Measurements of the properties of the Higgs boson using the ATLAS detector

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on behalf of the ATLAS collaboration

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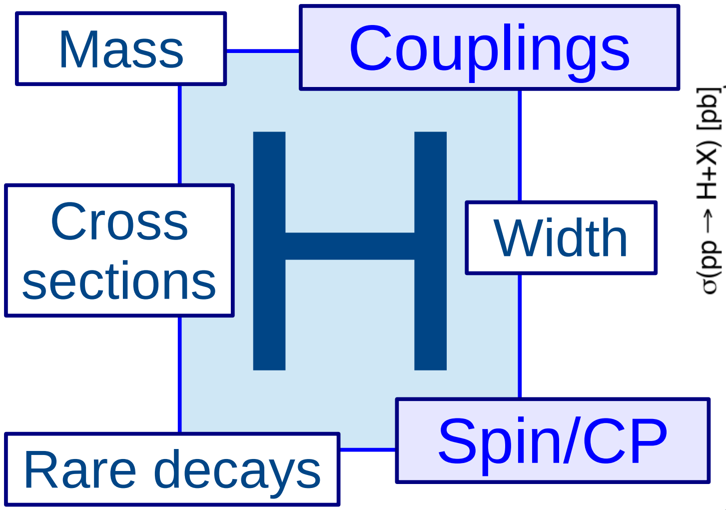
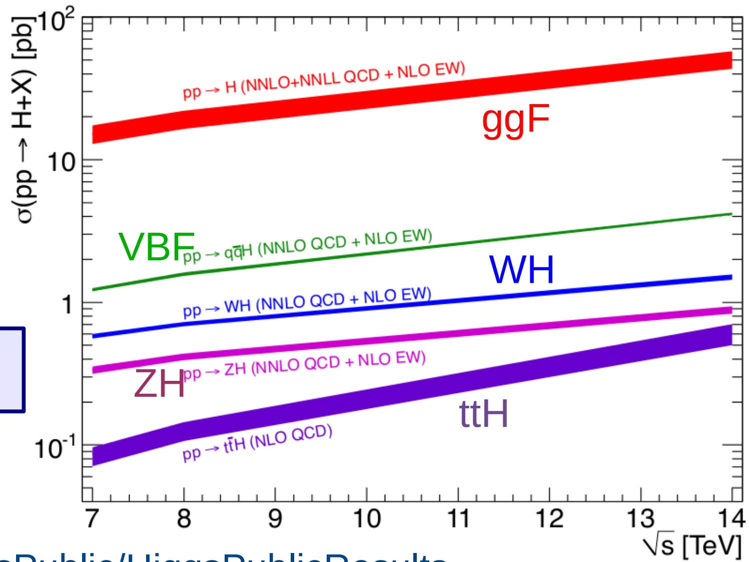
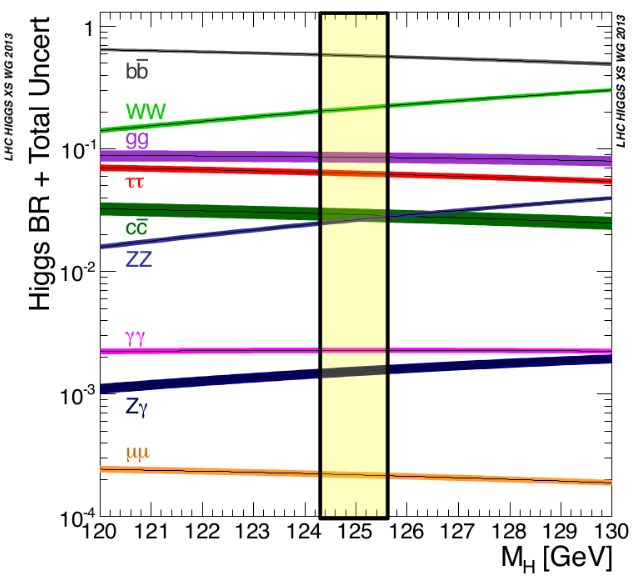
Higgs in Run1

Exciting **Run1** at **LHC**: **Higgs discovery** → **Higgs properties**

Given a Higgs mass all other Higgs **SM parameters** can be predicted and **tested**







ATLAS Higgs results
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults

ATLAS full √s = 7 TeV (4.7fb^{-1}) and √s = 8 TeV (20.3fb^{-1}) dataset available since early 2013 → reconstruction, analysis improved and better understanding of systematics → final **combinations**

Spin/CP

arXiv:1506.05669

Combination of bosonic decay channels:

- $H \to ZZ^* \to 4l$
- $H \to WW^* \to e\nu\mu\nu$
- $H \to \gamma\gamma$

Models under test:

- Spin 0, Spin 2 (Spin 1 is excluded from $H \to \gamma\gamma$ evidence)
- BSM CP-even, CP-odd, CP-mixing (*W/Z* channels)

Approach of the analysis: Effective Field Theory (**EFT**) → general effective Lagrangian with coefficients to accommodate different hypotheses :

- fixed spin parity test
- CP mixing

Λ~1TeV → EFT assumed valid up to $p_T^X < 300$ GeV

Spin-0: example for **H→ZZ*→4*l***

α: mixing angle $\Lambda: cut-off\ scale$

$$L_0^Z = [\cos(\alpha) \cdot \kappa_{SM} [\frac{1}{2} g_{HZZ} Z_\mu Z^\mu] - \frac{1}{4}\frac{1}{\Lambda}[\cos(\alpha) \cdot \kappa_{HZZ} Z_{\mu\nu} Z^{\mu\nu} + \sin(\alpha) \cdot \kappa_{AZZ} Z_{\mu\nu} \tilde{Z}^{\mu\nu}]] X_0$$

SM coupling BSM CP-even coupling BSM CP-odd coupling

Spin/CP observables

Exploit each channel information (topology, kinematic model differences, ...):

$H \rightarrow \gamma\gamma$

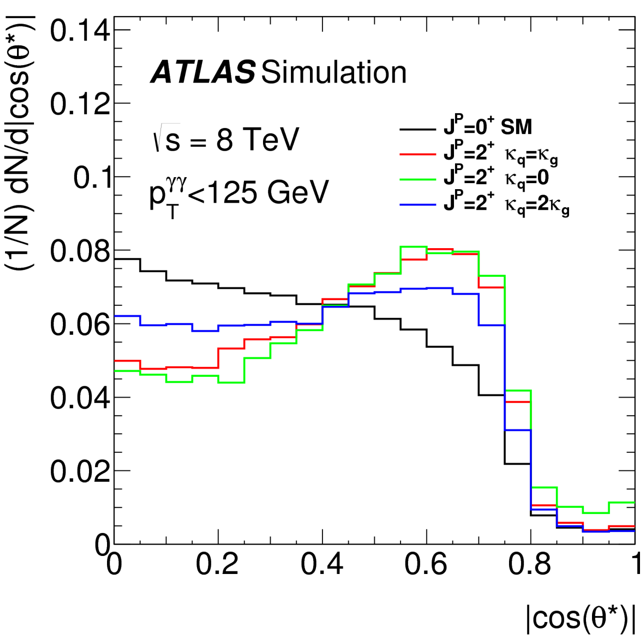
Categories using decay angle in Collins-Soper frame ($\cos\theta^*$) and p_T

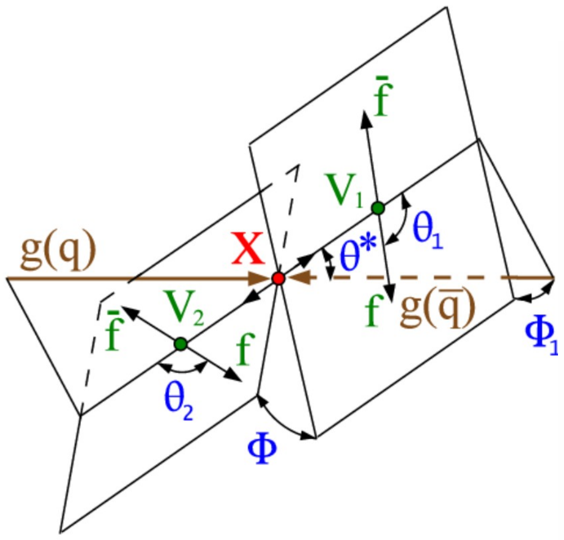
$H \rightarrow ZZ^* \rightarrow 4l$

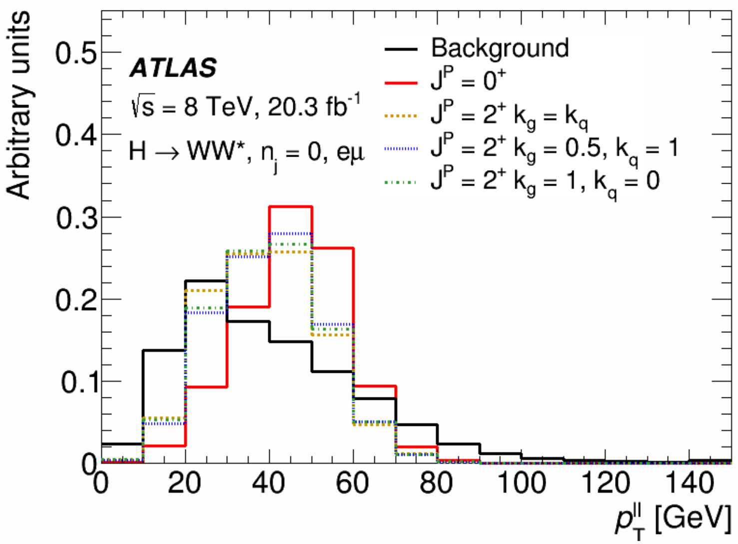
Full kinematic information available: matrix-element-based discriminant

