Precision Higgs Physics: Higgs couplings

HL/HE-LHC Physics Workshop: final jamboree

A. de Wit (DESY) on behalf of HL/HE-LHC WG2

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

Outline

- **Higgs boson measurements in Run 2**

- **Analysis procedures**

- **Results**

  - Combined measurement of Higgs boson couplings

  - Differential measurements

  - Width

  - Invisible decays

- **Summary and HE-LHC prospects**

DESY.

Higgs boson measurements in Run 2

- So far, Higgs boson properties in agreement with the SM expectation
  - Bosonic (Run 1) and 3d generation fermionic couplings (Run 2) observed - current precision on couplings ~10-30% (single-experiment)
  - 2nd generation fermion couplings still to be established
- Goal for the future: improve precision
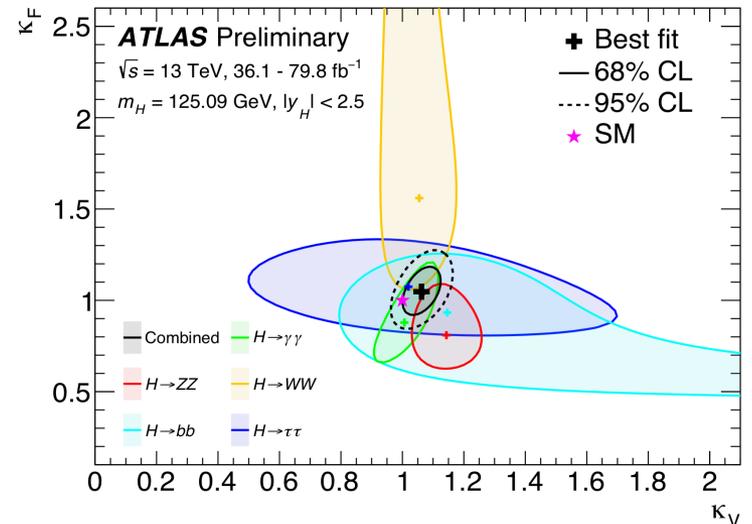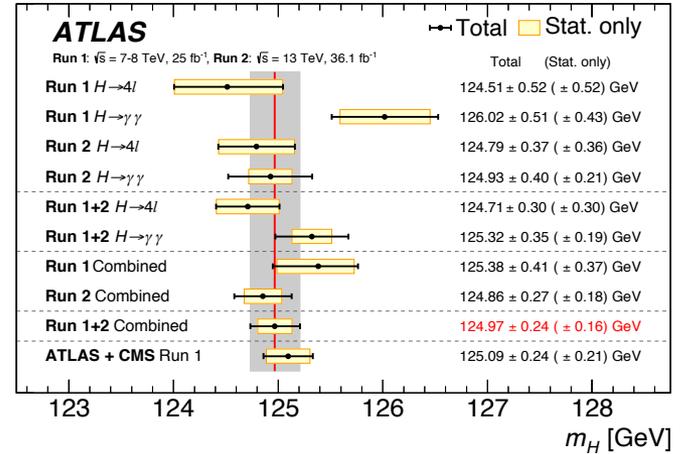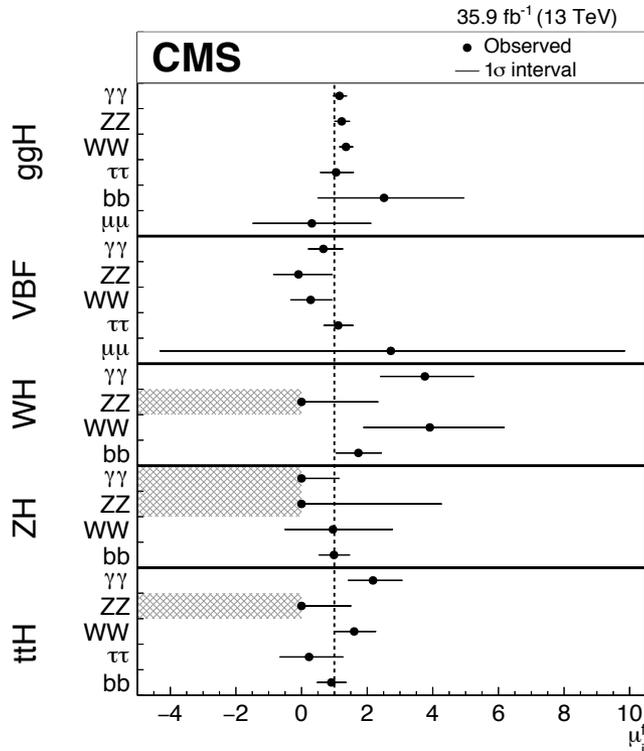
Analysis procedures

Analysis of simulated samples with HL-LHC conditions and detectors

- Generally for new, or significantly improved, analyses

Extrapolations from Run 2 data to 3 ab^{-1}

- Analyses that were already performed in Run 2
- Efficiencies, resolutions, fake rates assumed unchanged from the Run 2 values
- Main scenario **YR18 systematic uncertainties (S2)**:
  - **Most theoretical uncertainties scaled down by a factor 1/2, experimental uncertainties scaled down by $\sqrt{L}$ until they reach a defined lower limit.**
  - Scenario for comparison: using Run 2 systematic uncertainties (S1)
  - In all cases uncertainties due to the finite number of simulated events are neglected

All results presented in this talk included in the report from HE/HL-LHC WG 2: arXiv:1902.00134

Combined Higgs coupling measurements

Inputs

- Projection of combined measurements of Higgs boson couplings using data collected in 2015-2017 (ATLAS) and 2016 (CMS)

- Covers all main production (gluon fusion, VBF, VH, ttH) and decay modes ($\gamma\gamma$, ZZ, WW, bb, $\tau\tau$, $\mu\mu$, Zγ)

Selection of projected input analyses

H→γγ

H→ττ
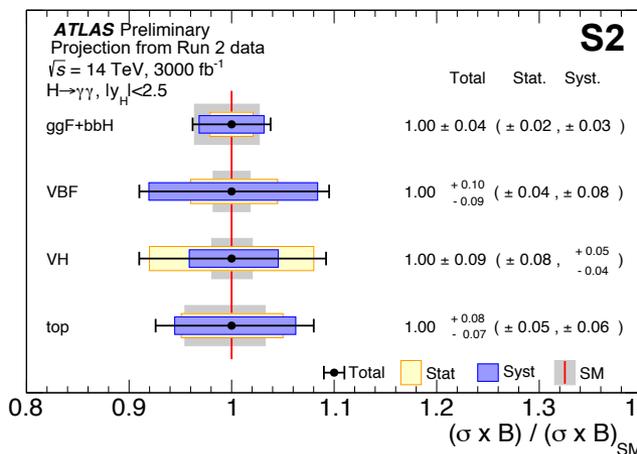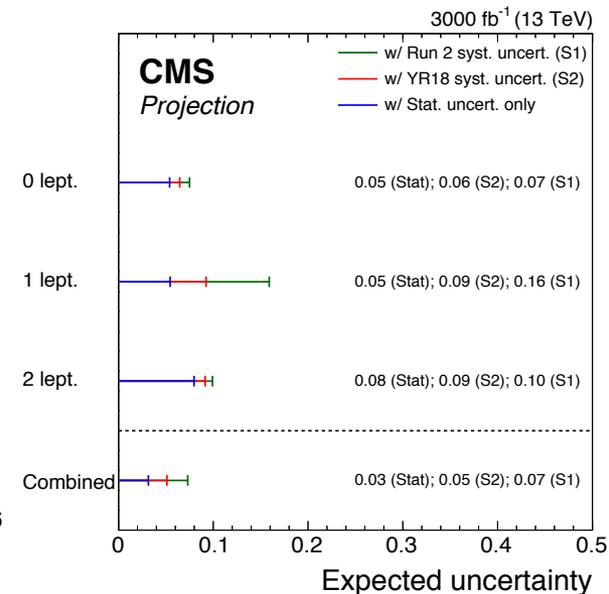
VH, H→bb

Combined Higgs coupling measurements

Production cross sections

S2

$\sqrt{s} = 14$ TeV, 3000 fb^{-1} per experiment

ATLAS and *CMS*

HL-LHC Projection

Legend:
- Total (gray)
- Statistical (blue)
- Experimental (green)
- Theory (red)

Uncertainty [%]

