PROSPECTS FOR HIGGS BOSON MEASUREMENTS AT THE HL-LHC

Nicola De Filippis

Politecnico & INFN, Bari and LPC-FNAL, Batavia

on behalf of the CMS collaboration

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Physics landscape at the end of Run 2

LHC experiments confirm that the SM is robust but it should not be the ultimate theory of particle physics, because of many questions:

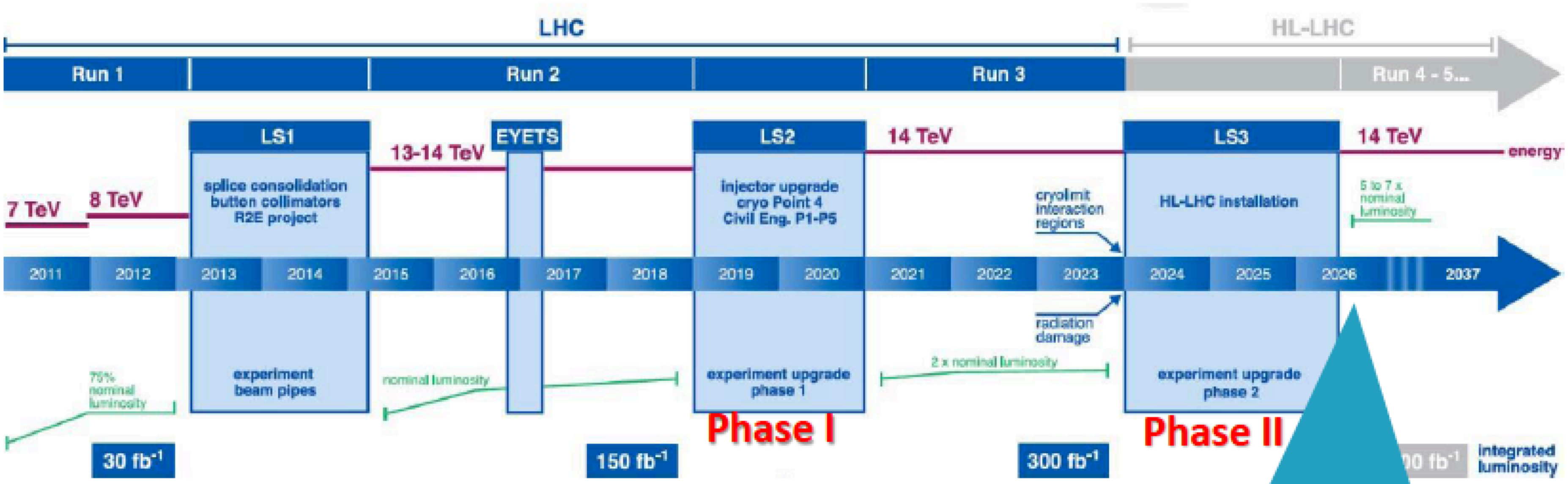
- *why is the Higgs boson so light ("naturalness"/fine-tuning/hierarchy problem) ?*
- *what is the the nature of the dark part (96% !) of the universe ?*
- *what is the origin of the matter-antimatter asymmetry ?*
- *why is gravity so weak ?*
- *Is supersymmetry realized in Nature?*
- *Inflation*

No excess in data for direct signs of new physics:

- Supersymmetry
- Long-lived particles
- New heavy resonances
- Dark Matter and its nature

Doing Precision measurements (Couplings, Cross Sections, Width, Differential Distributions,…) which might be an indirect sign of BSM physics

LHC and HL-LHC schedule

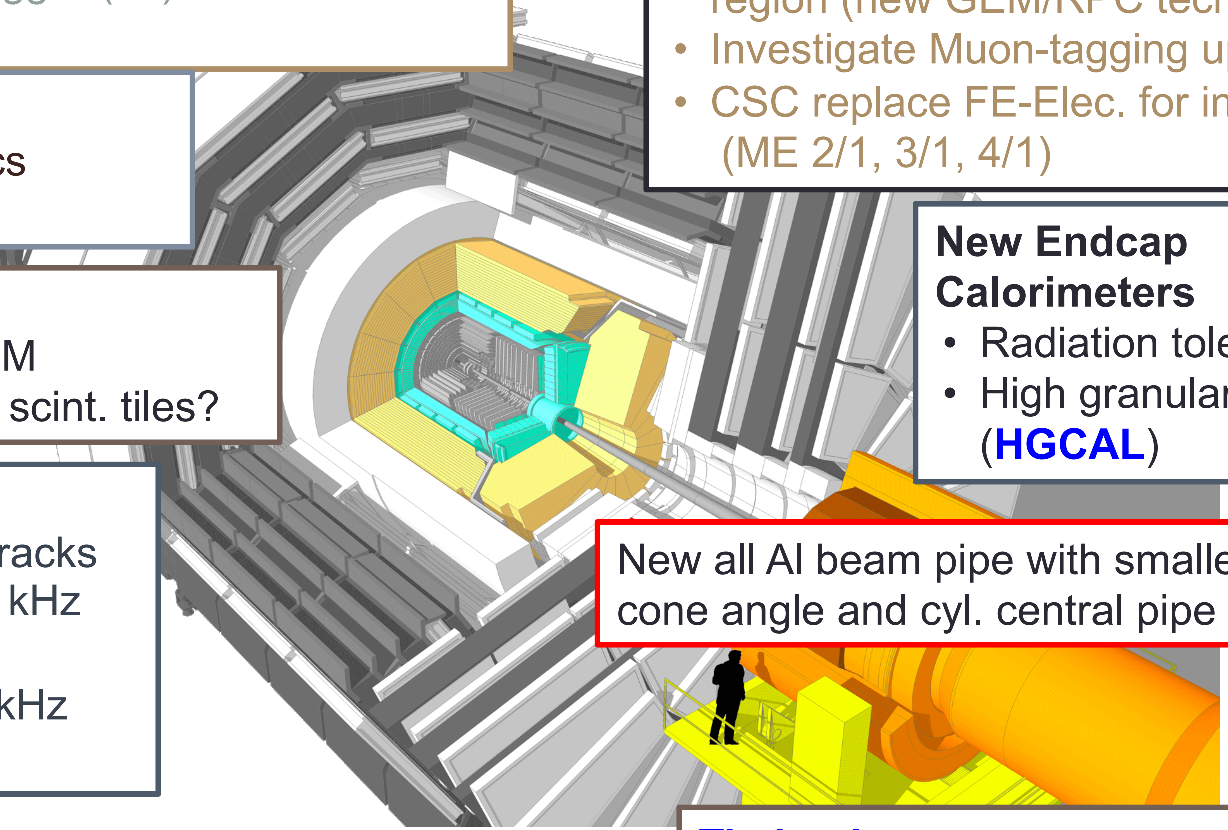


Luminosity

Nominal scenario: $\mathcal{L} = 5\times10^{34}\ \mathrm{cm^{-1}s^{-1}}$
for 3000/fb; Pile-up = 140

Ultimate Scenario: $\mathcal{L} = 7.5\times10^{34}\ \mathrm{cm^{-1}s^{-1}}$
for 4000/fb; Pile-up = 200
⇒25% increase in integrated lum.

CMS Phase 2 upgrade



New Tracker
- Radiation tolerant - high granularity - less material
- Tracks in hardware trigger (L1)
- Coverage up to η ~ 4

Barrel ECAL
- Replace FE electronics
- Cool detector/APDs

Barrel HCAL
- Replace HPD by SiPM
- Replace inner layers scint. tiles?

Trigger/DAQ
- L1 (hardware) with tracks and rate up ~ 750 kHz
- L1 Latency 12.5 μs
- HLT output rate 7.5 kHz
- New DAQ hardware

Muons
- Replace DT FE electronics
- Complete RPC coverage in forward region (new GEM/RPC technology)
- Investigate Muon-tagging up to η ~ 3
- CSC replace FE-Elec. for inner rings (ME 2/1, 3/1, 4/1)

New Endcap Calorimeters
- Radiation tolerant
- High granularity (**HGCAL**)

New all Al beam pipe with smaller cone angle and cyl. central pipe

Timing layer
- Timing resolution ~ 10 ps
- Space resolution ~ 10's of μm

Strategy for Higgs physics @ HL-LHC

Phase II Detector Upgrades:

- Radiation hardness
- Mitigate physics impact of high pileup
- → Object reconstruction efficiencies, resolutions and fake rates are assumed to be similar in the Run-2 and HL-LHC environments

Higgs@HL-LHC:

- Precision Measurements (Couplings, Cross Sections, Width, differential Distributions,…) → looking for deviations from the SM

- BSM Higgs direct searches: extra scalars, BSM Higgs resonances, exotic decays, anomalous couplings

- VBS scattering

- Rare decays and couplings: $H \rightarrow \mu\mu$, $H \rightarrow ee$, $H \rightarrow cc$, $H \rightarrow Z\gamma$

- Di-Higgs production ➜ Higgs self coupling

Analysis approaches for HL-LHC

- **Method 1: Full simulation (CMS)**: use of the most advanced geometry, algorithms and tuning, PU simulation

- **Method 2: Full analysis with parameterized detector performance (CMS)**: use DELPHES with up-to-date phase-2 detector performance (tracking, vertexing, timing, dedicated PUPPI jet algorithms, increased acceptance, performance of new detectors)

- **Method 3: truth + smearing (ATLAS):** truth-level events overlaid with jets (full sim) from pileup library, reconstruct particles (electrons, muons, jets, MET) from MC truth+overlay and smear their energy and p_T using appropriate smearing functions → cross checked with some of the 'real' data analyses

- **Method 4: projections (mostly CMS and LHCb)**
  - Existing signal and background samples (simulated at 13 TeV) scaled to higher lumi and $\sqrt{s}$ =14 TeV. Analysis steps (cuts) from present analyses.
  - 2 scenarios for uncertainties:
    - Scenario 1: all systematic uncertainties are kept unchanged with respect to those in current data analyses
    - Scenario 2: the theoretical uncertainties are scaled by a factor of 1/2, while other systematical uncertainties are scaled by $1/\sqrt{L}$

Modeling the projections for HL-LHC

Experimental uncertainties:

- Estimates of **ultimately achievable accuracy** based on the upgraded Phase-2 detectors studies (TDRs).
- Assumption that **sufficiently large simulation samples** will be available

- ID and isolation efficiencies for electrons and muons reduced to approximately 0.5%.
- hadronic τ lepton ID uncertainty reduced to approximately 2.5%.
- uncertainty in the overall jet energy scale (JES) reduced to 1% precision for jets with $p_T > 30$ GeV, driven primarily by improvements in the absolute scale and jet flavour calibrations

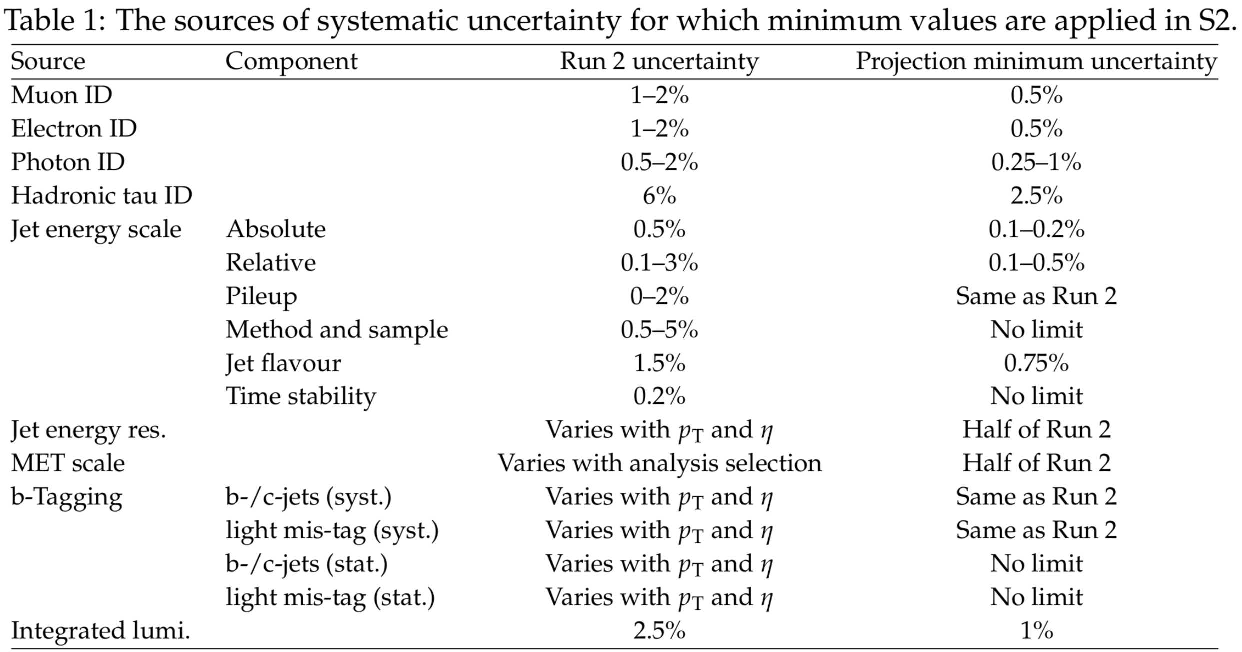


Table 1: The sources of systematic uncertainty for which minimum values are applied in S2.

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%

Theoretical uncertainties:

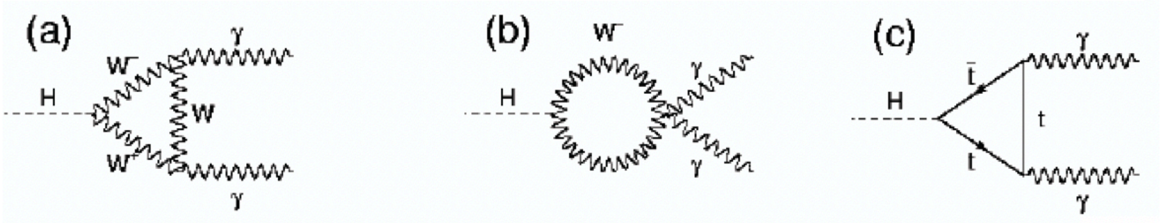
- Build upon existing/recent TH progress/studies
- Assume a scaling down by a constant factor
- **QCD calculations (1/2), understanding of PDFs (1/3), top p_T (1/2), etc.**

H→γγ

PAS FTR-18-011

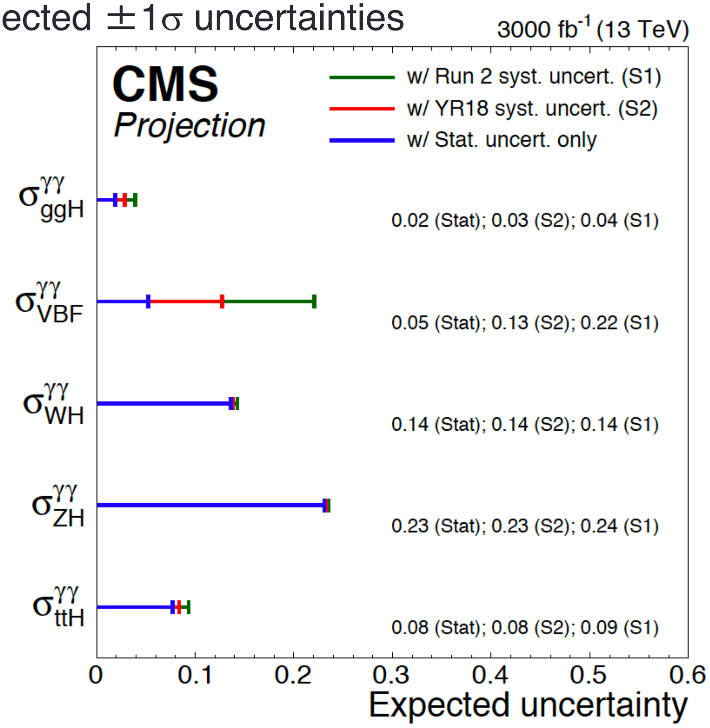
Projections for:

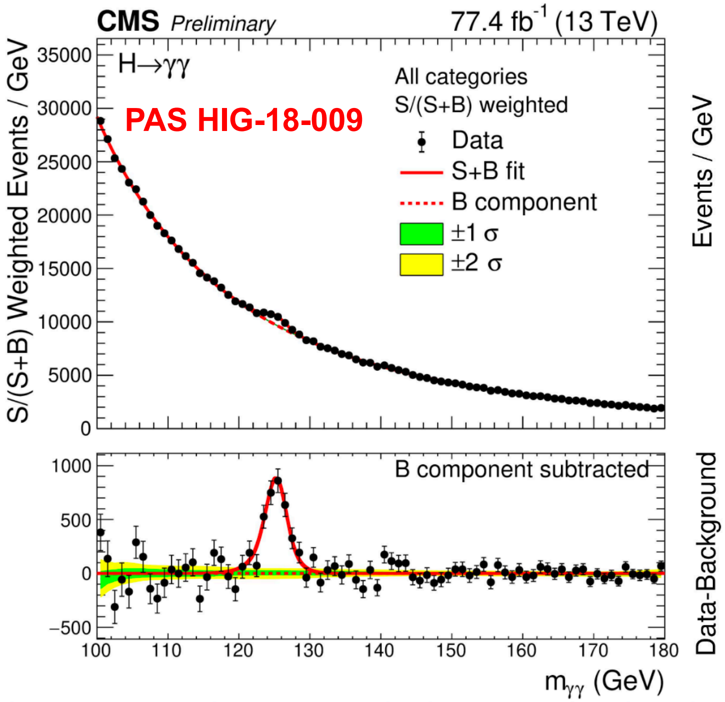
- H→γγ (ggH, VBF, VH, ttH)



two isolated photon candidates passing good quality requirements in the precision regions of the detectors

expected ±1σ uncertainties





The main systematic uncertainties are the background modeling uncertainty, missing higher order uncertainties causing event migrations between the bins, photon isolation efficiencies and jet uncertainties

Achievable precision @3000 fb^{-1} : less than 10 % (VH dominated by stat uncert.)

