# ATLAS and CMS prospects for single-Higgs measurements at HL-LHC





IRN Terascale, Annecy, 22 May 2019 LAPP



# On our menu today we have...

- Higgs boson couplings (gauge bosons, heavy fermions, muons)
- Higgs boson differential cross sections
- Higgs boson self coupling (indirect constraints)
- Mass
- Width
- Invisible decays
- Light quark couplings
- Beyond-Standard Model couplings: lepton-flavour violating decays

Before starting..



#### Sometimes present can be as unpredictable as the future

Unconventional diet



Unexpected visits



Unexpected long nights

emergency doctor



(fictional characters)

my daughter

Saturday Sunday Monday afternoon

Monday evening

However, let's try to forget this present and have fun with some physics predictions for the late '30s!!!



#### What is the HL-LHC?

- "natural", high-luminosity (HL) evolution of the LHC proton-proton collider
  - Planned to start in ~2026 after accelerator and detector upgrades ⇒ 3000/fb (per experiment) at 14 TeV by ~2038
- For comparison, the LHC so far has delivered "only"
  - 25/fb at 7-8 TeV in Run1 (2011–12)
  - 140/fb at 13 TeV in Run2 (2015–18) (most results so far based on 36 or 80/fb)
- However, these "modest" integrated luminosities already led to spectacular results:
  - Run1: Higgs boson discovery, mass ~125 GeV
  - Run2: Observation of all main Higgs boson production and decay modes
- Nonetheless, these measurements which so far agree with SM predictions are still affected by large uncertainties (mostly 10–20% or higher), with significant statistical component
  - Potential for significantly improved Higgs boson measurements at HL-LHC thanks to >10x larger dataset

#### What should we expect from the HL-LHC?

- Detailed studies to quantify expected sensitivities by ATLAS+CMS have been performed in the context of the Workshop on Physics at HL-LHC (link) for the Upgrade of European Strategy on Particle Physics
  - I will focus on single-Higgs production in this talk, though studies were also done for double-Higgs and non-Higgs physics, of course
- NOTE: few guesstimates were also performed for a high-energy (HE) -LHC scenario beyond the HL phase (15/ab at 27 TeV), but will not be shown here



#### General methodology of these studies

- Sensitivities have been extrapolated from the results of current published LHC analyses (w/ 36 of 80/fb of Run2), using the following ingredients:
- Signal and background yields have been scaled taking into account
  - **Luminosity** ratio HL-LHC/Run2 (3000/x, x=36, 80)
  - 14/13 TeV ratio of cross-sections (signal) or parton luminosities (bkg)
- Efficiencies, resolutions, fake rates have been assumed to be same as Run2
  - Supported by full-simulation (Geant4) studies of upgraded detectors
  - Notable exception: H→µµ (30–40% better invariant mass resolution)
  - Extended |η| acceptance of trackers (2.5→4.0) not fully exploited... but Higgs physics mostly central
- Two systematic uncertainty scenarios considered
  - main scenario ("YR18", or "S2"): most theory uncertainties down by 50%, experimental uncertainties down by √L until they reach a defined lower limit.
  - conservative scenario ("S1") for comparison, uses Run2 systematic uncertainties
  - uncertainties due to the finite number of simulated events are neglected

#### Mini overview of main Higgs analyses at (HL) LHC

#### Slide by M. Kado

Most channels already covered at the LHC Run 1 and Run 2 with only 3% (80 fb-1) of full HL-LHC dataset!

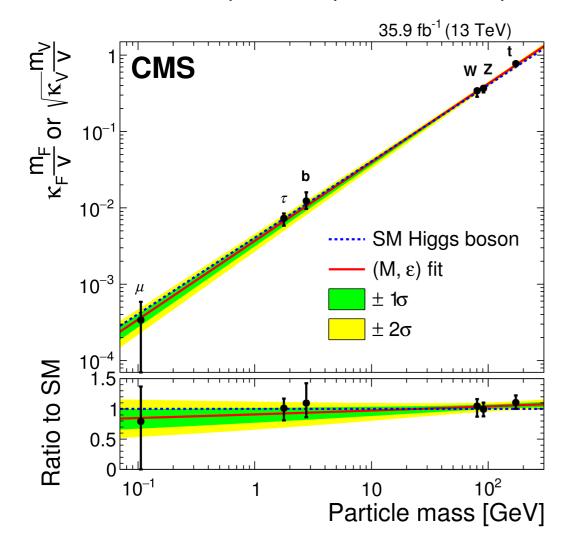
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	Channel categories	Br	ggF	VBF	VH	ttH
			g $g$ $g$ $g$ $g$ $g$ $g$ $g$ $g$ $g$	q $q$ $q$ $q$ $q$ $q$ $q$ $q$ $q$ $q$	$q'$ $W, Z$ $\overline{q}$ $H$ ~200 k vets produced	$g$ $000000$ $t$ $t$ $g$ $000000$ $\bar{t}$ $\bar{t}$ ~40 k evts produced
	Cross Section 13 TeV (8 TeV)		48.6 (21.4) pb*	3.8 (1.6) pb	2.3 (1.1) pb	0.5 (0.1) pb
Observed modes	γγ	0.2 %	<b>✓</b>	✓	✓	✓
	ZZ	3 %	<b>✓</b>	<b>✓</b>	✓	✓
	WW	22 %	✓	✓	✓	✓
	ττ	6.3 %	✓	✓	✓	✓
	bb	55 %	✓	✓	✓	✓
Remaining to be observed	Zγ and γγ*	0.2 %	✓	✓	✓	✓
	μμ	0.02 %	✓	✓	✓	✓
Strong limits will be sufficient	Invisible	0.1 %	<b>√</b> (monojet)	✓	✓	✓

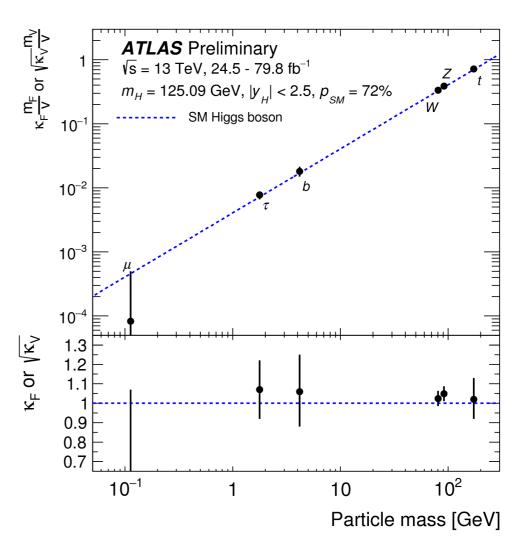
\*N3LO

 Not in the table but also performed are searches for even rarer decays (e.g. Vγ) and beyond-Standard Model (BSM) decays (e.g. lepton-flavor-violating or CP-violating ones)

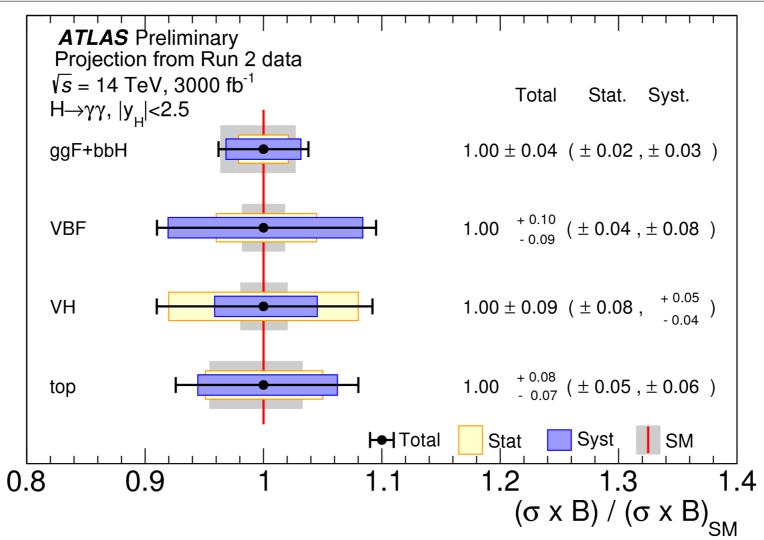
#### Higgs boson couplings at HL-LHC

- Largest Higgs boson couplings (top, bottom, W, Z, tau, mu) + effective couplings to photon and gluon are determined from combined fit to cross sections times branching ratios in all main production (gluon fusion, VBF, VH, ttH) and decay modes (γγ, ZZ, WW, ττ, bb, Zγ, μμ)
  - BR(H $\rightarrow$ XX)  $\Rightarrow$  X (but  $\gamma\gamma \Rightarrow t,W$ );  $\sigma_{ggF} \Rightarrow top$ ;  $\sigma_{VBF}$ ,  $\sigma_{VH} \Rightarrow V$  (W,Z);  $\sigma_{ttH} \Rightarrow top$
- Projection of combined measurements of Higgs boson couplings using data collected in 2015–2017 (ATLAS) and 2016 (CMS)



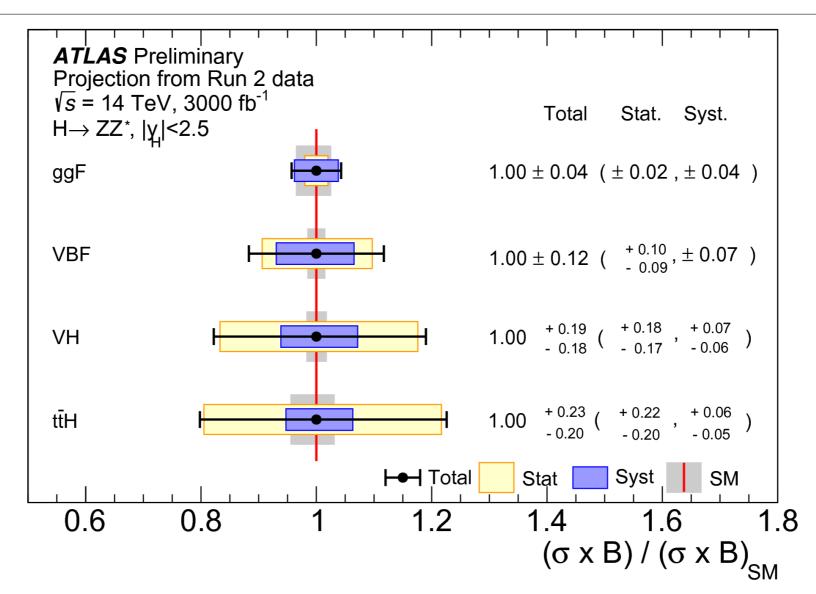


## Higgs boson couplings ( $\gamma$ , or W and t): $H \rightarrow \gamma \gamma$



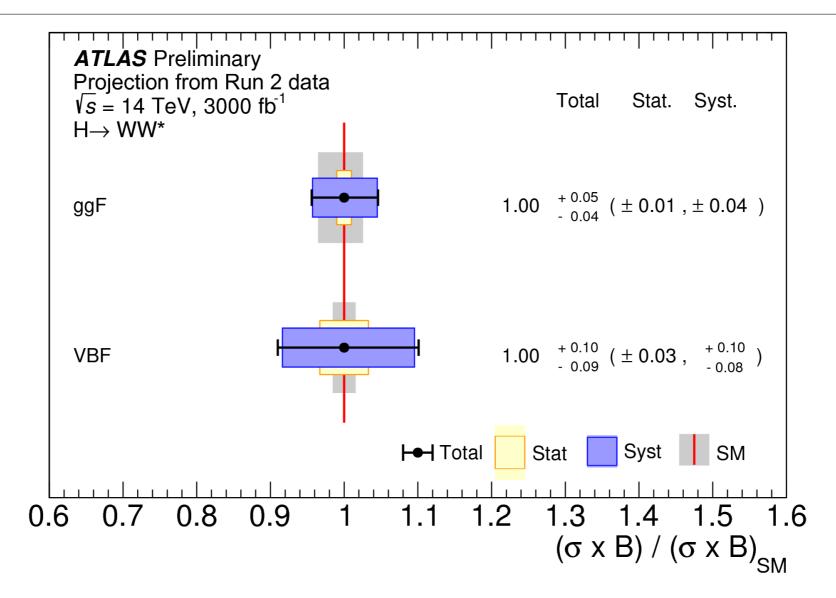
- ggF and VBF xsection measurements are systematically limited; VH xsection measurement is dominated by statistical uncertainty; ttH is in between
- Main systematic uncertainties:
  - ggF: photon isolation and identification efficiency, pileup
  - VBF: jet flavour composition; UE+PS modelling; QCD scale uncertainty on ggF
  - VH: photon isolation and identification efficiency, QCD scale uncertainty on VH
  - ttH: photon isolation efficiency, UE+PS modelling, ggF+heavy flavour (HF)

## Higgs boson couplings (Z): $H \rightarrow ZZ^* \rightarrow 4I$



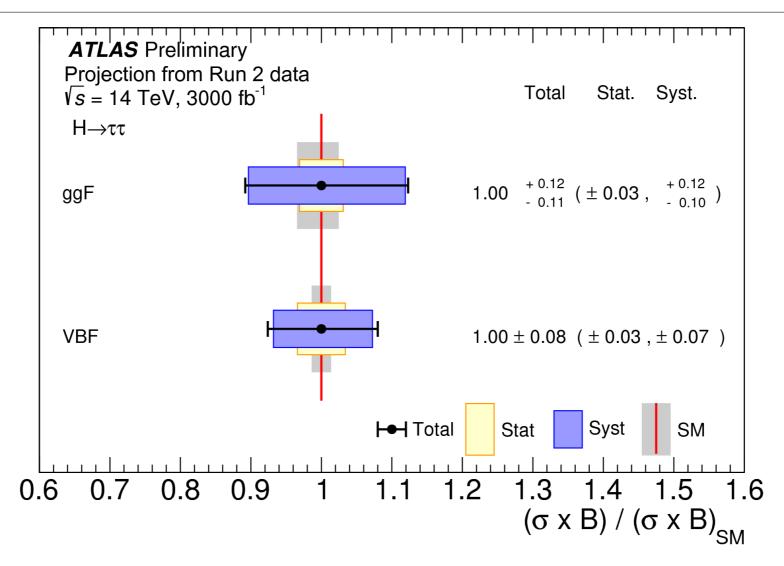
- ggF cross section measurement is limited by systematic uncertainties (lepton reconstruction and identification efficiencies, and pile-up modelling uncertainties)
- VBF, VH and top xsections are largely dominated by statistical uncertainty
  - Main sources of systematic uncertainties in VBF/VH/ttH: ggF+HF xsection; JES flavour composition; ggF QCD scale and p<sub>T</sub><sup>H</sup> uncertainties in VBF-like and VH(had)-like categories

## Higgs boson couplings (W): H→WW\*→IvIv



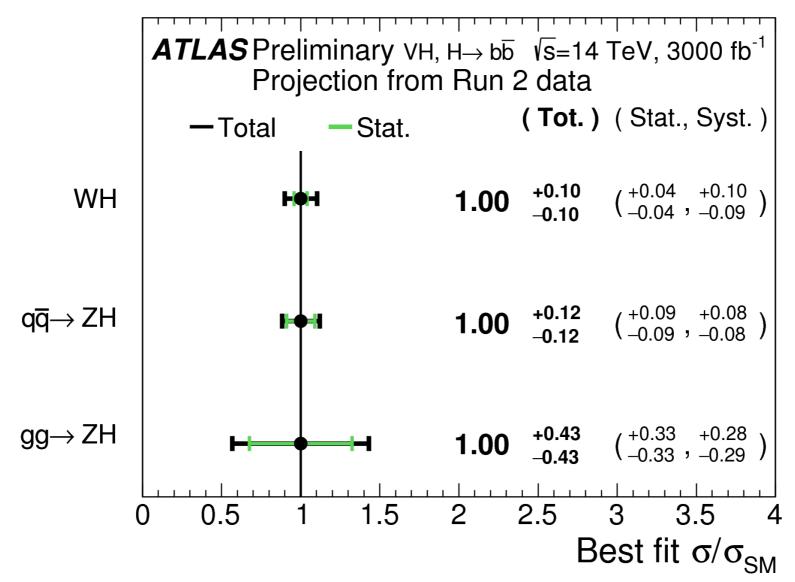
- ggF and VBF xsection measurements are limited by systematic uncertainties
- Main systematic uncertainties:
  - muon efficiency and fake rates for ggF
  - signal and background acceptance (ggF QCD scale, VBF ME, WW ME) for VBF

## Higgs boson couplings ( $\tau$ ): H $\rightarrow \tau\tau$



- ggF and VBF xsection measurements are limited by systematic uncertainties
- Main systematic uncertainties:
  - jet calibration and resolution, reconstruction of E<sub>T</sub><sup>miss</sup>
  - background modelling: the determination of the background normalisation from signal and control regions

## Higgs boson couplings (b): VH, H→bb



- WH: systematically limited; ZH: stat. and syst. uncertainties ~ equivalent
- Main systematic uncertainties from theory
  - W boson p<sub>T</sub> in W+HF jets
  - diboson normalisation and shape
  - QCD scale uncertainty for VH signal

## Higgs couplings (t): ttH (H→bb, H→multileptons)

NOTE: ttH(γγ) and ttH(ZZ) already shown in previous slides

#### ttH(bb):

- Expected precision on ttH xsection ~10–20%, systematically limited, depends on systematic uncertainty scenario and tt + HF background modelling (main uncertainty source together with signal modelling)
  - extrapolation assumes that reduction of tt + HF modelling uncertainties is limited to factors of two (S1) or three (S2) relative to uncertainty at 36/fb
- Analysis done so far in the "resolved" jet regime; studies in boosted regime using substructure techniques are ongoing, might lead to reduction of uncertainties
- ttH(multileptons, from WW, ZZ, тт):
  - Expected precision on ttH xsection ~15%, systematically limited by τ reconstruction (τ final states) or modelling of tt+V background (non-τ final states)

# Higgs boson couplings: $H \rightarrow Z\gamma \rightarrow II\gamma$

- Expected significance per experiment: 4.9 σ
- Projected uncertainties in S1:

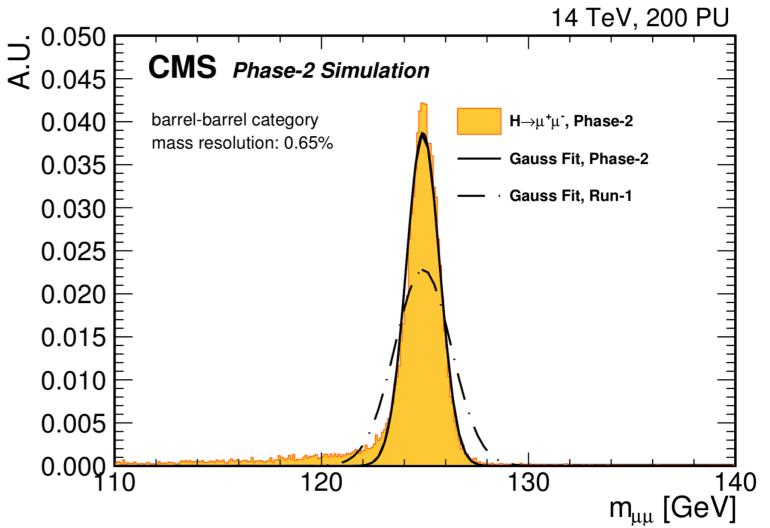
Scenario	$\Delta_{ m tot}/\sigma_{ m SM}$	$\Delta_{ m stat}/\sigma_{ m SM}$	$\Delta_{ m syst}/\sigma_{ m SM}$
HL-LHC S1	0.23	0.20	0.11

- Total relative uncertainty on pp→H→Zγ xsection times branching ratio: ±23%
- Results limited by statistical uncertainty in S1 and also thus in S2 scenario
- Improvement in m(llγ) resolution due to the improved tracker (muon channel) was not considered.