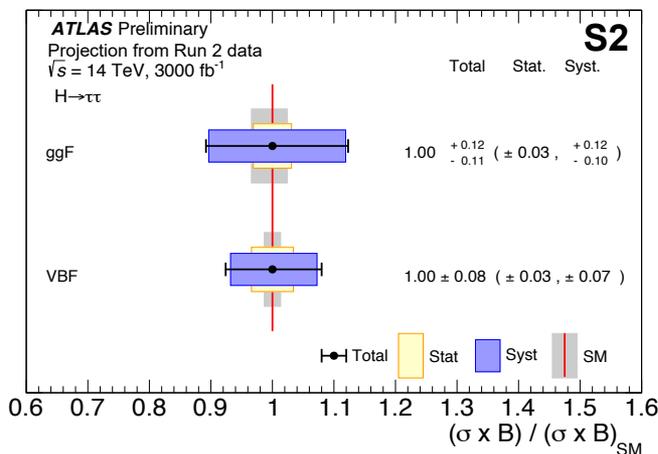|	Tot	Stat	Exp	Th
σ_{ggH}	**1.6**	0.7	0.8	1.2
σ_{VBF}	**3.1**	1.8	1.3	2.1
σ_{WH}	**5.7**	3.3	2.4	4.0
σ_{ZH}	**4.2**	2.6	1.3	3.1
σ_{ttH}	**4.3**	1.3	1.8	3.7

Expected relative uncertainty

Branching ratios

S2

$\sqrt{s} = 14$ TeV, 3000 fb^{-1} per experiment

ATLAS and *CMS*

HL-LHC Projection

Legend:
- Total (gray)
- Statistical (blue)
- Experimental (green)
- Theory (red)

Uncertainty [%]

	Tot	Stat	Exp	Th
$B^{\gamma\gamma}$	**2.6**	1.0	1.5	1.9
B^{ZZ}	**2.9**	1.2	1.5	2.2
B^{WW}	**2.8**	1.1	1.2	2.3
$B^{\tau\tau}$	**2.9**	1.4	1.3	2.2
B^{bb}	**4.4**	1.5	1.3	4.0
$B^{\mu\mu}$	**8.2**	7.4	1.5	3.0
$B^{Z\gamma}$	**19.1**	14.3	3.2	12.2

Expected relative uncertainty

$B^{\mu\mu}$ and $B^{Z\gamma}$ statistically limited.

Other branching ratios and cross sections dominated by theoretical uncertainties.

Combined Higgs coupling measurements

Consider coupling modifiers κ_j: $\quad \kappa_j^2 = \dfrac{\sigma_j}{\sigma_j^{SM}}$; $\quad \kappa_j^2 = \dfrac{\Gamma_j}{\Gamma_j^{SM}}$. Dependence on partial width ➜ coupling modifiers depend on each other.

Here: effective coupling modifiers (loops in γ, g and Zγ coupling not resolved)

Can also consider ratio of coupling modifiers λ_{ij}, $\lambda_{ij} = \dfrac{\kappa_i}{\kappa_j}$ with reference parameter $\kappa_{gZ} = \dfrac{\kappa_g \kappa_Z}{\kappa_H}$

Coupling modifiers

Ratios of coupling modifiers

Left panel — Coupling modifiers
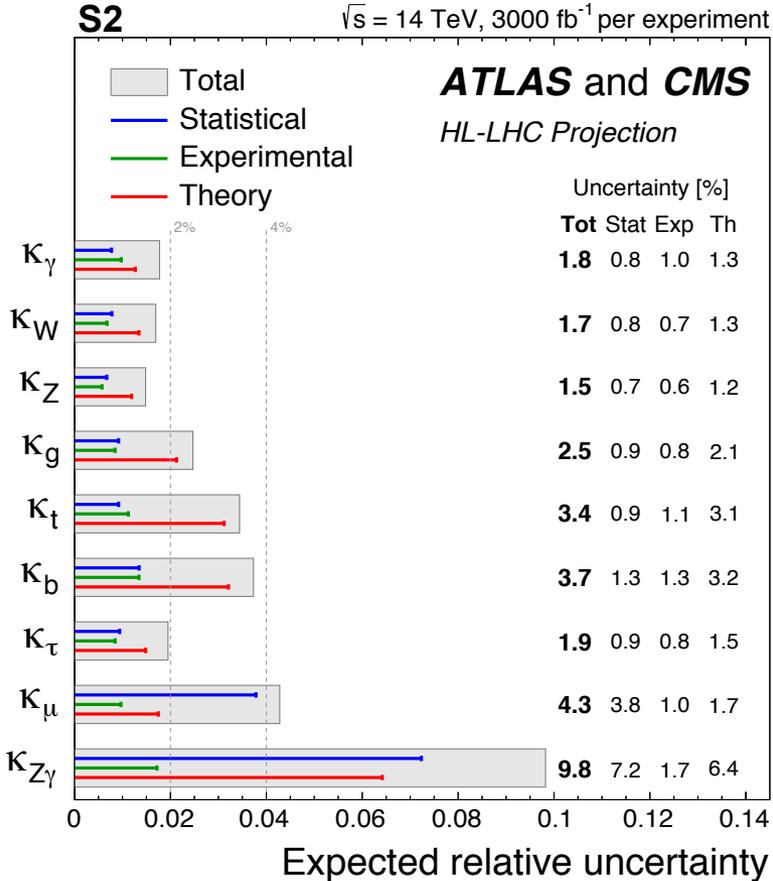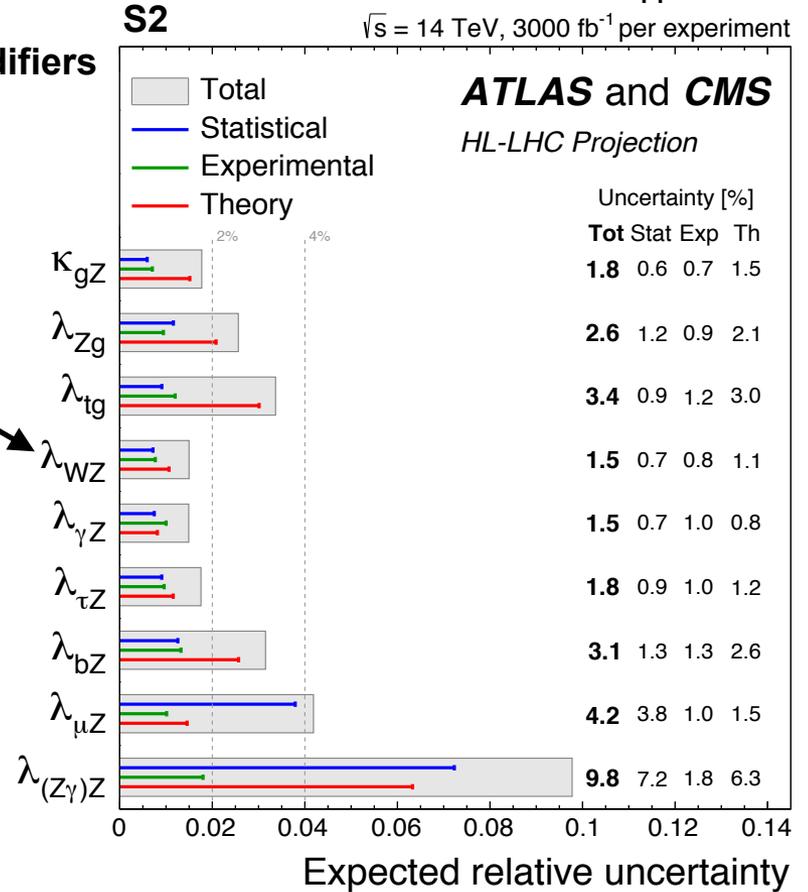
S2 — $\sqrt{s}$ = 14 TeV, 3000 fb^{-1} per experiment — *ATLAS* and *CMS* — HL-LHC Projection

Legend: Total (grey), Statistical (blue), Experimental (green), Theory (red)

	Uncertainty [%]			
	Tot	Stat	Exp	Th
κ_γ	**1.8**	0.8	1.0	1.3
κ_W	**1.7**	0.8	0.7	1.3
κ_Z	**1.5**	0.7	0.6	1.2
κ_g	**2.5**	0.9	0.8	2.1
κ_t	**3.4**	0.9	1.1	3.1
κ_b	**3.7**	1.3	1.3	3.2
κ_τ	**1.9**	0.9	0.8	1.5
κ_μ	**4.3**	3.8	1.0	1.7
$\kappa_{Z\gamma}$	**9.8**	7.2	1.7	6.4

Expected relative uncertainty

Right panel — Ratios of coupling modifiers

S2 — $\sqrt{s}$ = 14 TeV, 3000 fb^{-1} per experiment — *ATLAS* and *CMS* — HL-LHC Projection

