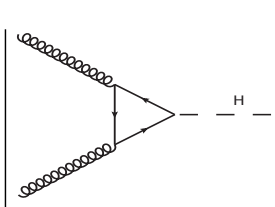
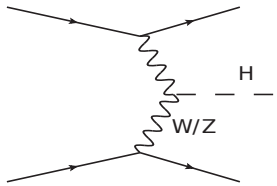
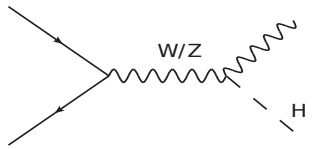
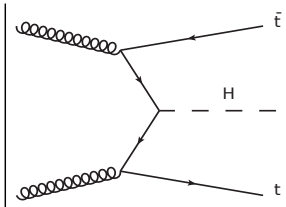
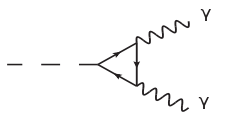
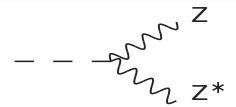
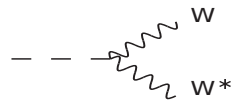
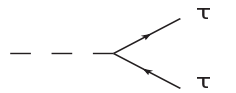
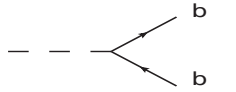
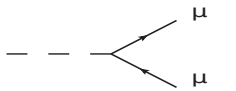
Combined Measurements of Higgs Boson Production and Decay at $\sqrt{s} = 13$ TeV with ATLAS

ATLAS-CONF-2019-005

Théo Megy, on behalf of the ATLAS collaboration

Introduction - Combination - ATLAS-CONF-2019-005

- Combined measurements of the Higgs boson production and decay:
  - **Inclusive signal strength and production cross sections**
  - **Simplified Template Cross Sections (STXS)**
  - Coupling strength measurements (κ-framework)
  - BSM interpretations

				
	79.8 fb^{-1}	79.8 fb^{-1}	79.8 fb^{-1}	79.8 fb^{-1}
	79.8 fb^{-1} + Off-shell	79.8 fb^{-1} + Off-shell	79.8 fb^{-1}	79.8 fb^{-1} / 36.1 fb^{-1}
	36.1 fb^{-1}	36.1 fb^{-1}		
	36.1 fb^{-1}	36.1 fb^{-1}		36.1 fb^{-1}
		24.5-30.6 fb^{-1}	79.8 fb^{-1}	36.1 fb^{-1}
	79.8 fb^{-1}	79.8 fb^{-1}		
$H \to$ invisible		36.1 fb^{-1}	36.1 fb^{-1}	36.1 fb^{-1}

Inputs and Combination

- **Input provided by each single analysis**
  - Contains the likelihood model
  - Inputs harmonised for combination
  - Different impact of signal theory systematics for cross sections and signal strength measurements

- **Combination**
  - Build **combined likelihood** from harmonised inputs

$$\mathcal{L}(\mu, \theta; \text{data}) = \prod_{c=1}^{N_{\text{categories}}} \mathcal{L}_c(\mu, \theta; \text{data}) \prod_{k=1}^{N_{\text{constraints}}} \mathcal{G}(\theta_k; \tilde{\theta}_k)$$

  - Equate Parameters of Interest acting on same signal truth category
  - Equate Nuisance Parameters (NP) when same uncertainty source

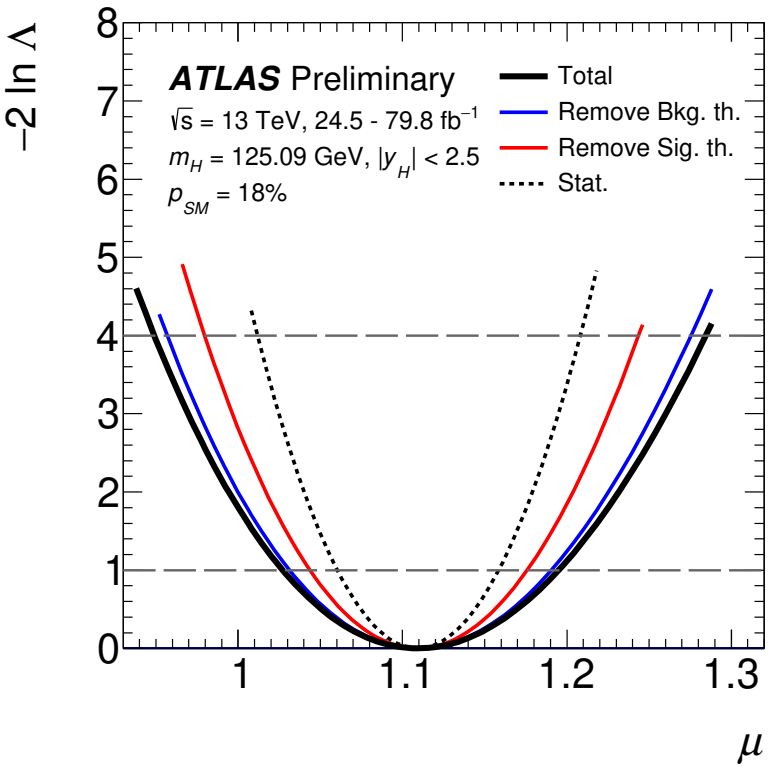
- Parameterisation of the combined likelihood for the various measurements

Inclusive Signal Strength

- Common factor μ scaling all Higgs processes

$$\mu = \mu_{if} = \frac{\sigma_i}{\sigma_i^{SM}} \times \frac{B_f}{B_f^{SM}}$$

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

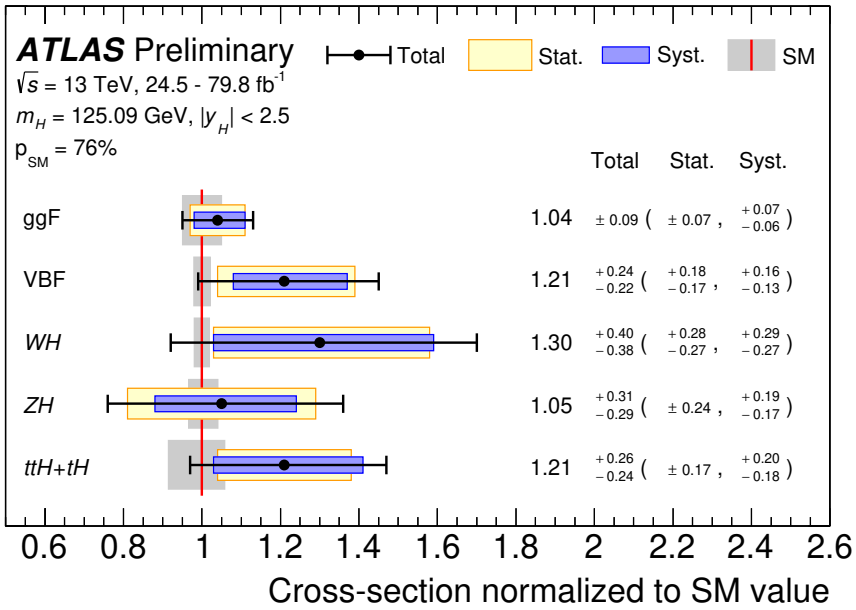


Uncertainty source	$\Delta\mu/\mu$ [%]
Statistical uncertainty	4.4
Systematic uncertainties	6.2
Theory uncertainties	**4.8**
Signal	**4.2**
Background	**2.6**
Experimental uncertainties (excl. MC stat.)	4.1
Luminosity	2.0
Background modeling	1.6
Jets, E_T^{miss}	1.4
Flavour tagging	1.1
Electrons, photons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

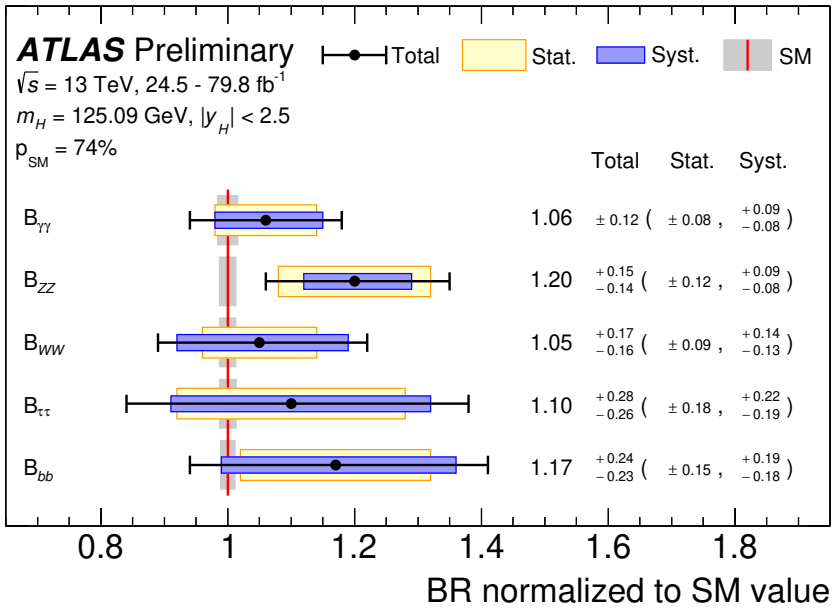
Cross Sections and Branching Ratios Measurements

