ATLAS+CMS Higgs combination: what have we learned?

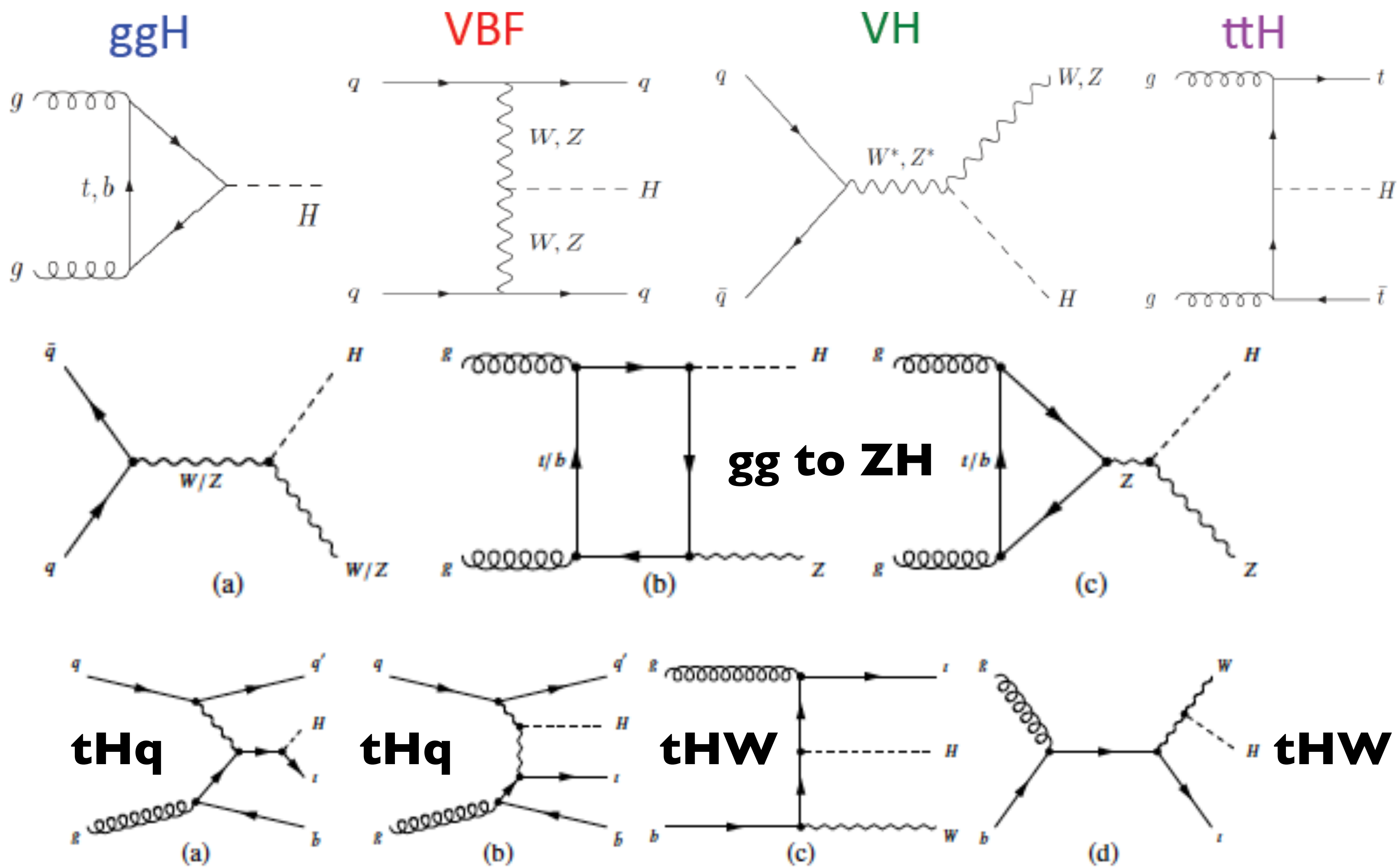
- **This discussion is based on the run-1 ATLAS+CMS Higgs combination paper**
  - **This is still the most relevant one for combined measurements of Higgs properties**
  - **I was ATLAS editor for this paper**

- **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] $\sqrt{s} = 7$ TeV	Cross section [pb] $\sqrt{s} = 8$ TeV	Order of calculation
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)
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$[ggZH]$	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 N^{3}LO 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

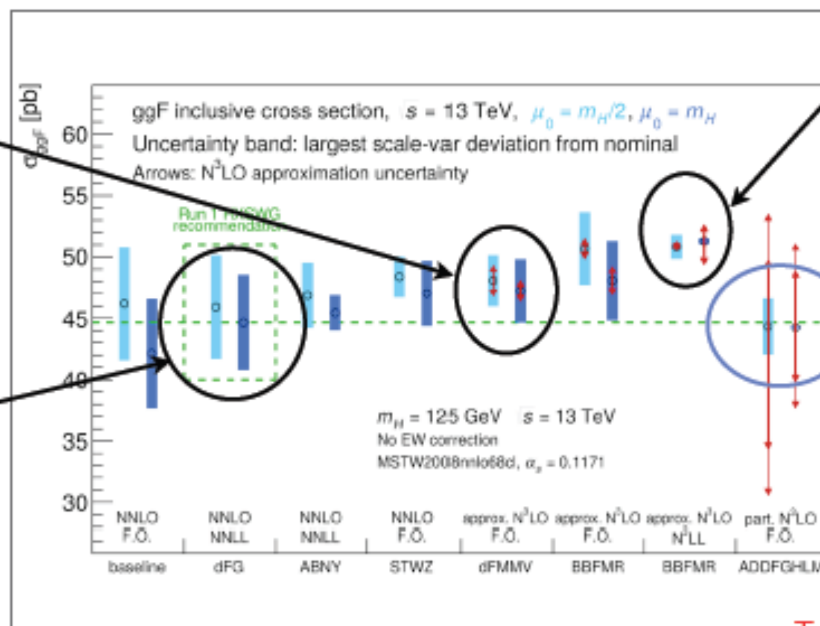
These three results are important since they give us a new perspective on the ultimate precision achievable on the theory side in the exploration of Higgs boson physics at the LHC. Another important lesson that these results seem to teach us is that -- beyond a certain level -- fixed order results are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

Theory: how precise do we need to be?

Estimates of N^{3}LO 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 N^{3}LO 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.

Good agreement with N3LO; obviously larger errors.



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

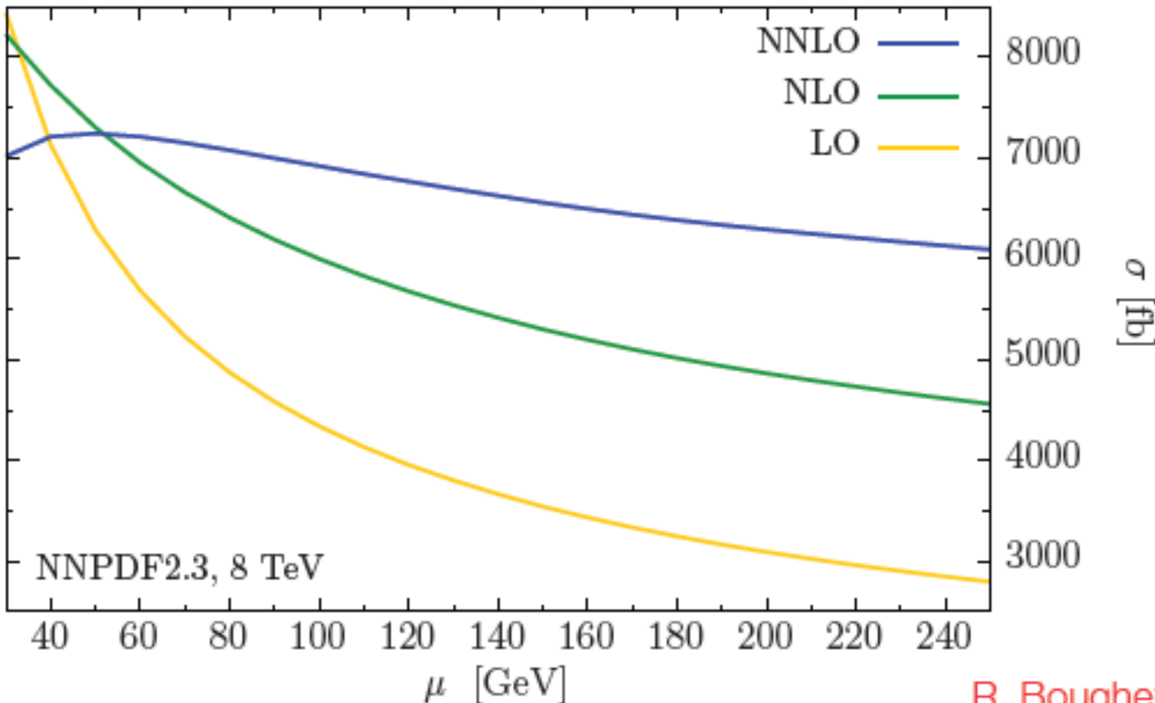
N3LO result

K. Melnikov

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.



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

$$\sigma_{\mathrm{NLO}} = 5.6^{+1.3}_{-1.1}\ \mathrm{pb}$$

$$\sigma_{\mathrm{NNLO}} = 6.7^{+0.5}_{-0.6}\ \mathrm{pb}$$

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

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

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

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

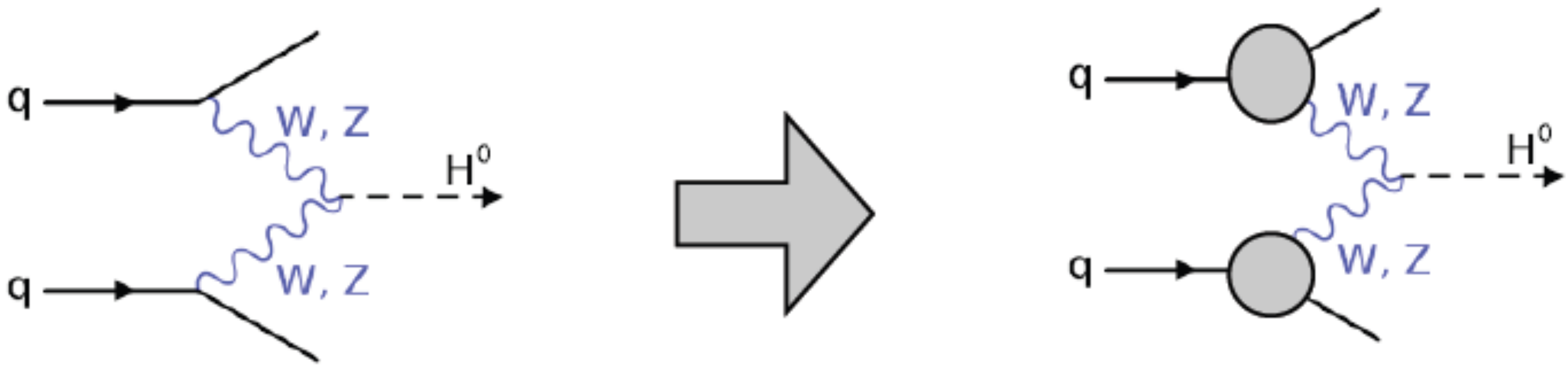
The difference between the ATLAS H+j measurements and the SM prediction is close to two standard deviations; the ratio of central values is larger than in the inclusive case.

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

K. Melnikov

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

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

	σ^{nocuts}[pb]	$\sigma^{\text{VBF cuts}}$[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

Theory: how precise do we need to be?

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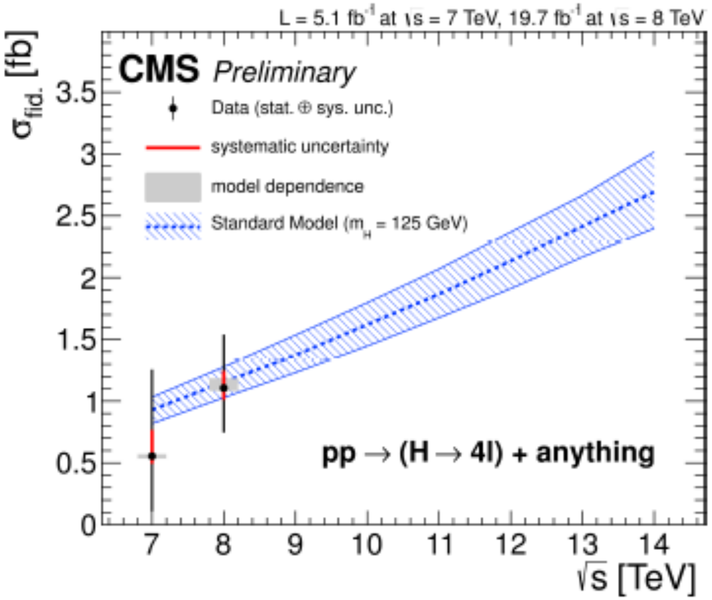
Theory: need for fiducial predictions, jet binning

Cross sections: fiducial measurements.

