Study of the decays of the Higgs boson to boson pairs at Run-II with the ATLAS experiment

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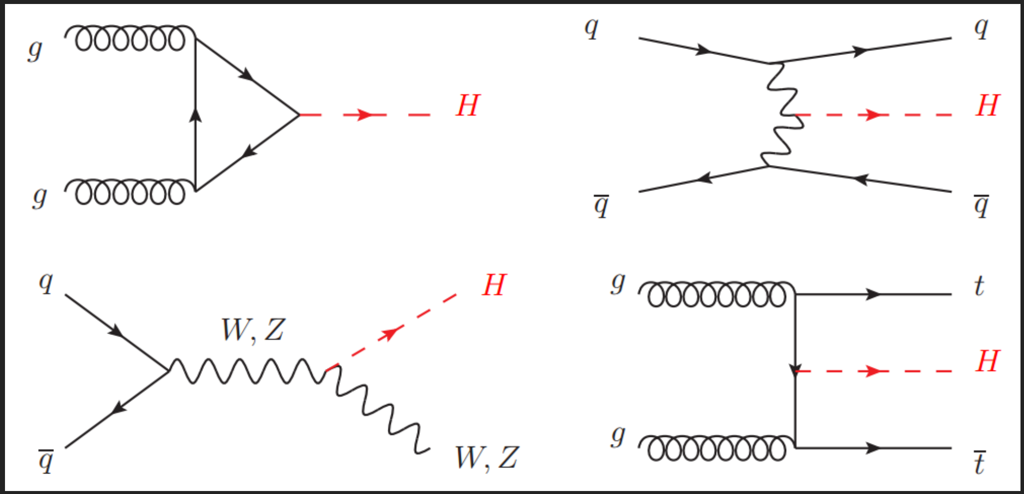
Outline

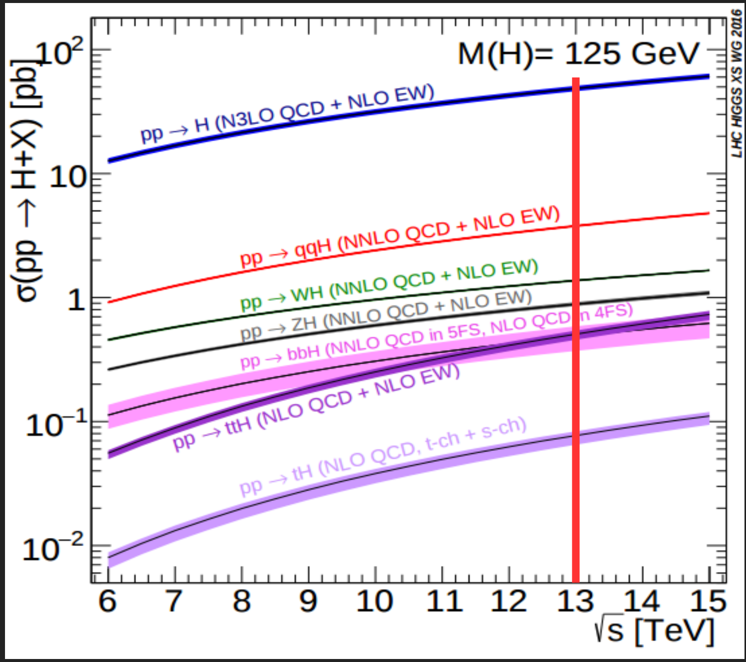
- Motivations for Higgs searches
- Run-2: summary results for Higgs decays to boson pairs
  - $H \rightarrow ZZ^{*} \rightarrow 4\ell$
  - $H \rightarrow WW^{*}$
  - $H \rightarrow \gamma\gamma$
- Combined measurements from $H \rightarrow ZZ^{*} \rightarrow 4\ell$ and $H \rightarrow \gamma\gamma$
- Recent results from CMS
- Conclusions and prospects

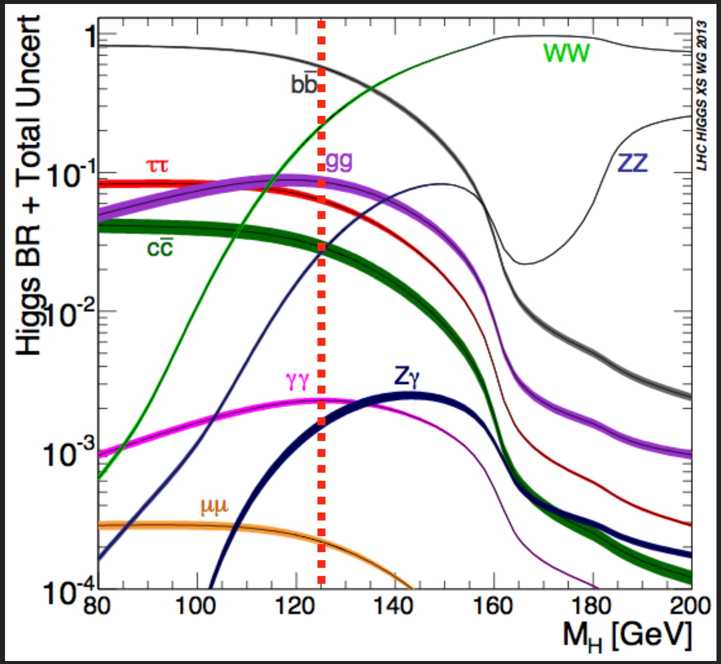
The Higgs boson at LHC

Higgs production at LHC



Production cross-sections





LHC Higgs Cross Section Working Group

Higgs branching-ratios
for vector boson decays:

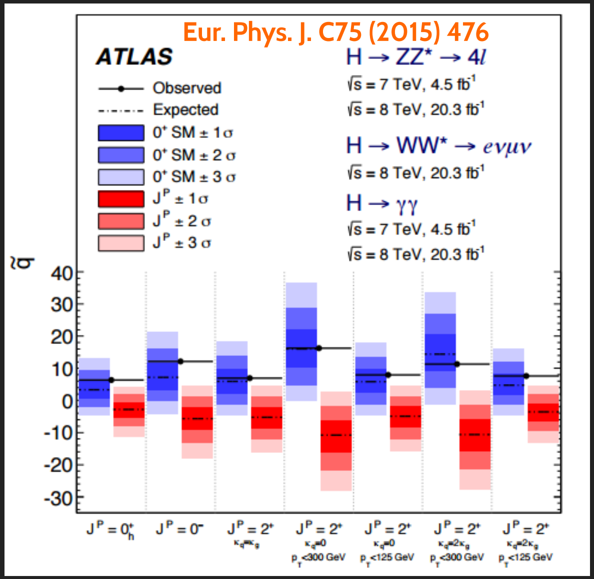
- BR(H→WW*) ~ 22%
- BR(H->ZZ*) ~ 3 %
- BR(H->γγ) ~ 0.23%

Main motivations for Higgs searches

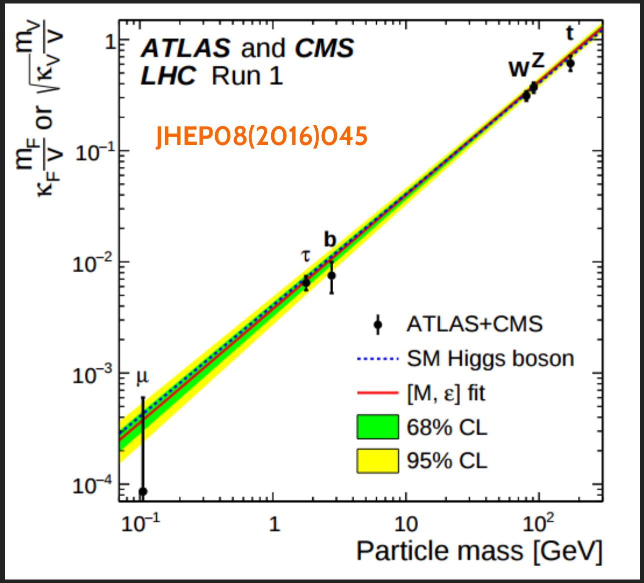
- The Higgs boson plays an important role in the SM: it provides mass to the elementary
- particles, through the electroweak spontaneous symmetry breaking (EWSB)

- It is a fantastic new tool to test the Standard Model of particle physics

- Several reasons to study the Higgs boson at 13 TeV:
  - Improving of the precision on the Higgs mass
  - Couplings with SM particles
  - Cross-section measurements
  - Spin-parity tests