H→ZZ→4l

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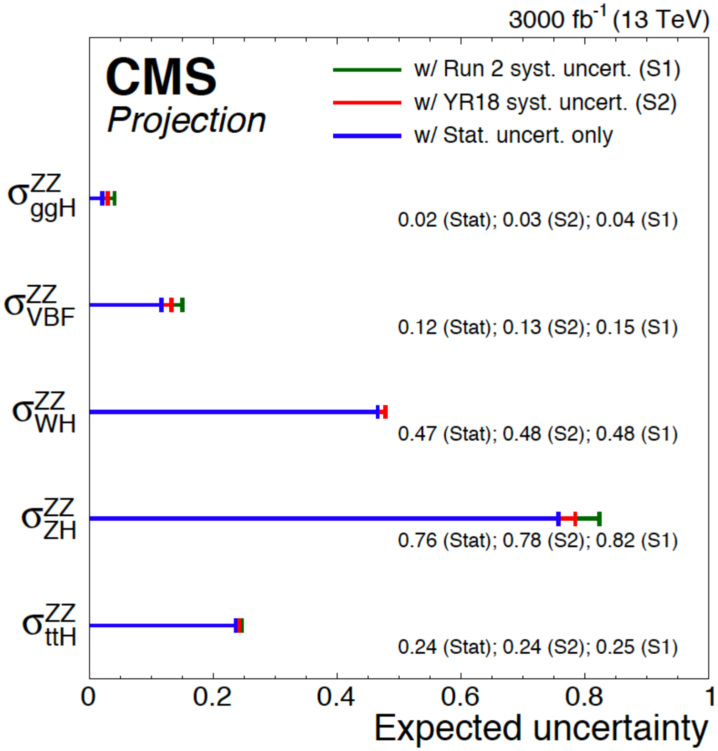
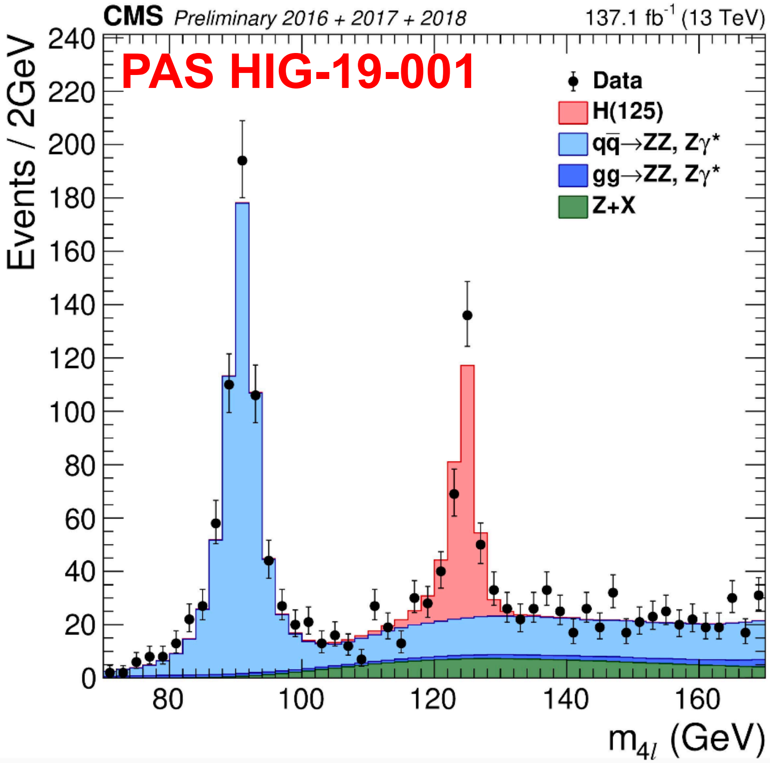
Projections for:

- H→ZZ→4l (ggH, VBF, VH, ttH)

at least two same-flavor opposite-sign di-lepton pairs, chosen from isolated e and μ candidates passing good quality requirements in acceptance





Dominant systematic uncertainties:

- for ggH: on the lepton reconstruction and identification efficiencies, and pile-up modeling uncertainties.
- for VBF and VH: on the jet energy scale and resolution, and by the missing higher order uncertainties + the parton shower modelling for ttH.

H→bb and H→ττ

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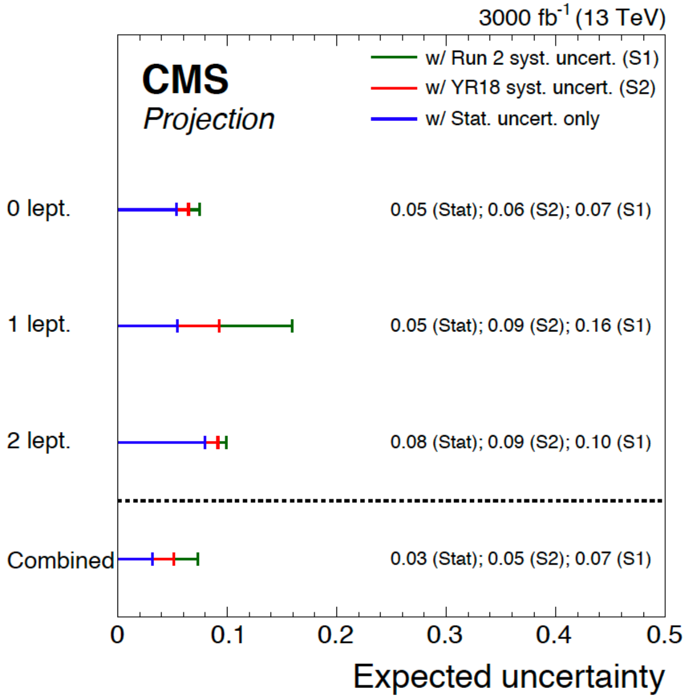
Projections for:

- VH, H→bb and boosted H→bb
- Leptonic decays of the vector boson for triggering and to reduce the multi-jet background
- Final states: two b-jets and either zero, one or two electrons or muons.

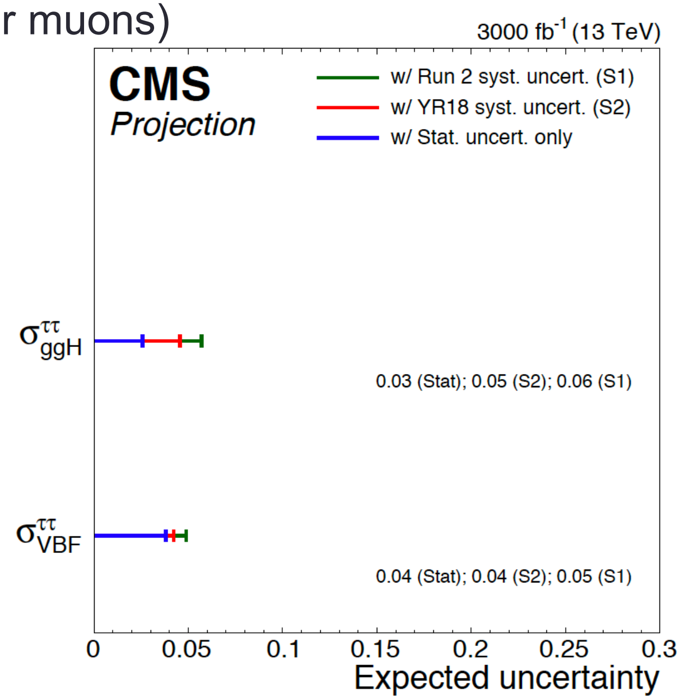


The largest component of the systematic uncertainty is theoretical. This arises from the uncertainty in the gluon-induced ZH (gg→ZH) production cross section due to QCD scale variations

Projections for:

- H→ττ (ggH, VBF)

Three subs-channels ($\tau_{lep}\tau_{lep}$, $\tau_{lep}\tau_{had}$ and $\tau_{had}\tau_{had}$) are defined by requirements on the number of hadronically decaying τ-leptons candidates and leptons (electrons or muons)



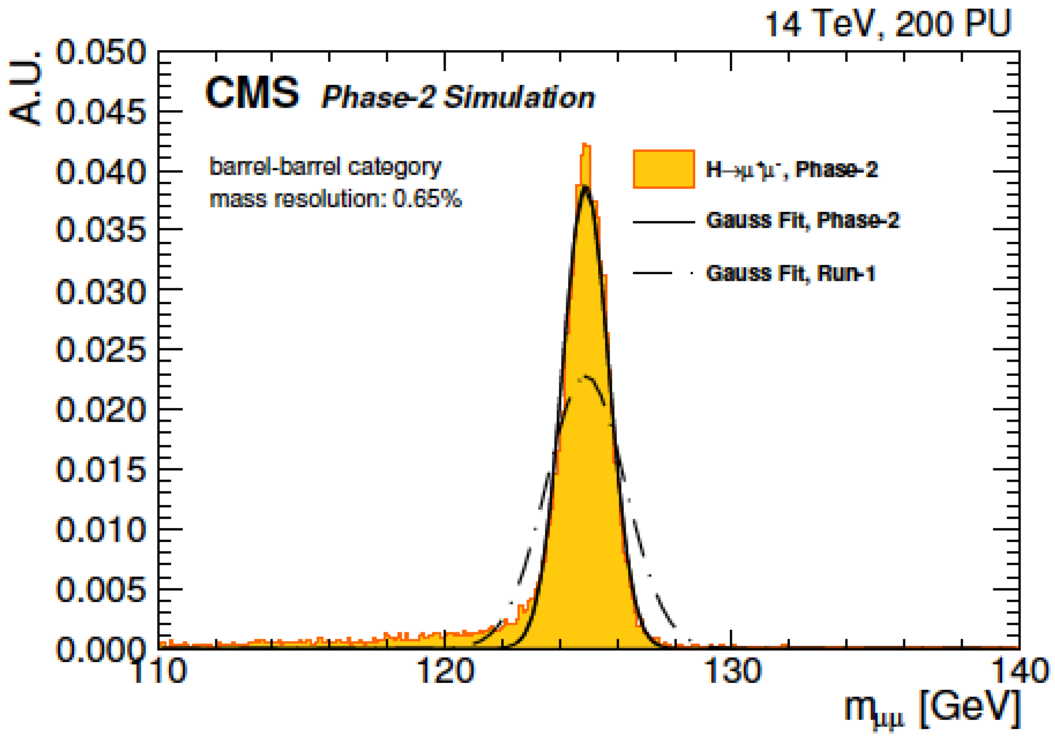
The dominant contributions to the systematic uncertainty come from:

- the experimental and background modeling errors
- the uncertainties on jet calibration and resolution, on the reconstruction of the E_t^{miss}
- the determination of the background normalization from signal and control region

Rare decays: H→μμ

TDR-17-001

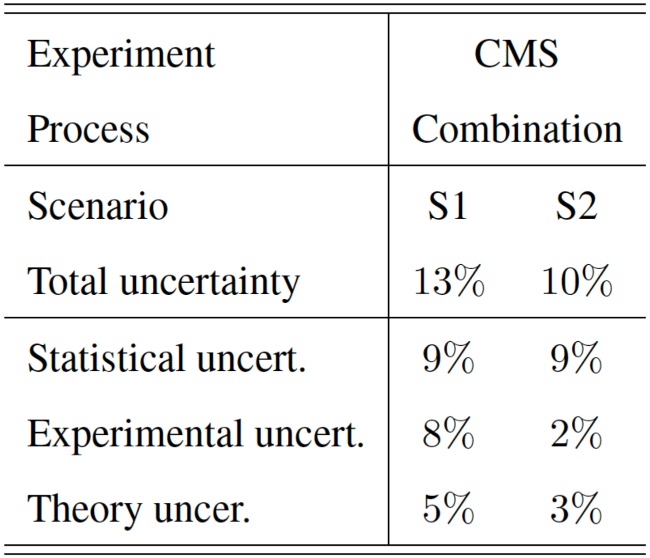
- Signature: 2 OS isolated muons, resonant peak at the Higgs mass over a falling background
- **BR(H→μμ)=0.022**. Only visible at HL-LHC
- di-muon invariant mass width is reduced in order to match the expected increase in performances due to the upgrade in the tracking system



CMS detector will be able to reach in the best category a di-muon mass resolution down to 0.65%

A simultaneous fit in all production modes

Expected precision on the signal strength measurement



Experiment	CMS	
Process	Combination	
Scenario	S1	S2
Total uncertainty	13%	10%
Statistical uncert.	9%	9%
Experimental uncert.	8%	2%
Theory uncer.	5%	3%

Higgs boson cross section

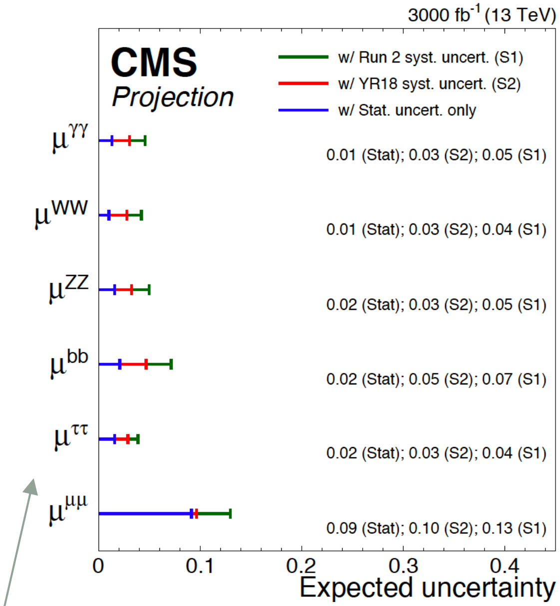
arXiv:1902.00134v1

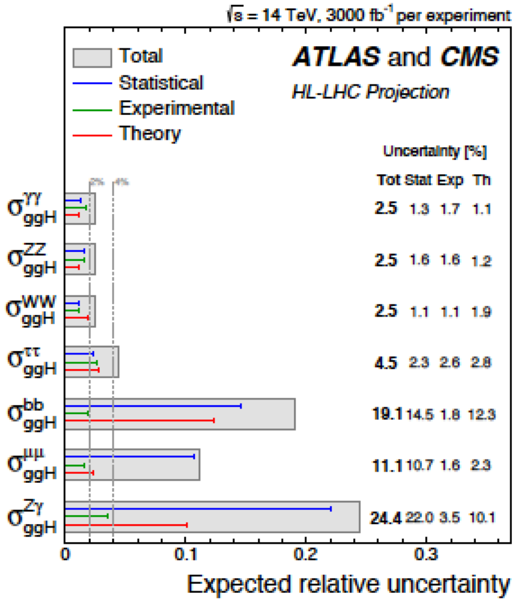
Projections for:

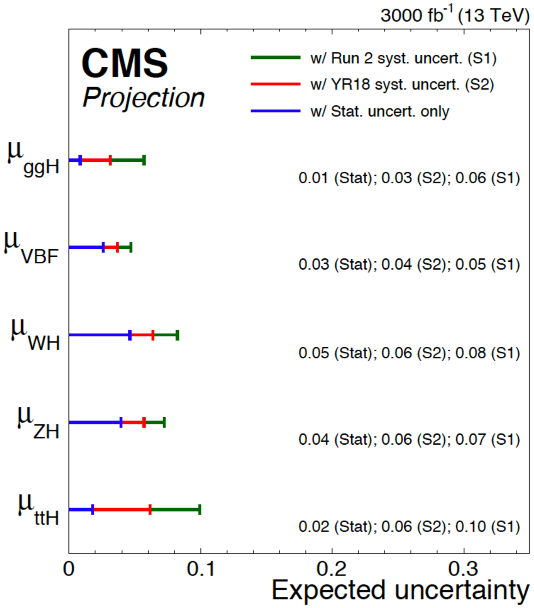
- H→ZZ→4l (ggH, VBF, VH, ttH)
- H→WW→2l2ν (ggH, VBF, VH)
- H→γγ (ggH, VBF, VH, ttH)
- H→ττ (ggH, VBF)
- VH, H→bb and boosted H→bb
- H→μμ (ggH and VBF)
- ttH, H→leptons, H→bb
  + studies about tH

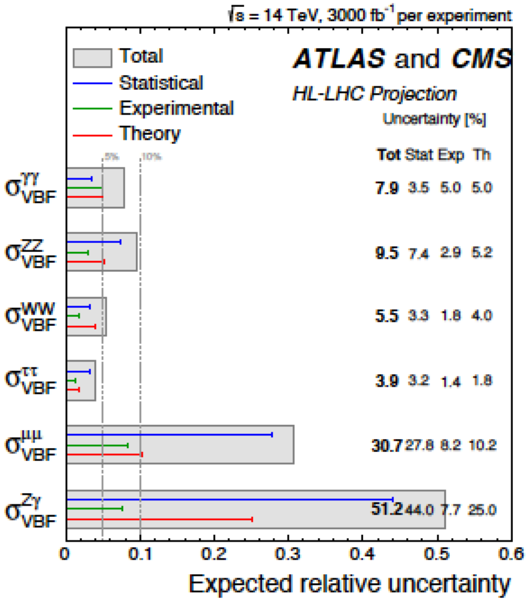
Systematic uncertainties will dominate, in particular theoretical uncertainties on signal and background are the main component for S2 scenario

CMS: S2 uncertainties range from 3–4%, with the exception of that on $\mu^{\mu\mu}$ at 10%.









