Determination of the Higgs boson properties with the ATLAS detector.

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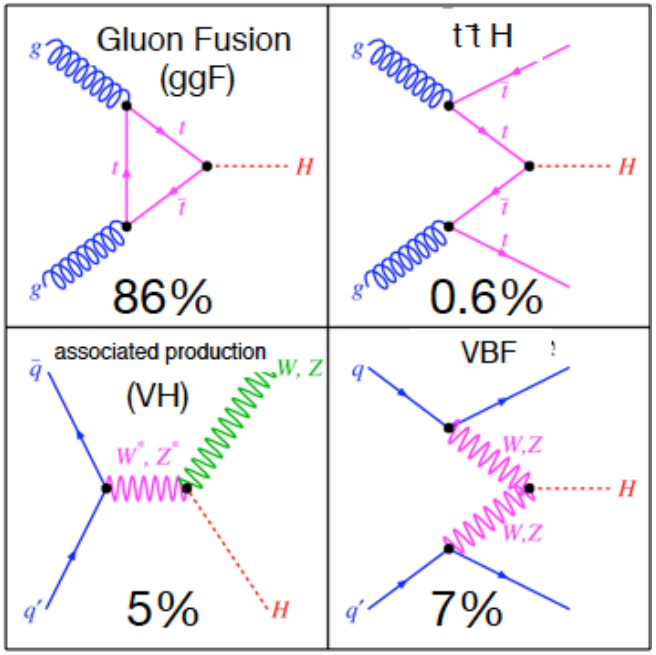
On behalf of the ATLAS Collaboration

ICHEP 2016, August 4th, Higgs parallel session

SM Higgs boson production @ LHC

Run 2 data brings more sensitivity to SM Higgs boson physics

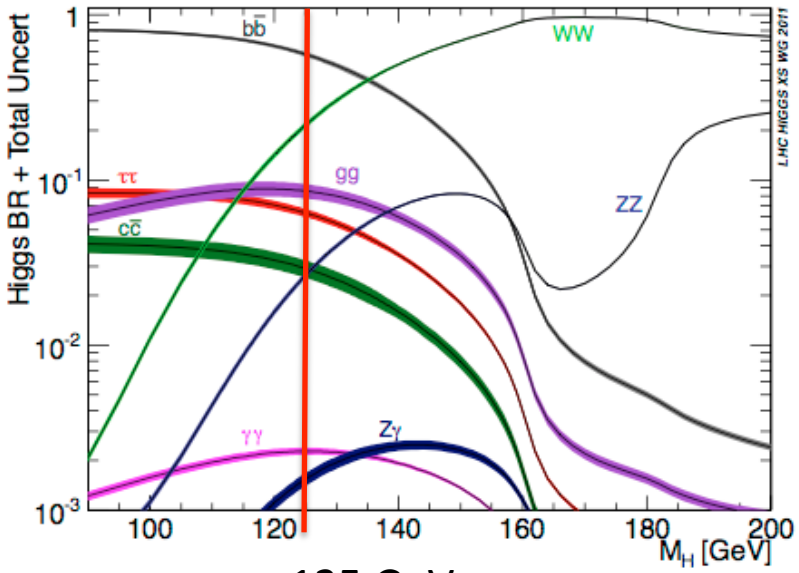
$\sqrt{s}$	SM Higgs boson theoretical production cross-section in pb^{-1} for $m_H = 125\ GeV$					
	ggF	VBF	WH	ZH	ttH	Total
7 TeV	$16.85^{+5.5\%}_{-7.7\%}$	$1.24^{+2.2\%}_{-2.2\%}$	$0.58^{+2.2\%}_{-2.3\%}$	$0.34^{+3.1\%}_{-2.8\%}$	$0.09^{+5.6\%}_{-10.0\%}$	19.1
8 TeV	$21.4^{+5.4\%}_{-7.6\%}$	$1.60^{+2.2\%}_{-2.2\%}$	$0.70^{+2.1\%}_{-2.2\%}$	$0.42^{+3.4\%}_{-2.9\%}$	$0.13^{+5.9\%}_{-10.1\%}$	24.25
13 TeV	$48.58^{+5.6\%}_{-7.4\%}$	$3.78^{+2.1\%}_{-2.1\%}$	$1.37^{+2.0\%}_{-2.0\%}$	$0.88^{+4.1\%}_{-3.5\%}$	$0.51^{+6.8\%}_{-9.8\%}$	55.12



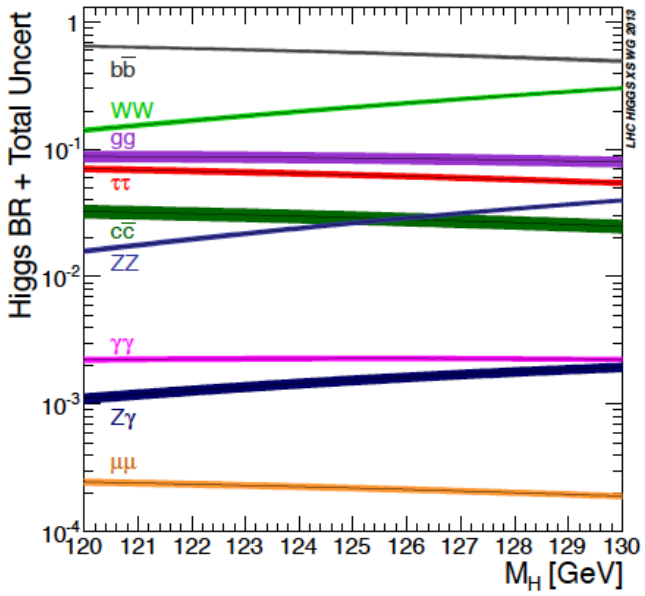
4 leading production processes with different signatures :

- Sensitive to different Higgs couplings
  - ggF, ttH : fermions (t,b)
  - VBF, VH : bosons (W,Z)
- Sub-dominant modes have cleaner final states that help improve S/B :
  - VBF : two jets with large Mjj and rapidity gap
  - WH,ZH : V boson final state (lν, ll, qq')
  - ttH : tt→WbWb, W→lν or qq' : many b-jets, l, E_T^{miss}.