	Uncertainty [%]			
	Tot	Stat	Exp	Th
κ_{gZ}	**1.8**	0.6	0.7	1.5
λ_{Zg}	**2.6**	1.2	0.9	2.1
λ_{tg}	**3.4**	0.9	1.2	3.0
λ_{WZ}	**1.5**	0.7	0.8	1.1
$\lambda_{\gamma Z}$	**1.5**	0.7	1.0	0.8
$\lambda_{\tau Z}$	**1.8**	0.9	1.0	1.2
λ_{bZ}	**3.1**	1.3	1.3	2.6
$\lambda_{\mu Z}$	**4.2**	3.8	1.0	1.5
$\lambda_{(Z\gamma)Z}$	**9.8**	7.2	1.8	6.3

Expected relative uncertainty
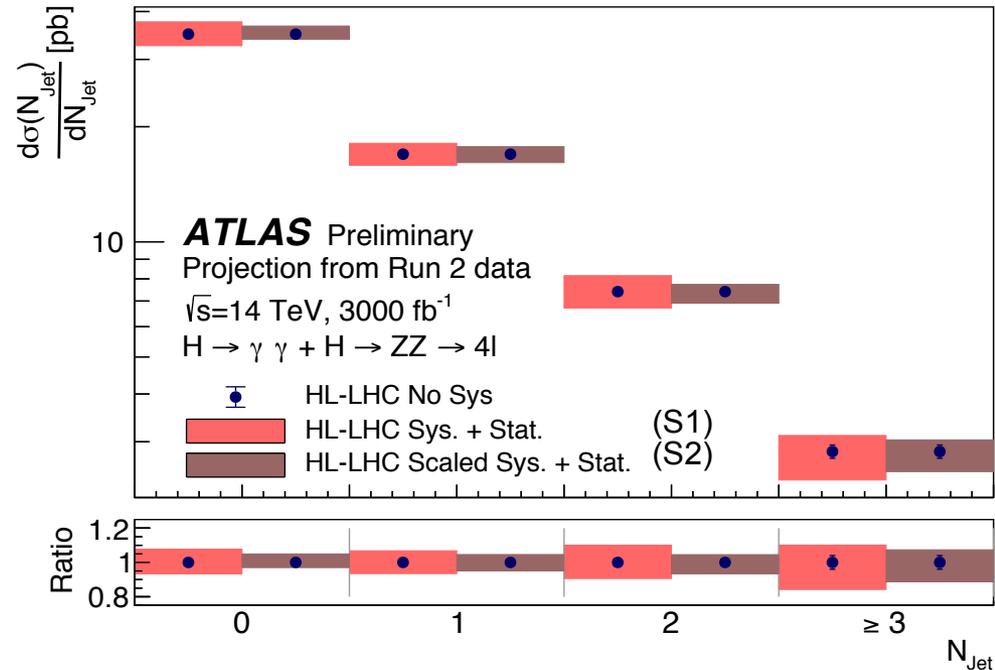
Uncertainties on the κ's 2-5%, apart from Zγ
Mostly limited by theoretical uncertainties
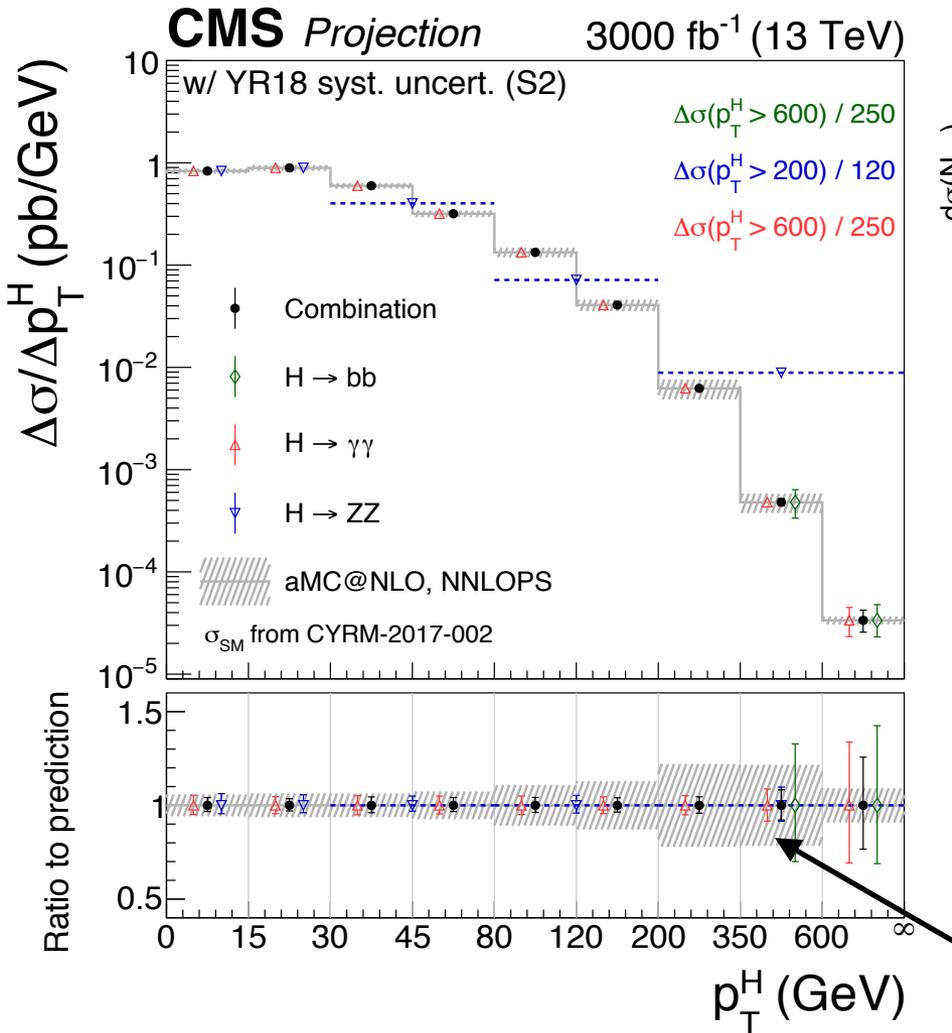
Uncertainties on the ratios of k's 1.5-4%,
With $\lambda_{\gamma Z}$ and λ_{WZ} most precisely measured

A. de Wit

Differential cross sections

Projection of H➔γγ and H➔ZZ➔4l differential cross sections

Precision ~10% for H p_T> 350 GeV, Statistically limited

Precision 5-15% depending on N_{jet} bin

Differential cross sections: probing Higgs-self coupling

- At NLO Higgs boson production modes include contributions involving the trilinear Higgs coupling ➜ ttH most sensitive

- Focus on ttH, H➜γγ using Delphes simulation

- At 95% CL: **-4.1<κ_λ<14.1** ➜ complementary to the stronger constraints from direct di-Higgs production (see talk later today!)

