CMS Higgs measurements at HL-LHC

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on behalf of the CMS Collaboration

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Main HIG results & sensitivity with LHC in Federica's talk

HL-LHC POTENTIAL in the HIGGS SECTOR

The availability of huge data samples at HL-LHC will enable accurate measurements and unprecedented sensitivity to rare phenomena:

what can we do with the Higgs boson?

2026-2036

$\mathcal{L}$ = 5-7.5x10^{34} cm^{-2}s^{-1}

L = 3000 fb^{-1}

PU 200

Precision measurements of H properties

Rare production and decay modes

HIGGS @ HL-LHC

Di-Higgs production

BSM Higgs searches

PHASE 2 UPGRADE

OUTLINE

Yellow Report 2018
reapprised estimate of the potential of HL-LHC

HIGGS @ HL-LHC

INTRODUCTION
systematics assumptions

Probing
SIGNAL STRENGTHS

Probing
COUPLING MODIFIERS

HIGGS DIFFERENTIAL CROSS SECTION
measurements

Probing
HIGGS SELF-COUPLING

HIGGS WIDTH

INTRODUCTION: systematics assumptions

- Challenging to predict the expected systematic uncertainties at the end of HL-LHC
- Limiting factor in several analyses
- Common set of guidelines to treat systematic uncertainties:

Theory (normalization & modeling): halved

MC statistics: neglected

Data statistics: reduced by a factor $1/\sqrt{L}$

Detector limitations: unchanged or revised from TDR studies

Uncertainties on **methods**: as latest published results

Luminosity: 1%

Experimental uncertainties
scaled down with $\sqrt{L}$ until a lower threshold

Baseline scenario defined as YR18 (S2)

compared with

Run 2 systematic uncertainties scenario (S1)

(event yields scale with luminosity and systematics uncertainties are unchanged w.r.t. Run 2)

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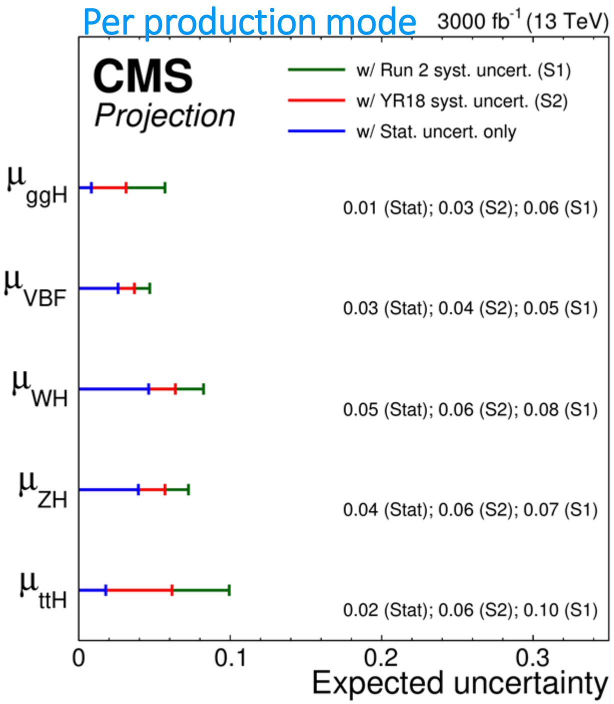
PROBING SIGNAL STRENGTHS

κ-framework description in backup

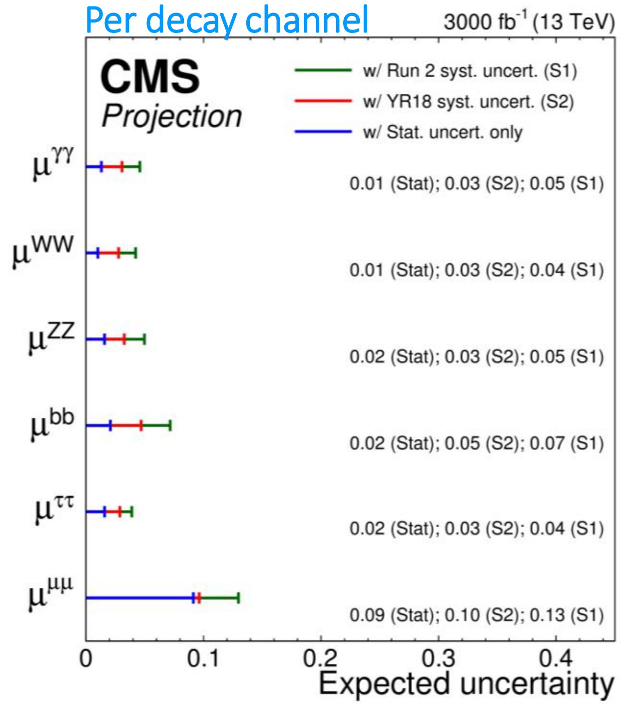
All main production modes and decay channels are included in the study
(**extrapolation** of results obtained with the 2015-2016 datasets = 36 fb^{-1} to 3000 fb^{-1})

- **Run 2**: signal strengths (μ) probed at the level of **12%** in best channels, up to **50%**

Per production mode



Per decay channel



HL-LHC:
percent level

The S2 uncertainties are around 3 - 6% and 3 - 4% per production mode and per decay mode, respectively

- The systematic uncertainty generally dominates in both S1 and S2
- S2 leads to a 30% improvement (reduced theory uncertainties)

CERN-LHCC-2017-009

PROBING SIGNAL STRENGTHS

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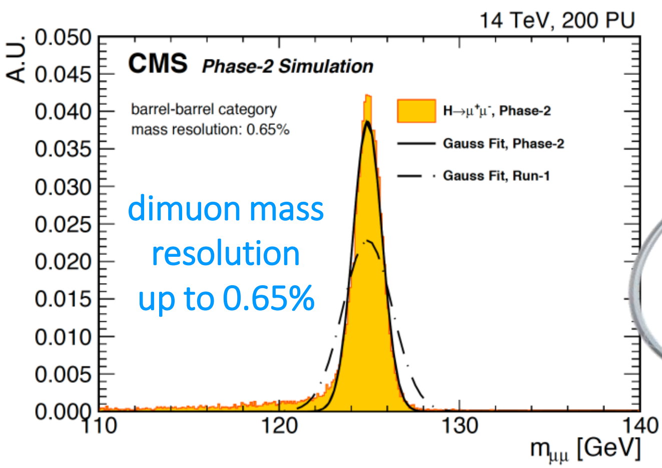
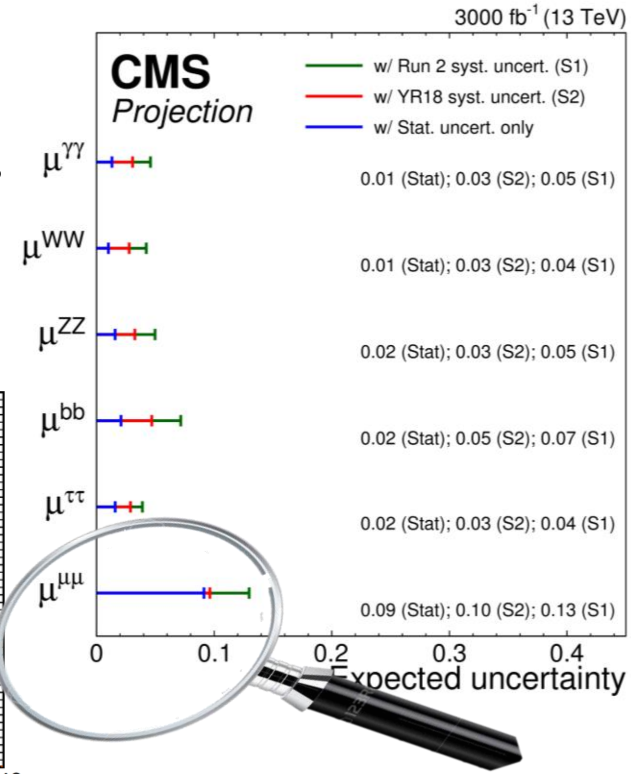
Probe coupling to 2nd generation

- Analysis optimized to have the best sensitivity to a SM Higgs
- Dimuon invariant mass width is reduced in order to match the increase in performances thanks to the tracker upgrade: **40% improvement** in the dimuon mass resolution





HL-LHC:
percent level

Only $\mu^{\mu\mu}$ remains statistically dominated

A precision between 13% (10%) can be achieved accordingly to the S1 (S2) scenario (44% at the end of LHC)

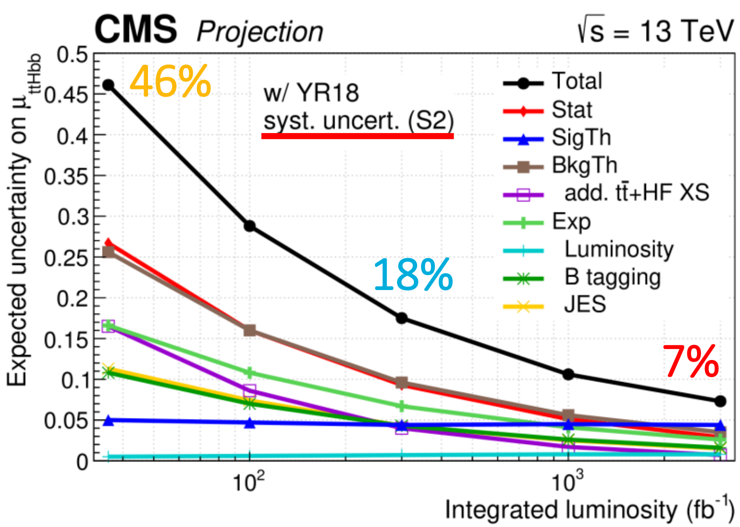
ttH and VH PRODUCTION MODES

Large **impact of the increasing integrated luminosity on the uncertainties** on μ_{ttH} and μ_{VHbb}

ttH

best direct probe of the top-Higgs Yukawa coupling

- Focused on ttH with H → bb



- Significance of 6 σ with 300 fb^{-1} of data in both S1-S2 scenarios!
- Gain related to improved bkg estimation: better constraint on prior uncertainties on the normalization of the tt+HF processes

Run2

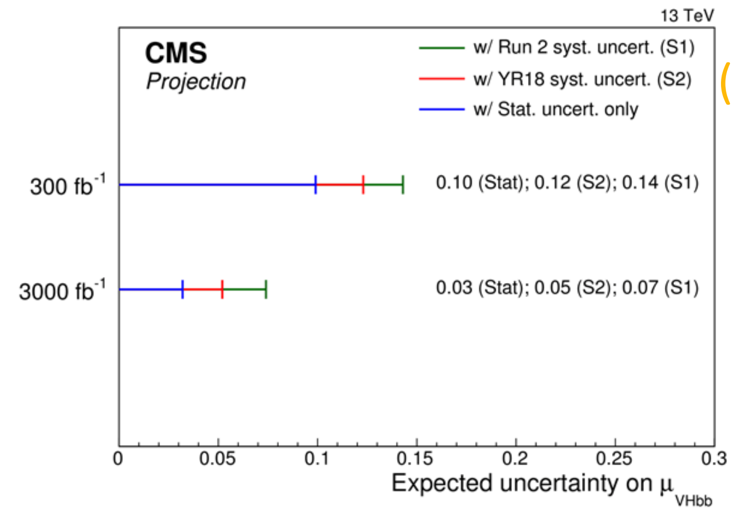
LHC

HL

VH

sensitive to study H → bb decay

- Largest systematic contribution: theory



- Large improvement: modeling of the W boson p_T (lumi scaling)
- Better knowledge of QCD scale variations in signal (gluon-induced ZH production) and backgrounds (V + jets)