SM Higgs boson decay modes



m_H ~125 GeV



Decay mode	Branching fraction [%]
$H \to bb$	57.5 ± 1.9
$H \to WW$	21.6 ± 0.9
$H \to gg$	8.56 ± 0.86
$H \to \tau\tau$	6.30 ± 0.36
$H \to cc$	2.90 ± 0.35
$H \to ZZ$	2.67 ± 0.11
$H \to \gamma\gamma$	0.228 ± 0.011
$H \to Z\gamma$	0.155 ± 0.014
$H \to \mu\mu$	0.022 ± 0.001

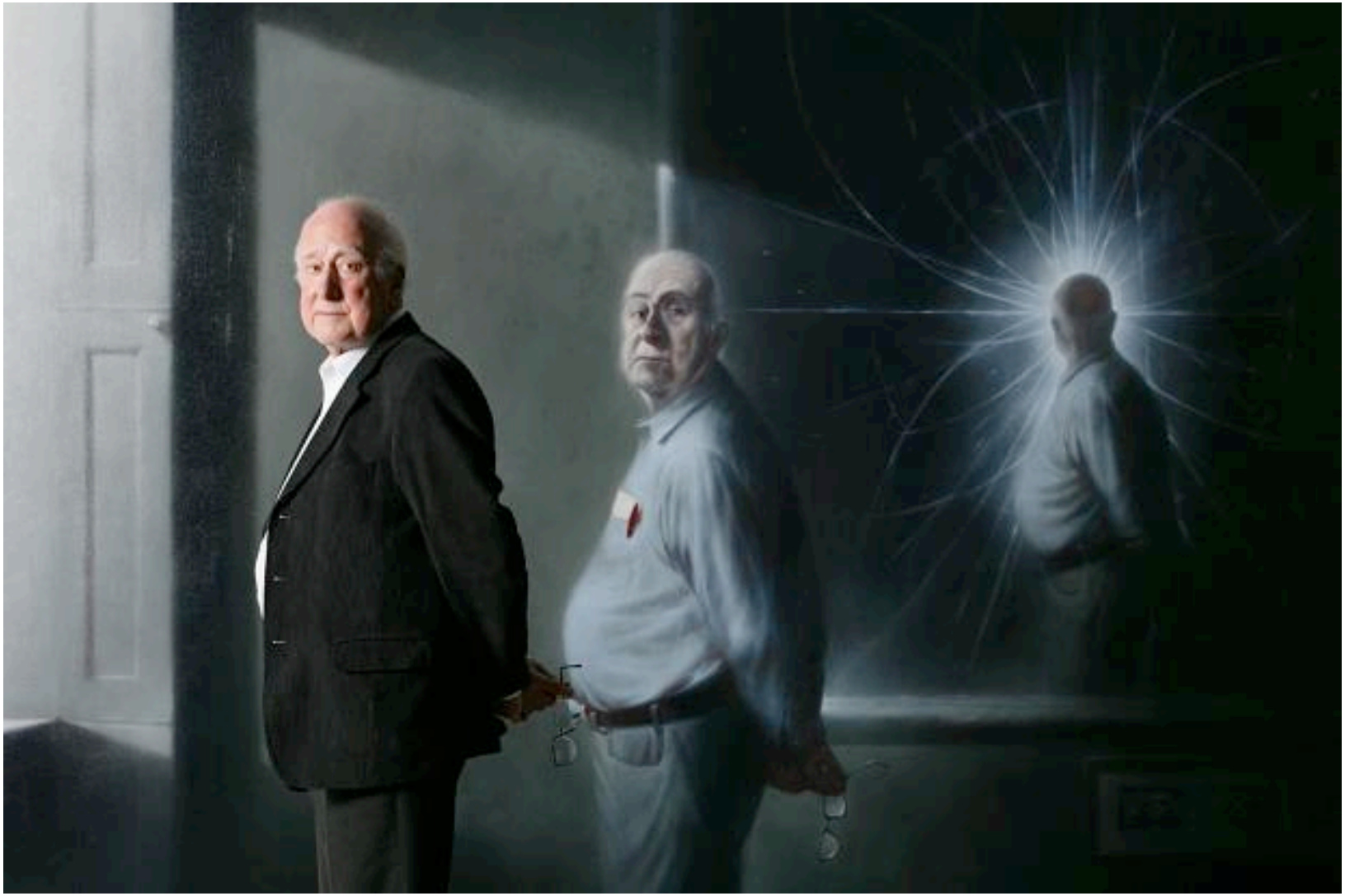
Nature is good with particle physicists :

@ 125 GeV many decays have a substantial BR

But not all of them can be isolated from bkg (cc, gg, …)

Low BR channels can have a higher S/B (γγ, 4l, …) than bb (high QCD background and lower resolution)

