Physics potential of future analyses at HL-LHC/HE-LHC (few analyses are covered)

Jyothsna Rani Komaragiri

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XVI Workshop on High Energy Physics Phenomenology

Indian Institute of Technology Guwahati

Guwahati

center for high energy physics

Indian Institute of Science, Bangalore, India

CERN Yellow Reports

WG Reports

862 pages

WG1 Standard Model Physics
http://arxiv.org/abs/arXiv:1902.04070 (219 pages)

WG2 Higgs Physics
http://arxiv.org/abs/arXiv:1902.00134 (364 pages)

WG3 Beyond Standard Model Physics
http://arxiv.org/abs/arXiv:1812.07831 (279 pages)

WG4 Flavour Physics
http://arxiv.org/abs/arXiv:1812.07638 (292 pages)

WG5 Heavy Ion Physics
http://arxiv.org/abs/arXiv:1812.06772 (207 pages)

(1361 pages)

"Volume 2" (collection of ATLAS and CMS public notes):
https://arxiv.org/abs/1902.10229 **(1369 pages)**

Executive summaries, submission to the European Strategy

HL-LHC
https://indico.cern.ch/event/765096/contributions/3295995/

HE-LHC
https://indico.cern.ch/event/765096/contributions/3296016/

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
- Top, SUSY, Dark Matter
- Summary and conclusions

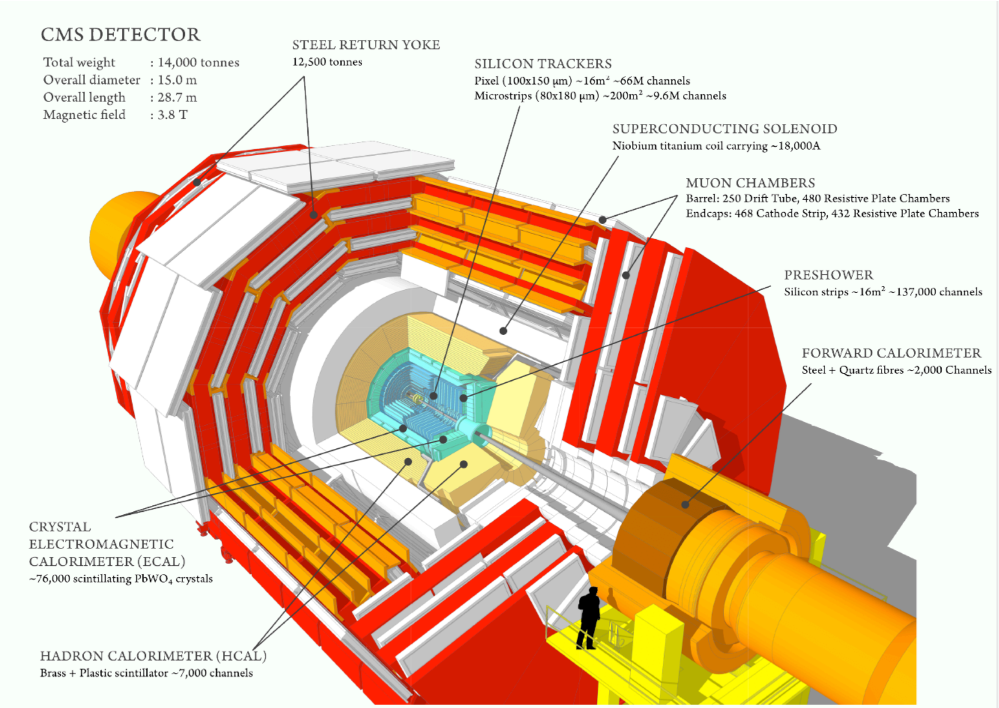
All projection results presented in this talk are included in
Volume2 HE/HL-LHC: arXiv:1902.10229 **(1369 pages)**

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**

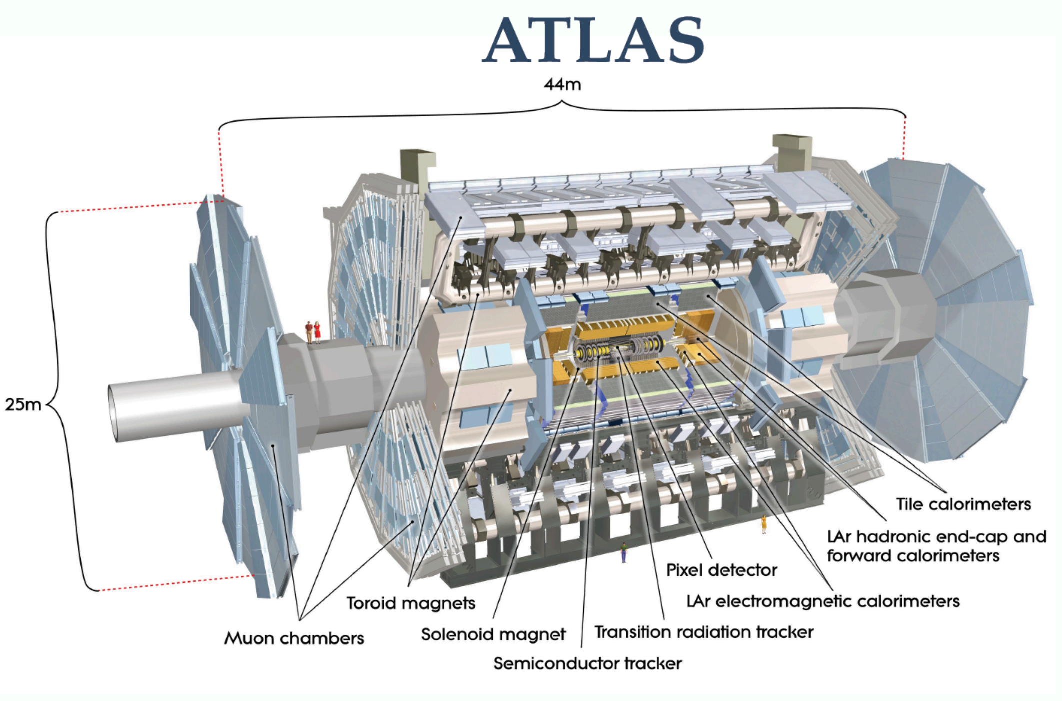
Upgrade of detectors

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)



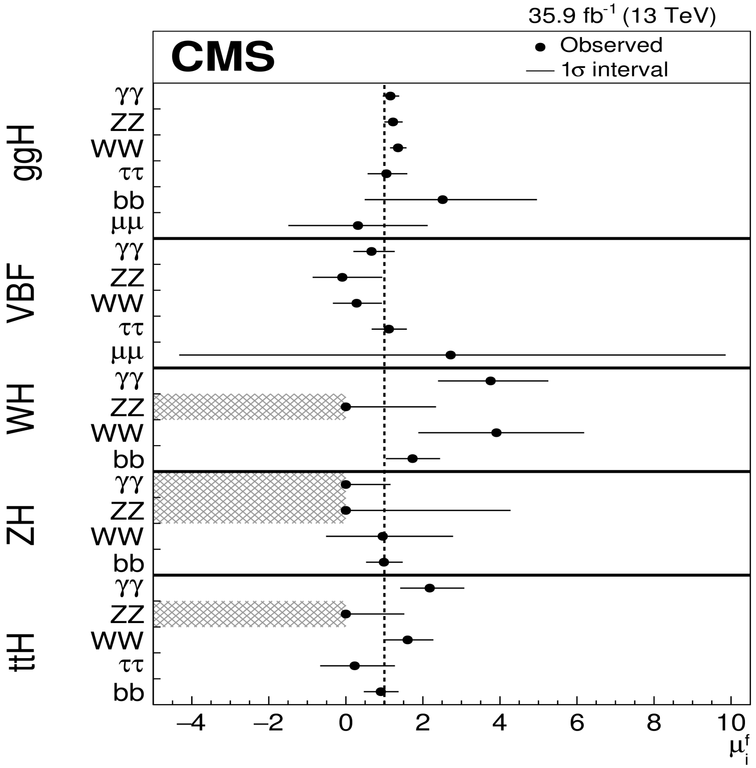
Challenges and Physics opportunities at HL-LHC

- **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**

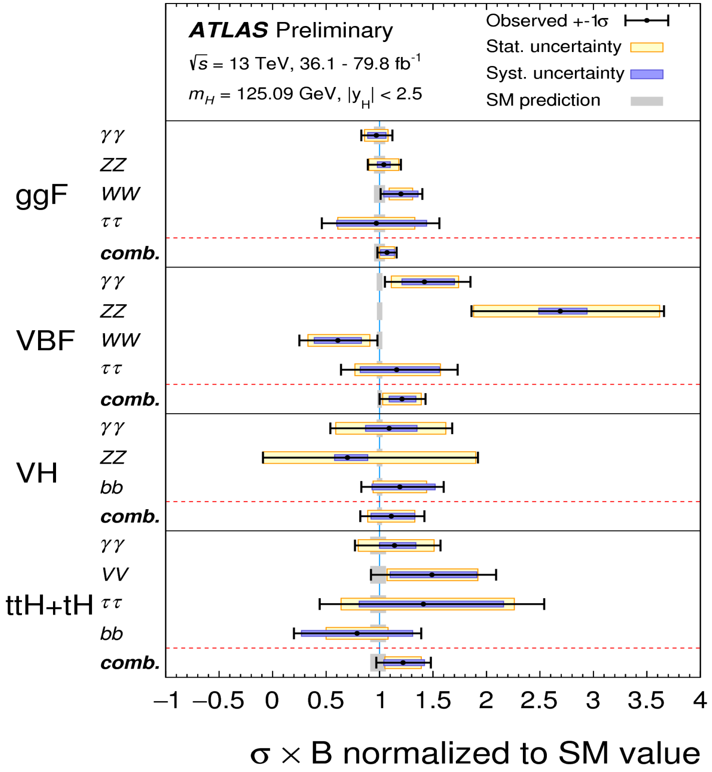
Higgs boson measurements at HL-LHC

Higgs boson measurements at Run-II

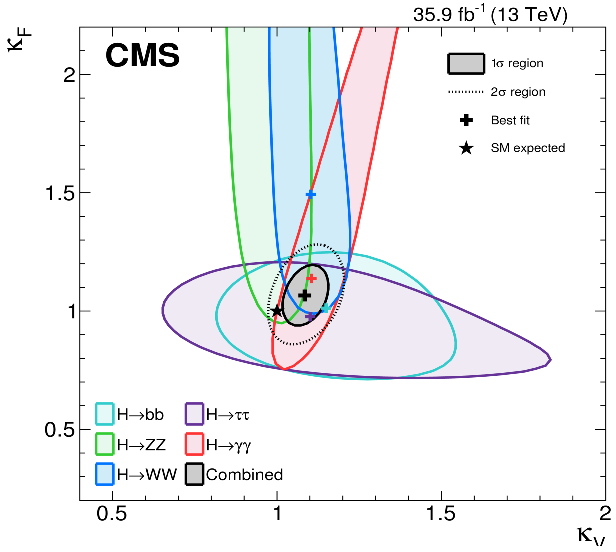
- Higgs boson properties are in agreement with the SM expectation
  - **Bosonic couplings (observed in Run-I) and 3rd generation fermionic coupling (observed in Run-II).**
    Current precision on couplings in ~10-30% (single experiment)
  - 2nd generation fermionic coupling still to be established (H→μμ)
    - **H→cc studies were not included in HL/HE-LHC projections**
- **Goal for the future is to improve precision**



arXiv:1809.10733



ATLAS-CONF-2018-031



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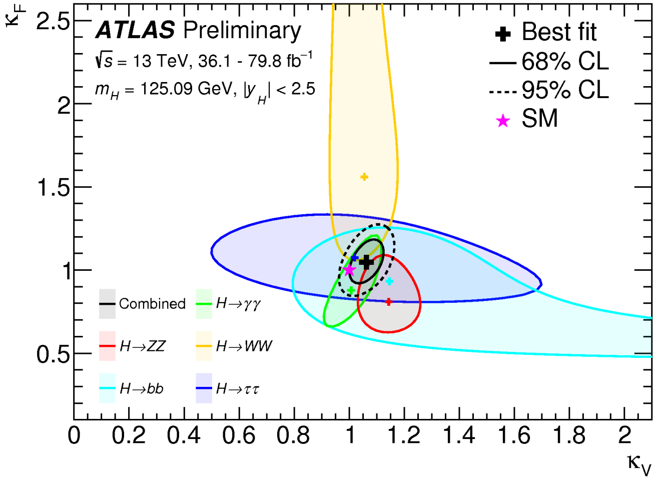