Higgs couplings formalism

arXiv:1307.1347v2

LHC Higgs Xsection WG

- Single resonance with mass of 125 GeV.
- Zero-width approximation

$$\sigma \cdot B\,(i \to H \to f) = \frac{\sigma_i \cdot \Gamma_f}{\Gamma_H}$$

- the tensor structure of the lagr. is the SM one → observed 0^+

Production modes

$$\frac{\sigma_{\mathrm{ggH}}}{\sigma^{\mathrm{SM}}_{\mathrm{ggH}}} = \begin{cases} \kappa_g^2(\kappa_b, \kappa_t, m_H) \\ \kappa_g^2 \end{cases}$$

$$\frac{\sigma_{\mathrm{VBF}}}{\sigma^{\mathrm{SM}}_{\mathrm{VBF}}} = \kappa^2_{\mathrm{VBF}}(\kappa_W, \kappa_Z, m_H)$$

$$\frac{\sigma_{\mathrm{WH}}}{\sigma^{\mathrm{SM}}_{\mathrm{WH}}} = \kappa^2_W$$

$$\frac{\sigma_{\mathrm{ZH}}}{\sigma^{\mathrm{SM}}_{\mathrm{ZH}}} = \kappa^2_Z$$

$$\frac{\sigma_{t\bar{t}H}}{\sigma^{\mathrm{SM}}_{t\bar{t}H}} = \kappa^2_t$$

$$\frac{\Gamma_{WW^{(*)}}}{\Gamma^{\mathrm{SM}}_{WW^{(*)}}} = \kappa^2_W$$

$$\frac{\Gamma_{ZZ^{(*)}}}{\Gamma^{\mathrm{SM}}_{ZZ^{(*)}}} = \kappa^2_Z$$

$$\frac{\Gamma_{b\bar{b}}}{\Gamma^{\mathrm{SM}}_{b\bar{b}}} = \kappa^2_b$$

$$\frac{\Gamma_{\tau^-\tau^+}}{\Gamma^{\mathrm{SM}}_{\tau^-\tau^+}} = \kappa^2_\tau$$

- coupling scale factors **K_i** are defined in such a way that:
  - the cross sections s_i and the partial decay widths G_i

  scale with **K^2_i** compared to the SM prediction

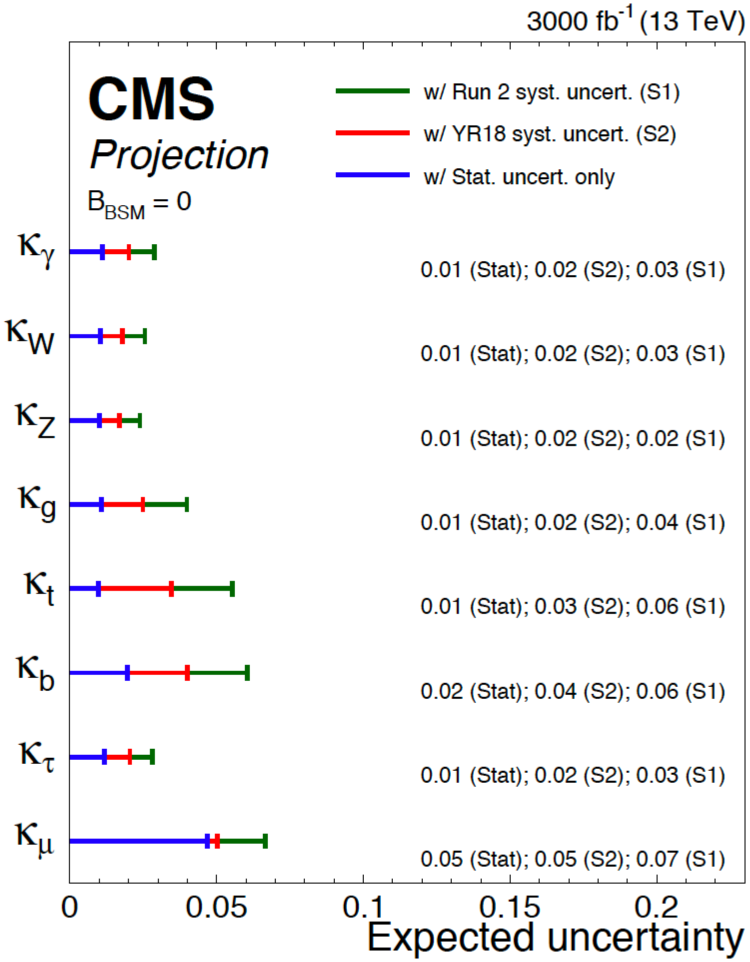
- deviations of **K_i** from unity → new physics BSM

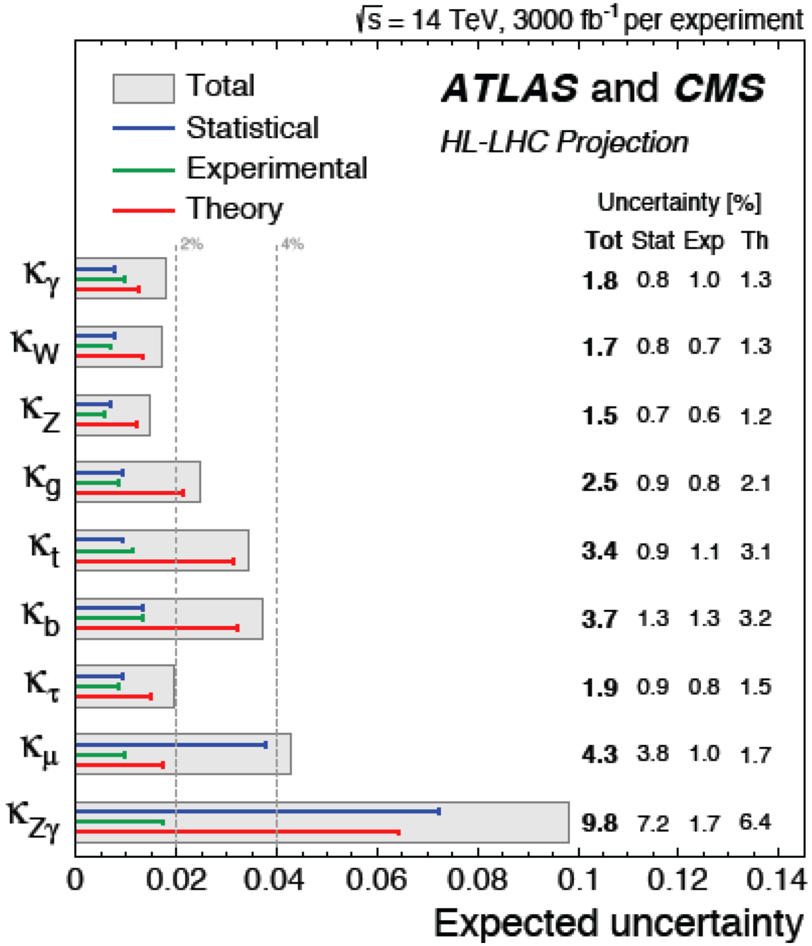
- Results from fits to the data using the profile likelihood ratio with κ_i couplings
  - as parameters of interest or as nuisance parameters

Higgs boson couplings

arXiv:1902.00134v1

- Results for couplings in κ-framework
- Six coupling modifiers corresponding to the tree-level Higgs boson couplings are defined: κ_t, κ_b, κ_τ, κ_μ, κ_W, κ_Z (+ κ_g, κ_γ, $\kappa_{Z\gamma}$) and $BR_{BSM} = 0$





Uncertainties on the κ's 2-5%, apart from k_μ and $k_{Z\gamma}$ mostly limited by statistical theoretical uncertainties

Differential Higgs cross sections

PAS FTR-18-011

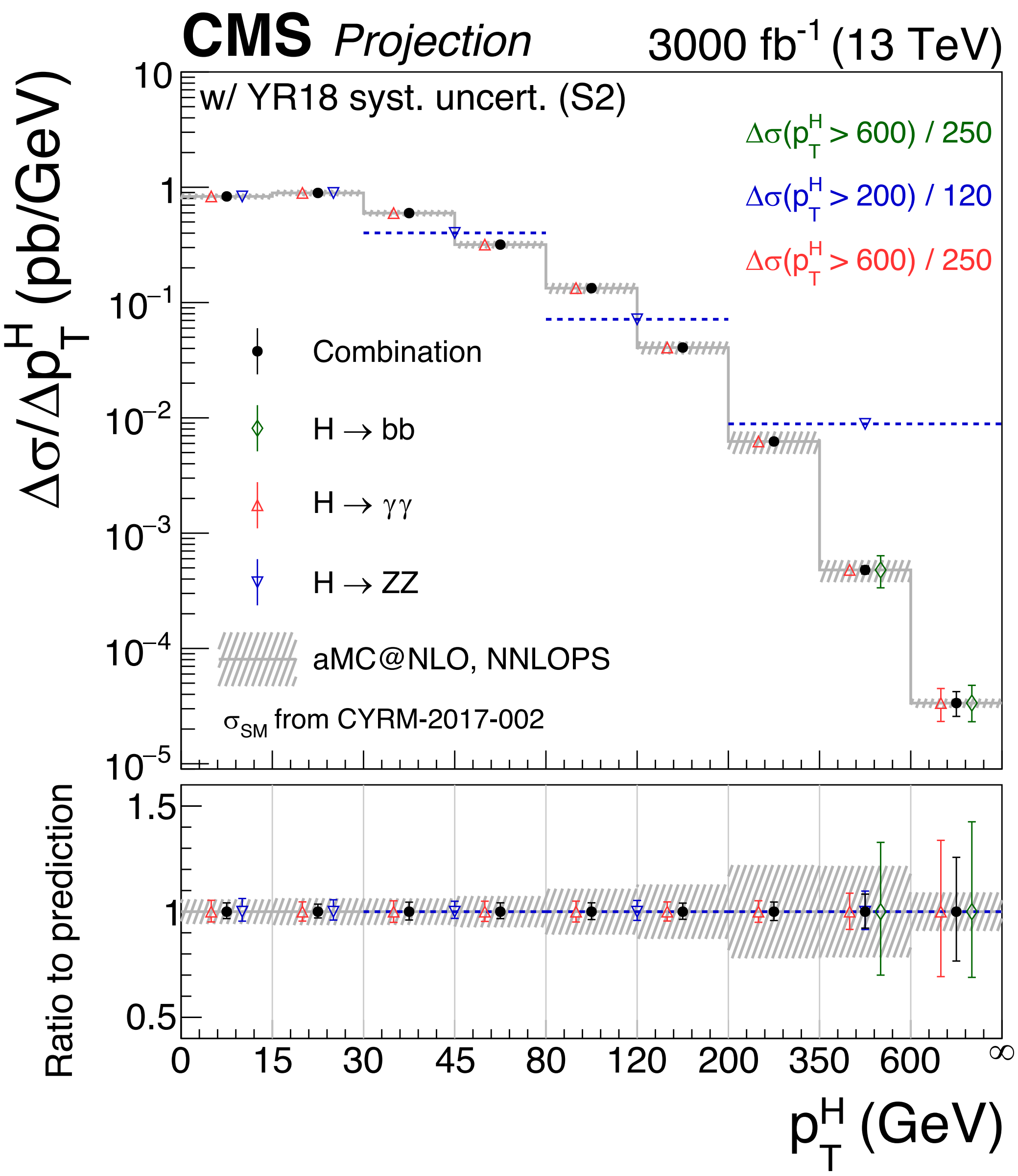
Looking at distortions of p_T^H differential distributions as potential new physics may reside in the tails
of the distribution, which cannot be measured in inclusive measurements

Combined differential cross sections using:

- $H\rightarrow\gamma\gamma$, $H\rightarrow ZZ\rightarrow 4l$
- + boosted $H\rightarrow bb$ in the high p_T^H tail

The uncertainties at 3000 fb^{-1}:

- in the higher p_T^H region are about a factor of ten smaller (statistically dominated) w.r.t. S1
- in the lower p_T^H region the reduced systematic uncertainties in S2 yield a reduction in the total uncertainty of up to 25% w.r.t S1 (and are no longer statistically dominated)



The Higgs potential

Higgs potential:

$$V(\phi) = -\mu^2\phi^2 + \lambda\phi^4$$

Standard Model:

$$\lambda_{hhh} = \frac{m_h^2}{2v^2}$$

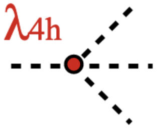
Expanding about minimum: $V(\phi) \to V(v+h)$

$$V = V_0 + \lambda v^2 h^2 + \lambda v h^3 + \frac{\lambda}{4} h^4$$

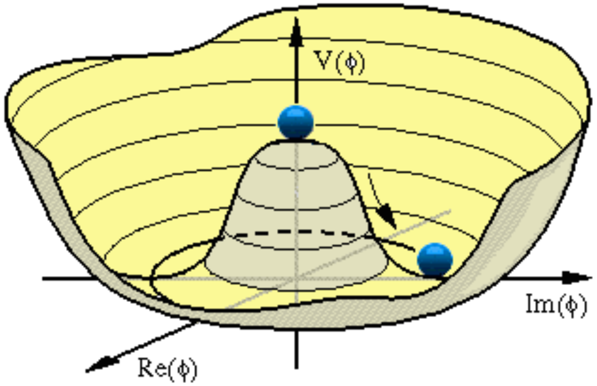
$$= V_0 + \frac{1}{2} m_h^2 h^2 + \underline{\frac{m_h^2}{2v^2}} v h^3 + \frac{1}{4} \underline{\frac{m_h^2}{2v^2}} h^4$$

Higgs mass term

hh-production



hhh-production



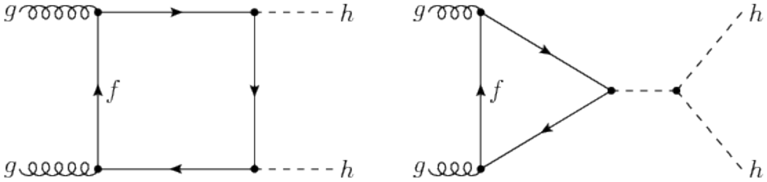
Why is it relevant?

- the strength of the triple and quartic couplings is fully fixed by the potential shape.
- It has implications on the stability of the Vacuum
- it could make the Higgs boson a good inflation field

Double Higgs production

Main probe for trilinear Higgs coupling λ_{HHH}. Diagrams interfere destructively in SM

ggF-hh:

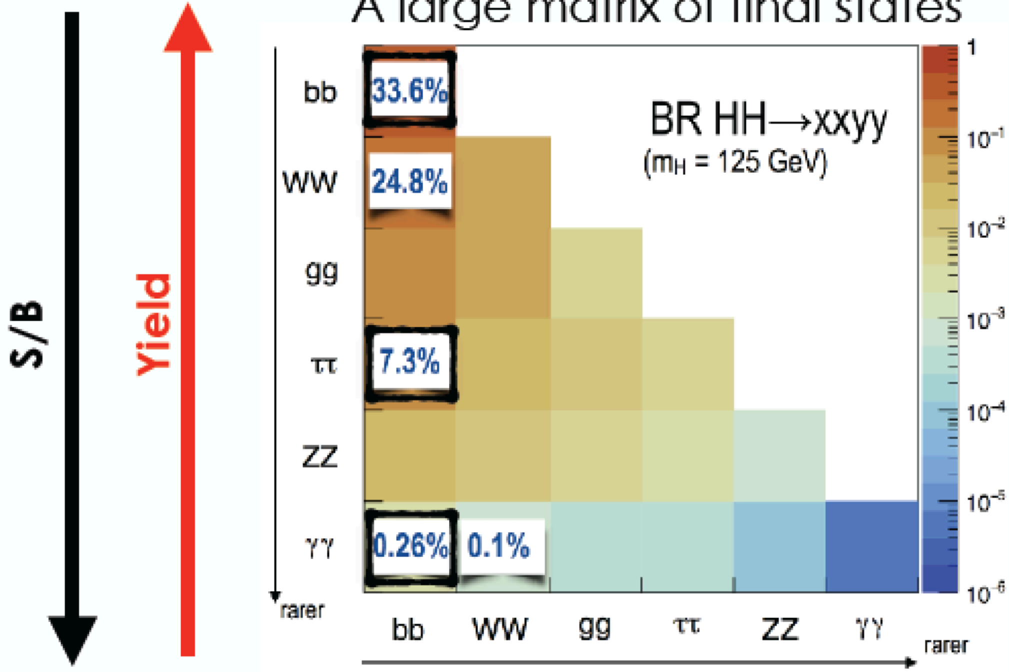


sensitive to possible BSM contribution:

Production mode	Cross section (14 TeV)
ggF-*hh*	~ 40 fb
VBF-*hh*	~2 fb
V-*hh*	~ 1 fb
tt-*hh*	~ 1 fb

arXiv:1212.5581

A large matrix of final states



bbbb largest statistics

bb(γγ,ττ) good compromise between statistics and S/B

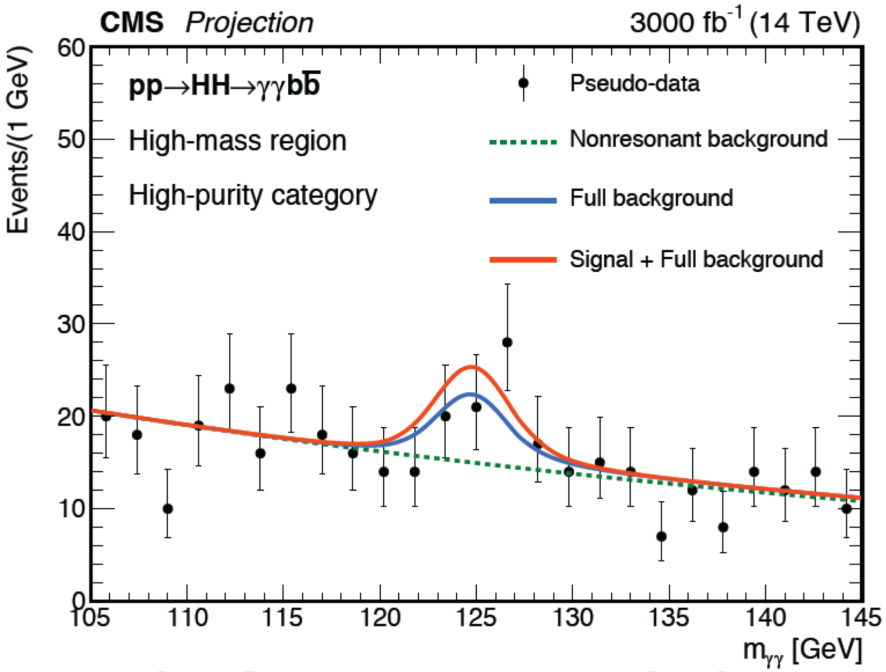
Not enough data in Run 2 to approach the SM sensitivity