Fiducial σ at 7 and 8 TeV



Fiducial σ CMS (8 TeV)

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

$H \to 4\ell$

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

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

$$\sigma^{\text{SM}}_{\text{fid}} = 31^{+4}_{-3}\ \text{fb}$$

$H \to \gamma\gamma$

Fiducial σ ATLAS (8 TeV)

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

$H \to 4\ell$

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

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

$$\sigma^{\text{SM}}_{\text{fid}} = 30.5 \pm 3.3\ \text{fb}$$

$H \to \gamma\gamma$

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

$$\sigma^{ggH}_{\text{fid,0j}} = 27.6^{+5.4}_{-5.3}(\text{stat})^{+4.1}_{-3.9}(\text{syst})\ \text{fb}$$

$$\sigma^{ggH,\text{SM}}_{\text{fid,0j}} = 19.9 \pm 3.3\ \text{fb}$$

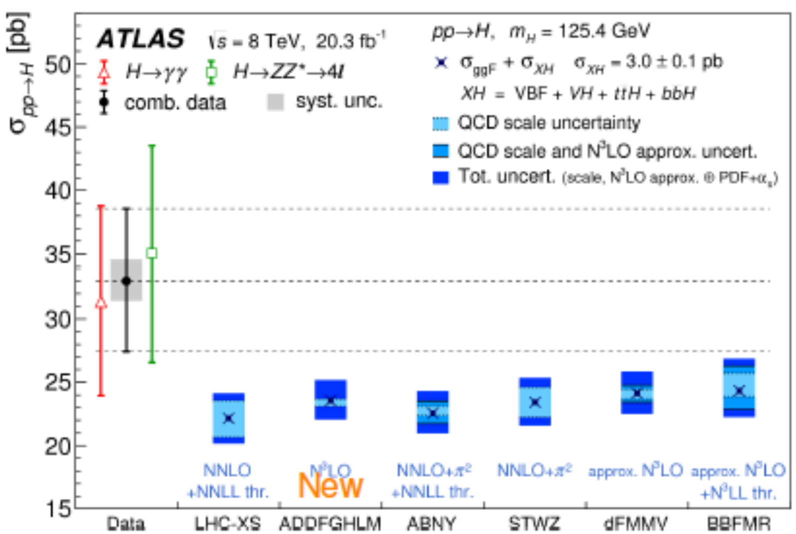
$$\sigma^{ggH}_{\text{fid,1j}} = 8.3^{+3.1}_{-3.0}(\text{stat})^{+3.7}_{-3.5}(\text{syst})\ \text{fb}$$

$$\sigma^{ggH,\text{SM}}_{\text{fid,1j}} = 7.3 \pm 1.8\ \text{fb}$$

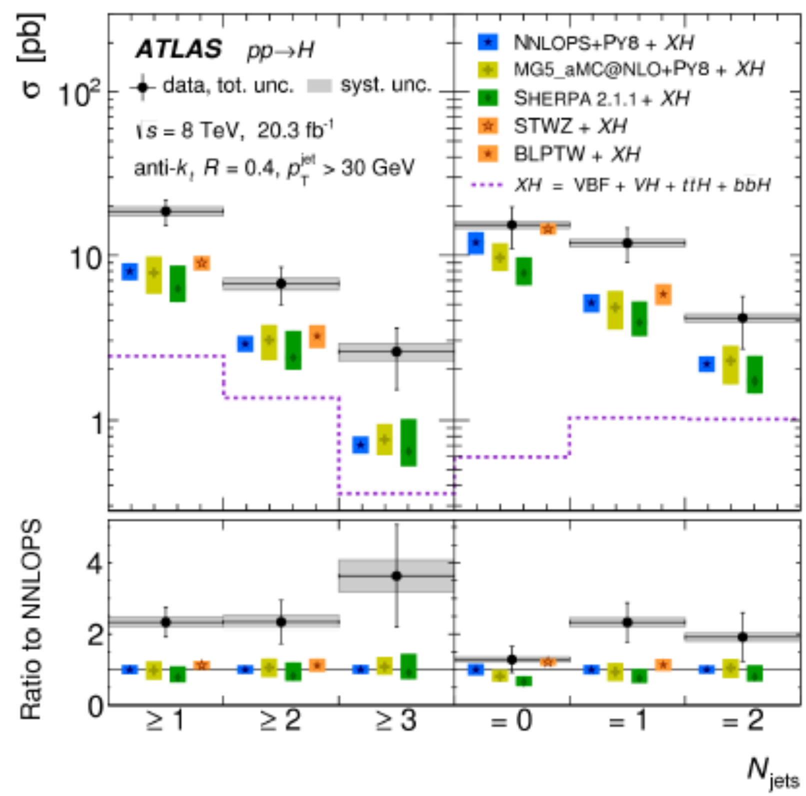
Theory: need for fiducial predictions, jet binning

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±1% ($H \to \gamma\gamma$) and 47±1% ($H \to 4\ell$)
  - ⋆ Assume SM branching fractions



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



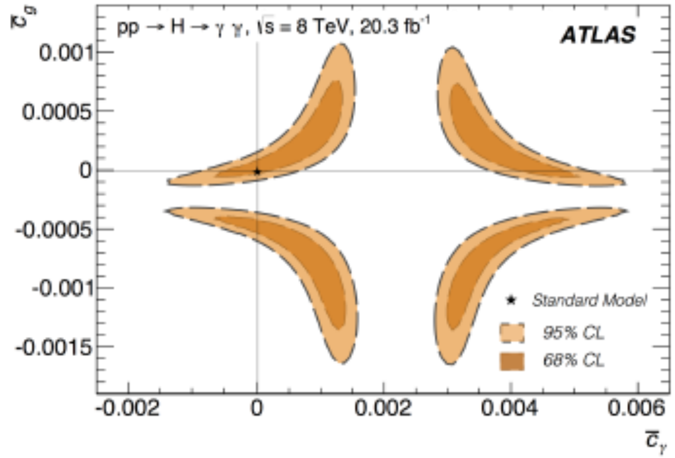
Theory: need for fiducial predictions, jet binning

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

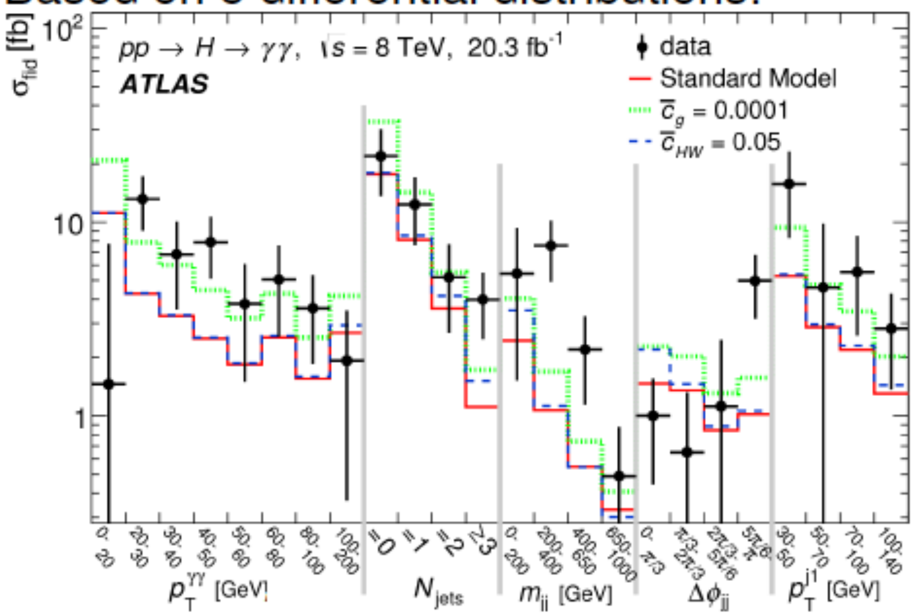
- Probe tensor structure and Higgs interactions
- Non-SM terms in effective Lagrangian describing Higgs–gauge boson interactions

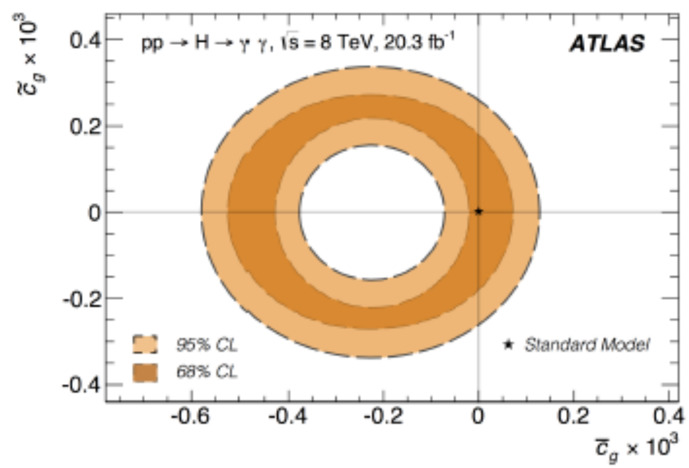
$$\mathcal{L} = \bar{c}_\gamma O_\gamma + \bar{c}_g O_g + \bar{c}_{HW} O_{HW} + \bar{c}_{HB} O_{HB} + \tilde{c}_\gamma \tilde{O}_\gamma + \tilde{c}_g \tilde{O}_g + \tilde{c}_{HW} \tilde{O}_{HW} + \tilde{c}_{HB} \tilde{O}_{HB}$$

[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

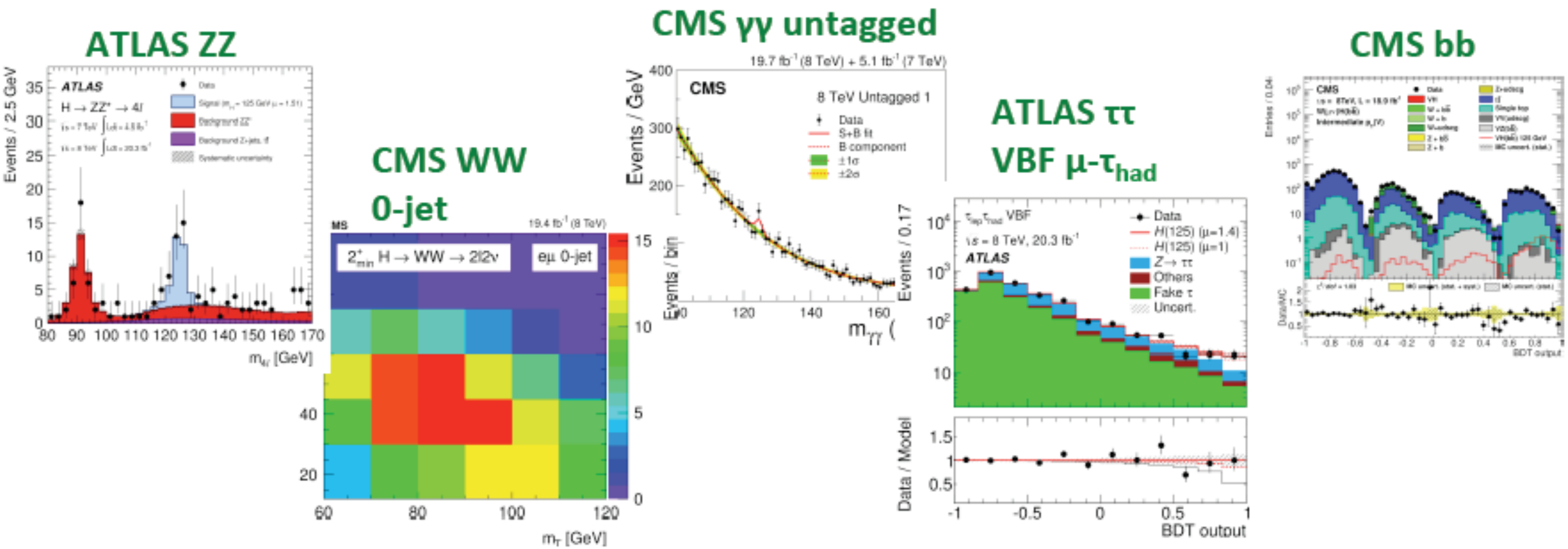
Decay / Production	Untagged	VBF	VH	ttH
H→γγ	■	■	■	■
H→ZZ→4l	■	■	■	■
H→WW→2l2ν	■	■	■	■
H→ττ	■	■	■	■
H→bb			■	■
H→μμ	■	■		

■	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



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

Signal yield

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

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

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

$$n_{\text{signal}}(k) = \mathcal{L}(k) \times \sum_i \sum_f \left\{\sigma_i \times A_i^f(k) \times \varepsilon_i^f(k) \times \text{BR}^f\right\},$$
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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 σ_i x 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
$\sigma(ggF)$	✓	$b-t$	$\kappa_g^2 \sim 1.06\cdot\kappa_t^2 + 0.01\cdot\kappa_b^2 - 0.07\cdot\kappa_t\kappa_b$
$\sigma(VBF)$	–	–	$\sim 0.74\cdot\kappa_W^2 + 0.26\cdot\kappa_Z^2$
$\sigma(WH)$	–	–	$\sim \kappa_W^2$
$\sigma(qq/qg \to ZH)$	–	–	$\sim \kappa_Z^2$
$\sigma(gg \to ZH)$	✓	$Z-t$	$\sim 2.27\cdot\kappa_Z^2 + 0.37\cdot\kappa_t^2 - 1.64\cdot\kappa_Z\kappa_t$
$\sigma(ttH)$	–	–	$\sim \kappa_t^2$
$\sigma(gb \to WtH)$	–	$W-t$	$\sim 1.84\cdot\kappa_t^2 + 1.57\cdot\kappa_W^2 - 2.41\cdot\kappa_t\kappa_W$
$\sigma(qb \to tHq)$	–	$W-t$	$\sim 3.4\cdot\kappa_t^2 + 3.56\cdot\kappa_W^2 - 5.96\cdot\kappa_t\kappa_W$
$\sigma(bbH)$	–	–	$\sim \kappa_b^2$
Partial decay width			
Γ^{ZZ}	–	–	$\sim \kappa_Z^2$
Γ^{WW}	–	–	$\sim \kappa_W^2$
$\Gamma^{\gamma\gamma}$	✓	$W-t$	$\kappa_\gamma^2 \sim 1.59\cdot\kappa_W^2 + 0.07\cdot\kappa_t^2 - 0.66\cdot\kappa_W\kappa_t$
$\Gamma^{\tau\tau}$	–	–	$\sim \kappa_\tau^2$
Γ^{bb}	–	–	$\sim \kappa_b^2$
$\Gamma^{\mu\mu}$	–	–	$\sim \kappa_\mu^2$
Total width for $BR_{BSM} = 0$			
Γ_H	✓	–	$\kappa_H^2 \sim 0.57\cdot\kappa_b^2 + 0.22\cdot\kappa_W^2 + 0.09\cdot\kappa_g^2 + 0.06\cdot\kappa_\tau^2 + 0.03\cdot\kappa_Z^2 + 0.03\cdot\kappa_c^2 + 0.0023\cdot\kappa_\gamma^2 + 0.0016\cdot\kappa_{Z\gamma}^2 + 0.0001\cdot\kappa_s^2 + 0.00022\cdot\kappa_\mu^2$

Coupling measurements: how is this done?

