

SM Higgs boson results with the ATLAS detector

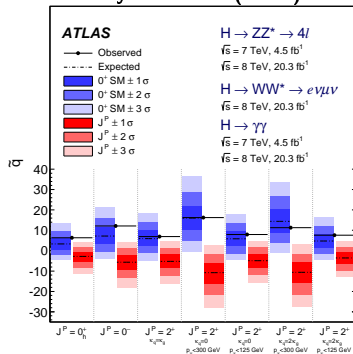
Dominik Duda (NIKHEF)
on behalf of the ATLAS collaboration



Introduction

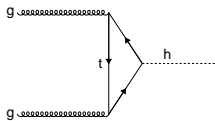
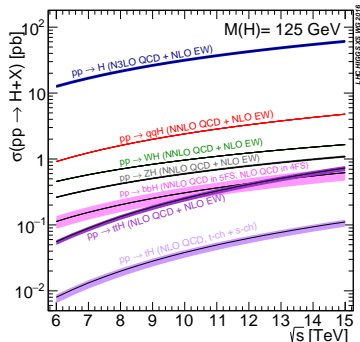
- Discovery of boson in 2012 is greatest success of the LHC experiments so far
- Subsequent measurements of the particle properties are consistent with the SM Higgs-boson.
- Higgs-boson mass measured by ATLAS and CMS:
 $m_H = 125.09 \pm 0.21(stat) \pm 0.11(syst)$
 - **Phys. Rev. Lett. 114, 191803**
- Spin and CP state of Higgs-boson are determined probing angular distribution of decay products
 - ATLAS data hints very strongly to a Spin^{CP} state of 0^+
 - Alternative models are rejected with a CL of more than 99.9%
- This talk focuses mainly on the latest ATLAS results on SM Higgs-boson analysis
- Further dedicated talks concerning $t\bar{t}H$ and BSM Higgs-boson searches:
 - Antonio Baroncelli: $t\bar{t}H$ measurements and combinations in ATLAS
 - Zhiqing Zhang: **Heavy Higgs searches in diboson final states in ATLAS**
 - Anna Kaczmarska: **Higgs boson BSM ATLAS**
 - Yee Chinn Yap: **Search for high mass resonances through 2γ channel in ATLAS**

Eur. Phys. J. C75 (2015) 476

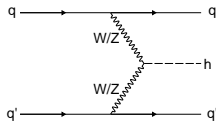


SM Higgs-boson production

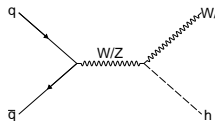
- 4 leading production processes with different signature:
 - Sensitive to different Higgs-couplings
 - ggF , $t\bar{t}H$: fermions(t,b)
 - VBF, VH: bosons(W,Z)
- Processes with the smaller cross sections have cleaner signature
 - VBF: two jets with large m_{jj} and $\Delta\eta_{jj}$
 - VH: Additional lepton(s), high $E_T^{miss.}$ or jets
 - $t\bar{t}H$: Additional leptons, high p_T (heavy flavour) jets and high $E_T^{miss.}$
- Cross sections at 13 TeV increased by a factor of 2.0 (or more) wrt to Run-I



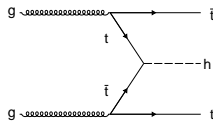
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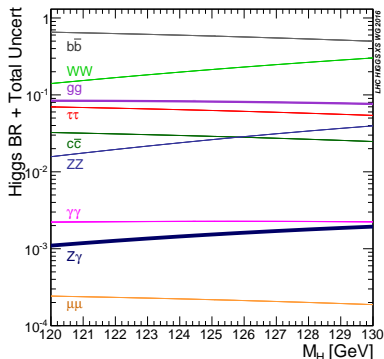
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SM Higgs-boson decay modes

Decay mode	Branching fraction [%]
$H \rightarrow b\bar{b}$	57.5 ± 1.9
$H \rightarrow WW^*$	21.6 ± 0.9
$H \rightarrow gg$	8.56 ± 0.86
$H \rightarrow \tau\tau$	6.30 ± 0.36
$H \rightarrow c\bar{c}$	2.90 ± 0.35
$H \rightarrow ZZ^*$	2.67 ± 0.11
$H \rightarrow \gamma\gamma$	0.228 ± 0.011
$H \rightarrow Z\gamma$	0.155 ± 0.014
$H \rightarrow \mu\mu$	0.022 ± 0.001