$H \rightarrow WW^* \rightarrow e\nu\mu\nu$

BDT with spin/CP sensitive variables: m_{ll}, p_T^{ll}, $\Delta\Phi_{ll}$ and m_T





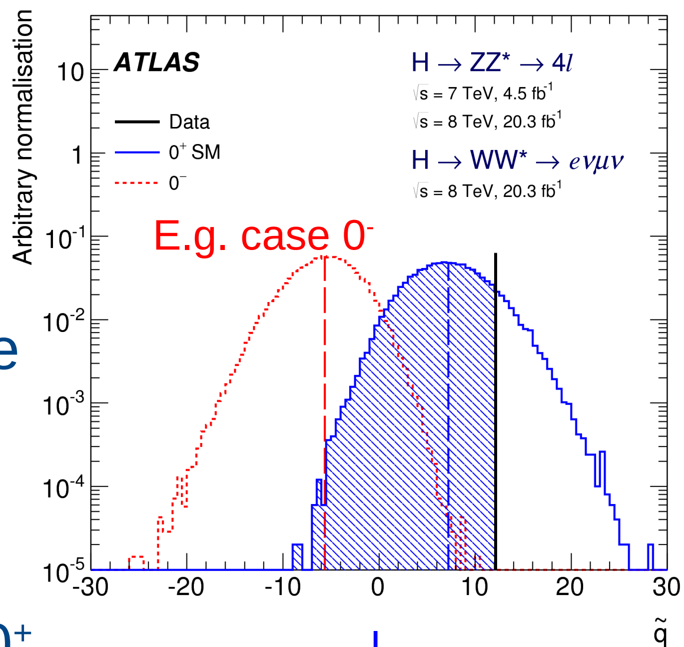


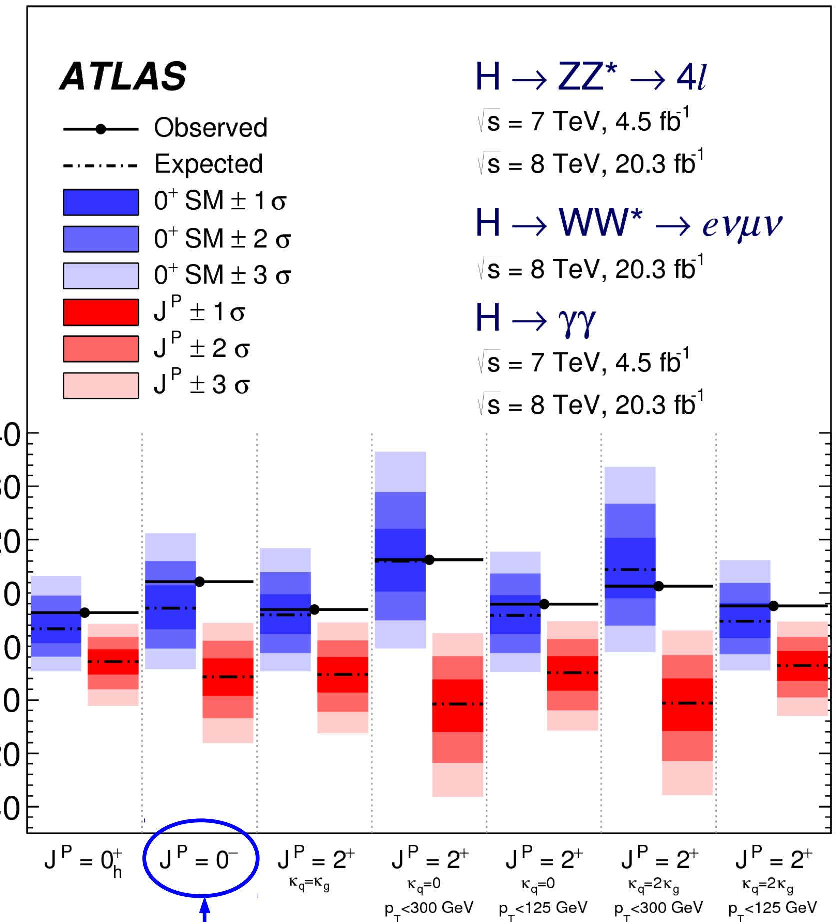
Spin/CP results

Test **fixed spin/parity** hypotheses alternative to SM 0^+

Universal and non-universal coupling scenarios considered

All non-SM spin hypotheses considered are **excluded** at >99.9% CL in favour to SM 0^+



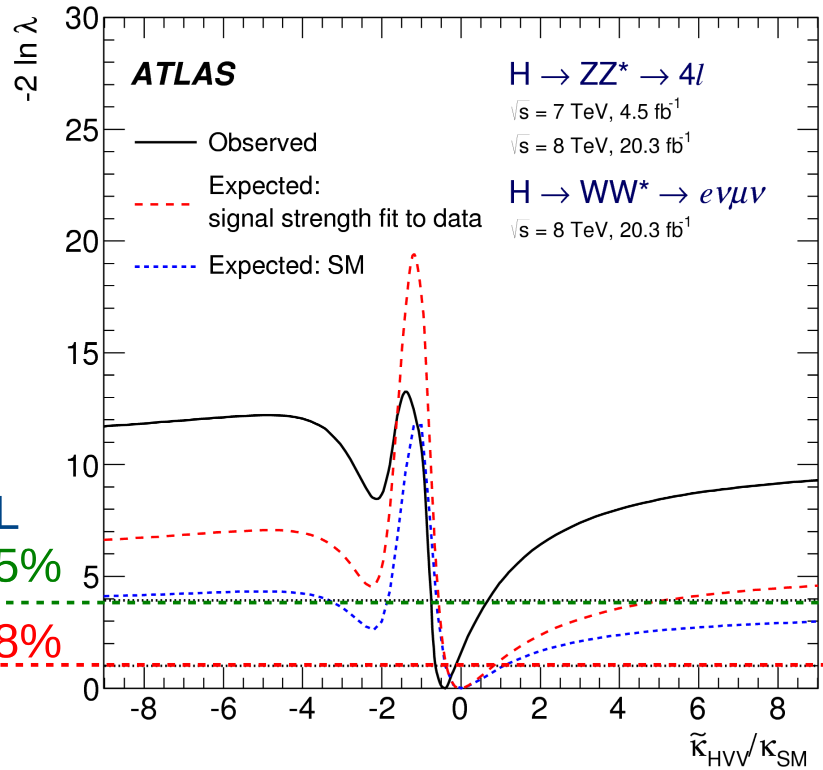


CP mixing

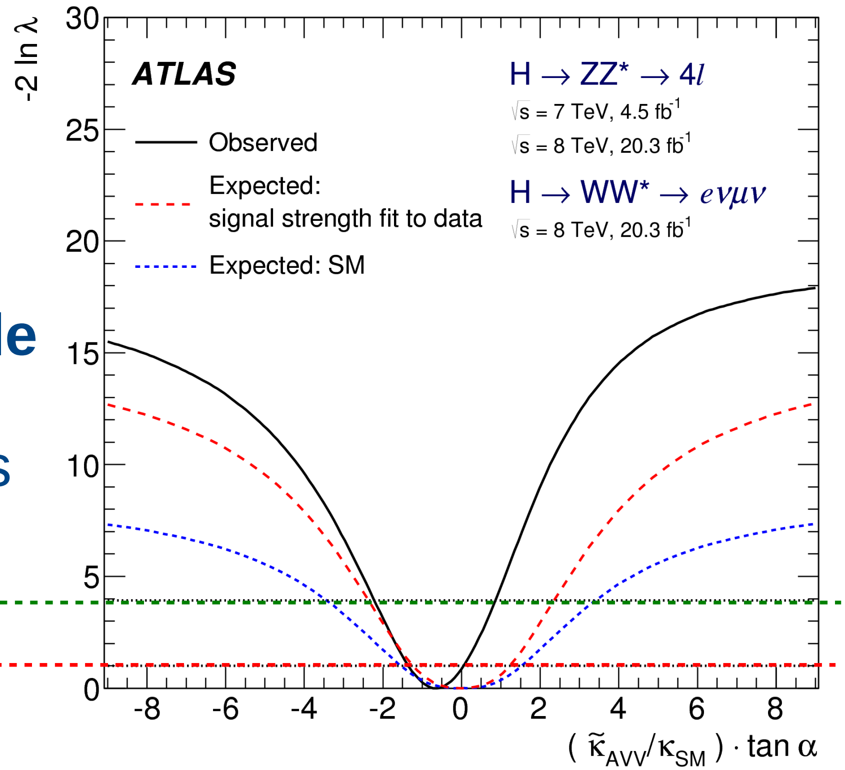
BSM hypothesis scenario: observed resonance is a **mixture** of SM spin-0 state and a **BSM spin-0 CP-even** or **CP-odd** state

Use $H \rightarrow ZZ^* \rightarrow 4l$ and $H \rightarrow WW^* \rightarrow e\nu\mu\nu$ to measure the ratios:

CL
95%
68%



Results **compatible with SM** predictions



Signal strengths/Couplings

arXiv:1507.04548

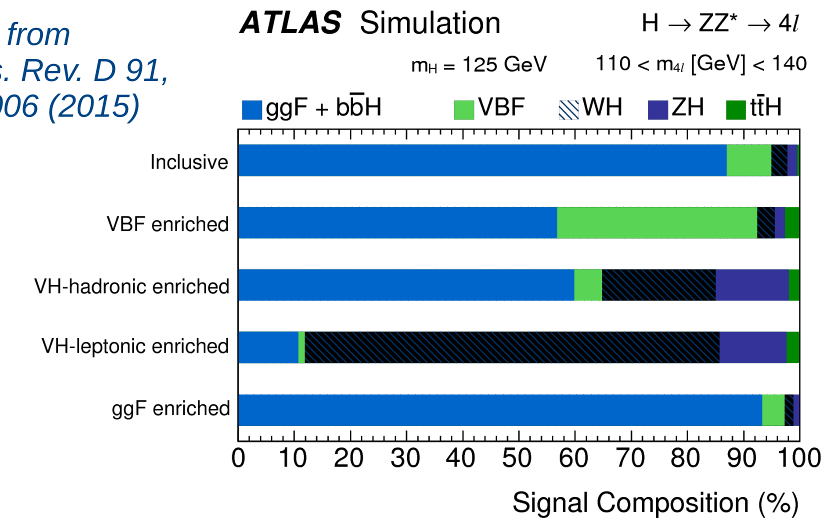
Combination of the following analysis:

- $H \to \gamma\gamma$
- $H \to ZZ^*$
- $H \to WW^*$
- $H \to Z\gamma$
- $H \to bb$
- $H \to \tau\tau$
- $H \to \mu\mu$
- ttH
- $H^* \to ZZ/WW$

Measurements:

- Signal strength $\mu = \frac{\sigma \cdot BR}{(\sigma \cdot BR)_{SM}}$
  - Production modes
  - Decay channels
- Coupling strength for several benchmark models

E.g. from Phys. Rev. D 91, 012006 (2015)



Approach of the analysis: **exclusive categories** to maximize sensitivity of different production modes, **global fit** to take into account contaminations inside categories and uncertainty correlations between different channels

Signal strength

Fix the Higgs mass to the ATLAS combined value value of 125.36 GeV

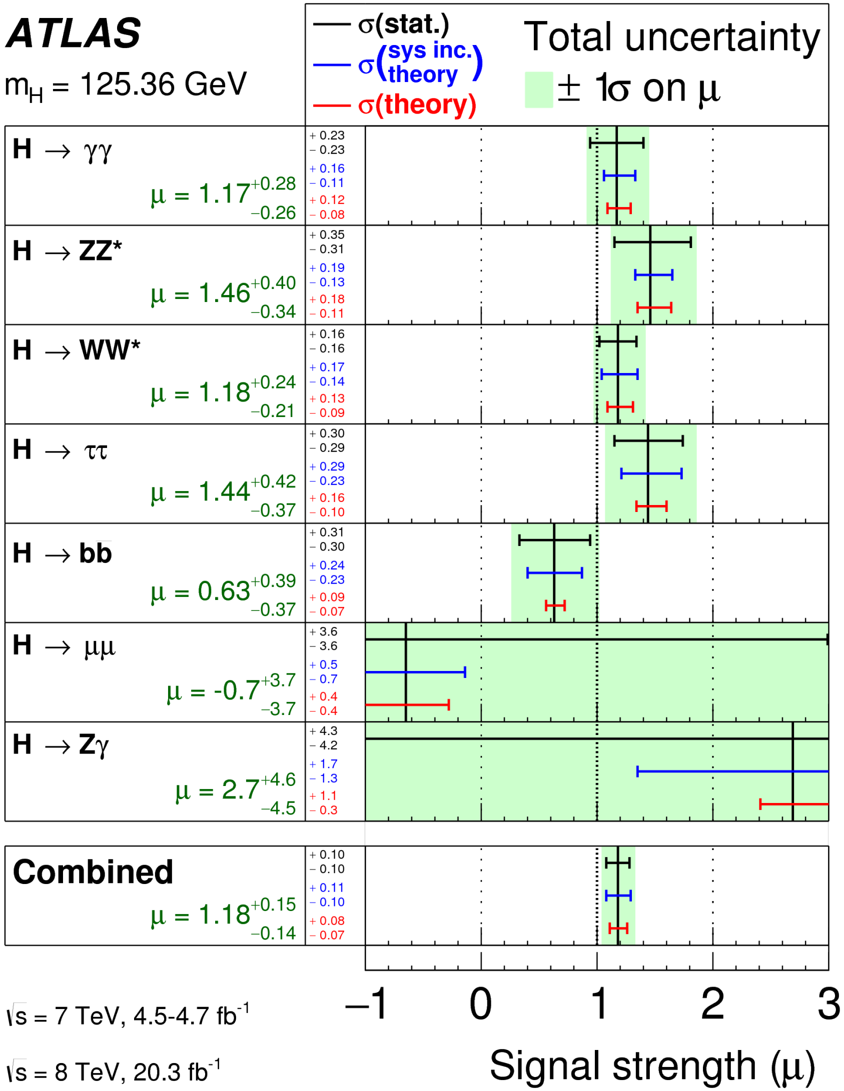
Combination imposing same signal strength in all channels

Best fit value:

$$\mu = 1.18^{+0.15}_{-0.14}$$

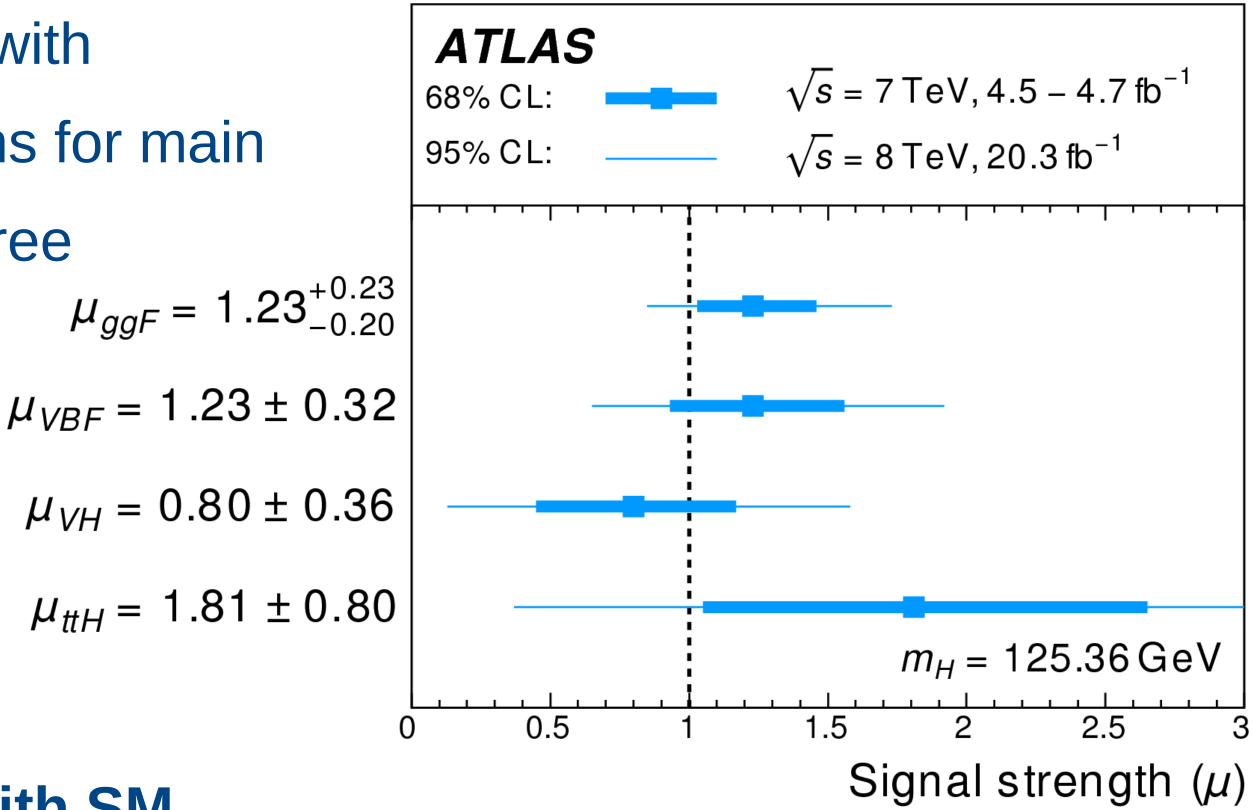
$$= 1.18 \pm 0.10\ (\text{stat}) \pm 0.07\ (\text{syst})\ ^{+0.08}_{-0.07}\ (\text{theo})$$

Consistent with SM (*p*-value of 18%)



Production signal strengths

Combination: **global fit** with individual signal strengths for main **production modes** as free parameters (assuming SM branching ratios)



Results in **agreement with SM**

Ratio of production cross sections

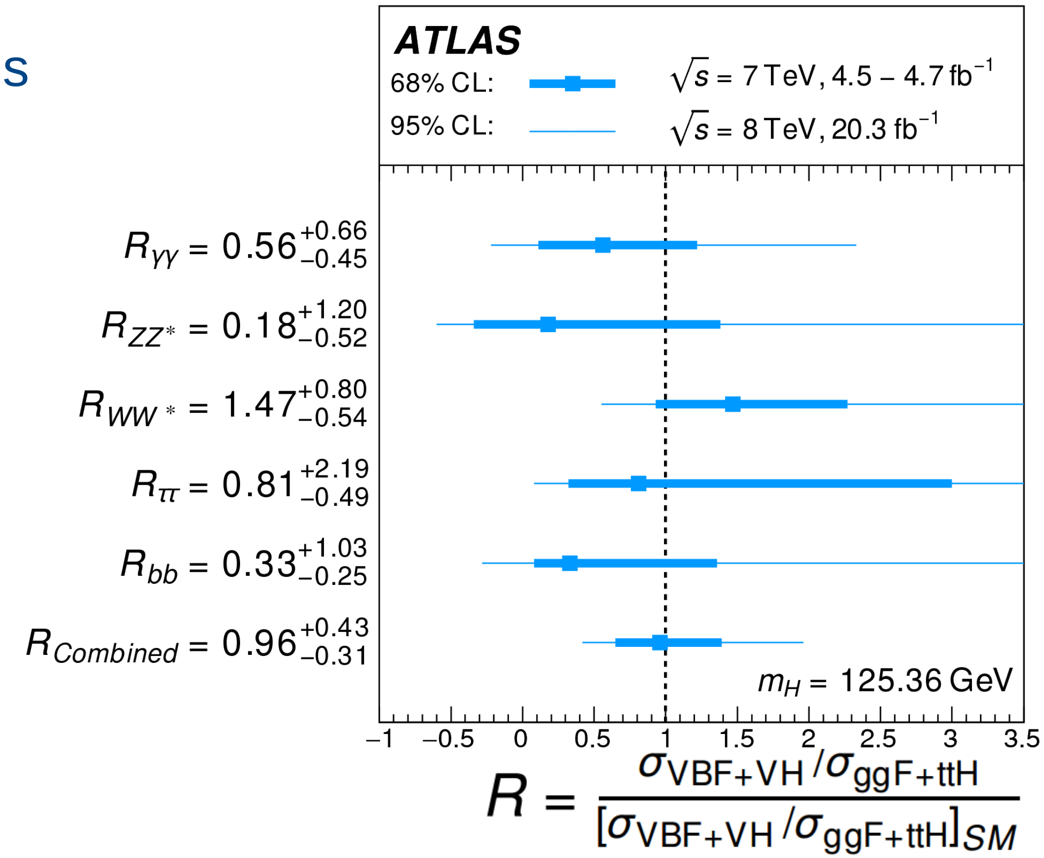
Ratio of cross sections:

- result independent of assumptions on inclusive cross section and BRs
- many systematic uncertainties cancel

Measured **significance** (in standard deviations) per **production** mode:

- ggF: > 5
- VBF: ~4.3
- ttH: ~2.5
- WH: ~2.1
- ZH: ~0.9
- VH: ~2.6

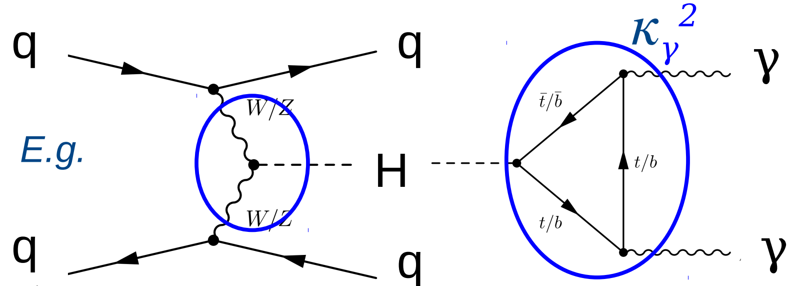
$\frac{\text{Boson}}{\text{Fermion}}$ mediated processes



Couplings studies

Framework → (LO) tree-level-motivated framework + assumptions: measure coupling strength scale factors κ_j relative to SM (SM: κ_j=1)

Combination of the different **production** modes and **decay** possibilities



$\sim 0.7 \cdot \kappa_W^2 + 0.3 \cdot \kappa_Z^2$

$\sim 1.6 \cdot \kappa_t^2 + 0.1 \cdot \kappa_W^2 + - 0.7 \cdot \kappa_t \kappa_W$

Benchmark models depending on the number of assumptions and constraints used to test couplings for:

- Fermions versus vectors (bosons)
- Symmetry between up- and down-type fermions
- Quarks versus leptons
- BSM contributions in loops and decays
- Generic models (all couplings as free parameters)

Fermion vs vector couplings

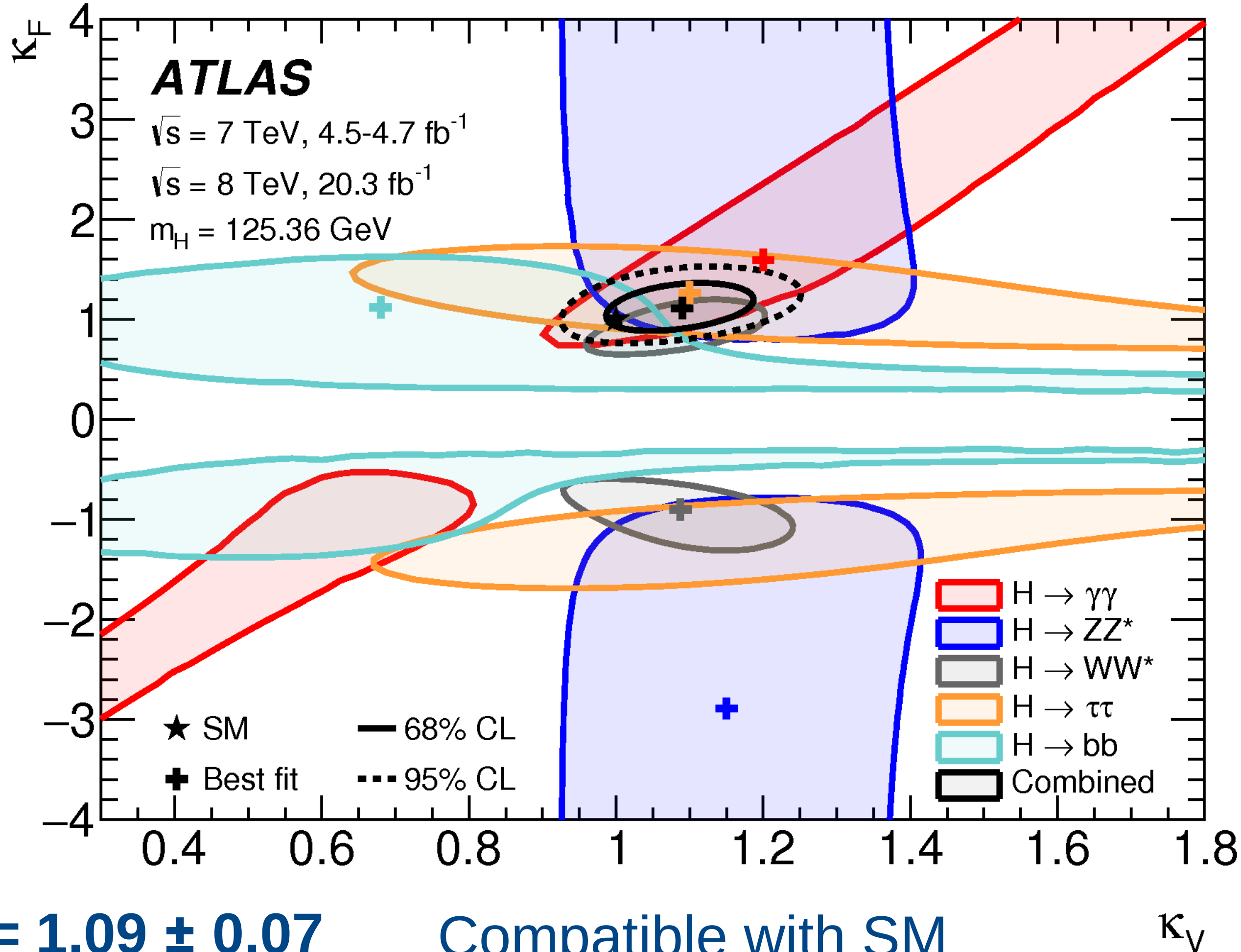
Probe coupling strength to **fermions** and **bosons**

Assumptions:

- no BSM in loops
- no BSM in decays
- universal coupling for fermions and bosons

$$\kappa_F = \kappa_t = \kappa_b = \kappa_\tau = \kappa_\mu$$

$$\kappa_V = \kappa_W = \kappa_Z$$



Best Fit:

$\kappa_F = 1.11 \pm 0.16$ $\kappa_V = 1.09 \pm 0.07$ Compatible with SM

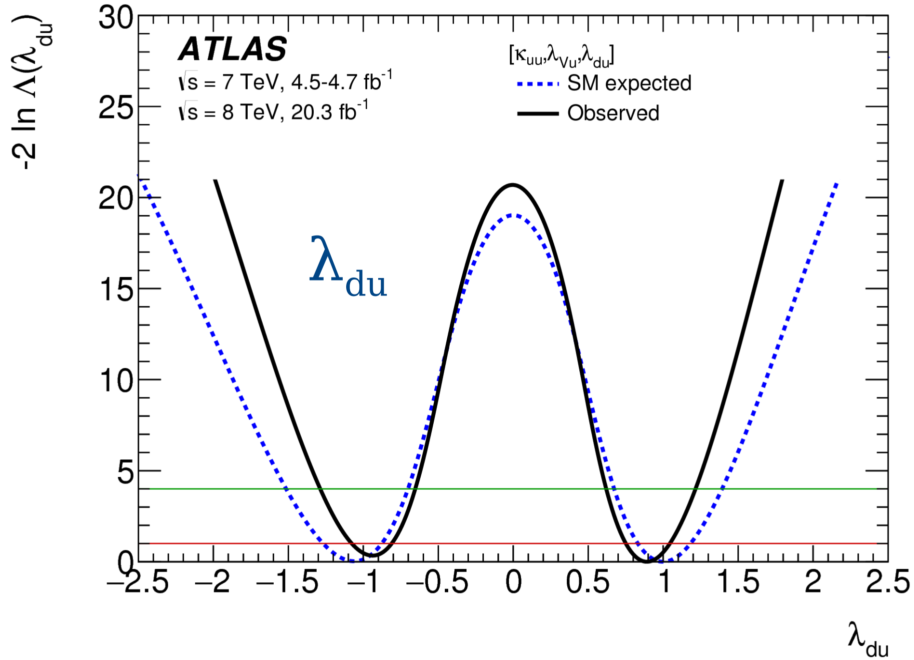
Fermion couplings

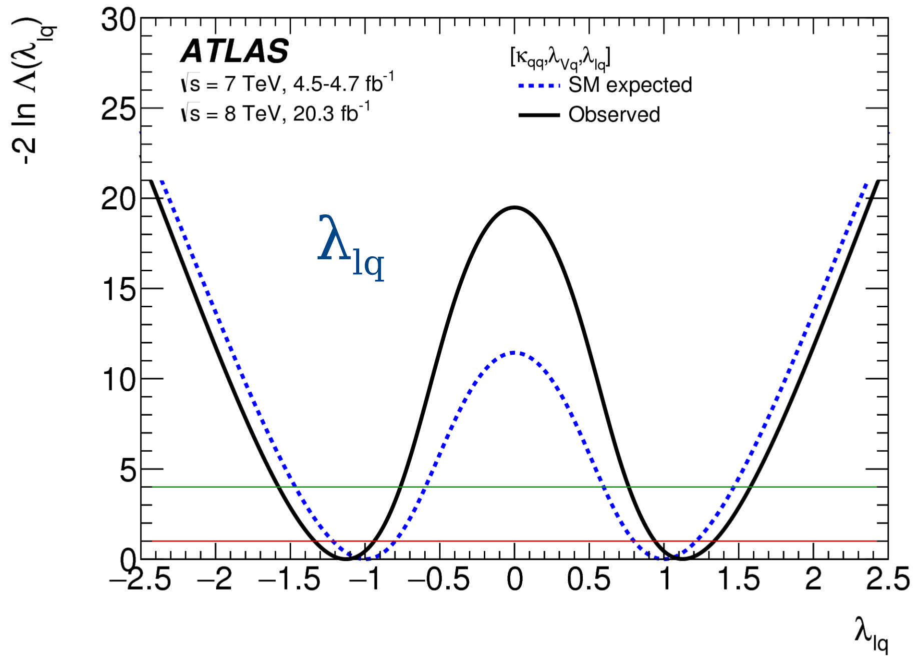
Test relations within the fermion coupling sector using ratios:

- up-down fermion symmetry
- lepton-quark symmetry

$$\lambda_{du} = \kappa_d / \kappa_u$$

Assumptions: only SM particles in vertex loops, vector boson couplings unified



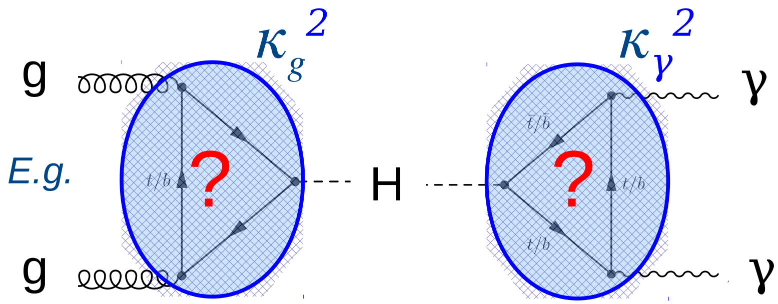


Coupling with **down-type** fermions found with significance of **4.5σ**

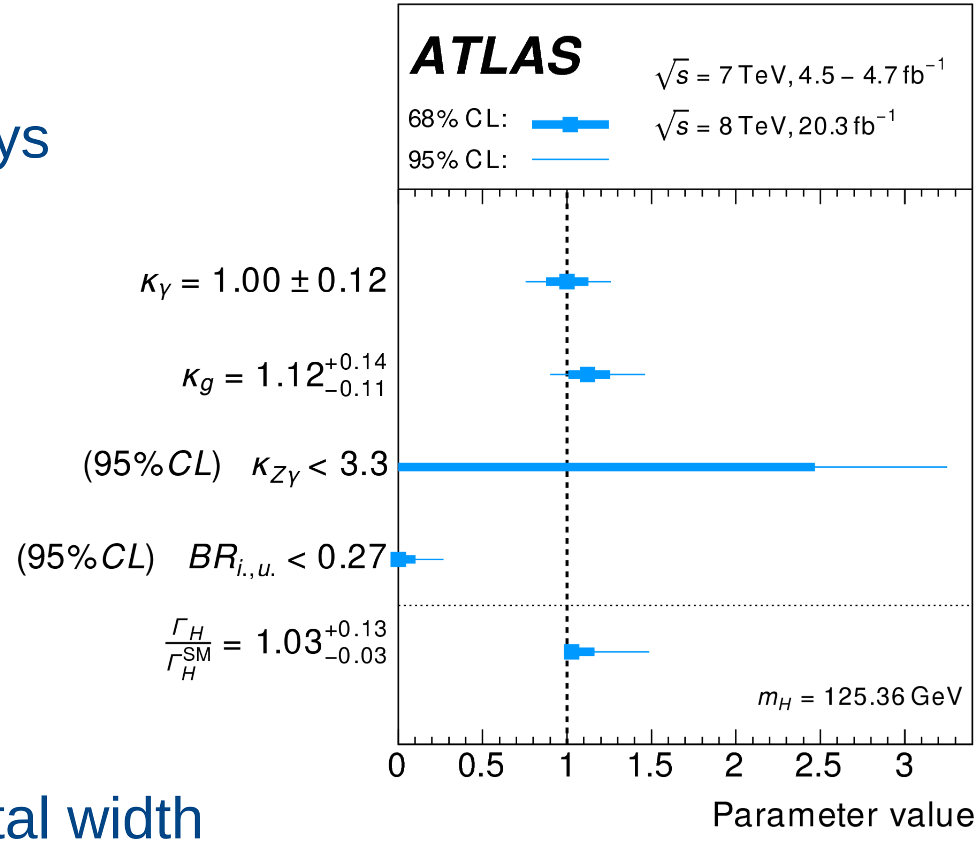
Coupling with **leptons** found with significance of **4.4σ**

BSM in loops and decays

Test contributions of **non-SM particles** in vertex loops and decays through effective scale factors



$\boldsymbol{\kappa_W = \kappa_Z = \kappa_t = \kappa_b = \kappa_\tau = \kappa_\mu = 1}$

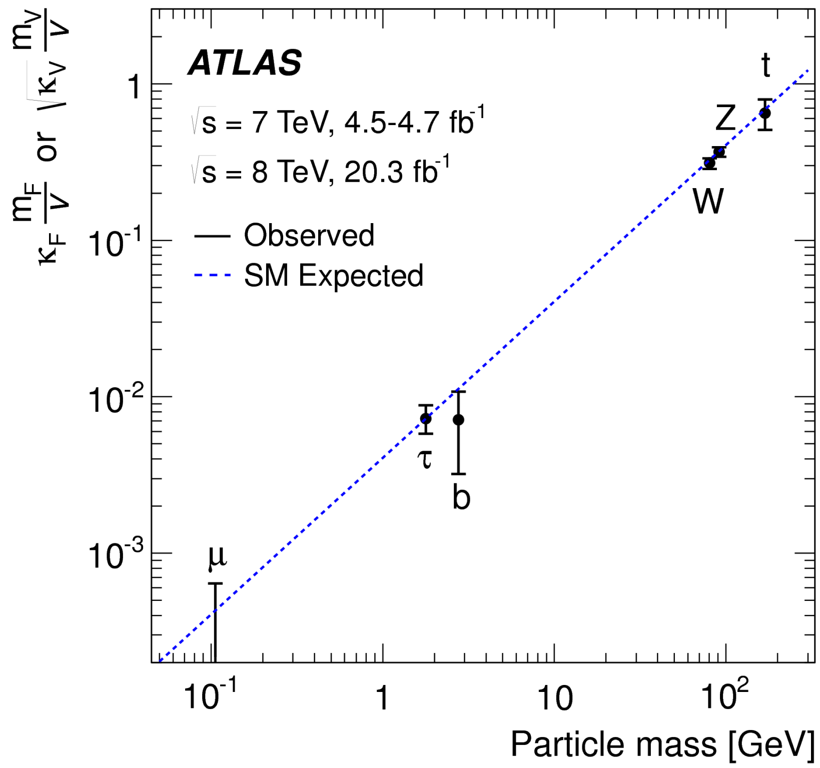


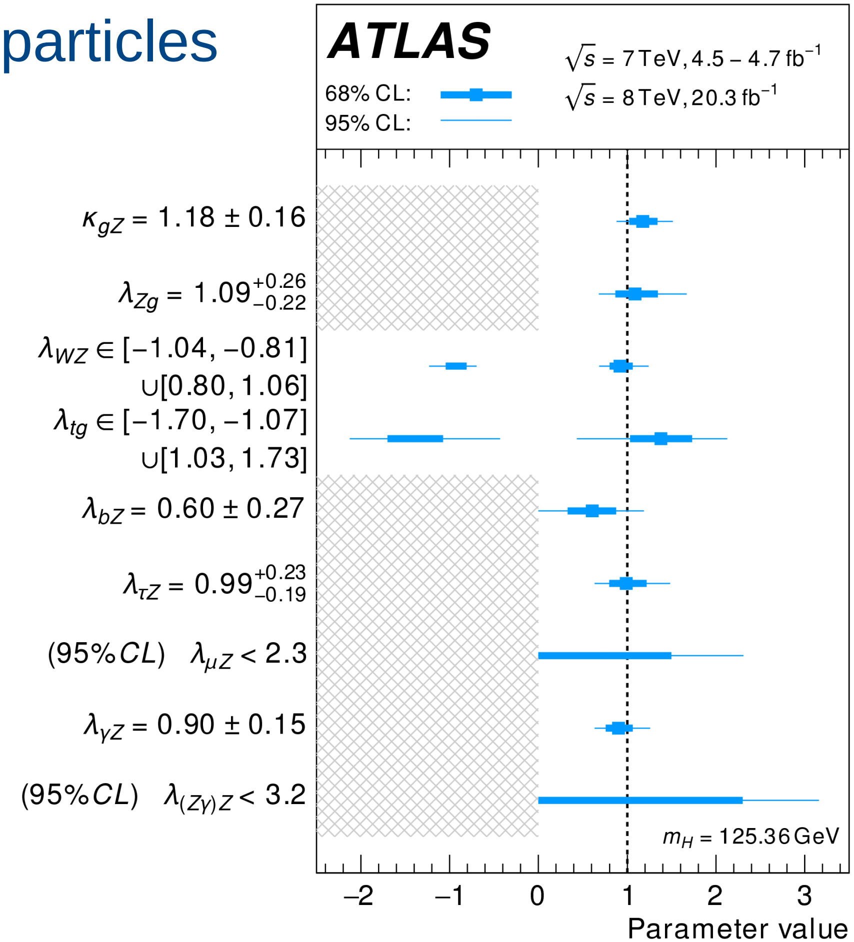
Allow contributions to the Higgs total width