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$\sigma(qb \to tHq)$	–	$W-t$	$\sim 3.4 \cdot \kappa_t^2 + 3.56 \cdot \kappa_W^2 - 5.96 \cdot \kappa_t \kappa_W$
$\sigma(bbH)$	–	–	$\sim \kappa_b^2$
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$\Gamma^{\tau\tau}$	–	–	$\sim \kappa_\tau^2$
Γ^{bb}	–	–	$\sim \kappa_b^2$
$\Gamma^{\mu\mu}$	–	–	$\sim \kappa_\mu^2$

- **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!!**

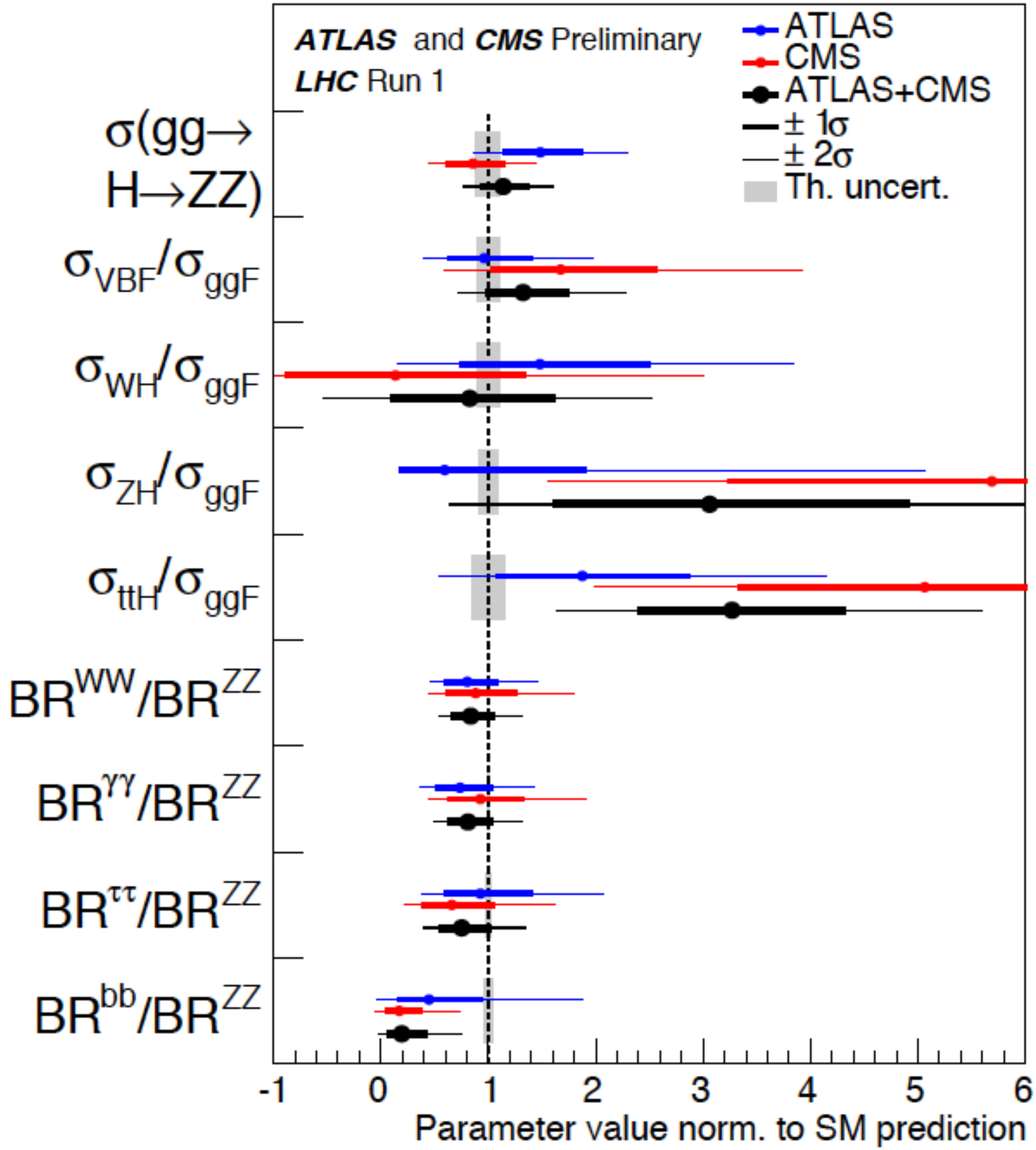
Coupling measurements: how is this done?

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

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

where $\sigma(gg \to H \to ZZ) = \sigma_{ggF} \cdot \mathrm{BR}^{ZZ}$ 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, $\mathrm{BR}^f/\mathrm{BR}^{ZZ}$ 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.



ATLAS and CMS Preliminary
LHC Run 1
ATLAS
CMS
ATLAS+CMS
± 1σ
± 2σ
Th. uncert.
σ(gg→H→ZZ)
σVBF/σggF
σWH/σggF
σZH/σggF
σttH/σggF
BRWW/BRZZ
BRγγ/BRZZ
BRττ/BRZZ
BRbb/BRZZ
-1
0
1
2
3
4
5
6
Parameter value norm. to SM prediction

Coupling measurements: how is this done?

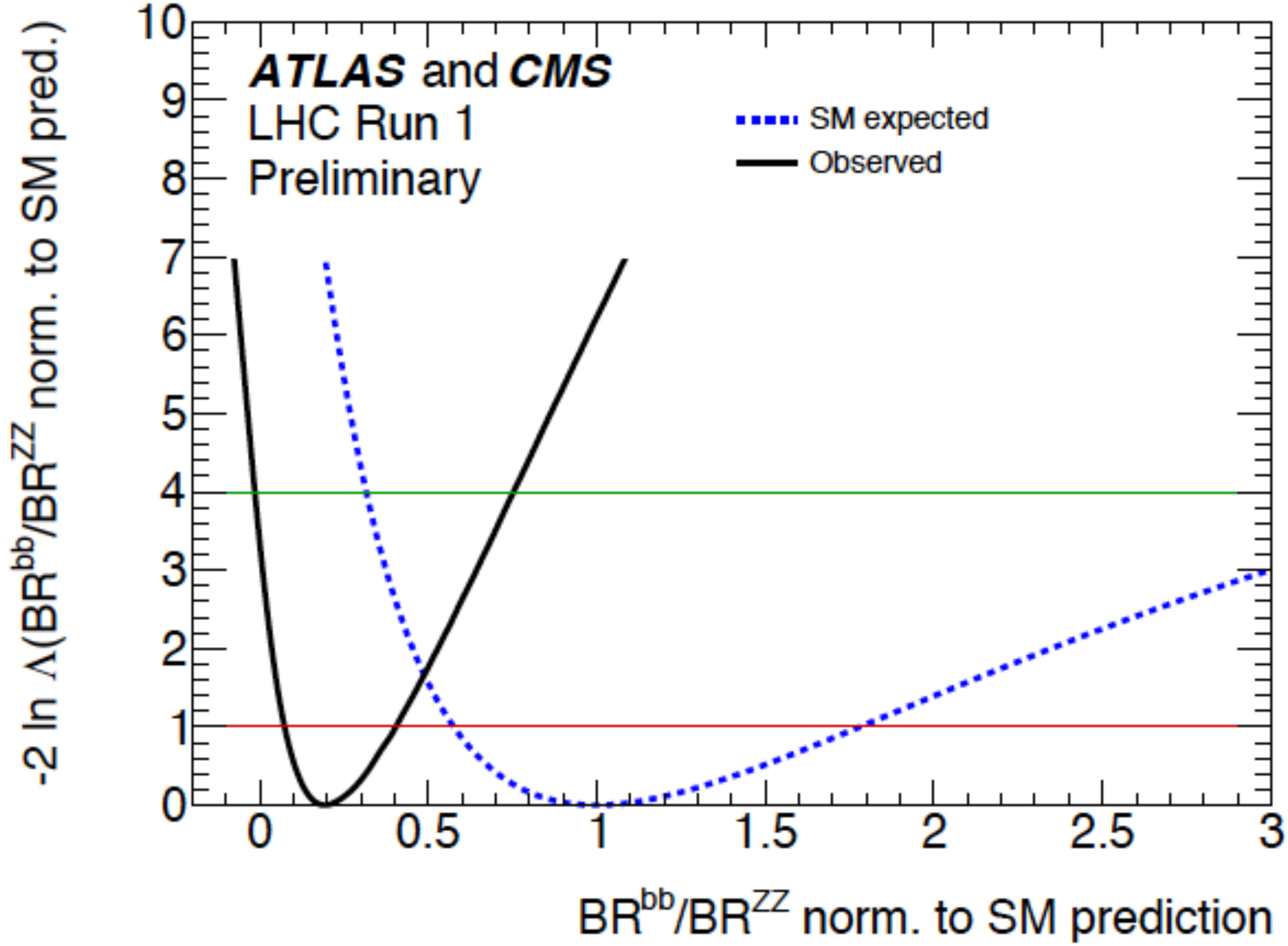
Parameter	SM prediction	Best-fit value	Uncertainty Stat	Uncertainty Syst	Best-fit value	Uncertainty Stat	Uncertainty Syst	Best-fit value	Uncertainty Stat	Uncertainty Syst
		ATLAS+CMS			ATLAS			CMS		
$\sigma(gg \to H \to ZZ)$ (pb)	0.513 ± 0.057	$0.58^{+0.11}_{-0.10}$ $\left(^{+0.11}_{-0.10}\right)$	$^{+0.11}_{-0.10}$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

Coupling measurements: how is this done?

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

- **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?

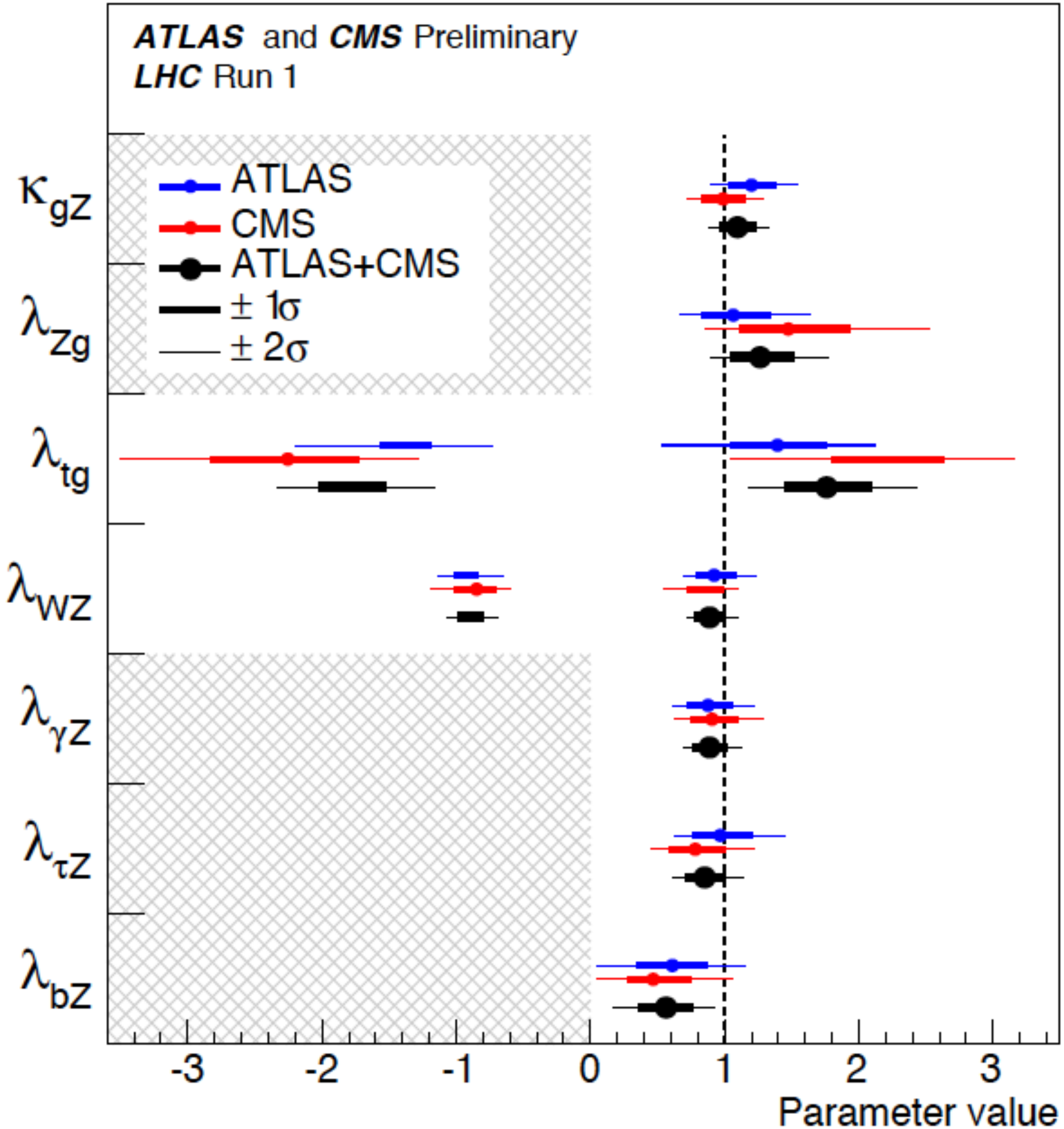
σ and BR ratio model	Coupling-strength ratio model
$\sigma(gg \to H \to ZZ)$	$\kappa_{gZ} = \kappa_g \cdot \kappa_Z / \kappa_H$
$\sigma_{VBF}/\sigma_{ggF}$	
σ_{WH}/σ_{ggF}	
σ_{ZH}/σ_{ggF}	$\lambda_{Zg} = \kappa_Z / \kappa_g$
$\sigma_{ttH}/\sigma_{ggF}$	$\lambda_{tg} = \kappa_t / \kappa_g$
BR^{WW}/BR^{ZZ}	$\lambda_{WZ} = \kappa_W / \kappa_Z$
$BR^{\gamma\gamma}/BR^{ZZ}$	$\lambda_{\gamma Z} = \kappa_\gamma / \kappa_Z$
$BR^{\tau\tau}/BR^{ZZ}$	$\lambda_{\tau Z} = \kappa_\tau / \kappa_Z$
BR^{bb}/BR^{ZZ}	$\lambda_{bZ} = \kappa_b / \kappa_Z$

