLAS+CMS Run-1	ATLAS(36.1 – 79.8 /fb)
VBF	5.4(4.6)	6.5(5.3)
VH	3.5(4.2)	5.3(4.8)
ttH	4.4(2.0)	5.8(5.3)

- Run 2 $H \rightarrow \gamma\gamma$ mass resolution: 1.4-2.1 GeV
- Run 2 $H \rightarrow ZZ^* \rightarrow 4l$ mass resolution: 1.6-2.4 GeV