Combined measurements of Higgs coupling properties and constraints on the Higgs self-coupling in the ATLAS experiment

Kunlin Ran

Higgs potential and BSM opportunity

Nanjing University

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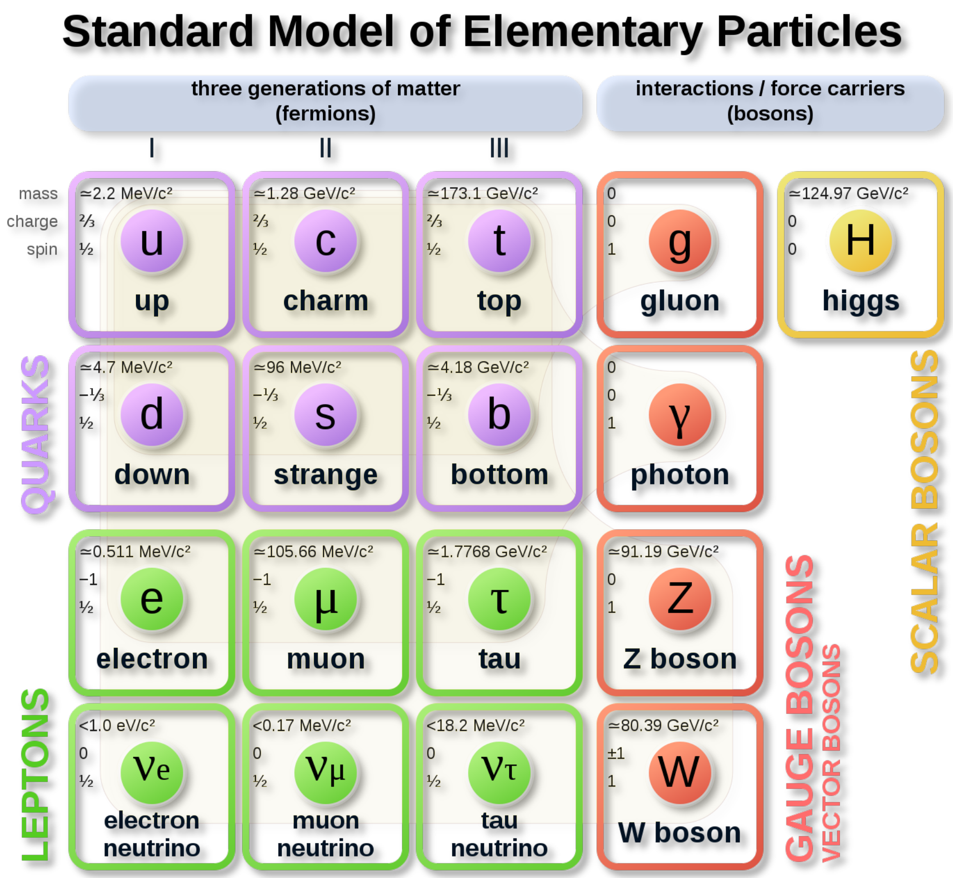
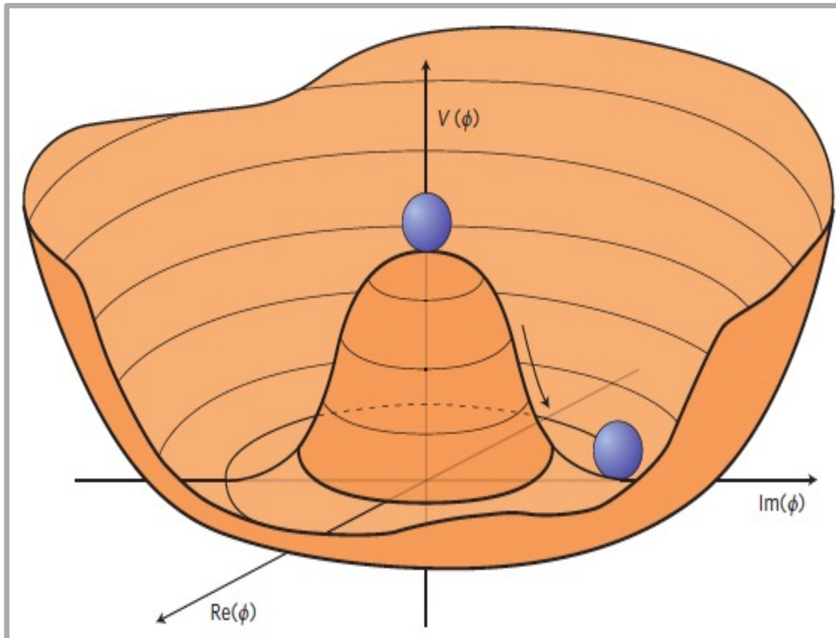
Standard model

- The **Standard Model** (SM) is one of the most successful theories in particle physics
- It introduces the electroweak spontaneous symmetry breaking trough the **Higgs mechanism**, predicts the existence of the **Higgs boson**, and gives **masses** of **element particles**

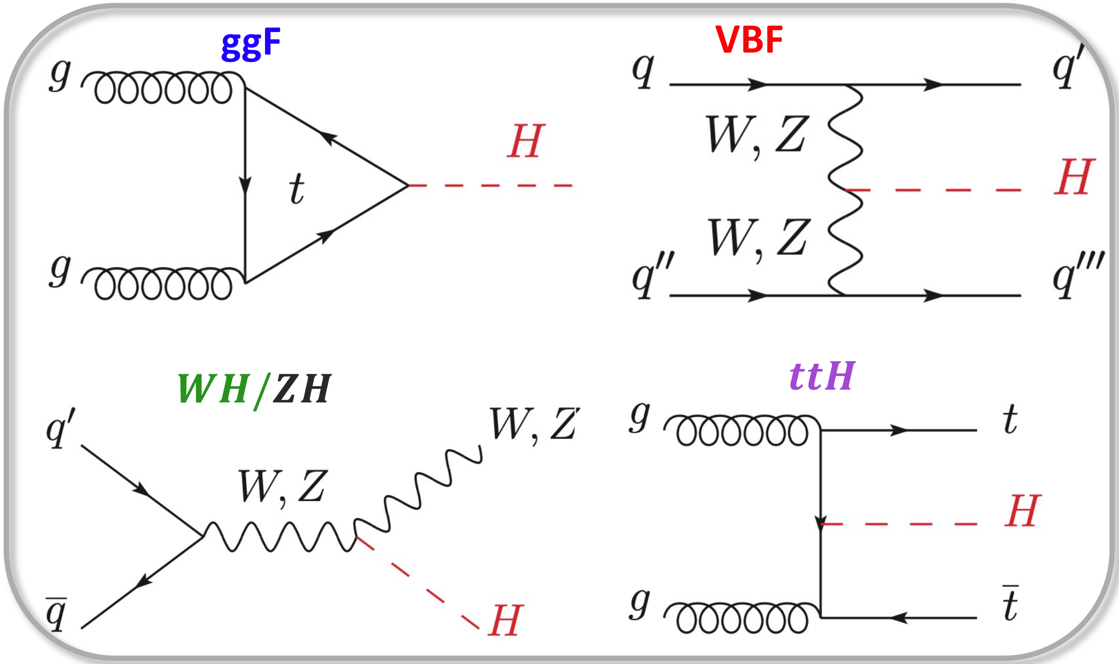


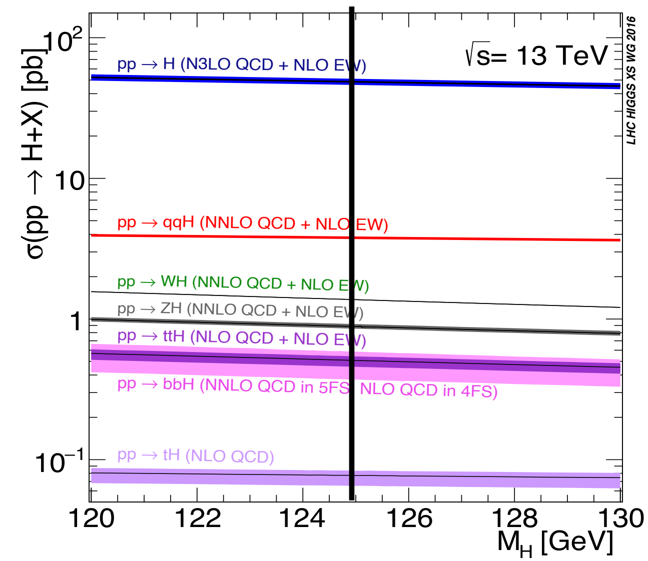
- **Higgs potential (SSB)**



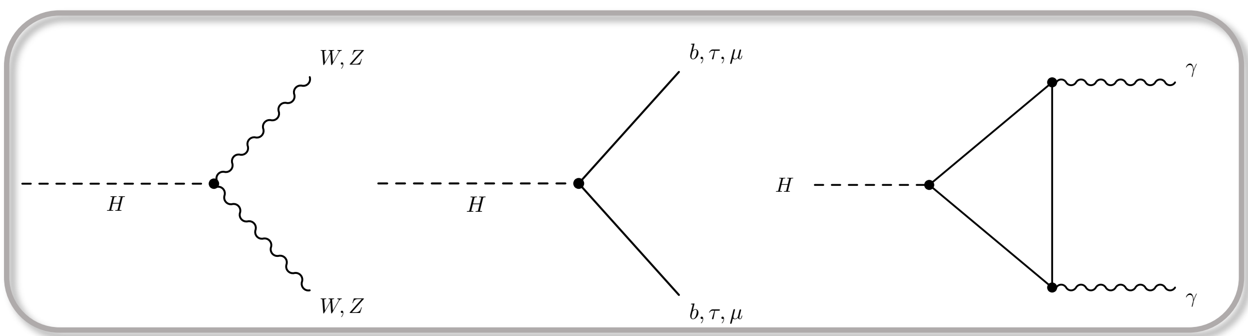
Higgs production/decay

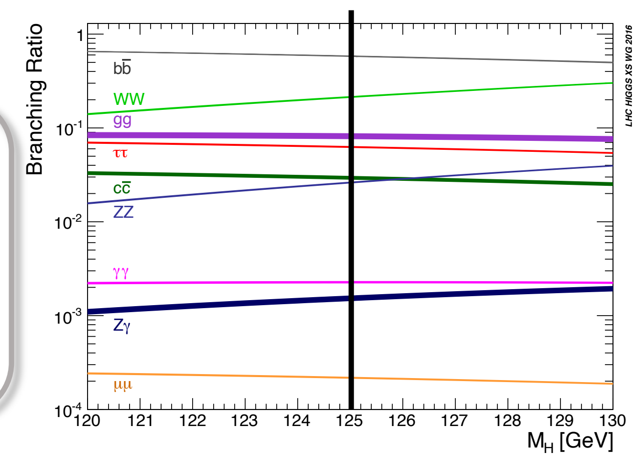
- Higgs major **production modes** in pp collisions at LHC





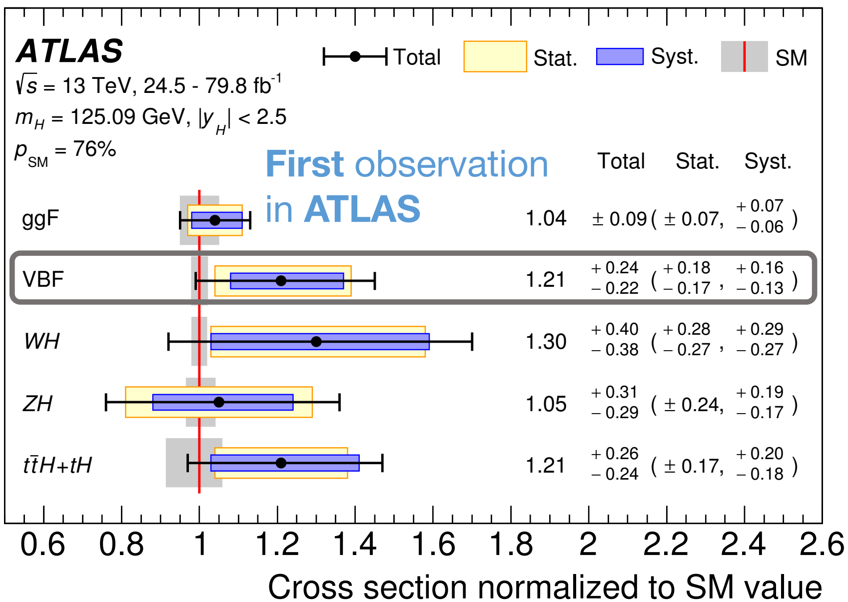
- Higgs **decay**

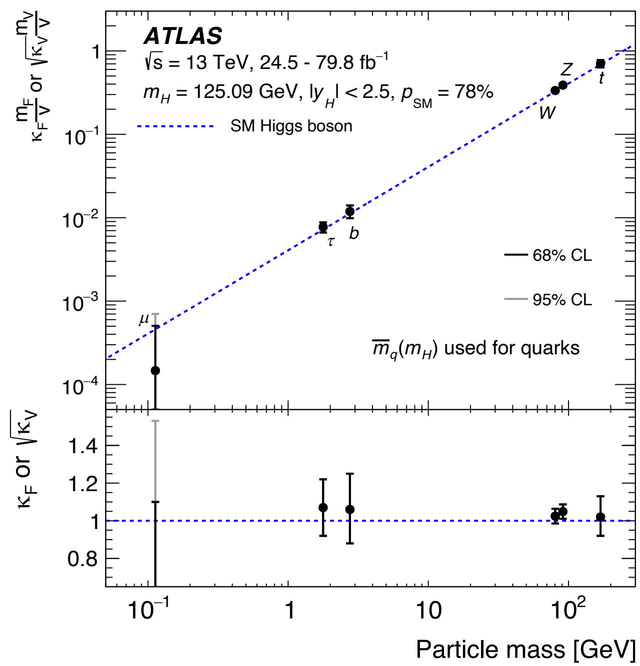




Previous coupling combination

- Following the **discovery of the Higgs** by the ATLAS and CMS, its **coupling properties** to other SM particles can be precisely probed in comprehensive ways, therefore providing stringent tests of the **SM validity**, which is the one of most important goals in the High Energy Physics
- **Run2 coupling combination measurements** at ATLAS with dataset up to **80 fb^{-1},** Phys. Rev. D 101 (2020) 012002
  - **Global** $\mu = 1.11^{+0.09}_{-0.08}$