# Higgs boson couplings: H→µµ

Extrapolation also accounts for 30–40% reduction in m<sub>μμ</sub> signal width due to upgraded trackers (m<sub>μμ</sub> resolution = 0.65% in CMS best-resolution category)

 Expected significance/ experiment > 8σ



 In both scenarios, the total uncertainty (10–15%) is dominated by the statistical component (9–13%)

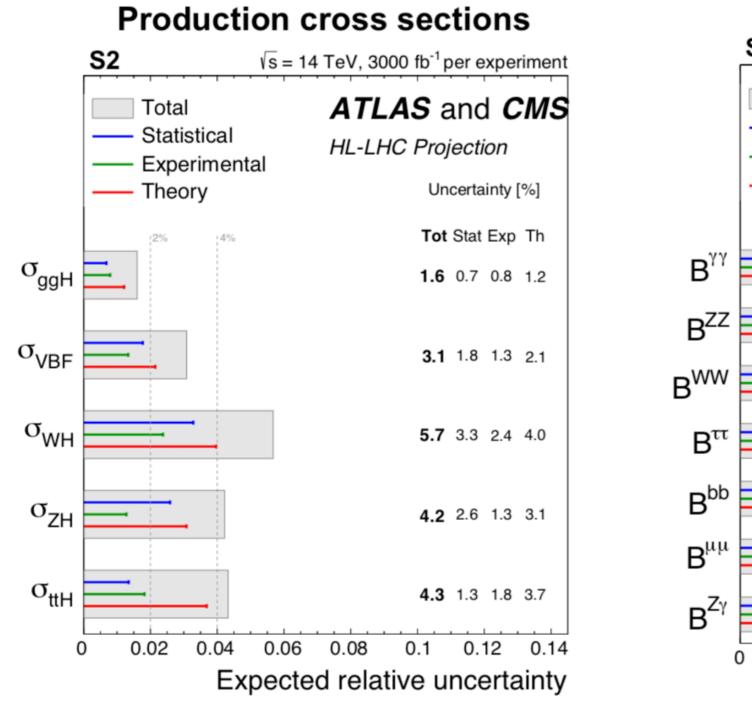
- Main systematic uncertainties: modelling of the signal
  - p<sub>T</sub><sup>H</sup> migration between categories
  - QCD scale uncertainties on ggF events migrating to VBF-like categories)

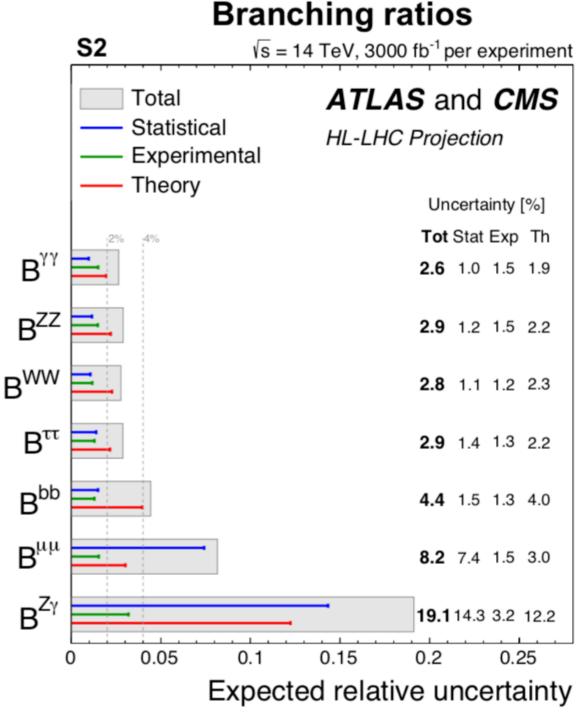
## Higgs boson couplings: combining ATLAS+CMS

#### Methodology:

- For each measurement the uncertainty is decomposed into four components: statistical, experimental, background and signal theory.
- The combination is done using the **BLUE** method, assuming that these components are independent within each experiment.
- Statistical and experimental uncertainties are treated as fully uncorrelated between the two experiments, while the signal and background theory uncertainties are assumed to be fully correlated.
- The combination is performed for each parameter individually. The effect of including the full covariances in a simultaneous combination of all parameters has been found to have a minor effect on the results
- The rare decay channels, H→µµ and H→Zγ, are excluded from the combination of production mode measurements because their sensitivities are negligible.

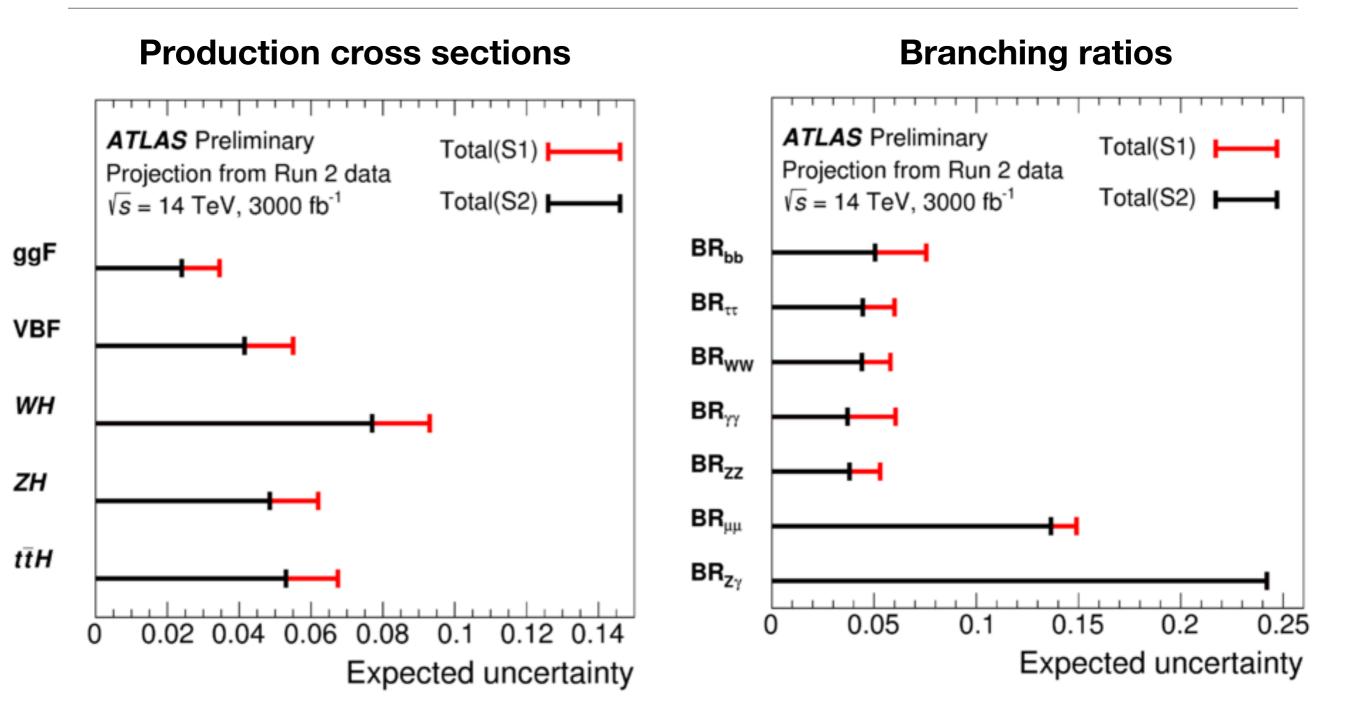
#### Higgs boson couplings: combining ATLAS+CMS





- Bpp and Bzy statistically limited (uncertainties 8-19%)
- Other branching ratios (2.6–4.4%) and cross sections (1.6–5.7%) dominated by theoretical uncertainties.

## Higgs boson couplings: S1 vs S2



• Going from S1 to S2 leads to a significant reduction (up to 40%) of the total uncertainties, except for stat limited measurements (Bµµ and BZŊ)

## Higgs boson couplings: k-framework interpretation

- Introduce 6 coupling modifiers corresponding to tree-level Higgs boson couplings: κw, κz, κt, κb, κτ and κμ. Assume κs=κb, κc=κt, κu=κd=1.
- · Cross-sections and partial widths are given by

$$\kappa_j^2 = \frac{\sigma_j}{\sigma_j^{SM}} ; \quad \kappa_j^2 = \frac{\Gamma_j}{\Gamma_j^{SM}}$$

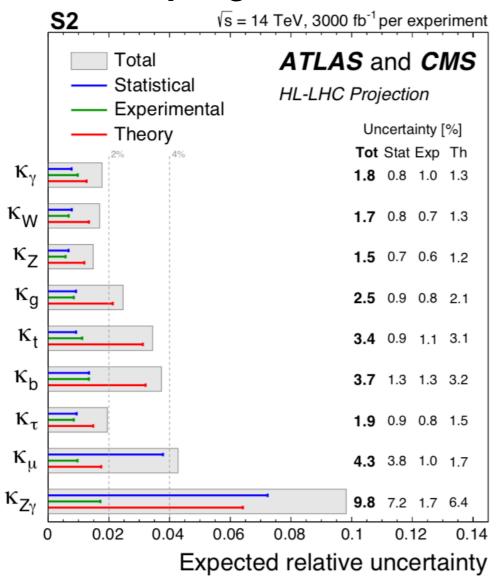
- Gluon, photon and  $Z\gamma$  coupling modifiers can be expressed as functions of the other six or parametrised as effective coupling modifiers  $\kappa_g$ ,  $\kappa_{\gamma}$ ,  $\kappa_{Z\gamma}$
- Total width modifier:  $\kappa_H = \Gamma_H/\Gamma_H^{SM} = \Sigma_j B_{SM}^j \kappa_j^2/(1 B_{BSM})$ 
  - Results assume either B<sub>BSM</sub>=0 (no decay to non-SM particles), or B<sub>BSM</sub>>=0 and |κ<sub>V</sub>|<=1 (as expected in several extensions of the SM)
- Results independent of assumptions on the width are provided in terms of ratios of modifiers and of a reference parameter:

$$\lambda_{ij} = \frac{\kappa_i}{\kappa_j}$$

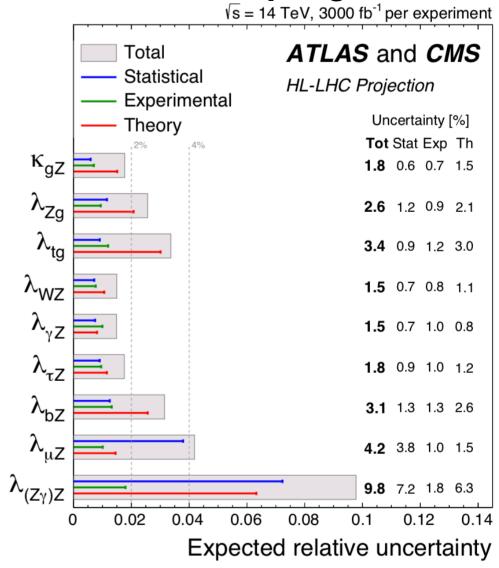
$$\kappa_{gZ} = \frac{\kappa_g \kappa_Z}{\kappa_H}$$

#### Higgs boson couplings: k-framework interpretation

#### **Coupling modifiers**

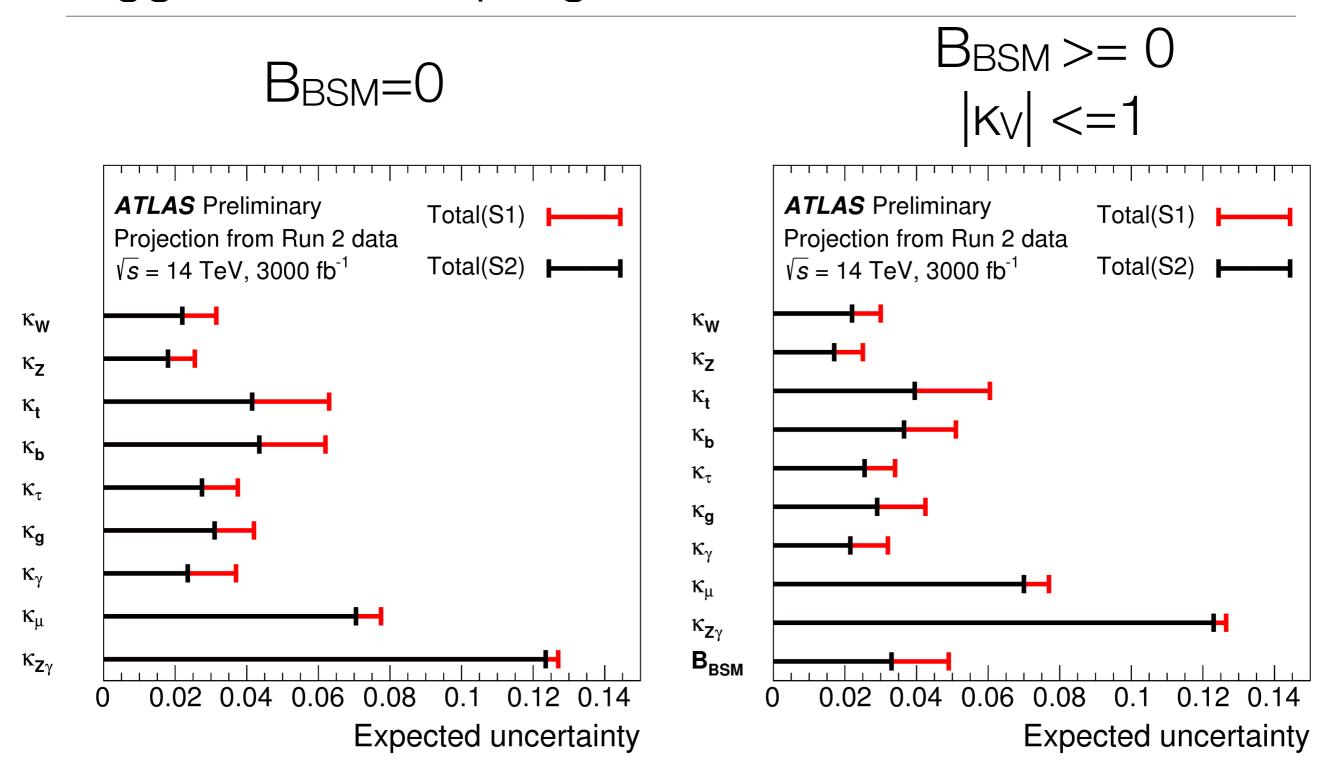


#### Ratios of coupling modifiers



- Uncertainties on the  $\kappa$ 's 1.5-4.3%, apart from  $Z\gamma$ . Mostly limited by theoretical uncertainties (except  $\kappa_{\mu}$ ,  $\kappa_{Z\gamma}$ )
- Uncertainties on the ratios of  $\kappa$ 's 1.5-4.2%, apart from  $Z\gamma Z$ .  $\lambda_{\gamma Z}$  and  $\lambda_{WZ}$  most precisely measured
- Expected upper limit for B<sub>BSM</sub> is B<sub>BSM</sub><2.5%</li>

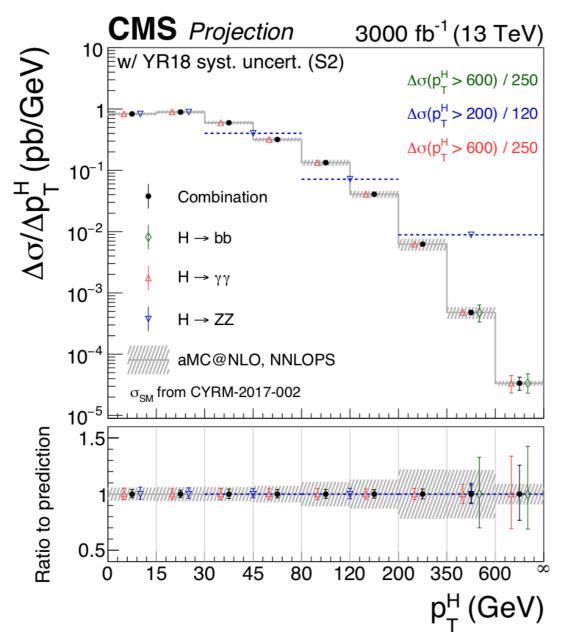
## Higgs boson couplings: S1 vs S2

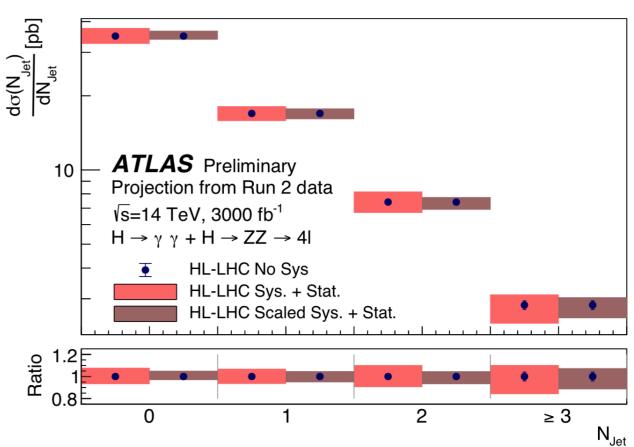


Going from S1 to S2 leads to 25-35% reduction of total uncertainties (per experiment), except for stat limited measurements (κ<sub>μ</sub>: -10%; κ<sub>Zγ</sub>: -2.5%)