In this parameterization BR^{ZZ}, BR^{WW}, σ_{WH}, σ_{WH} and σ_{VBF} are function of κ_Z and κ_W

e.g. for example

$\sigma_{WH}/\sigma_{ggF} \sim (\lambda_{WZ}/\lambda_{Zg})^2$

- **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 $\kappa_s = \kappa_b$

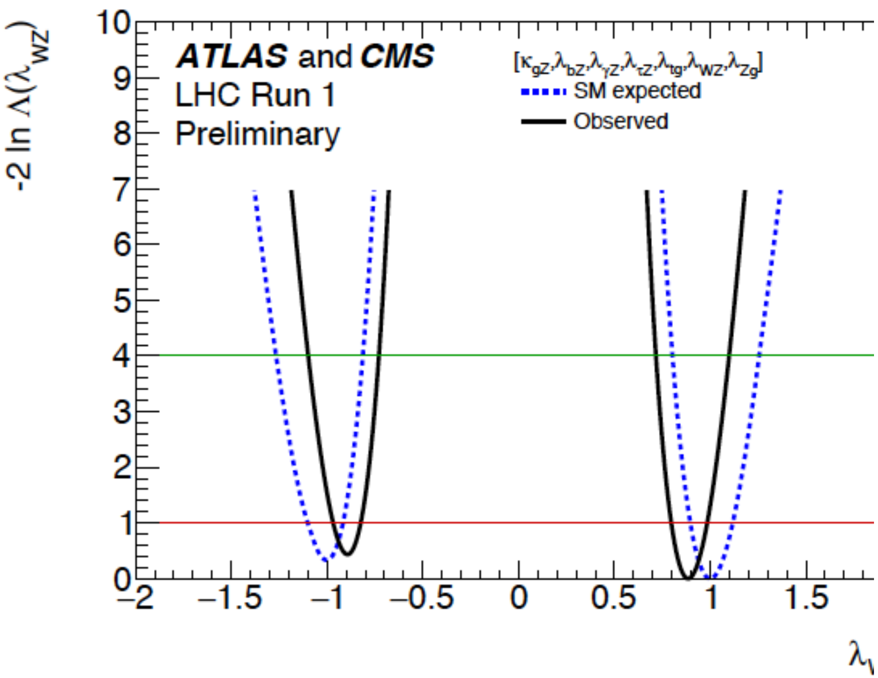

ATLAS and CMS Preliminary
LHC Run 1
ATLAS
CMS
ATLAS+CMS
± 1σ
± 2σ
κgZ
λZg
λtg
λWZ
λγZ
λτZ
λbZ
-3
-2
-1
0
1
2
3
Parameter value

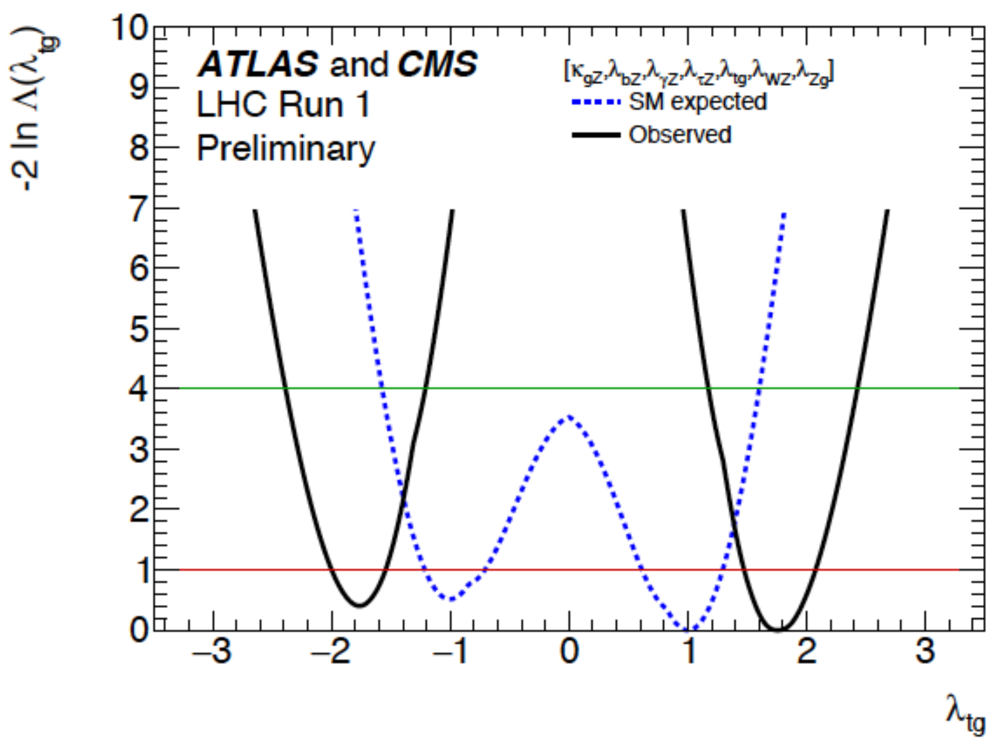
Coupling measurements: how is this done?

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

- **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)
- $$\mu_i = \frac{\sigma_i}{\sigma_i^{\text{SM}}} \quad \text{and} \quad \mu^f = \frac{\text{BR}^f}{\text{BR}^f_{\text{SM}}}. \qquad \mu_i^f \equiv \frac{\sigma_i \cdot \text{BR}^f}{(\sigma_i \cdot \text{BR}^f)_{\text{SM}}} = \mu_i \times \mu^f$$
- Most constrained parameterization: one single signal strength μ (and assuming the same at 7 and 8 TeV)

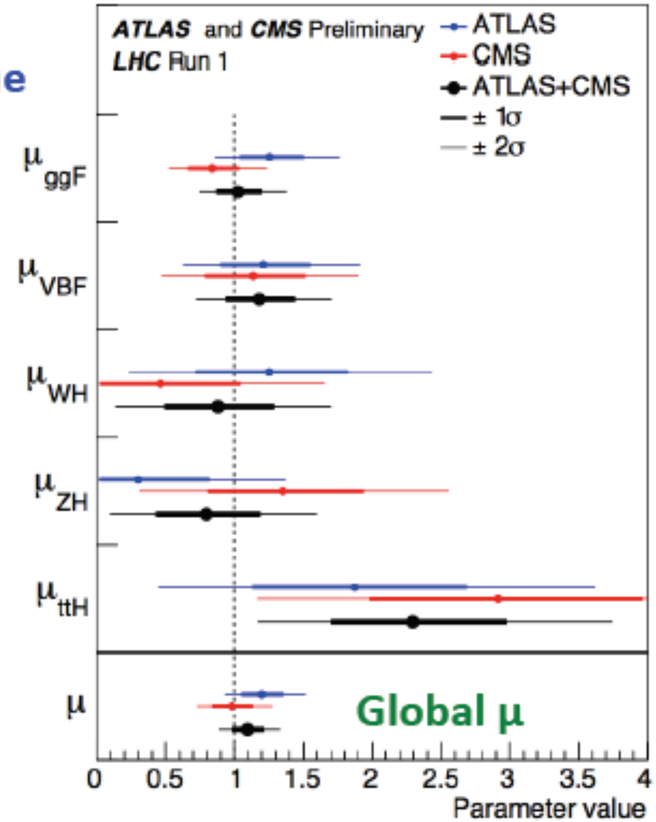
$$\mu = 1.09^{+0.11}_{-0.10} \quad = 1.09^{+0.07}_{-0.07}\,(\text{stat})\,^{+0.04}_{-0.04}\,(\text{expt})\,^{+0.03}_{-0.03}\,(\text{thbgd})^{+0.07}_{-0.06}\,(\text{thsig})$$

- 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

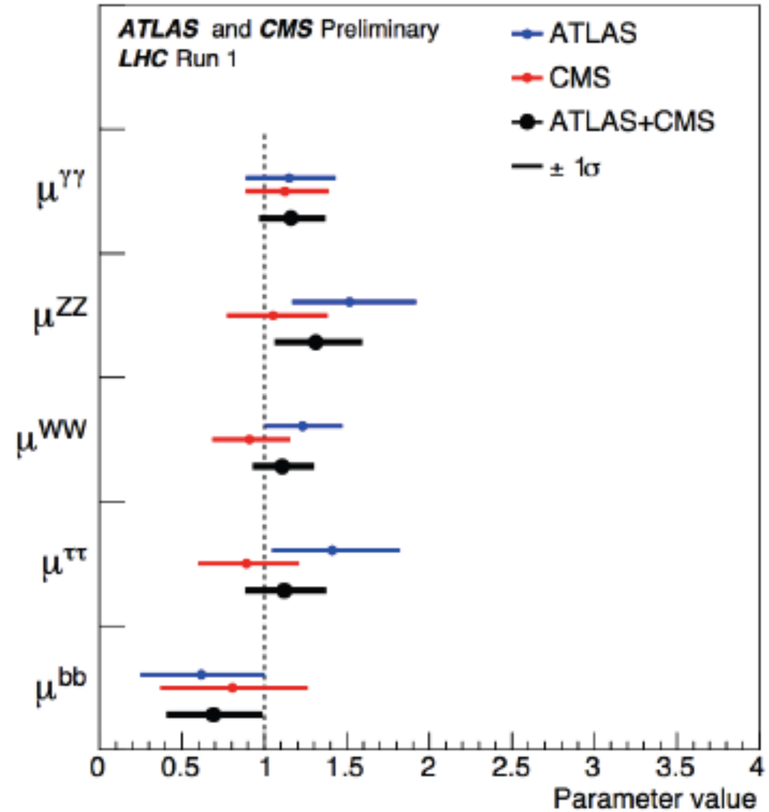
Stronger assumptions on signal strength

SM p-value 25%

SM BRs assumed



SM production σ assumed



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

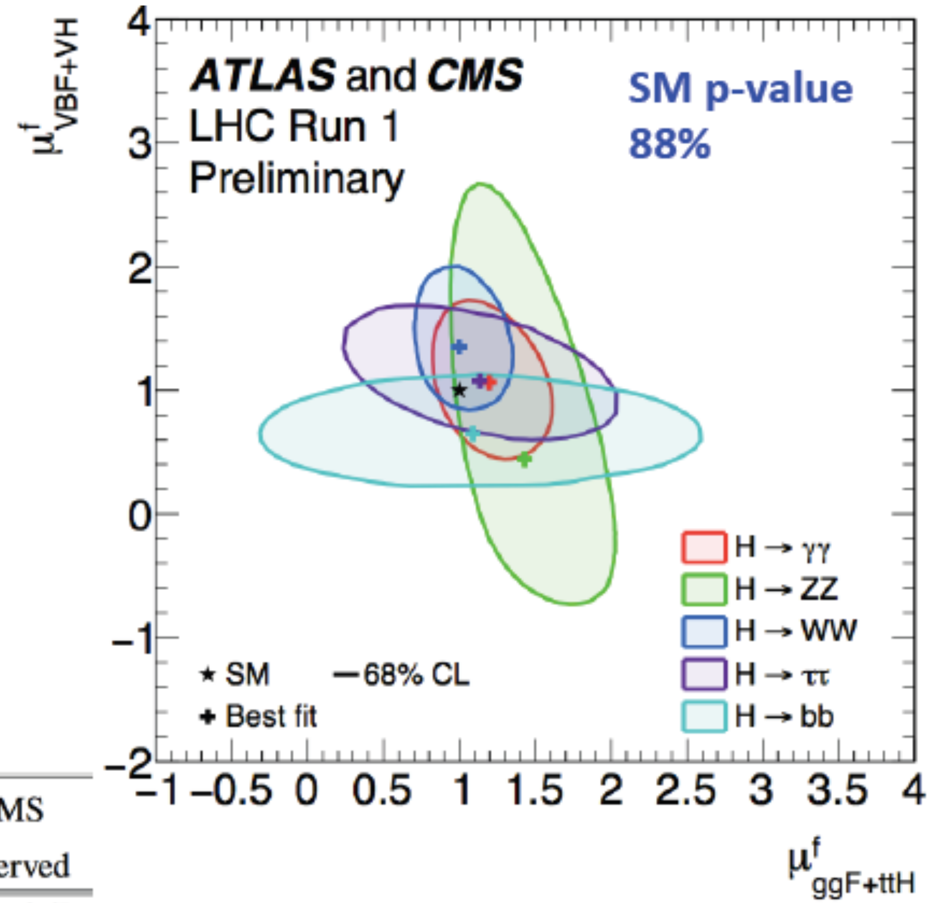
- Combination largely increases the sensitivity

