# ATLAS+CMS Higgs combination: what have we learned?

- **This discussion is based on the run-1 ATLAS+CMS Higgs combination paper**
  - **This is still the most relevant one for combined measurements of Higgs properties**
  - **I was ATLAS editor for this paper**

- **Some theoretical considerations**

- **Overview of main results**

- **This is therefore NOT a discussion of the difficulties encountered in each individual measurement (an individual measurement corresponds ideally to a specific Higgs production and decay**

Theory: how precise do we need to be?
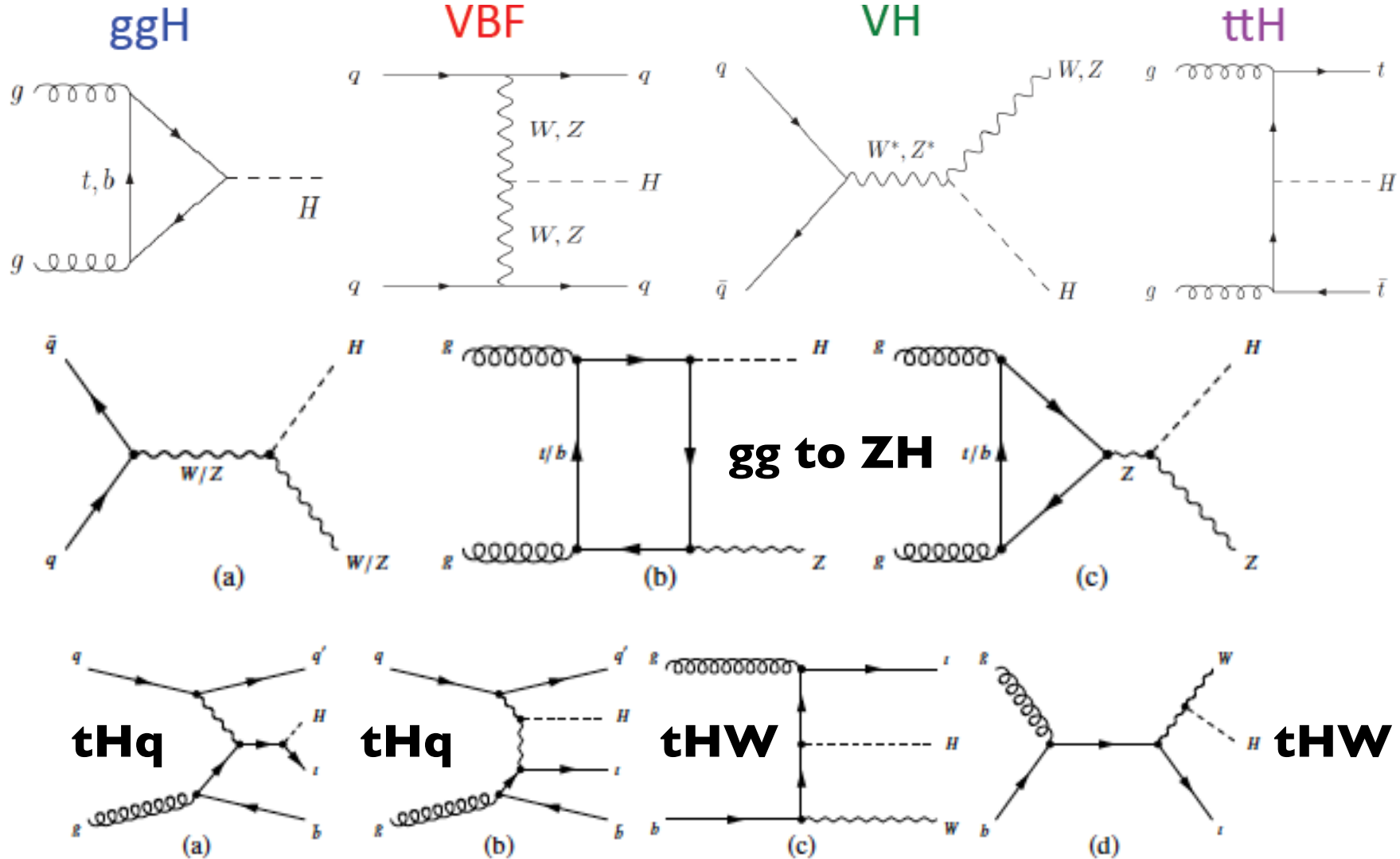
- **In BSM physics, both gg to ZH and tHq/tHW production processes may play an important role through interference effects**

Theory: how precise do we need to be?

Production process	Cross section [pb]		Order of calculation
	$\sqrt{s} = 7$ TeV	$\sqrt{s} = 8$ TeV	
ggF	15.0 ± 1.6	19.2 ± 2.0	NNLO(QCD)+NLO(EW)
VBF	1.22 ± 0.03	1.58 ± 0.04	NLO(QCD+EW)+~NNLO(QCD)
WH	0.577 ± 0.016	0.703 ± 0.018	NNLO(QCD)+NLO(EW)
ZH	0.334 ± 0.013	0.414 ± 0.016	NNLO(QCD)+NLO(EW)
$[ggZH]$	0.023 ± 0.007	0.032 ± 0.010	NLO(QCD)
bbH	0.156 ± 0.021	0.203 ± 0.028	5FS NNLO(QCD) + 4FS NLO(QCD)
ttH	0.086 ± 0.009	0.129 ± 0.014	NLO(QCD)
tH	0.012 ± 0.001	0.018 ± 0.001	NLO(QCD)
Total	17.4 ± 1.6	22.3 ± 2.0	

- **Today we have N³LO calculations for ggF, etc, etc (see K.Melnikov at LHCP)**
- **Does this help? Actually, less now than at the time of discovery. Why?**
  1. **Experiments have learned to do Higgs fiducial measurements, which are insensitive to the inclusive calculations**
  2. **Generic coupling measurements are expressed as ratios**

Theory: how precise do we need to be?

K. Melnikov

Instead, I want to spend most of my time talking about three recent results that may have a potential to significantly affect the way we think about the possibility to do precision Higgs physics at hadron colliders. They include:

1) the N^3LO QCD calculation of the inclusive Higgs boson production in gluon fusion;

Anastasiou, Duhr, Dulat, Furlan, Herzog, Mitzlberger etc.

2) the NNLO QCD calculation of the fiducial cross sections for the production of a Higgs boson and a jet at the LHC;

Boughezal, Caola, K.M., Petriello, Schulze
Boughezal, Focke, Giele, Liu, Petriello
Chen, Gehrmann, Glover, Jacqueir

3) the NNLO QCD calculation of the fiducial cross section for Higgs production in weak boson fusion at the LHC.

Cacciari, Dreyer, Kalberg, Salam, Zanderighi

These three results are important since they give us a new perspective on the ultimate precision achievable on the theory side in the exploration of Higgs boson physics at the LHC. Another important lesson that these results seem to teach us is that -- beyond a certain level -- fixed order results are indispensable and can not be substituted by their approximate estimates.
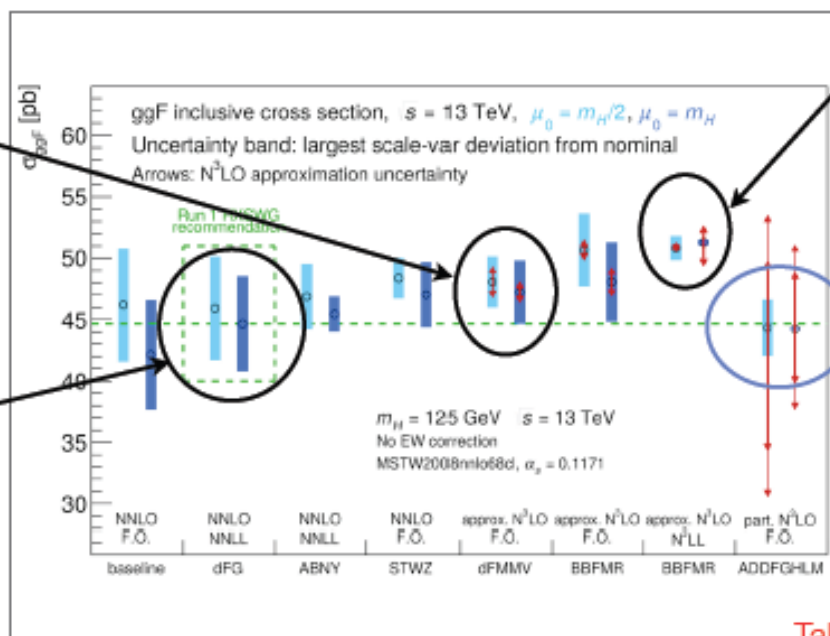
Theory: how precise do we need to be?

Estimates of N³LO Higgs production cross sections were attempted before an exact calculation using various approximations (essentially, emission or soft gluons or powers of π are assumed to be the dominant source of QCD corrections). The HXWG has assembled various predictions for the Higgs cross section made before the N³LO result became available. The picture below should tell us about the success or failure of these predictions. But it does not...; it leaves more questions than answers. However, the correct answer is important since it will teach us if approximate predictions for Higgs production cross section are reliable and to what extent.

The authors of this result claim the same increase of the cross-section relative to NNLO as the exact N3LO computation shows. Yet, the results on that plot are apparently different.

understand why this point is so much higher than everybody else and why the claimed precision is so high.

Good agreement with N3LO; obviously larger errors.

N3LO result

K. Melnikov

ggF inclusive cross section, s = 13 TeV, $\mu_0 = m_H/2$, $\mu_0 = m_H$
Uncertainty band: largest scale-var deviation from nominal
Arrows: N³LO approximation uncertainty

Run T HXWG recommendation

m_H = 125 GeV s = 13 TeV
No EW correction
MSTW2008nnlo68cl, α_s = 0.1171

| NNLO F.O. | NNLO NNLL | NNLO NNLL | NNLO F.O. | approx. N³LO F.O. | approx. N³LO F.O. | approx. N³LO N³LL | part. N³LO F.O. |
| baseline | dFG | ABNY | STWZ | dFMMV | BBFMR | BBFMR | ADDFGHLM |

Taken from the HXWG summary

Theory: how precise do we need to be?

The NNLO QCD corrections to H+jet production at the LHC were computed recently. They increase the H+jet production cross section by O(20%) and significantly reduce the scale dependence uncertainty . This is similar to corrections to the inclusive Higgs production cross section although corrections to H+j are slightly smaller.

NNPDF2.3, 8 TeV

$$\sigma_{LO} = 3.9^{+1.7}_{-1.1} \text{ pb}$$

$$\sigma_{NLO} = 5.6^{+1.3}_{-1.1} \text{ pb}$$
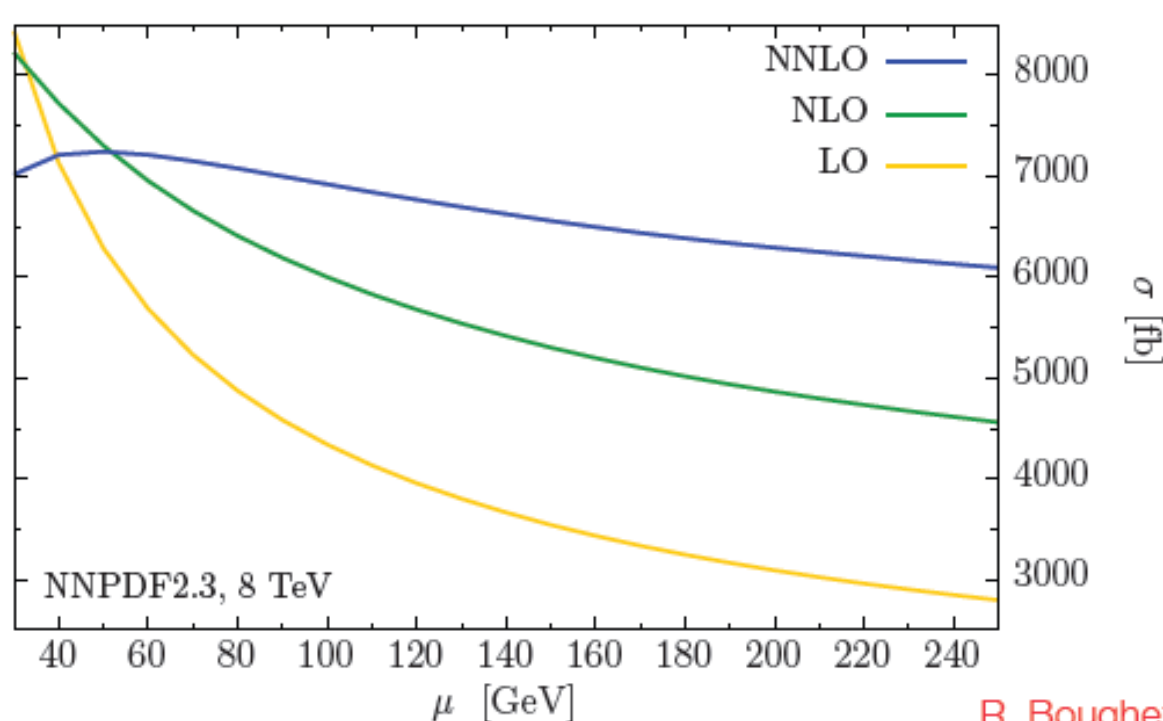
$$\sigma_{NNLO} = 6.7^{+0.5}_{-0.6} \text{ pb}$$

The cross sections for the anti-k_t algorithm with the jet transverse momentum cut of 30 GeV at the 8 TeV LHC.

R. Boughezal, F. Caola, K.M., F. Petriello, M. Schulze

K. Melnikov

Using these results and the N^3LO computation of the Higgs total cross section, one can find the fraction of Higgs boson events without detectable jet radiation.

Theory: how precise do we need to be?

The drawback of these results is that they still can not be used to describe fiducial volume cross sections since decays of the Higgs boson are not included. This is, however, easy to do since the Higgs boson is a scalar particle and no spin correlations are involved. What makes this calculation even more interesting is that there are measurements of the ATLAS and CMS collaborations at the 8 TeV LHC that can be directly compared to the results of the fiducial volume calculation (results are shown for infinitely heavy top quark).

Atlas cuts on photons and jets

$$\mathrm{anti-k}_t, \quad \Delta R = 0.4, \quad p_{j\perp} = 30 \text{ GeV}, \text{abs}(y_j) < 4.4$$
$$p_{\perp,\gamma_1} > 43.75 \text{ GeV}, \quad p_{\perp,\gamma_2} = 31.25 \text{ GeV}, \quad \Delta R_{\gamma j} > 0.4$$

$$\sigma^{\text{fid}}_{1j,\text{ATLAS}} = 21.5 \pm 5.3(\text{stat}) \pm 2.3(\text{syst}) \pm 0.6 \text{ lum fb}$$

$$\sigma^{\text{fid}}_{\text{LO}} = 5.43^{+2.32}_{-1.5} \text{ fb} \qquad \sigma^{\text{fid}}_{\text{NLO}} = 7.98^{+1.76}_{-1.46} \text{ fb} \qquad \sigma^{\text{fid}}_{\text{NNLO}} = 9.46^{+0.56}_{-0.84} \text{ fb}$$

The difference between the ATLAS H+j measurements and the SM prediction is close to two standard deviations; the ratio of central values is larger than in the inclusive case.

K. Melnikov

F. Caola, K.M., M. Schulze

Theory: how precise do we need to be?

The QCD corrections obtained in this approach are small (O(5%) NLO, O(3%) NNLO) ; it then seemed natural to assume that this size of QCD corrections will be indicative for the fiducial cross sections.
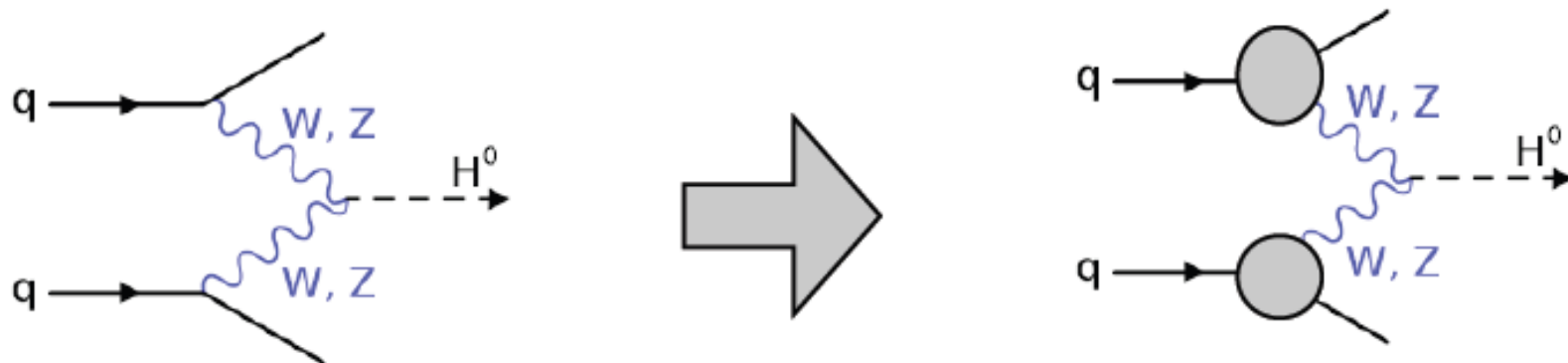
However, this assumption turns out to be incorrect and, in fact, one can get larger O(6-10%) corrections for fiducial (WBF cuts) cross sections and kinematic distributions. Often, the shape of those corrections seems rather different from both the NLO and/or parton shower predictions. The message -- again -- seems to be that fixed order computations are required beyond certain level of precision; approximate results may indicate their magnitude but not much beyond t

WBF cuts

$$p_{\perp}^{j_{1,2}} > 25 \text{ GeV}, \quad |y_{j_{1,2}}| < 4.5,$$
$$\Delta y_{j_1,j_2} = 4.5, \quad m_{j_1,j_2} > 600 \text{ GeV},$$
$$y_{j_1} y_{j_2} < 0, \quad \Delta R > 0.4$$

	$\sigma^{\text{nocuts}}[\text{pb}]$	$\sigma^{\text{VBF cuts}}[\text{pb}]$
LO	$4.032^{+0.057}_{-0.069}$	$0.957^{+0.066}_{-0.059}$
NLO	$3.929^{+0.024}_{-0.023}$	$0.876^{+0.008}_{-0.018}$
NNLO	$3.888^{+0.016}_{-0.012}$	$0.826^{+0.013}_{-0.014}$

Cacciari, Dreyer, Kalberg, Salam, Zanderighi

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Theory: need for fiducial predictions, jet binning

Cross sections: fiducial measurements.
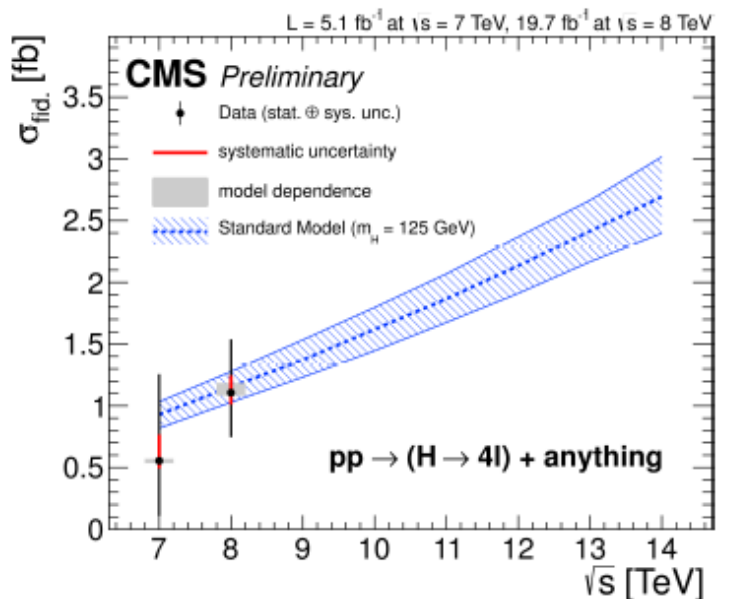
Fiducial σ CMS (8 TeV)

$$\sigma_{\text{fid}} = 1.11^{+0.41}_{-0.35}(\text{stat})^{+0.14}_{-0.10}(\text{syst})^{+0.08}_{-0.02}(\text{mod})\ \text{fb}$$

$$\sigma_{\text{fid}}^{\text{SM}} = 1.15^{+0.12}_{-0.13}\ \text{fb}$$

$$H \to 4\ell$$

Fiducial σ at 7 and 8 TeV

$$\sigma_{\text{fid}} = 32 \pm 10(\text{stat}) \pm 3(\text{syst})\ \text{fb}$$

$$\sigma_{\text{fid}}^{\text{SM}} = 31^{+4}_{-3}\ \text{fb} \qquad H \to \gamma\gamma$$

Fiducial σ ATLAS (8 TeV)

$$\sigma_{\text{fid}} = 2.11^{+0.53}_{-0.47}(\text{stat})^{+0.08}_{-0.08}(\text{syst})\ \text{fb}$$

$$\sigma_{\text{fid}}^{\text{SM}} = 1.30^{+0.13}_{-0.13}\ \text{fb}$$

$$H \to 4\ell$$

$$\sigma_{\text{fid}} = 43.2 \pm 9.4(\text{stat})^{+3.2}_{-2.9}(\text{syst}) \pm 1.2(\text{lumi})\ \text{fb}$$

$$\sigma_{\text{fid}}^{\text{SM}} = 30.5 \pm 3.3\ \text{fb} \qquad H \to \gamma\gamma$$

$H \to WW^* \to e\nu\mu\nu$ fiducial ggH cross section ATLAS (8 TeV)

$$\sigma_{\text{fid},0j}^{ggH} = 27.6^{+5.4}_{-5.3}(\text{stat})^{+4.1}_{-3.9}(\text{syst})\ \text{fb} \qquad \sigma_{\text{fid},1j}^{ggH} = 8.3^{+3.1}_{-3.0}(\text{stat})^{+3.7}_{-3.5}(\text{syst})\ \text{fb}$$

$$\sigma_{\text{fid},0j}^{ggH,\text{SM}} = 19.9 \pm 3.3\ \text{fb} \qquad \sigma_{\text{fid},1j}^{ggH,\text{SM}} = 7.3 \pm 1.8\ \text{fb}$$
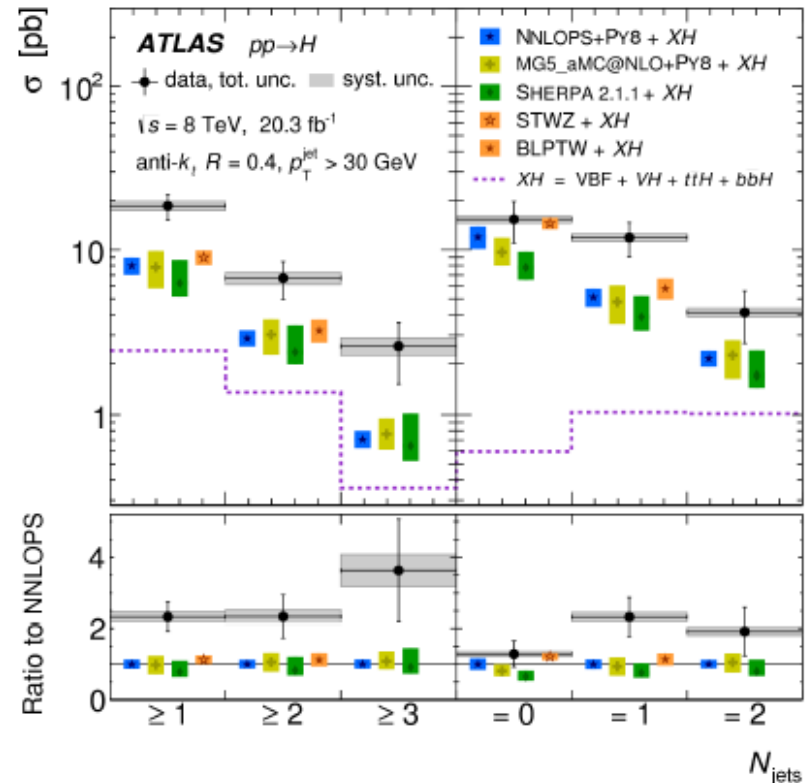
Theory: need for fiducial predictions, jet binning

Cross sections: combination.