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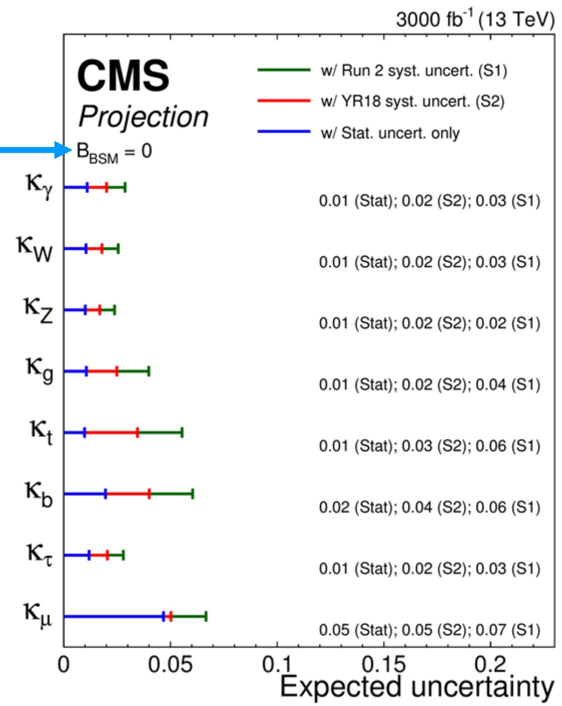
PROBING COUPLING MODIFIERS

κ-framework description in backup

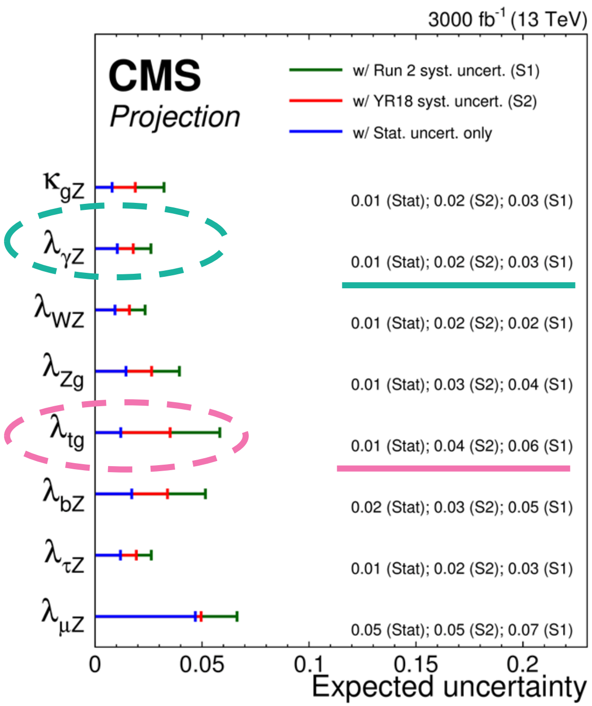
Current **Run 2 measurements (36 fb^{-1}) extrapolated** to 3000 fb^{-1}

- Most couplings known at a precision of 2 - 4%!
- Precision on ratios at percent level
- Signal theory uncertainties dominant in S1, significant in S2 for κ_t and κ_g
- Statistical uncertainties relevant for rare processes

Ratios of coupling modifiers: $\lambda_{ij} = \kappa_i/\kappa_j$, assumptions in Γ_H not needed (Ref: $\kappa_{gZ} = \kappa_g \cdot \kappa_Z/\kappa_H$)



Expected uncertainty on κ

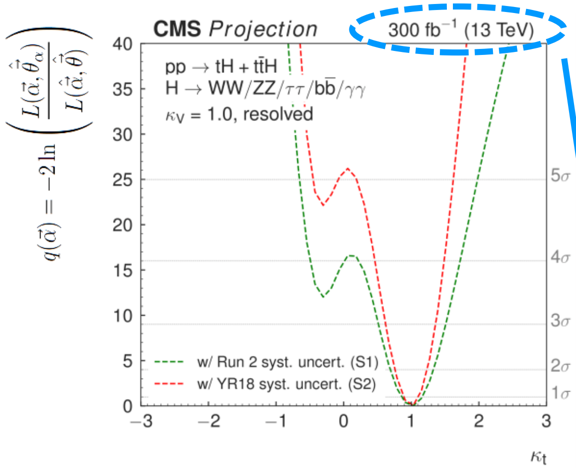


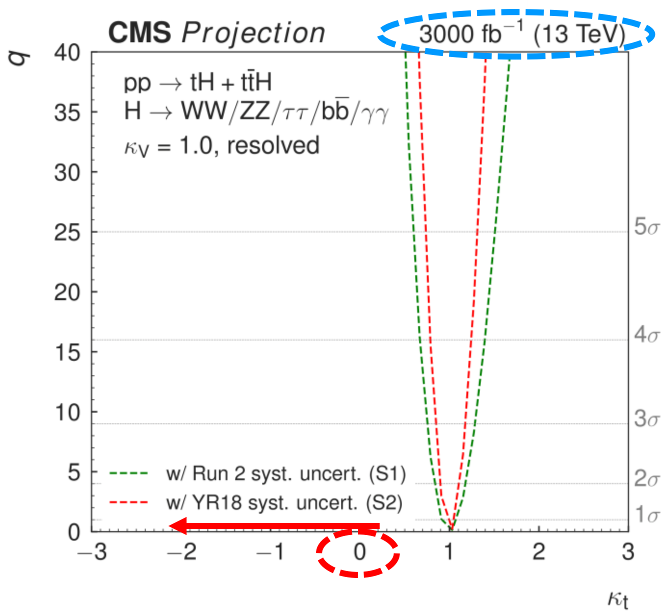
Expected uncertainty on λ

Probe of new physics in $H \to \gamma\gamma$ loop (1.4%)

Probe of new physics in $gg \to H$ (less than 4%)

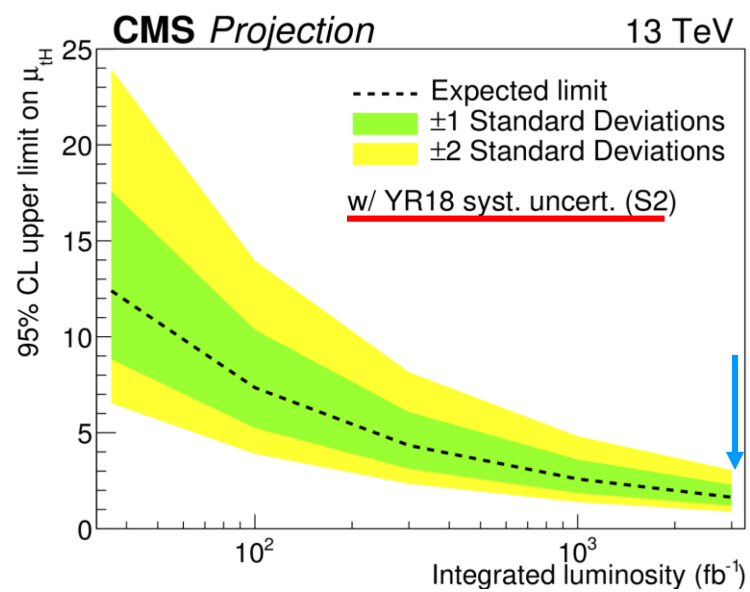
tH PRODUCTION PROCESS





q scan versus κ_t (κ_V = 1)

- Small cross section (**~70 fb**) due to interference between two LO processes including y_t and g_{HVV}
- Sensitive to the relative sign of κ_t and κ_V: it allows to remove the sign ambiguity
- Considered decay modes: H → bb, multilepton, $\gamma\gamma$
- A negative value of κ_t is disfavoured with a significance larger than 5 σ (3000 fb^{-1})

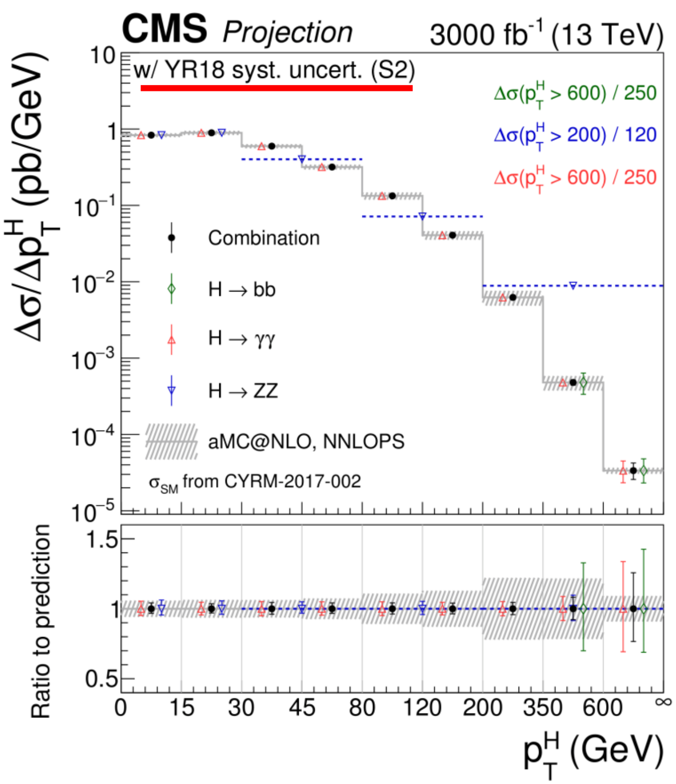


μ_{tH} upper limit at 95% CL (μ_{ttH} = 1)	
S1	2.35
S2	1.51
Run 2	25(12)

Sensitivity on μ_{tH} improves by a factor of 8 w.r.t. Run 2!

HIGGS DIFFERENTIAL CROSS-SECTION…

- The measurement of differential cross sections is the key to:
  - test SM predictions for full spectra of observables of interest
  - probe of BSM effects: sensitivity to new heavy particles in the loop



- p_T^H distribution particularly interesting, as potential new physics may manifest in the tails
- Most precisely measured with 4ℓ + $\gamma\gamma$
- Sensitivity at high p_T improved by boosted H → bb

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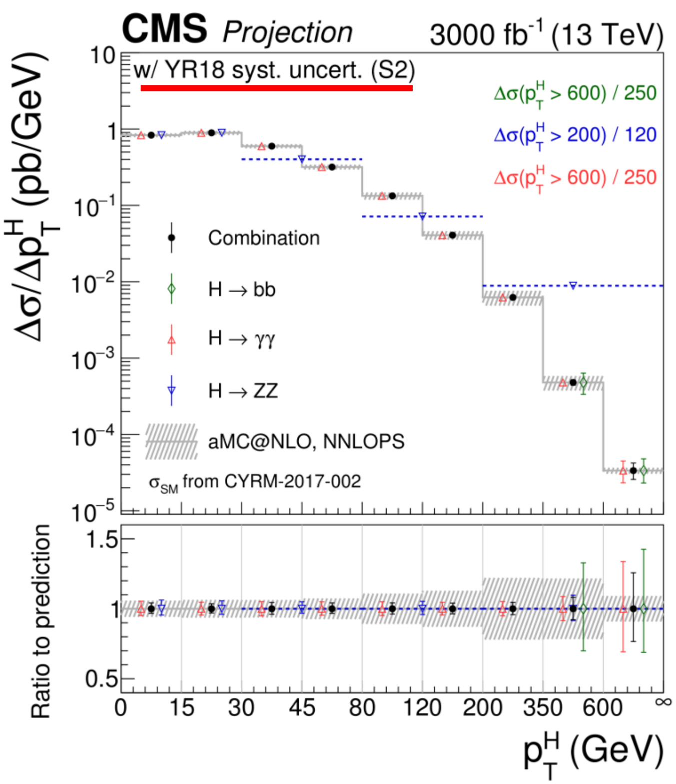

