Higgs boson properties: Recent HL/HE-LHC projections based on 3000 fb-1 at 14 TeV

Jyothsna Rani Komaragiri

On behalf of ATLAS and CMS Collaboration

24th April 2019

Standard Model @LHC 2019, Zurich

Indian Institute of Science, Bangalore, India

Outline

- The High Luminosity LHC Upgrade
  - Detector upgrades
  - Physics opportunities at HL-LHC
- Higgs properties and measurements
- HH prospects at HL-LHC and HE-LHC
- Summary and conclusions

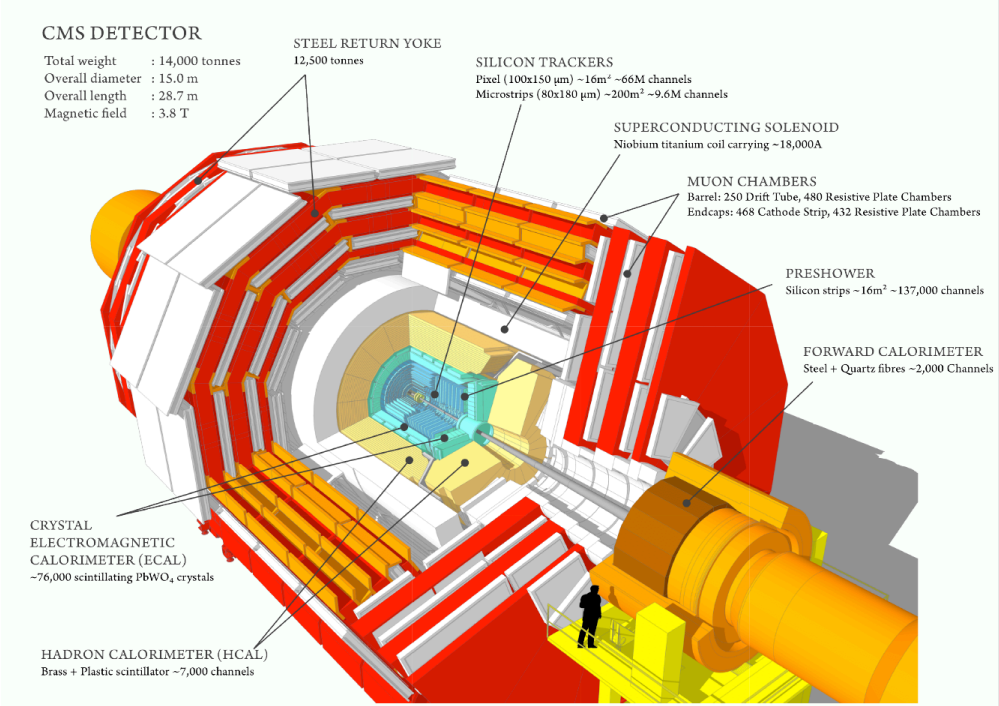
All projection results on Higgs and HH presented in this talk are included in the Yellow Report from HE/HL-LHC Working Group2: arXiv:1902.00134 **(364 pages)**

The High Luminosity LHC Upgrade

- **The High Luminosity LHC (HL-LHC), approved project, represents the ultimate evolution of LHC machine performance**
- **Operation at up to instantaneous luminosity of $L = 7.5 \times 10^{34}$ Hz/cm^2 (LHC Run-II: 2×10^{34} Hz/cm^2) to collect up to 3000 fb^{-1} of integrated luminosity**

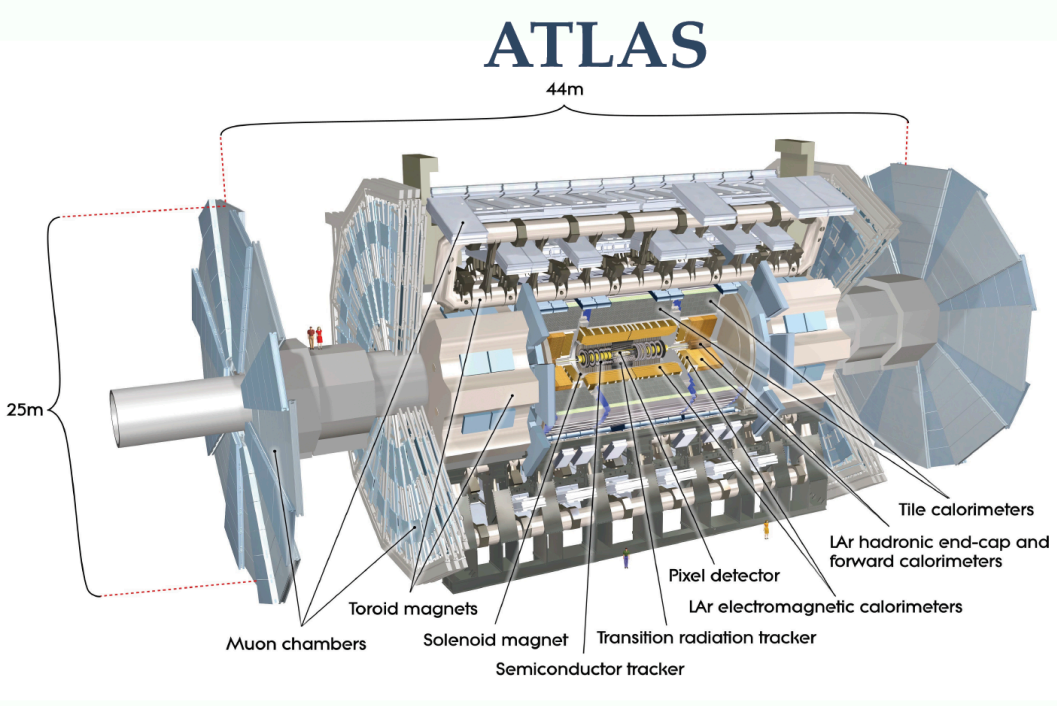
Upgrade of detectors

CMS



- CMS upgrade includes:
  - Extended **Inner Tracker** up to $|\eta|<4$
  - Improved **muon system coverage**
  - Precise **MIP timing layer** in barrel and endcap
  - **High Granularity endcap calorimeter**
  - DAQ and trigger systems (L1 and HLT - 7.5 kHz)

- ATLAS upgrade includes:
  - Extended **Inner Tracker** up to $|\eta|<4$
  - **Electronics upgrade** for Liquid Argon and Tile calorimeters, muon system
  - New **muon chamber in the inner barrel** region
  - **High Granularity Timing detector** in endcap
  - DAQ and trigger systems (L1 and HLT - 10 kHz)



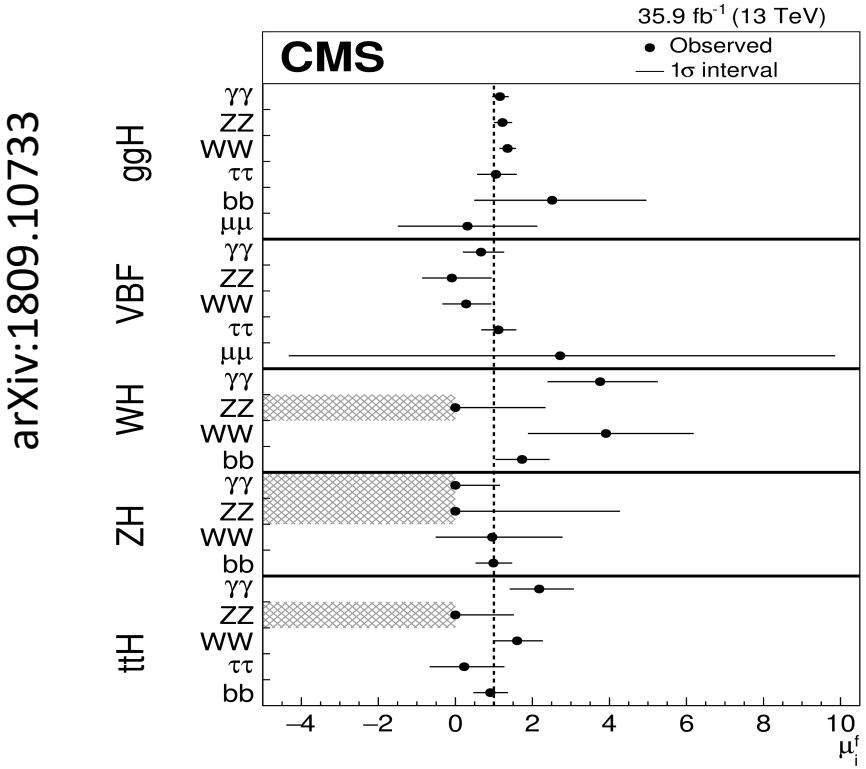
Challenges and Physics opportunities at HL-LHC

- **HL-LHC is an approved project and significant progress** has been made in the preparations.
  - Vast increase in the statistical reach with **3ab^{-1}** of integrated luminosity
  - Up to 200 p-p interactions per bunch crossing!
  - High Luminosity also implies challenging experimental conditions for trigger, particle reconstruction, performance, …..
- **Large data sample** benefits
  - Lower statistical uncertainties
  - Lower experimental systematic uncertainties (calibrations performed on larger dataset)
  - Lower uncertainties on background prediction (high statistic control samples allows more precise constraints)
- **Exploit full potential of upgraded detectors and large data sample**
  - Year-long workshop in 2017-2018
  - Collaboration of theorists and experimentalists (ALICE, ATLAS, CMS, LHCb) to assess reach and precision, identify new opportunities, explore new directions
  - Provided input to European Strategy of Particle Physics: HL-LHC and HE-LHC
- **HE-LHC is 27 TeV p-p collider providing 15ab^{-1} and similar experimental challenges as HL-LHC**

