Combined Higgs boson measurements at the ATLAS experiment

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on behalf of the ATLAS collaboration

Bari, Win2019

Introduction

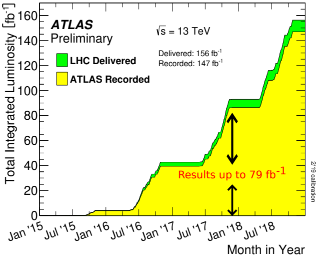
- Since the discovery of the Higgs boson in 2012 its properties have been measured with increasing precision

$\rightarrow$ probing the SM predictions

- Presenting the most recent Higgs boson combined measurements with the ATLAS detector
  - Signal strength, production mode cross-sections and branching ratios
  - Simplified template cross-sections (STXS)
  - κ-framework

- Combination input analyses

Analysis	L [fb^{-1}]	Ref.
$H \rightarrow \gamma\gamma$ (inc. $t\bar{t}H \rightarrow \gamma\gamma$)	79.8	[1,2,3]
$H \rightarrow ZZ^* \rightarrow 4\ell$ (inc. $t\bar{t}H \rightarrow 4\ell$)	79.8	[4,5]
$H \rightarrow WW^* \rightarrow e\nu\mu\nu$	36.1	[6]
$H \rightarrow \tau\tau$	36.1	[7]
VH, $H \rightarrow b\bar{b}$	79.8	[8,9]
VBF, $H \rightarrow b\bar{b}$	24.5 – 30.6	[10]
$t\bar{t}H$, $H \rightarrow b\bar{b}$ and $t\bar{t}H$ multilepton	36.1	[11,12]
$H \rightarrow \mu\mu$	79.8	[13]
$H \rightarrow$ invisible	36.1	[14,15,16]
Off-shell Higgs	36.1	[17]

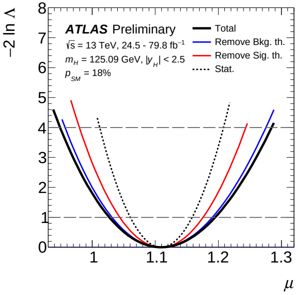


Signal strength, production mode cross-sections and branching ratios

Global signal strength

- First parametrization used to interpret the results is signal strength:

$$\mu_{if} = \frac{\sigma_i}{\sigma_i^{SM}} \times \frac{BR_f}{BR_f^{SM}} \qquad \text{for SM} \quad \mu_{if} = 1$$



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	4.1
Luminosity	2.0
Background modeling	1.6
Jets, $E_{\mathrm{T}}^{\mathrm{miss}}$	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

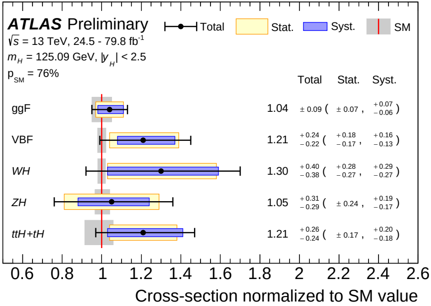
- Fixing scaling of σ and BR as in the SM, the global normalization μ results

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

- Consistent with the SM with a p-value=18%
- Measurement limited by systematic uncertainties
- Experimental and Theory uncertainty with same magnitude

Production cross-sections

- Branching ratio fixed to SM value, considering only σ_i



Process ($\lvert y_H\rvert < 2.5$)	Value [pb]	Uncertainty [pb] Total	Stat.	Exp.	Sig. th.	Bkg. th.	SM pred. [pb]	Significance 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	$^{+0.05}_{-0.04}$	$^{+0.08}_{-0.07}$	$0.586^{+0.034}_{-0.049}$	5.8 (5.4)	

- Consistent with the SM with a p-value=76%
- All main production modes have been observed (also WH and $ZH > 3\sigma$)