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- Most precisely measured with 4ℓ + $\gamma\gamma$
- Sensitivity at high p_T improved by boosted $H \to bb$

- Probe modeling of ggH up to about p_T^H = 1 TeV, with 8% precision for p_T^H of [350, 600] GeV
- Uncertainties in the high p_T^H region **reduced by a factor 10** (w.r.t. **20 – 30% with full Run2** dataset)
- The reduced systematics in S2 yield to a reduction up to 25% compared to S1

p_T^H [GeV]	0-10	10-15	15-20	20-30	30-45	45-80	80-120	120-200	200-350	350-600	600-∞
Combination	3.7%		3.3%		4.2%	3.7%	4.0%	3.8%	4.4%	8.0%	24.5%

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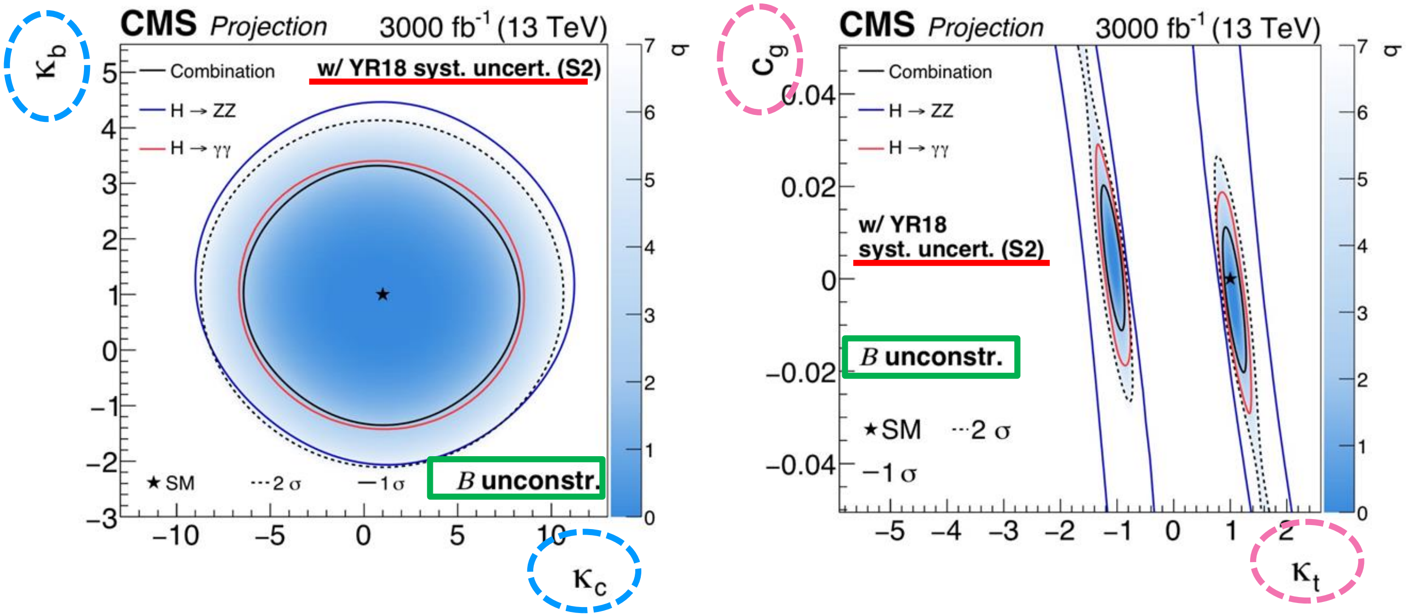
...AND CONSTRAINTS ON COUPLINGS

Results with fixed $\mathcal{B}$ in backup

- Possibility to constrain coupling modifiers fitting theoretical predictions for p_T^H to data
- Results are dependent on the assumptions on $\mathcal{B}$ under coupling variation

Assuming $\mathcal{B}$ freely floating: nuisance parameters with no prior constraint



No sensitivity to the κ_t sign

Sensitivity to κ_b/κ_c at low p_T and κ_t/c_g BSM at high p_T

- κ-framework: Yukawa coupling to b, c
- Run 2 resulting 95% CL intervals:
  $-33 < \kappa_c < 38$ & $-8.5 < \kappa_b < 18$

- EFT-based parametrization: effective coupling to g
- Heavy top mass limit ($\kappa_t = 0$, $c_g \approx 1/12$) distinguished from the point-like coupling to the gluon field

[CMS-PAS-FTR-18-020](CMS-PAS-FTR-18-020)

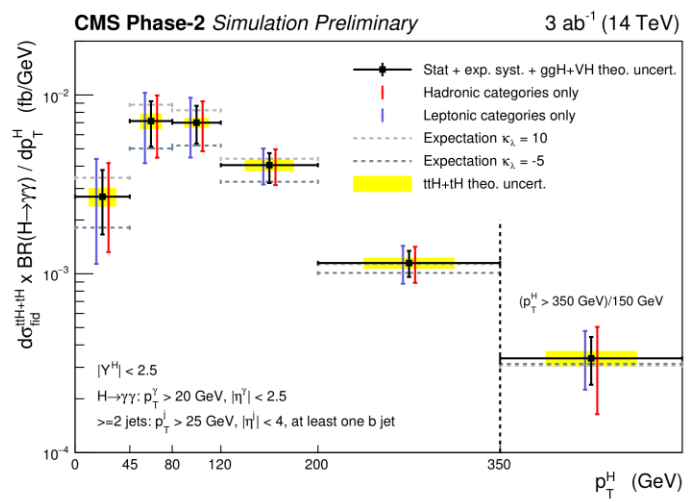
PROBING HIGGS SELF-COUPLING

HH results in Chiara's talk & backup

Constraints on the Higgs self-coupling via single-Higgs differential measurements:

ttH + tH (H → $\gamma\gamma$)

- At NLO Higgs boson production modes include contributions involving λ_{HHH}
- κ_λ-dependent radiative corrections modify external Higgs boson kinematics and single-Higgs production rates → ttH most sensitive
- Complementary limit to the stronger constraint from direct di-Higgs production

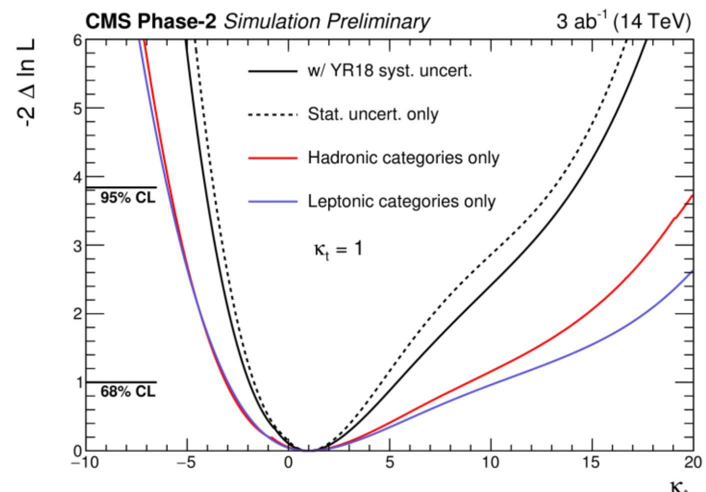


- **Delphes simulation**: CMS Phase-2 @ HL-LHC
- Both hadronic and leptonic decay channels
- Bin chosen to maximize sensitivity to κ_λ
- Uncertainty on differential cross section: 20-40%

Assuming all other Higgs couplings fixed to SM predictions:

$-1.9 < \kappa_\lambda < 5.3$ [68% CL]

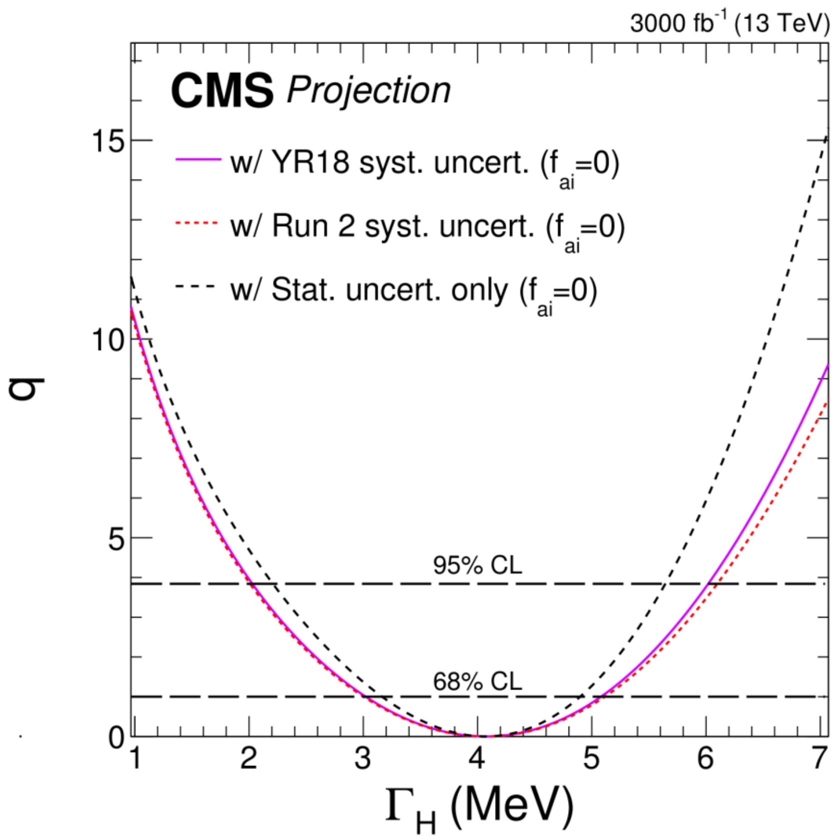
$-4.1 < \kappa_\lambda < 14.1$ [95% CL]



HIGGS WIDTH

The total decay width contains information about the Higgs interactions with all the fundamental particles (predictable both in the SM and its extensions)

- The SM Higgs boson width is ~4 MeV: direct measurement challenging also with HL-LHC statistics (limited by detector resolution)



Three approaches explored for HL

- Diphoton interference studies: weak constraints (~ 8-22 times SM) => only from ATLAS
- Fits in the κ-framework: 5% precision on Γ_H at 95% CL (theoretical constraints: $\kappa_V < 1$ and $B_{UNT} = 0$)
- Derive Γ_H using HZZ on-shell and off-shell production

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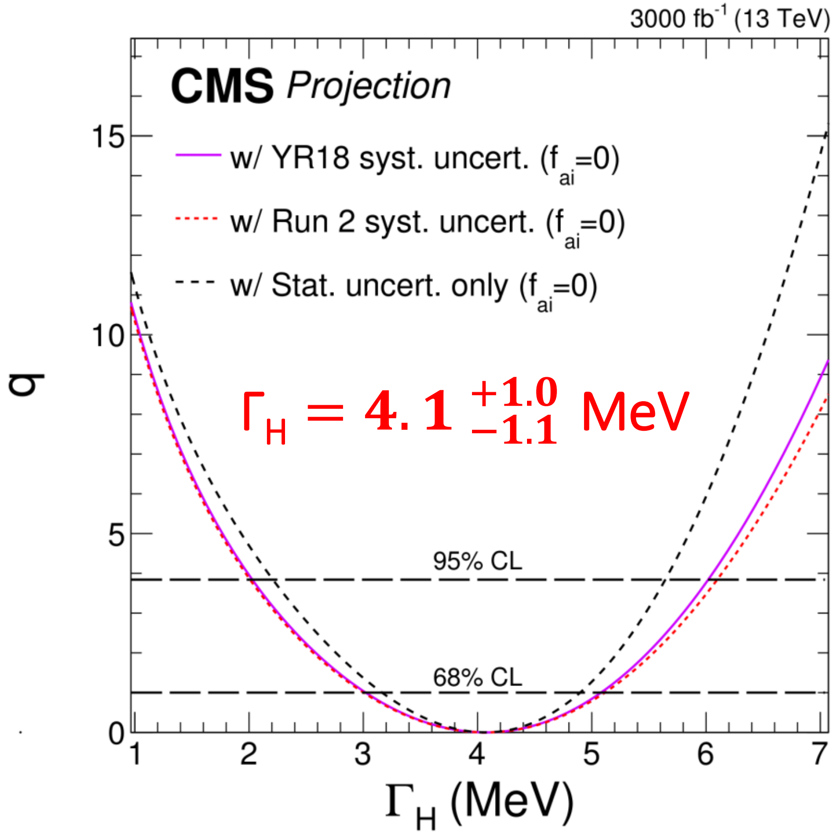

