$H \to J\psi\gamma$ Analysis Update and EB Request

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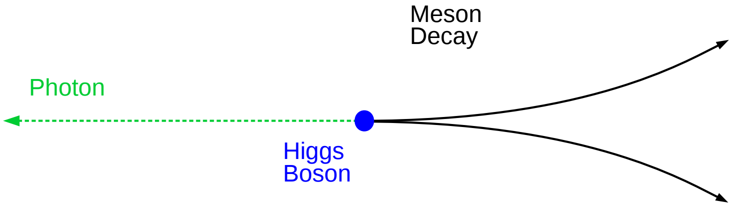
Meson Gamma Introduction



Fully reconstructed decay from the photon and meson decay products

- This signature produces a resonant bump in the three-body mass
- Distinct topology allows for triggering

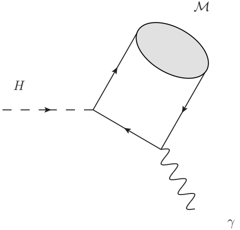
Direct Access to the Higgs Yukawa Couplings

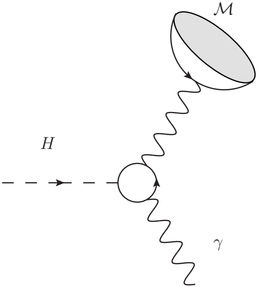
Currently direct evidence only exists for the 3rd generation Yukawa couplings

Final state is produced by two main contributions

- The first features the Yukawa coupling between the Higgs boson and the Meson ((M))
- The second is an indirect production which has no sensitivity to the Yukawa couplings
- Standard Model Predictions:
  - $\mathcal{B}(H \to J/\psi\gamma) = (2.99 \pm 0.16) \times 10^{-6}$†
  - $\mathcal{B}(H \to \psi(2S)\gamma) = (1.03 \pm 0.06) \times 10^{-6}$†
  - $\mathcal{B}(H \to \Upsilon(1S)\gamma) = (5.2^{+2.0}_{-1.7}) \times 10^{-9}$†
- Allows access to the second generation Yukawa couplings.
- Supplementary to direct $H \to c\bar{c}$ searches

  (Phys. Rev. Lett. 120 (2018) 211802)
- Searches also cover the analogous Z boson decay.





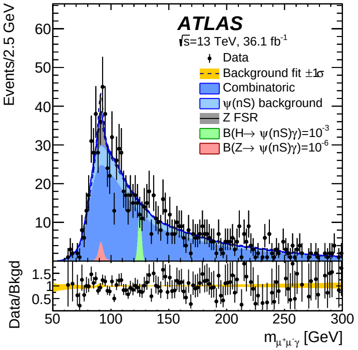
†Phys.Rev. D90 (2014) no.11, 113010

$\psi(nS)\gamma$ ATLAS Results Phys. Lett. B 786 (2018) 134

Prievious results based on 36.1 fb^{-1}

Branching fraction limit (95% CL)	Expected	Observed
$\mathcal{B}(H \to J/\psi\,\gamma)$ [10^{-4}]	$3.0^{+1.4}_{-0.8}$	3.5
$\mathcal{B}(H \to \psi(2S)\,\gamma)$ [10^{-4}]	$15.6^{+7.7}_{-4.4}$	19.8
$\mathcal{B}(Z \to J/\psi\,\gamma)$ [10^{-6}]	$1.1^{+0.5}_{-0.3}$	2.3
$\mathcal{B}(Z \to \psi(2S)\,\gamma)$ [10^{-6}]	$6.0^{+2.7}_{-1.7}$	4.5

Equivalent CMS result $7.6(5.2^{+2.5}_{-1.6}) \times 10^{-4}$ **(Eur. Phys. J. C 79 (2019)94)**