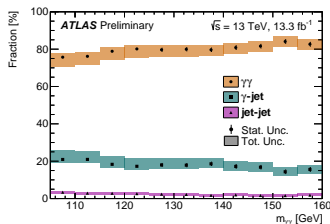
- At 125 GeV many Higgs-boson decays have a substantial BR
- But not all of them can be isolated from the backgrounds
 - gg, \dots
- Some channels with low BR have much higher signal-to-background ratios than e.g. the $gg \rightarrow H \rightarrow b\bar{b}$ decay channel
 - e.g. $H \rightarrow \gamma\gamma$ or $H \rightarrow ZZ^* \rightarrow 4\ell$ with a $BR(1.2 \cdot 10^{-4})$

$$H \rightarrow \gamma\gamma$$

<http://cds.cern.ch/record/2206210>
ATLAS-CONF-2016-067

$H \rightarrow \gamma\gamma$ measurements

- Measurements of fiducial, differential and production cross sections
 - Unbinned maximum likelihood fit on $m_{\gamma\gamma}$ spectrum in the range $105 \text{ GeV} < m_{\gamma\gamma} < 160 \text{ GeV}$
 - Signal model: Double-sided Crystal Ball function (around 125.09 GeV)
 - Background model: two dimensional sideband method (to estimate $\gamma\gamma$, γj , jj contribution)
- Object and event selection:



	diphoton baseline	VBF enhanced	single lepton
Photons		$ \eta < 1.37$ or $1.52 < \eta < 2.37$ $p_T^{\gamma 1} > 0.35 m_{\gamma\gamma}$ and $p_T^{\gamma 2} > 0.25 m_{\gamma\gamma}$	
Jets	-	$p_T > 30 \text{ GeV}$, $ y < 4.4$ $m_{jj} > 400 \text{ GeV}$, $ \Delta y_{jj} > 2.8$ $ \Delta\phi_{\gamma\gamma, jj} > 2.6$	-
Leptons	-	-	$p_T > 15 \text{ GeV}$ $ \eta < 2.47$

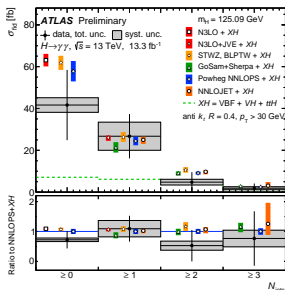
- Additional cuts/BDT to define event categories (production cross section measurements)
 - leptonic and hadronic $t\bar{t}H$ categories
 - VH categories corresponding to $W \rightarrow \ell\nu$, $Z \rightarrow \ell\ell$, $Z \rightarrow \nu\nu$, $V \rightarrow q\bar{q}$
 - VBF
 - gluon-fusion

Fiducial and differential cross sections

- Fiducial cross sections

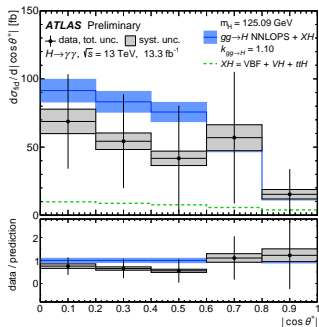
- No significant deviations form SM predictions for the three measurements

Fiducial region	Measured cross section (fb)	SM prediction (fb)
Baseline	43.2 ± 14.9 (stat.) ± 4.9 (syst.)	$62.8^{+3.4}_{-4.4}$ [N ³ LO + XH]
VBF-enhanced single lepton	4.0 ± 1.4 (stat.) ± 0.7 (syst.)	2.04 ± 0.13 [NNLOPS + XH]
	1.5 ± 0.8 (stat.) ± 0.2 (syst.)	0.56 ± 0.03 [NNLOPS + XH]



