Higgs measurements at the HL-LHC

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For the CMS and ATLAS collaborations

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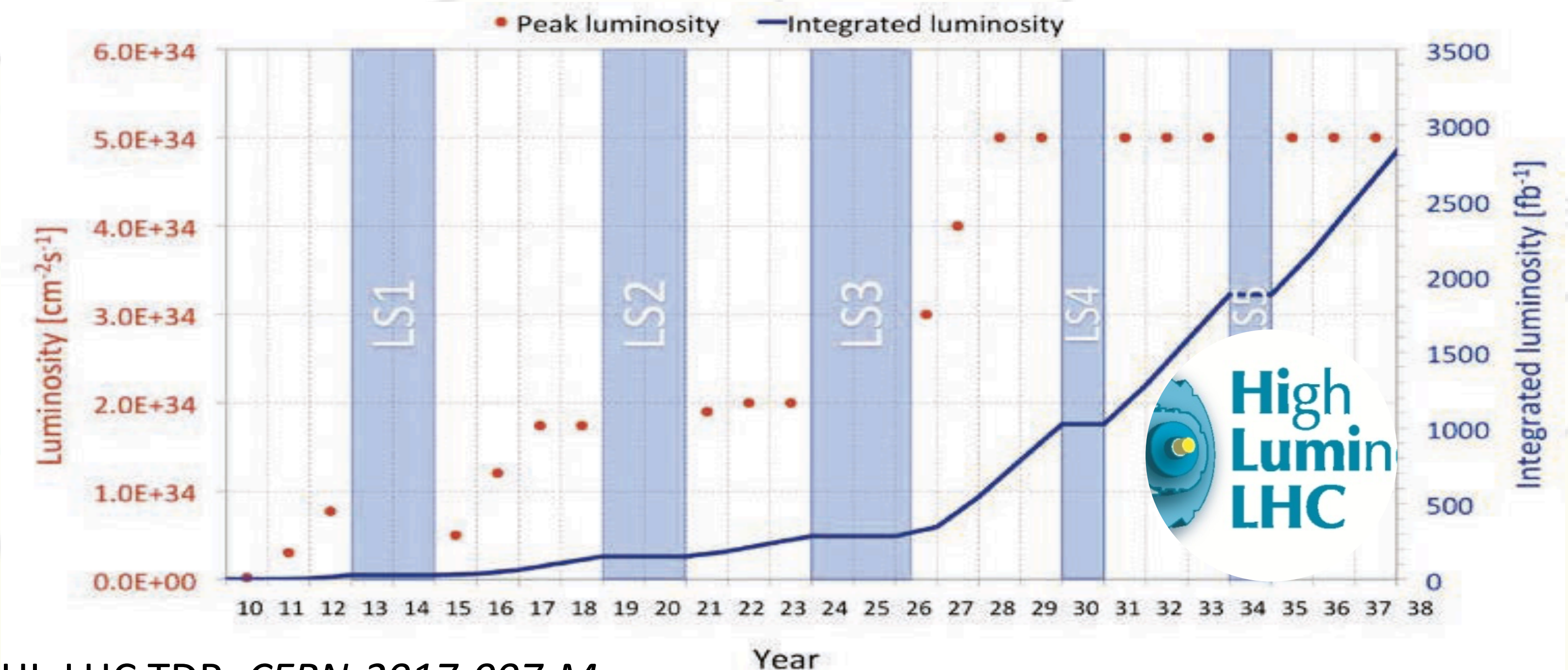
Expected HL-LHC dataset



HL-LHC TDR, *CERN-2017-007-M*

- So far we have collected **only ~5% (!)** of the total data-set.
- Many upgrades to the LHC and the detectors are needed to achieve the final goal.
- Large improvements on the Higgs properties are expected in the HL-LHC era.

Framework for extrapolations

- The projections are based on extrapolations of current Run II (13 TeV) published analyses on the following channels:

Search channel	Production modes
H → $\gamma\gamma$	ggH, VBF, VH, ttH
H → ZZ → 4l	ggH, VBF, VH, ttH
H → W^+W^- → $l^+\nu l^-\nu$	ggH, VBF, VH
H → $\tau^+\tau^-$	ggH, VBF
H → bb	VH, ttH, ggH boosted
H → leptons	ttH
H → $\mu^+\mu^-$	ggH, VBF
H → Zγ	ggH, VBF

- Fits to nominal "Asimov" data, scaled to the higher luminosities, and likelihood scans are performed to determine the uncertainties on signal strengths $\mu = \sigma * B/\sigma^{SM} * B^{SM}$, and coupling scale factors κ_i ("κ framework"):

$$\sigma_i \times \mathrm{B}(H \to f) = \frac{\sigma_i \times \Gamma_f}{\Gamma_H} = \frac{\kappa_i^2 \kappa_f^2}{\kappa_H^2} \sigma_i^{\mathrm{SM}} \times \mathrm{B}^{\mathrm{SM}}(H \to f)$$

Systematic uncertainty assumptions

Reference scenarios:

S1: conservative scenario using the uncertainties of the current Run II measurements assuming the higher pile-up effects will be compensated by detector upgrades.

S2: uncertainties approximately **half** the Run II values, assumes improvements due to detector upgrades and reduced uncertainties on the methods. Luminosity uncertainty ~1% and the uncertainty due to size of simulations is negligible.

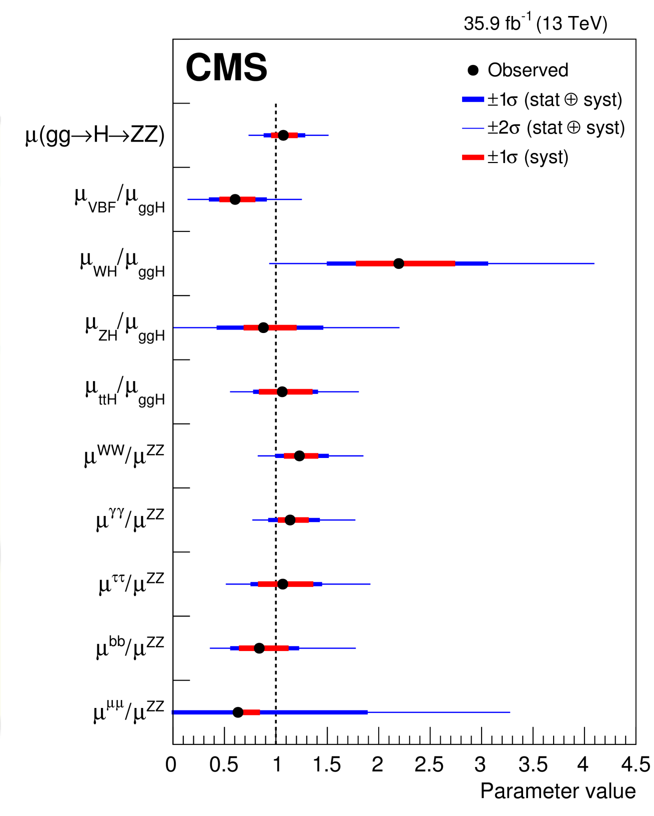
Table 1: The sources of systematic uncertainty for which minimum values are applied in S2.