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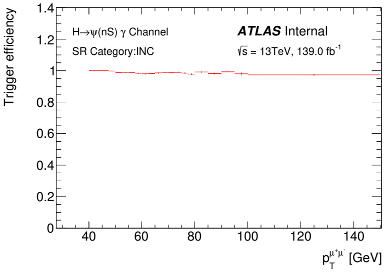
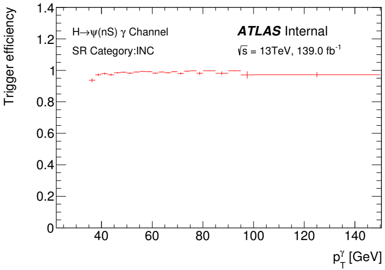
Triggers for $\psi(nS)\gamma$ and $\Upsilon(nS)\gamma$

Baseline from previous analysis, checks of the optimisation are ongoing

- **Photon + Muon triggers developed specifically for this topology**
  - HLT_g35_loose_L1EM22VHI_mu18noL1
  - HLT_g35_tight_icalotight_L1EM24VHI_mu18noL1
  - HLT_g25_medium_mu24
- Require both a photon and single muon at HLT
- But no L1Muon seed to increase acceptance
- Single muon chains also being investigated as support chains
- Collected $139\,\text{fb}^{-1}$ of the $\sqrt{s} = 13\,\text{TeV}$ dataset.





Derivation

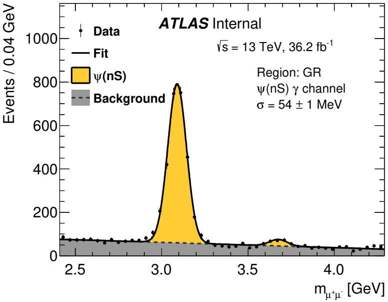
Analysis uses a derivation shared with other Meson Gamma searches

- Recently renamed HDBS2 from HIGG2D5
- Slimmed based on the low rate exclusive triggers
- Derivation Selection
  - J/ψ (Υ) mass Window
  - $\gamma_{PT} > 27$ GeV
  - Leading $\mu_{PT} > 17$ GeV
  - $\mu\mu_{PT} > 27$ GeV
- Events selected in the derivation are also decorated with refitted vertices for all muon pairs compatible with a meson decays (providing L_{xy} for the event selection)

Baseline $\psi(nS)\gamma$ and $\Upsilon(nS)\gamma$ Selection

Baseline from previous analysis, checks of the optimisation are ongoing

- Photon $p_T > 35$ GeV
  - Isolated in tracker and calorimeter
  - High purity photon identification
  - $\Delta\phi(\mathcal{M}, \gamma) > \pi/2$
- Muon Selection
  - Oppositely charged pair of muons
  - $p_T^{\mu\ \text{leading}} > 18$ GeV, $p_T^{\mu\ \text{subleading}} > 3$ GeV
  - $p_T^{\mu\mu}$ varies linearly with $m_{\mu\mu\gamma}$ from $34 \rightarrow 54.4$ GeV
  - Isolated in the tracker
  - Loose $m_{\mu\mu}$ requirement around the meson mass.
  - $L_{xy}/\sigma_{L_{xy}} < 3$



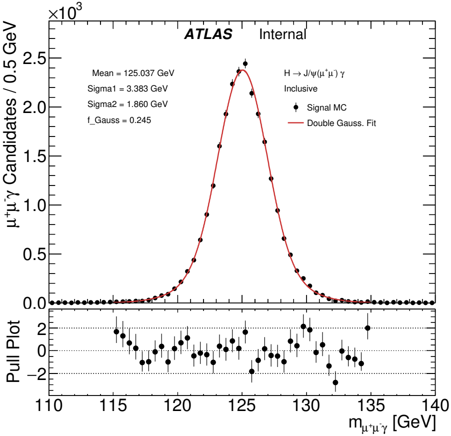
Signal Modeling

Several Higgs boson production modes considered with dedicated samples

- Gluon fusion
- Vector Boson Fusion
- WH, ZH, ttH associated production

Higgs boson decay simulation

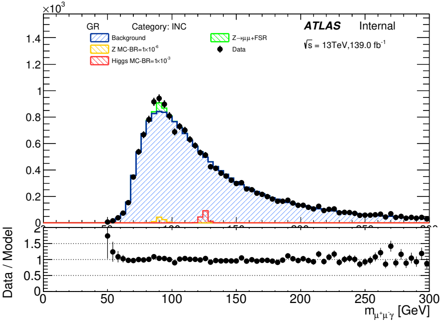
- Modeled in Pythia
- Meson helicity not simulated but accounted for by re-weighting sample
- Resolution extracted by a fit to a double Gaussian with common mean



