Higgs boson couplings to bosons with the ATLAS detector: run 1 legacy.

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DESY

on behalf of the ATLAS collaboration

XXIX Rencontres de Physique de la Vallée d'Aoste

La Thuile

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Introduction

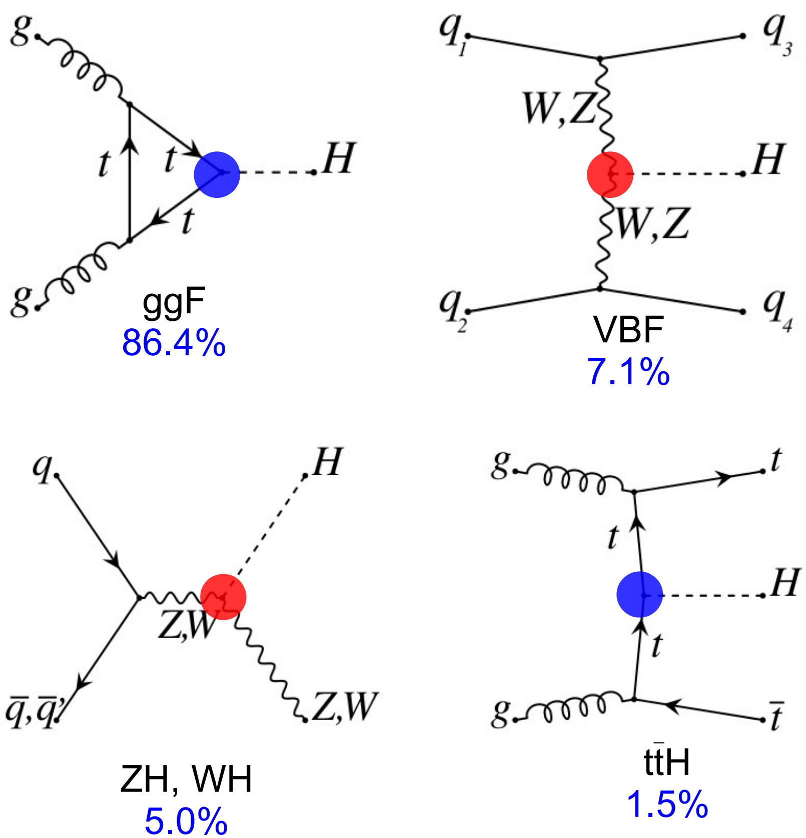
- Final measurements of the Higgs boson decaying into bosons with LHC run 1 data
  - $H \to WW^* \to l\nu l\nu$: submitted in December 2014
  - $H \to ZZ^* \to 4l$: published in January 2015
  - $H \to \gamma\gamma$: published in December 2014

- Benefits from final performance of objects calibration, identification, ...
- Improved analyses, to be sensitive to production modes

- Here, only discussion of couplings, mass discussed in the talk by A. Armbruster
  - $m_H = 125.36$ GeV considered here Phys. Rev. D. 90, 052004 (2014)

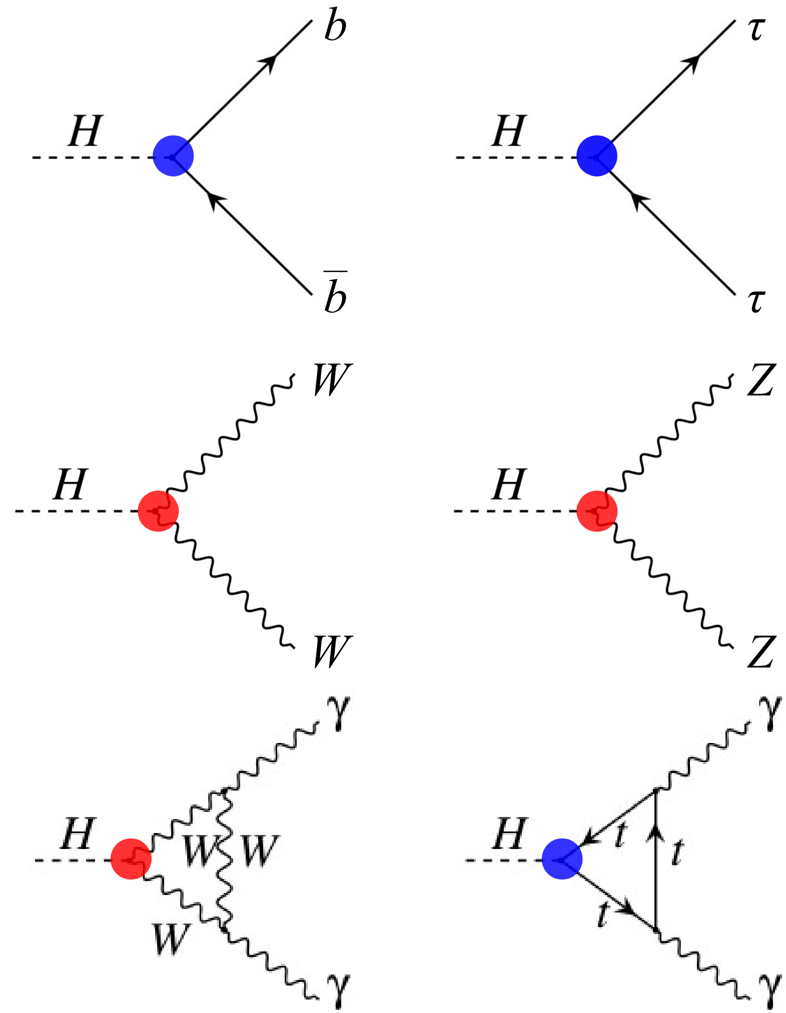
Higgs boson production and decays modes

- Production modes:



- : fermions
- : vector bosons

- Decay modes:



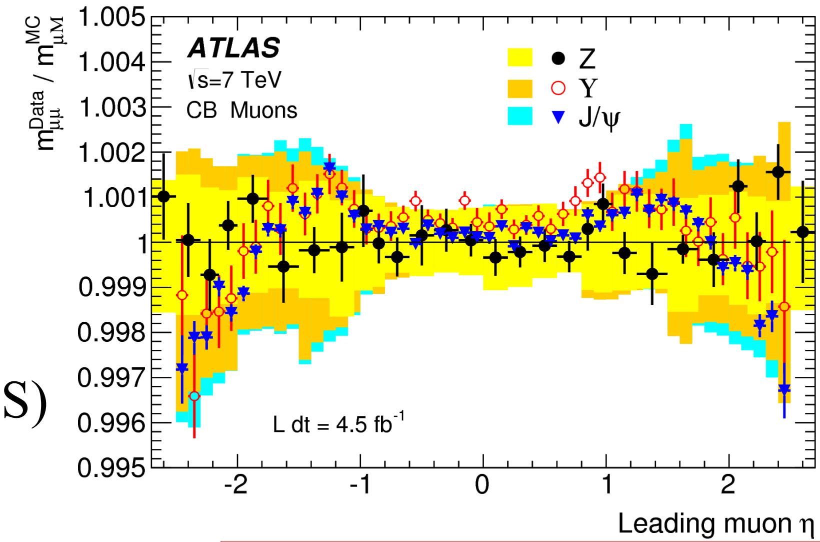
- Measuring cross-sections and partial widths ⇒ go back to couplings
- Parameter of interest: signal strength $\mu = N^{obs}/N^{SM}$

Improvements of performance

- Final performance for run 1

  Some examples:

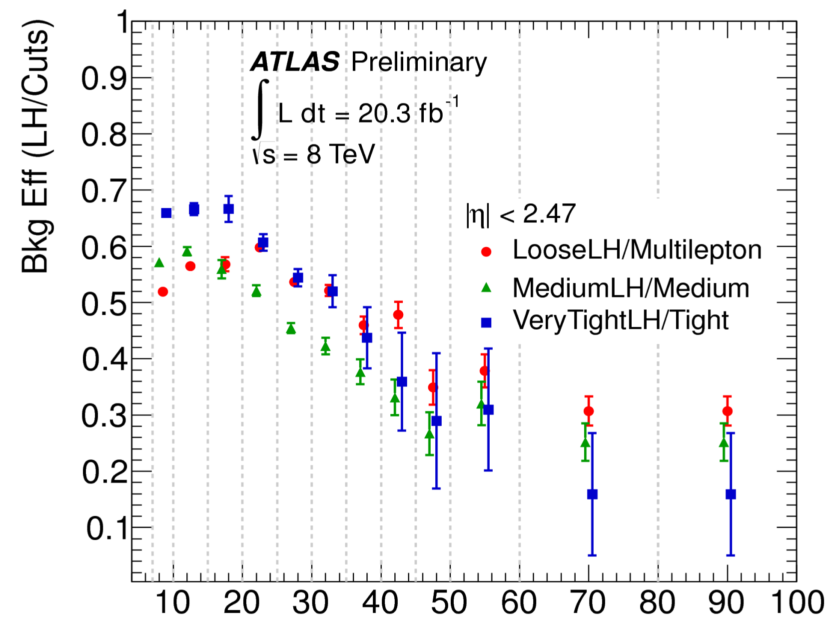
- Muon calibration
  - 0.04-0.2% uncertainty on energy scale (ES)



Eur. Phys. J. C 74 (2014) 3130

- e/γ calibration
  - e: 0.04% uncertainty on ES at 45 GeV
  - γ from Higgs boson: 0.3% uncertainty on ES
  - γγ mass resolution improved by 10%

- electron ID
  - >40% more rejection for same efficiency

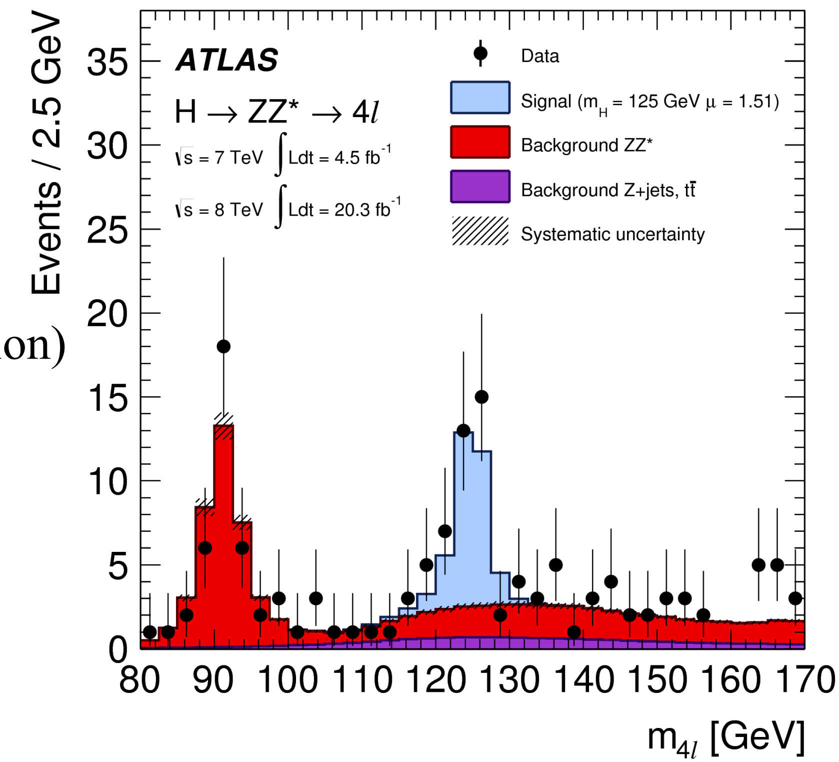


ATLAS-CONF-2014-032

$H \to ZZ^* \to 4l$

Phys. Rev. D 91, 012006 (2015)

- Two same-flavour, opposite-sign lepton pairs
  - well identified and isolated
  - $p_T^1 > 20/15/10/6\text{-}7$ GeV
  - FSR photon correction
  - Z-mass constraint (15% improvement on resolution)



- $50 < m_{12} < 106$ GeV
- $12\text{-}50 < m_{34} < 115$ GeV

- Number of events in $120 < m_{4l} < 130$ GeV
  - ZZ* from simulation
  - Z+jets and $t\bar{t}$ from data-driven estimates

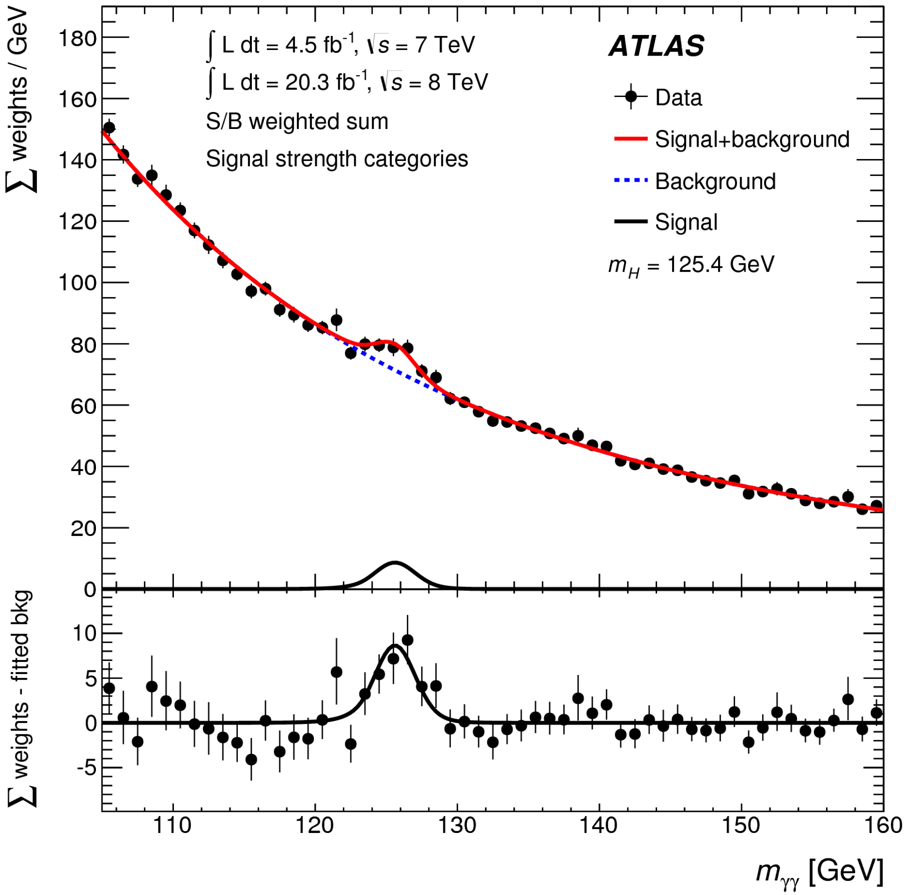
	Signal	ZZ	Z+jets, $t\bar{t}$	S/B	Total expected	Observed
7+8 TeV	16.2	7.4	3.0	1.6	26.6	37

H→γγ

Phys. Rev. D. 90, 112015 (2014)

- Two well identified and isolated photons
  - $E_T^{\gamma 1} > 0.35 * m_{\gamma\gamma}$, $E_T^{\gamma 2} > 0.25 * m_{\gamma\gamma}$
  - γγ purity: 77-84%
- Divide events in exclusive categories
  - with different resolution
  - with different S/B
- Signal+background fit of $m_{\gamma\gamma}$
- Number of expected signal events and measured background
  - window with 90% of signal