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:
  - $\mu_V^f = \mu^f_{VBF+VH}$
  - $\mu_F^f = \mu^f_{ggF+ttH}$
- $\mu_{V/}\mu_f$ can be measured in the different decay channels and combined:

$$\mu_{V/}\mu_f = 1.06\ ^{+0.35}_{-0.27}$$

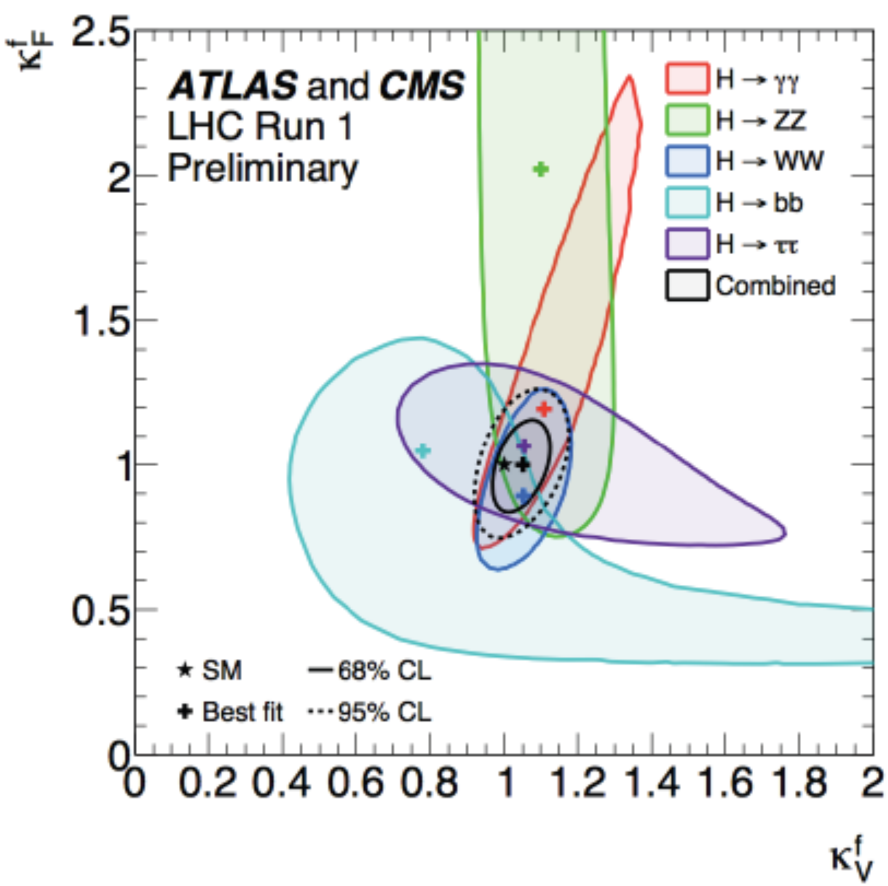


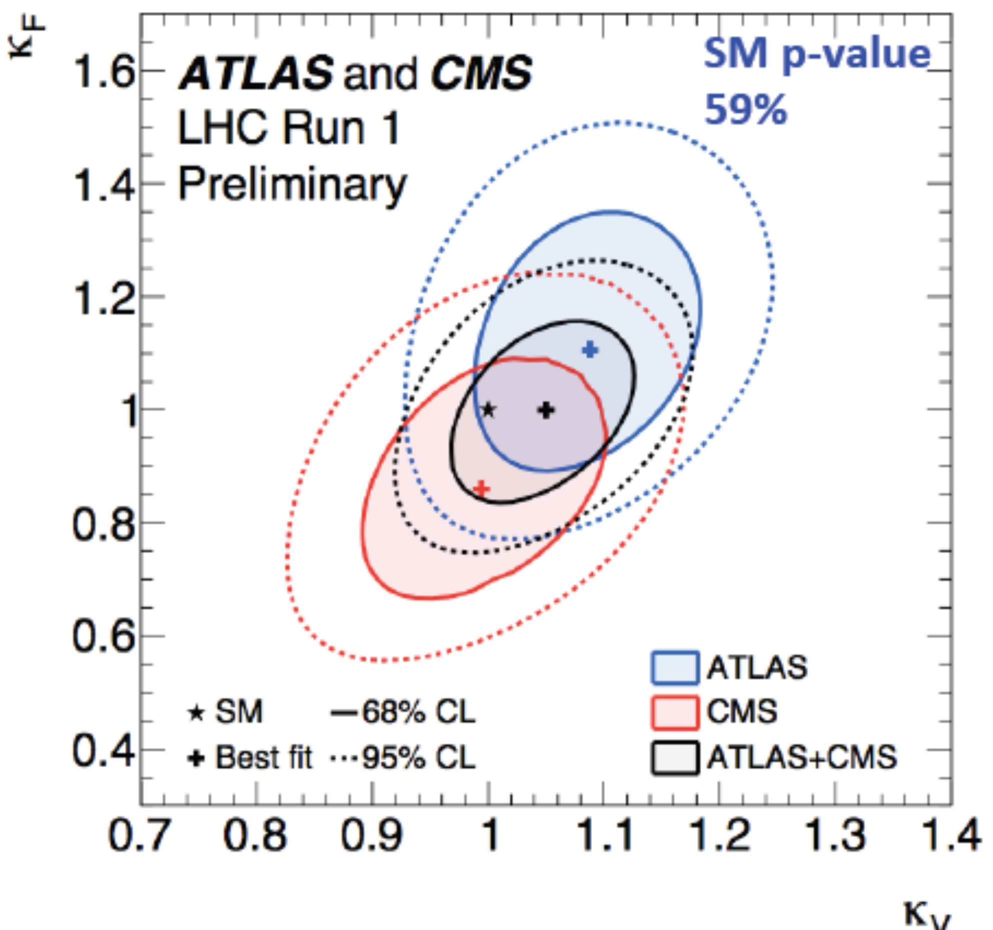
Parameter	ATLAS+CMS observed	ATLAS+CMS expected unc.	ATLAS observed	CMS observed
μ_V / μ_F	$1.06^{+0.35}_{-0.27}$	$^{+0.34}_{-0.26}$	$0.91^{+0.41}_{-0.30}$	$1.29^{+0.67}_{-0.46}$
$\mu_F^{\gamma\gamma}$	$1.13^{+0.24}_{-0.21}$	$^{+0.21}_{-0.19}$	$1.18^{+0.33}_{-0.29}$	$1.03^{+0.30}_{-0.26}$
μ_F^{ZZ}	$1.29^{+0.29}_{-0.25}$	$^{+0.24}_{-0.20}$	$1.54^{+0.44}_{-0.36}$	$1.00^{+0.33}_{-0.27}$
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

