Measurements of the Higgs boson properties at ATLAS

Rostislav Konoplich
On behalf of the ATLAS collaboration

Mitchell Workshop on Collider, Dark Matter and Neutrino Physics,

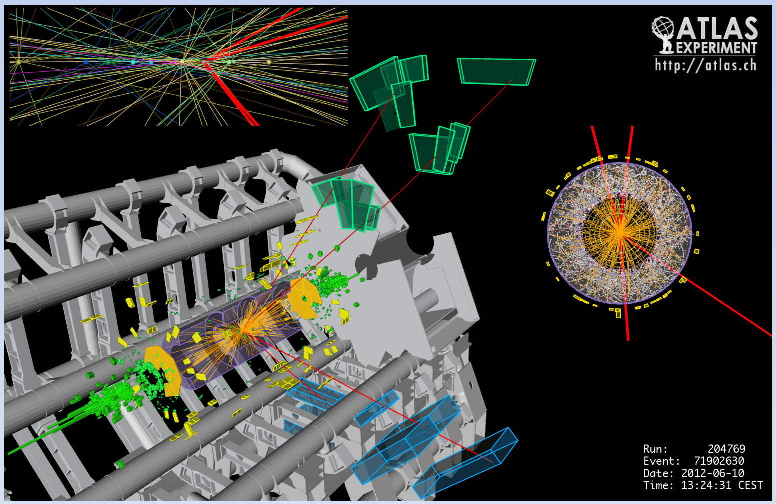
May 23-26, 2016

Outline

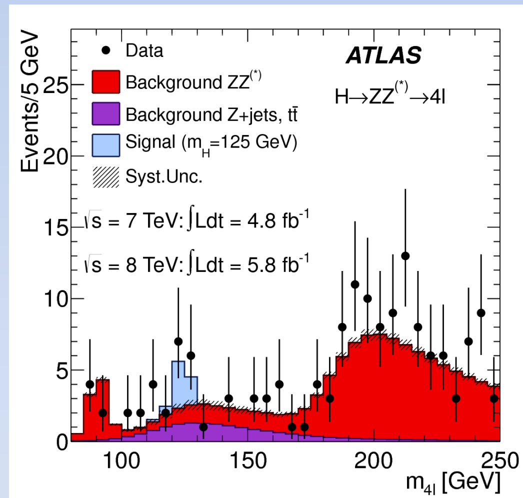
- Introduction
- SM cross sections and decay rates
- Combined measurements of Higgs boson production and decay rates (ATLAS + CMS)
- Spin/CP measurements
- Fiducial cross section measurements
- Other important results
- Summary

The Higgs Boson

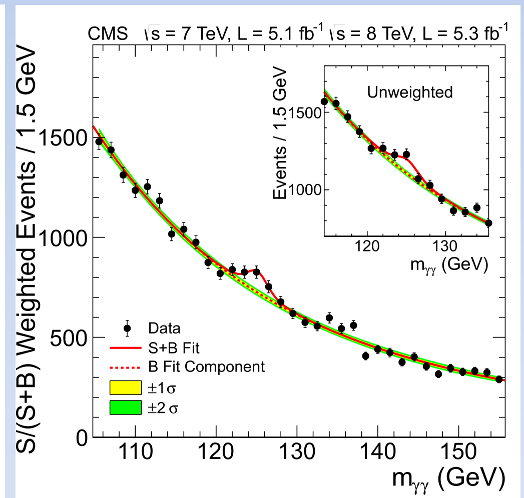
Year 2012.
Discovery of a new particle compatible with the SM Higgs boson by the ATLAS and CMS collaborations. A new era in particle physics and cosmology.



Phys.Lett. B716 (2012) 1



Phys.Lett. B716 (2012) 30



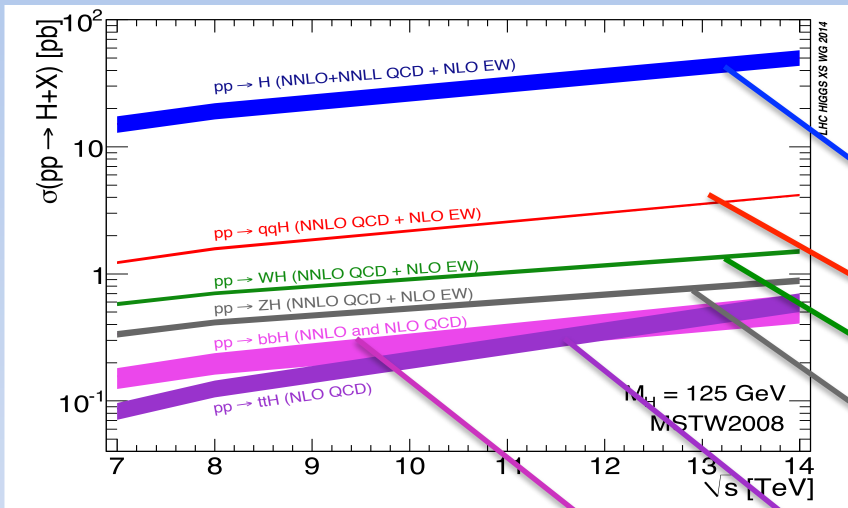
The ATLAS and CMS combination in the $H \rightarrow ZZ \rightarrow 4l$ and $H \rightarrow \gamma\gamma$ decay channels:

$m_H = 125.09 \pm 0.21\ (stat) \pm 0.11\ (syst)$, GeV

PRL 114 (2015) 191803

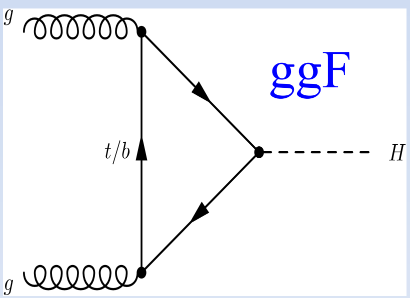
(A.Gritsan talk at this workshop)

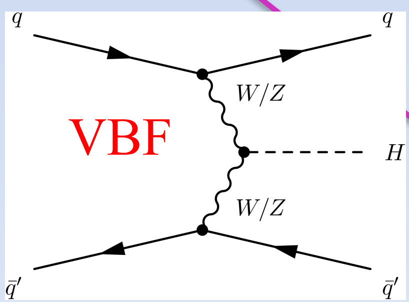
The SM Higgs Boson Production

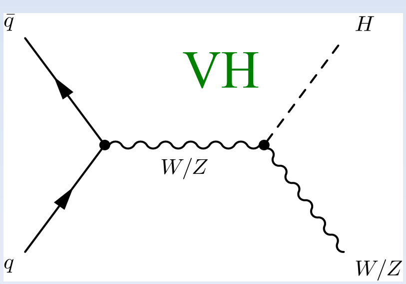


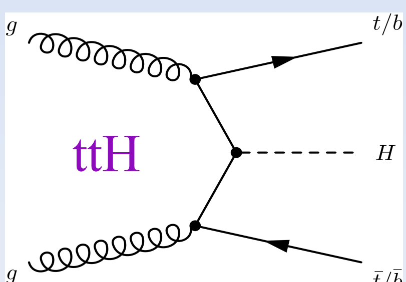
$$m_H = 125.09\ GeV$$

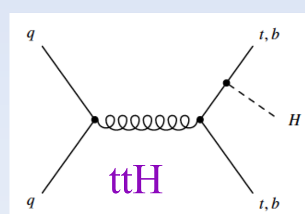
Production process	σ [pb] $\sqrt{s} = 7\ TeV$	σ [pb] $\sqrt{s} = 8\ TeV$
ggF	15.0 ± 1.6	19.2 ± 2.0
VBF	1.22 ± 0.03	1.58 ± 0.04
WH	0.577 ± 0.016	0.703 ± 0.018
ZH	0.334 ± 0.013	0.414 ± 0.016
ggZH	0.023 ± 0.007	0.032 ± 0.10
ttH	0.086 ± 0.009	0.129 ± 0.014
tH	0.012 ± 0.001	0.018 ± 0.001
bbH	0.156 ± 0.021	0.203 ± 0.028
Total	17.4 ± 1.6	22.3 ± 2.0

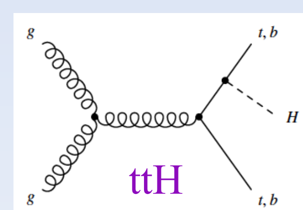






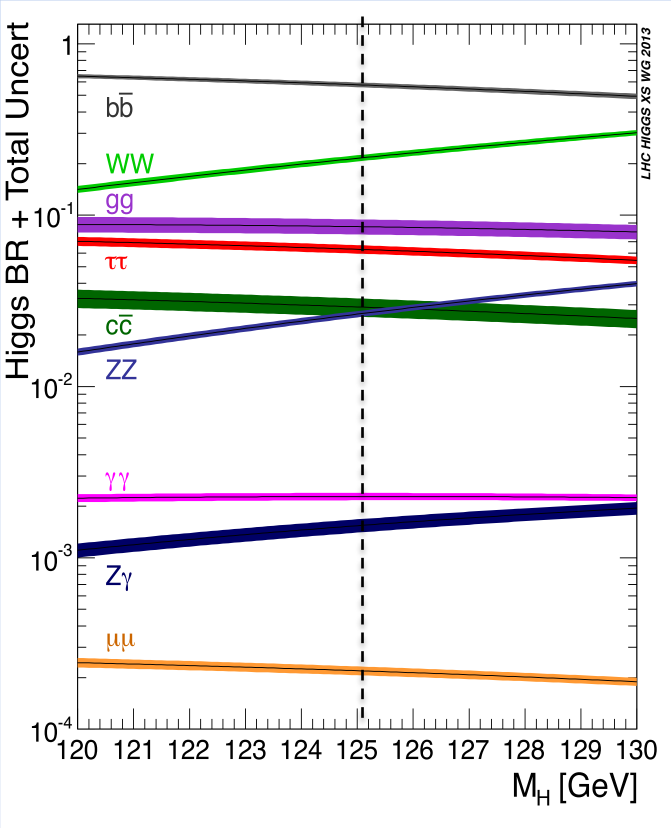






arXiv:1307.1347
ATLAS-CONF-2015-044
CMS-PAS-HIG-15-002

The SM Higgs boson decay



Decay mode	Branching ratio [%]
H → bb	57.5 ± 1.9
H → WW	21.6 ± 0.9
H → gg	8.56 ± 0.86
H → ττ	6.3 ± 0.36
H → cc	2.9 ± 0.35
H → ZZ	2.67 ± 0.11
H → γγ	0.228 ± 0.011
H → Zγ	0.155 ± 0.014
H → μμ	0.022 ± 0.001

arXiv:1307.1347

2-5% precision for the most important modes

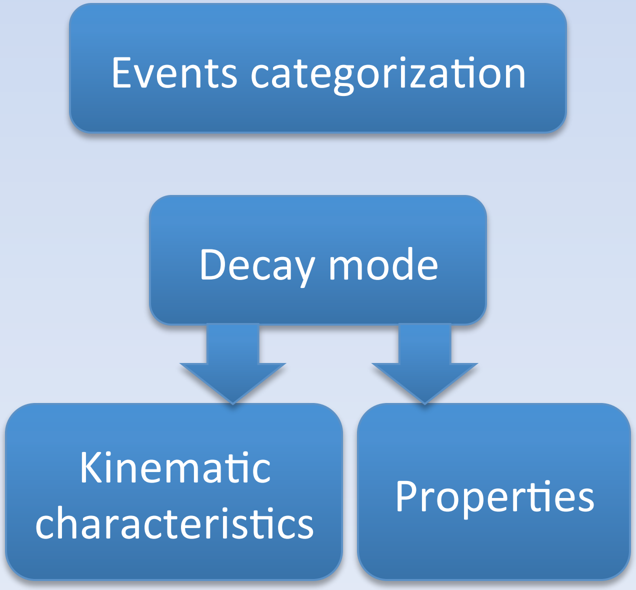
The SM Higgs boson width is small Γ ≈ 4 MeV.