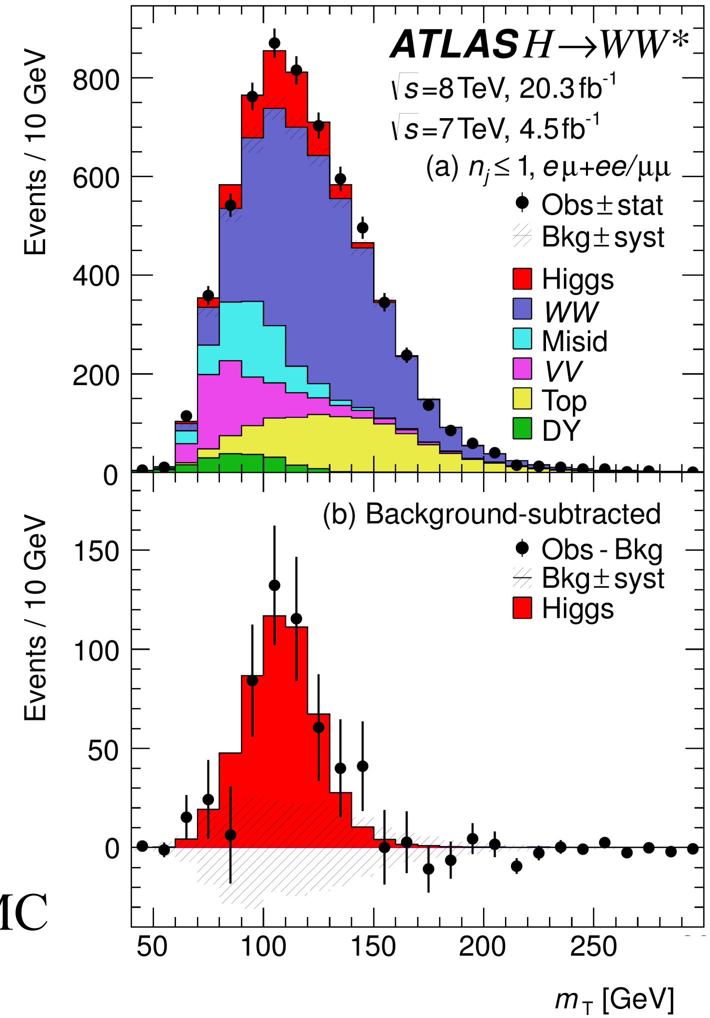
	signal	background	S/(S+B)
7+8 TeV	421.8	13196.4	0.03



$H \to WW^* \to l\nu l\nu$

submitted to Phys. Rev. D

- Two isolated well identified leptons
  - pT > 22/10 GeV
- E_T^{miss} cuts, Z veto, m_{ll}, $\Delta\varphi_{ll}$, etc
- Events divided in exclusive categories
  - eμ+μe, ee+μμ
  - 0, 1, 2 jets
- Background estimation
  - normalisation: data (CR)
  - extrapolation to SR: typically from MC
  - shape of discriminating variable: typically from MC

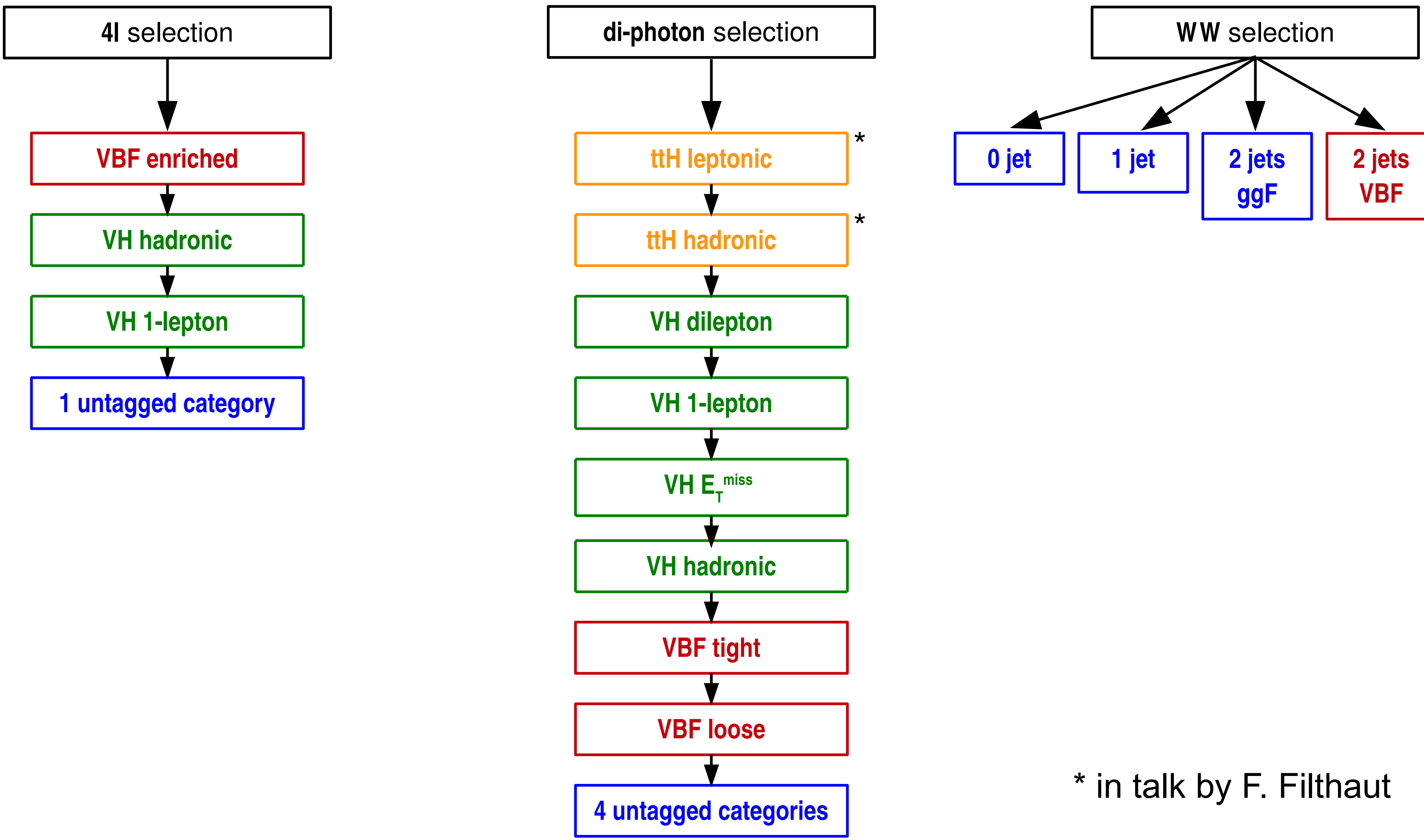


- Number of expected/observed events (7+8 TeV):

	Signal	Background	S/B	total expected	observed
0 jet	358	4005	0.09	4363	4344
1 jet	138	1746	0.08	1884	1900
2 jets, ggF	50	1017	0.05	1067	1017

Categorisation

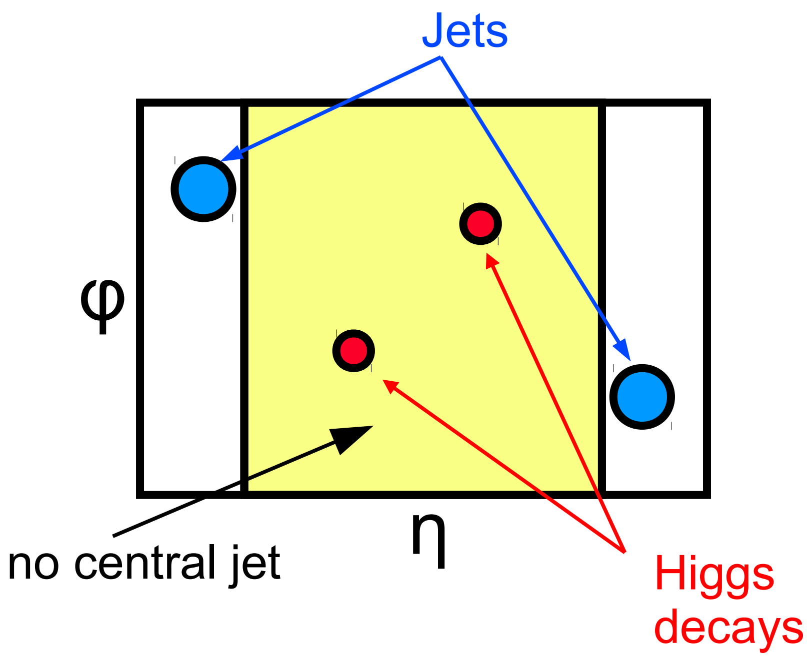
♦ Datasets divided in exclusive categories enriched in production modes

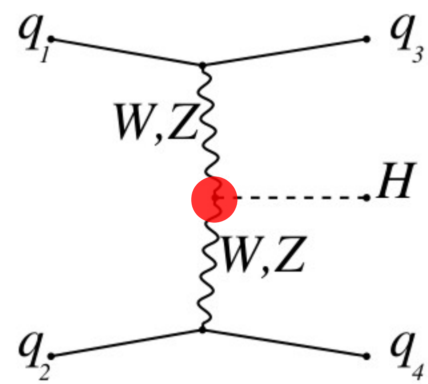


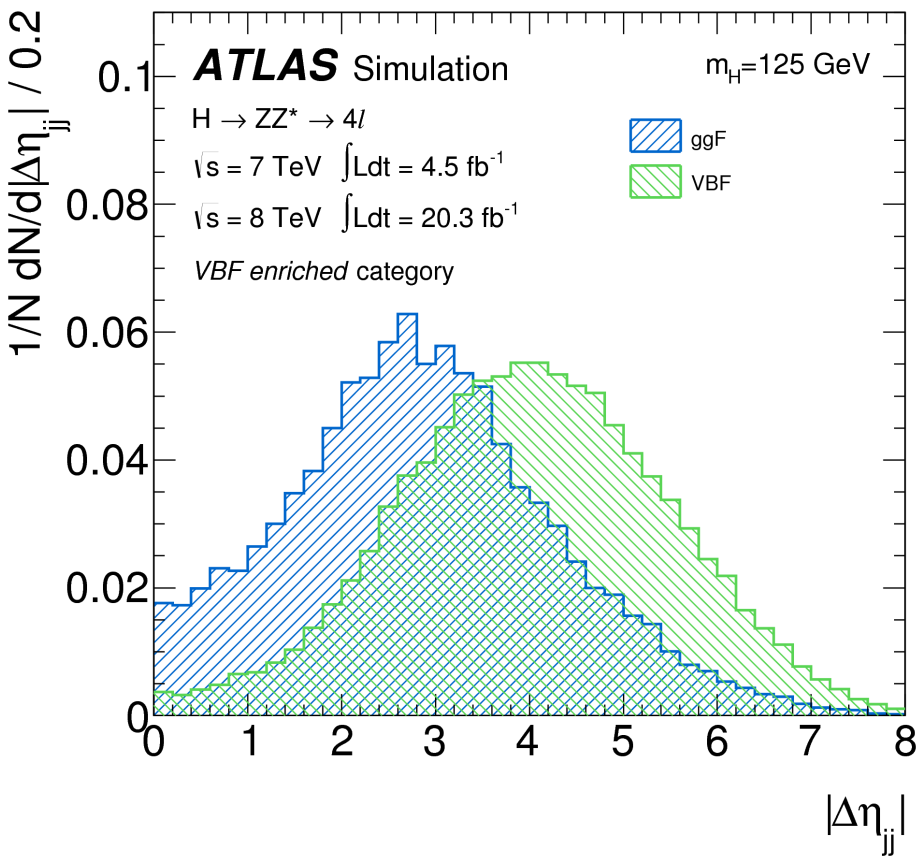
* in talk by F. Filthaut

VBF production mode (1)

- Cross-section at 125 GeV: 1.578 pb
- Higgs boson produced with 2 forward jets:





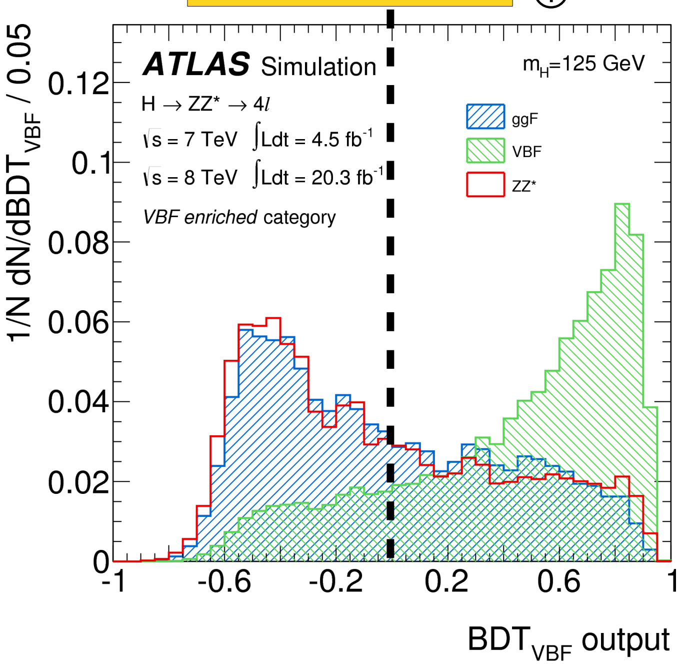


- Usual cuts:
  - $\Delta\eta_{jj}$
  - m_{jj}
  - veto 3rd central jet

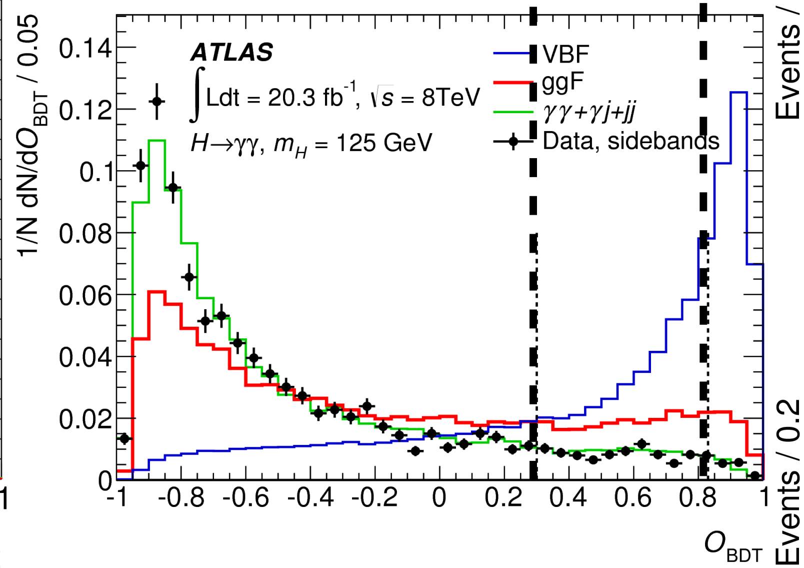
VBF production mode (2)

- BDT analyses for 4l, γγ, WW

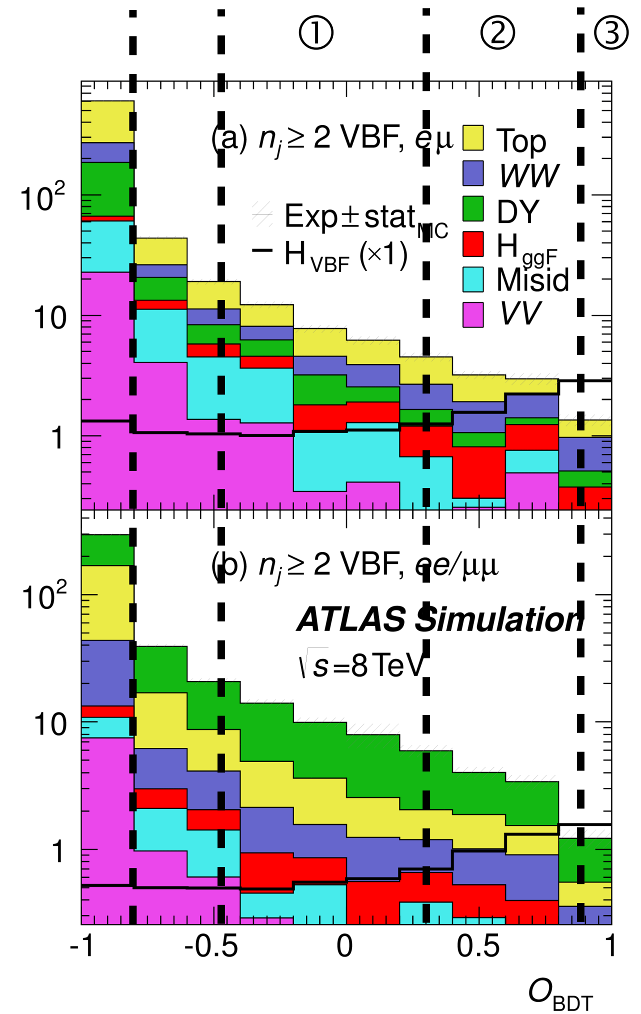
H → ZZ → 4l ①



H → γγ ① ②



H → WW → llνν ① ② ③



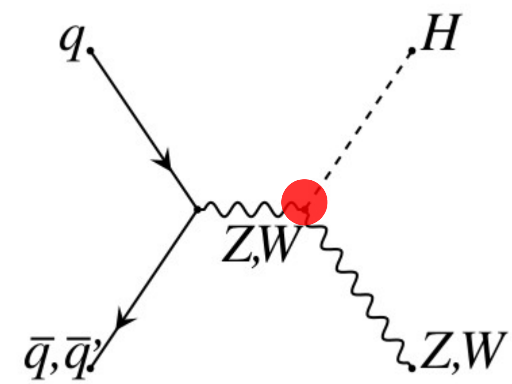
- Number of expected/observed events:

			signal	VBF/Higgs	background	observed
7+8 TeV	4l	bin1	1.13	55%	0.16	1
7+8TeV	γγ	bin 1	11.0	60%	44.0	
		bin 2	6.7	80%	6.7	
8 TeV	WW	bin 1	12.5	60%	82.0	90
		bin 2	10.0	80%	14.9	28
		bin 3	6.5	90%	2.3	12