#### Differential cross sections: p<sub>T</sub>H, N<sub>jet</sub>, ...

- Projection of  $H \rightarrow \gamma \gamma$ ,  $H \rightarrow ZZ^* \rightarrow 4I$  and (boosted)  $H \rightarrow bb$  differential cross sections as a function of  $p_T^H$  (all three channels),  $y^H$ ,  $N_{jet}$ ,  $p_{T^{j1}}$  (only  $\gamma \gamma + 4I$ )
- Cross sections are extrapolated to full fiducial volume for combination

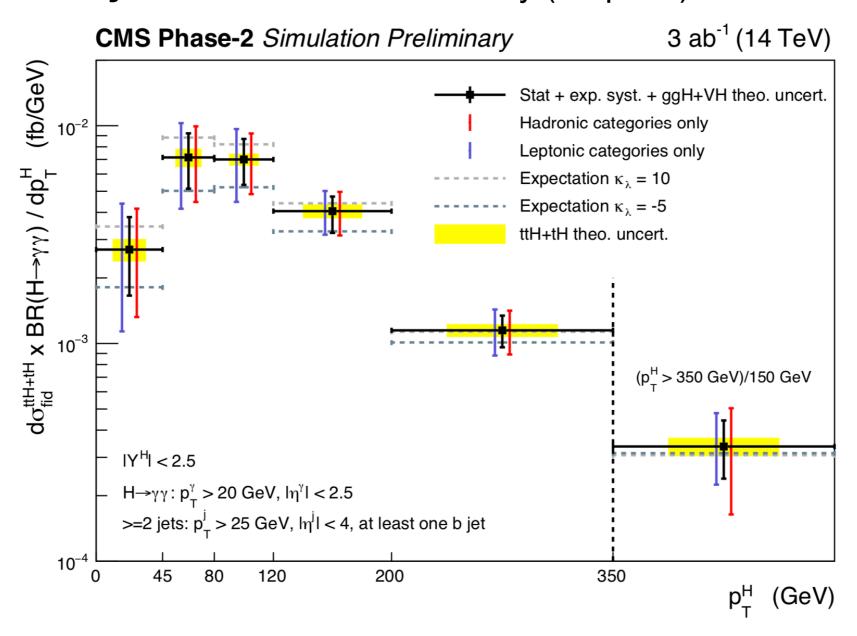




- N<sub>jet</sub>: uncertainties ~4% to ~8% in scenario S2, dominated by systematic component
- $p_T^H$ : 4–9% uncertainties, increasing w/  $p_T^H$ . Dominated by syst. except  $p_T^H$ > 350 GeV. High  $p_T^H$  region dominated by  $\gamma\gamma$  and bb.

## Differential cross sections: $p_T^H$ with $ttH(\gamma\gamma)$

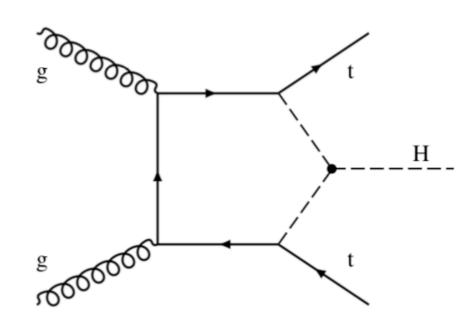
Not measured yet ⇒ fast-simulation study (Delphes)

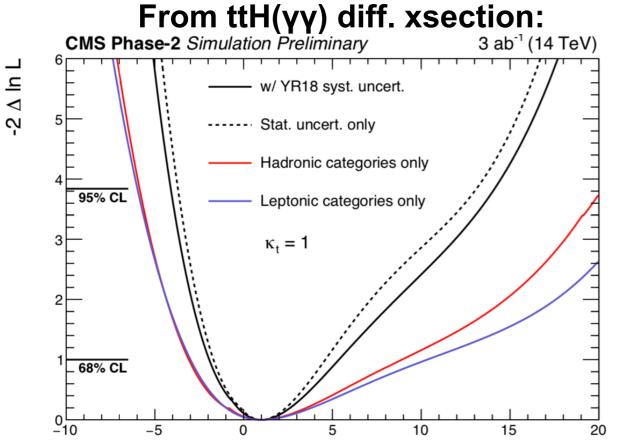


- Uncertainties ~20–40%, dominated by statistical component
- Main systematic uncertainties: reconstruction and identification efficiencies for photons and b jets; energy scale and resolution of reconstructed jets; rates of ggH and VH contamination

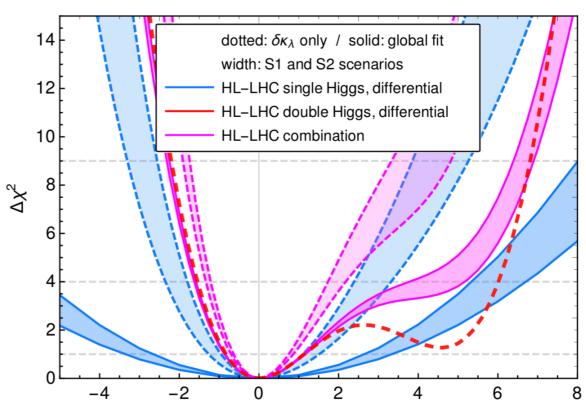
## Constraining the self-coupling w/ single-Higgs data

- Self-coupling induces higher-order corrections to single-Higgs production
- Can be constrained from rates or differential cross-sections of single-Higgs processes
  - Complementary to (stronger)
     constraints from di-Higgs (larger
     effects on smaller-rate processes)





#### From alobal fit of rates:



-4.1<κ<sub>λ</sub><14.1 at 95% CL (other couplings = SM)  $|κ_λ|<2-3$  at 95% CL (other couplings=SM) -7.1<κ<sub>λ</sub><14.1 at 95% CL (overall rate profiled)

#### Higgs boson mass

- Measured from invariant mass peak in high-resolution channels, γγ and 4I
- Current PDG average (ATLAS+CMS): m<sub>H</sub> = 125.18 ± 0.16 GeV
- With 36/fb of Run2 data γγ and 4l contribute similarly, but γγ is already systematically limited by the calibration, while 4l is statistically limited.
- Detailed studies of the calibration of the muons with the high-stat samples of HL-LHC have not been done yet. The ATLAS 4μ result has been extrapolated to 3000/fb in 4 hypothetical scenarios, leading to total uncertainty between 33 and 50 MeV (stat: 30 MeV).

	$\Delta_{ m tot} \ ({ m MeV})$	$\Delta_{\mathrm{stat}} \; (\mathrm{MeV})$	$\Delta_{\mathrm{syst}} \; (\mathrm{MeV})$
Current Detector	52	39	35
$\mu$ momentum resolution improvement by 30% or similar	47	30	37
$\mu$ momentum resolution/scale improvement of 30% / 50%	38	30	24
$\mu$ momentum resolution/scale improvement 30% / 80%	33	30	14

For CMS expect even better resolution due to strongest magnetic field
 => expect uncertainty <20 MeV combining ATLAS+CMS</li>

#### Higgs boson width

- 2 methods (on-shell / off-shell), both based on interference pp→H→X / pp→X
- On-shell methods rely only on on-shell decays. Two approaches:
  - Using shape information:
    - Real part of interference in X= $\gamma\gamma$  channel leads to shift of  $\gamma\gamma$  mass peak. In the SM ( $\Gamma_H^{SM}=4$  MeV)  $\Delta m_{\gamma\gamma}\sim O(30)$  MeV ( $\Delta m_{\gamma\gamma}\sim O(300)$  MeV for  $\Gamma=300$  MeV)
    - If photon calibration uncertainties remain similar to Run2, uncertainty on m(γγ)-m(4l) ~290 MeV => O(100)× Γ<sub>H</sub><sup>SM</sup>
    - Even with optimistic assumptions, hard to go below 10xΓ<sub>H</sub>SM
  - Using rate information:
    - Imaginary part of interference alters total rate. However, it is suppressed at
       LO by helicity conservation => small effects here, too
    - Recent phenomenological study including full NLO calculation of interference
      - Γ=Γ<sub>H</sub>SM => reduction of on-shell rate by ~2% in gg→H→γγ
      - 4% precision on γγ/4l xsection ratio => Γ <~15x Γ<sub>H</sub><sup>SM</sup>

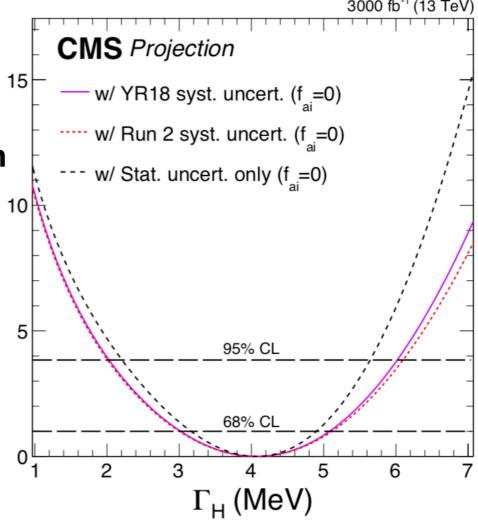
#### Higgs boson width with off-shell decays

Width can be inferred from ratio of off-shell/on-shell pp→H\*→ZZ xsections

$$\mu_{\text{on-shell}} = \frac{\sigma_{\text{on-shell}}^{gg \to H \to ZZ^*}}{\sigma_{\text{on-shell,SM}}^{gg \to H \to ZZ^*}} = \frac{\kappa_{g,\text{on-shell}}^2 \cdot \kappa_{Z,\text{on-shell}}^2}{\Gamma_H/\Gamma_H^{\text{SM}}}, \qquad \mu_{\text{off-shell}} = \frac{\sigma_{\text{off-shell}}^{gg \to H^* \to ZZ}}{\sigma_{\text{off-shell,SM}}^{gg \to H^* \to ZZ}} = \kappa_{g,\text{off-shell}}^2 \cdot \kappa_{Z,\text{off-shell,SM}}^2$$

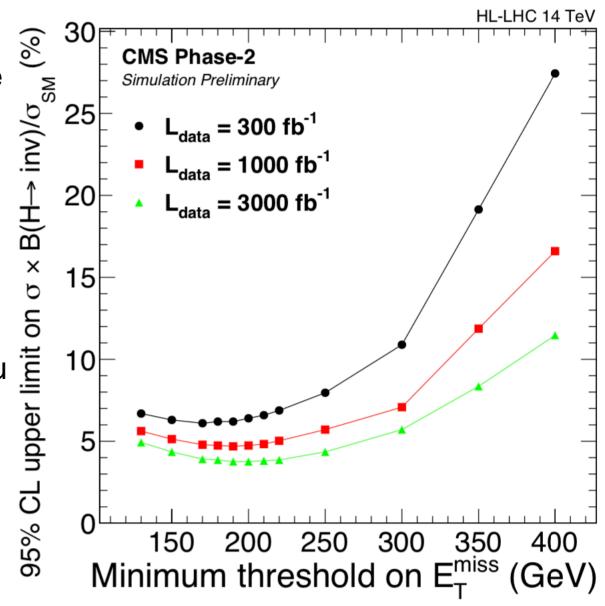
#### with some assumptions

- $k_{\text{off-shell}} >= k_{\text{on-shell}}$
- no new signals in search reason (except enhanced off-shell Higgs contribution)
- new physics that modifies the off-shell couplings also alters the phase of interference with ZZ\* continuum
- Current limits: Γ<14.4 MeV (ATLAS), <9.2 MeV (CMS)</li>
- ATLAS+CMS projections: single-experiment uncertainties ~ 1 MeV => 0.7 MeV after combination
- Modelling of the off-shell region is crucial and non trivial
  - irreducible, loop-induced gg→VV background interferes destructively with the signal => multi loop calculations are needed for good theoretical control of continuum background (top quark mass effects should also be estimated)



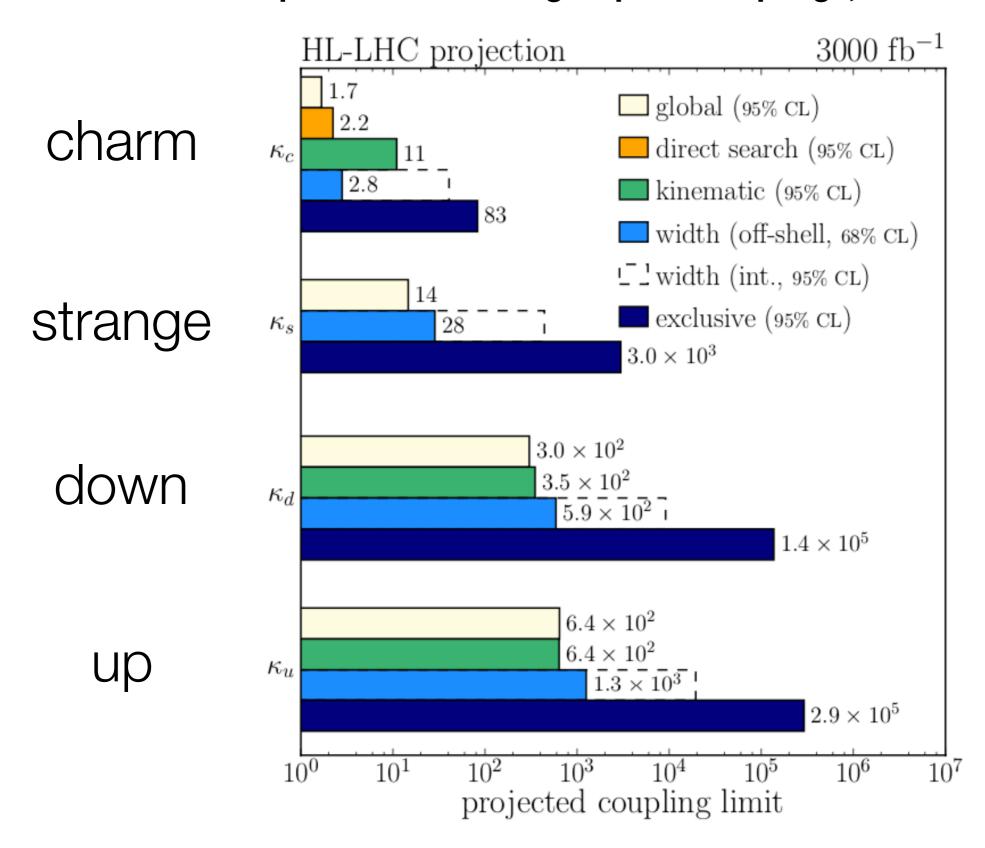
#### Invisible decays

- B<sub>inv</sub>SM~0.1% => any observable rate would be evidence for BSM physics
- LHC searches require production in association with a taggable object (Z-boson, VBF jets, or a single high-pT jet)
- Challenge: E<sub>T</sub><sup>miss</sup> spectrum relatively soft
   => resolution and pileup effects non-negligible
- Current analyses (30/fb): B<sub>inv</sub> <20-25%</li>
- Recent CMS study (fast simulation) of VBF+H(invisible): B<sub>inv</sub> <3.8% with optimised selection, not very sensitive to E<sub>T</sub><sup>miss</sup> resolution
  - limited by systematic uncertainties (e/mu identification, JES, ggF normalisation)
- With older ATLAS study of VH(invisible) channel (B<sub>inv</sub> <8%), assuming same performance for both detectors,</li>
   combination would lead to B<sub>inv</sub> < 2.5%</li>



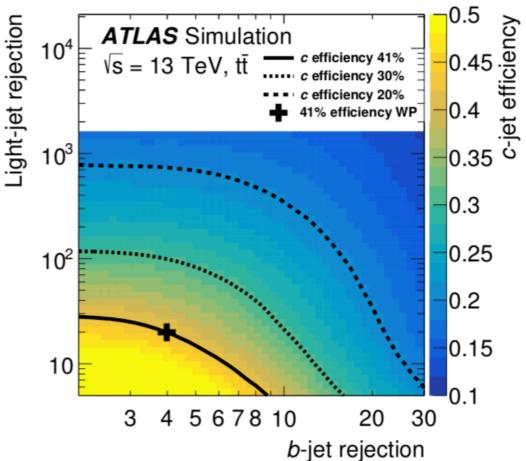
# Can we say something about light quark couplings?