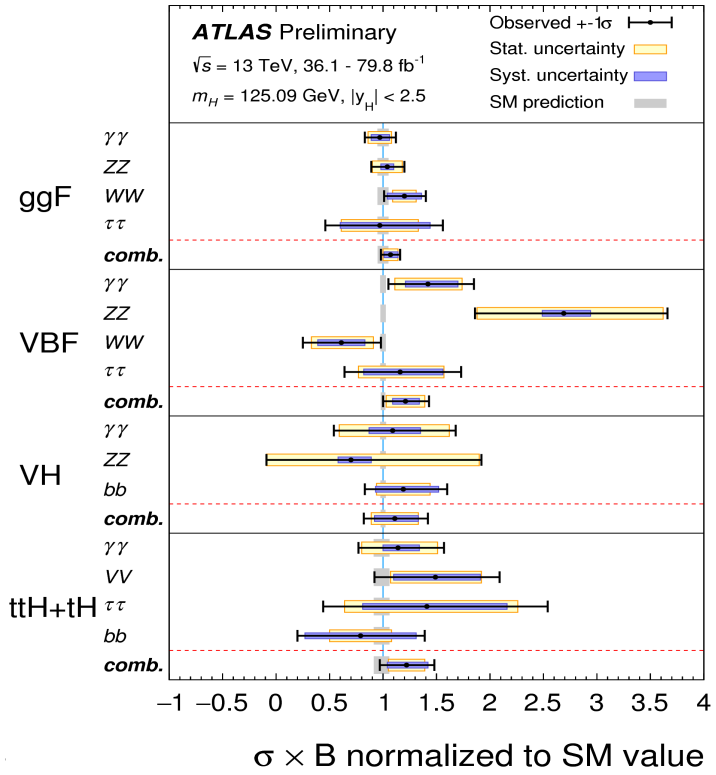
Higgs boson measurements at HL-LHC

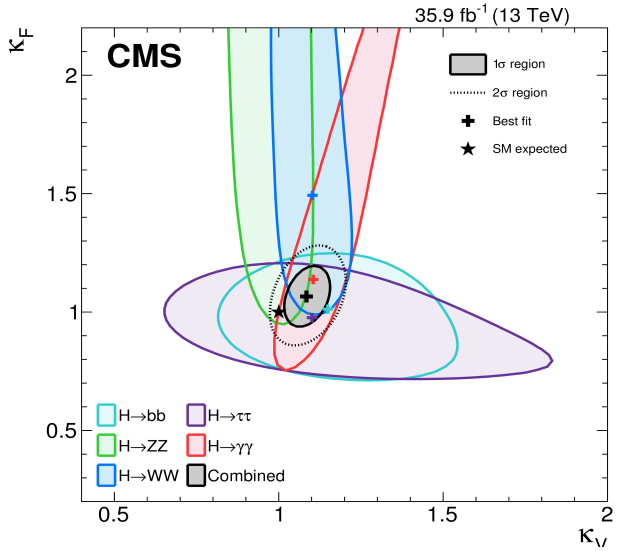
Higgs boson measurements at Run-II

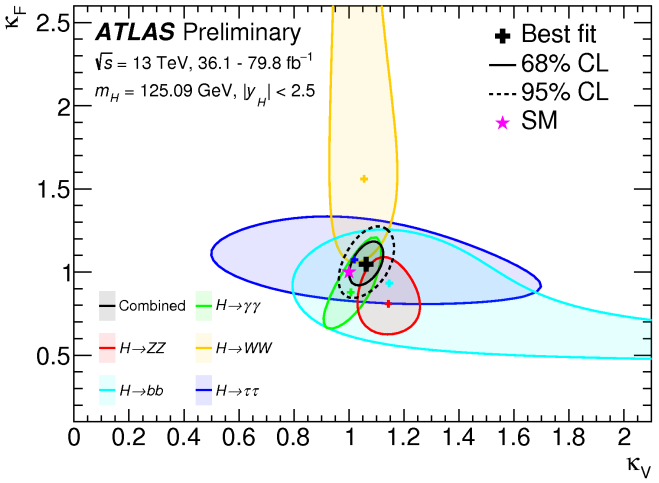
- Higgs boson properties are in agreement with the SM expectation
  - **Bosonic couplings (observed in Run-I) and 3rd generation fermionic coupling (observed in Run-II).** Current precision on couplings in ~10-30% (single experiment)
  - 2nd generation fermionic coupling still to be established
  - Bosonic couplings covered by C. Anastopoulos's talk
  - 2nd and 3rd generation fermionic couplings covered by S. Wozniewski's talk
  - Combined Higgs properties covered by S. Pataria's talk
- **Goal for the future is to improve precision**



arXiv:1809.10733







arXiv:1809.10733

ATLAS-CONF-2018-031

Analysis procedures for HL-LHC projections

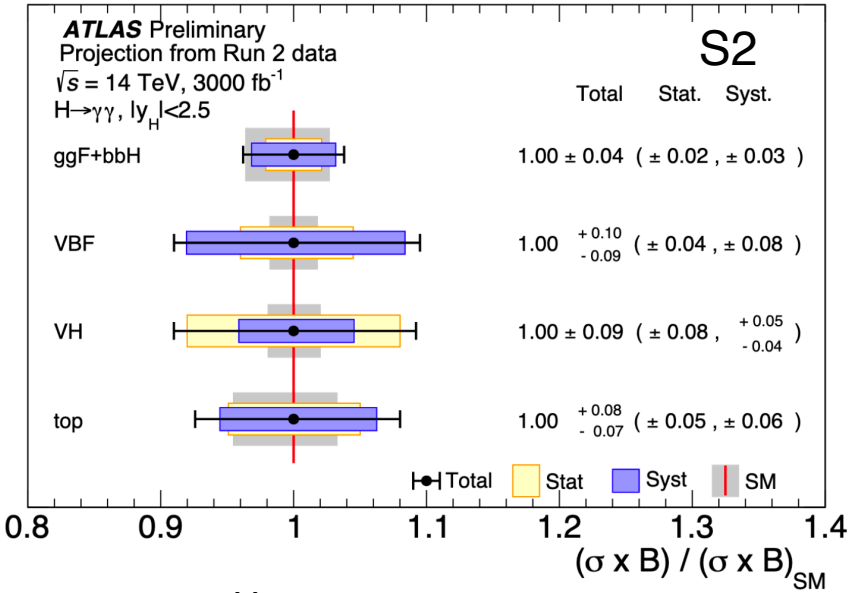
- **Analyses are performed using simulated samples produced with HL-LHC conditions using upgraded detectors**
  - This is the case for new and/or significantly improved analyses

- **Extrapolations from Run-II analyses to 3000 fb-1**
  - This is the case for the analyses already performed in Run-II
  - Efficiencies, resolutions and fake rates assumed to be same as Run-II (no change for projection studies)
  - **Main scenario Yellow Report18 systematic uncertainties (S2):**
    - **Most theoretical uncertainties scaled down by a factor 1/2, experimental uncertainties scaled down by √L**
    - **Scenario for comparison:** using same systematic uncertainties as that of Run-II (S1)
  - In all cases uncertainties due to the finite number of simulated events are neglected

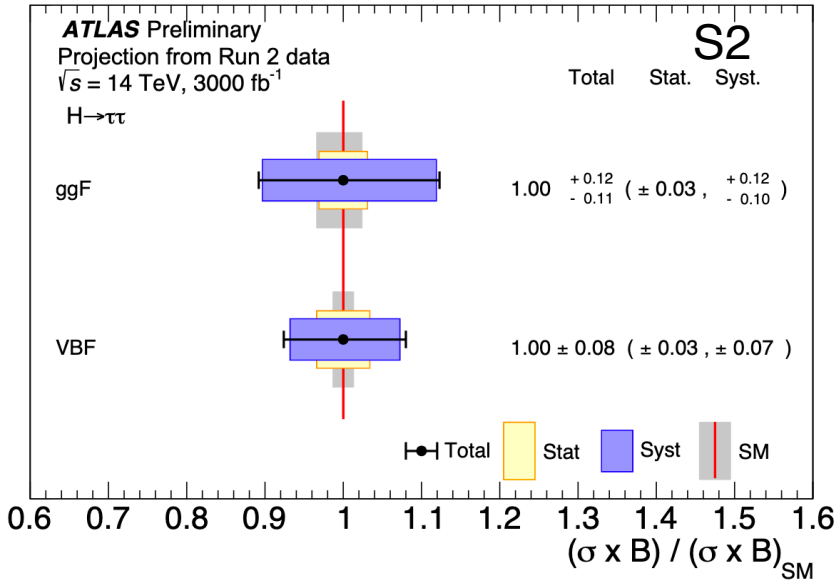
- **Reminder:** All projection results on Higgs presented in this talk are included in the Yellow Report (YR) from HE/HL-LHC WG 2: arXiv:1902.00134

Combined Higgs coupling measurements (1)

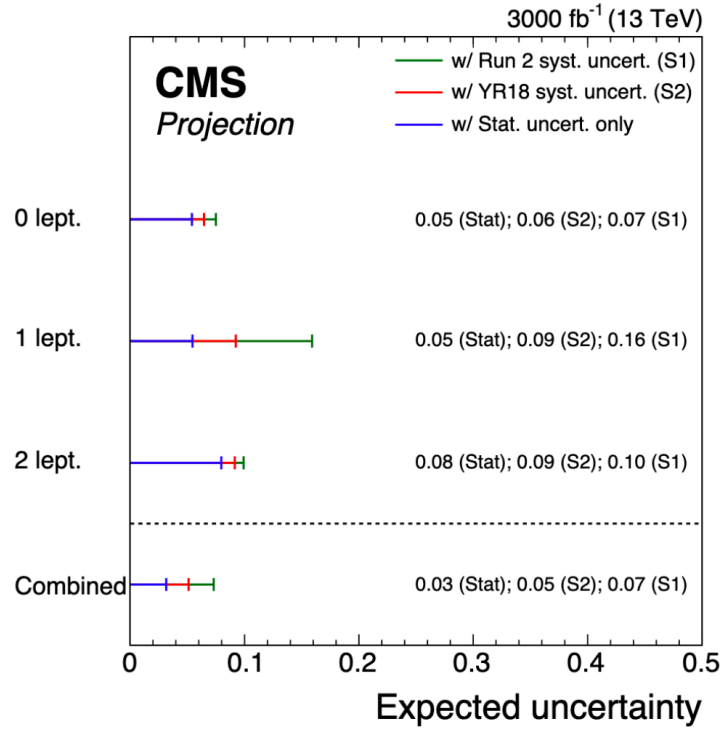
- Inputs used:
  - Projections of combined measurements of Higgs boson couplings using data collected in 2015-2017 (ATLAS) and 2016 (CMS)
  - Projections cover all main production (gluon fusion, VBF, VH, ttH) modes of Higgs and Higgs decay modes (γγ, ZZ, WW, bb, ττ, μμ, Zγ)
  - A couple of examples of projected analyses