Combined ATLAS and CMS measurements of the Higgs boson production and decay rates. Experimental inputs.

ATLAS-CONF-2015-044
CMS-PAS-HIG-15-002

≈ 600 exclusive categories:

- ❖ Increase the sensitivity of the analysis.
- ❖ Allow separation of production modes.



decay	ggF	VBF	VH	ttH
$H \to \gamma\gamma$	✔	✔	✔	✔
$H \to ZZ \to 4l$	✔	✔	✔	✔
$H \to WW \to 2l2\nu$	✔	✔	✔	✔
$H \to \tau\tau$	✔	✔	✔	✔
$H \to bb$	✗	✗	✔	✔
$H \to \mu\mu$	✔	✔	✗	✗
$H \to$ invisible	✗	✗	✗	✗

large background

CMS result exists, but not in time for combination

small cross section

searches performed but not included in this combination

1. SM tensor structure.
2. Narrow width approximation.

Measurements of signal strengths

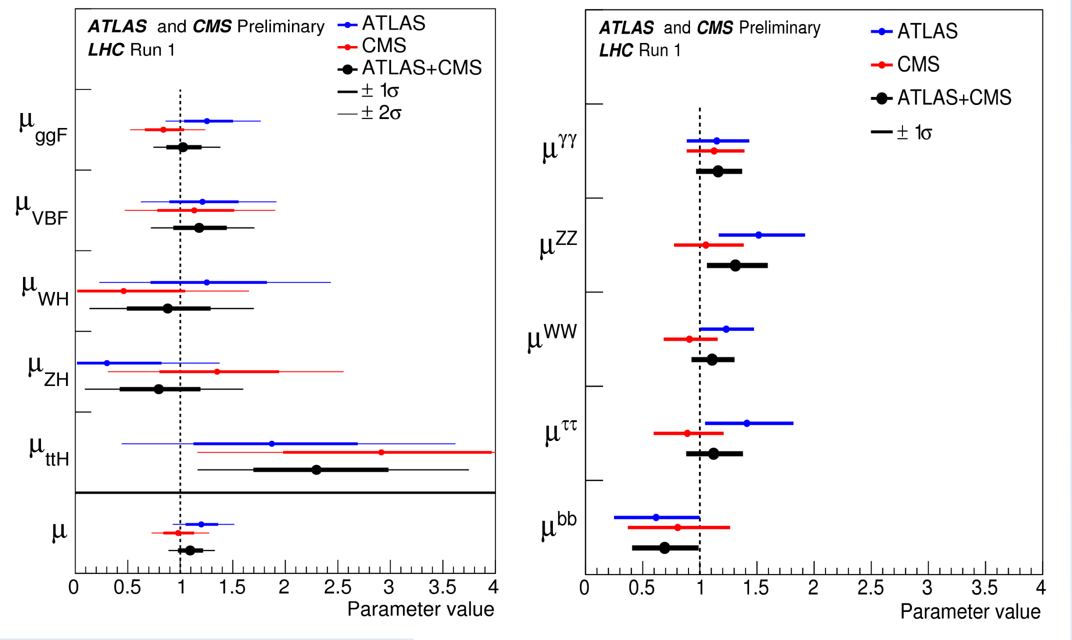
$$\mu_i^f \equiv \frac{\sigma_i \cdot B^f}{(\sigma_i)_{SM} \cdot (B^f)_{SM}} = \mu_i \cdot \mu^f$$

Only μ_i^f can be measured experimentally.
μ_i and μ^f separation requires Higgs narrow width.
Additional assumptions are necessary for a combination.

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

Theory uncertainties are dominated by ggF cross section uncertainties.

Significance [σ]		
Production	Measured	Expected
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		
$H \to \tau\tau$	5.5	5.0
$H \to bb$	2.6	3.7



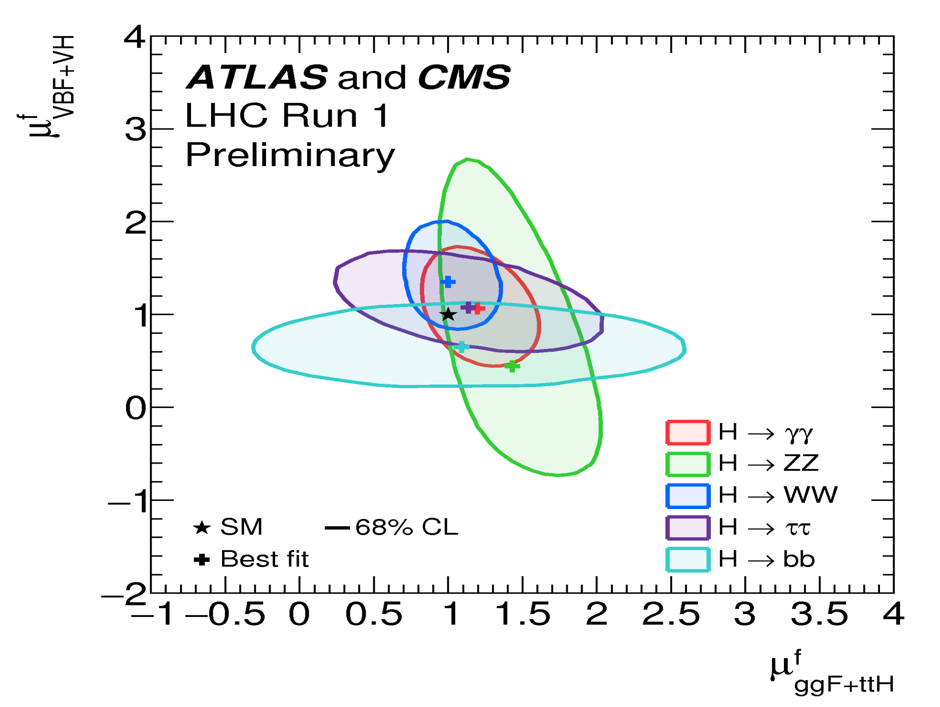
Production signal strength by decay channel

Deviations of Higgs couplings from the SM predictions can be tested by using two signal strengths for each decay channel f:

μ_F^f for the fermion-mediated production
μ_V^f for the vector-boson-mediated production.

No assumption on SM production or decay rates needed for individual channels.

The branching fraction cancels in μ_V^f to μ_F^f for each Higgs boson decay channel.

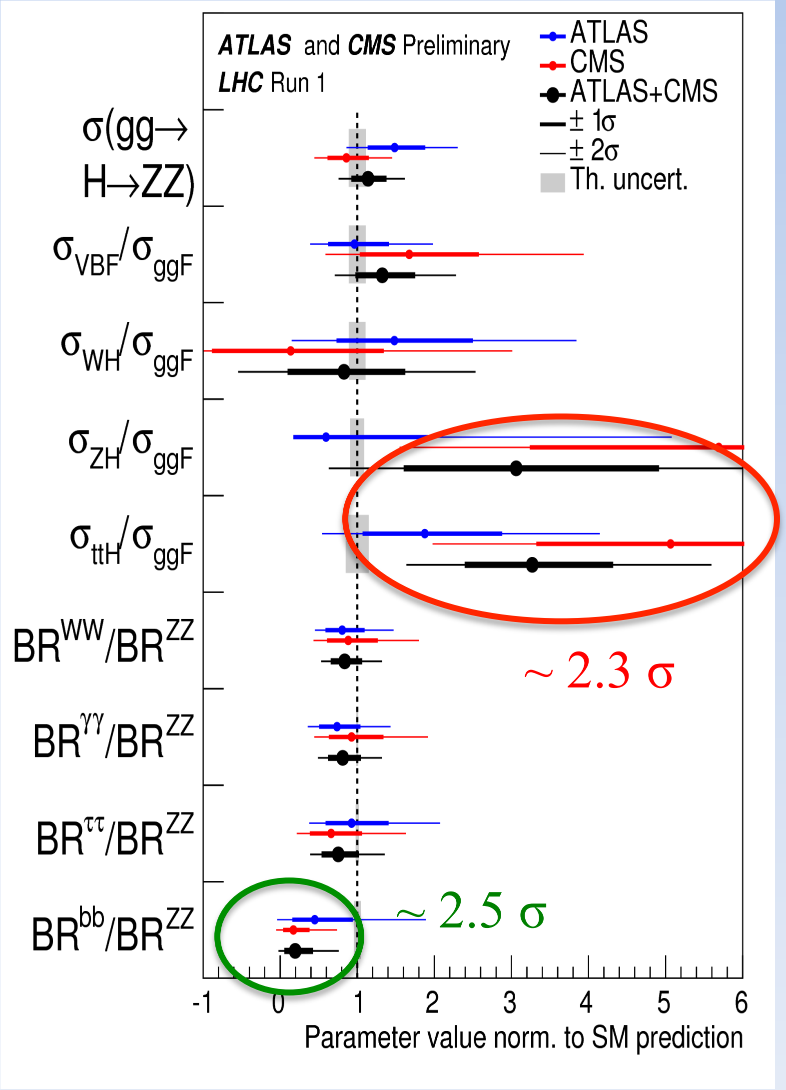


Measured combined ratio

$$\mu_{VBF+VH} / \mu_{ggF+ttH} = 1.06^{+0.35}_{-0.27}$$

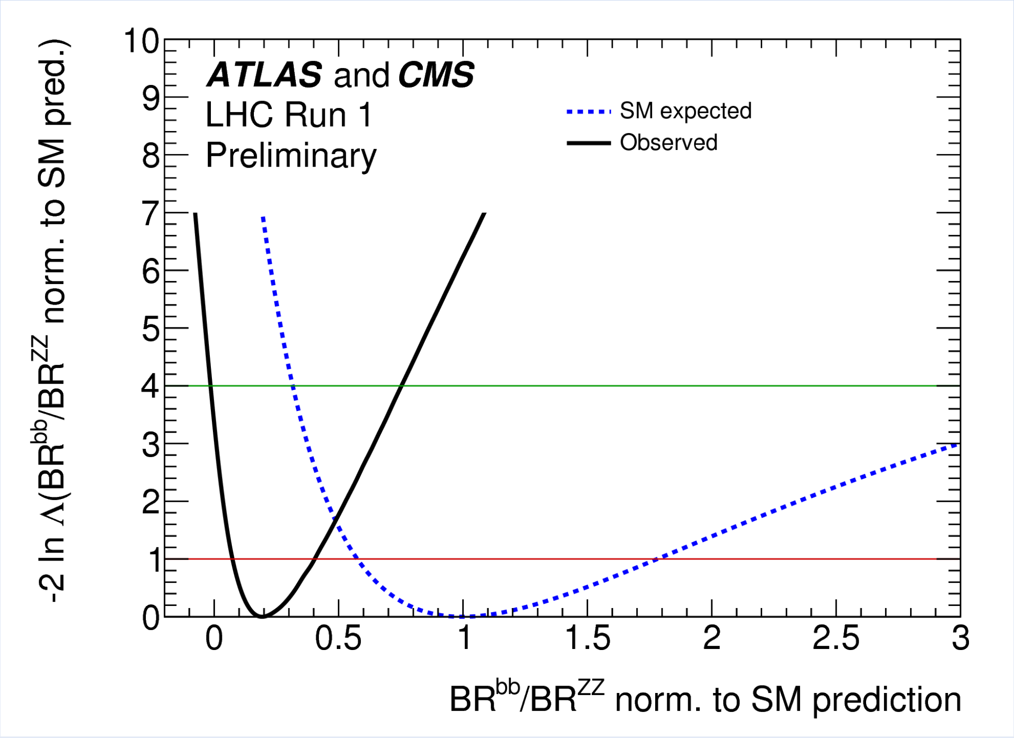
in agreement with the SM.