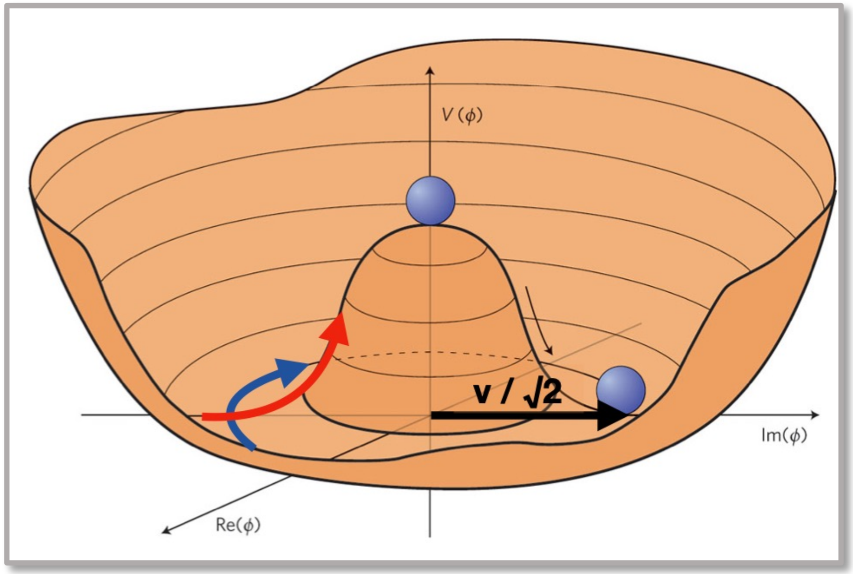




- The measurements are **consistent** with the **SM** prediction

The scalar sector and the self-coupling

$$V(\Phi^{+}\Phi) = -\boldsymbol{\mu}^{2}\Phi^{+}\Phi + \lambda(\Phi^{+}\Phi)^{2}$$

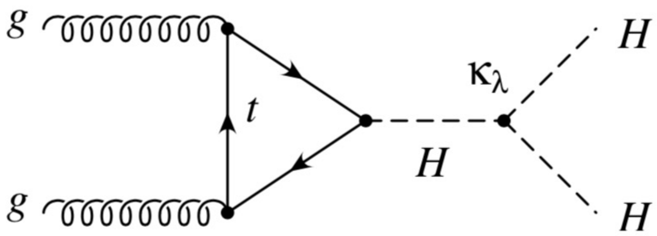


- **Higgs mechanism**: a scaler potential with a **vacuum expectation value ≠ 0** originates a **spontaneous breaking** of the electroweak symmetry
- $V(H) = \frac{1}{2}\boldsymbol{m_H^2}H^2 + \boldsymbol{\lambda_{HHH}v}H^3 + \frac{\mathbf{1}}{\mathbf{4}}\boldsymbol{\lambda_{HHHH}}H^4 - \frac{\lambda}{4}v^4$

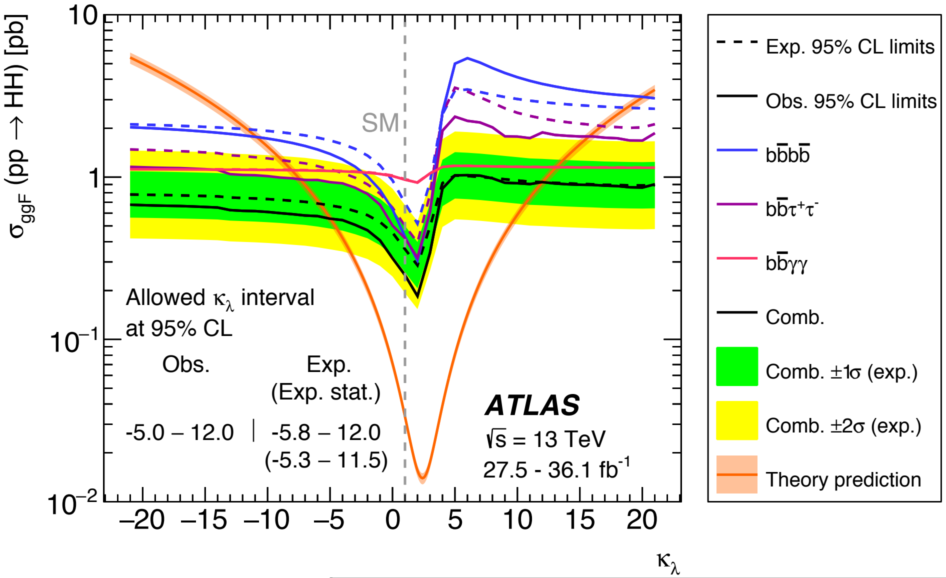
- To probe **the properties of the scaler sector** and to precisely describe the **Higgs potential shape** are very important for verifying the SM and for discovering new physics
- While the **trilinear self-coupling** is **unconstrained** in the LHC measurements
- Measuring the Higgs self-coupling is also one of the main goals of **HL-LHC** and **future colliders**

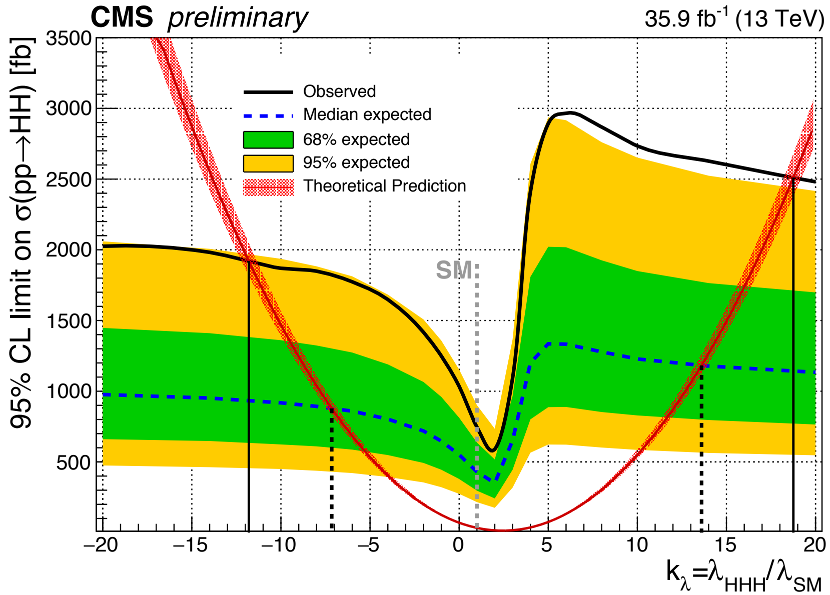
Constrain self-coupling in the HH measurement

- The non-resonant HH production processes (ggF) provide a unique chance to probe $\kappa_\lambda = \lambda_{HHH}/\lambda_{HHH}^{SM}$ with direct measurements



- Constrain the κ_λ by estimating the upper limits of the HH production (assuming SM H decay) with CLs approach





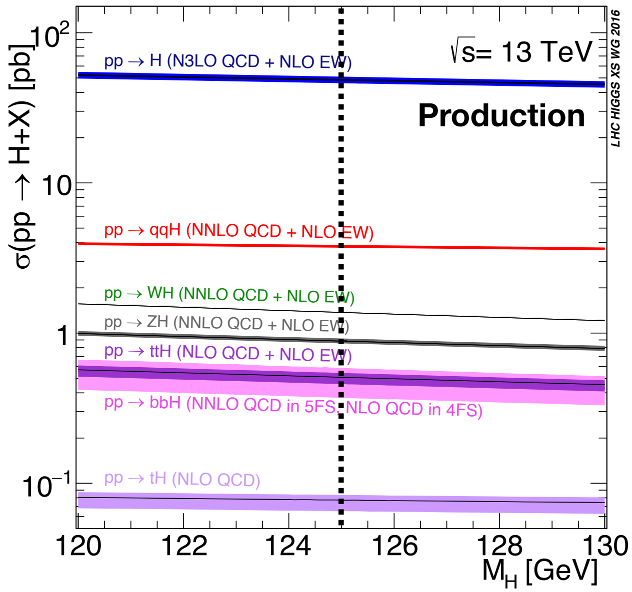
95% CL	Obs.	Exp.
ATLAS [arXiv:1906.02025]	[-5.0, 12.0]	[-5.8, 12.0]
CMS [CMS-PAS-HIG-17-030]	[-11.8, 18.8]	[-7.1, 13.6]

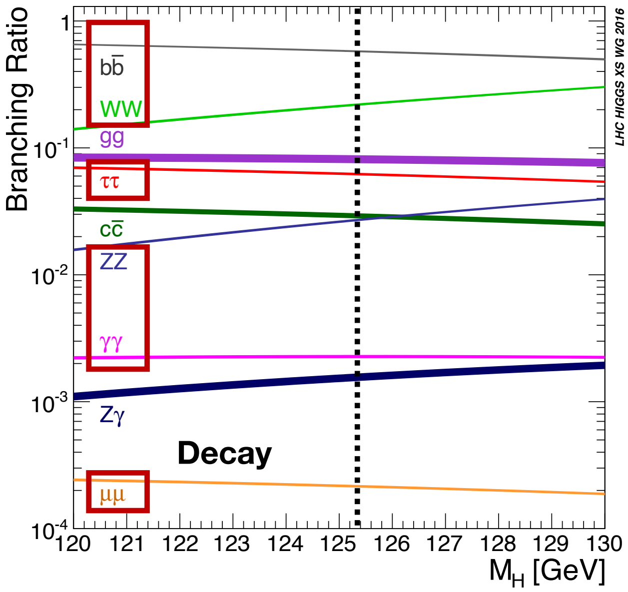
Outline

1. The **coupling combination** measurements are extended using the Run 2 dataset up to 139 fb^{-1}, to probe Higgs properties more precisely [ATLAS-CONF-2020-027, ATLAS-CONF-2020-053]

2. To constrain **Higgs self-coupling** by the NLO EW correction in the single-Higgs measurements and in the combination of the single-Higgs and di-Higgs measurements with Run 2 dataset up to 80 fb^{-1} [ATL-PHYS-PUB-2019-009, ATLAS-CONF-2019-049]

Combined production modes/decays





Analysis decay channel	Target Prod. Modes	$\mathcal{L}$ [fb^{-1}]
$H \to \gamma\gamma$	ggF, VBF, WH, ZH, $t\bar{t}H$, tH	139
$H \to ZZ^*$	ggF, VBF, WH, ZH, $t\bar{t}H(4\ell)$	139
	$t\bar{t}H$ excl. $H \to ZZ^* \to 4\ell$	36.1
$H \to WW^*$	ggF, VBF $t\bar{t}H$	36.1
$H \to \tau\tau$	ggF, VBF $t\bar{t}H$	36.1
	VBF	24.5 – 30.6
$H \to b\bar{b}$	WH, ZH	139
	$t\bar{t}H$	36.1
$H \to \mu\mu$	ggF, VBF, VH, $t\bar{t}H$	139
$H \to inv$	VBF	139

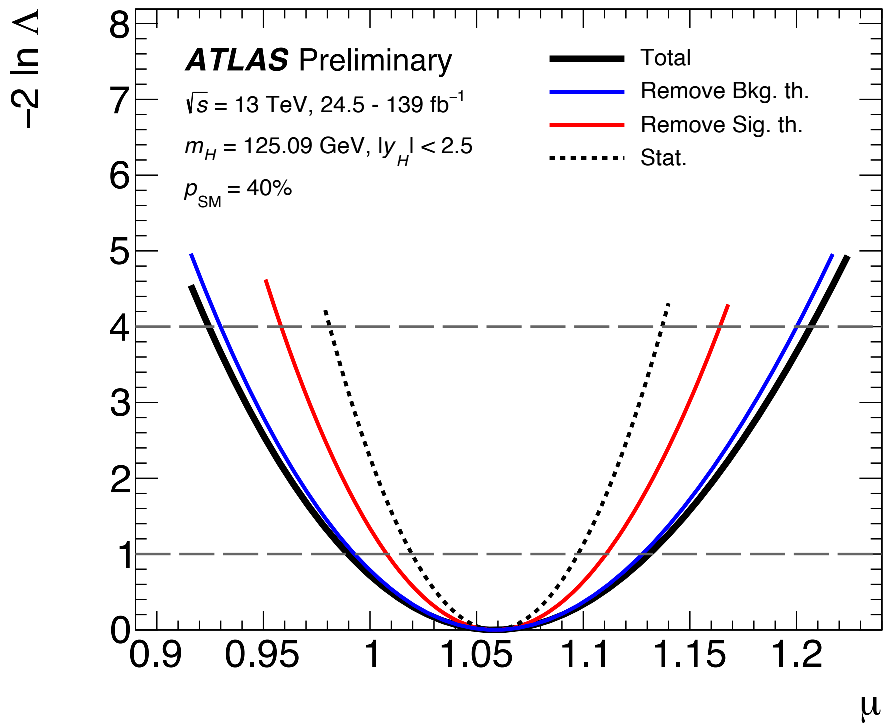
- $H \to b\bar{b}$, $H \to WW$, $H \to \tau\tau$
  - **Large BR**
  - low mass resolution
- $H \to ZZ^* \to 4l$, $H \to \gamma\gamma$
  - Low BR
  - **Excellent mass resolution**
  - High precision channels

Global signal strength

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

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

- $\mu = 1.06 \pm 0.07 = 1.06 \pm 0.04(stat.) \pm 0.03(exp.)^{+0.05}_{-0.04}(sig.th.) \pm 0.02(bkg.th.)$