SM hypothesis compatibility with best-fit point is 74%

Testing generic models

Generic model → all couplings for SM particles are free parameters





Assumption: no new particle in loops or decays

Most general: no assumption on loops and decays → **only coupling ratios** can be measured

Summary

Presented **Run1 ATLAS** measurements of the **Higgs** boson using $\sqrt{s}$ = 7 TeV and $\sqrt{s}$ = 8 TeV:

- **Spin/CP combination** of $H \rightarrow ZZ^* \rightarrow 4l$, $H \rightarrow WW^* \rightarrow e\nu\mu\nu$ and $H \rightarrow \gamma\gamma$ analysis
  - **Spin**: **all non-SM hypothesis considere**d are **excluded** at more than 99.9% CL
  - **CP**: distributions **compatible with SM** and limits set for BSM tensor couplings

- **Signal strength/coupling** combination of $H \rightarrow \gamma\gamma$, ZZ^*, WW^*, $Z\gamma$, bb, $\tau\tau$ and $\mu\mu$, ***ttH*** associated production (and **off-shell** coupling strength with the Higgs boson)
  - Combined yield relative to SM is

    $\boldsymbol{\mu = 1.18 \pm 0.10\ (\text{stat}) \pm 0.07\ (\text{syst})\ ^{+0.08}_{-0.07}\ (\text{theo})}$
  - **Production modes**: **gluon fusion confirmed** (significance exceeding 5σ), strong evidence for **VBF** (**4.3σ** significance)
  - Wide range of **benchmark coupling models** tested and limits set for **non-SM**

- **Looking forward to the new data coming!! Stay tuned!!**

Backup

SM Higgs production and decay

SM predictions of the Higgs boson (125.36 GeV) production cross sections and decay branching ratios and their uncertainties (*Handbook of LHC Higgs Cross Sections: 3. Higgs Properties (2013)*)

Production process	Cross section [pb] $\sqrt{s} = 7$ TeV	Cross section [pb] $\sqrt{s} = 8$ TeV
ggF	15.0 ± 1.6	19.2 ± 2.0
VBF	1.22 ± 0.03	1.57 ± 0.04
WH	0.573 ± 0.016	0.698 ± 0.018
ZH	0.332 ± 0.013	0.412 ± 0.013
bbH	0.155 ± 0.021	0.202 ± 0.028
ttH	0.086 ± 0.009	0.128 ± 0.014
tH	0.012 ± 0.001	0.018 ± 0.001
Total	17.4 ± 1.6	22.3 ± 2.0

Decay channel	Branching ratio [%]
$H \to b\bar{b}$	57.1 ± 1.9
$H \to WW^*$	22.0 ± 0.9
$H \to gg$	8.53 ± 0.85
$H \to \tau\tau$	6.26 ± 0.35
$H \to c\bar{c}$	2.88 ± 0.35
$H \to ZZ^*$	2.73 ± 0.11
$H \to \gamma\gamma$	0.228 ± 0.011
$H \to Z\gamma$	0.157 ± 0.014
$H \to \mu\mu$	0.022 ± 0.001

Spin-2 framework

Parametrized in couplings to fermions and vector bosons.

$$\mathcal{L}_2 = -\frac{1}{\Lambda}\left[\sum_V \kappa_V \mathcal{T}^V_{\mu\nu} X^{\mu\nu} + \sum_f \kappa_f \mathcal{T}^f_{\mu\nu} X^{\mu\nu}\right]$$

Production dominated by QCD → only including QCD production from quarks and gluons: κ_q , κ_g

Values of spin-2 quark and gluon couplings		p_T^X selections (GeV)	
$\kappa_q = \kappa_g$	Universal couplings	–	–
$\kappa_q = 0$	Low light-quark fraction	< 300	< 125
$\kappa_q = 2\kappa_g$	Low gluon fraction	< 300	< 125

EFT lagrangian allows for more complex processes with emission of one or more additional partons

Spin results: tables

Expected and observed *p*-values for different spin-parity hypothesis

Tested Hypothesis	$p^{\text{alt}}_{\text{exp},\mu=1}$	$p^{\text{alt}}_{\text{exp},\mu=\hat{\mu}}$	$p^{\text{SM}}_{\text{obs}}$	$p^{\text{alt}}_{\text{obs}}$	Obs. CL_s (%)
0^+_h	$2.5 \cdot 10^{-2}$	$4.7 \cdot 10^{-3}$	0.85	$7.1 \cdot 10^{-5}$	$4.7 \cdot 10^{-2}$
0^-	$1.8 \cdot 10^{-3}$	$1.3 \cdot 10^{-4}$	0.88	$< 3.1 \cdot 10^{-5}$	$< 2.6 \cdot 10^{-2}$
$2^+(\kappa_q = \kappa_g)$	$4.3 \cdot 10^{-3}$	$2.9 \cdot 10^{-4}$	0.61	$4.3 \cdot 10^{-5}$	$1.1 \cdot 10^{-2}$
$2^+(\kappa_q = 0;\ p_{\text{T}} < 300GeV)$	$< 3.1 \cdot 10^{-5}$	$< 3.1 \cdot 10^{-5}$	0.52	$< 3.1 \cdot 10^{-5}$	$< 6.5 \cdot 10^{-3}$
$2^+(\kappa_q = 0;\ p_{\text{T}} < 125GeV)$	$3.4 \cdot 10^{-3}$	$3.9 \cdot 10^{-4}$	0.71	$4.3 \cdot 10^{-5}$	$1.5 \cdot 10^{-2}$
$2^+(\kappa_q = 2\kappa_g;\ p_{\text{T}} < 300GeV)$	$< 3.1 \cdot 10^{-5}$	$< 3.1 \cdot 10^{-5}$	0.28	$< 3.1 \cdot 10^{-5}$	$< 4.3 \cdot 10^{-3}$
$2^+(\kappa_q = 2\kappa_g;\ p_{\text{T}} < 125GeV)$	$7.8 \cdot 10^{-3}$	$1.2 \cdot 10^{-3}$	0.80	$7.3 \cdot 10^{-5}$	$3.7 \cdot 10^{-2}$

Expected and observed best-fit values for CP mixing parameters

Coupling ratio	Best-fit value	95% CL Exclusion Regions	
Combined	Observed	Expected	Observed
$\tilde{\kappa}_{HVV}/\kappa_{\text{SM}}$	-0.48	$(-\infty, -0.55] \bigcup [4.80, \infty)$	$(-\infty, -0.73] \bigcup [0.63, \infty)$
$(\tilde{\kappa}_{AVV}/\kappa_{\text{SM}}) \cdot \tan\alpha$	-0.68	$(-\infty, -2.33] \bigcup [2.30, \infty)$	$(-\infty, -2.18] \bigcup [0.83, \infty)$

Production mode categories

Overview of the categories of the individual analysis included in the combination

Analysis	Signal		$\int \mathcal{L}dt$ [fb^{-1}]	
Categorisation or final states	Strength μ	Significance [s.d.]	7 TeV	8 TeV
$H \to \gamma\gamma$ [12]	1.17 ± 0.27	5.2 (4.6)	4.5	20.3
ttH: leptonic, hadronic			✓	✓
VH: one-lepton, dilepton, E_T^{miss}, hadronic			✓	✓
VBF: tight, loose			✓	✓
ggF: 4 p_{Tt} categories			✓	✓
$H \to ZZ^* \to 4\ell$ [13]	$1.44^{+0.40}_{-0.33}$	8.1 (6.2)	4.5	20.3
VBF			✓	✓
VH: hadronic, leptonic			✓	✓
ggF			✓	✓
$H \to WW^*$ [14,15]	$1.16^{+0.24}_{-0.21}$	6.5 (5.9)	4.5	20.3
ggF: (0-jet, 1-jet) $\otimes$ ($ee + \mu\mu$, $e\mu$)			✓	✓
ggF: $\geq$ 2-jet and $e\mu$				✓
VBF: $\geq$ 2-jet $\otimes$ ($ee + \mu\mu$, $e\mu$)			✓	✓
VH: opposite-charge dilepton, three-lepton, four-lepton			✓	✓
VH: same-charge dilepton				✓
$H \to \tau\tau$ [17]	$1.43^{+0.43}_{-0.37}$	4.5 (3.4)	4.5	20.3
Boosted: $\tau_{lep}\tau_{lep}, \tau_{lep}\tau_{had}, \tau_{had}\tau_{had}$			✓	✓
VBF: $\tau_{lep}\tau_{lep}, \tau_{lep}\tau_{had}, \tau_{had}\tau_{had}$			✓	✓
$VH \to Vb\bar{b}$ [18]	0.52 ± 0.40	1.4 (2.6)	4.7	20.3
0ℓ ($ZH \to \nu\nu b\bar{b}$): $N_{jet} = 2, 3$, $N_{btag} = 1, 2$, $p_T^V \in$ 100-120 and >120 GeV			✓	✓
1ℓ ($WH \to \ell\nu b\bar{b}$): $N_{jet} = 2, 3$, $N_{btag} = 1, 2$, p_T^V < and >120 GeV			✓	✓
2ℓ ($ZH \to \ell\ell b\bar{b}$): $N_{jet} = 2, 3$, $N_{btag} = 1, 2$, p_T^V < and >120 GeV			✓	✓