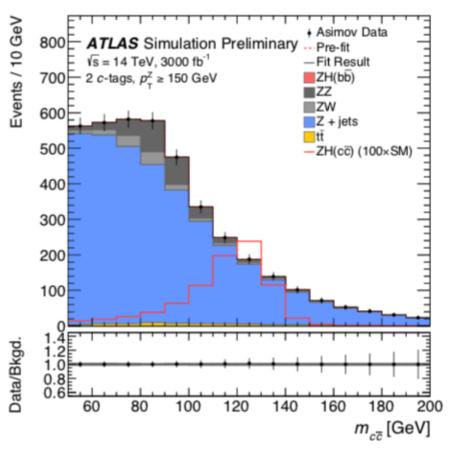
Several attempts to constrain light quark couplings, best limit for κ<sub>c</sub> <~1.7</li>



#### Charm coupling: direct search

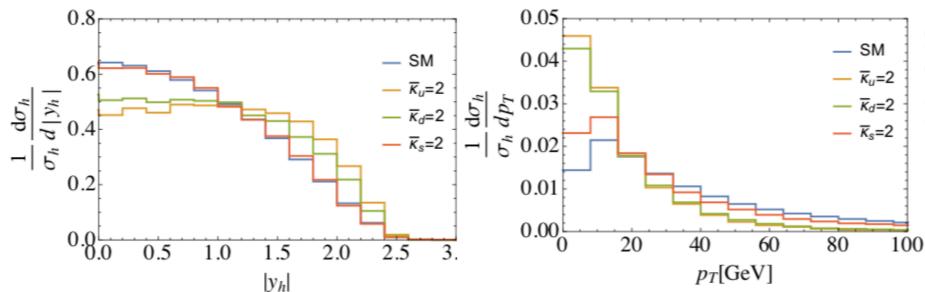
- From inclusive searches of H→cc (in VH)
- Need charm quark tagging and to disentangle other Higgs decays (such as H→bb)
- ATLAS H→cc:
  - Current limit w/ 36/fb: µ<~100</li>
  - Projection w/ 3000/fb (stat only): µ<~6</li>
    - Using tighter c-tagging than Run2: eff(c, b, l)=18%, 5%, 0.5%
  - Typical Run2 systematic uncertainty would increase limit by ~50%
  - Better c-tagging (light rejection x2.5)
     would decrease limit by ~10%

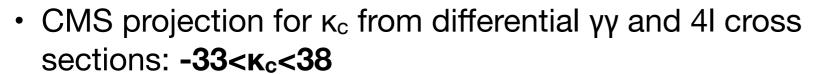




## Light quark couplings: kinematic

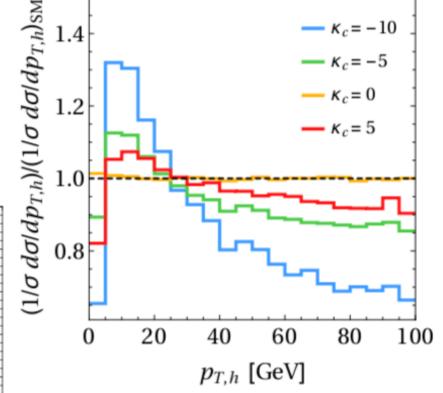
From differential distributions: enhanced u, d couplings lead to softer p<sub>T</sub><sup>H</sup> and more forward y<sup>H</sup> distributions from uu→h and dd→h. Enhanced c,s couplings lead to enhanced c,s-loops in gg→hj leading again to softer p<sub>T</sub><sup>H</sup> spectrum.

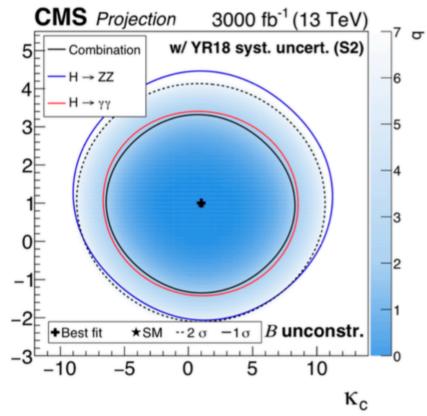






- SM ~22%
- y<sub>u</sub>, y<sub>d</sub> enhanced => larger (increased asymmetry of udbar vs dubar PDFs)
- y<sub>c</sub>, y<sub>s</sub> enhanced => smaller (symmetric csbar vs scbar PDFs)





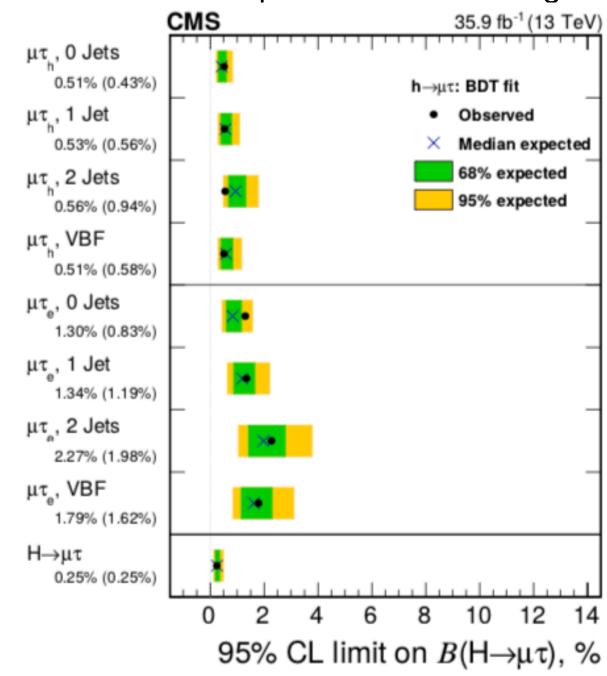
## Flavour violating decays

- Flavour violating Yukawa couplings constrained by low-energy flavour-changing neutral current measurements.
- Weaker constraints for flavour-violating couplings involving τ leptons

• strongest constraints on  $\kappa_{\tau\mu}$ ,  $\kappa_{\tau e}$ , from direct searches of lepton-flavour violating

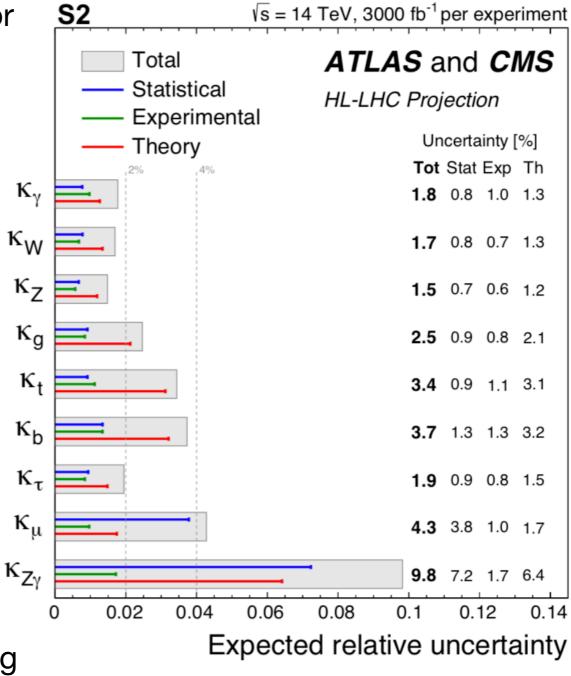
Higgs decays at LHC

- Current CMS results with 36/fb:
  - BR(μτ)<0.25%, BR(eτ)<0.61%
- Assuming both systematic and statistical errors scale with square root of the luminosity, expected limits with 3000/fb are:
  - BR( $\mu\tau$ ), BR( $e\tau$ ) < ~0.05%



#### Conclusion

- HL-LHC will open a new window on Higgs sector
  - %-level precision on Higgs couplings to bosons and 3rd generation fermions
  - access to couplings to 2nd generation fermions: μ to ~4%; hint of charm ~100% (inclusive searches and global fits)
  - Mass measurable to <20 MeV</li>
  - Width measurable to +-1 MeV (with some caveats)
  - Invisible decays: B<sub>inv</sub> < 2.5%</li>
  - Strong constraints on lepton-flavour or CP violating decays
- Single Higgs boson data can also be used to provide information on Higgs boson self-coupling complementary to double-Higgs production
- Many measurements limited by systematic uncertainties, important work needed from experimental and theoretical community to reduce them as assumed



More details..

#### Documentation

- Report from the WG2 of the Workshop on Physics at HL-LHC on Higgs Physics at the HL-LHC and HE-LHC: <a href="https://arxiv.org/abs/1902.00134">https://arxiv.org/abs/1902.00134</a>
- ATLAS HL-LHC projections: <a href="https://twiki.cern.ch/twiki/bin/view/AtlasPublic/UpgradePhysicsStudies">https://twiki.cern.ch/twiki/bin/view/AtlasPublic/UpgradePhysicsStudies</a>
- CMS HL-LHC projections: <a href="http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/FTR/">http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/FTR/</a>
- ATLAS performance projections: ATL-PHYS-PUB-2019-005, <a href="https://cds.cern.ch/">https://cds.cern.ch/</a>
  record/2655304/
- CMS performance projections: CMS-NOTE-2018-006, <a href="https://cds.cern.ch/record/2650976">https://cds.cern.ch/record/2650976</a>

# Systematic uncertainty projections

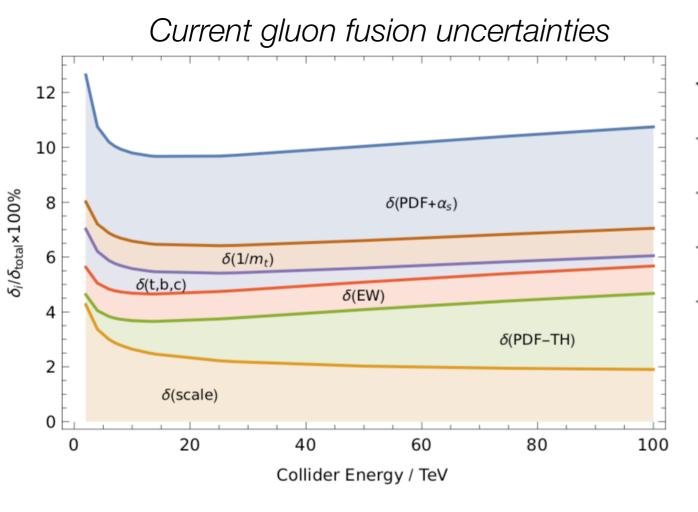
#### Experimental:

- ATLAS & CMS experts of physics objects reconstruction and detector systems scrutinised the current systematic uncertainties to determine which contributions are limited by statistics and which by more fundamental limitations.
- Predictions were made taking into account the increased integrated luminosity and expected potential gains in technique.
- Procedures were harmonised between the experiments
  - For all scenarios, the intrinsic statistical uncertainty in the measurement is reduced by a factor 1/√L
  - Systematics driven by **intrinsic detector limitations** are left unchanged, or revised according to detailed simulation studies of the upgraded detector.
  - Uncertainties on methods are kept at the same value as in the latest public results available, assuming that the harsher HL-LHC conditions will be compensated by method improvements
  - The uncertainty in the integrated luminosity of the data sample is assumed to be reduced down to 1% thanks to improvements in the calibration and use of new capabilities of the upgraded detectors

## Systematic uncertainty projections

#### Theoretical:

- most theory uncertainties are assumed to be reduced by a factor of two with respect to the current knowledge, thanks to foreseen improvements such as
  - higher-order calculations
  - reduced parton distribution functions (PDF) and α<sub>s</sub> uncertainties



#### Projected gluon fusion PDF uncertainties

E <sub>CM</sub>	Current	Scenario 1	Scenario 2	Scenario 3
13 TeV	$\pm 1.85\%$	$\pm 0.78\%$	$\pm 0.69\%$	$\pm 0.59\%$
14 TeV	$\pm 1.85\%$	$\pm 0.78\%$	$\pm 0.68\%$	$\pm 0.58\%$
27 TeV	$\pm 1.95\%$	$\pm 0.81\%$	$\pm 0.72\%$	$\pm 0.61\%$

3000/fb. Experimental systematic uncertainties are assumed to be equal, 0.7, or 0.4 w.r.t to current ones

## Performance Achievements and Goals (I): Trigger

	Run 1	Run 2	HL-LHC (ATLAS/CMS)
Single e (isolated)	25	27	22 / 27
Single $\mu$ (isolated)	25	27	20 / 18
Single photon	120	140	120*
Two photons	25,25	25,25	25, 25 / 22,16
Two taus	40,30	40,30	40,30 / 56,56
Four jets	45	45	45 /65
HT	700	700	375 / 350
MET	150	200	200

Numbers from ATLAS (very similar in CMS)

\*ATLAS

- Thresholds have remained approximately unchanged from Run 1 to Run 2 (came with changes in total bandwidth and different selection criteria, e.g. isolation)
- Towards HL-LHC expect even improvements w.r.t. Run 2, key aspects:
  - Increase readout rate 750-1000 kHz (currently 100 kHz)
  - Increased latency
  - Enhanced data processing capabilities, storage rate up to 10 kHz (currently 1-2 kHz)

Slide by M. Kado

## Higgs boson couplings: H→γγ

Prod. mode	Scenario	$\Delta_{ m tot}/\sigma_{ m SM}$	$\Delta_{ m stat}/\sigma_{ m SM}$	$\Delta_{ m exp}/\sigma_{ m SM}$	$\Delta_{ m sig}/\sigma_{ m SM}$	$\Delta\mu_{ m sig}$
$ggF+b\bar{b}H$	Run 2, $80  \text{fb}^{-1}$	$+0.15 \\ -0.14$	$+0.11 \\ -0.11$	$^{+0.09}_{-0.08}$	$+0.03 \\ -0.02$	$+0.08 \\ -0.06$
	HL-LHC S1	$+0.06 \\ -0.05$	$+0.02 \\ -0.02$	$^{+0.05}_{-0.05}$	$^{+0.01}_{-0.01}$	+0.07 $-0.06$
	HL-LHC S2	$^{+0.04}_{-0.03}$	$^{+0.02}_{-0.02}$	$^{+0.03}_{-0.03}$	$^{+0.01}_{-0.01}$	$+0.03 \\ -0.03$
VBF	Run 2, $80  \text{fb}^{-1}$	$^{+0.36}_{-0.31}$	$^{+0.30}_{-0.28}$	$^{+0.16}_{-0.11}$	$^{+0.13}_{-0.09}$	$+0.15 \\ -0.10$
	HL-LHC S1	$+0.14 \\ -0.13$	$+0.04 \\ -0.04$	$^{+0.08}_{-0.07}$	$^{+0.11}_{-0.10}$	$+0.11 \\ -0.10$
	HL-LHC S2	$^{+0.10}_{-0.09}$	$+0.04 \\ -0.04$	$^{+0.06}_{-0.06}$	$^{+0.06}_{-0.05}$	$+0.06 \\ -0.06$
$\overline{VH}$	Run 2, $80  \text{fb}^{-1}$	$+0.59 \\ -0.54$	$^{+0.54}_{-0.50}$	$^{+0.22}_{-0.20}$	$^{+0.12}_{-0.09}$	$+0.18 \\ -0.11$
	HL-LHC S1	$+0.11 \\ -0.10$	$^{+0.08}_{-0.08}$	$^{+0.06}_{-0.05}$	$^{+0.05}_{-0.04}$	$+0.09 \\ -0.08$
	HL-LHC S2	$+0.09 \\ -0.09$	$^{+0.08}_{-0.08}$	$^{+0.04}_{-0.03}$	$^{+0.03}_{-0.03}$	$+0.05 \\ -0.05$
top	Run 2, $80  \text{fb}^{-1}$	$^{+0.37}_{-0.32}$	$^{+0.34}_{-0.30}$	$^{+0.10}_{-0.07}$	$^{+0.10}_{-0.07}$	$+0.18 \\ -0.11$
	HL-LHC S1	$^{+0.11}_{-0.10}$	$+0.05 \\ -0.05$	$^{+0.07}_{-0.06}$	$^{+0.07}_{-0.07}$	$+0.13 \\ -0.11$
	HL-LHC S2	$^{+0.08}_{-0.08}$	$+0.05 \\ -0.05$	$^{+0.05}_{-0.04}$	$^{+0.04}_{-0.04}$	+0.07 $-0.06$

• Error reduction (S2): stat 6.5x, ggF 4.1x, VBF 3.5x, VH 6.3x, top 4.3x

## Higgs boson couplings: H→γγ



pileup reweighting

photon ID efficiency

luminosity

**UEPS VBF** 

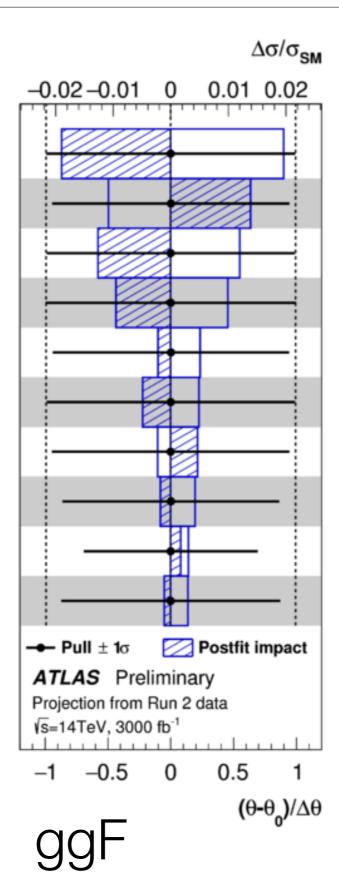
trigger efficiency

jet flavour composition VBF

JER

jet pileup ρ-topology

jet flavour composition ggF



jet flavour composition VBF

**UEPS VBF** 

QCD scale ggF, VBF-like 2j

QCD scale ggF, jet-bin 1↔2

photon isolation efficiency

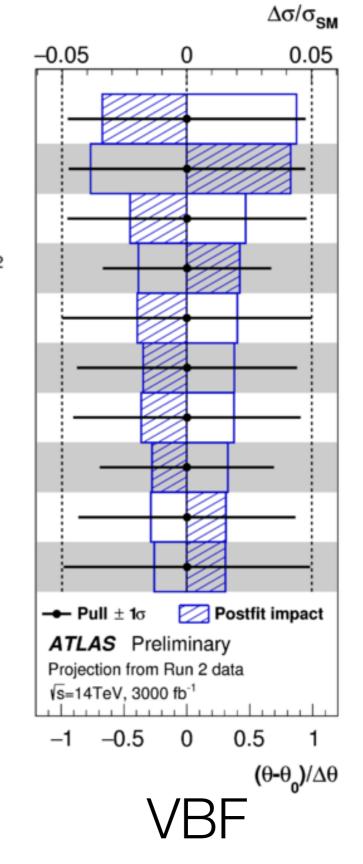
QCD scale ggF, p<sub>T</sub><sup>H</sup><120