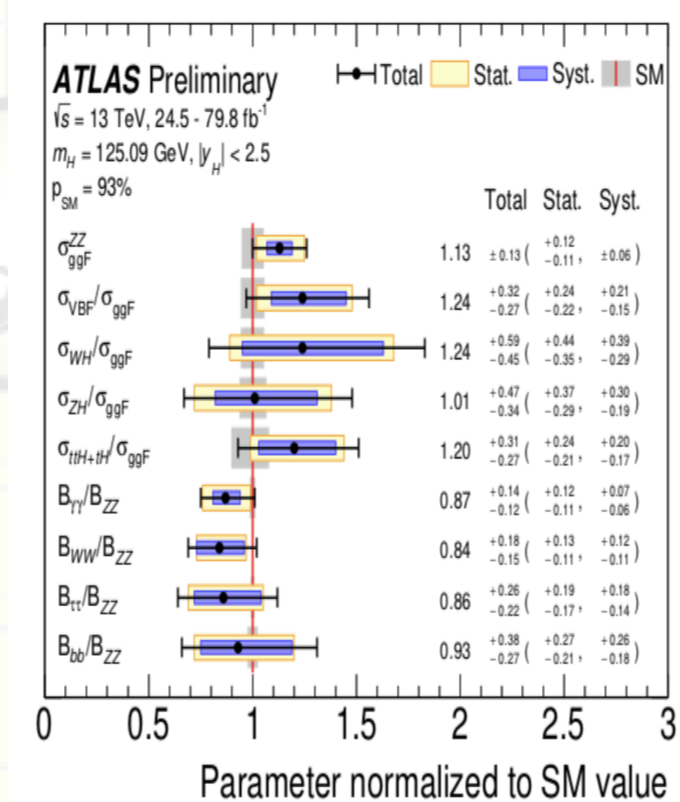
Source	Component	Run 2 uncertainty	Projection minimum uncertainty
Muon ID		1–2%	0.5%
Electron ID		1–2%	0.5%
Photon ID		0.5–2%	0.25–1%
Hadronic tau ID		6%	2.5%
Jet energy scale	Absolute	0.5%	0.1–0.2%
	Relative	0.1–3%	0.1–0.5%
	Pileup	0–2%	Same as Run 2
	Method and sample	0.5–5%	No limit
	Jet flavour	1.5%	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 follow the LHC Yellow Report 4.
More details can be found at: ATL-PHYS-PUB-2018-054 , CMS-PAS-FTR-18-011

Current signal strengths

Run 2 (36-80 fb^{-1})





- Production and decays already probed with **~12% precision** in best channels. Current global signal strengths:

[ATLAS-CONF-2019-005]
[CMS-HIG-17-031]

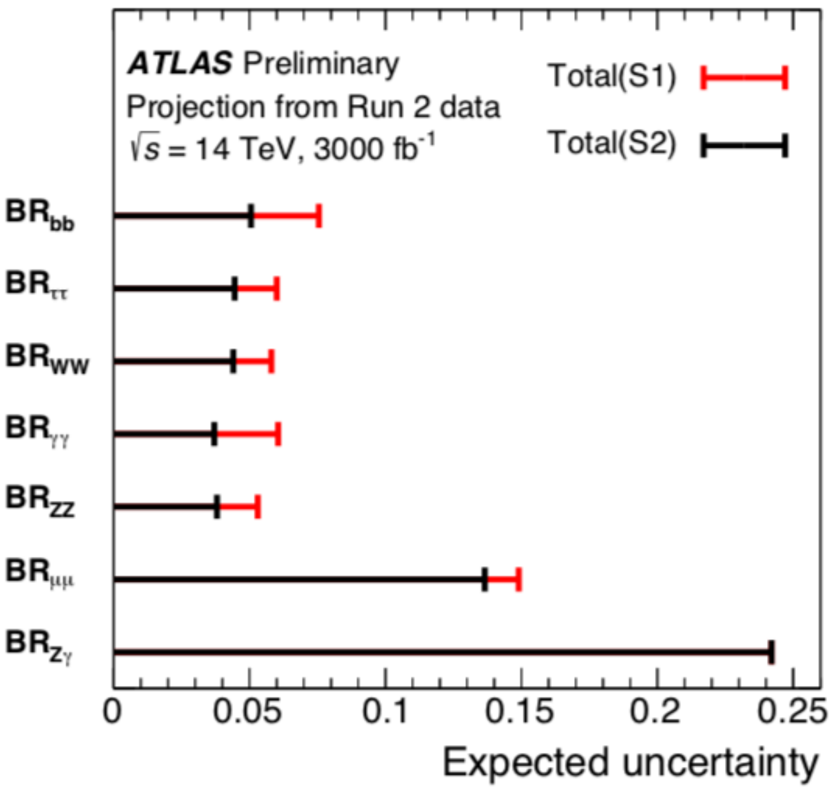
ATLAS : $\mu = 1.11^{+0.09}_{-0.08} = 1.11 \pm 0.05\,(\text{stat.})\,^{+0.05}_{-0.04}\,(\text{exp.})\,^{+0.05}_{-0.04}\,(\text{sig. th.}) \pm 0.03\,(\text{bkg. th.})$

CMS : $\mu = 1.17 \pm 0.10 = 1.17 \pm 0.06\,(\text{stat})\,^{+0.06}_{-0.05}\,(\text{sig theo}) \pm 0.06\,(\text{other syst})$

Largest exp. uncs.:
Lumi, e/γ
MC, Jet/MET
Bkg. model, b-tag.

Projected precision per decay

- The vector decays reach 3-4% precision, the fermion decays reach 4-5%.
- The dimuon and Zγ decays will be observed with 15% and 25% precision.
- S2 provides order of 30% improvement largely due to reduced theory uncertainties.