	95% CL limit		
$H \to Z\gamma$ [19]	$\mu < 11$ (9)	4.5	20.3
10 categories based on $\Delta\eta_{Z\gamma}$ and p_{Tt}		✓	✓
$H \to \mu\mu$ [20]	$\mu < 7.0$ (7.2)	4.5	20.3
VBF and 6 other categories based on η_μ and $p_T^{\mu\mu}$		✓	✓
ttH production [21,22,23]		4.5	20.3
$H \to b\bar{b}$: single-lepton, dilepton	$\mu < 3.4$ (2.2)		✓
$ttH \to$multileptons: categories on lepton multiplicity	$\mu < 4.7$ (2.4)		✓
$H \to \gamma\gamma$: leptonic, hadronic	$\mu < 6.7$ (4.9)	✓	✓
Off-shell H^* production [24]	$\mu < 5.1 - 8.6$ ($6.7 - 11.0$)		20.3
$H^* \to ZZ \to 4\ell$			✓
$H^* \to ZZ \to 2\ell 2\nu$			✓
$H^* \to WW \to e\nu\mu\nu$			✓

From signal strength to cross section

Tabled results for measured signal strengths (and cross section), assuming SM values for Higgs decay BRs

Production process	Signal strength μ at $m_H = 125.36$ GeV			
	$\sqrt{s} = 8$ TeV		Combined $\sqrt{s} = 7$ and 8 TeV	
ggF	$1.23\,^{+0.25}_{-0.21}$	$\left[\begin{smallmatrix}+0.16 & +0.10 & +0.16\\ -0.16 & -0.08 & -0.11\end{smallmatrix}\right]$	$1.23\,^{+0.23}_{-0.20}$	$\left[\begin{smallmatrix}+0.14 & +0.09 & +0.16\\ -0.14 & -0.08 & -0.12\end{smallmatrix}\right]$
VBF	$1.55^{+0.39}_{-0.35}$	$\left[\begin{smallmatrix}+0.32 & +0.17 & +0.13\\ -0.31 & -0.13 & -0.11\end{smallmatrix}\right]$	1.23 ± 0.32	$\left[\begin{smallmatrix}+0.28 & +0.13 & +0.11\\ -0.27 & -0.12 & -0.09\end{smallmatrix}\right]$
VH	0.93 ± 0.39	$\left[\begin{smallmatrix}+0.37 & +0.20 & +0.12\\ -0.33 & -0.18 & -0.06\end{smallmatrix}\right]$	0.80 ± 0.36	$\left[\begin{smallmatrix}+0.31 & +0.17 & +0.10\\ -0.30 & -0.17 & -0.05\end{smallmatrix}\right]$
ttH	1.62 ± 0.78	$\left[\begin{smallmatrix}+0.51 & +0.58 & +0.28\\ -0.50 & -0.54 & -0.10\end{smallmatrix}\right]$	1.81 ± 0.80	$\left[\begin{smallmatrix}+0.52 & +0.58 & +0.31\\ -0.50 & -0.55 & -0.12\end{smallmatrix}\right]$

Production process	Cross section [pb] at $\sqrt{s} = 8$ TeV	
ggF	23.9 ± 3.6	$\left[\begin{smallmatrix}+3.1 & +1.9 & +1.0\\ -3.1 & -1.6 & -1.0\end{smallmatrix}\right]$
VBF	2.43 ± 0.58	$\left[\begin{smallmatrix}+0.50 & +0.27 & +0.19\\ -0.49 & -0.20 & -0.16\end{smallmatrix}\right]$
VH	1.03 ± 0.53	$\left[\begin{smallmatrix}+0.37 & +0.22 & +0.13\\ -0.36 & -0.20 & -0.06\end{smallmatrix}\right]$
ttH	0.24 ± 0.11	$\left[\begin{smallmatrix}+0.07 & +0.08 & +0.01\\ -0.07 & -0.08 & -0.01\end{smallmatrix}\right]$

From signal strength to cross section

Best-fit value for combined signal strength

$$\mu(7\,\text{TeV}) = 0.75\,^{+0.32}_{-0.29} = 0.75\,^{+0.28}_{-0.26}\,(\text{stat.})\,^{+0.13}_{-0.11}\,(\text{syst.})\,^{+0.08}_{-0.05}\,(\text{theo.}),\ \text{and}$$

$$\mu(8\,\text{TeV}) = 1.28\,^{+0.17}_{-0.15} = 1.28 \pm 0.11\,(\text{stat.})\,^{+0.08}_{-0.07}\,(\text{syst.})\,^{+0.10}_{-0.08}\,(\text{theo.})$$

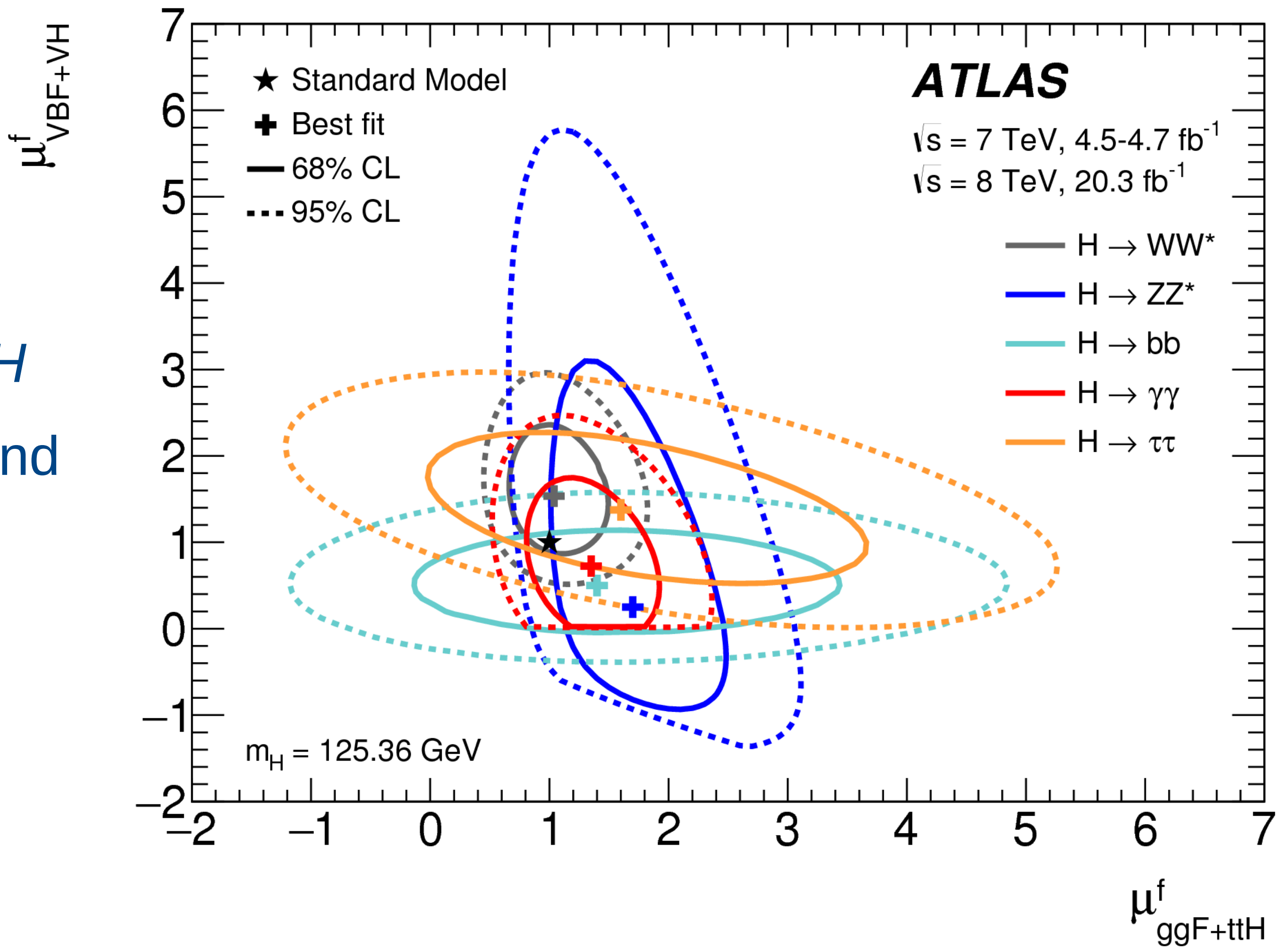
The signal strength measurements are extrapolated to total cross section measurements for each production process that summed result in the total Higgs boson production cross section:

$$\sigma_H(7\,\text{TeV}) = 22.1\,^{+7.4}_{-6.0}\,\text{pb} = 22.1\,^{+6.7}_{-5.3}\,(\text{stat.})\,^{+2.7}_{-2.3}\,(\text{syst.})\,^{+1.9}_{-1.4}\,(\text{theo.})\,\text{pb},\ \text{and}$$

$$\sigma_H(8\,\text{TeV}) = 27.7 \pm 3.7\,\text{pb} = 27.7 \pm 3.0\,(\text{stat.})\,^{+2.0}_{-1.7}\,(\text{syst.})\,^{+1.2}_{-0.9}\,(\text{theo.})\,\text{pb},$$