QCD scale ggF, p<sub>T</sub><sup>H</sup><60

jet pileup ρ-topology

**JER** 

jet flavour response VBF



## Higgs boson couplings: H→γγ

photon isolation efficiency

QCD scale VH

photon ID efficiency

QCD scale ggF, jet-bin 1↔2

pileup reweighting

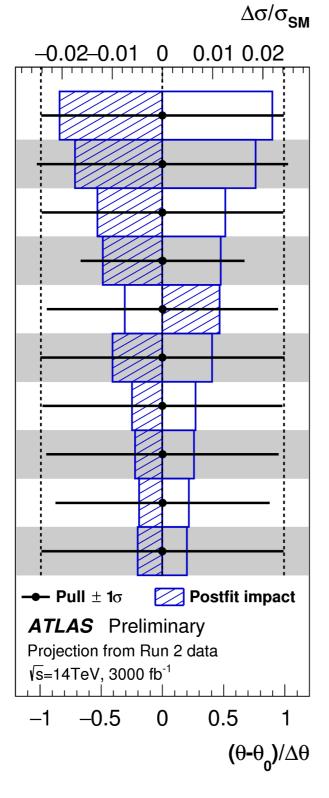
luminosity

electron ID efficiency

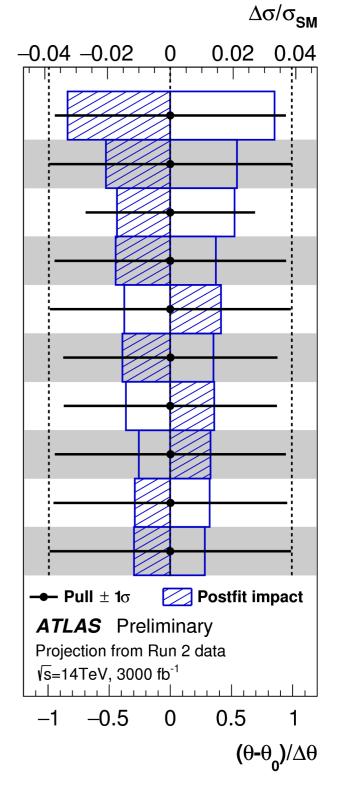
electron/photon energy scale

QCD scale ggF, p H < 120

trigger efficiency



**UEPS ttH** photon isolation efficiency jet pileup ρ-topology VH HF content b-jet tagging efficiency 1 ggF HF content jet flavour composition ggF pileup reweighting jet flavour composition ttH photon ID efficiency



VH

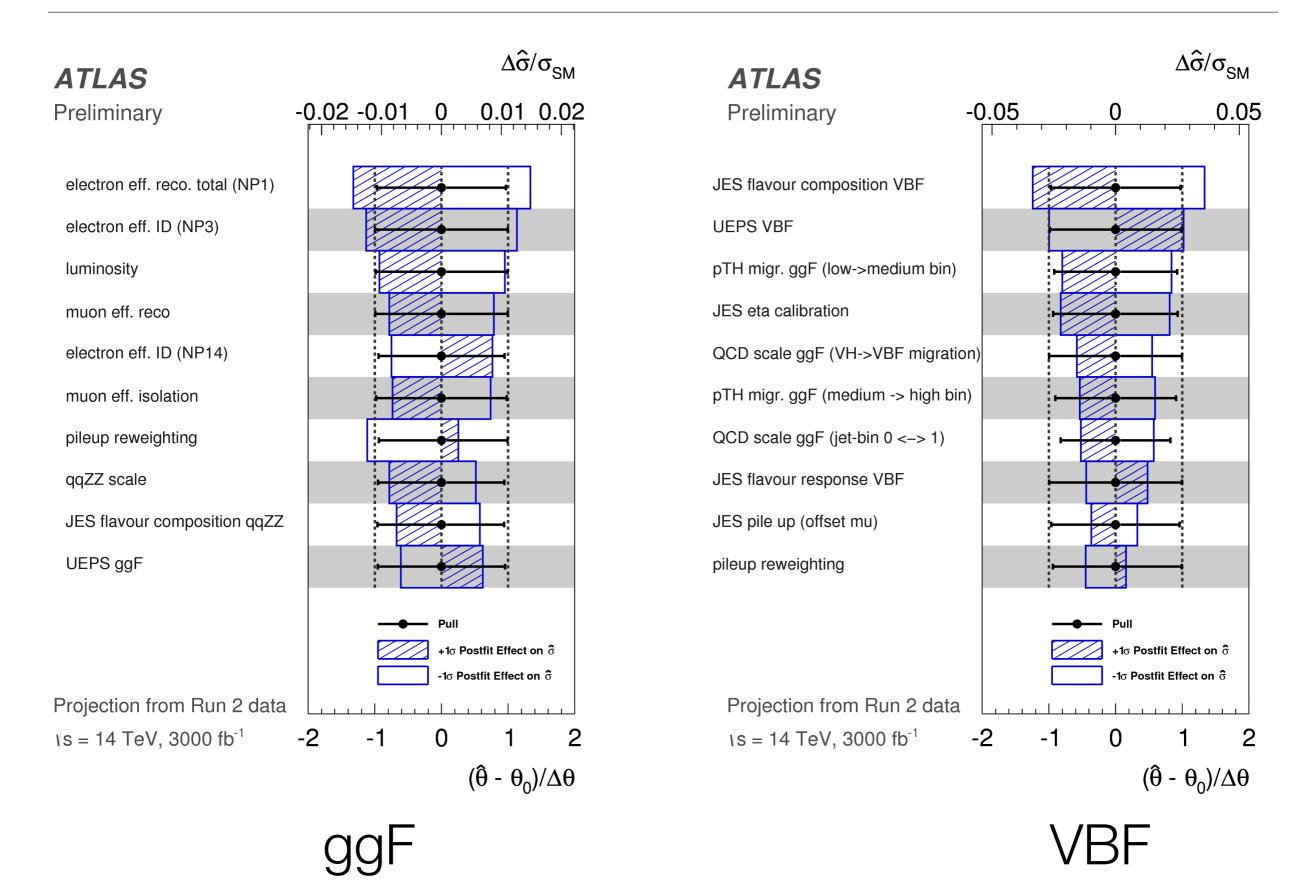
ttH

# Higgs boson couplings: H→ZZ\*→4I

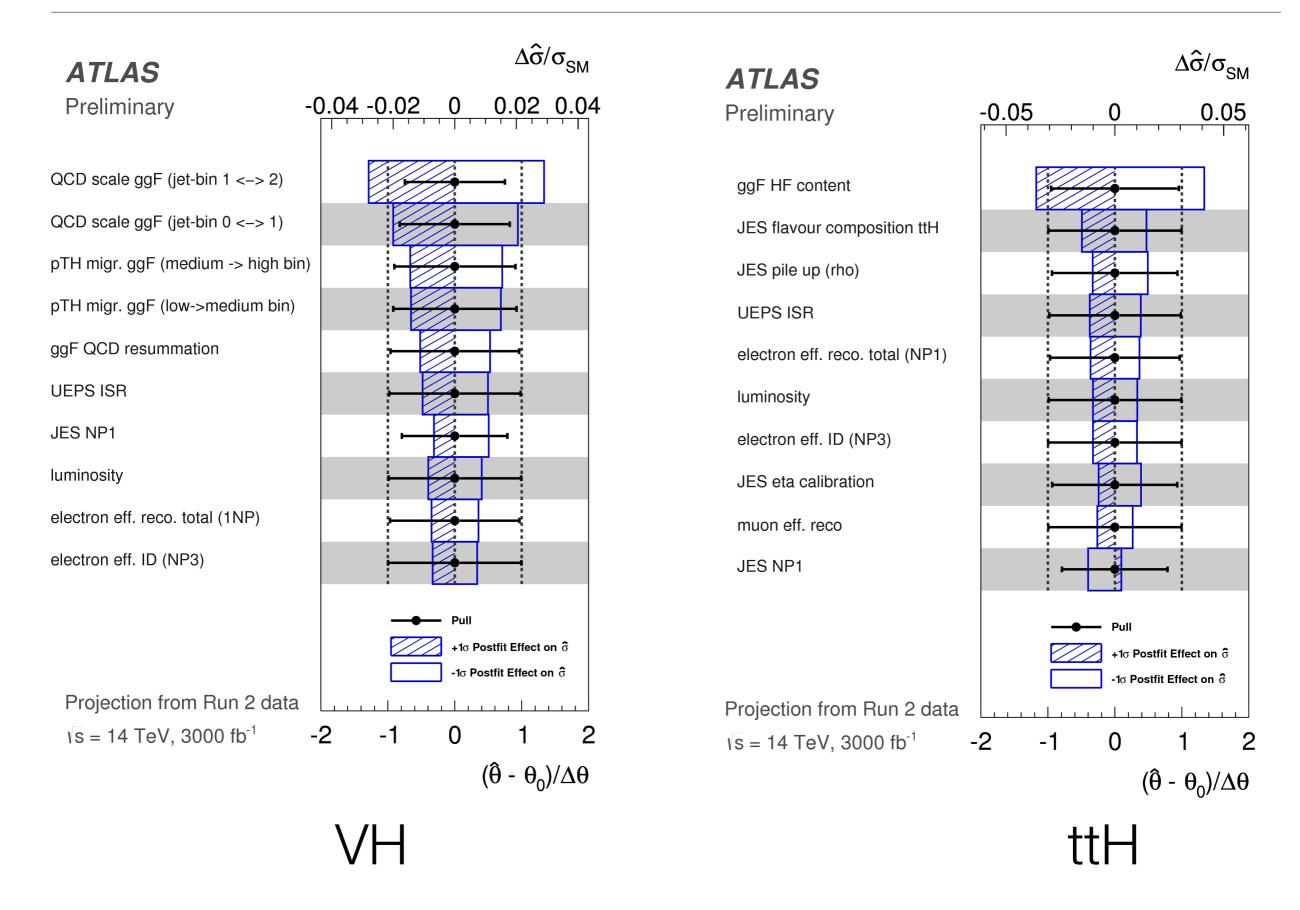
Prod. mode	Analysis	$\Delta_{ m tot}/\sigma_{ m SM}$	$\Delta_{ m stat}/\sigma_{ m SM}$	$\Delta_{ m exp}/\sigma_{ m SM}$	$\Delta_{ m sig}/\sigma_{ m SM}$	$\Delta_{ m bkg}/\sigma_{ m SM}$	$\Delta \mu_{ m sig}$
	Run 2, $80  \text{fb}^{-1}$	$+0.160 \\ -0.152$	$+0.143 \\ -0.136$	$+0.053 \\ -0.052$	$^{+0.043}_{-0.036}$	$+0.011 \\ -0.014$	$+0.070 \\ -0.052$
ggF	HL-LHC S1	$+0.056 \\ -0.055$	$+0.020 \\ -0.020$	$+0.042 \\ -0.043$	$^{+0.026}_{-0.024}$	$^{+0.007}_{-0.007}$	$+0.062 \\ -0.056$
	HL-LHC S2	$+0.043 \\ -0.043$	$+0.020 \\ -0.020$	$+0.035 \\ -0.035$	$^{+0.016}_{-0.015}$	$+0.006 \\ -0.006$	$+0.030 \\ -0.028$
	Run 2, $80  \text{fb}^{-1}$	$+0.782 \\ -0.598$	$+0.753 \\ -0.583$	$+0.157 \\ -0.095$	$^{+0.136}_{-0.074}$	$+0.014 \\ -0.029$	$+0.161 \\ -0.101$
VBF	HL-LHC S1	$+0.147 \\ -0.135$	$+0.097 \\ -0.094$	$+0.059 \\ -0.054$	$^{+0.088}_{-0.078}$	$^{+0.007}_{-0.008}$	$+0.087 \\ -0.072$
	HL-LHC S2	$+0.125 \\ -0.117$	$+0.097 \\ -0.094$	$+0.057 \\ -0.052$	$^{+0.051}_{-0.047}$	$^{+0.007}_{-0.006}$	$+0.053 \\ -0.050$
	Run 2, $80  \text{fb}^{-1}$	$+1.410 \\ -0.959$	$+1.381 \\ -0.946$	$+0.155 \\ -0.075$	$+0.228 \\ -0.137$	$+0.012 \\ -0.008$	$+0.283 \\ -0.144$
VH	HL-LHC S1	$+0.200 \\ -0.185$	$+0.176 \\ -0.167$	$^{+0.051}_{-0.042}$	$^{+0.082}_{-0.070}$	$^{+0.002}_{-0.001}$	$+0.124 \\ -0.084$
	HL-LHC S2	$+0.190 \\ -0.178$	$+0.176 \\ -0.167$	$+0.043 \\ -0.033$	$+0.064 \\ -0.056$	$   < 0.001 \\   < 0.001 $	$+0.077 \\ -0.062$
$tar{t}H$	Run 2, $80  \text{fb}^{-1}$	< 5.75		_			
	HL-LHC S1	$+0.246 \\ -0.213$	$+0.217 \\ -0.195$	$^{+0.056}_{-0.042}$	$^{+0.100}_{-0.074}$	$^{+0.020}_{-0.026}$	$+0.156 \\ -0.095$
	HL-LHC S2	$+0.226 \\ -0.202$	$+0.217 \\ -0.195$	$+0.042 \\ -0.032$	$^{+0.047}_{-0.037}$	$+0.010 \\ -0.015$	$\begin{array}{ c c c c } +0.074 \\ -0.051 \end{array}$

• Error reduction (S2): stat 6.5x, ggF 3.6x, VBF 5.8x, VH 6.4x, top > 6.5x

## Higgs boson couplings: H→ZZ\*→4I



## Higgs boson couplings: H→ZZ\*→4I



## Higgs boson couplings: H→WW\*→IvIv and H→ττ

## $H \rightarrow WW^* \rightarrow |V|V$

Prod. mode	Scenario	$\Delta_{ m tot}/\sigma_{ m SM}$	$\Delta_{ m stat}/\sigma_{ m SM}$	$\Delta_{ m exp}/\sigma_{ m SM}$	$\Delta_{ m sig}/\sigma_{ m SM}$	$\Delta_{ m bkg}/\sigma_{ m SM}$	$\Delta \mu_{ m sig}$
ggF	$\operatorname{Run} 2, 36  \mathrm{fb}^{-1}$	$+0.191 \\ -0.189$	$+0.099 \\ -0.098$	$+0.112 \\ -0.110$	$+0.047 \\ -0.036$	$+0.092 \\ -0.096$	$+0.077 \\ -0.058$
	HL-LHC S1	$+0.064 \\ -0.065$	$+0.010 \\ -0.010$	$^{+0.037}_{-0.037}$	$+0.040 \\ -0.039$	$+0.033 \\ -0.036$	$\begin{array}{ c c c c } +0.068 \\ -0.064 \end{array}$
	HL-LHC S2	$ \begin{array}{c c} +0.046 \\ -0.044 \end{array} $	$+0.010 \\ -0.010$	$+0.030 \\ -0.029$	$+0.023 \\ -0.020$	$+0.025 \\ -0.025$	+0.035 $-0.033$
VBF	Run 2, $36  \text{fb}^{-1}$	$+0.391 \\ -0.360$	$+0.332 \\ -0.311$	$+0.122 \\ -0.110$	$+0.115 \\ -0.098$	$+0.106 \\ -0.093$	$+0.119 \\ -0.099$
	HL-LHC S1	$+0.108 \\ -0.109$	$+0.033 \\ -0.033$	$^{+0.055}_{-0.048}$	$^{+0.070}_{-0.067}$	$^{+0.056}_{-0.064}$	$\begin{vmatrix} +0.073 \\ -0.070 \end{vmatrix}$
	HL-LHC S2	$+0.067 \\ -0.066$	$+0.033 \\ -0.033$	$+0.029 \\ -0.029$	$+0.038 \\ -0.037$	$+0.032 \\ -0.033$	+0.039 $-0.038$

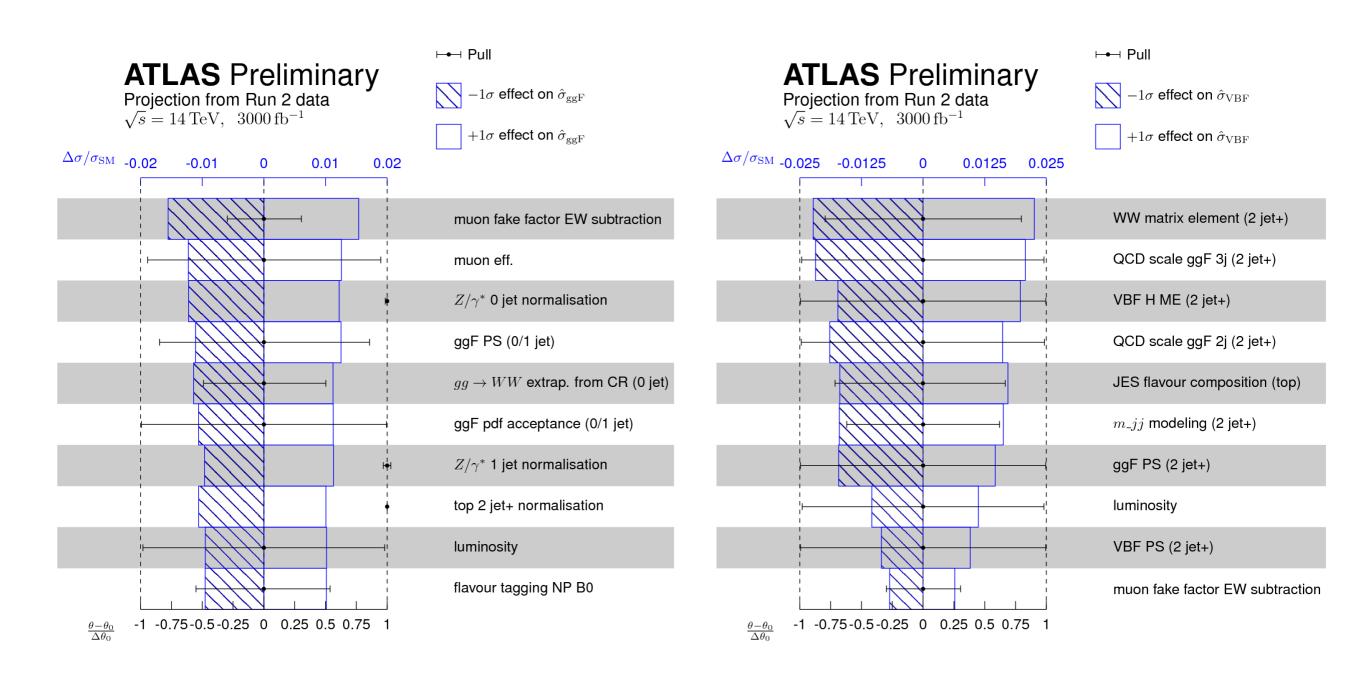
• Error reduction (S2): stat 9.8x, ggF 4.2x, VBF 5.6x