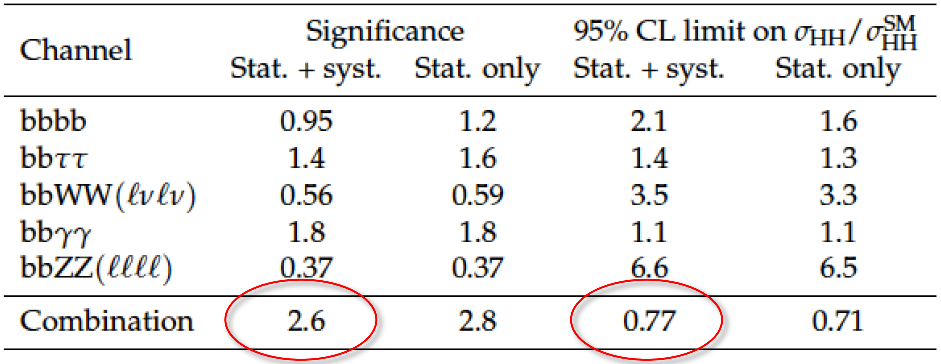
Prospects for HH measurements

PAS FTR-18-019

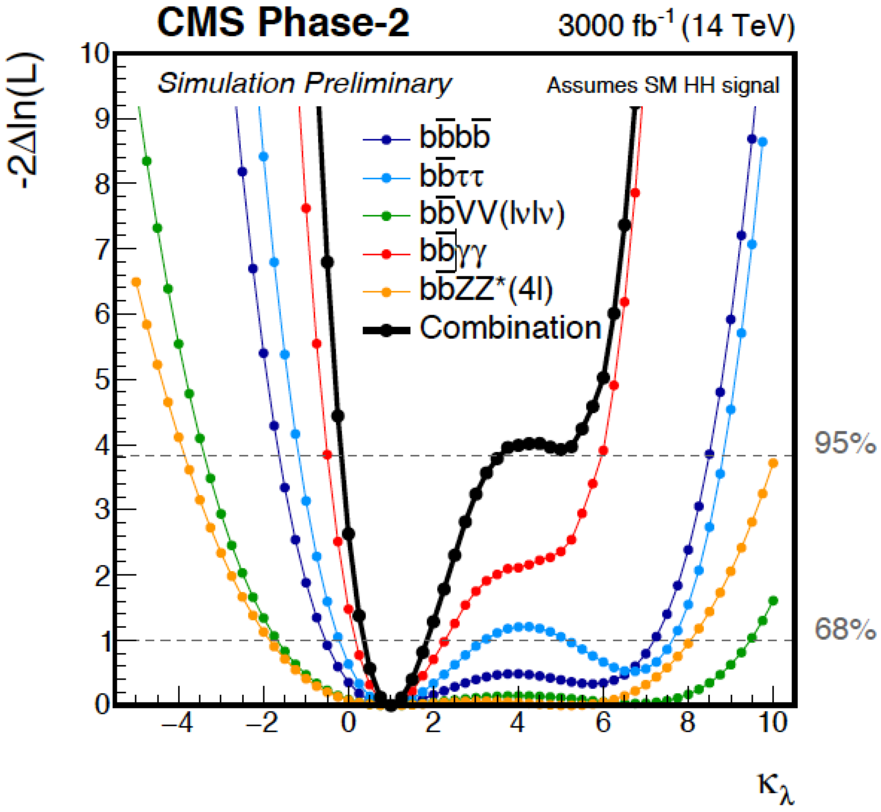
Search of Higgs boson pair (HH) production and the measurement of the Higgs boson self-coupling (λ_{HHH})

Decay channels: HH→ bbbb, **bb$\tau\tau$**, bbWW(→ll$\nu\nu$), **bb$\gamma\gamma$ (most sensitive)**, bbZZ(→4l)





Channel	Significance		95% CL limit on $\sigma_{HH}/\sigma^{SM}_{HH}$	
	Stat. + syst.	Stat. only	Stat. + syst.	Stat. only
bbbb	0.95	1.2	2.1	1.6
bb$\tau\tau$	1.4	1.6	1.4	1.3
bbWW($\ell\nu\ell\nu$)	0.56	0.59	3.5	3.3
bb$\gamma\gamma$	1.8	1.8	1.1	1.1
bbZZ($\ell\ell\ell\ell$)	0.37	0.37	6.6	6.5
Combination	2.6	2.8	0.77	0.71



Measurement of the $k_\lambda = \lambda_{HHH} / \lambda^{SM}_{HHH}$ in the range [0.4, 1.9] at the 68% CL

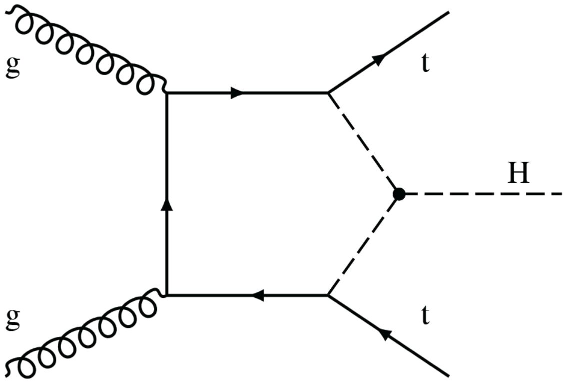
Differential XS and constraint on self coupling

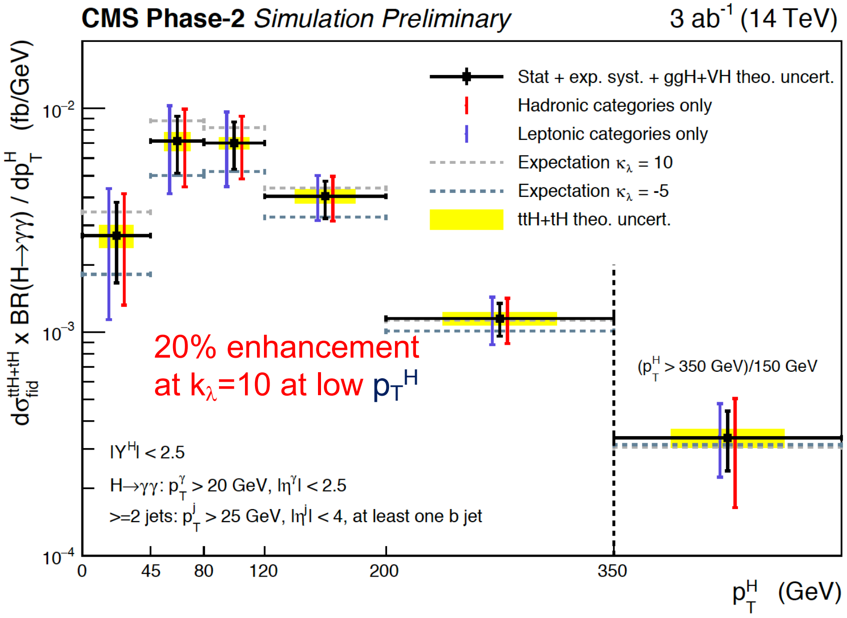
PAS FTR-18-020

Alternative approach: exploiting radiative corrections to inclusive and differential Higgs boson production rates → at NLO single Higgs boson production modes include contributions involving the λ_3 → sizeable contribution from ttH, tH, VH

Focus in ttH (+tH), $H \rightarrow \gamma\gamma$ using Delphes simulation and a strategy similar to the Run2

At 68% C.L.: $-1.9<k_\lambda<5.3$ → complementary to the stronger constraints from direct Higgs production

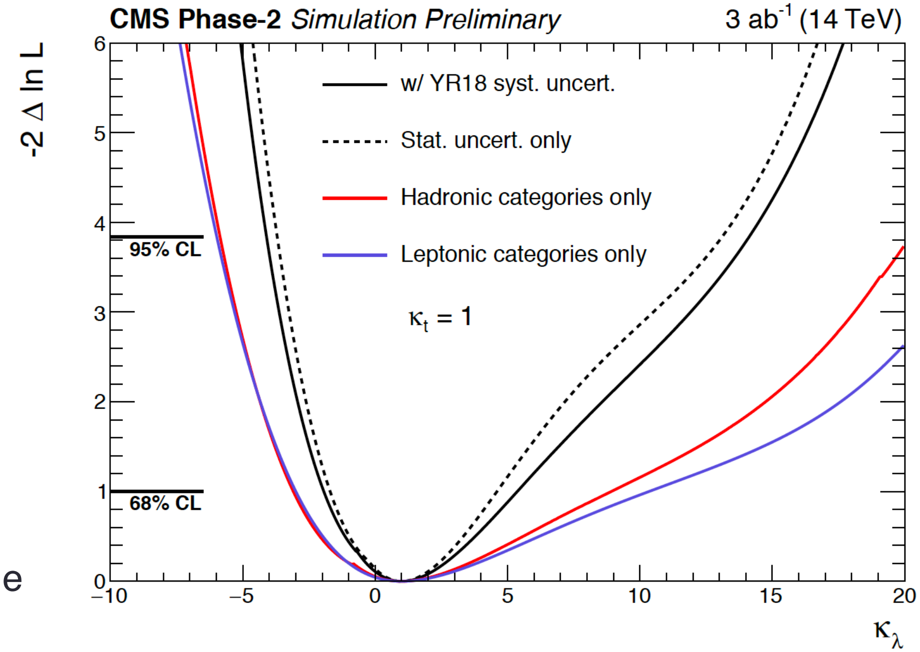




20% enhancement at k_λ=10 at low p_T^H

p_T^H allows to disentangle the effects of modified Higgs boson self-coupling values from other effects such as the presence of anomalous top–Higgs couplings.

The dependence of the single-Higgs boson differential xs is parameterised as a function of k_λ



Limits on the Higgs width

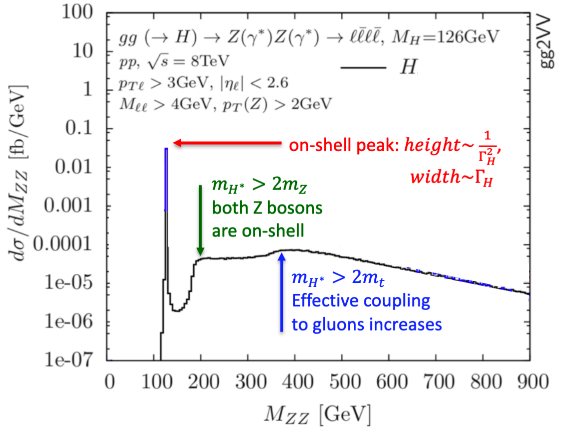
PAS FTR-18-011

Comparison of on-shell and off-shell rate in H→ZZ→4l constrain the Higgs boson width

- current constraint: Γ < 9.16 MeV @ 95% CL

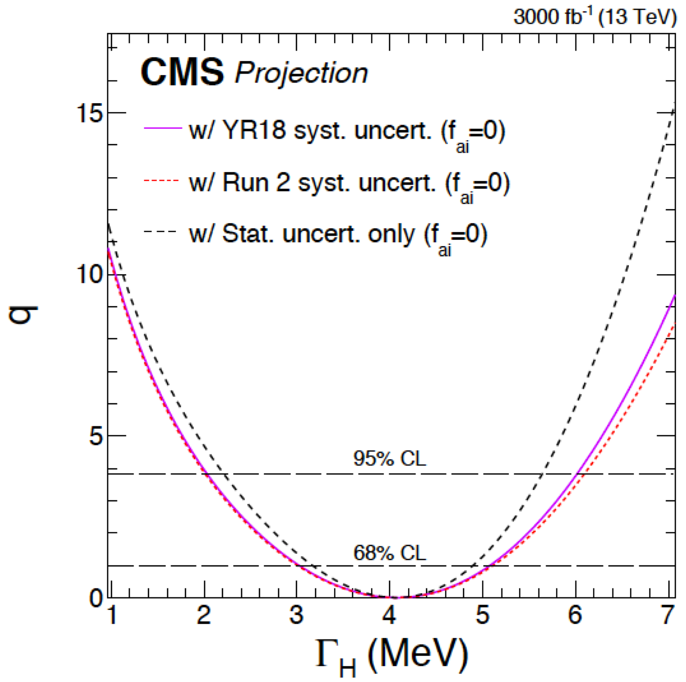
Off-peak to on-peak ratio

$$\boxed{\frac{\sigma^{\mathrm{off-shell}}}{\sigma^{\mathrm{on-shell}}} \sim \Gamma_{\mathrm{H}}}$$



Systematic uncertainty:

- theoretical uncertainties dominant over experimental ones ←dominant effect comes from the uncertainty in the NLO EW correction on the qq→4l simulation above the $2m_Z$ threshold
- approximate S2 in which the experimental uncertainties not reduced, while the theoretical uncertainties halved w.r.t S1
- 10% additional uncertainty applied on the QCD NNLO K factor on the gg



Precision reachable combining CMS and ATLAS predictions with 3000 fb^{-1}

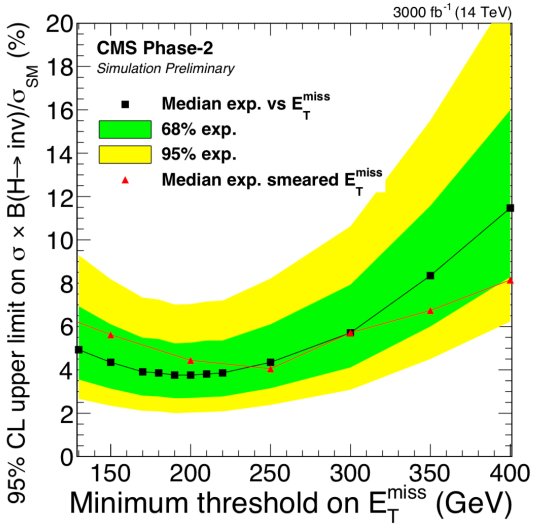
$$4.1^{+0.7}_{-0.8}\ \mathrm{MeV}$$ @68% C.L.

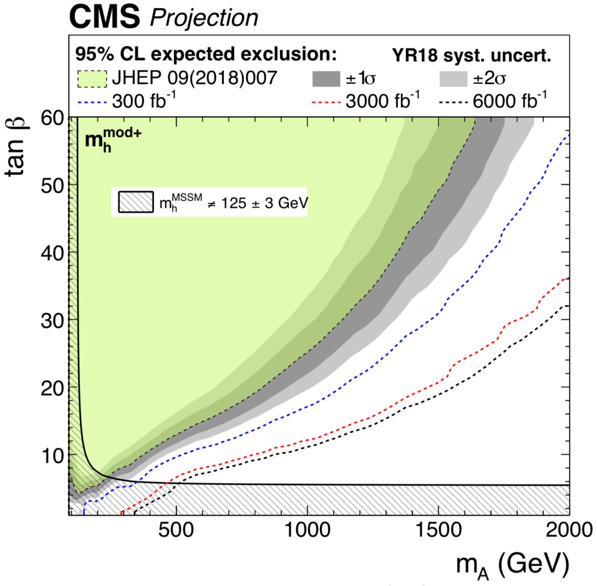
Γ_{H} (MeV)	S1	@95% C.L.	$[2.0, 6.1]$
Γ_{H} (MeV)	S2		$[2.0, 6.0]$

Sensitivity to BSM effects in Higgs physics

Several studies on probing the BSM effects in the Higgs physics :

- Probe for anomalous interactions & rare/exotic decays:
  - H→ invisible
    B_{INV} < 3,8% (compare to 22% @Run2) [FTR-18-016]
  - Exotic/rare/forbidden decays and signatures
    - **B_{BSM} < 6%** from couplings combination (compare to 34% @Run2) [FTR-18-011]
  - L1T TrackJet for BSM Higgs signatures
    - signatures with displaced jets [FTR-18-018]
  - Anomalous couplings and width:
    - significant improvement in limits on anom. coupl.
      Width: **$\Gamma_H \subset [2,6]$ MeV @ 95%CL** [FTR-18-011]
- Search for additional Higgs bosons and/or scalars :
  - MSSM H→ττ search [FTR-18-017]
  - High mass search X→ZZ->2l2q [FTR-18-040)





Summary/Conclusions

HL-LHC: potential for new physics discoveries and precision measurements in the Higgs sector:

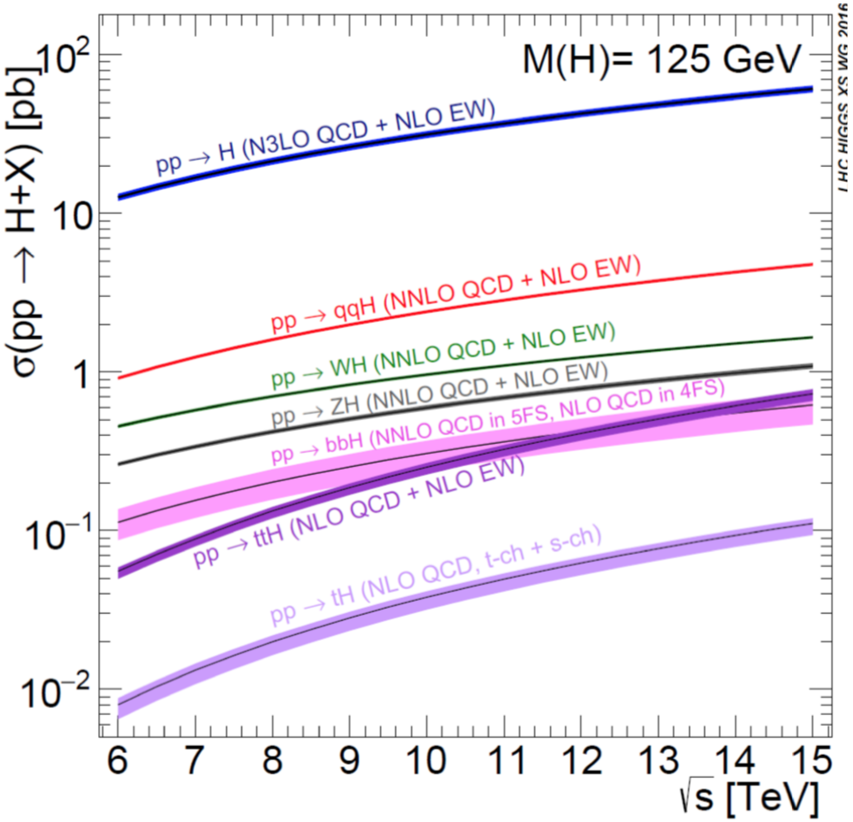
- Few per-cent level precision on most Higgs cross sections and couplings
- significance of about 2.6σ for HH production → triple self coupling
- Higgs width measurable to within 1 MeV
- sensitivity to BSM effects in Higgs physics derived

Many inclusive measurements limited by systematic uncertainties ➔ work needed from theoretical and experimental side

An exciting journey ahead!