Production cross-sections

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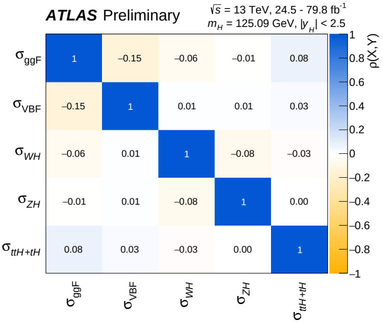
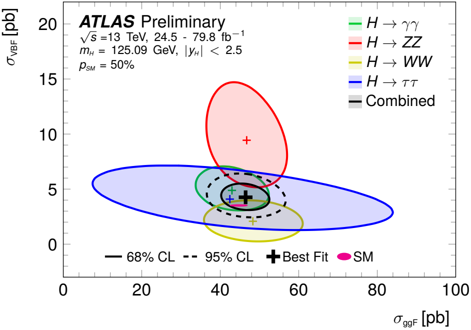
- Small correlation between the measured cross-sections
- Correlation of -15% between ggF and VBF

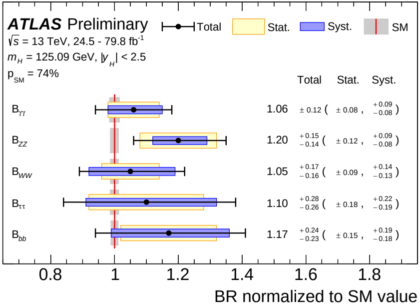




- Constraint mainly from $H \to \gamma\gamma$ (79.8 fb^{-1}) and $H \to WW^* \to e\nu\mu\nu$ (36.1 fb^{-1})

Branching ratio

- Cross-section fixed to SM value, considering only BR_f (Syst. include SM xsec unc.)

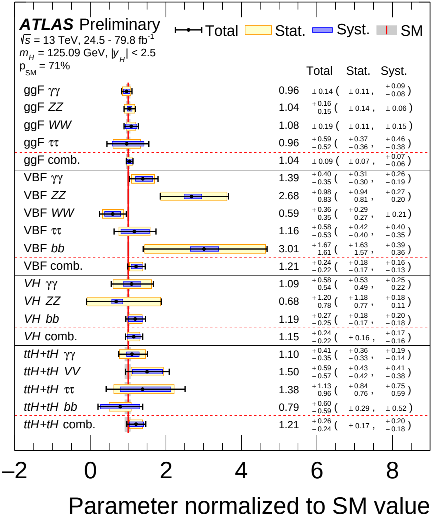


Branching ratio	Value	Uncertainty Total	Stat.	Exp.	Sig. theo.	Bkg. theo.
$B_{\gamma\gamma}/B^{SM}_{\gamma\gamma}$	1.06	±0.12	±0.08	$^{+0.08}_{-0.07}$	±0.05	±0.01
B_{ZZ}/B^{SM}_{ZZ}	1.20	$^{+0.15}_{-0.14}$	±0.12	±0.05	$^{+0.07}_{-0.05}$	±0.02
B_{WW}/B^{SM}_{WW}	1.05	$^{+0.17}_{-0.16}$	±0.09	±0.09	$^{+0.06}_{-0.05}$	±0.07
$B_{\tau\tau}/B^{SM}_{\tau\tau}$	1.10	$^{+0.28}_{-0.26}$	±0.18	$^{+0.17}_{-0.16}$	$^{+0.12}_{-0.08}$	$^{+0.06}_{-0.05}$
B_{bb}/B^{SM}_{bb}	1.17	$^{+0.24}_{-0.23}$	±0.15	±0.11	$^{+0.09}_{-0.06}$	$^{+0.13}_{-0.12}$

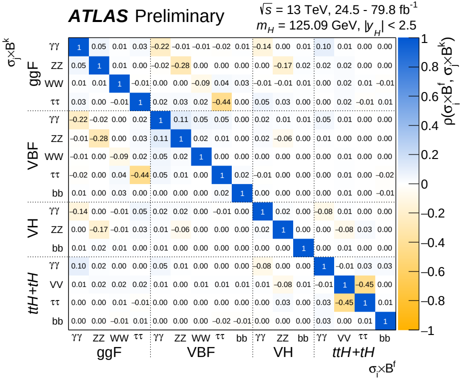
- All consistent with the SM with a p-value=75%