Analysis procedures for HL-LHC projections

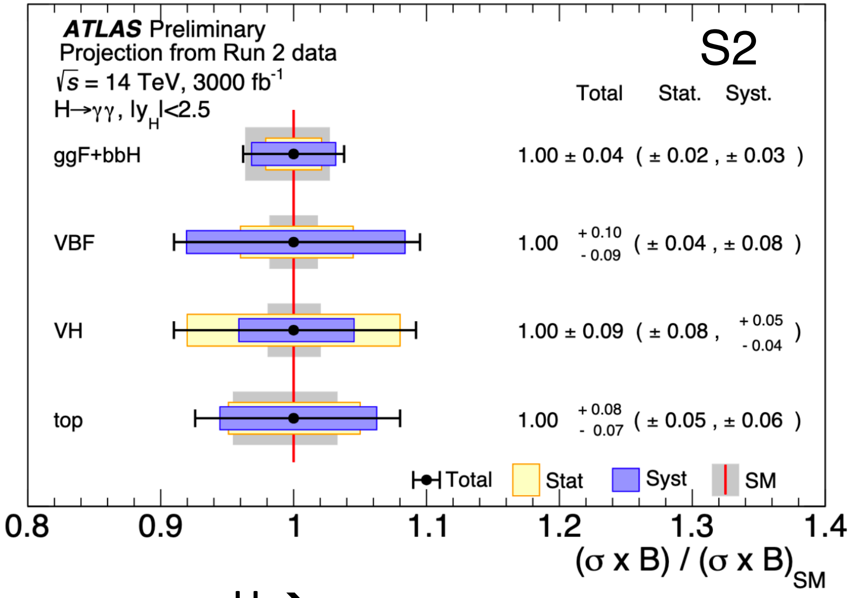
- **Analyses are performed using simulated samples produced with HL-LHC conditions using upgraded detectors**
  - This is the case for new and/or significantly improved analyses

- **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 $\sqrt{L}$**
    - **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

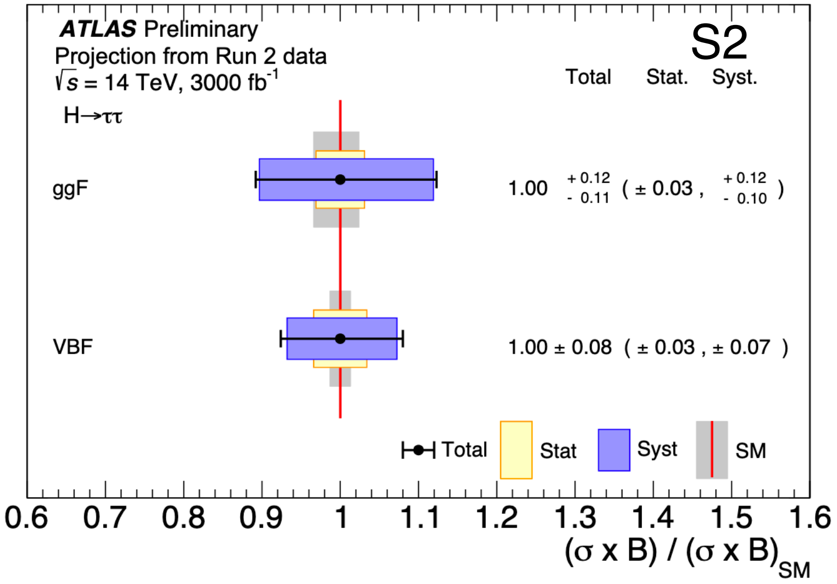
- **Reminder:** All projection results on Higgs presented in this talk are included in the Yellow Report (YR) from HE/HL-LHC WG 2: arXiv:1902.00134

Combined Higgs coupling measurements (1)

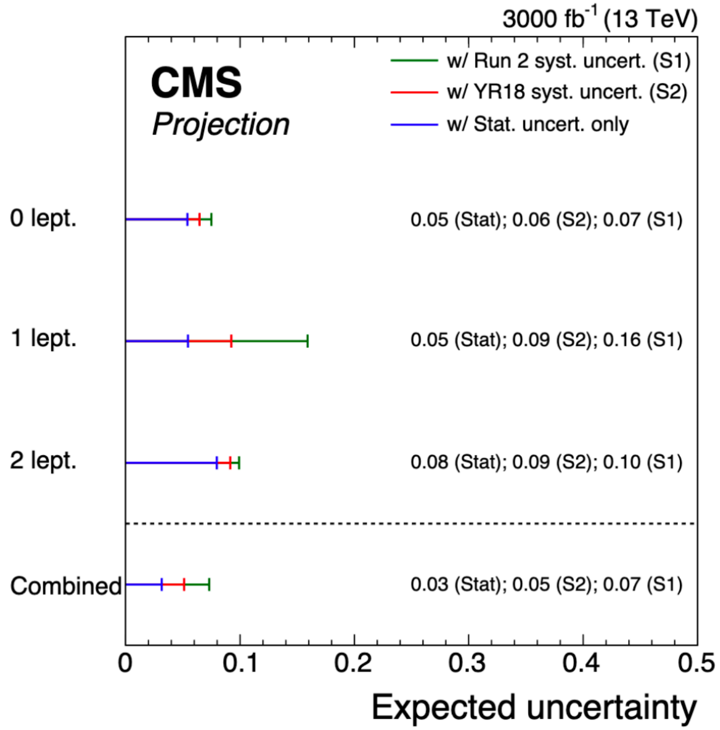
- Inputs used:
  - Projections of combined measurements of Higgs boson couplings using data collected in 2015-2017 (ATLAS) and 2016 (CMS)
  - Projections cover all main production (gluon fusion, VBF, VH, ttH) modes of Higgs and Higgs decay modes (γγ, ZZ, WW, bb, ττ, μμ, Zγ)
  - A couple of examples of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



H→γγ

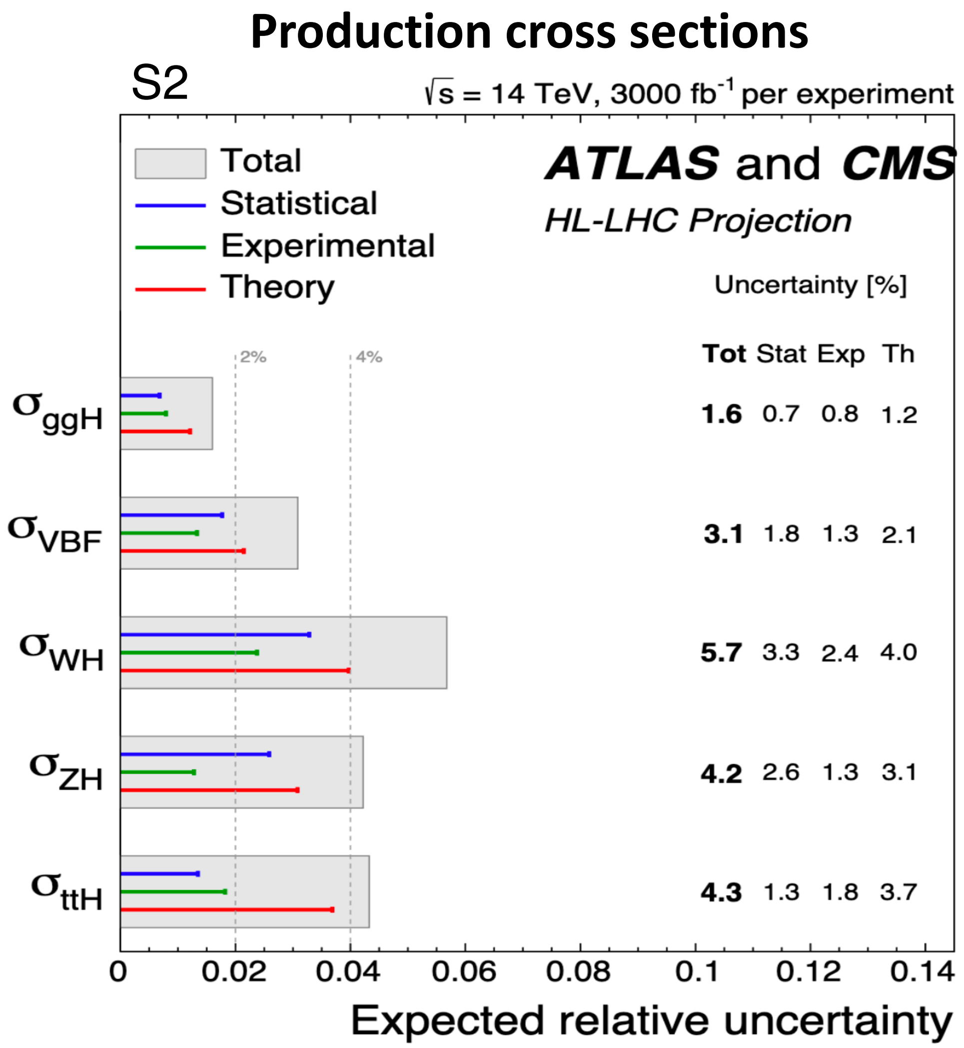


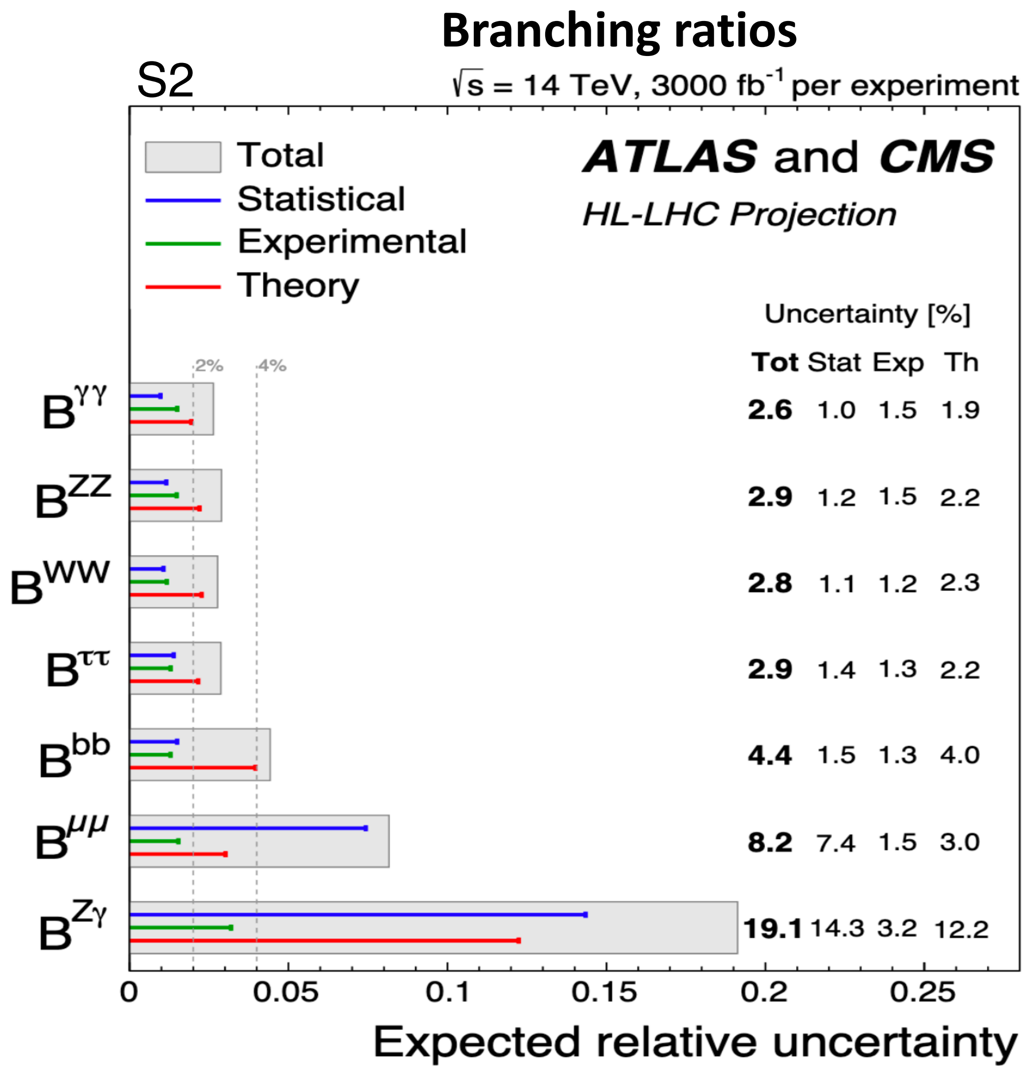
H→ττ



VH, H→bb

Combined Higgs coupling measurements (2)