Spin-parity tests



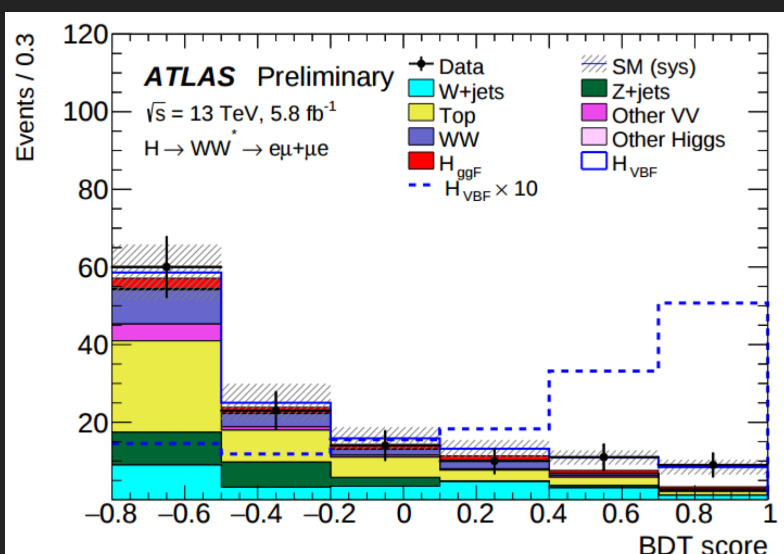
Couplings with SM particles

H→WW* (Run-2)

ATLAS-CONF-2016-112

- Integrated luminosity: 5.8 fb^{-1}
- Analysis restricted to two distinctive production modes
- Background normalizations estimated from data using CR
  CRs and SRs fit together to extract the NFs and signal strength

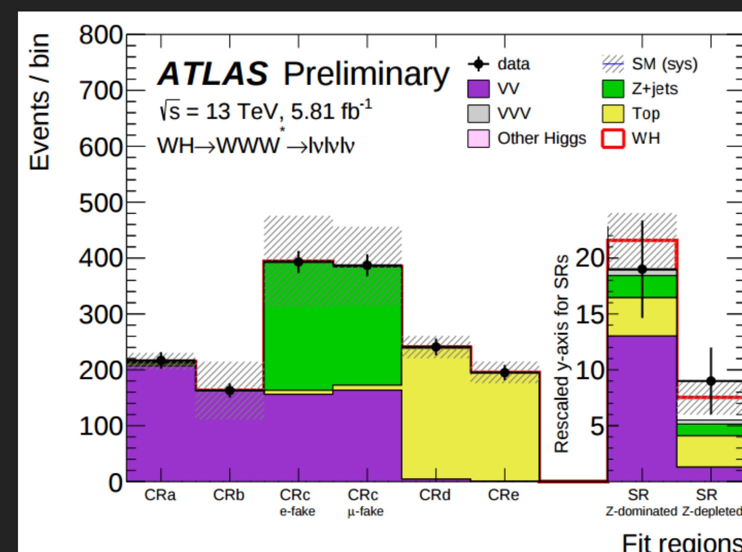
- VBF: eμ + 2 jets
- Different lepton flavours to reject Drell-Yan
- BDT used to select VBF Higgs topology



$$\mu_{\mathrm{VBF}} = 1.7^{+1.0}_{-0.8}(\mathrm{stat})^{+0.6}_{-0.4}(\mathrm{sys})$$

1.9σ (1.2σ exp)

- WH: 3ℓ events
- High MET, ≤ 1 jets
- two SR categories, split according to the presence of same flavor OS leptons



$$\mu_{WH} = 3.2^{+3.7}_{-3.2}(\mathrm{stat})^{+2.3}_{-2.7}(\mathrm{sys})$$

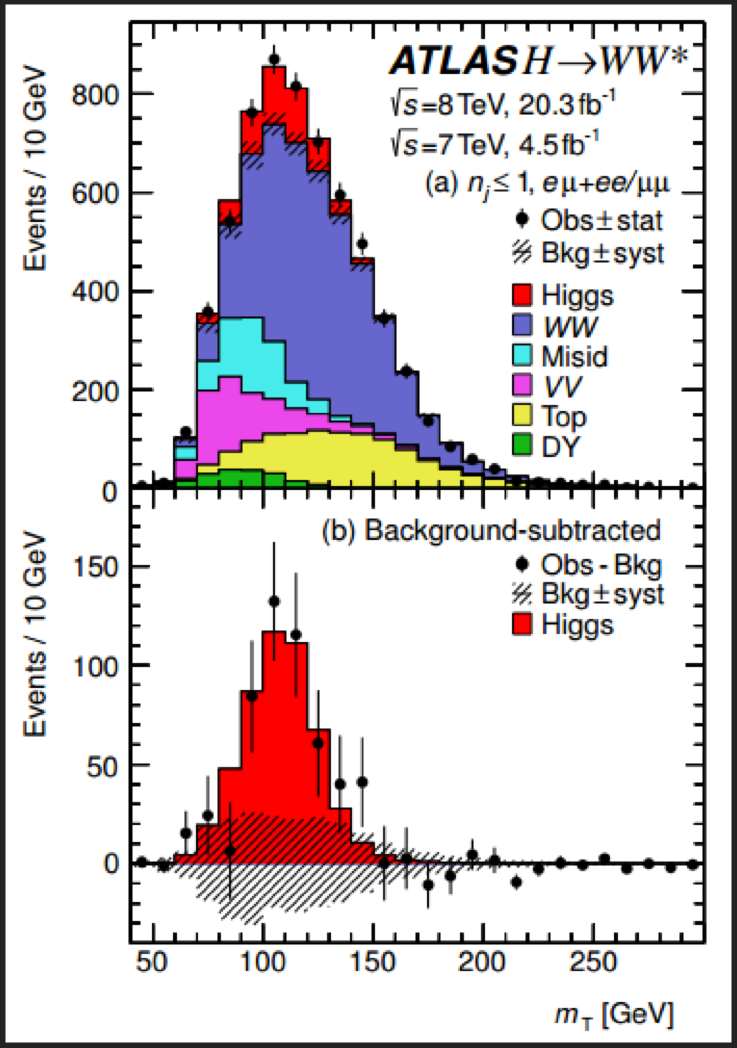
0.8σ (0.2 σ exp)

$H \to WW^*$ (Run-1)

arXiv:1412.2641v2

- Integrated luminosity: ~25 fb^{-1} (7 and 8 TeV)
- First observation of the $H \to WW^*$ decay (ggF, VBF)
  - Obs. (exp.) significance: 6.2 σ (5.8 σ)
- Evidence for the VBF production mode
  - Obs. significance: 3.2 σ

$$\mu = 1.09\ ^{+0.23}_{-0.21}$$
$$\mu_{\mathrm{ggF}} = 1.02\ ^{+0.29}_{-0.26}$$
$$\mu_{\mathrm{VBF}} = 1.27\ ^{+0.53}_{-0.45}$$



- Full combination among ggF, VBF, WH and ZH modes
- Obs. significance 6.5 σ
- Exp. significance 5.9 σ

H→ZZ*->4ℓ

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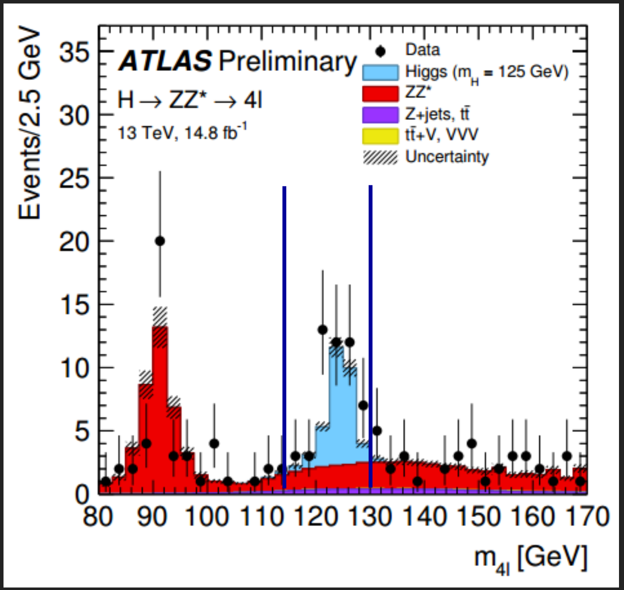
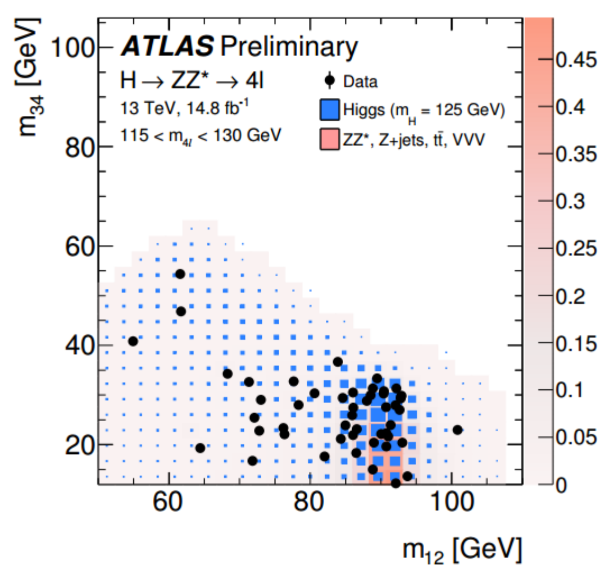
- Dataset: 14.8 fb^{-1} @ 13 TeV
- High resolution on the Higgs mass, good S/B (~2 in mass window)
- Non-resonant ZZ^* background is the only relevant background (irreducible background estimated from MC simulations)
- Fiducial cross-section extracted from events in the mass region 115 < m4ℓ < 130 GeV
- Cross-section: $\sigma^{4\ell}_{\text{fid,sum}} = 4.48^{+1.01}_{-0.89}$ fb SM: $\sigma^{4\ell}_{\text{fid,SM}} = 3.07^{+0.21}_{-0.25}$ fb
- Per decay channel:

Final state	measured σ_{fid} [fb]	$\sigma_{\text{fid,SM}}$ [fb]
4μ	$1.28\ ^{+0.48}_{-0.40}$	$0.93\ ^{+0.06}_{-0.08}$
$4e$	$0.81\ ^{+0.51}_{-0.38}$	$0.73\ ^{+0.05}_{-0.06}$
$2\mu 2e$	$1.29\ ^{+0.58}_{-0.46}$	$0.67\ ^{+0.04}_{-0.04}$
$2e2\mu$	$1.10\ ^{+0.49}_{-0.40}$	$0.76\ ^{+0.05}_{-0.06}$

$$\sigma_{tot} = \frac{N - N_B}{A \times \text{BR} \times L_{int} \times C}$$

$$\sigma_{fid} = \frac{N - N_B}{L_{int} \times C}$$





H→ZZ*->4ℓ

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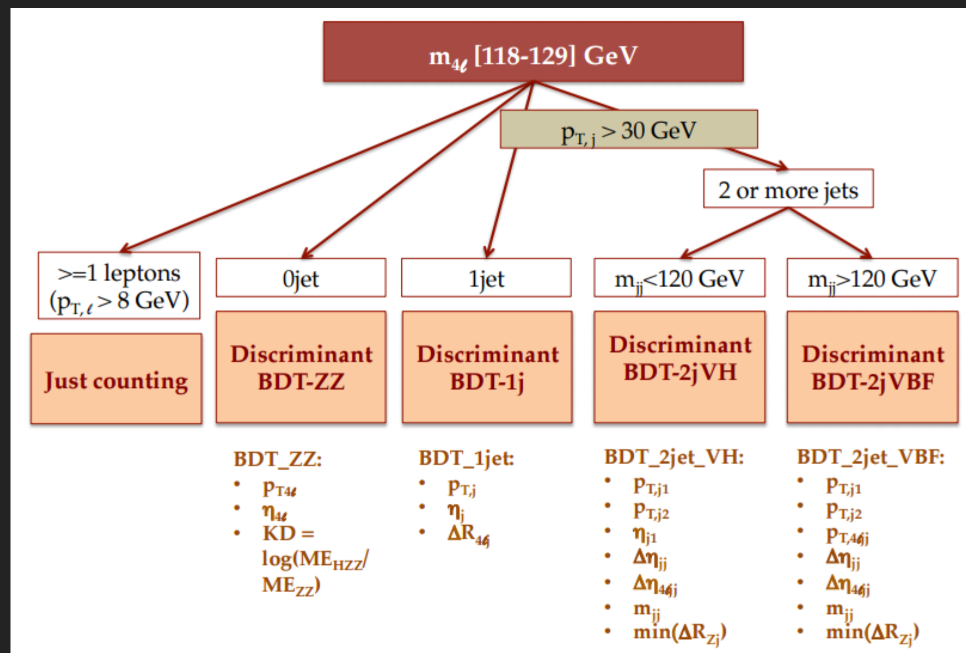
- Event categorization (based on BDTs) applied to distinguish among different production modes:



- Observed and expected cross-section times branching ratio for different production mechanisms:

$$\sigma_{\mathrm{ggF}+b\bar{b}H+t\bar{t}H} \cdot \mathcal{B}(H \to ZZ^*) = 1.80^{+0.49}_{-0.44}\ \mathrm{pb} \qquad \sigma_{\mathrm{SM,ggF}+b\bar{b}H+t\bar{t}H} \cdot \mathcal{B}(H \to ZZ^*) = 1.31 \pm 0.07\ \mathrm{pb}$$

$$\sigma_{\mathrm{VBF}} \cdot \mathcal{B}(H \to ZZ^*) = 0.37^{+0.28}_{-0.21}\ \mathrm{pb} \qquad \sigma_{\mathrm{SM,VBF}} \cdot \mathcal{B}(H \to ZZ^*) = 0.100 \pm 0.003\ \mathrm{pb}$$

$$\sigma_{\mathrm{VH}} \cdot \mathcal{B}(H \to ZZ^*) = 0^{+0.15}\ \mathrm{pb} \qquad \sigma_{\mathrm{SM,VH}} \cdot \mathcal{B}(H \to ZZ^*) = 0.059 \pm 0.002\ \mathrm{pb}$$

H->γγ

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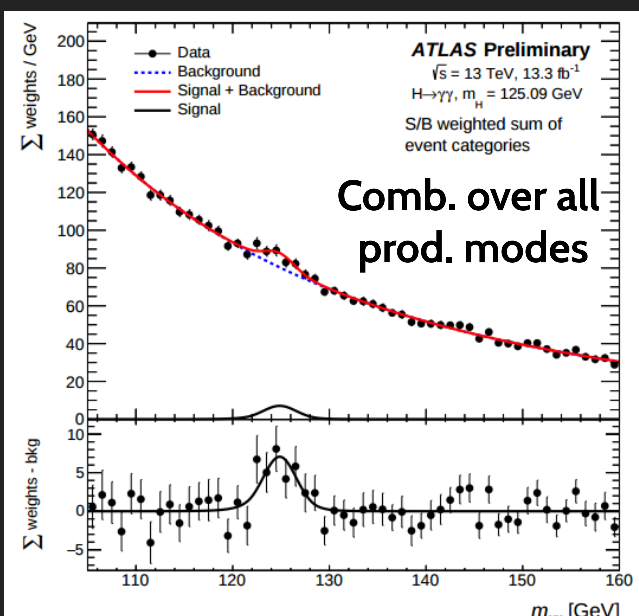
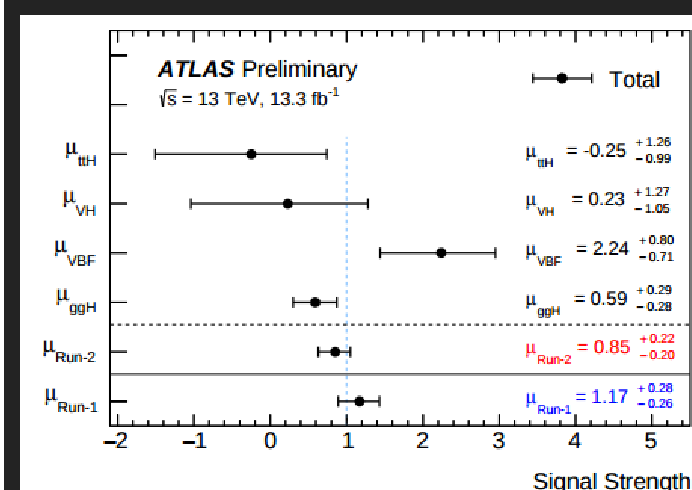
- Dataset: 13.3 fb^{-1} @ 13 TeV

