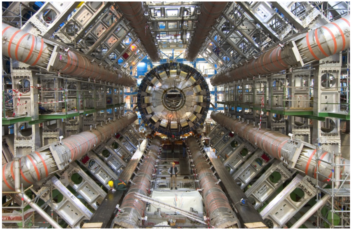
Searches for rare and non-Standard Model decays of the Higgs boson

Elliot Reynolds, for the ATLAS Collaboration

Wednesday, CIPANP 2018



ATLAS EXPERIMENT

PER ARDUA AD ALTA

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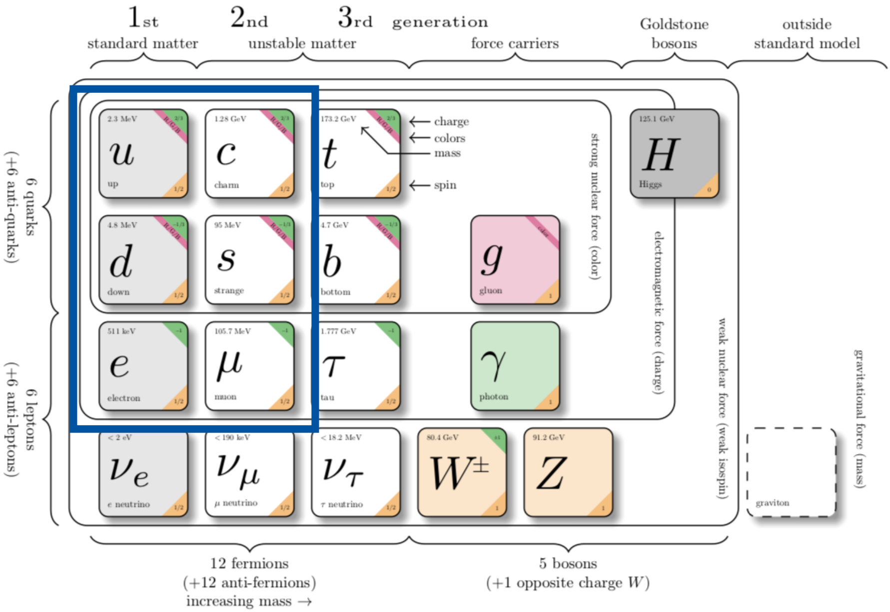
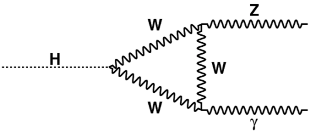
Introduction

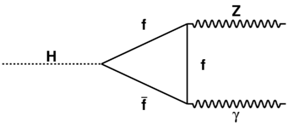
- Higgs discovery has opened a window to probe nature!
- Further studies required to establish nature of Higgs sector
- Rare decays
  - 1^{st} and 2^{nd} generation couplings?
  - Sensitive to modification from new physics
- BSM decays
  - $\text{BR}(H \to \text{unobserved}) \lesssim 20\%$ (indirect)
  - Extended Higgs sector?
  - Higgs as a dark matter portal?

Rare Decays

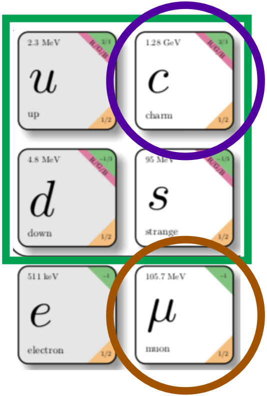


1st
2nd
3rd
generation
standard matter
unstable matter
force carriers
Goldstone bosons
outside standard model
6 quarks (+6 anti-quarks)
6 leptons (+6 anti-leptons)
2.3 MeV
u
up
1.28 GeV
c
charm
173.2 GeV
t
top
charge
colors
mass
spin
125.1 GeV
H
Higgs
4.8 MeV
d
down
95 MeV
s
strange
4.7 GeV
b
bottom
g
gluon
511 keV
e
electron
105.7 MeV
μ
muon
1.777 GeV
τ
tau
γ
photon
< 2 eV
ν_e
e neutrino
< 190 keV
ν_μ
μ neutrino
< 18.2 MeV
ν_τ
τ neutrino
80.4 GeV
$W^\pm$
91.2 GeV
Z
graviton
strong nuclear force (color)
electromagnetic force (charge)
weak nuclear force (weak isospin)
gravitational force (mass)
12 fermions
(+12 anti-fermions)
increasing mass →
5 bosons
(+1 opposite charge W)

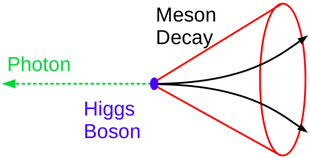


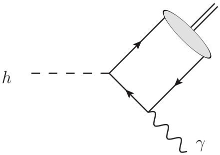


- Decays via loops:
  - $H \to Z\gamma$: $\sigma BR < \mathbf{6.6}\ \sigma_{SM} BR_{SM}$
- Invisible decays:
  - $H \to \text{invisible (direct)}$: $BR < \mathbf{67\%}$
- Direct decays to light fermions:
  - $H \to c\bar{c}$: $\sigma BR < \mathbf{110}\ \sigma_{SM} BR_{SM}$
  - $H \to \mu\mu$: $\sigma BR < \mathbf{2.8}\ \sigma_{SM} BR_{SM}$
- See $H \to f\bar{f}$ talk by Tatsuya Masubuchi
- Decays to mesons (next slides)

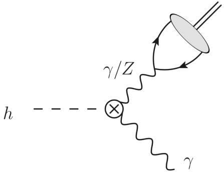


arXiv:1712.02758 and arXiv:1501.03276





Direct



Indirect

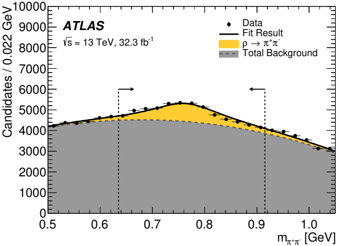
- Window to 1^{st} and 2^{nd} generation Yukawa couplings
- Distinctive topology to trigger and select events
- Target mesons:
  - ρ: $\mathrm{BR_{SM}}(H \to \rho\gamma) = 1.7 \times 10^{-5}$ †, $\rho \to \pi^+\pi^-$
  - ϕ: $\mathrm{BR_{SM}}(H \to \phi\gamma) = 2.3 \times 10^{-6}$ †, $\phi \to K^+K^-$
  - J/ψ: $\mathrm{BR_{SM}}(H \to J/\psi\gamma) = 2.8 \times 10^{-6}$ ‡, $J/\psi \to \mu^+\mu^-$
  - Υ: $\mathrm{BR_{SM}}(H \to \Upsilon(1S, 2S, 3S)\gamma) = (6.1, 2.0, 2.4) \times 10^{-10}$ ‡, $\Upsilon \to \mu^+\mu^-$

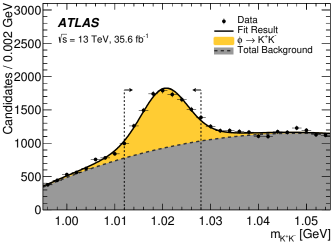
† arXiv:1505.03870 ‡ arXiv:1407.6695

$H \to M\gamma$ - Methods

arXiv:1712.02758 and arXiv:1501.03276

- ρ & ϕ trigger on tracks from meson decay and γ
- J/ψ & Υ trigger on muons
- Dominant backgrounds: jet+γ and dijet
- J/ψ & Υ events categorised as (un)converted γ and $\mu\mu$ in barrel (end-cap)
- Background estimates derived using a non-parametric data-driven method
- Signal modelled as (double) Gaussian in $m_{M\gamma}$

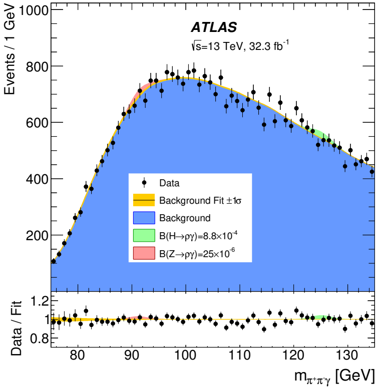


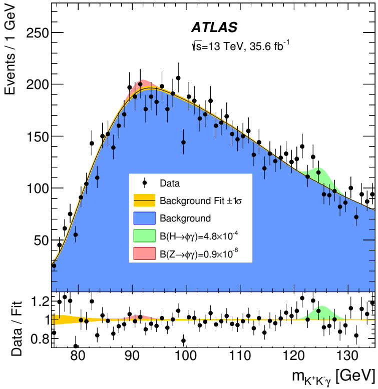


$H \to \rho\gamma$ & $\phi\gamma$ Results

arXiv:1712.02758

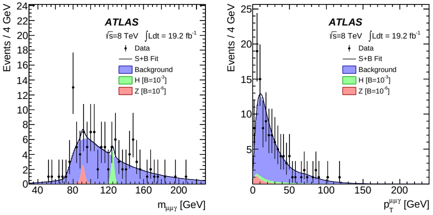
- No significant excess observed
- Unbinned maximum likelihood fits extract 95% CL limits of:
  - $\text{BR}(H \to \rho\gamma) < 8.8 \times 10^{-4}$ (**52**xSM)
  - $\text{BR}(H \to \phi\gamma) < 4.8 \times 10^{-4}$ (**208**xSM)
- Statistically limited