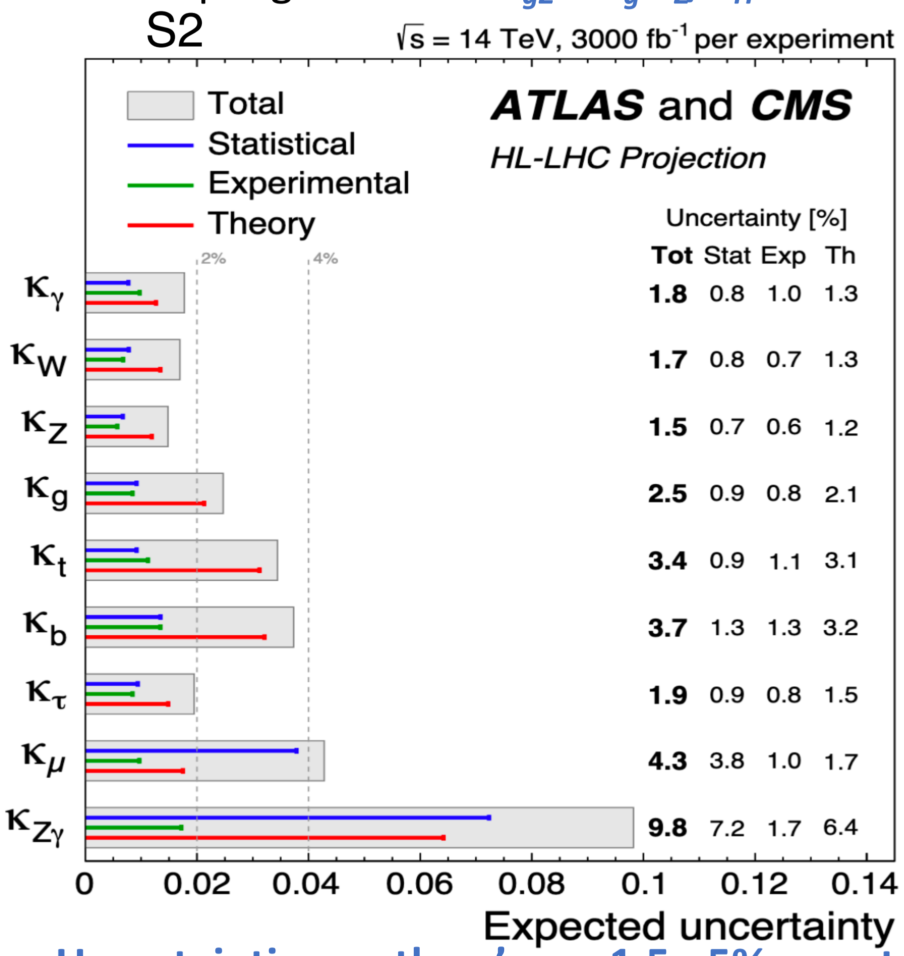


- **Cross sections and Branching ratios (except $B^{\mu\mu}$ and $B^{Z\gamma}$) are dominated by theoretical uncertainties**
- **Branching ratios: $B^{\mu\mu}$ and $B^{Z\gamma}$ statistically limited.**

Combined Higgs coupling measurements (3)

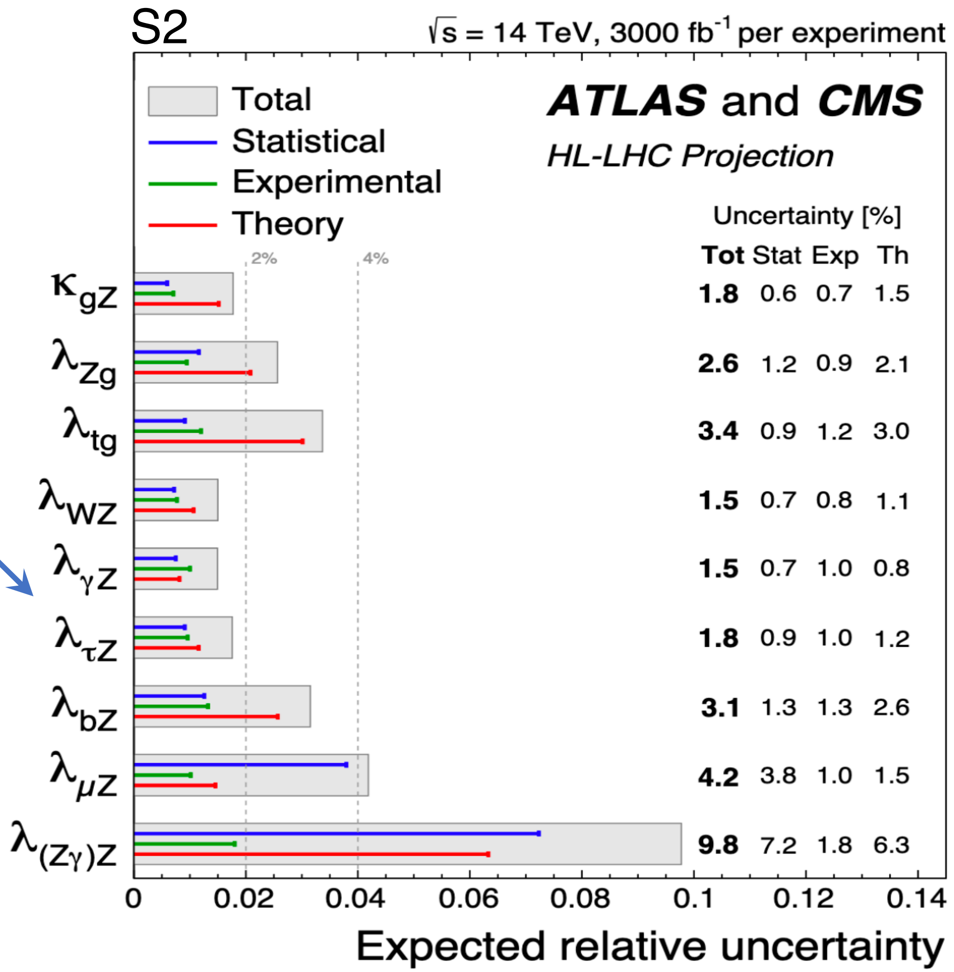
Coupling modifier or κ-framework: For a given production or decay mode j: $\kappa_j^2 = \sigma_j/\sigma_j^{SM}$ or $\kappa_j^2 = \Gamma^j/\Gamma^j_{SM}$

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

Higgs Summary at HL and HE-LHC

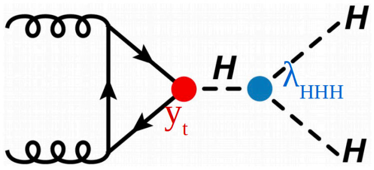
- Physics reach in the Higgs sector will be expanded at HL-LHC
  - **Percent level precision on most Higgs couplings**
- Many inclusive measurements limited by systematic uncertainties ➔ work needed from theoretical and experimental side to reduce these

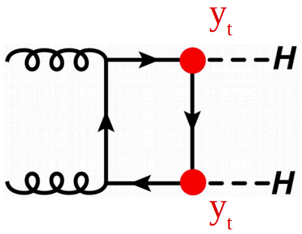
- Looking further ahead: HE-LHC
  - $15ab^{-1}$ at 27 TeV
  - κ_{μ} precision expected to reach 2%
  - Reduction of statistical uncertainty in Higgs coupling measurements

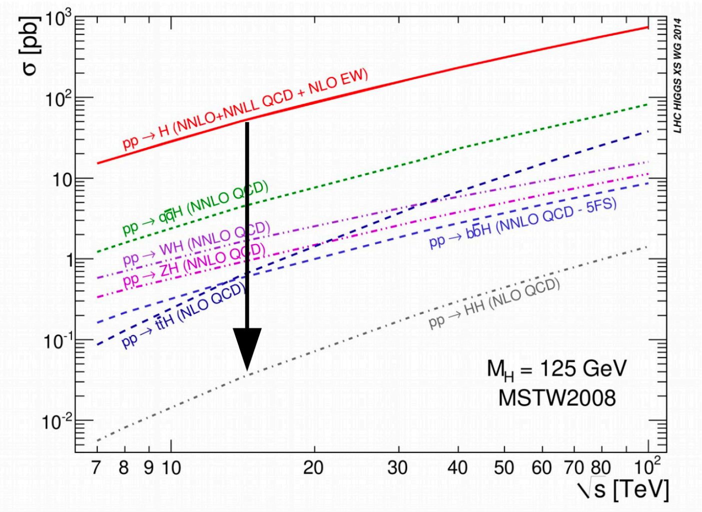
Higgs boson pair (HH) prospects at HL/HE-LHC

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)
  - **$\sigma(gg \to HH) \approx 0.1\% * \sigma(gg \to H)$**
  - **Small σ_{HH}** $\Longrightarrow$ need high luminosities
  - **Direct determination of λ from Higgs boson pair production**

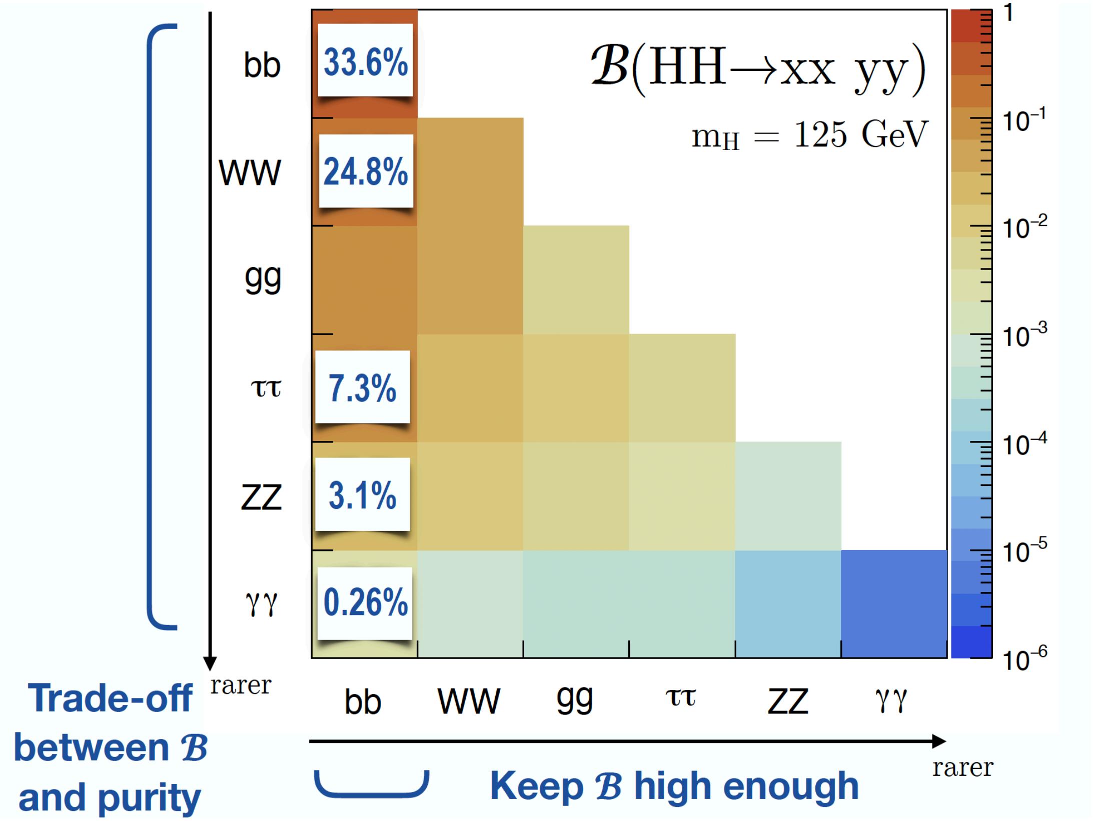






- BSM contributions can modify the Higgs boson coupling parameters and modify the HH cross section: define **$\kappa_\lambda = c_{hhh} = \lambda_{HHH} / \lambda_{HHH}^{SM}$**

Decay



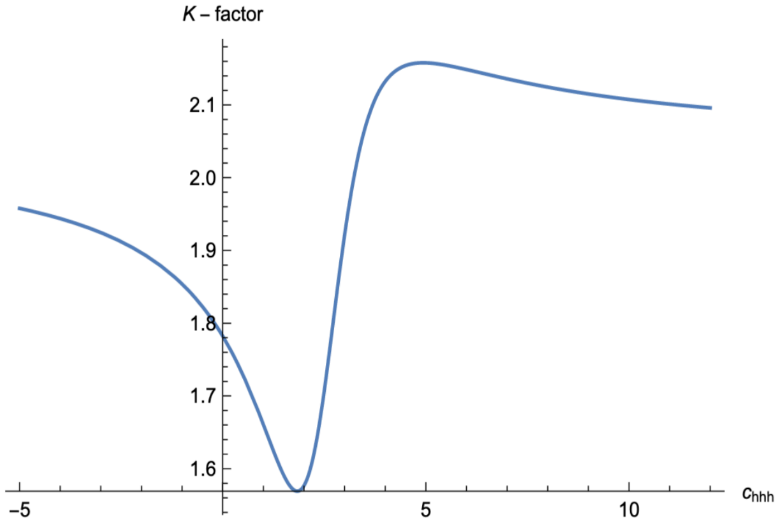
- Phenomenologically rich set of decay channels
  - Broad experimental coverage to increase sensitivity
- Many different signatures
  - All benefit from the upgraded ATLAS and CMS detectors

Higgs boson pair production cross section (1)