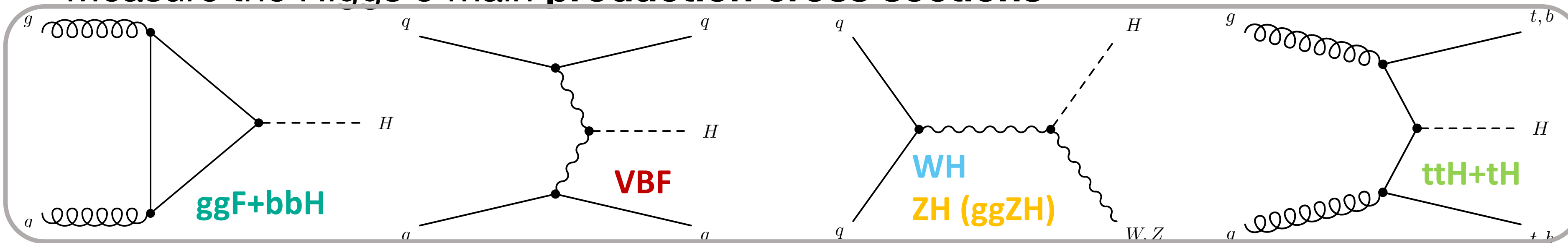


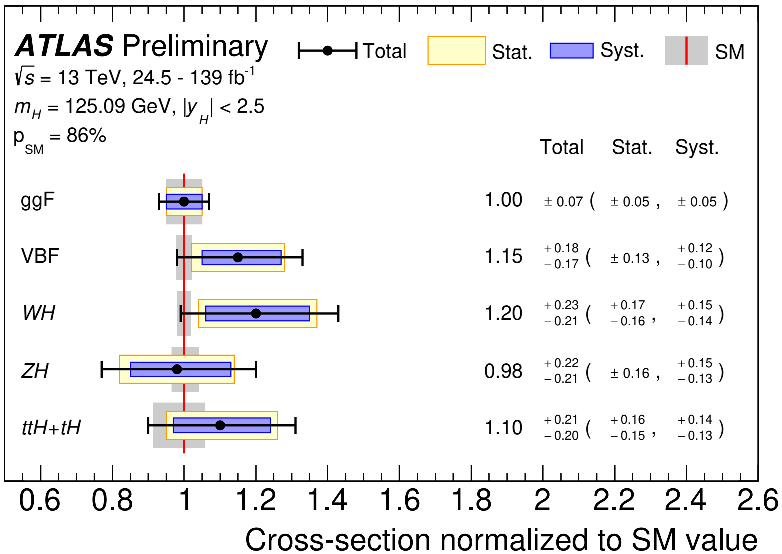
- **14%** improvement in accuracy comparing to 80 fb^{-1} combined measurement, **31%** improvement comparing to Run1 result

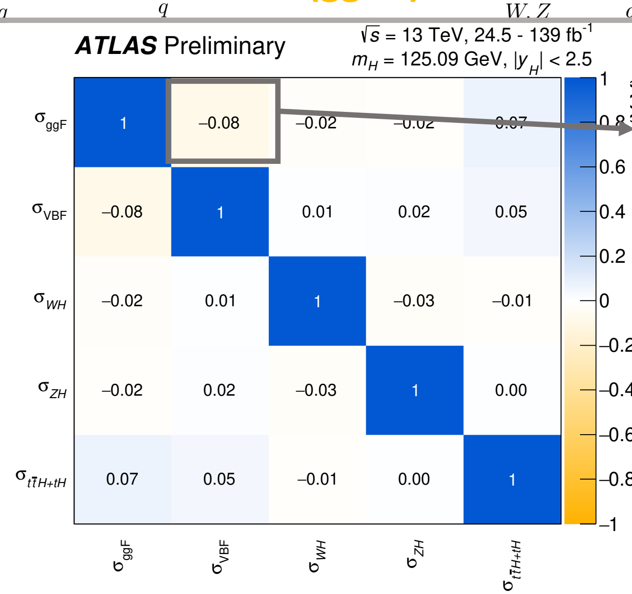
- Consistent with the SM: $p_{SM} = 40\%$
- The **precision** is dominantly constrained by the **systematical uncertainties**

Production cross sections

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







From **ggF** contributions in the **VBF-enriched** categories

Overall correlations are **small**

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

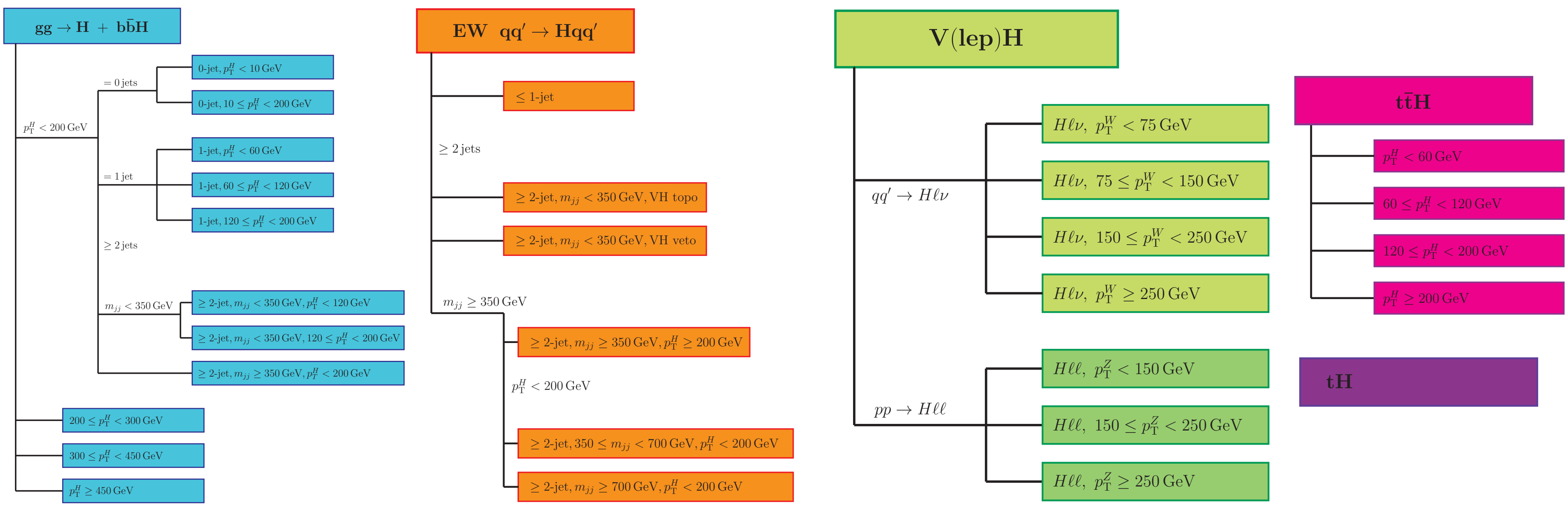
Process ($\lvert y_H\rvert < 2.5$)	Value [pb]	Uncertainty [pb] Total	Stat.	Syst.	Exp.	Sig. Th.	Bkg. Th.
ggF	44.7	± 3.1	± 2.2	± 2.2	$^{+1.8}_{-1.7}$	$^{+1.0}_{-0.9}$	$^{+0.9}_{-0.7}$
VBF	4.0	± 0.6	± 0.5	± 0.4	$^{+0.3}_{-0.2}$	± 0.3	± 0.1
WH	1.45	$^{+0.28}_{-0.25}$	$^{+0.20}_{-0.19}$	$^{+0.18}_{-0.17}$	$^{+0.13}_{-0.12}$	$^{+0.08}_{-0.06}$	$^{+0.10}_{-0.09}$
ZH	0.78	$^{+0.18}_{-0.17}$	± 0.13	$^{+0.12}_{-0.10}$	$^{+0.08}_{-0.07}$	$^{+0.07}_{-0.05}$	± 0.06
$t\bar{t}H + tH$	0.64	± 0.12	± 0.09	± 0.08	$^{+0.06}_{-0.05}$	$^{+0.03}_{-0.02}$	± 0.05

- **Firstly** observe **WH** mode in the ATLAS: 6.3σ (5.2σ)
- **All prod modes** are > 5σ

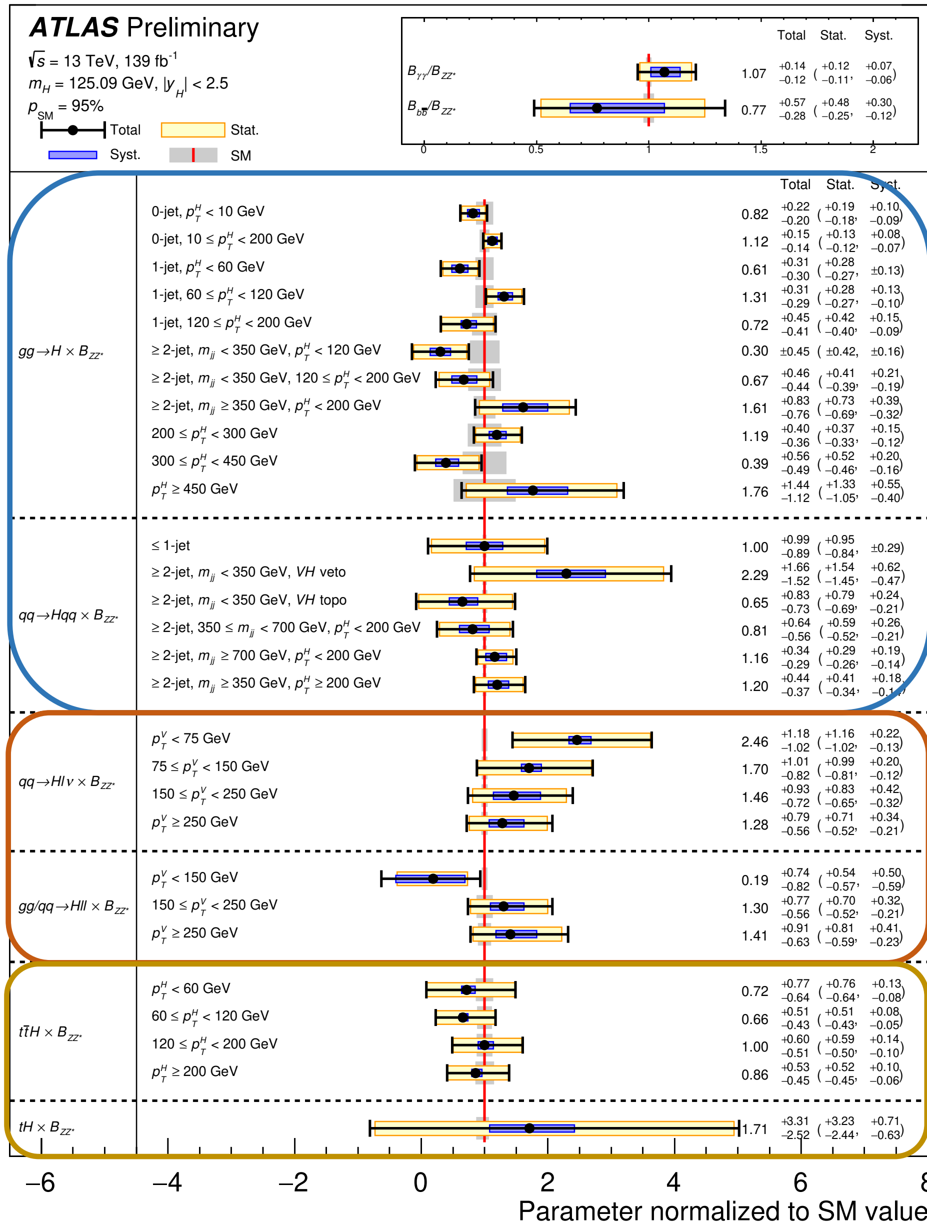
Simplified template cross section

- 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 1.2**



STXS measurements



From $H \to \gamma\gamma$, $H \to ZZ^*$ contributions

From $H \to bb$ contributions

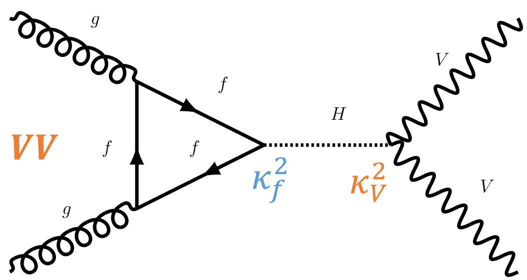
From $H \to \gamma\gamma$ contributions

- **Increased datasets** and **optimized analysis strategies** result in estimating the STXS in the **finest** kinematic regions so far
- Especially feasible to measure ttH and tH separately

κ framework

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

ggF, $H \to VV$

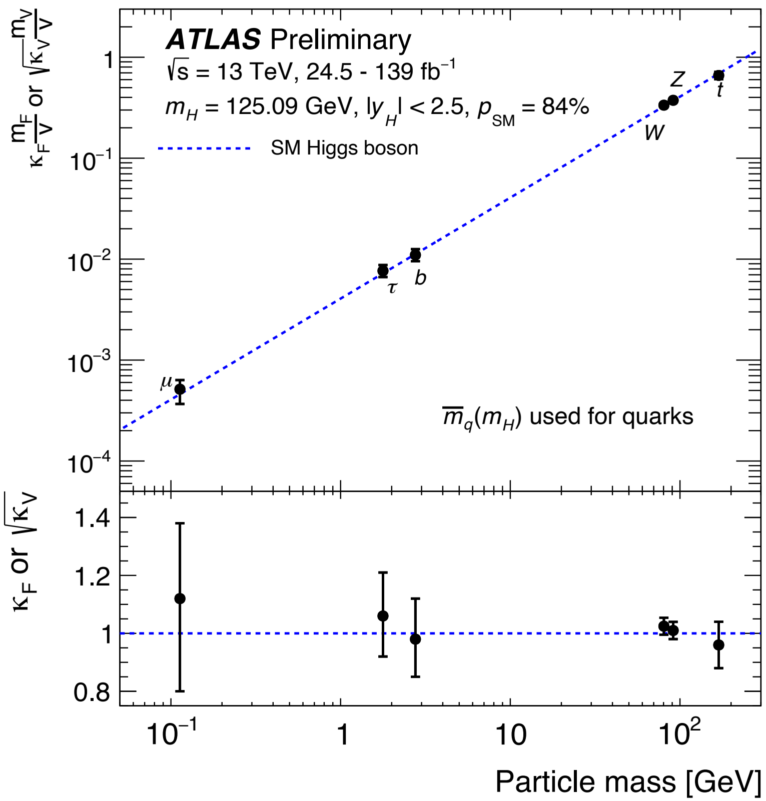


- **κ framework**
  - Coupling modifiers to **productions** and **decays**
- $\sigma_i \times B_f = \frac{\sigma_i(\kappa) \times \Gamma_f(\kappa)}{\Gamma_H}$, $\kappa_i^2 = \frac{\sigma_i}{\sigma_i^{SM}}$, $\kappa_f^2 = \frac{\Gamma_f}{\Gamma_f^{SM}}$
- $\kappa_H^2(\kappa, B_{inv}, B_{undet}) = \frac{\sum_j B_f^{SM} \kappa_j^2}{(1 - B_{inv} - B_{undet})}$
  - B_{inv}: ~0.1% from $H \to ZZ^* \to 4\nu$
  - B_{undet}: non-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

- $\kappa_W, \kappa_Z, \kappa_t(\kappa_c), \kappa_b(\kappa_s), \kappa_\tau, \kappa_\mu$
- **Assumption**
  - All $\kappa \geq 0$
  - Only SM particle contribute to Higgs vertices
  - $B_{inv} = B_{undet} = 0$