- Measure cross sections of the 5 main **production modes** and branching fractions of the 5 main **decay channels**

- Branching fractions fixed to SM



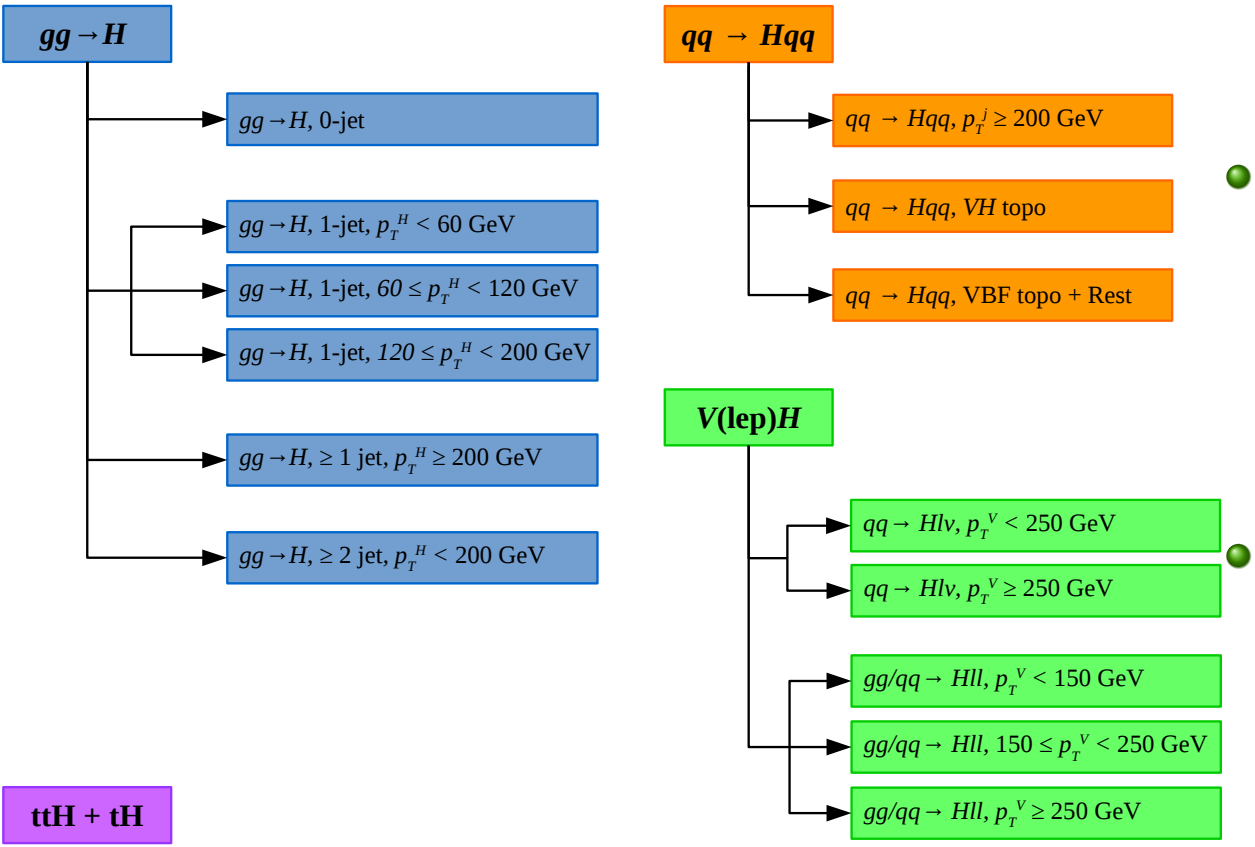
- Cross sections fixed to SM



- Measured (expected) significances:
  - ggF: » 5 σ
  - **VBF: 6.5 (5.3) σ**
  - VH: 5.3 (4.7) σ
  - ttH+tH: 5.8 (5.4) σ

Simplified Template Cross Sections (STXS)

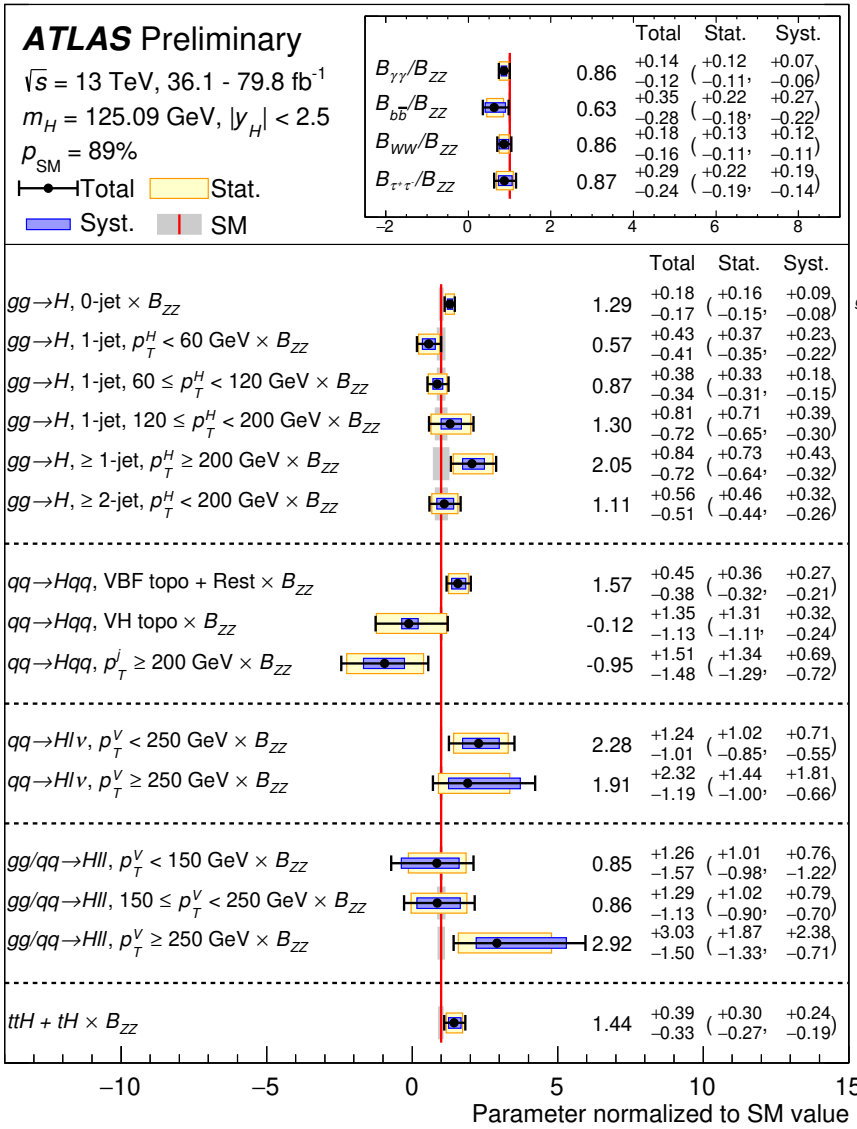
- Cross-section measurements in exclusive fiducial regions of phase space
- 1^{st} combined measurement of the stage 1 granularity including all input channels