### $H \rightarrow \tau \tau$

Prod. mode	Scenario	$\Delta_{ m tot}/\sigma_{ m SM}$	$\Delta_{ m stat}/\sigma_{ m SM}$	$\Delta_{ m exp}/\sigma_{ m SM}$	$\Delta_{ m sig}/\sigma_{ m SM}$	$\Delta_{ m bkg}/\sigma_{ m SM}$	$\Delta \mu_{ m sig}$
ggF	Run 2, $36  \text{fb}^{-1}$	+0.629 $-0.526$	+0.337 $-0.333$	$+0.365 \\ -0.420$	$+0.364 \\ -0.150$	$+0.139 \\ -0.133$	$+0.360 \\ -0.149$
	HL-LHC S1	$+0.231 \\ -0.185$	$^{+0.031}_{-0.031}$	$+0.060 \\ -0.062$	$+0.203 \\ -0.160$	$^{+0.080}_{-0.055}$	$+0.236 \\ -0.185$
	HL-LHC S2	$+0.123 \\ -0.108$	$+0.031 \\ -0.031$	$+0.041 \\ -0.039$	$+0.104 \\ -0.090$	$+0.031 \\ -0.024$	$+0.123 \\ -0.105$
VBF	Run 2, $36  \text{fb}^{-1}$	$+0.591 \\ -0.538$	$+0.390 \\ -0.373$	$+0.380 \\ -0.389$	$+0.149 \\ -0.078$	$+0.139 \\ -0.110$	$+0.180 \\ -0.091$
	HL-LHC S1	$+0.093 \\ -0.093$	$+0.034 \\ -0.034$	$+0.052 \\ -0.056$	$+0.063 \\ -0.053$	$+0.034 \\ -0.034$	$+0.081 \\ -0.075$
	HL-LHC S2	$+0.080 \\ -0.076$	$+0.034 \\ -0.034$	$+0.049 \\ -0.045$	$+0.027 \\ -0.033$	$+0.038 \\ -0.038$	$+0.042 \\ -0.042$

Error reduction (S2): stat 9.8x, ggF 5.0x, VBF 7.2x

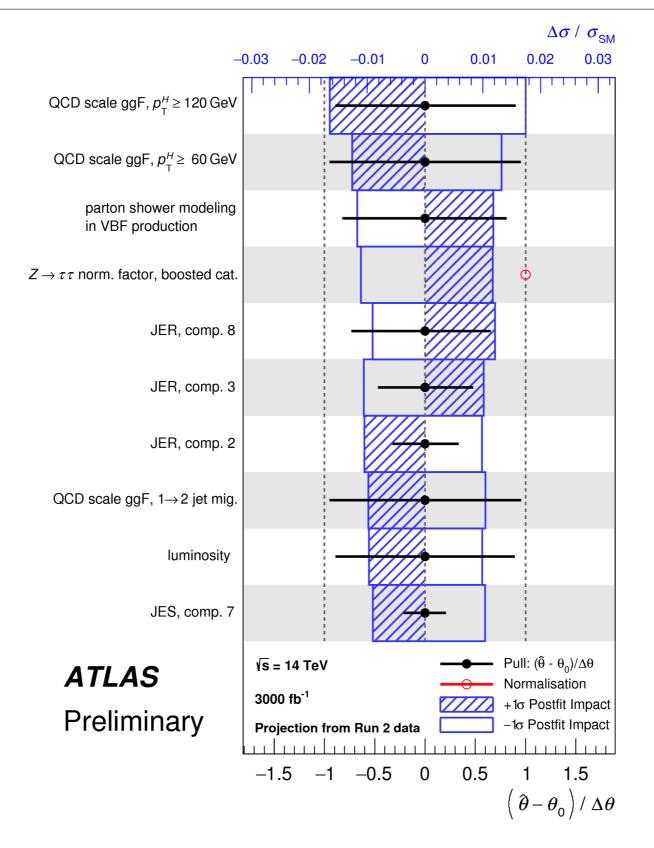
# Higgs boson couplings: H→WW\*→IvIv



ggF

**VBF** 

## Higgs boson couplings: H→ττ



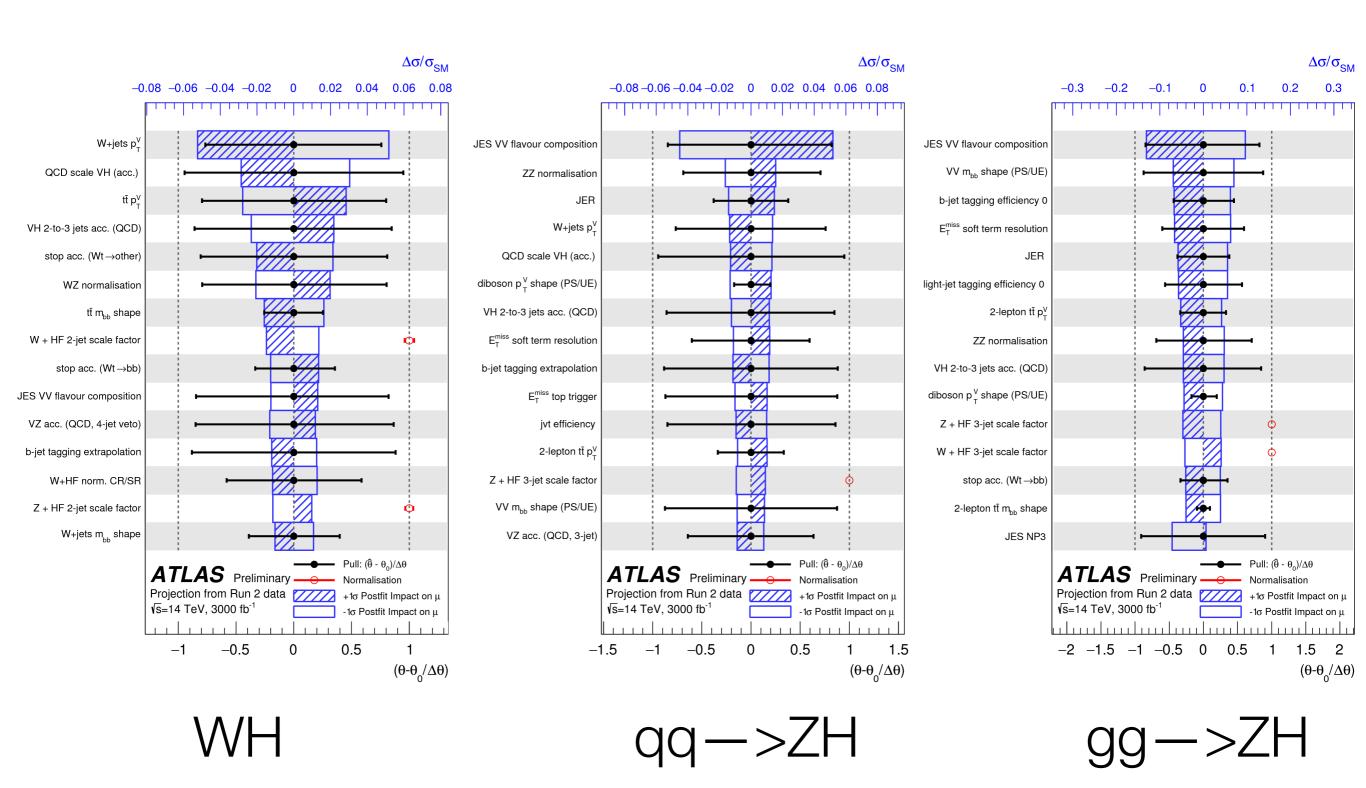
ggF+VBF

## Higgs boson couplings: VH, H→bb

Prod. mode	Scenario	$\Delta_{ m tot}/\sigma_{ m SM}$	$\Delta_{ m stat}/\sigma_{ m SM}$	$\Delta_{ m exp}/\sigma_{ m SM}$	$\Delta_{ m sig}/\sigma_{ m SM}$	$\Delta_{ m bkg}/\sigma_{ m SM}$	$\Delta \mu_{ m sig}$
WH	Run 2, 80 fb <sup>-1</sup>	$^{+0.462}_{-0.425}$	$+0.272 \\ -0.265$	$+0.157 \\ -0.127$	$^{+0.176}_{-0.075}$	$^{+0.224}_{-0.213}$	$+0.180 \\ -0.077$
	HL-LHC S1	$^{+0.149}_{-0.138}$	$+0.041 \\ -0.041$	$+0.048 \\ -0.047$	$^{+0.080}_{-0.070}$	$^{+0.108}_{-0.100}$	$+0.085 \\ -0.074$
	HL-LHC S2	$+0.104 \\ -0.100$	$+0.041 \\ -0.041$	$+0.044 \\ -0.043$	$+0.046 \\ -0.041$	$+0.072 \\ -0.069$	$+0.050 \\ -0.045$
$q\bar{q} \to ZH$	Run 2, 80 fb <sup>-1</sup>	+0.667 $-0.629$	$+0.578 \\ -0.562$	$+0.129 \\ -0.101$	$+0.175 \\ -0.105$	$^{+0.143}_{-0.126}$	$+0.180 \\ -0.105$
	HL-LHC S1	$+0.138 \\ -0.132$	$+0.090 \\ -0.089$	$+0.065 \\ -0.063$	$^{+0.061}_{-0.055}$	$^{+0.054}_{-0.048}$	+0.067 $-0.059$
	HL-LHC S2	$+0.121 \\ -0.118$	+0.090 -0.089	$+0.057 \\ -0.055$	$+0.031 \\ -0.028$	$+0.048 \\ -0.046$	+0.037 -0.033
gg  o ZH	Run 2, 80 fb <sup>-1</sup>	+2.629 $-2.608$	$+2.105 \\ -2.105$	$+0.606 \\ -0.677$	$+0.658 \\ -0.454$	$^{+1.012}_{-1.037}$	$+1.269 \\ -0.645$
	HL-LHC S1	$+0.498 \\ -0.490$	$+0.333 \\ -0.333$	$+0.249 \\ -0.250$	$^{+0.181}_{-0.140}$	$+0.207 \\ -0.218$	$+0.495 \\ -0.209$
	HL-LHC S2	$+0.432 \\ -0.433$	$+0.333 \\ -0.333$	$+0.208 \\ -0.204$	$+0.096 \\ -0.080$	$+0.177 \\ -0.181$	$+0.222 \\ -0.115$

• Error reduction (S2): stat 6.5x, WH 4.3x, qqZH 5.4x, ggZH 5.8x

## Higgs boson couplings: VH, H→bb

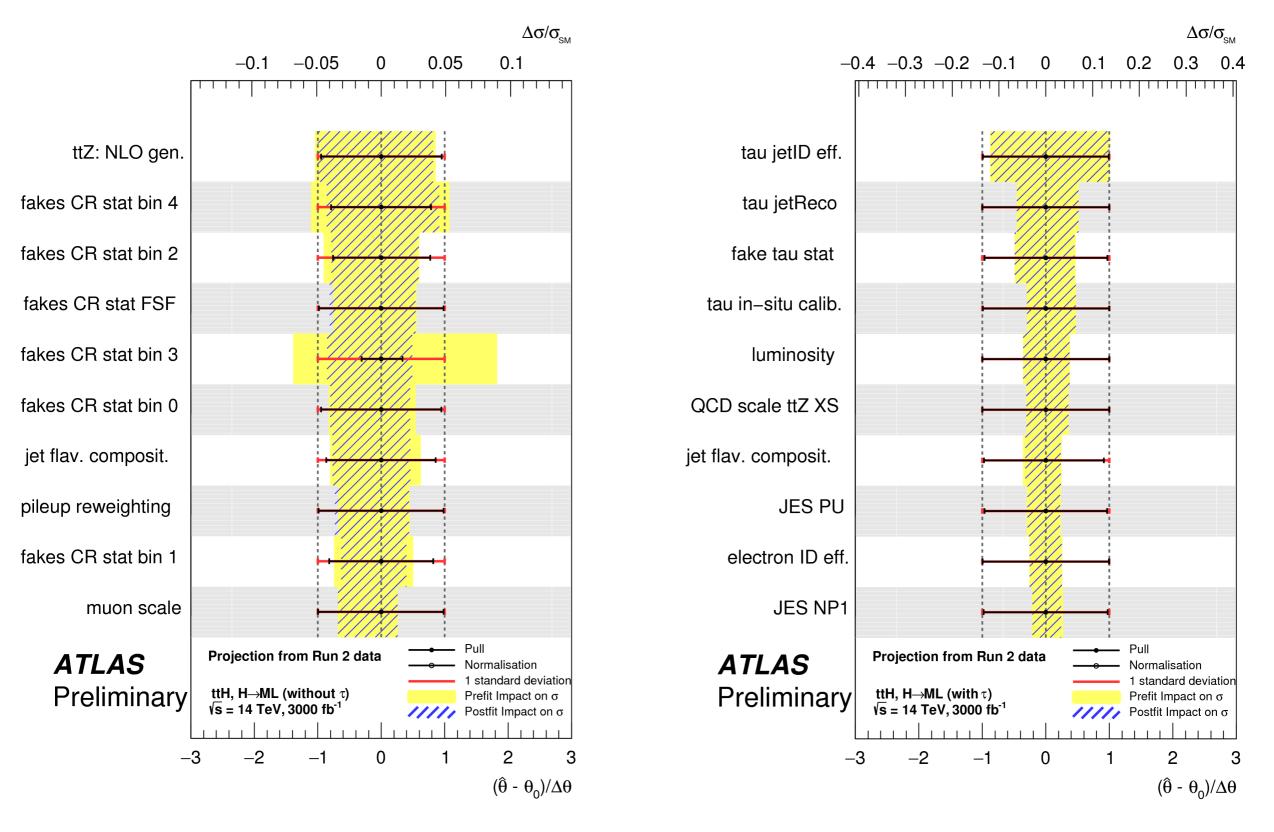


## Higgs boson couplings: ttH (H→bb, H→ML)

Final state	Scenario	$\Delta_{ m tot}/\sigma_{ m SM}$	$\Delta_{ m stat}/\sigma_{ m SM}$	$\Delta_{ m exp}/\sigma_{ m SM}$	$\Delta_{ m sig}/\sigma_{ m SM}$	$\Delta_{ m bkg}/\sigma_{ m SM}$	$\Delta \mu_{ m sig}$
$t\bar{t}H, H \to \mathrm{ML}$	Run 2, 36 fb <sup><math>-1</math></sup>	$^{+0.40}_{-0.40}$	$^{+0.33}_{-0.34}$	$^{+0.15}_{-0.15}$	$^{+0.10}_{-0.10}$	$^{+0.13}_{-0.13}$	$+0.13 \\ -0.13$
(no $\tau$ )	HL-LHC S1	$^{+0.18}_{-0.18}$	$^{+0.04}_{-0.04}$	$^{+0.13}_{-0.14}$	$^{+0.08}_{-0.08}$	$^{+0.12}_{-0.12}$	$^{+0.11}_{-0.11}$
	HL-LHC S2	$^{+0.17}_{-0.17}$	$^{+0.04}_{-0.04}$	$^{+0.12}_{-0.13}$	$^{+0.05}_{-0.05}$	$^{+0.09}_{-0.09}$	$^{+0.07}_{-0.07}$
$t\bar{t}H, H \to \mathrm{ML}$	Run 2, 36 fb <sup><math>-1</math></sup>	$+0.64 \\ -0.64$	$^{+0.54}_{-0.54}$	$+0.29 \\ -0.29$	$^{+0.10}_{-0.09}$	$^{+0.14}_{-0.13}$	$+0.13 \\ -0.13$
(with $ au$ )	HL-LHC S1	$^{+0.27}_{-0.28}$	$^{+0.07}_{-0.07}$	$^{+0.23}_{-0.23}$	$^{+0.09}_{-0.08}$	$^{+0.12}_{-0.12}$	$^{+0.11}_{-0.11}$
	HL-LHC S2	$^{+0.25}_{-0.25}$	$^{+0.07}_{-0.07}$	$^{+0.22}_{-0.22}$	$^{+0.05}_{-0.05}$	$^{+0.07}_{-0.07}$	$^{+0.07}_{-0.07}$
$t\bar{t}H, H \to b\bar{b}$	Run 2, 36 fb <sup><math>-1</math></sup>	$^{+0.61}_{-0.61}$	$^{+0.22}_{-0.22}$	$^{+0.27}_{-0.28}$	$^{+0.10}_{-0.09}$	$^{+0.47}_{-0.47}$	$+0.15 \\ -0.15$
(single lepton)	HL-LHC S1	$^{+0.25}_{-0.20}$	$^{+0.02}_{-0.02}$	$^{+0.10}_{-0.10}$	$^{+0.08}_{-0.06}$	$^{+0.22}_{-0.17}$	$^{+0.10}_{-0.11}$
	HL-LHC S2	$^{+0.18}_{-0.15}$	$^{+0.02}_{-0.02}$	$^{+0.09}_{-0.09}$	$^{+0.06}_{-0.05}$	$^{+0.14}_{-0.11}$	$^{+0.08}_{-0.07}$
$t\bar{t}H, H \to b\bar{b}$	Run 2, 36 fb <sup><math>-1</math></sup>	$+1.06 \\ -1.08$	$^{+0.51}_{-0.51}$	$^{+0.32}_{-0.31}$	$^{+0.11}_{-0.12}$	$+0.90 \\ -0.92$	$+0.14 \\ -0.14$
(dilepton)	HL-LHC S1	$^{+0.32}_{-0.26}$	$^{+0.06}_{-0.06}$	$^{+0.13}_{-0.13}$	$^{+0.08}_{-0.07}$	$^{+0.27}_{-0.21}$	$^{+0.11}_{-0.09}$
	HL-LHC S2	$^{+0.23}_{-0.20}$	$^{+0.06}_{-0.06}$	$^{+0.11}_{-0.11}$	$^{+0.06}_{-0.06}$	$^{+0.17}_{-0.15}$	$^{+0.08}_{-0.08}$

• Error reduction (S2): stat 9.5x, ttH ML w/o tau 2.4x, w/ tau 2.6x, bb single lepton 3x, dilepton 5.0x