Production cross-sections × branching ratios

- Considering the products $(\sigma \times \mathrm{BR})_{if}$

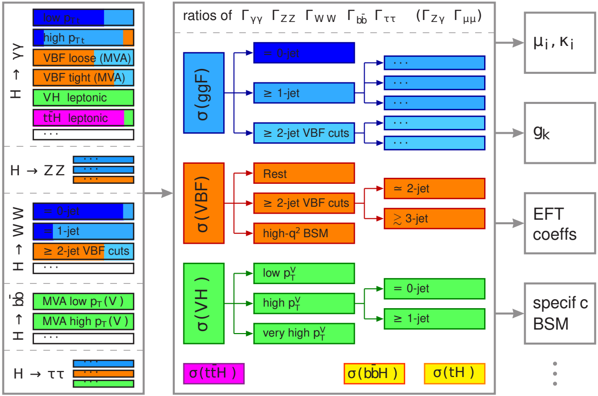


- Consistent with the SM with a p-value=71%
- Different level of ggF–VBF correlation in the analyses
  - Well separated in $H \to WW^*$ analysis

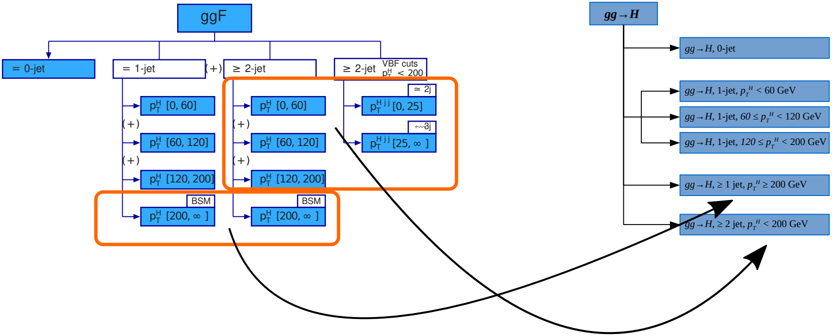


Simplified template cross-section framework

- Simplified template cross-section framework defines fiducial regions by using:
  - production mode, p_T^H , N_j, p_T^H , p_T^{Hjj}, p_T^V
  - sensitivity to BSM model
  - avoidance of large theory uncertainty in SM prediction
  - matching the experimental selection
- Measurement designed to split the events according to STXS



- Due to limited data statistics the current combined measurement is presented in a reduce splitting scheme
  - 11 $\rightarrow$ 6 bins for ggF
  - 5 $\rightarrow$ 3 bins for $qq \rightarrow Hqq$ (incl. VBF and VH)
  - 11 $\rightarrow$ 5 bins for V(lep)H+ggZH
    - 2 bins for WH
    - 3 bins for ZH+ggZH
  - 2 $\rightarrow$ 1 single bin $t\bar{t}H + tH$



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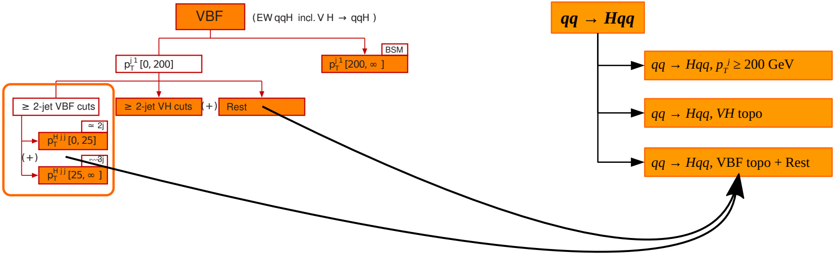

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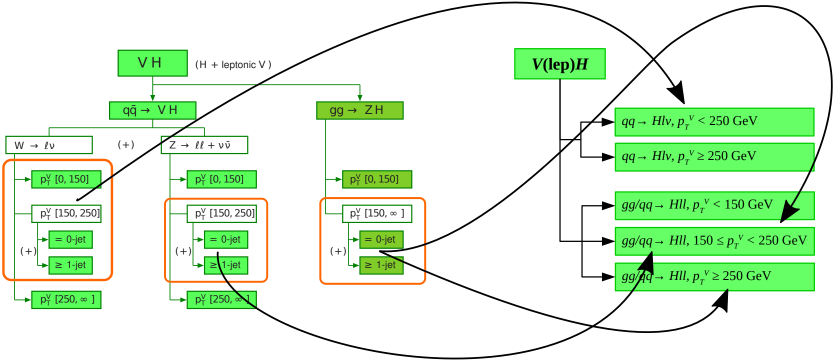
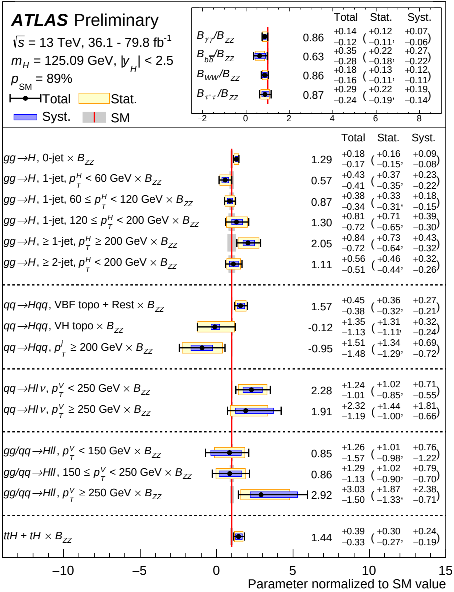