Ratios of Cross Sections and Branching Fractions



Channel i → H → f :

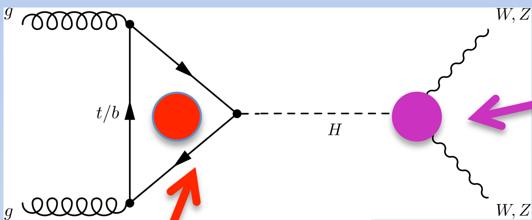
$$\sigma_i \cdot B^f = \sigma(gg \to H \to ZZ) \cdot \left(\frac{\sigma_i}{\sigma_{ggF}} \right) \cdot \left(\frac{B^f}{B^{ZZ}} \right)$$



Coupling Modifiers

$$\sigma_i \cdot B^f = \frac{\sigma_i(\vec{k}) \cdot \Gamma^f(\vec{k})}{\Gamma_H} \qquad k_i^2 = \sigma_i / \sigma_i^{SM} \;\; or \;\; k_f^2 = \Gamma^f / \Gamma^{f,\,SM}$$

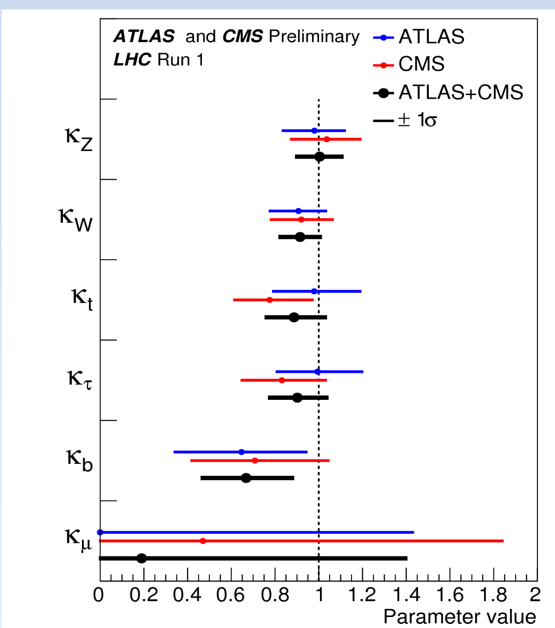
k modifiers describe deviations from the SM. k=1 → SM. The k-framework arXiv:1307.1347.



$$\Gamma_{W,Z} = k_{W,Z}^2 \Gamma_{W,Z}^{SM}$$

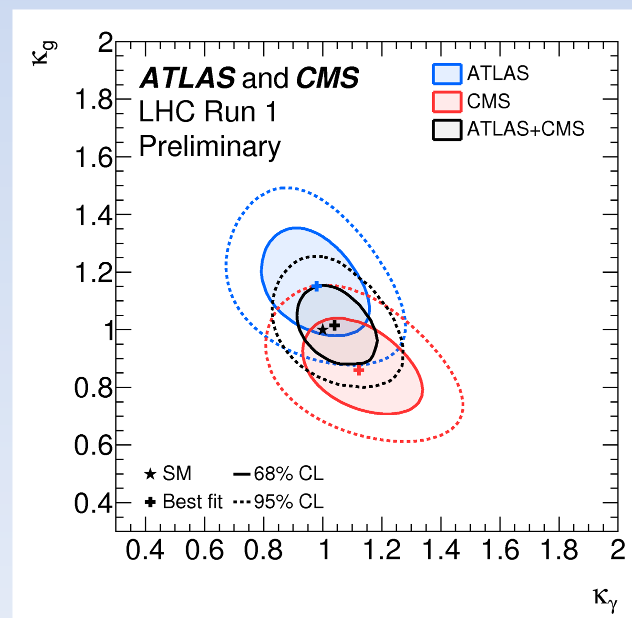
$$\sigma_{ggF} = k_g^2 \sigma_{ggF}^{SM} = (1.06k_t^2 + 0.01k_b^2 - 0.07k_b k_t)\sigma_{ggF}^{SM}$$

NNLO(QCD) + NLO(EW)



Assumptions:
SM physics in loops;
No invisible decays.

Constraints on tree-level couplings.

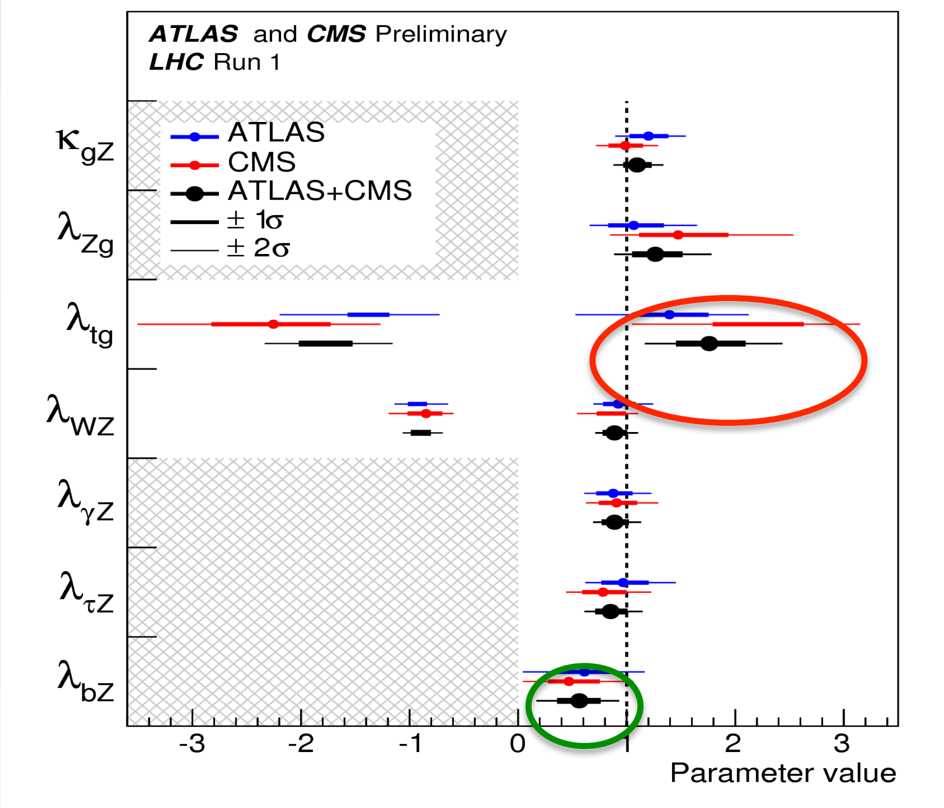


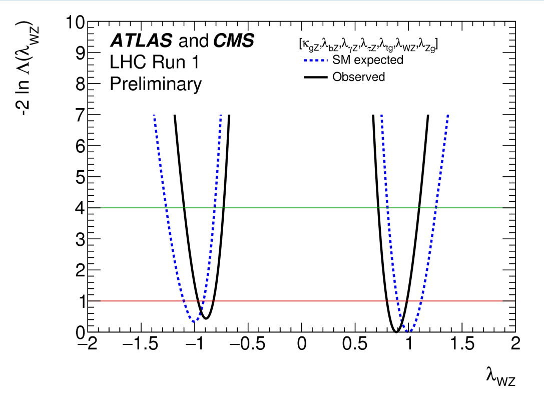
Ratios of Coupling Modifiers

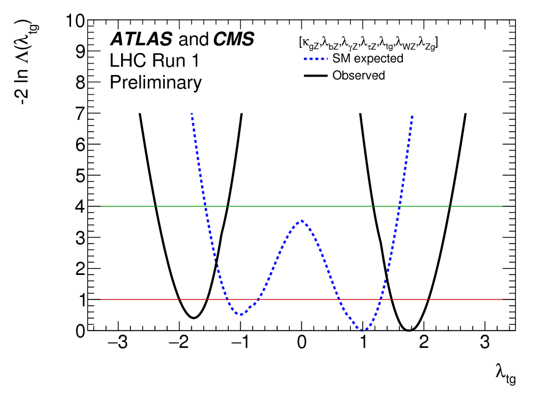
Conversion of σs and Bs ratios into k-framework using $\lambda_{ij} = k_i / k_j$.

$\sigma(gg \rightarrow H \rightarrow ZZ)$ ➡ $k_{gZ} = k_g k_Z / k_H$, $\sigma_{ZH} / \sigma_{ggF}$ ➡ $\lambda_{Zg} = k_Z / k_g$ and so on.

If $k_j \neq 1$ the Higgs boson width is modified by $k_H^2 = \sum_j B_{SM}^j k_j^2$.





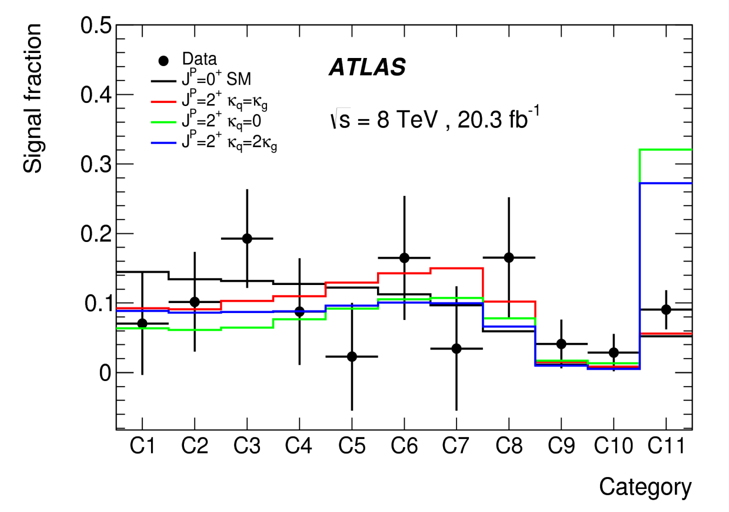


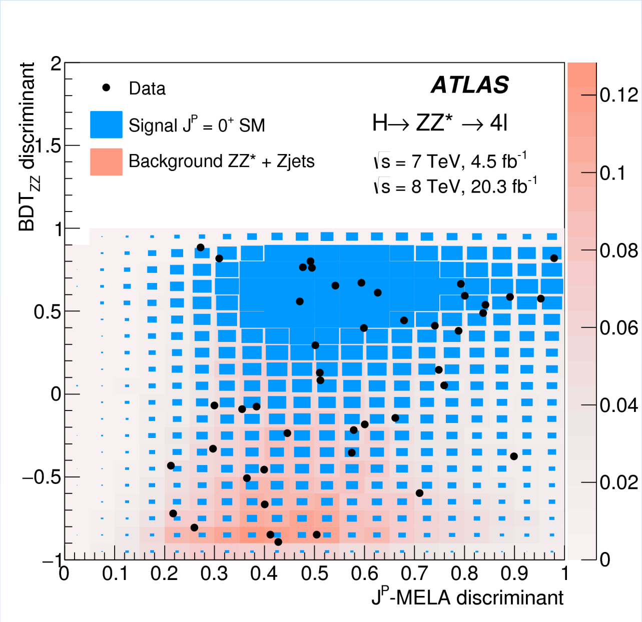
Individual Spin and Parity analyses at ATLAS

- $H \rightarrow \gamma\gamma$. Only spin-2 studies. Two sensitive variables: $\cos(\theta^*)$ and $p_T^{\gamma\gamma}$. Analysis in 11 event categories. Normalization through the fit of the observed $m_{\gamma\gamma}$ distribution.

- $H \rightarrow WW \rightarrow e\nu\mu\nu$. BDT discriminants, trained to distinguish the SM vs backgrounds, J=2 hypotheses vs background and $J^P=0^+$ vs $J^P=0^-$. Training variables: m_{ll}, p_T^{ll}, $\Delta\phi_{ll}$, m_T. 0-jet and 1-jet categories.