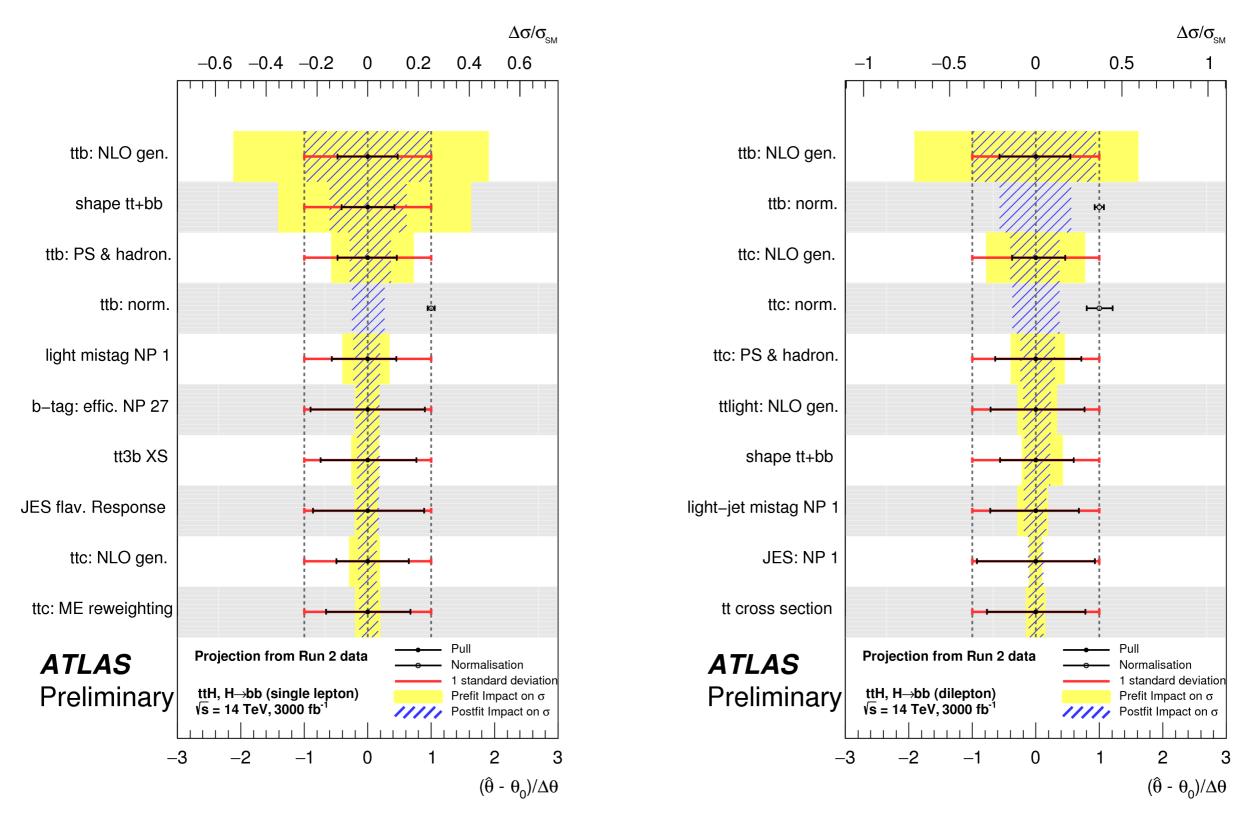
## Higgs boson couplings: ttH, H→ML



ML, no  $\tau$ 

ML,  $\tau$ 

## Higgs boson couplings: ttH, H→bb



bb (single lepton)

bb (dilepton)

## Higgs couplings: tH (H→bb, H→multileptons)

#### tH (ML+bb):

- 5x smaller than ttH, not observed yet
- due to interference between diagrams with t-H and W-H couplings, it allows access to the sign of the top-Higgs Yukawa coupling.
- Expect to set UL on μ<sub>tH</sub><1.5 in scenario S2.</li>

## Higgs boson couplings: $H\rightarrow \mu\mu$ and $H\rightarrow Z\gamma\rightarrow II\gamma$

$$H \rightarrow \mu\mu$$

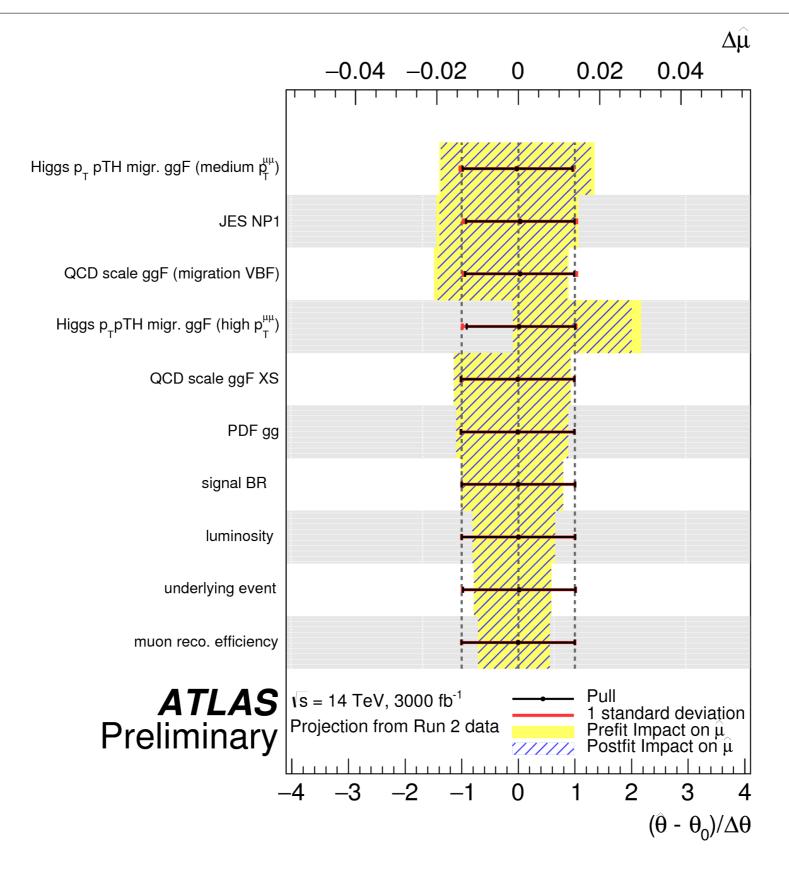
Scenario	$\Delta_{ m tot}/\sigma_{ m SM}$	$\Delta_{ m stat}/\sigma_{ m SM}$	$\Delta_{ m exp}/\sigma_{ m SM}$	$\Delta_{\mu_{ m sig}}/\sigma_{ m SM}$
Run 2, $79.8 \text{ fb}^{-1}$	$+1.04 \\ -1.06$	$+0.99 \\ -1.03$	$^{+0.03}_{-0.03}$	$^{+0.32}_{-0.27}$
HL-LHC S1	$^{+0.15}_{-0.14}$	$^{+0.12}_{-0.13}$	$^{+0.03}_{-0.03}$	$^{+0.08}_{-0.05}$
HL-LHC S2	$^{+0.13}_{-0.13}$	$^{+0.12}_{-0.13}$	$^{+0.02}_{-0.02}$	$^{+0.05}_{-0.04}$

 Error reduction (S2): stat 6.5x, tot: 8.1x => due to better 30% better invariant mass resolution

$$H \rightarrow Z \gamma \rightarrow II \gamma$$

Scenario	$\Delta_{ m tot}/\sigma_{ m SM}$	$\Delta_{ m stat}/\sigma_{ m SM}$	$\Delta_{ m syst}/\sigma_{ m SM}$
HL-LHC S1	0.23	0.20	0.11

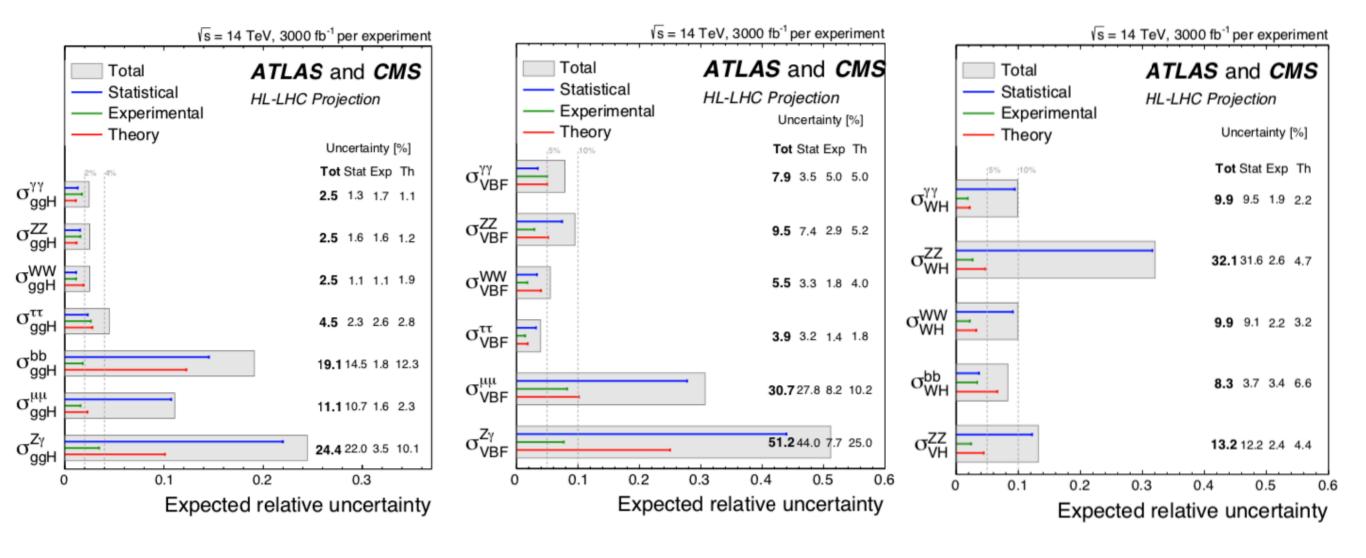
# Higgs boson couplings: H→µµ



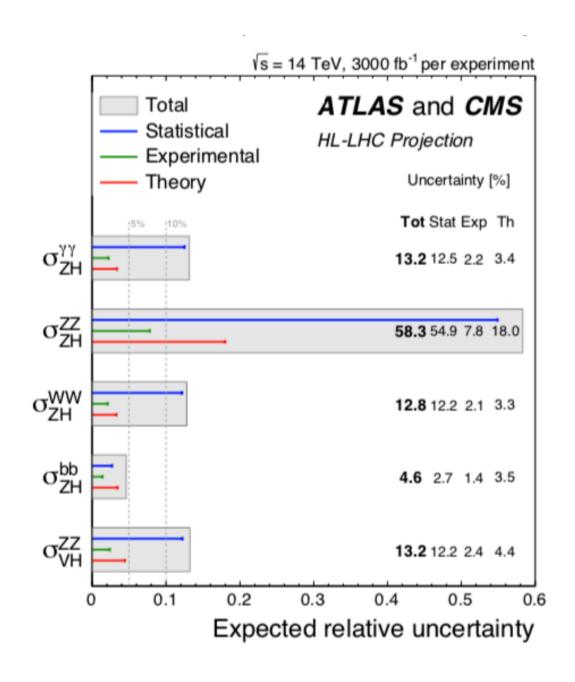
## Higgs boson couplings: combining ATLAS+CMS

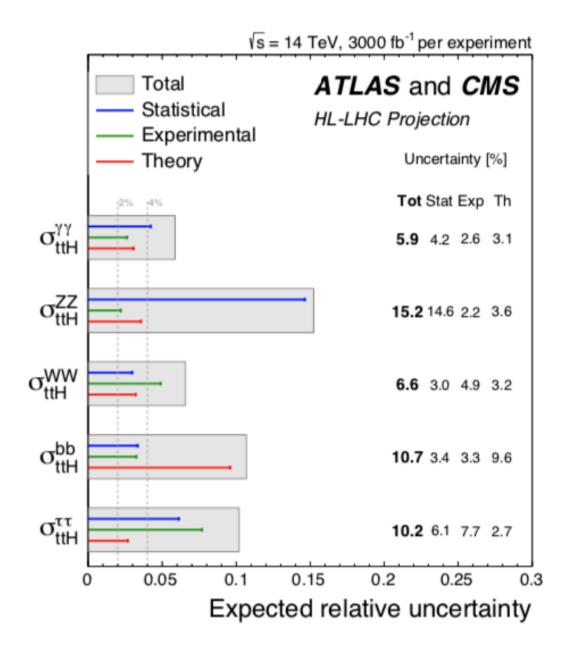
- Three type of combinations, determining different sets of parameters
  - x-sections\*branching ratios and x-section ratios: 1 per channel and production mode
  - production cross sections: combine decay channels assuming SM BRs
  - branching ratios: combine production modes assuming SM production cross-sections
- Treatment of theory uncertainties depends on combination performed:
  - xsections\*BR, or ratios: only uncertainties affecting the acceptance
  - production x-sections: uncertainties on SM branching ratios also included
  - branching ratios: uncertainties on SM cross sections (QCD scale and PDF+α<sub>S</sub> uncertainties) also included

# Higgs boson couplings: combination

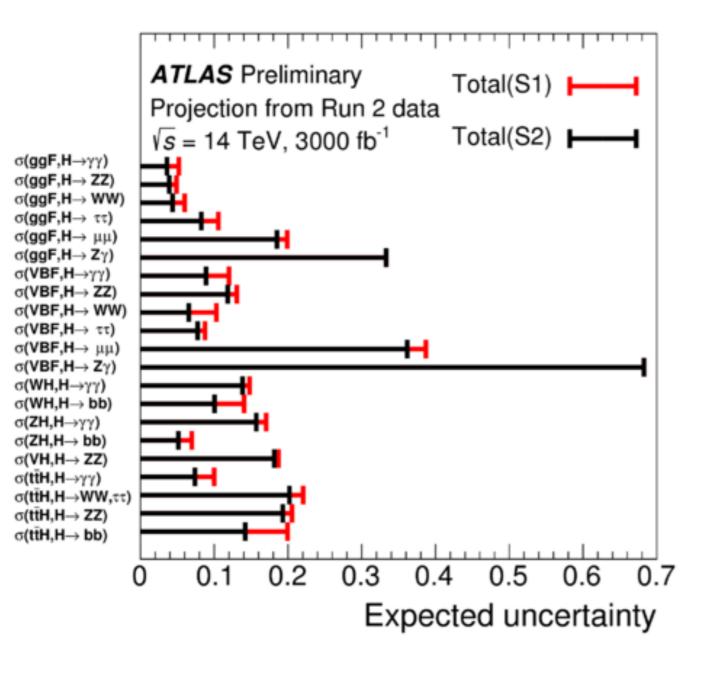


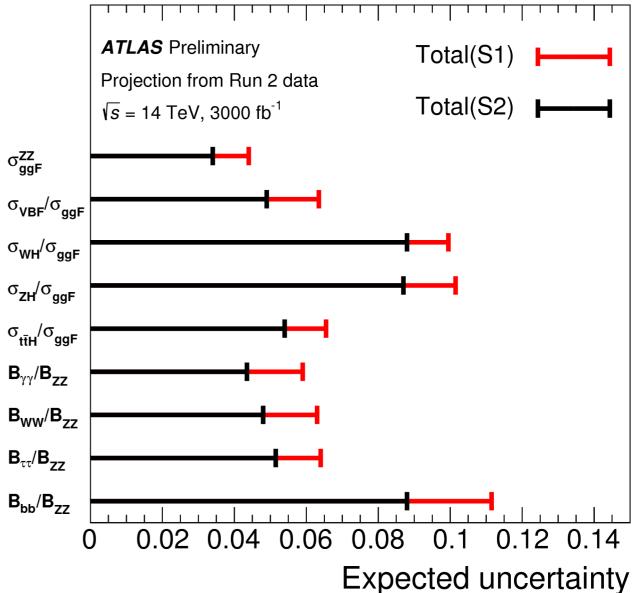
## Higgs boson couplings: combination





## Higgs boson couplings: combination S1 vs S2





# Higgs boson couplings: combination S1 vs S2

# w/o BSM decays

$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	$\begin{array}{c} +0.020 \\ -0.019 \\ +0.013 \\ -0.012 \\ +0.012 \\ -0.012 \\ +0.008 \\ -0.008 \\ -0.033 \\ -0.036 \end{array}$
$\kappa_Z  \begin{array}{ c c c c c c c c c c c c c c c c c c c$	-0.012 $+0.012$ $-0.012$ $+0.008$ $-0.008$ $+0.033$
$\begin{array}{ c c c c c c c c c c c c c c c c c c c$	-0.012 $+0.008$ $-0.008$ $+0.033$
HL-LHC S2   -0.018   -0.009   -0.009   -0.010	-0.008 $+0.033$
[ 0.000   0.011 0.010 -0.041	
HL-LHC S2 $\begin{vmatrix} +0.043 \\ -0.040 \end{vmatrix} \begin{vmatrix} +0.011 \\ -0.011 \end{vmatrix} \begin{vmatrix} +0.014 \\ -0.014 \end{vmatrix} \begin{vmatrix} +0.028 \\ -0.024 \end{vmatrix}$	$+0.026 \\ -0.027$
$\kappa_b$ HL-LHC S1 $^{+0.064}_{-0.060}$ $^{+0.016}_{-0.016}$ $^{+0.023}_{-0.022}$ $^{+0.038}_{-0.036}$	$+0.043 \\ -0.040$
HL-LHC S2 $\begin{vmatrix} +0.044 \\ -0.043 \end{vmatrix} \begin{vmatrix} +0.016 \\ -0.016 \end{vmatrix} \begin{vmatrix} +0.020 \\ -0.020 \end{vmatrix} \begin{vmatrix} +0.022 \\ -0.021 \end{vmatrix}$	$+0.029 \\ -0.028$
$\kappa_{\tau}$ HL-LHC S1 $^{+0.038}_{-0.037}$ $^{+0.011}_{-0.016}$ $^{+0.017}_{-0.016}$ $^{+0.026}_{-0.025}$	$+0.019 \\ -0.018$
HL-LHC S2 $\begin{vmatrix} +0.028 \\ -0.027 \end{vmatrix} \begin{vmatrix} +0.011 \\ -0.011 \end{vmatrix} \begin{vmatrix} +0.016 \\ -0.016 \end{vmatrix} \begin{vmatrix} +0.016 \\ -0.015 \end{vmatrix}$	$+0.013 \\ -0.012$
$\kappa_g$ HL-LHC S1 $^{+0.043}_{-0.041}$ $^{+0.010}_{-0.010}$ $^{+0.014}_{-0.014}$ $^{+0.033}_{-0.031}$	$+0.022 \\ -0.021$
HL-LHC S2 $\begin{vmatrix} +0.032 \\ -0.030 \end{vmatrix}$ $\begin{vmatrix} +0.010 \\ -0.010 \end{vmatrix}$ $\begin{vmatrix} +0.012 \\ -0.011 \end{vmatrix}$ $\begin{vmatrix} +0.022 \\ -0.021 \end{vmatrix}$	$^{+0.016}_{-0.016}$
$\kappa_{\gamma}$ HL-LHC S1 $^{+0.038}_{-0.036}$ $^{+0.009}_{-0.009}$ $^{+0.025}_{-0.024}$ $^{+0.022}_{-0.021}$	$+0.015 \\ -0.014$
HL-LHC S2 $\begin{vmatrix} +0.024 \\ -0.023 \end{vmatrix} \begin{vmatrix} +0.009 \\ -0.009 \end{vmatrix} \begin{vmatrix} +0.017 \\ -0.017 \end{vmatrix} \begin{vmatrix} +0.011 \\ -0.011 \end{vmatrix}$	$+0.009 \\ -0.009$
$\kappa_{\mu}$ HL-LHC S1 $^{+0.079}_{-0.076}$ $^{+0.062}_{-0.066}$ $^{+0.021}_{-0.018}$ $^{+0.041}_{-0.030}$	$+0.015 \\ -0.013$
HL-LHC S2 $\begin{vmatrix} +0.070 \\ -0.071 \end{vmatrix} \begin{vmatrix} +0.062 \\ -0.066 \end{vmatrix} \begin{vmatrix} +0.019 \\ -0.016 \end{vmatrix} \begin{vmatrix} +0.023 \\ -0.018 \end{vmatrix}$	$+0.009 \\ -0.009$
$\kappa_{Z\gamma}$ HL-LHC S1 $^{+0.128}_{-0.126}$ $^{+0.097}_{-0.107}$ $^{+0.028}_{-0.022}$ $^{+0.077}_{-0.061}$	$+0.015 \\ -0.012$
HL-LHC S2 $\begin{vmatrix} +0.124 \\ -0.123 \end{vmatrix} \begin{vmatrix} +0.097 \\ -0.107 \end{vmatrix} \begin{vmatrix} +0.027 \\ -0.022 \end{vmatrix} \begin{vmatrix} +0.071 \\ -0.056 \end{vmatrix}$	$+0.010 \\ -0.008$

