XXVI International Workshop on Deep Inelastic Scattering and Related Subjects

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

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on behalf of the ATLAS collaboration
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ATLAS EXPERIMENT

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Introduction

- Current experimental constraint on the branching ratio (BR) of the SM Higgs rare and non-SM decays is less than **34**% at 95% CL. (JHEP08(2016)045)

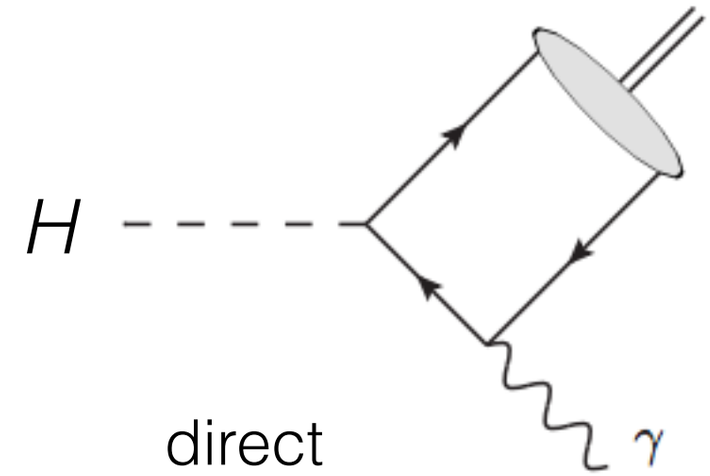
- There is still large room to explore for these interesting decays that can help
  - Examine the SM Higgs properties
  - Probe enhancement coming beyond the SM (BSM)

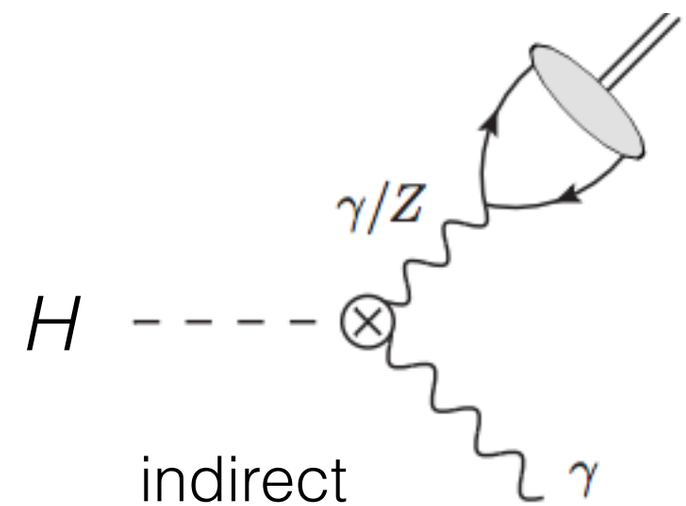
- Rare decays
  - H→meson+photon
  - H→Zγ (for heavy resonant searches, see Flavia's talk)
  - H→ fermions (see already Carlo's and Yiwen's talks)
  - "H*→HH", self-coupling (see Yaquan's and Giacomo's talks)

- Non-SM decays
  - H→aa, light bosons
  - H→invisible, dark matter (see William's talk)

Higgs decaying to a meson + a photon

- The Higgs rare decays to a meson and a photon, such as BR(H→ργ) at 10^{-5}, BR(H→φγ) at 10^{-6} exist in the SM
  - They can be used to probe Higgs couplings to the first and second quark generations and enhancement from BSM (Higgs compositeness etc.)
- The small decay amplitude is a result of
  - The smallness of Higgs-light-quark couplings
  - The destructive interference between the diagrams
- The **indirect** process predominantly contribute to the BR
- The latest ATLAS results of Higgs and Z bosons to φγ and ργ were published in arXiv:1712.02758 Dec 2017
  - Replacing last φγ results in Phys. Rev. Lett. 117, 111802





For earlier results on 8 TeV J/ψ and Υ see Phys. Rev. Lett. 114 (2015) 121801

arXiv:1712.02758

H→φγ and ργ: event selection

- The dominant decays of $\varphi \to K^+K^-$ and $\rho \to \pi^+\pi^-$ are chosen for the analysis
  - The final states include a pair of tracks and a photon
- Given soft kinematics, special triggers on ditracks originating from mesons are developed to increase the acceptance