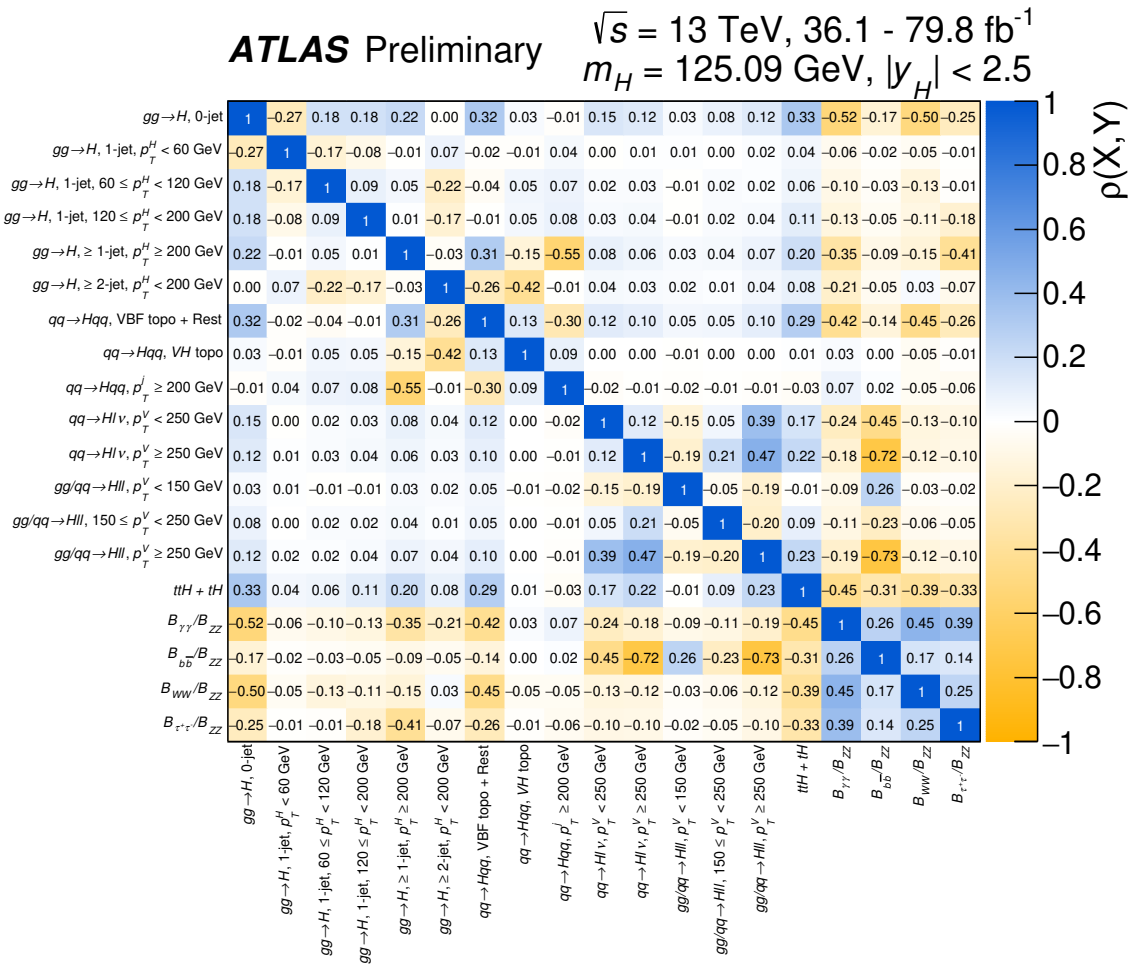


- Truth bins defined with kinematics of Higgs, jets and W/Z
  - ↪ Enhance sensitivity to deviations from SM
  - ↪ Avoid large theory uncertainties
  - ↪ Match experimental selections
- Merge groups of truth bins to
  - Increase statistical power
  - Reduce correlations

Simplified Template Cross Sections (STXS)

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





Simplified Template Cross Sections (STXS)

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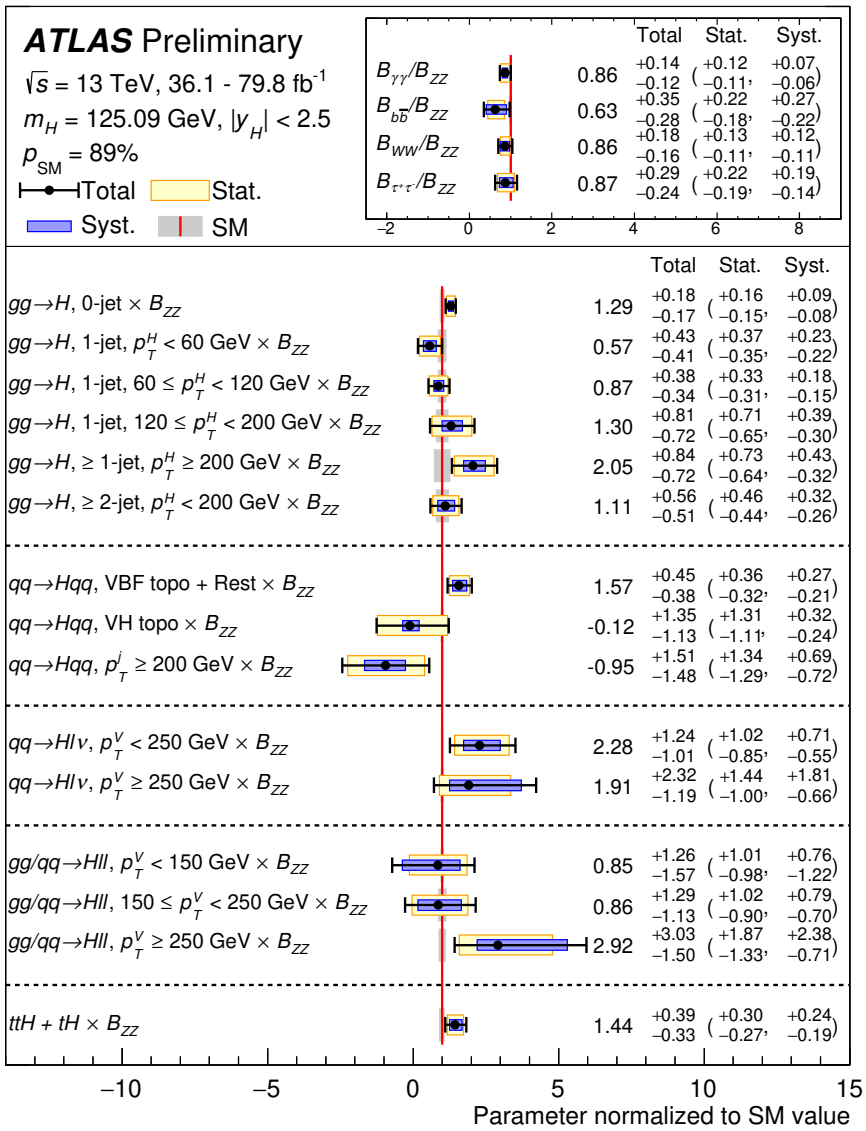


- Parameters constrained in same analysis category

$$B_{b\bar{b}}/B_{ZZ}$$ **-0.72**

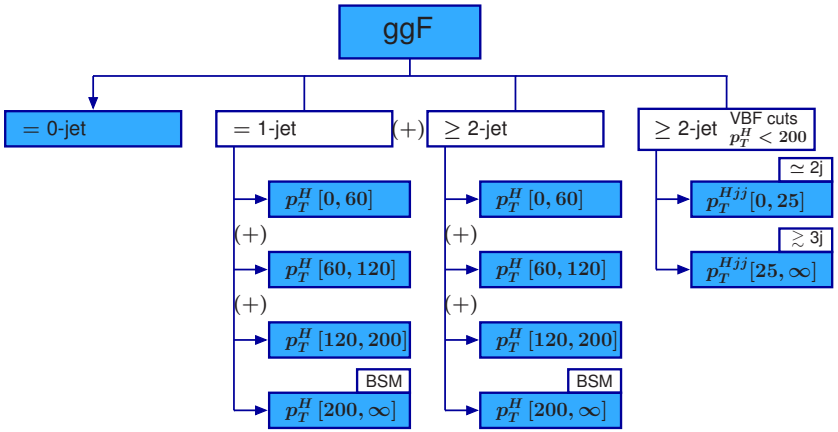
$$qq \to Hl\nu, p_T \geq 250\ \mathrm{GeV}$$

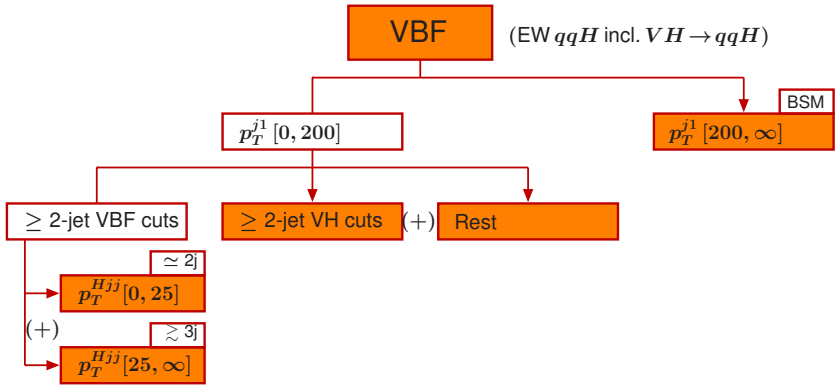
Summary

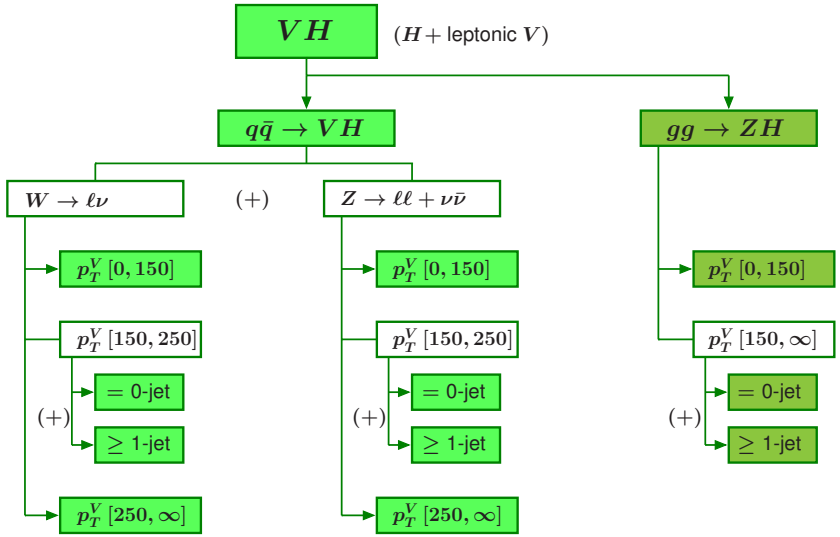
- **Combination of Higgs Run 2 analyses**:
  - Based on 2015-2016/7 data
  - Various modifications to harmonise inputs
- **ATLAS-CONF-2019-005**:
  - Inclusive cross-section measurements
    $\hookrightarrow 1^{st}$ observation of VBF by a single experiment
  - **1^{st} combined measurement of stage 1 STXS including all input channels**
  - Results interpreted in κ-framework and BSM models, reaching unprecedented precision
- Presented measurements are only a selection
- All measurements compatible with the SM