A. de Wit
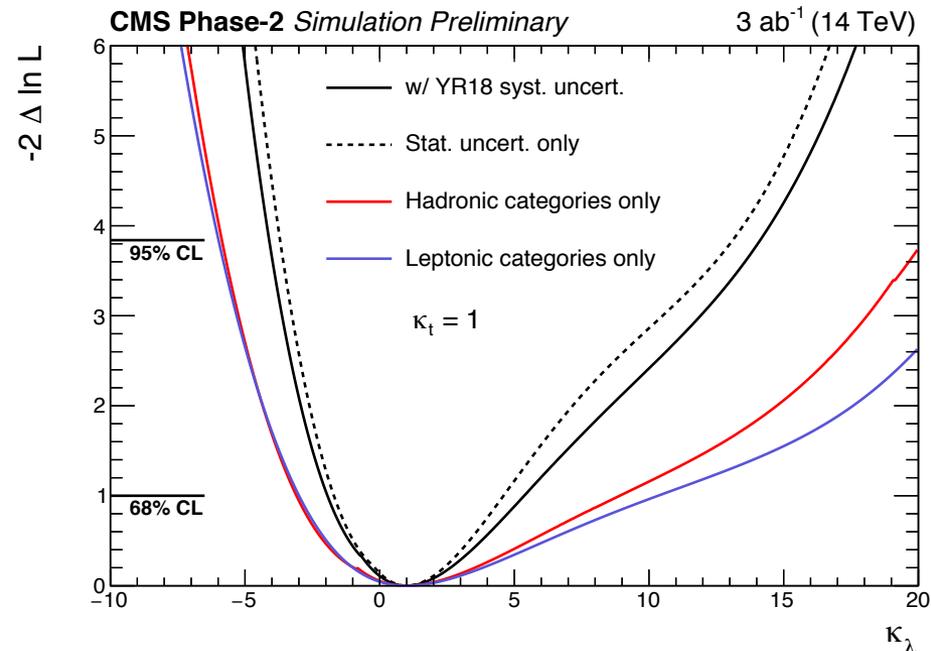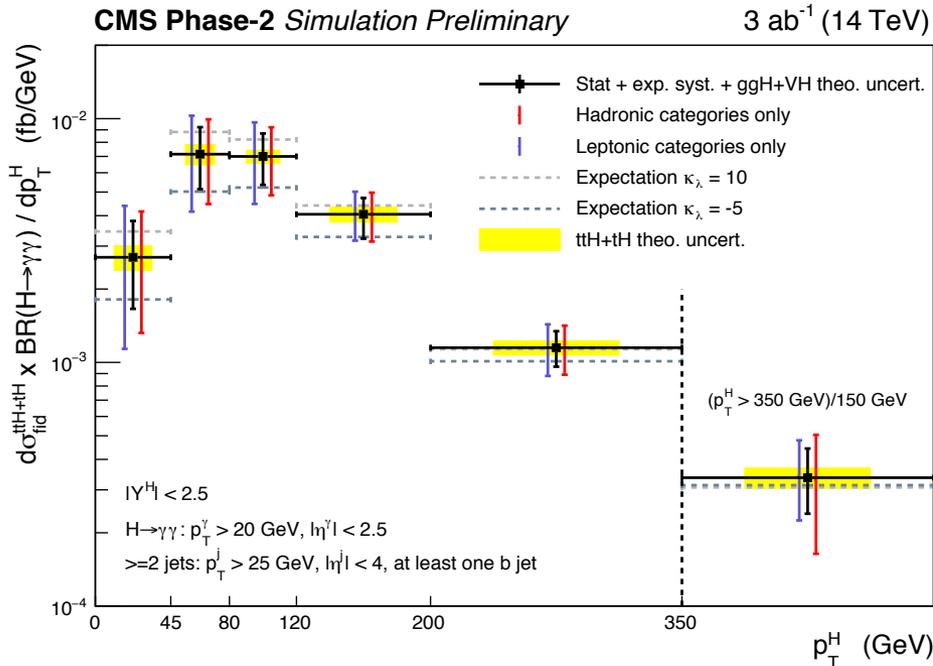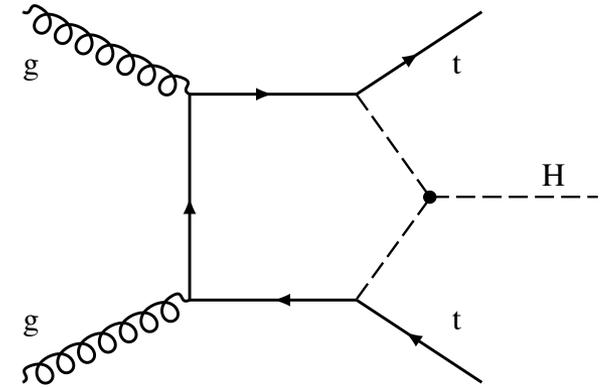
Width

- Comparison of on- and off-shell rates in H➔ZZ➔4l can constrain the Higgs boson width. Current constraint: Γ<14.4 MeV (ATLAS), Γ<9.2 MeV (CMS)

- CMS projection: $4.1\,^{+1.0}_{-1.1}$ MeV, ATLAS projection: $4.1\,^{+1.5}_{-2.1}$ MeV
  - ATLAS projection of Run 1 analysis, larger theoretical uncertainties than in CMS projection
- Assuming same sensitivity for ATLAS & CMS analyses, combined constraint **$4.1\,^{+0.7}_{-0.8}$ MeV**

DESY.
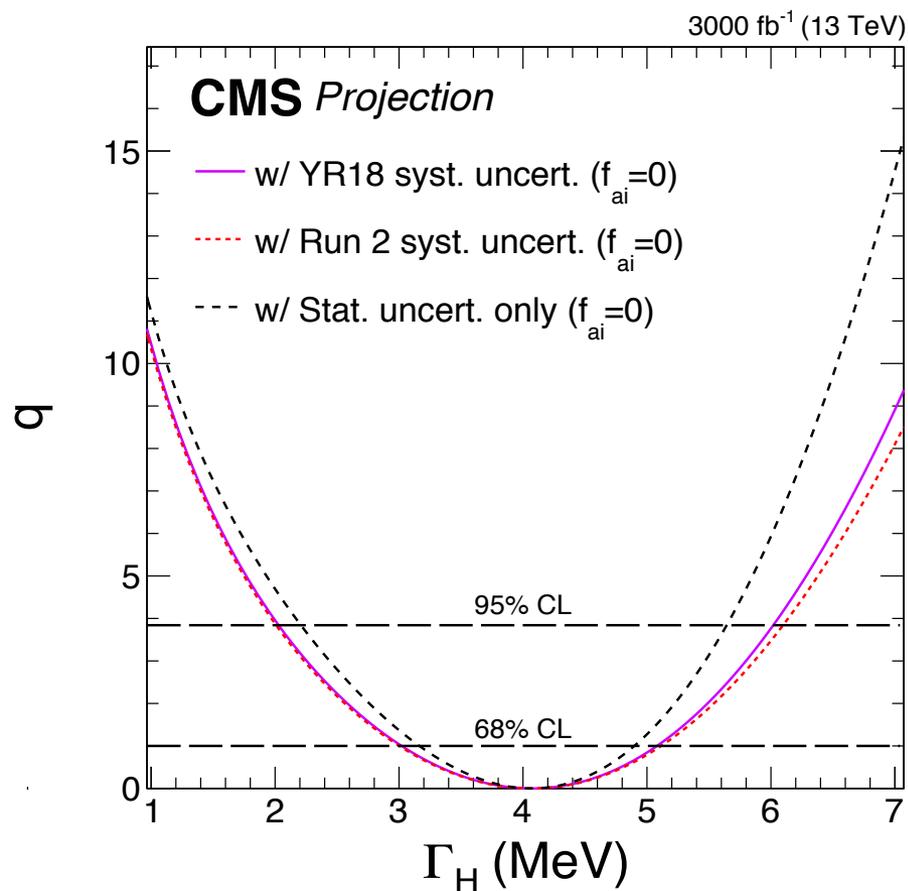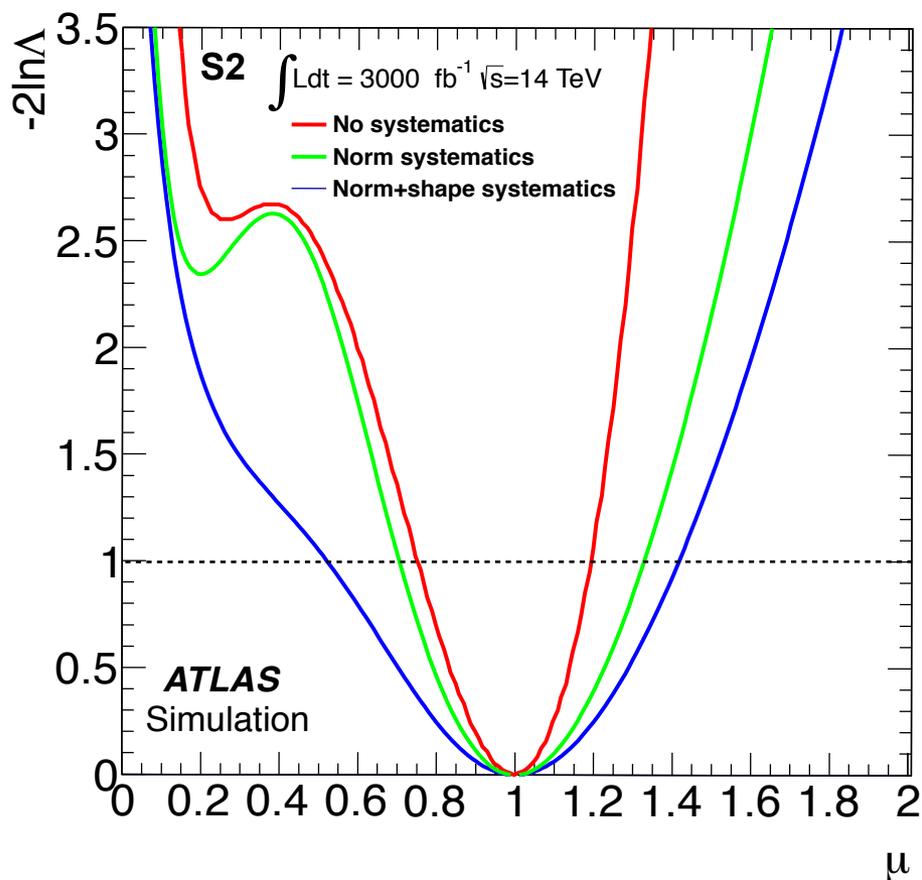
Invisible decays