Parameter	Result
κ_Z	1.02 ± 0.06
κ_W	1.05 ± 0.06
κ_b	$0.98\ ^{+\,0.14}_{-\,0.13}$
κ_t	$0.96\ \pm 0.08$
κ_τ	$1.06\ ^{+\,0.15}_{-\,0.14}$
κ_μ	$1.12\ ^{+\,0.26}_{-\,0.32}$

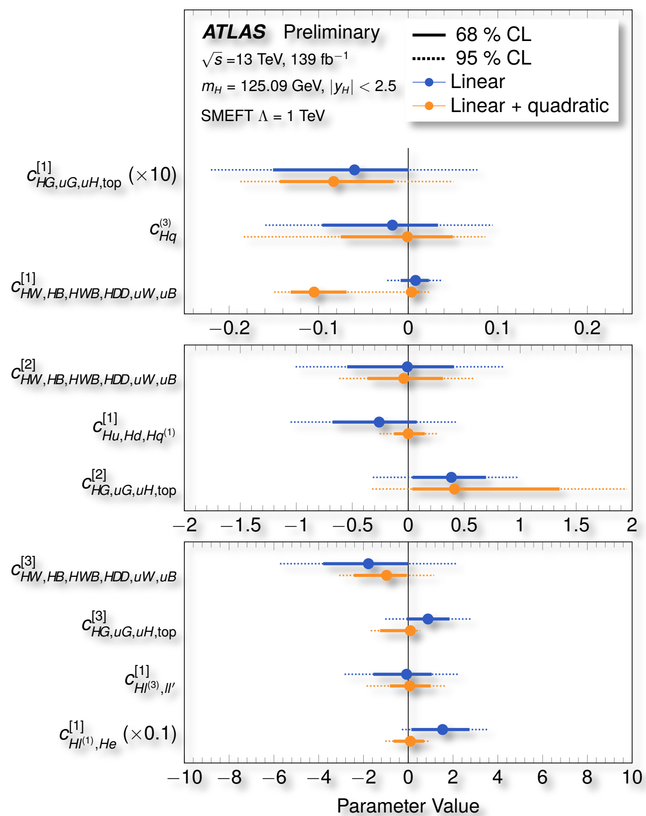
2.1σ (1.7σ)

- $\kappa_Z, \kappa_W, \kappa_b, \kappa_t$ precisions are largely improved (19%~25%) wrt 80 fb^{-1} combined measurement

SMEFT interpretations

- **Model independent** approach: **EFT**
  - It's systematically improvable with **higher-order perturbative** calculations
- **SMEFT** parameterize large energy scale ($\Lambda \gg v$, $\Lambda = 1$ TeV used) BSM effects at low energies
- **STXS** measurements are helpful to constrain coefficients associated to SMEFT operators, thus put constraints **on new physics at fixed scale Λ**

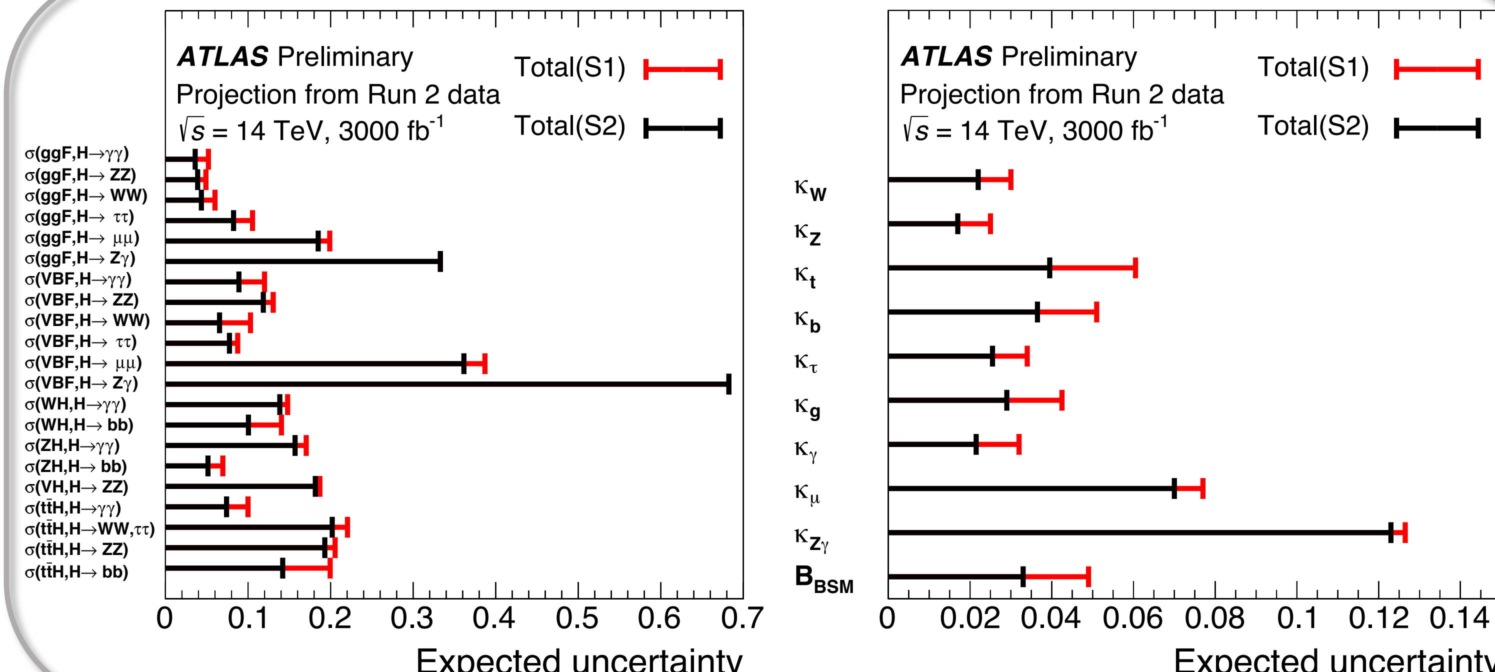
Parameter		Definition	Fit Parameter
$c_{Hq}^{(3)}$		$c_{Hq}^{(3)}$	✓
$c^{[i]}_{HW,HB,HWB,HDD,uW,uB}$	1	$-0.27c_{HW} - 0.84c_{HB} + 0.47c_{HWB} - 0.02c_{uW} - 0.05c_{uB}$	✓
	2	$-0.96c_{HW} + 0.19c_{HB} - 0.20c_{HWB} + 0.02c_{uB}$	✓
	3	$-0.08c_{HW} + 0.50c_{HB} + 0.86c_{HWB} + 0.07c_{HDD} + 0.03c_{uW} + 0.06c_{uB}$	✓
	4	$0.03c_{HWB} - 0.85c_{HDD} + 0.32c_{uW} + 0.43c_{uB}$	
	5	$-0.01c_{HW} + 0.07c_{HB} + 0.05c_{HWB} - 0.44c_{HDD} - 0.86c_{uW} - 0.23c_{uB}$	
	6	$-0.01c_{HW} + 0.06c_{HB} + 0.04c_{HWB} - 0.29c_{HDD} + 0.39c_{uW} - 0.87c_{uB}$	
$c^{[i]}_{HG,uG,uH,\mathrm{top}}$	1	$+0.999c_{HG} + 0.038c_{uG}$	✓
	2	$-0.03c_{HG} + 0.73c_{uG} - 0.03c_{qq}^{(1)} - 0.23c_{qq} - 0.05c_{qq}^{(3)} - 0.54c_{qq}^{(31)} - 0.02c_{uu} - 0.24c_{uu}^{(1)} - 0.04c_{ud}^{(8)} - 0.01c_{qu}^{(1)} - 0.15c_{qu}^{(8)} - 0.04c_{qd}^{(8)} - 0.18c_G + 0.06c_{uH}$	✓
	3	$-0.03c_{HG} + 0.67c_{uG} + 0.04c_{qq}^{(1)} + 0.25c_{qq} + 0.05c_{qq}^{(3)} + 0.55c_{qq}^{(31)} + 0.02c_{uu} + 0.26c_{uu}^{(1)} + 0.03c_{ud}^{(8)} + 0.01c_{qu}^{(1)} + 0.16c_{qu}^{(8)} + 0.03c_{qd}^{(8)} + 0.29c_G + 0.1c_{uH}$	✓
	4	$+0.11c_{uG} + 0.01c_{qq} - 0.018c_{qq}^{(3)} + 0.029c_{qq}^{(31)} + 0.012c_{uu}^{(1)} - 0.993c_{uH}$	
	5	$+0.02c_{qq} - 1.0c_{qq}^{(3)} + 0.06c_{qq}^{(31)} + 0.03c_{uu}^{(1)} + 0.02c_{qu}^{(8)} + 0.02c_{uH}$	
	6	$+0.07c_{uG} - 0.02c_{qq}^{(1)} + 0.07c_{qq} + 0.03c_{qq}^{(3)} + 0.32c_{qq}^{(31)} + 0.06c_{uu}^{(1)} + 0.04c_{ud}^{(8)} + 0.08c_{qu}^{(8)} + 0.04c_{qd}^{(8)} - 0.94c_G + 0.02c_{uH}$	
$c^{[1]}_{Hl^{(1)},He}$		$+0.78c_{Hl}^{(1)} - 0.62c_{He}$	✓
$c^{[2]}_{Hl^{(1)},He}$		$+0.62c_{Hl}^{(1)} + 0.78c_{He}$	
$c^{[1]}_{Hu,Hd,Hq^{(1)}}$		$-0.87c_{Hu} + 0.26c_{Hd} + 0.42c_{Hq}^{(1)}$	✓
$c^{[2]}_{Hu,Hd,Hq^{(1)}}$		$+0.41c_{Hu} - 0.09c_{Hd} + 0.91c_{Hq}^{(1)}$	
$c^{[3]}_{Hu,Hd,Hq^{(1)}}$		$-0.28c_{Hu} - 0.96c_{Hd} + 0.03c_{Hq}^{(1)}$	
$c^{[1]}_{Hl^{(3)},ll'}$		$0.87c_{Hl}^{(3)} - 0.50c'_{ll}$	✓
$c^{[2]}_{Hl^{(3)},ll'}$		$0.50c_{Hl}^{(3)} + 0.87c'_{ll}$	



Consistent with the SM

HL-LHC projections

- Many open questions like **hierarchy problem** and the **nature of dark matter** are possible to be addressed by **precise** measurements of Higgs boson properties, which is a high priority at **HL-LHC**
- **HL-LHC projection study** with combined **Run2 dataset up to 80 fb^{-1}** [ATL-PHYS-PUB-2018-054]
- $\mu = 1.000^{+0.038}_{-0.037}(1.000^{+0.025}_{-0.024})$, **S1: Same systematics** at Run2; **S2: Reduced systematics** expected at HL-LHC



Largely improved precisions!

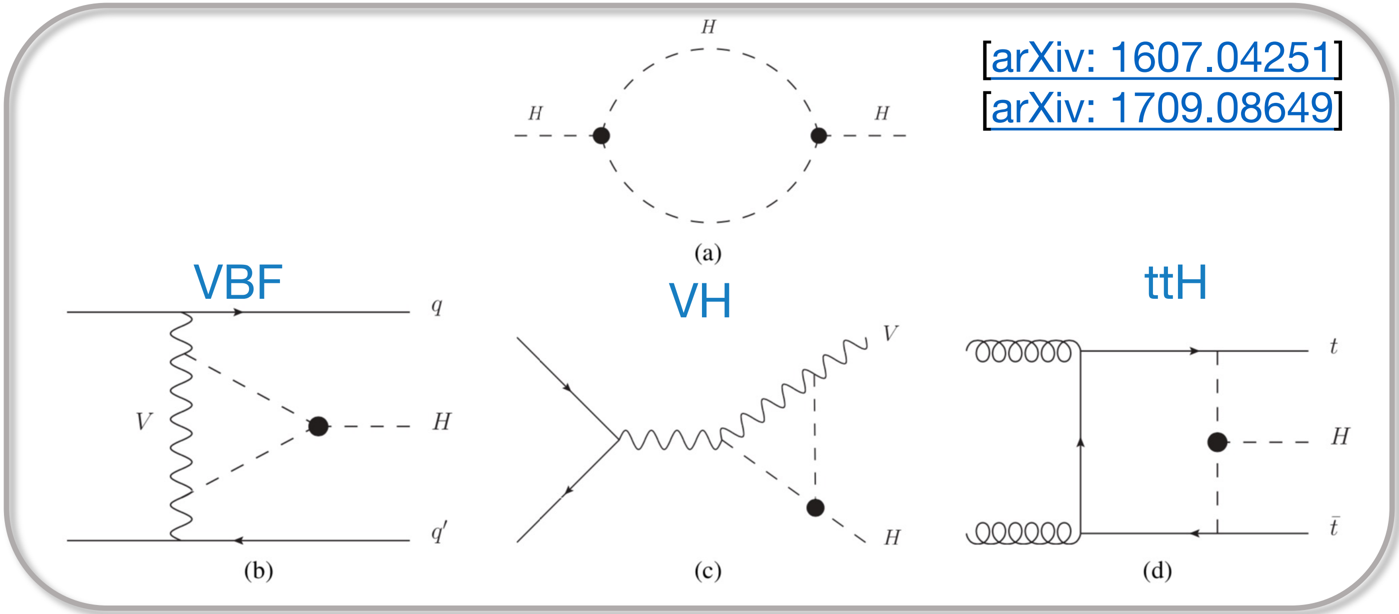
Allow to **observe** $H \to \mu\mu$, $H \to Z\gamma$

Constraints on the Higgs self-coupling

Combine single-Higgs and double-Higgs together to maximize the sensitivity to constrain κ_λ

Indirect measurement in the single-H

- Single Higgs processes do not depend on λ_{HHH} at LO, while its contributions need to be taken into account for the complete NLO EWK corrections
- λ_{HHH} contributes via Higgs self energy loop corrections and additional diagrams



- An indirect constraint on λ_{HHH} can be extracted by comparing the single-Higgs measured results and the SM predictions corrected for the λ_{HHH} -dependent NLO EW effects
  - Signal strength: $\mu_{if}(\kappa_\lambda) = \mu_i(\kappa_\lambda) \times \mu_f(\kappa_\lambda) \equiv \frac{\sigma_i(\kappa_\lambda)}{\sigma_{SM,i}} \times \frac{BR_f(\kappa_\lambda)}{BR_{SM,f}}$