VH (1)

- Cross-section at 125 GeV: 1.1 pb

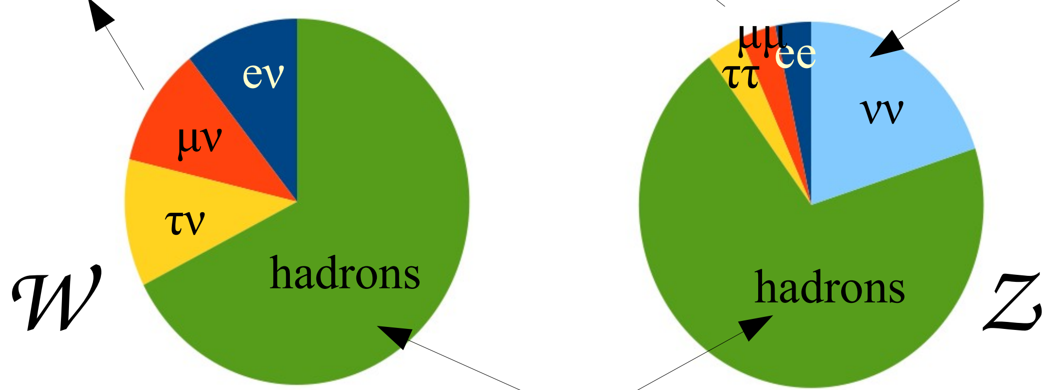
- Divide into categories depending on the W/Z decay



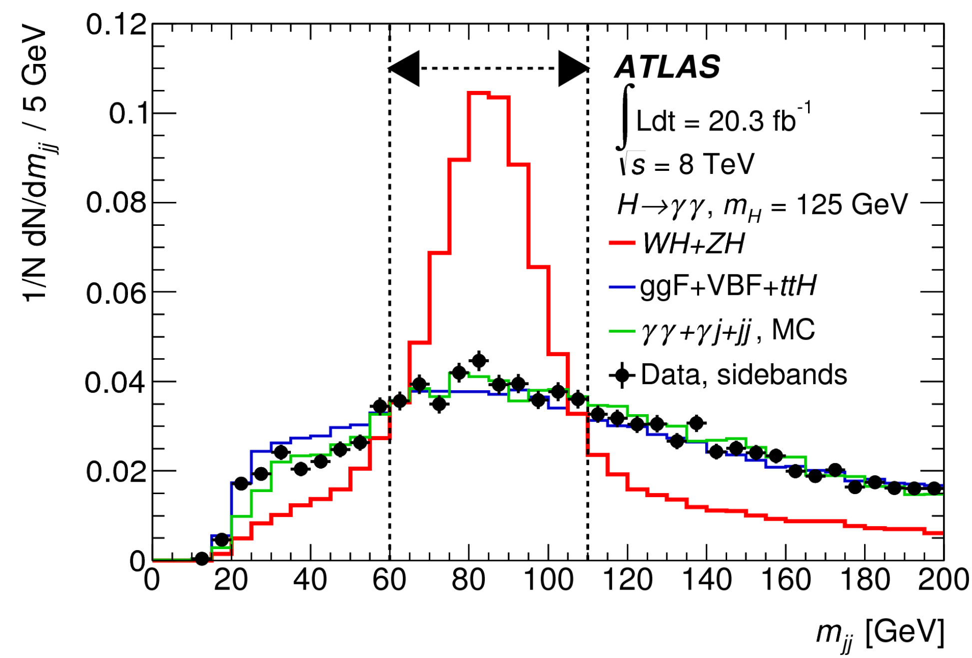
1 lepton + E_T^{miss}

2 leptons

0 lepton + E_T^{miss}

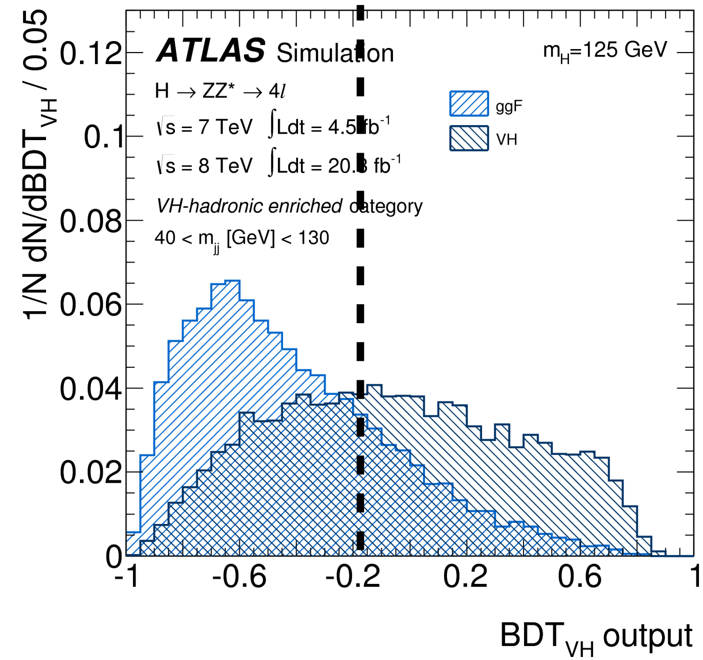


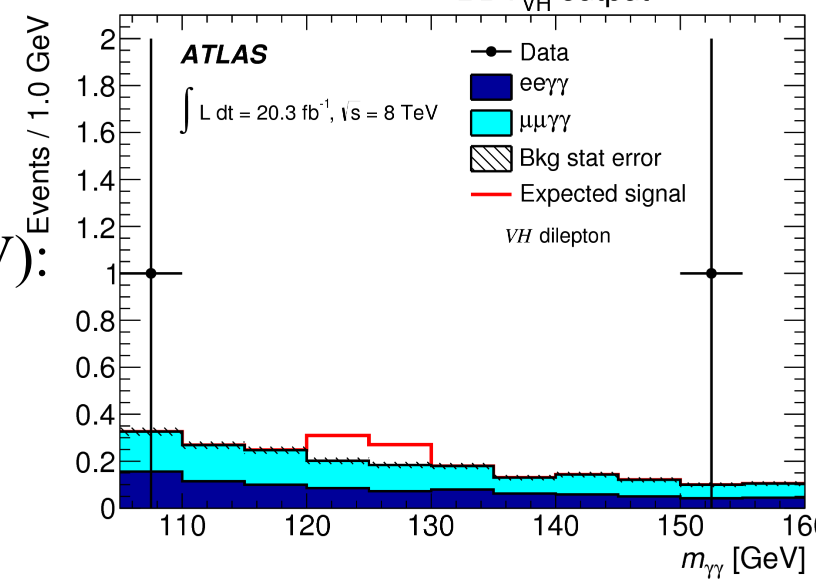
2 jets with m_{jj} close to 80-90 GeV



VH (2)

- ♦ H → ZZ → 4l
  - BDT analysis for VH hadronic
  - 1 additional lepton
- ♦ H → γγ
  - 2 leptons
  - 1 leptons + E_T^{miss}
  - 0 lepton + E_T^{miss}
  - VH hadronic





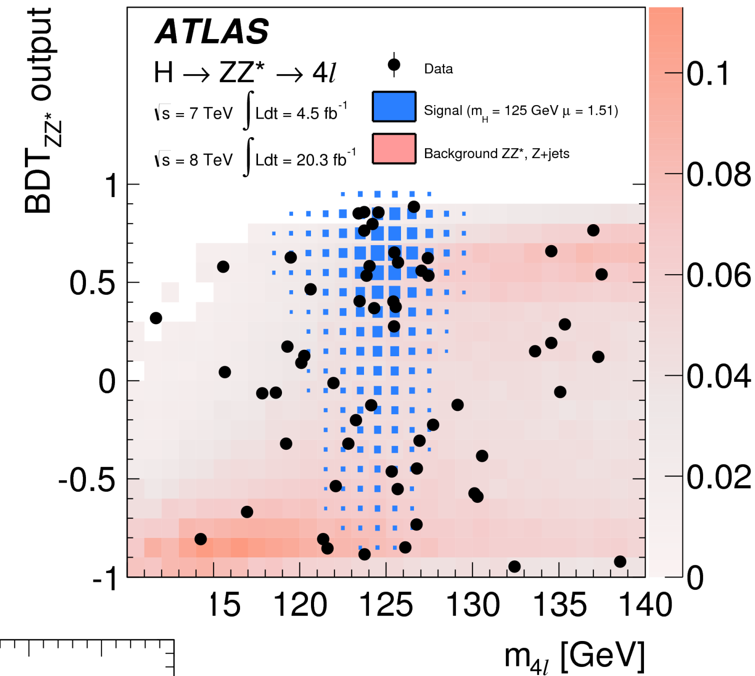
- ♦ Number of expected/observed events (7+8 TeV):

		signal	VH/Higgs	background	Observed
4l	hadronic	0.64	33%	0.18	0
	1 lepton	0.08	84%	0.03	0
γγ	2 leptons	0.4	99%	0.27	
	1 lepton	2.0	96%	4.4	
	ETmiss	1.4	88%	3.2	
	hadronic	3.8	49%	18	

H→ZZ*→4l: global results

$$\mu = \frac{N^{obs}}{N^{SM}}$$

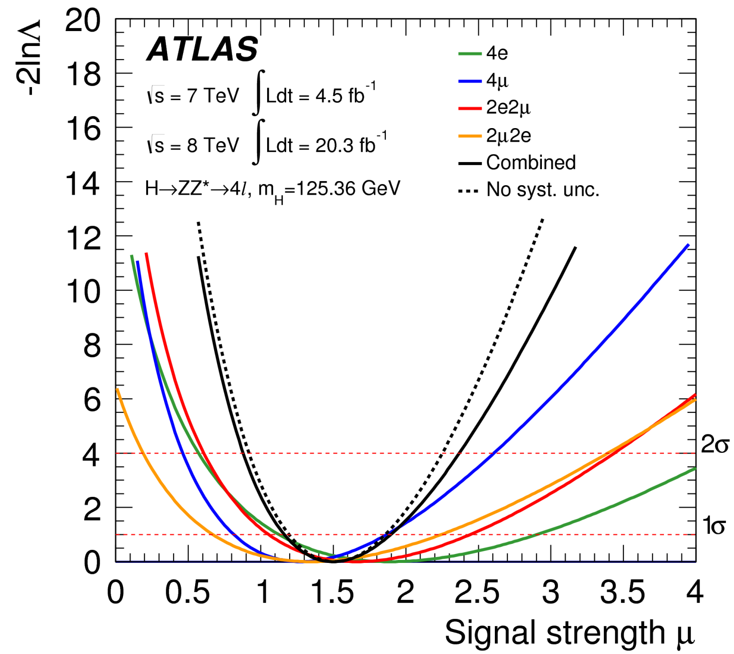
- 2D fit to m_{4l} and a BDT output designed to distinguish signal from ZZ* background
  - mass
  - inclusive μ



- Local significance at mH = 125.36 GeV
  - observed: 8.1 σ
  - expected: 6.2 σ

- Inclusive signal strength:

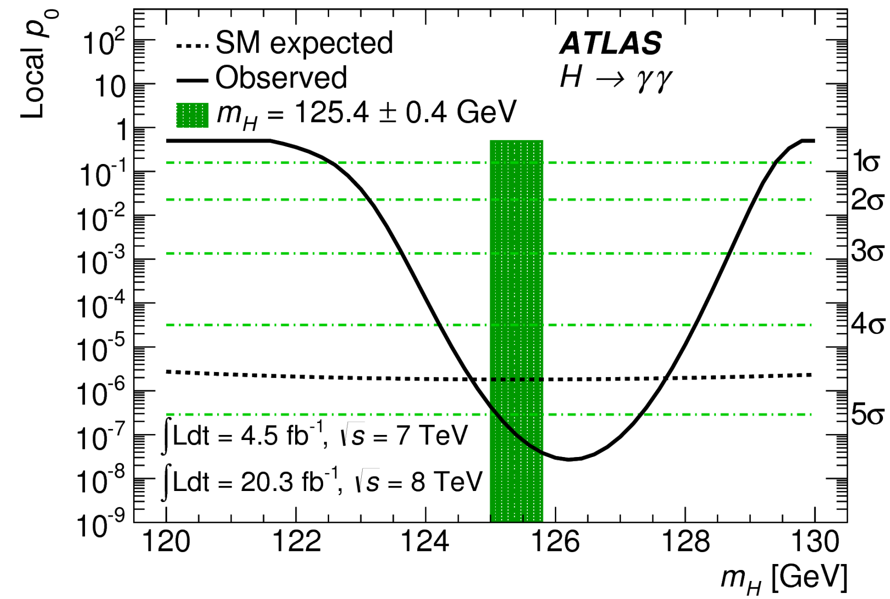
$$\mu = 1.50^{+0.35}_{-0.31}(\text{stat})^{+0.19}_{-0.13}(\text{syst})$$



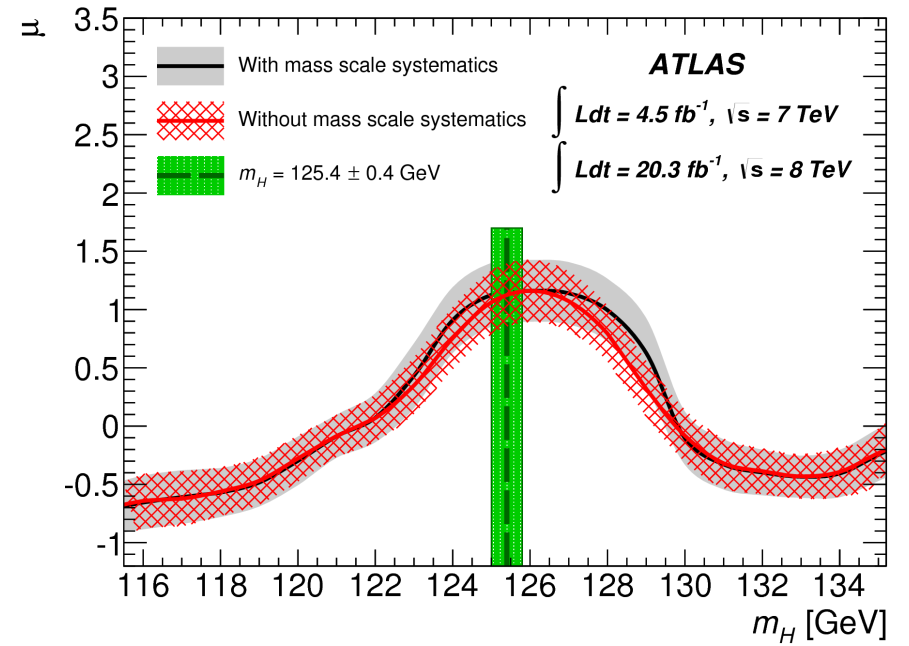
H→γγ: global results

$$\mu = \frac{N^{obs}}{N^{SM}}$$

- Local significance at mH = 125.36 GeV
  - observed: 5.2 σ
  - expected: 4.6 σ



- Signal strength:
  - $\mu = 1.17^{+0.23}_{-0.23}(\text{stat})^{+0.10}_{-0.08}(\text{syst})^{+0.12}_{-0.08}(\text{theo})$
  - main systematic uncertainties:
    - theory (yield): 0.09
    - resolution: 0.07
  - 0.7σ compatibility with SM prediction
  - only slight dependence on m_H