- $H \rightarrow ZZ \rightarrow 4l$. Inclusive in number of jets. 4μ, $4e$, $2e2\mu$, $2\mu2e$ final states. J^P-MELA discriminant based on the LO matrix elements to distinguish between SM and BSM J^P states. BDT_{ZZ} discriminant to distinguish resonant signal and non-resonant ZZ background.





Spin/CP measurements

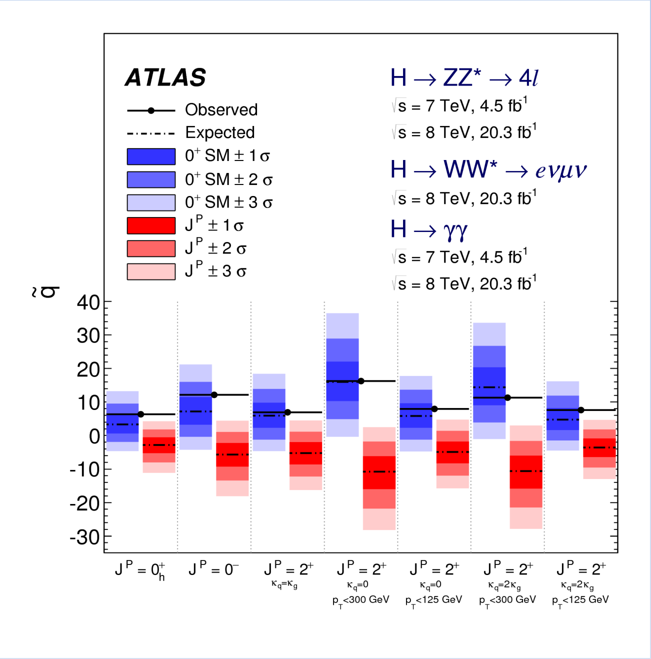
Eur. Phys. J. C75 (2015) 476

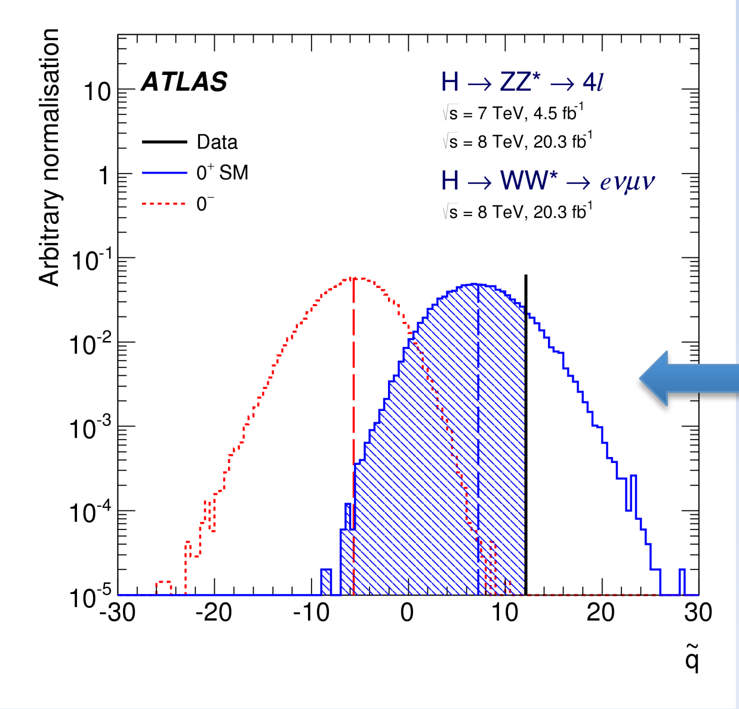
Distributions of the test statistic $\tilde{q}$ for the SM Higgs boson and for the J^P alternative hypotheses.

$\sqrt{s}$ = 7 TeV and 8 TeV, L = 25 fb^{-1}

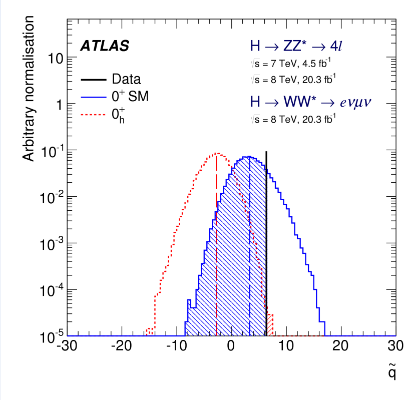
$H \to ZZ \to 4l$, $H \to WW \to e\nu\mu\nu$, $H \to \gamma\gamma$

All tested non SM spin models are excluded in favor of the SM spin 0 at more than 99.9% CL.





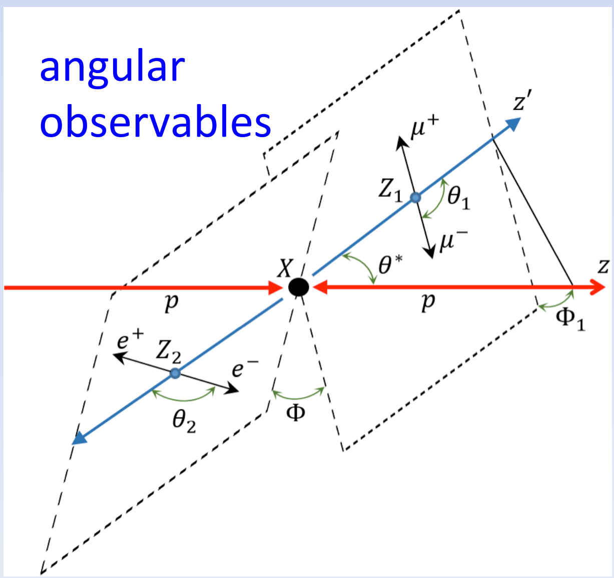
The observed values are indicated by the vertical solid line and the expected medians by the dashed lines. The shaded areas correspond to the integrals of the expected distributions used to compute the p -values for the rejection of each hypothesis.

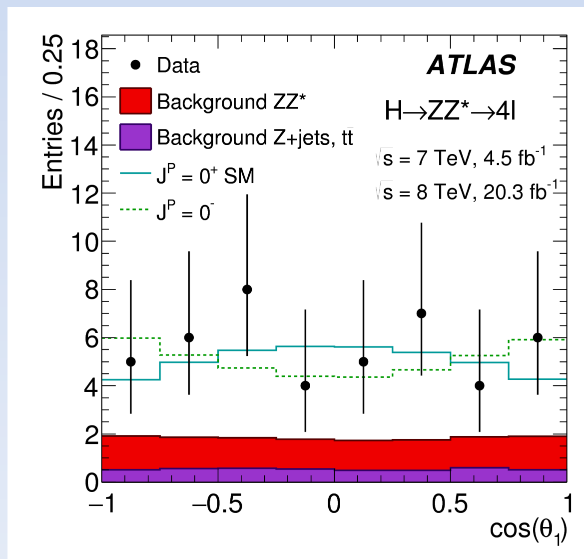


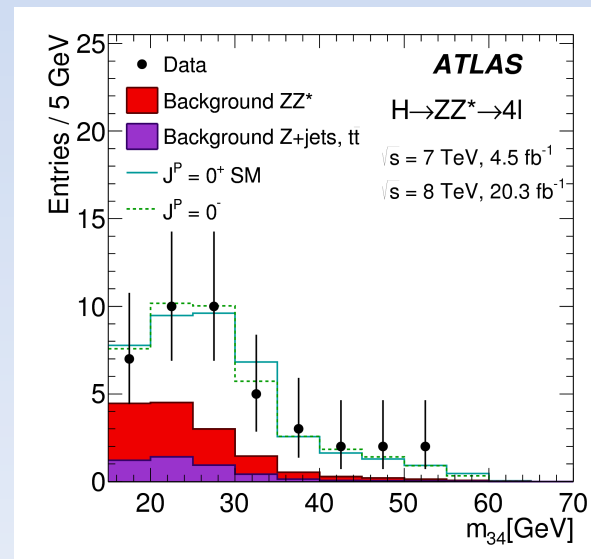
Tensor Structure

$$\mathcal{L}_0^V = \Big\{\cos(\alpha)\kappa_{SM}\left[\tfrac{1}{2}g_{HZZ}Z_\mu Z^\mu + g_{HWW}W^+_\mu W^{-\mu}\right] - \tfrac{1}{4}\tfrac{1}{\Lambda}\left[\cos(\alpha)\kappa_{HZZ}Z_{\mu\nu}Z^{\mu\nu} + \sin(\alpha)\kappa_{AZZ}Z_{\mu\nu}\tilde{Z}^{\mu\nu}\right] - \tfrac{1}{2}\tfrac{1}{\Lambda}\left[\cos(\alpha)\kappa_{HWW}W^+_{\mu\nu}W^{-\mu\nu} + \sin(\alpha)\kappa_{AWW}W^+_{\mu\nu}\tilde{W}^{-\mu\nu}\right]\Big\}X_0.$$

Fitting ratios of couplings $\frac{\tilde{k}_{HVV}}{k_{SM}}$ and $\frac{\tilde{k}_{AVV}}{k_{SM}}tg(\alpha)$ where $\tilde{k}_{XVV} = \frac{1}{4}\frac{v}{\Lambda}k_{XVV}$







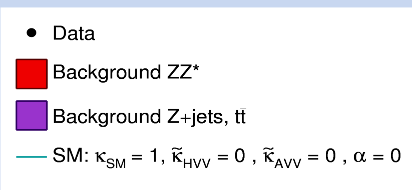
Optimal Observables

$$O_1(\kappa_{HVV}) = \frac{2\Re[\mathrm{ME}(\kappa_{SM}\neq 0;\ \kappa_{HVV},\kappa_{AVV}=0;\ \alpha=0)^* \cdot \mathrm{ME}(\kappa_{HVV}\neq 0;\ \kappa_{SM},\kappa_{AVV}=0;\ \alpha=0)]}{|\mathrm{ME}(\kappa_{SM}\neq 0;\ \kappa_{HVV},\kappa_{AVV}=0;\ \alpha=0)|^2},$$

$$O_2(\kappa_{HVV}) = \frac{|\mathrm{ME}(\kappa_{HVV}\neq 0;\ \kappa_{SM},\kappa_{AVV}=0;\ \alpha=0)|^2}{|\mathrm{ME}(\kappa_{SM}\neq 0;\ \kappa_{HVV},\kappa_{AVV}=0;\ \alpha=0)|^2},$$

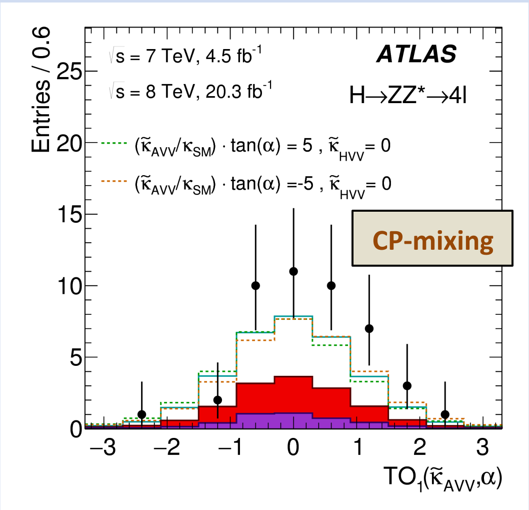
$$O_1(\kappa_{AVV},\alpha) = \frac{2\Re[\mathrm{ME}(\kappa_{SM}\neq 0;\ \kappa_{HVV},\kappa_{AVV}=0;\ \alpha=0)^* \cdot \mathrm{ME}(\kappa_{AVV}\neq 0;\ \kappa_{SM},\kappa_{HVV}=0;\ \alpha=\pi/2)]}{|\mathrm{ME}(\kappa_{SM}\neq 0;\ \kappa_{HVV},\kappa_{AVV}=0;\ \alpha=0)|^2},$$