H→γγ



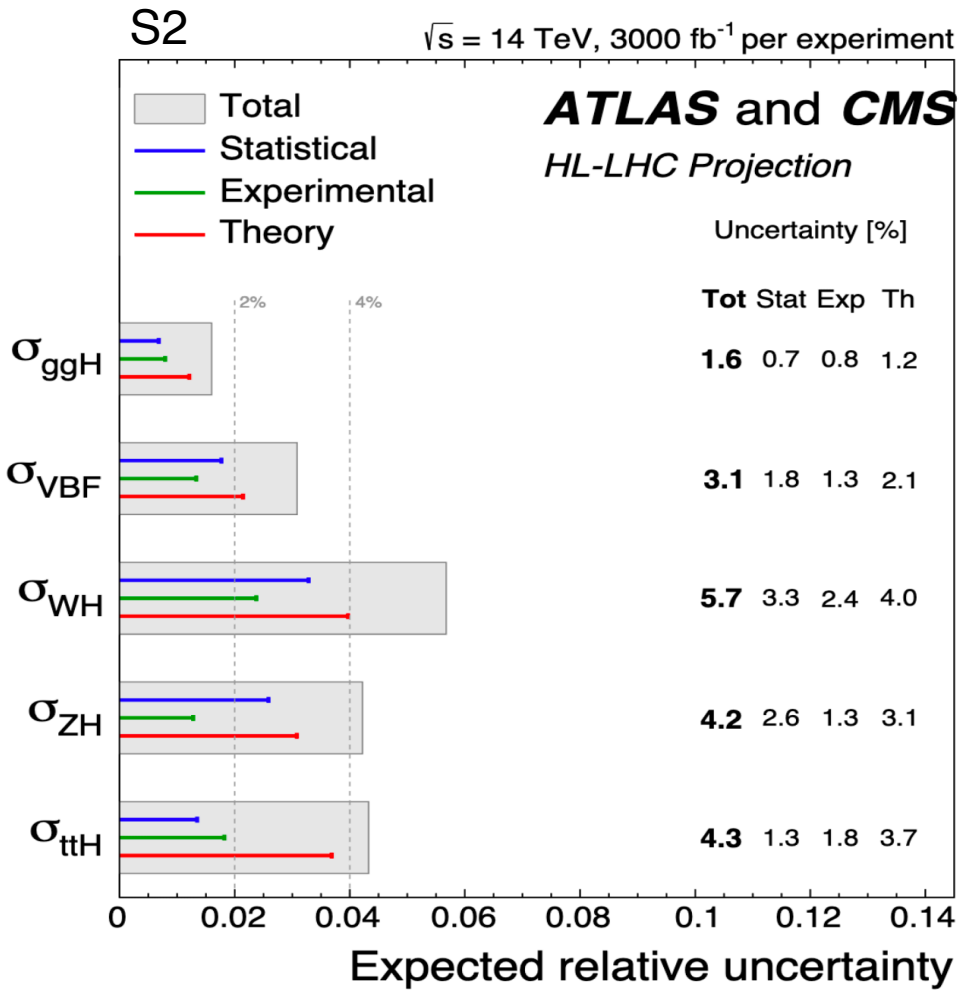
H→ττ



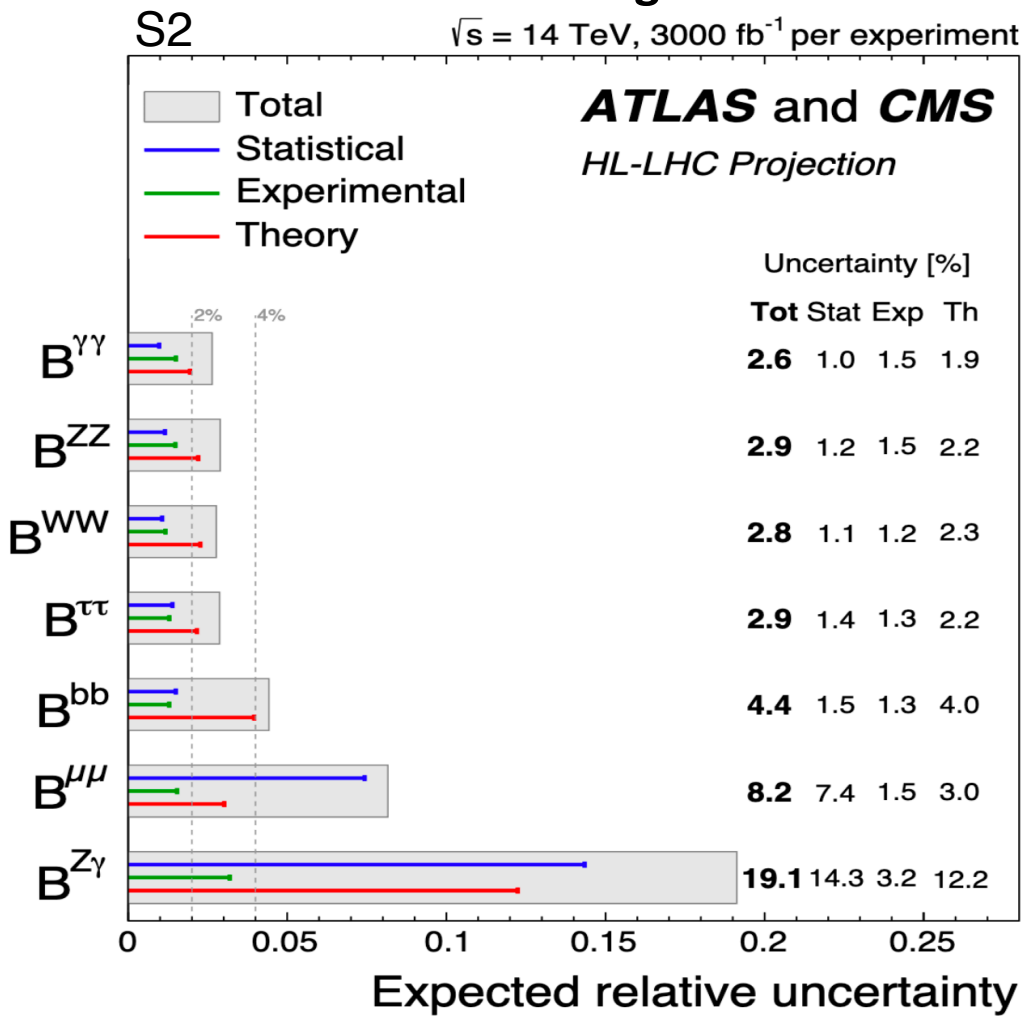
VH, H→bb

Combined Higgs coupling measurements (2)

Production cross sections



Branching ratios

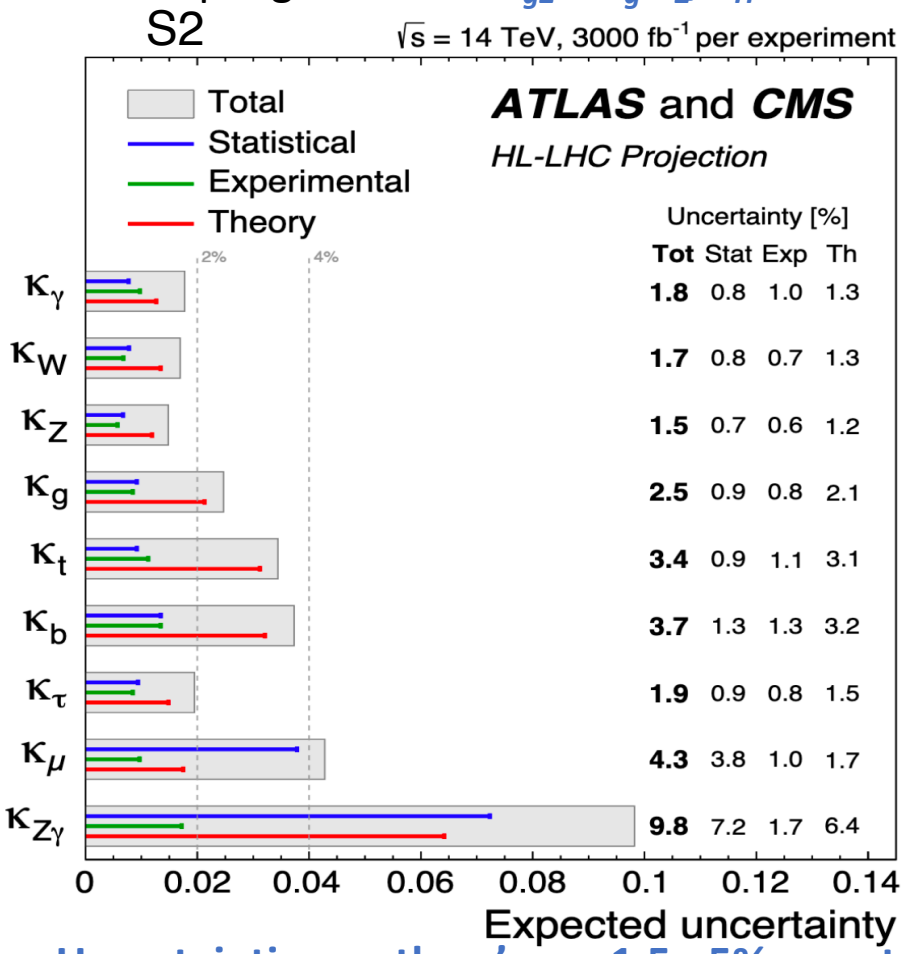


- **Cross sections and Branching ratios (except $B^{\mu\mu}$ and $B^{Z\gamma}$) are dominated by theoretical uncertainties**
- **Branching ratios: $B^{\mu\mu}$ and $B^{Z\gamma}$ statistically limited.**

Combined Higgs coupling measurements (3)

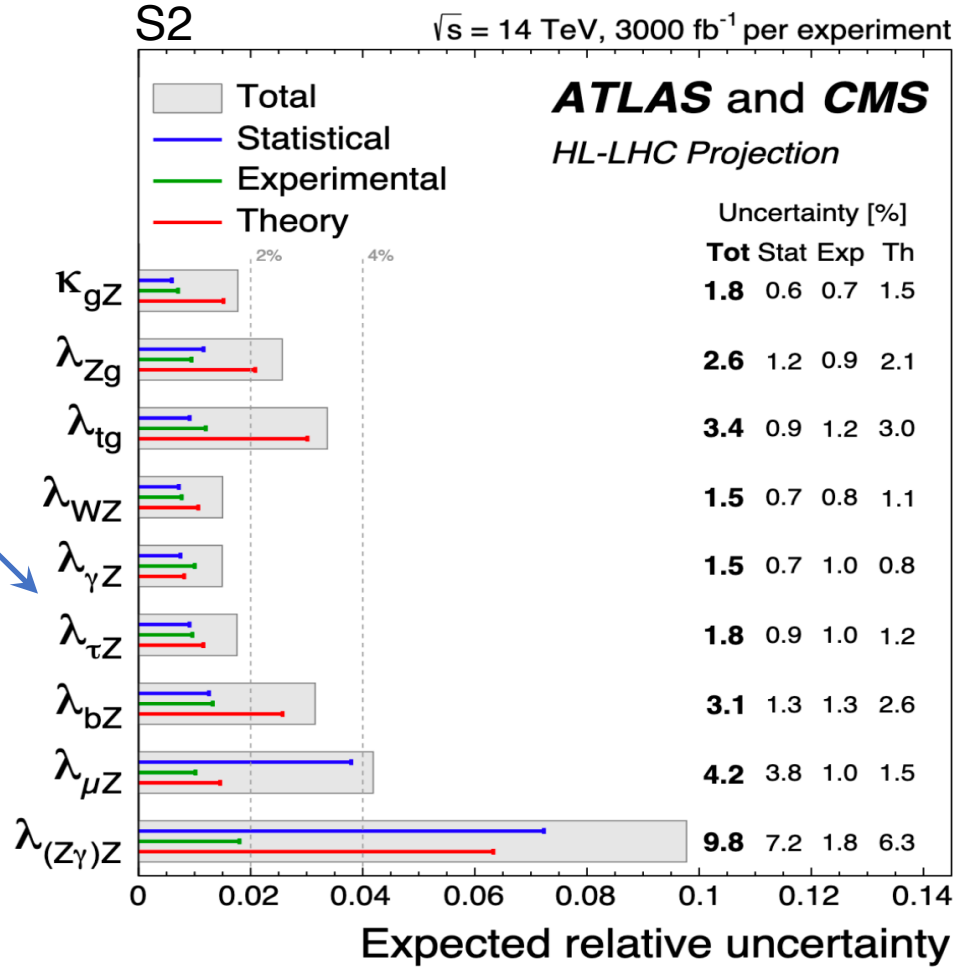
Coupling modifier or κ-framework: For a given production or decay mode j: $\kappa_j^2 = \sigma_j/\sigma_j^{\mathrm{SM}}$ or $\kappa_j^2 = \Gamma^j/\Gamma^j_{\mathrm{SM}}$

Projections are made for a parametrisation based on ratios of the coupling modifiers ($\lambda_{ij}=\kappa_i/\kappa_j$) together with a reference ratio of coupling modifiers $\kappa_{gZ} = \kappa_g \kappa_Z/\kappa_H$



Coupling modifiers

Ratios of coupling modifiers



- Uncertainties on the κ's are 1.5 - 5%, apart from Zγ
- Mostly limited by theoretical uncertainties and modelling of signal and backgrounds

- Uncertainties on the ratios of κ's 1.5-4%,
- With $\lambda_{\gamma Z}$ and λ_{WZ} most precisely measured

Combined Higgs coupling measurements at HE-LHC

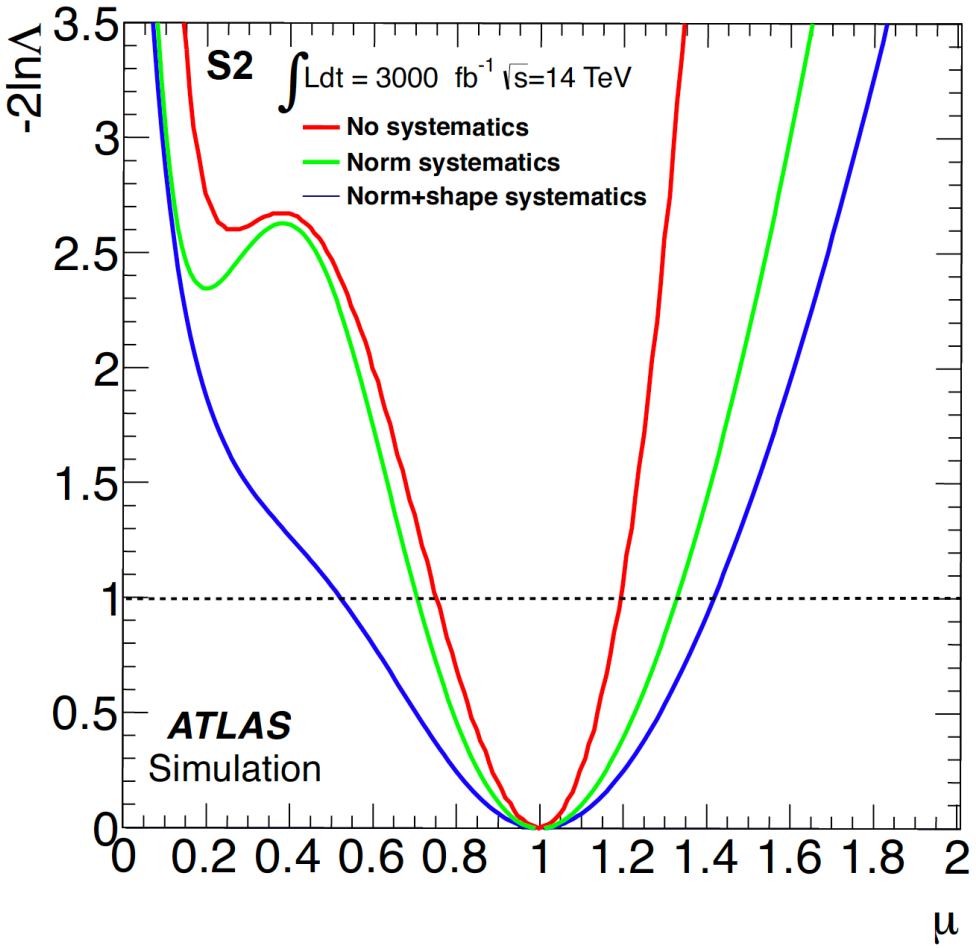
- **HE-LHC:** Two scenarios are assumed for the theoretical and modelling systematic uncertainties on the signal and backgrounds.
  - First (S2) is the foreseen baseline scenario at HL-LHC
  - Second (S2') is a scenario where theoretical and modelling systematic uncertainties are halved. This scenario would correspond to uncertainties roughly four times smaller than for current Run-II analyses.
- Note that HL-LHC measurements, whose precision is limited by systematic uncertainties, would also improve for scenario S2'