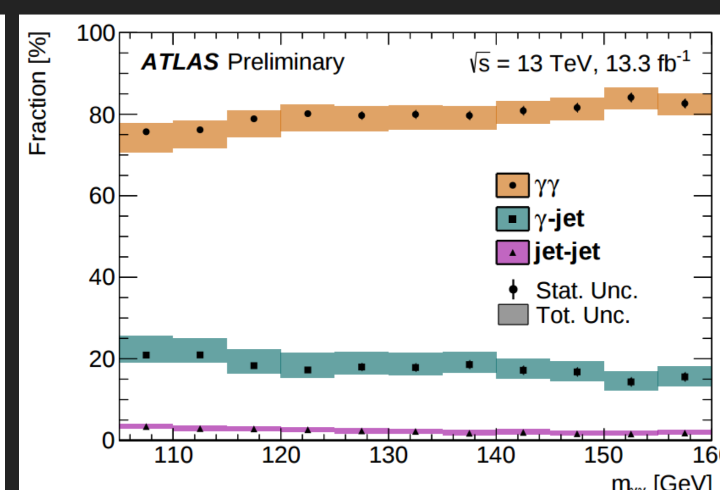
- Clean experimental signature and good invariant mass resolution
- Search performed exploiting all production mode categories
- Signal yield extracted from a simultaneous signal+background fit of the $m_{\gamma\gamma}$ distribution
- The non-resonant di-photon continuum background (γγ, γj, jj) is estimated directly from data using dedicated Control Regions (reversing isolation and ID requirements of the photons)
- Signal strength: μ = 0.85 ± 0.22 (obs. 4.7σ, exp. 5.4)
- Compatible with Run-1 value of μ = 1.17 ± 0.28

$$\sigma_{\text{fid}} = 43.2 \pm 14.9\,(\text{stat.}) \pm 4.9\,(\text{syst.})$$

$$\sigma_{\text{fid,SM}} = 62.8\,^{+3.4}_{-4.4}\ \text{fb}$$



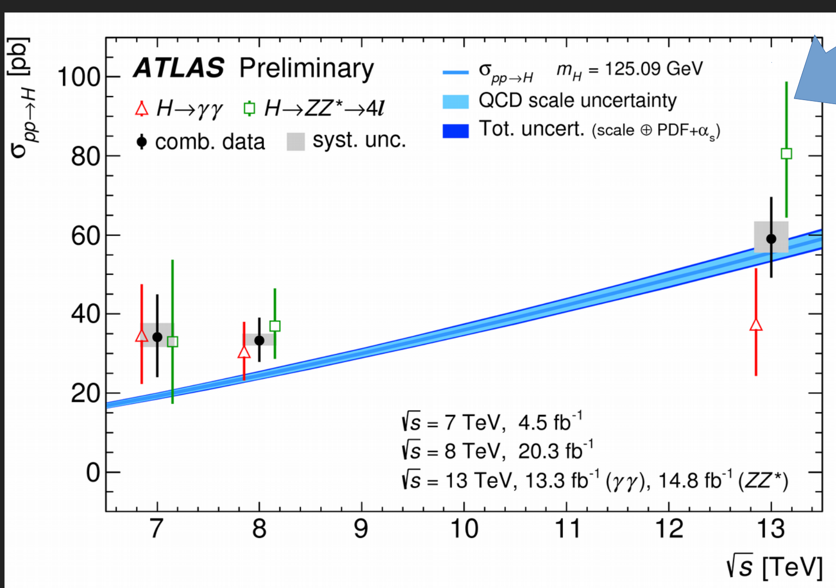




$H \to ZZ^* \to 4\ell$ and $H \to \gamma\gamma$ combination

ATLAS-CONF-2016-081

- Full combination @ 13 TeV: 13.3 fb^{-1} for $H \to \gamma\gamma$ and 14.8 fb^{-1} for $H \to ZZ^* \to 4\ell$
- Total cross-section measurement: no attempt is made to disentangle the different Higgs boson production modes
- Global signal strength: $\mu = 1.13 \pm 0.18$
  - Higgs confirmed @ 13 TeV !



Total pp → H+X cross sections measured at different centre-of-mass energies compared to Standard Model predictions at up to N3LO in QCD

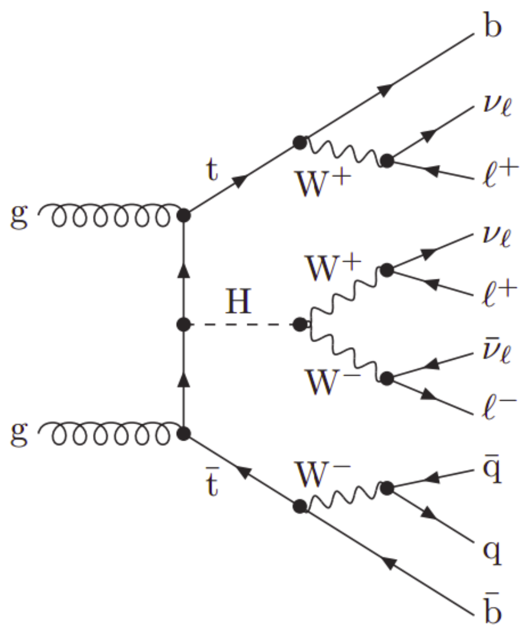
Decay channel	Total cross section ($pp \to H + X$) $\sqrt{s}$ =7 TeV	$\sqrt{s}$ =8 TeV	$\sqrt{s}$ =13 TeV
$H \to \gamma\gamma$	35^{+13}_{-12} pb	$30.5^{+7.5}_{-7.4}$ pb	37^{+14}_{-13} pb
$H \to ZZ^* \to 4\ell$	33^{+21}_{-16} pb	37^{+9}_{-8} pb	81^{+18}_{-16} pb
Combination	34 ± 10 (stat.) $^{+4}_{-2}$ (syst.) pb	$33.3^{+5.5}_{-5.3}$ (stat.) $^{+1.7}_{-1.3}$ (syst.) pb	$59.0^{+9.7}_{-9.2}$ (stat.) $^{+4.4}_{-3.5}$ (syst.) pb
SM predictions [7]	19.2 ± 0.9 pb	24.5 ± 1.1 pb	$55.5^{+2.4}_{-3.4}$ pb

ttH in multilepton final states

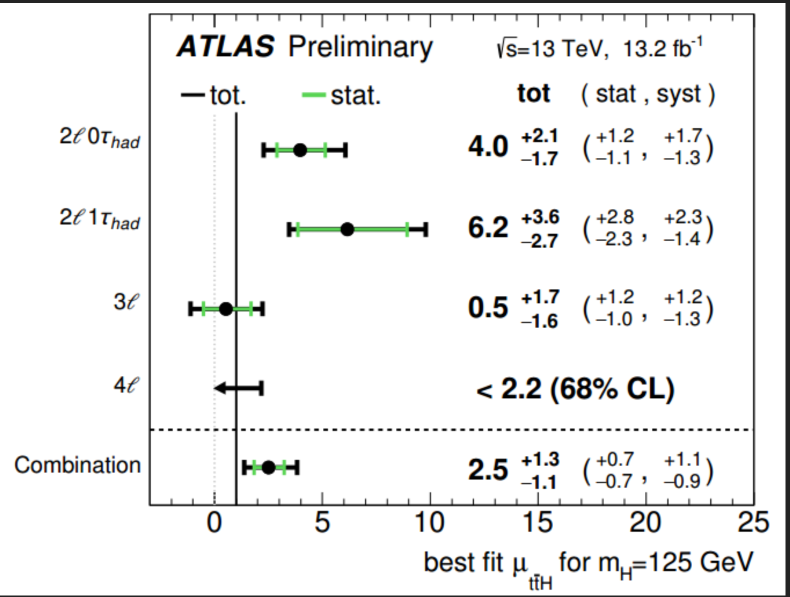
ATLAS-CONF-2016-058

- ttH channels sensitive to H-Top Yukawa coupling
- Benefit at 13 TeV: σ (13 TeV) = 3.9 x σ (8 TeV)
- Results already limited by the systematic uncertainties!
- Several signal regions, according to the lepton multiplicity and flavour composition
- Multilepton final states ensure small background
- Sensitive to additional tt+W/Z backgrounds (very hard to control with data)
- Obs. significance: 2.2 σ

See S. Biondi's talk



	4l	3l	1l2tau	ee5j	em5j	mm5j
$H \to WW$	72%	74%	46%	76%	77%	79%
$H \to ZZ$	9%	4%	2%	2%	3%	3%
$H \to \tau\tau$	18%	20%	51%	17%	17%	17%
$H \to bb$	< 1%	1%	1%	4%	3%	1%
$H \to \mu\mu$	2%	1%	< 1%	< 1%	< 1%	< 1%
$H \to other$	< 1%	< 1%	< 1%	< 1%	< 1%	< 1%