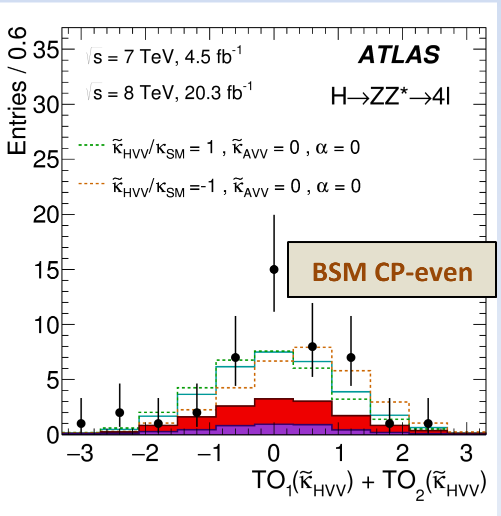
$$O_2(\kappa_{AVV},\alpha) = \frac{|\mathrm{ME}(\kappa_{AVV}\neq 0;\ \kappa_{SM},\kappa_{HVV}=0;\ \alpha=\pi/2)|^2}{|\mathrm{ME}(\kappa_{SM}\neq 0;\ \kappa_{HVV},\kappa_{AVV}=0;\ \alpha=0)|^2}.$$

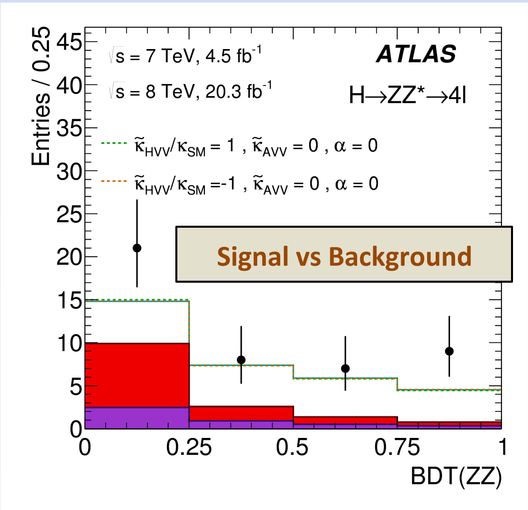


Optimal observables sensitive to k_{SM} , k_{HVV} *and* k_{AVV} .

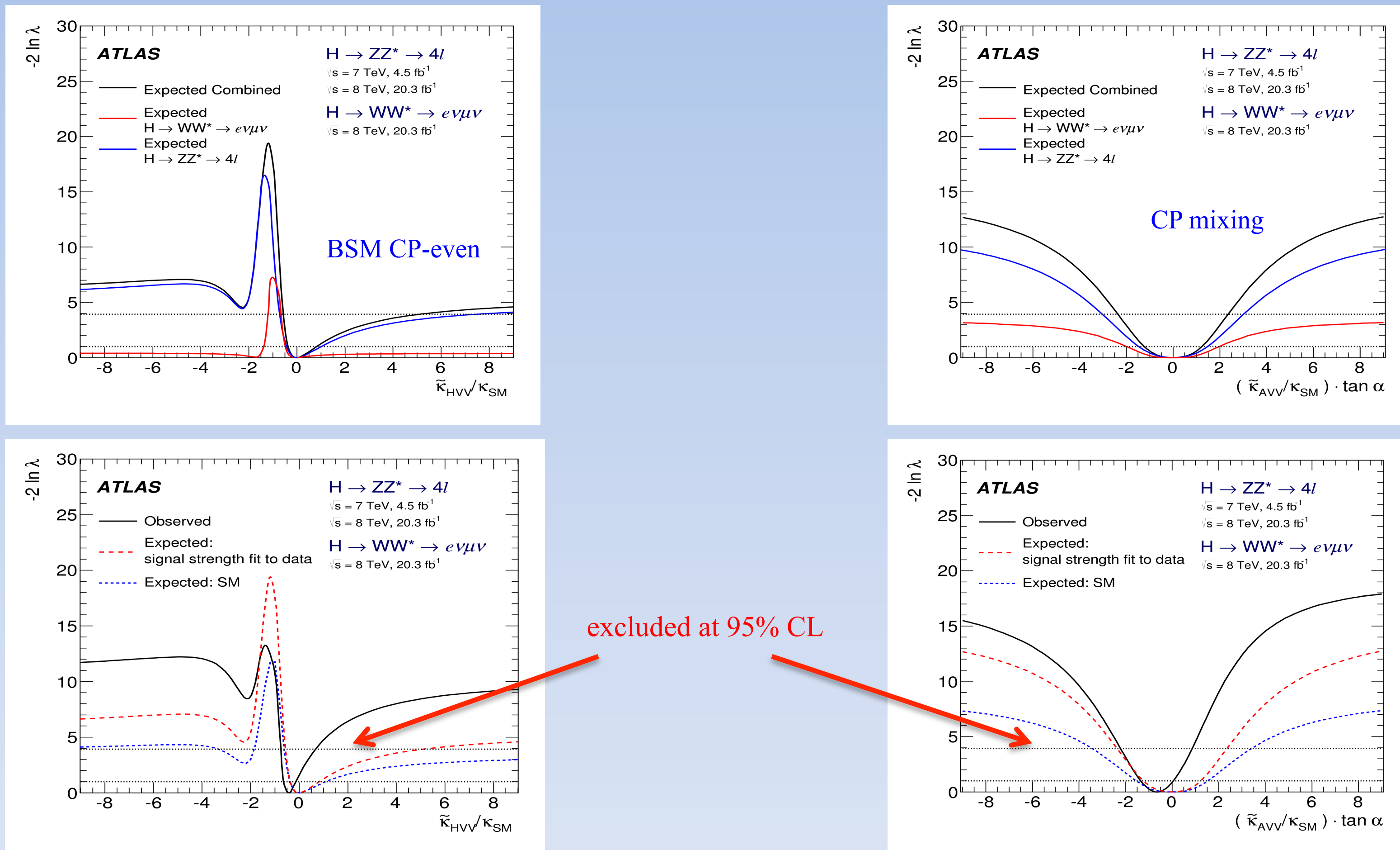
Only shapes of the OOs were used in this analysis, not rates.







Tensor Structure



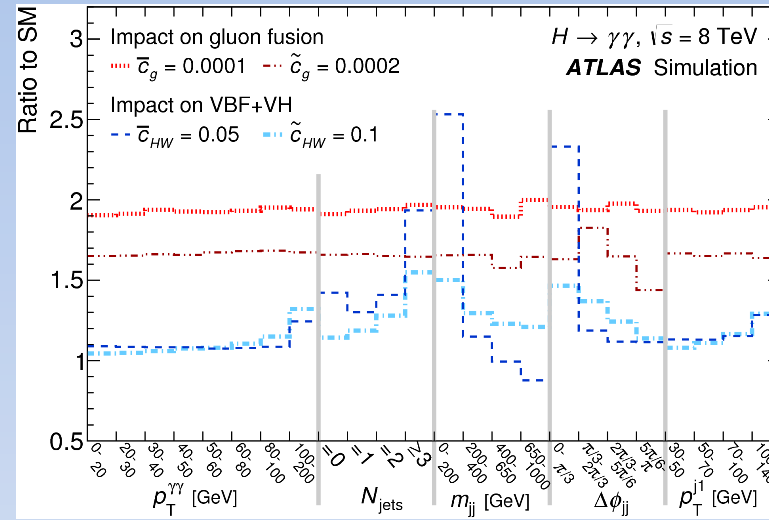
Coupling ratio	Best-fit value	95% CL Exclusion Regions	
Combined	Observed	Expected	Observed
$\tilde{\kappa}_{HVV}/\kappa_{SM}$	-0.48	$(-\infty, -0.55] \bigcup [4.80, \infty)$	$(-\infty, -0.73] \bigcup [0.63, \infty)$
$(\tilde{\kappa}_{AVV}/\kappa_{SM}) \cdot \tan\alpha$	-0.68	$(-\infty, -2.33] \bigcup [2.30, \infty)$	$(-\infty, -2.18] \bigcup [0.83, \infty)$

Constraints using differential cross sections

$\sqrt{s} = 8$ TeV, $L = 20.3$ fb^{-1} , $H \to \gamma\gamma$

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

where c_i are Wilson coefficients.

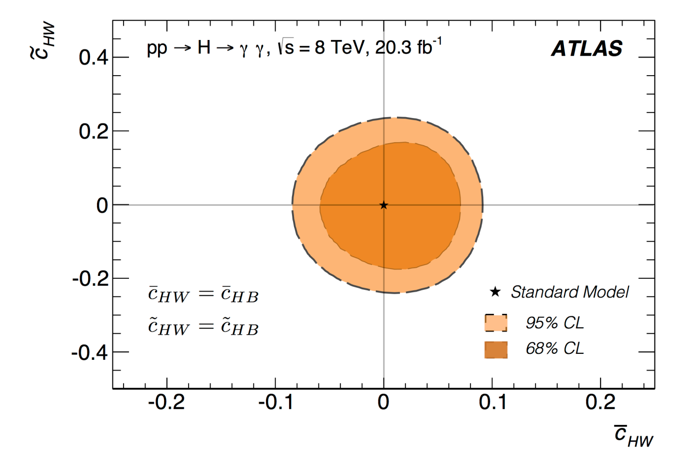


A simultaneous fit to five differential cross sections:

$$p_T^{\gamma\gamma} \ , N_{jets} \ , p_T^{j_{lead}} \ , m_{jj} \ , \Delta\Phi_{jj} \ .$$

Analysis is sensitive to c_γ , c_g , c_{HW} , c_{HB} .

Coefficient	95% $1 - CL$ limit
$\bar{c}_\gamma$	[-7.4, 5.7]$\times 10^{-4}$ $\cup$ [3.8, 5.1]$\times 10^{-3}$
$\tilde{c}_\gamma$	[-1.8, 1.8]$\times 10^{-3}$
$\bar{c}_g$	[-0.7, 1.3]$\times 10^{-4}$ $\cup$ [-5.8, -3.8]$\times 10^{-4}$
$\tilde{c}_g$	[-2.4, 2.4]$\times 10^{-4}$
$\bar{c}_{HW}$	[-8.6, 9.2]$\times 10^{-2}$
$\tilde{c}_{HW}$	[-0.23, 0.23]



PLB 753 (2016) 69

Limits obtained are of a factor of 7 stronger than those in $H \to ZZ$ analysis.