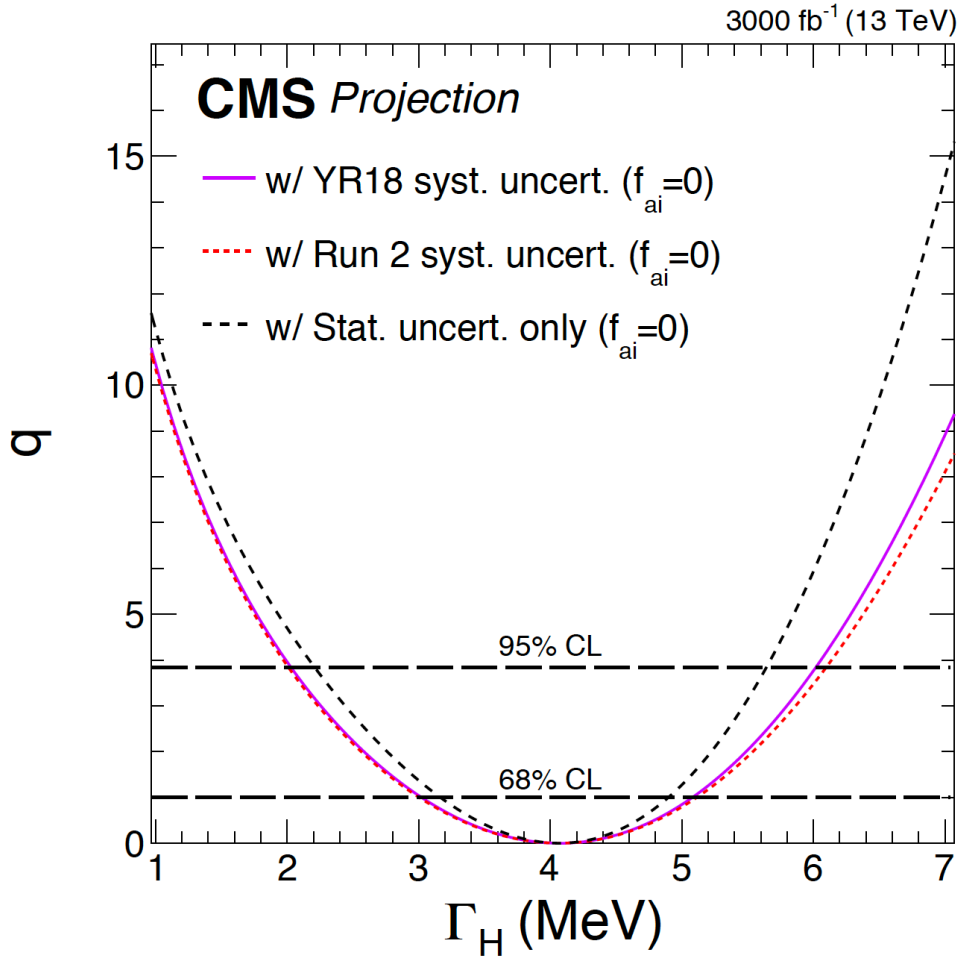
Expected uncertainty on coupling modifiers at HE-LHC, 15 ab-1 @27 TeV

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

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**





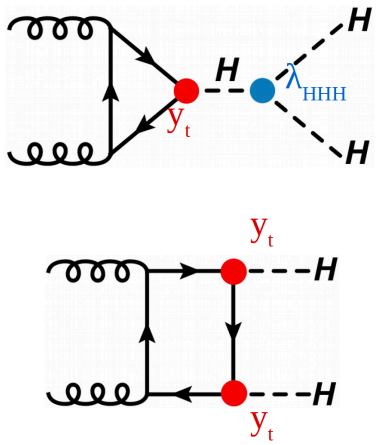
Higgs Summary at HL and HE-LHC

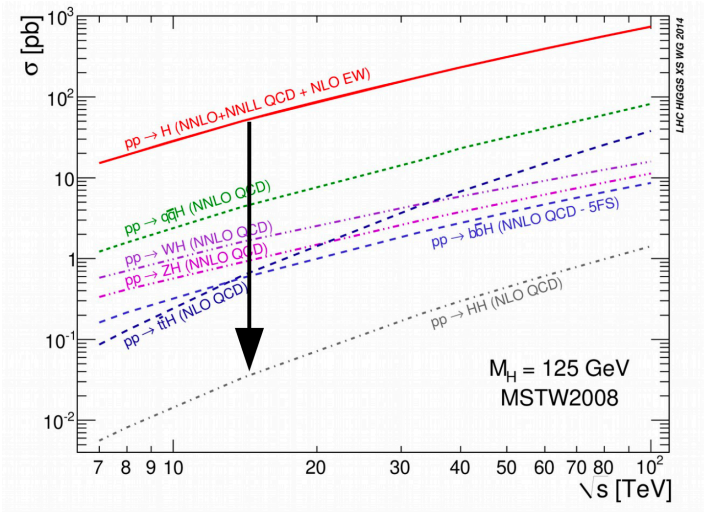
- Physics reach in the Higgs sector will be expanded at HL-LHC
  - **Percent level precision on most Higgs couplings**
  - **Width measurable to within 1 MeV**
- Many inclusive measurements limited by systematic uncertainties ➔ work needed from theoretical and experimental side to reduce these
- Looking further ahead: HE-LHC
  - $15ab^{-1}$ at 27 TeV
  - κ_μ precision expected to reach 2%
  - Reduction of statistical uncertainty in Higgs coupling measurements

Higgs boson pair (HH) prospects at HL/HE-LHC

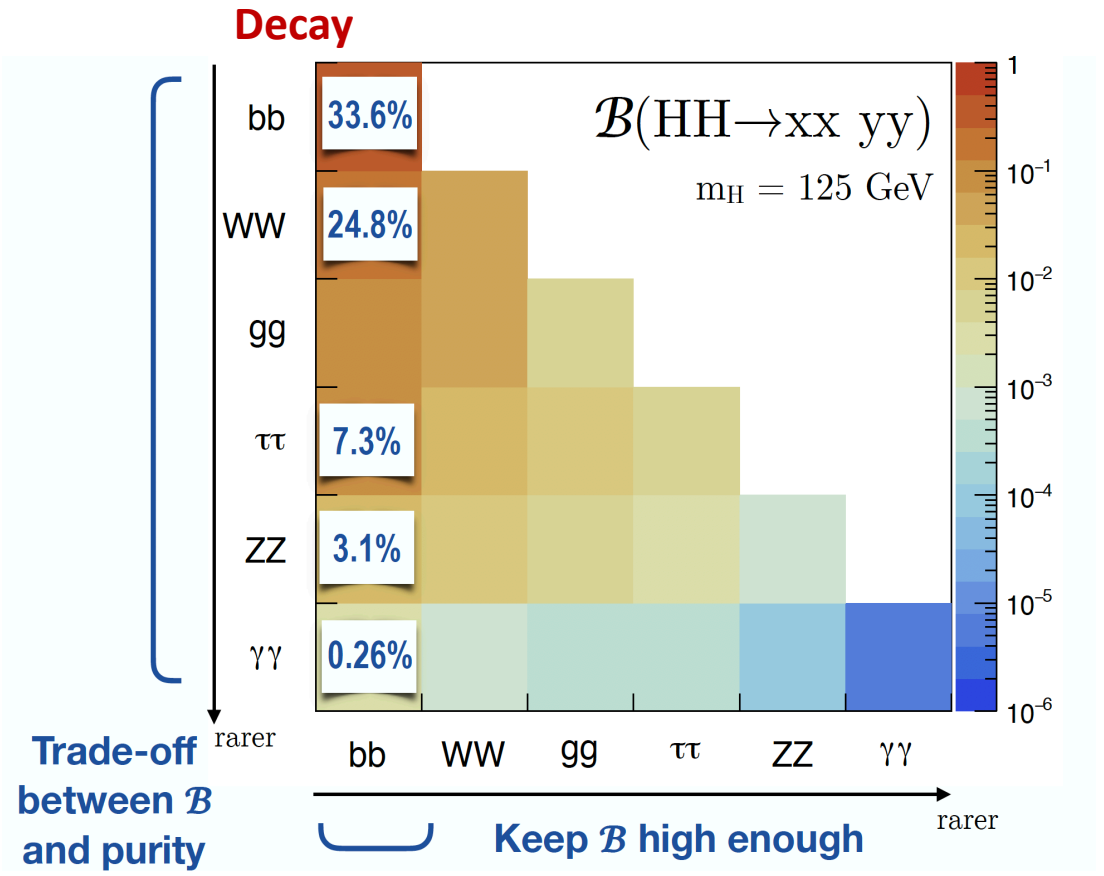
Higgs boson pair production and decay

- **Non-resonant production: rare** process in the SM
  - Production is dominated by gluon fusion
    - Other rarer modes (ex: VBF HH production)
  - **σ(gg→HH) ≈ 0.1%*σ(gg→H)**
  - **Small σ_{HH} ⟹** need high luminosities
  - **Direct determination of λ from Higgs boson pair production**





- BSM contributions can modify the Higgs boson coupling parameters and modify the HH cross section: define $\kappa_\lambda = c_{hhh} = \lambda_{HHH} / \lambda_{HHH}^{SM}$



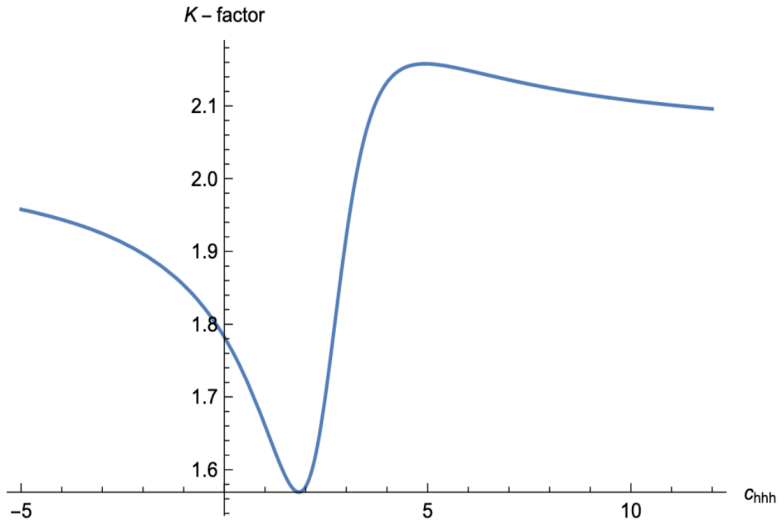
- Phenomenologically rich set of decay channels
  - Broad experimental coverage to increase sensitivity
- Many different signatures
  - All benefit from the upgraded ATLAS and CMS detectors