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- Derive Γ_H using HZZ on-shell and off-shell production

- Model-dependent assumptions on κ: same on-shell and off-shell couplings
- Important to control potential BSM effects through complementary measurements

→ Values outside [2,6] excluded at 95% CL (S2)!
From Run 2 results: [0.08, 9.16]

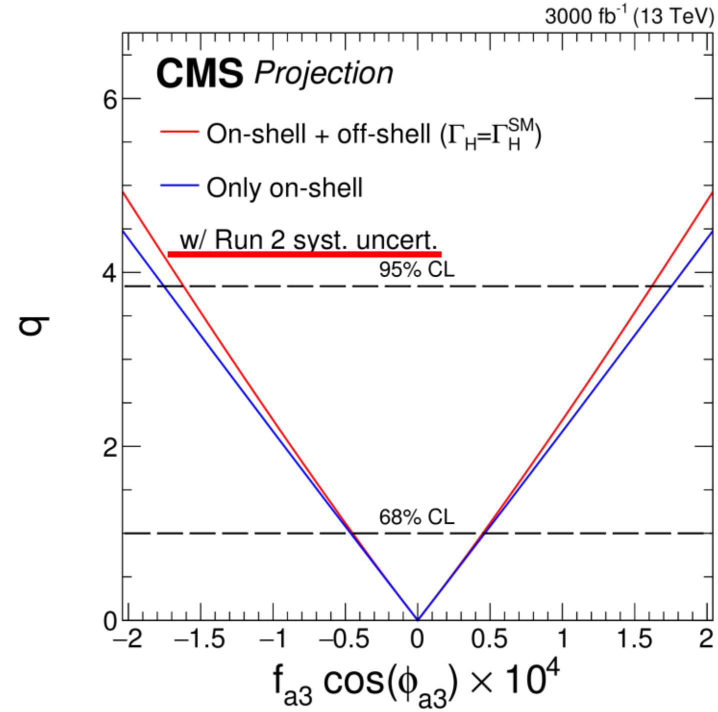
ANOMALOUS HZZ COUPLINGS

Reference (theory)

Tensor structure of HVV couplings can be probed using anomalous coupling a_3 in the $H \rightarrow ZZ^* \rightarrow 4\ell$ decay

- Anomalous contributions in the spin-0 tensor structure of HVV interactions characterized by coefficients a_2, a_3, Λ_1, Λ_Q
- Contribution to the total cross section parametrized in terms of the fractions f_{ai} and phases ϕ_{ai}

- Only tensor structure proportional to a_3 considered (both on-shell and off-shell method)
- Enhancement of off-shell signal production expected in the presence of either anomalous HVV couplings or larger Γ_H

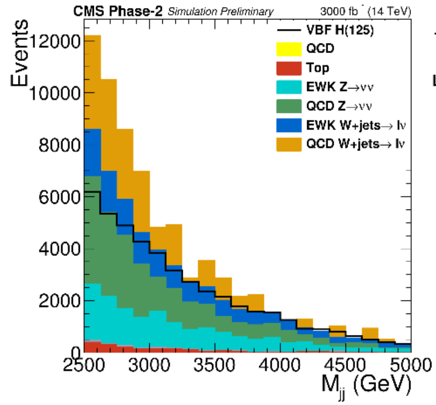


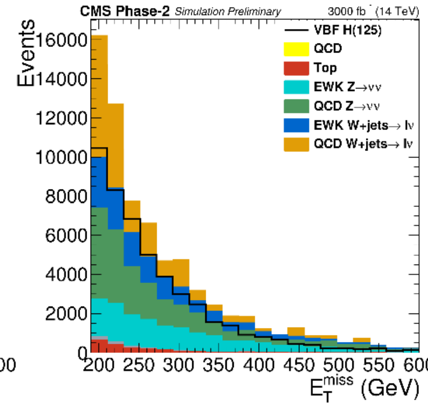
Parameter	Scenario	95% CL interval	Run 2
$f_{a3}\cos(\phi_{a3})$	Only on-shell	[-1.8, 1.8] x 10^{-4}	[-0.163, 0.090]
$f_{a3}\cos(\phi_{a3})$	On-shell and off-shell	[-1.6, 1.6] x 10^{-4}	[-0.0067, 0.0050]

HIGGS INVISIBLE WIDTH

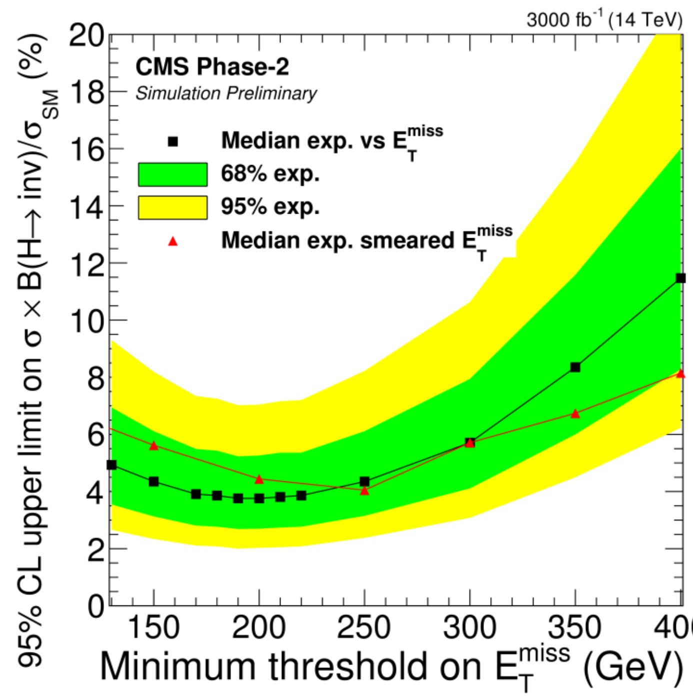
- **Connection** between **Higgs and Dark Matter**: in SM Higgs is predicted to have a very small B to invisible particles:

  0.1% from H → 4ν decays
- Sensitivity dominated by the VBF channel





- Search for Higgs decaying invisibly @ 14 TeV (VBF channel)
  - **Delphes simulation**: CMS Phase-2 @ HL-LHC
  - Analysis re-optimized for HL conditions (PU 200): minimum thresholds of 2500 GeV (190 GeV) on the dijet mass (E_T^{miss})
  - Systematics dominated
  - No significant impact of E_T^{miss} degradation



Assuming SM production:

B_{INV} < 3.8% at 95% CL

w.r.t. ~20% @ 95% CL from Run 2 results

CONCLUSIONS

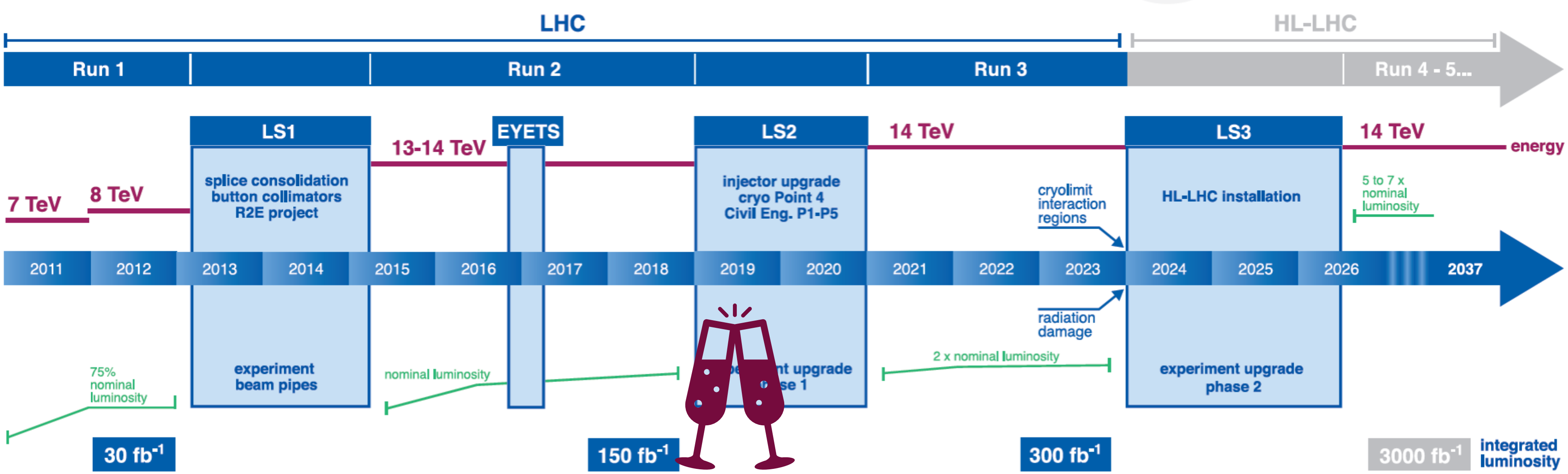
- Most of the measurements of the Higgs properties well established in Run 2 analyses
- HL-LHC: first Higgs factory
  - The determination of Higgs properties is a primary target of HL-LHC physics measurements
  - Unprecedented opportunities with the HL-LHC datasets
- Projections on a large variety of Higgs measurements at HL-LHC presented
  - Percent level precision on most Higgs couplings
  - Width measurable to within 1 MeV
  - Sensitivity to BSM physics enhanced
- Systematic uncertainties dominant (large effect of theoretical uncertainties even in S2)
  - Great effort from theoretical and experimental side needed

A very broad program of Higgs boson physics is ahead of us!

THANK YOU!