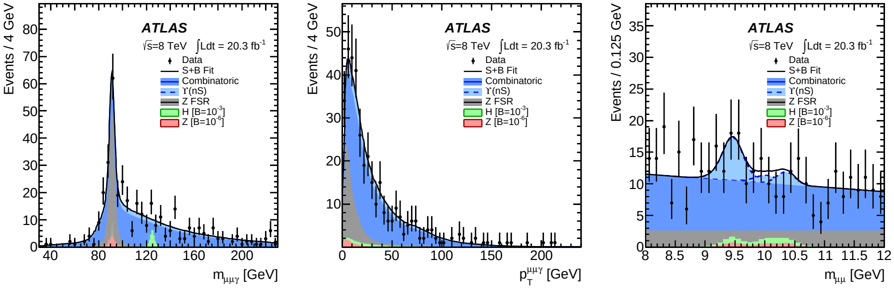




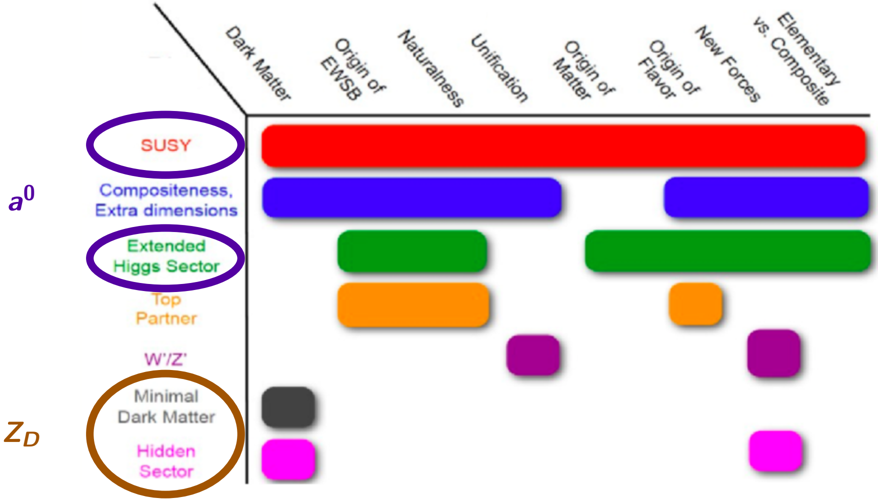
arXiv:1501.03276

- No significant excess observed
- Unbinned maximum likelihood fits extract 95% CL limits of:
  - $\mathrm{BR}(H \to J/\psi\gamma) < \mathbf{1.5 \times 10^{-3}}$
  - $\mathrm{BR}(H \to \Upsilon(1S, 2S, 3S)\gamma) < \mathbf{(1.3, 1.9, 1.3) \times 10^{-6}}$
- Statistically limited





BSM Decays

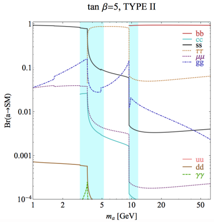


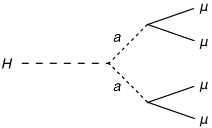
Tracy Berry, IoP 2017

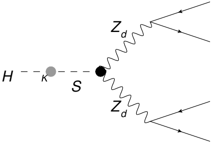
$H \to a^0 a^0$ & $Z_D Z_D \to \ell\ell\ell\ell$ - Overview

arXiv:1802.03388

- Dual interpretation analysis:
  - Pseudoscalar a^0 from 2HDM+s†, 4μ only
  - Vector Z_D from Higgs mixing in HAHM‡
- Dual range analysis:
  - Low mass: $1 < m_{a^0\ \&\ Z_D} < 15$ GeV, 4μ only
  - High mass: $15 < m_{a^0\ \&\ Z_D} < 60$ GeV, $4\mu + 2\mu 2e + 4e$
- Select quadruplet with min: $\Delta m = |m_{12} - m_{34}|$
- Observable: $\langle m \rangle = (m_{12} + m_{34})/2$







Low Mass Yields

Process	Yield
$ZZ^* \to 4\ell$	0.10 ± 0.01
$H \to ZZ^* \to 4\ell$	0.1 ± 0.1
VVV/VBS	0.06 ± 0.03
Heavy flavour	0.07 ± 0.04
Total	0.4 ± 0.1
Data	0

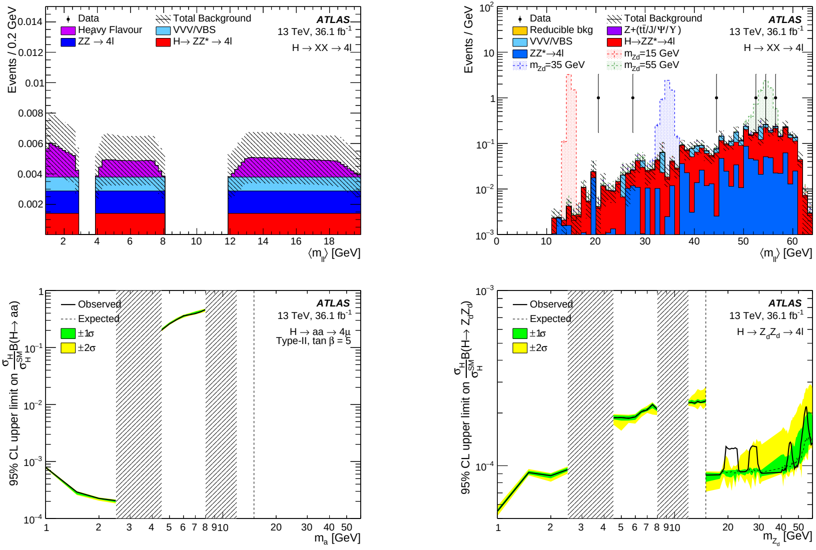
High Mass Yields

Process	Yield
$ZZ^* \to 4\ell$	0.8 ± 0.1
$H \to ZZ^* \to 4\ell$	2.6 ± 0.3
VVV/VBS	0.51 ± 0.18
$Z + (t\bar{t}/J/\Psi) \to 4\ell$	0.004 ± 0.004
Reducible Background	Negligible
Total	3.9 ± 0.3
Data	6

†arXiv:1002.1956 ‡arXiv:1412.0018

$H \to a^0 a^0$ & $Z_D Z_D \to \ell\ell\ell\ell$ - Results

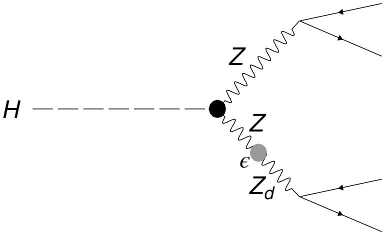
arXiv:1802.03388



$H \to ZZ_D \to \ell\ell\ell\ell$ - Overview

arXiv:1802.03388

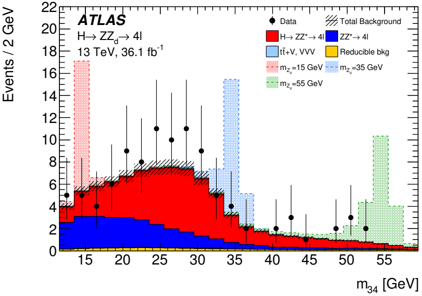
- Z_D arises from kinetic mixing to Z in HAHM†
- Search range: $15 < m_{Z_D} < 55$ GeV
- Quadruplet with dilepton mass closest to m_Z selected
- Dominant backgrounds: ZZ^* and $H \to ZZ^*$
- Dominant backgrounds estimated in MC
- Small fake lepton background estimated using data-driven method

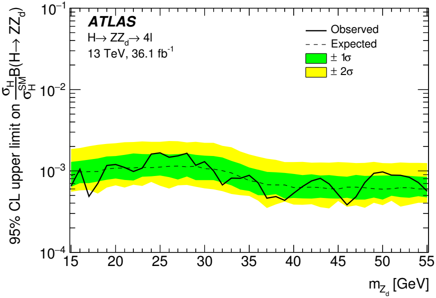


† arXiv:1412.0018

arXiv:1802.03388

Process	$2\ell 2\mu$	$2\ell 2e$	Total
$H \to ZZ^* \to 4\ell$	34.3 ± 3.6	21.4 ± 3.0	55.7 ± 6.3
$ZZ^* \to 4\ell$	16.9 ± 1.2	9.0 ± 1.1	25.9 ± 2.0
Reducible background	2.1 ± 0.6	2.7 ± 0.7	4.8 ± 1.1
VVV, $t\bar{t} + V$	0.20 ± 0.05	0.20 ± 0.04	0.40 ± 0.06
Total expected	53.5 ± 4.3	33.3 ± 3.4	86.8 ± 7.5
Observed	65	37	102

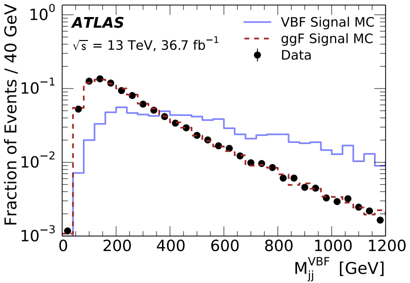




$H \to a^0 a^0 \to \gamma\gamma jj$ - Overview

arXiv:1803.11145

- Sensitive to models where fermionic decays are suppressed
- Jets are gluon-induced
- Search range: $20 < m_{a_0} < 60$ GeV
- VBF production mode targeted:
  - $m_{jj}^{\max} > 500$ GeV
  - Significant contribution from ggF production mode
- $100 < m_{jj\gamma\gamma} < 150$ GeV
- Main backgrounds: $\gamma\gamma$jj and jjjj