Theoretical model: production mode

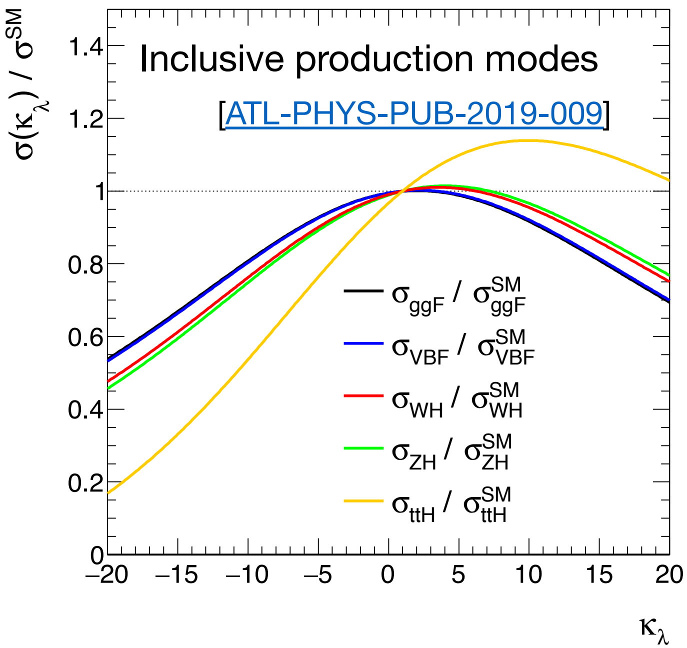
$$\mu_i(\kappa_\lambda, \kappa_i) = \frac{\sigma^{BSM}}{\sigma^{SM}} = Z_H^{BSM}(\kappa_\lambda)\left[\kappa_i^2 + \frac{(\kappa_\lambda - 1)C_1^i}{K_{EW}^i}\right]$$

$$Z_H^{BSM}(\kappa_\lambda) = \frac{1}{1-(\kappa_\lambda^2-1)\delta Z_H},\ \delta Z_H = -1.536\times10^{-3}$$

- $K_{EW}^i = \frac{\sigma_{NLO}^{SM,i}}{\sigma_{LO}^{SM,i}}$: Complete NLO EW correction for the production
- C_1^i: process and kinematics-dependent linear coefficient that provides the sensitivity of the measurement to κ_λ
- $\kappa_i^2 = \frac{\sigma_{LO,i}^{BSM}}{\sigma_{LO,i}^{SM}}$: Modifiers to other Higgs boson couplings in the κ-framework
  - Only κ_F (all fermions) and κ_V (all weak vector bosons) are considered

[arXiv: 1607.04251]
[arXiv: 1709.08649]

production mode	ggF	VBF	ZH	WH	$t\bar{t}H$
inclusive $C_1^i \times 100$	0.66	0.63	1.19	1.03	3.52
K_{EW}^i	1.049	0.932	0.947	0.93	1.014
κ_i^2	κ_F^2	κ_V^2	κ_V^2	κ_V^2	κ_F^2



Theoretical model: decay rate

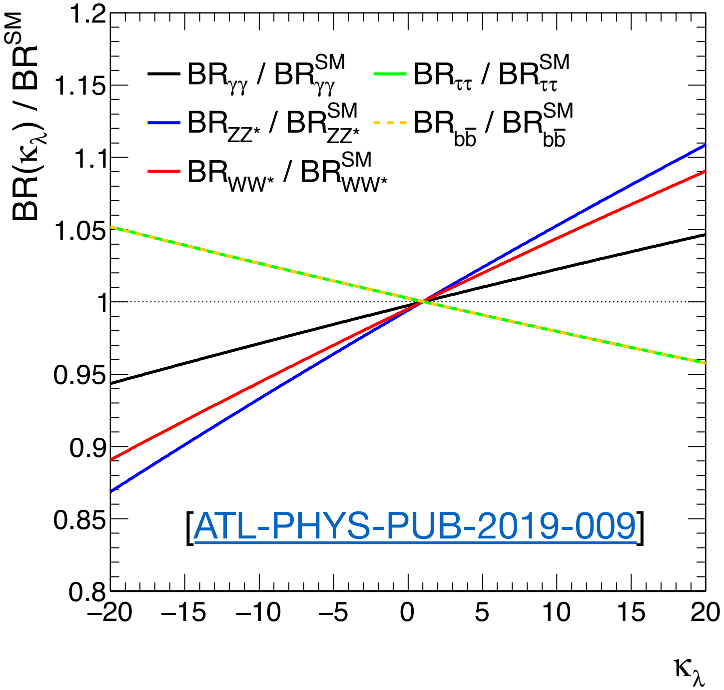
- Higgs boson decay rates

$$\mu_f(\kappa_\lambda, \kappa_f) = \frac{BR_f^{BSM}}{BR_f^{SM}} = \frac{\kappa_f^2 + (\kappa_\lambda - 1)C_1^f}{\sum_j BR_j^{SM}\left[\kappa_j^2 + (\kappa_\lambda - 1)C_1^j\right]}$$

- C_1^f: linear coefficient provides the sensitivity to κ_λ

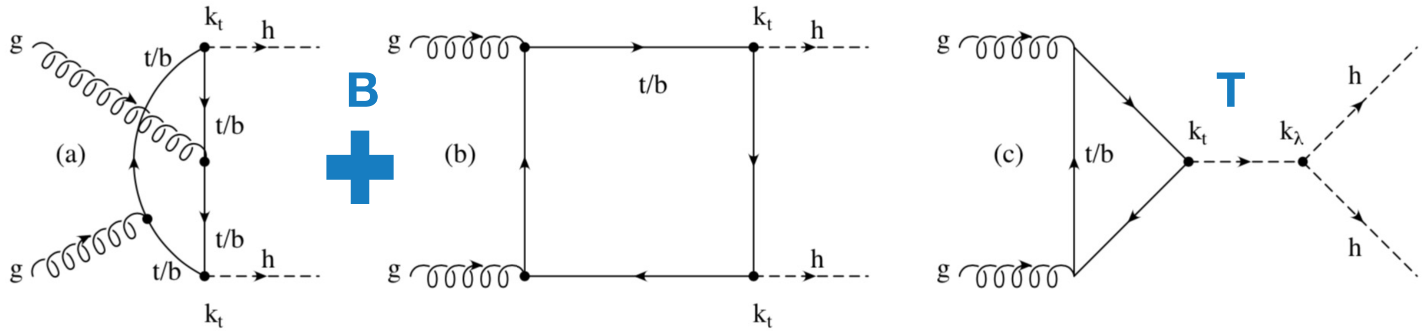
[arXiv: 1607.04251]
[arXiv: 1709.08649]

decay mode	$H \to \gamma\gamma$	$H \to WW^*$	$H \to ZZ^*$	$H \to b\bar{b}$	$H \to \tau\tau$
$C_1^f \times 100$	0.49	0.73	0.82	0	0
κ_f^2	$1.59\kappa_V^2 + 0.07\kappa_F^2 - 0.67\kappa_V\kappa_F$	κ_V^2	κ_V^2	κ_F^2	κ_F^2



Theory model and interpretation in the double-Higgs

- The double-Higgs production



- The amplitude of the HH production can be parameterized as a function of ttH coupling $\kappa_t = g_{ttH}/g_{ttH}^{SM}$ and HHH coupling $\kappa_\lambda = g_{HHH}/g_{HHH}^{SM}$

$$A(\kappa_t, \kappa_\lambda) = \kappa_t^2 B + \kappa_t \kappa_\lambda T$$

- Omitting the integral on the final phase space and on the PDFs for simplicity
- $\sigma(pp \to HH) \sim \kappa_t^4 \left[|B|^2 + \frac{\kappa_\lambda}{\kappa_t}(B^* T + T B^*) + \left(\frac{\kappa_\lambda}{\kappa_t}\right)^2 |T|^2 \right]$
- κ_t^4 appears in the normalization, the signal acceptance depends only from κ_λ/κ_t
- When estimating $\sigma(pp \to HH)$, global normalization factors (κ_t^4) don't play a role
  - ⇒ HH-only measurement can't measure κ_λ and κ_t at the same time, κ_t is fixed to the SM in HH analysis alone

Data and input measurement

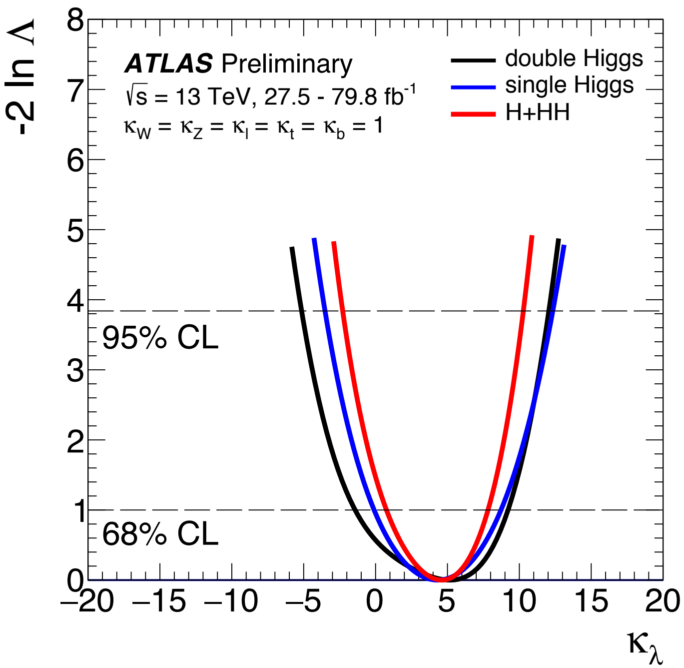
- Constrain Higgs self-coupling in the combination using **datasets up to 80 fb^{-1}**

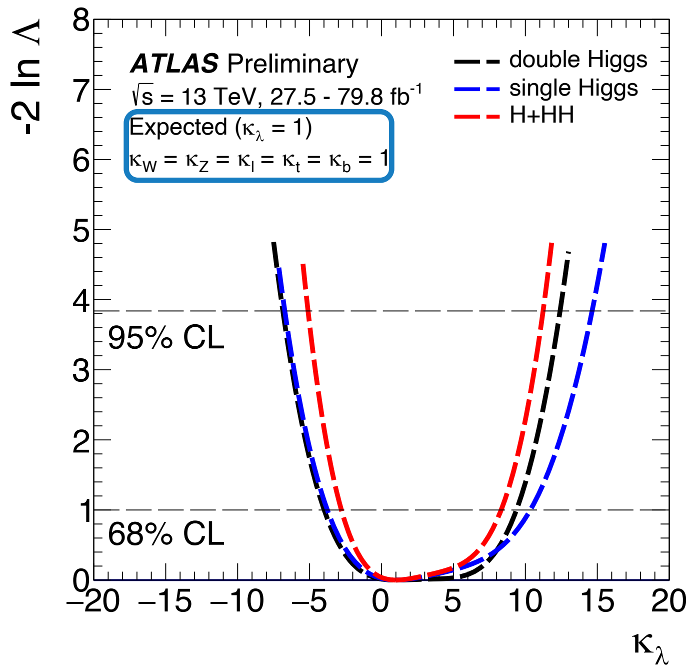
Analysis	Integrated luminosity (fb^{-1})
$H \to \gamma\gamma$	79.8
$H \to ZZ^* \to 4\ell$ (including $t\bar{t}H$, $H \to ZZ^* \to 4\ell$)	79.8
$H \to WW^* \to e\nu\mu\nu$	36.1
$H \to \tau\tau$	36.1
$VH, H \to b\bar{b}$	79.8
$t\bar{t}H, H \to b\bar{b}$ and $t\bar{t}H$ multilepton	36.1
$HH \to b\bar{b}b\bar{b}$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

- Within each of the single-Higgs and the double-Higgs analyses all the categories are orthogonal by definition
- The single-Higgs and double-Higgs categories are not all orthogonal
  - The overlap has been studied, the $ttH(\gamma\gamma)$ categories have been removed as they show large overlap with the $HH \to bb\gamma\gamma$ categories
  - Also the impact on the combined limits of removing $ttH(\gamma\gamma)$ categories is smaller w.r.t removing $HH \to bb\gamma\gamma$ categories

κ_λ-only results

- A likelihood fit is performed to constrain κ_λ in the combination of single-Higgs and double-Higgs
- All other Higgs boson couplings are fixed to the SM ($\kappa_t = \kappa_b = \kappa_l = \kappa_W = \kappa_Z = 1$)





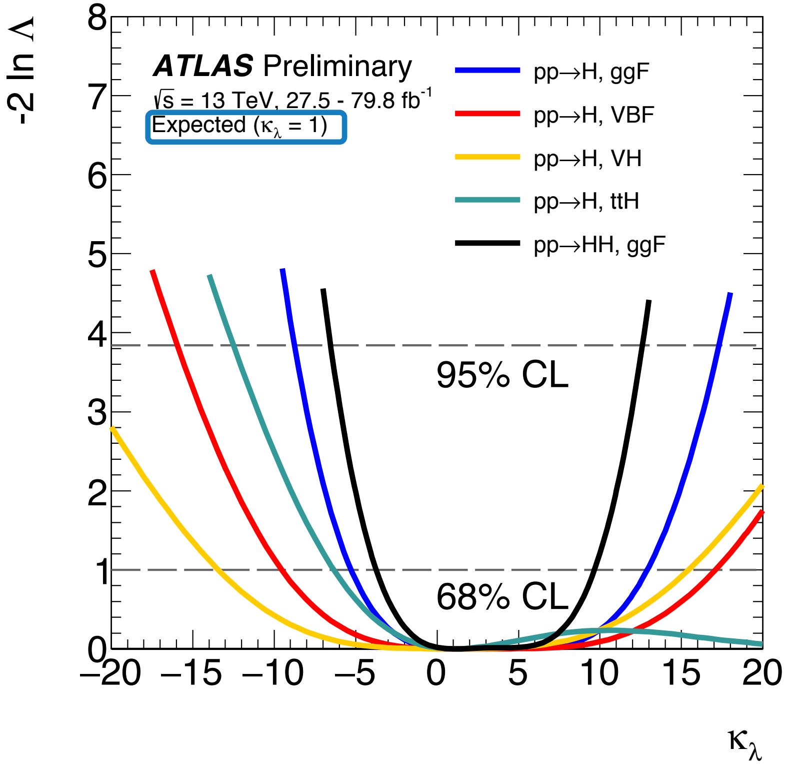
- $\kappa_\lambda = 4.6^{+3.2}_{-3.8} = 4.6^{+2.9}_{-3.5}(stat.)^{+1.2}_{-1.2}(exp.)^{+0.7}_{-0.5}(sig.th.)^{+0.6}_{-1.0}(bkg.th.)$ (obs.)
- $\kappa_\lambda = 1.0^{+7.3}_{-3.8} = 1.0^{+6.2}_{-3.0}(stat.)^{+3.0}_{-1.7}(exp.)^{+1.8}_{-1.2}(sig.th.)^{+1.7}_{-1.1}(bkg.th.)$ (exp.)