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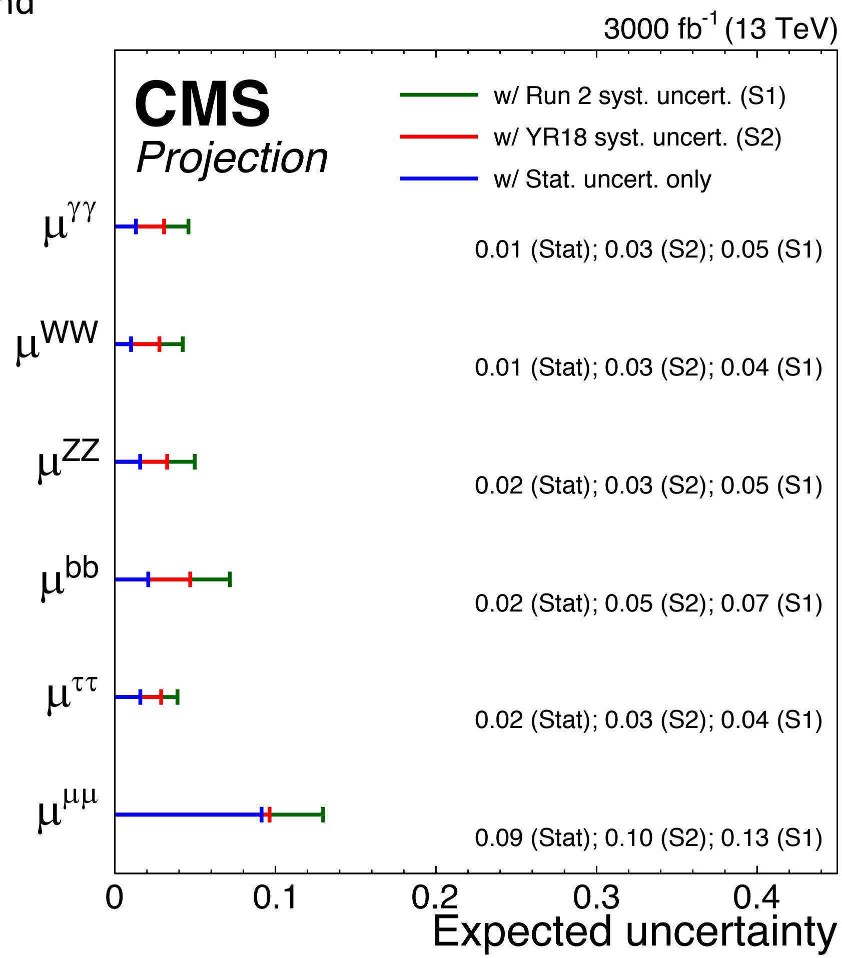
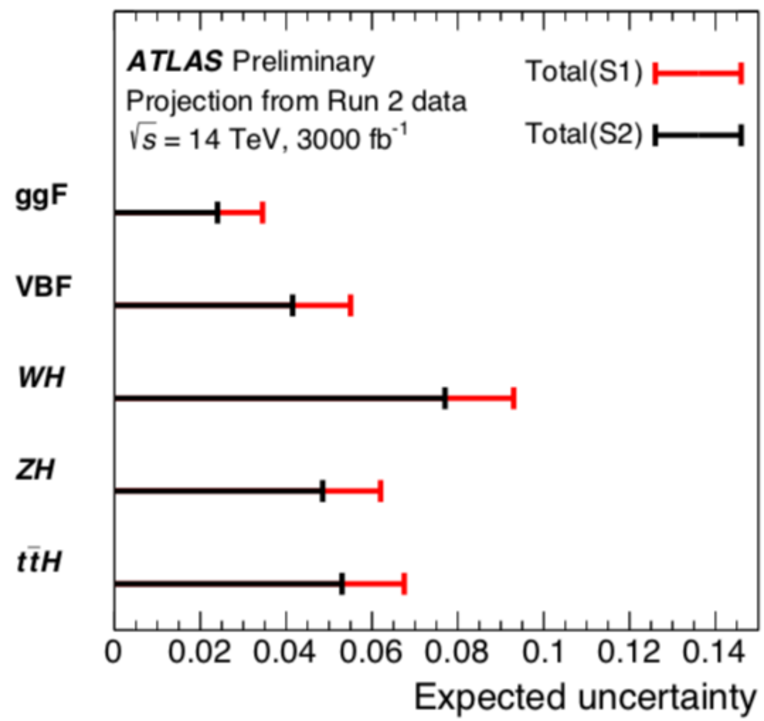


CMS-PAS-FTR-18-011

Projected precision per production

- ggF will be measured at ~3% (best case) and WH at ~8% (worst case).



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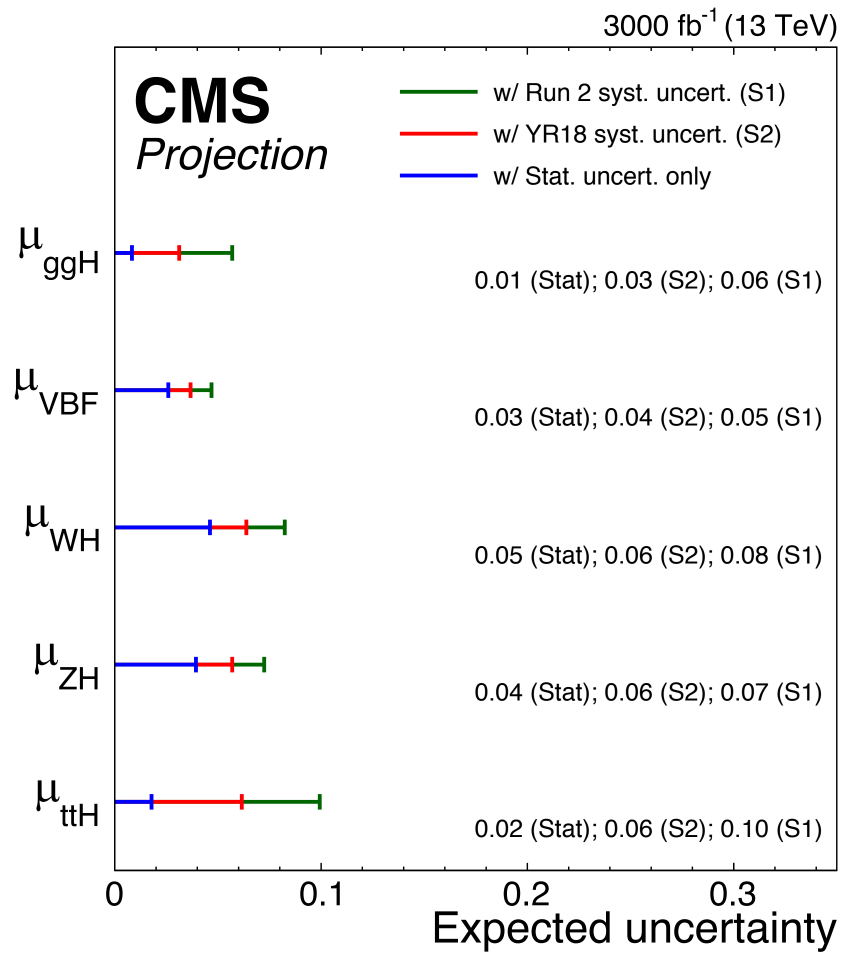
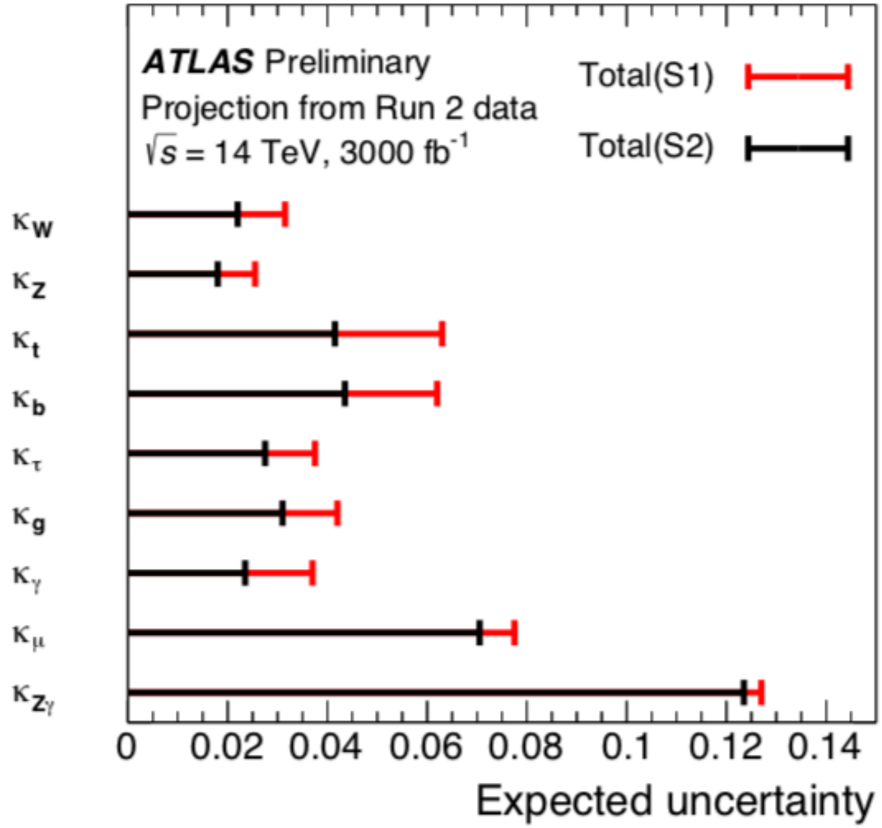