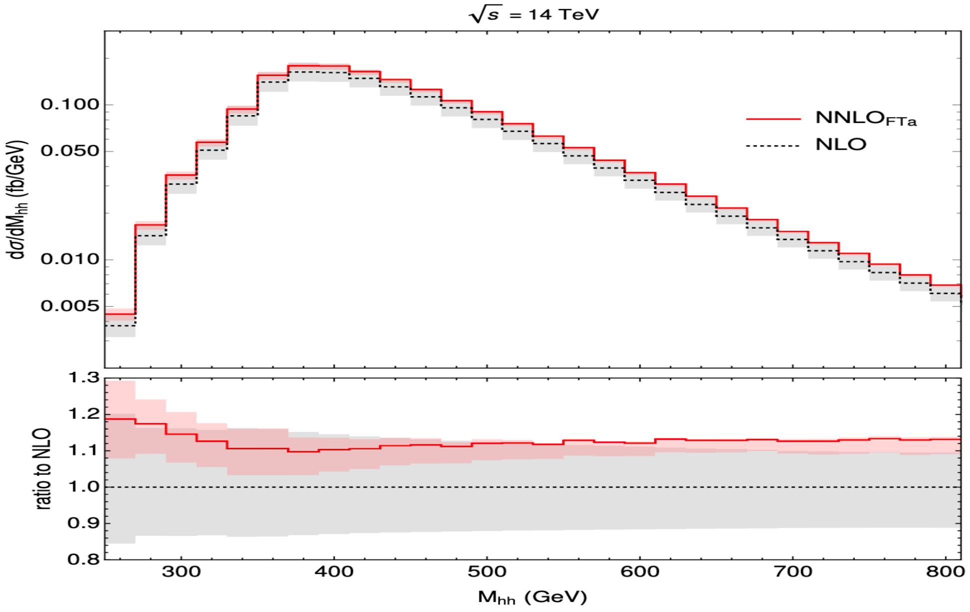
- SM calculation
  - ggF: State of the art NNLO with finite m_t effects
  - Other production modes: NLO with full m_t dependence
- Higgs **self-coupling variations** with full m_t dependence at NLO
  - LO to NLO K-factors vary from 1.57 to 2.16

$\sqrt{s}$ [TeV]	$\mathrm{NNLO_{FTa}}$ [fb]	m_t unc.	PDF unc.	α_S unc.	PDF+α_S unc.
14	$36.69^{+2.1\%}_{-4.9\%}$	±2.7%	±2.1%	±2.1%	±3.0%
27	$139.9^{+1.3\%}_{-3.9\%}$	±3.4%	±1.7%	±1.8%	±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	$0.963^{+2.1\%}_{-2.3\%} \pm 1.5\%$	$1.48^{+2.3\%}_{-2.5\%} \pm 1.7\%$	$8.21^{+1.1\%}_{-0.7\%} \pm 1.8\%$	$5.27^{+2.0\%}_{-3.7\%} \pm 2.5\%$	$0.254^{+3.8\%}_{-2.8\%} \pm 3.6\%$

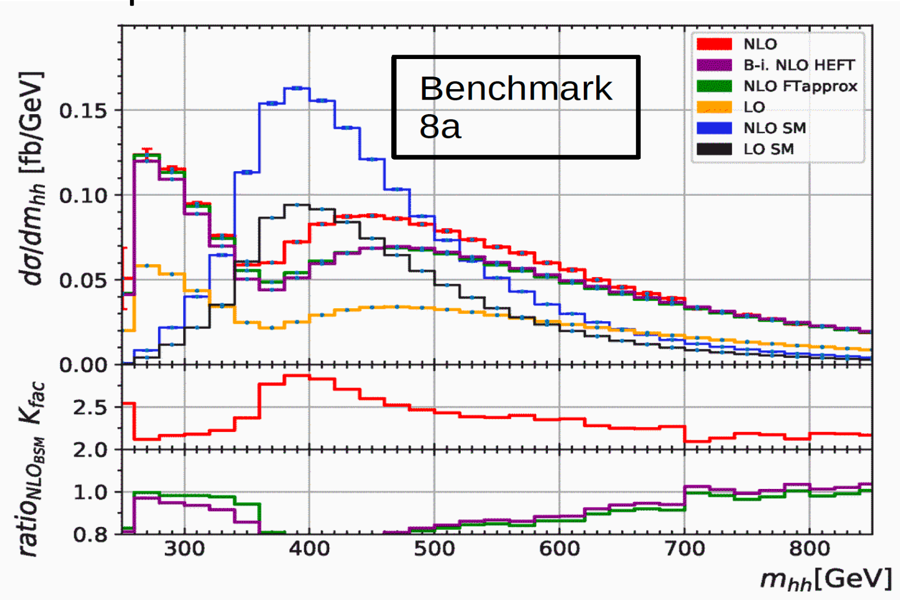


m_{HH} differential cross sections

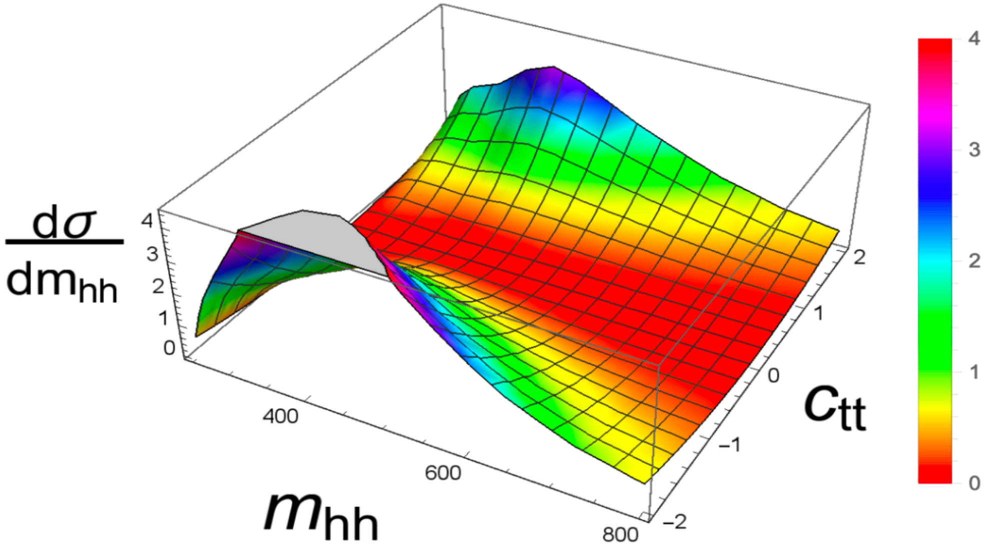


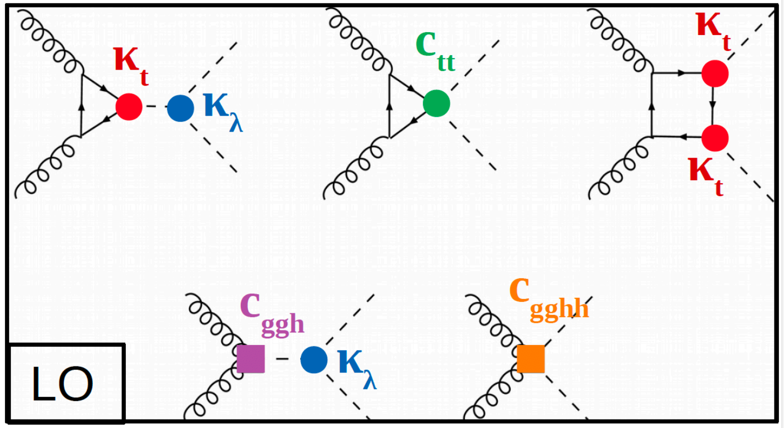
Higgs boson pair production cross section (2)

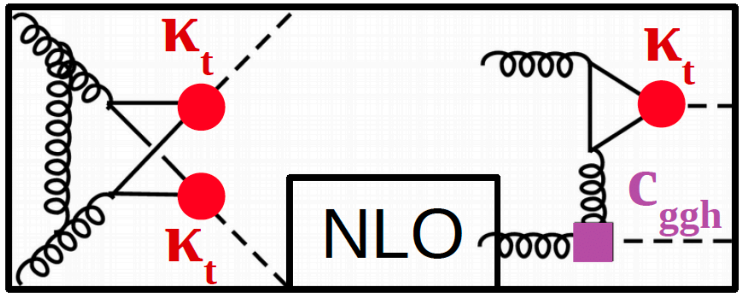
- **BSM model:** Non-linear EFT
- Cross sections and m_{hh} at NLO QCD for some selected benchmark points



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





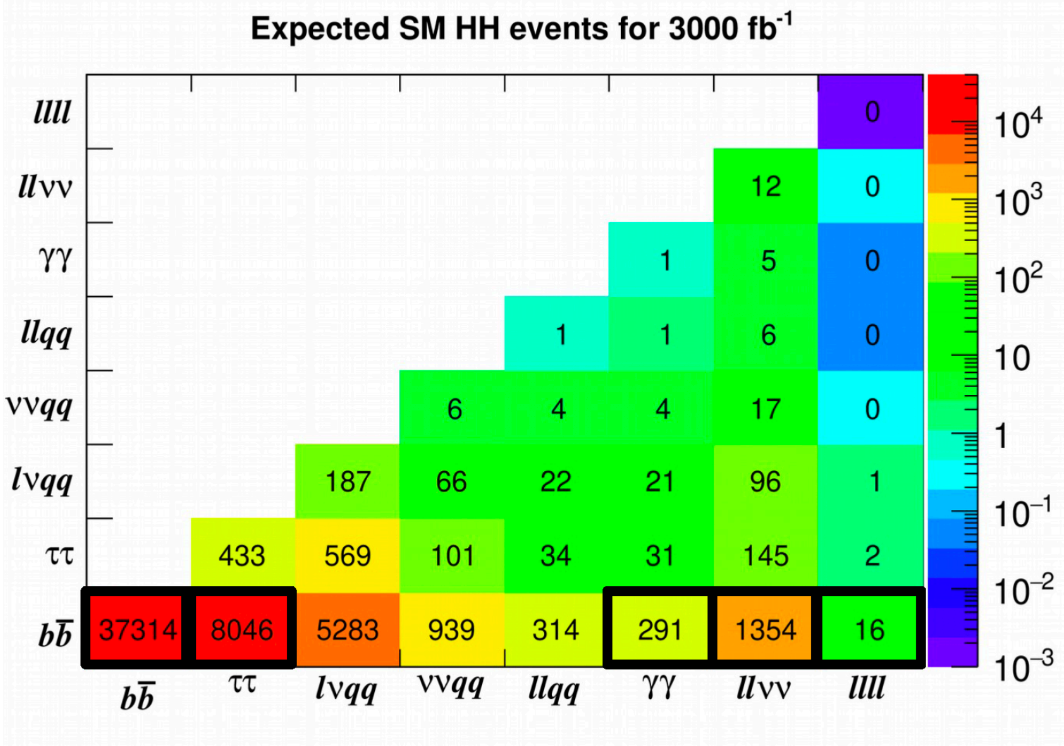


Benchmark	c_{hhh}	c_t	c_{tt}	c_{ggh}	c_{gghh}
5a	1	1	0	2/15	4/15
6	2.4	1	0	2/15	1/15
7	5	1	0	2/15	1/15
8a	1	1	1/2	4/15	0
SM	1	1	0	0	0

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 ☺

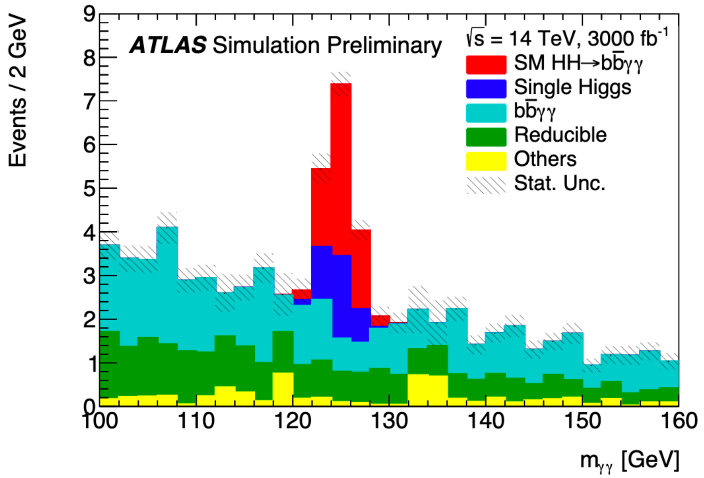


- **Systematic uncertainties:** common agreement between ATLAS and CMS
  - performance uncertainties scaled by 0.5 to 1
  - theoretical uncertainties divided by 2
  - MC statistical uncertainties neglected

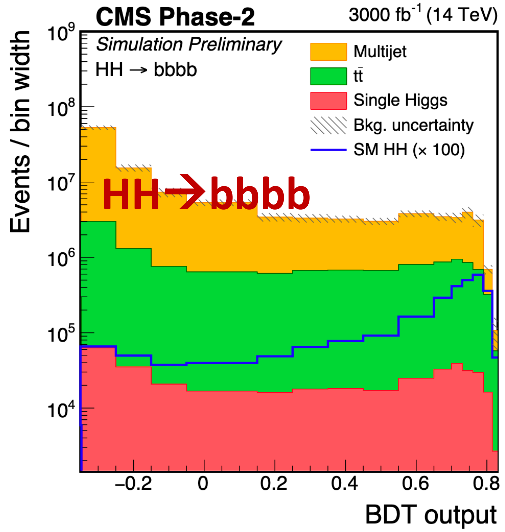
HH Experimental prospects, analysis methods