Test of CP invariance in VBF

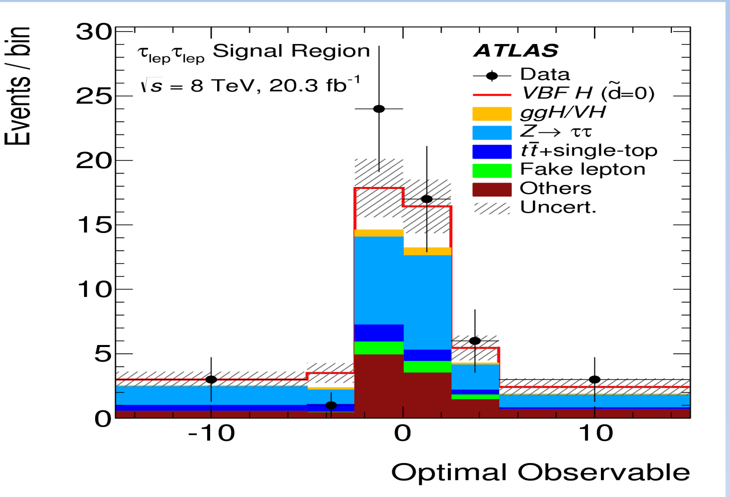
$\sqrt{s}$ = 7 TeV and 8 TeV, L = 25 fb^{-1}

$H \rightarrow \tau_{lep}\,\tau_{had}\ /\ \tau_{lep}\,\tau_{lep}$ + 2 jets tagging VBF

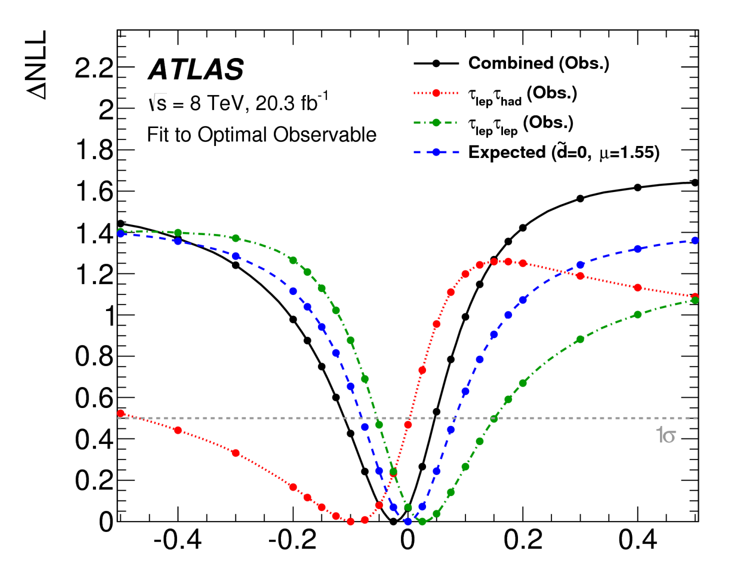
A CP-odd Optimal Observable is employed

$$OO = 2\,\mathrm{Re}(M^{*}_{SM} M_{CP-odd}) / |\,M_{SM}\,|^2$$

$$\tilde{g}_{H\gamma\gamma} = \tilde{g}_{HZZ} = \tilde{g}_{HWW}/2 = (g/2m_W)\tilde{d}$$



- This 68% CL result is a factor of 10 better than the one previously obtained by the ATLAS experiment from $H \rightarrow VV$:
  observed [-0.11, 0.05], expected [-0.08, 0.08].
- This analysis has no sensitivity to constrain a 95% CL interval with the dataset currently available. Higher statistics and additional Higgs boson decay channels should improve sensitivity.



arXiv:1602.04516

Fiducial Higgs cross section measurements

ATLAS-CONF-2015-060	$H \to \gamma\gamma$ 13 TeV
ATLAS-CONF-2015-059	$H \to ZZ \to 4l$ 13 TeV
ATLAS-CONF-2015-069	$H \to ZZ \to 4l$ and $H \to \gamma\gamma$ 13 TeV
JHEP 09 (2014) 112	$H \to \gamma\gamma$ 8 TeV
PLB 738 (2014) 234	$H \to ZZ \to 4l$ 8 TeV
arXiv:1604.02997	$H \to WW \to l\nu l\nu$ 8 TeV

$$\sigma_{tot} = \frac{N_s}{A \cdot B \cdot C \cdot L_{\text{int}}} = \frac{\sigma_{fid}}{A \cdot B}$$

- ❑ N_s is the number of observed signal events
- ❑ L_{int} is the integrated luminosity
- ❑ B is the Higgs boson branching fraction
- ❑ A is the acceptance in the fiducial region
- ❑ C is a correction factor accounting for detector resolution and efficiency
- ❑ A and B are theory dependent.

How to measure a fiducial cross section?

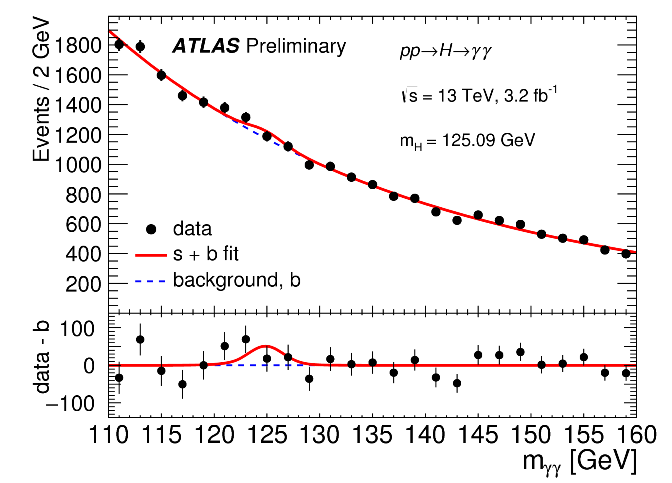
- Define a fiducial region that closely matches the detector acceptance (and all the analysis cuts in ATLAS)
- Choose observables to study processes of interest
- Extract a signal from reconstructed events
- Apply correction (unfolding) for detector effects

σ_{fid} is less model dependent than σ_{tot}

Event Selection

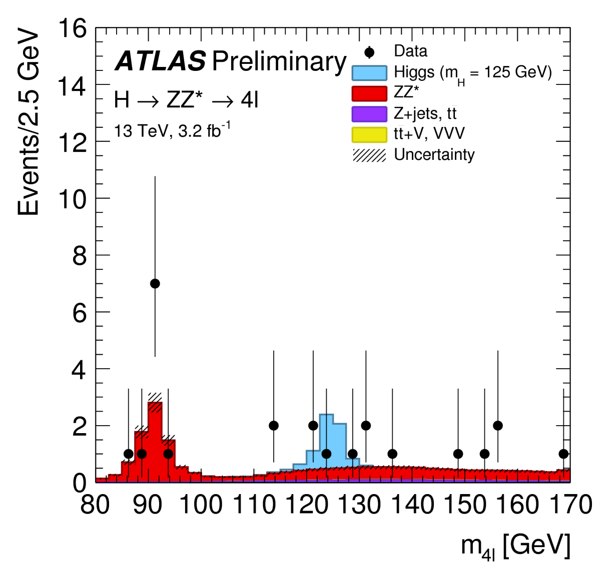
$H \to \gamma\gamma$ 13 TeV 3.2 fb^{-1}

Event Selection	
Two highest-p_T photons:	$\|\eta^\gamma\| < 2.37$
Relative-p_T:	$E^\gamma_{T,1}/m_{\gamma\gamma} \geq 0.35, E^\gamma_{T,2}/m_{\gamma\gamma} \geq 0.25$
Mass window:	$105\,\text{GeV} \leq m_{\gamma\gamma} < 160\,\text{GeV}$
Photon isolation:	$E_{T,\text{iso}} < 0.1 \times E^\gamma_T + 1\,\text{GeV}$

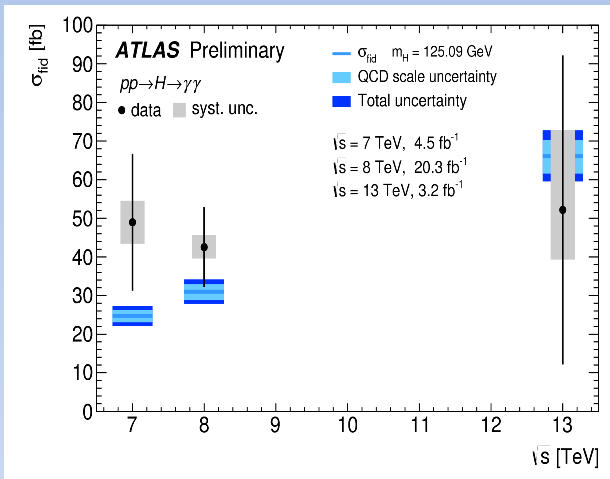


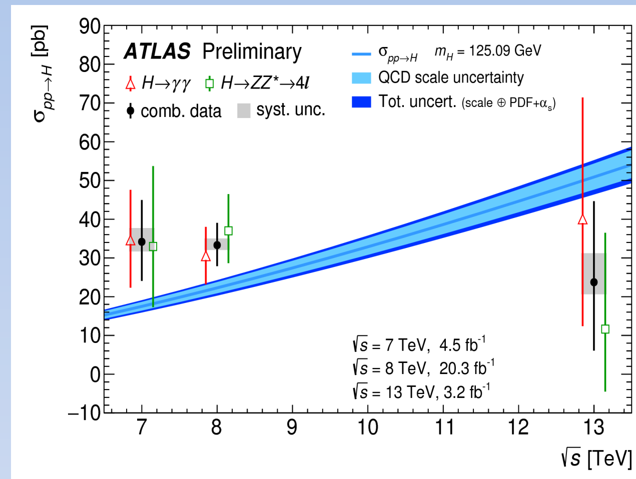
$H \to ZZ \to 4l$ 13 TeV 3.2 fb^{-1}

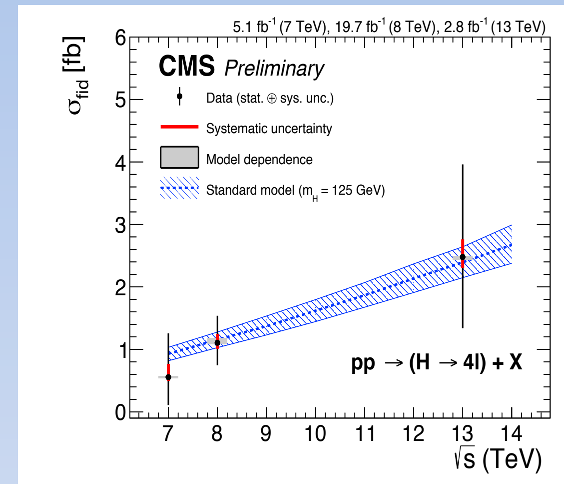
Lepton definition	
Muons: $p_T > 6$ GeV, $\|\eta\| < 2.7$	Electrons: $p_T > 7$ GeV, $\|\eta\| < 2.47$
Pairing	
Leading pair:	SFOS lepton pair with smallest $\|m_Z - m_{\ell\ell}\|$
Sub-leading pair:	Remaining SFOS lepton pair with smallest $\|m_Z - m_{\ell\ell}\|$
Event selection	
Lepton kinematics:	Leading lepton $p_T > 20, 15, 10$ GeV
Mass requirements:	$50 < m_{12} < 106$ GeV; $12 < m_{34} < 115$ GeV
Lepton separation:	$\Delta R(\ell_i, \ell_j) > 0.1(0.2)$ for same (opposite) flavour leptons
J/ψ veto:	$m(\ell_i, \ell_j) > 5$ GeV for all SFOS lepton pairs
Mass window:	$118 < m_{4\ell} < 129$ GeV