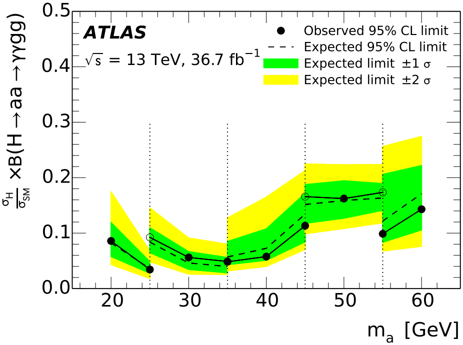
	Photon requirements: TightLoose	Photon requirements: TightTight
$\|m_{jj} - m_{\gamma\gamma}\| > x_R$	A	C
$\|m_{jj} - m_{\gamma\gamma}\| \leq x_R$	B	D

$m_{\gamma\gamma}$ regime	Definition	Range of m_a values	x_R [GeV]
1	17.5 GeV $< m_{\gamma\gamma} <$ 27.5 GeV	20 GeV $\leq m_a \leq$ 25 GeV	12
2	22.5 GeV $< m_{\gamma\gamma} <$ 37.5 GeV	25 GeV $\leq m_a \leq$ 35 GeV	12
3	32.5 GeV $< m_{\gamma\gamma} <$ 47.5 GeV	35 GeV $\leq m_a \leq$ 45 GeV	16
4	42.5 GeV $< m_{\gamma\gamma} <$ 57.5 GeV	45 GeV $\leq m_a \leq$ 55 GeV	20
5	52.5 GeV $< m_{\gamma\gamma} <$ 65.0 GeV	55 GeV $\leq m_a \leq$ 60 GeV	24

arXiv:1803.11145

$m_{\gamma\gamma}$ regime	A	B	C	D	Relative closure uncert.	Predicted background yield
1	15	4	28	4	0.50	6^{+7}_{-4}
2	22	6	34	15	0.32	8^{+7}_{-4}
3	12	16	29	26	0.20	37^{+23}_{-14}
4	8	12	19	38	0.21	27^{+22}_{-12}
5	6	20	20	36	0.20	66^{+56}_{-28}

- Likelihood fit performed across various mass regions and ABCD categories
- No significant excess is observed
- Dominant uncertainties are statistical

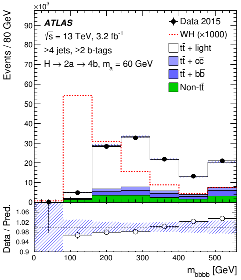


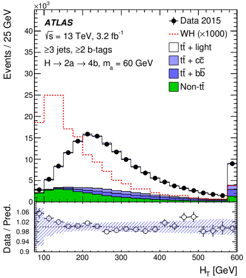
$WH \to \ell\nu a^0 a^0 \to \ell\nu 4b$ - Overview

arXiv:1606.08391

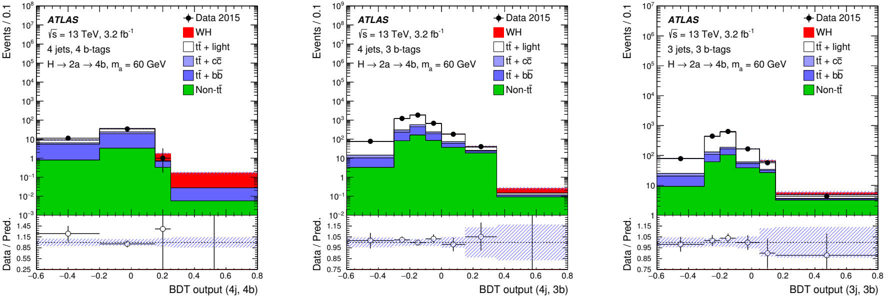
- Search range: $20 < m_{a^0} < 60$ GeV
- Produced in association with $W(\ell\nu)$
- 8 event categories: (n_{jets}=3,4,5+)x(n_{b-tags}=2,3,4+)
- 3 SRs: (4j,4b), (4j,3b) and (3j,3b)
- Dominant background: $t\bar{t}$ (+jj)
- BDT discriminant in SRs and H_T used in CRs

Region		m_{bbb}	m_{bbbb}	$\Delta m^{bb}_{\rm min}$	$H_{\rm T}$	$p_{\rm T}^{W}$	$\Delta R^{bb}_{\rm av}$	$\Delta R^{\ell b}_{\rm min}$	m_{bbj}	$m_{\rm T2}$
	(3j, 3b)	✓			✓	✓	✓	✓		
Signal	(4j, 3b)	✓			✓	✓	✓		✓	
	(4j, 4b)		✓	✓	✓		✓			✓
Control					✓					

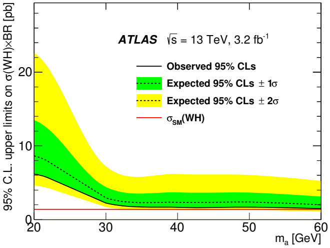




arXiv:1606.08391



- Binned simultaneous likelihood fit across all 3 SR and all 5 CR
- Does not reach sensitivity to BR assuming σ_{SM}
- Most sensitive categories statistically limited



Rare & BSM Searches Not Presented

Search	95% CL Limit	Reference
Rare Decays		
$ZH \to \ell\ell c\bar{c}$	$\sigma BR < 110\ \sigma_{SM} BR_{SM}$	arXiv:1802.04329
$H \to \mu\mu$	$\sigma BR < 2.8\ \sigma_{SM} BR_{SM}$	arXiv:1705.04582
$ZH \to \ell\ell$ invisible	BR$<$ 67%	arXiv:1708.09624
$H \to Z\gamma$	$\sigma BR < 6.6\ \sigma_{SM} BR_{SM}$	arXiv:1708.00212
BSM Searches		
$H \to e\tau$	BR$<$ 1.04%	arXiv:1604.07730
$H \to \mu\tau$	BR$<$ 1.43%	
$H \to a^0 a^0 \to \mu\mu\tau\tau$	BR$<\sim$ (3.5 – 100)%	arXiv:1505.01609
$H \to a^0 a^0 \to \gamma\gamma\gamma\gamma$	BR$<\sim$ (0.02 – 0.2)%	arXiv:1509.05051

Summary Table

- Summarised below are all the searches presented in this talk
- Challenging measurements due to low $S/\sqrt{B}$
- HL-LHC dataset expected to improve $H \to J/\psi\gamma$ limit to: $\sim$**15**xSM

Search	95% CL Limit	Reference
Rare Decays		
$H \to \rho\gamma$	$\sigma BR < 52\ \sigma_{SM} BR_{SM}$	arXiv:1712.02758
$H \to \phi\gamma$	$\sigma BR < 208\ \sigma_{SM} BR_{SM}$	
$H \to J/\psi\gamma$	BR$<$ 0.15%	arXiv:1501.03276
$H \to \Upsilon\gamma$	BR$<$ $(0.13 - 0.19)$%	
BSM Searches		
$H \to a^0 a^0 \to 4\mu$	BR$<\sim$ $(0.02 - 100)$%	arXiv:1802.03388
$H \to Z_D Z_D \to 4\ell$	BR$<\sim$ $(5 - 30) \times 10^{-5}$	
$H \to Z Z_D \to 4\ell$	BR$<\sim$ 0.1%	
$H \to a^0 a^0 \to \gamma\gamma jj$	BR$<\sim$ 10%	arXiv:1803.11145
$WH \to \ell\nu a^0 a^0 \to \ell\nu 4b$	(1.5-6.2) pb	arXiv:1606.08391

Thank you for listening!

Search	95% CL Limit	Reference
Rare Decays		
$H \to \rho\gamma$	$\sigma BR < 52\ \sigma_{SM} BR_{SM}$	arXiv:1712.02758
$H \to \phi\gamma$	$\sigma BR < 208\ \sigma_{SM} BR_{SM}$	
$H \to J/\psi\gamma$	BR$< 0.15\%$	arXiv:1501.03276
$H \to \Upsilon\gamma$	BR$< (0.13 - 0.19)\%$	
BSM Searches		
$H \to a^0 a^0 \to 4\mu$	BR$<\sim (0.02 - 100)\%$	arXiv:1802.03388
$H \to Z_D Z_D \to 4\ell$	BR$<\sim (5 - 30) \times 10^{-5}$	
$H \to Z Z_D \to 4\ell$	BR$<\sim 0.1\%$	
$H \to a^0 a^0 \to \gamma\gamma jj$	BR$<\sim 10\%$	arXiv:1803.11145
$WH \to \ell\nu a^0 a^0 \to \ell\nu 4b$	(1.5-6.2) pb	arXiv:1606.08391

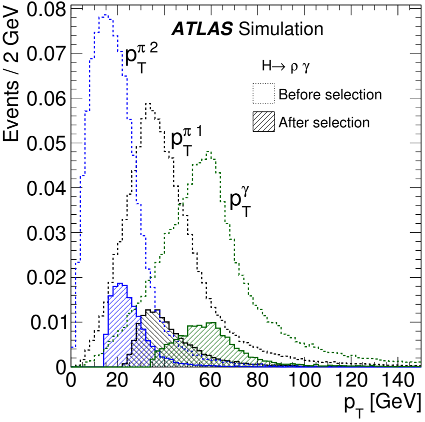
Backup Slides

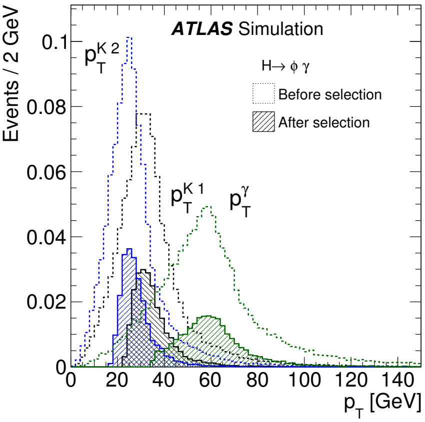
- Datasets used in searches
- $H \to M\gamma$ backup materials
- $H \to a^0 a^0$ & $Z_D Z_D \to \ell\ell\ell\ell$ backup materials
- $H \to Z Z_D \to \ell\ell\ell\ell$ backup materials
- $H \to a^0 a^0 \to \gamma\gamma jj$ backup materials
- $WH \to \ell\nu a^0 a^0 \to \ell\nu 4b$ backup materials