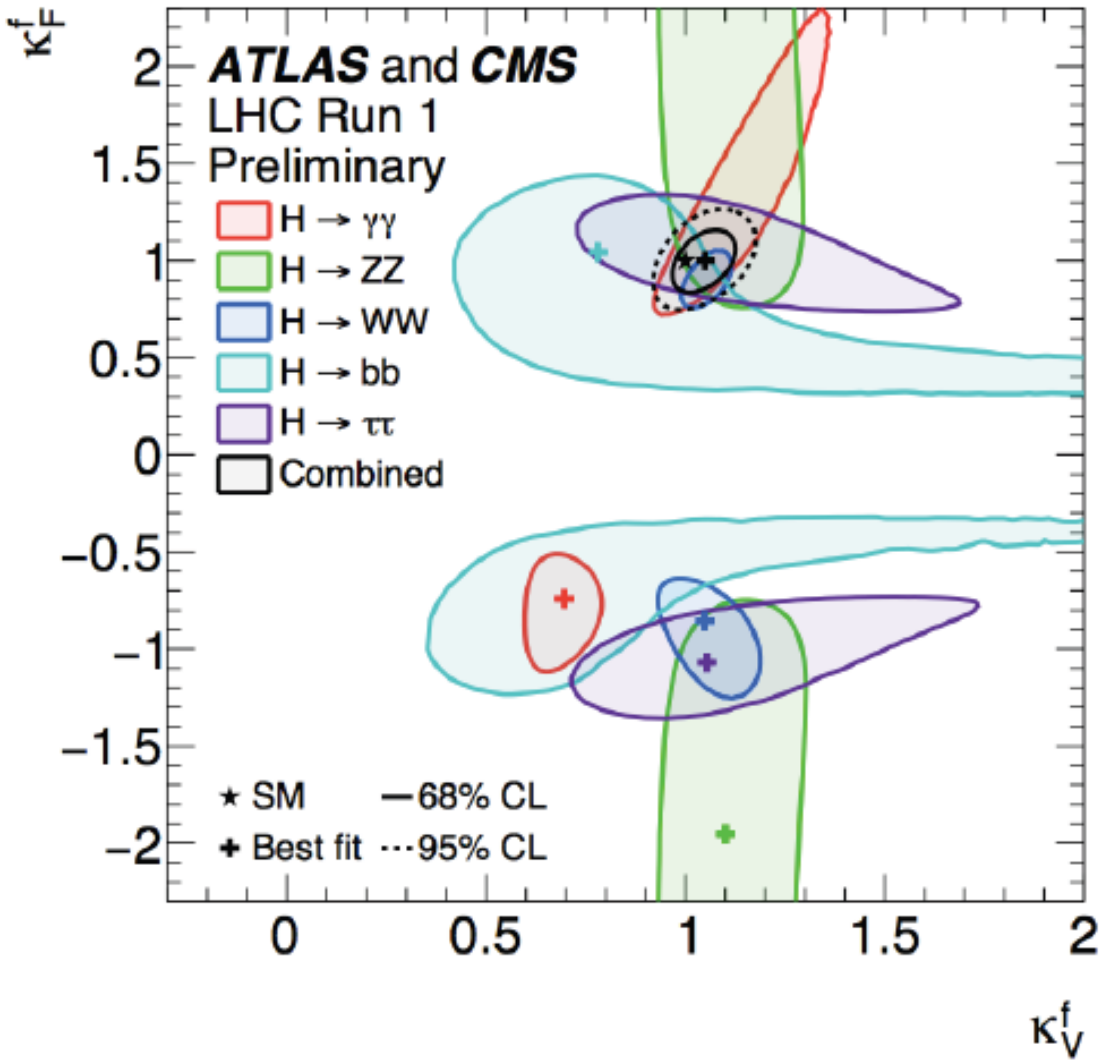




All results in agreement with SM ($\kappa_V = \kappa_f = 1$) within 1σ

Stronger assumptions on κ coupling modifiers

- Negative couplings would change sign of interference

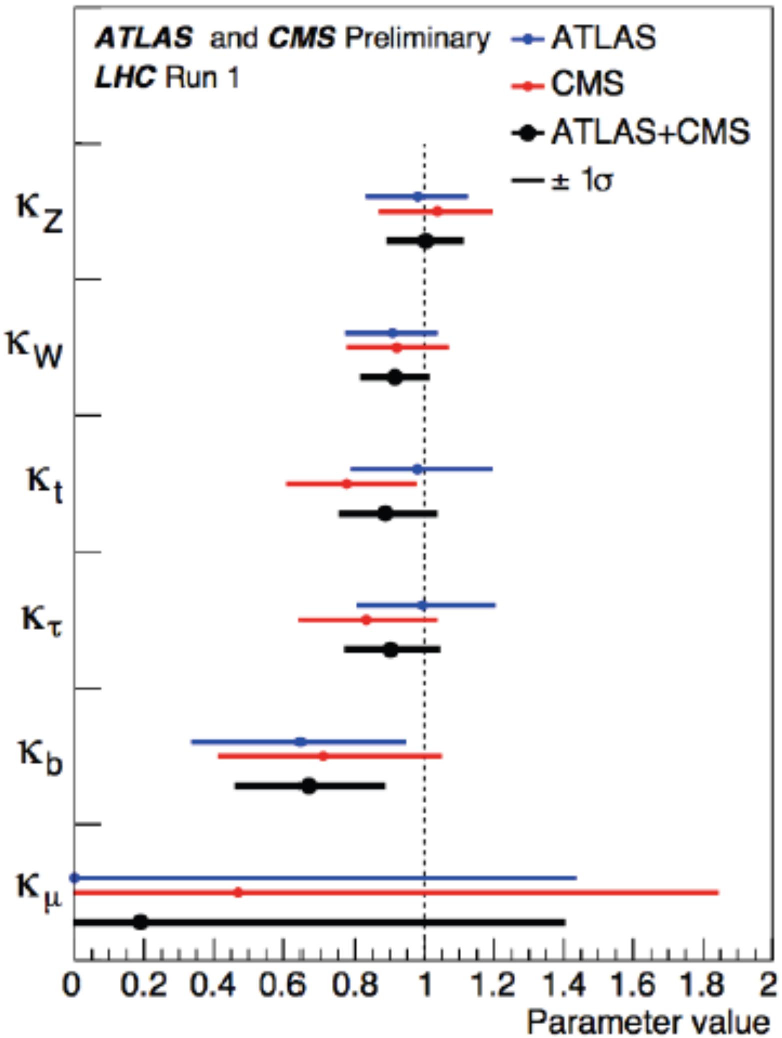


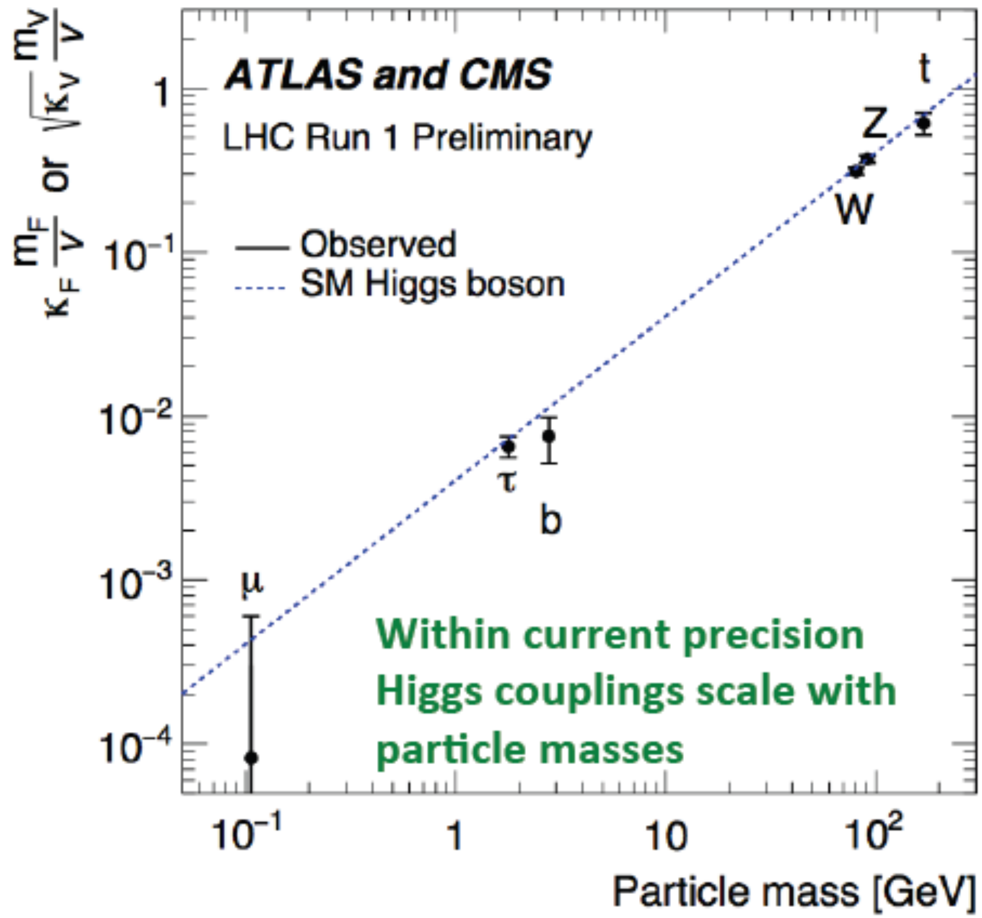
Almost 5σ exclusion of $\kappa_F<0$

- 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.



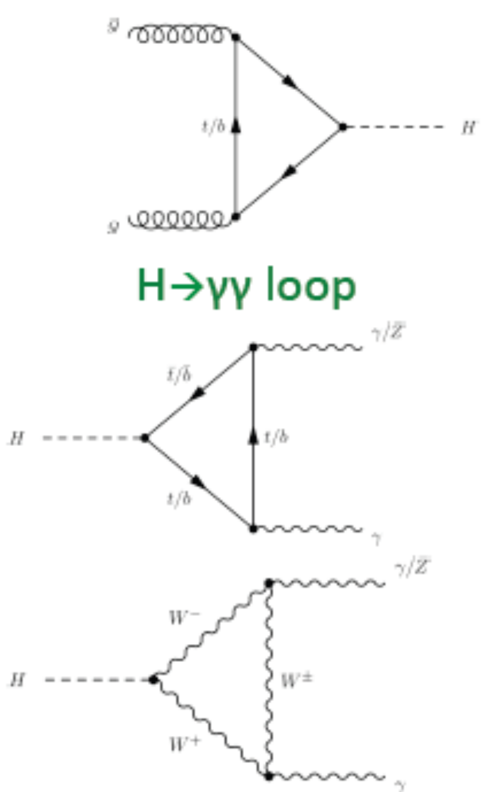


Stronger assumptions on κ coupling modifiers

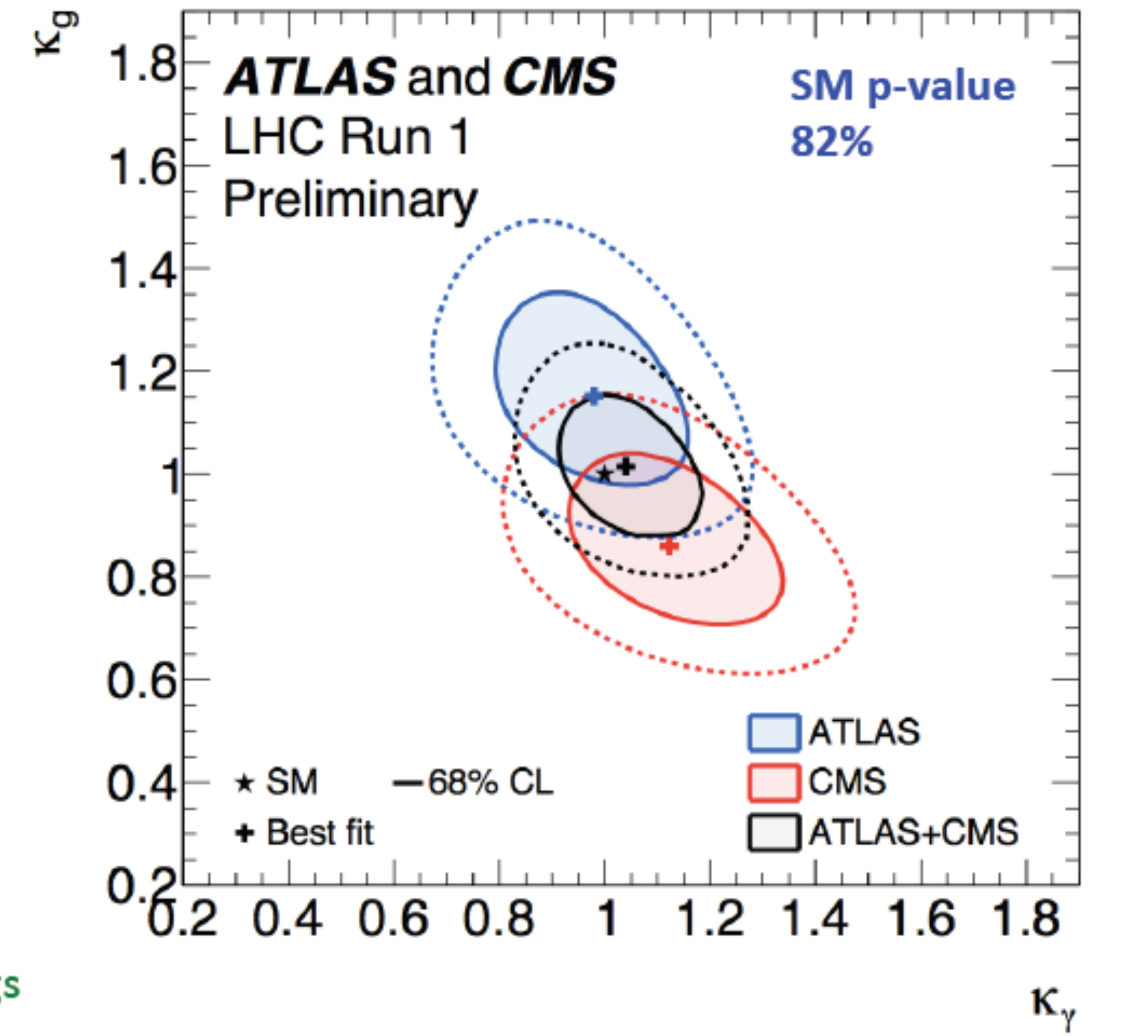
- Assuming tree level couplings as in the SM and only modifications to the two main loops of ggF and H→γγ

ggF loop

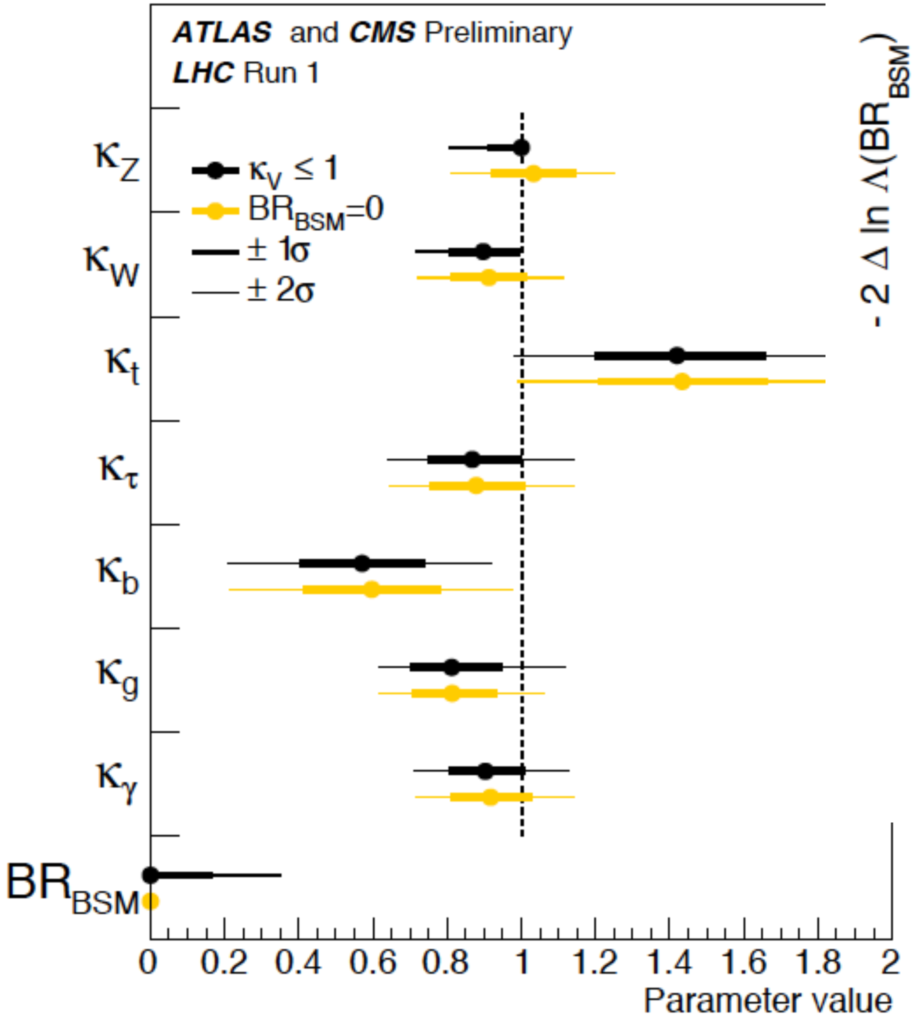
H→γγ loop

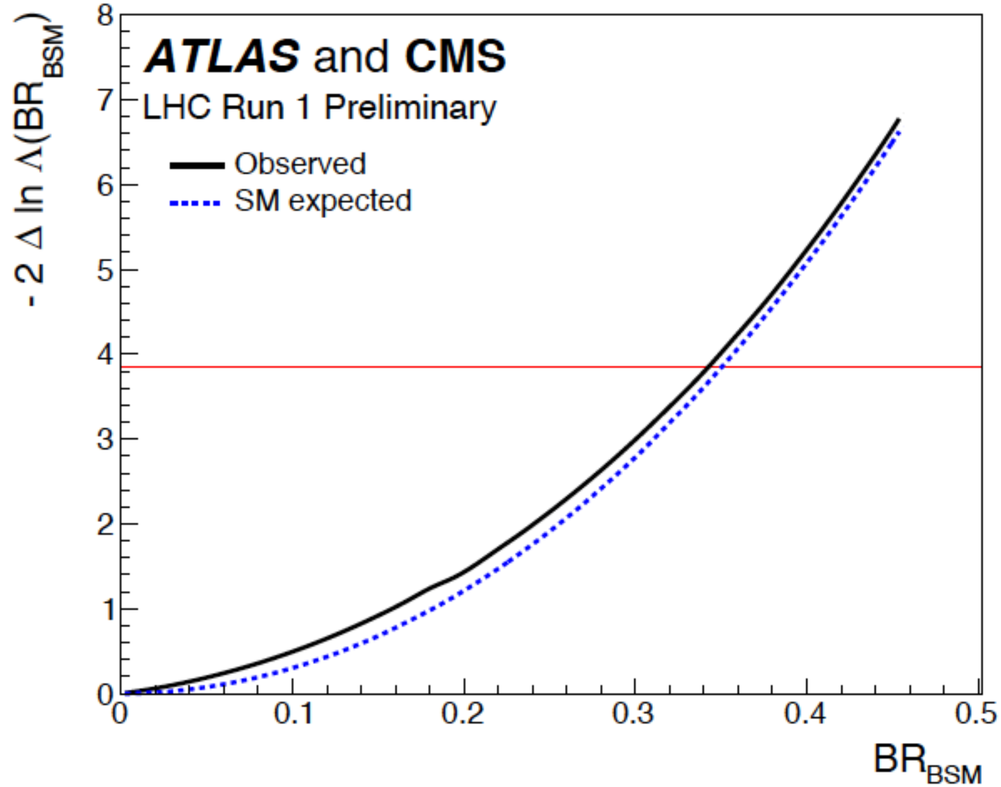


Additional heavy fermions or charged Higgs boson would modify the effective couplings



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 $\kappa_Z < 1$**
- **In the latter case, extract limit on $BR_{BSM} <$ 34% at 95 CL**

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

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

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[b] *Dipartimento di Fisica Teorica, Università di Torino, Italy 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.