CMS-PAS-FTR-18-011

Projected precision on couplings

- Uncertainty on the coupling modifiers is roughly half the uncertainty on the corresponding signal strength.
- Only κ_μ and $\kappa_{Z\gamma}$ remain statistically dominated.



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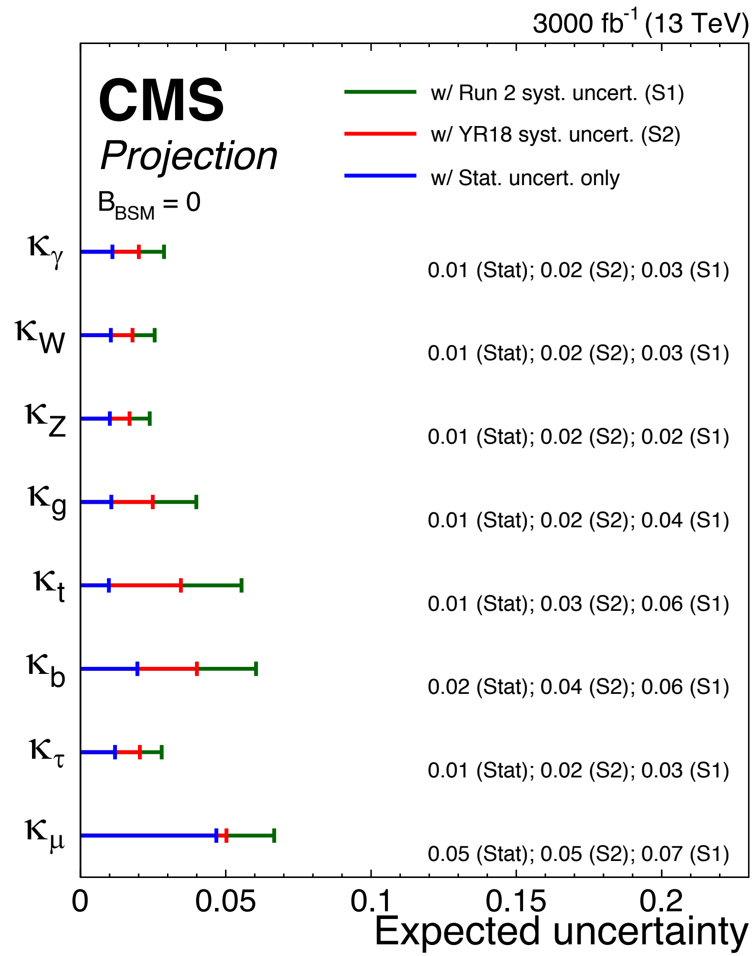
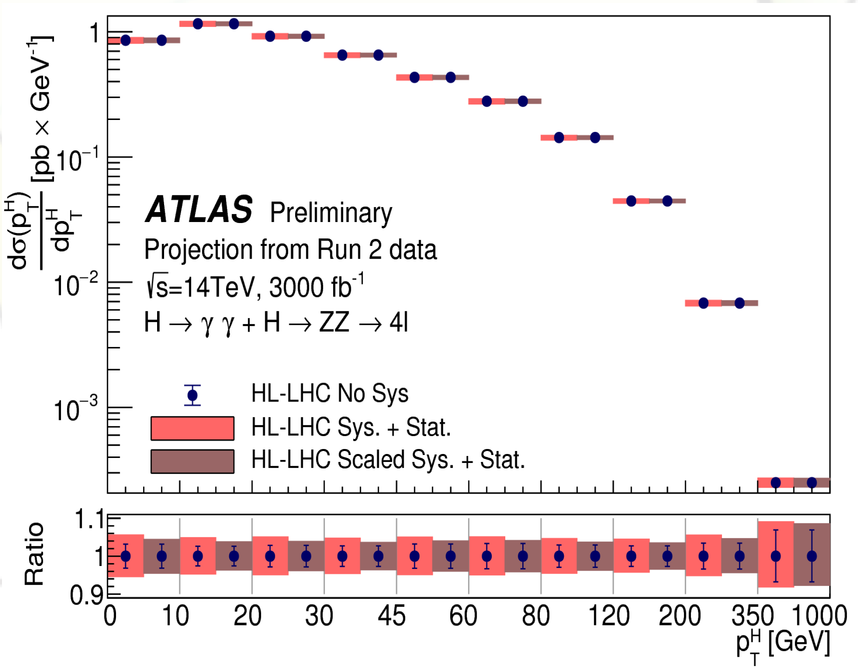
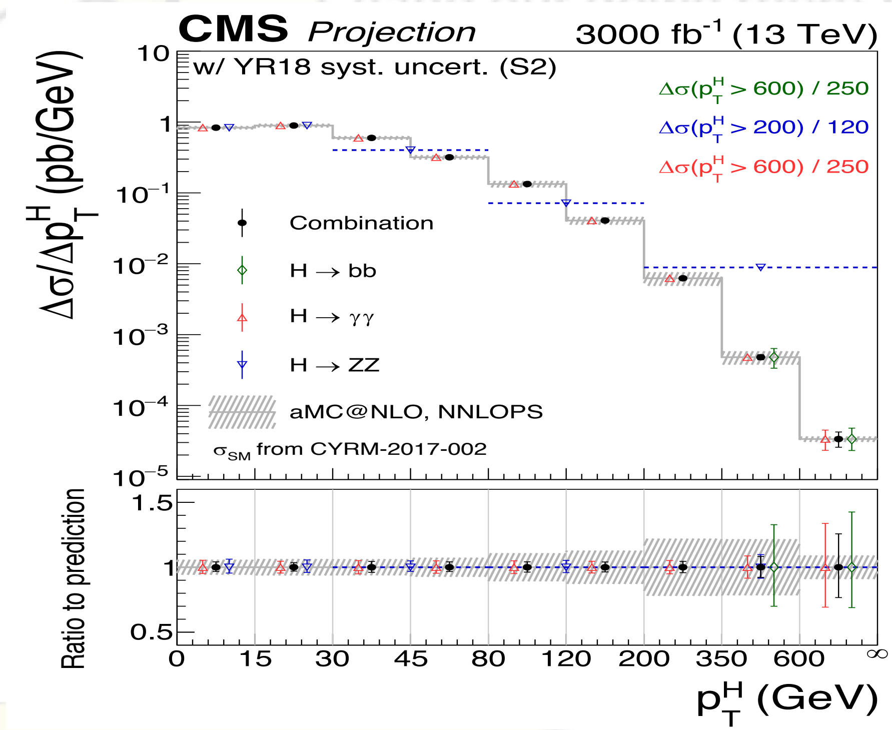