Backup

STXS Stage 1


ggF
= 0-jet
= 1-jet
(+)
≥ 2-jet
≥ 2-jet VBF cuts $p_T^H < 200$
p_T^H [0, 60]
(+)
p_T^H [60, 120]
(+)
p_T^H [120, 200]
BSM
p_T^H [200, ∞]
p_T^H [0, 60]
(+)
p_T^H [60, 120]
(+)
p_T^H [120, 200]
BSM
p_T^H [200, ∞]
≃ 2j
p_T^{Hjj}[0, 25]
≳ 3j
p_T^{Hjj}[25, ∞]


VBF
(EW qqH incl. $VH \to qqH$)
p_T^{j1} [0, 200]
BSM
p_T^{j1} [200, ∞]
≥ 2-jet VBF cuts
≥ 2-jet VH cuts
(+)
Rest
≃ 2j
p_T^{Hjj}[0, 25]
(+)
≳ 3j
p_T^{Hjj}[25, ∞]


VH
(H + leptonic V)
$q\bar{q} \to VH$
$gg \to ZH$
$W \to \ell\nu$
(+)
$Z \to \ell\ell + \nu\bar{\nu}$
p_T^V [0, 150]
p_T^V [150, 250]
(+)
= 0-jet
≥ 1-jet
p_T^V [250, ∞]
p_T^V [0, 150]
p_T^V [150, 250]
(+)
= 0-jet
≥ 1-jet
p_T^V [250, ∞]
p_T^V [0, 150]
p_T^V [150, ∞]
(+)
= 0-jet
≥ 1-jet

STXS Workspaces Conversion

- **mu workspace**: affect $n_{t,r}$, n_t and $BR\sigma_t$

$$n_r = \sum_t \frac{n_{t,r}}{n_t} \frac{1+\theta\delta_{tr}}{1+\theta\delta_t} .\mathcal{L}.(BR\sigma_t)(1+\theta\delta_t).\mu_t$$

$$= \sum_t \frac{n_{t,r}}{n_t} (1+\theta\delta_{tr}) .\mathcal{L}.(BR\sigma_t).\mu_t$$

- **xs workspace**: only affect $n_{t,r}$ and n_t

$$n_r = \sum_t \frac{n_{t,r}}{n_t} \frac{1+\theta\delta_{tr}}{1+\theta\delta_t} .\mathcal{L}.(BR\sigma_t).\mu_t$$

with θ Nuisance Parameter (NP) and δ systematic variation

STXS Workspaces Merging

- Uncertainty of merged STXS bins:
- **mu workspace**:

$$n_r = \sum_t \frac{n_{t,r}}{n_t}(1+\theta\delta_{tr}).\mathcal{L}.(BR\sigma_t)(1+\theta\delta_t).\mu_t$$

- **xs workspace**:

$$n_r = \sum_t \frac{n_{t,r}}{n_t} \frac{1+\theta\delta_{tr}}{1+\theta\frac{\sum_i n_i\delta_i}{\sum_i n_i}}.\mathcal{L}.(BR\sigma_t).\mu_t$$

- Inject additional theory uncertainty to each merged bin: $\Delta_t = \delta_t - \frac{\sum_i n_i^{SM}\delta_i}{\sum_i n_i^{SM}}$

Modification of Inputs

- **Further modifications of input workspaces**:
- Luminosity uncertainty splitting:
  - Correlation between analysis on 2015-2017 and 2015-2016 data considered
  - Uncertainty split between correlated and uncorrelated part

Lumi uncertainty	Total (%)	Uncorrelated (%)	Correlated (%)
36.1 fb^{-1}	2.0	1.61	1.51
79.8 fb^{-1}	2.1	1.27	

- Re-implementation of branching ratio uncertainty
  - BR uncertainty depends on theoretical and parametric uncertainties
  - Implemented with single NP in input workspaces
  - Split into different contributions for combination

$\Rightarrow$ Public results reproduced with merged and modified workspaces

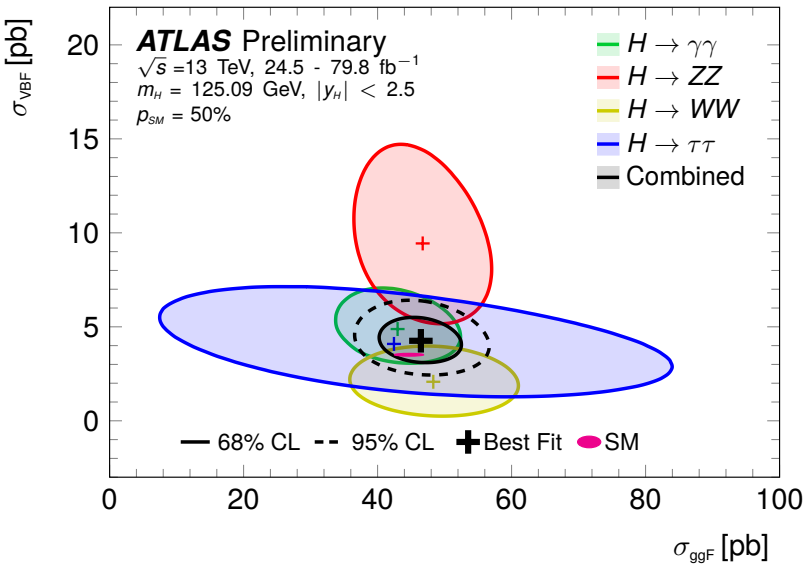
Combination - Correlation Scheme

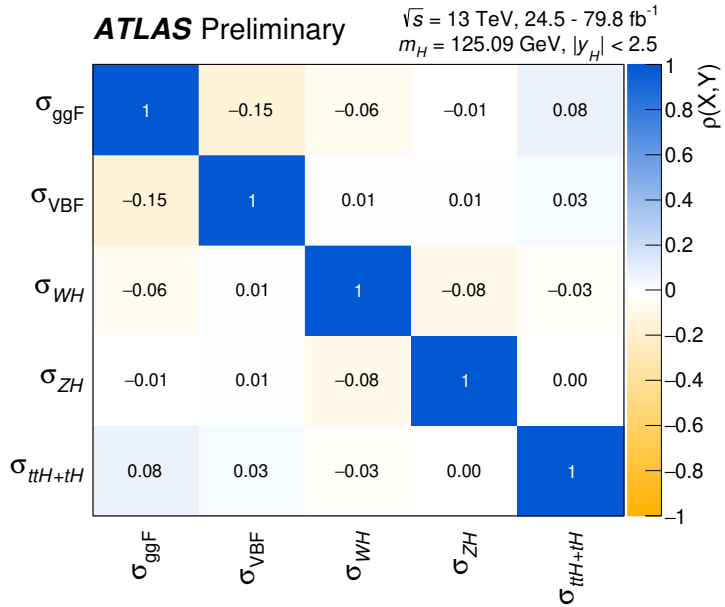
- **Theoretical uncertainties**:
  - Uncertainties on signal:
    QCD scale, PDF, α_s, underlying event and parton shower, branching ratio
  - Generally evaluated following harmonised recipes
    $\Rightarrow$ Correlated between channels when possible
  - Uncertainties on background not correlated
- **Experimental uncertainties**:
  - Correlation recommendations provided by performance groups
- Effect of (un-)correlating NPs checked when:
  - Different reconstruction releases used (r21 vs r20.7)
  - Different uncertainty models used
  - Constrained or strongly pulled NPs observed in input channels

Combination - Correlation Scheme

- **Correlations checks**:
  - Performed on combined workspace with production modes granularity
  - Check impact of (de)correlating NPs on combined results
    $\hookrightarrow$ Changes in central value and uncertainties
  - **Checks performed if impact of NP $>$ 1% on a given PoI**