Datasets Used in Searches

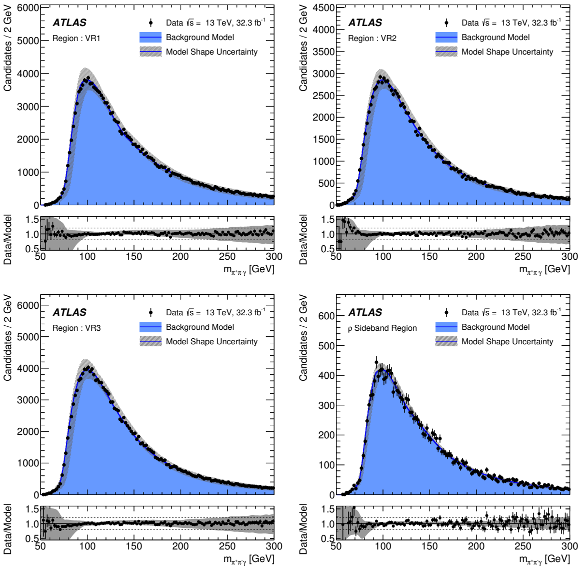
Search	Luminosity	Dataset
Rare Decays		
$H \to \rho\gamma$	$35.6\ fb^{-1}$	2015+2016
$H \to \phi\gamma$	$32.3\ fb^{-1}$	
$H \to J/\psi\gamma$	$19.2\ fb^{-1}$	2012
$H \to \Upsilon\gamma$	$20.3\ fb^{-1}$	
BSM Searches		
$H \to a^0a^0 \to 4\mu$		2015+2016
$H \to Z_DZ_D \to 4\ell$	$36.1\ fb^{-1}$	
$H \to ZZ_D \to 4\ell$		
$H \to a^0a^0 \to \gamma\gamma jj$	$36.7\ fb^{-1}$	2015+2016
$WH \to \ell\nu a^0a^0 \to \ell\nu 4b$	$3.2\ fb^{-1}$	2015

$H \to M\gamma$ Backup Materials

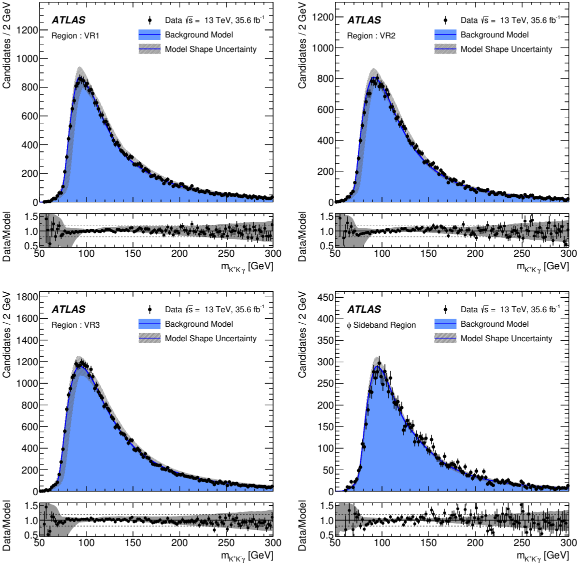

ATLAS Simulation
H→ ρ γ
Before selection
After selection
$p_T^{\pi\ 2}$
$p_T^{\pi\ 1}$
p_T^{γ}
Events / 2 GeV
p_T [GeV]
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0
20
40
60
80
100
120
140


ATLAS Simulation
H→ φ γ
Before selection
After selection
$p_T^{K\ 2}$
$p_T^{K\ 1}$
p_T^{γ}
Events / 2 GeV
p_T [GeV]
0
0.02
0.04
0.06
0.08
0.1
0
20
40
60
80
100
120
140

$H \to \rho\gamma$ Validation Regions



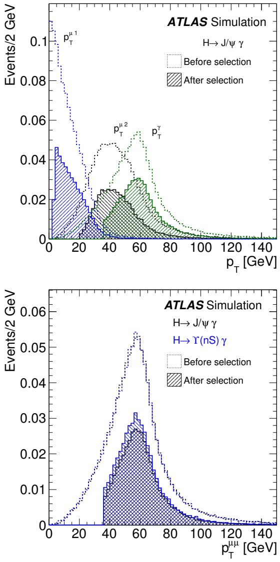
$H \to \phi\gamma$ Validation Regions



	Observed yields (Mean expected background)					Expected signal yields	
	Mass range [GeV]					H	Z
	All	81–101		120–130		$[\mathcal{B} = 10^{-4}]$	$[\mathcal{B} = 10^{-6}]$
$\phi\gamma$	12051	3364	(3500 ± 30)	1076	(1038 ± 9)	15.6 ± 1.5	83 ± 7
$\rho\gamma$	58702	12583	(12660 ± 60)	5473	(5450 ± 30)	17.0 ± 1.7	7.5 ± 0.6

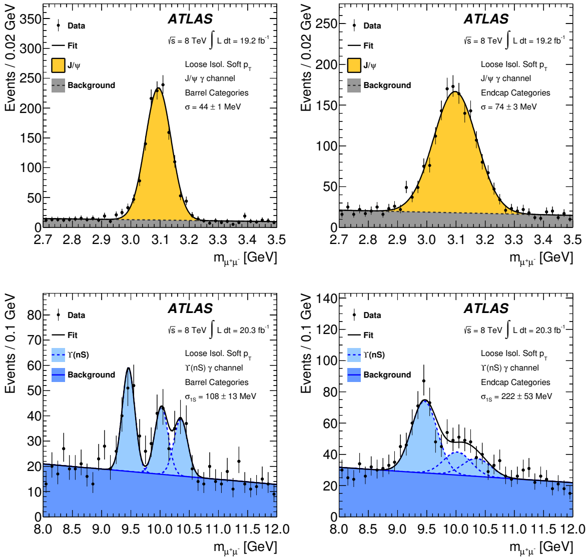
Branching Fraction Limit (95% CL)	Expected	Observed
$\mathcal{B}(H \to \phi\gamma)$ [10^{-4}]	$4.2^{+1.8}_{-1.2}$	4.8
$\mathcal{B}(Z \to \phi\gamma)$ [10^{-6}]	$1.3^{+0.6}_{-0.4}$	0.9
$\mathcal{B}(H \to \rho\gamma)$ [10^{-4}]	$8.4^{+4.1}_{-2.4}$	8.8
$\mathcal{B}(Z \to \rho\gamma)$ [10^{-6}]	33^{+13}_{-9}	25

Source of systematic uncertainty	Yield uncertainty
Total H cross section	6.3%
Total Z cross section	2.9%
Integrated luminosity	3.4%
Photon ID efficiency	2.5%
Trigger efficiency	2.0%
Tracking efficiency	6.0%



ATLAS Simulation
H→ J/ψ γ
H→ ϒ(nS) γ
Before selection
After selection
Events/2 GeV
p_T [GeV]
p_T^μμ [GeV]
p_T^γ [GeV]

$H \to J/\psi\gamma$ & $\Upsilon\gamma$ Peaks in CR



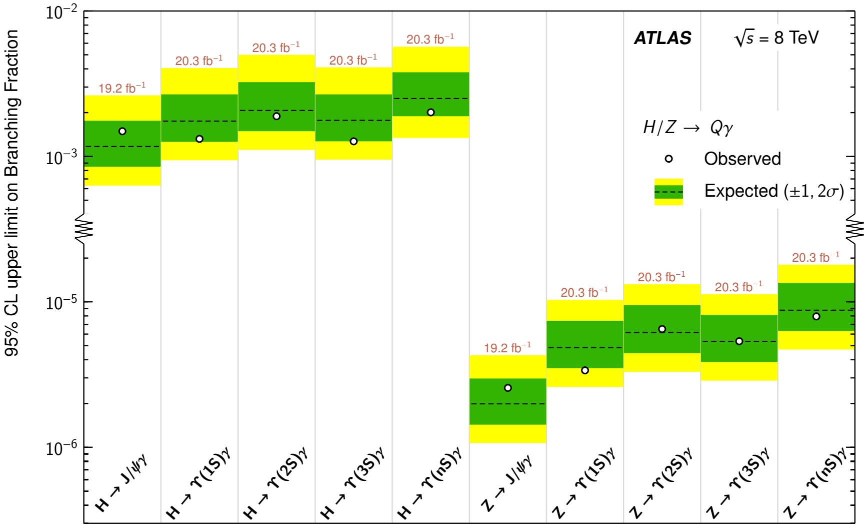
$H \to J/\psi\gamma$ & $\Upsilon\gamma$ Yield Table