# w/ BSM decays and $|k_V| < 1$

POI	Scenario	$\Delta_{ m tot}$	$\Delta_{ m stat}$	$\Delta_{ m exp}$	$\Delta_{ m sig}$	$\Delta_{ m bkg}$
$\kappa_W$	HL-LHC S1	$+0.000 \\ -0.030$	$+0.000 \\ -0.008$	$+0.000 \\ -0.013$	$+0.000 \\ -0.019$	$+0.000 \\ -0.018$
	HL-LHC S2	$+0.000 \\ -0.022$	$+0.000 \\ -0.008$	$+0.000 \\ -0.011$	$+0.000 \\ -0.011$	$+0.000 \\ -0.012$
$\kappa_Z$	HL-LHC S1	$+0.000 \\ -0.025$	$+0.000 \\ -0.008$	$^{+0.000}_{-0.011}$	$^{+0.000}_{-0.017}$	$+0.000 \\ -0.012$
	HL-LHC S2	$+0.000 \\ -0.017$	$+0.000 \\ -0.008$	$+0.000 \\ -0.009$	$+0.000 \\ -0.010$	$+0.000 \\ -0.007$
$\kappa_t$	HL-LHC S1	$+0.063 \\ -0.058$	$+0.013 \\ -0.011$	$^{+0.017}_{-0.016}$	$+0.054 \\ -0.041$	$+0.025 \\ -0.036$
	HL-LHC S2	+0.039 $-0.040$	$+0.013 \\ -0.011$	$^{+0.015}_{-0.014}$	$+0.027 \\ -0.024$	$+0.020 \\ -0.026$
$\kappa_b$	HL-LHC S1	$+0.043 \\ -0.059$	$+0.013 \\ -0.016$	$+0.018 \\ -0.022$	$+0.028 \\ -0.035$	+0.023 $-0.039$
	HL-LHC S2	+0.031 $-0.042$	+0.013 $-0.016$	$+0.015 \\ -0.020$	$+0.017 \\ -0.020$	$+0.016 \\ -0.027$
$\kappa_{ au}$	HL-LHC S1	$+0.032 \\ -0.036$	$+0.010 \\ -0.011$	$+0.016 \\ -0.016$	$+0.022 \\ -0.025$	$+0.014 \\ -0.017$
	HL-LHC S2	$+0.024 \\ -0.027$	$+0.010 \\ -0.011$	$^{+0.015}_{-0.016}$	$^{+0.014}_{-0.015}$	$+0.009 \\ -0.012$
$\kappa_g$	HL-LHC S1	$+0.042 \\ -0.043$	$^{+0.012}_{-0.010}$	$+0.013 \\ -0.014$	$+0.036 \\ -0.033$	$+0.013 \\ -0.021$
	HL-LHC S2	+0.028 $-0.030$	$+0.012 \\ -0.010$	$^{+0.011}_{-0.011}$	$+0.020 \\ -0.021$	$+0.009 \\ -0.016$
$\kappa_{\gamma}$	HL-LHC S1	$+0.029 \\ -0.035$	$+0.008 \\ -0.009$	$+0.024 \\ -0.024$	$+0.013 \\ -0.013$	$+0.005 \\ -0.019$
	HL-LHC S2	$+0.020 \\ -0.023$	$+0.008 \\ -0.009$	$^{+0.016}_{-0.017}$	$^{+0.008}_{-0.010}$	$+0.004 \\ -0.009$
$\kappa_{\mu}$	HL-LHC S1	$+0.078 \\ -0.076$	$+0.062 \\ -0.066$	$+0.021 \\ -0.018$	$+0.041 \\ -0.031$	$+0.009 \\ -0.012$
	HL-LHC S2	+0.069 $-0.071$	$+0.062 \\ -0.066$	$+0.019 \\ -0.016$	$+0.022 \\ -0.018$	$+0.005 \\ -0.008$
$\kappa_{Z\gamma}$	HL-LHC S1	$+0.127 \\ -0.126$	$+0.097 \\ -0.107$	$+0.028 \\ -0.022$	$+0.069 \\ -0.061$	$+0.034 \\ -0.011$
	HL-LHC S2	$+0.123 \\ -0.123$	$+0.096 \\ -0.098$	$+0.031 \\ -0.049$	$+0.070 \\ -0.056$	$+0.005 \\ -0.007$
$B_{BSM}$	HL-LHC S1	$+0.049 \\ -0.000$	$^{+0.014}_{-0.000}$	$+0.019 \\ -0.000$	$+0.034 \\ -0.000$	$+0.026 \\ -0.000$
	HL-LHC S2	+0.033 $-0.000$	$+0.015 \\ -0.000$	$+0.015 \\ -0.000$	$+0.019 \\ -0.000$	$+0.017 \\ -0.000$

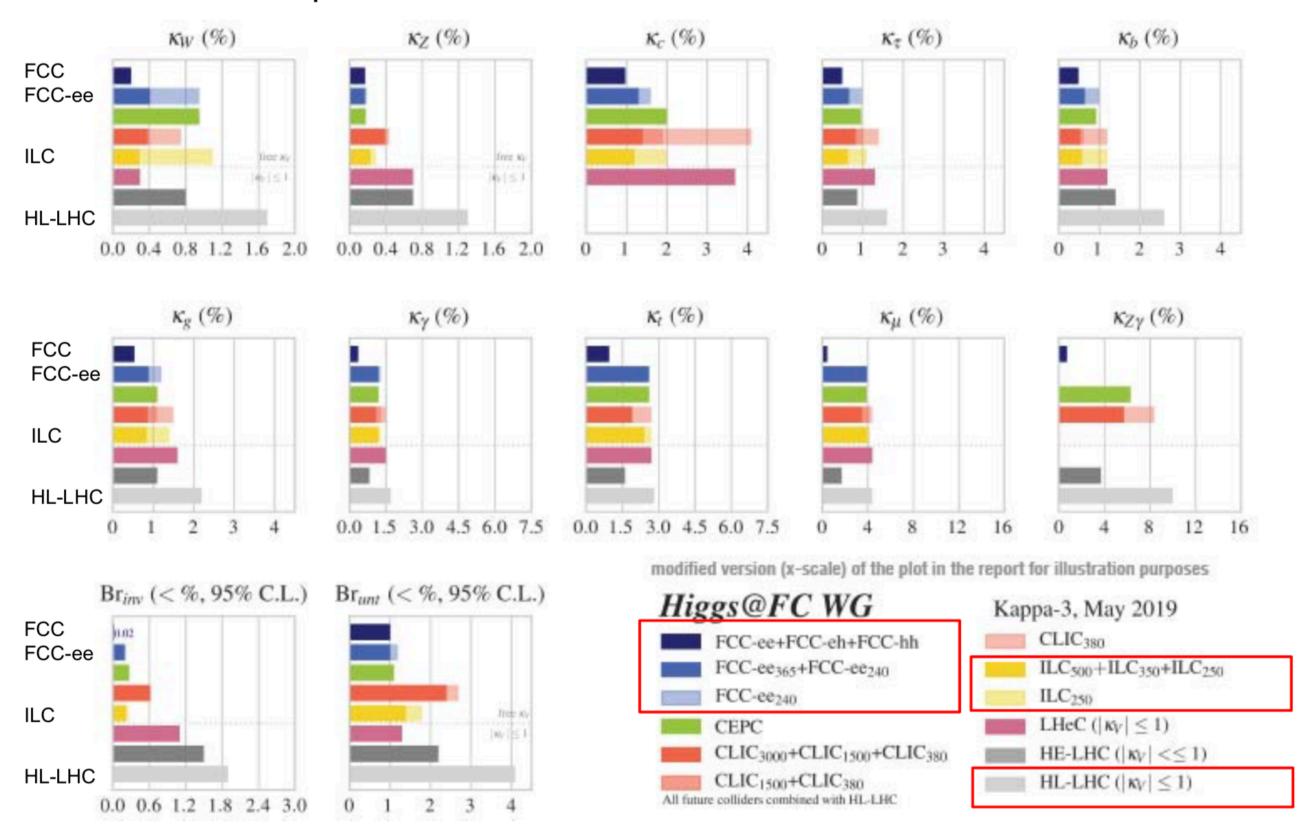
## Higgs boson couplings: k-framework interpretation

- Rough projections have been done for HE-LHC assuming that the experimental performance and systematic uncertainties are unchanged with respect to the current LHC experiments.
- Two scenarios are assumed for the theoretical and modelling systematic uncertainties on the signal and backgrounds
  - S2: same as HL-LHC S2
  - S2': theoretical and modelling systematic uncertainties further halved

Coupling	S2	S2'
$k_{\gamma}$	1.6	1.2
$k_W$	1.5	1.0
$k_Z$	1.3	0.8
$k_q$	2.2	1.3
$k_t^{\sigma}$	3.2	1.9
$k_b$	3.5	2.1
$k_{ au}$	1.7	1.1
$k_{\mu}$	2.2	1.7
$k_{Z\gamma}$	6.9	4.1

## Higgs couplings: comparison of future colliders

#### Obtenues après combinaison avec les résultats attendus au HL-LHC



#### Electrons

Table 3: Representative values for systematic uncertainties for electrons at the HL-LHC. These uncertainties are consistent with the Run 2 uncertainties with the exception of the combination of the reconstruction, identification and isolation efficiency at high  $p_{\rm T}$  (above 200 GeV), where dedicated studies at CMS were used as an ATLAS approximation. [15]

Electron Parameter	Range	Uncertainty
Energy scale	Energy scale $p_{\rm T} \approx 45 \; {\rm GeV}$	
	high $p_{\rm T}$ , up to 200 GeV	0.3%
Reconstruction + Identification Efficiency (ID)	$p_{\rm T} \approx 45 \; {\rm GeV}$	0.5%
Reconstruction + ID + Isolation Efficiency	$p_{\rm T} > 200 {\rm GeV}$	2%

#### Muons

Table 4: Run 2 systematic uncertainties for muons, which are also assumed for ATLAS running at the HL-LHC. [15]

Muon Parameter	Range	Run 2 Uncertainty
Reconstruction + Identification Efficiency	$p_{\rm T} < 200 \; {\rm GeV}$	0.1%
	$200 \text{ GeV} < p_{\text{T}} < 1 \text{ TeV}$	2-20%
Resolution	$p_{\rm T} < 200 \; {\rm GeV}$	5%
	$200 \text{ GeV} < p_{\text{T}} < 1 \text{ TeV}$	10-20%
Energy Scale	$p_{\rm T} < 200 \; {\rm GeV}$	0.05%
Isolation Efficiency	All working points	0.5%

• Photons: The baseline assumption is that systematic uncertainties will remain unchanged from Run 2 values at the HL-LHC, with the exception of the combination of the reconstruction, identification and isolation efficiency, which is reduced from the Run 2 value with a scale factor of 0.8 from expected improvements in the understanding of the current methodology and, to a smaller degree, the increased dataset available.

Table 5: Some representative values for systematic uncertainties for photons at the HL-LHC. These uncertainties are consistent with the Run 2 uncertainties with the exception of the combination of the reconstruction, identification and isolation, where a scale factor of 0.8 has been applied. [15]

Photon Parameter	Range	Uncertainty
Energy scale	$p_{\rm T} \approx 60~{\rm GeV}$	0.3%
	high $p_{\rm T}$ , up to 200 GeV	0.5%
Resolution	$p_{\rm T} \approx 60~{\rm GeV}$	10%
Reconstruction + ID + Isolation	$p_{\rm T}$ < 200 GeV	2%

Table 6: Expected jet energy scale (JES) uncertainties at the HL-LHC in the "baseline" and "optimistic" scenarios.

Uncertainity component	Percentage Uncertainty	Percentage Uncertainty
	(Baseline Estimate)	(Optimistic Estimate)
Absolute JES scale	1% - 2%	1% - 2%
Pileup	0 - 4%	0 - 2%
JET flavour composition	0 - 1%	0 - 0.5%
JET flavour response	0 - 1.5%	0 - 0.8%

Jets: each of the main components of the overall jet energy scale (JES) uncertainty are
expected to remain constant or decrease in the transition from Run 2 to the HL-LHC. Two
estimates are presented, a default labelled "baseline" and an "optimistic" estimate that
assumes an improved understanding of the MC modelling of jet fragmentation and
improved understanding of the effects of pileup on the JES

Table 6: Expected jet energy scale (JES) uncertainties at the HL-LHC in the "baseline" and "optimistic" scenarios.

Uncertainity component	Percentage Uncertainty	Percentage Uncertainty
	(Baseline Estimate)	(Optimistic Estimate)
Absolute JES scale	1% - 2%	1% - 2%
Pileup	0 - 4%	0 - 2%
JET flavour composition	0 - 1%	0 - 0.5%
JET flavour response	0 - 1.5%	0 - 0.8%

Table 7: Representative values for systematic uncertainties for flavour tagging at the HL-LHC. [15]

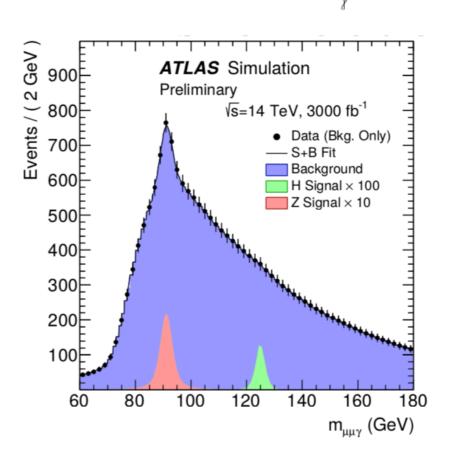
Uncertainty	Expected value at HL-LHC	Comments
<i>b</i> -jet efficiency	1%	$30 < p_{\rm T} < 300  {\rm GeV}$
<i>b</i> -jet efficiency	2-6%	$p_{\rm T} > 300  {\rm GeV}$
<i>c</i> -jet efficiency	2%	all working points
light-jet mistag	5 - 15%	working-point dependent

- Hadronic tau's: Run2 efficiency uncertainties scaled down by 0.9 (0.45) in the S1 (S2) scenario for 1-prong taus; *in situ* uncertainties on the tau energy scale are scaled down by 0.6, which is found by taking the current measurements and setting the sources of statistical uncertainty equal to zero. Other tau lepton-related systematic uncertainties are expected to remain similar to what they are in Run 2.
- **luminosity**: goal of 1% extremely challenging, will be pursued profiting from the experience from previous runs, hardware upgrades to the Beam Conditions Monitor (BCM) and Luminosity Cherenkov Integrating Detector (LUCID), and the new HGTD
  - The new BCM will be mounted on a ring within the pixel detector of the ITk and will have smaller sensor pads to accommodate higher occupancy levels at  $\langle \mu \rangle \approx 200$
  - The LUCID-3 detector is foreseen to use quartz fibre bundles in place of quartz counters.
  - The HGTD will have a bunch-by-bunch luminosity capability, and should have excellent linearity owing to the relatively low occupancy.
  - In addition to these detectors, the LAr and Tile calorimeters, and measurements based on track-counting and reconstructed Z-boson counting, will be used to monitor the long-term stability of the various luminosity measurements, and the linearity between the low-luminosity VdM scans used to establish the absolute calibration and the physics data-taking regime.

## Light quark couplings: exclusive final states

- From rates of H→Vγ, V=qqbar meson (J/ψ, φ, ρ)
- Complicated by destructive interference with H→γ\*γ
- Expected BRs ~ 2-3e-6 (J/ψ, φ), 2e-5 (ρ)
- Current limits 50-500x worse
- ATLAS (old) projection for J/ψγ:

	$\mathcal{B}(H \to J\psi\gamma)$
SM	$2.9 \times 10^{-6}$
Run 1	$1.5 \times 10^{-3}$
HL-LHC	$4.4 \times 10^{-5}$



- Recent pheno studies of 3 final states J/ψγ, φγ, ργ
  - match ATLAS projection for J/ψγ
  - expected limits on couplings: 83 (c), 3000 (s), 1.5-3e5 (d,u)

## CP-violating decays

- CP-violating flavour-diagonal Yukawa couplings, κ ̃<sub>fi</sub>, are in general **well constrained from bounds on the electric dipole moments (EDMs)** (electron, neutron, mercury)
- Such constraints are derived under the assumption of no cancellation with other contributions to EDMs beyond the Higgs contributions.
- If the assumptions do not hold, the constraints on top and tau CP-violating Yukawas can be weaker, and ttH(bb) and H→ττ can provide bounds

$$\mathcal{L}_{ttH} = y_t \bar{t}(\cos \alpha - i\gamma_5 \sin \alpha) tH$$

Phenomenological study (stat. errors only, fast simulation):