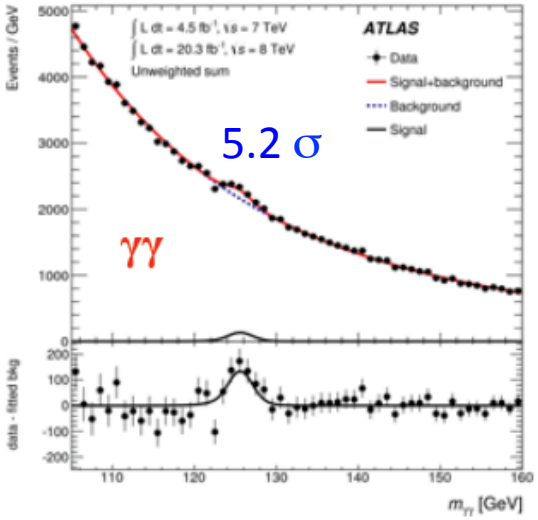
Lessons on SM Higgs @ LHC run 1



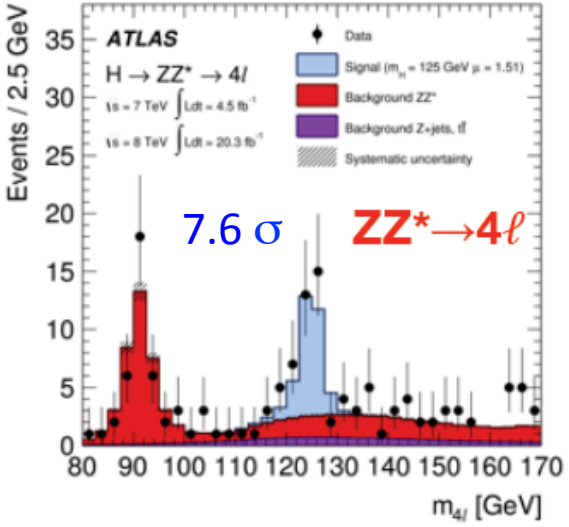
Ken Currie, 2008

“Higgs boson” also discovered in several single channels in Run 1

Phys. Rev. D90 (2014) 112015



Phys. Rev. D91 (2015) 012006



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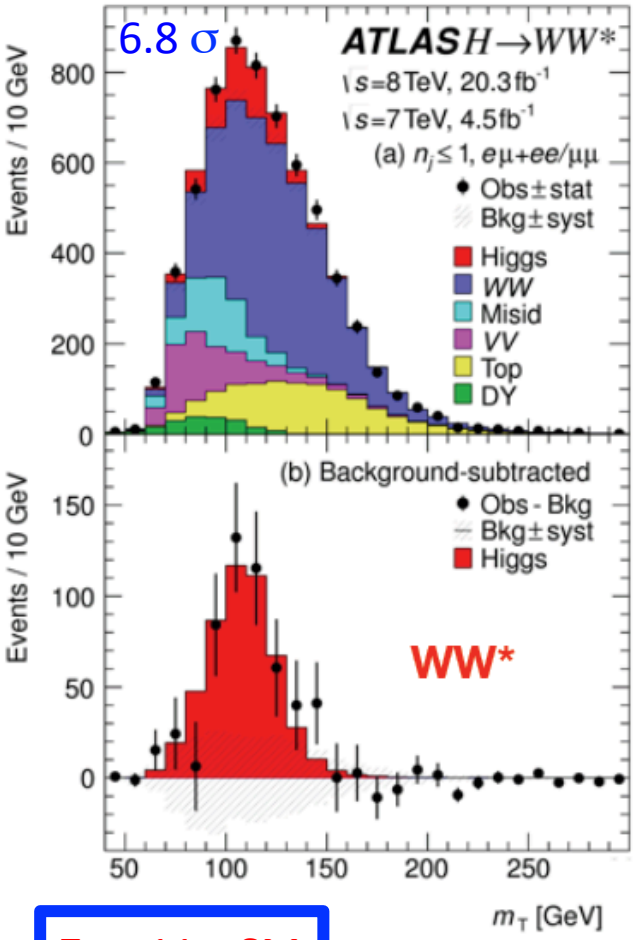
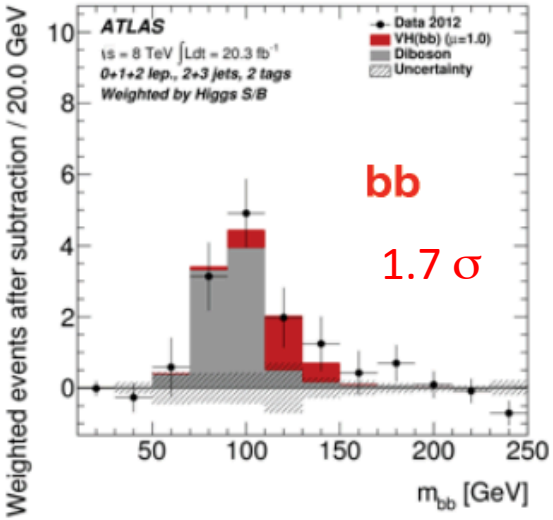
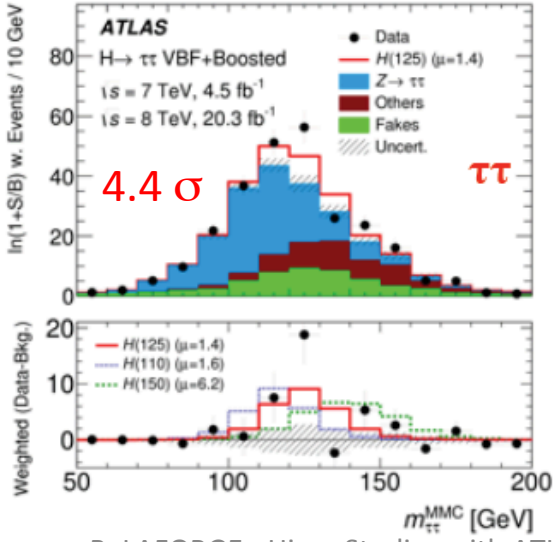


JHEP 01 (2015) 069



JHEP 04 (2015) 117



Zγ < 11 x SM

μμ < 7 x SM

Higgs Boson Properties from Run 1

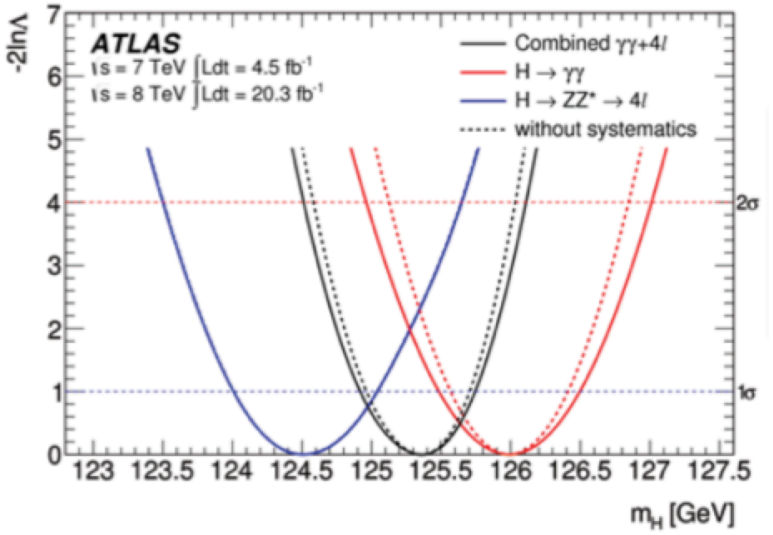
Mass : *Phys. Rev. D90 (2014) 052004*

Using H→γγ and H→ZZ→4l, ATLAS measured

m_H = 125.36 +/- 0.37+/-0.18 GeV/c^2

$$m_H = 125.09 \pm 0.21\,(\text{stat.}) \pm 0.11\,(\text{syst.})\ \text{GeV}$$

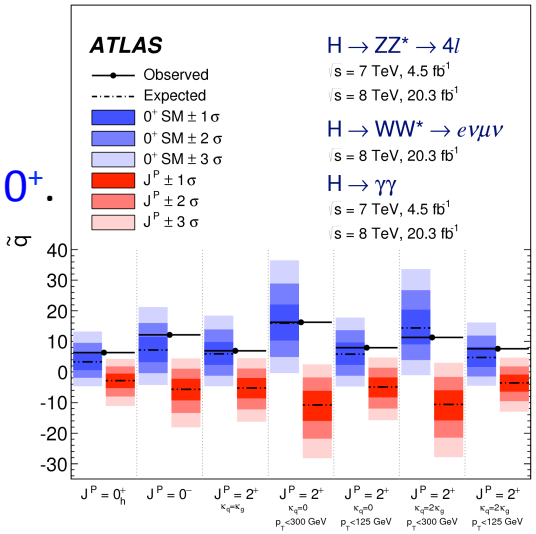
(ATLAS + CMS) Phys. Rev. Lett. 114, 191803, 2015



Once m_H is known, SM predicts the Higgs coupling to all other SM particles

Spin and CP quantum numbers: *Eur. Phys. J. C75 (2015) 476*

Using H→γγ, H→ZZ→4l, H→WW angular distributions, ATLAS tested different spin/CP hypotheses against SM model prediction 0^+.