- But: harder Higgs-boson p_T spectrum in data w.r.t. NNLOPS predictions

- With a p -value of 2.3σ .
- Consistent with Run-I measurements of ATLAS

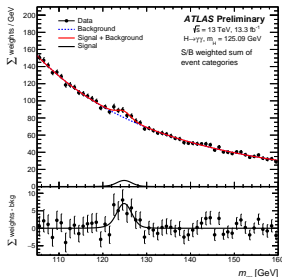


- $\sigma_{\text{fid.}}$ vs. $|\cos \Theta^*|$
 - Compatible with SM predictions of a CP-even scalar particle
- Measurements are still statistically dominated

Total $H \rightarrow \gamma\gamma$ production cross section and signal strength

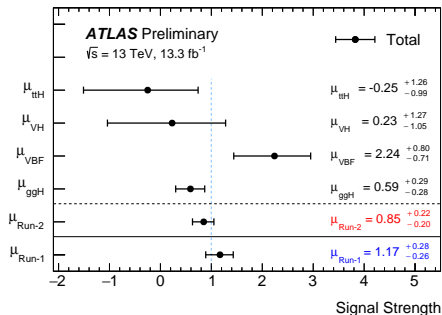
- In total considering 13 event categories
- Total uncertainties dominated by
 - Statistics
- Signal strength:

$$\mu = \frac{\sigma \times BR_{\text{measured}}}{\sigma \times BR_{\text{SM}}}$$



- Observed significance of the signal is 4.7σ , while 5.4σ is expected

$$\begin{aligned} \sigma_{\text{ggH}} \times BR(H \rightarrow \gamma\gamma) &= 65_{-31}^{+32} \text{ fb} \\ \sigma_{\text{VBF}} \times BR(H \rightarrow \gamma\gamma) &= 19.2_{-6.1}^{+6.8} \text{ fb} \\ \sigma_{\text{VH}} \times BR(H \rightarrow \gamma\gamma) &= 1.2_{-5.4}^{+6.5} \text{ fb} \\ \sigma_{\text{ttH}} \times BR(H \rightarrow \gamma\gamma) &= -0.3_{-1.1}^{+1.4} \text{ fb} \end{aligned}$$



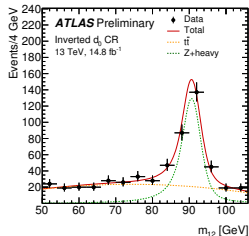
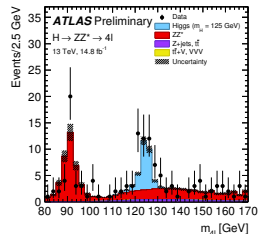
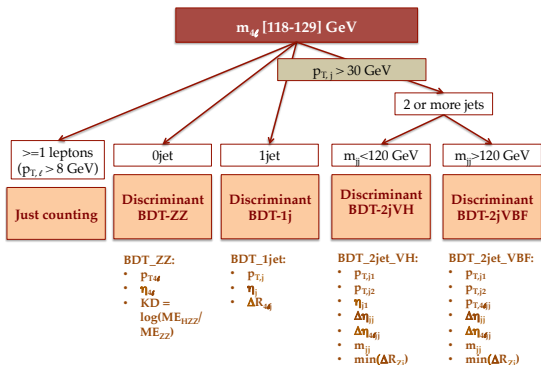
- Measurements agree with SM predictions within 1 to 2σ

$$H \rightarrow ZZ^*$$

<http://cds.cern.ch/record/2206253>
ATLAS-CONF-2016-079

Xsec & properties measurements in $H \rightarrow ZZ^* \rightarrow 4\ell$ events

- Decays via $H \rightarrow ZZ^* \rightarrow 4\ell$ provide high sensitivity for measurements in the Higgs-sector
- Measurement in $118 \text{ GeV} < m_{4\ell} < 129 \text{ GeV}$



- Z+jets and $t\bar{t}$ backgrounds estimated data-driven outside the Higgs-peak region
 - Unbinned LH-fit on discriminating variable
 - Use transfer factor to extrapolate to SR

Xsec & properties measurements in $H \rightarrow ZZ^* \rightarrow 4\ell$ events

- Combined fiducial cross sections:

$$\sigma_{\text{fid.,comb}}^{4\ell} = 4.54_{-0.89}^{+1.01} \text{ fb}$$

- SM expectation:

$$\sigma_{\text{fid.,SM}}^{4\ell} = 3.07_{-0.25}^{+0.21} \text{ fb}$$

- Total cross section:

$$\sigma_{\text{tot}} = 81_{-16}^{+18} \text{ pb}$$

- Compatible to SM expectation within 1.6σ

- Cross section per production mode:

- Measured:

$$\sigma_{\text{gg}H+b\bar{b}H+t\bar{t}H} \times \mathcal{BR}(H \rightarrow ZZ^*) = 1.80_{-0.44}^{+0.49} \text{ pb}$$

$$\sigma_{\text{VBF}} \times \mathcal{BR}(H \rightarrow ZZ^*) = 0.37_{-0.21}^{+0.28} \text{ pb}$$

$$\sigma_{\text{VH}} \times \mathcal{BR}(H \rightarrow ZZ^*) = 0^{+1.5} \text{ pb}$$

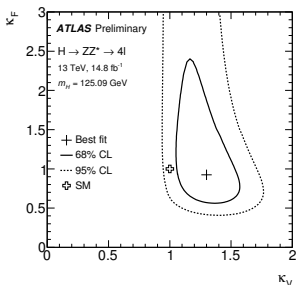
- Expected:

$$\sigma_{\text{SM,gg}H+b\bar{b}H+t\bar{t}H} \times \mathcal{BR}(H \rightarrow ZZ^*) = 1.31 \pm 0.07 \text{ pb}$$

$$\sigma_{\text{SM,VBF}} \times \mathcal{BR}(H \rightarrow ZZ^*) = 0.100 \pm 0.003 \text{ pb}$$

$$\sigma_{\text{SM,VH}} \times \mathcal{BR}(H \rightarrow ZZ^*) = 0.059 \pm 0.002 \text{ pb}$$

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



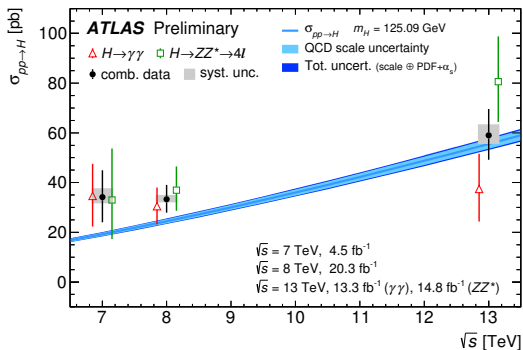
- κ_i are coupling-strength scale factors
- Results also on BSM couplings (back-up)

Combination of $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^*$ results

<http://cds.cern.ch/record/2206272>
ATLAS-CONF-2016-081

Combination of $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^*$ results

- Inclusive production cross section (full event sample)
 - Correct for detector effects and extrapolate to full phase space
 - Statistical uncertainties are dominant
 - No deviation from SM is found**



Decay channel	Total cross section ($pp \rightarrow H + X$)		
	$\sqrt{s} = 7$ TeV	$\sqrt{s} = 8$ TeV	$\sqrt{s} = 13$ TeV
$H \rightarrow \gamma\gamma$	35^{+13}_{-12} pb	$30.5^{+7.5}_{-7.4}$ pb	37^{+14}_{-13} pb
$H \rightarrow ZZ^* \rightarrow 4l$	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

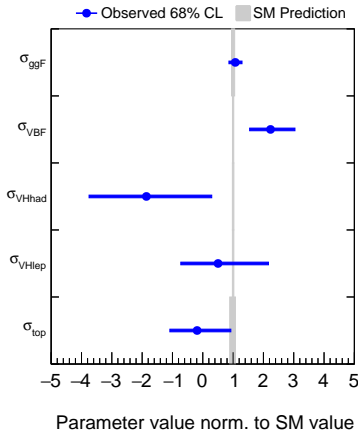
Combination of $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^*$ results

- Production cross sections
 - Assume SM \mathcal{BR}
 - With fiducial requirement $|y_H| < 2.5$
 - Data is categorised
- Fit simultaneously in 7 regions
- No sensitivity yet to VH and $t\bar{t}H$
- ggF shows good agreement to SM predictions**