- Measured 19 parameters:
  - cross-section in STXS region i × branching ratio of $H \to ZZ$
  - the ratio of each branching fraction over the $H \to ZZ$ one.

$$(\sigma \times \mathrm{B})_{if} = (\sigma \times \mathrm{B})_{i,ZZ} \cdot \left(\frac{\mathrm{B}_f}{\mathrm{B}_{ZZ}}\right).$$

- All consistent with the SM with a *p*-value=89%



κ-framework

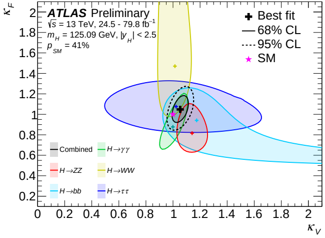
κ-framework: vector boson–fermions, loops coupling

- LO-approximated framework introducing coupling strength modifiers κ

$$\sigma_i \times \mathrm{BR}^f = \frac{\sigma_i(\boldsymbol{\kappa}) \times \Gamma^f(\boldsymbol{\kappa})}{\Gamma_H}, \quad \text{with} \quad \kappa_j^2 = \frac{\sigma_j}{\sigma_j^{\mathrm{SM}}} \quad \text{and} \quad \kappa_j^2 = \frac{\Gamma^j}{\Gamma^j_{\mathrm{SM}}}.$$

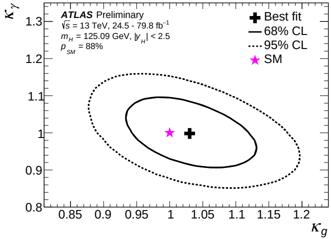
- Γ_H modified by a factor κ_H, defined as $\kappa_H^2 = \sum_j BR^f_{\mathrm{SM}} \kappa_j^2$, with no additional BSM new particle contribution

  - vector boson: $\kappa_V = \kappa_W = \kappa_Z$
  - fermions: $\kappa_F = \kappa_t = \kappa_b = \kappa_\tau = \kappa_\mu$



- $\kappa_V = 1.05 \pm 0.04 \quad \kappa_F = 1.05^{+0.09}_{-0.08}$
- p-value=41% w.r.t SM

- Probing contributions of new particles either in loops or in new final states
- Effective coupling modifiers κ_g and κ_γ

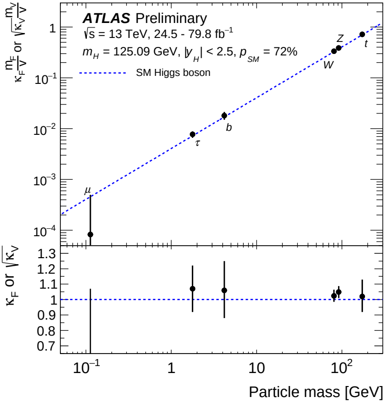


- $\kappa_\gamma = 1.00 \pm 0.06 \quad \kappa_g = 1.03^{+0.07}_{-0.06}$
- p-value=88% w.r.t SM

- Generic parametrization assuming no new particles in loops and decays
- coupling strengths to W, Z, t, b, τ and μ are treated independently
- including $H \to \mu\mu$ (79.8 fb^{-1})

Parameter	Result
κ_Z	$1.11^{+0.08}_{-0.08}$
κ_W	1.05 ± 0.08
κ_b	$1.05^{+0.19}_{-0.18}$
κ_t	$1.02^{+0.11}_{-0.10}$
κ_τ	$1.06^{+0.16}_{-0.15}$
κ_μ	< 1.49 at 95% CL.