Higgs boson pair production cross section (1)

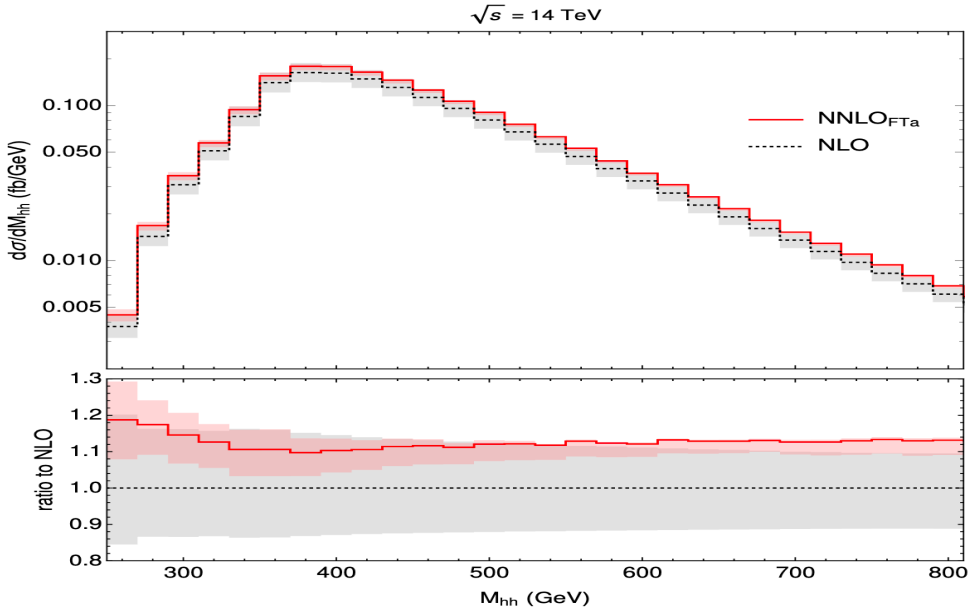
- SM calculation
  - ggF: State of the art NNLO with finite m_t effects
  - Other production modes: NLO with full m_t dependence
- Higgs **self-coupling variations** with full m_t dependence at NLO
  - LO to NLO K-factors vary from 1.57 to 2.16

$\sqrt{s}$ [TeV]	$\mathrm{NNLO_{FTa}}$ [fb]	m_t unc.	PDF unc.	α_S unc.	PDF+α_S unc.
14	$36.69^{+2.1\%}_{-4.9\%}$	$\pm 2.7\%$	$\pm 2.1\%$	$\pm 2.1\%$	$\pm 3.0\%$
27	$139.9^{+1.3\%}_{-3.9\%}$	$\pm 3.4\%$	$\pm 1.7\%$	$\pm 1.8\%$	$\pm 2.5\%$

$\sqrt{s}$ (TeV)	ZHH	WHH	VBF HH	$ttHH$	$tjHH$
14	$0.359^{+1.9\%}_{-1.3\%} \pm 1.7\%$	$0.573^{+2.0\%}_{-1.4\%} \pm 1.9\%$	$1.95^{+1.1\%}_{-1.5\%} \pm 2.0\%$	$0.948^{+3.9\%}_{-13.5\%} \pm 3.2\%$	$0.0383^{+5.2\%}_{-3.3\%} \pm 4.7\%$
27	$0.963^{+2.1\%}_{-2.3\%} \pm 1.5\%$	$1.48^{+2.3\%}_{-2.5\%} \pm 1.7\%$	$8.21^{+1.1\%}_{-0.7\%} \pm 1.8\%$	$5.27^{+2.0\%}_{-3.7\%} \pm 2.5\%$	$0.254^{+3.8\%}_{-2.8\%} \pm 3.6\%$

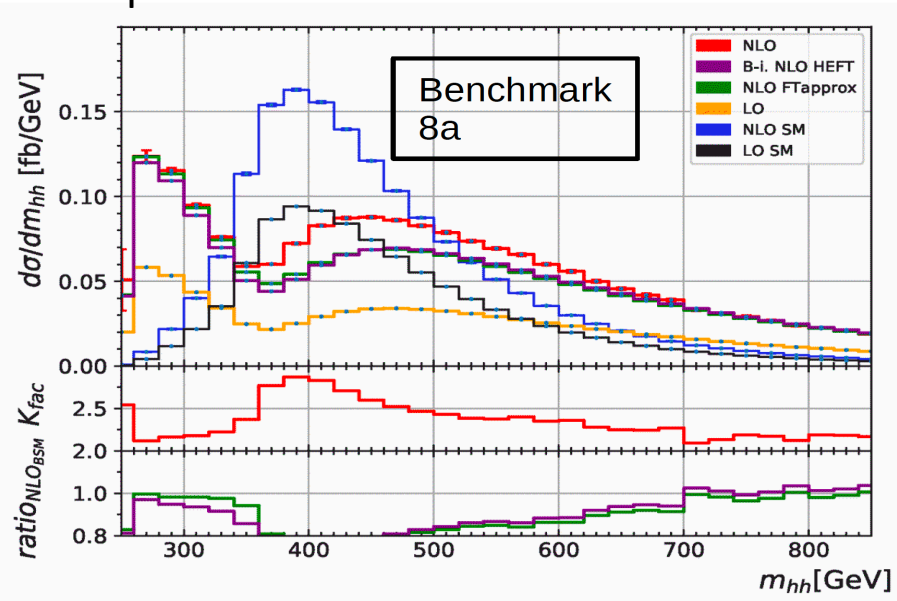


m_{HH} differential cross sections

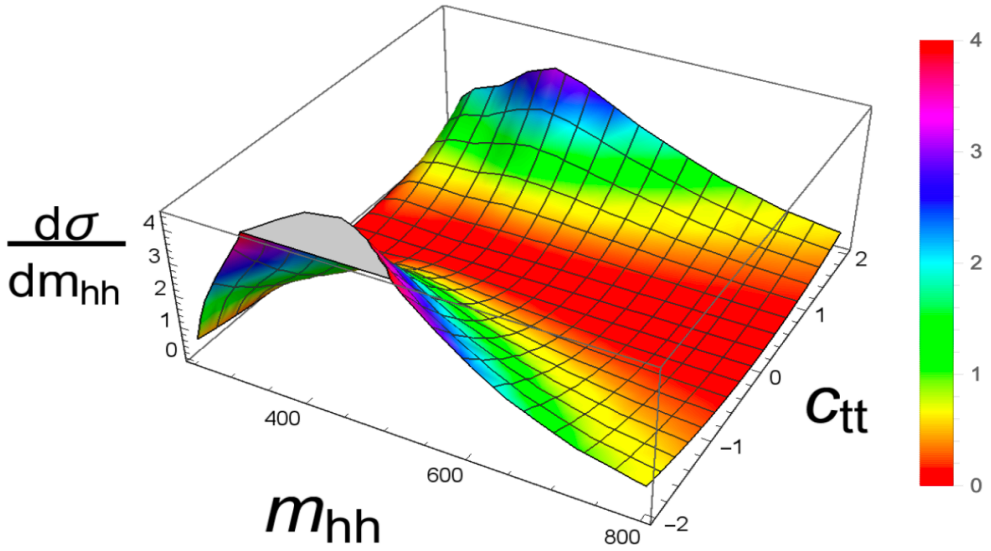


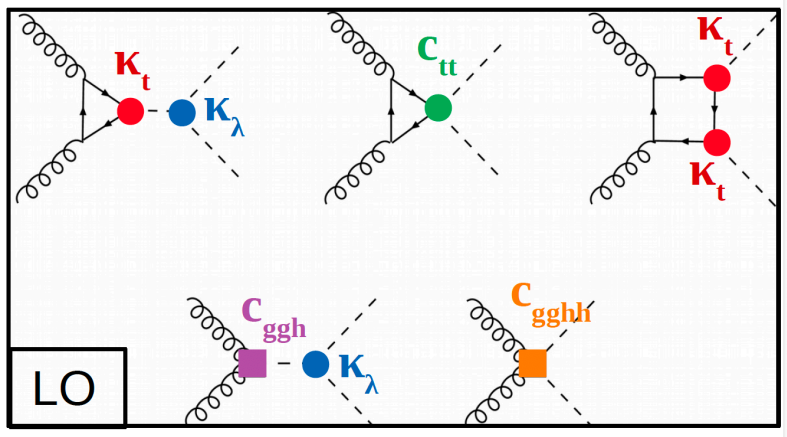
Higgs boson pair production cross section (2)

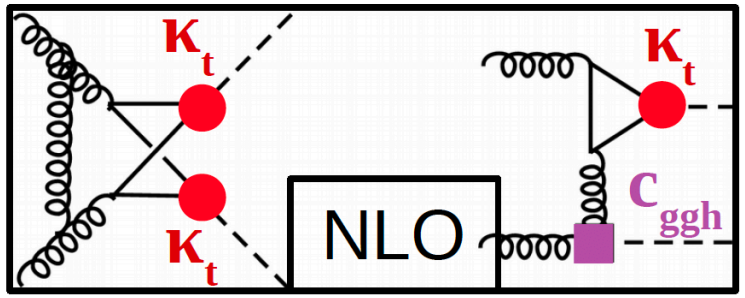
- **BSM model:** Non-linear EFT
- Cross sections and m_{hh} at NLO QCD for some selected benchmark points



- Full NLO results are obtained for any values of the 5 modifying parameters





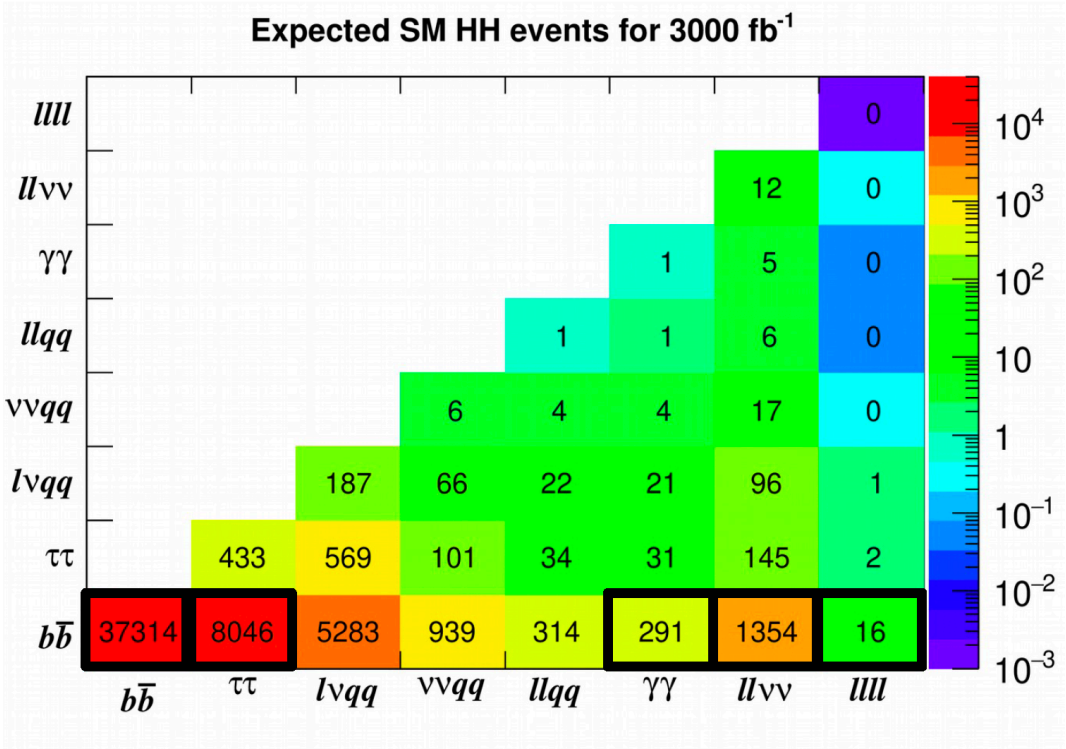


Benchmark	c_{hhh}	c_t	c_{tt}	c_{ggh}	c_{gghh}
5a	1	1	0	2/15	4/15
6	2.4	1	0	2/15	1/15
7	5	1	0	2/15	1/15
8a	1	1	1/2	4/15	0
SM	1	1	0	0	0