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

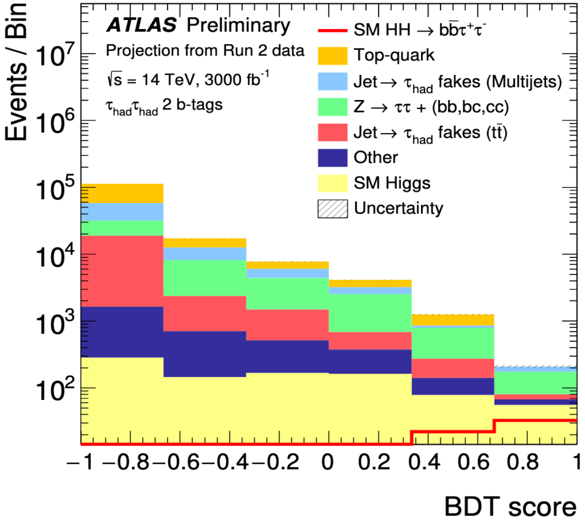
HH→bbγγ



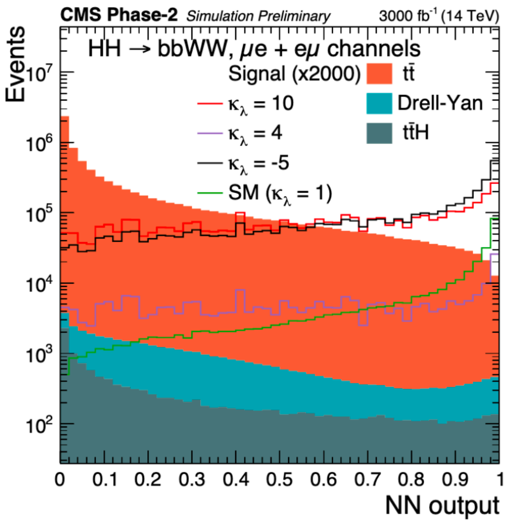
- Few examples:



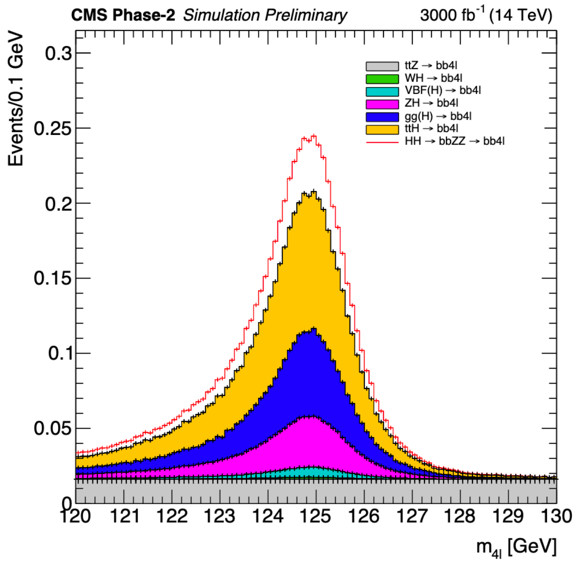
HH→bbττ



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

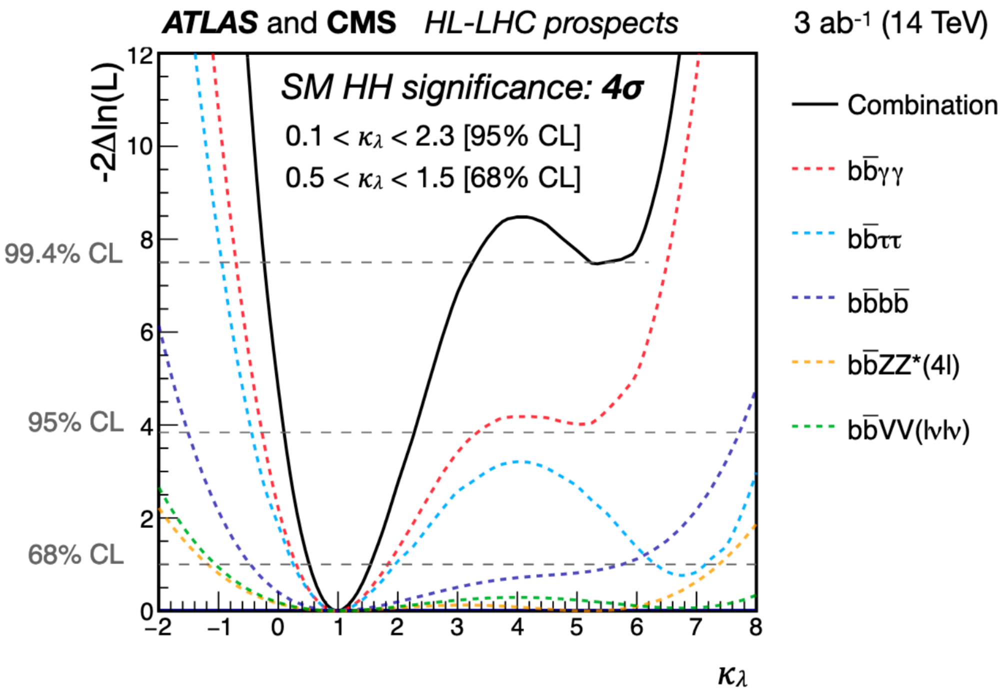
HH Experimental prospects, results

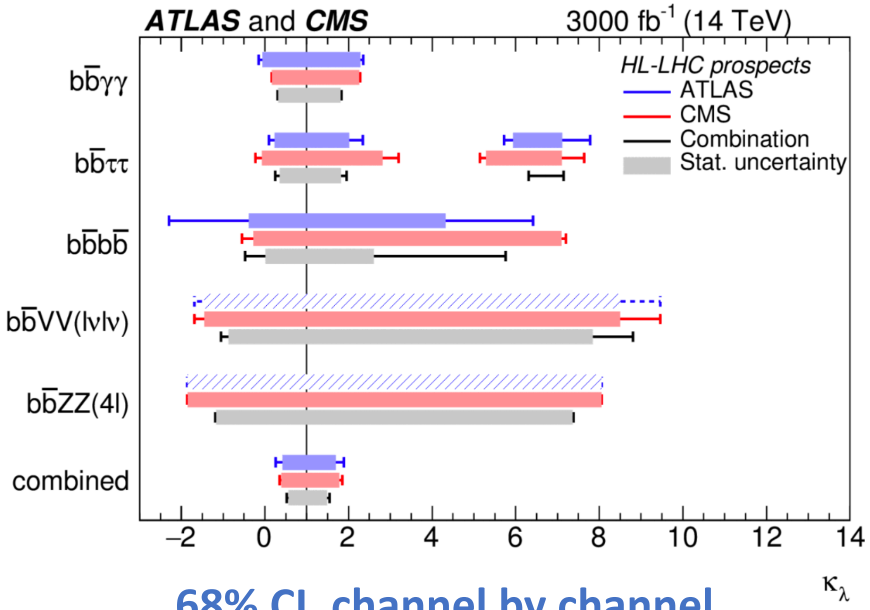
- Expected **significance** with and without systematics at HL-LHC
  - **4σ expected with ATLAS+CMS!**

	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 4.5		Combined 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

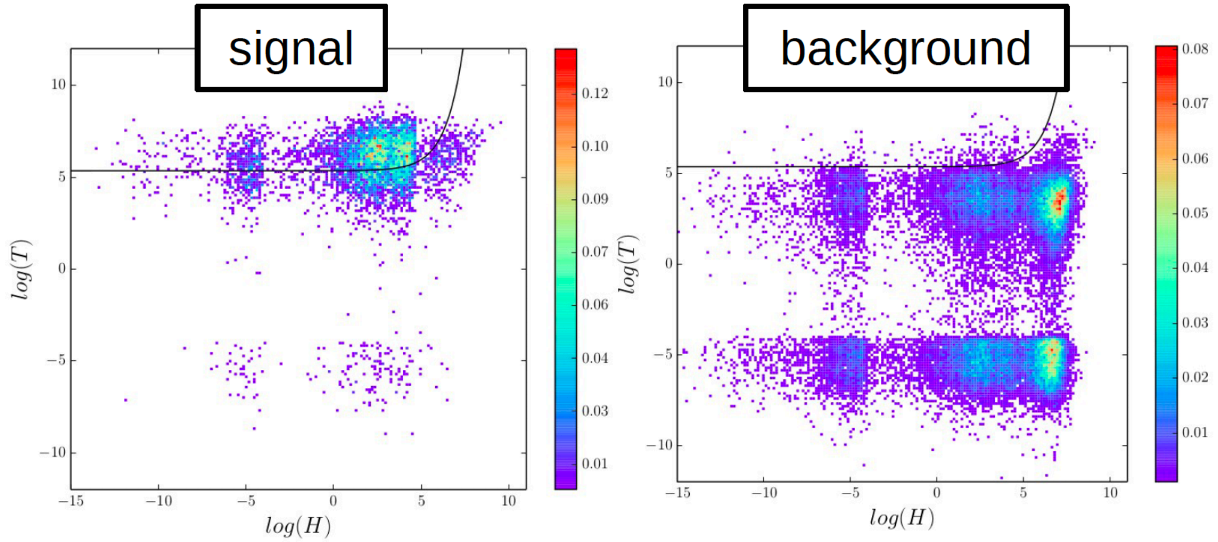




68% CI, channel by channel

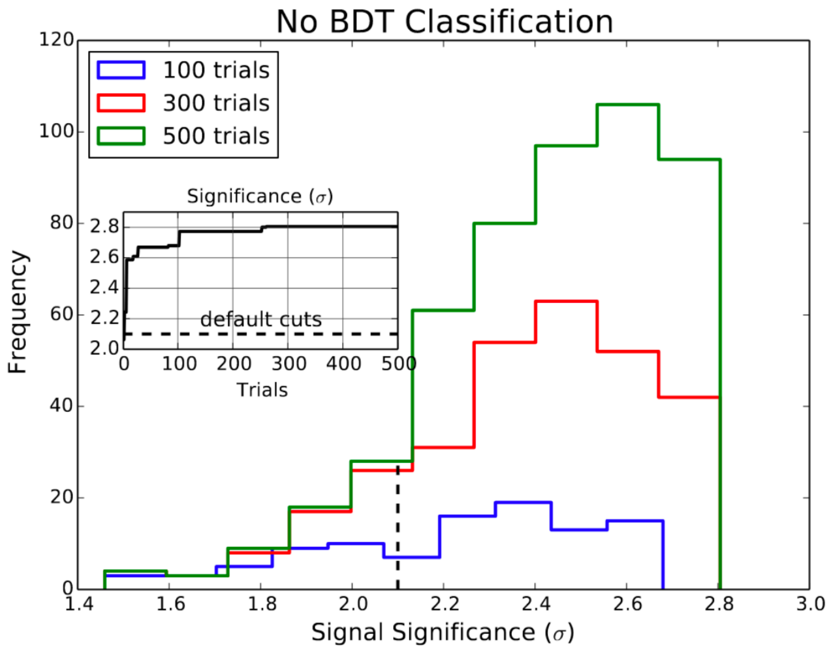
HH at HL-LHC, alternative methods

- **HH→bbWW(→lνlν):** 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



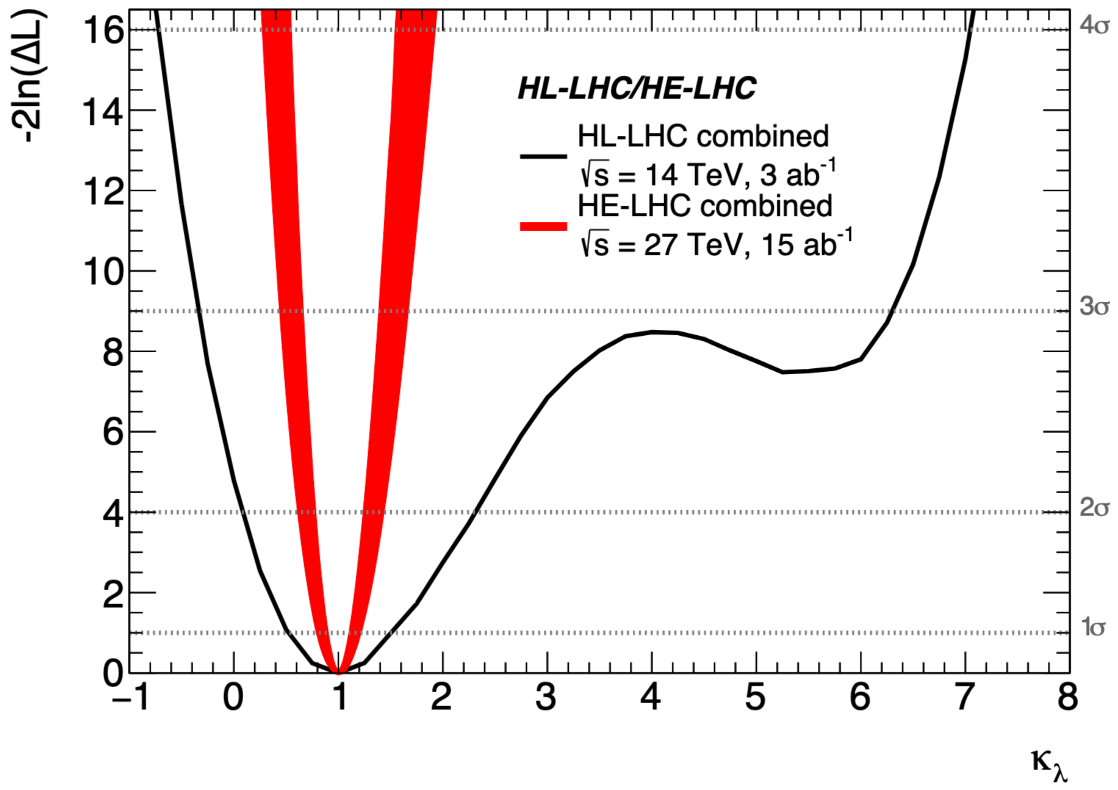
- No pile-up included, but shows the potential of sophisticated techniques: **could achieve up to 4σ**
  - illustrated in the Yellow Report with ATLAS and CMS using MVA techniques