- Sacrifice some model independence for combining $H \to \gamma\gamma$ and $H \to 4\ell$ to gain statistical power
  - ★ Extrapolate to full photon and lepton phase space
    - ► Fiducial acceptance of $60\pm1\%$ ($H \to \gamma\gamma$) and $47\pm1\%$ ($H \to 4\ell$)
  - ★ Assume SM branching fractions
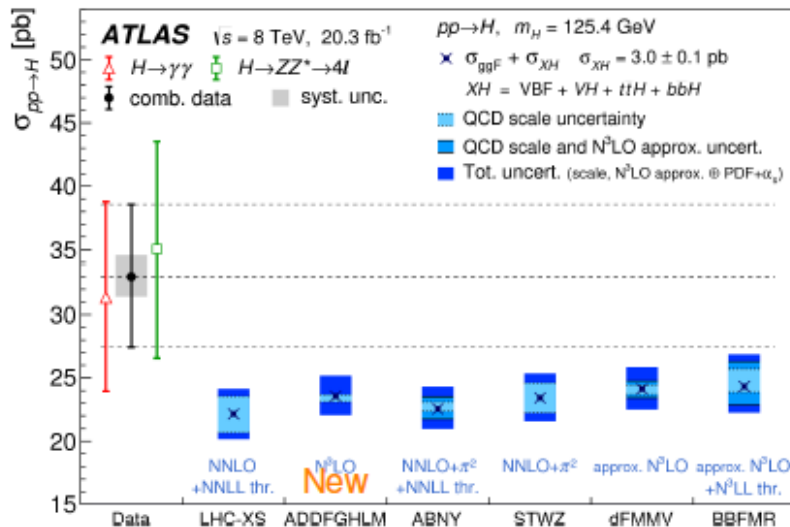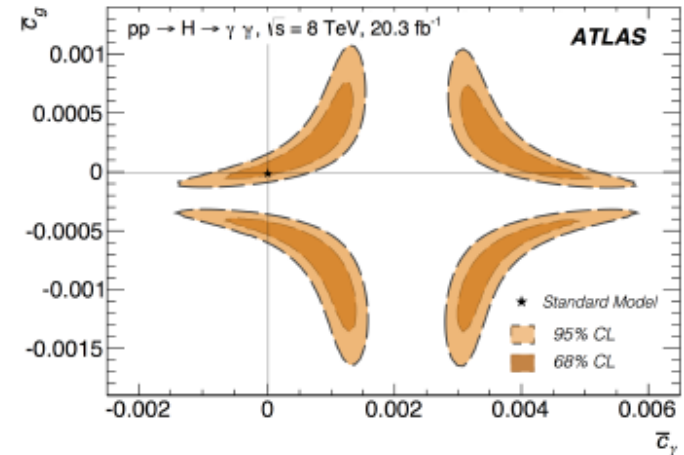

p-values 5.5% (LHC-XS) and 9% (ADDFGHLM)

Theory: need for fiducial predictions, jet binning

Cross sections: ATLAS $H \to \gamma\gamma$ interpretation.

- Probe tensor structure and Higgs interactions
- Non-SM terms in effective Lagrangian describing Higgs–gauge boson interactions

$$\mathcal{L} = \bar{c}_\gamma O_\gamma + \bar{c}_g O_g + \bar{c}_{HW} O_{HW} + \bar{c}_{HB} O$$
$$+ \tilde{c}_\gamma \tilde{O}_\gamma + \tilde{c}_g \tilde{O}_g + \tilde{c}_{HW} \tilde{O}_{HW} + \tilde{c}_{HB} \tilde{O}$$

[arXiv:1508.02507 [hep-ex]]

Based on 5 differential distributions:

Coupling measurements: how is this done?

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# Coupling measurements: how is this done?

Mainly ggF

Decay / Production	Untagged	VBF	VH	ttH
H→γγ	🟩	🟩	🟩	🟩
H→ZZ→4l	🟩	🟩	🟩	🟩
H→WW→2l2ν	🟩	🟩	🟩	🟩
H→ττ	🟩	🟩	🟩	🟩
H→bb			🟩	🟩
H→μμ	🟩	🟩		

🟩	Combined

- **Other production channels such as bbH, gg to ZH, tH are included resp. in ggF, ZH and ttH since they are not accessible as specific channels (nor will they be in run 2)**
- **With much larger statistics, it would be interesting to measure specifically the signal strength or effective coupling squared for any of the above i to H to f processes, where i denotes the production and f denotes the decay**

Coupling measurements: how is this done?

- Many different final discriminant distributions combined
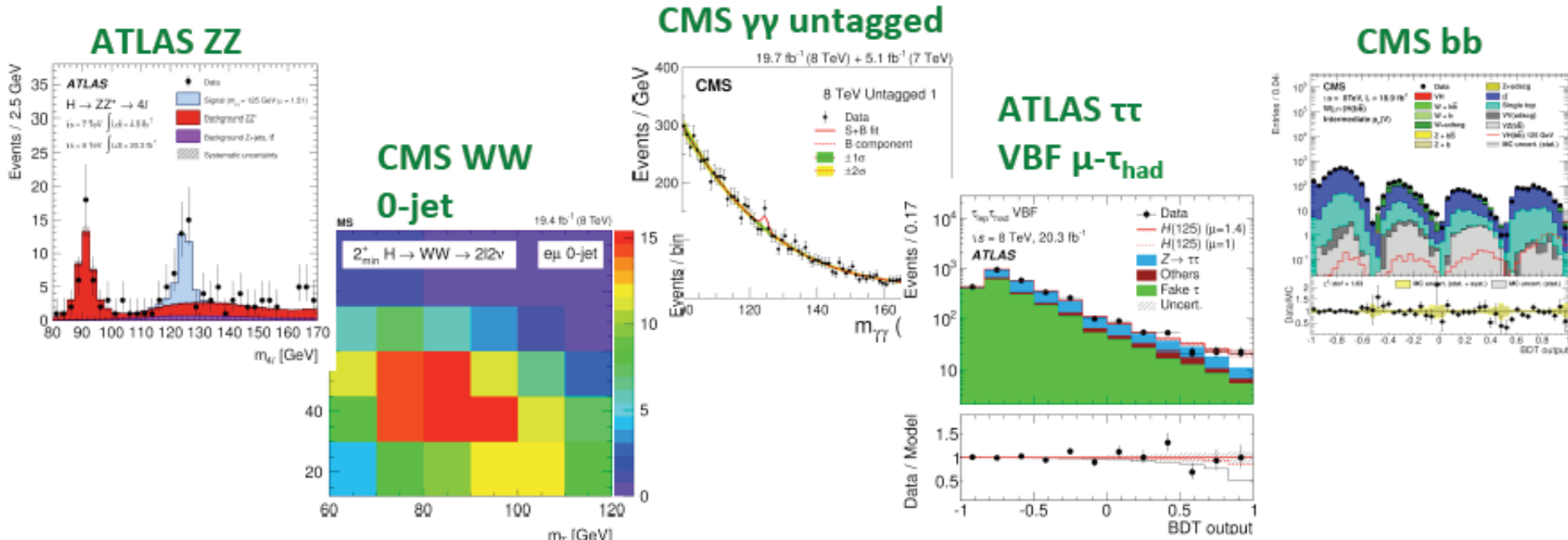
ATLAS ZZ

CMS WW 0-jet

CMS γγ untagged

ATLAS ττ VBF μ-τ_had

CMS bb

- Purity varies between categories (especially for production modes)
- A total of O(100) categories for each experiment are combined

Signal yield

$$n_{\text{signal}}(k) = \mathcal{L}(k) \times \sum_i \sum_f \left\{ \sigma_i \times A_i^f(k) \times \varepsilon_i^f(k) \times \mathrm{BR}^f \right\},$$

$$= \mathcal{L}(k) \times \sum_i \sum_f \mu_i \mu^f \left\{ \sigma_i^{\mathrm{SM}} \times A_i^f(k) \times \varepsilon_i^f(k) \times \mathrm{BR}_{\mathrm{SM}}^f \right\}$$

L: integrated luminosity,
A: acceptance,
E: efficiency

Coupling measurements: how is this done?

Channel	References for individual publications		Signal strength [μ] from results in this paper (Section 5.2)		Signal significance [σ]	
	ATLAS	CMS	ATLAS	CMS	ATLAS	CMS
$H \rightarrow \gamma\gamma$	[51]	[52]	$1.15^{+0.27}_{-0.25}$ $\left(^{+0.26}_{-0.24}\right)$	$1.12^{+0.25}_{-0.23}$ $\left(^{+0.24}_{-0.22}\right)$	5.0 (4.6)	5.6 (5.1)
$H \rightarrow ZZ \rightarrow 4\ell$	[53]	[54]	$1.51^{+0.39}_{-0.34}$ $\left(^{+0.33}_{-0.27}\right)$	$1.05^{+0.32}_{-0.27}$ $\left(^{+0.31}_{-0.26}\right)$	6.6 (5.5)	7.0 (6.8)
$H \rightarrow WW$	[55,56]	[57]	$1.23^{+0.23}_{-0.21}$ $\left(^{+0.21}_{-0.20}\right)$	$0.91^{+0.24}_{-0.21}$ $\left(^{+0.23}_{-0.20}\right)$	6.8 (5.8)	4.8 (5.6)
$H \rightarrow \tau\tau$	[58]	[59]	$1.41^{+0.40}_{-0.35}$ $\left(^{+0.37}_{-0.33}\right)$	$0.89^{+0.31}_{-0.28}$ $\left(^{+0.31}_{-0.29}\right)$	4.4 (3.3)	3.4 (3.7)
$H \rightarrow bb$	[38]	[39]	$0.62^{+0.37}_{-0.36}$ $\left(^{+0.39}_{-0.37}\right)$	$0.81^{+0.45}_{-0.42}$ $\left(^{+0.45}_{-0.43}\right)$	1.7 (2.7)	2.0 (2.5)
$H \rightarrow \mu\mu$	[60]	[61]	-0.7 ± 3.6 (± 3.6)	0.8 ± 3.5 (± 3.5)		
ttH production	[28,62,63]	[65]	$1.9^{+0.8}_{-0.7}$ $\left(^{+0.72}_{-0.66}\right)$	$2.9^{+1.0}_{-0.9}$ $\left(^{+0.88}_{-0.80}\right)$	2.7 (1.6)	3.6 (1.3)

Coupling measurements: how is this done?

- Purity varies between categories (especially for production modes)
- A total of O(100) categories for each experiment are combined

Signal yield

$$n_{\text{signal}}(k) = \mathcal{L}(k) \times \sum_i \sum_f \left\{ \sigma_i \times A_i^f(k) \times \varepsilon_i^f(k) \times \text{BR}^f \right\},$$

$$= \mathcal{L}(k) \times \sum_i \sum_f \mu_i \mu^f \left\{ \sigma_i^{\text{SM}} \times A_i^f(k) \times \varepsilon_i^f(k) \times \text{BR}_{\text{SM}}^f \right\}$$

L: integrated luminosity,
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- **Cannot measure σ_i, BR^f or μ_i, μ_f at the same time, need to measure ratios or make additional assumptions**
- **Measuring ratios is done through a generic parameterisation of the above yields or of $\sigma_i \times \text{BR}^f$, such that there is no dependence on the inclusive theory cross section uncertainties (signal strength measurements) or such that one tests directly for deviations of the couplings of the Higgs boson from their SM values (κ framework)**
- **Additional assumptions in the narrow-width approximation allow measurements of production or decay signal strengths**
- **Additional assumptions about BSM physics (for example BR_BSM = 0) allow measurements of absolute coupling strengths**

$$\Gamma_H = \frac{\kappa_H^2 \cdot \Gamma_H^{\text{SM}}}{1 - \text{BR}_{\text{BSM}}},$$

Coupling measurements: how is this done?

Production	Loops	Interference	Multiplicative factor
$\sigma(ggF)$	✓	$b - t$	$\kappa_g^2 \sim$ $1.06 \cdot \kappa_t^2 + 0.01 \cdot \kappa_b^2 - 0.07 \cdot \kappa_t \kappa_b$
$\sigma(VBF)$	–	–	$\sim$ $0.74 \cdot \kappa_W^2 + 0.26 \cdot \kappa_Z^2$
$\sigma(WH)$	–	–	$\sim$ κ_W^2
$\sigma(qq/qg \to ZH)$	–	–	$\sim$ κ_Z^2
$\sigma(gg \to ZH)$	✓	$Z - t$	$\sim$ $2.27 \cdot \kappa_Z^2 + 0.37 \cdot \kappa_t^2 - 1.64 \cdot \kappa_Z \kappa_t$
$\sigma(ttH)$	–	–	$\sim$ κ_t^2
$\sigma(gb \to WtH)$	–	$W - t$	$\sim$ $1.84 \cdot \kappa_t^2 + 1.57 \cdot \kappa_W^2 - 2.41 \cdot \kappa_t \kappa_W$
$\sigma(qb \to tHq)$	–	$W - t$	$\sim$ $3.4 \cdot \kappa_t^2 + 3.56 \cdot \kappa_W^2 - 5.96 \cdot \kappa_t \kappa_W$
$\sigma(bbH)$	–	–	$\sim$ κ_b^2
Partial decay width			
Γ^{ZZ}	–	–	$\sim$ κ_Z^2
Γ^{WW}	–	–	$\sim$ κ_W^2
$\Gamma^{\gamma\gamma}$	✓	$W - t$	$\kappa_\gamma^2 \sim$ $1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.66 \cdot \kappa_W \kappa_t$
$\Gamma^{\tau\tau}$	–	–	$\sim$ κ_τ^2
Γ^{bb}	–	–	$\sim$ κ_b^2
$\Gamma^{\mu\mu}$	–	–	$\sim$ κ_μ^2
Total width for $BR_{BSM} = 0$			
Γ_H	✓	–	$\kappa_H^2 \sim$ $0.57 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.09 \cdot \kappa_g^2 +$ $+ 0.06 \cdot \kappa_\tau^2 + 0.03 \cdot \kappa_Z^2 + 0.03 \cdot \kappa_c^2 +$ $+ 0.0023 \cdot \kappa_\gamma^2 + 0.0016 \cdot \kappa_{Z\gamma}^2 +$ $+ 0.0001 \cdot \kappa_s^2 + 0.00022 \cdot \kappa_\mu^2$

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$\sigma(qq/qg \to ZH)$	–	–	$\sim$	κ_Z^2
$\sigma(gg \to ZH)$	✓	$Z-t$	$\sim$	$2.27 \cdot \kappa_Z^2 + 0.37 \cdot \kappa_t^2 - 1.64 \cdot \kappa_Z \kappa_t$
$\sigma(ttH)$	–	–	$\sim$	κ_t^2
$\sigma(gb \to WtH)$	–	$W-t$	$\sim$	$1.84 \cdot \kappa_t^2 + 1.57 \cdot \kappa_W^2 - 2.41 \cdot \kappa_t \kappa_W$
$\sigma(qb \to tHq)$	–	$W-t$	$\sim$	$3.4 \cdot \kappa_t^2 + 3.56 \cdot \kappa_W^2 - 5.96 \cdot \kappa_t \kappa_W$
$\sigma(bbH)$	–	–	$\sim$	κ_b^2
Partial decay width				
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$\Gamma^{\tau\tau}$	–	–	$\sim$	κ_τ^2
Γ^{bb}	–	–	$\sim$	κ_b^2
$\Gamma^{\mu\mu}$	–	–	$\sim$	κ_μ^2

- **The numerical factors depend on m_H but not only! They account for state-of-the-art QCD and EW corrections, so eg gg fusion and H to gg decay will not have the same expression exactly. Worse, the factors depend on kinematics!!**

Coupling measurements: how is this done?

The product of the cross section and the branching ratio of $i \to H \to f$ can then be expressed using the ratios as:

$$\sigma_i \cdot BR^f = \sigma(gg \to H \to ZZ) \times \left(\frac{\sigma_i}{\sigma_{ggF}}\right) \times \left(\frac{BR^f}{BR^{ZZ}}\right), \tag{10}$$

where $\sigma(gg \to H \to ZZ) = \sigma_{ggF} \cdot BR^{ZZ}$ under the narrow width approximation. With $\sigma(gg \to H \to ZZ)$ constraining the normalisation, the ratios in Eq. 10 can be determined separately, based on the five production processes (ggF, VBF, WH, ZH and ttH) and five decay modes ($H \to ZZ$, $H \to WW$, $H \to \gamma\gamma$, $H \to \tau\tau$ and $H \to bb$). The combined fit results can be presented as a function of nine parameters of interest: one reference cross section times branching ratio, $\sigma(gg \to H \to ZZ)$, four ratios of production cross sections, σ_i/σ_{ggF} and four ratios of branching ratios, BR^f/BR^{ZZ} as shown in Table 6.