HH Experimental prospects, introduction

- Either do **extrapolations** from existing Run-2 analyses, or perform dedicated studies with **smeared/parametric detector response** (Delphes), corresponding to pile-up of 200
  - Summary of channels from ATLAS and CMS:

	ATLAS	CMS	
bbbb	extrapolation	parametric	Largest BR ☺ Large multijet and tt bkg ☹
bbττ	extrapolation	parametric	Sizeable BR ☺ Relatively small bkg ☺
bbγγ	smearing	parametric	Small BR ☹ Good diphoton resolution ☺ Relatively small bkg ☺
bbVV (→lνlν)		parametric	Large BR ☺ Large bkg ☹
bbZZ (→4l)		parametric	Very small BR ☹ Very small bkg ☺

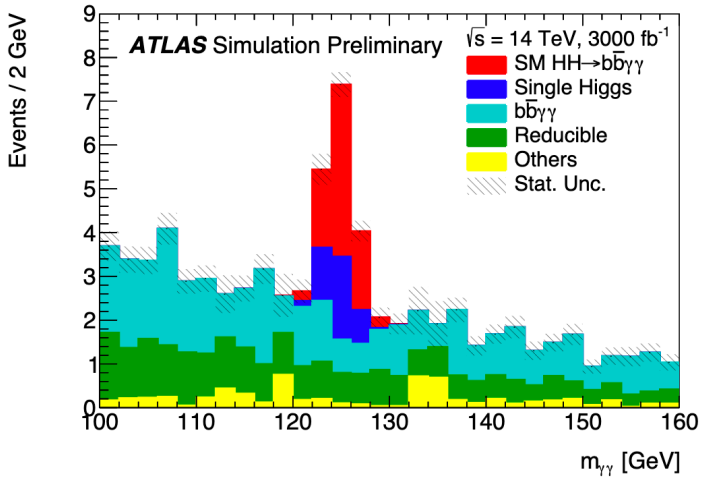


- **Systematic uncertainties:** common agreement between ATLAS and CMS
  - performance uncertainties scaled by 0.5 to 1
  - theoretical uncertainties divided by 2
  - MC statistical uncertainties neglected

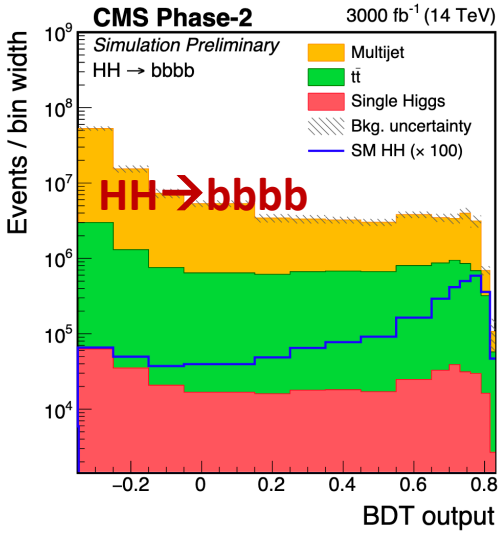
HH Experimental prospects, analysis methods

- General analysis strategy:
  - candidate mass consistent with SM Higgs boson
  - multivariate methods to reject background
  - use m_{HH} when possible
- Few examples:

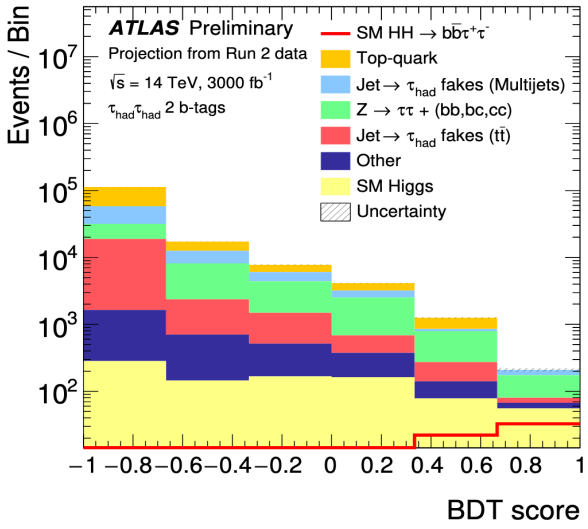
HH→bbγγ



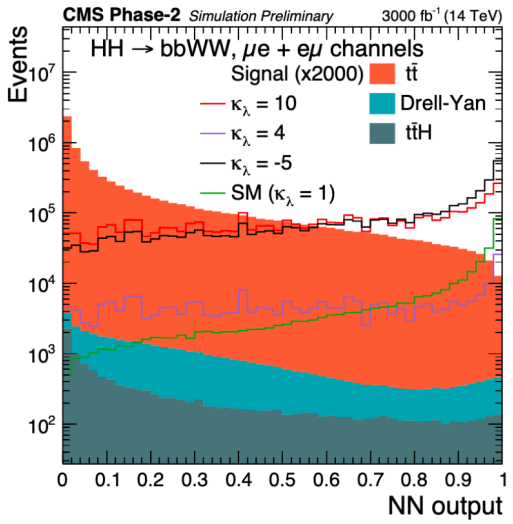
HH→bbbb



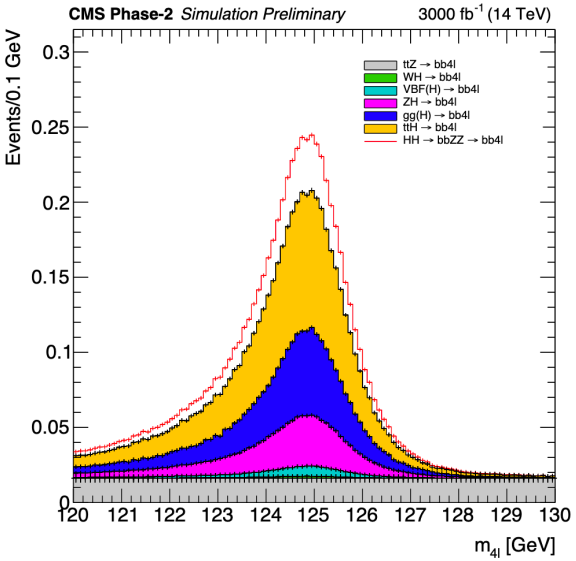
HH→bbττ



HH→bbWW



HH→bbZZ



- Note: Some inputs or systematics with large unknowns
  - Multijet background modelling for HH→ bbbb
  - τ ID and fake-rate
  - …..
  - There is scope to improve on these

HH Experimental prospects, results

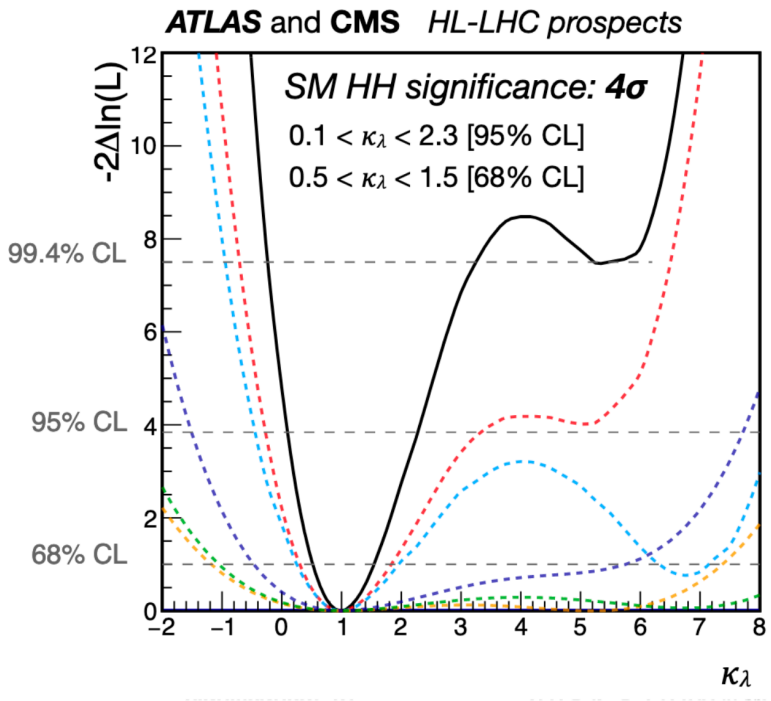
- Expected **significance** with and without systematics at HL-LHC
  - **4σ expected with ATLAS+CMS!**

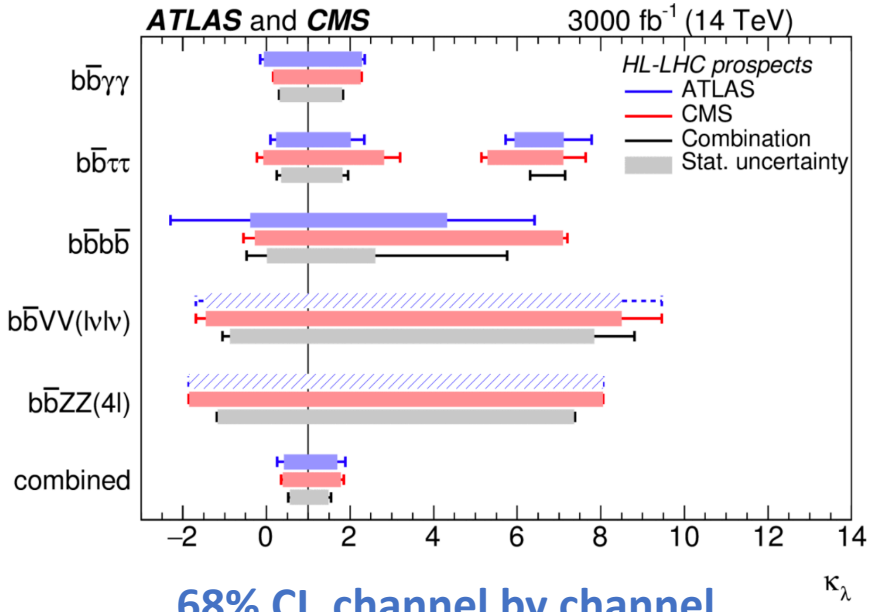
	Statistical-only		Statistical + Systematic	
	ATLAS	CMS	ATLAS	CMS
$HH \to b\bar{b}b\bar{b}$	1.4	1.2	0.61	0.95
$HH \to b\bar{b}\tau\tau$	2.5	1.6	2.1	1.4
$HH \to b\bar{b}\gamma\gamma$	2.1	1.8	2.0	1.8
$HH \to b\bar{b}VV(ll\nu\nu)$	-	0.59	-	0.56
$HH \to b\bar{b}ZZ(4l)$	-	0.37	-	0.37
combined	3.5	2.8	3.0	2.6
	Combined		Combined	
	4.5		4.0	

- Measurement of μ (SM signal injected):
  - ~25% (30%) without (with) systematics
  - μ = 0 (no SM HH signal) excluded at 95% CL