	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

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

ATLAS Preliminary $m_H=125.09$ GeV
 $\sqrt{s}=13$ TeV, 13.3 fb^{-1} ($\gamma\gamma$), 14.8 fb^{-1} (ZZ)



$$H \rightarrow b\bar{b}$$

<http://cds.cern.ch/record/2206813>
ATLAS-CONF-2016-091

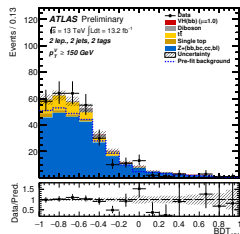
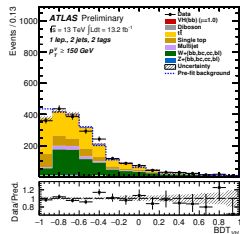
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ATLAS-CONF-2016-063

VH \rightarrow Vbb

- ggF and VBF produced Higgs-bosons decaying via $H \rightarrow b\bar{b}$ have overwhelming large backgrounds
 - VH production modes are good candidates to discover $H \rightarrow b\bar{b}$ decays
- Targeting VH modes including $Z \rightarrow \nu\nu$, $Z \rightarrow \ell\ell$ and $W \rightarrow \ell\nu$ decays
 - Thus final states with 0, 1 or 2 charge leptons
- Categorise events (and using two sets of BDTs)
 - VH vs. all backgrounds
 - VZ vs. other backgrounds

Selection	0-lepton	1-lepton	2-lepton
Trigger	E_T^{miss}	Lowest unrescaled single lepton	
Leptons	0 loose lepton	1 tight lepton	2 loose leptons (≥ 1 medium lepton)
Lepton pair	-	-	Same flavour opposite-charge for $\mu\mu$
E_T^{miss}	> 150 GeV	> 30 GeV (e sub-channel)	-
m_{ll}	-	-	$71 < m_{ll} < 121$ GeV
S_T	> 120 (2 jets), > 150 GeV (3 jets)	-	-
Jets	Exactly 2 or 3 signal jets		Exactly 2 or ≥ 3 signal jets
b-jets	2 b-tagged signal jets		
Leading jet p_T	> 45 GeV		
$\min\Delta\phi(E_T^{\text{miss}}, \text{jet})$	$> 20^\circ$	-	-
$\Delta\phi(E_T^{\text{miss}}, h)$	$> 120^\circ$	-	-
$\Delta\phi(\text{jet1}, \text{jet2})$	$< 140^\circ$	-	-
$\Delta\phi(E_T^{\text{miss}}, E_{T, \text{trk}}^{\text{miss}})$	$< 90^\circ$	-	-
p_T^{miss} regions	[0, 150] GeV (2-lepton), [150, ∞] GeV		

Channel	Categories					
	2 b-tagged jets					
	$p_T^{\text{miss}} < 150$ GeV			$p_T^{\text{miss}} > 150$ GeV		
	2 jets	3 jets	≥ 3 jets	2 jets	3 jets	≥ 3 jets
0 lepton	-	-	-	BDT	BDT	-
1 lepton	-	-	-	BDT	BDT	-
2 lepton	BDT	-	BDT	BDT	-	BDT



Measured signal strength for $VH \rightarrow Vb\bar{b}$

- BDT response is fitted simultaneously in the 8 regions
- Systematic uncertainties with largest impact on fit
 - b -tagging and mistagging of c -jets
 - Modelling of $W+b\bar{b}$ and $Z+b\bar{b}$ backgrounds
- Fitted value of signal strength parameter

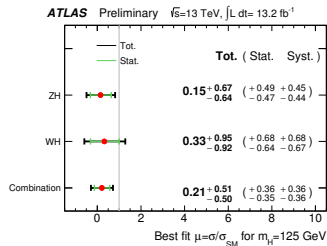
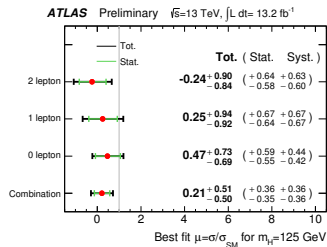
$$\mu = 0.21_{-0.35}^{+0.36} \pm 0.36(stat.)$$