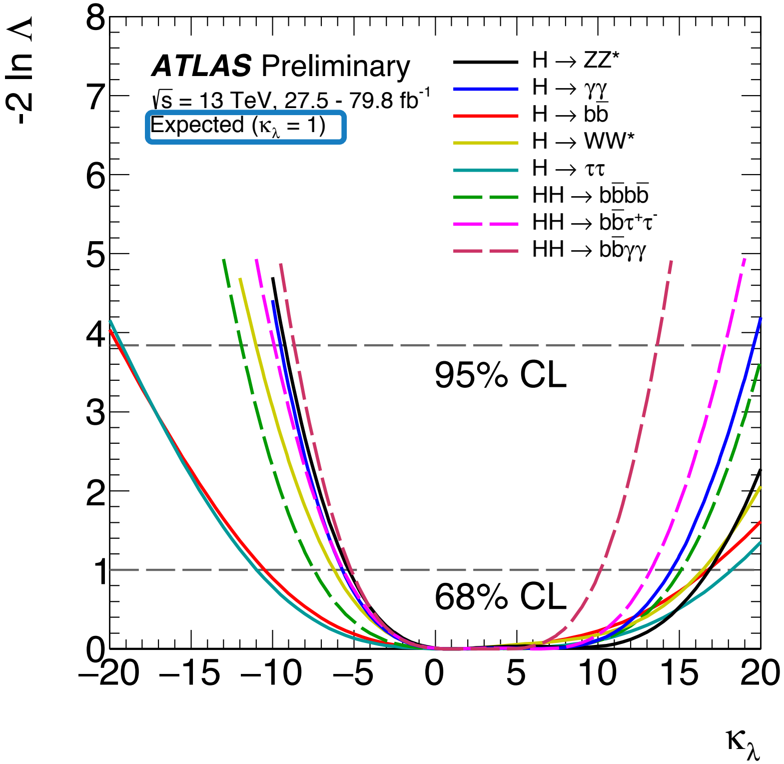
95% CL	Obs.	Exp.
H [ATL-PHYS-PUB-2019-009]	[-3.2, 11.9]	[-6.2, 14.4]
HH [arXiv:1906.02025]	[-5.0, 12.0]	[-5.8, 12.0]
H+HH [ATLAS-CONF-2019-049]	[-2.3, 10.3]	[-5.1, 11.2]

- The combination can better constrain κ_λ by 17%-26%

Higgs production/decay contributions

- Contributions from the different production and decay modes



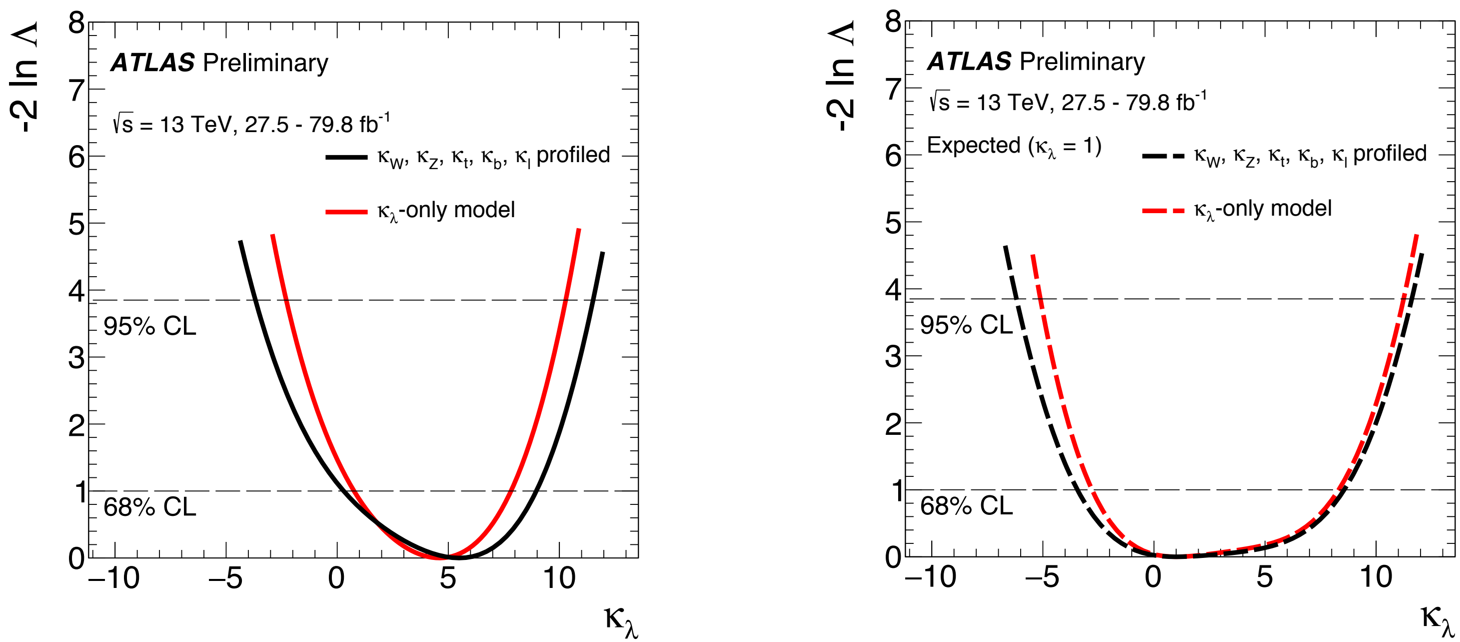


[ATLAS-CONF-2019-049]

- HH production is the most sensitive channel among all Higgs production processes, followed by SH, ggF
- $HH \to bb\gamma\gamma$, $HH \to bb\tau\tau$ give dominant contributions in constraining κ_λ, followed by $H \to \gamma\gamma$

Generic model

- To give the most generic measurement, a likelihood fit is performed to constrain simultaneously κ_λ, κ_W, κ_Z, κ_t, κ_b and κ_l



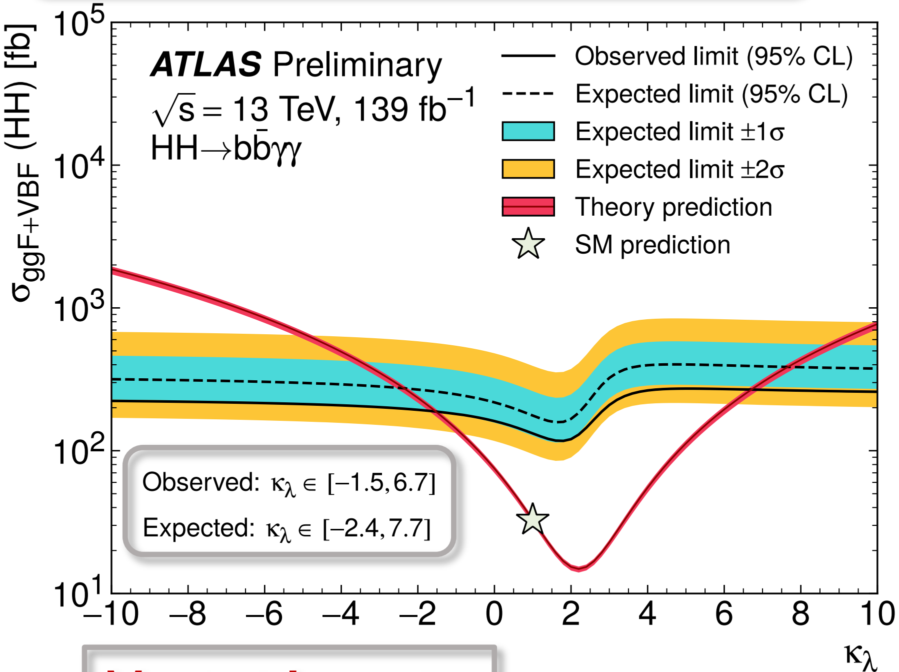
[ATLAS-CONF-2019-049]

Model	$\kappa_W{}^{+1\sigma}_{-1\sigma}$	$\kappa_Z{}^{+1\sigma}_{-1\sigma}$	$\kappa_t{}^{+1\sigma}_{-1\sigma}$	$\kappa_b{}^{+1\sigma}_{-1\sigma}$	$\kappa_\ell{}^{+1\sigma}_{-1\sigma}$	$\kappa_\lambda{}^{+1\sigma}_{-1\sigma}$	κ_λ [95% CL]	
κ_λ-only	1	1	1	1	1	$4.6^{+3.2}_{-3.8}$	[−2.3, 10.3]	obs.
						$1.0^{+7.3}_{-3.8}$	[−5.1, 11.2]	exp.
Generic	$1.03^{+0.08}_{-0.08}$	$1.10^{+0.09}_{-0.09}$	$1.00^{+0.12}_{-0.11}$	$1.03^{+0.20}_{-0.18}$	$1.06^{+0.16}_{-0.16}$	$5.5^{+3.5}_{-5.2}$	[−3.7, 11.5]	obs.
	$1.00^{+0.08}_{-0.08}$	$1.00^{+0.08}_{-0.08}$	$1.00^{+0.12}_{-0.12}$	$1.00^{+0.21}_{-0.19}$	$1.00^{+0.16}_{-0.15}$	$1.0^{+7.6}_{-4.5}$	[−6.2, 11.6]	exp.

- Only the single-Higgs and double-Higgs combination could give enough sensitivity to exploit the generic model

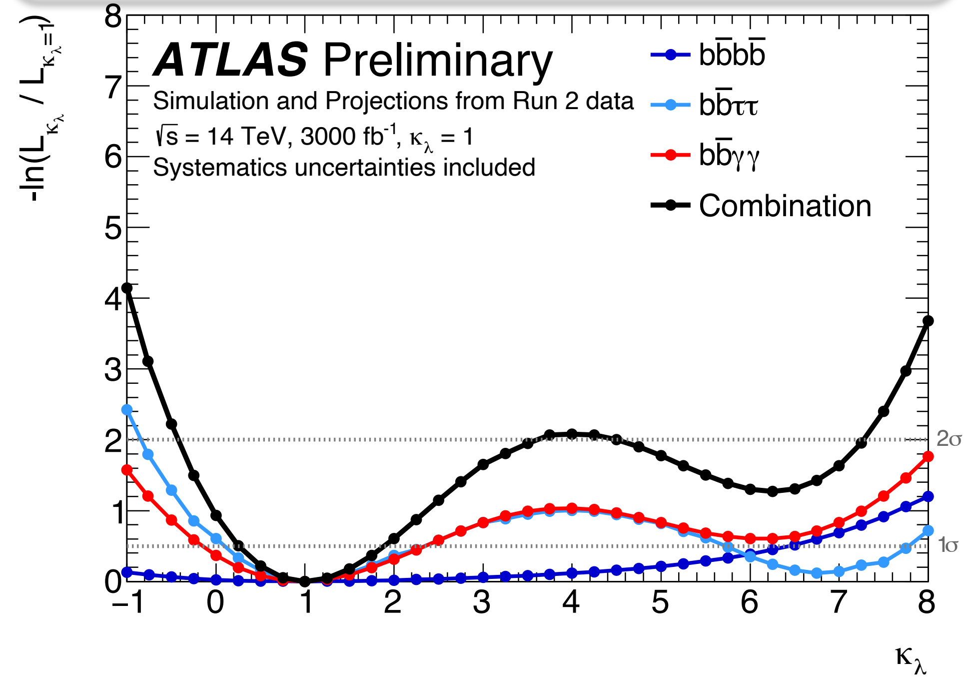
Latest κ_λ results/HL-LHC projections

$HH \rightarrow bb\gamma\gamma$ analysis @ 139 fb^{-1} [ATLAS-CONF-2021-016]



Most **stringent constraint** on κ_λ

HL-LHC projection by combining $bbbb$, $bb\tau\tau$, $bb\gamma\gamma$ with **Run2 datasets up to 36 fb^{-1}** [ATL-PHYS-PUB-2018-053]



95% CL	Obs.	Exp.
H+HH up to 80 fb^{-1}	[-2.3, 10.3]	[-5.1, 11.2]
HH to bbyy @ 139 fb-1	[-1.5, 6.7]	[-2.4, 7.7]

Scenario	1σ CI	2σ CI
Statistical uncertainties only	$0.4 \leq \kappa_\lambda \leq 1.7$	$-0.10 \leq \kappa_\lambda \leq 2.7 \cup 5.5 \leq \kappa_\lambda \leq 6.9$
Systematic uncertainties	$0.25 \leq \kappa_\lambda \leq 1.9$	$-0.4 \leq \kappa_\lambda \leq 7.3$

Summary

- **Higgs coupling properties** have been measured in ATLAS by combining Run2 data up to 139 fb^{-1} [ATLAS-CONF-2020-027, ATLAS-CONF-2020-053]

- **Global signal strength** $\mu = 1.06 \pm 0.07$
  - 31% higher precision w.r.t Run1: $1.09^{+0.11}_{-0.10}$
- Higgs **production cross sections** and **decay BR** are measured as well
  - **Firstly** observe **WH** mode in the ATLAS, **all 5 prod modes** are $> 5\sigma$
- **Finest** measurements of **STXS stage 1.2** regions are performed
- **Higgs couplings** are directly measured within **κ frameworks**
- 2HDM, MSSM and EFT **interpretations** are performed, **no derivations from the SM predictions are observed**

- New round of coupling combination is ongoing by including full Run2 **HWW, Htautau, Hbb** channels (aiming to be public this year)
- **Precise measurements** of Higgs boson properties at **HL-LHC** are helpful to address open questions about the universe
  - The **accuracies** of Higgs production and decay mode measurements are **largely improved**, possible to **observe Higgs rare decays** (ie $H \to \mu\mu$, $H \to Z\gamma$)

Summary

- The HH searches (up to 36.1 fb^{-1}) provide a unique chance to probe the Higgs self-coupling $\kappa_\lambda = \lambda_{HHH}/\lambda_{SM}$ with direct measurements, the observed 95% CL is [-5.0, 12.0]