- **The equation above is free of any theory uncertainties on the inclusive cross sections. However, the yields in each channel assume the SM Higgs boson production and decay kinematics and are subject to theory uncertainties (QCD scales, PDFs, jet binning, parton shower, underlying event).**
- **Note that in this parameterisation, as in all signal strength parameterisations, the assumptions for the unaccessible decay channels are different from the ones in the κ framework.**
- **Here H to cc and H to gg are included in H to bb.
  And H to Zγ is included in H to γγ.**

Parameter	SM prediction	Best-fit value	Uncertainty Stat	Syst	Best-fit value	Uncertainty Stat	Syst	Best-fit value	Uncertainty Stat	Syst
		ATLAS+CMS			ATLAS			CMS		
$\sigma(gg \to H \to ZZ)$ (pb)	0.513 ± 0.057	$0.58\,^{+0.11}_{-0.10}\,\binom{+0.11}{-0.10}$	$^{+0.11}_{-0.10}\,\binom{+0.11}{-0.09}$	$^{+0.03}_{-0.02}\,\binom{+0.03}{-0.02}$	$0.76\,^{+0.19}_{-0.17}\,\binom{+0.16}{-0.14}$	$^{+0.19}_{-0.16}\,\binom{+0.16}{-0.13}$	$^{+0.05}_{-0.04}\,\binom{+0.04}{-0.03}$	$0.44\,^{+0.14}_{-0.11}\,\binom{+0.15}{-0.13}$	$^{+0.13}_{-0.11}\,\binom{+0.15}{-0.13}$	$^{+0.05}_{-0.03}\,\binom{+0.04}{-0.03}$
$\sigma_{VBF}/\sigma_{ggF}$	0.082 ± 0.009	$0.11\,^{+0.03}_{-0.03}\,\binom{+0.03}{-0.02}$	$^{+0.03}_{-0.02}\,\binom{+0.02}{-0.02}$	$^{+0.02}_{-0.01}\,\binom{+0.02}{-0.01}$	$0.08\,^{+0.03}_{-0.03}\,\binom{+0.04}{-0.03}$	$^{+0.03}_{-0.02}\,\binom{+0.04}{-0.03}$	$^{+0.02}_{-0.01}\,\binom{+0.02}{-0.01}$	$0.14\,^{+0.07}_{-0.05}\,\binom{+0.04}{-0.03}$	$^{+0.06}_{-0.05}\,\binom{+0.04}{-0.03}$	$^{+0.04}_{-0.02}\,\binom{+0.02}{-0.01}$
σ_{WH}/σ_{ggF}	0.037 ± 0.004	$0.03\,^{+0.03}_{-0.03}\,\binom{+0.02}{-0.02}$	$^{+0.02}_{-0.02}\,\binom{+0.02}{-0.02}$	$^{+0.01}_{-0.01}\,\binom{+0.01}{-0.01}$	$0.05\,^{+0.04}_{-0.03}\,\binom{+0.03}{-0.02}$	$^{+0.03}_{-0.02}\,\binom{+0.03}{-0.02}$	$^{+0.02}_{-0.01}\,\binom{+0.02}{-0.01}$	$0.01\,^{+0.04}_{-0.04}\,\binom{+0.03}{-0.02}$	$^{+0.04}_{-0.03}\,\binom{+0.03}{-0.02}$	$^{+0.02}_{-0.02}\,\binom{+0.02}{-0.01}$
σ_{ZH}/σ_{ggF}	0.022 ± 0.002	$0.07\,^{+0.04}_{-0.03}\,\binom{+0.02}{-0.01}$	$^{+0.03}_{-0.03}\,\binom{+0.01}{-0.01}$	$^{+0.02}_{-0.02}\,\binom{+0.01}{-0.00}$	$0.01\,^{+0.03}_{-0.01}\,\binom{+0.03}{-0.01}$	$^{+0.02}_{-0.01}\,\binom{+0.02}{-0.01}$	$^{+0.02}_{-0.01}\,\binom{+0.01}{-0.01}$	$0.13\,^{+0.08}_{-0.05}\,\binom{+0.02}{-0.01}$	$^{+0.06}_{-0.05}\,\binom{+0.02}{-0.01}$	$^{+0.04}_{-0.03}\,\binom{+0.01}{-0.01}$
$\sigma_{ttH}/\sigma_{ggF}$	0.0067 ± 0.0010	$0.022\,^{+0.007}_{-0.006}\,\binom{+0.004}{-0.004}$	$^{+0.005}_{-0.005}\,\binom{+0.003}{-0.003}$	$^{+0.004}_{-0.003}\,\binom{+0.003}{-0.002}$	$0.013\,^{+0.007}_{-0.005}\,\binom{+0.006}{-0.004}$	$^{+0.005}_{-0.004}\,\binom{+0.005}{-0.004}$	$^{+0.004}_{-0.003}\,\binom{+0.004}{-0.003}$	$0.034\,^{+0.016}_{-0.012}\,\binom{+0.007}{-0.005}$	$^{+0.012}_{-0.010}\,\binom{+0.005}{-0.004}$	$^{+0.010}_{-0.006}\,\binom{+0.004}{-0.004}$
BR^{WW}/BR^{ZZ}	$8.10 \pm < 0.01$	$6.8\,^{+1.7}_{-1.3}\,\binom{+2.2}{-1.7}$	$^{+1.5}_{-1.2}\,\binom{+2.0}{-1.6}$	$^{+0.7}_{-0.5}\,\binom{+0.9}{-0.7}$	$6.5\,^{+2.2}_{-1.6}\,\binom{+3.5}{-2.4}$	$^{+2.0}_{-1.5}\,\binom{+3.3}{-2.2}$	$^{+0.9}_{-0.6}\,\binom{+1.3}{-0.9}$	$7.2\,^{+2.9}_{-2.1}\,\binom{+3.2}{-2.2}$	$^{+2.6}_{-1.8}\,\binom{+2.9}{-2.0}$	$^{+1.3}_{-0.9}\,\binom{+1.4}{-1.0}$
$BR^{\gamma\gamma}/BR^{ZZ}$	0.085 ± 0.001	$0.069\,^{+0.018}_{-0.015}\,\binom{+0.025}{-0.019}$	$^{+0.018}_{-0.014}\,\binom{+0.024}{-0.019}$	$^{+0.004}_{-0.003}\,\binom{+0.006}{-0.004}$	$0.063\,^{+0.024}_{-0.018}\,\binom{+0.040}{-0.027}$	$^{+0.023}_{-0.017}\,\binom{+0.039}{-0.027}$	$^{+0.008}_{-0.005}\,\binom{+0.011}{-0.006}$	$0.079\,^{+0.033}_{-0.023}\,\binom{+0.035}{-0.025}$	$^{+0.032}_{-0.023}\,\binom{+0.034}{-0.024}$	$^{+0.010}_{-0.006}\,\binom{+0.008}{-0.005}$
$BR^{\tau\tau}/BR^{ZZ}$	2.36 ± 0.05	$1.8\,^{+0.6}_{-0.5}\,\binom{+0.9}{-0.7}$	$^{+0.5}_{-0.4}\,\binom{+0.8}{-0.6}$	$^{+0.3}_{-0.2}\,\binom{+0.5}{-0.3}$	$2.2\,^{+1.1}_{-0.8}\,\binom{+1.5}{-1.0}$	$^{+0.9}_{-0.6}\,\binom{+1.3}{-0.9}$	$^{+0.6}_{-0.4}\,\binom{+0.8}{-0.5}$	$1.6\,^{+0.9}_{-0.6}\,\binom{+1.2}{-0.9}$	$^{+0.8}_{-0.5}\,\binom{+1.0}{-0.7}$	$^{+0.5}_{-0.3}\,\binom{+0.7}{-0.4}$
BR^{bb}/BR^{ZZ}	21.6 ± 1.0	$4.2\,^{+4.6}_{-2.6}\,\binom{+16.9}{-9.1}$	$^{+2.8}_{-2.0}\,\binom{+13.9}{-7.9}$	$^{+3.6}_{-1.7}\,\binom{+9.5}{-4.4}$	$9.7\,^{+10.2}_{-5.8}\,\binom{+29.4}{-11.8}$	$^{+7.4}_{-4.4}\,\binom{+24.3}{-10.5}$	$^{+7.0}_{-3.8}\,\binom{+16.7}{-5.4}$	$3.7\,^{+4.1}_{-2.4}\,\binom{+29.4}{-11.9}$	$^{+3.1}_{-1.9}\,\binom{+23.4}{-10.4}$	$^{+2.7}_{-1.6}\,\binom{+17.7}{-5.9}$

Coupling measurements: how is this done?

Parameter	SM prediction	Best-fit value	Stat	Expt	Thbgd	Thsig
		ATLAS+CMS				
$\sigma(gg \to H \to ZZ)$ (pb)	0.513 ± 0.057	$0.58\ ^{+0.11}_{-0.10}$ $\binom{+0.11}{-0.10}$	$^{+0.11}_{-0.10}$ $\binom{+0.11}{-0.09}$	$^{+0.02}_{-0.02}$ $\binom{+0.02}{-0.02}$	$^{+0.01}_{-0.01}$ $\binom{+0.01}{-0.01}$	$^{+0.01}_{-0.01}$ $\binom{+0.01}{-0.01}$
$\sigma_{VBF}/\sigma_{ggF}$	0.082 ± 0.009	$0.11\ ^{+0.03}_{-0.03}$ $\binom{+0.03}{-0.02}$	$^{+0.03}_{-0.02}$ $\binom{+0.02}{-0.02}$	$^{+0.01}_{-0.01}$ $\binom{+0.01}{-0.01}$	$^{+0.01}_{-0.00}$ $\binom{+0.00}{-0.00}$	$^{+0.01}_{-0.01}$ $\binom{+0.01}{-0.01}$
		ATLAS+CMS				
$\sigma(gg \to H \to WW)$ (pb)	4.15 ± 0.47	$3.97\ ^{+0.63}_{-0.60}$ $\binom{+0.65}{-0.62}$	$^{+0.46}_{-0.45}$ $\binom{+0.47}{-0.46}$	$^{+0.32}_{-0.29}$ $\binom{+0.33}{-0.30}$	$^{+0.24}_{-0.23}$ $\binom{+0.26}{-0.25}$	$^{+0.16}_{-0.12}$ $\binom{+0.16}{-0.12}$
$\sigma_{VBF}/\sigma_{ggF}$	0.082 ± 0.009	$0.11\ ^{+0.03}_{-0.03}$ $\binom{+0.03}{-0.02}$	$^{+0.03}_{-0.02}$ $\binom{+0.02}{-0.02}$	$^{+0.01}_{-0.01}$ $\binom{+0.01}{-0.01}$	$^{+0.01}_{-0.00}$ $\binom{+0.01}{-0.00}$	$^{+0.01}_{-0.01}$ $\binom{+0.01}{-0.01}$

- **Overall precision on H to WW is the best**

- **But systematic uncertainty is much smaller for H to ZZ**

Coupling measurements: how is this done?
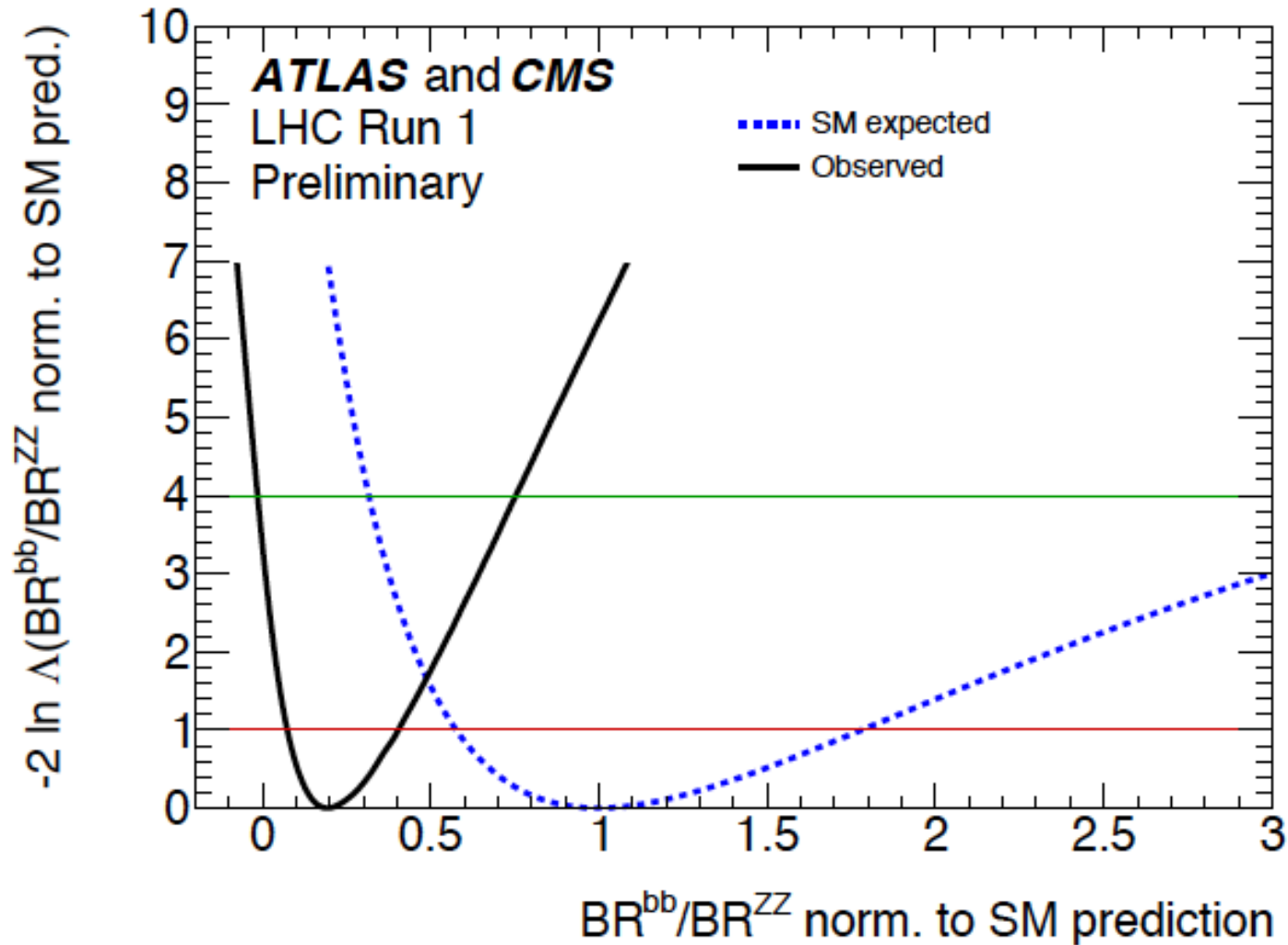
- **In this parameterisation, the rather high values of σ_{ttH} and σ_{ZH} observed, especially by CMS, are not observed in H to bb decays, so BR^{bb} decreases**
- **This is much less the case when measuring μ^{bb} assuming SM for production**

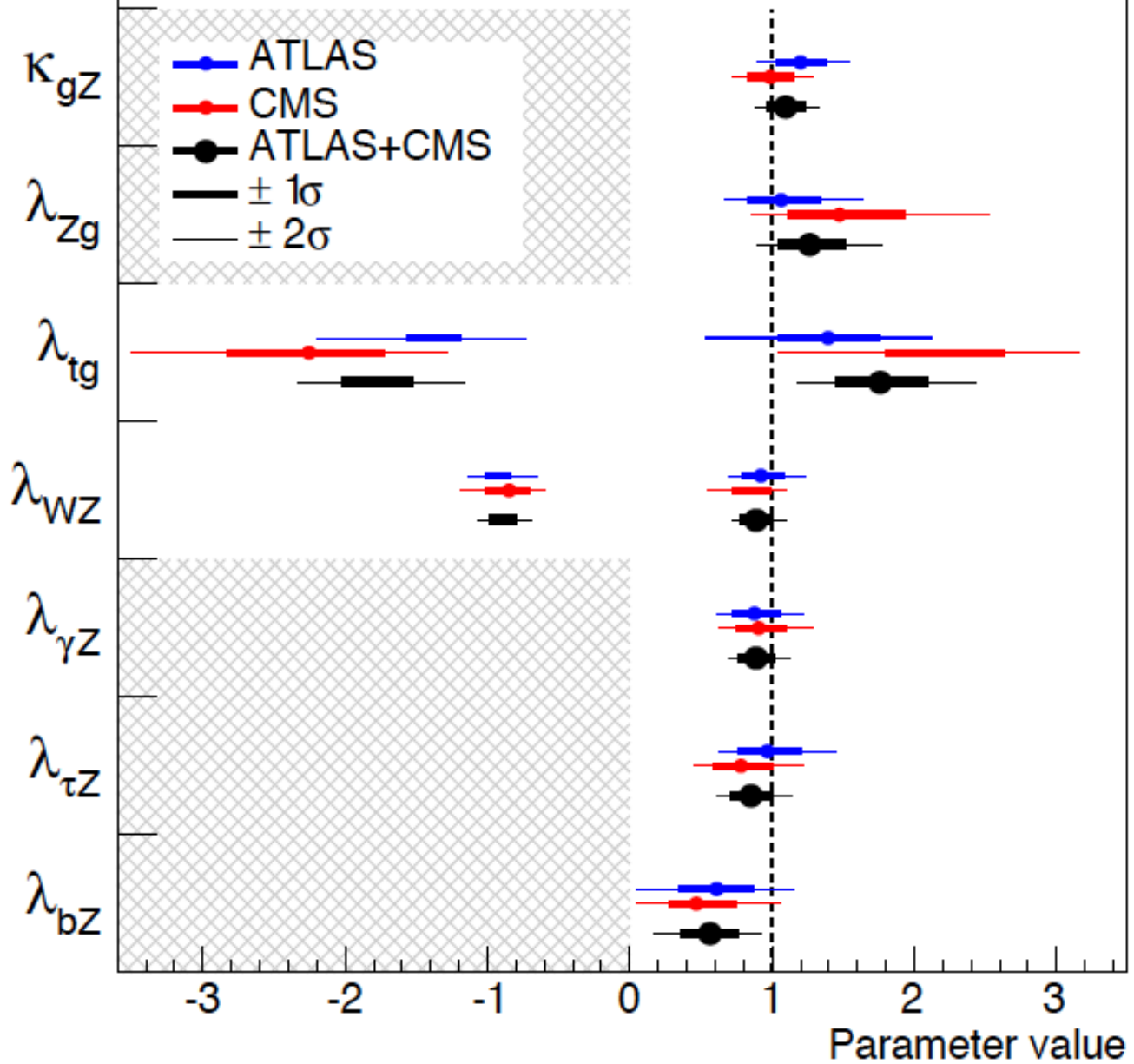# Coupling measurements: how is this done?

σ and BR ratio model	Coupling-strength ratio model	
$\sigma(gg \to H \to ZZ)$	$\kappa_{gZ} = \kappa_g \cdot \kappa_Z / \kappa_H$	In this parameterization
$\sigma_{VBF}/\sigma_{ggF}$		BR^{ZZ}, BR^{WW}, σ_{WH},
σ_{WH}/σ_{ggF}		σ_{WH} and σ_{VBF} are
σ_{ZH}/σ_{ggF}	$\lambda_{Zg} = \kappa_Z/\kappa_g$	function of κ_Z and κ_W
$\sigma_{ttH}/\sigma_{ggF}$	$\lambda_{tg} = \kappa_t/\kappa_g$	e.g. for example
BR^{WW}/BR^{ZZ}	$\lambda_{WZ} = \kappa_W/\kappa_Z$	$\sigma_{WH}/ \sigma_{ggF} \sim (\lambda_{WZ}/\lambda_{zg})^2$
BR$^{\gamma\gamma}$/BR^{ZZ}	$\lambda_{\gamma Z} = \kappa_\gamma/\kappa_Z$	
BR$^{\tau\tau}$/BR^{ZZ}	$\lambda_{\tau Z} = \kappa_\tau/\kappa_Z$	
BR^{bb}/BR^{ZZ}	$\lambda_{bZ} = \kappa_b/\kappa_Z$	

- **In the κ framework, H to ZZ was chosen as a reference a long time ago (before data-taking).**
- **The relationships between the two parameterisations can be seen in the table above.**
- **The two are not equivalent, however, because the additional assumptions concerning small channels are different,**
  namely in the κ framework $\kappa_c = \kappa_t$, $\kappa_\mu = \kappa_\tau$, and $\kappa_s = \kappa_b$

...sion, September 2020

Coupling measurements: how is this done?

Parameter	Best-fit value	Uncertainty Stat	Syst	Best-fit value	Uncertainty Stat	Syst	Best-fit value	Uncertainty Stat	Syst
	ATLAS+CMS			ATLAS			CMS		
$\kappa_{gZ} = \kappa_g \cdot \kappa_Z / \kappa_H$	$1.10^{+0.11}_{-0.11}$	$^{+0.09}_{-0.09}$	$^{+0.07}_{-0.06}$	$1.20^{+0.16}_{-0.15}$	$^{+0.14}_{-0.14}$	$^{+0.08}_{-0.06}$	$0.99^{+0.14}_{-0.13}$	$^{+0.12}_{-0.12}$	$^{+0.07}_{-0.06}$
	$\left(^{+0.11}_{-0.11}\right)$	$\left(^{+0.09}_{-0.09}\right)$	$\left(^{+0.06}_{-0.05}\right)$	$\left(^{+0.16}_{-0.15}\right)$	$\left(^{+0.14}_{-0.13}\right)$	$\left(^{+0.07}_{-0.06}\right)$	$\left(^{+0.15}_{-0.14}\right)$	$\left(^{+0.13}_{-0.12}\right)$	$\left(^{+0.07}_{-0.06}\right)$
$\lambda_{Zg} = \kappa_Z / \kappa_g$	$1.26^{+0.23}_{-0.19}$	$^{+0.18}_{-0.16}$	$^{+0.15}_{-0.12}$	$1.06^{+0.26}_{-0.21}$	$^{+0.21}_{-0.18}$	$^{+0.14}_{-0.11}$	$1.47^{+0.44}_{-0.34}$	$^{+0.34}_{-0.28}$	$^{+0.29}_{-0.19}$
	$\left(^{+0.20}_{-0.17}\right)$	$\left(^{+0.15}_{-0.14}\right)$	$\left(^{+0.12}_{-0.10}\right)$	$\left(^{+0.28}_{-0.23}\right)$	$\left(^{+0.23}_{-0.20}\right)$	$\left(^{+0.16}_{-0.11}\right)$	$\left(^{+0.27}_{-0.23}\right)$	$\left(^{+0.22}_{-0.19}\right)$	$\left(^{+0.17}_{-0.12}\right)$
$\lambda_{tg} = \kappa_t / \kappa_g$	$1.76^{+0.32}_{-0.29}$	$^{+0.21}_{-0.20}$	$^{+0.23}_{-0.20}$	$1.39^{+0.34}_{-0.33}$	$^{+0.25}_{-0.24}$	$^{+0.23}_{-0.22}$	$-2.25^{+0.51}_{-0.55}$	$^{+0.39}_{-0.36}$	$^{+0.39}_{-0.30}$
	$\left(^{+0.29}_{-0.39}\right)$	$\left(^{+0.20}_{-0.21}\right)$	$\left(^{+0.21}_{-0.24}\right)$	$\left(^{+0.38}_{-0.54}\right)$	$\left(^{+0.28}_{-0.28}\right)$	$\left(^{+0.26}_{-0.33}\right)$	$\left(^{+0.42}_{-0.64}\right)$	$\left(^{+0.31}_{-0.33}\right)$	$\left(^{+0.29}_{-0.46}\right)$
$\lambda_{WZ} = \kappa_W / \kappa_Z$	$0.89^{+0.10}_{-0.09}$	$^{+0.09}_{-0.08}$	$^{+0.04}_{-0.04}$	$0.92^{+0.14}_{-0.12}$	$^{+0.13}_{-0.11}$	$^{+0.05}_{-0.04}$	$-0.85^{+0.13}_{-0.15}$	$^{+0.13}_{-0.11}$	$^{+0.07}_{-0.06}$
	$\left(^{+0.12}_{-0.10}\right)$	$\left(^{+0.11}_{-0.09}\right)$	$\left(^{+0.05}_{-0.04}\right)$	$\left(^{+0.18}_{-0.15}\right)$	$\left(^{+0.16}_{-0.13}\right)$	$\left(^{+0.07}_{-0.06}\right)$	$\left(^{+0.17}_{-0.14}\right)$	$\left(^{+0.15}_{-0.13}\right)$	$\left(^{+0.07}_{-0.07}\right)$
$\lambda_{\gamma Z} = \kappa_\gamma / \kappa_Z$	$0.89^{+0.11}_{-0.10}$	$^{+0.11}_{-0.09}$	$^{+0.04}_{-0.03}$	$0.88^{+0.16}_{-0.14}$	$^{+0.15}_{-0.13}$	$^{+0.04}_{-0.03}$	$0.91^{+0.17}_{-0.14}$	$^{+0.16}_{-0.13}$	$^{+0.05}_{-0.04}$
	$\left(^{+0.13}_{-0.12}\right)$	$\left(^{+0.13}_{-0.11}\right)$	$\left(^{+0.04}_{-0.03}\right)$	$\left(^{+0.20}_{-0.17}\right)$	$\left(^{+0.19}_{-0.17}\right)$	$\left(^{+0.06}_{-0.04}\right)$	$\left(^{+0.18}_{-0.16}\right)$	$\left(^{+0.17}_{-0.15}\right)$	$\left(^{+0.05}_{-0.04}\right)$
$\lambda_{\tau Z} = \kappa_\tau / \kappa_Z$	$0.85^{+0.14}_{-0.12}$	$^{+0.12}_{-0.10}$	$^{+0.07}_{-0.06}$	$0.97^{+0.22}_{-0.18}$	$^{+0.18}_{-0.15}$	$^{+0.11}_{-0.09}$	$0.78^{+0.20}_{-0.17}$	$^{+0.16}_{-0.15}$	$^{+0.10}_{-0.08}$
	$\left(^{+0.17}_{-0.15}\right)$	$\left(^{+0.14}_{-0.13}\right)$	$\left(^{+0.09}_{-0.08}\right)$	$\left(^{+0.27}_{-0.23}\right)$	$\left(^{+0.23}_{-0.19}\right)$	$\left(^{+0.14}_{-0.12}\right)$	$\left(^{+0.23}_{-0.20}\right)$	$\left(^{+0.19}_{-0.17}\right)$	$\left(^{+0.12}_{-0.11}\right)$
$\lambda_{bZ} = \kappa_b / \kappa_Z$	$0.56^{+0.18}_{-0.18}$	$^{+0.12}_{-0.11}$	$^{+0.10}_{-0.11}$	$0.61^{+0.24}_{-0.24}$	$^{+0.20}_{-0.18}$	$^{+0.14}_{-0.15}$	$0.47^{+0.26}_{-0.17}$	$^{+0.17}_{-0.15}$	$^{+0.15}_{-0.16}$
	$\left(^{+0.25}_{-0.22}\right)$	$\left(^{+0.21}_{-0.18}\right)$	$\left(^{+0.14}_{-0.11}\right)$	$\left(^{+0.36}_{-0.29}\right)$	$\left(^{+0.31}_{-0.24}\right)$	$\left(^{+0.18}_{-0.14}\right)$	$\left(^{+0.38}_{-0.37}\right)$	$\left(^{+0.32}_{-0.25}\right)$	$\left(^{+0.20}_{-0.17}\right)$