CMS-PAS-FTR-18-011

Differential distributions

- Production distributions provide important tests of the SM and BSM models. These will be most precisely measured with the combination of the 4-lepton and diphoton channels as shown below.
- We expect to probe up to about p_T^H = 1 TeV with about 10% precision.

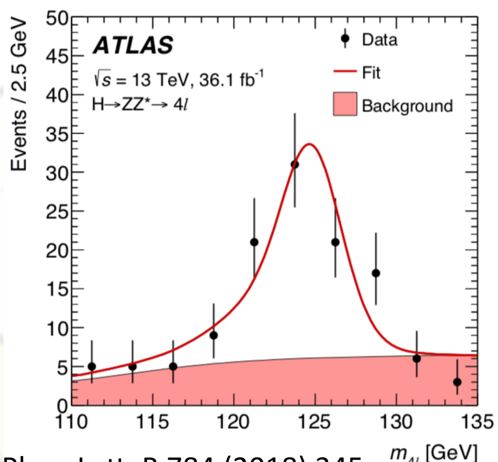




ATL-PHYS-PUB-2018-040

CMS-PAS-FTR-18-011

Mass and width



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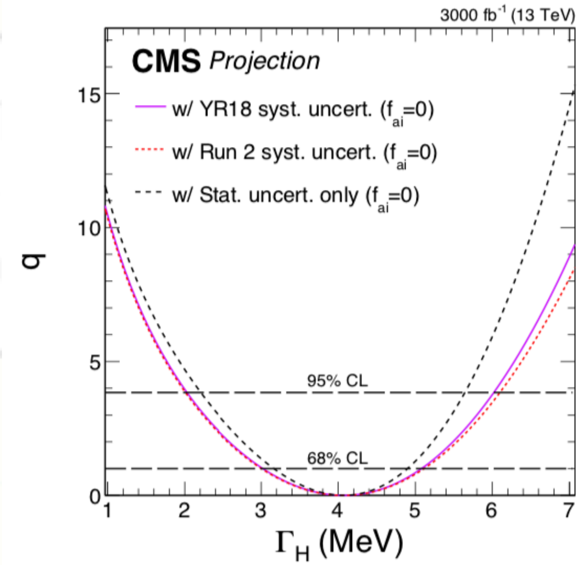
- 4 lepton (ZZ*) channel has the best precision on the Higgs mass and width.
- The precision on the **mass value** will be driven by the muon channel. The table shows the expected precision for different scenarios. The improvements are due to upgrades in the tracker.
- The off-shell event counting method gives $\mathbf{\Gamma_H \in [2.0,6.1]}$ at 95% CL in scenario S2.



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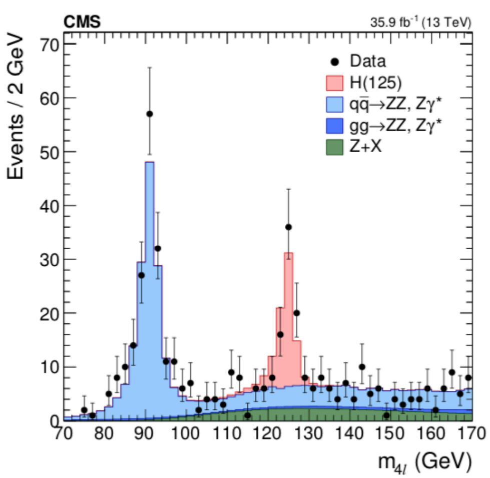


J. High Energ. Phys. (2017) 2017: 47

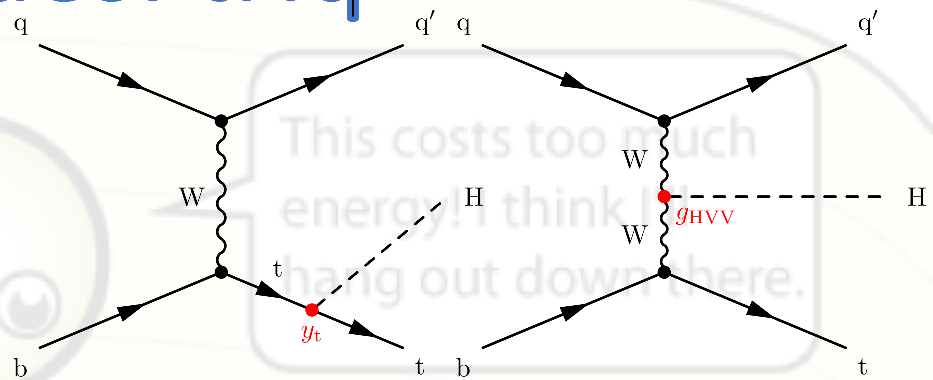
Expected Higgs mass precision with 3000 fb^{-1} using the ATLAS detector.

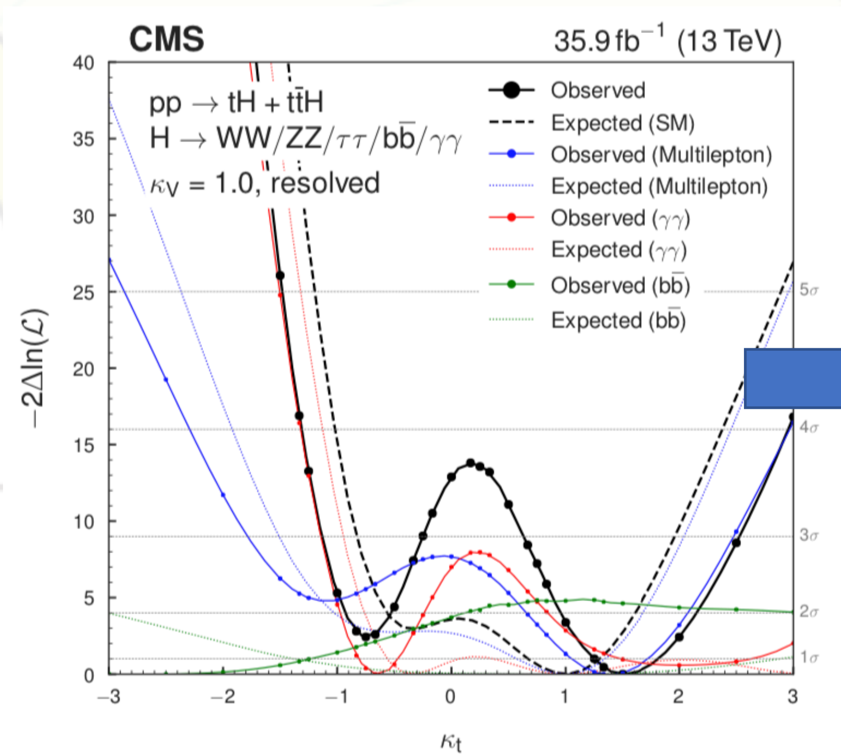
	Δ_{tot} (MeV)	Δ_{stat} (MeV)	Δ_{syst} (MeV)
Current Detector	52	39	35
μ momentum resolution improvement by 30% or similar	47	30	37
μ momentum resolution/scale improvement of 30% / 50%	38	30	24
μ momentum resolution/scale improvement 30% / 80%	33	30	14