Cross Sections







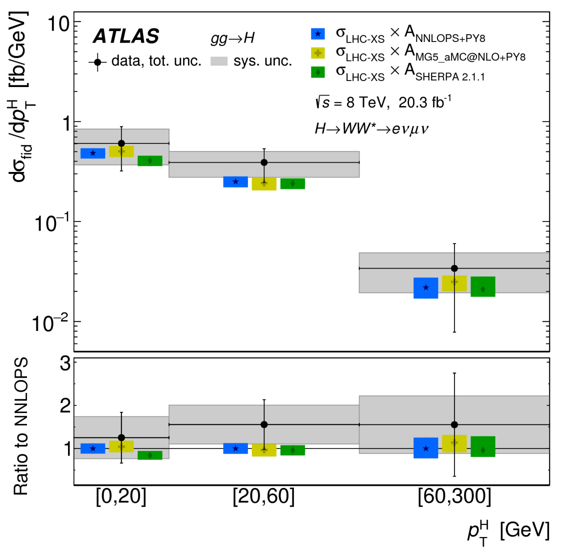
No significant deviations from the SM

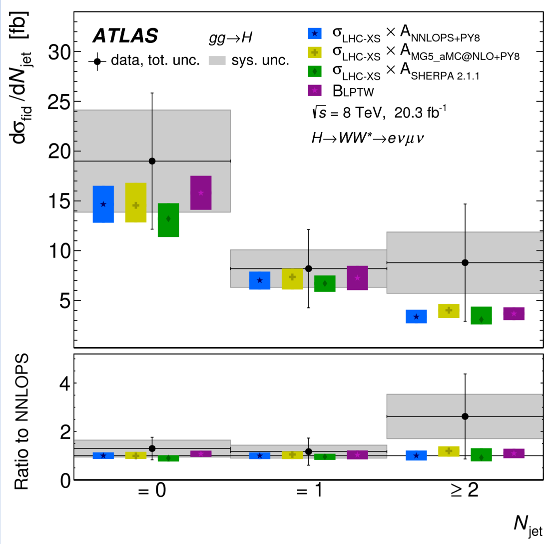
	7 TeV	8 TeV	13 TeV
Acceptance factor			
$H \to \gamma\gamma$	0.620 ± 0.007	0.611 ± 0.012	0.570 ± 0.006
$H \to ZZ^* \to 4\ell$	0.467 ± 0.010	0.460 ± 0.010	0.427 ± 0.006
Fiducial cross section [fb]			
$H \to \gamma\gamma$	49 ± 18	43 ± 10	52^{+40}_{-37}
$H \to ZZ^* \to 4\ell$	$1.9^{+1.2}_{-0.9}$	2.1 ± 0.5	$0.6^{+1.3}_{-0.9}$
Total cross section [pb]			
$H \to \gamma\gamma$	35^{+13}_{-12}	$30.5^{+7.5}_{-7.4}$	40^{+31}_{-28}
$H \to ZZ^* \to 4\ell$	33^{+21}_{-16}	37^{+9}_{-8}	12^{+25}_{-16}
Combination	34 ± 10 (stat.) $^{+4}_{-2}$ (syst.)	$33.3^{+5.5}_{-5.3}$ (stat.) $^{+1.7}_{-1.3}$ (syst.)	24^{+20}_{-17} (stat.) $^{+7}_{-3}$ (syst.)
LHC-XS	17.5 ± 1.6	22.3 ± 2.0	$50.9^{+4.5}_{-4.4}$

First H → WW → eνμν fiducial cross sections results.

Object selection	
Electrons	$p_T > 15GeV$, $\|\eta\| < 1.37$ or $1.52 < \|\eta\| < 2.47$
Muons	$p_T > 15GeV$, $\|\eta\| < 2.5$
Jets	$p_T > 25GeV$ if $\|\eta\| < 2.4$, $p_T > 30GeV$ if $2.4 \leq \|\eta\| < 4.5$
Event selection	
Preselection	$p_T^{lead}(\ell) > 22GeV$
	$m_{\ell\ell} > 10GeV$
	$p_T^{miss} > 20GeV$
Topology	$\Delta\phi_{\ell\ell} < 1.8$
	$m_{\ell\ell} < 55GeV$

The selections defining the fiducial region for the cross section measurements.





$$\sigma_{ggF}^{fid} = 36.0 \pm 7.2(stat) \pm 6.4(sys) \pm 1.0(lumi),\ fb$$

$$LHC - XS : \sigma_{ggF}^{fid} = 25.1 \pm 2.6\ \ fb$$

These measurements probe directly:

- The Higgs boson production and decay
- The jet activity produced in association with the Higgs boson

Differential distributions show good agreement with the SM.

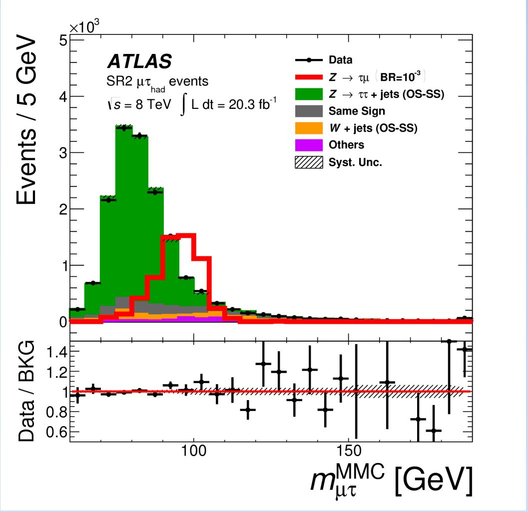
Search for LFV decays of H and Z

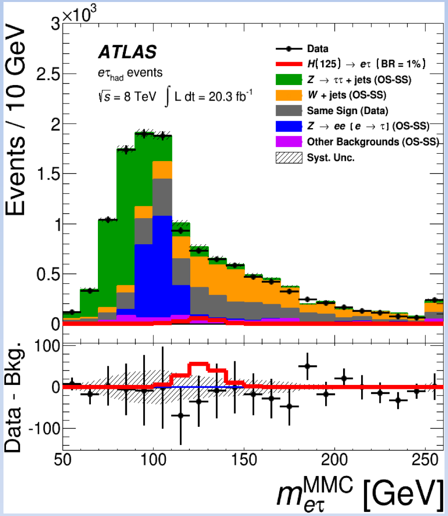
arXiv:1604.07730

Search for

$H \rightarrow e\,\tau_{had}$, $Z \rightarrow \mu\,\tau_{had}$

$H \rightarrow e\,\tau_{lep}$, $H \rightarrow \mu\,\tau_{lep}$



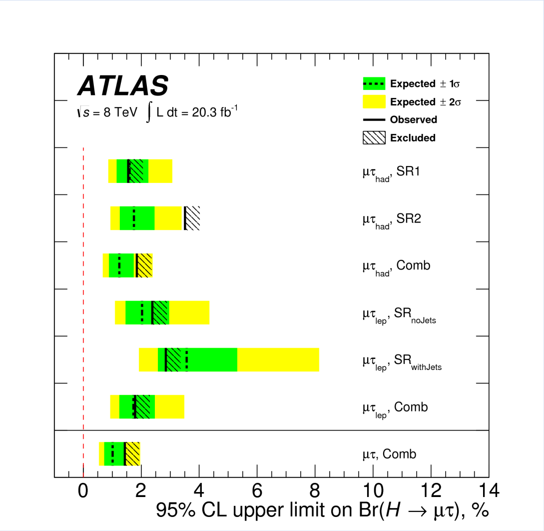


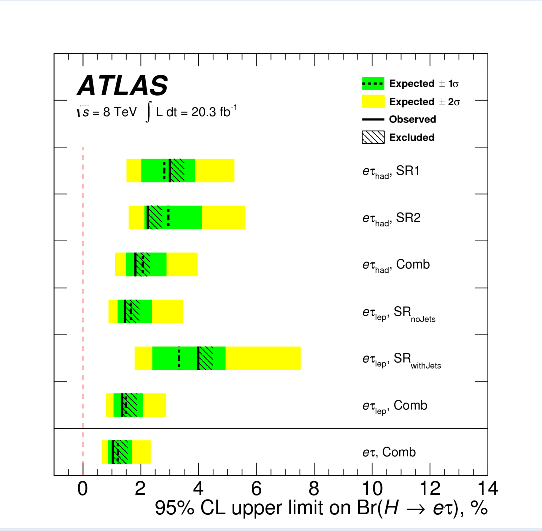
Upper limits at the 95% CL:

B($H \rightarrow e\,\tau$) < 1.04 %

B($H \rightarrow \mu\,\tau$) < 1.43 %

B($Z \rightarrow \mu\,\tau$) < 1.69 10^{-5} %





Other Important Results

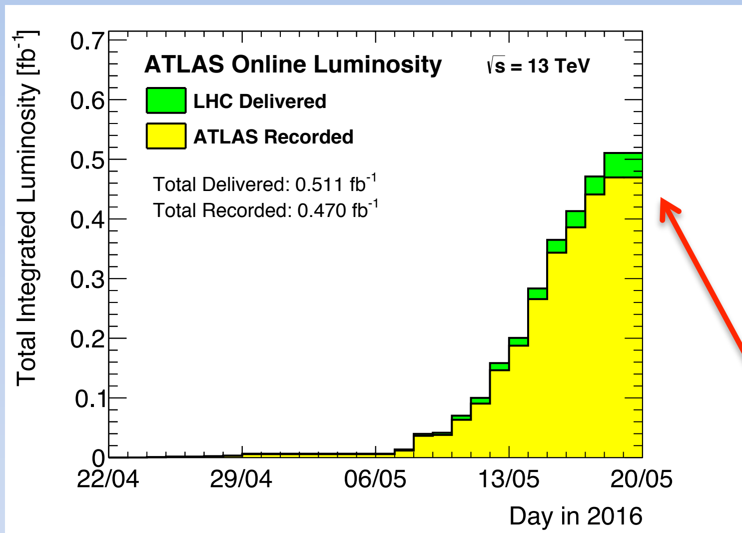
- Search for the BSM Higgs (L.Hauswald talk at this workshop)
- Search for Higgs boson production in association with a pair of top quarks (ttH) [arXiv:1604.03812]
- Search for pair production of Higgs bosons in the bbbb final state [ATLAS-CONF-2016-017]
- Search for invisible decays of a Higgs boson [JHEP 01 (2016) 172]
- Measurements of the total and differential cross sections combining $H \to ZZ \to 4l$ and $H \to \gamma\gamma$ at 8 TeV [PRL 115 (2015) 091801]
- Constraints on the off-shell Higgs boson signal strength [EPJC 75 (2015) 335]

Summary

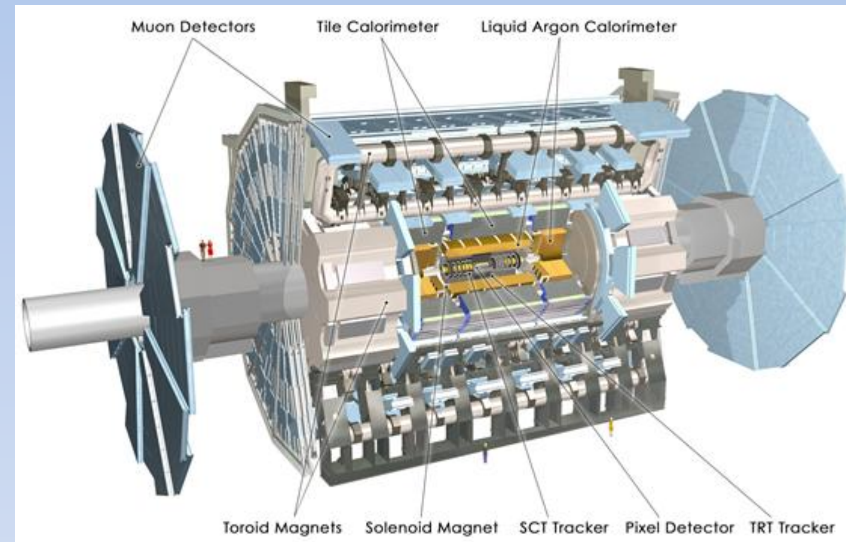
- First results of measurements of the Higgs boson properties at 13 TeV .
- ATLAS and CMS results at 7, 8, and 13 TeV don't contradict the Standard Model.
- VBF production mechanism and $H \to \tau\tau$ decay were discovered and evidence for VH and ttH was found.
- Combination of ATLAS and CMS results reduces uncertainties in the Higgs boson parameters (improvement approximately by a factor of $\sqrt{2}$).
- The precision of measurements will be improved this year with the expected increase of data samples.