KEYWORDS: Higgs Physics, QCD, Hadron-Hadron Scattering

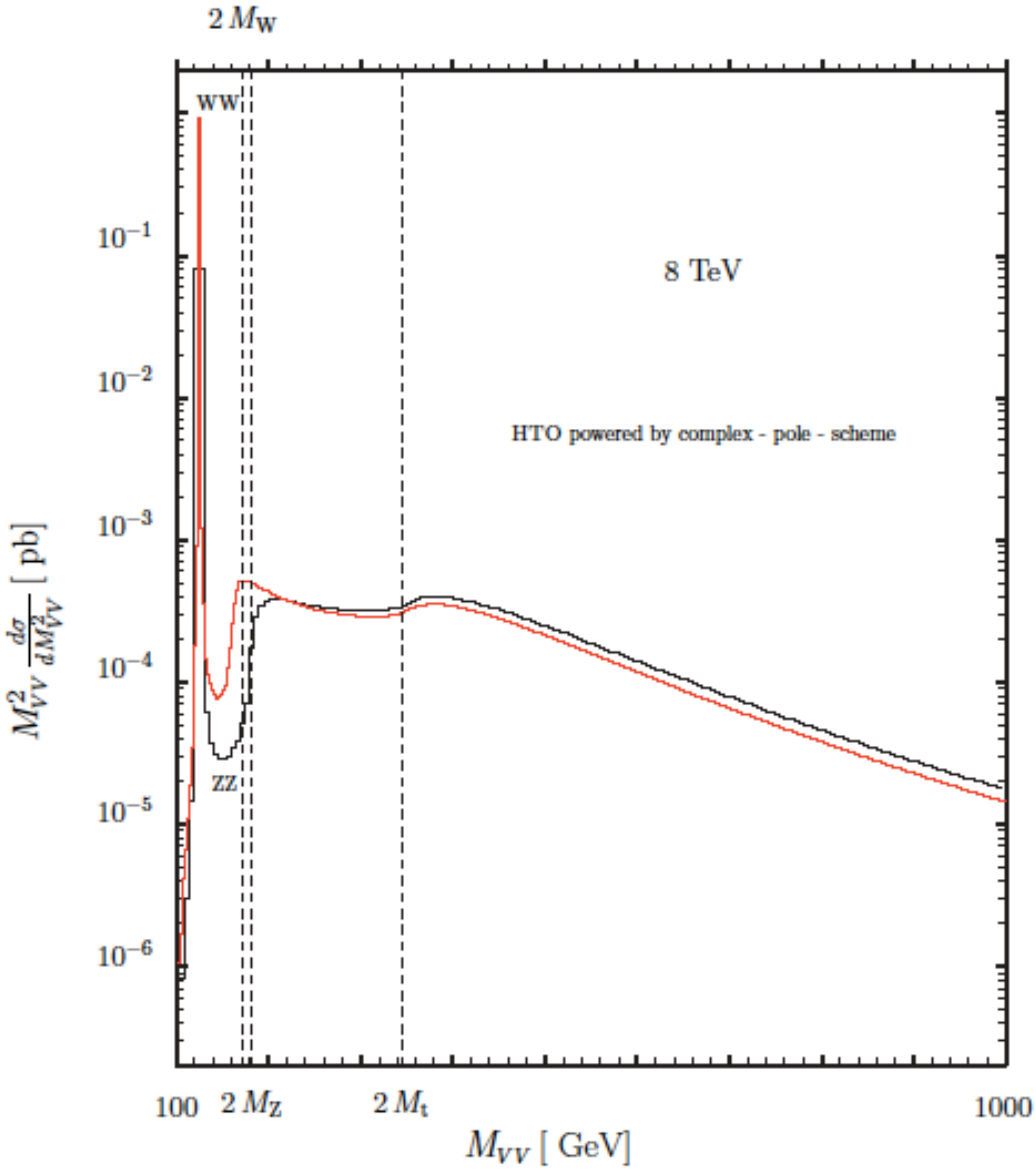


Figure 2. The NNLO ZZ (black) and WW (red) invariant mass distributions in $gg \to VV$ for $\mu_H = 125\,\text{GeV}$.

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 $gg \to ZZ$ 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 $H \to VV$ above M_{VV} may even be stronger in WBF, because $\sigma(q\bar{q} \to q\bar{q}H)$ decreases less rapidly than $\sigma(gg \to H)$ with increasing Higgs invariant mass.[5]

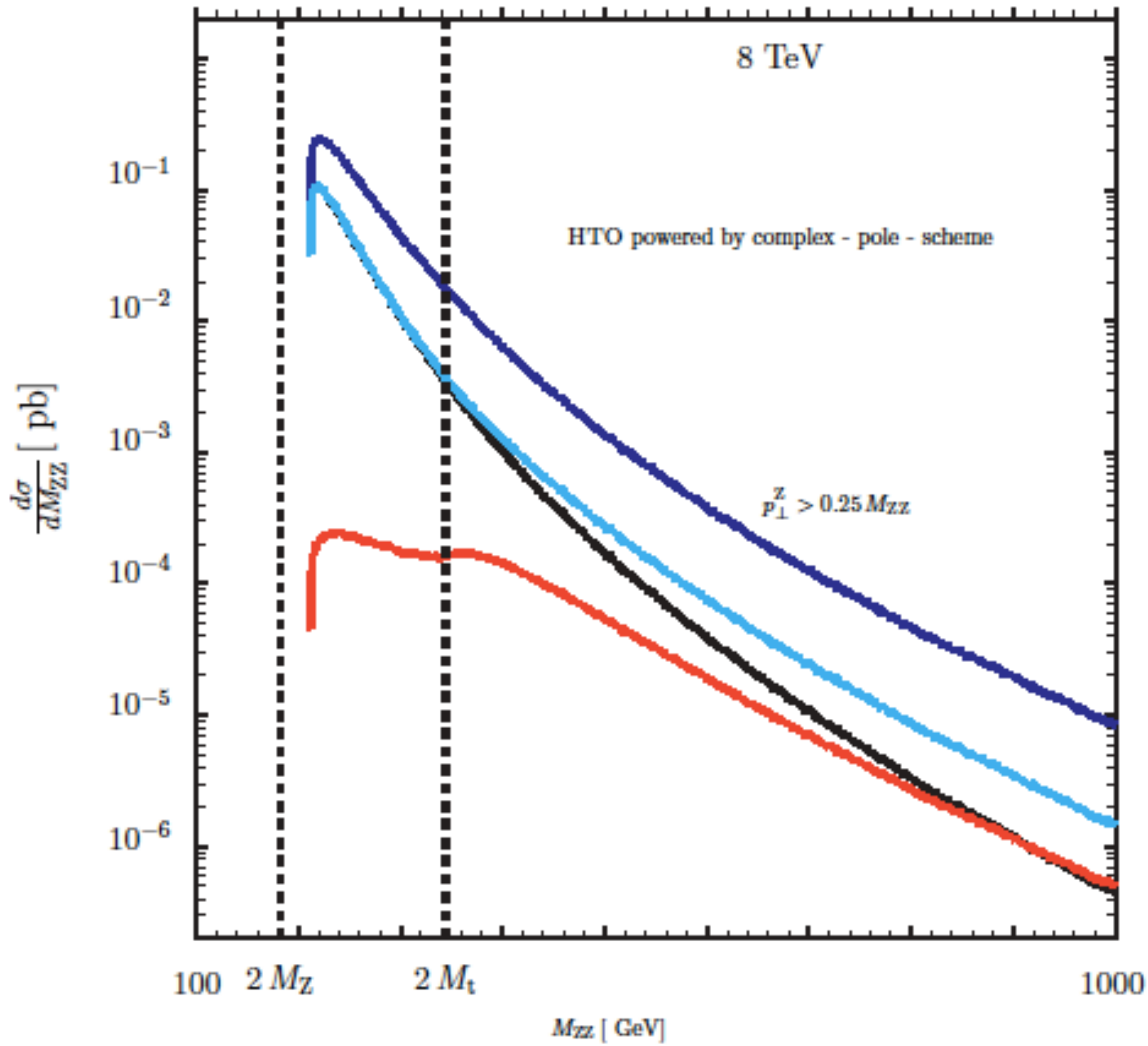


Figure 3. The LO ZZ invariant mass distribution $gg \to ZZ$ for $\mu_H = 125\,\text{GeV}$. The black line is the total, the red line gives the signal while the cyan line gives signal plus background; the blue line includes the $q\bar{q} \to ZZ$ contribution.

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*

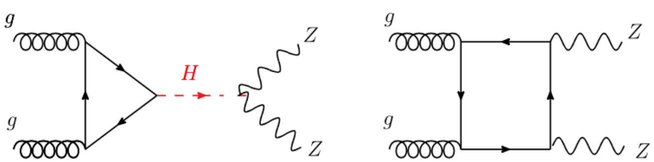
We point out that existing measurements of $pp \to ZZ$ cross-section at the LHC in a broad range of ZZ invariant masses allow one to derive a model-independent upper bound on the Higgs boson width, thanks to strongly enhanced off-shell Higgs contribution. Using CMS data and considering events in the 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 ${\rm Br}(H \to {\rm inv}) < 0.84$ (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 $\Gamma_H \sim 10\,\Gamma_H^{\rm SM}$.

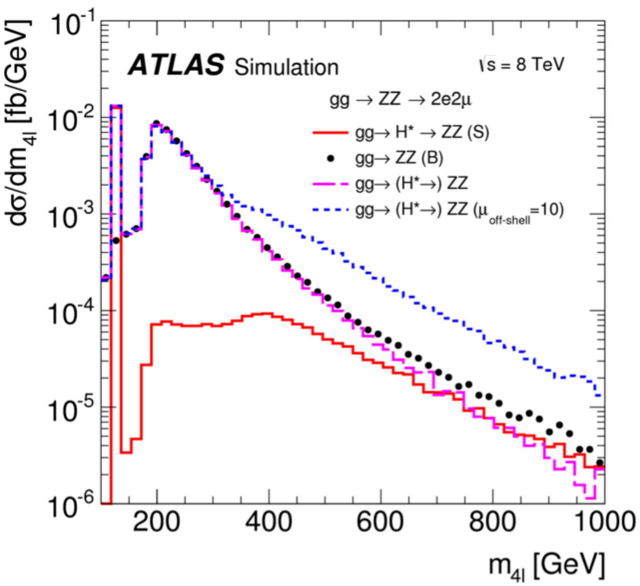
Extraction of Higgs boson width from off-shell measurements : a brief overview

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)

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!

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

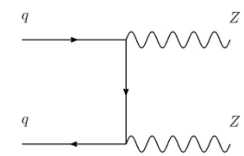
$$\mu_{on\ shell} = \frac{(\kappa_t^2 \kappa_V^2)_{on\ shell}}{\Gamma_H / \Gamma_H^{SM}}$$

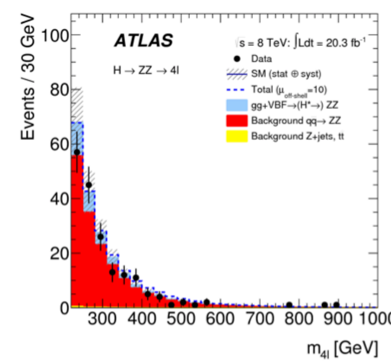
$$(\kappa_t^2 \kappa_V^2)_{on\ shell} = (\kappa_t^2 \kappa_V^2)_{off\ shell}$$

$$\Gamma_H = \frac{\mu_{off\ shell}}{\mu_{on\ shell}} \times \Gamma_H^{SM}$$

Highly non trivial due to:

- The negative interference
- The large other backgrounds



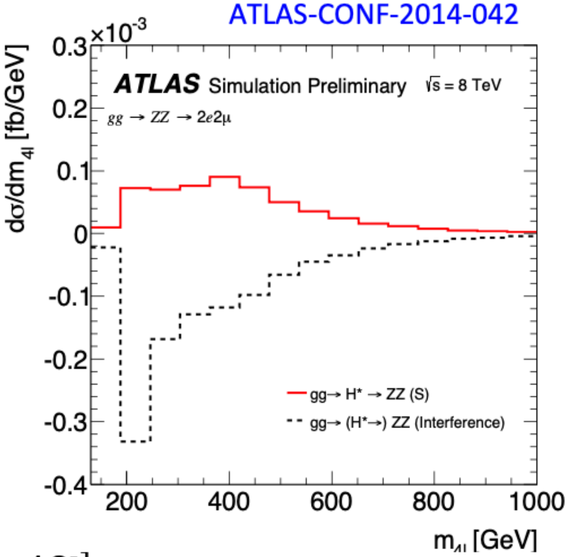


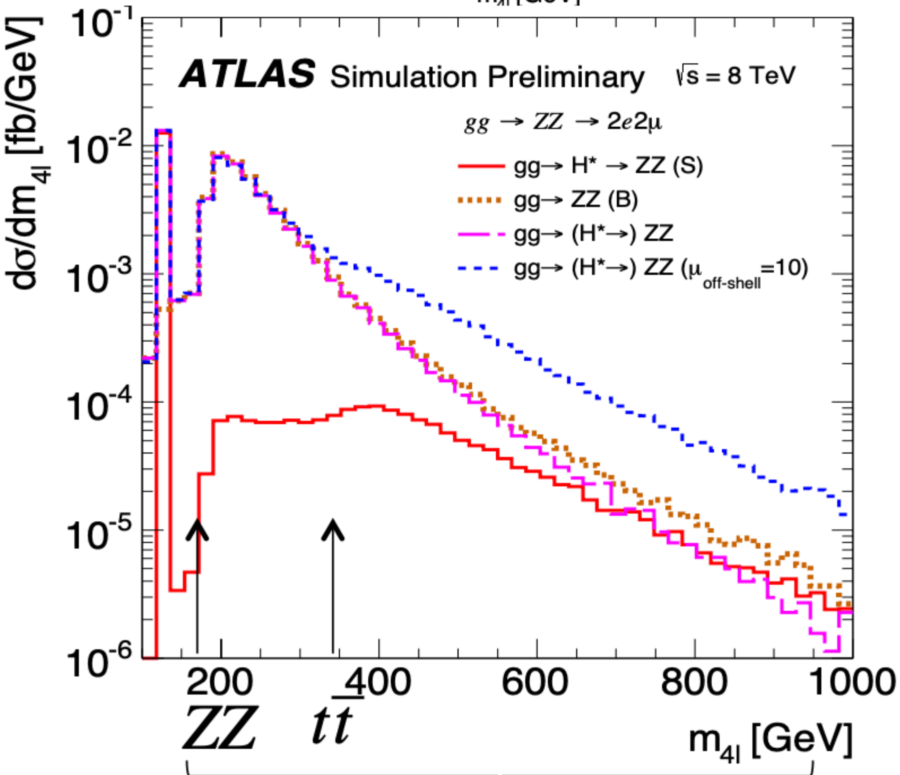
Limits on the total width are currently at approximately 15 MeV