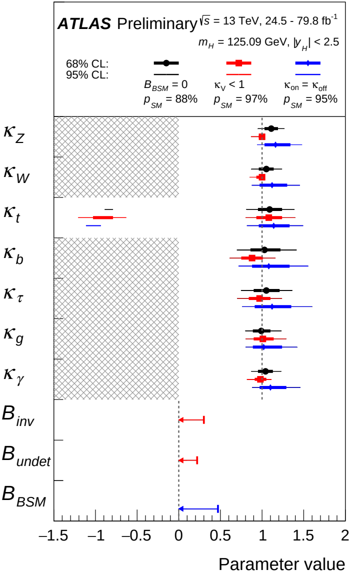
- p-value of SM $= 72\%$



- Including a Higgs boson branching fraction to invisible or undetected decays, the Higgs boson width is expressed as

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

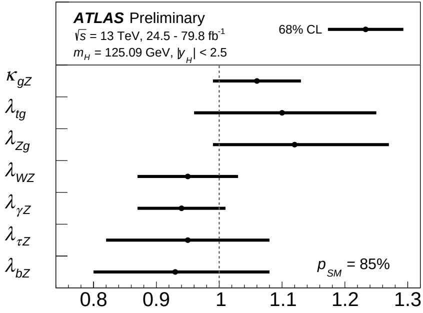
- No BSM contributions to the total width ($B_{\text{inv}} = B_{\text{undet}} = 0$).
- Both B_{inv} and B_{undet} are added as free parameters to the model.
  - Including $H \to$ invisible (36.1 fb^{-1})
  - $\kappa_W \leq 1$ and $\kappa_Z \leq 1$
- Additional single free parameter $B_{\text{BSM}} = B_{\text{inv}} = B_{\text{undet}}$ is added to the model.
  - Including Off-shell $H \to ZZ^* \to 4\ell$ and $H \to ZZ^* \to 2\ell 2\nu$ (36.1 fb^{-1})



κ-framework: independent to Higgs width

- Scale factors expressed as ratios of scale factors that can be measured independent of any assumptions on the Higgs boson total width
- Most model-independent determination of coupling-strength in the κ-framework.

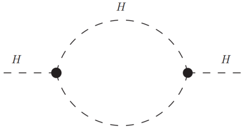
Parameter	Definition in terms of κ modifiers
κ_{gZ}	$\kappa_g\kappa_Z/\kappa_H$
λ_{tg}	κ_t/κ_g
λ_{Zg}	κ_Z/κ_g
λ_{WZ}	κ_W/κ_Z
$\lambda_{\gamma Z}$	κ_γ/κ_Z
$\lambda_{\tau Z}$	κ_τ/κ_Z
λ_{bZ}	κ_b/κ_Z



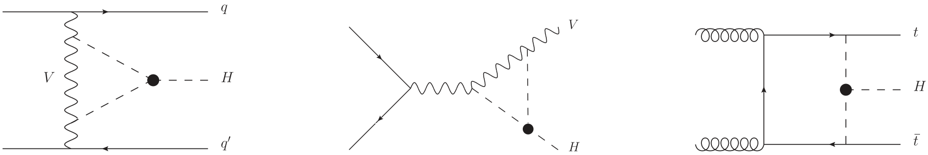
- $\lambda_{\gamma Z}$ sensitive to new charged particles contributing to the $H \to \gamma\gamma$ loop in w.r.t to $H \to ZZ^*$ decays.
- λ_{tg} sensitive to new coloured particles contributing through the ggF loop as compared to ttH
- All compatible with SM, p-value $= 85\%$

Higgs Self-Coupling

- Single Higgs production does not depend on trilinear-coupling λ_3 at LO
- Two types of NLO EW corrections that depend on λ_3
  - one universal $O(\lambda_3^2)$ due to Higgs loops