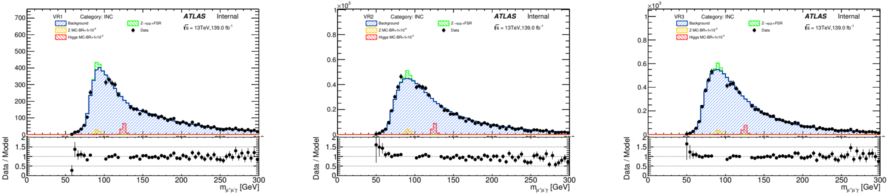
Background Modelling

Background dominated by multijet and γ-jet events

- Background shows a kinematic peak at $\approx$ 100GeV.
- Also resonant contribution from $Z \rightarrow \mu\mu +$ FSR
- Difficult to generate a reliable Monte Carlo sample with a large acceptance to the signal region
- Instead a nonparametric data driven method is used to model this shape
- An alternative would be to use a polynomial fit as used by CMS



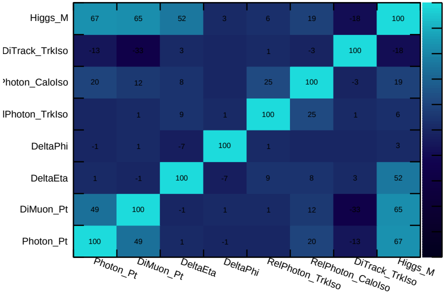
Background Checks

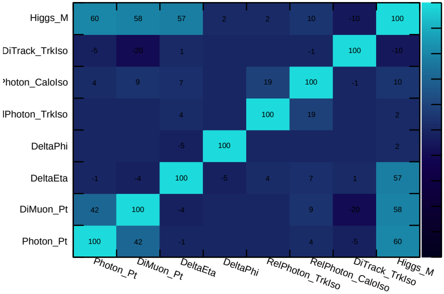


- Three validation regions are defined in order to test the background model.
- Each of these independently re-applies a selection loosened for the generation region.
  - VR1:GR with sliding di-muon pt requirement
  - VR2:GR with FixedCutTightTrackOnly di-muon isolation working point
  - VR3:GR with FixedCutTight photon isolation working point

Blinded validation regions show good prediction for the efficiency of each selection and the effect on the background shape

Background Correlations





We also use a Machine Learning based approach to test our model.

- A further diagnostic for the background model is to compare the correlations between the real data events and the generated pseudo candidates.
- More detailed studies are on going to see if it is possible to train a ML categorisation to tell data background from manufactured background events and use this classification to show where the generation is failing.
- Currently the track isolation variables are listed by TMVA as being the most discriminant so these are the top priority for optimisation.