H→WW*→lνlν: global results

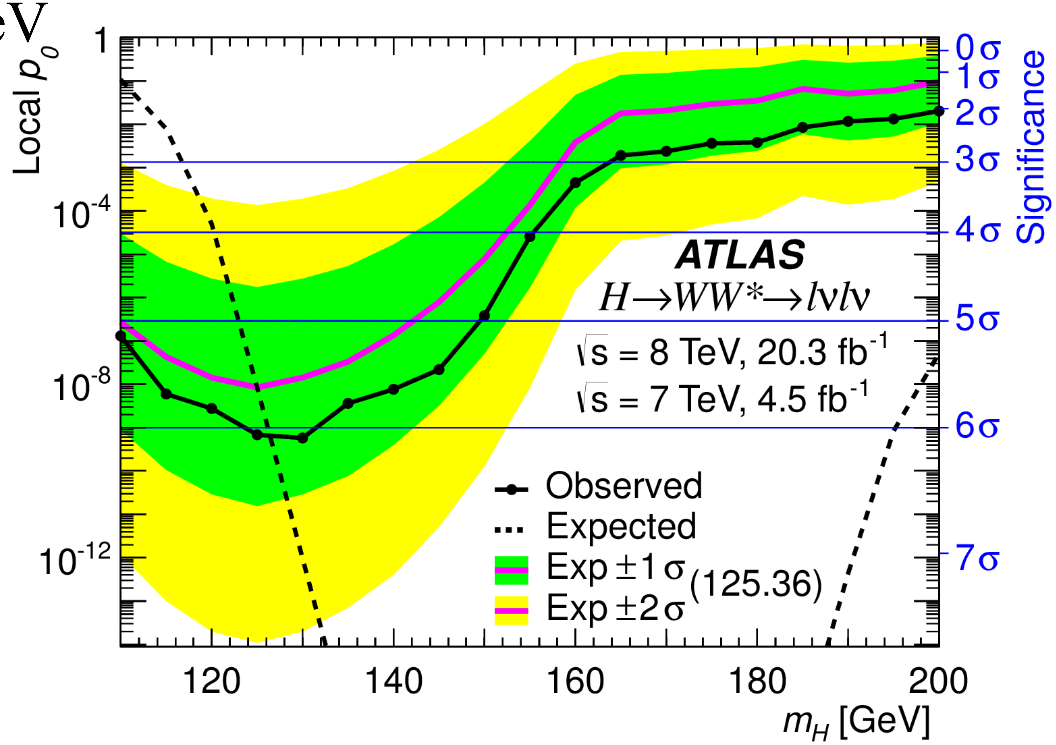
$\mu = \frac{N^{obs}}{N^{SM}}$

- Fit procedure:
  - binned likelihood function
    - ggF: m_T, $p_T^{sublead}$, m_{ll}
    - VBF: BDT discriminant
  - simultaneous fit to all the categories (SR, CR, 7/8TeV)

- Local significance at m_H = 125.36 GeV
  - observed: 6.1 σ
  - expected: 5.8 σ

- Inclusive signal strength:

$$\mu = 1.09^{+0.16}_{-0.15}(\text{stat})^{+0.17}_{-0.14}(\text{syst})$$



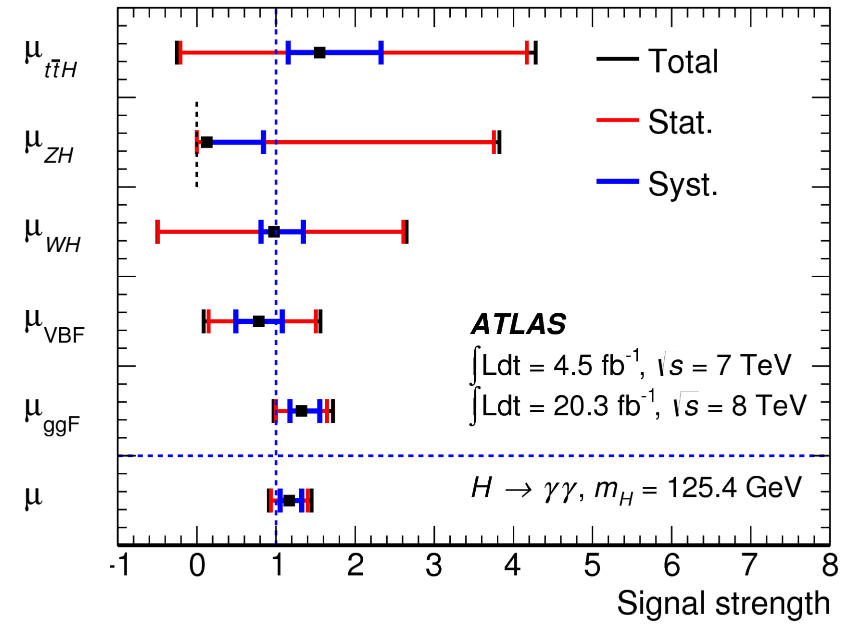
Results for couplings (1)

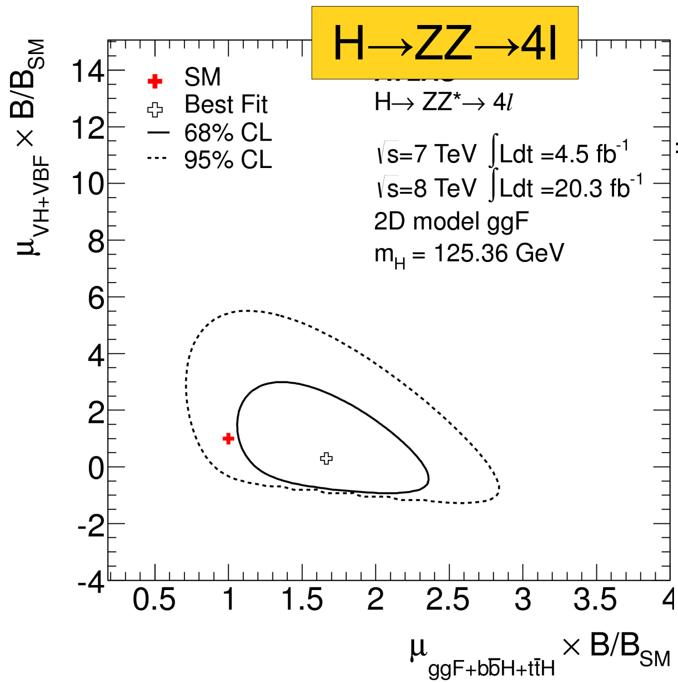
$$\mu = \frac{N^{obs}}{N^{SM}}$$

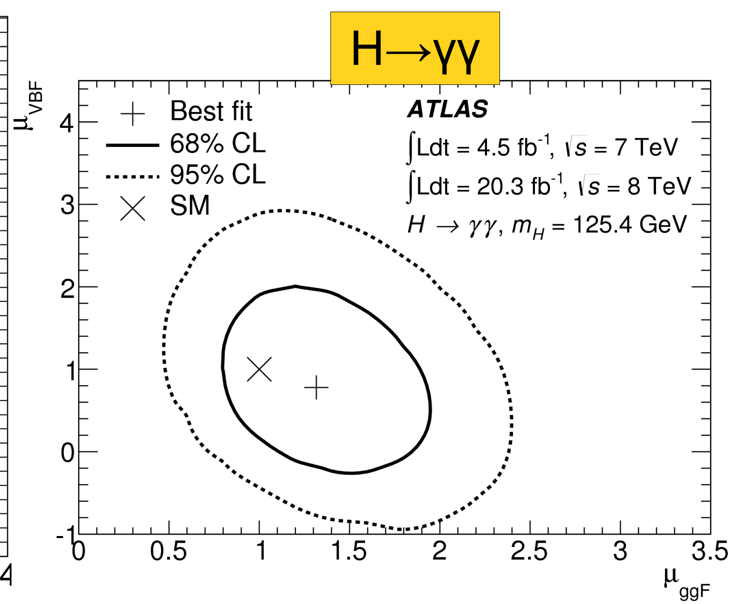
- Signal strength μ /production mode:

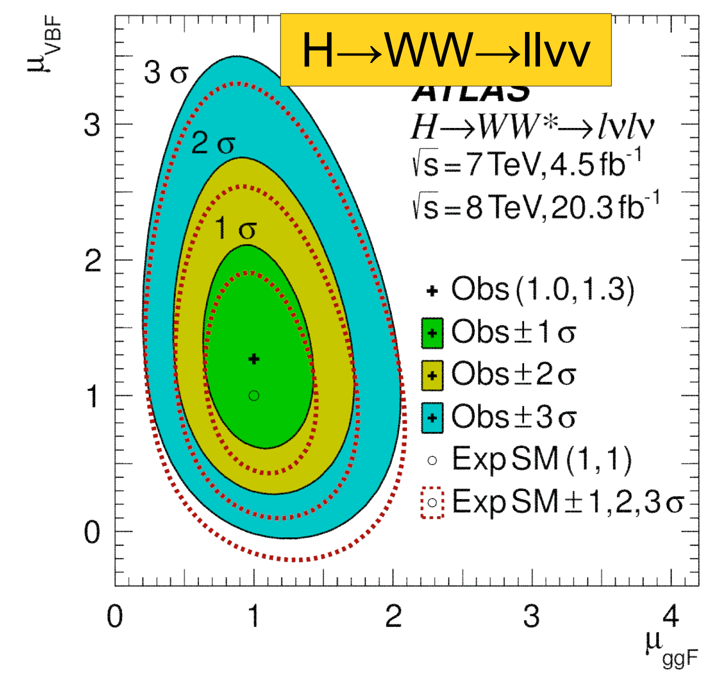
	4l	γγ	WW
ggF	$1.7^{+0.5}_{-0.4}$	1.32 ± 0.38	$1.02^{+0.29}_{-0.26}$
VBF	$0.3^{+1.6}_{-0.9}$	0.8 ± 0.7	$1.27^{+0.53}_{-0.45}$
WH		1.0 ± 1.6	
ZH		$0.1^{+3.7}_{-0.1}$	
ttH		$1.6^{+2.7}_{-1.8}$	

  - all compatible with SM expectation





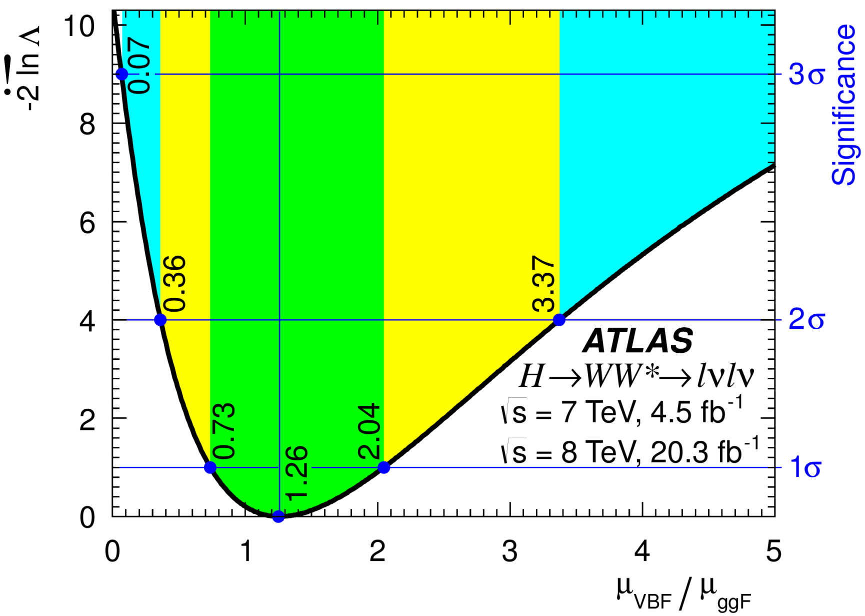




Results for couplings (2)

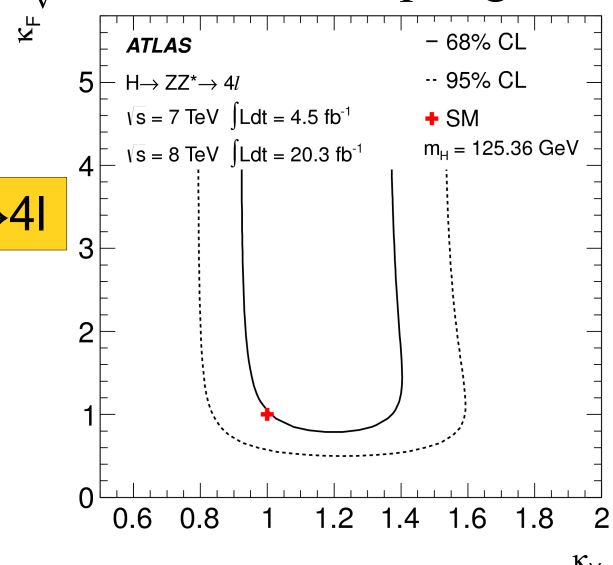
$$\mu = \frac{N^{obs}}{N^{SM}}$$

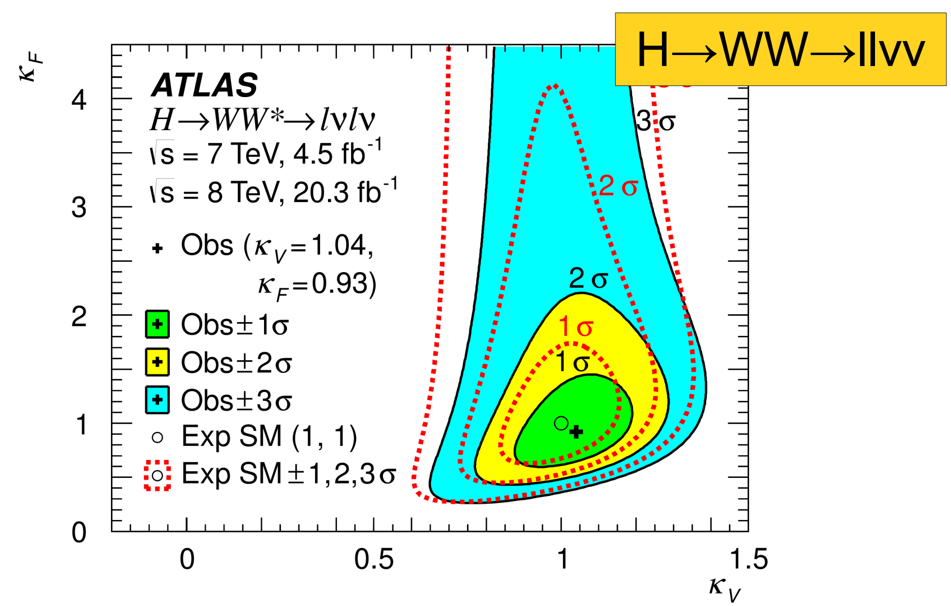
- **Evidence** of **VBF** production in **WW** channel!
  - 3.2σ observed
  - 2.7σ expected



- Couplings scale factors κ to compare to SM prediction
  - κ_F for fermionic couplings
  - κ_V for bosonic couplings