- Current observed (expected) limits on B_{inv} at 95% CL:

  - ATLAS: < 26% (17%)

  - CMS: < 22% (17%)

- VBF production mode dominates sensitivity ➔ HL-LHC sensitivity studied using Delphes simulation

- With optimised selection: **B_{inv}<3.8%** at 95% CL with 3 ab^{-1} at HL-LHC

- Degradation of E_T^{miss} resolution does not impact the sensitivity significantly

- Combining with previous ATLAS projection of VH channel, and assuming both experiments would perform equally well in both channels: **B_{inv}<2.5%** at 95% CL

3000 fb^{-1} (14 TeV)

CMS Phase-2
Simulation Preliminary

- Median exp. vs E_T^{miss}
- 68% exp.
- 95% exp.
- Median exp. smeared E_T^{miss}

y-axis: 95% CL upper limit on $\sigma \times B(H\rightarrow inv)/\sigma_{SM}$ (%)

x-axis: Minimum threshold on E_T^{miss} (GeV)
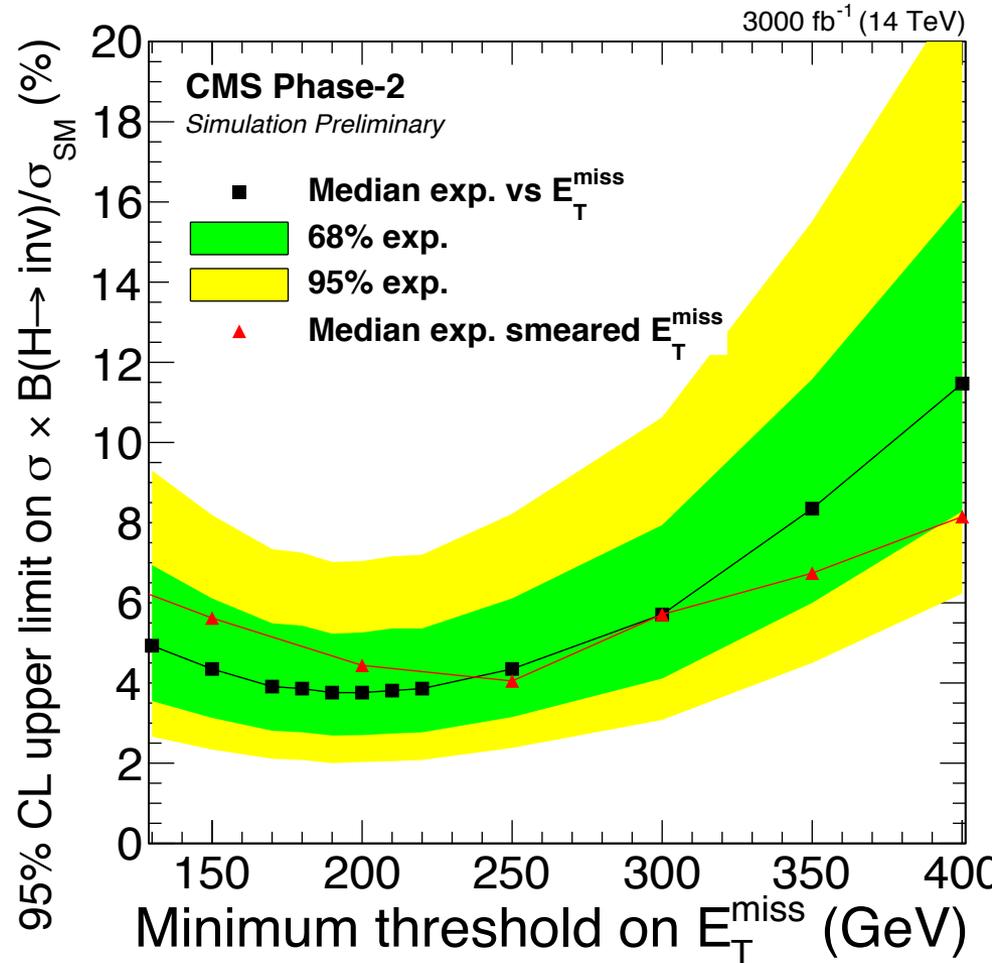
Summary & HE-LHC prospects

- Physics reach in the Higgs sector will be expanded at HL-LHC

    - Per-cent level precision on most Higgs couplings

    - B_{inv} < 2.5% @ 95% CL

    - Width measurable to within 1 MeV

- Many inclusive measurements limited by systematic uncertainties ➔ work needed from theoretical and experimental side to reduce these

- **Looking further ahead: HE-LHC**

    - 15ab^{-1} at $\sqrt{s} = 27$ TeV

    - κ_μ precision expected to reach 2%

    - ttH/ttZ ratio ~ per cent level precision

    - Reduction of statistical uncertainty in other Higgs coupling measurements

	Tot	Stat	Exp	Th
κ_γ	**1.8**	0.8	1.0	1.3
κ_W	**1.7**	0.8	0.7	1.3
κ_Z	**1.5**	0.7	0.6	1.2
κ_g	**2.5**	0.9	0.8	2.1
κ_t	**3.4**	0.9	1.1	3.1
κ_b	**3.7**	1.3	1.3	3.2
κ_τ	**1.9**	0.9	0.8	1.5
κ_μ	**4.3**	3.8	1.0	1.7
$\kappa_{Z\gamma}$	**9.8**	7.2	1.7	6.4

S2 — $\sqrt{s}$ = 14 TeV, 3000 fb^{-1} per experiment — **ATLAS** and **CMS** HL-LHC Projection — Uncertainty [%] — Expected relative uncertainty

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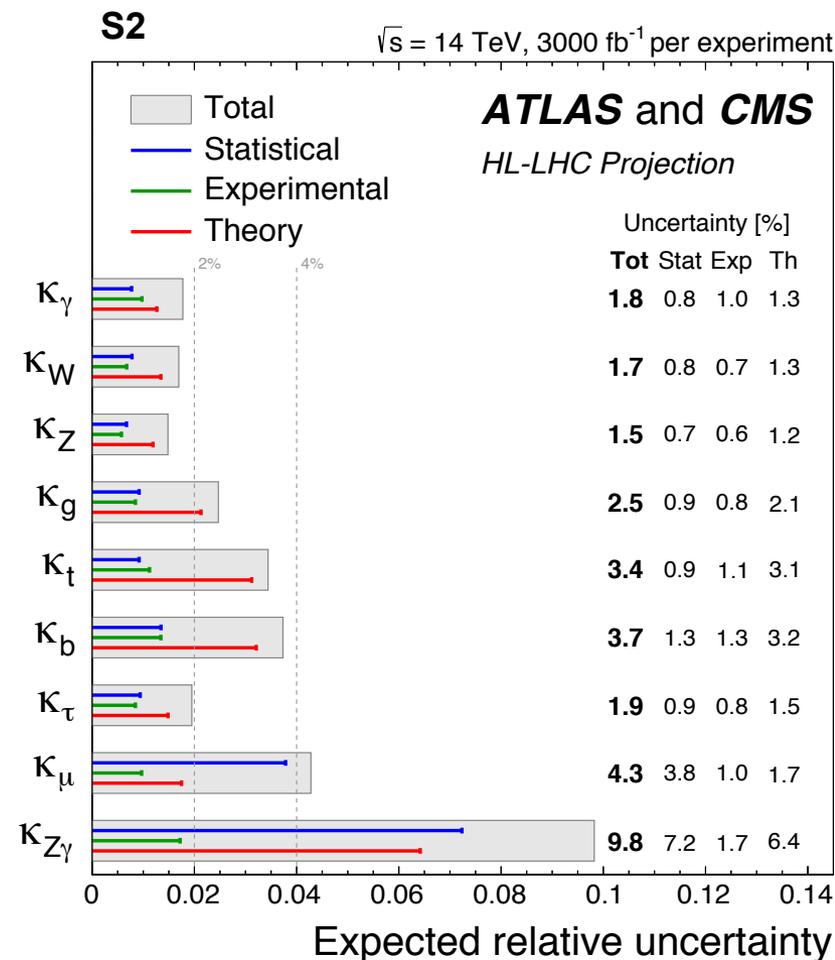
Backup