ATL-PHYS-PUB-2018-054

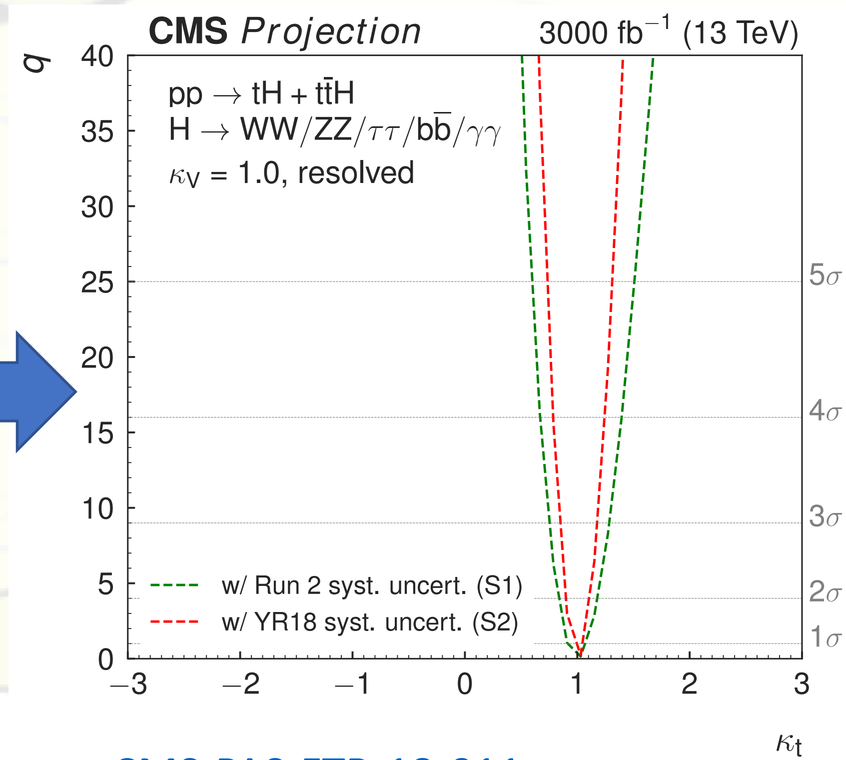
Rare production modes: tHq

- Production of single top and a Higgs boson (tH) has a small crossection of ~70 fb, but is sensitive to the sign of k_t. The estimation below expects to remove the sign ambiguity.





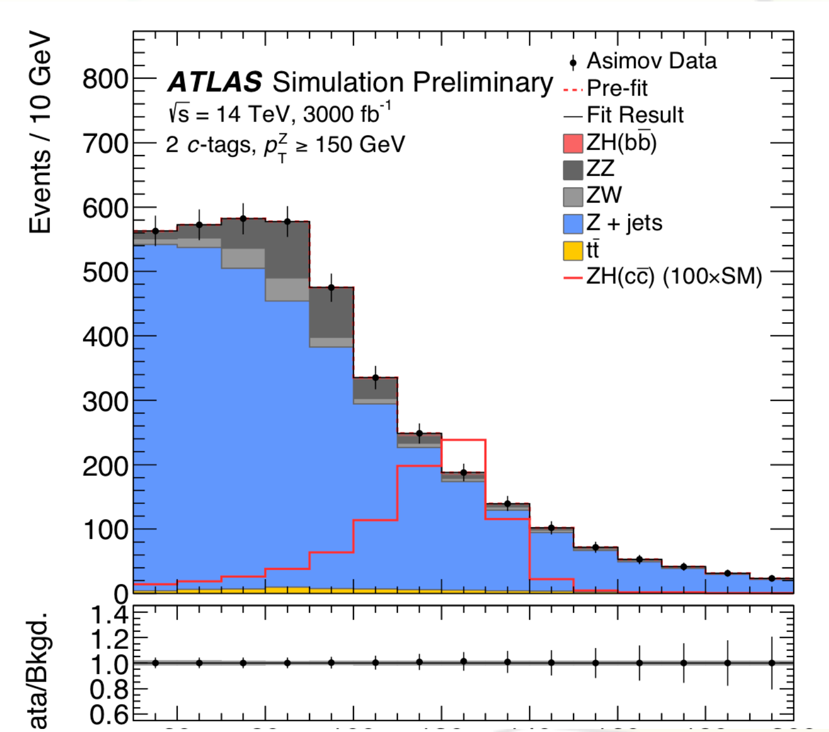
CMS-HIG-18-009

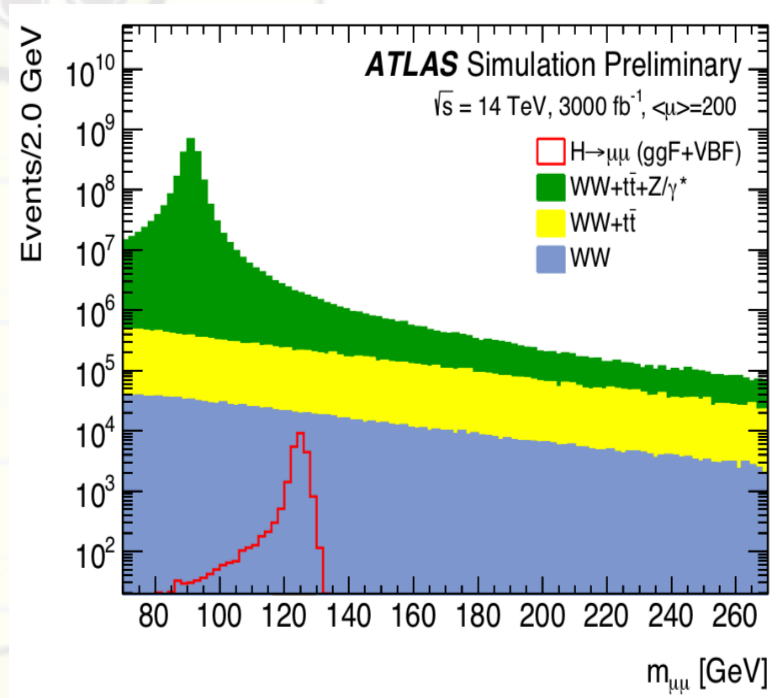


CMS-PAS-FTR-18-011

Rare decays: H→cc̄ , H→μ⁺μ⁻, H→Zγ

- Expected significance with 3000 fb^{-1}: >9σ for **H→μμ** and 4.9σ for **H→Zγ**
- Limit on the ***ZH(cc̄)*** : μ < 6.3 at 95%CL
in the absence of systematic uncertainties, and about 40% higher with typical systematics. Such a limit would provide strong constraints on new physics models.