H→ZZ→4l





- Inputs to global coupling fits

One step further: cross-sections

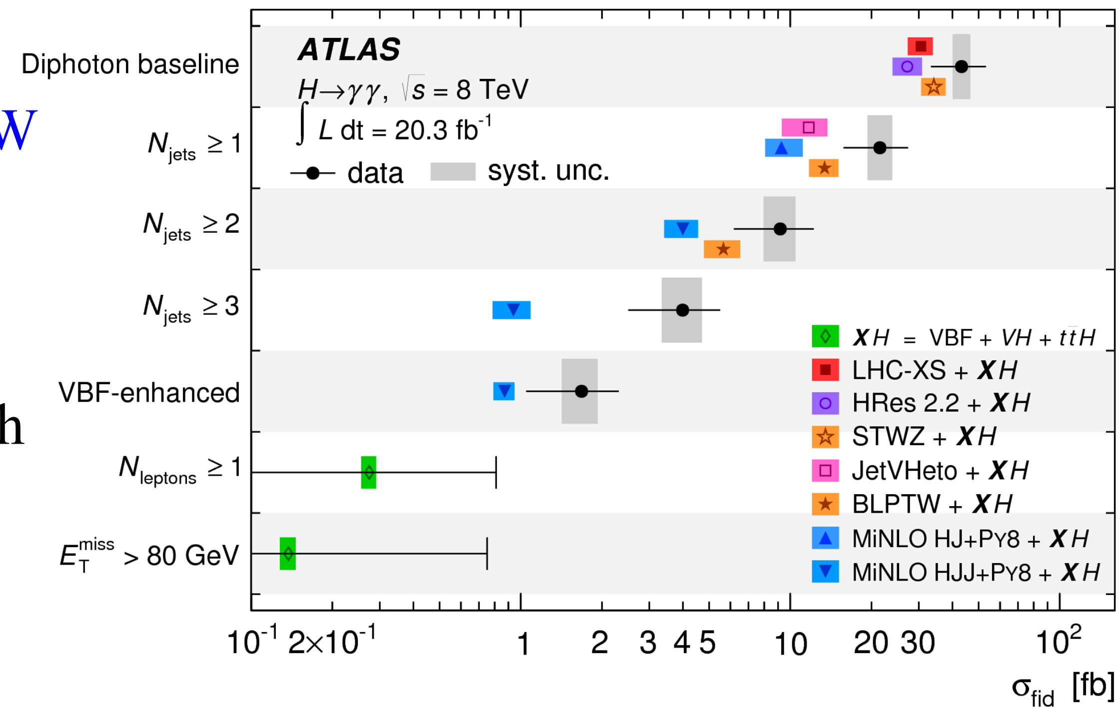
- Computed from number of observed signal events: $\sigma_{fid(tot)} \cdot BR = \frac{N^{sig,obs}}{(A).C.L}$
  - A = acceptance correction factor
  - C = detector correction factor
  - L = integrated luminosity

- Allows easier comparison to theory predictions

JHEP09(2014)112

- **Total** cross-sections in ZZ, γγ, WW
- **Fiducial** cross-sections in ZZ, γγ

- All measurements compatible with expectation within ~2σ



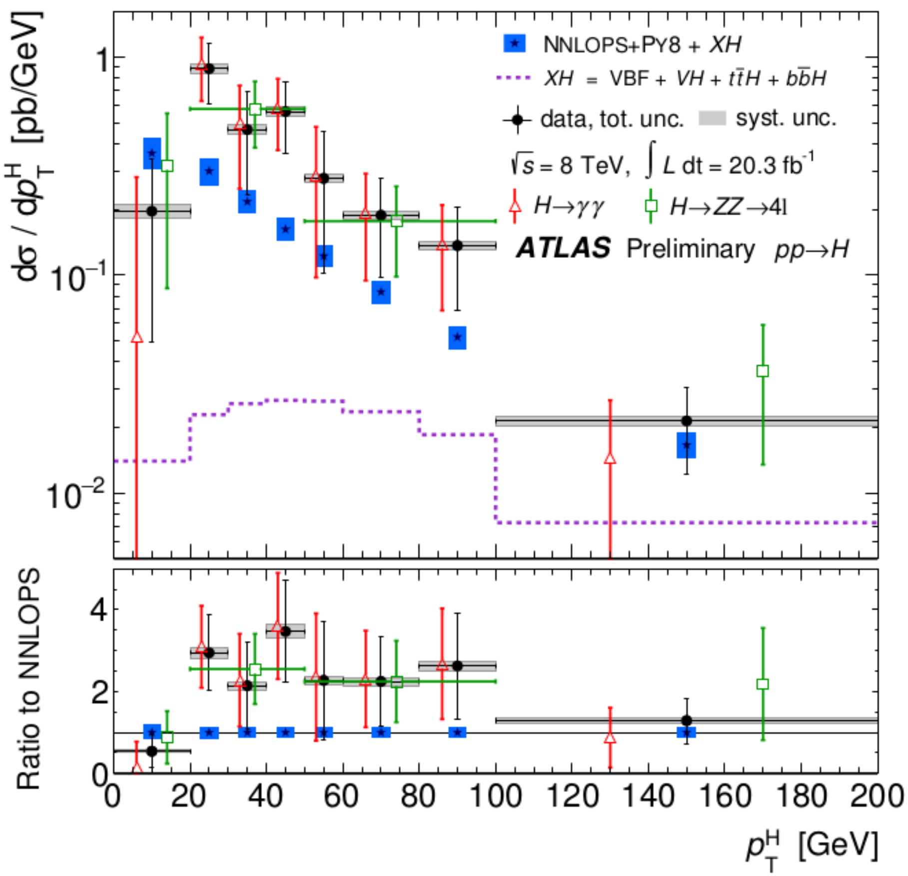
One step further: differential cross-sections

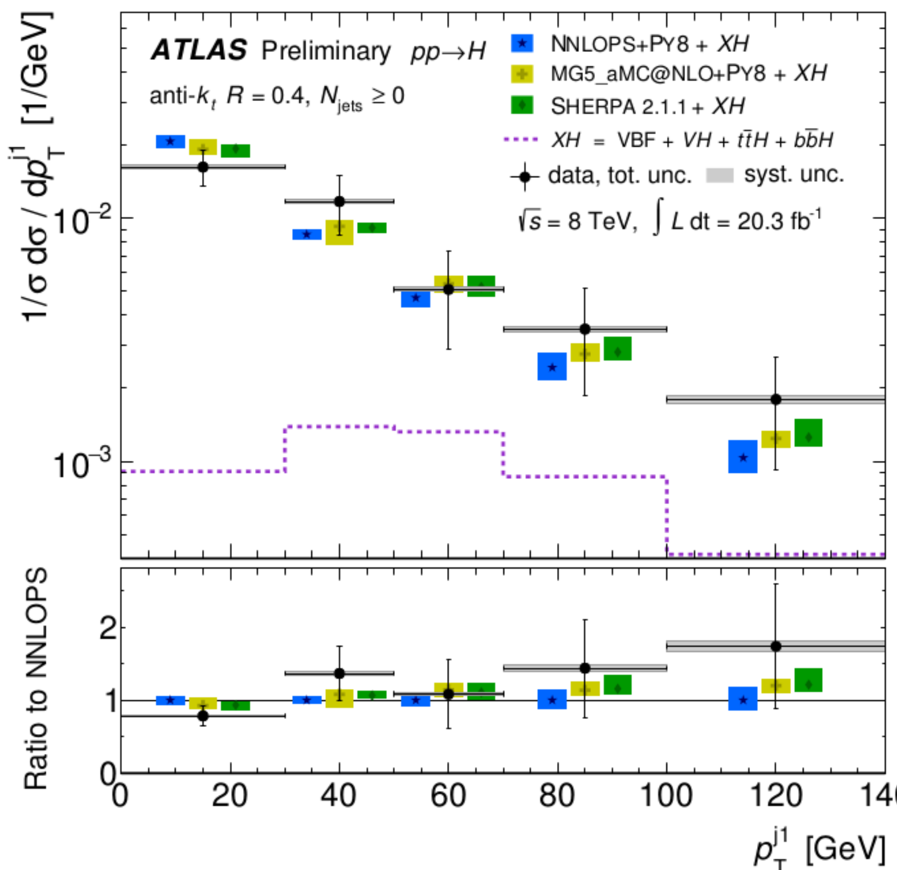
- Variables sensitive to
  - Higgs production
  - spin/CP
  - QCD effect
- New! Combination of γγ and 4l channels (reduces uncertainty by ~30%)

Phys Lett B738 (2014)

JHEP09(2014)112

combination to be submitted





Conclusions

- Final ATLAS results on study of the Higgs boson decaying into bosons with run 1 data
- Separate production modes to go back to couplings
  - data divided in categories enriched in production modes
- Signal strengths /production modes compatible with expectations
- Total, fiducial and differential cross-sections
- More on the combinations of the different channels in the talk by A. Armbruster

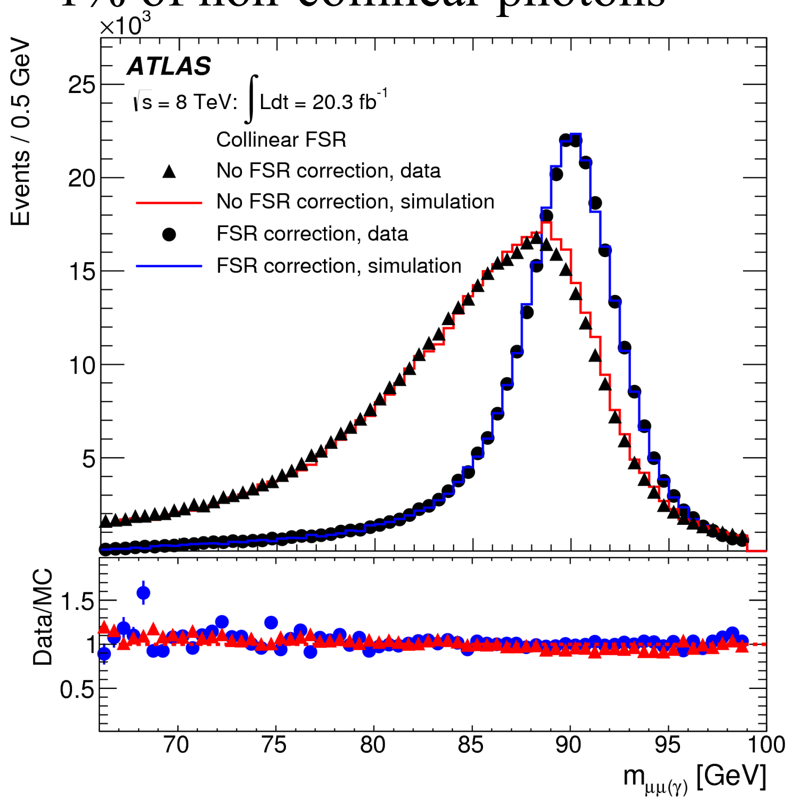
Back-up slides

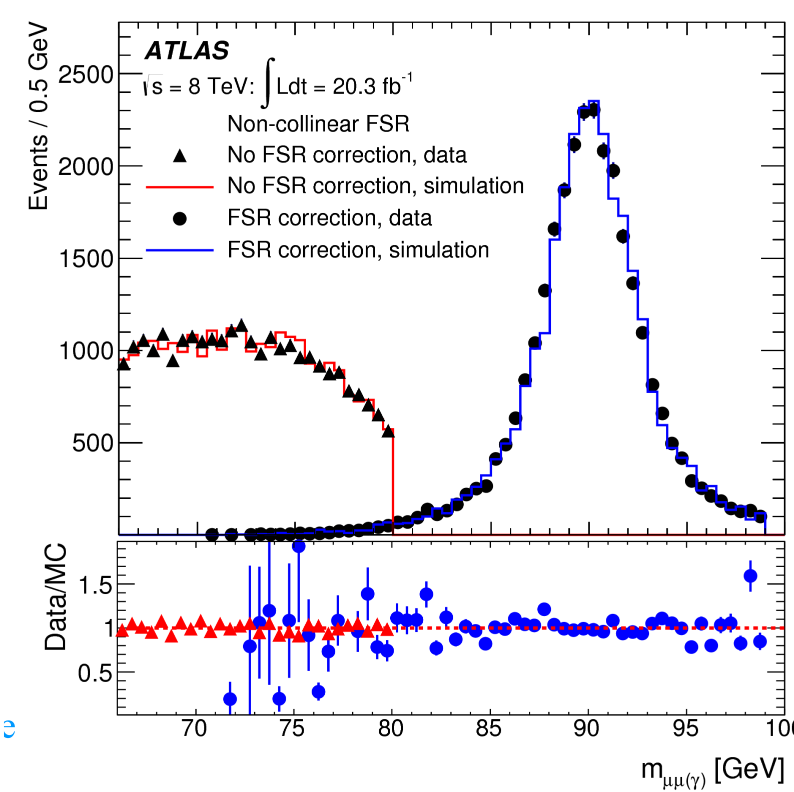
$H \rightarrow 4l$: selection

- Two same-flavour, opposite sign lepton pairs
- $p_T^1 > 20$ GeV, $p_T^2 > 15$ GeV, $p_T^3 > 10$ GeV, $p_T^4 > 7/6$ (e/μ) GeV
- $50 < m_{12} < 106$ GeV
- $m_{min} < m_{34} < 115$ GeV with m_{min} from 12 to 50 GeV for $m_{4l} < 190$ GeV, 50 GeV above
- $\Delta R > 0.1$ between same flavour leptons, $\Delta R > 0.2$ otherwise
- $|d_0|/\sigma d_0 < 6.5/3.5$ (e/μ)
- $p_T^{iso,\ track,\ \Delta R=0.2}/p_T < 0.15$
- $E_T^{iso,\ calo,\ \Delta R=0.2}/E_T$
  - $< 0.3/0.2$ (7/8 TeV) for electrons
  - <0.3 for muons, <0.15 for standalone muons
- Selection efficiency:

H → 4l: FSR recovery

- Some FSR photons can be identified in the calorimeter and incorporated to the 4-lepton measurements
- Efficiency of recovery:
  - 70% for collinear photons (85% purity)
  - 60% for non-collinear photons (95% purity)
- Expected fraction of corrected events:
  - 4% of collinear photons
  - 1% of non-collinear photons





H → 4l: background

- ZZ,WZ: from simulation
- Z+jets, tt: data-driven
  - llll+μμ: simultaneous unbinned fit of four orthogonal control regions
  - llll+ee: simultaneous unbinned fit of nblayer and rTRT in 3ll+X control region
  - extrapolated to signal region with transfer factors
- Number of expected and observed events in 120 < m4l < 130 GeV:

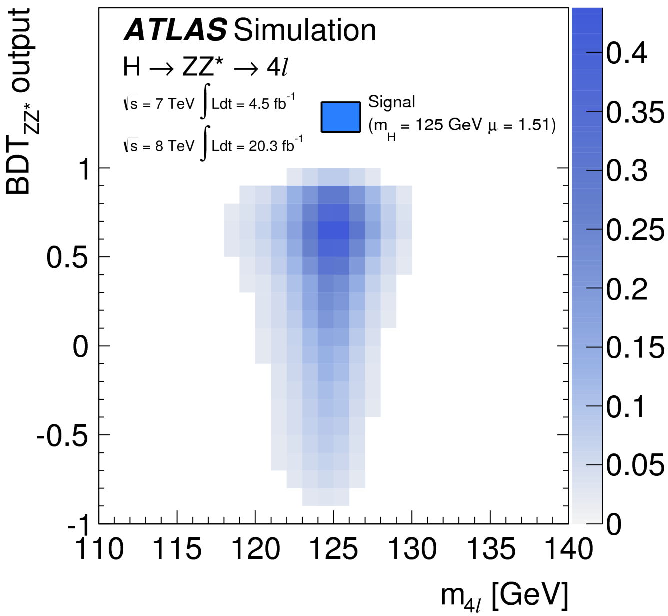
Final state	Signal full mass range	Signal	ZZ^*	$Z+\text{jets}, t\bar{t}$	S/B	Expected	Observed
			$\sqrt{s}=7$ TeV				
4μ	1.00 ± 0.10	0.91 ± 0.09	0.46 ± 0.02	0.10 ± 0.04	1.7	1.47 ± 0.10	2
$2e2\mu$	0.66 ± 0.06	0.58 ± 0.06	0.32 ± 0.02	0.09 ± 0.03	1.5	0.99 ± 0.07	2
$2\mu 2e$	0.50 ± 0.05	0.44 ± 0.04	0.21 ± 0.01	0.36 ± 0.08	0.8	1.01 ± 0.09	1
$4e$	0.46 ± 0.05	0.39 ± 0.04	0.19 ± 0.01	0.40 ± 0.09	0.7	0.98 ± 0.10	1
Total	2.62 ± 0.26	2.32 ± 0.23	1.17 ± 0.06	0.96 ± 0.18	1.1	4.45 ± 0.30	6
			$\sqrt{s}=8$ TeV				
4μ	5.80 ± 0.57	5.28 ± 0.52	2.36 ± 0.12	0.69 ± 0.13	1.7	8.33 ± 0.6	12
$2e2\mu$	3.92 ± 0.39	3.45 ± 0.34	1.67 ± 0.08	0.60 ± 0.10	1.5	5.72 ± 0.37	7
$2\mu 2e$	3.06 ± 0.31	2.71 ± 0.28	1.17 ± 0.07	0.36 ± 0.08	1.8	4.23 ± 0.30	5
$4e$	2.79 ± 0.29	2.38 ± 0.25	1.03 ± 0.07	0.35 ± 0.07	1.7	3.77 ± 0.27	7
Total	15.6 ± 1.6	13.8 ± 1.4	6.24 ± 0.34	2.00 ± 0.28	1.7	22.1 ± 1.5	31
			$\sqrt{s}=7$ TeV and $\sqrt{s}=8$ TeV				
4μ	6.80 ± 0.67	6.20 ± 0.61	2.82 ± 0.14	0.79 ± 0.13	1.7	9.81 ± 0.64	14
$2e2\mu$	4.58 ± 0.45	4.04 ± 0.40	1.99 ± 0.10	0.69 ± 0.11	1.5	6.72 ± 0.42	9
$2\mu 2e$	3.56 ± 0.36	3.15 ± 0.32	1.38 ± 0.08	0.72 ± 0.12	1.5	5.24 ± 0.35	6
$4e$	3.25 ± 0.34	2.77 ± 0.29	1.22 ± 0.08	0.76 ± 0.11	1.4	4.75 ± 0.32	8
Total	18.2 ± 1.8	16.2 ± 1.6	7.41 ± 0.40	2.95 ± 0.33	1.6	26.5 ± 1.7	37