- $Spin^{CP}$ 0^+ is very compatible with ATLAS data
- Alternative models are all rejected with more than 99.9% CL

Production and decay strengths

ATLAS analysis used several parameters known as production and decay strengths which are the ratios between actual production cross-sections or branching ratios and SM predictions:

Production (initial state) $\mu_i = \frac{\sigma_i}{(\sigma_i)_{SM}}$ and $\mu_f = \frac{BR_f}{(BR_f)_{SM}}$ Decay (final state)

Maximum profile likelihood technique is used to infer these parameters from correlation between signal rates in various channels c:

$$n_s^c = \sum_i \sum_f \mu_i (\sigma_i)_{SM} \times \mu_f (BR_f)_{SM} \times A_{if}^c \times \varepsilon_{if}^c \times \mathcal{L}^c$$

Measured Predicted Estimated

- Simplest model: one overall signal strength $\mu = \mu_i * \mu_f$
- $\mu = 1.18^{+0.15}_{-0.14}$ [±0.10 (stat) ±0.07 (syst) $^{+0.08}_{-0.07}$ (theo)] Eur. Phys. J. C (2016) 76: 6.
- systematic error dominated by background estimates; theory error due to uncertainty on SM x-sections, BRs and kinematic distributions

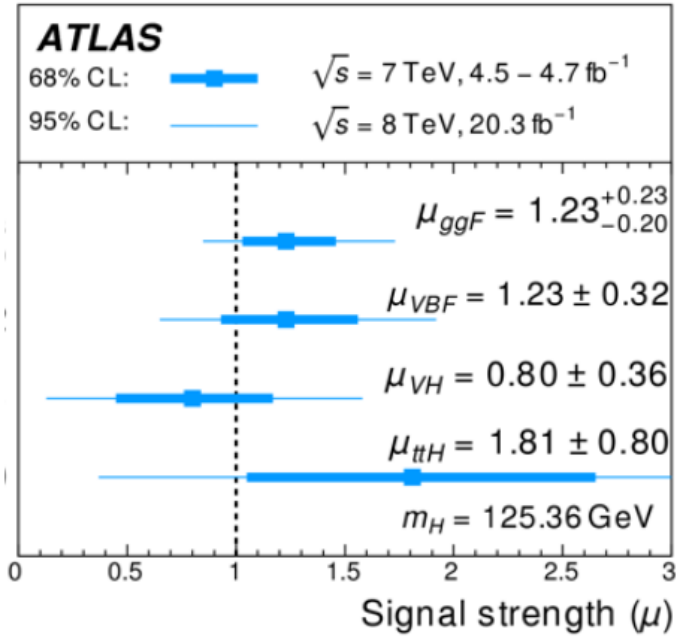
Production and decay strengths

Eur. Phys. J. C (2016) 76: 6.

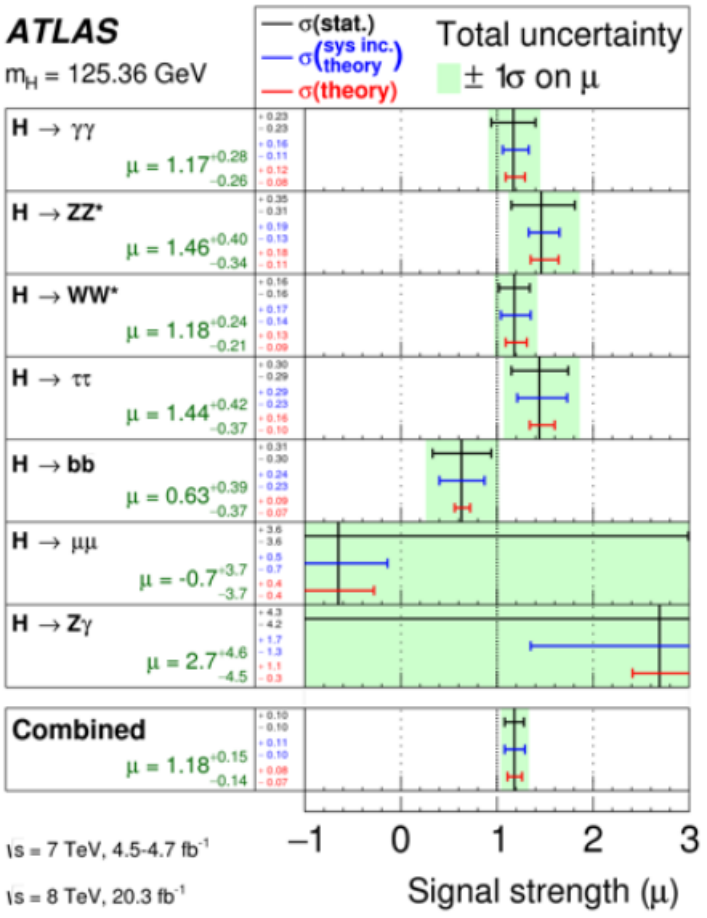
If one allows different strengths :