Category	Observed (Expected Background)					Signal	
		Mass Range [GeV]				Z	H
	All	80–100		115–135		$\mathcal{B}$ $[10^{-6}]$	$\mathcal{B}$ $[10^{-3}]$
				$J/\psi\,\gamma$			
BU	30	9	(8.9±1.3)	5	(5.0±0.9)	1.29±0.07	1.96±0.24
BC	29	8	(6.0±0.7)	3	(5.5±0.6)	0.63±0.03	1.06±0.13
EU	35	8	(8.7±1.0)	10	(5.8±0.8)	1.37±0.07	1.47±0.18
EC	23	6	(5.6±0.7)	2	(3.0±0.4)	0.99±0.05	0.93±0.12
				$\Upsilon(nS)\,\gamma$			
BU	93	42	(39±6)	16	(12.9±2.0)	1.67±0.09	2.6±0.3
BC	71	32	(27.7±2.4)	5	(9.7±1.2)	0.79±0.04	1.45±0.18
EU	125	49	(47±6)	16	(17.8±2.4)	2.24±0.12	2.5±0.3
EC	85	31	(31±5)	18	(12.3±1.9)	1.55±0.08	1.60±0.20

$H \to J/\psi\gamma$ & $\Upsilon\gamma$ Limits Table

	95% CL_s Upper Limits				
	J/ψ	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$	$\sum^n \Upsilon(nS)$
$\mathcal{B}(Z \to \mathcal{Q}\,\gamma)$ [10^{-6}]					
Expected	$2.0^{+1.0}_{-0.6}$	$4.9^{+2.5}_{-1.4}$	$6.2^{+3.2}_{-1.8}$	$5.4^{+2.7}_{-1.5}$	$8.8^{+4.7}_{-2.5}$
Observed	2.6	3.4	6.5	5.4	7.9
$\mathcal{B}(H \to \mathcal{Q}\,\gamma)$ [10^{-3}]					
Expected	$1.2^{+0.6}_{-0.3}$	$1.8^{+0.9}_{-0.5}$	$2.1^{+1.1}_{-0.6}$	$1.8^{+0.9}_{-0.5}$	$2.5^{+1.3}_{-0.7}$
Observed	1.5	1.3	1.9	1.3	2.0
$\sigma(pp \to H) \times \mathcal{B}(H \to \mathcal{Q}\,\gamma)$ [fb]					
Expected	26^{+12}_{-7}	38^{+19}_{-11}	45^{+24}_{-13}	38^{+19}_{-11}	54^{+27}_{-15}
Observed	33	29	41	28	44

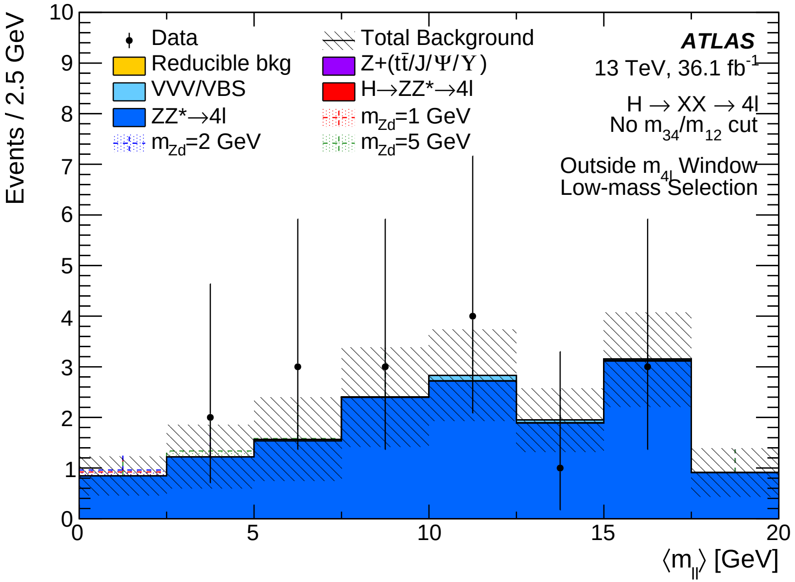
$H \to J/\psi\gamma$ & $\Upsilon\gamma$ Limits Plot



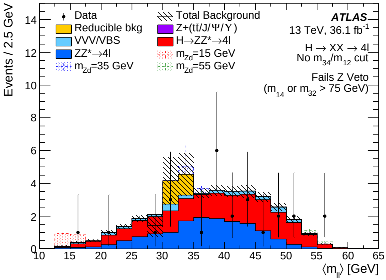
$H \to a^0 a^0$ & $Z_D Z_D \to \ell\ell\ell\ell$
Backup Materials

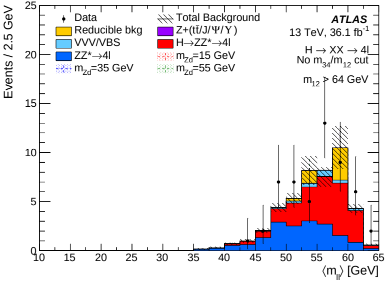
$H \to a^0 a^0$ & $Z_D Z_D \to \ell\ell\ell\ell$ Event Selection

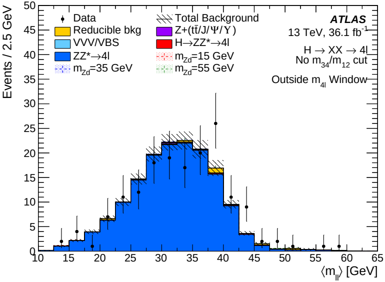
	$H \to ZX \to 4\ell$ ($15\ GeV < m_X < 55\ GeV$)	$H \to XX \to 4\ell$ ($15\ GeV < m_X < 60\ GeV$)	$H \to XX \to 4\mu$ ($1\ GeV < m_X < 15\ GeV$)
QUADRUPLET SELECTION	- Require at least one quadruplet of leptons consisting of two pairs of same-flavour opposite-sign leptons - Three leading-p_T leptons satisfying $p_T > 20$ GeV, 15 GeV, 10 GeV - At least three muons are required to be reconstructed by combining ID and MS tracks in the 4μ channel		
	- Select best quadruplet (per channel) to be the one with the (sub)leading dilepton mass (second) closest to the Z mass - $50\ GeV < m_{12} < 106\ GeV$ - $12\ GeV < m_{34} < 115\ GeV$ - $m_{12,34,14,32} > 5$ GeV	Leptons in the quadruplet are responsible for firing at least one trigger. In the case of multi-lepton triggers, all leptons of the trigger must match to leptons in the quadruplet	
	$\Delta R(\ell, \ell') > 0.10$ (0.20) for same-flavour (different-flavour) leptons in the quadruplet		-
QUADRUPLET RANKING	Select first surviving quadruplet from channels, in the order: 4μ, $2e2\mu$, $2\mu 2e$, $4e$	Select quadruplet with smallest $\Delta m_{\ell\ell} = \lvert m_{12} - m_{34} \rvert$	
EVENT SELECTION	$115\ GeV < m_{4\ell} < 130\ GeV$		$120\ GeV < m_{4\ell} < 130\ GeV$
		$m_{34}/m_{12} > 0.85$ Reject event if: $(m_{J/\Psi} - 0.25\ GeV) < m_{12,34,14,32} < (m_{\Psi(2S)} + 0.30\ GeV)$, or $(m_{\Upsilon(1S)} - 0.70\ GeV) < m_{12,34,14,32} < (m_{\Upsilon(3S)} + 0.75\ GeV)$	
		$10\ GeV < m_{12,34} < 64\ GeV$ $4e$ and 4μ channels: $5\ GeV < m_{14,32} < 75\ GeV$	$0.88\ GeV < m_{12,34} < 20$ GeV No restriction on alternative pairing


Data
Total Background
Reducible bkg
Z+(tt̄/J/Ψ/Υ)
VVV/VBS
H→ZZ*→4l
ZZ*→4l
m_Zd=1 GeV
m_Zd=2 GeV
m_Zd=5 GeV
ATLAS
13 TeV, 36.1 fb-1
H → XX → 4l
No m34/m12 cut
Outside m4l Window
Low-mass Selection
Events / 2.5 GeV
⟨m_ll⟩ [GeV]
0
1
2
3
4
5
6
7
8
9
10
0
5
10
15
20

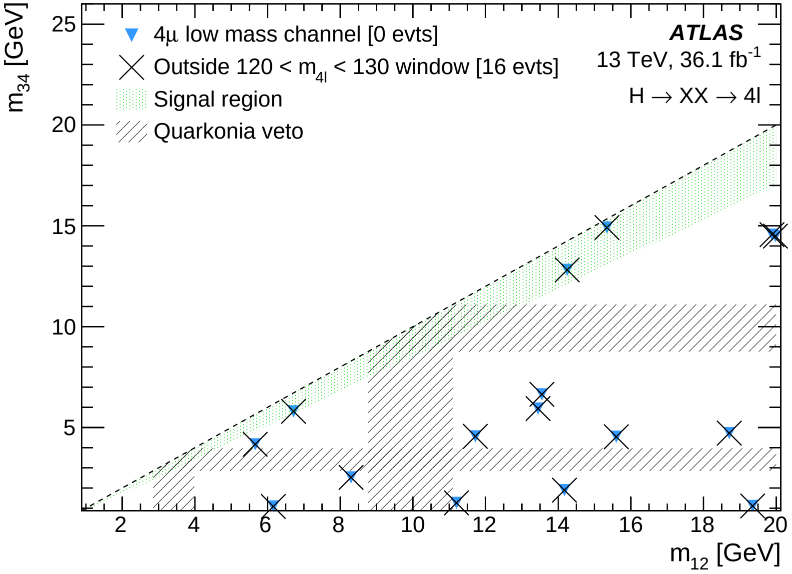
$H \to a^0 a^0$ & $Z_D Z_D \to \ell\ell\ell\ell$ High Mass VRs