BACK UP

LHC/HL-LHC PLANS



Starting in **2026**, LHC will operate in the high luminosity mode (HL-LHC) for about ten years:

- Instantaneous luminosity ~ 5-7.5 x 10^{34} $cm^{-2}s^{-1}$
- Until 200 pileup events
- About 300 fb^{-1} per year → 3000 fb^{-1} by **2036**

- Higgs factory: HL-LHC will produce ~150M Higgs

κ-framework

2

Results given for a parametrization based on the coupling strength modifiers, the so-called

κ-framework

- Extensively used characterization of Higgs coupling properties in terms of individual coupling modifiers, corresponding to tree-level Higgs boson couplings to each particle (κ_W, κ_Z, κ_t, κ_b, κ_c, κ_τ, κ_μ), and three additional effective coupling modifiers (κ_g, κ_γ, $\kappa_{Z\gamma}$):

$$\boxed{\mu_i^f \equiv \frac{\sigma_i \cdot B_f}{\sigma_i^{SM} \cdot B_f^{SM}} = \frac{\kappa_i^2 \cdot \kappa_f^2}{\kappa_H^2}}$$

where

$$\boxed{\kappa_\mathrm{i}^2 = \frac{\sigma_\mathrm{i}}{\sigma_\mathrm{i}^\mathrm{SM}} \quad \text{or} \quad \kappa_\mathrm{i}^2 = \frac{\Gamma_\mathrm{i}}{\Gamma_\mathrm{i}^\mathrm{SM}}}$$

- Simple way to parametrize potential deviations in the couplings of the Higgs to bosons and fermions according to the SM predictions

- The κ-framework can be generalized to incorporate a BSM width (invisible and untagged decays):

$$\boxed{\Gamma_\mathrm{H} = \frac{\kappa_\mathrm{H}^2 . \Gamma_\mathrm{H}^\mathrm{SM}}{1 - \mathrm{B}_\mathrm{BSM}} \quad \text{where} \quad \kappa_\mathrm{H}^2 = \sum_\mathrm{j} \mathrm{B}_\mathrm{SM}^\mathrm{j} \kappa_\mathrm{j}^2}$$

SYSTEMATIC UNCERTAINTIES ASSUMPTIONS

3

COMMON GUIDING PRINCIPLES FOR YR18:

- **Statistics-driven sources**: data → √L, simulation → 0 account for larger data sample statistics available to better understand full potential of HL-LHC
- **MC statistics:** neglected
- **Theoretical uncertainties** typically halved applies to both normalization (cross section) and modeling due to higher-order calculation and PDF improvements

- **Uncertainties on methods** kept as latest published results
- **Intrinsic detector limitations** left unchanged, or revised using full simulation tools for detailed analysis of expected performance (large effort for TDR preparation)
- **Trigger thresholds** for common objects are expected to remain similar to the current ones or to even decrease (assumption that pileup effects are compensated by detector upgrades improvement and algorithmic developments)

- **Integrated luminosity**: 1% (better understanding of calibration methods, new capabilities of the upgraded detectors.)

SYSTEMATIC UNCERTAINTIES ASSUMPTIONS

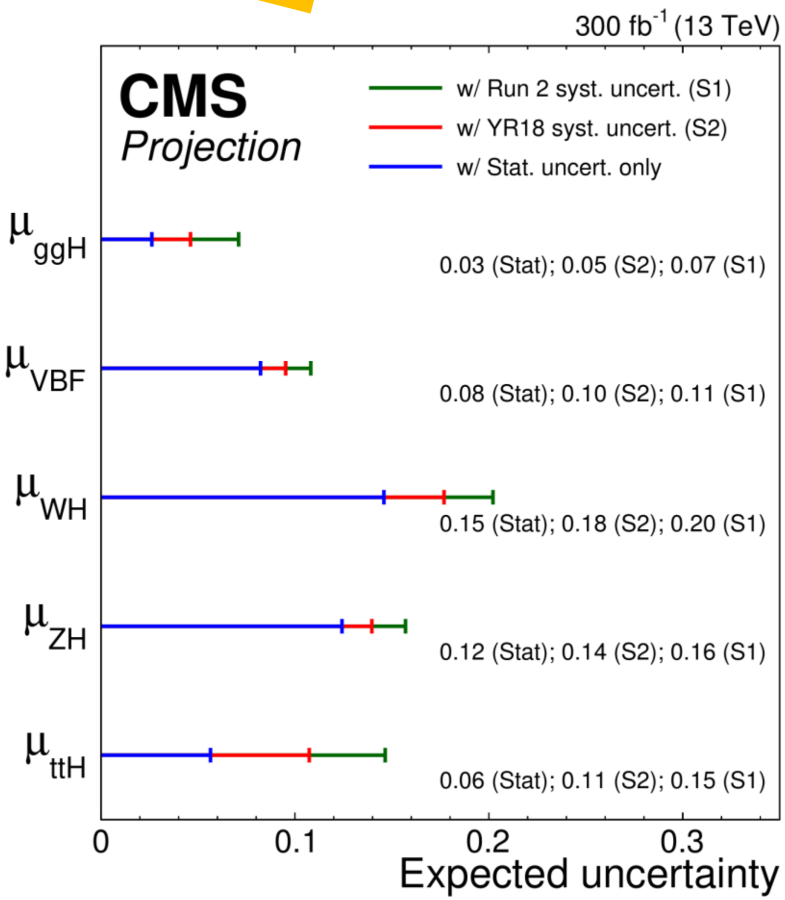
SOURCES of SYSTEMATIC UNCERTAINTY for which minimum values are applied in S2:

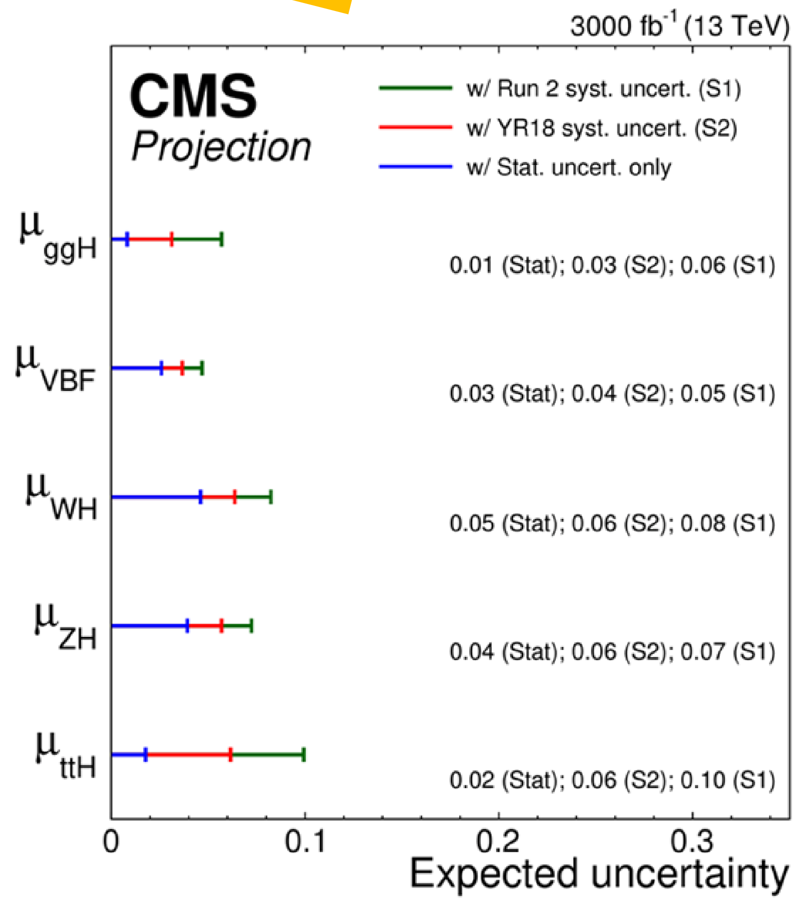
Source	Component	Run 2 uncertainty	Projection minimum uncertainty
Muon ID		1–2%	0.5%
Electron ID		1–2%	0.5%
Photon ID		0.5–2%	0.25–1%
Hadronic tau ID		6%	2.5%
Jet energy scale	Absolute	0.5%	0.1–0.2%
	Relative	0.1–3%	0.1–0.5%
	Pileup	0–2%	Same as Run 2
	Method and sample	0.5–5%	No limit
	Jet flavour	1.5%	0.75%
	Time stability	0.2%	No limit
Jet energy res.		Varies with p_T and η	Half of Run 2
MET scale		Varies with analysis selection	Half of Run 2
b-Tagging	b-/c-jets (syst.)	Varies with p_T and η	Same as Run 2
	light mis-tag (syst.)	Varies with p_T and η	Same as Run 2
	b-/c-jets (stat.)	Varies with p_T and η	No limit
	light mis-tag (stat.)	Varies with p_T and η	No limit
Integrated lumi.		2.5%	1%