Coupling measurements in Run 2

Production and decay

ATLAS

Process ($|y_H| < 2.5$)	Value [pb]	Uncertainty [pb]					SM pred. [pb]	Significance obs. (exp.)
		Total	Stat.	Exp.	Sig. th.	Bkg. th.		
ggF	47.8	±4.0	±3.1	$^{+2.7}_{-2.2}$	±0.9	±1.3	44.7 ± 2.2	-
VBF	4.25	$^{+0.77}_{-0.74}$	±0.63	$^{+0.39}_{-0.35}$	$^{+0.25}_{-0.21}$	$^{+0.14}_{-0.11}$	3.515 ± 0.075	6.5 (5.3)
WH	1.89	$^{+0.63}_{-0.58}$	$^{+0.45}_{-0.42}$	$^{+0.29}_{-0.28}$	$^{+0.25}_{-0.16}$	$^{+0.23}_{-0.22}$	1.204 ± 0.024	4.1 (3.7)
ZH	0.59	$^{+0.33}_{-0.32}$	$^{+0.27}_{-0.25}$	±0.14	$^{+0.08}_{-0.02}$	±0.11	$0.794^{+0.033}_{-0.027}$	
$t\bar{t}H+tH$	0.71	±0.15	±0.10	±0.07	$^{+0.05}_{-0.04}$	$^{+0.08}_{-0.07}$	$0.586^{+0.034}_{-0.050}$	5.8 (5.3)

Branching ratio	Value	Uncertainty				
		Total	Stat.	Exp.	Sig. theo.	Bkg. theo.
$B_{\gamma\gamma}/B_{\gamma\gamma}^{SM}$	1.08	$^{+0.13}_{-0.12}$	±0.08	$^{+0.08}_{-0.07}$	$^{+0.06}_{-0.05}$	±0.01
B_{ZZ}/B_{ZZ}^{SM}	1.20	$^{+0.15}_{-0.14}$	±0.12	±0.05	$^{+0.07}_{-0.06}$	±0.02
B_{WW}/B_{WW}^{SM}	1.14	±0.17	±0.10	±0.10	$^{+0.07}_{-0.06}$	$^{+0.08}_{-0.07}$
$B_{\tau\tau}/B_{\tau\tau}^{SM}$	1.11	$^{+0.29}_{-0.26}$	±0.18	$^{+0.17}_{-0.16}$	$^{+0.13}_{-0.09}$	$^{+0.06}_{-0.05}$
B_{bb}/B_{bb}^{SM}	1.07	$^{+0.32}_{-0.30}$	$^{+0.19}_{-0.18}$	±0.14	$^{+0.12}_{-0.08}$	$^{+0.19}_{-0.18}$

ATLAS-CONF-2018-031

CMS

Production process	Best fit value	Uncertainty	
		stat.	syst.
ggH	1.22	$^{+0.14}_{-0.12}$ ($^{+0.11}_{-0.11}$)	$^{+0.08}_{-0.08}$ ($^{+0.07}_{-0.07}$) $^{+0.12}_{-0.10}$ ($^{+0.09}_{-0.08}$)
VBF	0.73	$^{+0.30}_{-0.27}$ ($^{+0.29}_{-0.27}$)	$^{+0.24}_{-0.23}$ ($^{+0.24}_{-0.23}$) $^{+0.17}_{-0.15}$ ($^{+0.16}_{-0.15}$)
WH	2.18	$^{+0.58}_{-0.55}$ ($^{+0.53}_{-0.51}$)	$^{+0.46}_{-0.45}$ ($^{+0.43}_{-0.42}$) $^{+0.34}_{-0.32}$ ($^{+0.30}_{-0.29}$)
ZH	0.87	$^{+0.44}_{-0.42}$ ($^{+0.43}_{-0.41}$)	$^{+0.39}_{-0.38}$ ($^{+0.38}_{-0.37}$) $^{+0.20}_{-0.18}$ ($^{+0.19}_{-0.17}$)
ttH	1.18	$^{+0.30}_{-0.27}$ ($^{+0.28}_{-0.25}$)	$^{+0.16}_{-0.16}$ ($^{+0.16}_{-0.15}$) $^{+0.26}_{-0.21}$ ($^{+0.23}_{-0.20}$)

Decay mode	Best fit value	Uncertainty	
		stat.	syst.
$H \to bb$	1.12	$^{+0.29}_{-0.29}$ ($^{+0.28}_{-0.27}$)	$^{+0.19}_{-0.18}$ ($^{+0.18}_{-0.18}$) $^{+0.22}_{-0.22}$ ($^{+0.21}_{-0.20}$)
$H \to \tau\tau$	1.02	$^{+0.26}_{-0.24}$ ($^{+0.24}_{-0.22}$)	$^{+0.15}_{-0.15}$ ($^{+0.15}_{-0.14}$) $^{+0.21}_{-0.19}$ ($^{+0.19}_{-0.17}$)
$H \to WW$	1.28	$^{+0.17}_{-0.16}$ ($^{+0.14}_{-0.13}$)	$^{+0.09}_{-0.09}$ ($^{+0.09}_{-0.09}$) $^{+0.14}_{-0.13}$ ($^{+0.11}_{-0.10}$)
$H \to ZZ$	1.06	$^{+0.19}_{-0.17}$ ($^{+0.18}_{-0.16}$)	$^{+0.16}_{-0.15}$ ($^{+0.15}_{-0.14}$) $^{+0.11}_{-0.08}$ ($^{+0.10}_{-0.08}$)
$H \to \gamma\gamma$	1.20	$^{+0.18}_{-0.14}$ ($^{+0.14}_{-0.12}$)	$^{+0.13}_{-0.11}$ ($^{+0.10}_{-0.10}$) $^{+0.12}_{-0.09}$ ($^{+0.09}_{-0.07}$)
$H \to \mu\mu$	0.68	$^{+1.25}_{-1.24}$ ($^{+1.20}_{-1.17}$)	$^{+1.24}_{-1.24}$ ($^{+1.18}_{-1.17}$) $^{+0.13}_{-0.11}$ ($^{+0.19}_{-0.03}$)

arXiv:1809.10733

DESY.

Coupling measurements in Run 2

Coupling modifiers

ATLAS

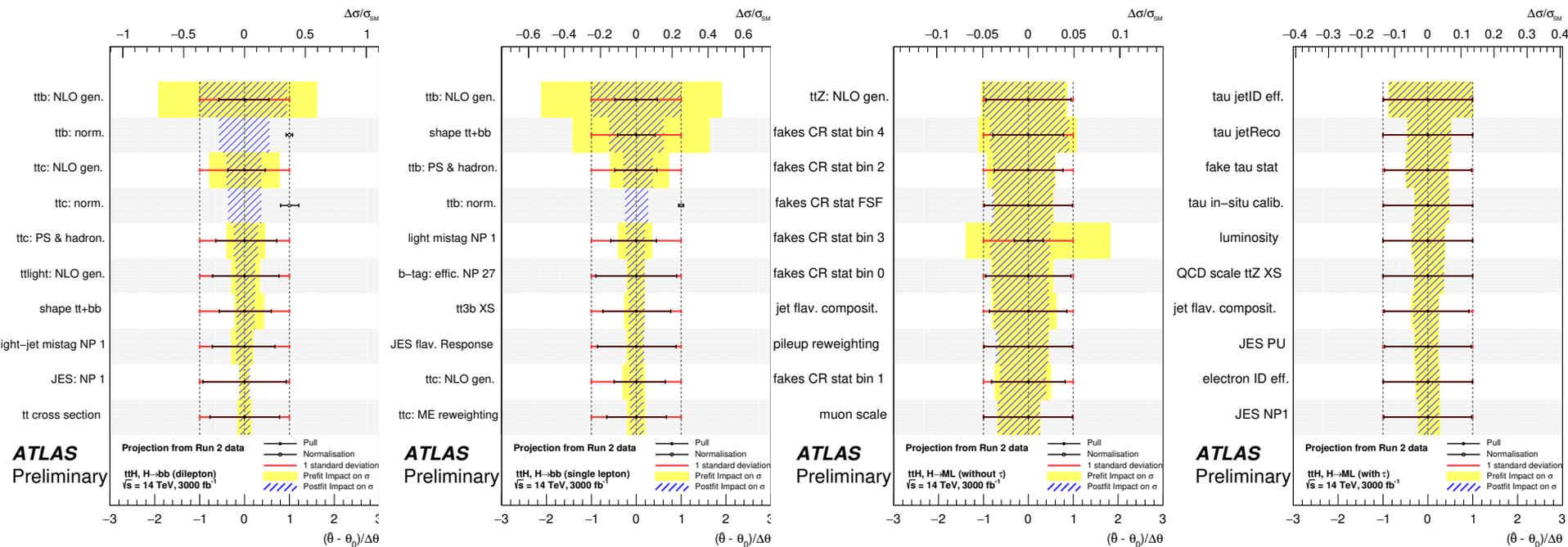| Parameter	(a) no BSM	(b) with BSM
κ_Z	1.07 ± 0.10	restricted to $\kappa_Z \le 1$
κ_W	1.07 ± 0.11	restricted to $\kappa_W \le 1$
κ_b	$0.97^{+0.24}_{-0.22}$	$0.85^{+0.13}_{-0.14}$
κ_t	$1.09^{+0.15}_{-0.14}$	$1.05^{+0.14}_{-0.13}$
κ_τ	$1.02^{+0.17}_{-0.16}$	0.95 ± 0.13
κ_γ	$1.02^{+0.09}_{-0.12}$	$0.98^{+0.05}_{-0.08}$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