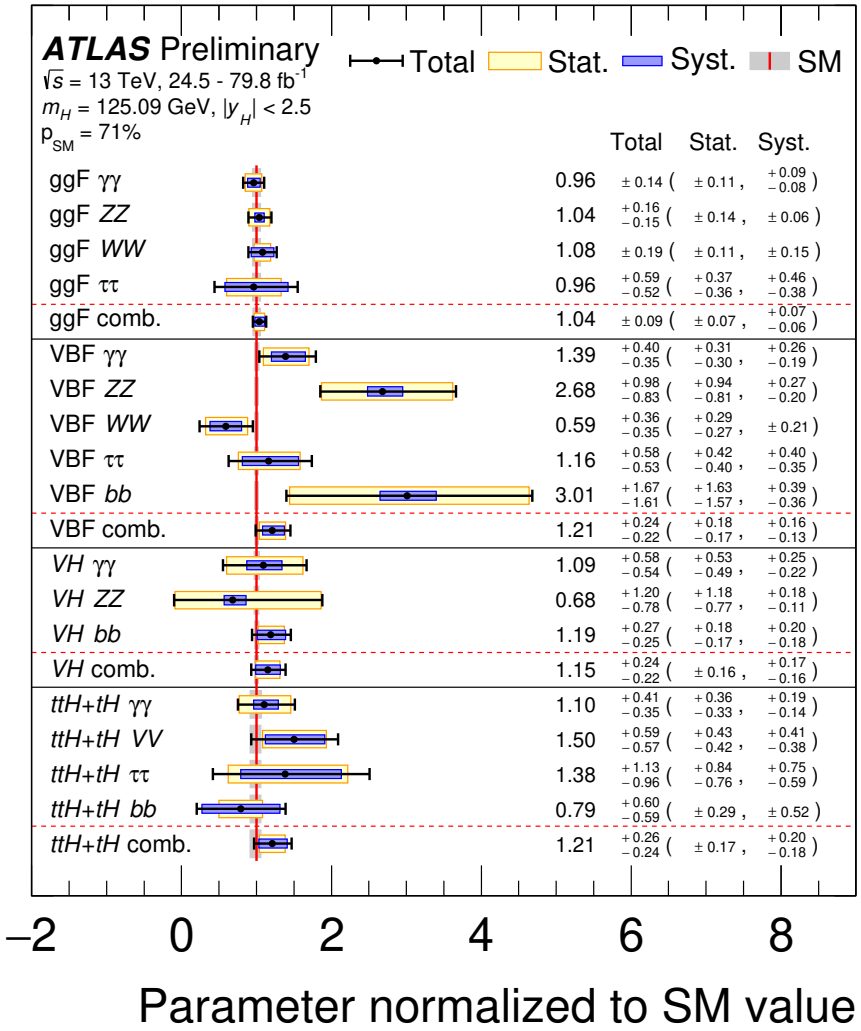
Simplified Template Cross Sections

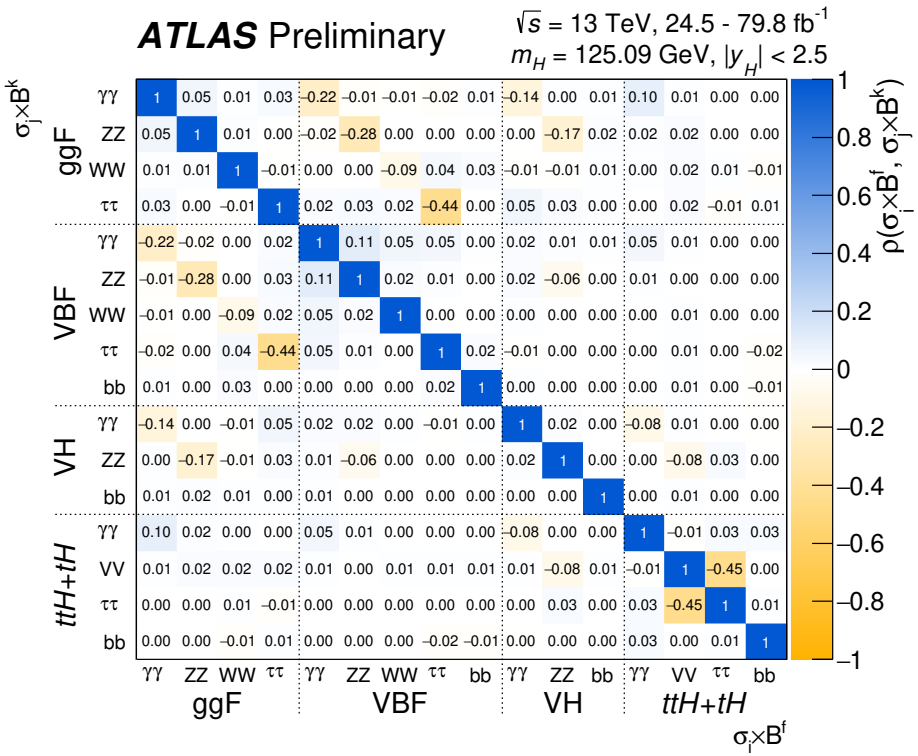




Cross-sections measurements - $\sigma \times$BR

- Measure $\sigma \times$BR for ggF, VBF, VH and ttH+tH in relevant decay channels
  - Remove uncertainties on branching ratios



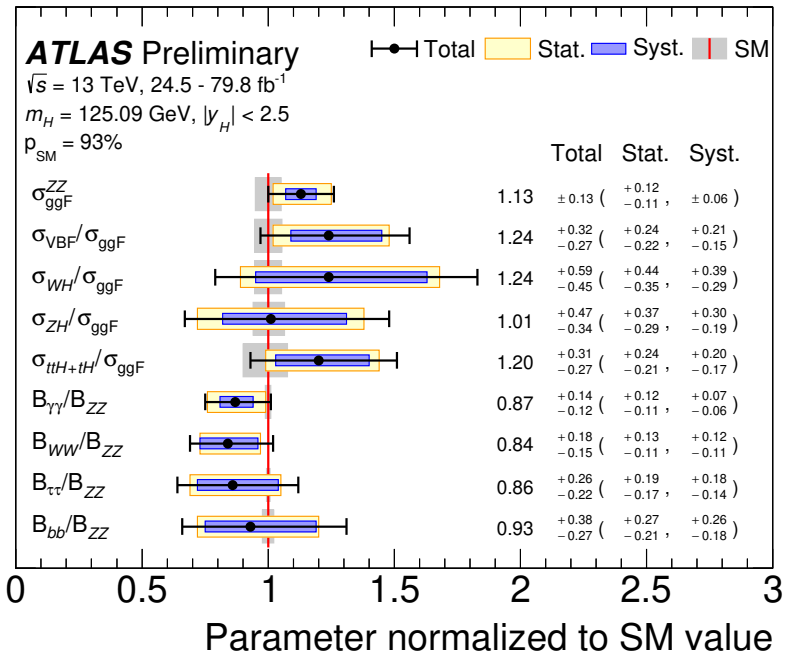


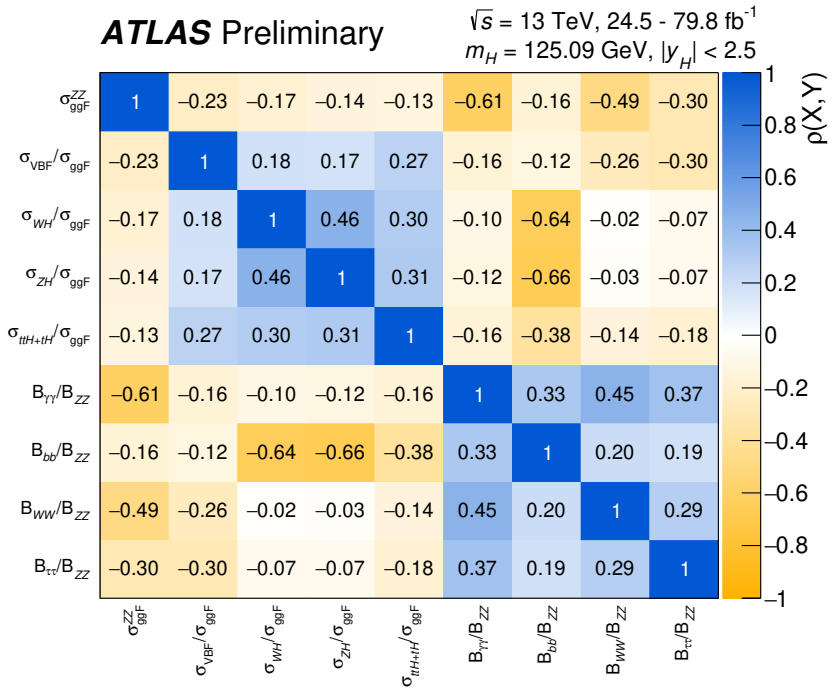
Cross-sections measurements - Ratios of production modes

- Measure ratios of cross sections and branching ratios
  - $gg \to H \to ZZ$ as reference
- Production modes XS in individual decay channels reparametrised as

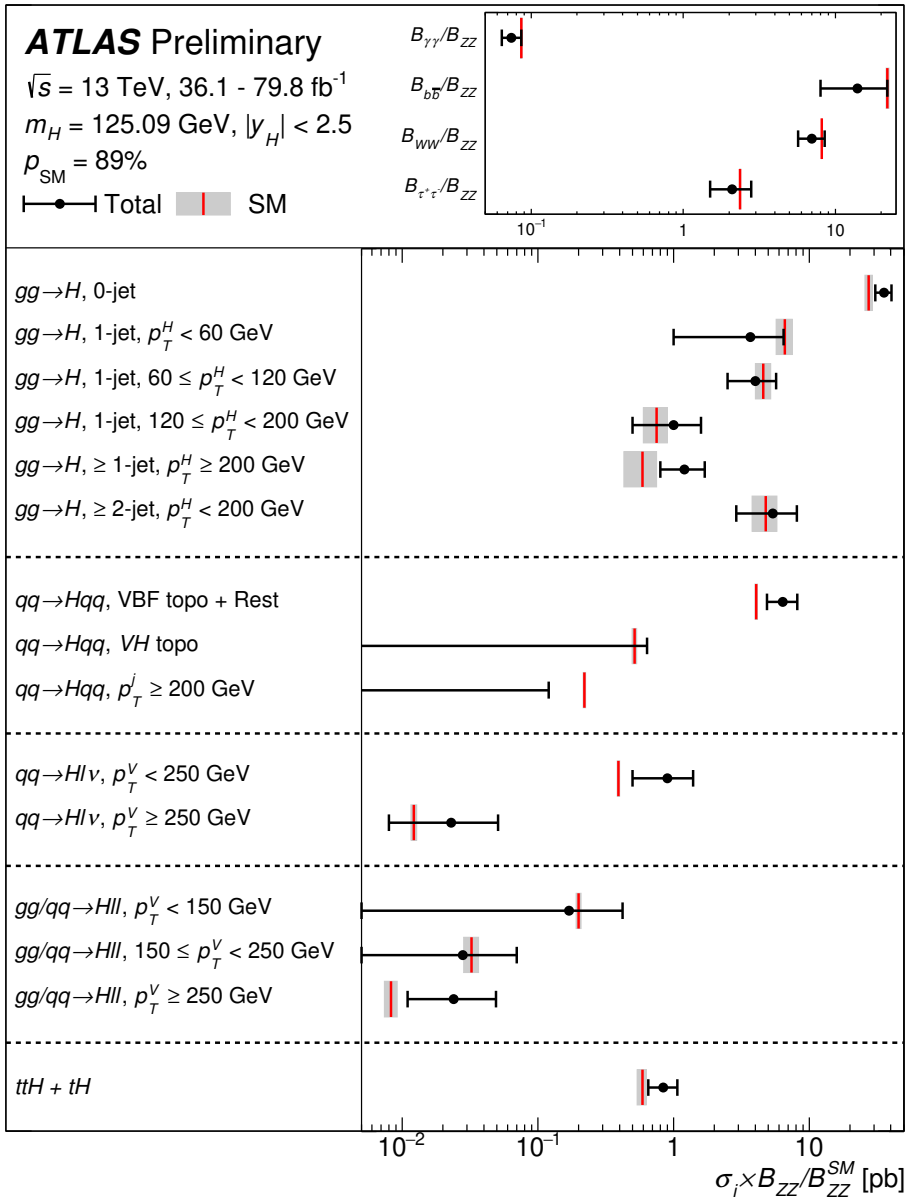
$$(\sigma \times BR)_{if} = \sigma^{ZZ}_{ggF} \cdot \frac{\sigma_i}{\sigma_{ggF}} \cdot \frac{B_f}{B_{ZZ}}$$