- Thus compare observed significance of 0.42σ to expected sensitivity of 1.94σ
- Validate analysis strategy by performing fit on VZ BDT output, which gives:

$$\mu = 0.91_{-0.27}^{+0.32} \pm 0.17(stat.)$$

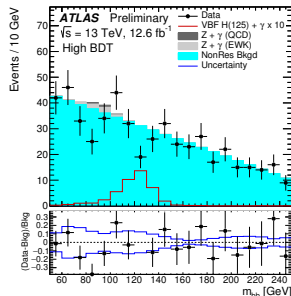
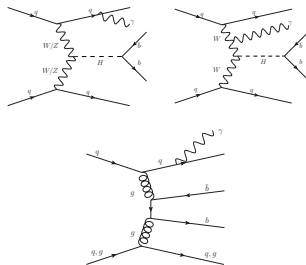
- The observed significance of this result is 3.2σ , while the expected sensitivity is 3.0σ

Dataset	Limit		p_0		Significance	
	Exp.	Obs.	Exp.	Obs.	Exp.	Obs.
0-lepton	$1.4_{-0.4}^{+0.6}$	2.0	0.07	0.15	1.45	1.02
1-lepton	$2.0_{-0.6}^{+0.8}$	2.1	0.15	0.46	1.04	0.10
2-lepton	$1.8_{-0.5}^{+0.7}$	1.7	0.13	0.57	1.14	-0.17
Combined	$1.0_{-0.3}^{+0.4}$	1.2	0.03	0.34	1.94	0.42



Search for $b\bar{b}\gamma jj$ signatures

- Search for SM $H \rightarrow b\bar{b}$ events produced via **VBF** and in association with a **photon**.
- Advantage of photon selection:
 - Suppression of QCD backgrounds
 S/B is improved by an order of magnitude w.r.t. $b\bar{b}jj$ channel
 - Trigger on high- p_T photons
- Use BDT (with 7 input quantities) to further reduce non-resonant backgrounds
 - Input quantities show good data/mc agreement except for $\Delta\eta_{jj}$ (thus apply reweighting)
- Observed and expected 95% CL upper limits on $\sigma \times BR$ are 4.0 and $6.0^{+2.3}_{-1.7}$ times the SM expectation.
- Signal strength on $H\gamma$ production is found to be $-3.9^{+2.8}_{-2.7}$

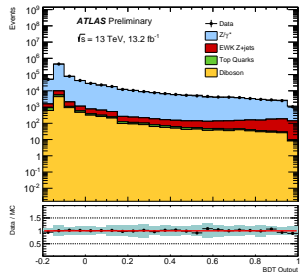
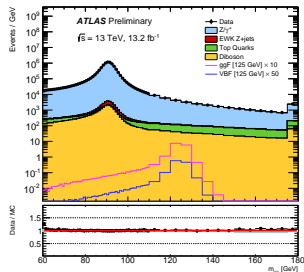


$$H \rightarrow \mu\mu$$

<http://cds.cern.ch/record/2206079>
ATLAS-CONF-2016-041

Search for Higgs bosons decaying into di-muons

- Sensitive channel to probe couplings to 2nd-generation fermions
- Classify di-muon events into disjoint phase spaces
 - Three $p_T^{\ell\ell}$ slices
 - Two regions based on the muon $|\eta|$
 - VBF topology
- VBF topology uses boosted decision tree
 - Fourteen input variables
 - 51.3% (2.4%) of sig. (bkg.) pass cut on output
- Obtain background shape and normalization from **fit to di-muon mass spectra**
 - Sig.: Sum of Crystal Ball and Gaussian
 - Bkg: Breit-Wigner convolved with Gaussian and exponential function divided by $m_{\ell\ell}^3$
- Dominant uncertainties
 - Statistics
 - ggF: 13-22% Higgs p_T mismodelling
 - VBF: 5% JES and 4% multi parton interaction



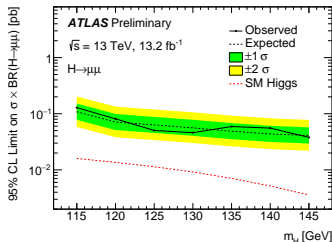
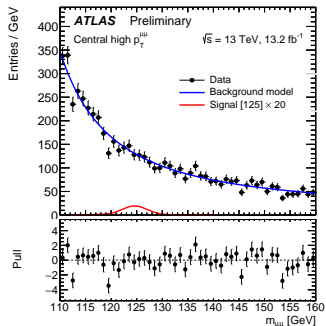
Search for Higgs bosons decaying into di-muons