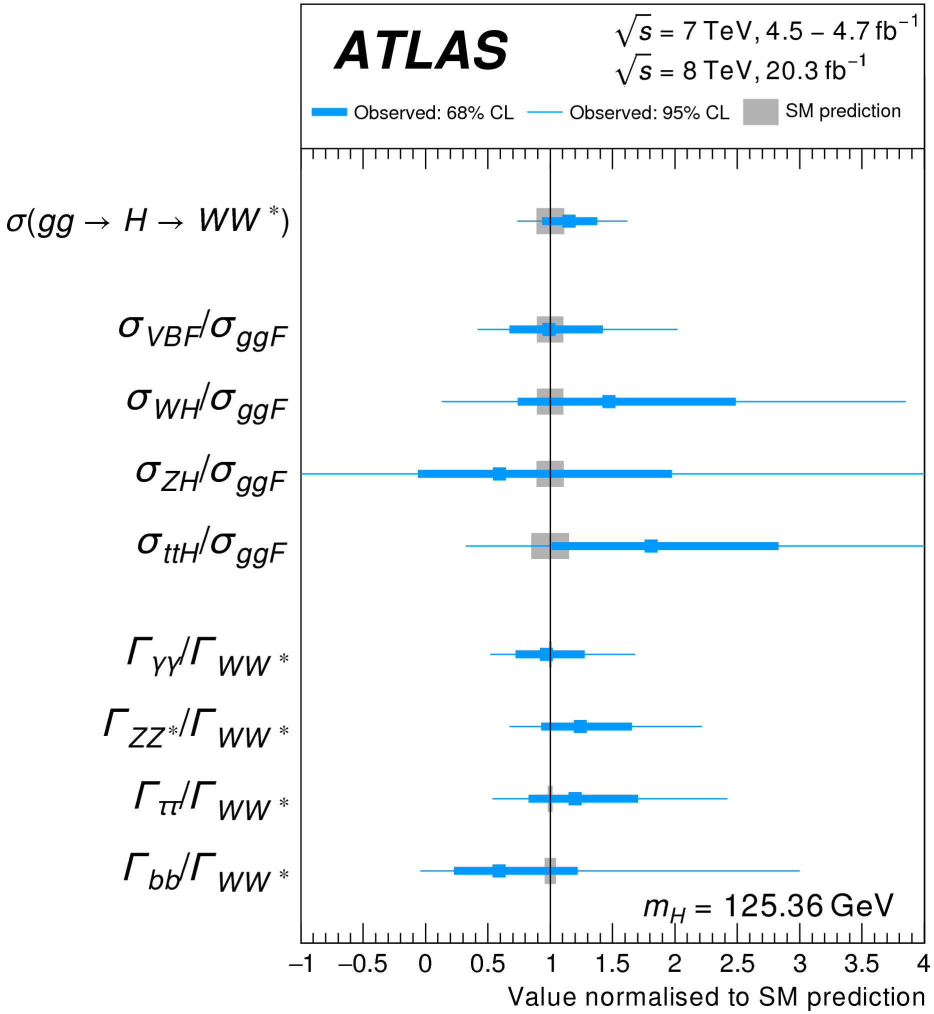
Fermion vs boson coupling

SM values are assumed for the relative contribution between ggF and *ttH* and between VBF and *VH* production



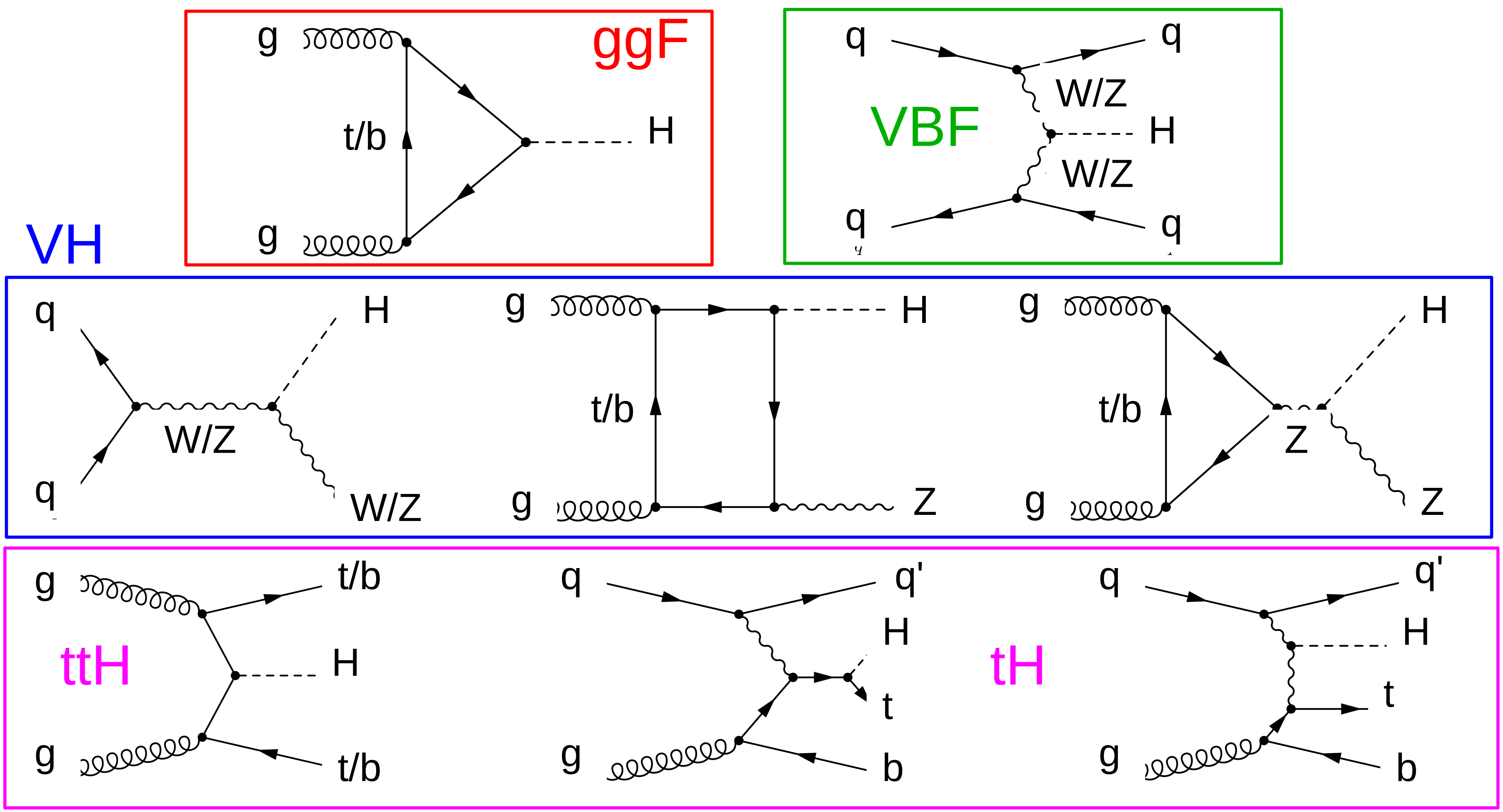
Ratio of cross sections and of partial decay width

$gg \rightarrow H \rightarrow WW^*$ cross section and ratios of cross sections and partial decay widths relative to their SM values



Couplings: production modes

The 8 different production modes considered in the coupling measurement



κ-framework

Production	Loops	Interference	Expression in fundamental coupling-strength scale factors
$\sigma(\text{ggF})$	✓	b–t	$\kappa_g^2 \sim 1.06 \cdot \kappa_t^2 + 0.01 \cdot \kappa_b^2 - 0.07 \cdot \kappa_t \kappa_b$
$\sigma(\text{VBF})$	-	-	$\sim 0.74 \cdot \kappa_W^2 + 0.26 \cdot \kappa_Z^2$
$\sigma(WH)$	-	-	$\sim \kappa_W^2$
$\sigma(q\bar{q} \to ZH)$	-	-	$\sim \kappa_Z^2$
$\sigma(gg \to ZH)$	✓	Z–t	$\kappa_{ggZH}^2 \sim 2.27 \cdot \kappa_Z^2 + 0.37 \cdot \kappa_t^2 - 1.64 \cdot \kappa_Z \kappa_t$
$\sigma(bbH)$	-	-	$\sim \kappa_b^2$
$\sigma(ttH)$	-	-	$\sim \kappa_t^2$
$\sigma(gb \to WtH)$	-	W–t	$\sim 1.84 \cdot \kappa_t^2 + 1.57 \cdot \kappa_W^2 - 2.41 \cdot \kappa_t \kappa_W$
$\sigma(qb \to tHq')$	-	W–t	$\sim 3.4 \cdot \kappa_t^2 + 3.56 \cdot \kappa_W^2 - 5.96 \cdot \kappa_t \kappa_W$
Partial decay width			
$\Gamma_{b\bar{b}}$	-	-	$\sim \kappa_b^2$
Γ_{WW}	-	-	$\sim \kappa_W^2$
Γ_{ZZ}	-	-	$\sim \kappa_Z^2$
$\Gamma_{\tau\tau}$	-	-	$\sim \kappa_\tau^2$
$\Gamma_{\mu\mu}$	-	-	$\sim \kappa_\mu^2$
$\Gamma_{\gamma\gamma}$	✓	W–t	$\kappa_\gamma^2 \sim 1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.66 \cdot \kappa_W \kappa_t$
$\Gamma_{Z\gamma}$	✓	W–t	$\kappa_{Z\gamma}^2 \sim 1.12 \cdot \kappa_W^2 + 0.00035 \cdot \kappa_t^2 - 0.12 \cdot \kappa_W \kappa_t$
Total decay width			
Γ_H	✓	$W-t$ $b-t$	$\kappa_H^2 \sim 0.57 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.09 \cdot \kappa_g^2 + 0.06 \cdot \kappa_\tau^2 + 0.03 \cdot \kappa_Z^2 + 0.03 \cdot \kappa_c^2 + 0.0023 \cdot \kappa_\gamma^2 + 0.0016 \cdot \kappa_{Z\gamma}^2 + 0.00022 \cdot \kappa_\mu^2$