- Remove theory uncertainties on branching ratio



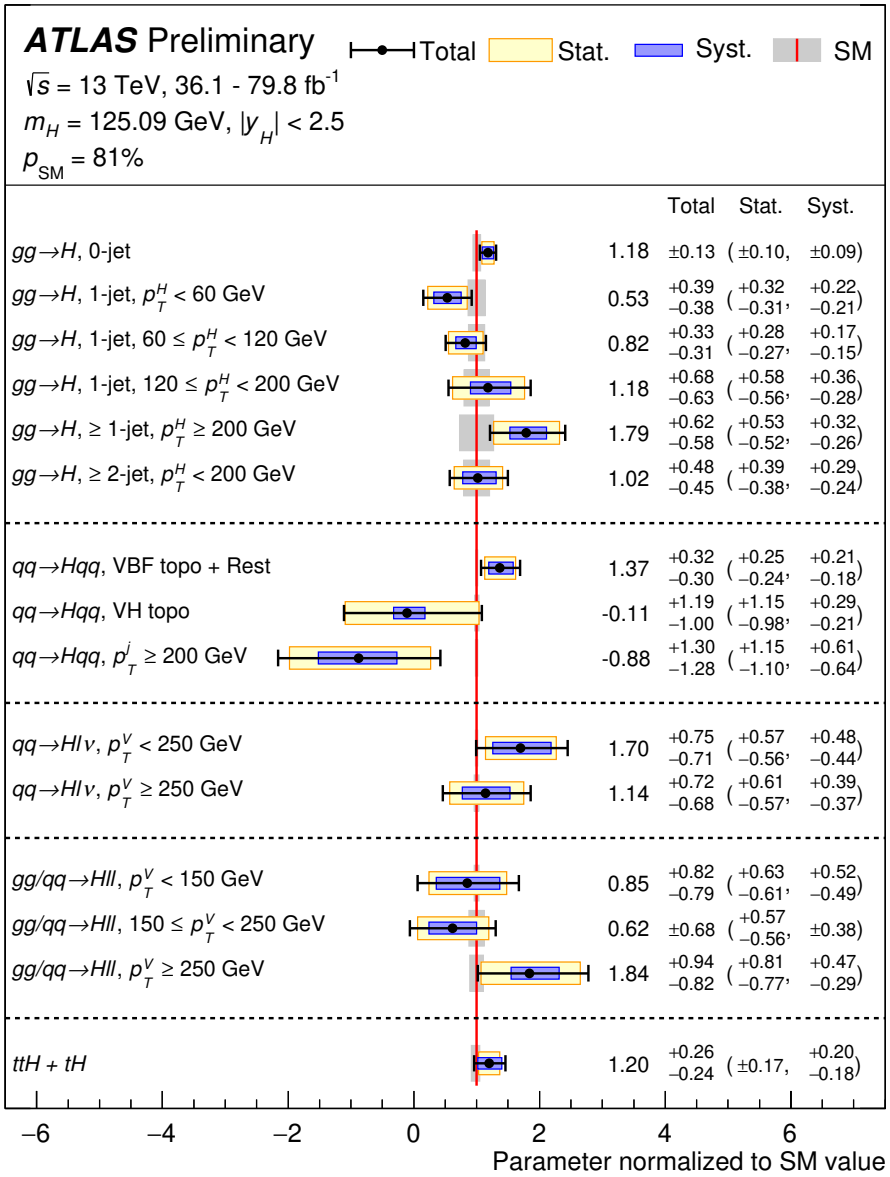


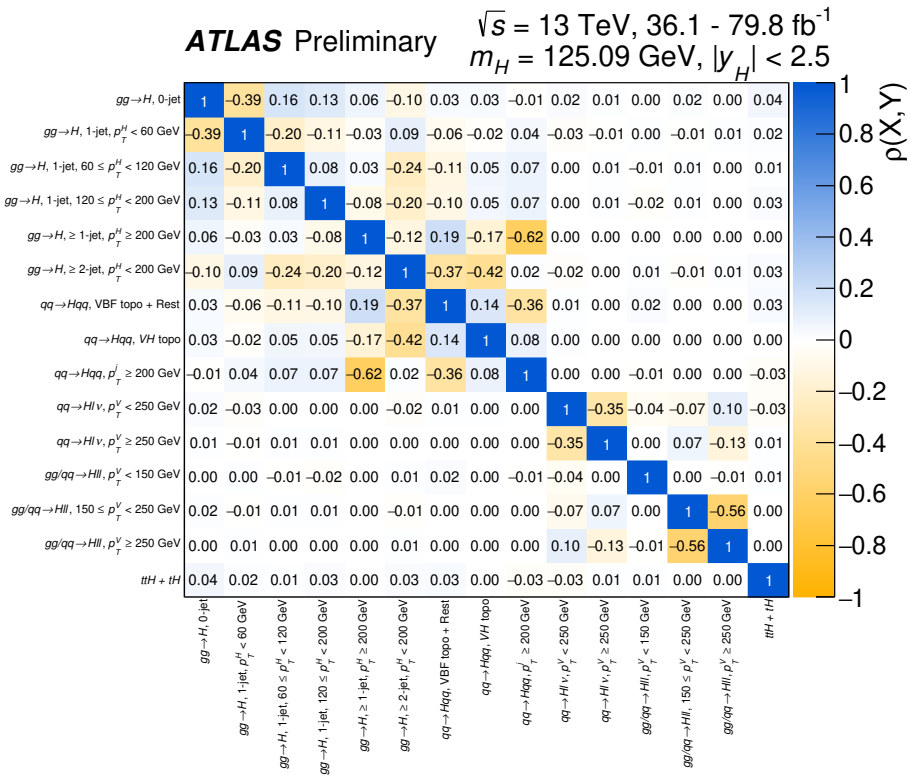
Simplified Template Cross Sections



Simplified Template Cross Sections

- Branching ratios fixed to SM expectations





Coupling Strength Measurements - Introduction

- Consistent treatment of Higgs couplings in production and decay modes
- Couplings expressed in terms of LO **coupling strength modifiers κ**:

$$(\sigma \times \mathrm{B})_{if} = \kappa_i^2 \sigma_i^{SM} \frac{\kappa_f^2 \Gamma_f^{SM}}{\kappa_H^2 \Gamma_H^{SM}}$$