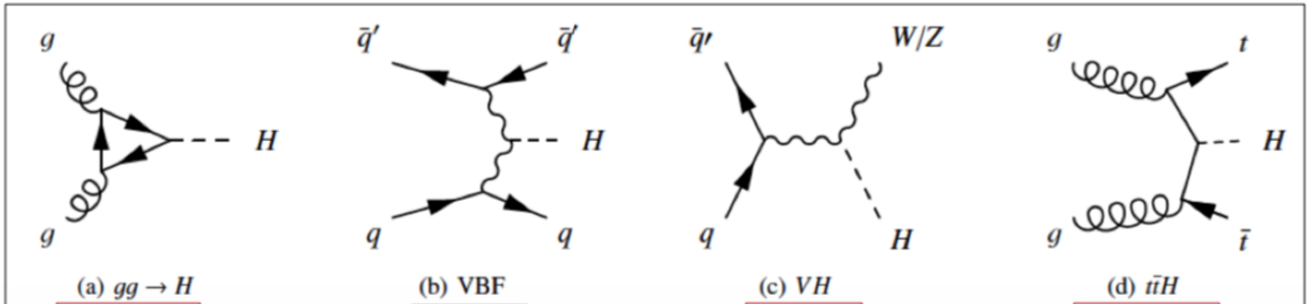
Backup

SM Higgs production at the LHC



- ggF: dominant, larger initial state radiation from gluons
- VBF: two forward jets with high mass and large rapidity gap
- VH: vector boson (lν, ll’, qq’)
- ttH: many b-jets, leptons, E_T^{miss}

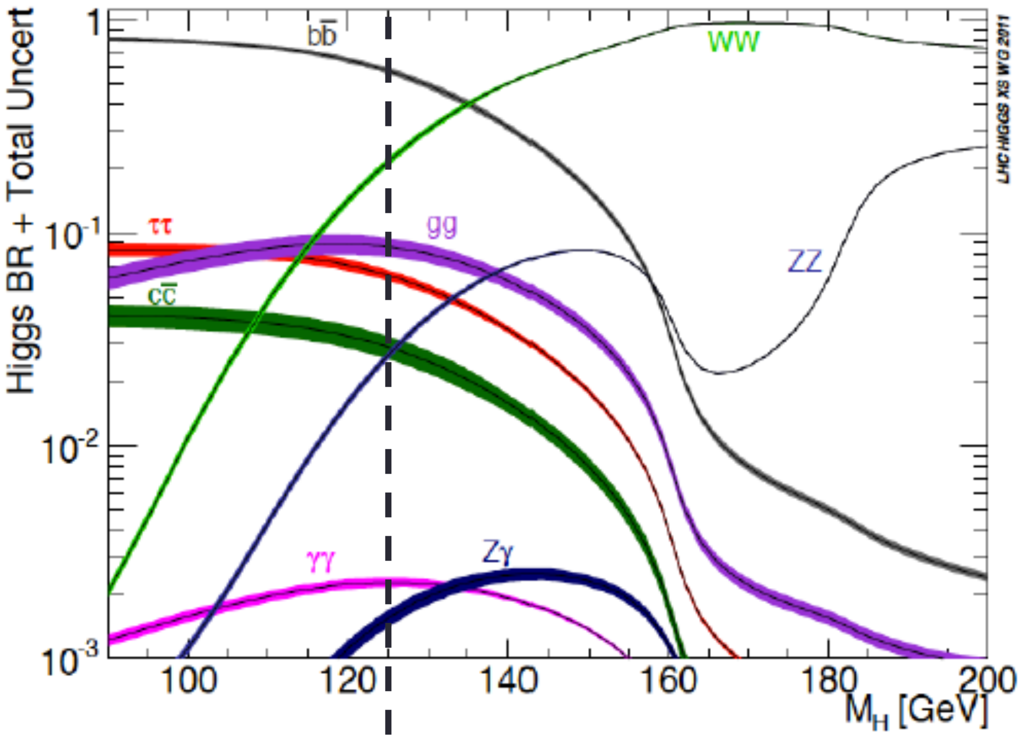
Total cross-section = 56 pb at 13 TeV

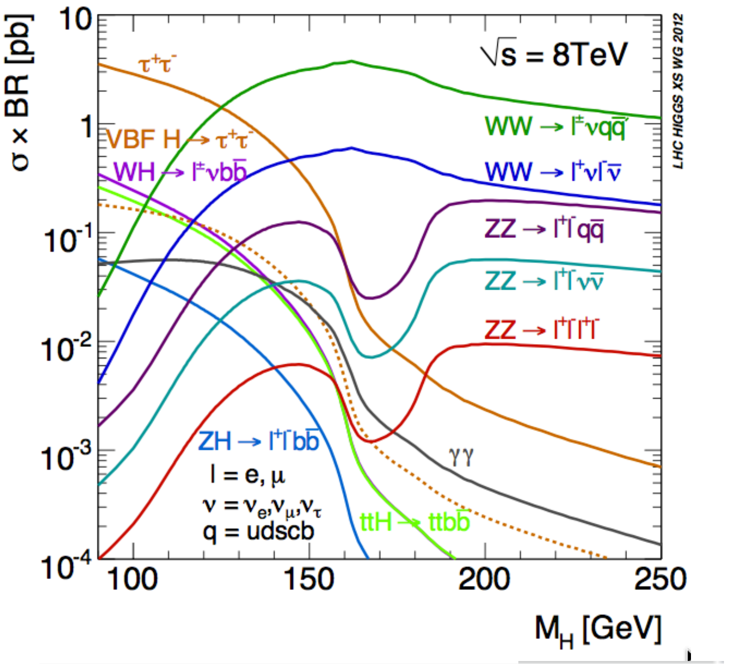


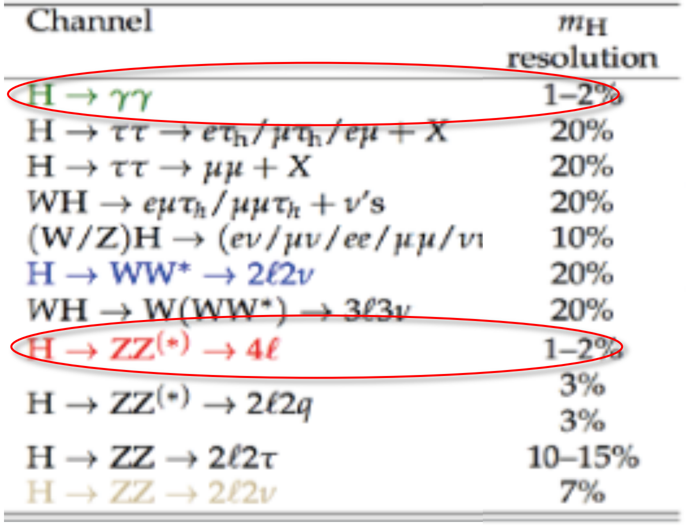
(a) $gg \to H$ (b) VBF (c) VH (d) $t\bar{t}H$

87% 7% 5% <1%

Higgs decay channels







Channel	m_H resolution
$H \to \gamma\gamma$	1–2%
$H \to \tau\tau \to e\tau_h/\mu\tau_h/e\mu + X$	20%
$H \to \tau\tau \to \mu\mu + X$	20%
$WH \to e\mu\tau_h/\mu\mu\tau_h + \nu$'s	20%
$(W/Z)H \to (e\nu/\mu\nu/ee/\mu\mu/\nu$	10%
$H \to WW^* \to 2\ell 2\nu$	20%
$WH \to W(WW^*) \to 3\ell 3\nu$	20%
$H \to ZZ^{(*)} \to 4\ell$	1–2%
$H \to ZZ^{(*)} \to 2\ell 2q$	3% 3%
$H \to ZZ \to 2\ell 2\tau$	10–15%
$H \to ZZ \to 2\ell 2\nu$	7%

At m_H =125 GeV:

- H(bb) = 57.8%
- H(WW) = 21.4%
- H(gg) = 8.19%
- H(ττ) = 6.27%
- H(ZZ) = 2.62%

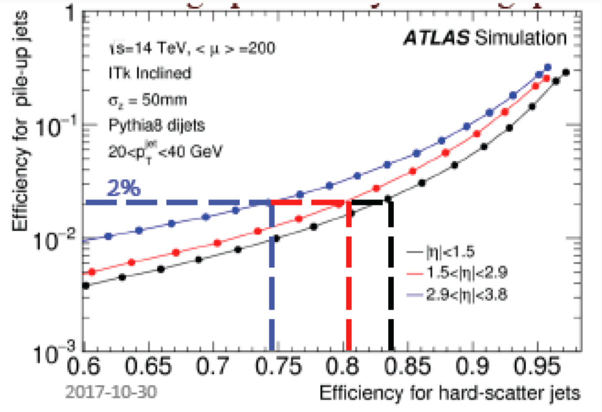
- H(cc) = 2.89%
- H(γγ) = 0.23%
- H(Zγ) = 0.15 %
- H(μμ) = 0.02%

Detector performance for Phase 2 upgrade

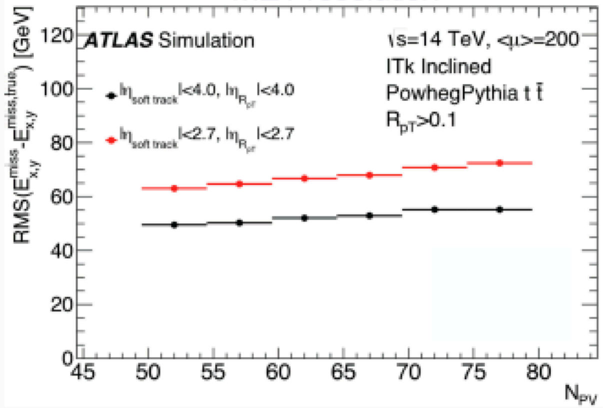
Detector performance after Phase-2 upgrades:

- Effective pileup mitigation
- Overall performance similar or better than during Run 2
- Extended capabilities with new algorithms

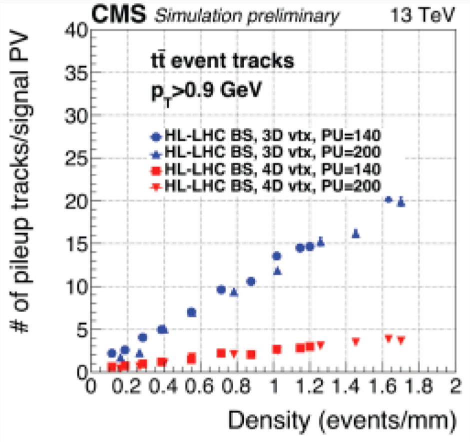
Jets



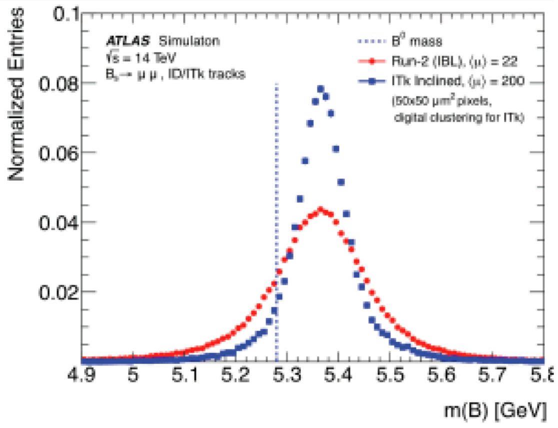
MET resolution



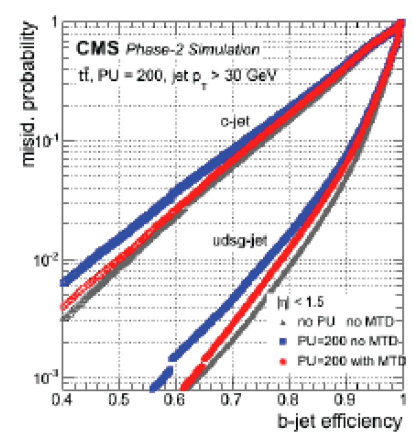
Pile-up suppression



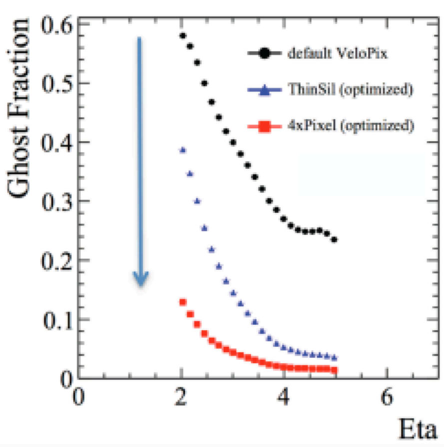
Mass resolution



B-tagging



LHCb Vertex Locator

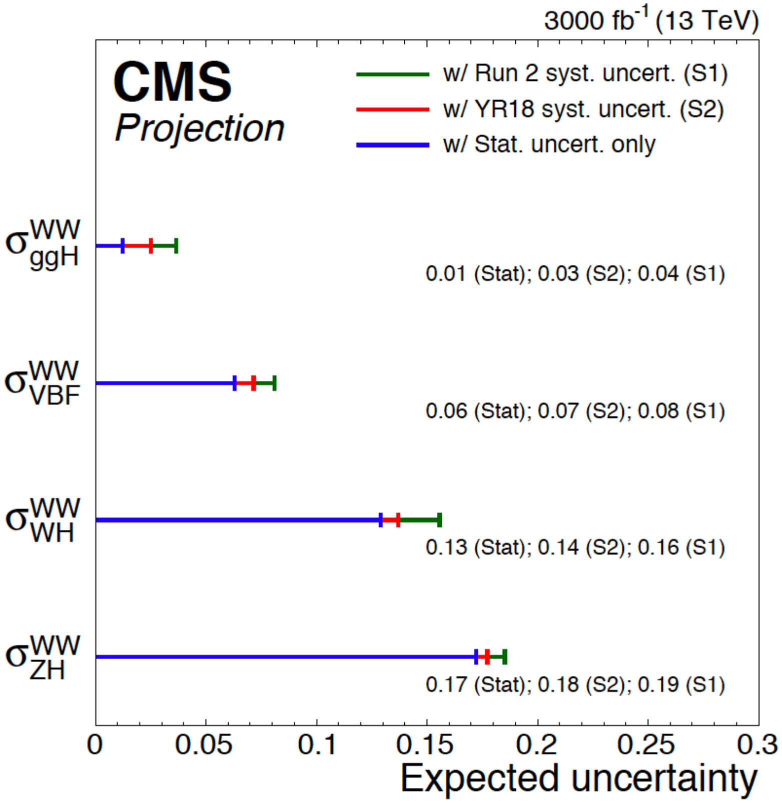


H→WW→2l2ν

Projections for:

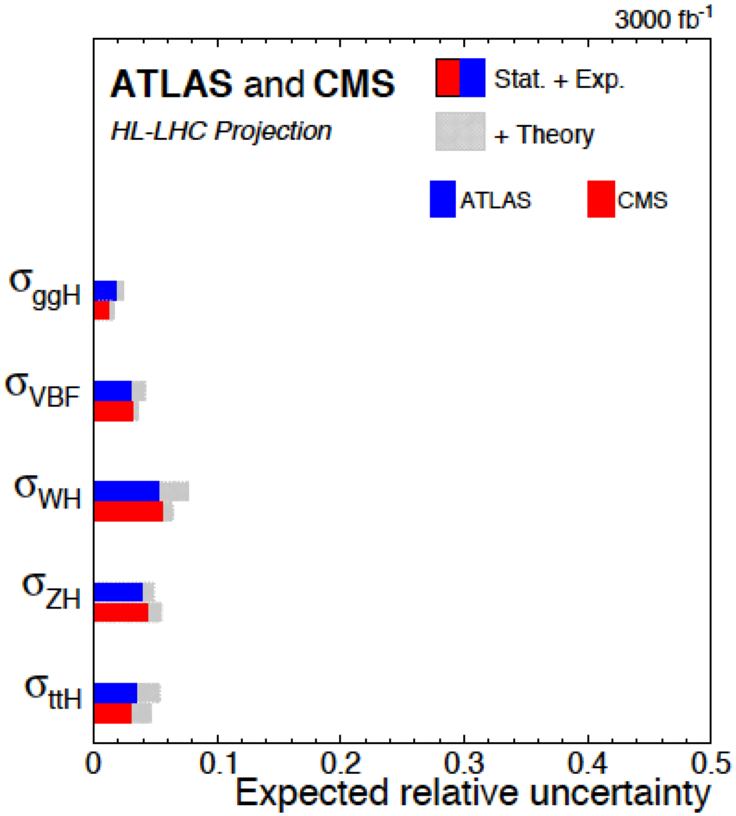
- H→WW→2l2ν (ggH, VBF, VH)