By production mode, assuming μ_f=1

And $\mu_{bbH}=\mu_{ggF}$, $\mu_{tH}=\mu_{ttH}$, $\mu_{WH}=\mu_{ZH}$



by decay mode

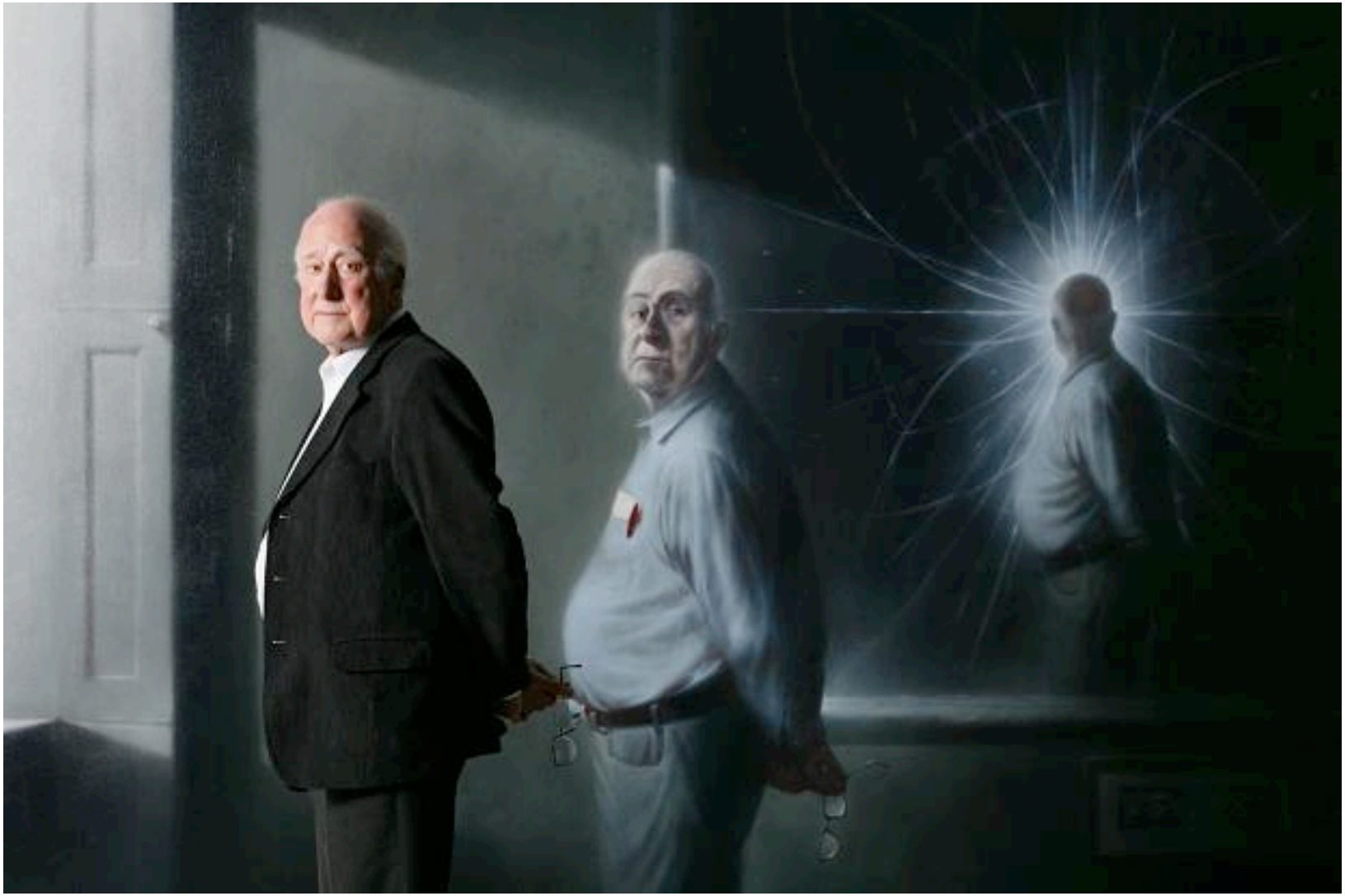


assuming μ_i=1

The new boson seems very SM Higgs like (all μ's~1)
Decay : no sensitivity to $\mu\mu$, $Z\gamma$

ttH : 2.4 σ evidence (Physics Letters B 749 (2015) 519-541)

SM Higgs @ LHC run 2



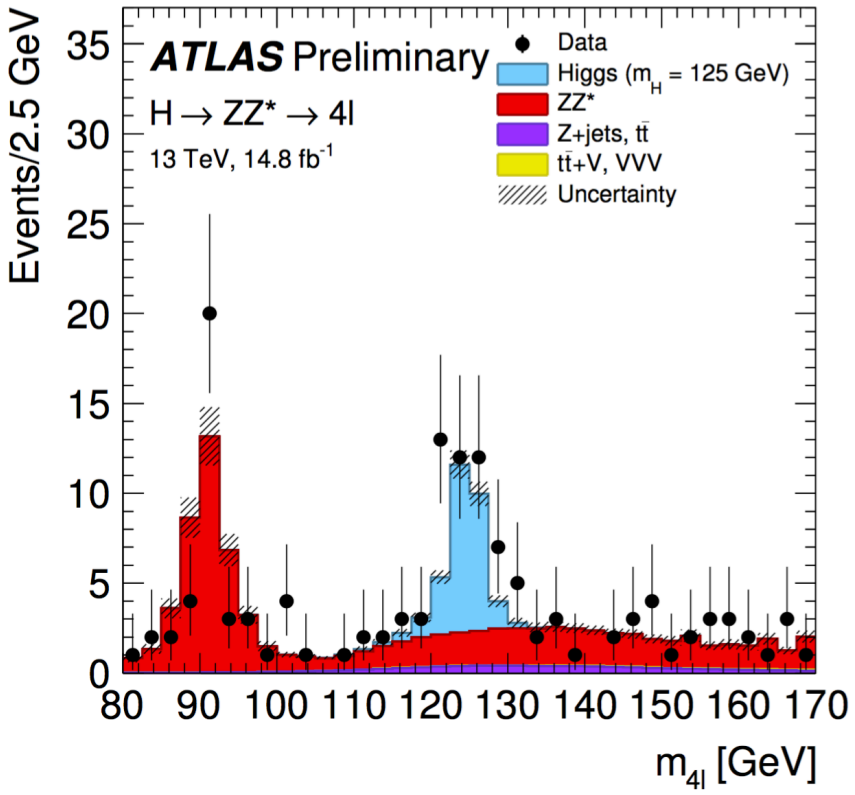
Ken Currie, 2008

Higgs Production & decay at 13 TeV in ATLAS

Higgs boson production is observed at 13 TeV with 4-lepton (14.8 /fb)and $\gamma\gamma$ events (13.3 /fb) using 13 TeV data