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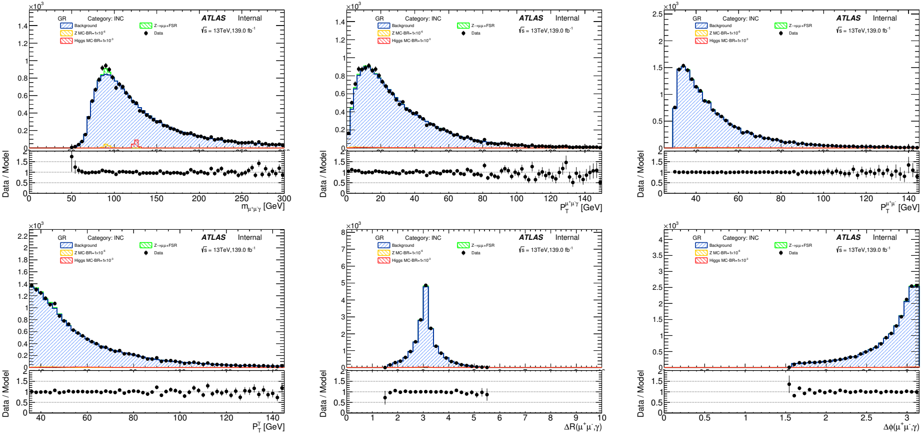
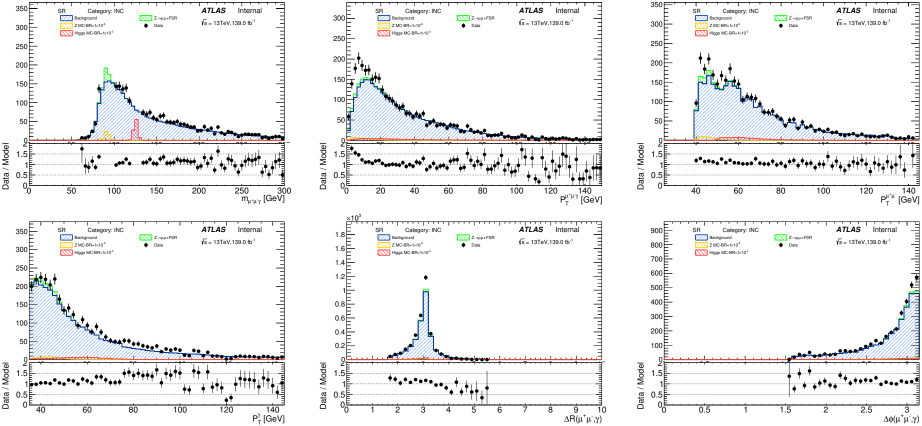
Control Plots ψ(nS) GR



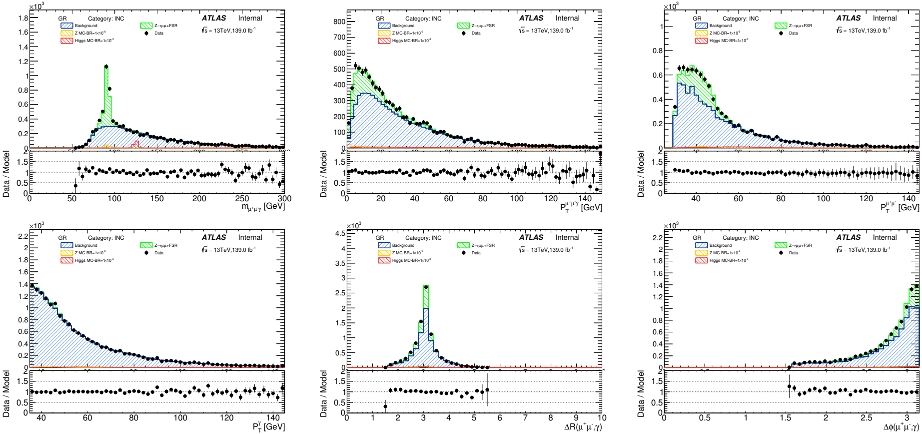
No significant discrepancies visible

Control Plots ψ(nS) SR



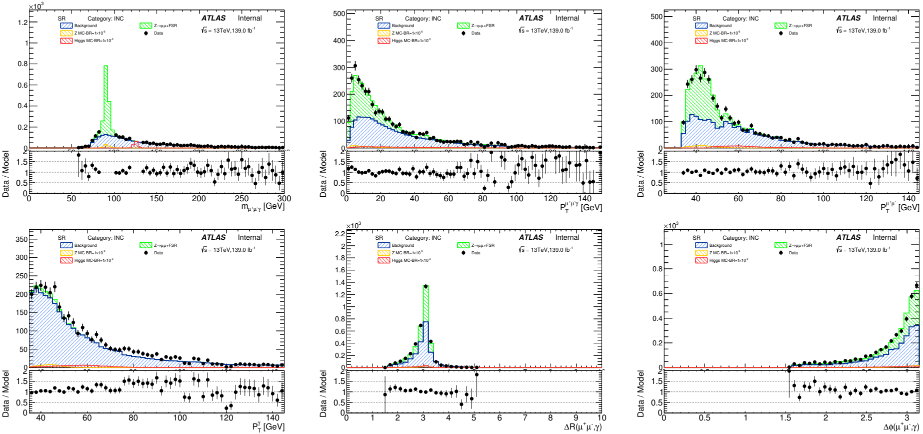
No significant discrepancies, however some issues still persist here