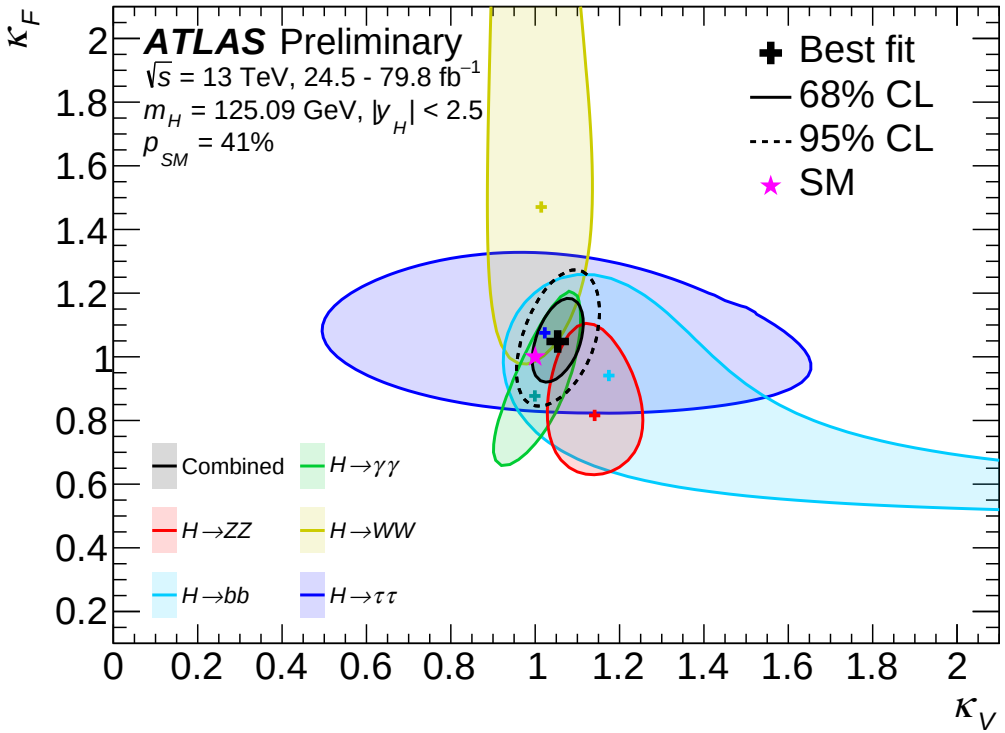
- Assumptions:
  - Assume $\kappa_c = \kappa_t$ and $\kappa_s = \kappa_b$
  - Loop processes can be expressed as effective coupling strengths (κ_g, κ_γ) or in terms SM contribution to the loop
  - B_{inv}, B_{undet}: BSM contributions to invisible and undetected branching fractions

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

  - $B_{BSM} = B_{inv} + B_{undet}$
  - Assumption on B_{inv}, B_{undet} depend on parameterisation

Fermion and Gauge Boson Coupling

- Universal coupling strength for bosons $\kappa_V = \kappa_W = \kappa_Z$
  and fermions $\kappa_F = \kappa_t = \kappa_b = \kappa_\tau = \kappa_\mu$
- Assume no BSM contributions to loops and decays



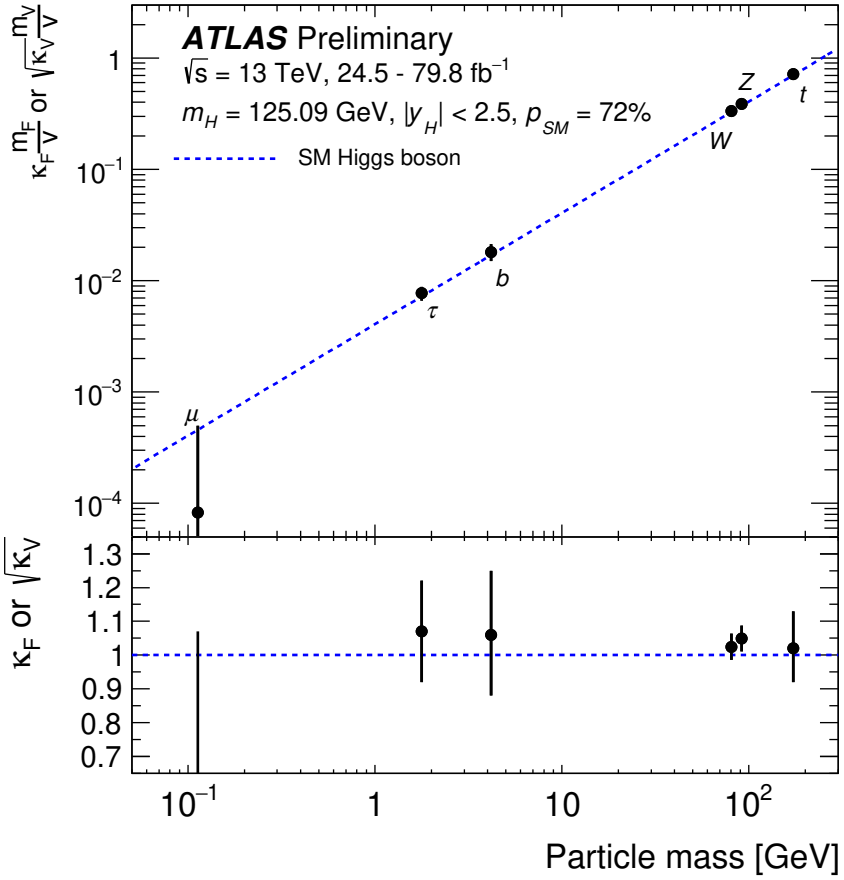
- Best fit values:

$\kappa_V = 1.05 \pm 0.04$

$\kappa_F = 1.05 \pm 0.09$

Coupling Strength Measurements - Generic Parameterisation

- Measure all SM couplings, with only SM contributions to loops and decays
  - $H \to \mu\mu$ included

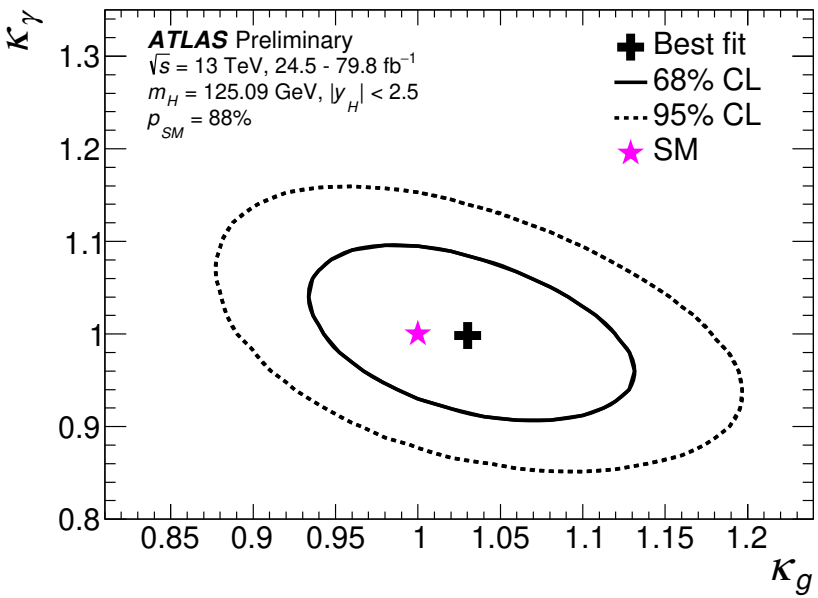


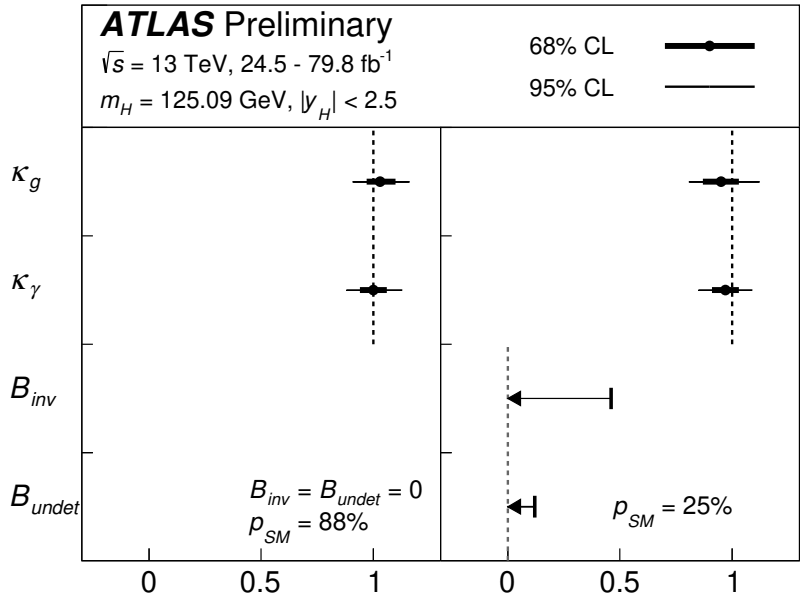
Parameter	Result
κ_Z	1.10 ± 0.08
κ_W	1.05 ± 0.08
κ_b	$1.06^{+0.19}_{-0.18}$
κ_t	$1.02^{+0.11}_{-0.10}$
κ_τ	1.07 ± 0.15
κ_μ	< 1.51 at 95% CL.