- Binned maximum likelihood fit to observed $m_{\ell\ell}$ distribution in range 110 – 160 GeV
 - Simultaneously in all seven categories
- No evidence for $H \rightarrow \mu\mu$ contribution found
- For $m_H = 125.09$ GeV, the observed (expected) upper limit on $\sigma \times BR(H \rightarrow \mu\mu)$ at the 95% CL is 4.4 (5.5) times the SM prediction.
- The measured signal strength is

$$\mu_S = -2.3^{+2.7}_{-2.7}$$

- Combination with Run I results gives an observed (expected) upper limit that is 3.5 (4.3) as well as

$$\mu_S = -1.5^{+2.1}_{-2.4}$$



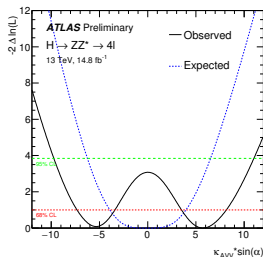
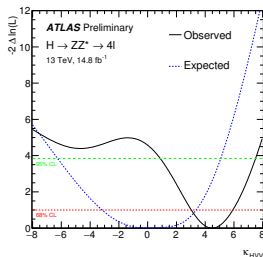
Summary and conclusions

- Presented 13 TeV results on the latest measurements of fiducial, differential and total production cross sections in Higgs-decays to
 - two photons
 - two Z-bosons, which further decay to four charged leptons
 - two bottom quarks
 - two muons
- Measurements are consistent with the SM predictions
 - But statistical uncertainties are still dominant
- Exciting times ahead of us as new data arrives daily.
- Also: Looking forward to publications for analyses based on $H \rightarrow \tau\tau$, $H \rightarrow WW^*$ or $H \rightarrow Z\gamma$ decays
 - Require more time to reach similar sensitivity as what was achieved for Run-I
- Also: first measurements based on $t\bar{t}H$
 - For more details see talk by Antonio Baroncelli

Back-up

Xsec & properties measurements in $H \rightarrow ZZ^* \rightarrow 4\ell$ events

- Yields in the exclusive event category are also sensitive to BSM contribution to HZZ coupling
 - Use MadGraph5_aMC@NLO samples
 - Use Higgs characterisation framework
 - Effective field theory
- Limits on the parameters $\kappa_{HV V}$ and $\kappa_{AV V} \sin \alpha$ are derived with a fit on the yields in each category
- Additional information from kinematic observables in the decay is not used
- Agreement between $\kappa_{HV V} = 0$ ($\kappa_{AV V} \sin \alpha = 0$) and the observed value is 2.1σ (1.8σ)



Not excluded range at 95% CL	$\kappa_{HV V}$		$\kappa_{AV V} \cdot \sin \alpha$	
	expected	observed	expected	observed
	[-6.3, 5.1]	[0.9, 7.5]	[-6.3, 6.5]	[-9.7, 11.0]

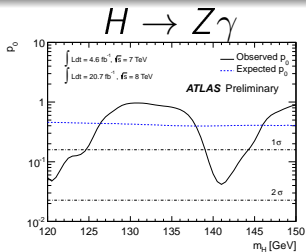
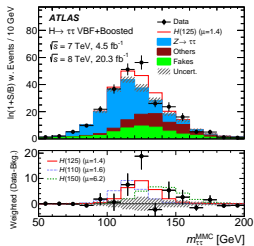
$H \rightarrow \tau\tau, H \rightarrow WW \text{ \& } H \rightarrow Z\gamma$
Run-I results only

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Some Run-1 results



- $H \rightarrow \tau\tau$:
 - Excess over the SM bkg. is found with an observed (expected) significance of 4.5σ (3.4σ)
- $H \rightarrow Z\gamma$:
 - Expected and observed limits are 13.5 and 18.2 times the Standard Model predictions
- $H \rightarrow WW^*$:
 - ggF: Observed signal excess over bkg's of 6.1σ , while 5.8σ were expected.
 - VBF: Evidence of signal excess over background of 3.2σ .