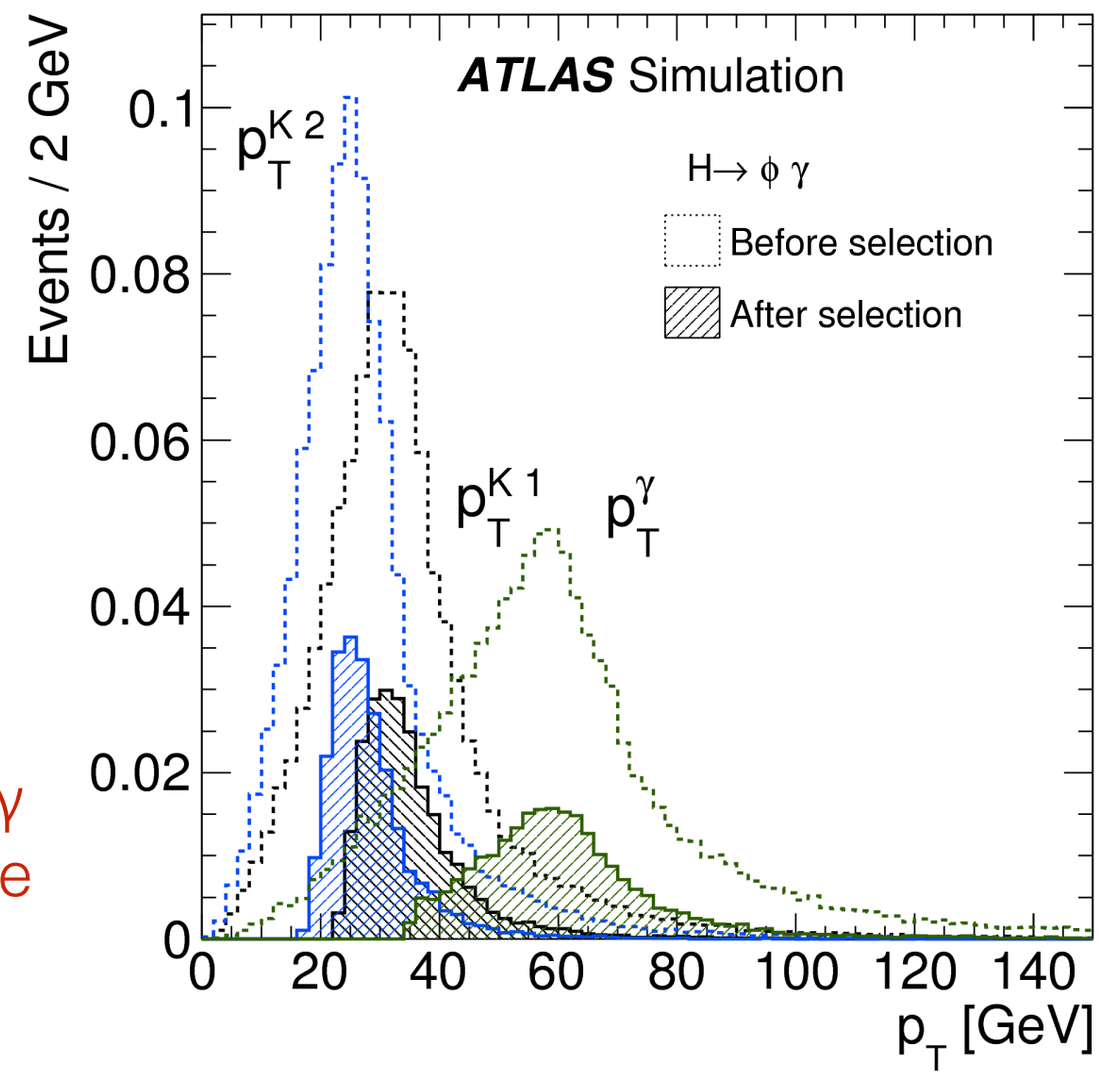


Table shows φγ selections while ργ's are similar

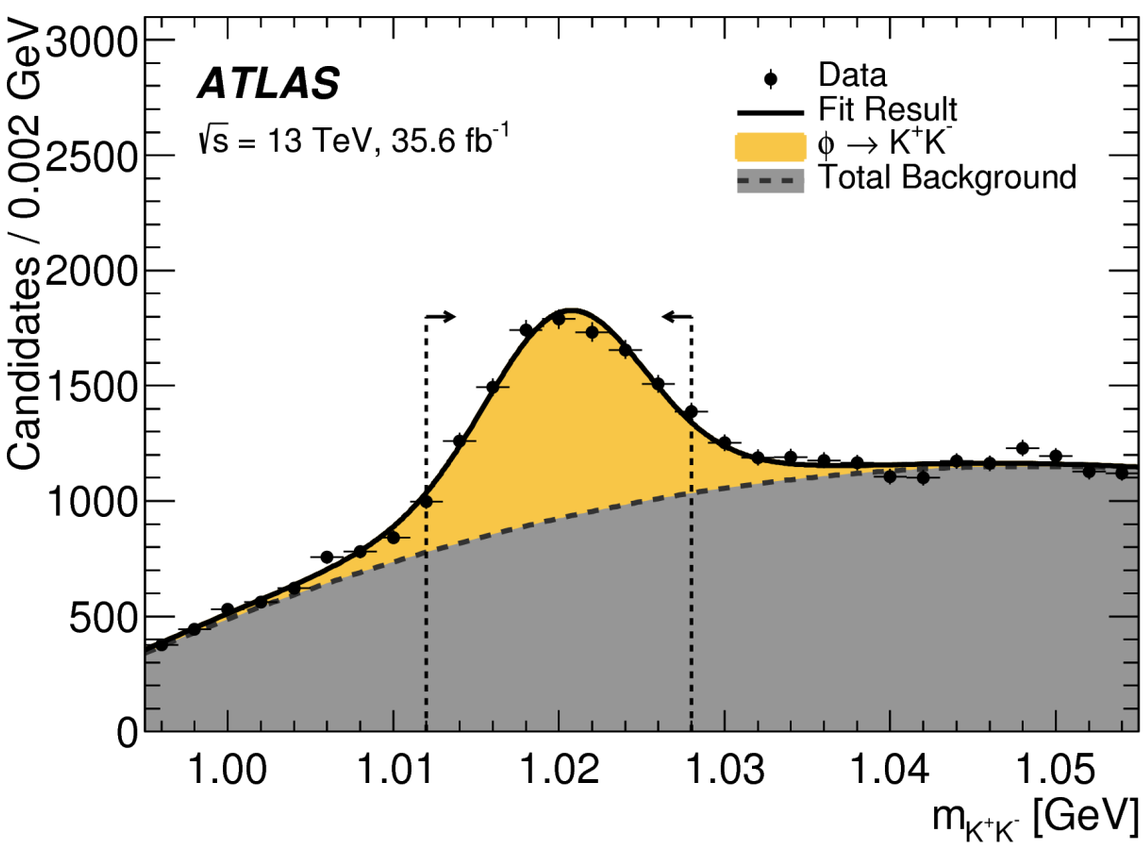
p_T >15 GeV, at least one with p_T > 20 GeV		
$\lvert\eta\rvert$<2.5		
Opposite charge		
ditrack p_T^{K+K-} cut	p_T>35 GeV	Overall selection efficiency
$\lvert m_{K+K-} - m_\phi\rvert$ < 8 MeV	$\lvert\eta\rvert$<2.37 removing 1.37<$\lvert\eta\rvert$<1.52	**ε(φγ) ~ 17%** **ε(ργ) ~ 10%**
φ isolation	photon isolation	$\Delta\phi(K^+K^-,\gamma) > \pi/2$
Meson (2 tracks)	**Photon**	**Meson+photon**