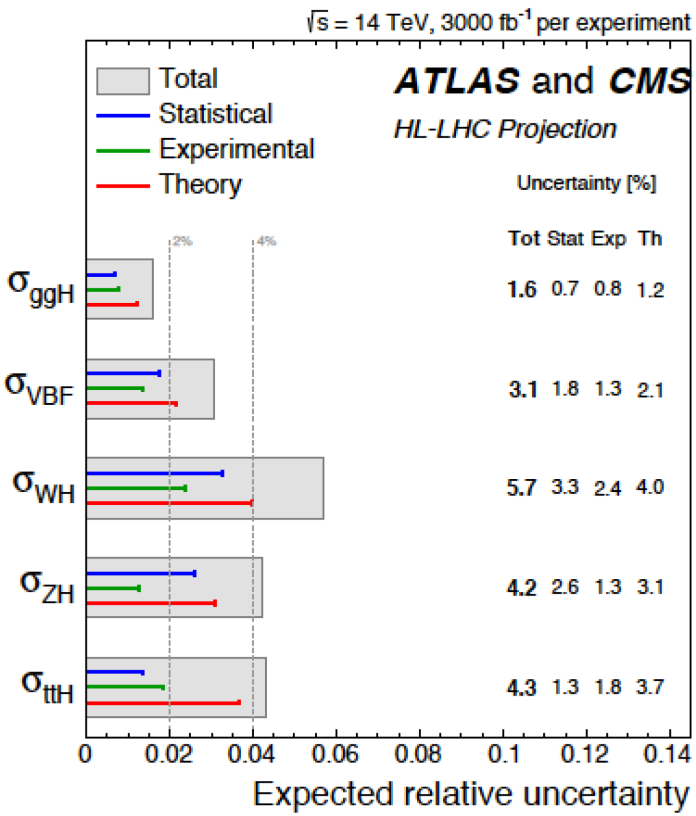
events that contain two opposite-charged isolated leptons passing good quality requirements in the precision region of the detectors and missing ansverse momentum



The measurement of the ggH cross section by branching fraction is dominated by theoretical PDF uncertainty, followed by experimental uncertainties affecting the signal acceptance, including uncertainties on the jet energy scale and flavour composition, and lepton mis-identification.

Higgs boson cross section

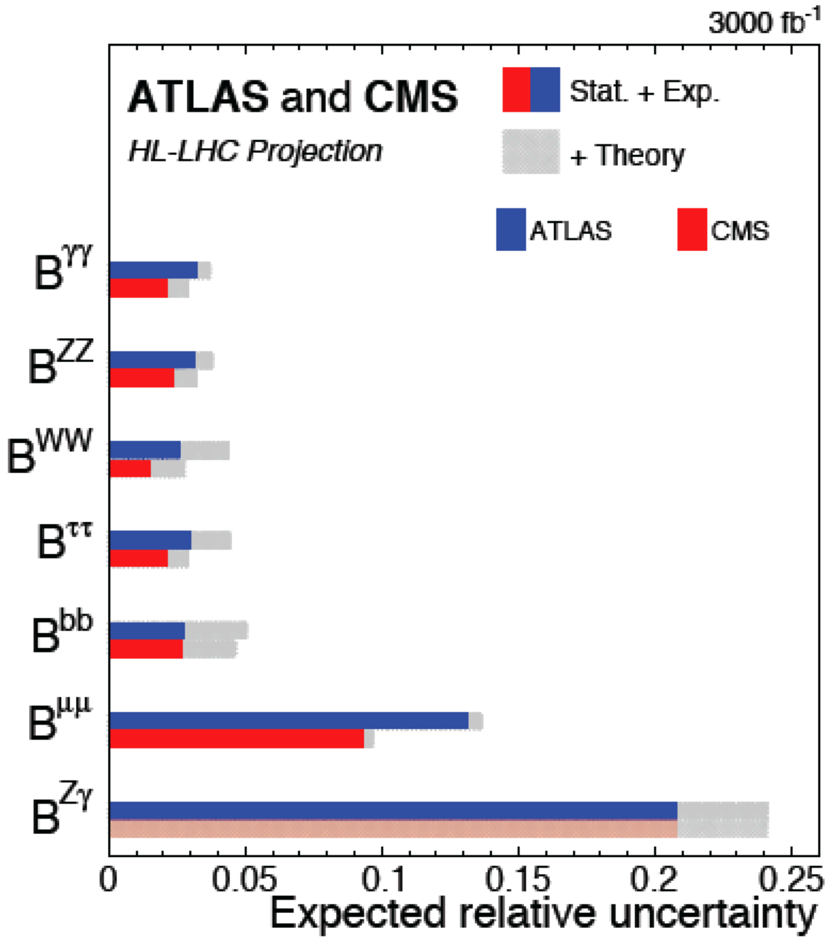


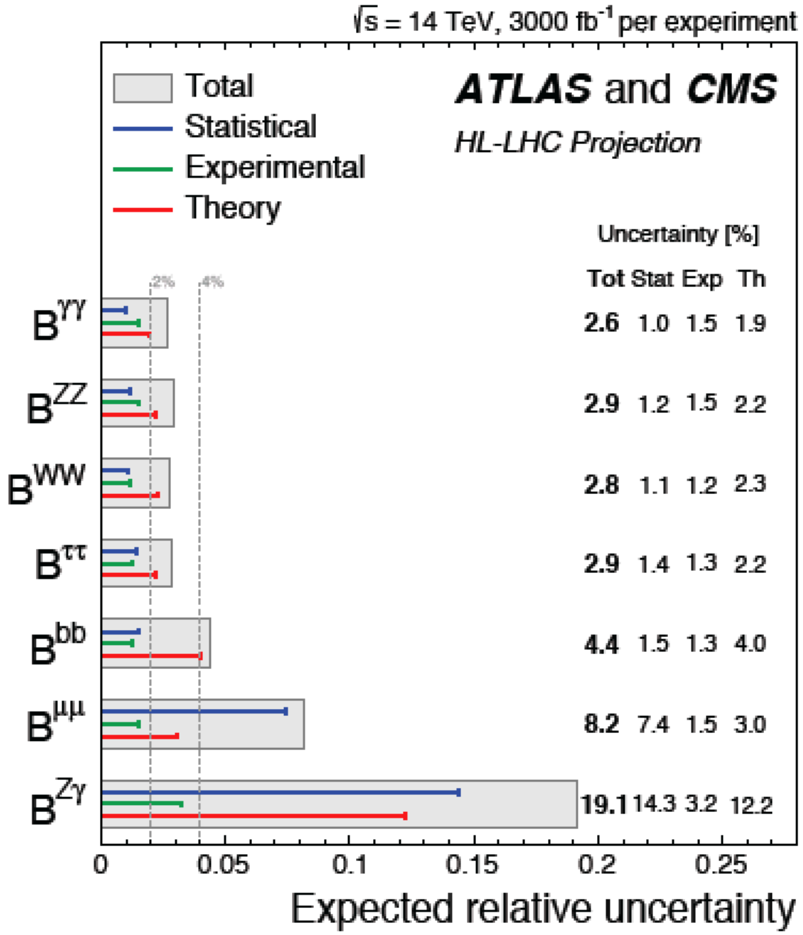


		ATLAS				
		3000 fb^{-1} uncertainty [%]				
		Total	Stat	Exp	SigTh	BkgTh
σ_{ggH}	S1	3.5	0.8	2.1	2.1	1.6
	S2	2.4	0.8	1.7	1.2	1.0
σ_{VBF}	S1	5.5	2.0	2.7	3.7	2.1
	S2	4.2	2.0	2.3	2.2	1.7
σ_{WH}	S1	9.3	4.0	4.0	5.1	5.4
	S2	7.7	4.0	3.4	3.3	4.5
σ_{ZH}	S1	6.2	3.4	2.4	3.4	3.0
	S2	4.8	3.4	1.8	2.0	2.1
σ_{ttH}	S1	6.7	1.9	3.1	3.7	4.3
	S2	5.3	1.9	2.8	2.4	3.3

		CMS				
		3000 fb^{-1} uncertainty [%]				
		Total	Stat	Exp	SigTh	BkgTh
σ_{ggH}	S1	2.4	0.8	1.2	1.6	0.9
	S2	1.7	0.8	0.9	0.9	0.6
σ_{VBF}	S1	4.1	2.6	2.1	2.0	1.3
	S2	3.5	2.6	1.6	1.8	0.3
σ_{WH}	S1	8.1	4.6	5.2	2.6	3.3
	S2	6.4	4.6	3.2	1.5	2.7
σ_{ZH}	S1	6.7	3.9	2.1	4.3	2.5
	S2	5.4	3.9	1.7	2.4	2.3
σ_{ttH}	S1	5.8	1.8	3.1	1.9	4.1
	S2	4.6	1.8	2.4	1.1	3.4

Higgs boson branching ratios



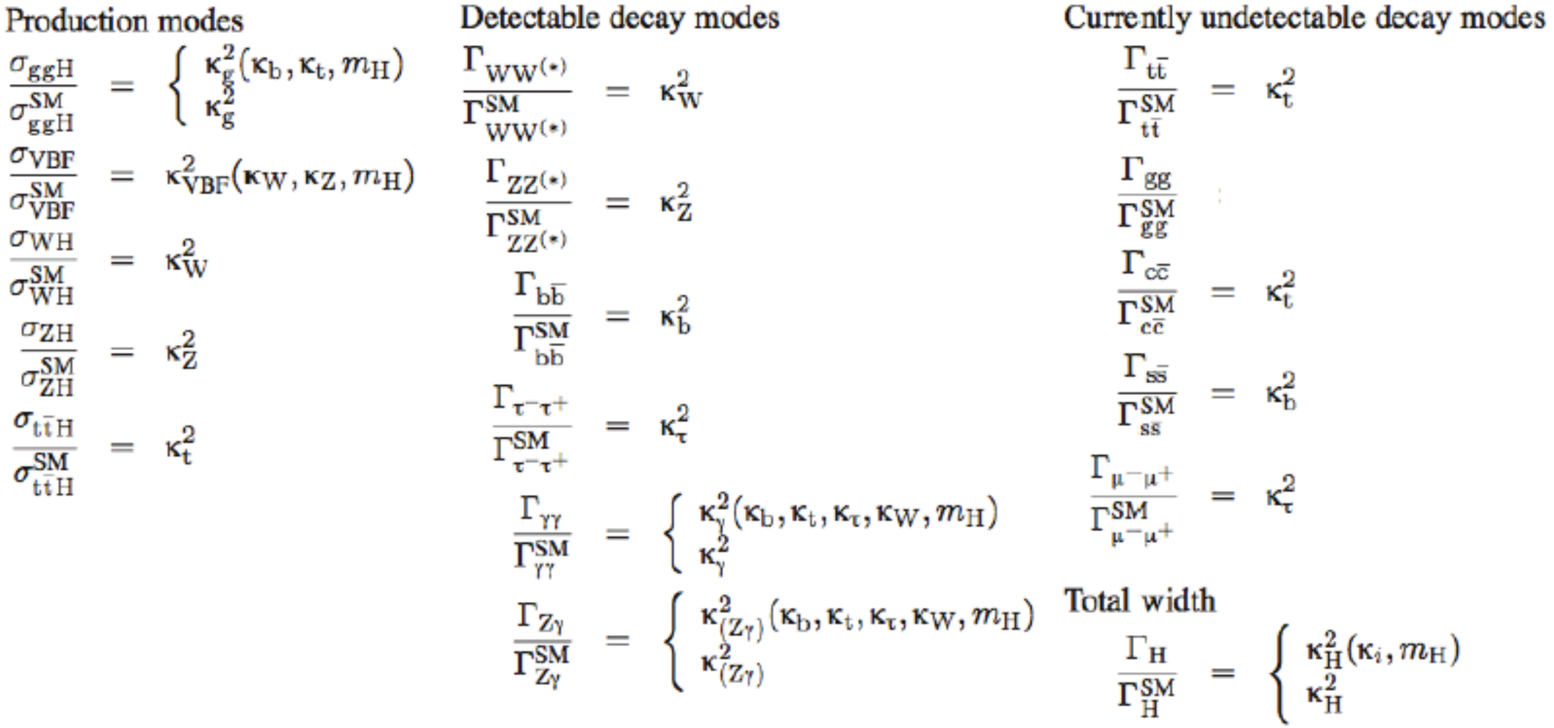


For the combined ATLAS-CMS extrapolation

- uncertainty range from 2 to 4%, with the exception of that on B(μμ) at 8% and on B(Zγ) at 19%.

Higgs couplings formalism

arXiv:1307.1347v2



Production modes

$$\frac{\sigma_{ggH}}{\sigma^{SM}_{ggH}} = \begin{cases} \kappa_g^2(\kappa_b, \kappa_t, m_H) \\ \kappa_g^2 \end{cases}$$

$$\frac{\sigma_{VBF}}{\sigma^{SM}_{VBF}} = \kappa_{VBF}^2(\kappa_W, \kappa_Z, m_H)$$

$$\frac{\sigma_{WH}}{\sigma^{SM}_{WH}} = \kappa_W^2$$

$$\frac{\sigma_{ZH}}{\sigma^{SM}_{ZH}} = \kappa_Z^2$$

$$\frac{\sigma_{t\bar{t}H}}{\sigma^{SM}_{t\bar{t}H}} = \kappa_t^2$$

Detectable decay modes

$$\frac{\Gamma_{WW^{(*)}}}{\Gamma^{SM}_{WW^{(*)}}} = \kappa_W^2$$

$$\frac{\Gamma_{ZZ^{(*)}}}{\Gamma^{SM}_{ZZ^{(*)}}} = \kappa_Z^2$$

$$\frac{\Gamma_{b\bar{b}}}{\Gamma^{SM}_{b\bar{b}}} = \kappa_b^2$$

$$\frac{\Gamma_{\tau^-\tau^+}}{\Gamma^{SM}_{\tau^-\tau^+}} = \kappa_\tau^2$$

$$\frac{\Gamma_{\gamma\gamma}}{\Gamma^{SM}_{\gamma\gamma}} = \begin{cases} \kappa_\gamma^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, m_H) \\ \kappa_\gamma^2 \end{cases}$$

$$\frac{\Gamma_{Z\gamma}}{\Gamma^{SM}_{Z\gamma}} = \begin{cases} \kappa_{(Z\gamma)}^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, m_H) \\ \kappa_{(Z\gamma)}^2 \end{cases}$$

Currently undetectable decay modes

$$\frac{\Gamma_{t\bar{t}}}{\Gamma^{SM}_{t\bar{t}}} = \kappa_t^2$$

$$\frac{\Gamma_{gg}}{\Gamma^{SM}_{gg}}$$

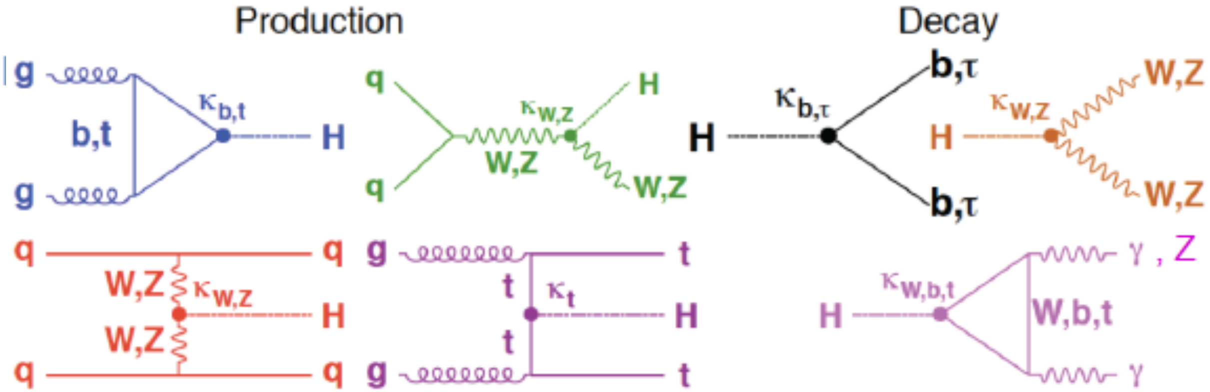
$$\frac{\Gamma_{c\bar{c}}}{\Gamma^{SM}_{c\bar{c}}} = \kappa_t^2$$

$$\frac{\Gamma_{s\bar{s}}}{\Gamma^{SM}_{s\bar{s}}} = \kappa_b^2$$

$$\frac{\Gamma_{\mu^-\mu^+}}{\Gamma^{SM}_{\mu^-\mu^+}} = \kappa_\tau^2$$

Total width

$$\frac{\Gamma_H}{\Gamma^{SM}_H} = \begin{cases} \kappa_H^2(\kappa_i, m_H) \\ \kappa_H^2 \end{cases}$$



$$\Gamma_H = \Sigma_{SM}\,\Gamma_Y \quad (+\,\Gamma_{BSM})$$

Contributions from **new physics** through Γ_{BSM} and loop processes

Differential Higgs cross sections

Relative uncertainties on the projected p_T H spectrum measurements

S1

3000 fb^{-1} ATLAS

$p_T{}^H$ [GeV]	0-10	10-15	15-20	20-30	30-45	45-60	60-80	80-120	120-200	200-350	350-1000
H → γγ	6.5%	5.9%		6.2%	6.0%	6.5%	6.7%	6.0%	5.4%	6.3%	9.5%
H → ZZ	9.0%	8.1%	8.9%	6.9%	6.3%	6.8%	6.8%	6.2%	6.7%	13.2%	24.3
Combination	5.5%	4.8%		5.0%	4.7%	5.0%	5.1%	4.6%	4.4%	5.4%	8.7%