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

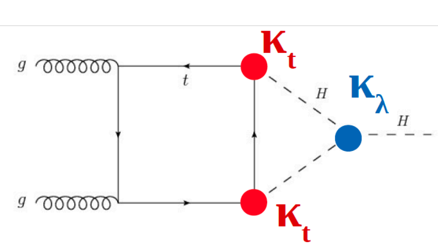
- Phenomenology study: **15% precision on κ_λ**
  - realistic detector performance
  - no pile-up considered (μ=800-1000)
  - interesting categorisation of b-jets

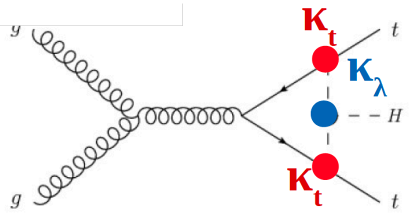
- κ_λ could be measured with a 68% CI of **10 to 20 %**
  - without uncertainties
  - effect of pile-up?
  - contribution of ggF+jets?

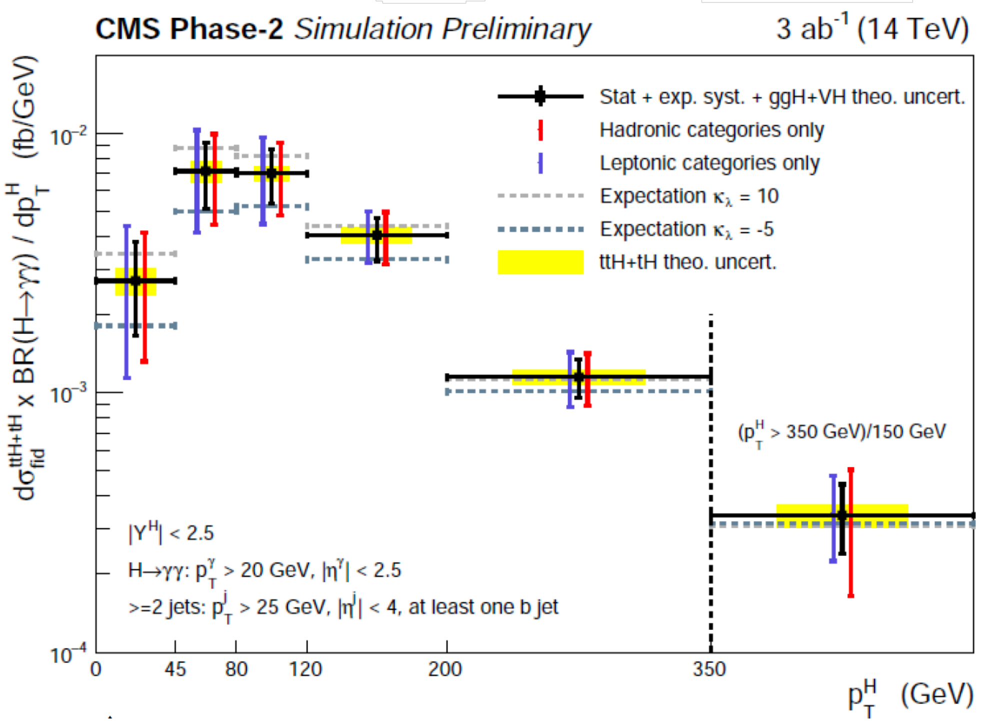


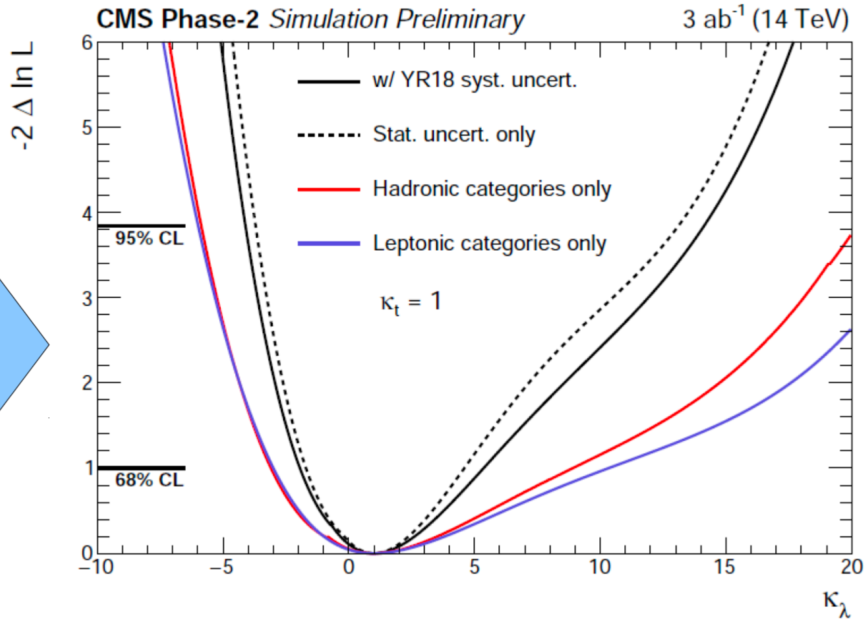
Indirect probe via Single Higgs

- 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:





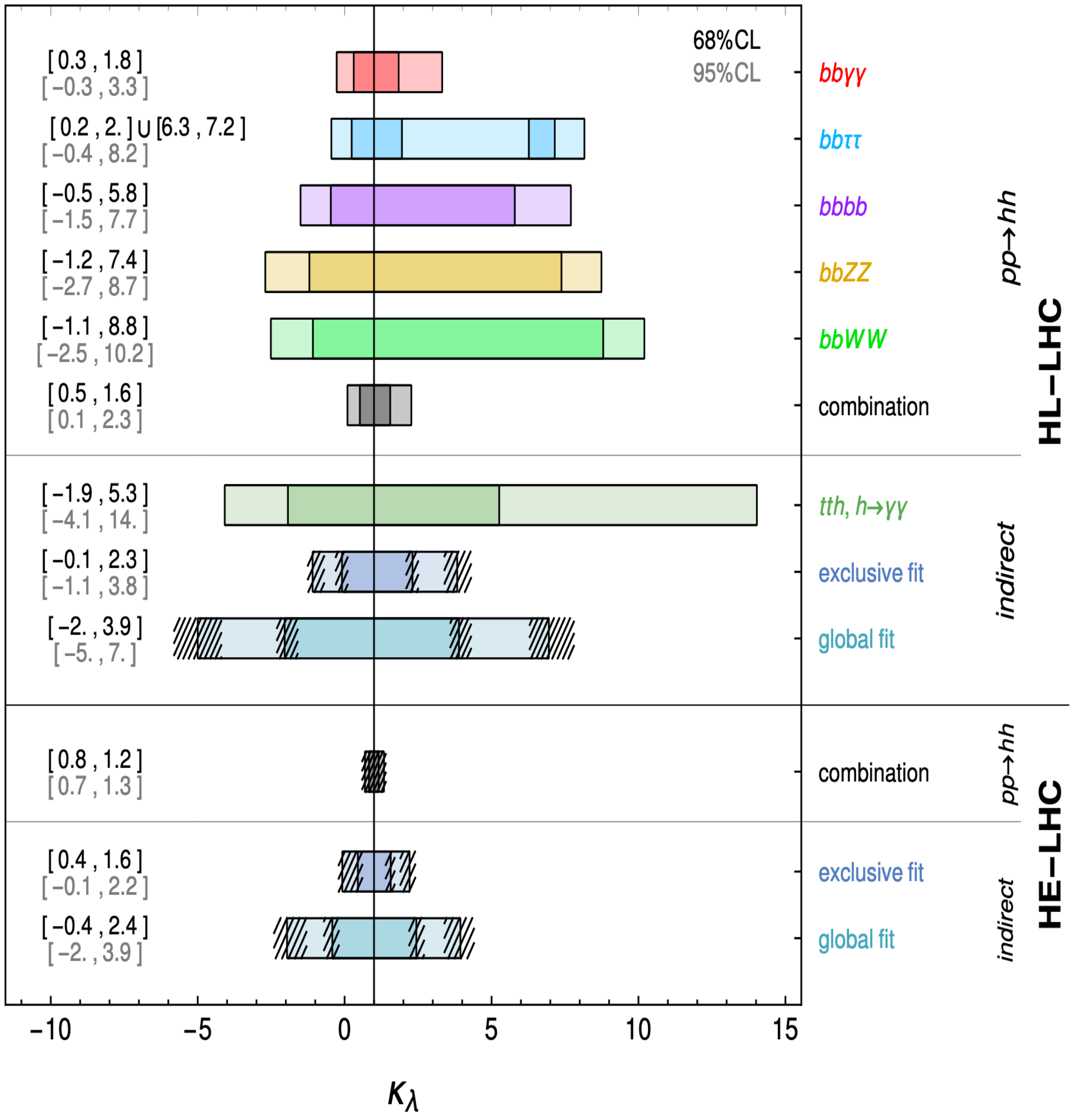




- 68% CI: **-1.9 < κ_λ < 5.3** if only κ_λ varied
- First test with experimental "data", more channels to be added

HH summary at HL and HE-LHC

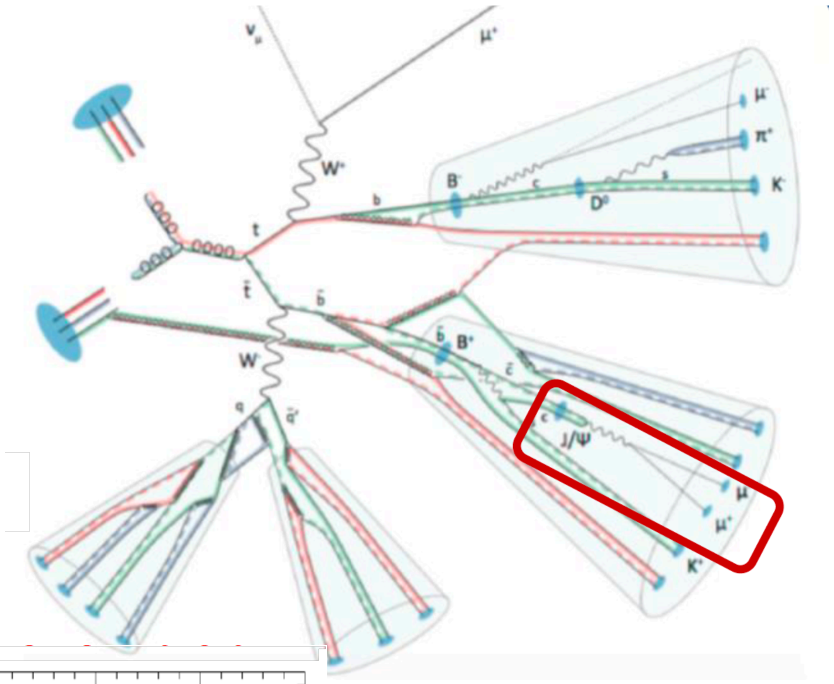
- State-of-the-art computations of the cross-sections and m_{HH} available
- State-of-the art experimental studies on direct measurements
  - coherent results by ATLAS and CMS
  - **went from ~2σ last year to a combined significance of 4σ!**
  - **first real measurements possible, ex. precision on κ_λ: 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