SIGNAL STRENGTHS per production mode

300 fb^{-1}

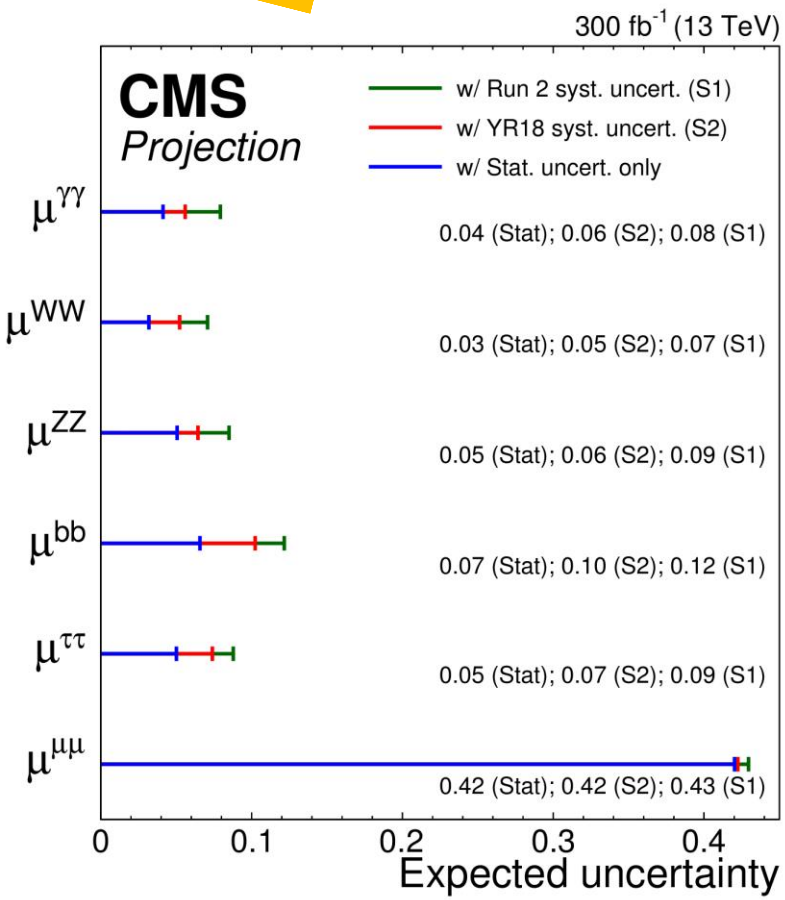
3000 fb^{-1}



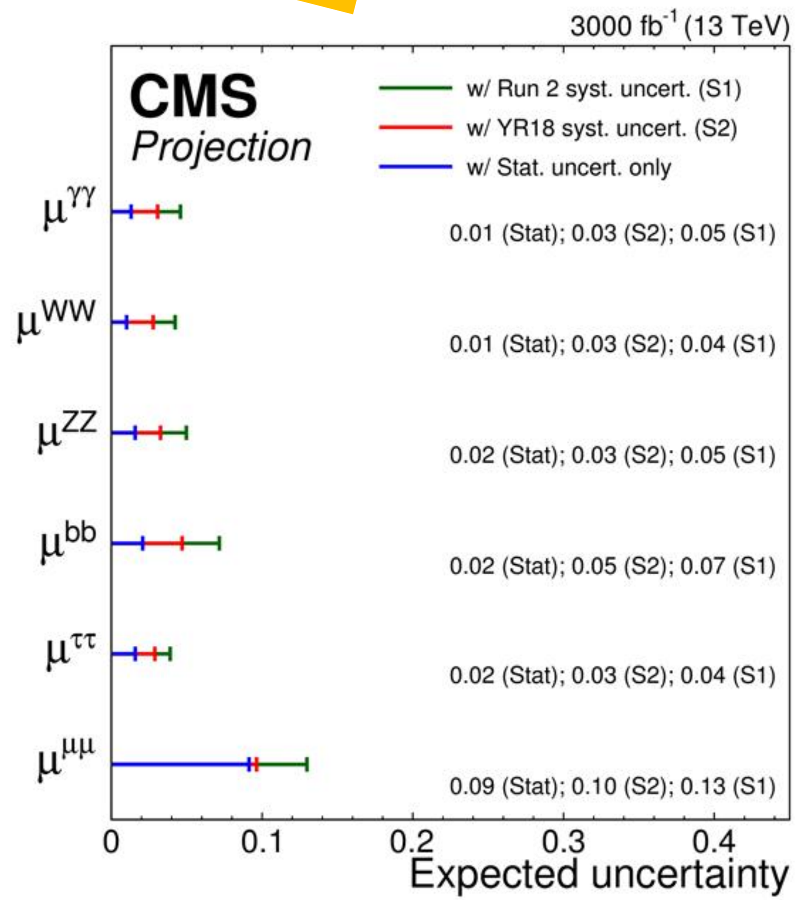


SIGNAL STRENGTHS per decay mode

300 fb^{-1}



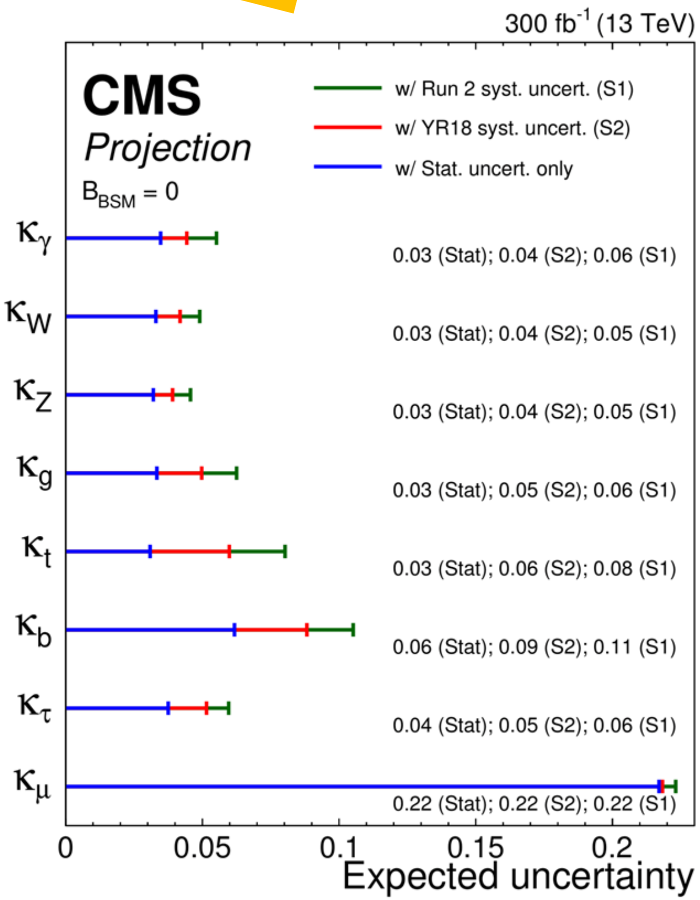
3000 fb^{-1}

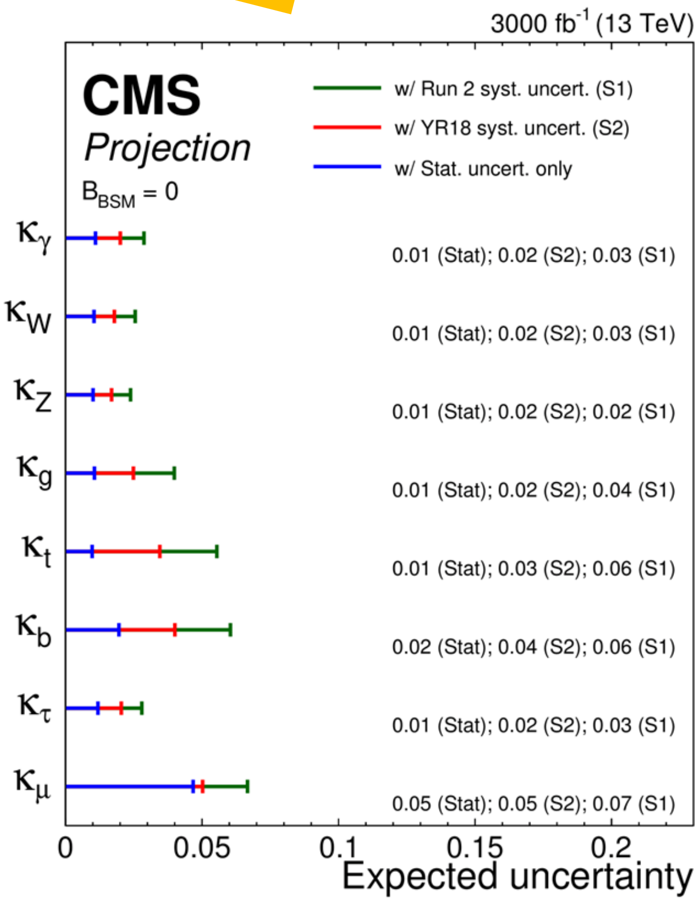


PROBING COUPLING MODIFIERS

300 fb^{-1}

3000 fb^{-1}





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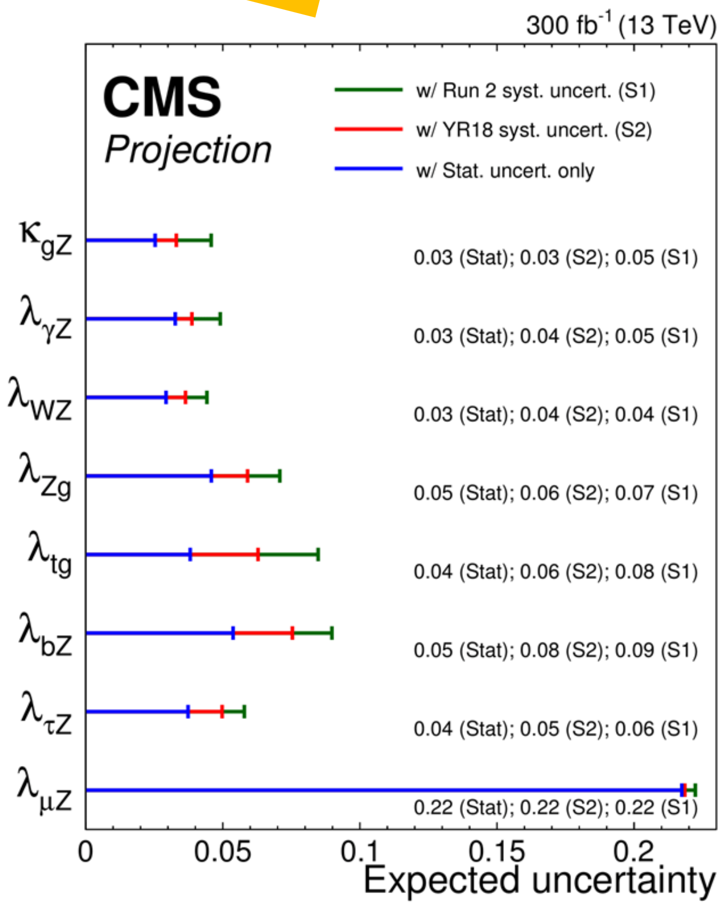

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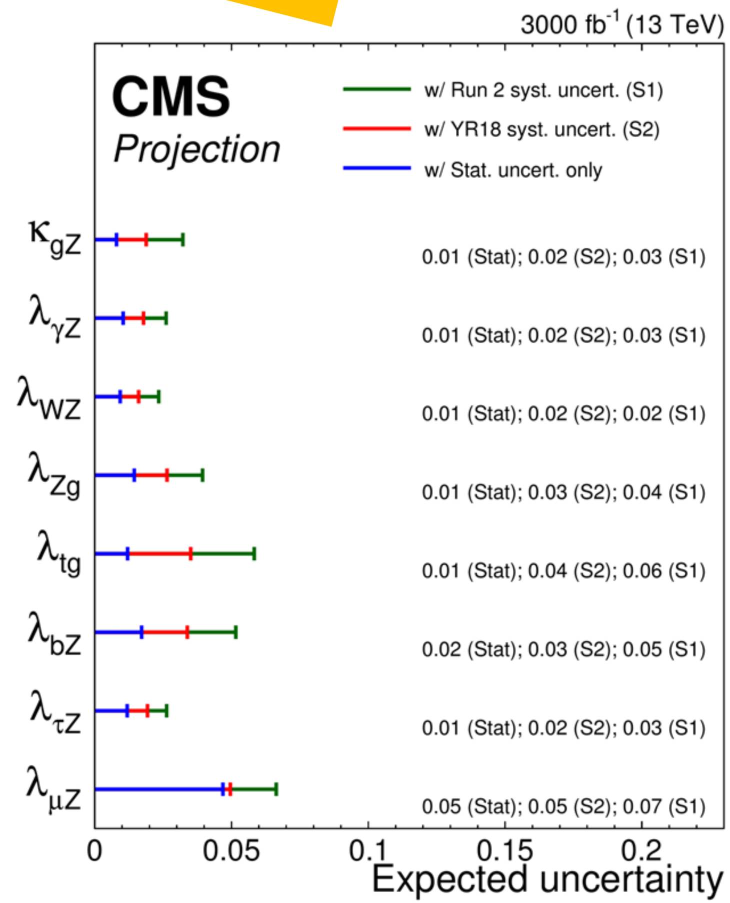

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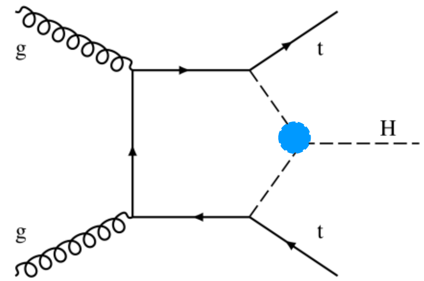
ttH production with H→bb

- H → bb + single- and dilepton decay channel of the tt system
- Dedicated multivariate techniques to discriminate signal vs bkg from tt+jets production (BDT, DNN)
- Background estimated from simulation and separated in five distinct processes (tt+HF): tt+bb, tt+b, tt+2b, tt+cc, tt+LF

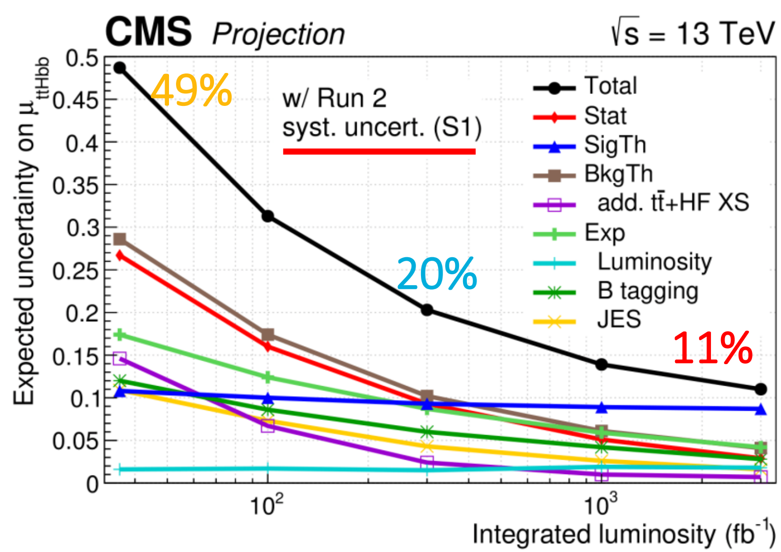


Run 2 result

→ obs (exp) significance at 1.6 σ (2.2 σ)