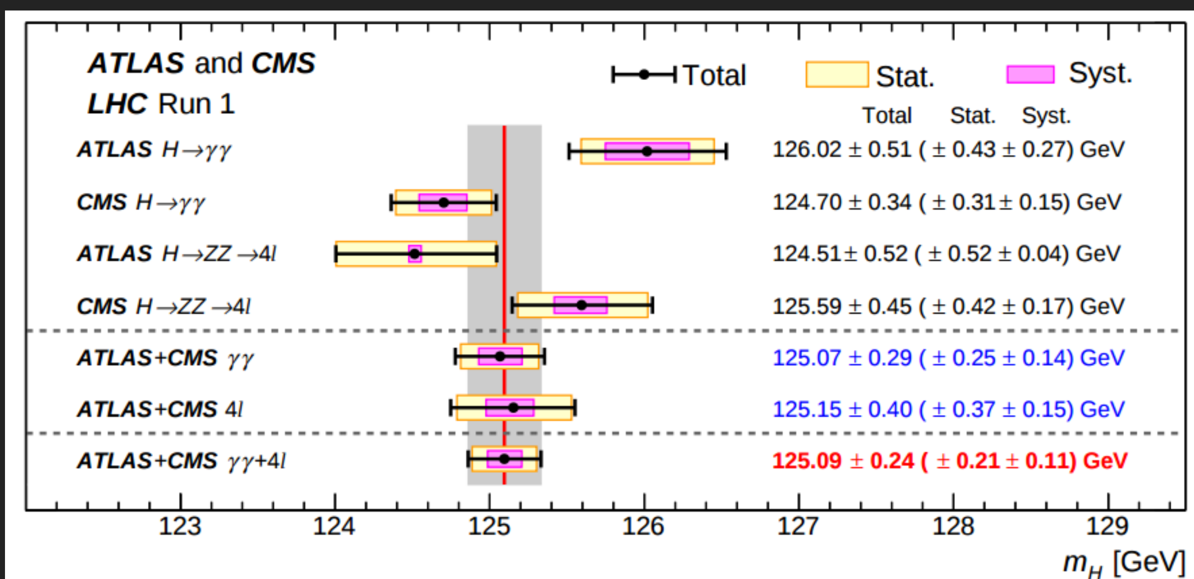


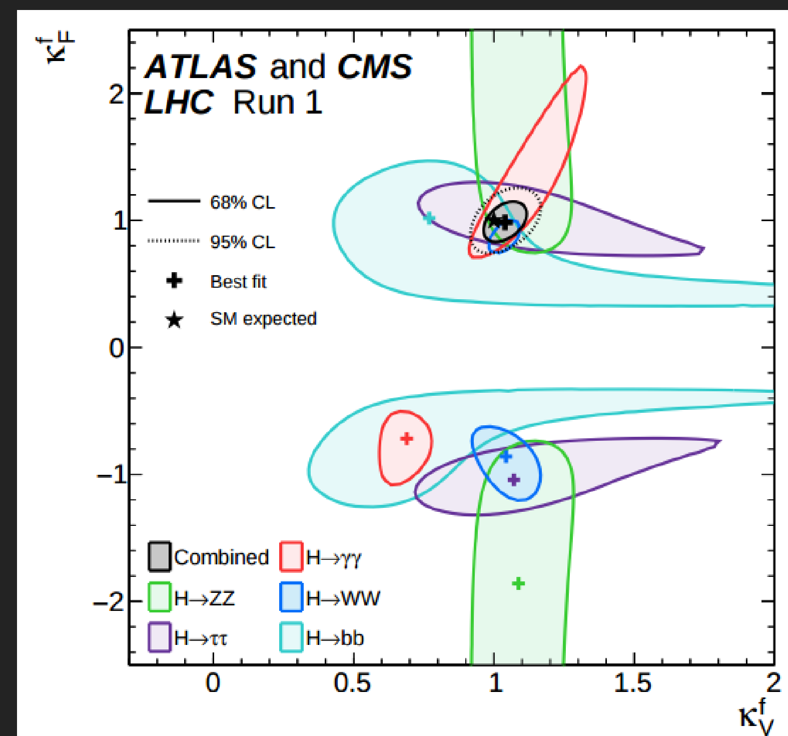
Run-1: mass and couplings

- Run-1 gave us one of the biggest discoveries in HEP
- The best available measurements on Higgs mass and couplings come from ATLAS+CMS Run-1 combination
- Mass measurement: combination of H→γγ and H→ZZ*→4l
  - Dominant sources of systematic uncertainty from calibrations, energy scale and energy resolution
- Vector and fermion coupling modifiers have been tested using different Higgs decays modes
  - Measurements in good agreement with the SM prediction

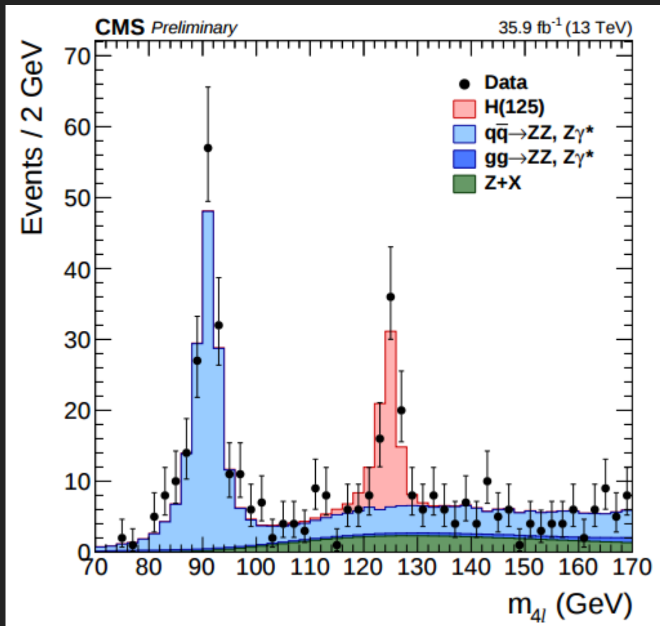
PhysRevLett.114.191803

JHEP08(2016)045

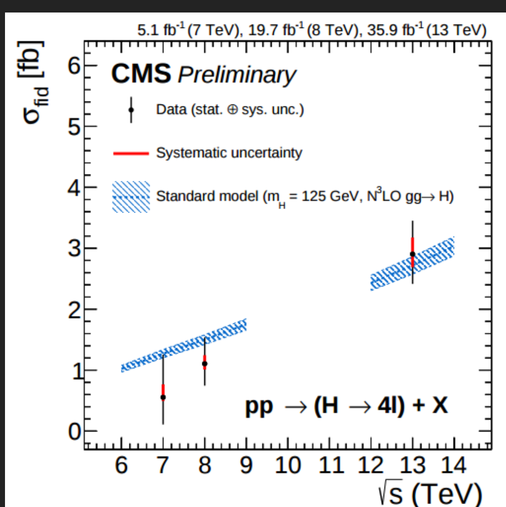


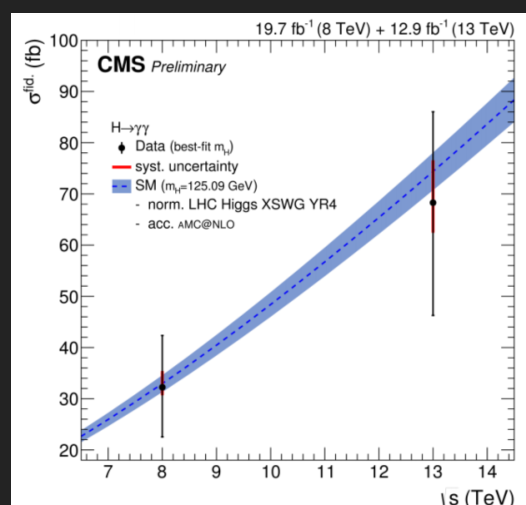


Summary from CMS



- 4-lepton analysis with ~ 36 fb^{-1} at 13 TeV
- Events classified into mutually exclusive categories, related to the production mechanisms
- Combination: $\mu = 1.05^{+0.19}_{-0.17} = 1.05^{+0.15}_{-0.14}(\text{stat.})^{+0.11}_{-0.09}(\text{sys.})$
- New mass measurement presented by CMS collaboration at Moriond EW 2017
- $m_H = 125.26 \pm 0.20\ (\text{stat.}) \pm 0.08\ (\text{syst.})$ GeV
  - Syst. unc. mainly dominated by lepton momentum scale





CMS PAS HIG-16-020

CMS PAS HIG-16-041

- Measurement of the fiducial cross sections at 7, 8 and 13 TeV, using $H\to ZZ^*\to 4l$ and $H\to\gamma\gamma$ channels

Conclusions and prospects

- Run-2 data used to study h(125) production and improve our understanding of the Standard Model
- Higgs decays to vector bosons used for precision tests on production rates, mass and coupling measurements
- The direct measurement of the Higgs coupling to Top quark (ttH) is one of the main challenges for ATLAS Run-2
- New results expected for the summer conferences with ~ 36 fb^{-1}
  - Don't forget about H→fermions and BSM Higgs results !