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

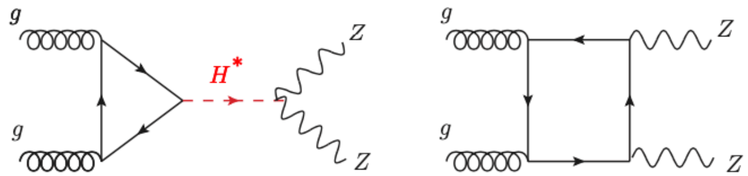
$$\Gamma_H = 4.2^{+1.5}_{-2.1}\ MeV$$

Off Shell Higgs coupling properties Measurement





Far Off Shell domain



$$\mu_{OffShell} \equiv \frac{\sigma_{OffShell}^{gg\to H^*\to ZZ}}{(\sigma_{OffShell}^{gg\to H^*\to ZZ})_{SM}} = (\kappa_g^2 \kappa_V^2)_{OffShell}$$

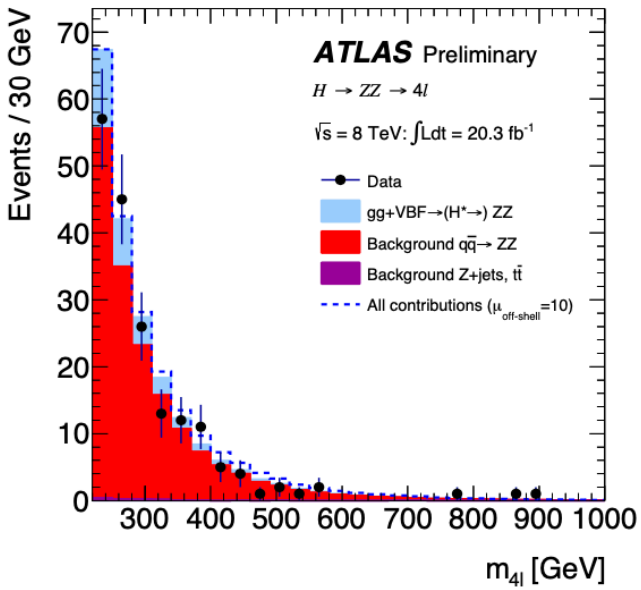
Higgs boson as a propagator

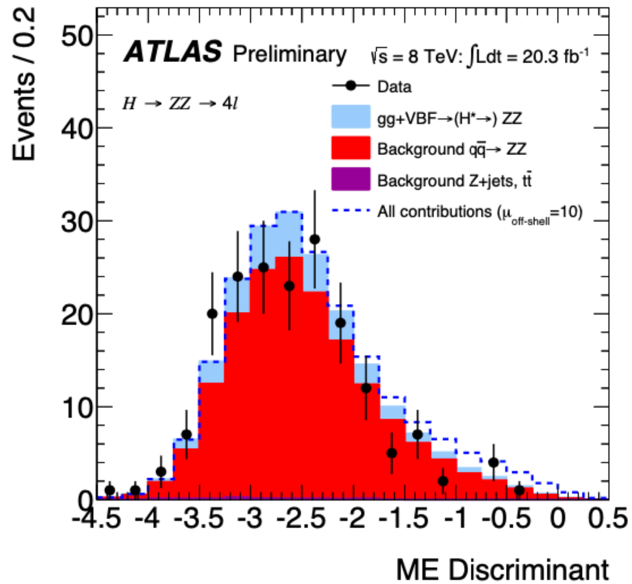
- New physics that affects the Higgs couplings and not the continuum
- LO description of the continuum (gg2VV), use of k-factor: no assumption made on bkg k-factor

$$R_{H^*}^{b} = \frac{k_{gg\to ZZ}}{k_{gg\to H^*\to ZZ}}$$

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

Exploring the High mass region in 4l and 2l2v





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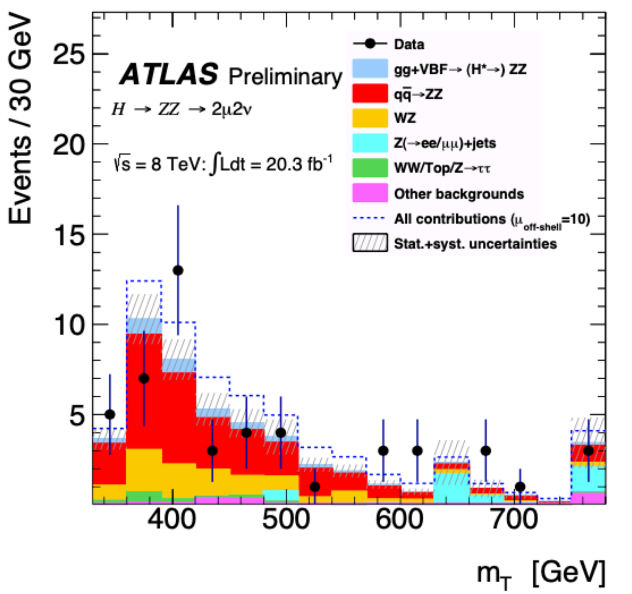
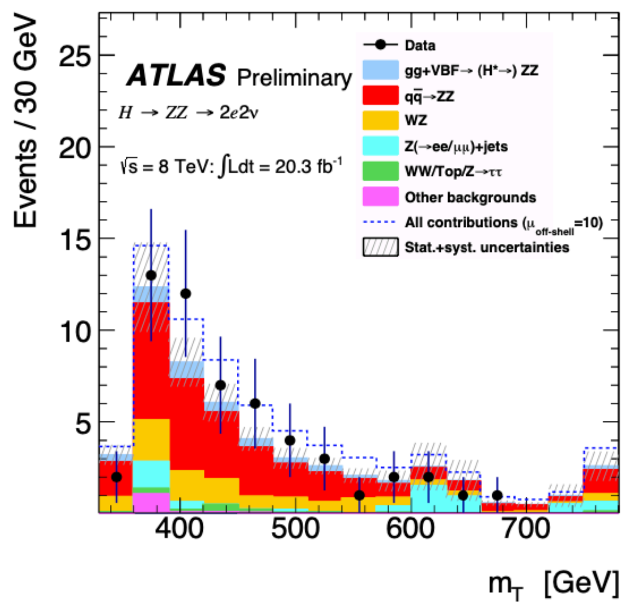
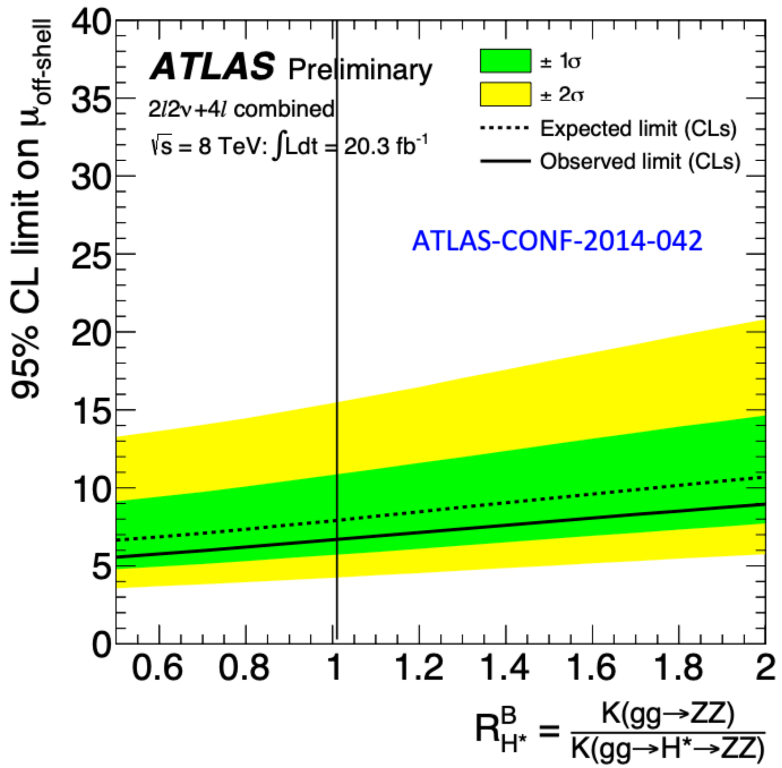
Use of two channels:

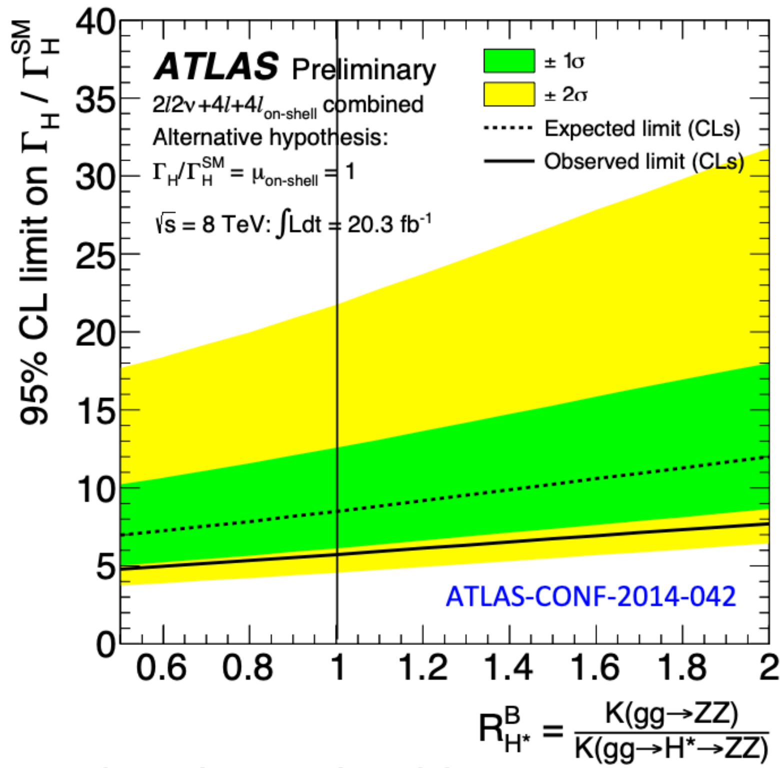
- 4l analysis with Mass and ME
- llvv analysis cut based
- Main background qq continuum includes EW k-factor





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)

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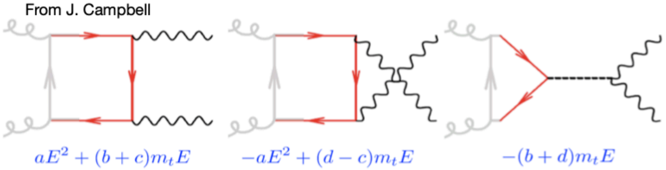
Extraction of Higgs boson width from off-shell measurements : a brief overview

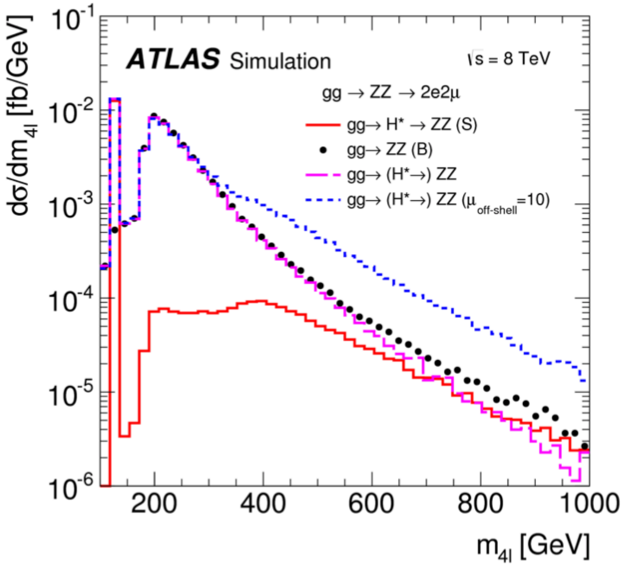
Off Shell Higgs

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





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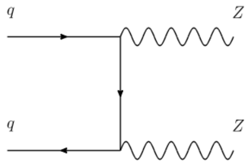

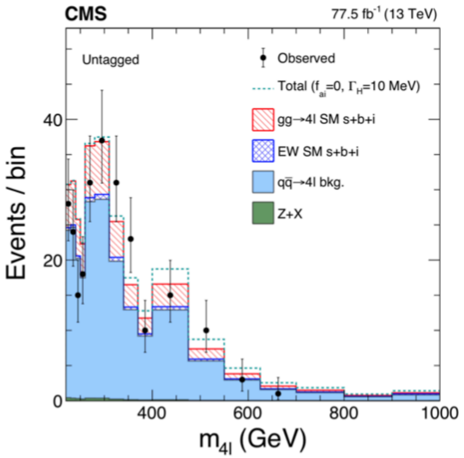

Limits on the total width are currently at approximately **10 MeV** (and exclude 0 at 95% CL).

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%