3000 fb^{-1} CMS

$p_T{}^H$ [GeV]	0-15	15-30	30-45	45-80	80-120	120-200	200-350	350-600	600-∞
H → γγ	5.1%	6.8%	7.1%	6.9%	7.1%	6.7%	7.1%	9.9%	32.5%
H → ZZ	5.4%	5.7%	5.0%		5.5%		9.6%		
H → bb	none							38.2%	37.1%
Combination	4.7%	4.4%	5.0%	4.7%	4.8%	4.7%	5.2%	8.5%	25.4%
6000 fb^{-1}									
Combination	4.0%	3.7%	4.0%	3.9%	4.0%	4.0%	4.3%	6.3%	18.3%

S2

3000 fb^{-1} ATLAS

$p_T{}^H$ [GeV]	0-10	10-15	15-20	20-30	30-45	45-60	60-80	80-120	120-200	200-350	350-1000
H → γγ	5.3%	4.6%		4.9%	4.7%	5.4%	5.7%	4.9%	4.2%	5.1%	8.7%
H → ZZ	8.3%	7.6%	8.3%	6.3%	5.7%	6.2%	6.3%	5.7%	6.4%	13.1%	23.2%
Combination	4.5%	3.8%		3.9%	3.6%	4.1%	4.2%	3.7%	3.5%	4.5%	8.2%

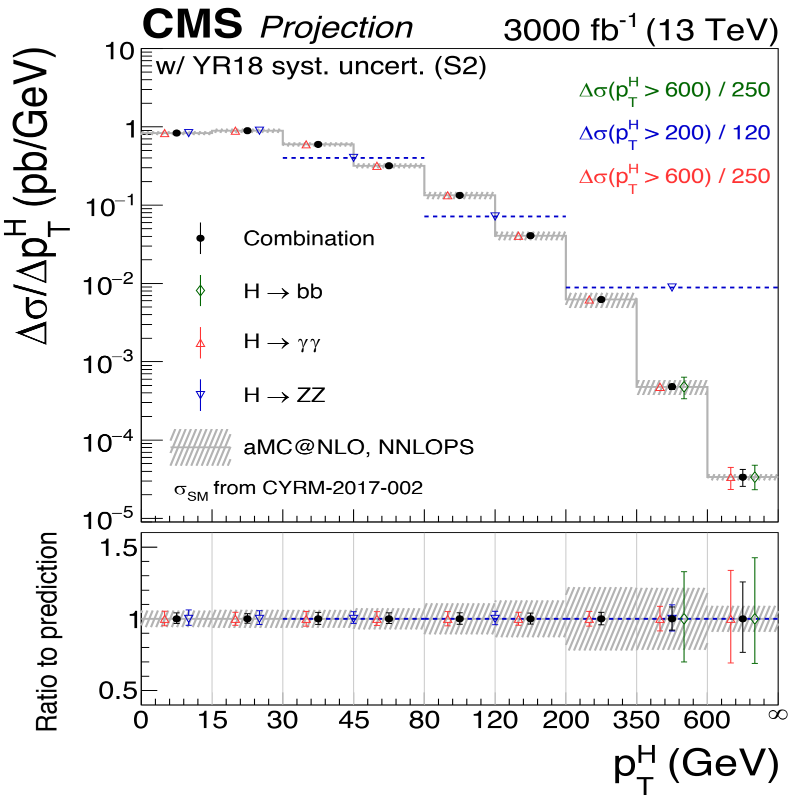
3000 fb^{-1} CMS

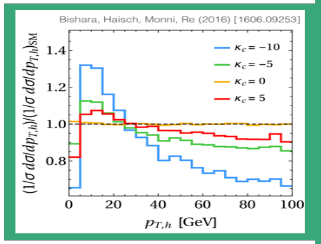
$p_T{}^H$ [GeV]	0-15	15-30	30-45	45-80	80-120	120-200	200-350	350-600	600-∞
H → γγ	5.1%	4.6%	5.1%	4.8%	4.9%	4.5%	5.1%	8.6%	32.2%
H → ZZ	5.4%	4.8%	4.1%		4.7%		9.1%		
H → bb	none							31.4%	36.8%
Combination	3.7%	3.3%	4.2%	3.7%	4.0%	3.8%	4.4%	8.0%	24.5%
6000 fb^{-1}									
Combination	2.9%	2.6%	3.2%	2.9%	3.0%	2.9%	3.2%	5.8%	17.9%

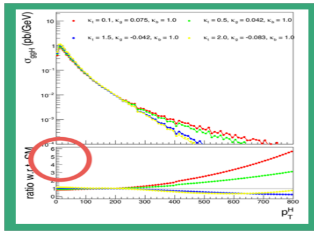
Higgs boson properties

Projections based on Run-2 combined differential XS (HIG-17-028):

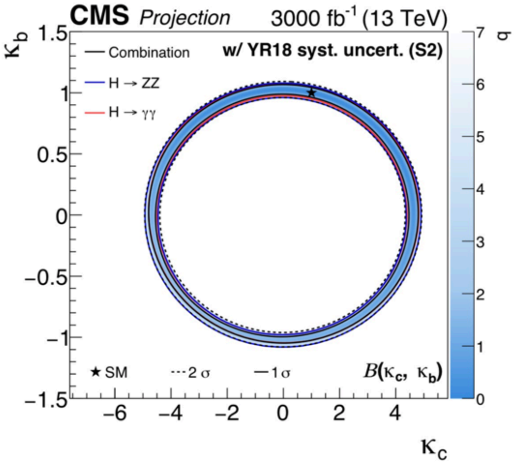
- Channels: H→γγ, H→ZZ→4l, boosted H→bb (in the high p_T^H tail)
- Constraints on effective kb, kc, kt, cg couplings (competitive with direct probes).



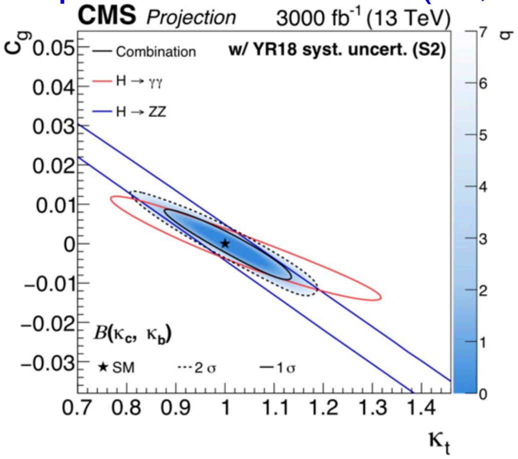




Expected 2D limits in (cg, kt)



Expected 2D limits in (kb, kc)



Reduction of uncertainties @3ab^{-1}:

- High-p_T^H region: x10
- Low-p_T^H region: x4

Anomalous HVV interactions

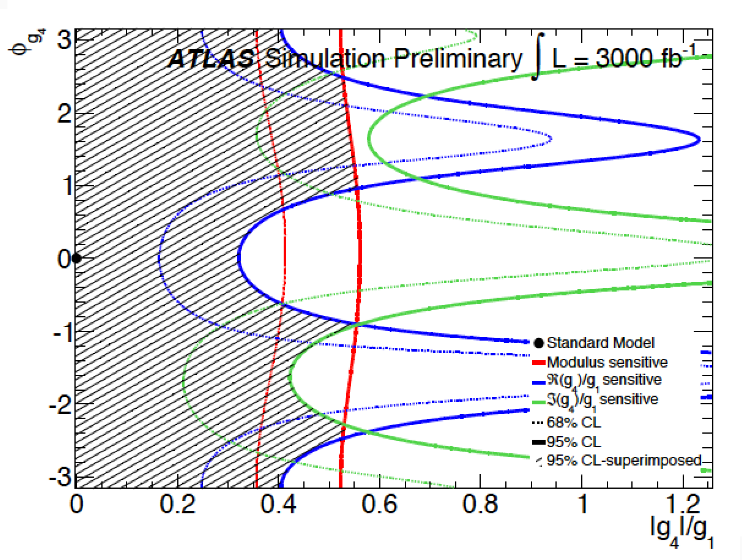
Performance to be estimated using the H→ 4ℓ analysis @13 TeV.

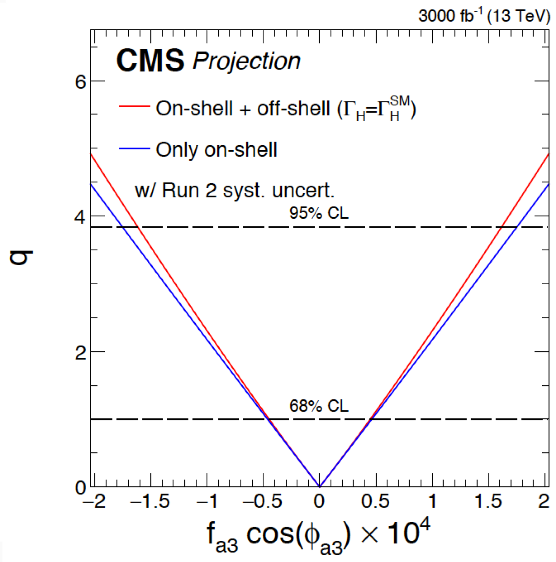
- Parameterisation of decay amplitude:

$$A = \frac{1}{v}\left[\overset{\text{SM}}{a_1^{VV}} + \overset{\text{leading momentum expansion}}{\frac{\kappa_1^{VV} q_1^2 + \kappa_2^{VV} q_2^2}{\left(\Lambda_1^{VV}\right)^2} + \frac{\kappa_3^{VV}(q_1+q_2)^2}{\left(\Lambda_Q^{VV}\right)^2}}\right] m_{V1}^2 \epsilon_{V1}^* \epsilon_{V2}^* + \overset{\text{higher order cp-even}}{a_2^{VV}} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + \overset{\text{cp-odd}}{a_3^{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$

Powerful constraints on anomalous couplings:

- Exploiting information from:
  - H decay (on-shell)
  - H on-shell production
  - H off-shell production:
- Sensitivity driven by on-shell production-level info. Some model dependance from assumption on HWW/HZZ relation.





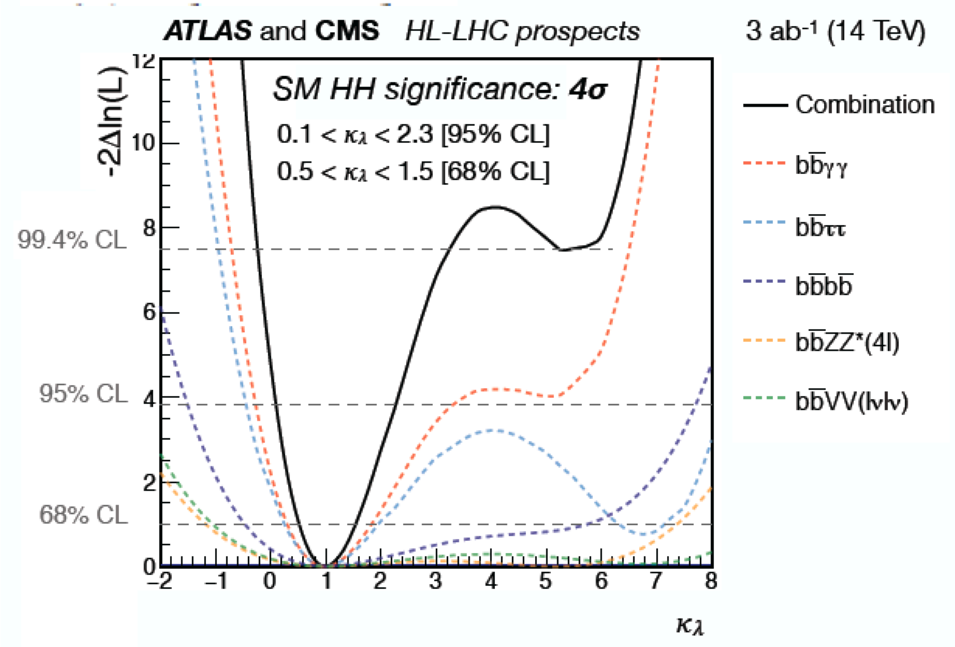
Parameter	Information from	95% CL interval
f_{a3}	decay	$\pm 120 \cdot 10^{-4}$
f_{a3}	decay & production	$\pm 1.8 \cdot 10^{-4}$
f_{a3}	decay & production & off-shell	$\pm 1.6 \cdot 10^{-4}$

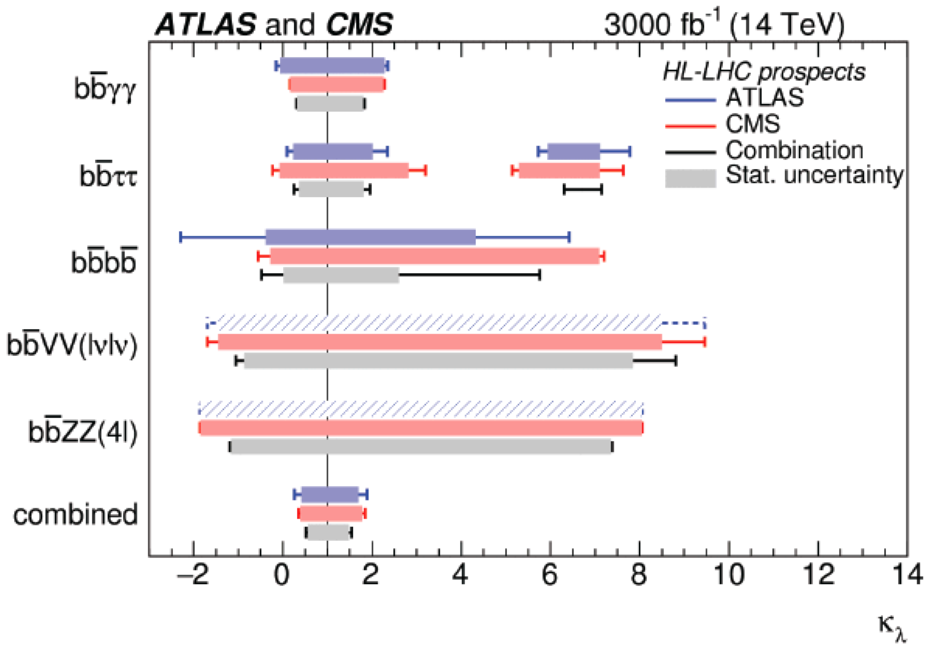
Constraints on fractional CP-odd presence $<1.6 \cdot 10^{-4}$

HH: CMS and ATLAS combined

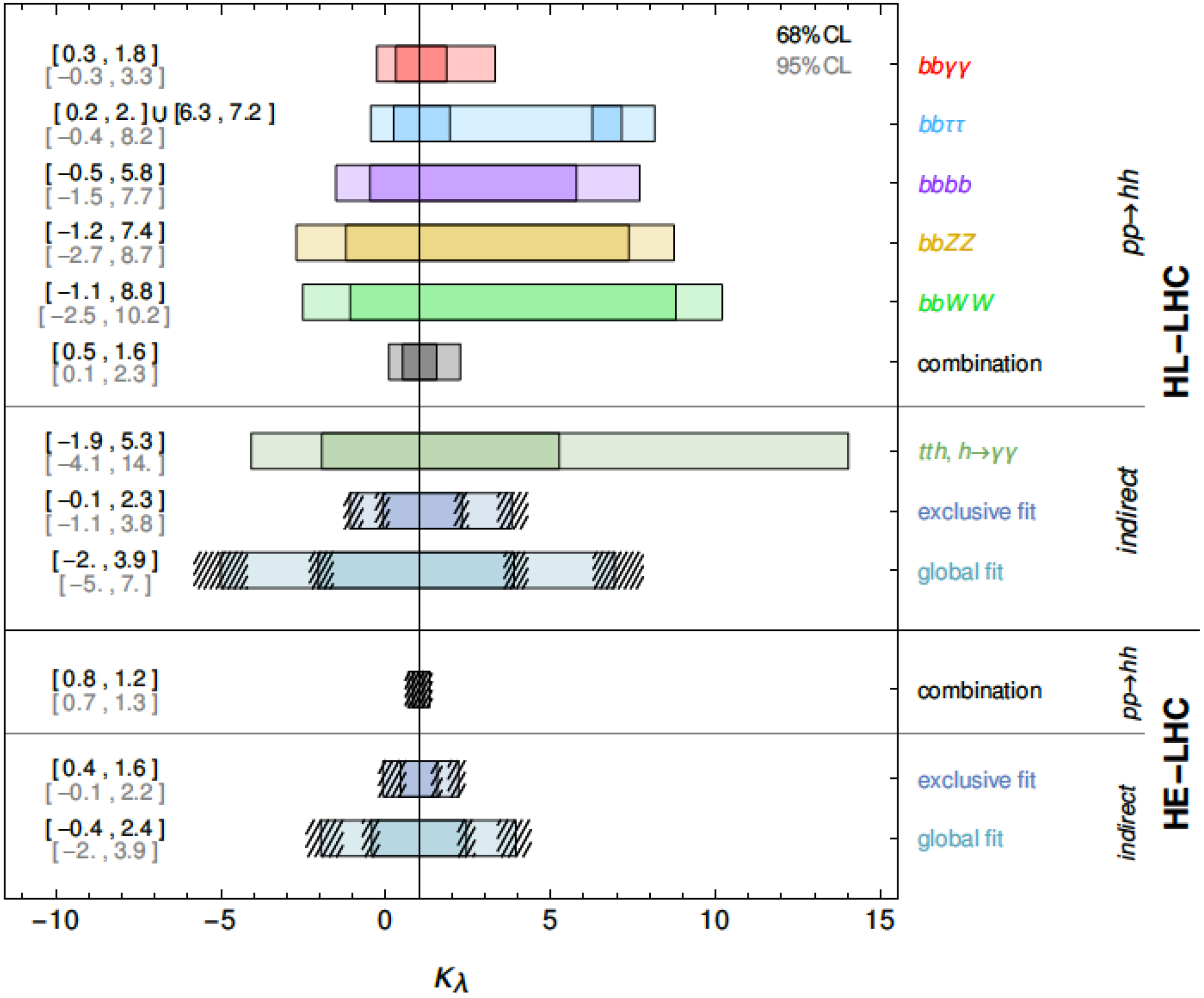
	Statistical-only		Statistical + Systematic	
	ATLAS	CMS	ATLAS	CMS
$HH \to b\bar{b}b\bar{b}$	1.4	1.2	0.61	0.95
$HH \to b\bar{b}\tau\tau$	2.5	1.6	2.1	1.4
$HH \to b\bar{b}\gamma\gamma$	2.1	1.8	2.0	1.8
$HH \to b\bar{b}VV(ll\nu\nu)$	-	0.59	-	0.56
$HH \to b\bar{b}ZZ(4l)$	-	0.37	-	0.37
combined	3.5	2.8	3.0	2.6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

$$\kappa_\lambda = \lambda_{\mathrm{HHH}}/\lambda_{\mathrm{HHH}}^{\mathrm{SM}}.$$