Back-up slides

H→WW* (VBF)

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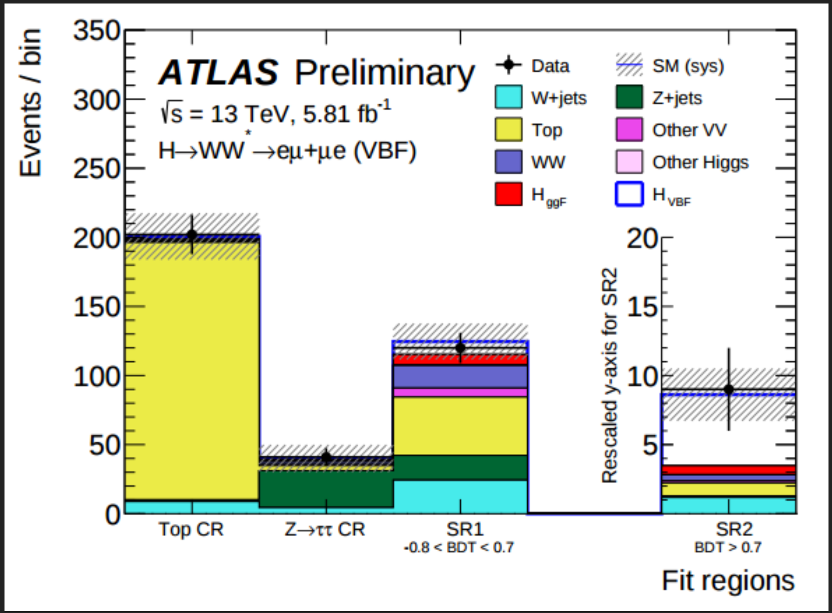
Category	SR1	SR2	Top CR	Z+jets CR
VBF	9.3 ± 3.6	5.1 ± 1.8	1.7 ± 0.6	1.1 ± 0.4
Other Higgs	8.0 ± 4.0	0.7 ± 0.4	1.1 ± 0.2	1.2 ± 0.0
WW	13.0 ± 8.0	0.4 ± 0.2	1.4 ± 0.5	2.0 ± 0.9
Other *VV*	6.6 ± 2.6	0.2 ± 0.1	0.2 ± 0.0	0.8 ± 0.2
Top quark	42.2 ± 7.6	0.9 ± 0.7	186 ± 17	3.6 ± 1.6
W+jets	24.3 ± 9.2	1.2 ± 0.7	8.8 ± 4.0	4.4 ± 2.2
Z+jets	18.0 ± 9.9	0.1 ± 0.1	1.3 ± 1.0	27 ± 10
Total background	115 ± 13	3.5 ± 1.9	199 ± 17	38.8 ± 9.8
Observed	120	9	202	41



H→WW* systematics (VBF and WH)

ATLAS-CONF-2016-112

Source	$\Delta\mu_{\mathrm{VBF}}/\mu_{\mathrm{VBF}}$ [%]
Statistical	+60 / -50
Fake factor, sample composition	+18 / -15
MC statistical	±15
VBF generator	+14 / -5
WW generator	+11 / -7
QCD scale for ggF signal for $N_{\mathrm{jet}} \geq 3$	+8 / -7
Jet energy resolution	+8 / -7
b-tagging	+8 / -6
Pile-up	+8 / -6
QCD scale for ggF signal for $N_{\mathrm{jet}} \geq 2$	±6
JES flavour composition	+6 / -4
WW renormalisation scale	±5
Total systematic	+33 / -26
Total uncertainty	+70 / -50

Source	$\Delta\mu_{WH}/\mu_{WH}$ [%]
Statistical	+120 / -100
MC statistical	+60 / -70
Pile-up	+22 / -26
Jet energy resolution	+22 / -23
Top-quark generator	+17 / -20
b-tagging	+10 / -11
Top-quark PS/UE	+7 / -8
JES flavour comp.	+8 / -5
JES η intercalibration	+7 / -6
$WZ/W\gamma^*$ generator	+7 / -6
Top-quark QCD scales	+6 / -7
$WZ/W\gamma^*$ resum. scale	±5
Total systematic	+70 / -80
Total uncertainty	+140 / -130

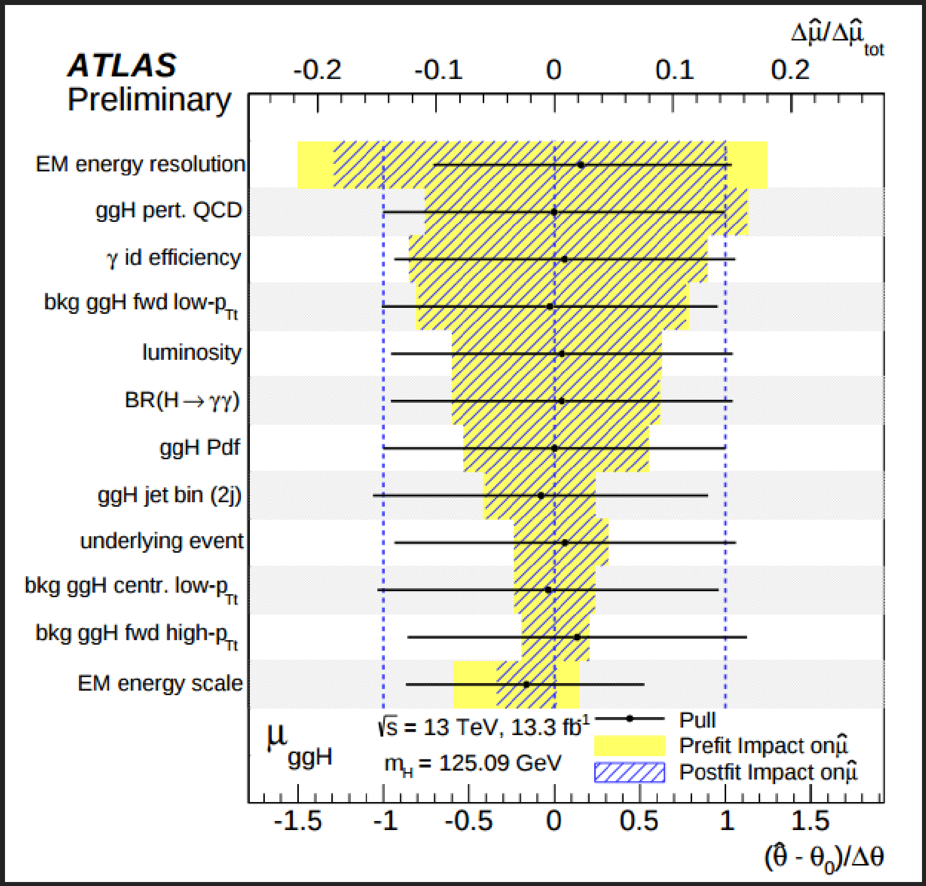
$H \to ZZ \to 4\ell$ (SR selections)

ATLAS-CONF-2016-079

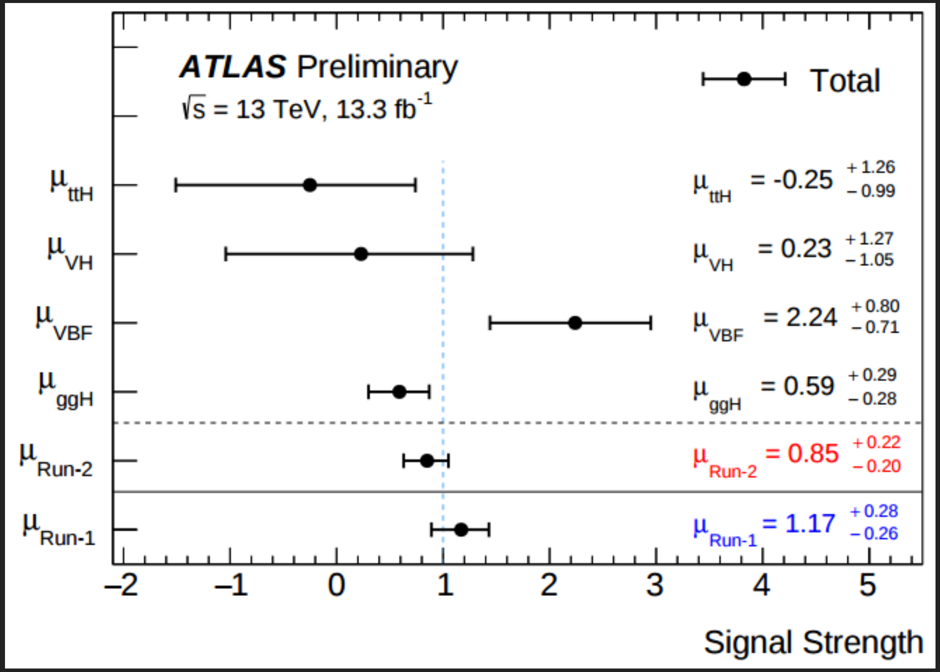
Lepton definition	
Muons: $p_T > 5$ GeV, $\|\eta\| < 2.7$	Electrons: $p_T > 7$ GeV, $\|\eta\| < 2.47$
Pairing	
Leading pair:	SFOS lepton pair with smallest $\|m_Z - m_{\ell\ell}\|$
Sub-leading pair:	Remaining SFOS lepton pair with smallest $\|m_Z - m_{\ell\ell}\|$
Event selection	
Lepton kinematics:	Leading leptons $p_T > 20, 15, 10$ 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:	$115 < m_{4\ell} < 130$ GeV