→ μ = 0.72 ± 0.45

- Background modelling: largest limitation because of theory uncertainties
- Total expected uncertainty given by:
  - Statistical unc. of the fit
  - Theoretical unc. on signal (generation of ttH sample) and bkg (generation of tt sample) + additional 50% tt+HF xsec unc.
  - Experimental uncertainties (lumi, B tagging, JES)



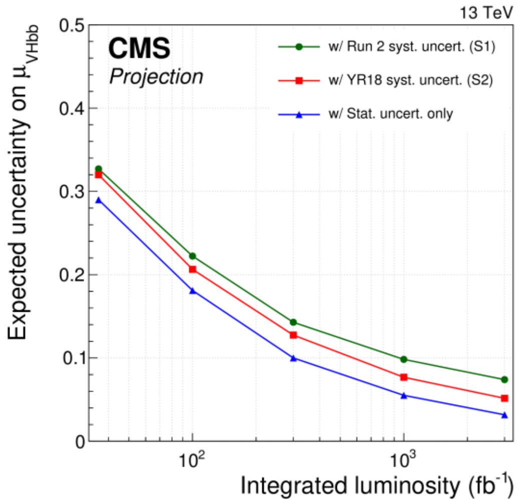
Run2 LHC HL

VH production with H→bb

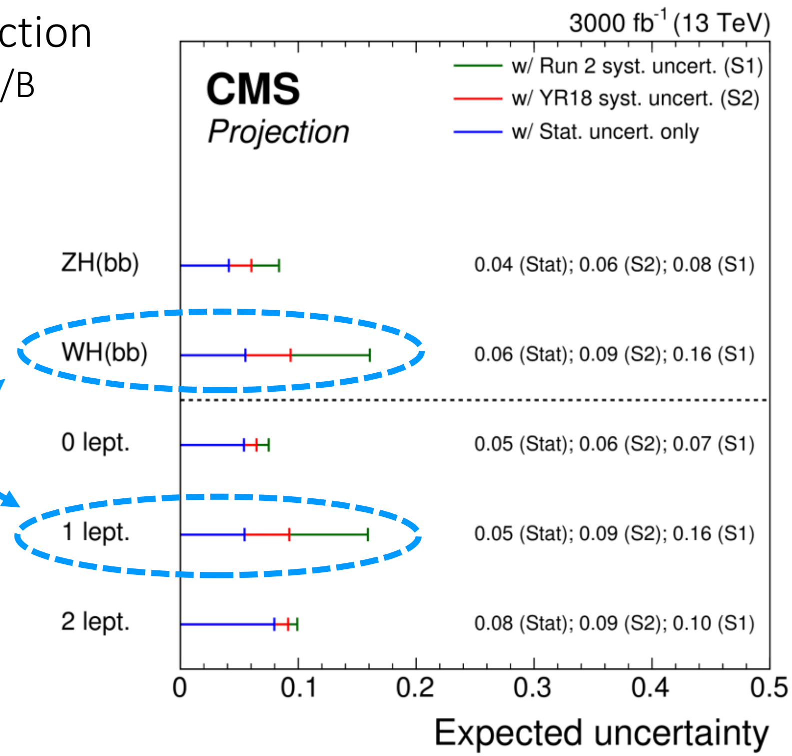
- H → bb + leptonic decays of the vector boson associated to H (0/1/2 lepton categories) to trigger and to reduce the multi-jet background
  - b jets identified using a combined multivariate (CMVA) tagging algorithm with 3 thresholds
  - Multivariate energy regression techniques to improve b jet energy resolution
- Major backgrounds: V + HF/LF jets and tt production
  - dedicated CR to control bkg + BDT to discriminate S/B

Run 2 result

$$\mu_{\mathrm{VHbb}} = 1.19\,^{+0.21}_{-0.20}(stat)\,^{+0.34}_{-0.32}\,(syst)$$



Largest improvement between S1 and S2 in the 1ℓ channel (most sensitive to WH production mode)



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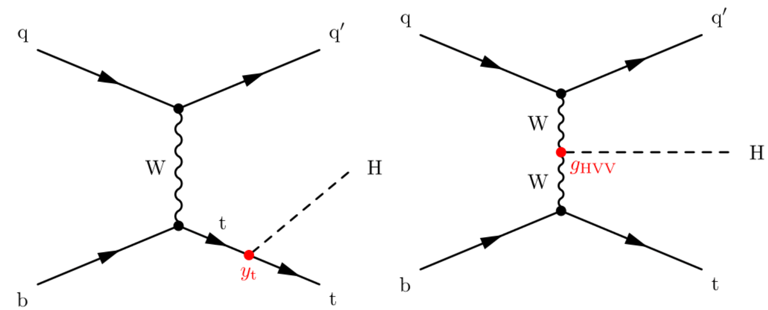
tH PRODUCTION PROCESS

- tHq and tHW: t-channel production of the tHq final state is the dominant one



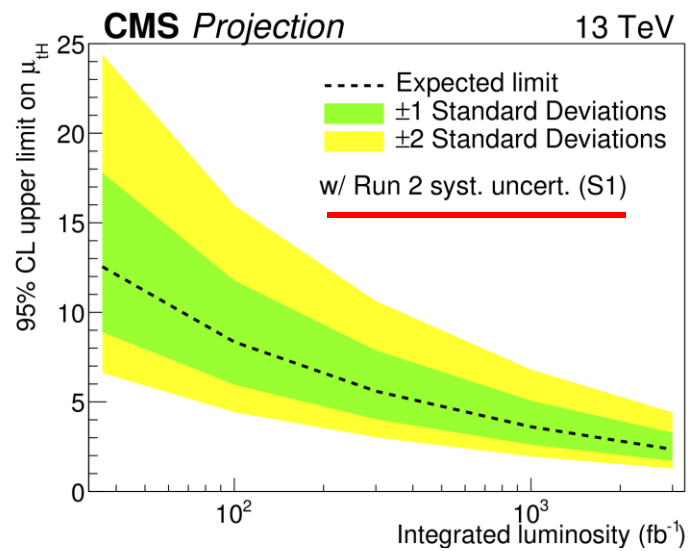
- Combination of Run 2 analyses used in the extrapolation:
  - ➢ $H \rightarrow bb$
  - ➢ Multilepton final state (WW, ZZ, ττ)
  - ➢ Presence of at least one central b tagged jet and an isolated lepton from top required + presence of a light quark jet at high pseudorapidity
  - ➢ MVA techniques to discriminate signal and tt+jets bkg

Run 2 result

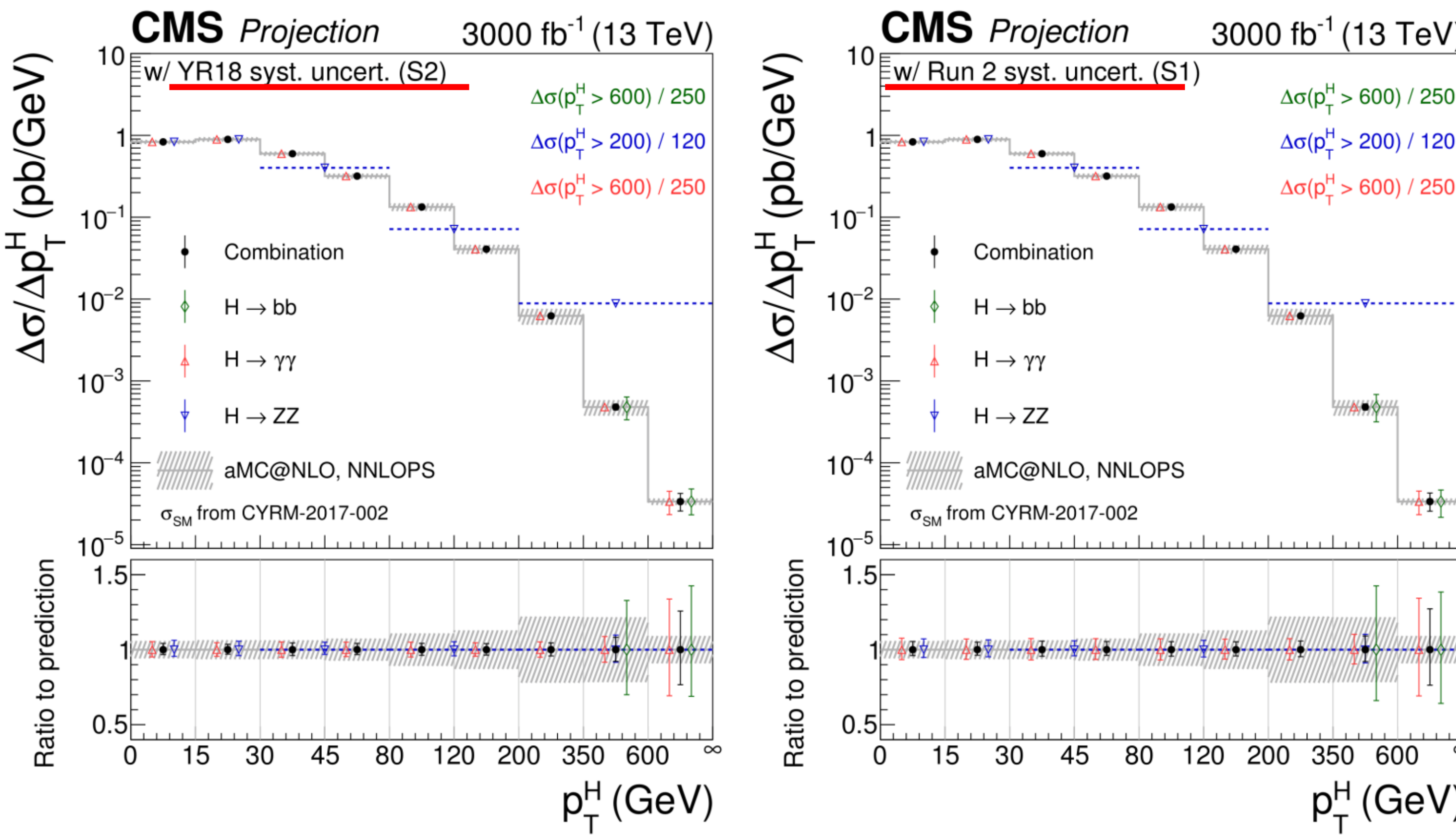
κ_t excluded outside [-0.9, -0.5] and [1.0, 2.1] at 95% CL

- μ_{tH} evaluated considering μ_{ttH} floating and fixed: in case 2, unc. reduced by around 10% at 3000 fb^{-1}

  → precise simultaneous measurement of μ_{ttH} needed to have the optimal sensitivity to the tH channel