ATLAS-CONF-2018-031

CMS

$\mathcal{B}_{BSM} = 0$				$\mathcal{B}_{BSM} > 0,\ |\kappa_V| < 1$			
		Uncertainty				Uncertainty	
Parameter	Best fit	stat	syst	Parameter	Best fit	stat	syst
κ_Z	$1.00 \begin{smallmatrix}+0.11\\-0.11\end{smallmatrix} \left(\begin{smallmatrix}+0.11\\-0.11\end{smallmatrix}\right)$	$\begin{smallmatrix}+0.09\\-0.09\end{smallmatrix} \left(\begin{smallmatrix}+0.09\\-0.09\end{smallmatrix}\right)$	$\begin{smallmatrix}+0.06\\-0.07\end{smallmatrix} \left(\begin{smallmatrix}+0.06\\-0.06\end{smallmatrix}\right)$	κ_Z	$-0.87 \begin{smallmatrix}+0.08\\-0.08\end{smallmatrix} \left(\begin{smallmatrix}+0.00\\-0.12\end{smallmatrix}\right)$	$\begin{smallmatrix}+0.07\\-0.06\end{smallmatrix} \left(\begin{smallmatrix}+0.00\\-0.10\end{smallmatrix}\right)$	$\begin{smallmatrix}+0.04\\-0.04\end{smallmatrix} \left(\begin{smallmatrix}+0.00\\-0.06\end{smallmatrix}\right)$
κ_W	$-1.13 \begin{smallmatrix}+0.16\\-0.13\end{smallmatrix} \left(\begin{smallmatrix}+0.12\\-0.12\end{smallmatrix}\right)$	$\begin{smallmatrix}+0.15\\-0.10\end{smallmatrix} \left(\begin{smallmatrix}+0.09\\-0.09\end{smallmatrix}\right)$	$\begin{smallmatrix}+0.06\\-0.08\end{smallmatrix} \left(\begin{smallmatrix}+0.07\\-0.07\end{smallmatrix}\right)$	κ_W	$-1.00 \begin{smallmatrix}+0.09\\-0.00\end{smallmatrix} \left(\begin{smallmatrix}+0.00\\-0.12\end{smallmatrix}\right)$	$\begin{smallmatrix}+0.07\\-0.00\end{smallmatrix} \left(\begin{smallmatrix}+0.00\\-0.00\end{smallmatrix}\right)$	$\begin{smallmatrix}+0.05\\-0.00\end{smallmatrix} \left(\begin{smallmatrix}+0.00\\-0.07\end{smallmatrix}\right)$
κ_t	$0.98 \begin{smallmatrix}+0.14\\-0.14\end{smallmatrix} \left(\begin{smallmatrix}+0.14\\-0.15\end{smallmatrix}\right)$	$\begin{smallmatrix}+0.08\\-0.08\end{smallmatrix} \left(\begin{smallmatrix}+0.08\\-0.09\end{smallmatrix}\right)$	$\begin{smallmatrix}+0.12\\-0.11\end{smallmatrix} \left(\begin{smallmatrix}+0.12\\-0.12\end{smallmatrix}\right)$	κ_t	$1.02 \begin{smallmatrix}+0.19\\-0.15\end{smallmatrix} \left(\begin{smallmatrix}+0.18\\-0.15\end{smallmatrix}\right)$	$\begin{smallmatrix}+0.13\\-0.09\end{smallmatrix} \left(\begin{smallmatrix}+0.13\\-0.09\end{smallmatrix}\right)$	$\begin{smallmatrix}+0.13\\-0.13\end{smallmatrix} \left(\begin{smallmatrix}+0.13\\-0.12\end{smallmatrix}\right)$
κ_τ	$1.02 \begin{smallmatrix}+0.17\\-0.17\end{smallmatrix} \left(\begin{smallmatrix}+0.16\\-0.15\end{smallmatrix}\right)$	$\begin{smallmatrix}+0.11\\-0.13\end{smallmatrix} \left(\begin{smallmatrix}+0.11\\-0.11\end{smallmatrix}\right)$	$\begin{smallmatrix}+0.12\\-0.10\end{smallmatrix} \left(\begin{smallmatrix}+0.12\\-0.11\end{smallmatrix}\right)$	κ_τ	$0.93 \begin{smallmatrix}+0.13\\-0.13\end{smallmatrix} \left(\begin{smallmatrix}+0.14\\-0.15\end{smallmatrix}\right)$	$\begin{smallmatrix}+0.08\\-0.09\end{smallmatrix} \left(\begin{smallmatrix}+0.09\\-0.10\end{smallmatrix}\right)$	$\begin{smallmatrix}+0.11\\-0.10\end{smallmatrix} \left(\begin{smallmatrix}+0.11\\-0.11\end{smallmatrix}\right)$
κ_b	$1.17 \begin{smallmatrix}+0.27\\-0.31\end{smallmatrix} \left(\begin{smallmatrix}+0.25\\-0.23\end{smallmatrix}\right)$	$\begin{smallmatrix}+0.18\\-0.29\end{smallmatrix} \left(\begin{smallmatrix}+0.18\\-0.17\end{smallmatrix}\right)$	$\begin{smallmatrix}+0.20\\-0.10\end{smallmatrix} \left(\begin{smallmatrix}+0.17\\-0.16\end{smallmatrix}\right)$	κ_b	$0.91 \begin{smallmatrix}+0.17\\-0.16\end{smallmatrix} \left(\begin{smallmatrix}+0.19\\-0.22\end{smallmatrix}\right)$	$\begin{smallmatrix}+0.11\\-0.12\end{smallmatrix} \left(\begin{smallmatrix}+0.14\\-0.16\end{smallmatrix}\right)$	$\begin{smallmatrix}+0.13\\-0.11\end{smallmatrix} \left(\begin{smallmatrix}+0.13\\-0.15\end{smallmatrix}\right)$
κ_g	$1.18 \begin{smallmatrix}+0.16\\-0.14\end{smallmatrix} \left(\begin{smallmatrix}+0.14\\-0.12\end{smallmatrix}\right)$	$\begin{smallmatrix}+0.10\\-0.09\end{smallmatrix} \left(\begin{smallmatrix}+0.10\\-0.09\end{smallmatrix}\right)$	$\begin{smallmatrix}+0.12\\-0.10\end{smallmatrix} \left(\begin{smallmatrix}+0.10\\-0.09\end{smallmatrix}\right)$	κ_g	$1.16 \begin{smallmatrix}+0.18\\-0.13\end{smallmatrix} \left(\begin{smallmatrix}+0.17\\-0.12\end{smallmatrix}\right)$	$\begin{smallmatrix}+0.14\\-0.09\end{smallmatrix} \left(\begin{smallmatrix}+0.13\\-0.09\end{smallmatrix}\right)$	$\begin{smallmatrix}+0.12\\-0.10\end{smallmatrix} \left(\begin{smallmatrix}+0.11\\-0.09\end{smallmatrix}\right)$
κ_γ	$1.07 \begin{smallmatrix}+0.14\\-0.15\end{smallmatrix} \left(\begin{smallmatrix}+0.12\\-0.12\end{smallmatrix}\right)$	$\begin{smallmatrix}+0.09\\-0.14\end{smallmatrix} \left(\begin{smallmatrix}+0.10\\-0.09\end{smallmatrix}\right)$	$\begin{smallmatrix}+0.09\\-0.05\end{smallmatrix} \left(\begin{smallmatrix}+0.07\\-0.07\end{smallmatrix}\right)$	κ_γ	$0.96 \begin{smallmatrix}+0.09\\-0.09\end{smallmatrix} \left(\begin{smallmatrix}+0.09\\-0.11\end{smallmatrix}\right)$	$\begin{smallmatrix}+0.06\\-0.08\end{smallmatrix} \left(\begin{smallmatrix}+0.07\\-0.09\end{smallmatrix}\right)$	$\begin{smallmatrix}+0.06\\-0.06\end{smallmatrix} \left(\begin{smallmatrix}+0.05\\-0.07\end{smallmatrix}\right)$
κ_μ	$0.80 \begin{smallmatrix}+0.59\\-0.80\end{smallmatrix} \left(\begin{smallmatrix}+0.51\\-1.01\end{smallmatrix}\right)$	$\begin{smallmatrix}+0.56\\-0.81\end{smallmatrix} \left(\begin{smallmatrix}+0.50\\-1.01\end{smallmatrix}\right)$	$\begin{smallmatrix}+0.17\\-0.00\end{smallmatrix} \left(\begin{smallmatrix}+0.09\\-0.09\end{smallmatrix}\right)$	κ_μ	$0.72 \begin{smallmatrix}+0.50\\-0.72\end{smallmatrix} \left(\begin{smallmatrix}+0.49\\-1.01\end{smallmatrix}\right)$	$\begin{smallmatrix}+0.50\\-0.71\end{smallmatrix} \left(\begin{smallmatrix}+0.48\\-1.00\end{smallmatrix}\right)$	$\begin{smallmatrix}+0.00\\-0.07\end{smallmatrix} \left(\begin{smallmatrix}+0.06\\-0.08\end{smallmatrix}\right)$
				$\mathcal{B}_{inv}$	$0.07 \begin{smallmatrix}+0.08\\-0.07\end{smallmatrix} \left(\begin{smallmatrix}+0.09\\+0.00\end{smallmatrix}\right)$	$\begin{smallmatrix}+0.03\\-0.03\end{smallmatrix} \left(\begin{smallmatrix}+0.04\\-0.00\end{smallmatrix}\right)$	$\begin{smallmatrix}+0.07\\-0.06\end{smallmatrix} \left(\begin{smallmatrix}+0.08\\-0.00\end{smallmatrix}\right)$
				$\mathcal{B}_{undet}$	$0.00 \begin{smallmatrix}+0.17\\+0.00\end{smallmatrix} \left(\begin{smallmatrix}+0.20\\+0.00\end{smallmatrix}\right)$	$\begin{smallmatrix}+0.14\\-0.00\end{smallmatrix} \left(\begin{smallmatrix}+0.17\\-0.00\end{smallmatrix}\right)$	$\begin{smallmatrix}+0.09\\-0.00\end{smallmatrix} \left(\begin{smallmatrix}+0.11\\-0.00\end{smallmatrix}\right)$