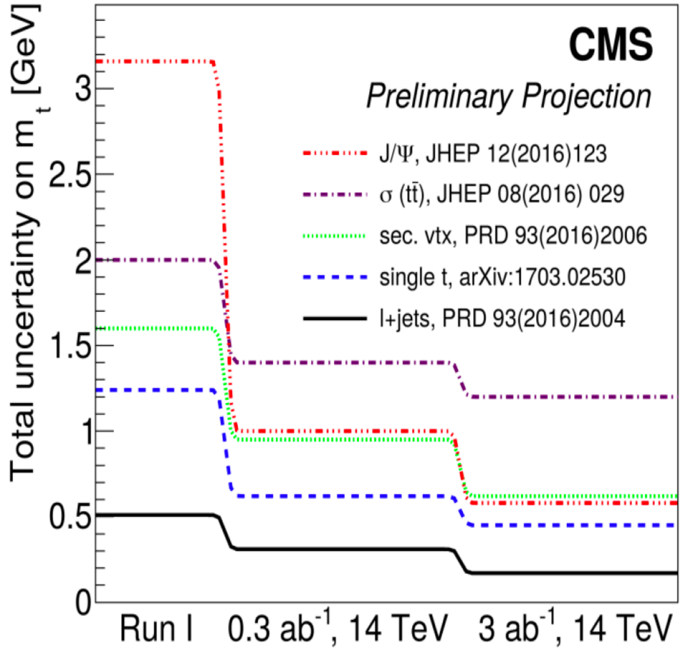


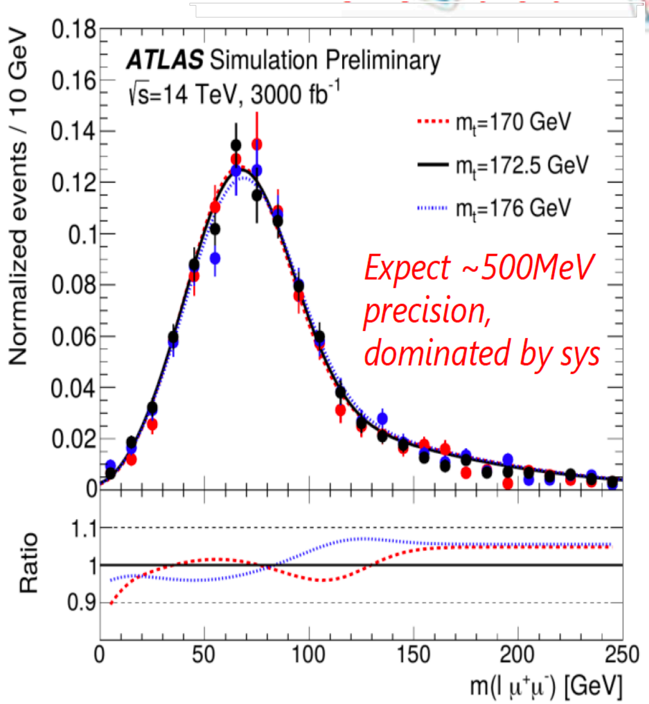
Top, SUSY and Dark Matter

Top quark mass at HL-LHC

- Top quark mass: Another free parameter in SM
- Current uncertainty is: 500 MeV
- Complementary approaches allow to further reduce the uncertainties
  - **One such approach accessible at HL-LHC is: Rare b decaying into J/ψ →$\mu\mu$ events**
  - This is sensitive to m_t and orthogonal to jet based measurement

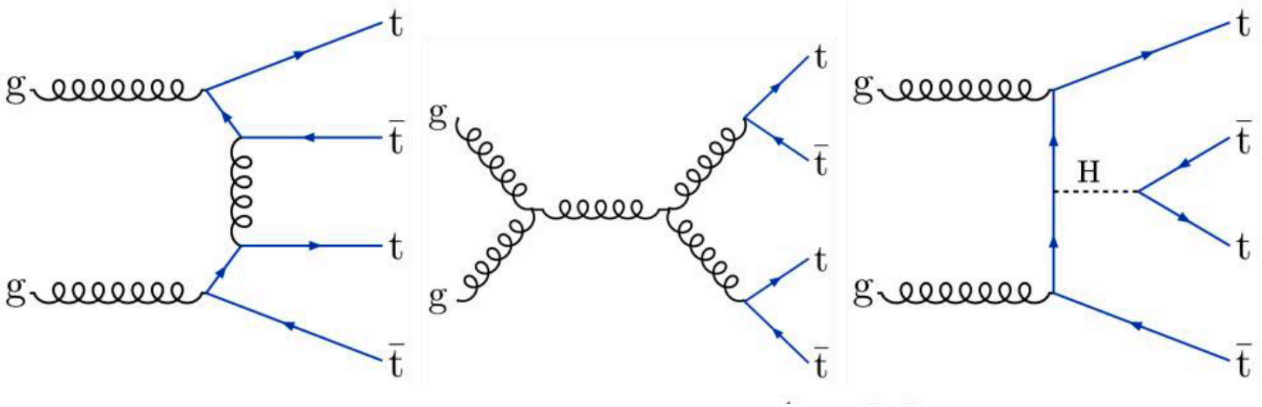


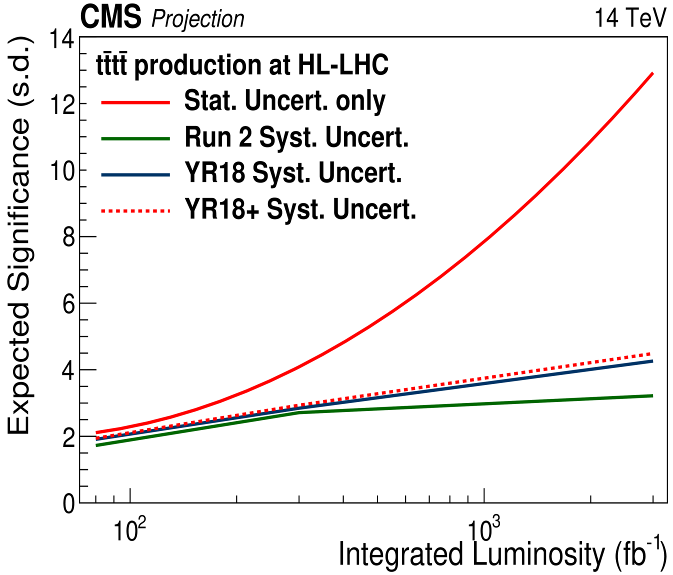


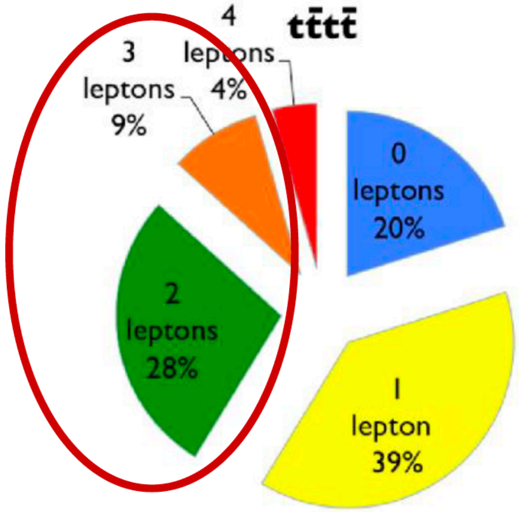


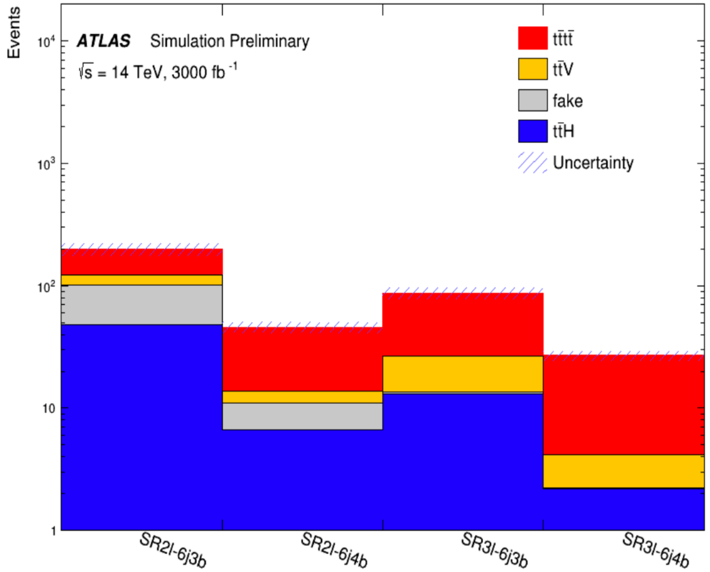
4 tops production

- Rare process sensitive to BSM Physics
- Current sensitivity 1σ with events with two or three leptons
- Expected uncertainty @HL-LHC 20-30%
- Expect evidence of tttt with 3ab^{-1} at HL-LHC



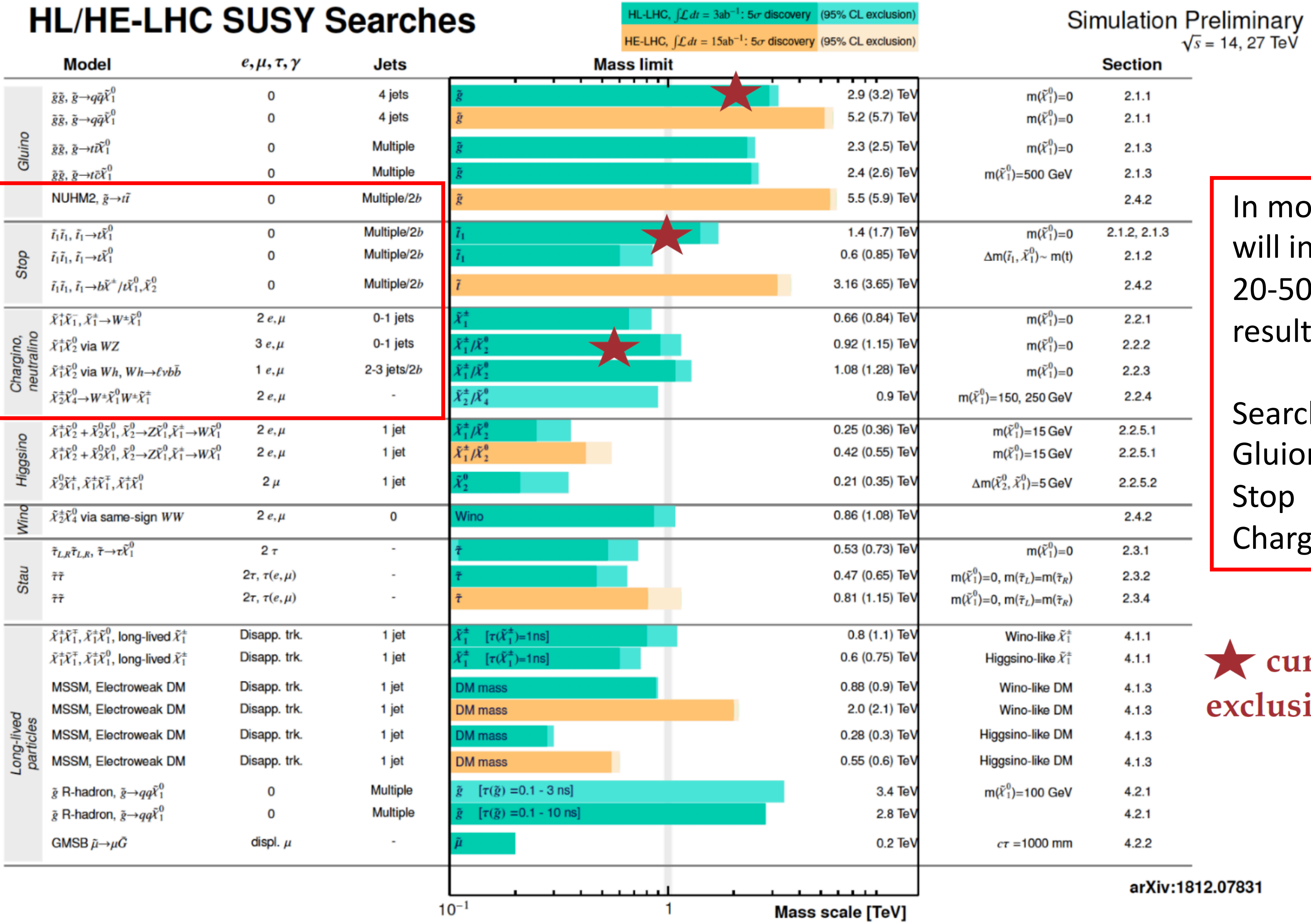






Int. Luminosity	$\sqrt{s}$	*Stat. only* (%)	*Run-2* (%)	*YR18* (%)	*YR18+* (%)
300 fb^{-1}	14 TeV	+30, −28	+43, −39	+36, −34	+36, −33
3 ab^{-1}	14 TeV	±9	+28, −24	+20, −19	±18
3 ab^{-1}	27 TeV	±2	+15, −12	+9, −8	+8, −7
15 ab^{-1}	27 TeV	±1			

SUSY Searches Reach



In most of these scenarios HL-LHC will increase present mass reach by 20-50% (compared to available Run-II results).