Control Plots $\Upsilon(nS)$ GR



No significant discrepancies

Control Plots ϒ(nS) SR



No significant discrepancies

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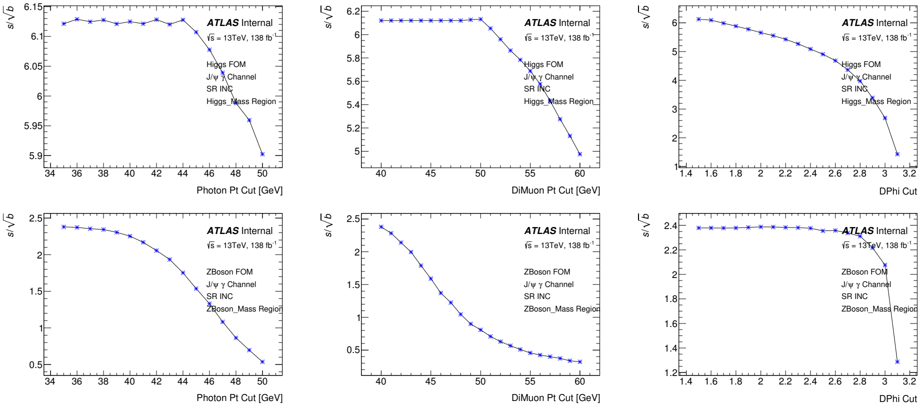
Optimisation Studies

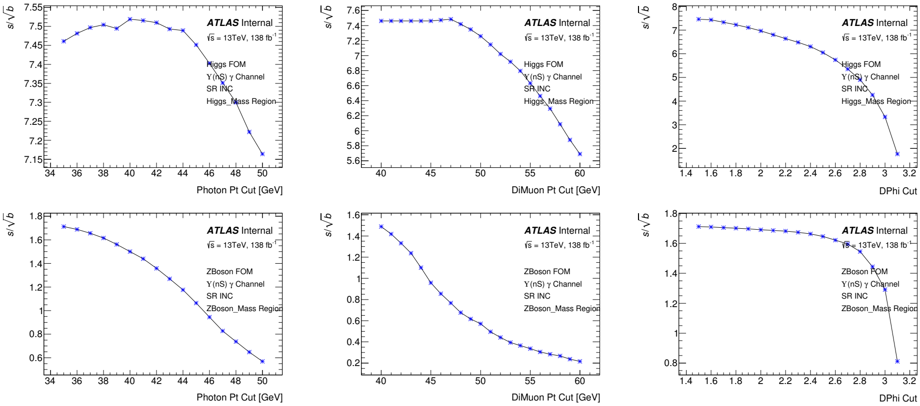
- Check to see if current SR cuts are optimal
- Plot *s*/*sqrtb* as a function of photon and di-muon pt cuts
- Trying to find a way to minimize ZFSR in the background

Optimisation Studies $\psi(nS)$



$\mathcal{B}(H \to \Upsilon(nS)\gamma) = 1 \times 10^{-3}$, $\mathcal{B}(Z \to \Upsilon(nS)\gamma) = 1 \times 10^{-6}$ is assumed and an integrated luminosity of 139.0fb^{-1}.

Optimisation Studies $\Upsilon(nS)$



$\mathcal{B}\left(H \to \Upsilon(nS)\gamma\right) = 1 \times 10^{-3}$, $\mathcal{B}\left(Z \to \Upsilon(nS)\gamma\right) = 1 \times 10^{-6}$ is assumed and an integrated luminosity of 139.0fb^{-1}.