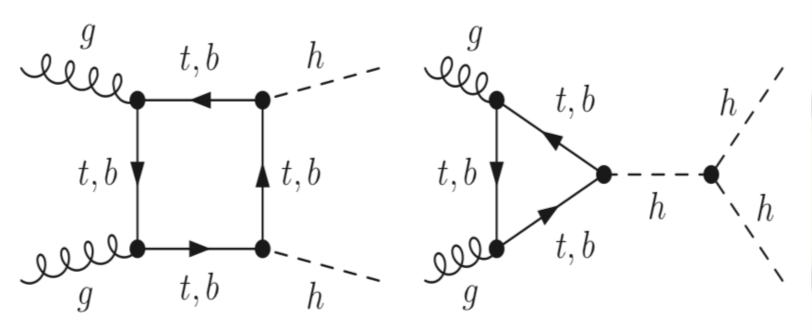




ATL-PHYS-PUB-2018-016

ATL-PHYS-PUB-2018-006

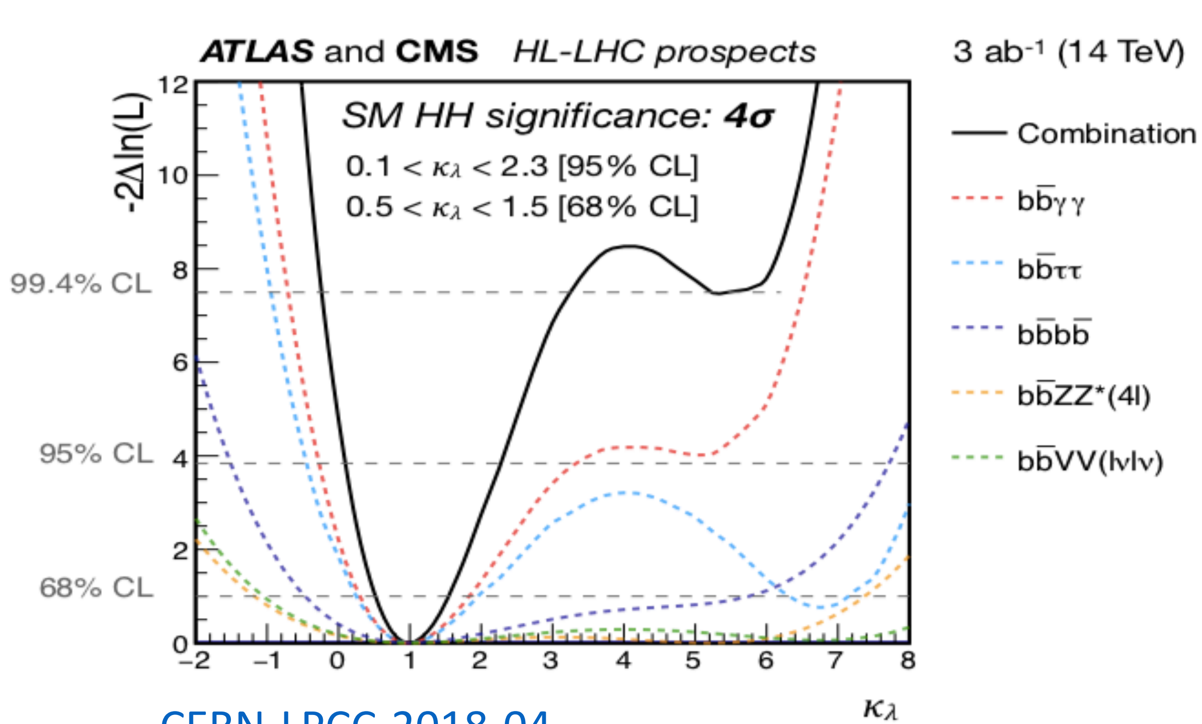
Di-Higgs (HH) production



- Sensitive to Higgs self-coupling (λ_{HHH}), small cross-section (~36 fb).
- Evidence at 2.6σ (3.0σ) is expected by CMS (ATLAS) for the detection of di-Higgs production.

ATL-PHYS-PUB-2018-053

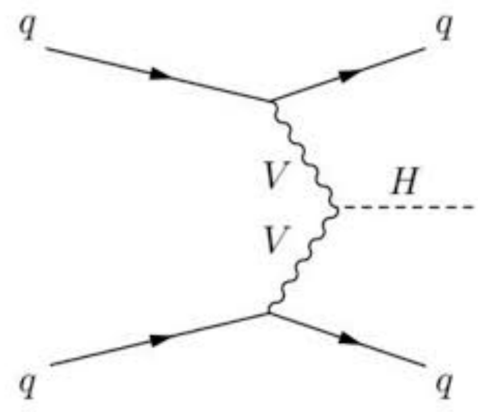
CMS-PAS-FTR-18-019

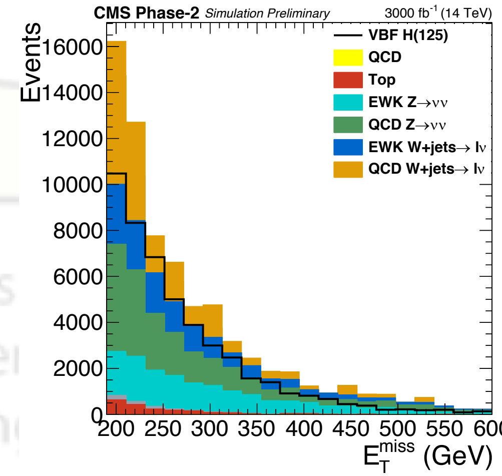


CERN-LPCC-2018-04

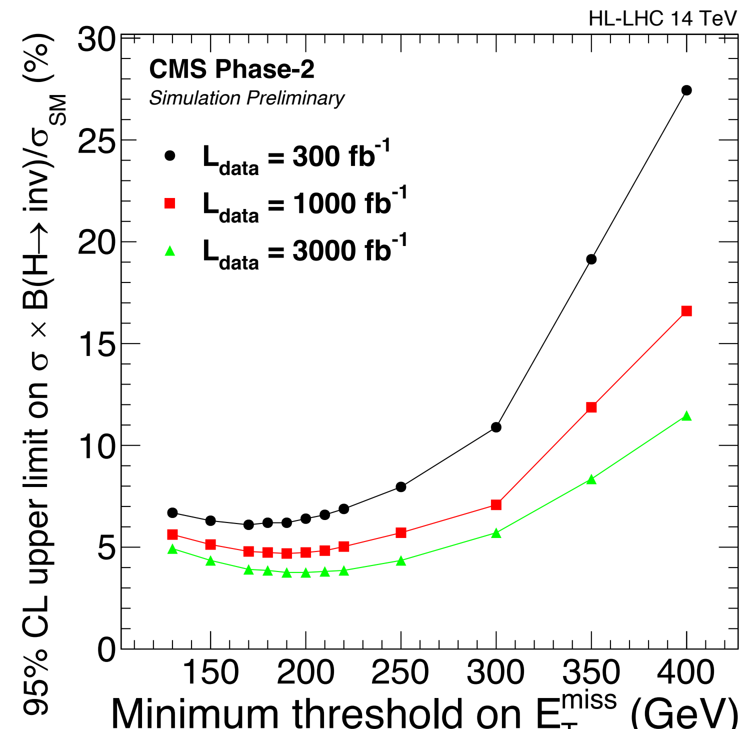
- 95% CL the limits expected on λ/λ^{SM} are: [-0.18,3.6] for CMS [-0.40,7.3] for ATLAS
- Combined: **[0.1,2.3]** this excludes λ_{HHH} =0.