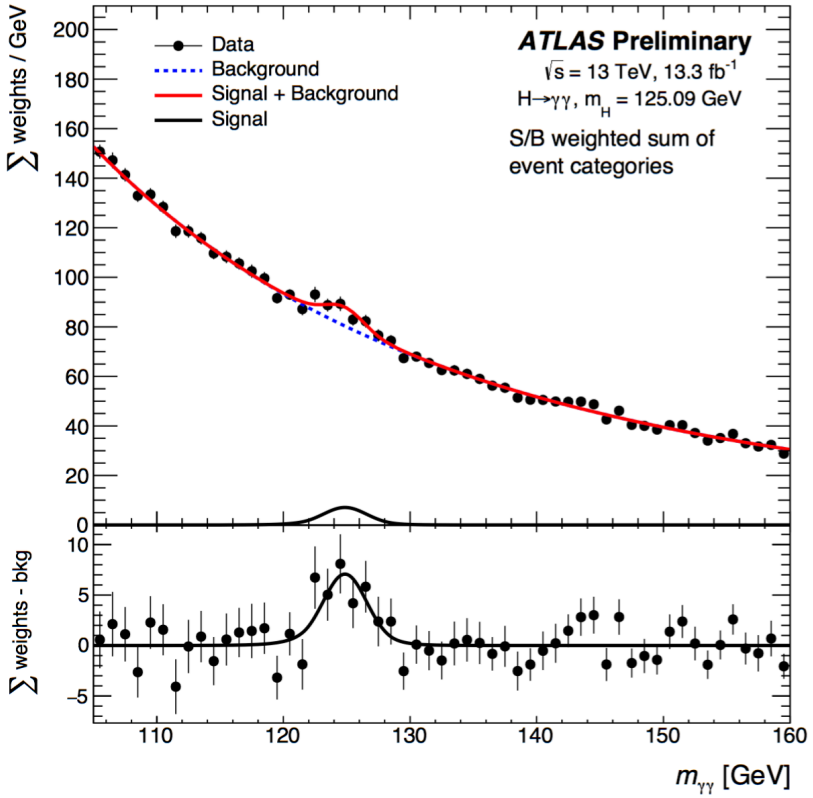
New!

ATLAS-CONF-2016-079



See Atlas talk from Ludovica Aperio Bella

ATLAS-CONF-2016-067



See Atlas talk from Andrew Pilkington

Higgs boson combination at Run 2 using ZZ(4ℓ) and $\gamma\gamma$ final states

ATLAS-CONF-2016-081

Which data ?

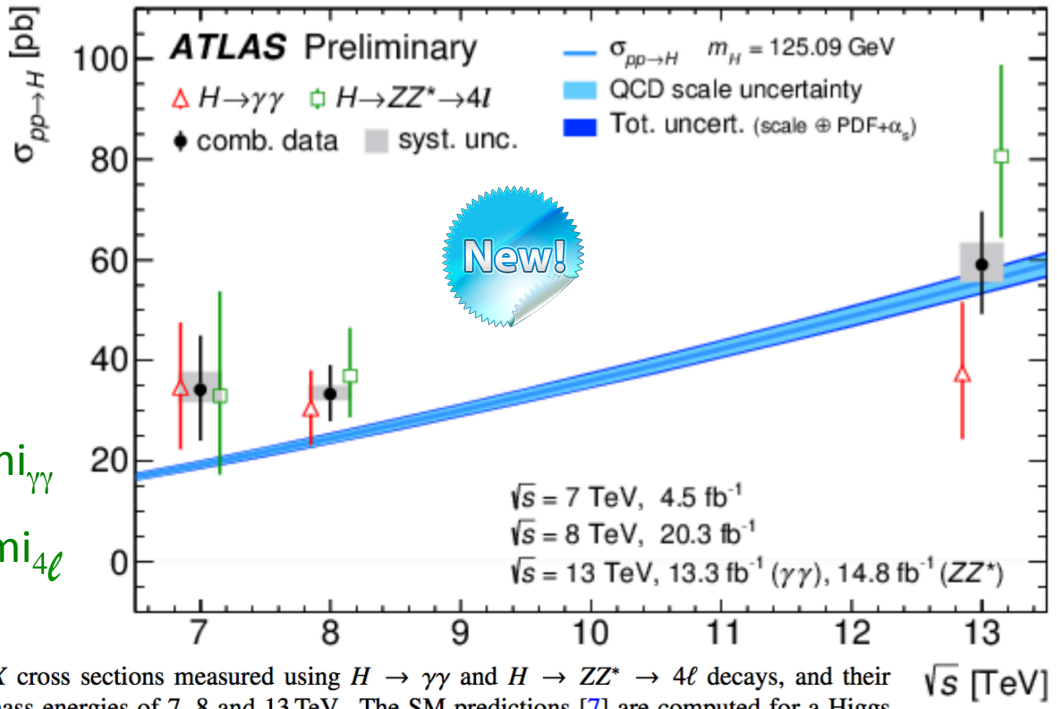
Inclusive samples H→$\gamma\gamma$ and H→Z→4l
No categorisation

Which fit is performed ?

Fit total cross-section using SM BR, acceptance from SM MC samples

$N_{\gamma\gamma} = \sigma_{pp\to H} * BR_{SM(\gamma\gamma)} * Eff. * Acc. * Lumi_{\gamma\gamma}$

$N_{4\ell} = \sigma_{pp\to H} * BR_{SM(4\ell)} * Eff. * Acc. * Lumi_{4\ell}$



Use profiled likelihood ratio fit with ~200 nuisance parameters θ and get vector α (params of interest: here $\sigma_{pp\to H}$)

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

Table 8: Total $pp \to H + X$ cross sections measured using $H \to \gamma\gamma$ and $H \to ZZ^* \to 4\ell$ decays, and their combination, for centre-of-mass energies of 7, 8 and 13 TeV. The SM predictions [7] are computed for a Higgs boson mass of 125.09 GeV [9].

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

Higgs boson combination at Run 2 using ZZ and γγ final states

ATLAS-CONF-2016-081

Data: 13.5 /fb γγ & 14.8 /fb ZZ

$H \to ZZ^* \to 4\ell$	
Category	Target
VH-leptonic	VHlep
0-jet	ggF
1-jet	ggF
2-jet VBF-like	VBF
2-jet VH-like	VHhad

$H \to \gamma\gamma$	
Category	Target
$t\bar{t}H$ leptonic	top
$t\bar{t}H$ hadronic	top
VH dilepton	VHlep
VH one-lepton	VHlep
VH Emiss	VHlep
VH hadronic loose	VHhad
VH hadronic tight	VHhad
VBF loose	VBF
VBF tight	VBF
ggH central low-p_{Tt}	ggF
ggH central high-p_{Tt}	ggF
ggH fwd low-p_{Tt}	ggF
ggH fwd high-p_{Tt}	ggF

Now, use categorized data to become sensitive to production processes and fit a single parameter In all categories simultaneously

$$\mu = \frac{\sigma \times \mathrm{B}}{\sigma^{\mathrm{SM}} \times \mathrm{B}^{\mathrm{SM}}}$$

$N_{cat} = \sum_{\text{Production processes}} \mu * \sigma_{SM} * BR_{SM} * Eff * Acceptance * Lumi$ in each category

Global signal strength after fit is: $\mu = 1.13^{+0.18}_{-0.17}$

Higgs production is observed with 10 σ significance (8.6 expected) with 13 TeV data in aggreement with SM expectations

Higgs boson combination at Run 2 using ZZ and γγ final states

Which fit performed ?