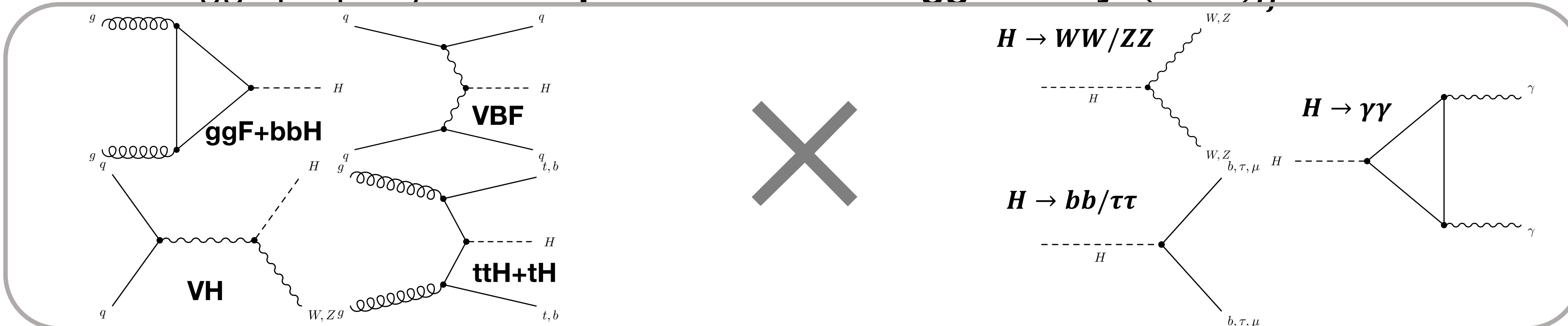
- The single-Higgs analysis (up to 80 fb^{-1}) shows an alternative and complementary approach to constrain the Higgs self-coupling, providing **similar sensitivity:** [-3.2, 11.9] at 95% CL
- Furthermore, κ_λ is constrained by **combining** single-Higgs analyses and double-Higgs analyses, which improves the constraining power on κ_λ by **17%-26%:** [-2.3, 10.3] at 95% CL

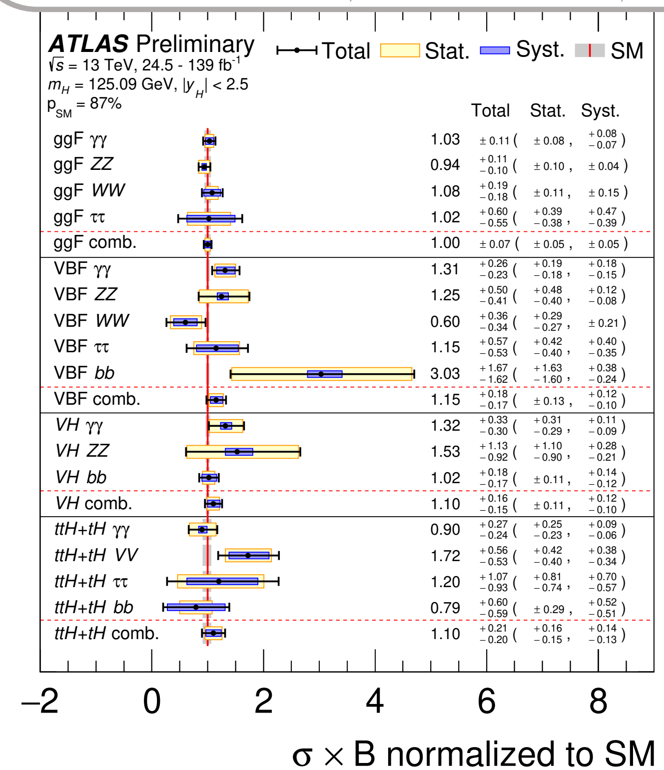
- The latest and **the most stringent** constraint on κ_λ is performed in the $\boldsymbol{HH \to bb\gamma\gamma}$ analysis with full Run2 data at ATLAS: [-1.5, 6.7] at 95% CL
- The **combination** of full **Run2 HH analyses** (non-resonant $bb\tau\tau$, $bb\gamma\gamma$) is ongoing, expecting better constraints on κ_λ and other coupling parameters

Backup

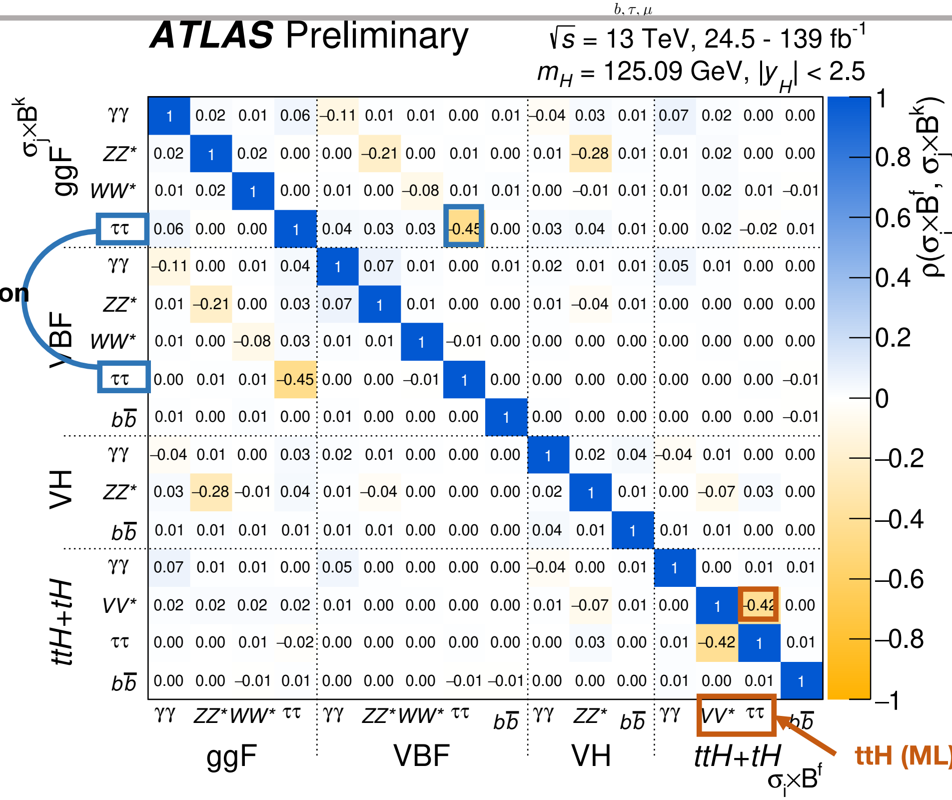
Production cross sections × BR

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



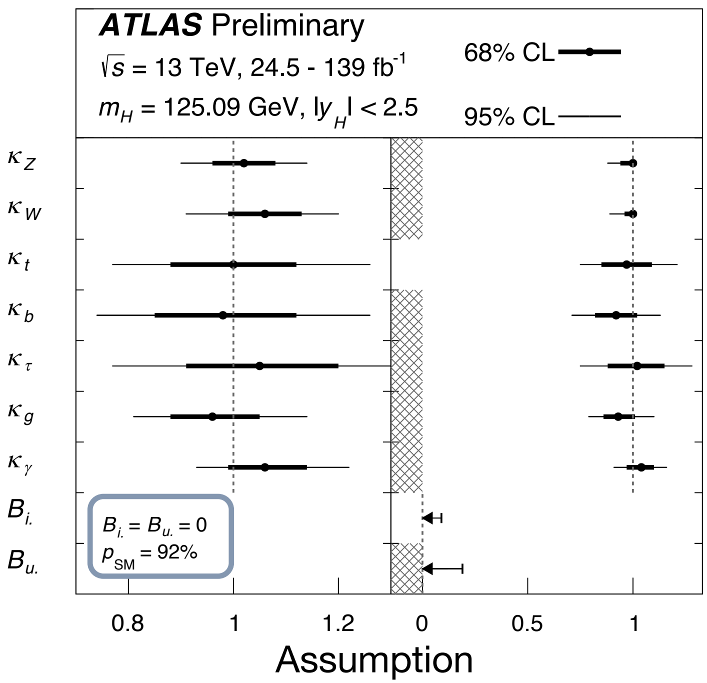


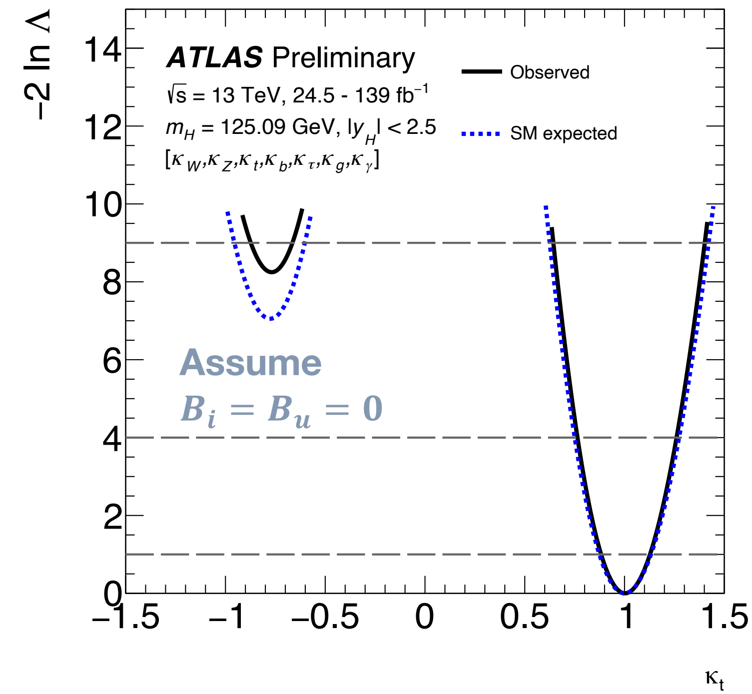
Cross contamination in $H \to \tau\tau$



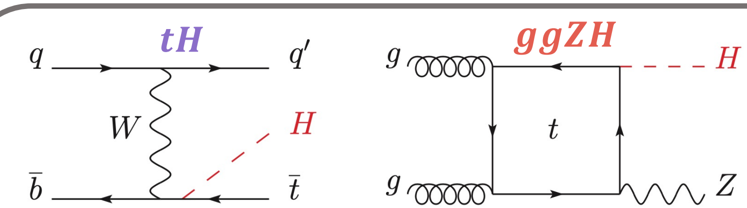
Generic model with/without BSM contributions

- κ_W, κ_Z, $\kappa_t(\kappa_c)$, $\kappa_b(\kappa_s)$, κ_τ, $\boldsymbol{\kappa_\gamma}$, $\boldsymbol{\kappa_g}$, $(\boldsymbol{B_{inv}}, \boldsymbol{B_{undet}})$
- All $\kappa \geq 0$ except $\boldsymbol{\kappa_t}$ **without loss of generality**





Parameter	(a) $B_{i.} = B_{u.} = 0$	(b) $B_{i.}$ free, $B_{u.} \geq 0$, $\kappa_{W,Z} \leq 1$
κ_Z	1.02 ± 0.06	> 0.88 at 95% CL
κ_W	1.06 ± 0.07	> 0.89 at 95% CL
κ_b	$0.98\ ^{+\,0.14}_{-\,0.13}$	0.92 ± 0.10
κ_t	1.00 ± 0.12	0.97 ± 0.12
κ_τ	$1.05\ ^{+\,0.15}_{-\,0.14}$	$1.02\ ^{+\,0.13}_{-\,0.14}$
κ_γ	$1.06\ ^{+\,0.08}_{-\,0.07}$	$1.04\ ^{+\,0.06}_{-\,0.07}$
κ_g	$0.96\ ^{+\,0.09}_{-\,0.08}$	$0.93\ ^{+\,0.08}_{-\,0.07}$
$B_{i.}$	-	< 0.09 at 95% CL
$B_{u.}$	-	< 0.19 at 95% CL

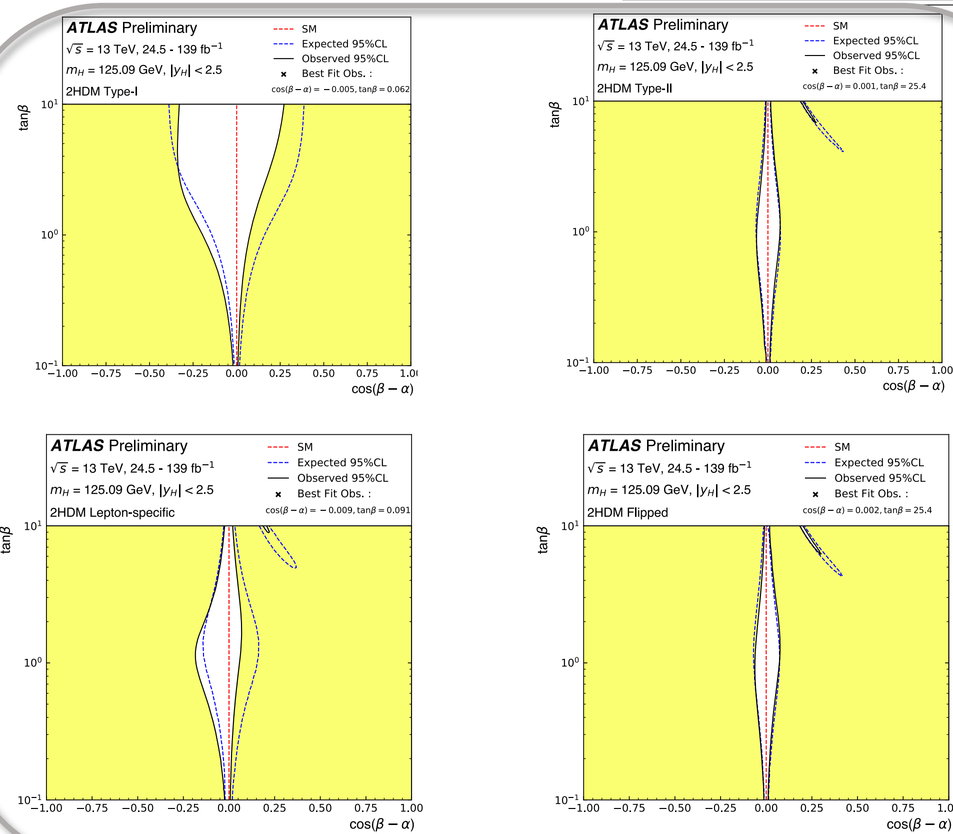


Significance for excluding the **negative** $\boldsymbol{\kappa_t}$: 2.9σ (2.7σ), mostly due to the $\boldsymbol{tH}$ (κ_t, κ_W) and $\boldsymbol{gg \to ZH}$ (κ_t, κ_Z) contributions