Invisible decays





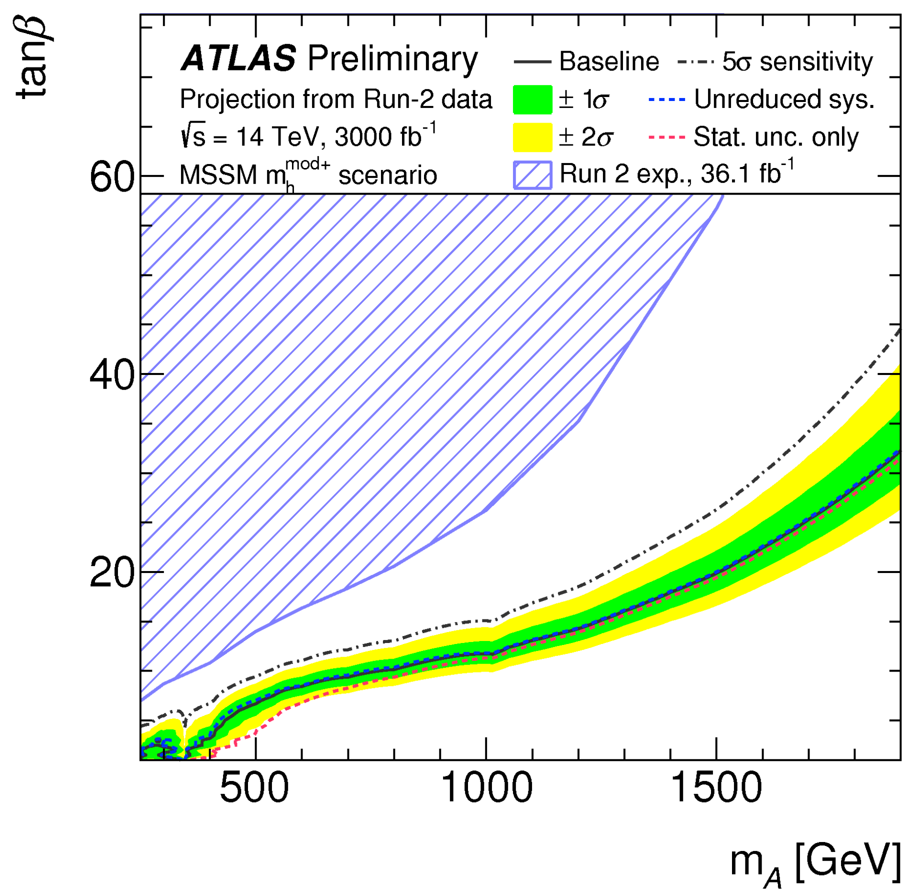
- The expected 95% CL upper limits on the branching ratio of the standard model Higgs boson to invisible particles are presented as a function of the lower threshold applied on the transverse missing energy.
- The 95% CL upper limit assuming standard model VBF production is expected to be at 3.8% for a threshold value of 190 GeV.

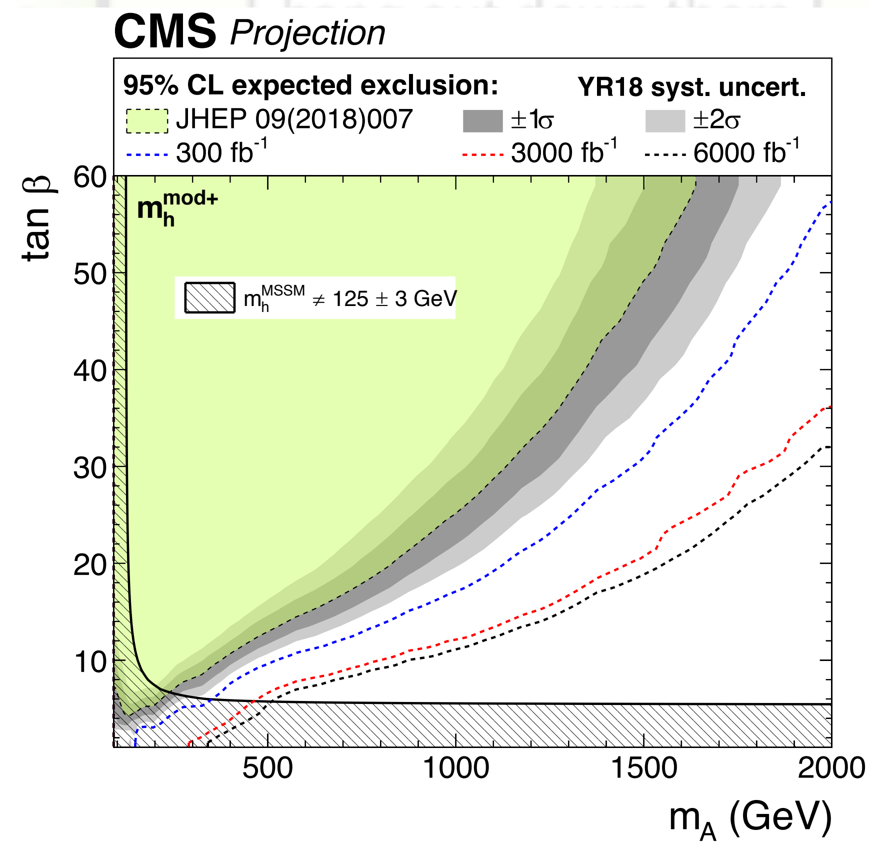


CMS-PAS-FTR-18-016

MSSM Higgs search

- MSSM benchmarks are probed with the $\tau^+\tau^-$ channel up to m_A = 2 TeV
- The exclusion for m_h^{mod+} model is shown below.





ATL-PHYS-PUB-2018-050

CMS-PAS-FTR-18-017

Summary

- The Higgs boson is yet to be fully explored. Currently <5% of the LHC potential has been used. The HL-LHC promises to deliver a much larger dataset where precision measurements will be possible.
- With the upgrades and expected improvements, the uncertainties on the coupling parameters and differential distributions will be reduced to a few percent enabling tests of the SM and BSM physics.
- We will be sensitive to rare decays and production modes like $\mu\mu$, $Z\gamma$, tH, and HH. The phase space for BSM models will be largely reduced.