- Measurement of κ_λ:
  - **68% CI of 50%**
  - **2nd minimum**

  excluded at 99.4% CL thanks to the m_{HH} shape information

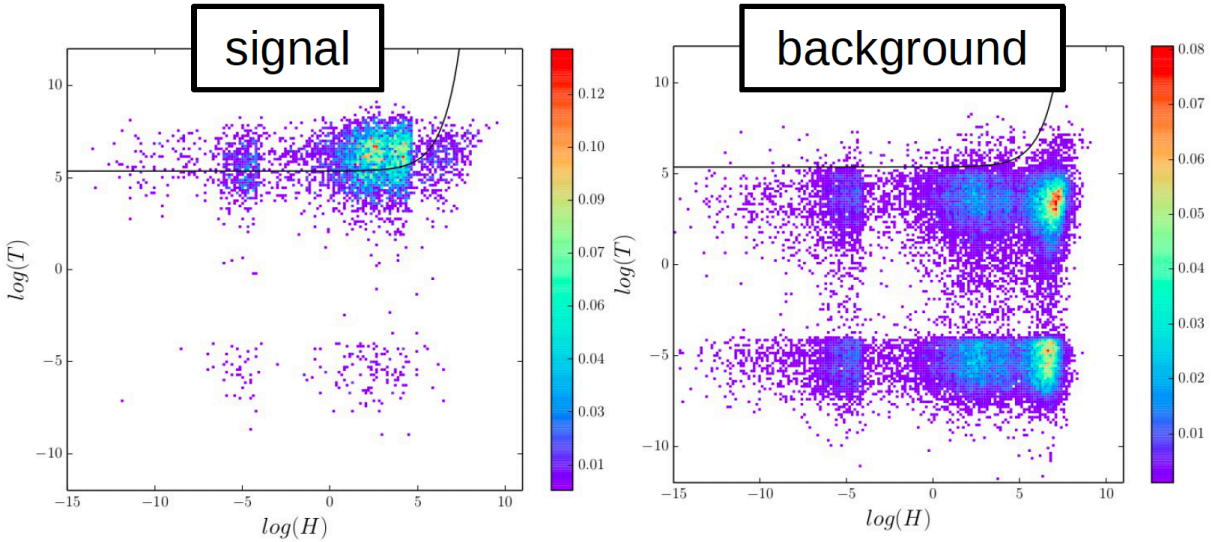




68% CI, channel by channel

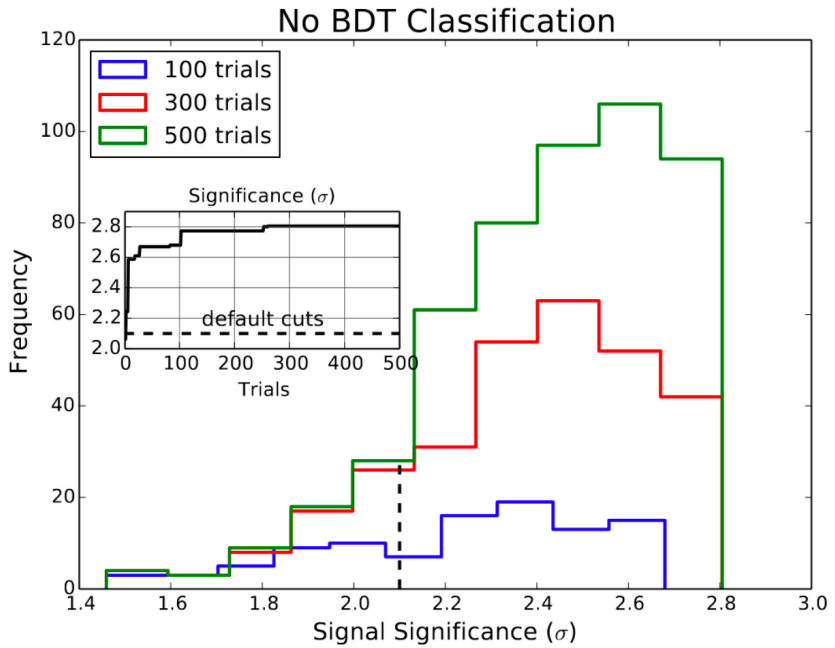
HH at HL-LHC, alternative methods

- HH→bbWW(→lvlv): Introduce two new variables
  - Topness (T): degree of consistency with di-lepton tt production
  - Higgsness (H): compatibility with Higgs and W masses



- Could enhance the significance **from 0.6 to 1.4-3.0σ**
  - effect of pile-up on Topness and Higgsness?

- HH→bbγγ:
  - Bayesian optimisation and BDT compared to cut-based



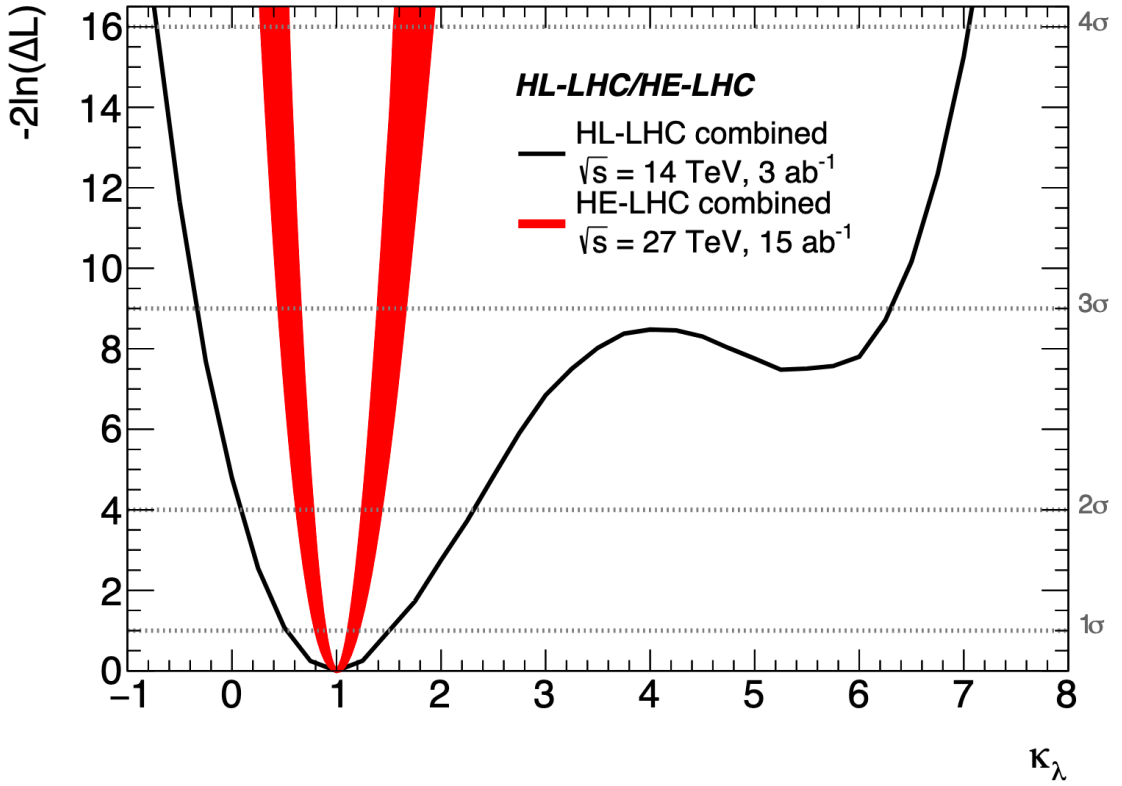
- No pile-up included, but shows the potential of sophisticated techniques: **could achieve up to 4σ**
  - illustrated in the Yellow Report with ATLAS and CMS using MVA techniques

HH extrapolation at HE-LHC

- **Extrapolation** of ATLAS HL-LHC results to HE-LHC
  - only scale cross-section to 27 TeV (*4) and luminosity to 15 ab-1 (*5), no systematic uncertainties
  - **bbττ channel:** significance: 10.7σ, precision on **κ_λ: 20%**
  - **bbγγ channel:** significance: 7.1σ, precision on **κ_λ: 40%**
    - pessimistic because analysis not optimised for measurement of κ_λ

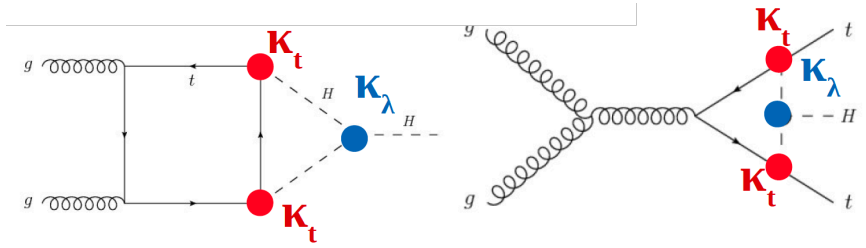
- Phenomenology study: **15% precision on κ_λ**
  - realistic detector performance
  - no pile-up considered (μ=800-1000)
  - interesting categorisation of b-jets

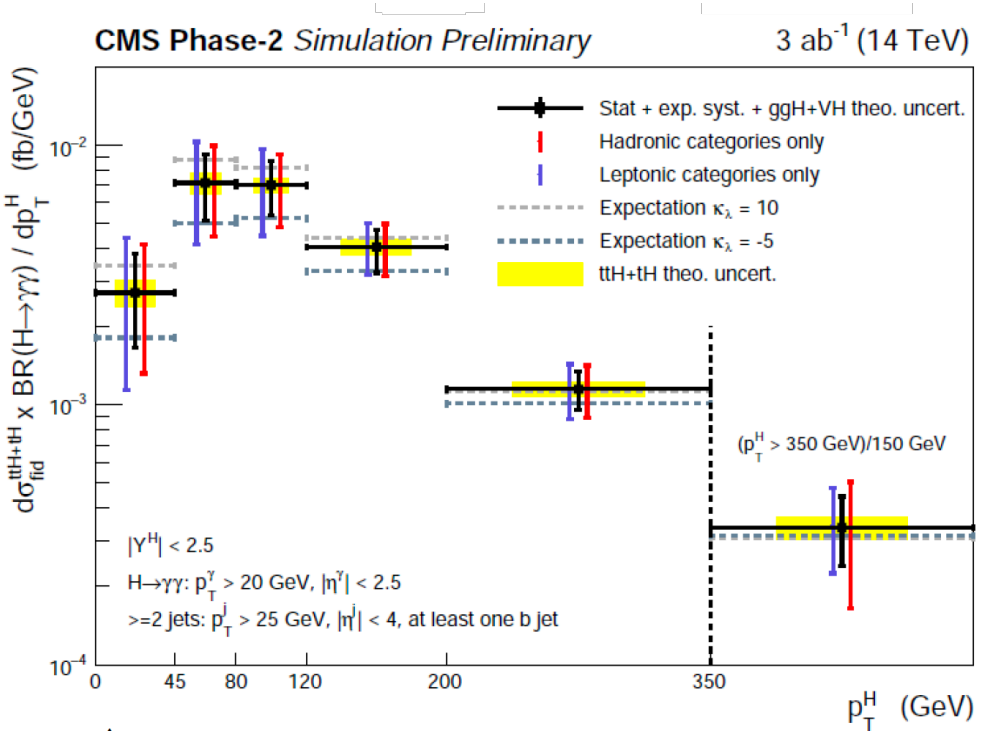
- κ_λ could be measured with a 68% CI of **10 to 20 %**
  - without uncertainties
  - effect of pile-up?
  - contribution of ggF+jets?