H→γγ

ATLAS-CONF-2016-067

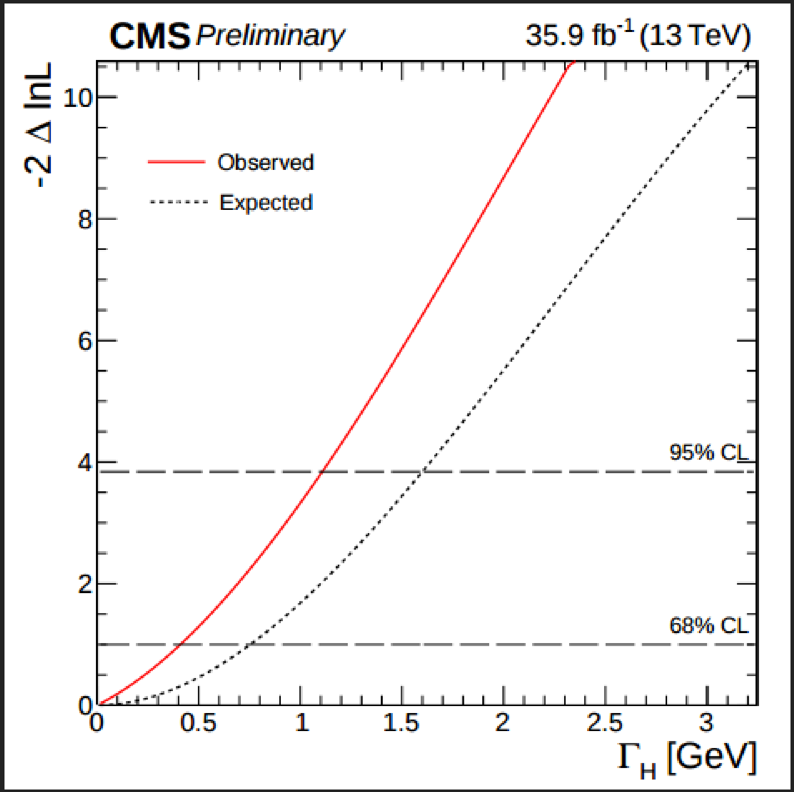


ggF systematic



Higgs boson width (CMS)

CMS PAS HIG-16-041



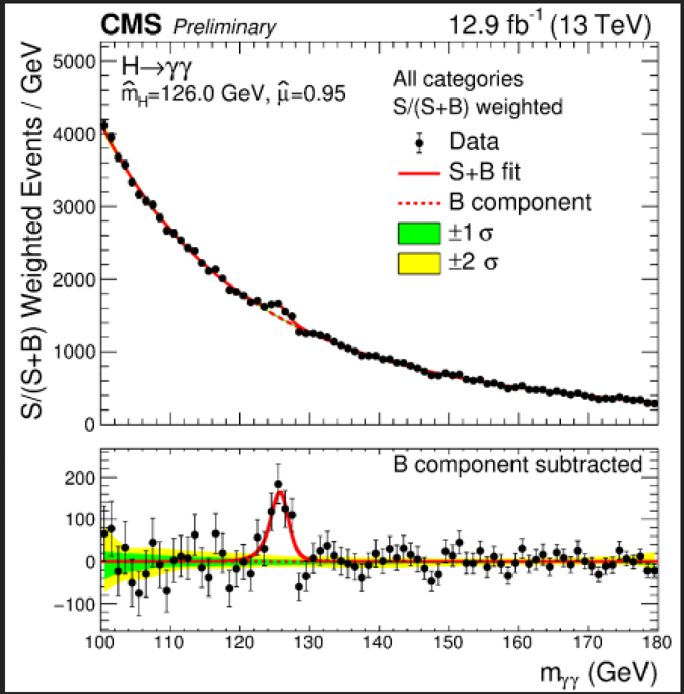
- Measurement of the Higgs boson width using on-shell production in the range $105 < m_{4l} < 140$ GeV

Parameter	$m_{4\ell}$ range	Expected	Observed
Γ_H (GeV)	[105, 140]	$0.00^{+0.75}_{-0.00}$ [0.00, 1.60]	$0.00^{+0.41}_{-0.00}$ [0.00, 1.10]

- Main uncertainty from the four-lepton mass resolution
- $\Gamma_H < 1.10$ GeV at 95% C.L.

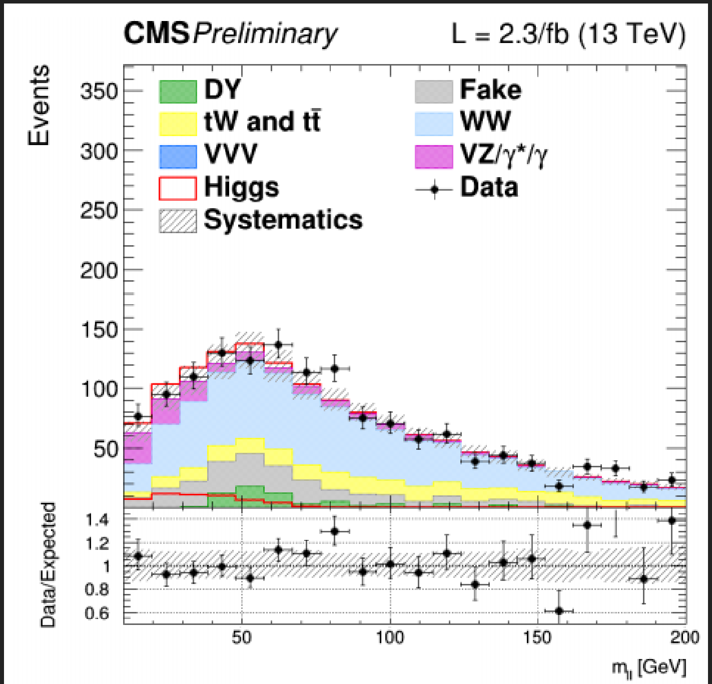
H→γγ and H→WW* (CMS)

CMS PAS HIG-16-020



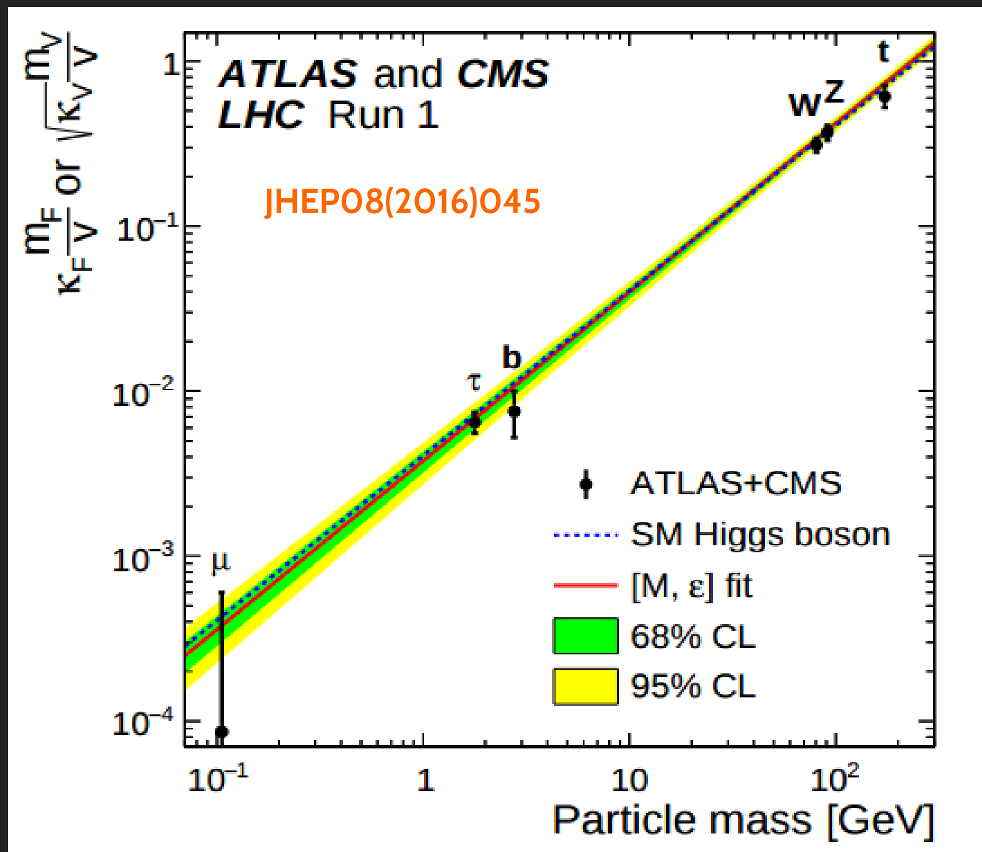
- Di-photon invariant mass spectrum
- The maximum observed significance is 6.1 σ at 126 GeV
- Best fit μ = 0.95 ± 0.20