- In these measurements, despite the ratios, the theory uncertainties on the inclusive cross sections are cannot be removed.
- Nevertheless, some ratios have small theory uncertainties, eg $\lambda_{\gamma Z}$ and λ_{WZ}

Coupling measurements: how is this done?
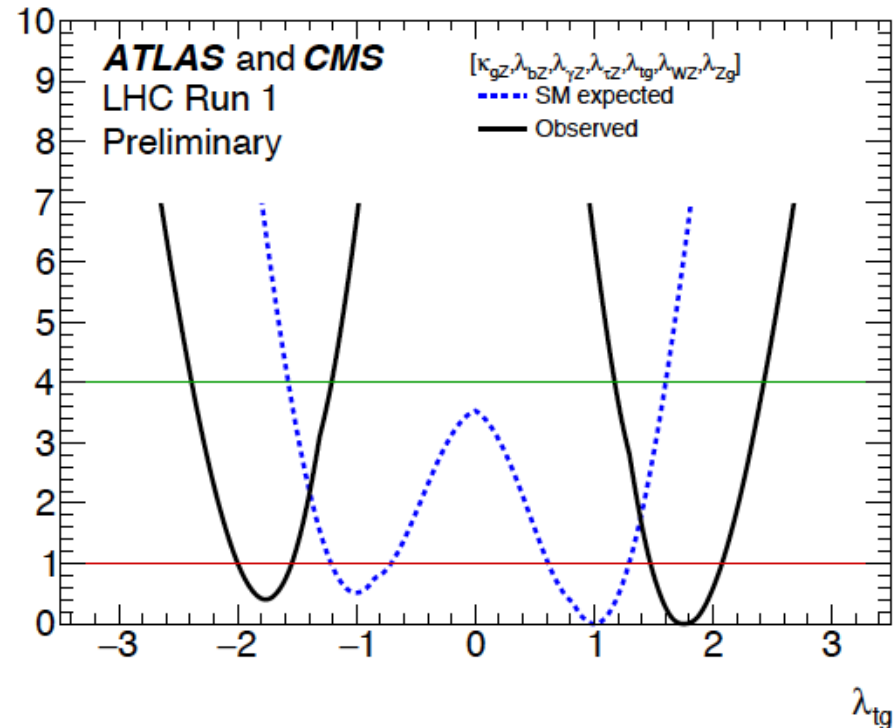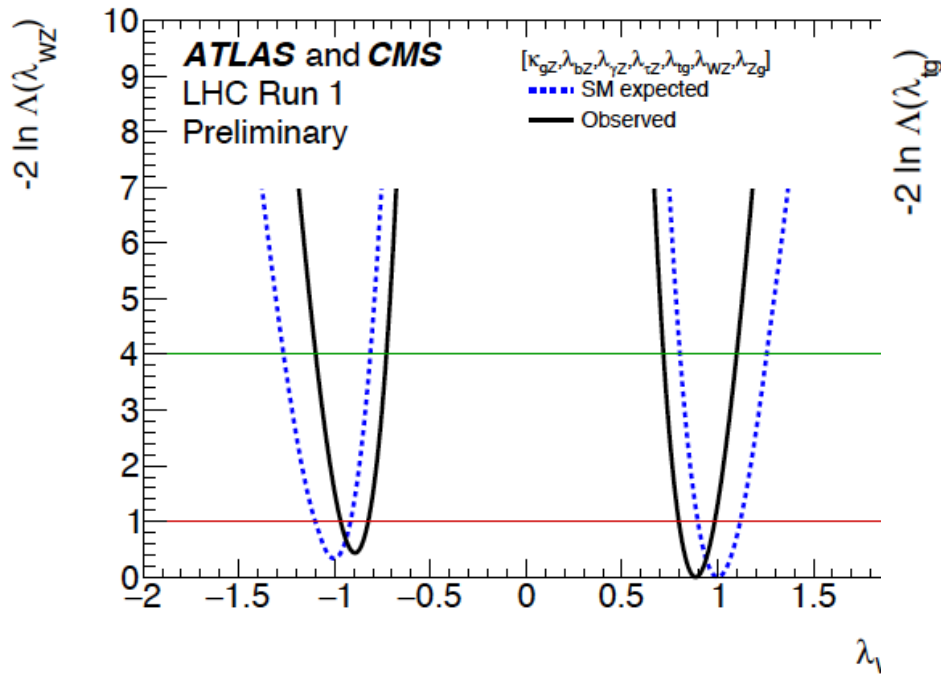
- **All parameters are allowed to have relative negative sign wrt each other in principle.**
- **Two can be tested currently since we have two processes involving interference effects which can be strong (gg to ZH and tH).**
- **As shown by the figures above, there is some sensitivity, but it is still marginal.**
- **This is similar to the better known κ_F vs κ_V plot**

Stronger assumptions on signal strength: assess compatibility of measurements with SM

- μ is the so called signal strength (μ=1 in the SM)

- $$\mu_i = \frac{\sigma_i}{\sigma_i^{\text{SM}}} \quad \text{and} \quad \mu^f = \frac{\text{BR}^f}{\text{BR}_{\text{SM}}^f} \qquad \mu_i^f \equiv \frac{\sigma_i \cdot \text{BR}^f}{(\sigma_i \cdot \text{BR}^f)_{\text{SM}}} = \mu_i \times \mu^f$$

- Most constrained parameterization: one single signal strength μ (and assuming the same at 7 and 8 TeV)

$$\mu = 1.09^{+0.11}_{-0.10} \quad = 1.09^{+0.07}_{-0.07} \text{ (stat)} {}^{+0.04}_{-0.04} \text{ (expt)} {}^{+0.03}_{-0.03} \text{ (thbgd)} {}^{+0.07}_{-0.06} \text{ (thsig)}$$

- Expected uncertainties very similar to observed

- Signal theory uncertainty due to QCD scale and PDF as large as statistical uncertainty. Being reduced from the theory side

Stronger assumptions on signal strength

SM BRs assumed

SM production σ assumed

SM p-value 25%
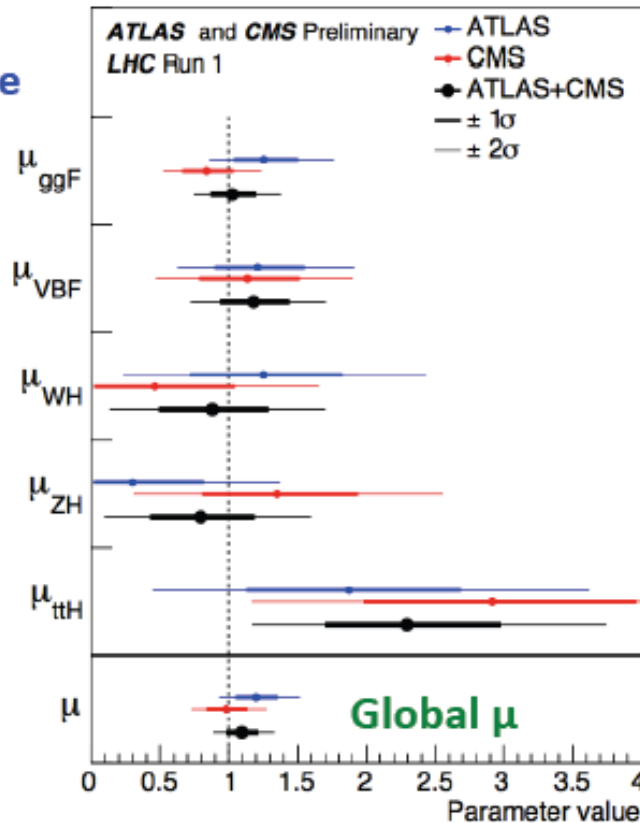
SM p-value 60%
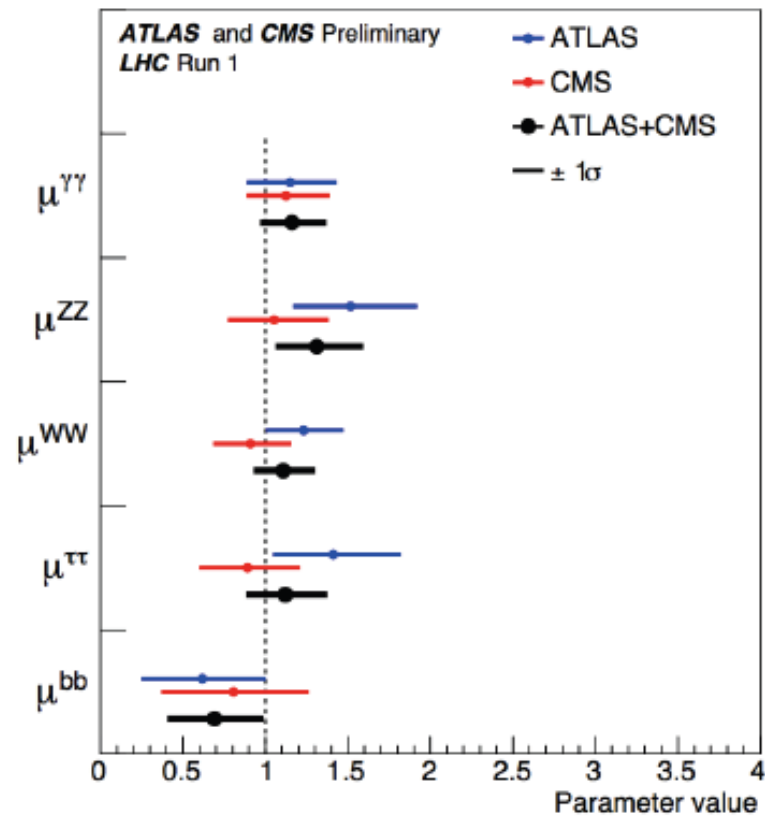
- Signal strengths in different channels are consistent with 1 (SM)

- Largest difference in ttH: 2.3σ excess with respect to SM

Stronger assumptions on signal strength

- Comparing likelihood of the best-fit with $\mu_{prod}=0$ and $\mu^{decay}=0$ we obtain:

Production process	Observed Significance(σ)	Expected Significance (σ)
VBF	**5.4**	**4.7**
WH	2.4	2.7
ZH	2.3	2.9
VH	3.5	4.2
ttH	4.4	2.0
Decay channel		
H→ττ	**5.5**	**5.0**
H→bb	2.6	3.7

- Combination largely increases the sensitivity

VBF and H→ττ now established at over 5 σ. Same as ggF and H→ZZ, γγ, WW from single experiments

Stronger assumptions on signal strength

- Can also fit μ_V^f vs μ_F^f per decay:

  - $\mu_V^f = \mu_{VBF+VH}^f$
  - $\mu_F^f = \mu_{ggF+ttH}^f$

- μ_V/μ_f can be measured in the different decay channels and combined:

$$\mu_V/\mu_f = 1.06\ ^{+0.35}_{-0.27}$$
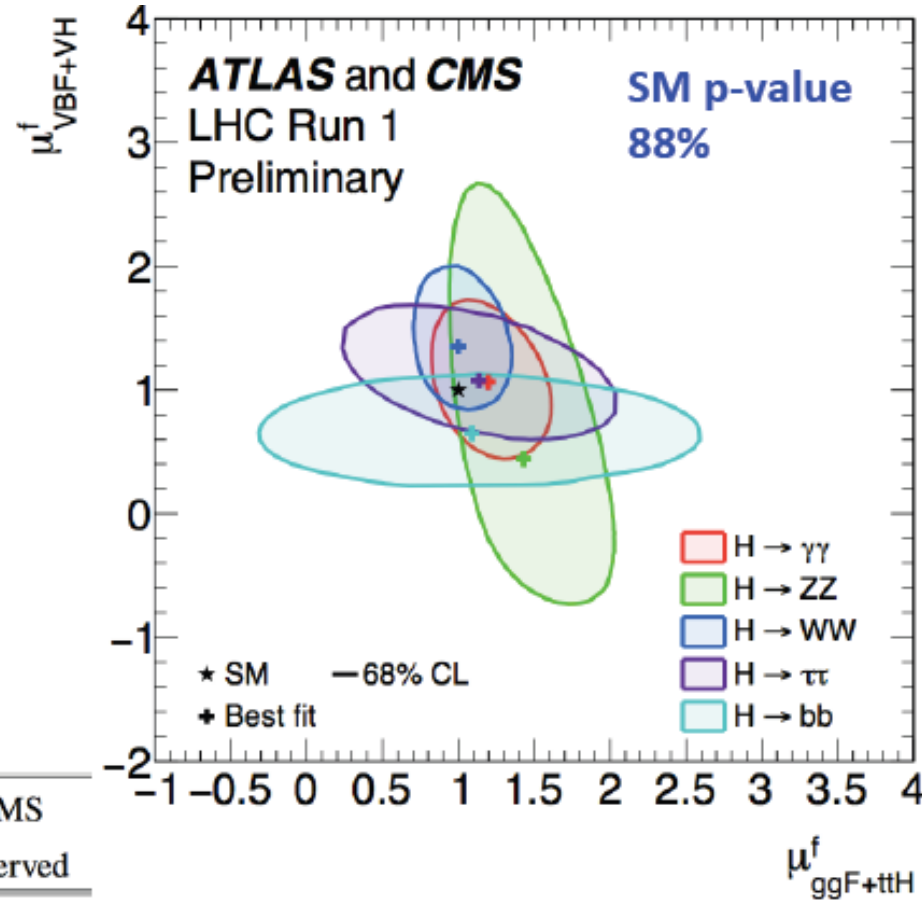
Parameter	ATLAS+CMS observed	ATLAS+CMS expected unc.	ATLAS observed	CMS observed
μ_V/μ_F	$1.06^{+0.35}_{-0.27}$	$^{+0.34}_{-0.26}$	$0.91^{+0.41}_{-0.30}$	$1.29^{+0.67}_{-0.46}$
$\mu_F^{\gamma\gamma}$	$1.13^{+0.24}_{-0.21}$	$^{+0.21}_{-0.19}$	$1.18^{+0.33}_{-0.29}$	$1.03^{+0.30}_{-0.26}$
μ_F^{ZZ}	$1.29^{+0.29}_{-0.25}$	$^{+0.24}_{-0.20}$	$1.54^{+0.44}_{-0.36}$	$1.00^{+0.33}_{-0.27}$
μ_F^{WW}	$1.08^{+0.22}_{-0.19}$	$^{+0.19}_{-0.17}$	$1.26^{+0.29}_{-0.25}$	$0.85^{+0.25}_{-0.22}$
$\mu_F^{\tau\tau}$	$1.07^{+0.35}_{-0.28}$	$^{+0.32}_{-0.27}$	$1.50^{+0.66}_{-0.49}$	$0.75^{+0.39}_{-0.29}$
$\mu_F^{b\bar{b}}$	$0.65^{+0.37}_{-0.28}$	$^{+0.45}_{-0.34}$	$0.67^{+0.58}_{-0.42}$	$0.64^{+0.54}_{-0.36}$

SM p-value 62%

Stronger assumptions on κ coupling modifiers: test for presence of BSM physics in Higgs sector

- All vector and fermion couplings are scaled by κ_V and κ_F
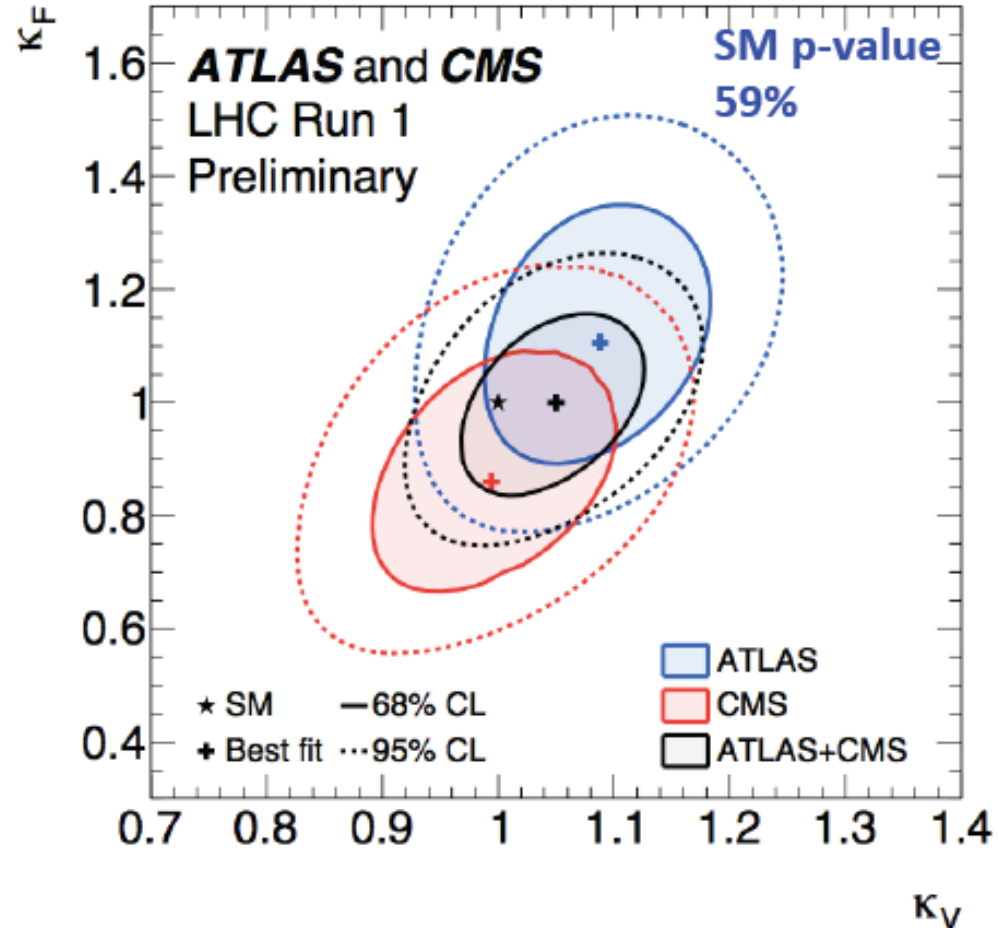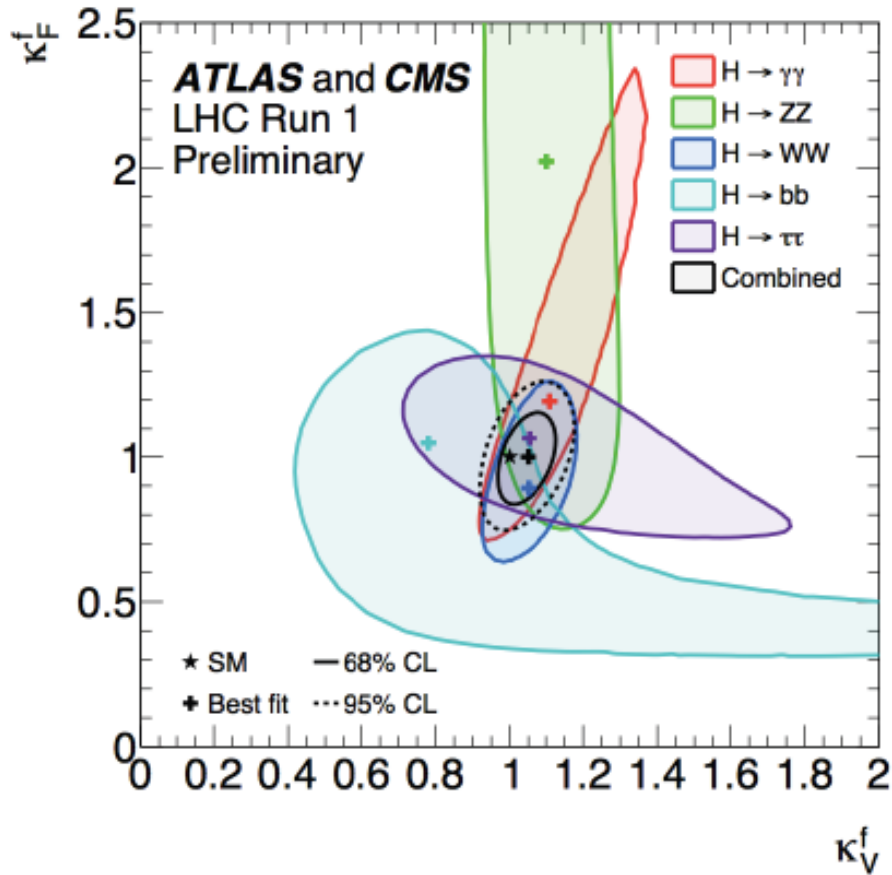
All results in agreement with SM ($\kappa_V = \kappa_f = 1$) within 1σ