  - one linear $O(\lambda_3)$ that is both process and kinematics dependent

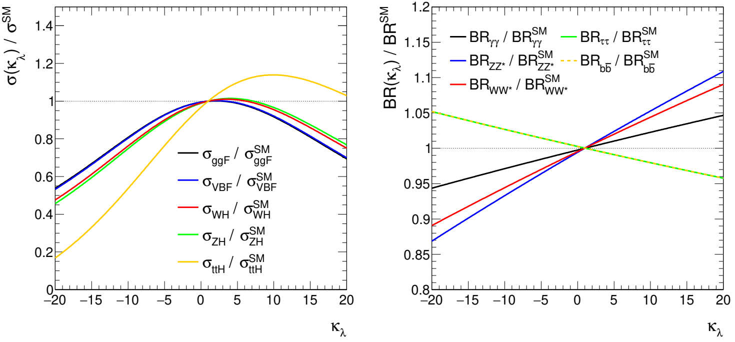


- To study this possible modifications we can introduce a coupling modifier κ_λ, defined as

$$\lambda_3 = \kappa_\lambda \lambda_3^{SM}$$

- Parametrizing the fit with

$$\mu_i^f(\kappa_\lambda) \equiv \mu_i(\kappa_\lambda) \times \mu^f(\kappa_\lambda)$$



- Not only global normalization but also differential distribution affected

→ exploiting full STXS informations for *VH* and *VBF* production modes

Higgs Self-coupling

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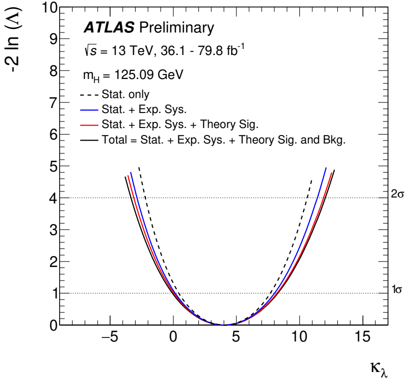
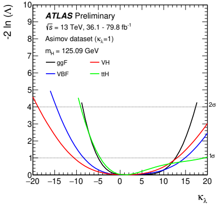
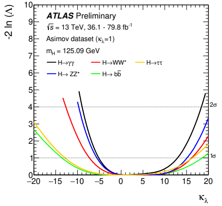






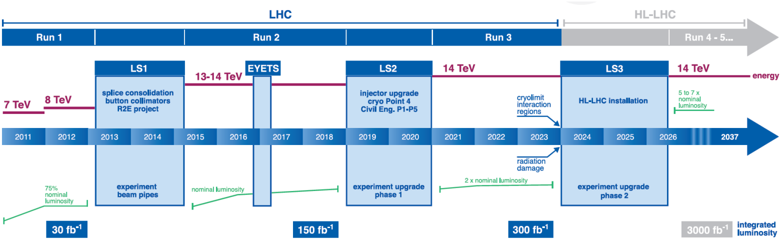
- dominant contribution from
  - ggF and $t\bar{t}H$ production mode
  - $\gamma\gamma$, ZZ and WW decay channels

$$\kappa_\lambda = 4.0^{+4.3}_{-4.1} = 4.0^{+3.7}_{-3.6}\,(\text{stat.})\,^{+1.6}_{-1.5}\,(\text{exp.})\,^{+1.3}_{-0.9}\,(\text{sig. th.})\,^{+0.8}_{-0.9}\,(\text{bkg. th.}$$

- strong assumption: BSM only affecting κ_λ
- 95% C.L. : $-3.2 < \kappa_\lambda < 11.9$ (observed), $-6.2 < \kappa_\lambda < 14.4$ (expected)
- complementary to the limit from ATLAS HH 36.1 fb^{-1} combination:
  - $-5.0 < \kappa_\lambda < 12.1$ (observed)
  - $-5.8 < \kappa_\lambda < 12.0$ (expected)

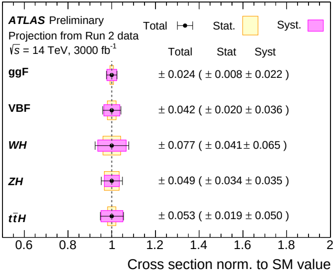
HL-LHC

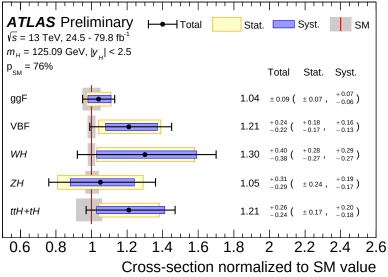
HL-LHC



- Higgs measurement projection to 3000 fb^{-1} and $\sqrt{s} = 14$ TeV
- Same Run 2 detector performance considered (improved performance of ATLAS will compensate for higher pileup)
- Two scenarios for systematic uncertainties:
  - S1: same values of current Run 2 analyses
    - unc. on the modeling of the continuum background and MC statistics negligible (also for S2)
  - S2: reduced sys. reflecting the situation expected at the end of the HL-LHC
    - all theory uncertainties for signal and background are halved
    - unc. on integrated luminosity is set to 1%
- Only S2 results shown