Searches in SUSY using b-tagging:
Gluions
Stop
Chargino/Neutralino

★ current exclusion limit

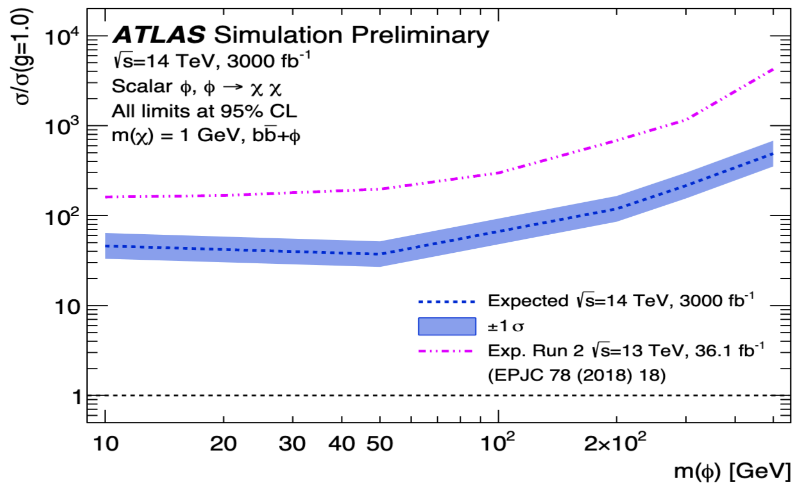
Dark Matter and Heavy Flavour

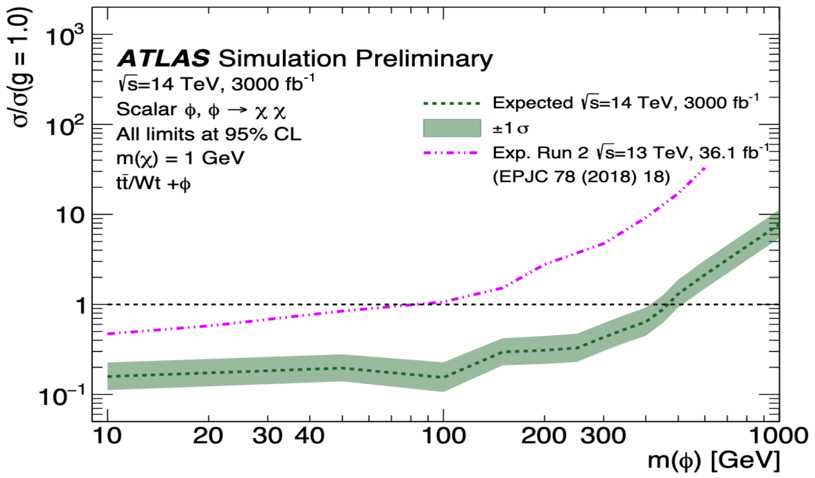
DM Simplified model with scalar/pseudo scalar mediators: DM+tt, DM+Wt, DM+bb

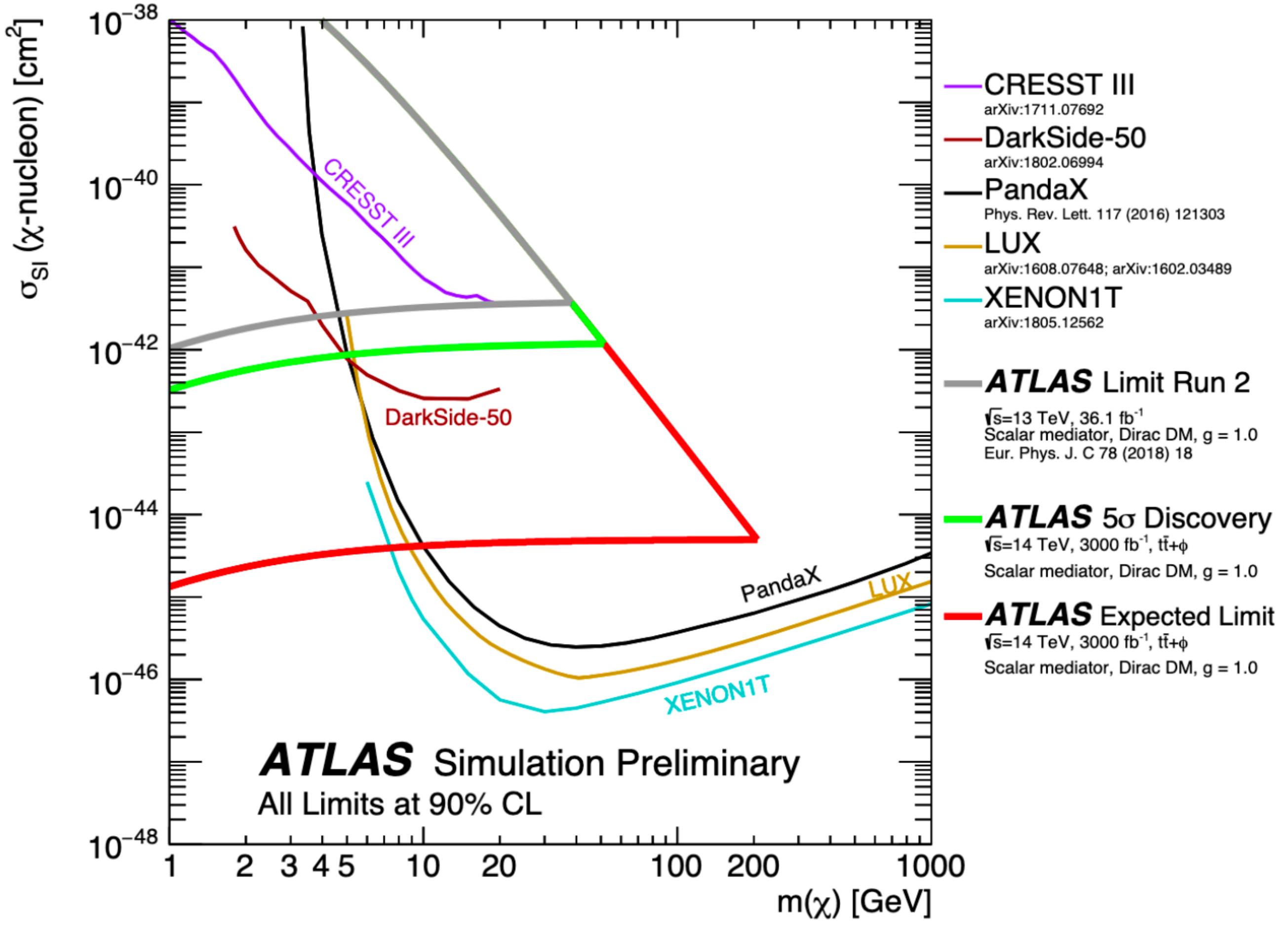
For Scalar/pseudoscalar+bb:

the exclusion potential at the HL-LHC is found to improve by a factor of ~3−9 with respect to Run-II

Results are converted into spin-independent DM-nucleon Scattering cross section to compare with the Direct detection experiments







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
  - Detection of rare processes “4 tops”
  - Enhanced reach for BSM physics
- There is scope to improve further:
  - Alternative methods for $HH \to bbWW(\to l\nu l\nu)$ and $HH \to bb\gamma\gamma$ to increase the significance
  - Indirect probes using Single Higgs in ttH
  - Improving the reconstruction algorithms of objects
  - ……..
  - ……..
  - Many more

Thanks

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

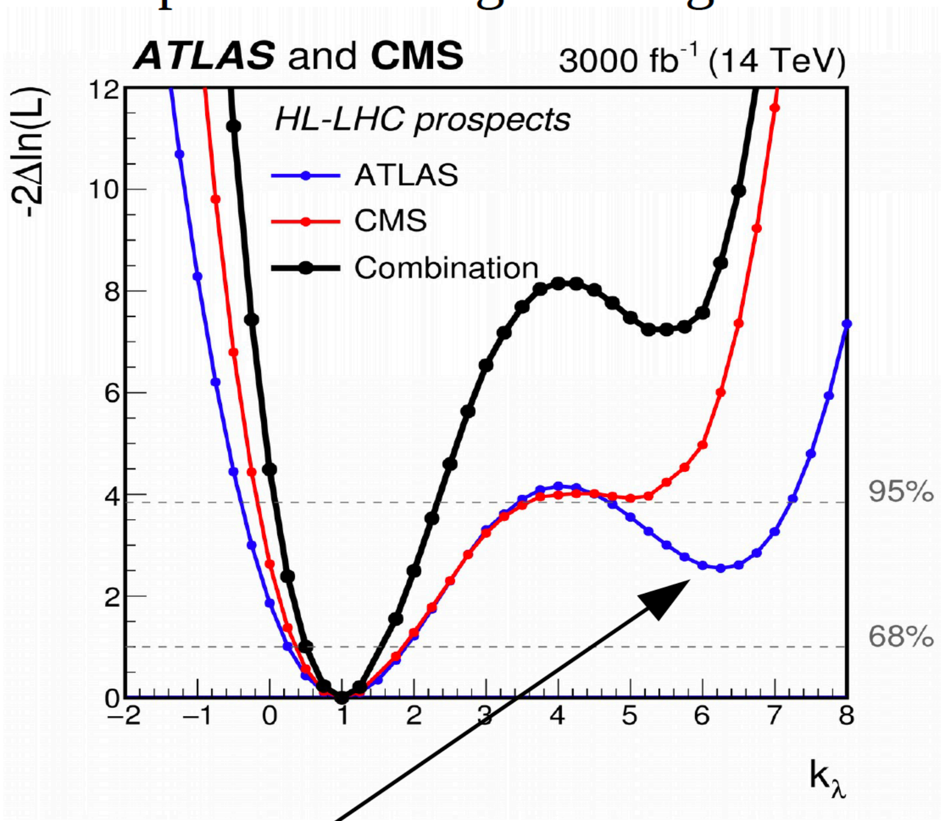
CMS

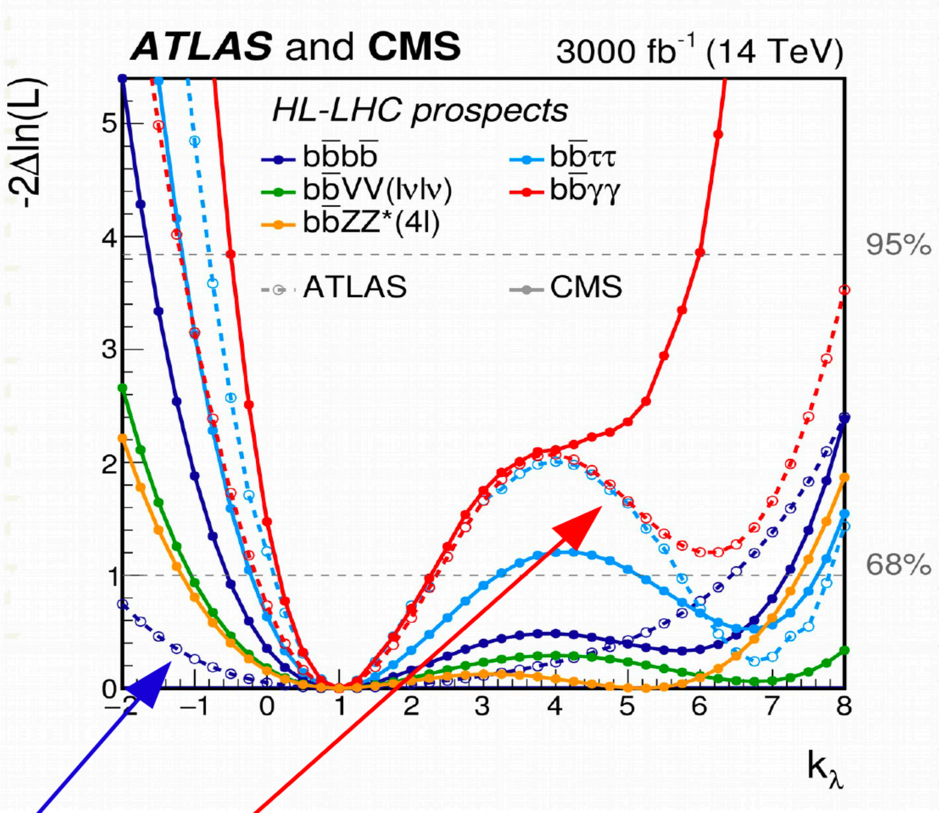
$\mathcal{B}_{BSM} = 0$				$\mathcal{B}_{BSM} > 0,\ \lvert\kappa_V\rvert < 1$			
		Uncertainty				Uncertainty	
Parameter	Best fit	stat	syst	Parameter	Best fit	stat	syst
κ_Z	$1.00\,^{+0.11}_{-0.11}\ \left(^{+0.11}_{-0.11}\right)$	$^{+0.09}_{-0.09}\ \left(^{+0.09}_{-0.09}\right)$	$^{+0.06}_{-0.07}\ \left(^{+0.06}_{-0.06}\right)$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

arXiv:1809.10733

Combined results (ATLAS+CMS)

- Comparison of negative log-likelihood ratios:





- Difference on 2nd minimum mainly from the $b\bar{b}\gamma\gamma$ 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: $b\bar{b}b\bar{b}$ + other smaller channels