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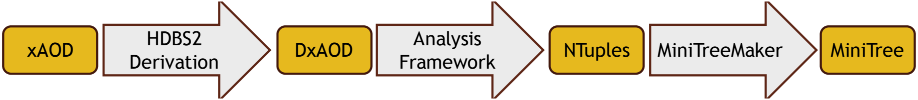
Expected Limits

The limits are currently being worked on. Background only fitting is working, however signal + background limit setting is not. Hopefully we will have something by tomorrow more than this...

Current Workflow



- All xAODs have been produced
- All DxAODs except 1 have been produced with HDBS2 (a small sample of ttH was missed in production)
- BhamAnalysis Framework uses AnalysisBase 21.2.87
- MiniTreeMaker allows for "quick" plotting and analysis of results

Timeline / Outlook

- We have now processed the full Run-2 dataset and most of the MC into our analysis NTuples
- The background estimate is progressing well
- Studies ongoing should provide some improvements over the existing 2015+2016 result
- We are targeting the result for the Moriond timescale
- Finishing RnD this month!
  - Finalize limit setting
  - Finalize incorporation of all MC signal and bkgd
  - Finish optimization

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Analysis Team

- Will Heidorn - analysis framework, analysis development, trigger performance
- Konstantinos Nikolopoulos - supervision, trigger development
- Rhys Owen - analysis framework, analysis development, background modeling, trigger development
- Soeren Prell - supervision

CutFlow $J\psi$

	Signal						Data
	ggF	VBF	WH	ZH	ttH	Z	H + Z
Starting events	364.53	31.01	11.43	7.20	4.29	469.90	1.62×10^7
Preselection	151.72	13.71	4.45	2.85	2.20	144.63	1.62×10^7
Passed Trigger	143.15	12.84	4.19	2.69	2.07	122.78	3.11×10^6
p_T^μ > 3 GeV,	143.15	12.84	4.19	2.69	2.07	122.78	153 201
Leading p_T^μ > 18 GeV,	140.77	12.53	4.07	2.62	1.98	117.34	148 200
Photon:- tight,p_T^γ > 35 GeV,	134.45	11.70	3.81	2.45	1.84	105.42	116 460
$p_T^{\mu\mu}$ >30 GeV,	131.73	11.37	3.71	2.38	1.78	101.60	101 770
$m_{\mu\mu}$ requirement,	131.72	11.36	3.70	2.38	1.77	101.31	74 712
$\Delta\phi(Q\,\gamma) > \pi/2$	121.02	7.98	2.68	1.70	0.94	97.90	63 403
$\lvert L_{xy}/\sigma(L_{xy})\rvert < 3.0$	119.60	7.88	2.64	1.68	0.92	96.95	31 780
Pass GR	118.08	7.76	2.55	1.63	0.82	95.72	17 687
Pass SR	72.14	4.60	1.47	0.94	0.42	51.88	3441

Cut Flow in signal MC. $\mathcal{B}(H \to J/\psi\gamma) = 1 \times 10^{-3}$, $\mathcal{B}(Z \to J/\psi\gamma) = 1 \times 10^{-6}$ is assumed and an integrated luminosity of 139.0fb^{-1}. Preselection includes the following selection requirements: Photons:-medium, $p_T^\gamma > 27$ GeV, η req.; Muons:-segment tagged or combined, $p_T^\mu > 3$ GeV, $|\eta^\mu| < 2.5$; and 2.2 GeV $< m_{\mu\mu} <$ 4.3 GeV.