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DESY.

ttH, H→bb
(dilepton)

ttH, H→bb
(single-lepton)

ttH, H→ll
(no τ)

ttH, H→ll
(with τ)

Important systematic uncertainties related
to background modelling, tau ID

Combined Higgs coupling measurements

Comparison of individual ATLAS and CMS contributions to measurement of coupling modifiers and ratios of coupling modifiers
Projected sensitivities similar for both experiments!
Small differences due to slightly different systematic uncertainty treatment
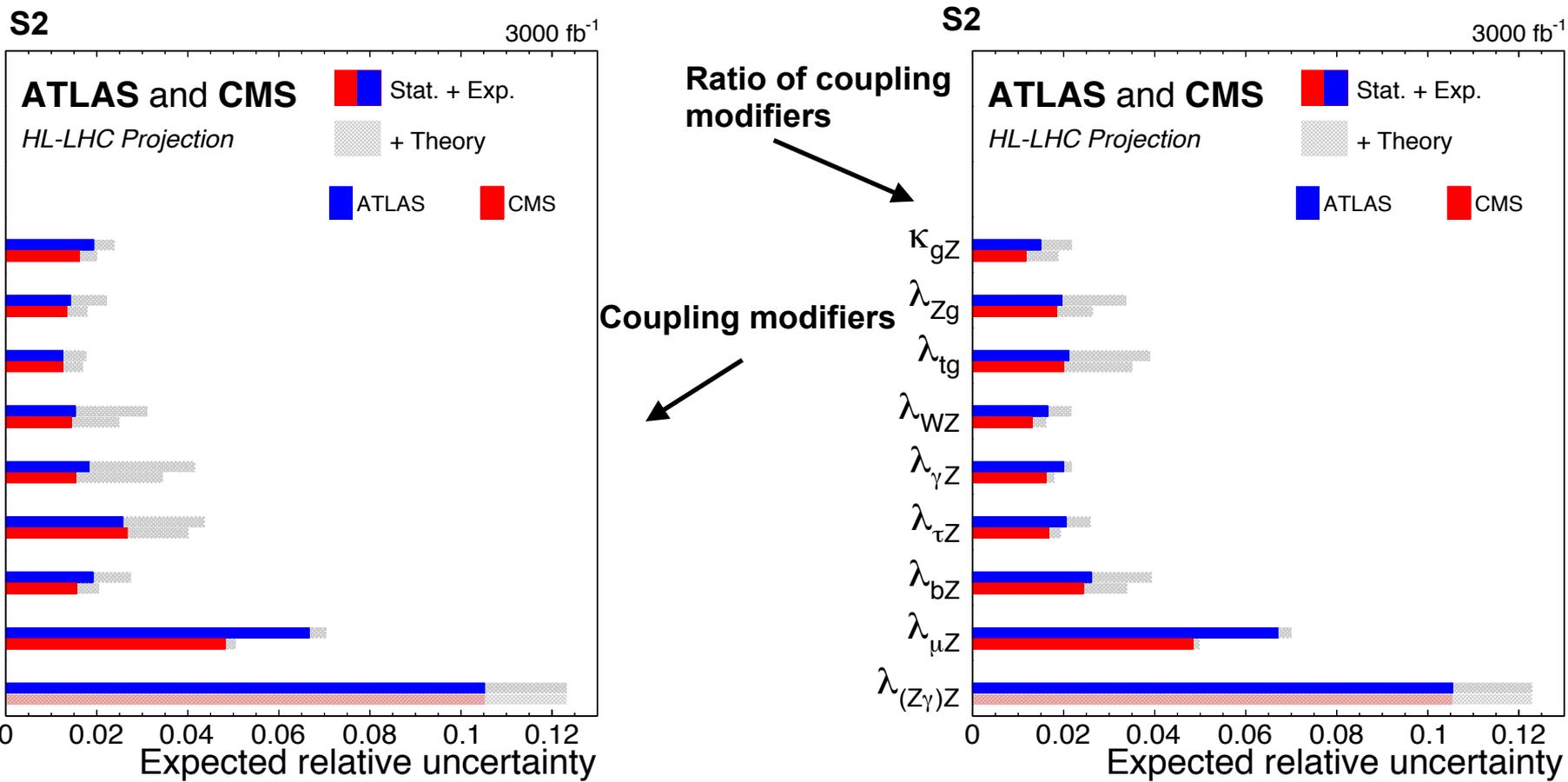
Higgs couplings at HE-LHC

Coupling	S2	S2'
k_γ	1.6	1.2
k_W	1.5	1.0
k_Z	1.3	0.8
k_g	2.2	1.3
k_t	3.2	1.9
k_b	3.5	2.1
k_τ	1.7	1.1
k_μ	2.2	1.7
$k_{Z\gamma}$	6.9	4.1

Expected uncertainty on coupling modifiers at HE-LHC, 15 ab^{-1} @ $\sqrt{s} = 27$ TeV

S2' theoretical and modelling systematic uncertainties halved with respect to S2.

Anomalous HVV interactions

$$f_{g_i} = \frac{|g_i|^2 \sigma_i^2}{|g_1|^2 \sigma_1^2 + |g_2|^2 \sigma_2^2 + |g_4|^2 \sigma_4^2}; \quad \phi_{g_i} = \arg\left(\frac{g_i}{g_1}\right).$$

$g_{1,2,3}$ interactions with gauge bosons, g_4 interaction with Higgs boson
Can also characterise with a_2, a_3, Λ_1 and Λ_Q.
$a_2 <> g_2$; $a_3 <> g_4$ ➔ in the SM a_3/g_4 are 0