Stronger assumptions on κ coupling modifiers

- Negative couplings would change sign of interference

Almost 5σ exclusion of $\kappa_F < 0$
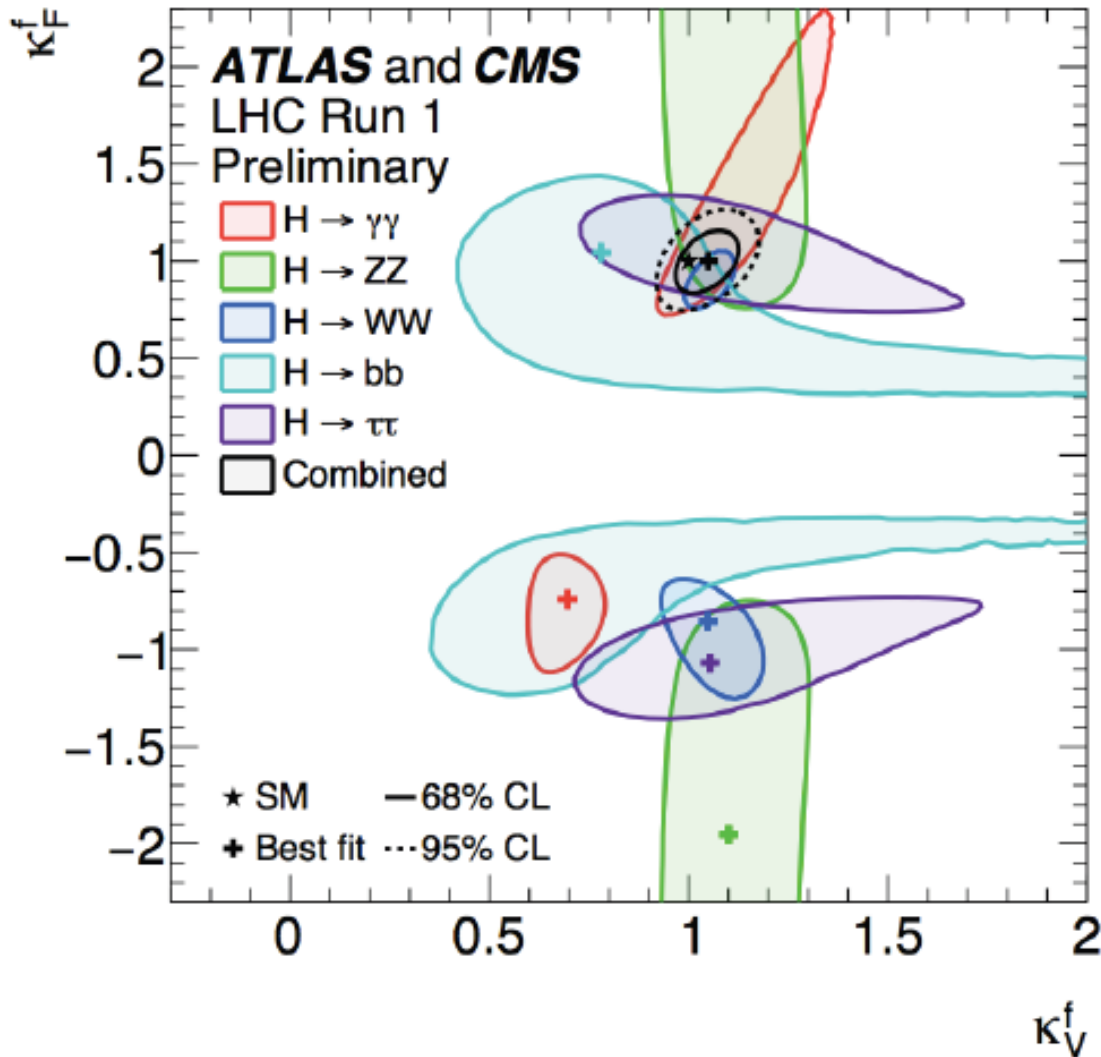
- The other two quadrants are symmetric with respect to (0,0), all physical quantities only depend on a product of two κ's

Stronger assumptions on κ coupling modifiers: no BSM physics in the loops nor in the decays

- Fitting the 5 main tree level coupling modifiers + κ_μ and resolving all the loops.

ATLAS and **CMS** Preliminary
LHC Run 1

- ATLAS
- CMS
- ATLAS+CMS
- ± 1σ

κ_Z
κ_W
κ_t
κ_τ
κ_b
κ_μ

Parameter value

ATLAS and CMS
LHC Run 1 Preliminary

— Observed
---- SM Higgs boson

t
Z
W
τ
b
μ

$\kappa_F \frac{m_F}{v}$ or $\sqrt{\kappa_V} \frac{m_V}{v}$

Particle mass [GeV]

Within current precision Higgs couplings scale with particle masses
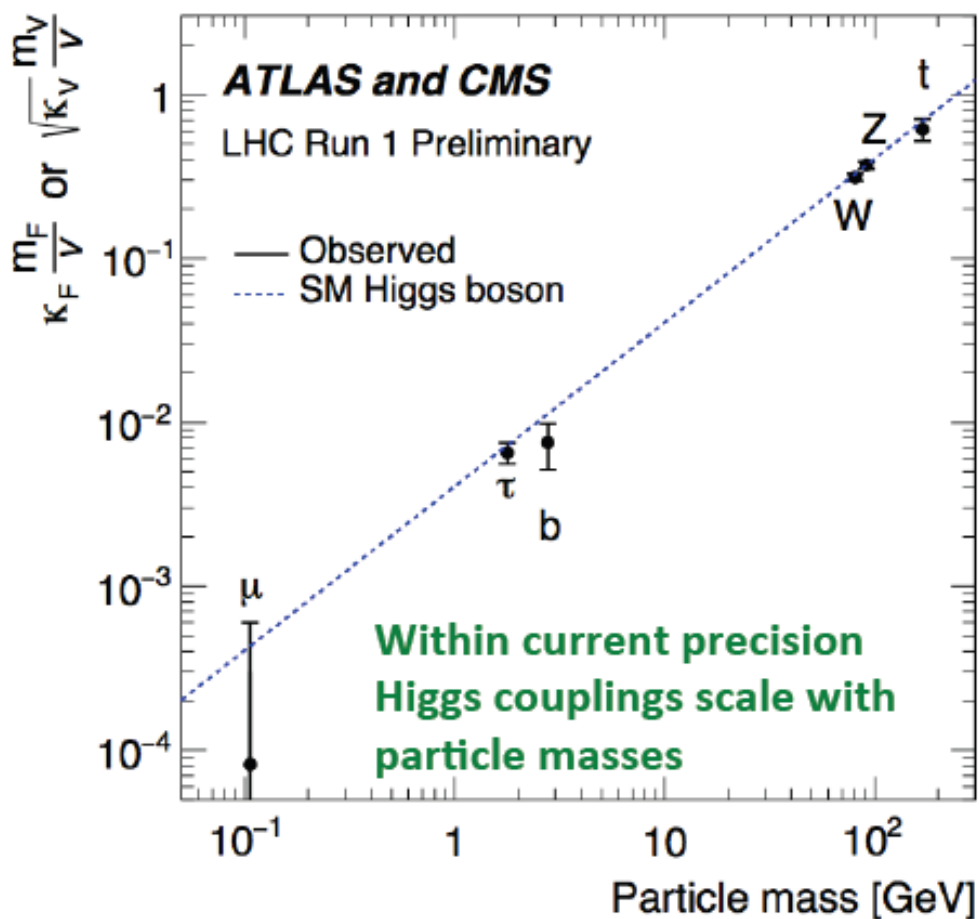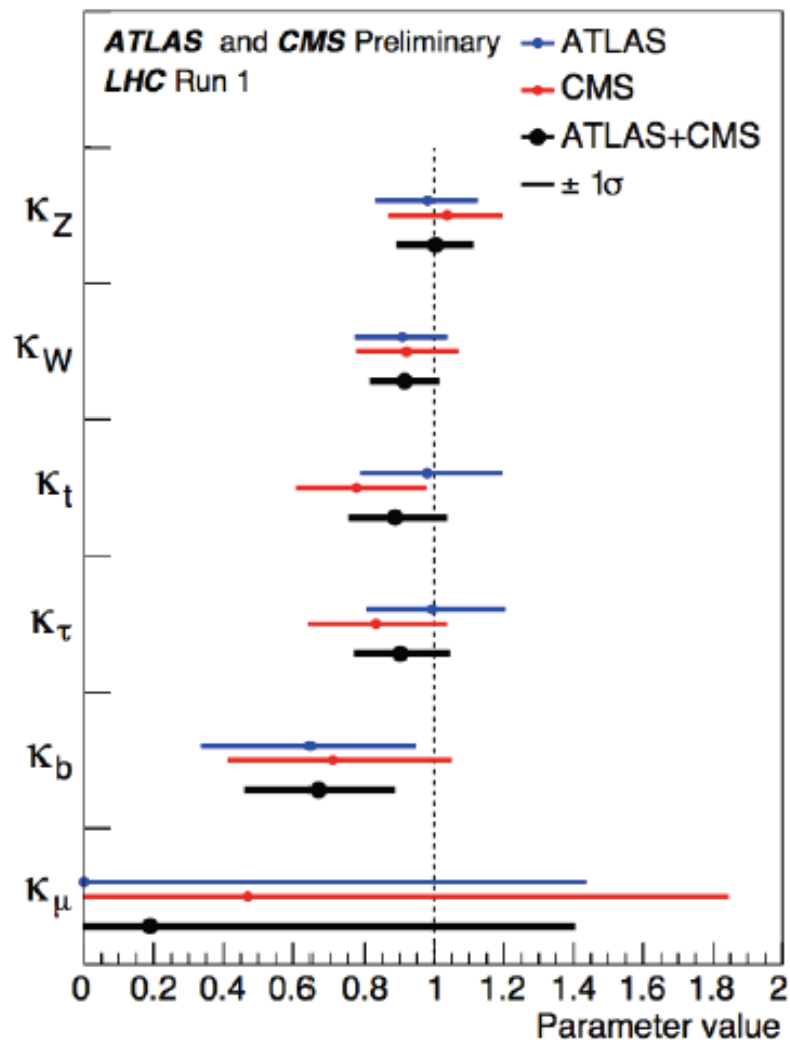
Stronger assumptions on κ coupling modifiers

- Assuming tree level couplings as in the SM and only modifications to the two main loops of ggF and H→γγ

ggF loop
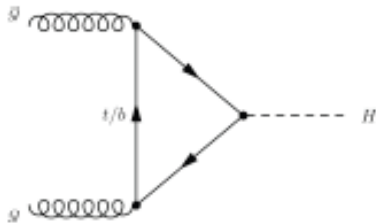
H→γγ loop
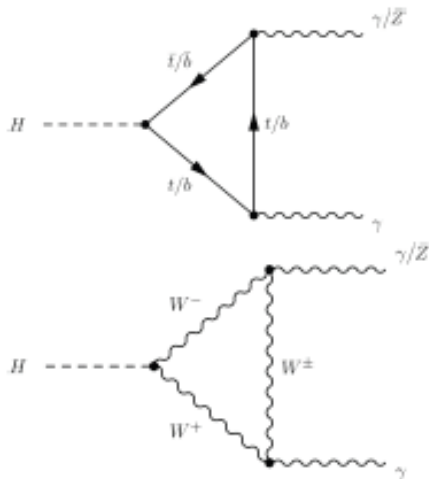
Additional heavy fermions or charged Higgs boson would modify the effective couplings

ATLAS and CMS
LHC Run 1
Preliminary

SM p-value
82%

★ SM   ⎯68% CL
+ Best fit

☐ ATLAS
☐ CMS
☐ ATLAS+CMS

κ_g

κ_γ
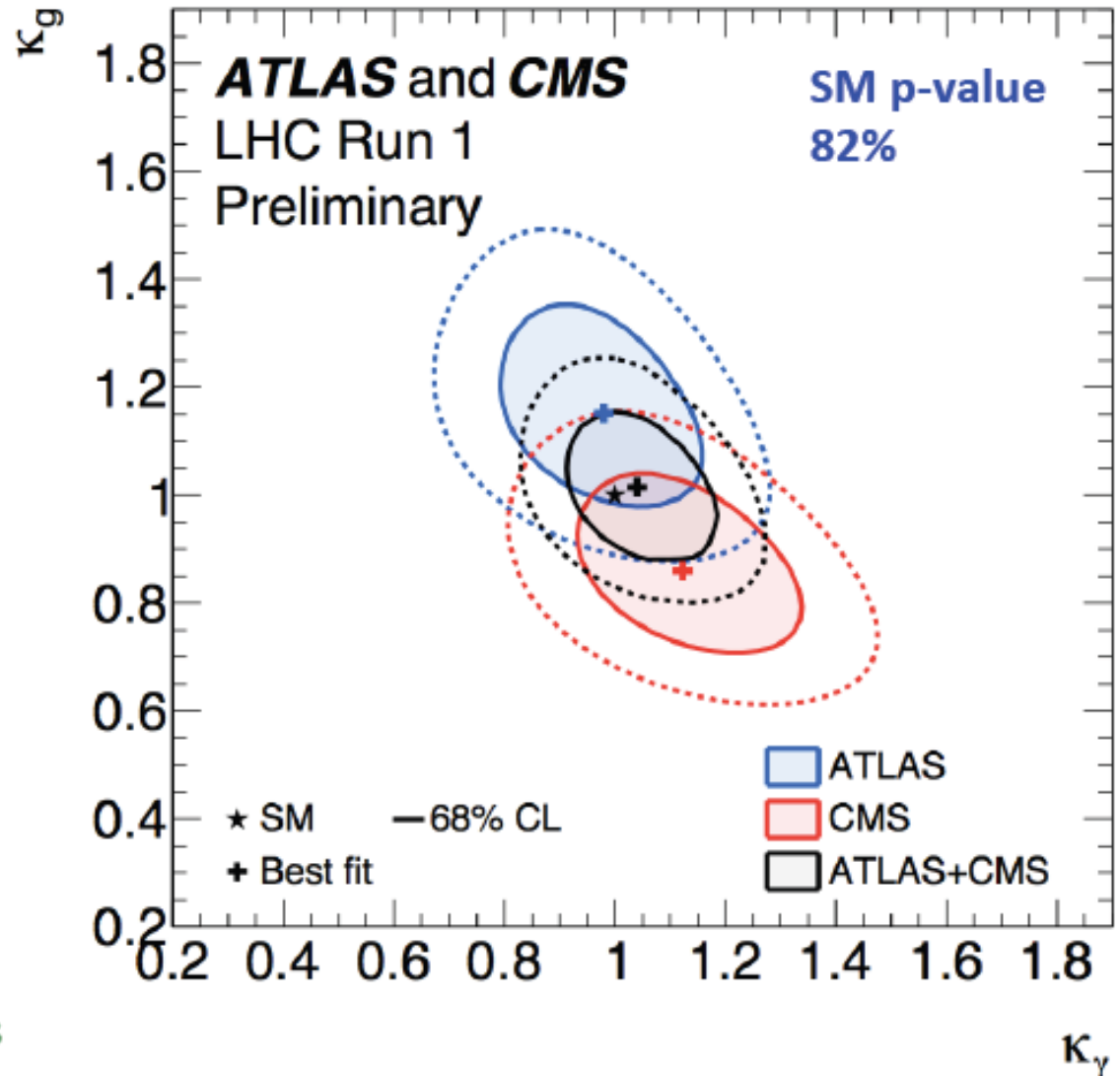
Higgs width

Extraction of Higgs boson width from off-shell measurements : a brief overview

Stronger assumptions on κ coupling modifiers:
BSM physics in the loops only or in both loops and decays
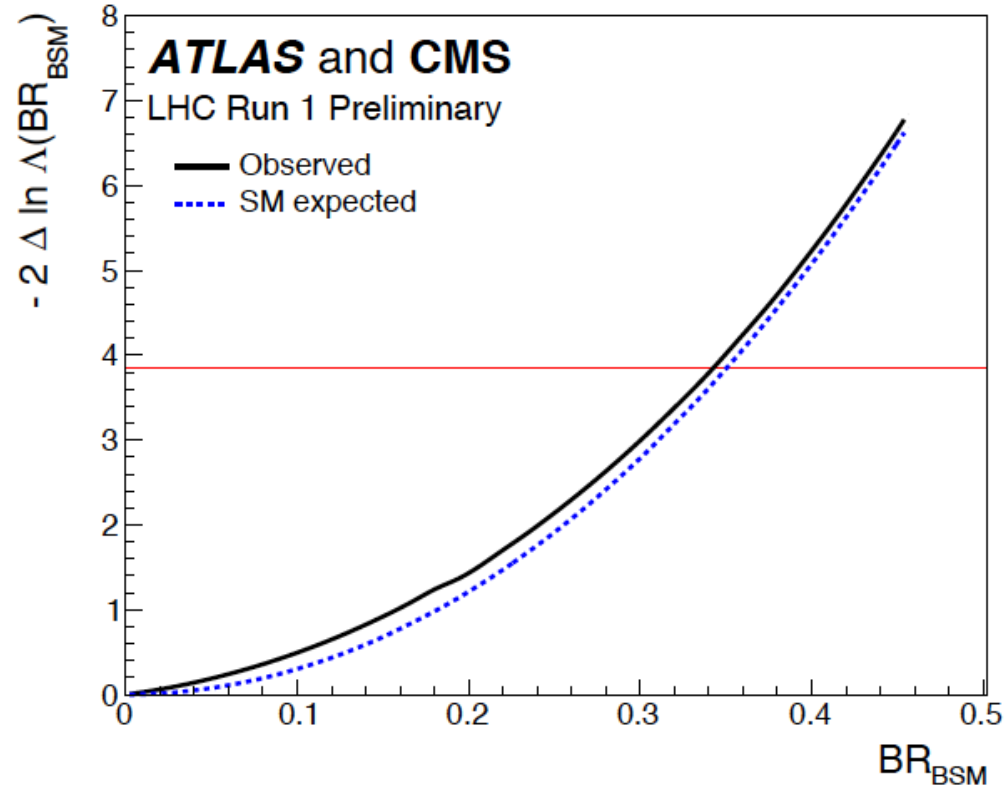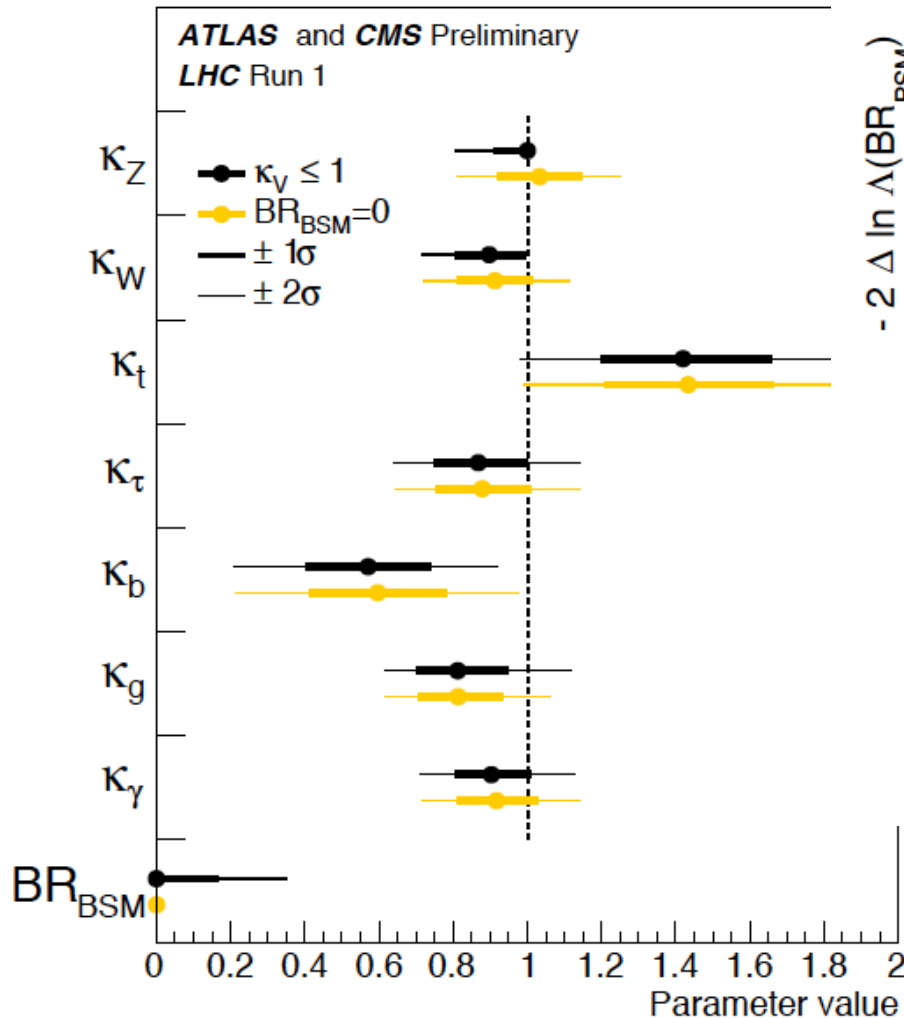
- **Here assume either BR$_{BSM}$ = 0 or κ$_W$ and κ$_Z$ < 1**
- **In the latter case, extract limit on BR$_{BSM}$ < 34% at 95 CL**

searches H->invisible

✦ ATLAS has an updated combination:

- ✦ Full Run2 (VBF+ttH) + Run1 (VBF+ZH+VHhad)

- ✦ first re-interpretation of SUSY tt+MET searches for H->inv signal

✦ CMS: only ZH-> ll+MET updated to full Run2
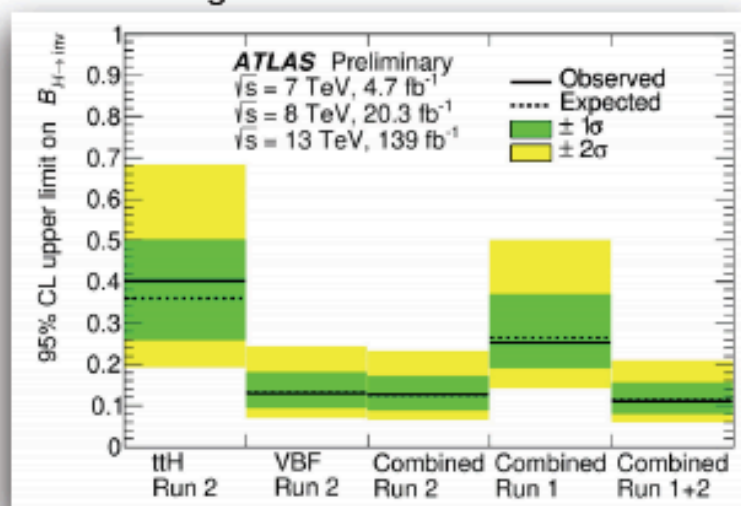
- ✦ H->inv Br 95% U.L.: **11% (11%) obs. (exp)**

  - ✦ [dominated by VBF Run2 (13%)]

  - ✦ asked few times why we didn't include previous ZH or status of the full Run2 one

- ✦ *ongoing ATLAS ll+MET analysis has ~20% UL exp. … and more to come*

  - ✦ VBF improvement, VBF+γ, VHhad, more ttH channels
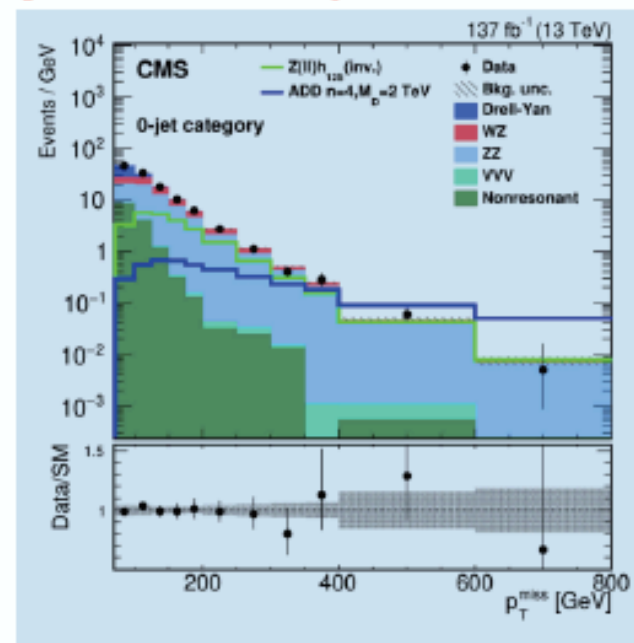
- ✦ not so stat. limited

Total systematic uncertainty	0.11
Statistical uncertainty	0.089
Total uncertainty	0.14

- ✦ H->inv Br 95% U.L.:

  - ✦ ZH (full Run2): **29% (25%) obs. (exp)** [was ~40% in 36fb⁻¹]

  - ✦ previous Run1+Run2(36fb⁻¹) combo: **19% (15%) obs. (exp)**

Higgs width from offshell measurements

Measurement of Off-Shell signal strength And constraints on the Higgs boson width

Probing the Higgs boson as a propagator:

- N. Kauer and G. Passarino, Inadequacy of zero-width approximation for a light Higgs boson signal, JHEP 1208 (2012) 116, arXiv:1206.4803.

- F. Caola and K. Melnikov, Constraining the Higgs boson width with ZZ production at the LHC, Phys.Rev. D88 (2013) 054024, arXiv:1307.4935.

- J. M. Campbell, R. K. Ellis, and C. Williams, Bounding the Higgs width at the LHC, JHEP 1404 (2014) 060, arXiv:1311.3589.

- J. M. Campbell, R. K. Ellis, and C. Williams, Bounding the Higgs width at the LHC, Phys.Rev. D89 (2014) 053011, arXiv:1312.1628.

- A. Azatov, C. Grojean, A. Paul and E. Salvioni, Taming the Off-Shell Higgs boson, CERN-PH-TH-2014-108, arXiv:1406:6338

Inadequacy of zero-width approximation for a light Higgs boson signal

Nikolas Kauer[a] and **Giampiero Passarino**[b]

[a] *Department of Physics, Royal Holloway, University of London,*
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INFN, Sezione di Torino, Italy

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ABSTRACT: In the Higgs search at the LHC, a light Higgs boson ($115\,\text{GeV} \lesssim M_H \lesssim 130\,\text{GeV}$) is not excluded by experimental data. In this mass range, the width of the Standard Model Higgs boson is more than four orders of magnitude smaller than its mass. The zero-width approximation is hence expected to be an excellent approximation. We show that this is not always the case. The inclusion of off-shell contributions is essential to obtain an accurate Higgs signal normalisation at the 1% precision level. For $gg\,(\to H) \to VV$, $V = W, Z$, $\mathcal{O}(10\%)$ corrections occur due to an enhanced Higgs signal in the region $M_{VV} > 2\,M_V$, where also sizable Higgs-continuum interference occurs. We discuss how experimental selection cuts can be used to exclude this region in search channels where the Higgs invariant mass cannot be reconstructed. We note that the $H \to VV$ decay modes in weak boson fusion are similarly affected.
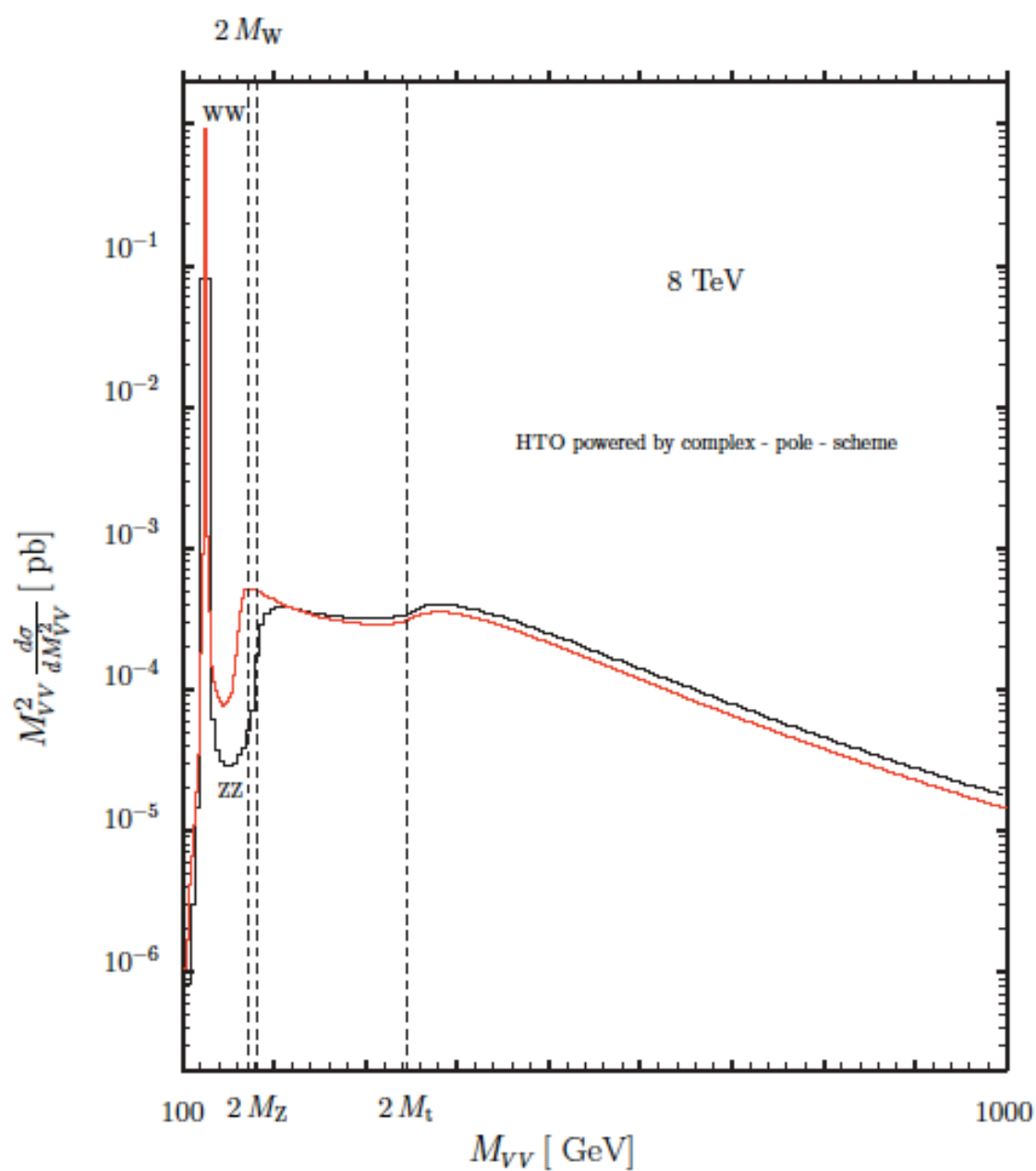
Figure 2. The NNLO ZZ (black) and WW (red) invariant mass distributions in $gg \to VV$ for $\mu_H = 125\,\text{GeV}$.

Extraction of Higgs boson width from off-shell measurements : a brief overview

	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

Table 1. Total cross-section for the processes $gg \to H \to ZZ$ and $gg \to H \to$ all; the part of the cross-section coming from the region $M_{ZZ} > 2\,M_Z$ is explicitly shown, as well as the ratio.

In this section, we consider the signal (S) in the complex-pole scheme (CPS) of Refs. [54, 74, 75]

$$\sigma_{gg \to ZZ}(S) = \sigma_{gg \to H \to ZZ}(M_{ZZ}) = \frac{1}{\pi}\,\sigma_{gg \to H}\,(M_{ZZ})\,\frac{M_{ZZ}^4}{\left|M_{ZZ}^2 - s_H\right|^2}\,\frac{\Gamma_{H \to ZZ}\,(M_{ZZ})}{M_{ZZ}}, \quad (2.8)$$

where s_H is the Higgs complex pole, parametrized by $s_H = \mu_H^2 - i\,\mu_H\,\gamma_H$. Note that γ_H is not the on-shell width, although the numerical difference is tiny for low values of μ_H, as shown in Ref. [54].

mass distribution is shown in Fig. 2. It confirms that, above the peak, the distribution is decreasing until the effects of the VV threshold become effective with a visible increase followed by a plateau, by another jump at the $t\bar{t}$-threshold, beyond which the signal distribution decreases almost linearly (on a logarithmic scale). For $gg \to H \to \gamma\gamma$ the effect is drastically reduced and confined to the region $M_{\gamma\gamma}$ between 157 GeV and 168 GeV, where the distribution is already five orders of magnitude below the peak.

Extraction of Higgs boson width from off-shell measurements : a brief overview

Of course, the signal per se is not a physical observable and one should always include background and interference. In Fig. 3 we show the complete LO result for $gg \rightarrow ZZ$ calculated with HTO with a cut of $0.25\,M_{ZZ}$ on the transverse momentum of the Z. The large destructive effects of the interference above the resonant peak wash out the peculiar structure of the signal distribution. If one includes the region $M_{ZZ} > 2\,M_Z$ in the analysis then the conclusion is: interference effects are relevant also for the low Higgs mass region, at least for the $ZZ(WW)$ final state. It is worth noting again that the discussed effect on

To conclude our inclusive analysis, we note that our findings are driven by the interplay between the q^2-dependence of the Higgs propagator and the decay matrix element. They should hence not only apply to Higgs production in gluon fusion, but also to Higgs production in weak boson fusion (WBF). The enhancement for $H \rightarrow VV$ above M_{VV} may even be stronger in WBF, because $\sigma(q\bar{q} \rightarrow q\bar{q}H)$ decreases less rapidly than $\sigma(gg \rightarrow H)$ with increasing Higgs invariant mass.[5]
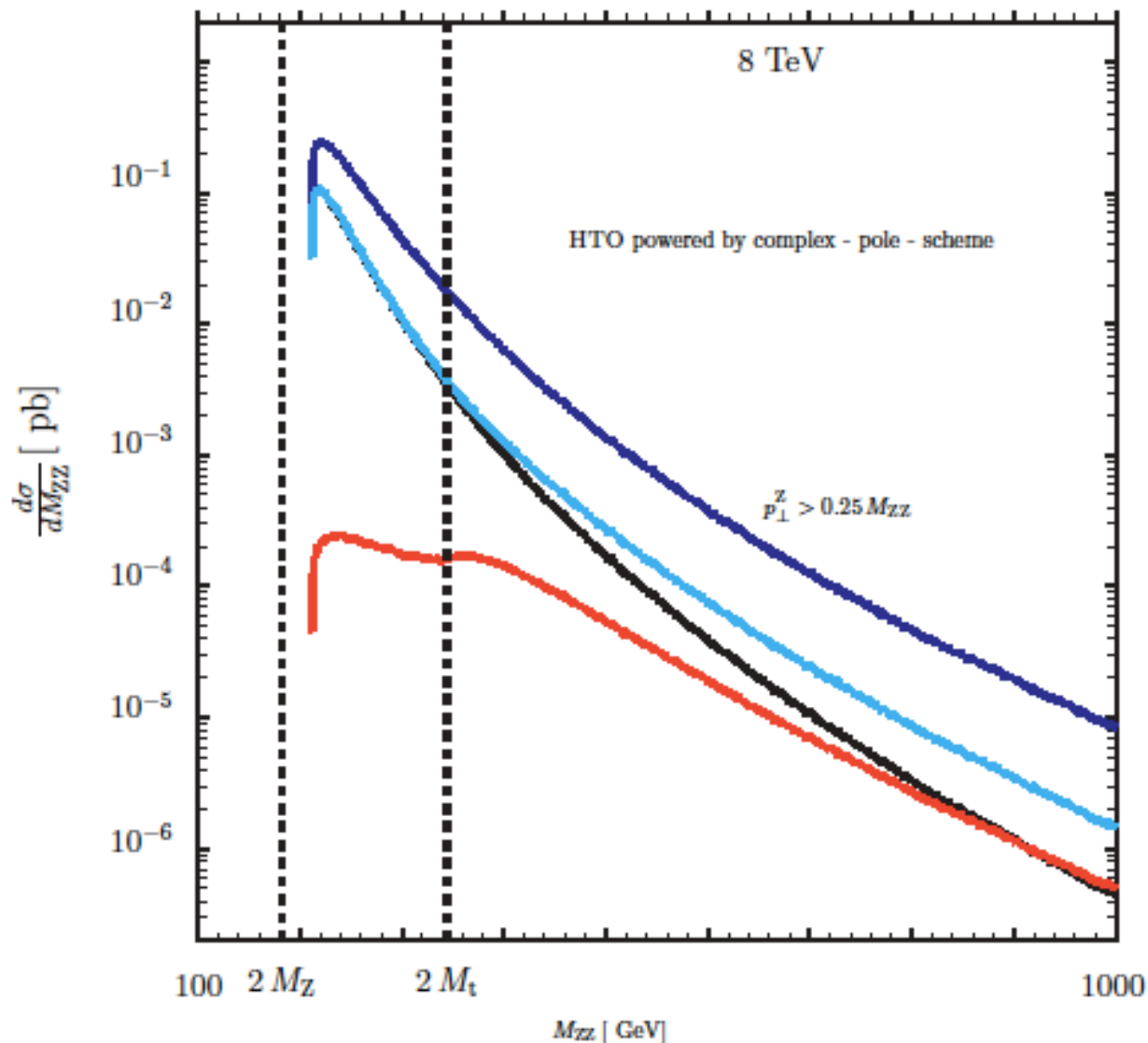
Figure 3. The LO ZZ invariant mass distribution $gg \to ZZ$ for $\mu_H = 125\,\mathrm{GeV}$. The black line is the total, the red line gives the signal while the cyan line gives signal plus background; the blue line includes the $q\bar{q} \to ZZ$ contribution.

Extraction of Higgs boson width from off-shell measurements : a brief overview

Constraining the Higgs boson width with ZZ production at the LHC

Fabrizio Caola[1,*] and Kirill Melnikov[1,†]

[1]Department of Physics and Astronomy, Johns Hopkins University, Baltimore, USA

We point out that existing measurements of $pp \to ZZ$ cross-section at the LHC in a broad range of ZZ invariant masses allow one to derive a model-independent upper bound on the Higgs boson width, thanks to strongly enhanced off-shell Higgs contribution. Using CMS data and considering events in the interval of ZZ invariant masses from 100 to 800 GeV, we find $\Gamma_H \leq 38.8\,\Gamma_H^{\rm SM} \approx 163$ MeV, at the 95% confidence level. Restricting ZZ invariant masses to $M_{ZZ} \geq 300$ GeV range, we estimate that this bound can be improved to $\Gamma_H \leq 21\,\Gamma_H^{\rm SM} \approx 88$ MeV. Under the assumption that all couplings of the Higgs boson to Standard Model particles scale in a universal way, our result can be translated into an upper limit on the branching fraction of the Higgs boson decay to invisible final states. We obtain $\mathrm{Br}(H \to \mathrm{inv}) < 0.84\,(0.78)$, depending on the range of ZZ invariant masses that are used to constrain the width. We believe that an analysis along these lines should be performed by experimental collaborations in the near future and also in run II of the LHC. We estimate that such analyses can, eventually, be sensitive to a Higgs boson width as small as $\Gamma_H \sim 10\,\Gamma_H^{\rm SM}$.