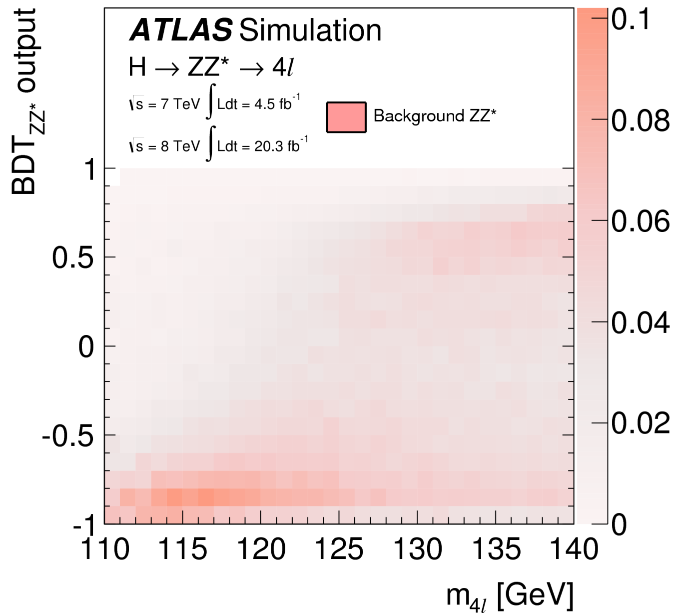
$H \rightarrow 4l$: multivariate discriminants

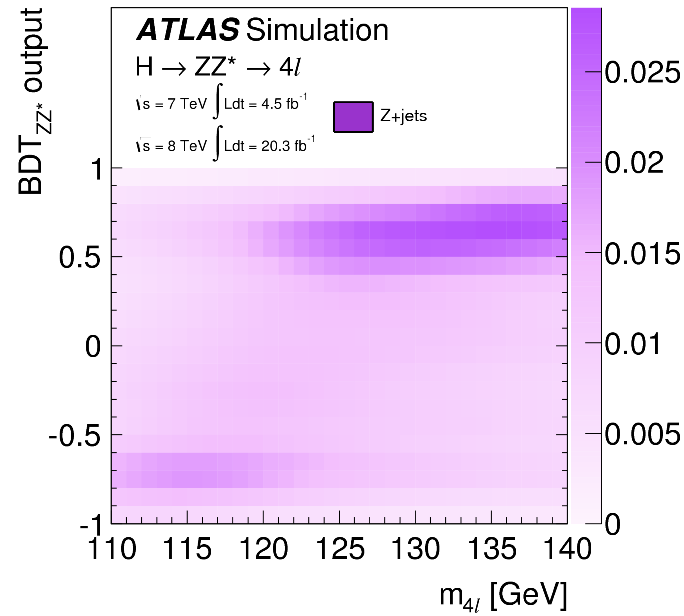
	input variables	sample	usage
BDT_{ZZ^*}	KD_{ZZ^*}, pT4l, η4l	$115 < m_{4l} < 130$ GeV signal vs ZZ	fitting observable in ggF enriched
BDT_{VBF}	mjj, Δηjj, pTj1, pTj2, ηj1	mjj > 130 GeV VBF vs ggF	categories fitting observable in VBF enriched
BDT_{VH}	mjj, Δηjj, pTj1, pTj2, ηj1	40 < mjj < 130 GeV VH vs ggF	category selection requirement for VH had category

H → 4l: ggF enriched category

- Signal:
- Background ZZ*:
- Background Z+jets:

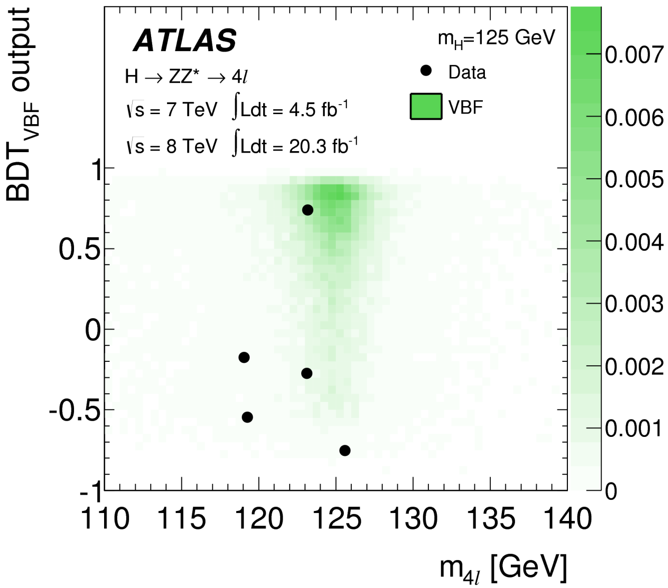


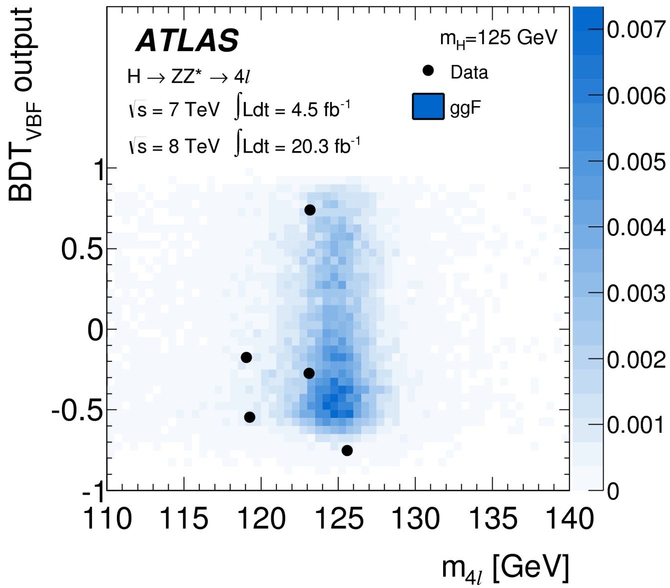


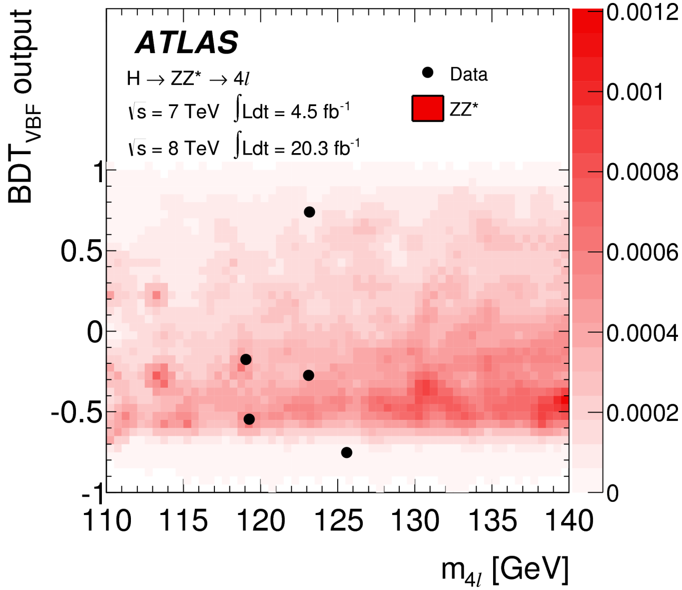


$H \rightarrow 4l$: VBF enriched category

- VBF:
- ggF:
- Background ZZ*:







H → 4l: systematic uncertainties (1)

- For the combined analysis:

Source of uncertainty	4μ	$2e2\mu$	$2\mu 2e$	$4e$	combined
Electron reconstruction and identification efficiencies	–	1.7%	3.3%	4.4%	1.6%
Electron isolation and impact parameter selection	–	0.07%	1.1%	1.2%	0.5%
Electron trigger efficiency	–	0.21%	0.05%	0.21%	<0.2%
$\ell\ell + ee$ backgrounds	–	–	3.4%	3.4%	1.3%
Muon reconstruction and identification efficiencies	1.9%	1.1%	0.8%	–	1.5%
Muon trigger efficiency	0.6%	0.03%	0.6%	–	0.2%
$\ell\ell + \mu\mu$ backgrounds	1.6%	1.6%	–	–	1.2%
QCD scale uncertainty					6.5%
PDF, α_s uncertainty					6.0%
$H \to ZZ^*$ branching ratio uncertainty					4.0%

H → 4l: systematic uncertainties (2)

- In the different production mode categories:

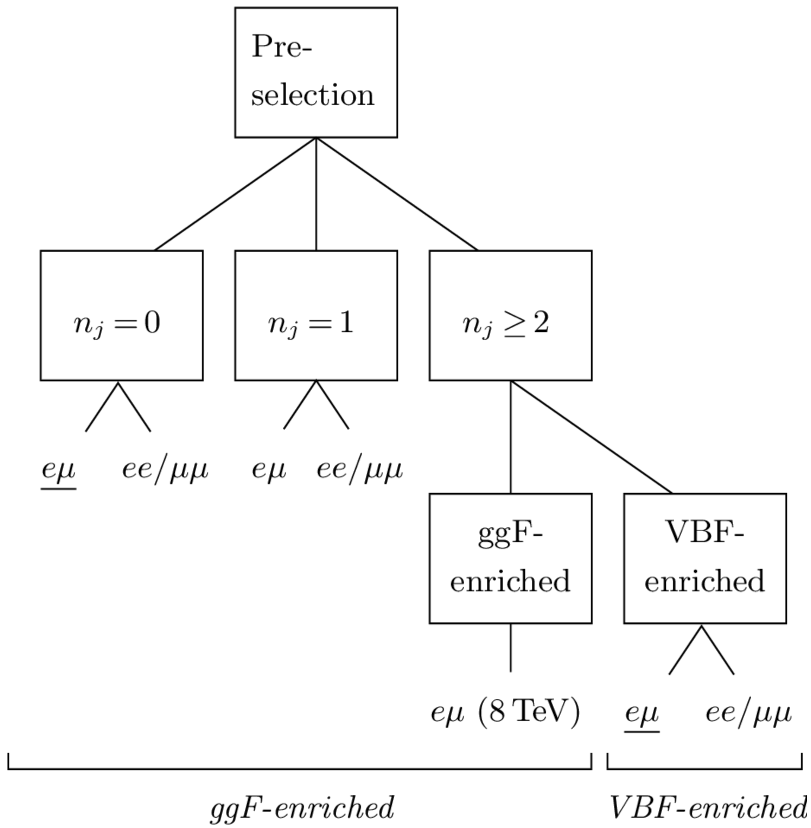
Process	$gg \to H, q\bar{q}/gg \to b\bar{b}H/t\bar{t}H$	$qq' \to Hqq'$	$q\bar{q} \to W/ZH$	ZZ^*
	VBF enriched category			
Theoretical cross section	20.4%	4%	4%	8%
Underlying event	6.6%	1.4%	–	–
Jet energy scale	9.6%	4.8%	7.8%	9.6%
Jet energy resolution	0.9%	0.2%	1.0%	1.4%
Total	23.5%	6.4%	8.8%	12.6%
	VH-hadronic enriched category			
Theoretical cross section	20.4%	4%	4%	2%
Underlying event	7.5%	3.1%	–	–
Jet energy scale	9.4%	9.3%	3.7%	12.6%
Jet energy resolution	1.0%	1.7%	0.6%	1.8%
Total	23.7%	10.7%	5.5%	12.9%
	VH-leptonic enriched category			
Theoretical cross section	12%	4%	4%	5%
Leptonic VH-specific cuts	1%	1%	5%	–
Jet energy scale	8.8%	9.9%	1.7%	3.2%
Total	14.9%	10.7%	6.6%	5.9%
	ggF enriched category			
Theoretical cross section	12%	4%	4%	4%
Jet energy scale	2.2%	6.6%	4.0%	1.0%
Total	12.2%	7.7%	5.7%	4.1%

H → 4l: changes wrt last public paper

- Phys. Lett. B 726 (2013)
- electron identification: likelihood method: improve bkg rejection for same efficiency
- electron transverse energy measurement improved: refined cluster energy reconstruction + combination of cluster energy and track momentum
- energy scale of electrons and momentum scale of muons improved
- correction of FSR for non-collinear photons
- BDT against ZZ* background
- better estimate of ll+jets and $t\bar{t}$ bkg
- VH category with two jets + BDT for VBF

H→WW: analysis strategy

- Exclusive categories based on jet multiplicity and lepton flavour



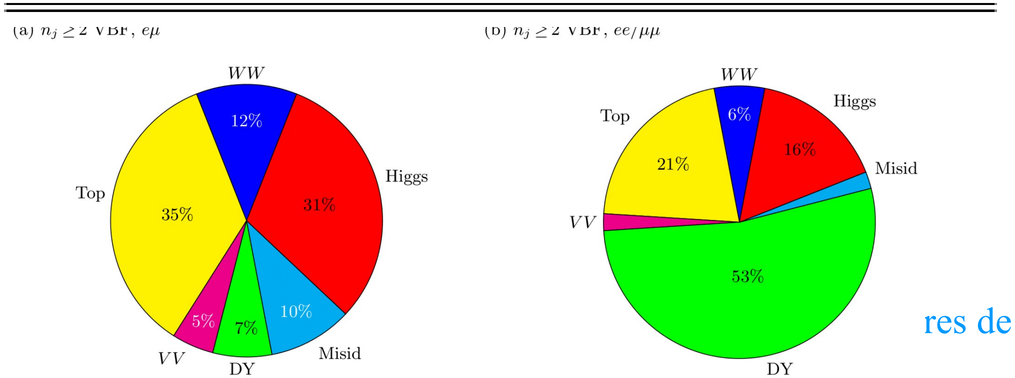
- Most sensitive categories:
  - Njet = 0 and eμ for ggF
  - Njet ≥ 2 and eμ for VBF