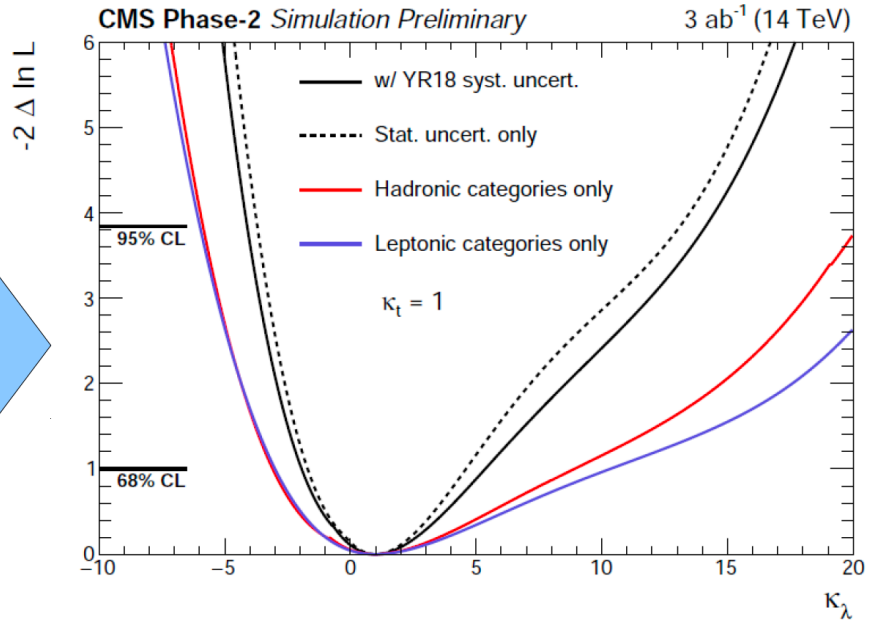


Indirect probe via Single Higgs

- Single-Higgs production: Higgs self-interaction only via one-loop corrections (ie two loop-level for ggF)
- κ_λ-dependent corrections to the tree-level cross-sections, depends on:
  - production mode → mainly **ttH**, tH, VH
- Method applied to **ttH(→γγ)** differential cross-section measurement:



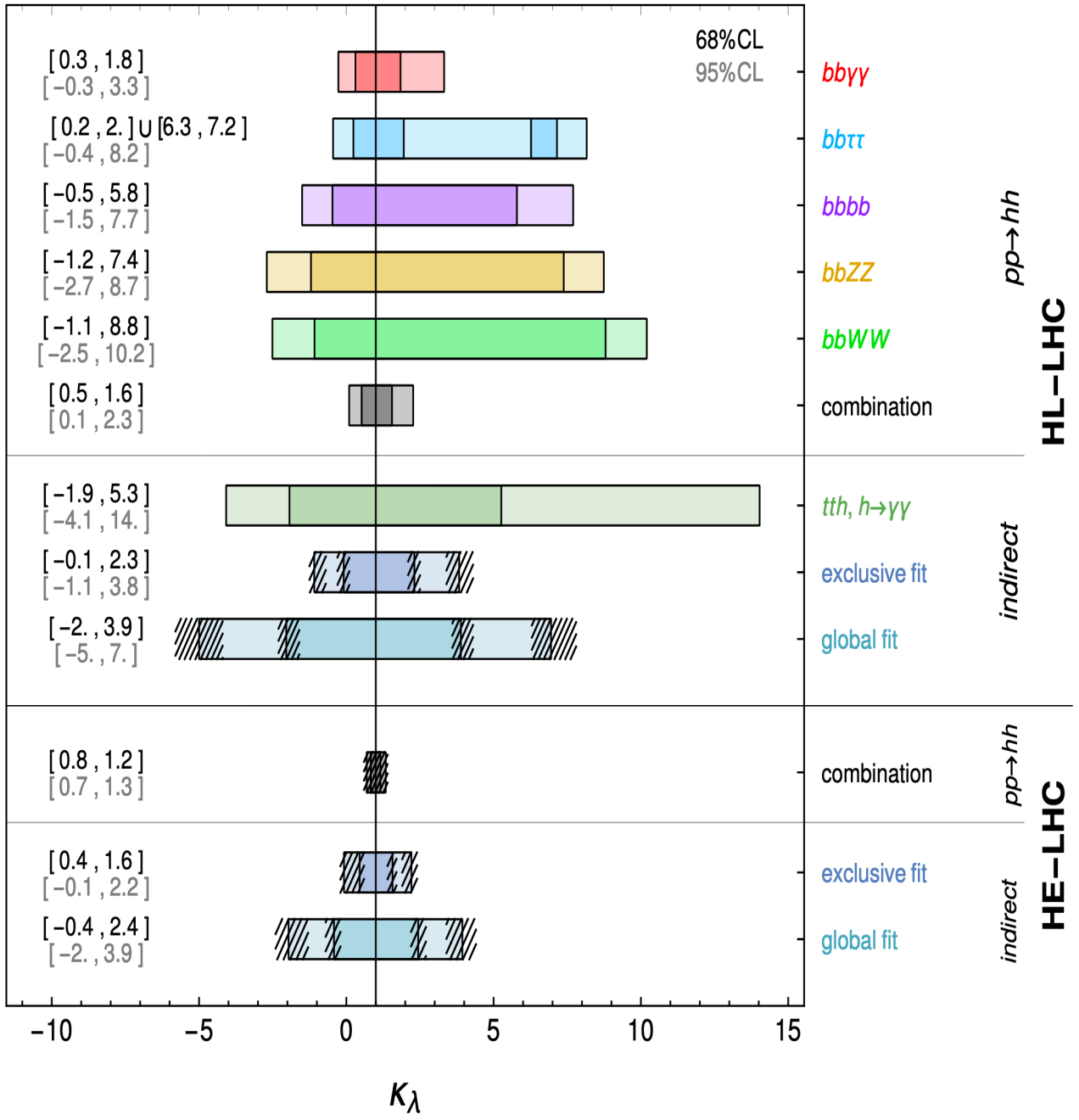




- 68% CI: **$-1.9 < \kappa_\lambda < 5.3$** if only κ_λ varied
- First test with experimental "data", more channels to be added

HH summary at HL and HE-LHC

- State-of-the-art computations of the cross-sections and m_{HH} available
- State-of-the art experimental studies on direct measurements
  - coherent results by ATLAS and CMS
  - **went from ~2σ last year to a combined significance of 4σ!**
  - **first real measurements possible, ex. precision on κ_λ: 50%**
  - There is room for improvement
- Nice developments on indirect constraints
  - single-Higgs differential cross-sections, global fits
- Estimates of sensitivity at HE-LHC
  - experimental and phenomenology



Summary

- HL-LHC opens up new possibilities in terms of:
  - Access to yet unobserved couplings
  - Precise measurement of couplings, width and mass
  - Higgs self couplings
- Projections of Higgs properties for single and diHiggs are also looked at HE-LHC
- There is scope to improve further:
  - Alternative methods for HH→bbWW(→lνlν) and HH→bbγγ to increase the significance
  - Indirect probes using Single Higgs in ttH
  - Improving the reconstruction algorithms of objects
  - ……..
  - ……..
  - Many more

BACKUP

Higgs coupling measurements at Run-II

Coupling modifiers

ATLAS

Parameter	(a) no BSM	(b) with BSM
κ_Z	1.07 ± 0.10	restricted to $\kappa_Z \leq 1$
κ_W	1.07 ± 0.11	restricted to $\kappa_W \leq 1$
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

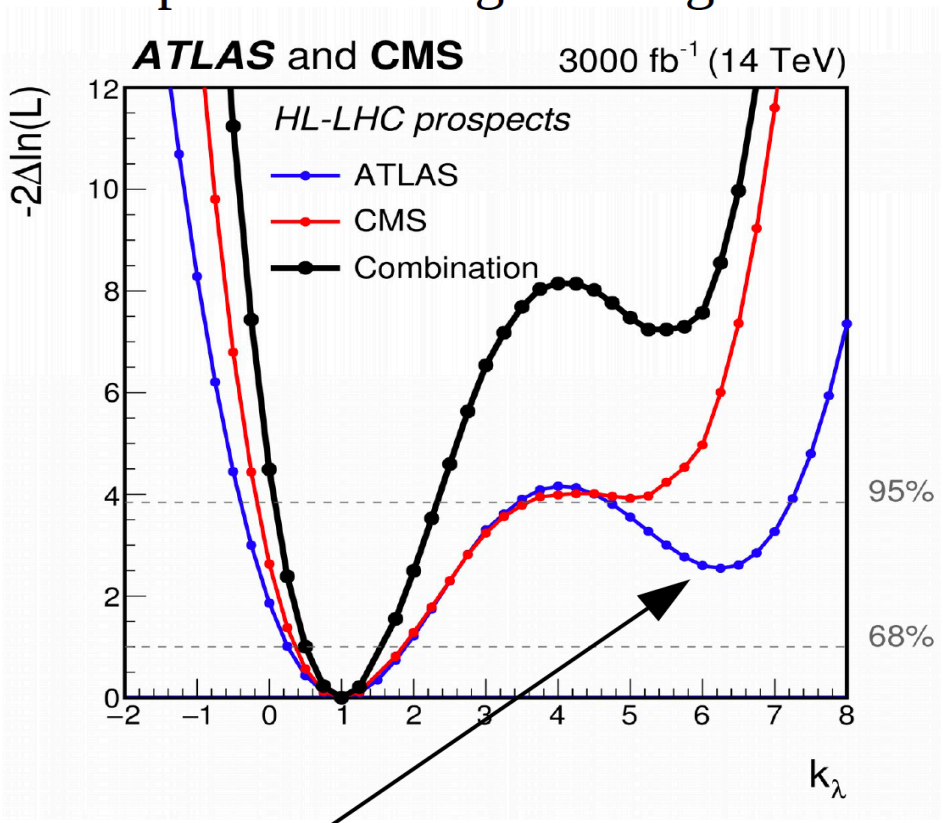
CMS

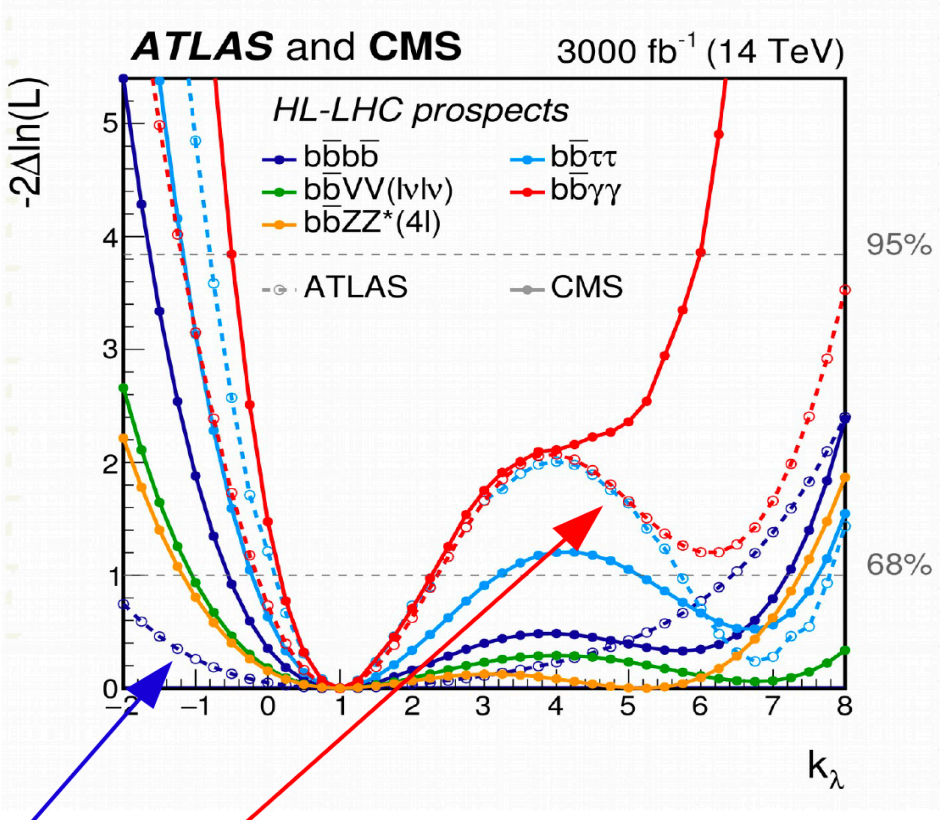
$\mathcal{B}_{BSM} = 0$				$\mathcal{B}_{BSM} > 0,\ \lvert\kappa_V\rvert < 1$			
		Uncertainty				Uncertainty	
Parameter	Best fit	stat	syst	Parameter	Best fit	stat	syst
κ_Z	$1.00\ ^{+0.11}_{-0.11}\ (^{+0.11}_{-0.11})$	$^{+0.09}_{-0.09}\ (^{+0.09}_{-0.09})$	$^{+0.06}_{-0.07}\ (^{+0.06}_{-0.06})$	κ_Z	$-0.87\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

arXiv:1809.10733

Combined results (ATLAS+CMS)

- Comparison of negative log-likelihood ratios:





- Difference on 2nd minimum mainly from the bb̄γγ channel: 3 categories of m_{HH} (especially a low-m_{HH} one) to remove the degeneracy around κ_λ=6 (while this low-m_{HH} category has no effect around 1)
- CMS slightly better below 1: bb̄bb̄ + other smaller channels