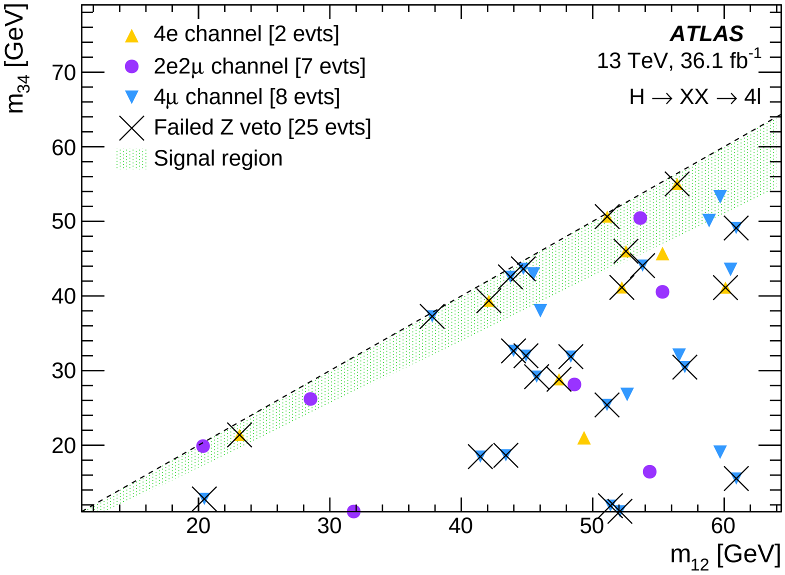




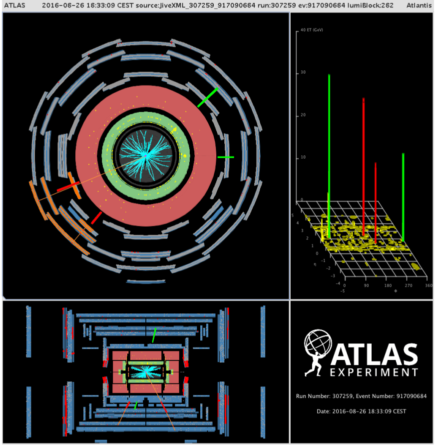
$H \rightarrow a^0 a^0$ & $Z_D Z_D \rightarrow \ell\ell\ell\ell$ Low Mass SR

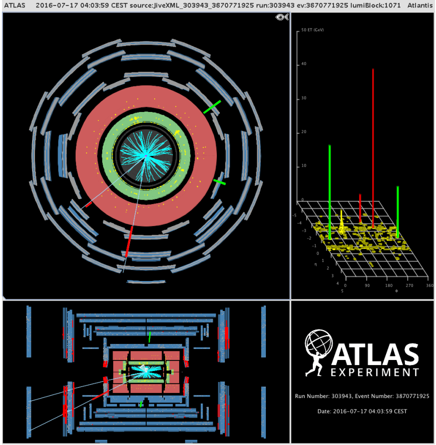


$H \to a^0 a^0$ & $Z_D Z_D \to \ell\ell\ell\ell$ High Mass SR



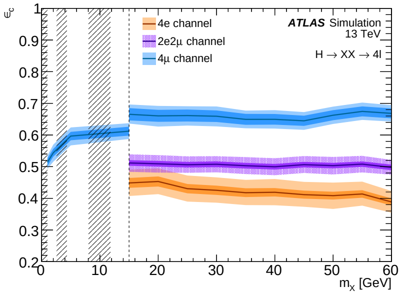
$H \to a^0 a^0$ & $Z_D Z_D \to \ell\ell\ell\ell$ High Mass Event Displays

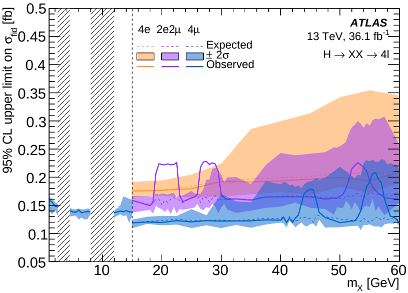




	$H \to ZX \to 4\ell$ ($15\ GeV < m_X < 55\ GeV$)	$H \to XX \to 4\ell$ ($15\ GeV < m_X < 60\ GeV$)	$H \to XX \to 4\mu$ ($1\ GeV < m_X < 15\ GeV$)
Electrons	Dressed with prompt photons within $\Delta R = 0.1$ $p_{\mathrm{T}} > 7\ GeV$ $\lvert\eta\rvert < 2.5$		
Muons	Dressed with prompt photons within $\Delta R = 0.1$ $p_{\mathrm{T}} > 5\ GeV$ $\lvert\eta\rvert < 2.7$		
Quadruplet	Three leading-p_{T} leptons satisfy $p_{\mathrm{T}} > 20$ GeV, 15 GeV, 10 GeV		
	$\Delta R > 0.1$ (0.2) between SF (OF) leptons		-
	$50\ GeV < m_{12} < 106$ GeV $12\ GeV < m_{34} < 115$ GeV $115\ GeV < m_{4\ell} < 130$ GeV $m_{12,34,14,32} > 5$ GeV	$m_{34}/m_{12} > 0.85$	
		$10\ GeV < m_{12,34} < 64$ GeV $5\ GeV < m_{14,32} < 75\ GeV$ if $4e$ or 4μ	$0.88\ GeV < m_{12,34} < 20\ GeV$
		Reject event if either of: $(m_{J/\psi} - 0.25\ GeV) < m_{12,34,14,32} < (m_{\psi(2S)} + 0.30\ GeV)$ $(m_{\Upsilon(1S)} - 0.70\ GeV) < m_{12,34,14,32} < (m_{\Upsilon(3S)} + 0.75\ GeV)$	

$H \to a^0 a^0$ & $Z_D Z_D \to \ell\ell\ell\ell$ Model Independent Limits





$H \to ZZ_D \to \ell\ell\ell\ell$ Backup Materials

$H \to ZZ_D \to \ell\ell\ell\ell$ Event Selection

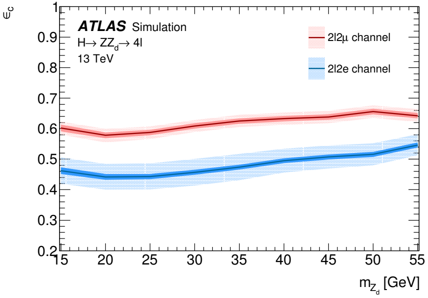
	$H \to ZX \to 4\ell$ ($15\ GeV < m_X < 55\ GeV$)	$H \to XX \to 4\ell$ ($15\ GeV < m_X < 60\ GeV$)	$H \to XX \to 4\mu$ ($1\ GeV < m_X < 15\ GeV$)
QUADRUPLET SELECTION	- Require at least one quadruplet of leptons consisting of two pairs of same-flavour opposite-sign leptons - Three leading-p_T leptons satisfying $p_T > 20$ GeV, 15 GeV, 10 GeV - At least three muons are required to be reconstructed by combining ID and MS tracks in the 4μ channel		
	- Select best quadruplet (per channel) to be the one with the (sub)leading dilepton mass (second) closest to the Z mass - $50\ GeV < m_{12} < 106\ GeV$ - $12\ GeV < m_{34} < 115\ GeV$ - $m_{12,34,14,32} > 5$ GeV	Leptons in the quadruplet are responsible for firing at least one trigger. In the case of multi-lepton triggers, all leptons of the trigger must match to leptons in the quadruplet	
	$\Delta R(\ell, \ell') > 0.10$ (0.20) for same-flavour (different-flavour) leptons in the quadruplet		-
QUADRUPLET RANKING	Select first surviving quadruplet from channels, in the order: 4μ, $2e2\mu$, $2\mu2e$, $4e$	Select quadruplet with smallest $\Delta m_{\ell\ell} = \|m_{12} - m_{34}\|$	
EVENT SELECTION	$115\ GeV < m_{4\ell} < 130\ GeV$		$120\ GeV < m_{4\ell} < 130\ GeV$
		$m_{34}/m_{12} > 0.85$ Reject event if: $(m_{J/\Psi} - 0.25\ GeV) < m_{12,34,14,32} < (m_{\Psi(2S)} + 0.30\ GeV)$, or $(m_{\Upsilon(1S)} - 0.70\ GeV) < m_{12,34,14,32} < (m_{\Upsilon(3S)} + 0.75\ GeV)$	
		$10\ GeV < m_{12,34} < 64\ GeV$ $4e$ and 4μ channels: $5\ GeV < m_{14,32} < 75\ GeV$	$0.88\ GeV < m_{12,34} < 20$ GeV No restriction on alternative pairing

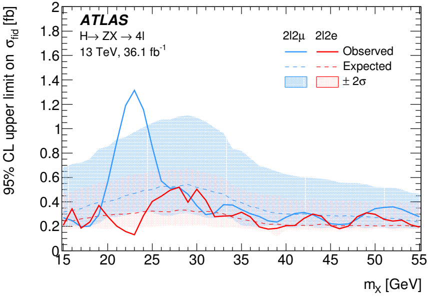
Process	$2\ell 2\mu$	$2\ell 2e$	Total
$H \to ZZ^* \to 4\ell$	34.3 ± 3.6	21.4 ± 3.0	55.7 ± 6.3
$ZZ^* \to 4\ell$	16.9 ± 1.2	9.0 ± 1.1	25.9 ± 2.0
Reducible background	2.1 ± 0.6	2.7 ± 0.7	4.8 ± 1.1
VVV, $t\bar{t} + V$	0.20 ± 0.05	0.20 ± 0.04	0.40 ± 0.06
Total expected	53.5 ± 4.3	33.3 ± 3.4	86.8 ± 7.5
Observed	65	37	102