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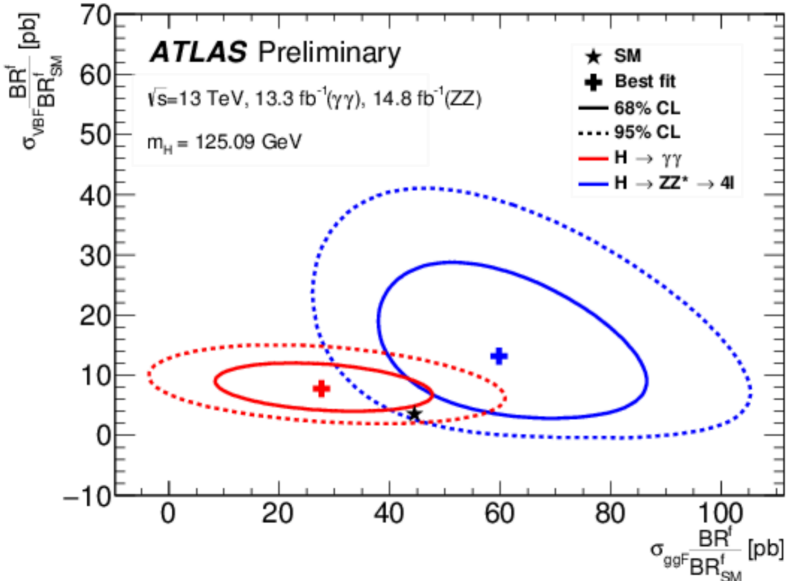
σ_i: cross-section fiducial definition is $|y_H|<2.5$

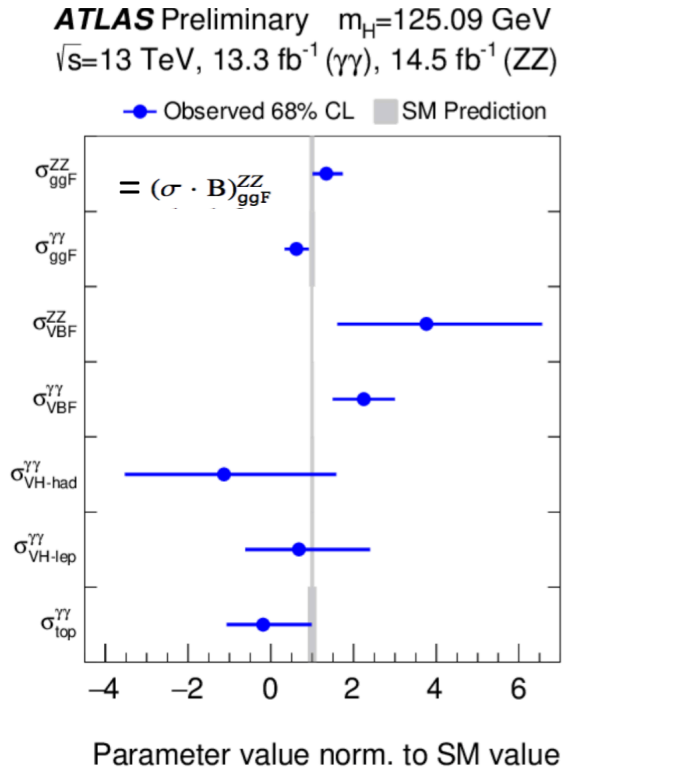
Use categorised data and allow different production cross-section (restricted to fiducial region) and different BR (7 parameters)

$b\bar{b}H$ is coupled with $gg \to H$ by assuming SM predictions for the ratios of the two processes, tH is coupled with ttH, by assuming SM predictions for the ratios of the $pp \to tH$ and the $pp \to t\bar{t}H$ cross sections, together reported as "top".

WH and ZH are merged, separately for the leptonic and the hadronic V decays[1], into $V(\to q\bar{q})H$ and $V(\to \text{leptons})H$, reported as "VHhad" and "VHlep" , respectively. The merging assumes the SM prediction for the ratio of the production cross sections and includes the contributions from both $q\bar{q} \to VH$ and $gg \to ZH$.



New!



Decay mode	ggF	VBF	VHhad	VHlep	top
$H \to \gamma\gamma$	$(\sigma \cdot B)^{\gamma\gamma}_{ggF}$	$(\sigma \cdot B)^{\gamma\gamma}_{VBF}$	$(\sigma \cdot B)^{\gamma\gamma}_{VHhad}$	$(\sigma \cdot B)^{\gamma\gamma}_{VHlep}$	$(\sigma \cdot B)^{\gamma\gamma}_{top}$
$H \to ZZ^*$	$(\sigma \cdot B)^{ZZ}_{ggF}$	$(\sigma \cdot B)^{ZZ}_{VBF}$	fixed to SM	fixed to SM	fixed to SM

Good agreement with SM

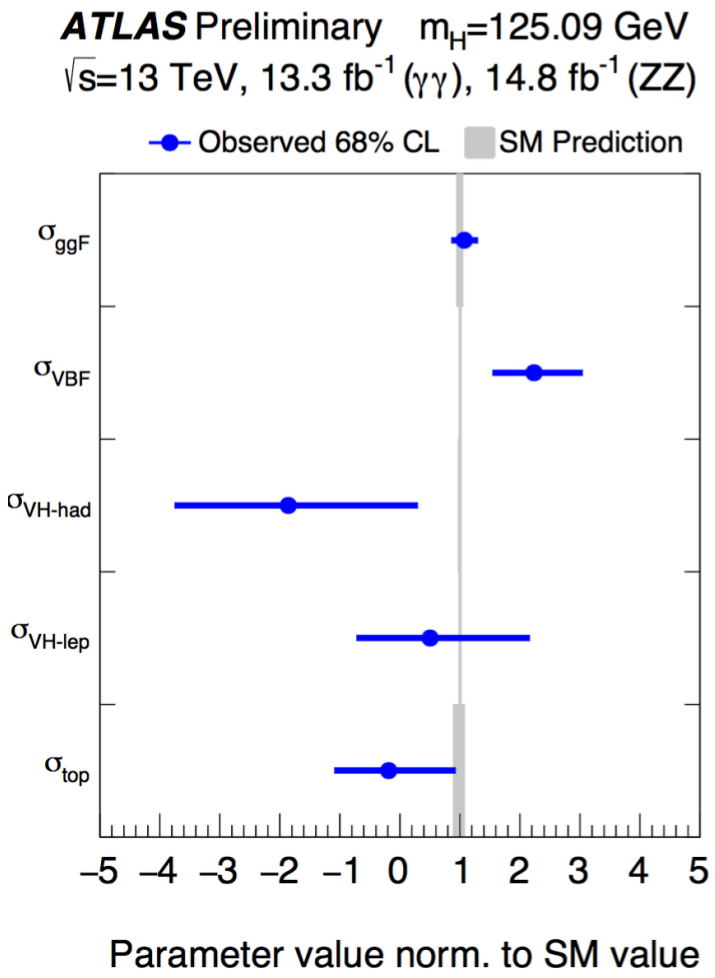
Higgs boson combination at Run 2 using ZZ and gg final states