HIGGS DIFFERENTIAL CROSS-SECTION…

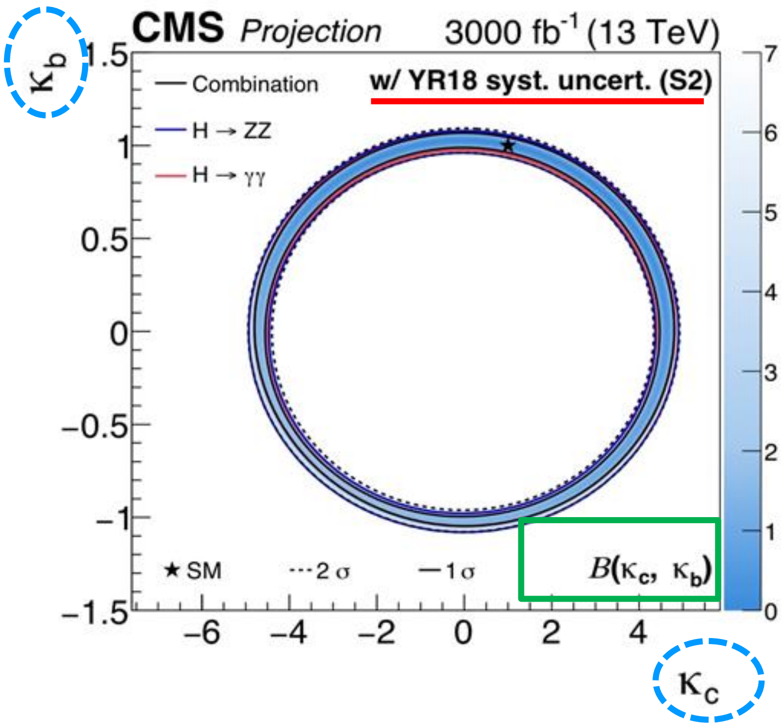


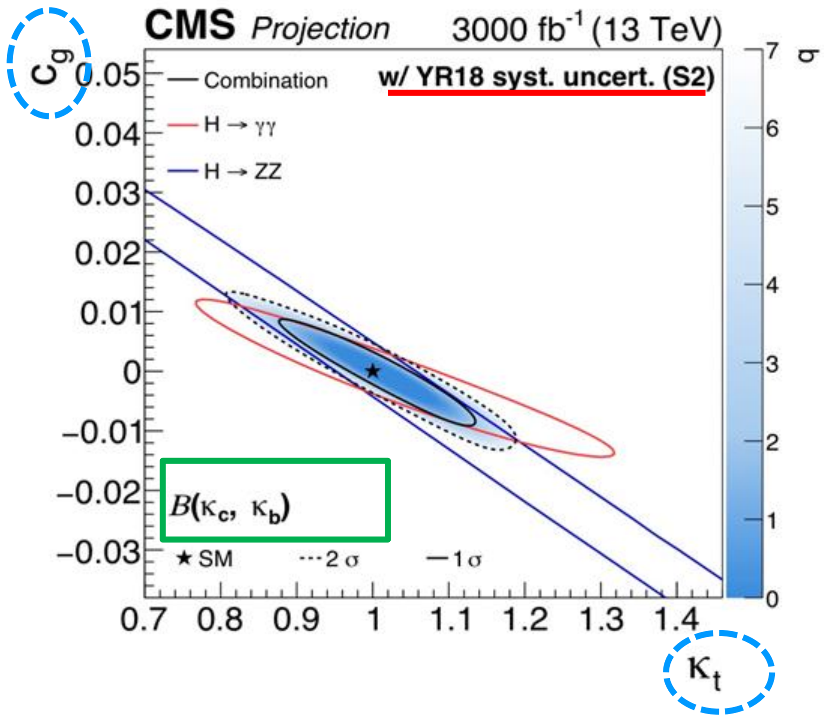
Most precisely measured with 4ℓ + $\gamma\gamma$

Boosted H → bb improves the sensitivity at high p_T

…and CONSTRAINTS ON COUPLINGS

Assuming B scaling with couplings according to SM predictions:





Sensitivity to κ_b/κ_c at low p_T and κ_t/c_g BSM at high p_T

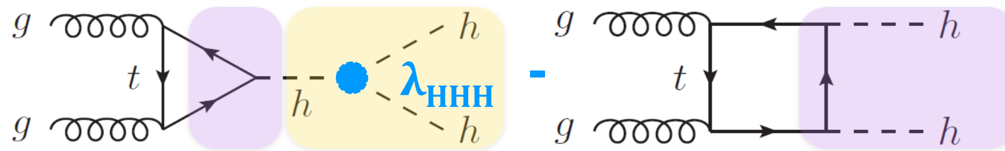
- κ-framework: Yukawa coupling to b, c
- Run 2 resulting 95% CL intervals:
  $-4.9 < \kappa_c < 4.8$ & $-1.1 < \kappa_b < 1.1$

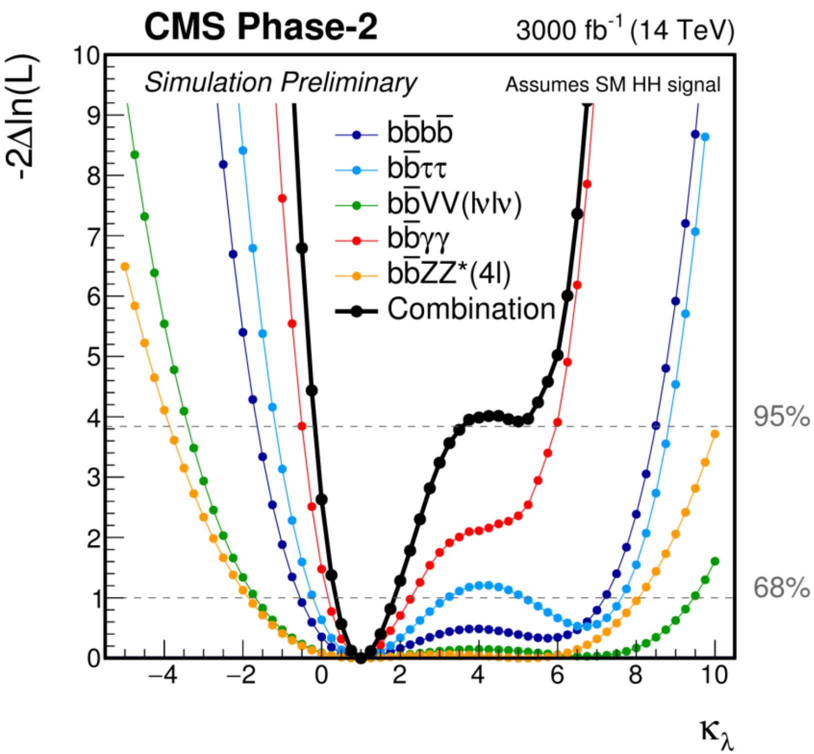
- EFT-based parametrization: effective coupling to g
- Heavy top mass limit, given by $\kappa_t = 0$ and $c_g \approx 1/12$, excluded

PROBING HIGGS SELF-COUPLING

Constraints on the Higgs self-coupling from direct di-Higgs production

- Non-resonant production: rare SM process (**36.69 fb at 14 TeV**)
- Sensitive to BSM effects





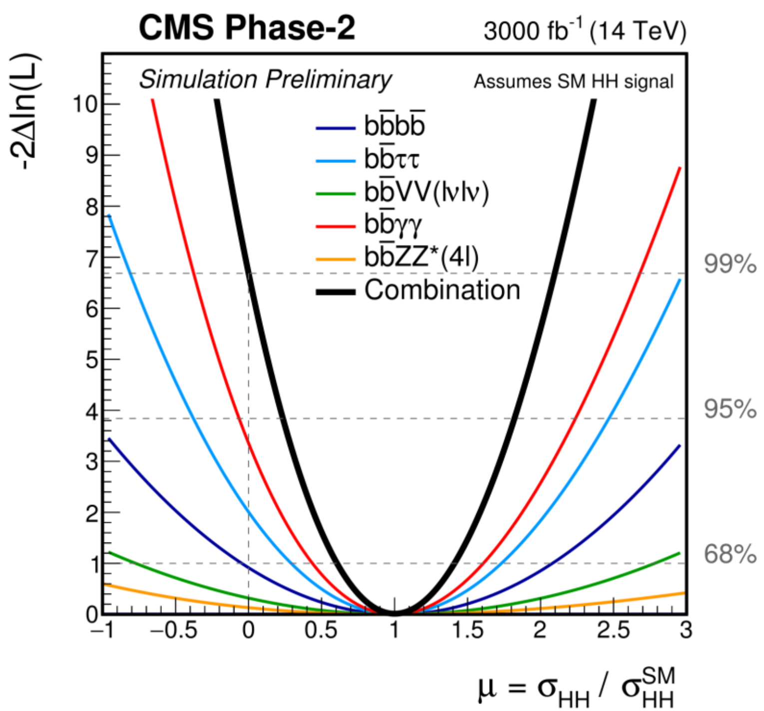
- **Delphes simulation**: CMS Phase-2 @ HL-LHC
- Five considered decay channels:
  bbbb, bbττ, bbγγ, bbVV(ℓνℓν), bbZZ*(4ℓ)
- General analysis strategy: candidate mass consistent with SM Higgs boson, multivariate methods to reject background, use m_{HH} when possible

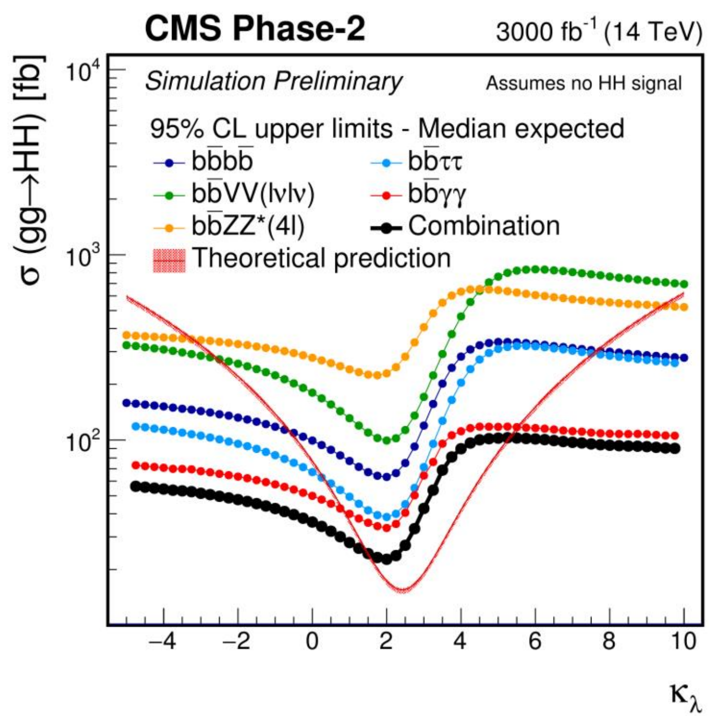
- Evidence for HH expected at 2.6 σ at 3000 fb^{-1}

κ_λ confidence intervals	
68% CL	[0.35, 1.9]
95% CL	[-0.18, 3.6]

CMS-PAS-FTR-18-019

PROBING HIGGS SELF-COUPLING





HH	bbbb	bbττ	bbγγ	bbVV(ℓνℓν)	bbZZ*(4ℓ)	Combination
Significance (σ)	0.95	1.4	1.8	0.56	0.37	2.6
Limit @ 95% CL	2.1	1.4	1.1	3.5	6.6	0.77

ANOMALOUS HVV COUPLINGS

Reference

$$A(HVV) \sim \left[a_1^{VV} + \frac{\kappa_1^{VV} q_{V1}^2 + \kappa_2^{VV} q_{V2}^2}{(\Lambda_1^{VV})^2}\right] m_{V1}^2 \epsilon_{V1}^* \epsilon_{V2}^* + a_2^{VV} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3^{VV} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$

where $f^{(i)\mu\nu} = \epsilon_{Vi}^{\mu} q_{Vi}^{\nu} - \epsilon_{Vi}^{\nu} q_{Vi}^{\mu}$ is the field strength tensor of a gauge boson with momentum q_{Vi} and polarization vector ϵ_{Vi}, $\tilde{f}_{\mu\nu}^{(i)} = \frac{1}{2}\epsilon_{\mu\nu\rho\sigma} f^{(i),\rho\sigma}$ is the dual field strength tensor, the superscript * designates a complex conjugate, m_{V1} is the pole mass of the Z or W vector boson (while the cases with the massless vector bosons are discussed below), and Λ_1 is the scale of BSM physics and is a free parameter of the model.