CutFlow $\psi(2S)$

	Signal						Data
	ggF	VBF	WH	ZH	ttH	Z	H + Z
Starting events	48.82	4.16	1.53	0.97	0.33	63.17	1.62×10^7
Preselection	20.17	1.79	0.59	0.38	0.16	18.84	1.62×10^7
Passed Trigger	19.07	1.67	0.56	0.36	0.16	15.93	3.11×10^6
p_T^μ > 3 GeV,	19.07	1.67	0.56	0.36	0.16	15.93	153 201
Leading p_T^μ > 18 GeV,	18.77	1.63	0.54	0.35	0.15	15.17	148 200
Photon:- tight,p_T^γ > 35 GeV,	17.94	1.53	0.51	0.33	0.14	13.59	116 460
$p_T^{\mu\mu}$ >30 GeV,	17.58	1.48	0.49	0.32	0.13	13.13	101 770
$m_{\mu\mu}$ requirement,	17.58	1.48	0.49	0.32	0.13	13.11	74 712
$\Delta\phi(Q\,\gamma) > \pi/2$	16.11	1.03	0.35	0.23	0.07	12.66	63 403
$\|L_{xy}/\sigma(L_{xy})\| < 3.0$	15.93	1.02	0.35	0.23	0.07	12.53	31 780
Pass GR	15.75	1.00	0.34	0.22	0.06	12.40	17 687
Pass SR	9.62	0.58	0.19	0.12	0.03	6.77	3441

Cut Flow in signal MC. $\mathcal{B}(H \to \psi(2S)\gamma) = 1 \times 10^{-3}$, $\mathcal{B}(Z \to \psi(2S)\gamma) = 1 \times 10^{-6}$ is assumed and an integrated luminosity of 139.0fb^{-1}. Preselection includes the following selection requirements: Photons: -medium, $p_T^\gamma > 27$ GeV, η req.; Muons:-segment tagged or combined, $p_T^\mu > 3$ GeV, $|\eta^\mu| < 2.5$; and 2.2 GeV $< m_{\mu\mu} <$ 4.3 GeV.

CutFlow $\Upsilon(1S)$

	Signal						Data
	ggF	VBF	WH	ZH	ttH	Z	H + Z
Starting events	151.18	12.92	4.75	3.00	1.79	196.42	1.62×10^7
Preselection	64.61	5.63	1.85	1.18	0.90	59.86	1.62×10^7
Passed Trigger	61.79	5.36	1.77	1.13	0.85	51.55	3.11×10^6
p_T^μ > 3 GeV,	61.79	5.36	1.77	1.13	0.85	51.55	153 201
Leading p_T^μ > 18 GeV,	60.81	5.22	1.71	1.10	0.80	49.41	148 200
Photon:- tight, p_T^γ > 35 GeV,	57.79	4.85	1.60	1.02	0.74	43.97	116 460
$p_T^{\mu\mu}$ >30 GeV,	56.75	4.67	1.55	0.99	0.71	42.08	101 770
$m_{\mu\mu}$ requirement,	56.72	4.67	1.54	0.99	0.70	41.42	23 623
$\Delta\phi(Q\,\gamma) > \pi/2$	52.02	3.26	1.10	0.70	0.38	40.23	19 489
$\lvert L_{xy}/\sigma(L_{xy})\rvert < 3.0$	51.55	3.23	1.09	0.69	0.37	39.86	13 443
Pass GR	50.92	3.17	1.06	0.67	0.33	39.38	9005
Pass SR	33.47	2.03	0.66	0.42	0.18	29.12	3647

$\Upsilon(1S)\gamma$ Cut Flow in signal MC. $\mathcal{B}(H \to \Upsilon(1S)\gamma) = 1 \times 10^{-3}$, $\mathcal{B}(Z \to \Upsilon(1S)\gamma) = 1 \times 10^{-6}$ is assumed and an integrated luminosity of 139.0fb^{-1}. Preselection includes the following selection requirements: Photons:-medium, $p_T^\gamma > 15$ GeV, η req.; Muons:-segment tagged or combined, $p_T^\mu > 3$ GeV, $|\eta^\mu| < 2.5$; and 2 GeV $< m_{\mu\mu} <$ 14 GeV.