Extraction of Higgs boson width from off-shell measurements : a brief overview

Off Shell Higgs
Study the Higgs boson as a propagator

Study the 4-leptons spectrum in the high mass regime where the Higgs boson acts as a propagator

Measuring the Higgs contribution is then independent of the total width of the Higgs boson (sensitive to the product off shell of the Higgs boson to the coupling to the top and Z)

Highly non trivial due to:
- The negative interference
- The large other backgrounds

Assuming that these couplings run as in the Standard Model and measuring them on shell allows for a measurement of the width of the Higgs boson!

$$\mu_{off\,shell} = \left(\kappa_t^2 \kappa_V^2\right)_{off\,shell}$$

$$\mu_{on\,shell} = \frac{\left(\kappa_t^2 \kappa_V^2\right)_{on\,shell}}{\Gamma_H/\Gamma_H^{SM}}$$

$$\left(\kappa_t^2 \kappa_V^2\right)_{on\,shell} = \left(\kappa_t^2 \kappa_V^2\right)_{off\,shell}$$

$$\Gamma_H = \frac{\mu_{off\,shell}}{\mu_{on\,shell}} \times \Gamma_H^{SM}$$
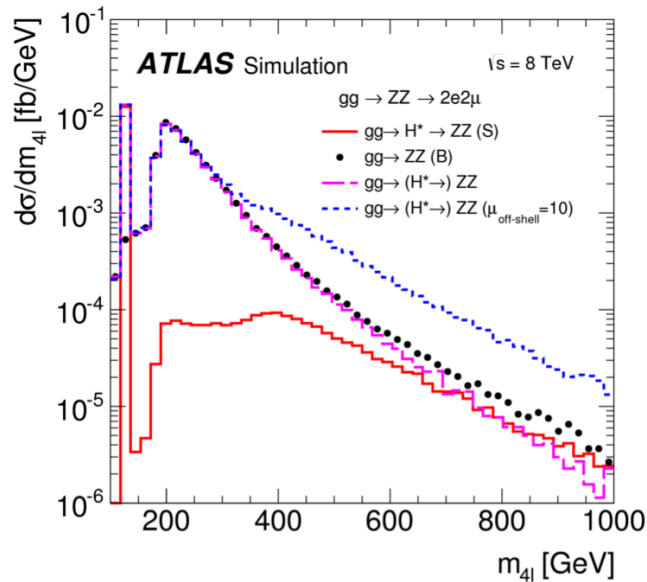
Limits on the total width are currently at approximately 15 MeV

Preliminary HL-LHC results show that a reasonable sensitivity can be obtained with 3 ab-1:

$$\Gamma_H = 4.2^{+1.5}_{-2.1}\,MeV$$

ATLAS-CONF-2014-042
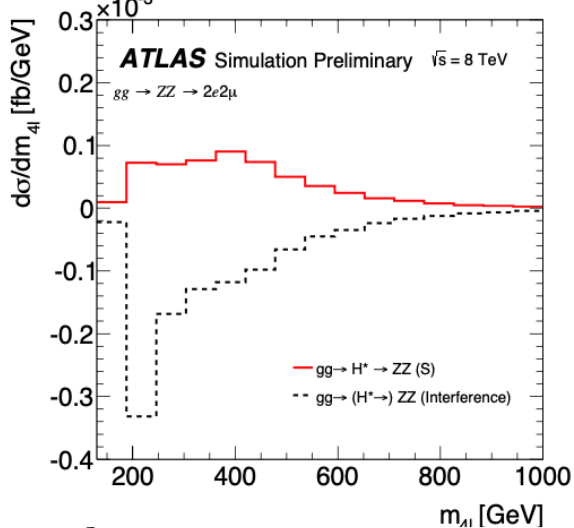
Off Shell Higgs coupling properties Measurement
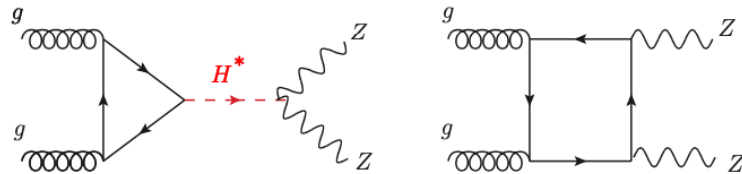
$$\mu_{OffShell} \equiv \frac{\sigma^{gg \to H^* \to ZZ}_{OffShell}}{(\sigma^{gg \to H^* \to ZZ}_{OffShell})_{SM}} = (\kappa_g^2 \kappa_V^2)_{OffShell}$$

Higgs boson as a propagator

- New physics that affects the Higgs couplings and not the continuum

- LO description of the continuum (gg2VV), use of k-factor: no assumption made on bkg k-factor

$$R^b_{H^*} = \frac{k_{gg \to ZZ}}{k_{gg \to H^* \to ZZ}}$$

- Uncertainty of 30% on the interference term w.r.t. to chosen continuum k-factor

49
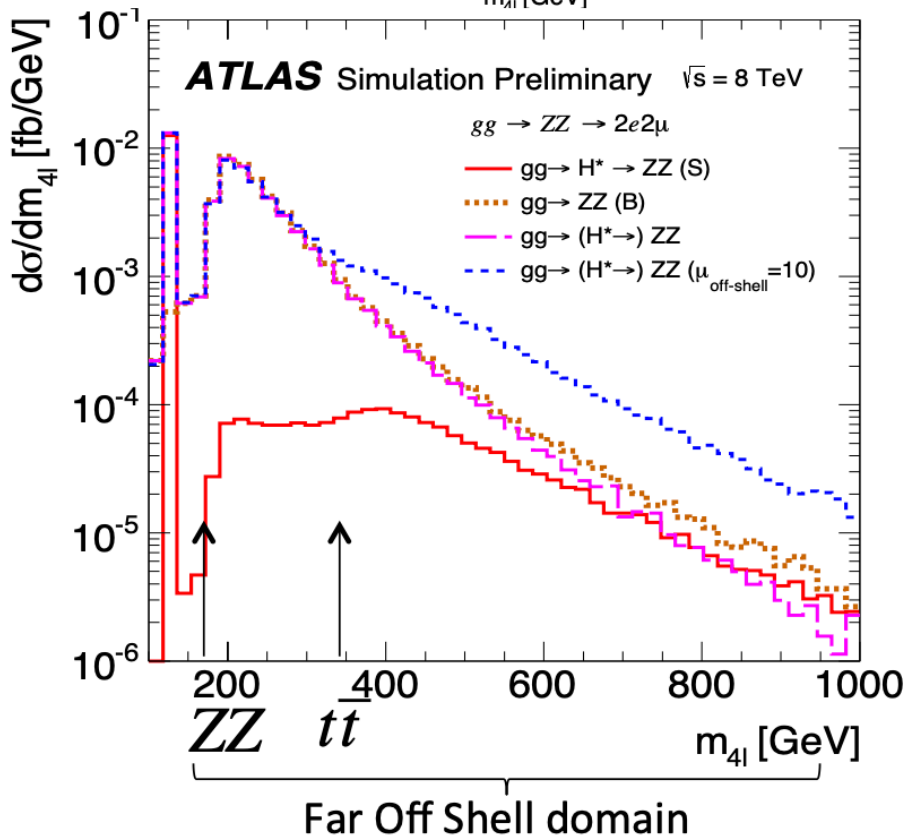
Exploring the High mass region in 4l and 2l2ν

ATLAS-CONF-2014-042
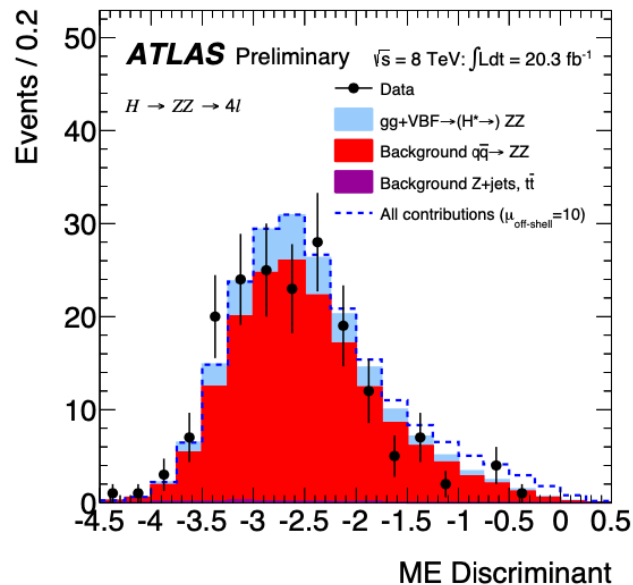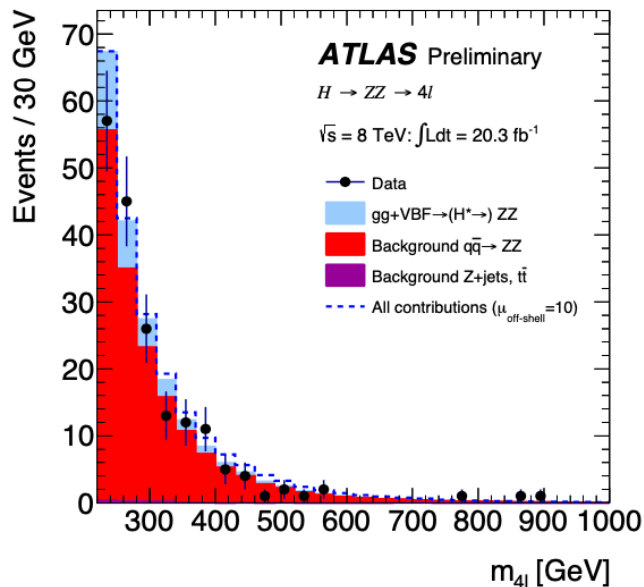
Use of two channels:

- 4l analysis with Mass and ME

- llνν analysis cut based

- Main background qq continuum includes EW k-factor
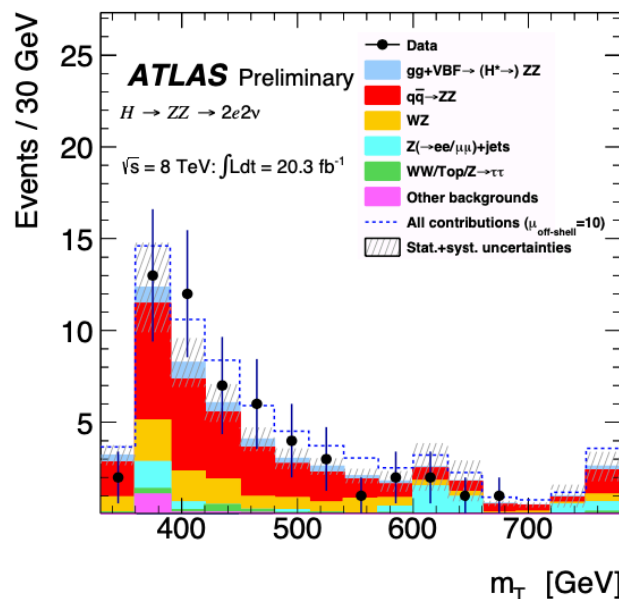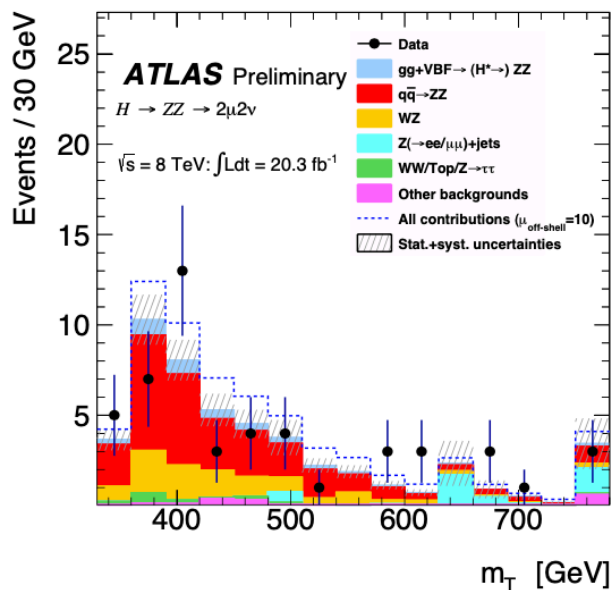
CLs limits on Off-Shell signal strength

Agnostic to k-factor!

R=1 (Verified in the soft colinear approximation)
(G. Passarino)

95% CL limit obs. (exp.)
$\mu_{OffShell} < 6.7 \ (7.9)$
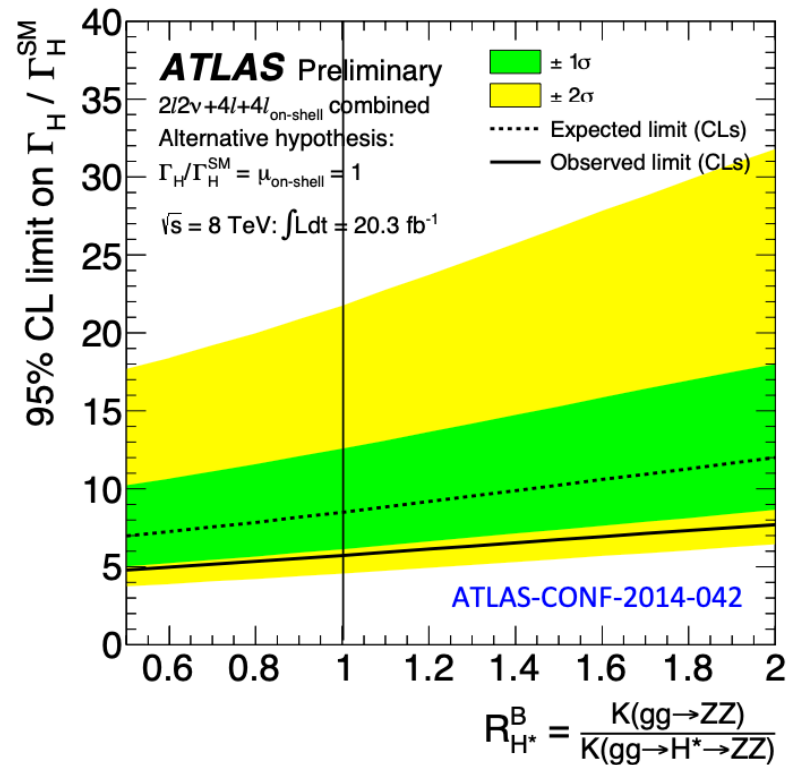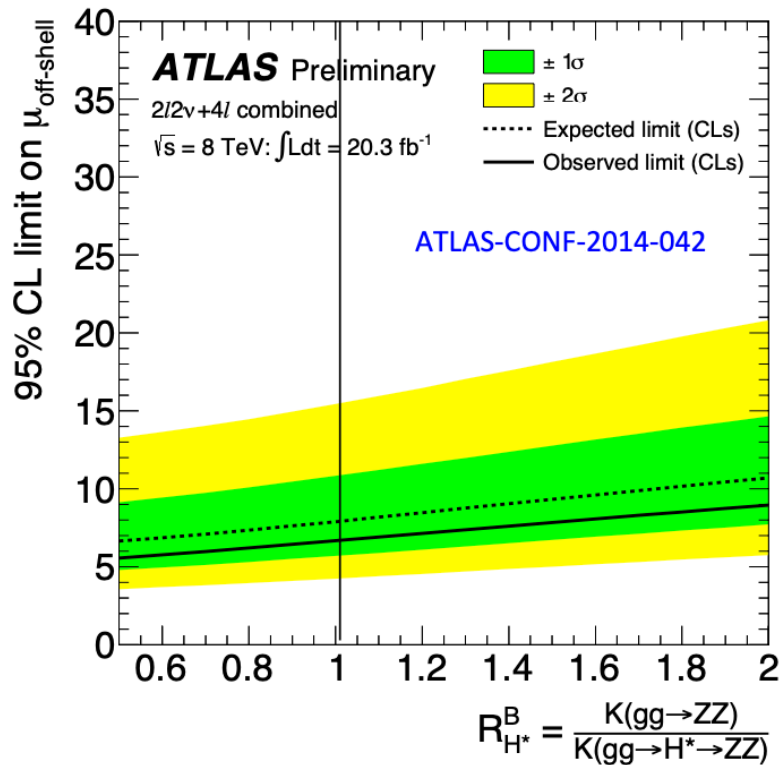
...and on the total width

$$\mu_{OnShell} \equiv \frac{(\kappa_g^2 \kappa_V^2)_{OnShell}}{\Gamma_H / \Gamma_H^{SM}}$$

Assuming* $\mu_{OffShell} = \mu_{OnShell} \times \Gamma_H / (\delta_H)_{SM}$

Equivalent to $(\kappa_g^2 \kappa_V^2)_{OnShell} = (\kappa_g^2 \kappa_V^2)_{OffShell}$

*Particularly sensitive to running of the effective coupling κ_g in the production (through loop)

95% CL limit obs. (exp.)
$\Gamma_H / \Gamma_H^{SM} < 5.7 \ (8.5)$

ATLAS-CONF-2014-042

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Extraction of Higgs boson width from off-shell measurements : a brief overview

Off Shell Higgs
Study the Higgs boson as a propagator

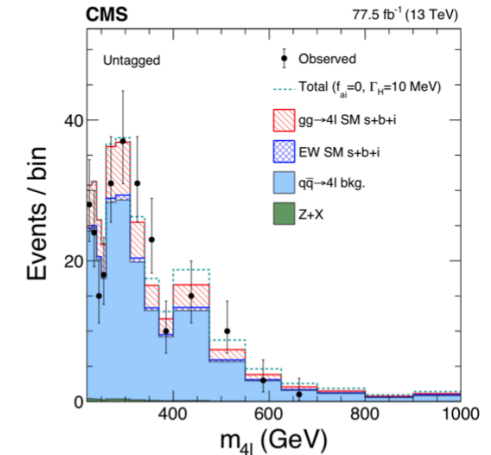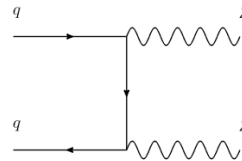Study the 4-leptons spectrum in the high mass regime where the Higgs boson acts as a propagator

From J. Campbell

$$aE^2 + (b+c)m_t E \qquad -aE^2 + (d-c)m_t E \qquad -(b+d)m_t E$$

ATLAS Simulation $\sqrt{s}$ = 8 TeV

$gg \to ZZ \to 2e2\mu$

- $gg \to H^* \to ZZ$ (S)
- $gg \to ZZ$ (B)
- $gg \to (H^* \to) ZZ$
- $gg \to (H^* \to) ZZ$ ($\mu_{off\text{-}shell}$ =10)
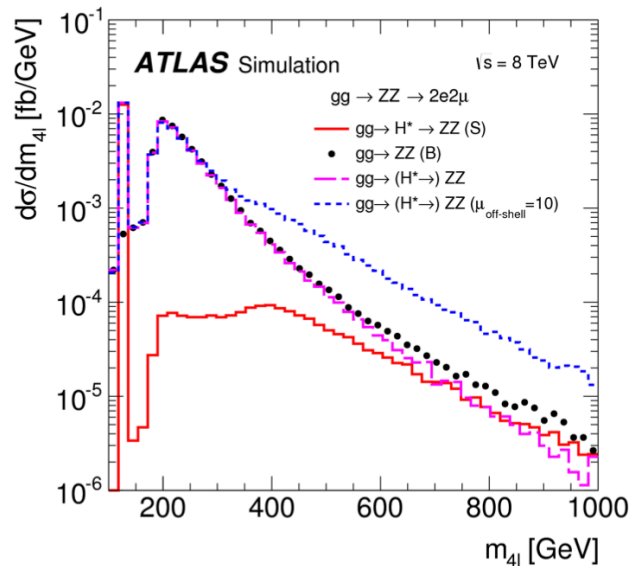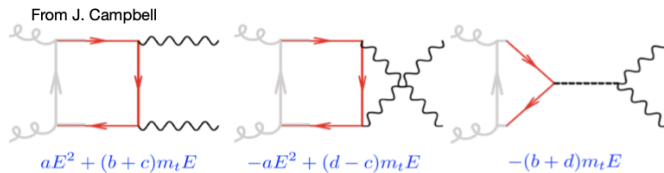
Measuring the Higgs contribution is then independent of the total width of the Higgs boson (sensitive to the product **off shell** of the Higgs boson to the coupling to the top and Z)

Assuming that these couplings run as in the Standard Model and measuring them **on shell** allows for a measurement of the width of the Higgs boson!

Highly non trivial due to:

- The negative interference
- The large other backgrounds

CMS — 77.5 fb⁻¹ (13 TeV)

Untagged

- Observed
- Total (f$_{ai}$=0, Γ_H=10 MeV)
- gg→4l SM s+b+i
- EW SM s+b+i
- q$\bar{q}$→4l bkg.
- Z+X

Limits on the total width are currently at approximately **10 MeV** (and exclude 0 at 95% CL).
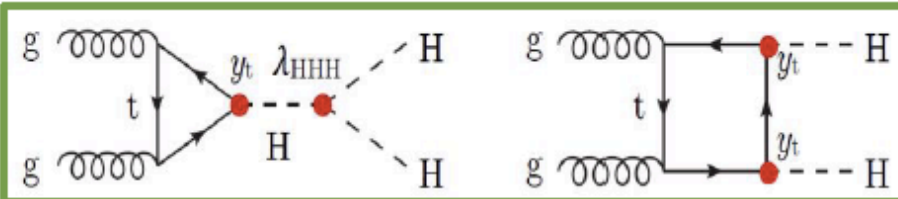
HL-LHC: $\Gamma_H = 4.1^{+1.0}_{-1.1}$ MeV

Preliminary HL-LHC results show that a reasonable sensitivity can be obtained with 3 ab⁻¹
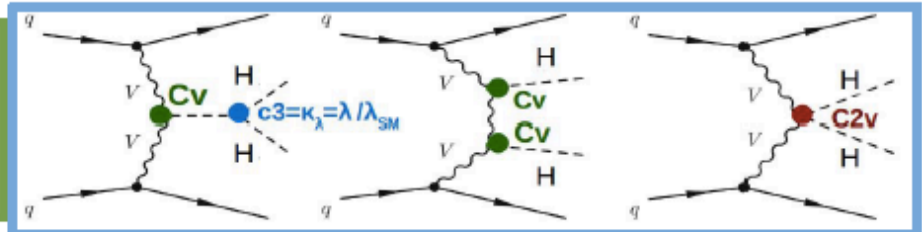
Future-ee 0.2%

Higgs self-coupling and stability of the universe

Higgs pair production in Standard Model

ggHH LO

**VBFHH LO**

c_i / κ_r: modifier of SM coupling

❖ HH is the only process for the direct access of trilinear self Higgs coupling (λ_{HHH}) at the LHC, which dictates the shape of the Higgs potential.

❖ The standard model value of $\lambda_{HHH} = m_H^2/2v^2 \sim 0.13$

❖ **Gluon-gluon fusion (ggHH)** : the largest production mode of HH at the LHC, cross section with N²LO QCD accuracy, $\sigma_{ggHH} = 31.05$ fb @13 TeV [1].

❖ **Vector Boson fusion (VBFHH)** : the sub-lead mode, at N³LO, $\sigma_{VBFHH} = 1.73$ fb [2].