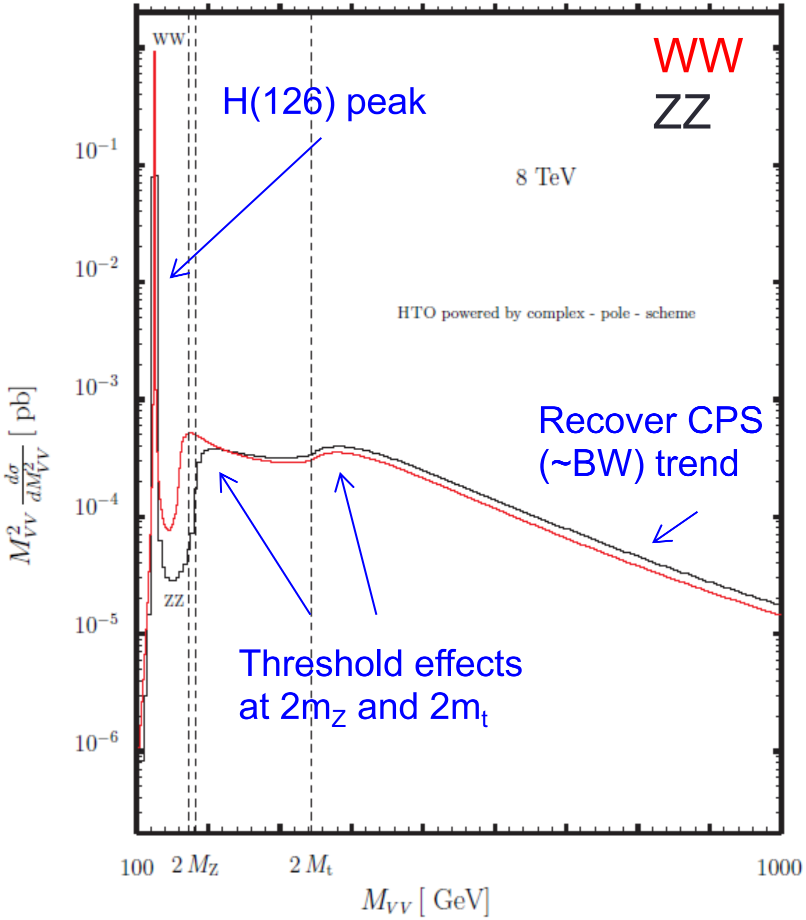


Constraints on the trilinear coupling



Constraint on the Γ_H from H*(126)→ZZ

gluon-gluon fusion production



H(126) peak

Recover CPS (~BW) trend

Threshold effects at $2m_Z$ and $2m_t$

Off-shell H*(126)→VV (V=W,Z)

- In N. Kauer and G. Passarino, JHEP 08 (2012) 11 it has been shown that the off-shell production cross section is sizeable at high ZZ invariant mass
- that comes from a peculiar cancellation between BW trend and Γ(H→VV)
- Enhancement of **7.6%** of total cross section in the ZZ final state

	Tot[pb]	$M_{ZZ} > 2\,M_Z$[pb]	R[%]
$gg \to H \to$ all	19.146	0.1525	0.8
$gg \to H \to ZZ$	0.5462	0.0416	7.6

Constraint on the Γ_H from $H^*(126) \rightarrow ZZ$

F. Caola, K. Melnikov (Phys. Rev. D88 (2013) 054024) and
J. Campbell et al. (arXiv:1311.3589)
showed how this feature can be turned into a **constraint on the total Higgs width**

$$\frac{d\sigma_{gg\to H\to ZZ}}{dm^2_{ZZ}} \propto g_{ggH}g_{HZZ}\frac{F(m_{ZZ})}{(m^2_{ZZ}-m^2_H)^2+m^2_H\Gamma^2_H} \Rightarrow \sigma^{on-peak}_{gg\to H\to ZZ} \propto \frac{g^2_{ggH}g^2_{HZZ}}{\Gamma_H}, \quad \sigma^{off-peak}_{gg\to H\to ZZ} \propto g^2_{ggH}g^2_{HZZ}$$

→ so measuring the ratio of $\sigma^{off\text{-}peak}$ and $\sigma^{on\text{-}peak}$ → measurement of Γ_H

$$\sigma^{on-peak}_{gg\to H\to ZZ} = \frac{\kappa^2_g\kappa^2_Z}{r}(\sigma\cdot BR)_{SM} \equiv \mu(\sigma\cdot BR)_{SM}$$

$$\frac{d\sigma^{off-peak}_{gg\to H\to ZZ}}{dm_{ZZ}} = \kappa^2_g\kappa^2_Z\cdot\frac{d\sigma^{off-peak,SM}_{gg\to H\to ZZ}}{dm_{ZZ}} = \mu r\frac{d\sigma^{off-peak,SM}_{gg\to H\to ZZ}}{dm_{ZZ}}$$

$$\kappa_g = g_{ggH}/g^{SM}_{ggH}$$
$$\kappa_Z = g_{HZZ}/g^{SM}_{HZZ},$$
$$\boxed{r = \Gamma_H/\Gamma^{SM}_H}$$

Once μ is fixed a determination of r is obtained and so for Γ_H :

μ from CMS 4l paper arXiv:1312.5333
and provide result in **two** ways:

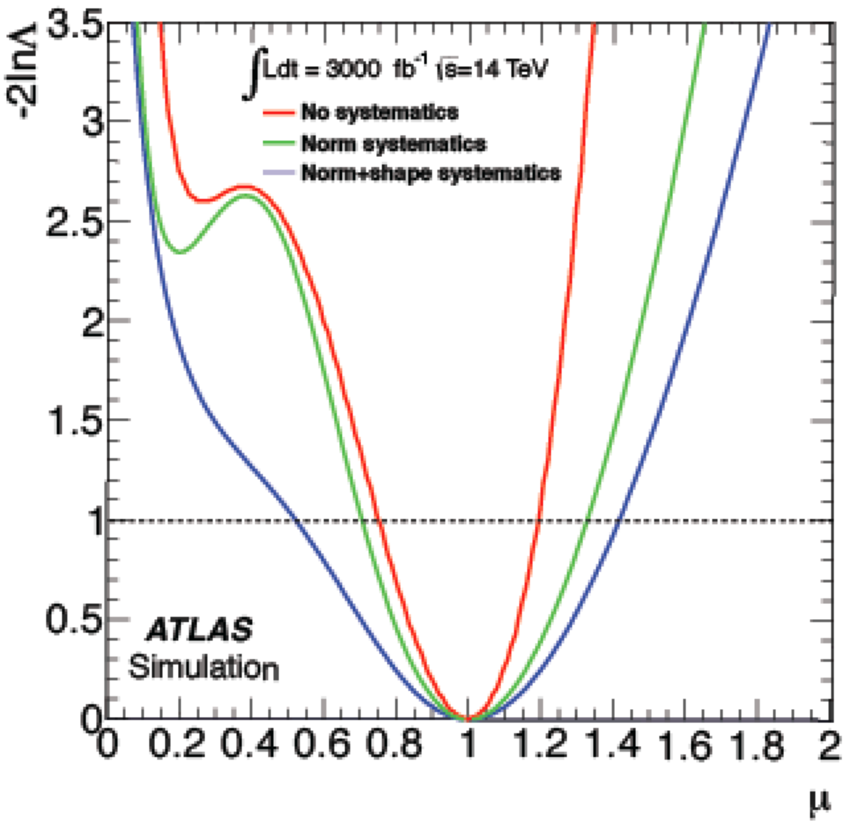
“μ expected”: use expected signal strength

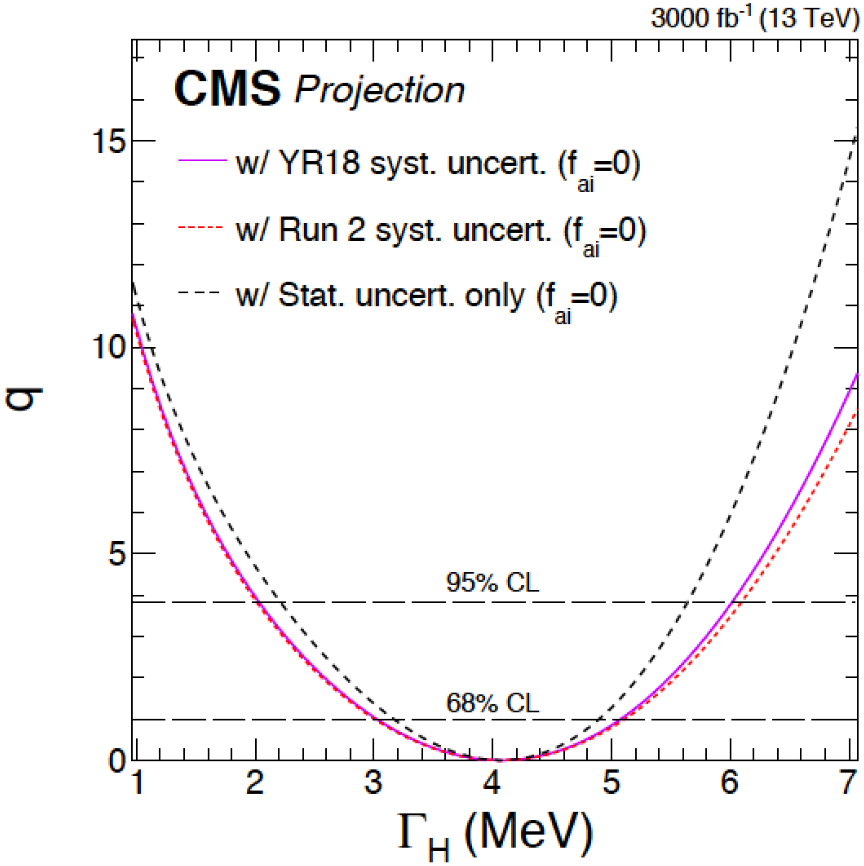
“μ observed”: use observed signal strength

The interference with continuum gg → ZZ is taken into account at high mass → **gg2VV/MCFM**
VBF production is 10% at high mass → **PHANTOM**

Limits on the Higgs 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: $4.1^{+1}_{-1.1}$ MeV, ATLAS projection: $4.1^{+1.5}_{-2.1}$ MeV
  - ATLAS projection based on Run I analysis, used large theoretical uncertainties that have been reduced in the meantime
- Assuming ATLAS analysis would have same sensitivity as CMS analysis at HL-LHC, combined constraint on the width **$4.1^{+0.7}_{-0.8}$ MeV**

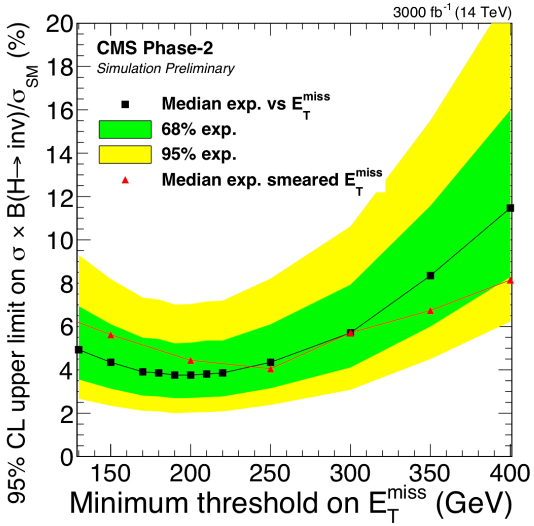


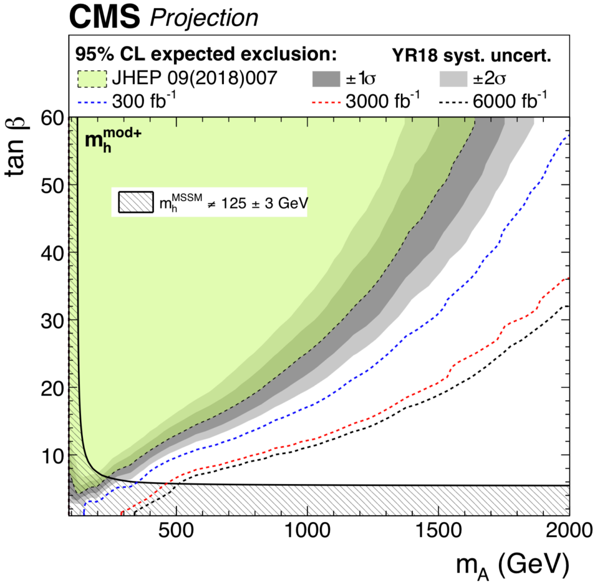


Sensitivity to BSM effects in Higgs physics

Several studies on probing the BSM effects in the Higgs physics :

- Probe for anomalous interactions & rare/exotic decays:
  - H→ invisible
    B_{INV} < 3,8% (compare to 22% @Run2) [FTR-18-016]
  - Exotic/rare/forbidden decays and signatures
    - **B_{BSM} < 6%** from couplings combination
      (compare to 34% @Run2) [FTR-18-011]
  - L1T TrackJet for BSM Higgs signatures
    - signatures with displaced jets [FTR-18-018]
  - Anomalous couplings and width:
    - significant improvement in limits on anom. coupl.
      Width: **$\Gamma_H \subset$ [2,6] MeV @ 95%CL** [FTR-18-011]
- Search for additional Higgs bosons and/or scalars :
  - MSSM H→ττ search [FTR-18-017]
  - High mass search X→ZZ->2l2q
    [FTR-18-040)





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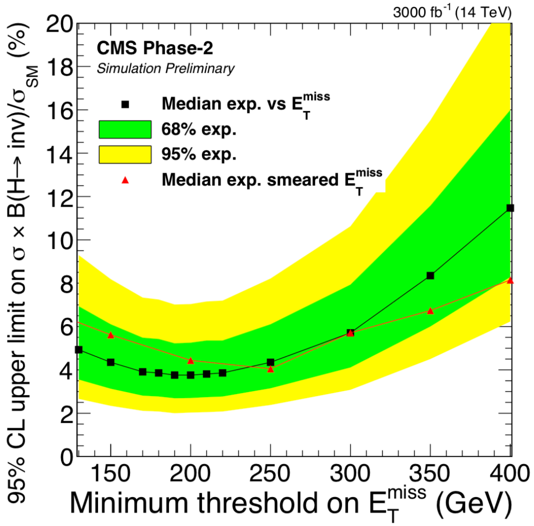

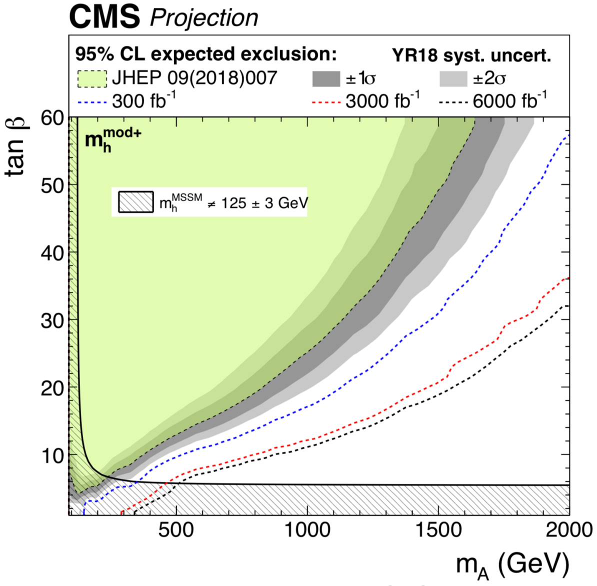

Higgs to Invisible decays

- Current observed (expected) limits on B_{inv} at 95% CL:
  - ATLAS: < 26% (17%)
  - CMS: < 22% (17%)
- VBF production mode dominates sensitivity → HL-LHC sensitivity studied using Delphes simulation
- With optimised selection: **B_{inv}<3.8%** at 95% CL with 3000 fb^{-1} at HL-LHC
- Degradation of E_T^{miss} resolution does not impact the sensitivity significantly
- Combining with previous ATLAS projection of VH channel, and assuming both experiments would perform equally well in both channels: **B_{inv}<2.5%** at 95% CL