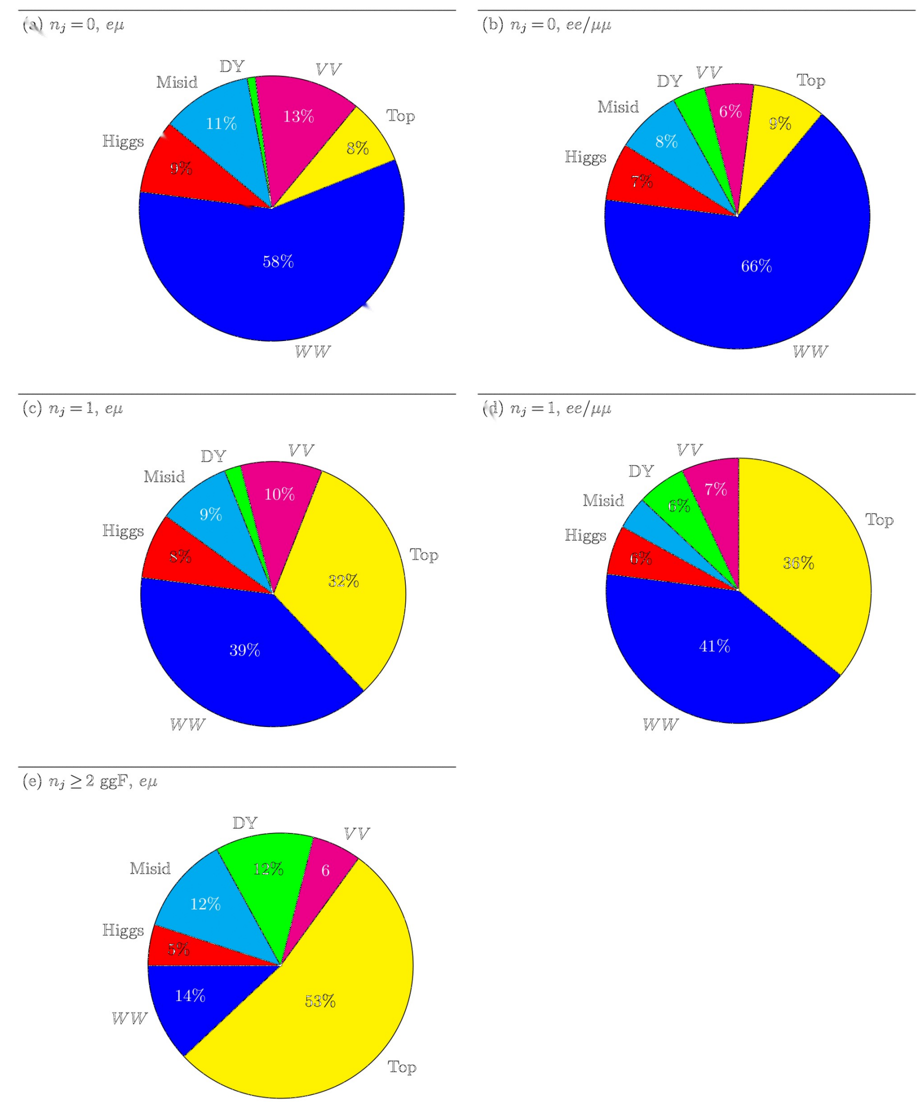
H→WW: selection

Objective		ggF-enriched			VBF-enriched
		$n_j = 0$	$n_j = 1$	$n_j \geq 2$ ggF	$n_j \geq 2$ VBF
Preselection	All n_j	$p_T^{\ell 1} > 22$ for the leading lepton ℓ_1			
	All n_j	$p_T^{\ell 2} > 10$ for the subleading lepton ℓ_2			
	All n_j	Opposite-charge leptons			
	All n_j	$m_{\ell\ell} > 10$ for the $e\mu$ sample			
	All n_j	$m_{\ell\ell} > 12$ for the $ee/\mu\mu$ sample			
	All n_j	$\lvert m_{\ell\ell} - m_Z \rvert > 15$ for the $ee/\mu\mu$ sample			
		$p_T^{\rm miss} > 20$ for $e\mu$	$p_T^{\rm miss} > 20$ for $e\mu$	$p_T^{\rm miss} > 20$ for $e\mu$	No MET requirement for $e\mu$
		$E_{\rm T,rel}^{\rm miss} > 40$ for $ee/\mu\mu$	$E_{\rm T,rel}^{\rm miss} > 40$ for $ee/\mu\mu$	-	-
Reject backgrounds	DY	$p_{\rm T,rel}^{\rm miss\,(trk)} > 40$ for $ee/\mu\mu$	$p_{\rm T,rel}^{\rm miss\,(trk)} > 35$ for $ee/\mu\mu$	-	$p_T^{\rm miss} > 40$ for $ee/\mu\mu$
	DY	$f_{\rm recoil} < 0.1$ for $ee/\mu\mu$	$f_{\rm recoil} < 0.1$ for $ee/\mu\mu$	-	$E_T^{\rm miss} > 45$ for $ee/\mu\mu$
	DY	$p_T^{\ell\ell} > 30$	$m_{\tau\tau} < m_Z - 25$	$m_{\tau\tau} < m_Z - 25$	$m_{\tau\tau} < m_Z - 25$
	DY	$\Delta\phi_{\ell\ell,\rm MET} > \pi/2$	-	-	-
	Misid.	-	$m_T^{\ell} > 50$ for $e\mu$	-	-
	Top	$n_j = 0$	$n_b = 0$	$n_b = 0$	$n_b = 0$
	Top	-	-	-	$p_T^{\rm sum}$ inputs to BDT
	Top	-	-	-	$\Sigma m_{\ell j}$ inputs to BDT
VBF topology		-	-	See Sec. IV D for rejection of VBF & VH ($W, Z \to jj$), where $H \to WW^*$	m_{jj} inputs to BDT Δy_{jj} inputs to BDT ΣC_ℓ inputs to BDT $C_{\ell 1} < 1$ and $C_{\ell 2} < 1$ $C_{j3} > 1$ for j_3 with $p_T^{j3} > 20$ $O_{\rm BDT} \geq -0.48$
$H \to WW^* \to \ell\nu\ell\nu$ decay topology		$m_{\ell\ell} < 55$ $\Delta\phi_{\ell\ell} < 1.8$ No m_T requirement	$m_{\ell\ell} < 55$ $\Delta\phi_{\ell\ell} < 1.8$ No m_T requirement	$m_{\ell\ell} < 55$ $\Delta\phi_{\ell\ell} < 1.8$ No m_T requirement	$m_{\ell\ell}$ inputs to BDT $\Delta\phi_{\ell\ell}$ inputs to BDT m_T inputs to BDT

H→WW: background

Name	Process	Feature(s)
WW	WW	Irreducible
Top quarks		
$t\bar{t}$	$t\bar{t} \to WbW\bar{b}$	Unidentified b-quarks
t	tW	Unidentified b-quark
	$t\bar{b}$, $tq\bar{b}$	q or b misidentified as ℓ; unidentified b-quarks
Misidentified leptons (Misid.)		
Wj	$W+$jet(s)	j misidentified as ℓ
jj	Multijet production	jj misidentified as $\ell\ell$; misidentified neutrinos
Other dibosons		
VV	$W\gamma$	γ misidentified as e
	$W\gamma^*$, WZ, $ZZ \to \ell\ell\,\ell\ell$	Unidentified lepton(s)
	$ZZ \to \ell\ell\,\nu\nu$	Irreducible
	$Z\gamma$	γ misidentified as e; unidentified lepton
Drell-Yan (DY)		
$ee/\mu\mu$	$Z/\gamma^* \to ee,\ \mu\mu$	Misidentified neutrinos
$\tau\tau$	$Z/\gamma^* \to \tau\tau \to \ell\nu\nu\,\ell\nu\nu$	Irreducible

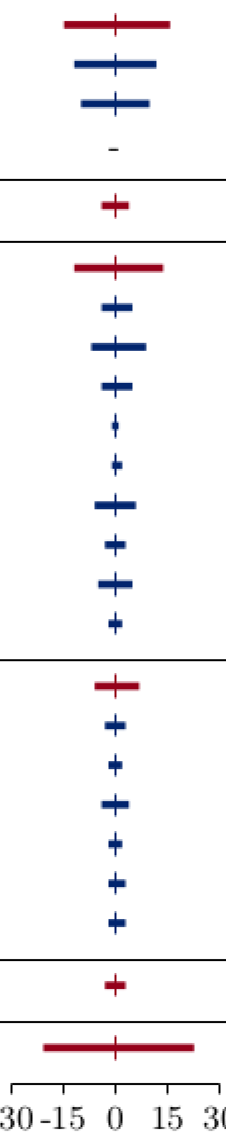




H→WW: systematic uncertainties

- Three major categories of uncertainties:
  - stat: for backgrounds which use data for normalization (sample statistics)
  - experimental: leptons, jets, ETmiss, pTmiss, charge mis-identification, …
  - theo.: x-sec scale, acceptance, modelling . . .
- Leading sources of uncertainties on μ:
  - WW generator modelling (on the mT shape and extrapolation)
  - ggF, QCD scale on the total x-sec
  - top generator modeling (on the extrapolation),
  - corrections to the mis-identification factor, ...

Source	Observed $\mu = 1.09$ Error +	−	Plot of error (scaled by 100)
Data statistics	0.16	0.15	
Signal regions	0.12	0.12	
Profiled control regions	0.10	0.10	
Profiled signal regions	-	-	-
MC statistics	0.04	0.04	
Theoretical systematics	0.15	0.12	
Signal $H \to WW^* \mathcal{B}$	0.05	0.04	
Signal ggF cross section	0.09	0.07	
Signal ggF acceptance	0.05	0.04	
Signal VBF cross section	0.01	0.01	
Signal VBF acceptance	0.02	0.01	
Background WW	0.06	0.06	
Background top quark	0.03	0.03	
Background misid. factor	0.05	0.05	
Others	0.02	0.02	
Experimental systematics	0.07	0.06	
Background misid. factor	0.03	0.03	
Bkg. $Z/\gamma^* \to ee, \mu\mu$	0.02	0.02	
Muons and electrons	0.04	0.04	
Missing transv. momentum	0.02	0.02	
Jets	0.03	0.02	
Others	0.03	0.02	
Integrated luminosity	0.03	0.03	
Total	0.23	0.21	



H→WW: fit model

- Fit procedure:
  - binned likelihood function constructed as a product of Poisson probabilities and systematic constraints,
  - profile likelihood ratio test statistic is used
  - simultaneous fit to all the categories (SR, CR, 7/8TeV)
- Free parameters:
  - μ - signal strength parameter
  - β – background normalization
  - θ - uncertainty constraint parameter

SR category i				Fit var.
n_j, flavor	$\otimes\, m_{\ell\ell}$	$\otimes\, p_T^{\ell 2}$	$\otimes\, \ell_2$	
$n_j = 0$				
$e\mu$	$\otimes\, [10, 30, 55]$	$\otimes\, [10, 15, 20, \infty]$	$\otimes\, [e, \mu]$	m_T
$ee/\mu\mu$	$\otimes\, [12, 55]$	$\otimes\, [10, \infty]$		m_T
$n_j = 1$				
$e\mu$	$\otimes\, [10, 30, 55]$	$\otimes\, [10, 15, 20, \infty]$	$\otimes\, [e, \mu]$	m_T
$ee/\mu\mu$	$\otimes\, [12, 55]$	$\otimes\, [10, \infty]$		m_T
$n_j \geq 2$ ggF				
$e\mu$	$\otimes\, [10, 55]$	$\otimes\, [10, \infty]$		m_T
$n_j \geq 2$ VBF				
$e\mu$	$\otimes\, [10, 50]$	$\otimes\, [10, \infty]$		O_{BDT}
$ee/\mu\mu$	$\otimes\, [12, 50]$	$\otimes\, [10, \infty]$		O_{BDT}

H→WW: cross-sections

- Total cross-sections (pb):

		observed	expected
7 GeV	σ_{ggF}.BR(H → WW*)	2.0 ± 1.7 (stat) +1.2-1.1 (syst)	3.3 ± 0.4
8 GeV	σ_{ggF}.BR(H → WW*)	4.6 ± 0.9 (stat) +0.8-0.7 (syst)	4.6 ± 0.5
	σ_{VBF}.BR(H → WW*)	0.51 +0.17-0.15 (stat) +0.13-0.08 (syst)	0.35 ± 0.02

- Fiducial cross-sections
  - fiducial volume definition:

Type	$n_j = 0$	$n_j = 1$
Preselection	$p_T^{\ell 1} > 22$ $p_T^{\ell 2} > 10$ Opposite charge ℓ $m_{\ell\ell} > 10$ $p_T^{\nu\nu} > 20$	
n_j-dependent	$\Delta\phi_{\ell\ell,\nu\nu} > \pi/2$	-
	$p_T^{\ell\ell} > 30$	-
	-	$m_T^{\ell} > 50$
	-	$m_{\tau\tau} < 66$
	$m_{\ell\ell} < 55$	$m_{\ell\ell} < 55$
	$\Delta\phi_{\ell\ell} < 1.8$	$\Delta\phi_{\ell\ell} < 1.8$

  - cross-sections in fb:

		observed	expected
8 GeV	σ_{ggF}, 0 jet	27.6 +5.4-5.3 (stat) +4.1-3.9 (syst)	19.9 ± 3.3
	σ_{ggF}, 1 jet	8.3 +3.1-3.0 (stat) +3.1-3.0 (syst)	7.3 ± 1.8

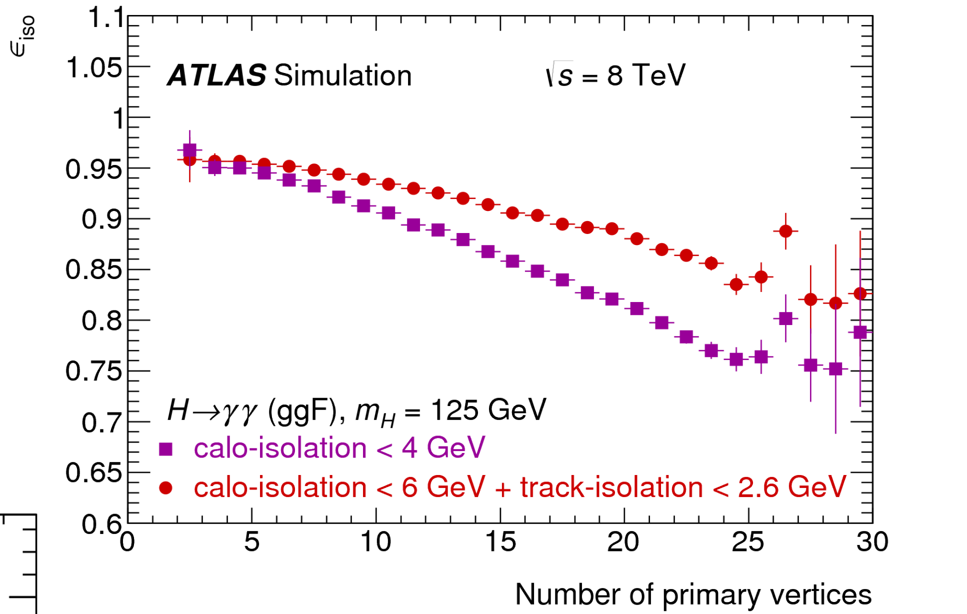
$H \to WW$: changes wrt last public paper

- Phys. Lett. B 726 (2013)
- optimized object and event selection: pT , mT resolution, ...
- increased signal acceptance: lower lepton pT thresholds, electron likelihood
- background estimation techniques : b-tagging efficiency from data, jj estimate, Z + jets sample for Wj estimate, ...
- optimized VBF signal category
- new analysis category ($N_{jet} \geq 2$ ggF-enriched),
- more powerful statistical treatment (binned in m_T and p_T^{l2})

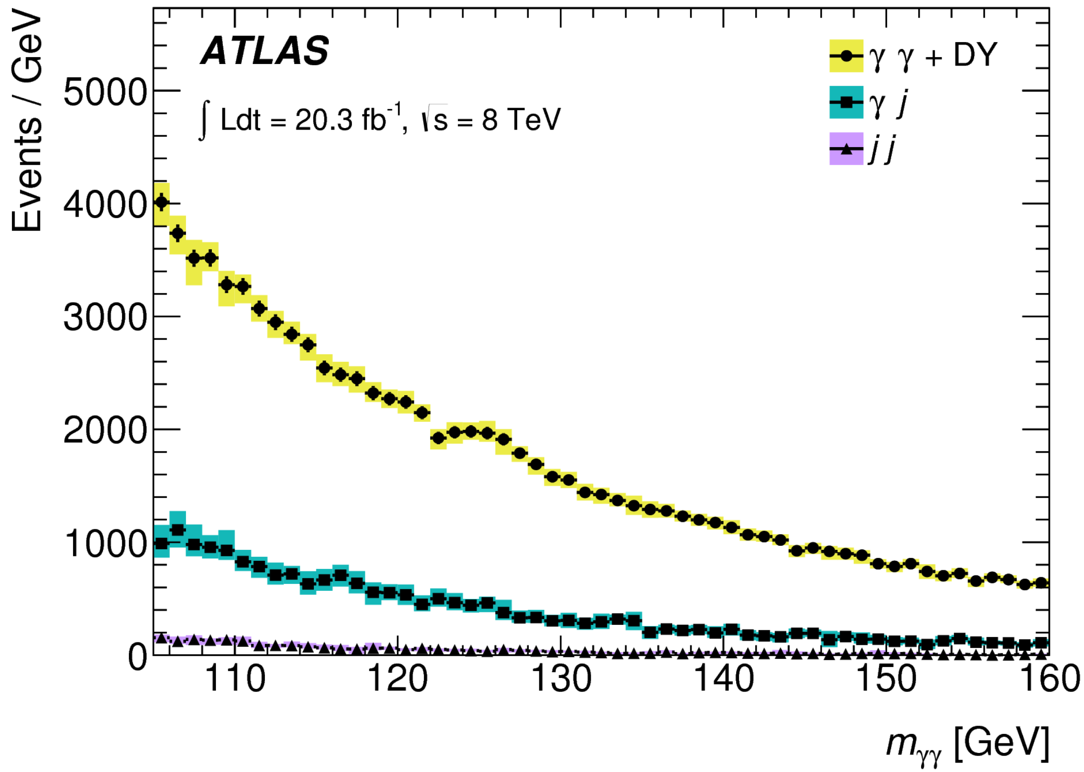
- 50% increase in the expected sensitivity