❖ VBFHH: **unique** process for accessing the coupling of Higgs pair with a pair of weak gauge bosons (VVHH, V = W/Z)

✦ **2y + 2 b-jets + (2 jets for VBF):**

   ✦ b-jets: pt>25 GeV, highest b-tag score, m_{bb} in [70,190]

   ✦ VBF jets: p_T>40/30 GeV, highest m_{jj}
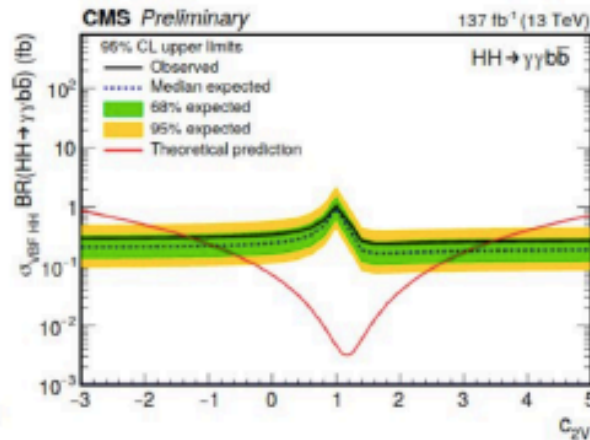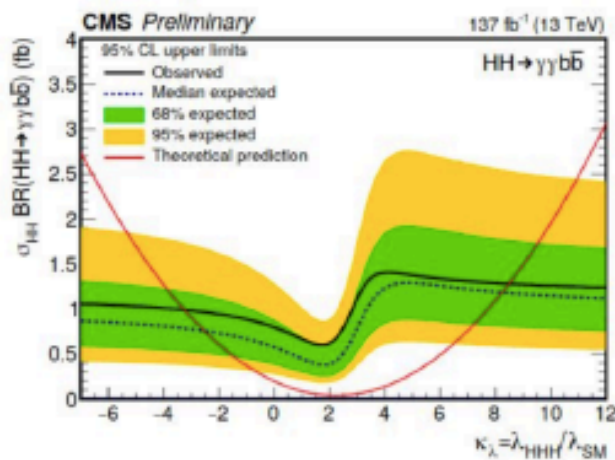
✦ **several MVAs used** (variables in backUp)**:**

   ✦ isolate different production modes (also in bins of MX)

   ✦ reject main ttH background

   ✦ SM signal and BSM benchmarks used in the training together
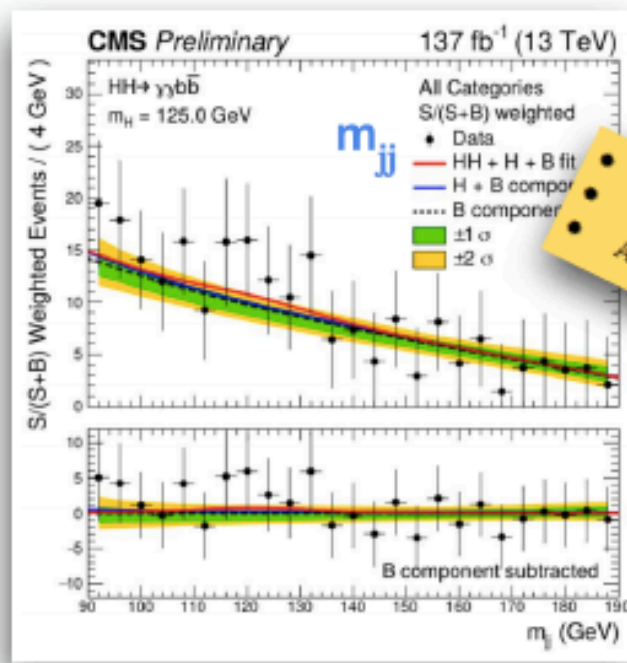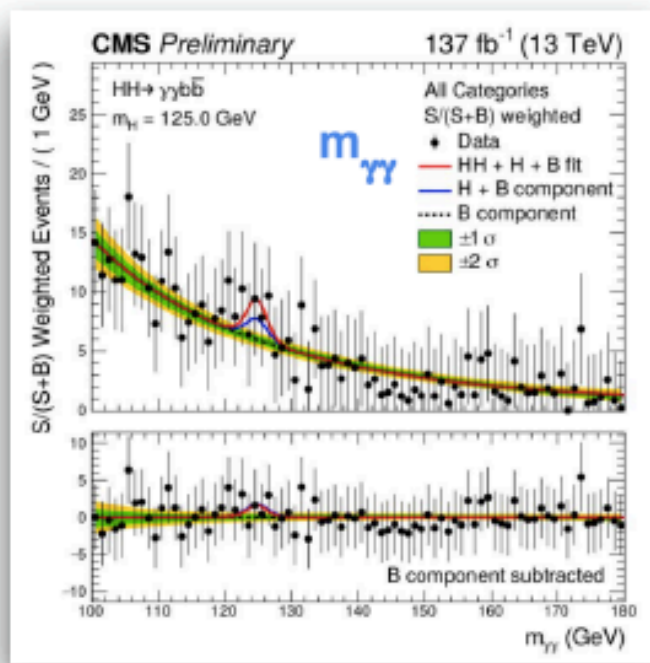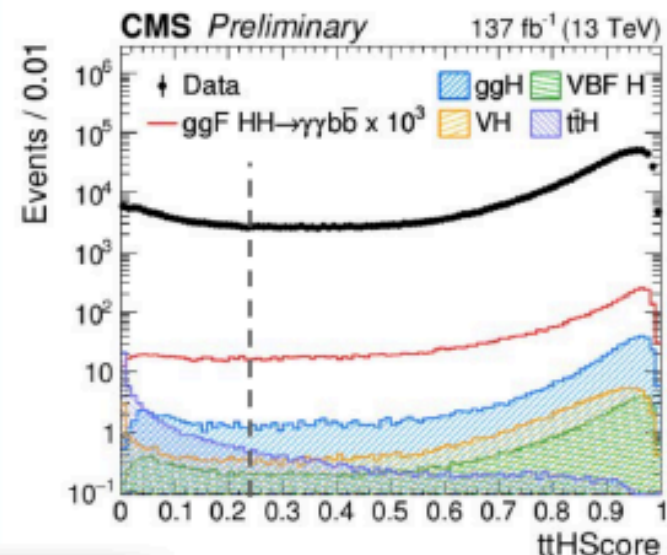
Total 14 categories based on MX & MVA
Simultaneous 2D fit to $m_{\gamma\gamma}$ x m_{jj} distributions
Assuming no $m_{\gamma\gamma}$ ~ m_{jj} correlation

S. Mukherjee

Allowed range @ 95% CL

Observed: $-3.3 < \kappa_\lambda < 8.5$
Expected: $-2.5 < \kappa_\lambda < 8.2$

Observed: $-1.3 < C_{2V} < 3.5$
Expected: $-0.9 < C_{2V} < 3.0$

Best-to-date !

95% CL Upper Limit on (inclusive cross section*BR) :

ATLAS VBF HH->4b result:

$-0.6 < K_{2V} < 2.9$

$-0.9 < K_{2V} < 3.1$

| Inclusive HH (* SM)	
Observed	7.7
Expected	5.2

Fir

36 fb⁻¹ results ~ 20

-- Statistically dominated analysis
-- Total impact of systematics on signal strengths is around 2%
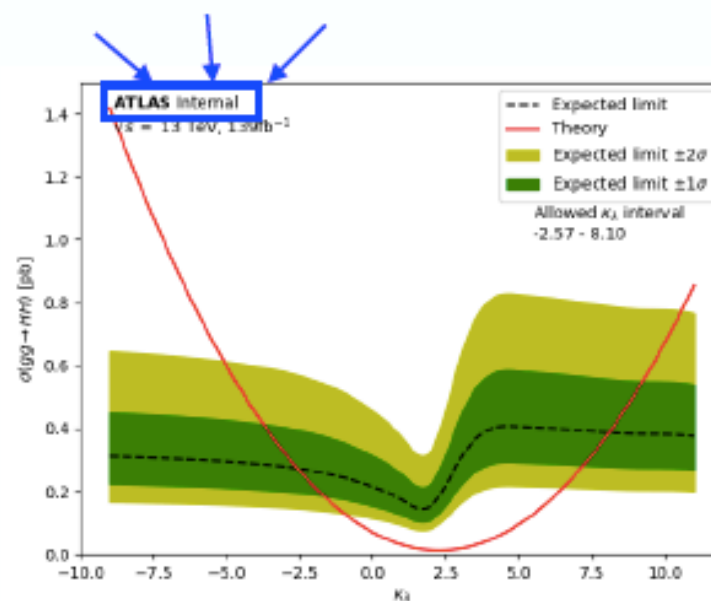
✦ *x4 reduction of upper limit with x4 more data*

✦ **ATLAS full Run2 result expected in early 2021:**

✦ analysis selection / categorisation has been frozen

✦ systematics are being evaluated (impact expected to be small) [few %]
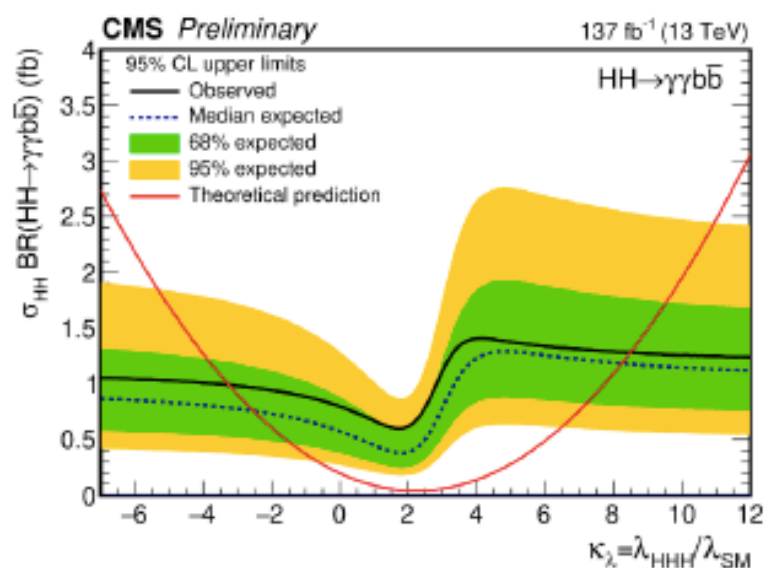
CMS:

✦ exp. constrain of k_λ is [-2.5, 8.2]

✦ exp. limit on SM HH: **5.2 times** prediction

ATLAS:

✦ exp. constrain of k_λ is [-2.6, 8.1]

✦ exp. limit on SM HH: **5.5 times** prediction

ATLAS results competitive with CMS one!

✦ **Theory predictions are crucial and theory uncertainties will play a larger role when more data and more experimental precision is achieved (HL-LHC)**

✦ **Developments ongoing on all fronts:**

  ✦ refinement of N3LO predictions: full NLO QCD-EW corrections, H+jets @ NNLO including fiducial cuts

  ✦ full high pt prediction at NLO and approximated top mass effects @ NLO (caveat: large uncertainties from top mass schema unc: 25% @ 1 TeV)

  ✦ N³LL improves precision at low p_T Higgs

  ✦ benchmarking different generators

  ✦ beyond NextLeadingLog in parton showers

  ✦ reduction of negative weights in NLO generators

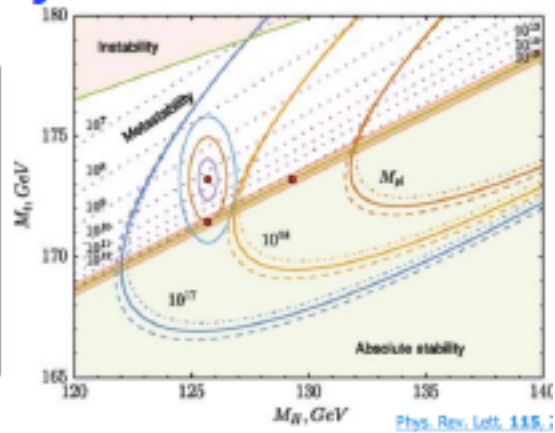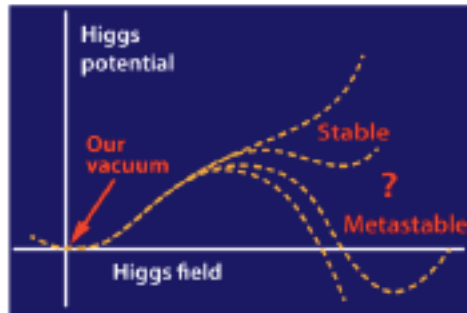 ✦ PDF for HL-LHC: including latest experimental inputs from Hera / LHC

LHC HIGGS WG workshop this week
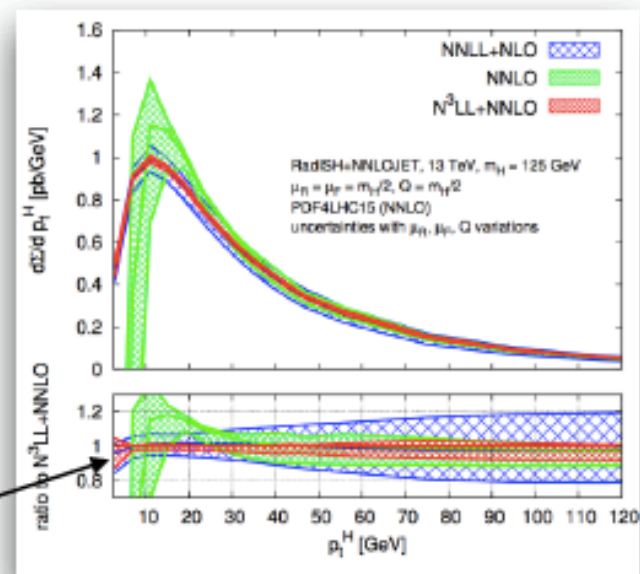
▶ Good agreement between different MC generators when using similar setups / assumptions
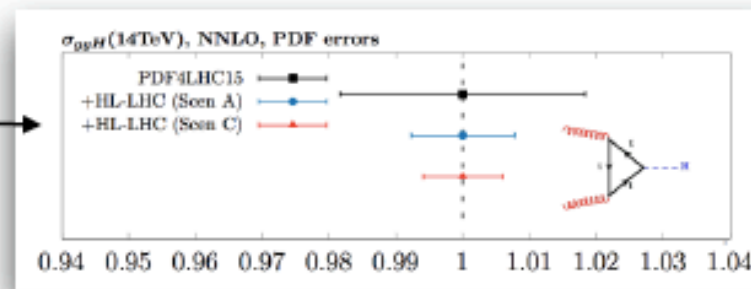
But no sign yet of NNLO MC generator for Higgs production and decay! ☹

theory side:

Phys. Rev. Lett. 115,

C. Grojean

The **Higgs** boson is the **simplest Q-bit**/particle:
as far as we know, it has no spin, no charge, no structure.
This vacancy can make its richness:
e.g., unlike other SM particle, it can easily couple to a Hidden Sector.
The **intricacy** of the Higgs boson lies in its **simplicity**
(aka **naturalness**)

J. Shelton

NMSSM

composite H

EWBG

H portal DM

➤ Why expect new physics near the weak scale?

  ➤ co-responsible for generating it

  ➤ stabilize it

  ➤ thermal dark matter

  ➤ ...why not?

➤ Light, neutral particles: exotic Higgs decays

Stability of the Electroweak Vacuum: Gauge Independence and Advanced Precision

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We perform a manifestly gauge-independent analysis of the vacuum stability in the standard model including two-loop matching, three-loop renormalization group evolution, and pure QCD corrections through four loops. All these ingredients are exact, except that light-fermion masses are neglected. We in turn apply the criterion of nullifying the Higgs self-coupling and its beta function in the modified minimal-subtraction scheme and a recently proposed consistent method for determining the true minimum of the effective Higgs potential that also avoids gauge dependence. Exploiting our knowledge of the Higgs-boson mass, we derive an upper bound on the pole mass of the top quark by requiring that the standard model be stable all the way up to the Planck mass scale and conservatively estimate the theoretical uncertainty. This bound is compatible with the Monte Carlo mass quoted by the Particle Data Group at the 1.3σ level.

https://arxiv.org/pdf/1507.08833.pdf

sion data [2]. Besides completing the SM particle multiplet and confirming the Higgs mechanism of mass generation via the spontaneous breaking of the EW symmetry proposed by Englert, Higgs (The Nobel Prize in Physics 2013), and Brout, this groundbreaking discovery also has fundamental cosmological consequences by allowing conclusions regarding the fate of the Universe via the analysis of the vacuum stability [3]. In fact, owing to an intriguing conspiracy of the SM particle masses, chances are that the Higgs potential develops a second minimum, as deep as the one corresponding to the vacuum with expectation value (VEV) $v = 2^{-1/4}G_F^{-1/2} = 246$ GeV in which we live, at a field value of the order of the Planck mass $M_P = 1.22 \times 10^{19}$ GeV [4, 5]. This would imply that the SM be stable all the way up to the energy scale where the unification with gravity is expected to take place anyways, which would diminish the necessity for grand unified theories at lower scales. EW symmetry breaking might thus be determined by Planck-scale physics [5], and the existence of a relationship between M_P and SM parameters might signify a reduction of fundamental couplings. Of course, experimental facts that the SM fails to explain, such as the smallness of the neutrino masses, the strong CP problem, the existence of dark matter, and the baryon asymmetry in the Universe, would then still call for an extension.
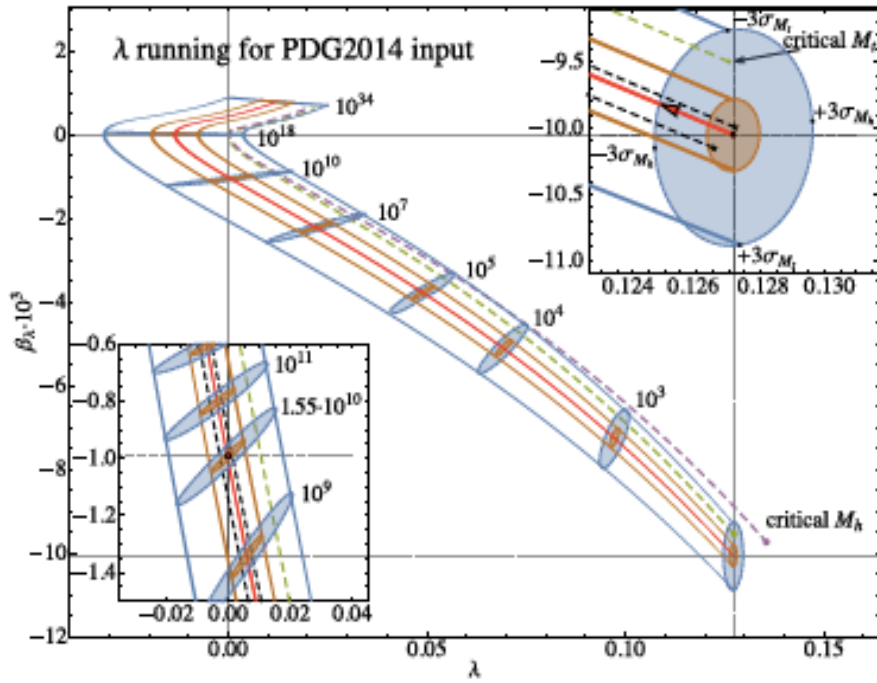
FIG. 1: RG evolution of $\lambda(\mu)$ from μ^{thr} to μ^{cri} and beyond in the (λ, β_λ) plane for default input values and matching scale (red solid line), effects of 1σ (brown solid lines) and 3σ (blue solid lines) variation in M_t^{MC}, theoretical uncertainty due to the variation of ξ from $1/2$ to 2 (upper and lower black dashed lines with asterisks in the insets), and results for M_t^{cri} (green dashed line) and M_H^{cri} (purple dashed line). The 1σ (brown ellipses) and 3σ (blue ellipses) contours due to the errors in M_t^{MC} and M_H are indicated for selected values of μ. The insets in the upper right and lower left corners refer to $\mu = M_t^{\text{MC}}$ and $\mu = 1.55 \times 10^{10}$ GeV, respectively.
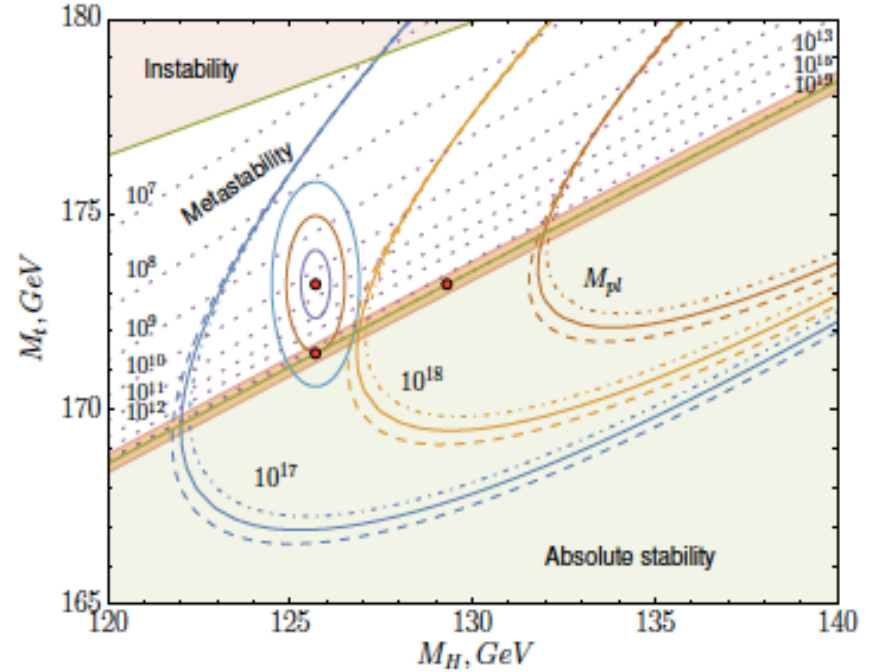
FIG. 2: Phase diagram of vacuum stability (light-green shaded area), metastability, and instability (pink shaded area) in the (M_H, M_t) plane, contours of $\lambda(\mu^0) = 0$ for selected values of μ^0 (purple dotted lines), contours of $\beta_\lambda(\mu^0) = 0$ for selected values of μ^0 (solid parabolalike lines) with uncertainties due to 1σ error in $\alpha_s^{(5)}(M_Z)$ (dashed and dot-dashed lines), critical line of Eq. (2) (solid green line) with uncertainty due to 1σ error in $\alpha_s^{(5)}(M_Z)$ (orange shaded band), and critical points with M_t^{cri} (lower red bullet) and M_H^{cri} (right red bullet). The present world average of (M_t^{MC}, M_H) (upper left red bullet) and its 1σ (purple ellipse), 2σ (brown ellipse), and 3σ (blue ellipse) contours are marked for reference.

As our final result, we hence quote the combined value $\widehat{M}_t^{\mathrm{cri}} = (171.54 \pm 0.30 {}^{+0.26}_{-0.41})$ GeV, which is compatible with $M_t^{\mathrm{MC}} = (173.21 \pm 0.87)$ GeV at the 1.3σ level. In view of this and the present lack of knowledge of the precise relationship between and M_t^{MC} and M_t mentioned above, the familiar notion [10, 11] that our vacuum is metastable is likely to be premature [24].

[24] S. Alekhin, A. Djouadi, and S. Moch, Phys. Lett. B **716**, 214 (2012).