- Comparison between exp. 3000 fb^{-1} and obs. 80 fb^{-1} measurements





- Cross-sections dominated by systematic uncertainties (except for *ZH*)
- Precision improved by $\sim$ 3–5 times

HL-LHC

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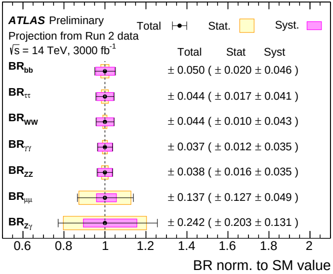
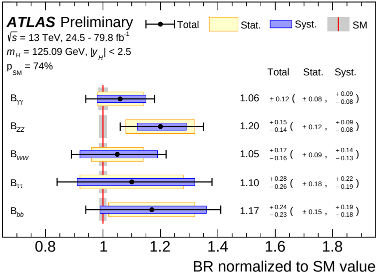
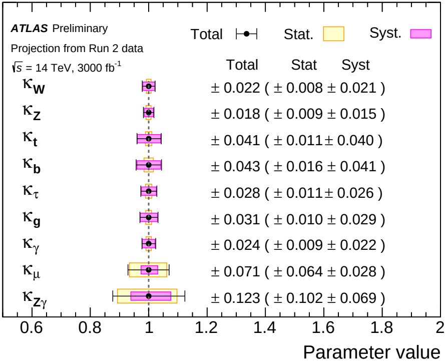
- Comparison between exp. 3000 fb^{-1} and obs. 80 fb^{-1} measurements





- Sensitive to branching ratio of rarer process $Z\gamma$ and $\mu\mu$ (expected to be observed)
- Precision improved by $\sim$ 3–7 times



- Uncertainties at the level of $\sim$ 2–4% and systematic limited (except for κ_μ and $\kappa_{Z\gamma}$)

Conclusion

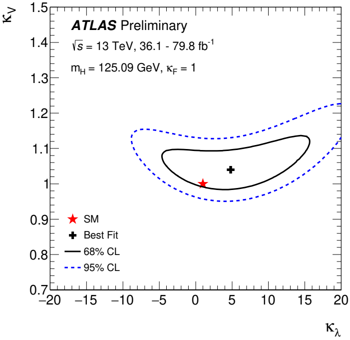
- Most recent combined Higgs measurements with the ATLAS detector have been presented
- Input analyses with an integrated luminosity up to 80 fb^{-1}

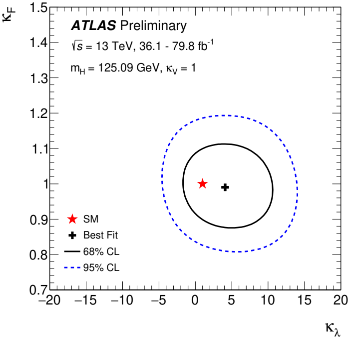
  $\rightarrow$ stay tuned for the full Run 2/legacy analyses with L= 140 fb^{-1}
- The measurements presented agree well with the SM expectation
- Also new constraint of the Higgs self coupling using single Higgs production mode have been presented.
  - 95% C.L. $-3.2 < \kappa_\lambda < 11.9$
- At HL-LHC expected:
  - cross-section measurement at 5% accuracy
  - observation of Higgs rare decays

Thank you for your attention

Back-up

POIs	Granularity	$\kappa_F{}^{+1\sigma}_{-1\sigma}$	$\kappa_V{}^{+1\sigma}_{-1\sigma}$	$\kappa_\lambda{}^{+1\sigma}_{-1\sigma}$	κ_λ [95% C.L.]
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	$4.1^{+4.3}_{-4.1}$ $1.0^{+8.8}_{-4.4}$	$[-3.2, 11.9]$ $[-6.3, 14.4]$





- Fitting κ_λ-κ_V-κ_F or fitting κ_λ-$\kappa_H = \kappa_V = \kappa_F$ results in nearly no sensitivity to κ_λ (for $|\kappa_\lambda| < 20$)