2HDM interpretations

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

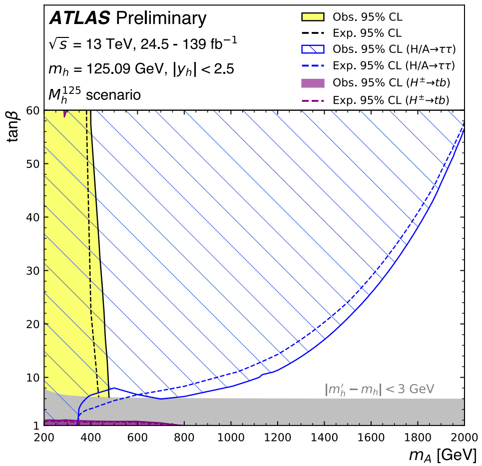
Coupling scale factor	Type I	Type II	Lepton-specific	Flipped
κ_V	$\sin(\beta-\alpha)$			
κ_u	$\cos(\alpha)/\sin(\beta)$			
κ_d	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$
κ_ℓ	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$-\sin(\alpha)/\cos(\beta)$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

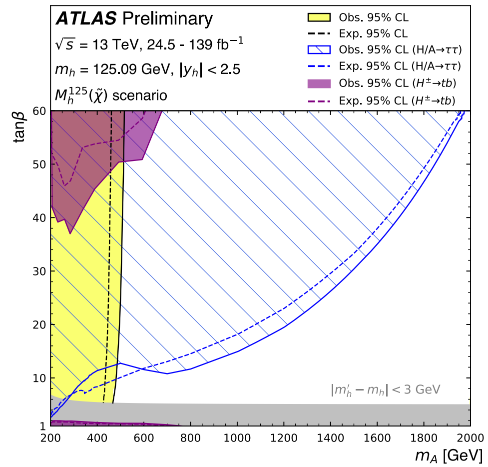


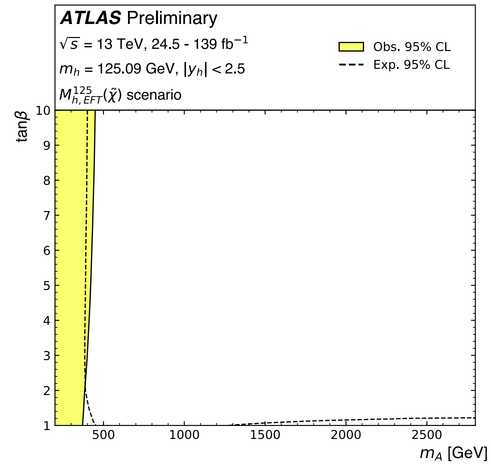
Data are consistent with the alignment limit at $\boldsymbol{\cos(\beta-\alpha) = 0}$ **(SM)**

MSSM interpretations

- **Model dependent** approach: **MSSM**
  - 6 scenarios: M_h^{125}, $M_h^{125}(\tilde{\chi})$, $M_h^{125}(\tilde{\tau})$, $M_h^{125}(\text{alignment})$, $M_{h,EFT}^{125}$, $M_{h,EFT}^{125}(\tilde{\chi})$ [Eur. Phys. J. C 79 (2019) 617, Eur. Phys. J. C 79 (2019) 279]

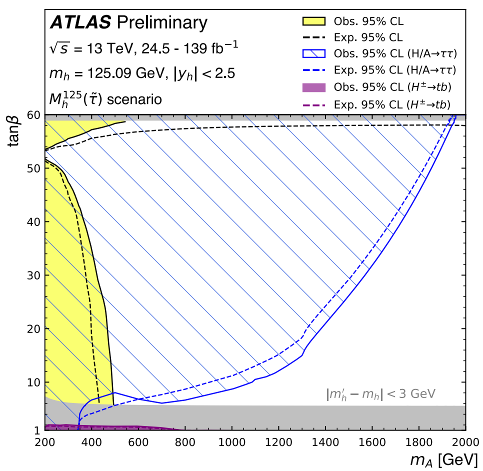


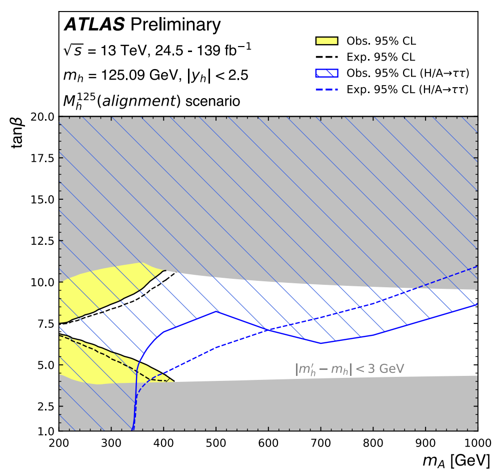


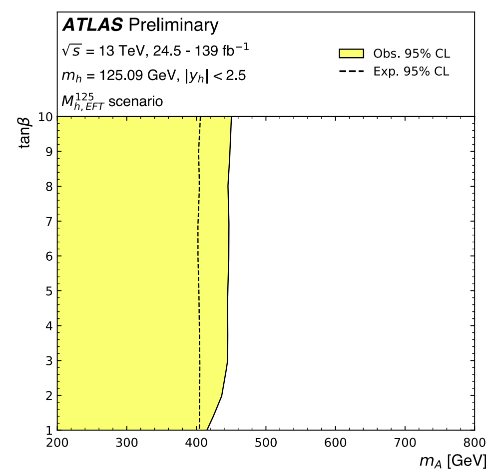


Generally excludes **low m_A regime**

Results are **complementary** to limits from **direct searches** of additional Higgs bosons

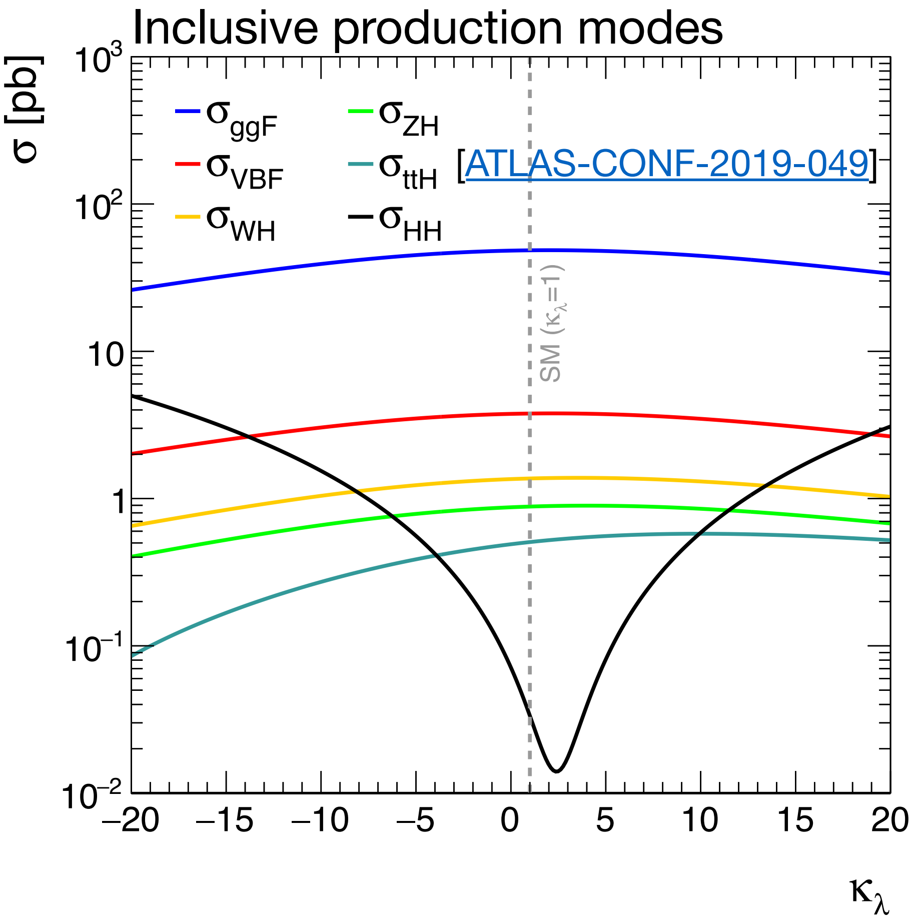


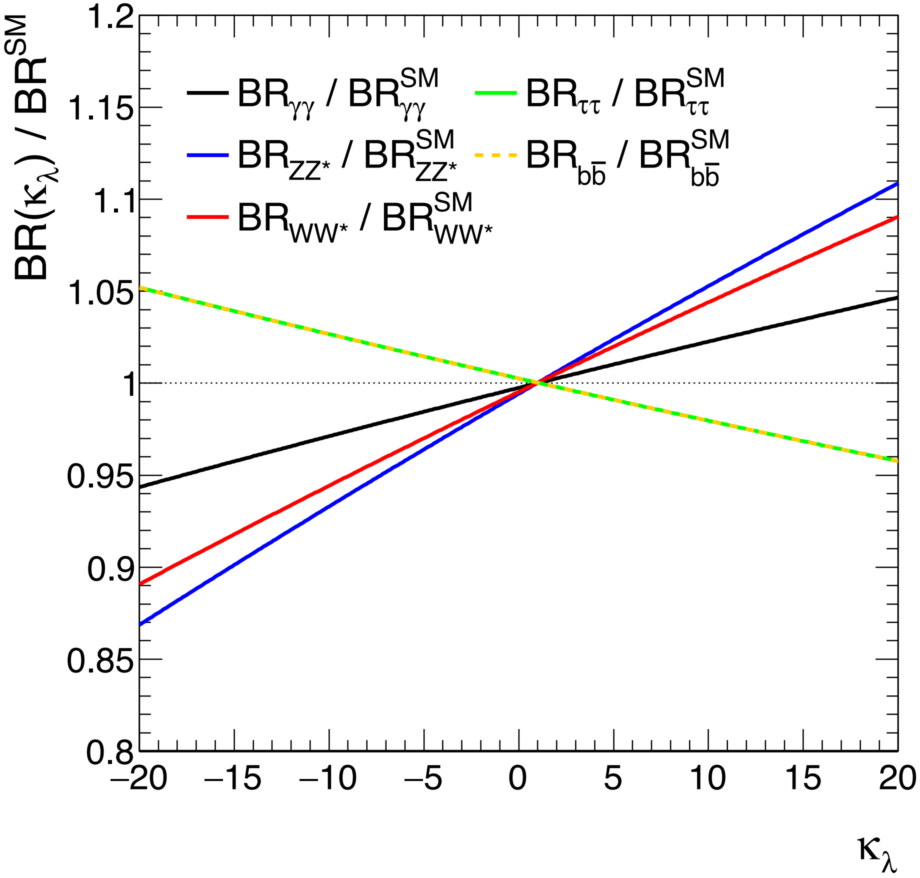




Theoretical model and parameterization

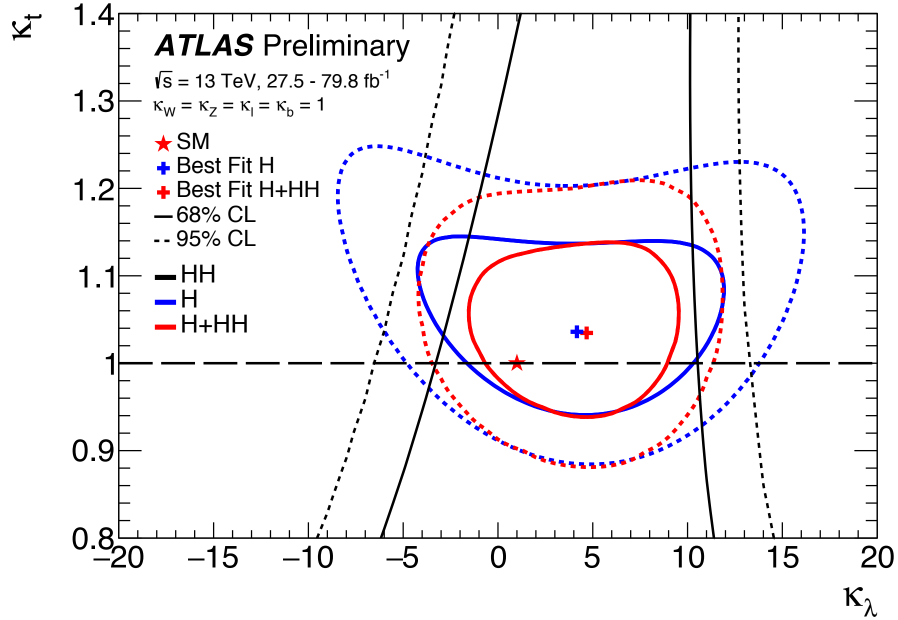
- Parametrization of single Higgs is used consistently in double-Higgs analyses for single-Higgs backgrounds and Higgs decay branching ratios

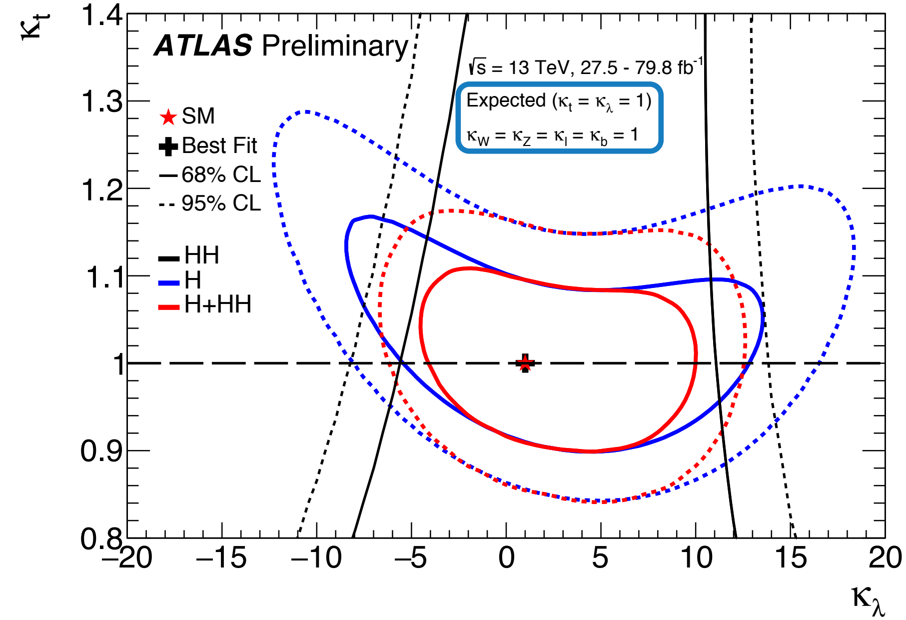




$\kappa_\lambda - \kappa_t$ measurement

- By fitting together double-Higgs and single-Higgs, κ_λ and κ_t can be constrained at the same time





[ATLAS-CONF-2019-049]

- The double-Higgs analysis alone doesn't have sensitivity to constrain κ_λ and κ_t simultaneously