$H \to ZZ_D \to \ell\ell\ell\ell$ Fiducial Region

	$H \to ZX \to 4\ell$ ($15\ GeV < m_X < 55\ GeV$)	$H \to XX \to 4\ell$ ($15\ GeV < m_X < 60\ GeV$)	$H \to XX \to 4\mu$ ($1\ GeV < m_X < 15\ GeV$)
Electrons	Dressed with prompt photons within $\Delta R = 0.1$ $p_{\mathrm{T}} > 7\ GeV$ $\lvert\eta\rvert < 2.5$		
Muons	Dressed with prompt photons within $\Delta R = 0.1$ $p_{\mathrm{T}} > 5\ GeV$ $\lvert\eta\rvert < 2.7$		
Quadruplet	Three leading-p_{T} leptons satisfy $p_{\mathrm{T}} > 20$ GeV, 15 GeV, 10 GeV		
	$\Delta R > 0.1$ (0.2) between SF (OF) leptons		-
	$50\ GeV < m_{12} < 106$ GeV $12\ GeV < m_{34} < 115$ GeV $115\ GeV < m_{4\ell} < 130$ GeV $m_{12,34,14,32} > 5$ GeV	$m_{34}/m_{12} > 0.85$	
		$10\ GeV < m_{12,34} < 64$ GeV $5\ GeV < m_{14,32} < 75\ GeV$ if $4e$ or 4μ	$0.88\ GeV < m_{12,34} < 20\ GeV$
		Reject event if either of: $(m_{J/\psi} - 0.25\ GeV) < m_{12,34,14,32} < (m_{\psi(2S)} + 0.30\ GeV)$ $(m_{\Upsilon(1S)} - 0.70\ GeV) < m_{12,34,14,32} < (m_{\Upsilon(3S)} + 0.75\ GeV)$	

$H \to ZZ_D \to \ell\ell\ell\ell$ Model Independent Limits

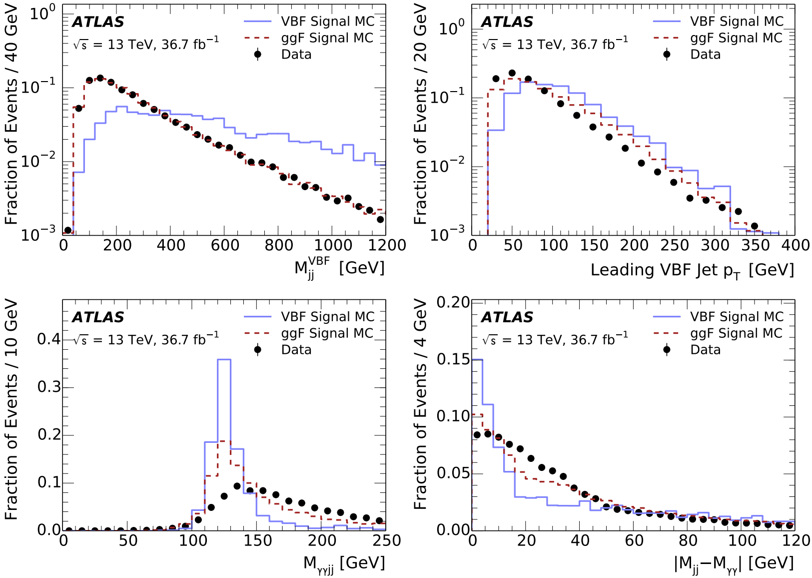




$H \to a^0 a^0 \to \gamma\gamma jj$ Backup Materials

	Selection	
L1 trigger	`L1_2EM15VH`	
Primary HLT trigger	`HLT_g35_loose_g25_loose`	`HLT_2g22_tight`
Photon Selection	≥ 2 photons with $E_{\mathrm{T}} > 30$ GeV ≥ 1 photon with $E_{\mathrm{T}} > 40$ GeV	≥ 2 photons with $E_{\mathrm{T}} > 27$ GeV
Jet Selection	≥ 4 jets, central or forward	
VBF Selection	$m_{jj}^{\mathrm{VBF}} > 500$ GeV & VBF Leading Jet $p_{\mathrm{T}} > 60$ GeV	

$H \to a^0 a^0 \to \gamma\gamma jj$ Kinematic Distributions



$H \to a^0 a^0 \to \gamma\gamma jj$ Efficiencies

m_a [GeV]	$m_{\gamma\gamma}$ regime	Efficiency $(\times 10^{-5})$			
		A	B	C	D
20	1	$0.50^{+0.16}_{-0.14}$	1.2 ± 0.4	3.9 ± 1.1	6.2 ± 1.8
25	1	$0.67^{+0.27}_{-0.33}$	$2.6^{+0.5}_{-0.6}$	5.8 ± 1.4	15 ± 4
25	2	$0.67^{+0.27}_{-0.33}$	$2.6^{+0.5}_{-0.6}$	5.8 ± 1.4	15 ± 4
30	2	1.22 ± 0.34	3.3 ± 0.9	$7.6^{+1.4}_{-1.6}$	25^{+5}_{-6}
35	2	1.8 ± 1.1	2.7 ± 1.2	9.3 ± 2.6	27 ± 6
35	3	$0.53^{+1.20}_{-0.24}$	4.1 ± 1.2	$6.1^{+1.2}_{-1.6}$	31 ± 7
40	3	1.2 ± 0.4	3.3 ± 1.0	$7.9^{+1.7}_{-2.4}$	26 ± 6
45	3	2.5 ± 1.0	4.1 ± 1.3	$7.7^{+1.7}_{-2.0}$	19 ± 5
45	4	2.2 ± 0.9	4.4 ± 1.4	$5.9^{+1.5}_{-2.2}$	22 ± 5
50	4	0.93 ± 0.30	4.4 ± 1.2	$5.0^{+1.3}_{-1.0}$	24 ± 5
55	4	0.37 ± 0.11	3.3 ± 0.9	$5.4^{+1.3}_{-1.4}$	21 ± 5
55	5	0.23 ± 0.16	3.6 ± 1.0	3.4 ± 0.8	24 ± 6
60	5	$0.77^{+0.32}_{-0.30}$	3.9 ± 1.0	4.9 ± 1.4	23 ± 6

$H \to a^0 a^0 \to \gamma\gamma jj$ Best Fit Values

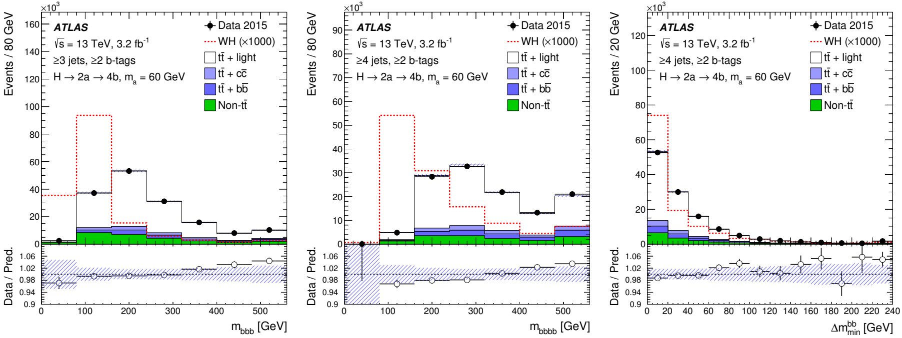
$m_{\gamma\gamma}$ regime	m_a [GeV]	μ_{S}	μ_{bkg}	τ_{B}	τ_{C}
1	20	-7±18	11±17	0.5±0.4	2.9±3.1
2	30	8±8	7±6	0.68±0.32	4.3±3.1
3	40	-30±80	60±70	0.35±0.19	0.67±0.33
4	50	22±28	16±23	0.5±0.4	0.9±1.0
5	60	-290±260	340±340	0.21±0.05	0.24±0.05