CutFlow $\Upsilon(2S)$

	Signal						Data
	ggF	VBF	WH	ZH	ttH	Z	H + Z
Starting events	117.68	10.06	3.71	2.34	1.40	152.07	1.62×10^7
Preselection	49.28	4.48	1.43	0.92	0.73	46.13	1.62×10^7
Passed Trigger	47.15	4.26	1.37	0.88	0.70	39.67	3.11×10^6
p_T^{μ} > 3 GeV,	47.15	4.26	1.37	0.88	0.70	39.67	153 201
Leading p_T^{μ} > 18 GeV,	46.33	4.14	1.33	0.86	0.67	37.87	148 200
Photon:- tight, p_T^{γ} > 35 GeV,	43.91	3.86	1.23	0.80	0.62	33.11	116 460
$p_T^{\mu\mu}$ >30 GeV,	42.94	3.72	1.19	0.77	0.60	31.54	101 770
$m_{\mu\mu}$ requirement,	42.93	3.72	1.19	0.77	0.59	31.28	23 623
$\Delta\phi(\mathcal{Q}\,\gamma) > \pi/2$	39.44	2.60	0.85	0.55	0.31	30.25	19 489
$\lvert L_{xy}/\sigma(L_{xy})\rvert < 3.0$	39.02	2.58	0.85	0.54	0.31	30.00	13 443
Pass GR	38.54	2.54	0.82	0.52	0.28	29.73	9005
Pass SR	25.57	1.62	0.51	0.33	0.15	21.73	3647

$\Upsilon(2S)\gamma$ Cut Flow in signal MC. $\mathcal{B}(H \to \Upsilon(2S)\gamma) = 1 \times 10^{-3}$, $\mathcal{B}(Z \to \Upsilon(2S)\gamma) = 1 \times 10^{-6}$ is assumed and an integrated luminosity of 139.0fb^{-1}. Preselection includes the following selection requirements: Photons:-medium, $p_T^{\gamma} > 15$ GeV, η req.; Muons:-segment tagged or combined, $p_T^{\mu} > 3$ GeV, $|\eta^{\mu}| < 2.5$; and 2 GeV $< m_{\mu\mu} <$ 14 GeV.

CutFlow $\Upsilon(3S)$

	Signal						Data
	ggF	VBF	WH	ZH	ttH	Z	H + Z
Starting events	133.40	11.33	4.19	2.63	1.57	173.55	1.62×10^7
Preselection	56.07	5.00	1.64	1.03	0.80	52.67	1.62×10^7
Passed Trigger	53.83	4.74	1.57	0.99	0.77	45.81	3.11×10^6
p_T^μ > 3 GeV,	53.83	4.74	1.57	0.99	0.77	45.81	153 201
Leading p_T^μ > 18 GeV,	52.87	4.60	1.52	0.96	0.73	43.72	148 200
Photon:- tight, p_T^γ > 35 GeV,	50.39	4.28	1.41	0.89	0.67	38.61	116 460
$p_T^{\mu\mu}$ >30 GeV,	49.28	4.14	1.37	0.86	0.65	36.97	101 770
$m_{\mu\mu}$ requirement,	49.28	4.13	1.36	0.85	0.64	36.68	23 623
$\Delta\phi(Q\,\gamma) > \pi/2$	45.18	2.83	0.97	0.61	0.34	35.44	19 489
$\lvert L_{xy}/\sigma(L_{xy})\rvert < 3.0$	44.71	2.80	0.96	0.60	0.33	35.00	13 443
Pass GR	44.15	2.75	0.93	0.58	0.30	34.55	9005
Pass SR	28.67	1.73	0.58	0.36	0.16	25.03	3647

$\Upsilon(3S)\gamma$ Cut Flow in signal MC. $\mathcal{B}(H \to \Upsilon(3S)\gamma) = 1 \times 10^{-3}$, $\mathcal{B}(Z \to \Upsilon(3S)\gamma) = 1 \times 10^{-6}$ is assumed and an integrated luminosity of 139.0fb^{-1}. Preselection includes the following selection requirements: Photons:-medium, $p_T^\gamma > 15$ GeV, η req.; Muons:-segment tagged or combined, $p_T^\mu > 3$ GeV, $|\eta^\mu| < 2.5$; and 2 GeV $< m_{\mu\mu} <$ 14 GeV.