CMS PAS HIG-15-003



- Target: ggF production, H→WW*→lνlν
- Leptons with different flavour (e and μ), 0 or 1 jet
- Integrated luminosity: 2.3 fb^{-1}
- Best fit μ = 0.3 ± 0.5
- Observed (expected) significance: 0.7 σ (2.0 σ)

Couplings with SM particles



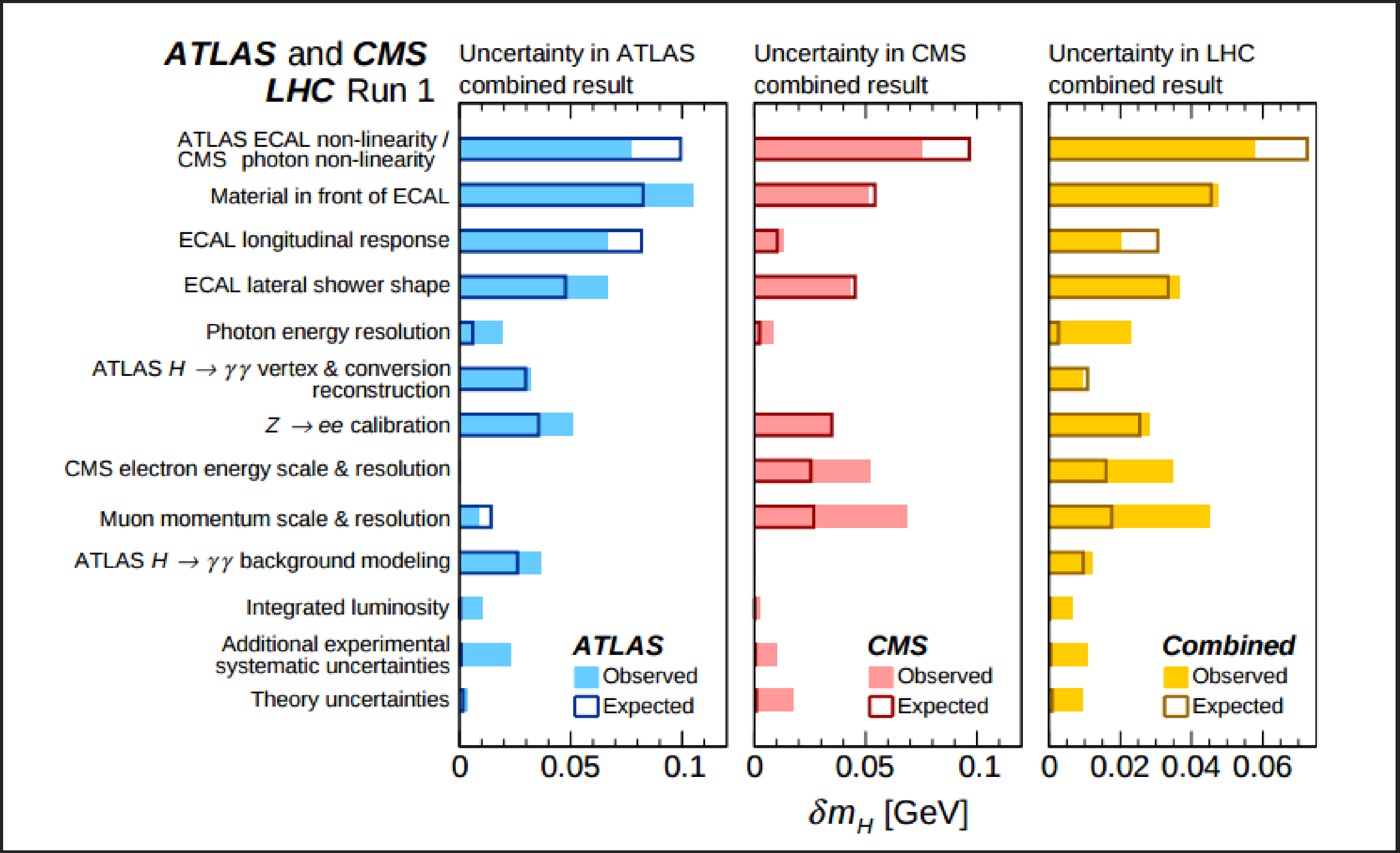
$$\boxed{g_V \sim \frac{\kappa_V \cdot m_V^2}{\nu^2}}$$

$$\boxed{\lambda_f \sim \frac{\kappa_f m_f}{\nu}}$$

- In SM, coupling of Higgs to fermions ∝ mf and for massive weak bosons ∝ mV²
- Good agreement with expectation from SM across wide particle mass range

Run-1: mass measurement

CMS-HIG-14-042
ATLAS-HIGG-2014-14



Run-1: mass measurement

CMS-HIG-14-042
ATLAS-HIGG-2014-14

	Uncertainty in ATLAS results [GeV]: observed (expected)		Uncertainty in CMS results [GeV]: observed (expected)		Uncertainty in combined result [GeV]: observed (expected)	
	$H \to \gamma\gamma$	$H \to ZZ \to 4\ell$	$H \to \gamma\gamma$	$H \to ZZ \to 4\ell$	ATLAS	CMS
Scale uncertainties:						
ATLAS ECAL non-linearity / CMS photon non-linearity	0.14 (0.16)	–	0.10 (0.13)	–	0.02 (0.04)	0.05 (0.06)
Material in front of ECAL	0.15 (0.13)	–	0.07 (0.07)	–	0.03 (0.03)	0.04 (0.03)
ECAL longitudinal response	0.12 (0.13)	–	0.02 (0.01)	–	0.02 (0.03)	0.01 (0.01)
ECAL lateral shower shape	0.09 (0.08)	–	0.06 (0.06)	–	0.02 (0.02)	0.03 (0.03)
Photon energy resolution	0.03 (0.01)	–	0.01 (<0.01)	–	0.02 (<0.01)	<0.01 (<0.01)
ATLAS $H \to \gamma\gamma$ vertex & conversion reconstruction	0.05 (0.05)	–	–	–	0.01 (0.01)	–
$Z \to ee$ calibration	0.05 (0.04)	0.03 (0.02)	0.05 (0.05)	–	0.02 (0.01)	0.02 (0.02)
CMS electron energy scale & resolution	–	–	–	0.12 (0.09)	–	0.03 (0.02)
Muon momentum scale & resolution	–	0.03 (0.04)	–	0.11 (0.10)	<0.01 (0.01)	0.05 (0.02)
Other uncertainties:						
ATLAS $H \to \gamma\gamma$ background modeling	0.04 (0.03)	–	–	–	0.01 (0.01)	–
Integrated luminosity	0.01 (<0.01)	<0.01 (<0.01)	0.01 (<0.01)	<0.01 (<0.01)	0.01 (<0.01)	
Additional experimental systematic uncertainties	0.03 (<0.01)	<0.01 (<0.01)	0.02 (<0.01)	0.01 (<0.01)	0.01 (<0.01)	0.01 (<0.01)
Theory uncertainties	<0.01 (<0.01)	<0.01 (<0.01)	0.02 (<0.01)	<0.01 (<0.01)	0.01 (<0.01)	
Systematic uncertainty (sum in quadrature)	0.27 (0.27)	0.04 (0.04)	0.15 (0.17)	0.16 (0.13)	0.11 (0.10)	
Systematic uncertainty (nominal)	0.27 (0.27)	0.04 (0.05)	0.15 (0.17)	0.17 (0.14)	0.11 (0.10)	
Statistical uncertainty	0.43 (0.45)	0.52 (0.66)	0.31 (0.32)	0.42 (0.57)	0.21 (0.22)	
Total uncertainty	0.51 (0.52)	0.52 (0.66)	0.34 (0.36)	0.45 (0.59)	0.24 (0.24)	
Analysis weights	19% (22%)	18% (14%)	40% (46%)	23% (17%)	–	