$H \to a^0 a^0 \to \gamma\gamma jj$ Limits

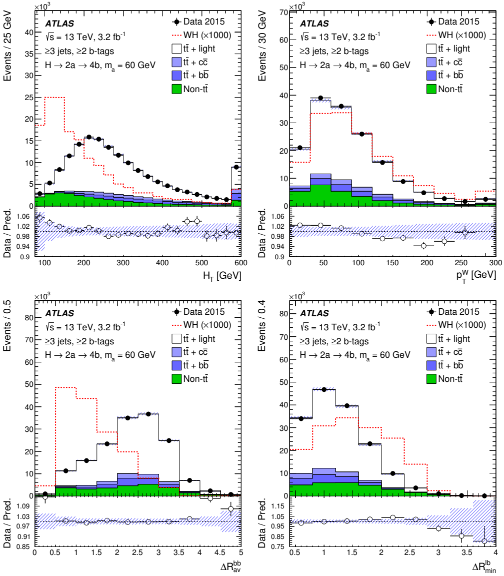
$m_{\gamma\gamma}$ regime	m_a [GeV]	μ_S	$\sigma_H \times B(H \to aa \to \gamma\gamma gg)$ [pb]	$\frac{\sigma_H}{\sigma_{SM}} \times B(H \to aa \to \gamma\gamma gg)$
1	20	$10.8\left(10.4^{+4.6}_{-3.1}\right)$	$4.8\left(4.6^{+2.1}_{-1.4}\right)$	$0.086\left(0.082^{+0.037}_{-0.025}\right)$
1	25	$10.4\left(10.9^{+3.8}_{-2.5}\right)$	$1.9\left(2.0^{+0.7}_{-0.5}\right)$	$0.034\left(0.036^{+0.013}_{-0.008}\right)$
2	25	$28\left(25^{+8}_{-6}\right)$	$5.1\left(4.7^{+1.4}_{-1.1}\right)$	$0.092\left(0.084^{+0.026}_{-0.019}\right)$
2	30	$29\left(24^{+11}_{-6}\right)$	$3.1\left(2.6^{+1.1}_{-0.7}\right)$	$0.056\left(0.046^{+0.021}_{-0.012}\right)$
2	35	$27\left(22^{+9}_{-6}\right)$	$2.7\left(2.2^{+0.9}_{-0.6}\right)$	$0.049\left(0.040^{+0.016}_{-0.011}\right)$
3	35	$30\left(36^{+18}_{-9}\right)$	$2.7\left(3.2^{+1.6}_{-0.8}\right)$	$0.048\left(0.057^{+0.028}_{-0.014}\right)$
3	40	$31\left(39^{+19}_{-12}\right)$	$3.2\left(4.0^{+2.0}_{-1.2}\right)$	$0.058\left(0.073^{+0.035}_{-0.022}\right)$
3	45	$45\left(53^{+15}_{-20}\right)$	$6.3\left(7.5^{+2.1}_{-2.8}\right)$	$0.113\left(0.134^{+0.038}_{-0.050}\right)$
4	45	$74\left(68^{+16}_{-15}\right)$	$9.2\left(8.4^{+2.0}_{-1.9}\right)$	$0.166\left(0.152^{+0.036}_{-0.034}\right)$
4	50	$79\left(77^{+17}_{-16}\right)$	$9.0\left(8.8^{+2.0}_{-1.8}\right)$	$0.162\left(0.159^{+0.036}_{-0.032}\right)$
4	55	$73\left(69^{+11}_{-10}\right)$	$9.7\left(9.1^{+1.5}_{-1.2}\right)$	$0.173\left(0.163^{+0.026}_{-0.022}\right)$
5	55	$48\left(59^{+41}_{-19}\right)$	$5.5\left(6.8^{+4.7}_{-2.1}\right)$	$0.10\left(0.12^{+0.08}_{-0.04}\right)$
5	60	$67\left(81^{+24}_{-31}\right)$	$8.0\left(9.5^{+2.8}_{-3.6}\right)$	$0.14\left(0.17^{+0.05}_{-0.07}\right)$

Source of Uncert.	$m_{\gamma\gamma}$ regime 1 $m_a = 20\ GeV$	2 $m_a = 30\ GeV$	3 $m_a = 40\ GeV$	4 $m_a = 50\ GeV$	5 $m_a = 60\ GeV$
Statistical	0.73	0.51	0.89	1.13	0.92
Closure	0.44	0.27	0.39	0.64	0.89
Modelling	0.35	0.34	0.46	0.42	0.65
Jet	0.58	0.38	0.25	0.90	0.71
Photon	0.06	0.05	0.10	0.12	0.13
Lumi and Pile-up	0.06	0.04	0.27	0.14	0.32

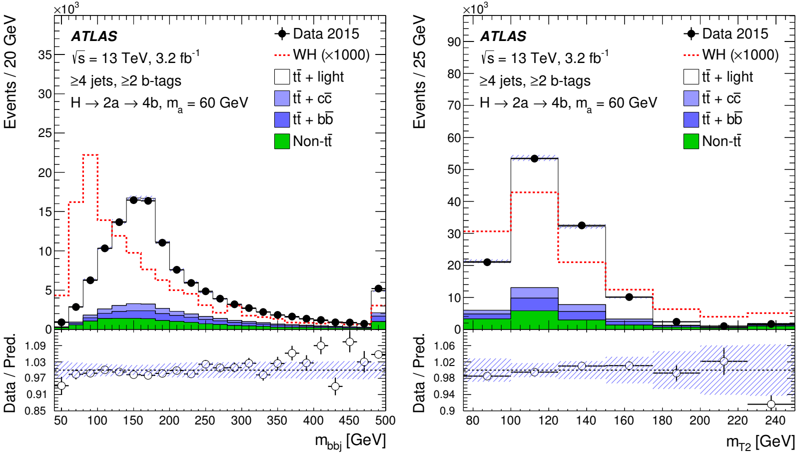
$WH \to \ell\nu a^0 a^0 \to \ell\nu 4b$
Backup Materials


ATLAS
√s = 13 TeV, 3.2 fb⁻¹
≥3 jets, ≥2 b-tags
H → 2a → 4b, m_a = 60 GeV
Data 2015
WH (×1000)
tt̄ + light
tt̄ + cc̄
tt̄ + bb̄
Non-tt̄
Events / 80 GeV
Data / Pred.
m_bbb [GeV]
≥4 jets, ≥2 b-tags
m_bbbb [GeV]
Events / 20 GeV
Δm^bb_min [GeV]

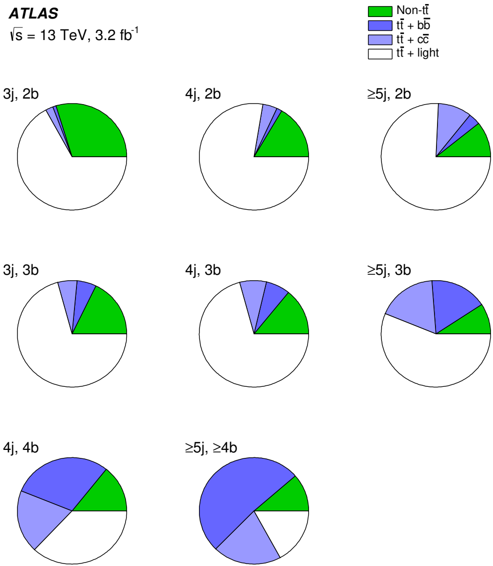
$WH \to \ell\nu a^0 a^0 \to \ell\nu 4b$ Kinematic Distributions (2/3)



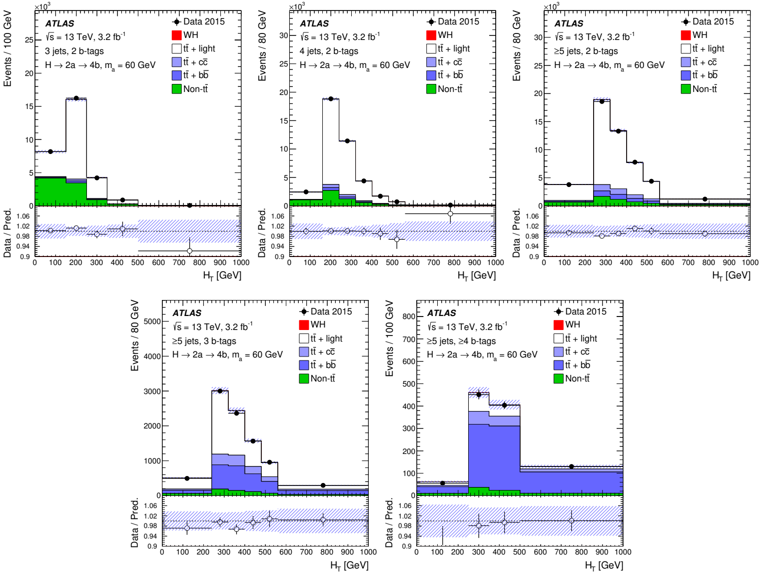
$WH \to \ell\nu a^0 a^0 \to \ell\nu 4b$ Kinematic Distributions (3/3)



$WH \to \ell\nu a^0 a^0 \to \ell\nu 4b$ Background Breakdown



$WH \to \ell\nu a^0 a^0 \to \ell\nu 4b$ H_T CRs



$WH \to \ell\nu a^0 a^0 \to \ell\nu 4b$ Yields

Process	(3j, 3b)	(4j, 3b)	(4j, 4b)
$t\bar{t}$ + light	1089 ± 76	2940 ± 180	53 ± 16
$t\bar{t} + c\bar{c}$	70 ± 28	280 ± 110	21 ± 11
$t\bar{t} + b\bar{b}$	172 ± 55	610 ± 160	74 ± 15
$t\bar{t} + \gamma/W/Z$	0.8 ± 0.1	4 ± 1	0.4 ± 0.1
W + jets	93 ± 31	129 ± 40	2 ± 1
Z + jets	18 ± 12	14 ± 10	–
Single-top-quark	135 ± 13	208 ± 17	8 ± 1
Multijet	48 ± 20	67 ± 28	4 ± 2
Dibosons	4 ± 1	9 ± 1	0.6 ± 0.4
$t\bar{t} + H$	0.7 ± 0.1	4 ± 1	0.8 ± 0.2
Total	1640 ± 58	4270 ± 130	165 ± 15
Data	1646	4302	166
$WH,\ H \to 2a \to 4b$			
$m_a = 60\ GeV$	10 ± 2	9 ± 1	3 ± 1
$m_a = 40\ GeV$	11 ± 2	10 ± 2	2 ± 1
$m_a = 20\ GeV$	6 ± 1	5 ± 1	0.7 ± 0.2

Systematic uncertainty [%]	WH, $H \to 2a \to 4b$	$t\bar{t}$ + light	$t\bar{t} + c\bar{c}$	$t\bar{t} + b\bar{b}$
Luminosity	4	4	4	4
Lepton efficiencies	1	1	1	1
Jet efficiencies	6	4	4	4
Jet energy resolution	5	1	3	1
Jet energy scale	4	2	4	3
b-tagging efficiency	17	5	5	9
c-tagging efficiency	1	6	12	4
Light-jet-tagging efficiency	2	29	5	3
Theoretical cross sections	–	5	5	5
$t\bar{t}$: modelling	–	6	45	26
$t\bar{t}$+HF: normalisation	–	–	35	18
$t\bar{t}$+HF: modelling	–	–	–	5
Signal modelling	7	–	–	–
Total	21	31	54	21