H→γγ: selection

- $E_T^{\gamma1}/m_{\gamma\gamma} > 0.35$, $E_T^{\gamma2}/m_{\gamma\gamma} > 0.25$
- tight identification
- $E_T^{iso,calo} < 6$ GeV, $E_T^{iso,track} < 2.6$ GeV



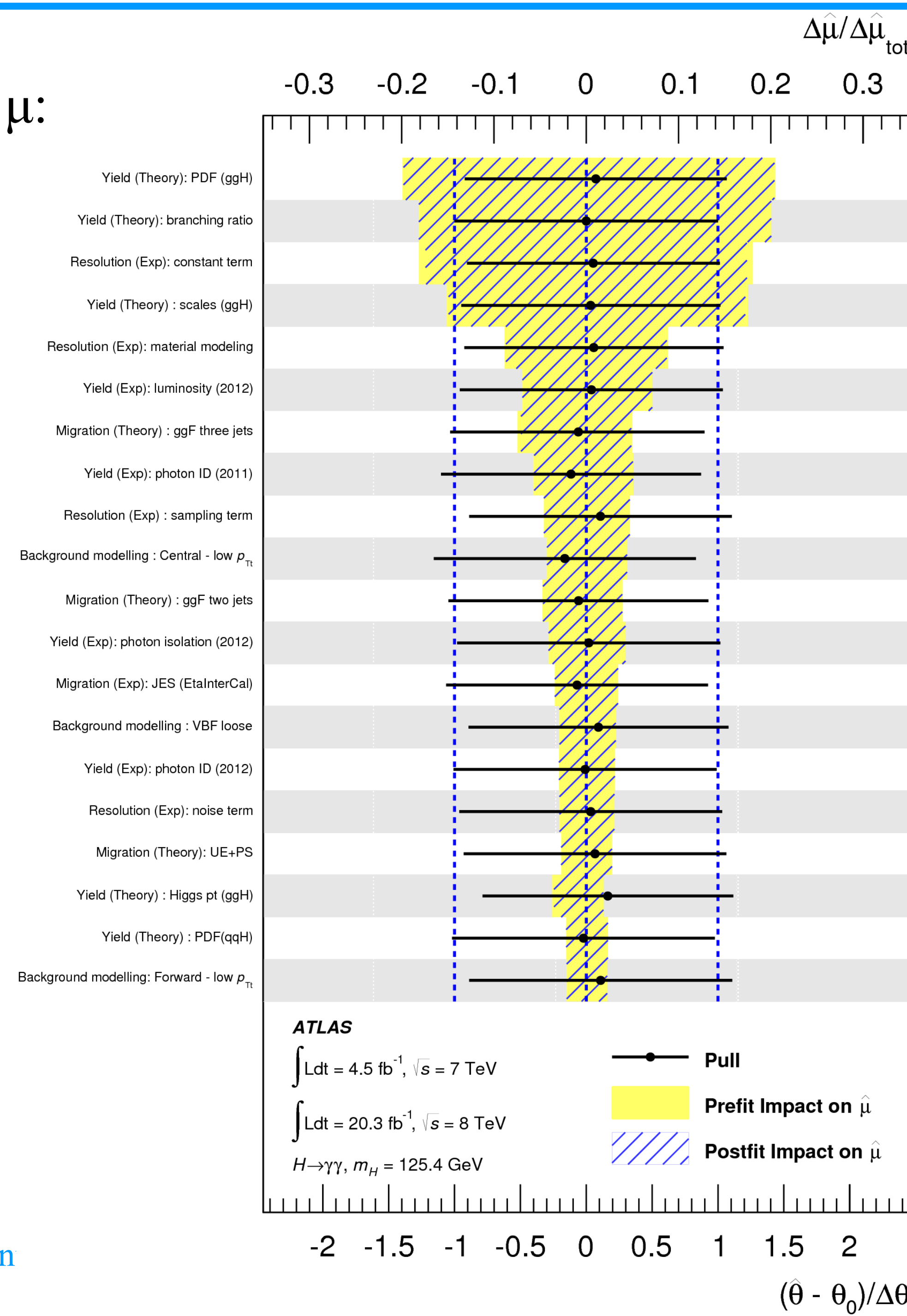
- γγ purity: 77±3% at 8 TeV



H→γγ: systematic uncertainties

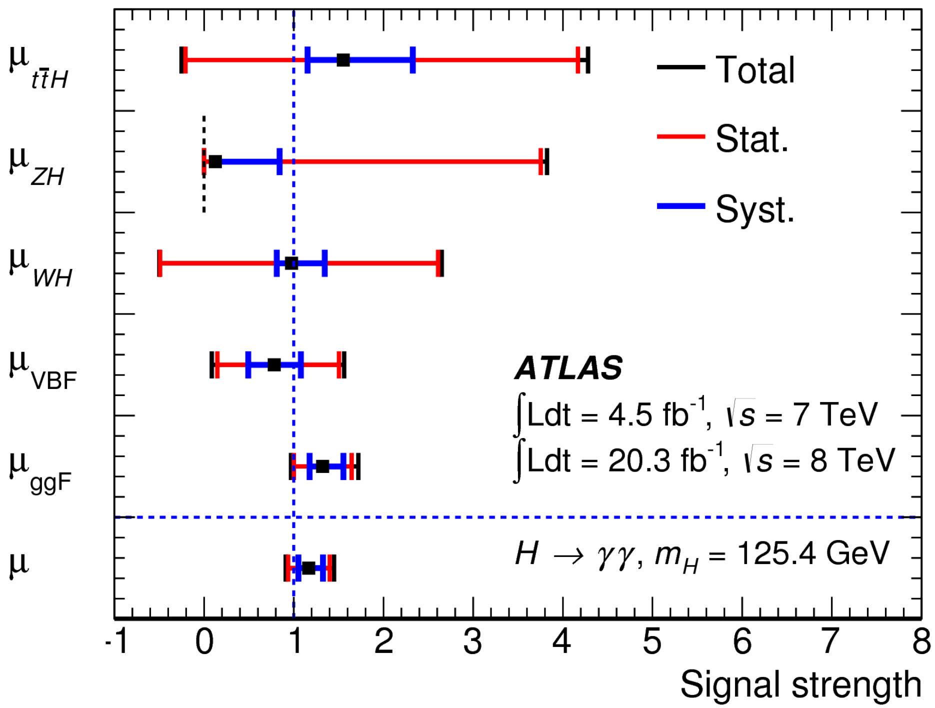
♦ Main systematics and impact on μ:

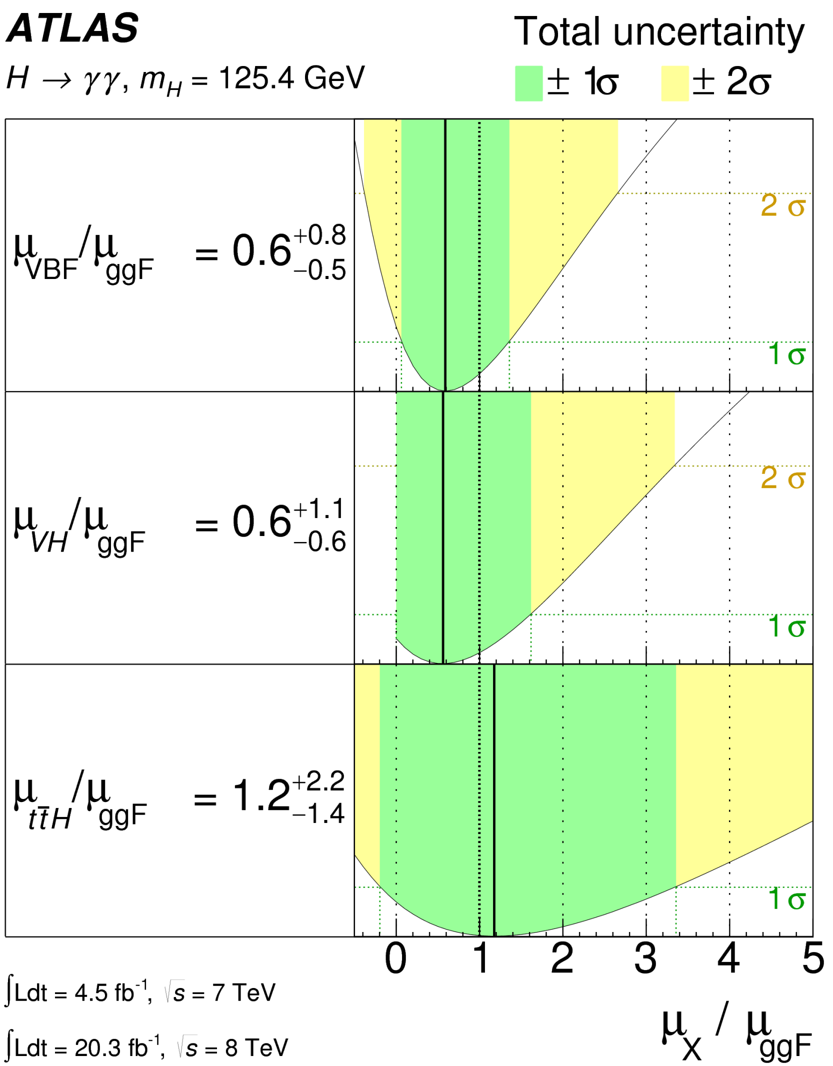
Uncertainty group	$\sigma_{\mu}^{syst.}$
Theory (yield)	0.09
Experimental (yield)	0.02
Luminosity	0.03
MC statistics	< 0.01
Theory (migrations)	0.03
Experimental (migrations)	0.02
Resolution	0.07
Mass scale	0.02
Background shape	0.02



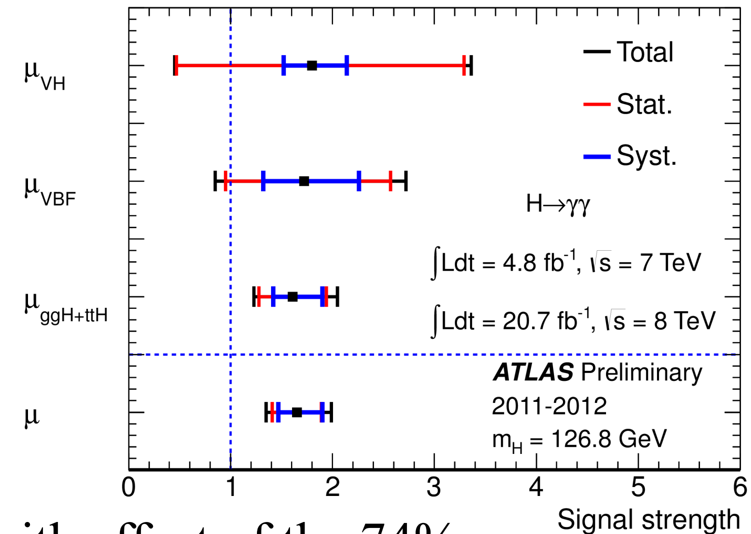
H→γγ: results

- Signal strength /production mode:





H→γγ: compatibility of results



- checked with jackknife resampling technique
- Phys. Lett. B 726 (2013) : $\mu = 1.55^{+0.33}_{-0.28}$
  - 142681 events selected there
  - 111791 events selected in current analysis
  - 104407 events selected in both
  - significance of the 0.4 difference between the μ (with effect of the 74% correlation between the two measurements): 2.3 σ.
- Mass measurement : $\mu = 1.29 \pm 0.30$
  - compatible within 1σ
- Fiducial cross-sections: $\mu \approx 1.4$ (8 TeV only)
  - compatible within 1.2σ

$H\rightarrow\gamma\gamma$: changes wrt last public paper

- Phys. Lett. B 726 (2013)
- Relative $E_T/m_{\gamma\gamma}$ cuts
- Improved material description
- Improved calibrations
  - mass resolution improved by 10%
  - resolution uncertainty reduced by factor 2
- Reduced uncertainties on photon ID and isolation
- Categories changed
  - added ttH leptonic, hadronic
  - split VH into 1-lepton (WH) and 2-lepton (ZH)
  - reduce number of untagged categories (without loss of sensitivity)

- 10% gain on combined signal strength

$H \to \gamma\gamma$: Total and fiducial cross-sections

- Fiducial volume:
  - photons with $E_T^{\gamma 1}/m_{\gamma\gamma} > 0.35$, $E_T^{\gamma 2}/m_{\gamma\gamma} > 0.25$, $|\eta| < 2.37$
  - particle isolation (in $\Delta R = 0.4$) <14 GeV
- Results:

Fiducial region	Measured cross section (fb)
Baseline	$43.2 \pm 9.4\,(\text{stat.})^{+3.2}_{-2.9}\,(\text{syst.}) \pm 1.2\,(\text{lumi})$
$N_{\text{jets}} \geq 1$	$21.5 \pm 5.3\,(\text{stat.})^{+2.4}_{-2.2}\,(\text{syst.}) \pm 0.6\,(\text{lumi})$
$N_{\text{jets}} \geq 2$	$9.2 \pm 2.8\,(\text{stat.})^{+1.3}_{-1.2}\,(\text{syst.}) \pm 0.3\,(\text{lumi})$
$N_{\text{jets}} \geq 3$	$4.0 \pm 1.3\,(\text{stat.}) \pm 0.7\,(\text{syst.}) \pm 0.1\,(\text{lumi})$
VBF-enhanced	$1.68 \pm 0.58\,(\text{stat.})^{+0.24}_{-0.25}\,(\text{syst.}) \pm 0.05\,(\text{lumi})$
$N_{\text{leptons}} \geq 1$	< 0.80
$E_T^{\text{miss}} > 80$ GeV	< 0.74

Fiducial region	Theoretical prediction (fb)	Source
Baseline	30.5 ± 3.3	LHC-XS [57] + XH
	$34.1^{+3.6}_{-3.5}$	STWZ [99] + XH
	$27.2^{+3.6}_{-3.2}$	HRes [103] + XH
$N_{\text{jets}} \geq 1$	13.8 ± 1.7	BLPTW [106] + XH
	$11.7^{+2.0}_{-2.4}$	JetVHeto [107] + XH
	$9.3^{+1.8}_{-1.2}$	MiNLO HJ + XH
$N_{\text{jets}} \geq 2$	5.65 ± 0.87	BLPTW + XH
	$3.99^{+0.56}_{-0.59}$	MiNLO HJJ + XH
$N_{\text{jets}} \geq 3$	0.94 ± 0.15	MiNLO HJJ + XH
VBF-enhanced	0.87 ± 0.08	MiNLO HJJ + XH
$N_{\text{leptons}} \geq 1$	0.27 ± 0.02	XH
$E_T^{\text{miss}} > 80$ GeV	0.14 ± 0.01	XH

- Total cross-section: $31.4 \pm 7.2(\text{stat}) \pm 1.6(\text{sys})$ pb

$H \rightarrow 4l$: Total and fiducial cross-sections

- Fiducial volume:

- Results:
  - $\sigma_{fid} = 2.11 \pm 0.53$ (stat) $\pm$ 0.08(syst) fb

- Total cross-section:
  - 5.1 ± 8.4(stat) ± 1.8(syst) pb

Lepton selection	
Muons:	$p_T > 6$ GeV, $\lvert\eta\rvert < 2.7$
Electrons:	$p_T > 7$ GeV, $\lvert\eta\rvert < 2.47$
Lepton pairing	
Leading pair:	SFOS lepton pair with smallest $\lvert m_Z - m_{\ell\ell}\rvert$
Subleading pair:	Remaining SFOS lepton pair with smallest $\lvert m_Z - m_{\ell\ell}\rvert$
Event selection	
Lepton kinematics:	$p_T > 20, 15, 10$ 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- (different-) 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