ATLAS-CONF-2016-081

Which fit performed ?

Use categorised data and allow different production cross-section (restricted to fiducial region) and assume SM BR (5 parameters)

	Best fit value (pb)	SM prediction (pb)
σ_{ggF}	$47.8^{+9.8}_{-9.4}$	44.5 ± 2.3
σ_{VBF}	$7.9^{+2.8}_{-2.4}$	3.52 ± 0.07
σ_{VHhad}	$-2.5^{+2.9}_{-2.6}$	1.36 ± 0.03
σ_{VHlep}	$0.32^{+1.07}_{-0.79}$	0.64 ± 0.02
σ_{top}	$-0.11^{+0.67}_{-0.54}$	0.60 ± 0.06



No sensitivity yet to VH and ttH

Higgs boson combination at Run 2 using ZZ and gg final states

ATLAS-CONF-2016-081

Which fit is performed ?

Use categorised data and allow different production cross-section (restricted to fiducial region) and different BR

Use as a reference (from SM):

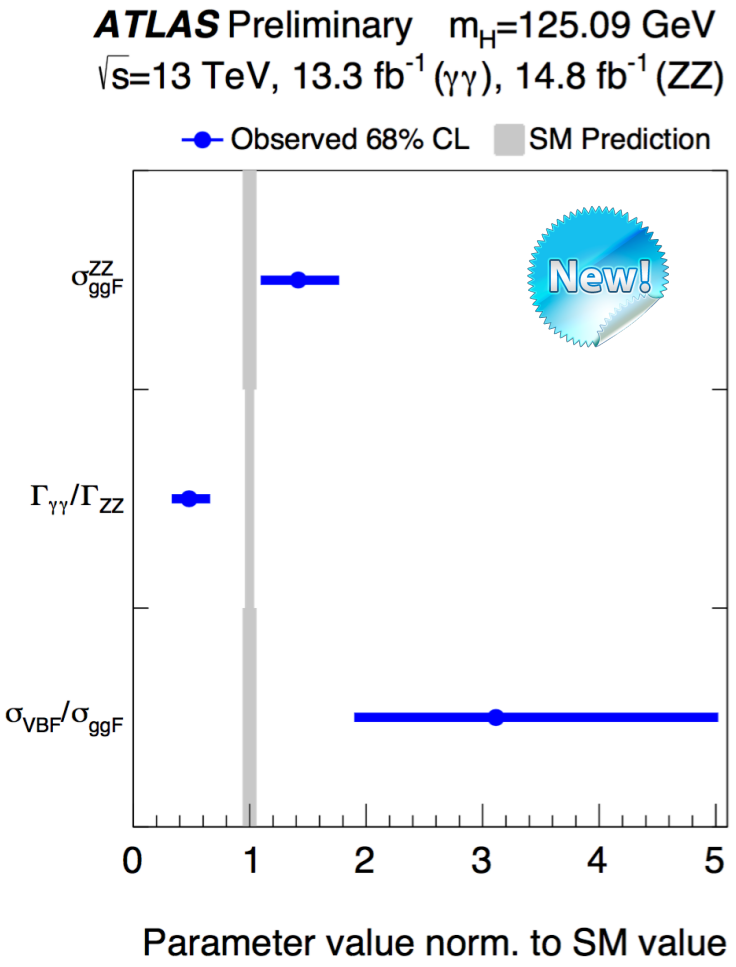
- ggF cross-section
- H→ZZ Branching ratio

$$(\sigma \cdot \mathrm{B})_i^f = (\sigma \cdot \mathrm{B})_{\mathrm{ggF}}^{ZZ} \cdot \left(\frac{\sigma_i}{\sigma_{\mathrm{ggF}}}\right) \cdot \left(\frac{\mathrm{B}^f}{\mathrm{B}^{ZZ}}\right)$$

Then fit 3 parameters only :

Parameter	Best-fit value	SM prediction
$(\sigma \cdot \mathrm{B})_{\mathrm{ggF}}^{ZZ}$ (pb)	$1.67\ ^{+0.41}_{-0.37}$	1.18 ± 0.07
$\sigma_{\mathrm{VBF}}/\sigma_{\mathrm{ggF}}$	$0.25\ ^{+0.15}_{-0.10}$	0.079 ± 0.004
$\mathrm{B}^{\gamma\gamma}/\mathrm{B}^{ZZ}$	$0.041\ ^{+0.015}_{-0.013}$	0.086 ± 0.003

σ_i: cross-section fiducial definition is $|y_H|<2.5$



No sensitivity yet to VH and ttH, fit VBF, ggF and $B_{\gamma\gamma}/B_{ZZ}$ and profile the other ratios in the fit

Conclusions

LHC Run 2 provides data beyond expectations

ATLAS detector is working well and reconstruction keeps collision pile-up under control.
Very quick analysis of the data to be able to include data taken less than 2 weeks ago !

Higgs boson observed with 13 TeV data with ~10 σ significance

Higgs boson properties measured with Run 2 data with both diphoton and 4 leptons data
- a first measurement of Higgs boson cross-section done with 13 TeV data
- a first analysis of production processes cross-sections done with 13 TeV data
  production in good agreement with Standard Model expectations

Sensitivity on rare decays increasing but no observation yet of $H \rightarrow \mu\mu$, $H \rightarrow Z\gamma$
→ see talks by C. Grefe and Davide Gerbaudo this week

Lot of new measurements to come with expected ~30 /fb of data in 2016

Stay tuned…