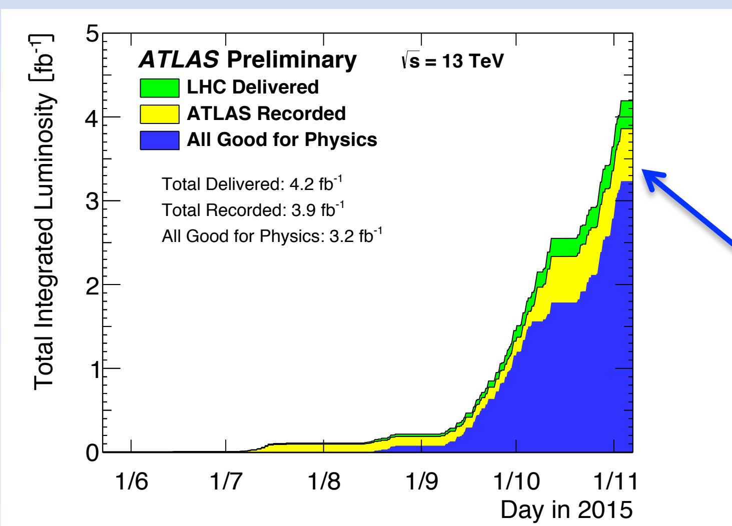
Backup

Luminosity

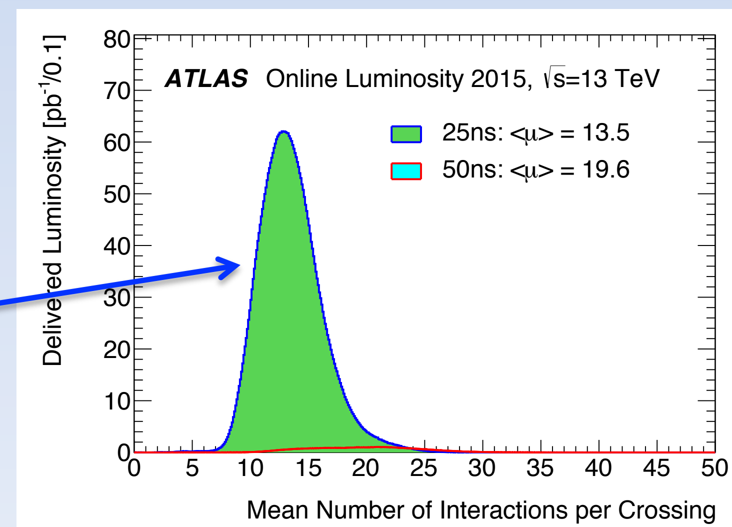


2016

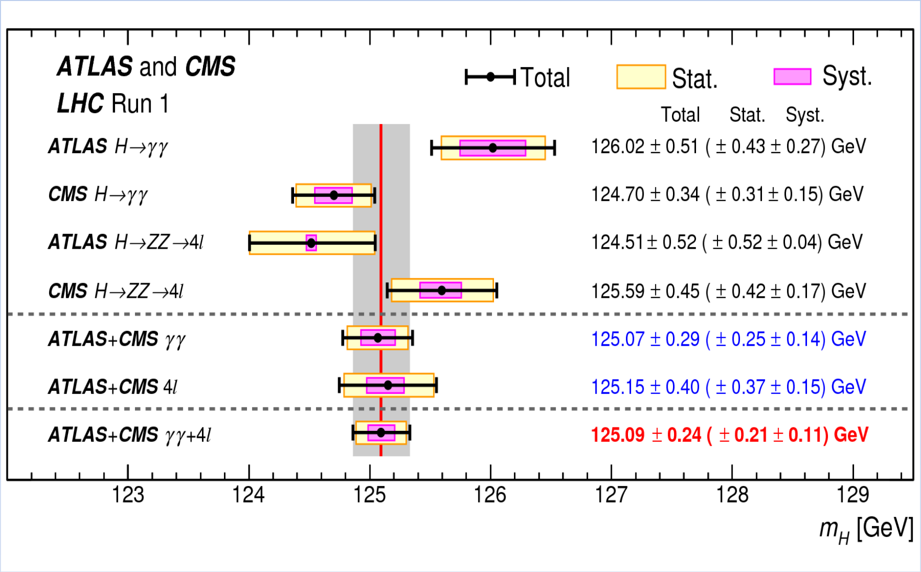


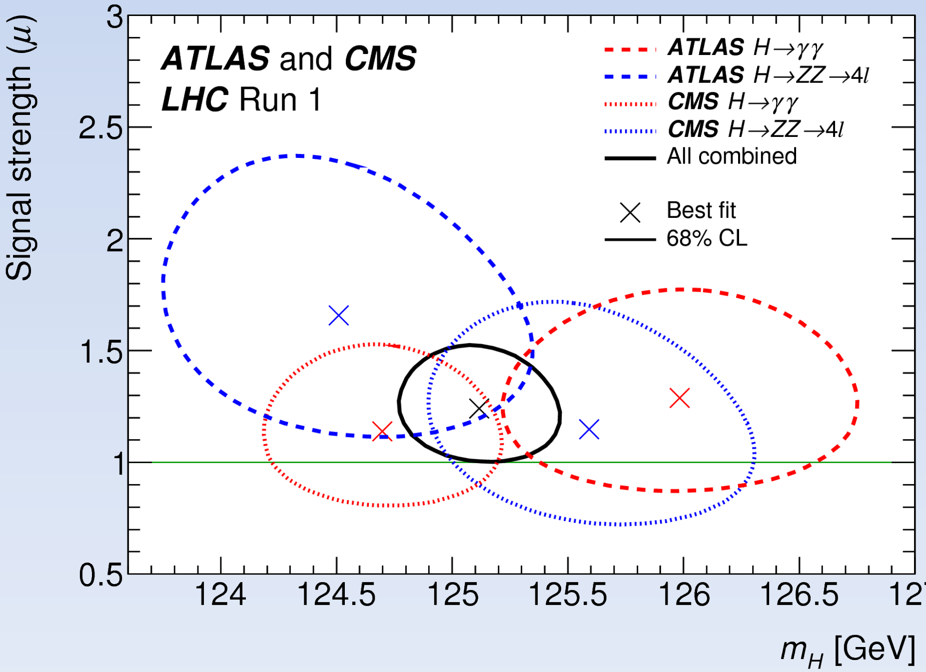


2015



Combined Measurement of the Higgs Boson Mass





Statistical Treatment

$$\Lambda(\vec{\alpha}) = \frac{L(\vec{\alpha}, \hat{\hat{\vec{\theta}}}(\vec{\alpha}))}{L(\hat{\vec{\alpha}}, \hat{\vec{\theta}})}$$

profile likelihood ratio

$\vec{\alpha}$ parameters of interest

$\vec{\theta}$ nuisance parameters (reflect experimental and theoretical uncertainties, ~4200 in combination)

$\hat{\vec{\alpha}}$, $\hat{\vec{\theta}}$ maximize L, $\hat{\hat{\vec{\theta}}}(\vec{\alpha})$ maximizes L for a given $\vec{\alpha}$

Systematic uncertainties correlated between experiments:

1. Signal theory uncertainties like QCD scales, UEPS, PDFs, Higgs BRs are the most important.
2. Background theory uncertainties.
3. Uncertainties related to the measurement of the integrated luminosity.

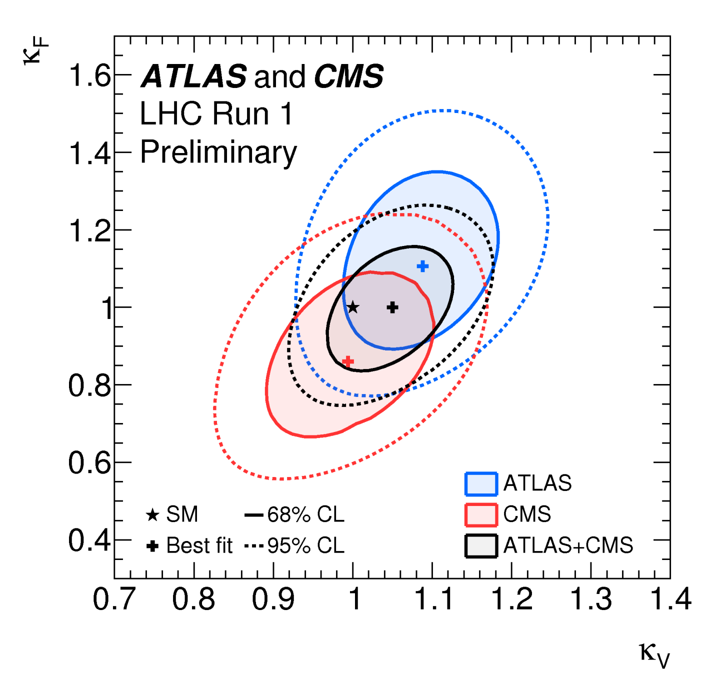
PDF uncertainties are uncorrelated between channels, except WH/ZH (correlated) and ggF/ttH (anticorrelated).

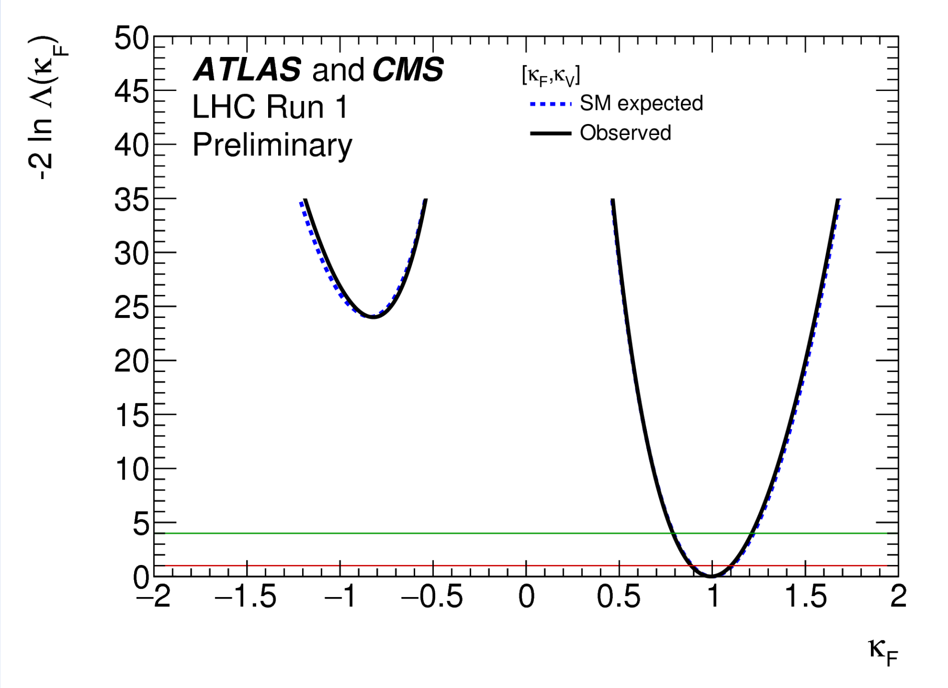
Higgs BRs correlations are negligible, except WW and ZZ modes (correlated).

Higgs couplings to fermions and bosons

SM physics in loops.
No BSM decays.
k_f , k_V ≥ 0

$k_f < 0$ strongly disfavored by the the combination





Tensor Structure. Individual channels

Coupling ratio	Best-fit value	95% CL Exclusion Regions	
$H \to ZZ^* \to 4\ell$	Observed	Expected	Observed
$\tilde{\kappa}_{HVV}/\kappa_{SM}$	-0.2	$(-\infty, -0.75] \bigcup [6.95, \infty)$	$(-\infty, -0.75] \bigcup [2.45, \infty)$
$(\tilde{\kappa}_{AVV}/\kappa_{SM}) \cdot \tan\alpha$	-0.8	$(-\infty, -2.95] \bigcup [2.95, \infty)$	$(-\infty, -2.85] \bigcup [0.95, \infty)$

Coupling ratio	Best-fit value	95% CL Exclusion Regions	
$H \to WW^* \to e\nu\mu\nu$	Observed	Expected	Observed
$\tilde{\kappa}_{HVV}/\kappa_{SM}$	-1.3	$[-1.2, -0.7]$	$(-\infty, -2.2] \bigcup [-1, -0.85] \bigcup [0.4, \infty)$
$(\tilde{\kappa}_{AVV}/\kappa_{SM}) \cdot \tan\alpha$	-0.2	n.a.	$(-\infty, -6] \bigcup [5, \infty)$