Probing BSM in Loops and Decays

- Measure effective couplings to gluons κ_g and photons κ_γ
- B_{inv}, B_{undet} enter Γ_H parameterisation
  - Searches for $H \rightarrow$invisible included in combination to constrain B_{inv}

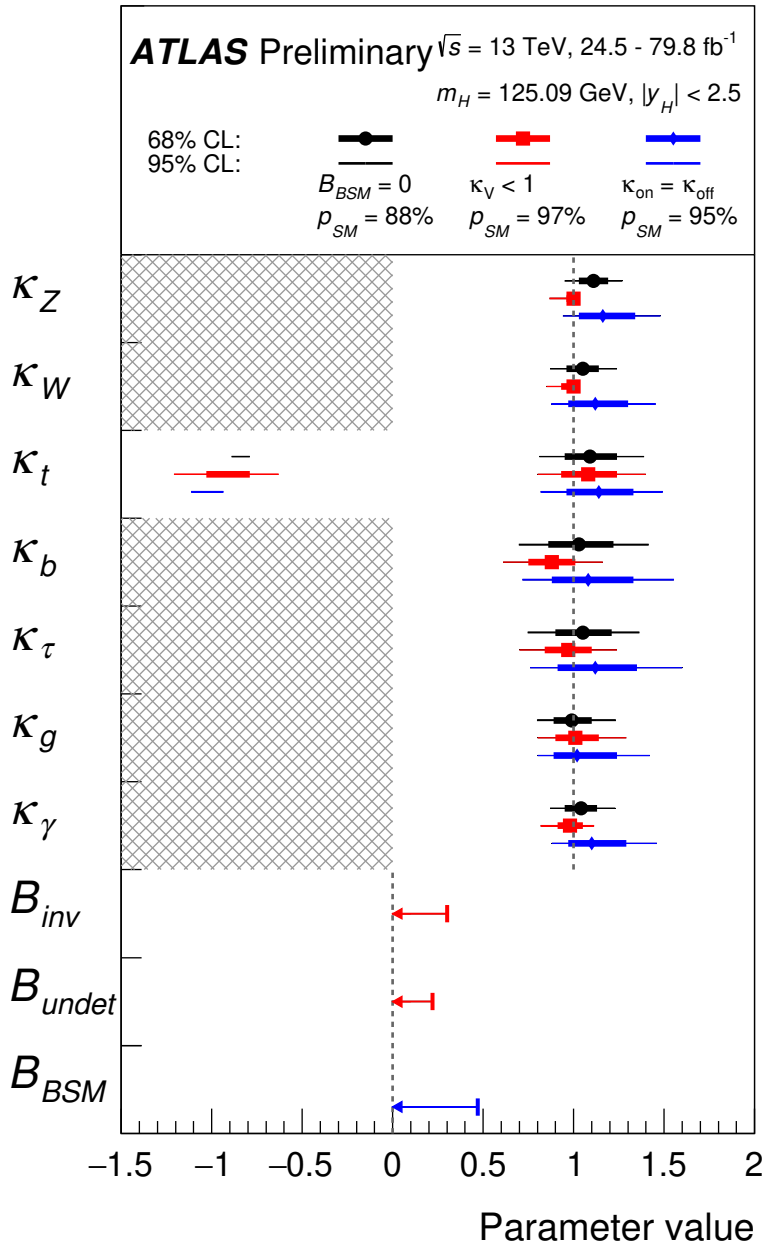
Assume $B_{inv} = B_{undet} = 0$





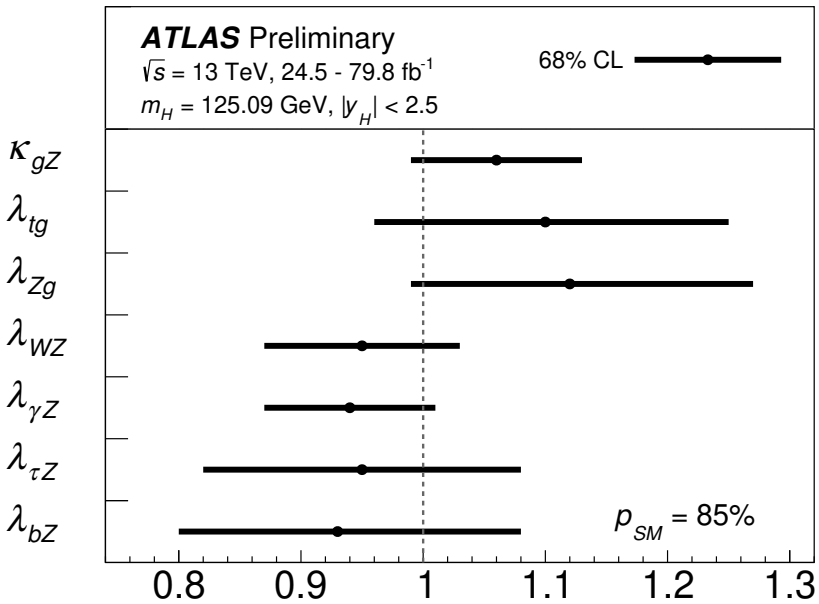
Generic Parameterisations

- Same modifiers as previous model, except κ_g, κ_γ used
- $B_{inv} = B_{undet} = 0$
- Measure B_{inv},B_{undet}: $\kappa_V < 1$
  ($H \rightarrow$ invisible included)
- Measure B_{BSM}: $\kappa_{on} = \kappa_{off}$
  (Off-shell analysis included)



Generic Parameterisations

- Measure ratios of coupling strengths
- Γ_H dependence cancelled $\Rightarrow$ No assumption needed

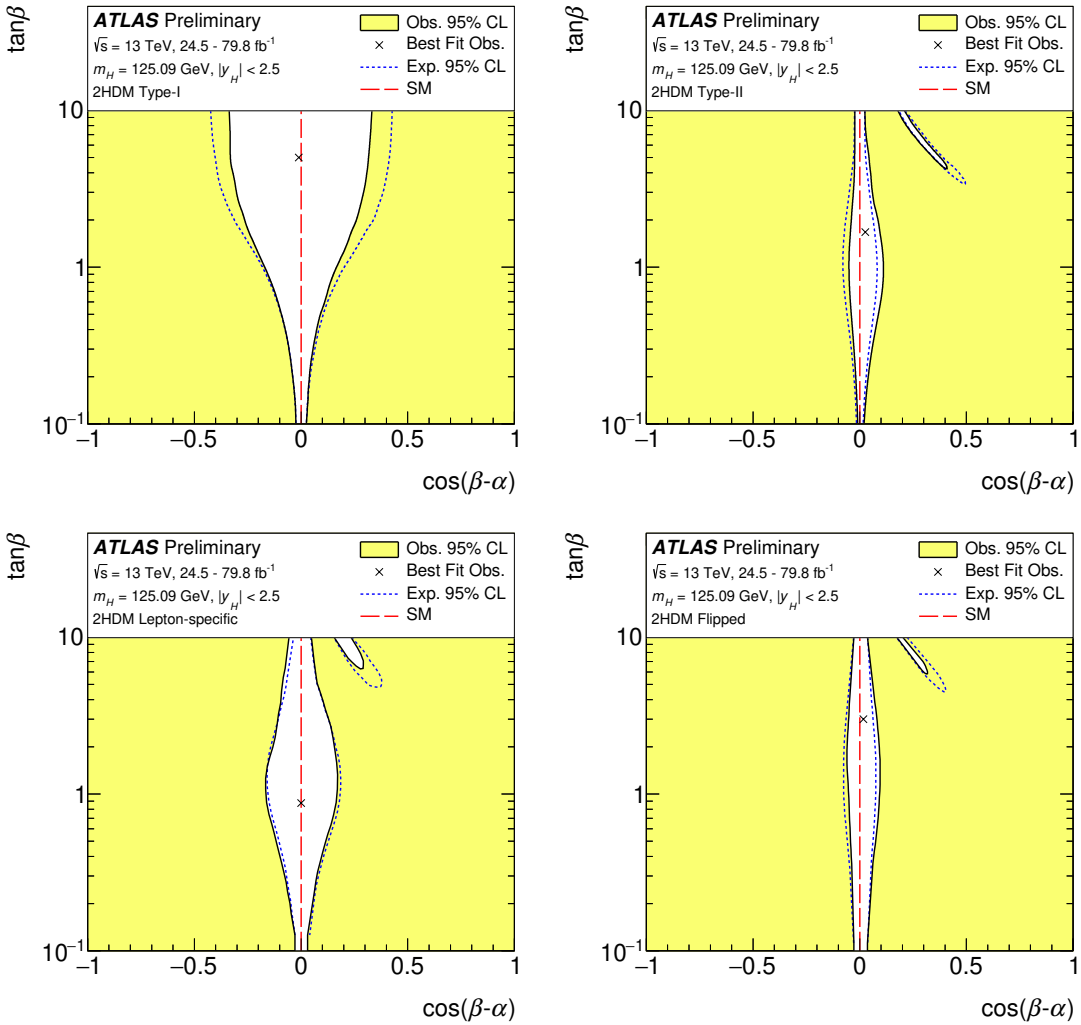


Parameter	Definition in terms of κ modifiers	Result
κ_{gZ}	$\kappa_g\kappa_Z/\kappa_H$	1.06 ± 0.07
λ_{tg}	κ_t/κ_g	$1.10^{+0.15}_{-0.14}$
λ_{Zg}	κ_Z/κ_g	$1.12^{+0.15}_{-0.13}$
λ_{WZ}	κ_W/κ_Z	0.95 ± 0.08
$\lambda_{\gamma Z}$	κ_γ/κ_Z	0.94 ± 0.07
$\lambda_{\tau Z}$	κ_τ/κ_Z	0.95 ± 0.13
λ_{bZ}	κ_b/κ_Z	$0.93^{+0.15}_{-0.13}$

BSM Interpretations - 2 Higgs Doublet Models

- Extension of Higgs sector with additional Higgs doublet
- Light CP-even scalar h identified with observed Higgs boson

- Couplings re-expressed in term of α,β
- α: Mixing angle of the 2 neutral scalars
- $tan\beta = \frac{v_2}{v_1}$
- 4 types of models ensuring no tree-level FCNC



BSM Interpretation - hMSSM

- Simplified MSSM model: requires strong assumptions
- Similar to type II 2HDM
- Couplings re-expressed in terms of $tan\beta$, m_A (CP-odd scalar), m_Z and m_h