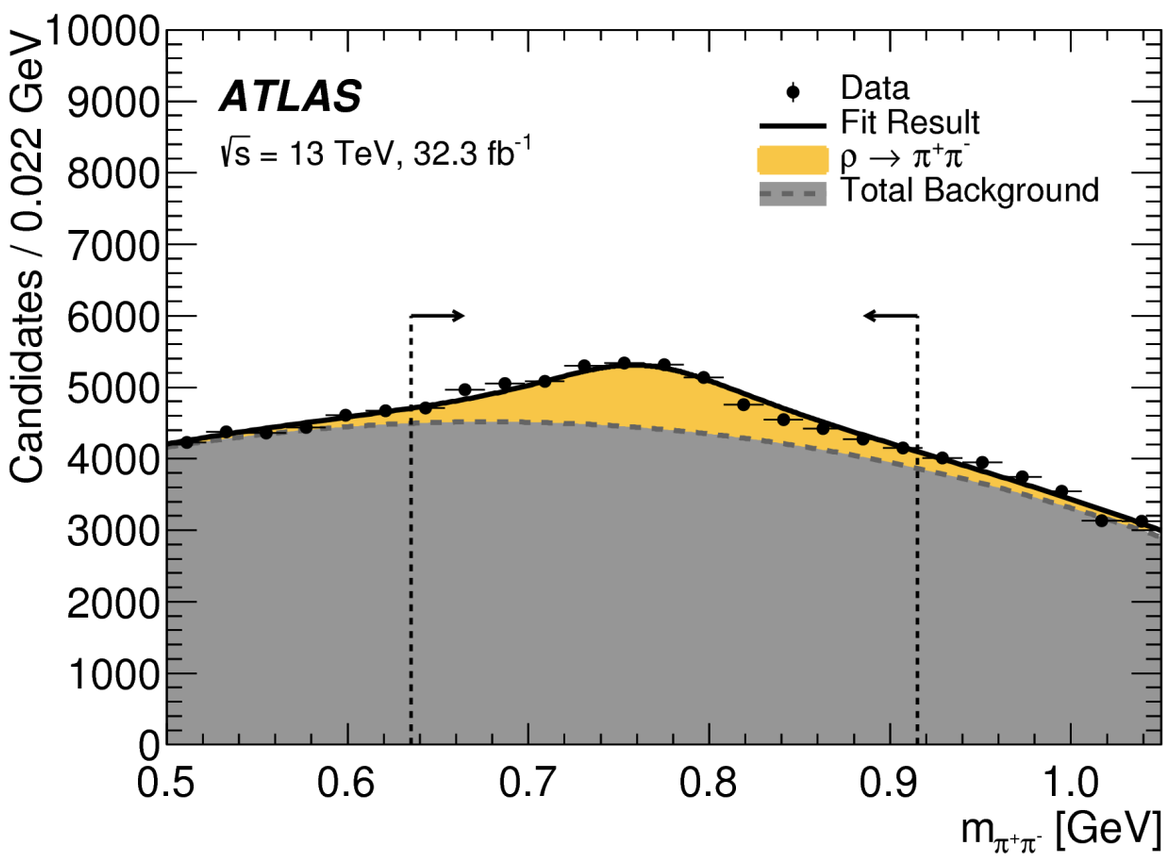
arXiv:1712.02758

H→φγ and ργ: mass resolution

- The $m(K^+K^-)$ resolution is 4 MeV compared to 4.3 MeV of φ natural width, while $m(\pi^+\pi^-)$ has much broader distribution given larger ρ width

- The mass resolutions of $m(K^+K^-\gamma)$ and $m(\pi^+\pi^-\gamma)$ that are used as the final fit template are both 1.8%



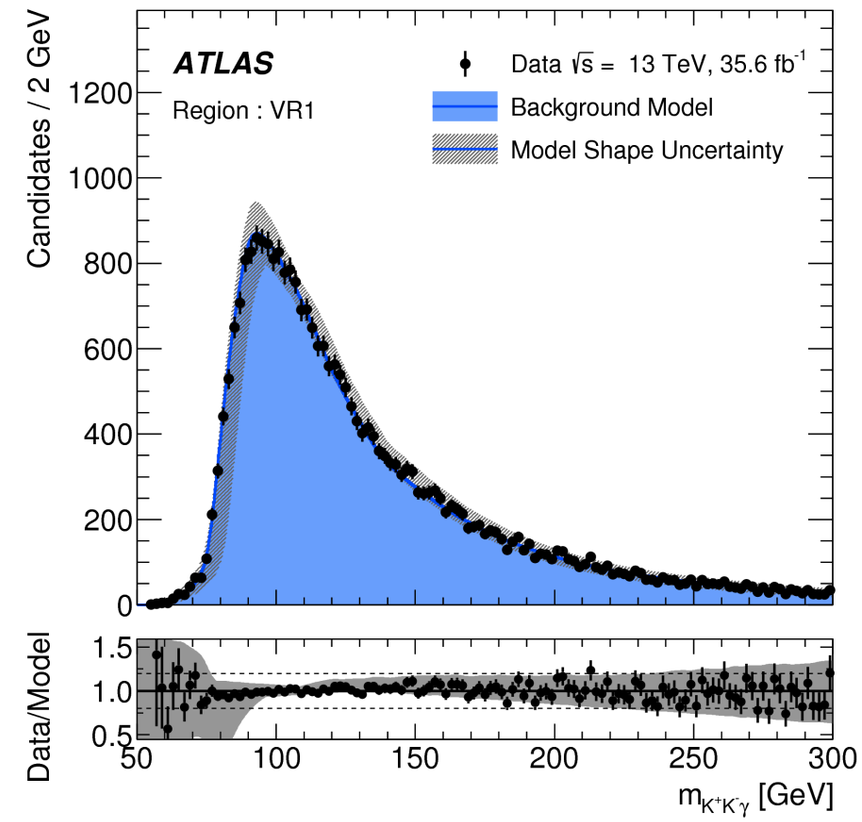


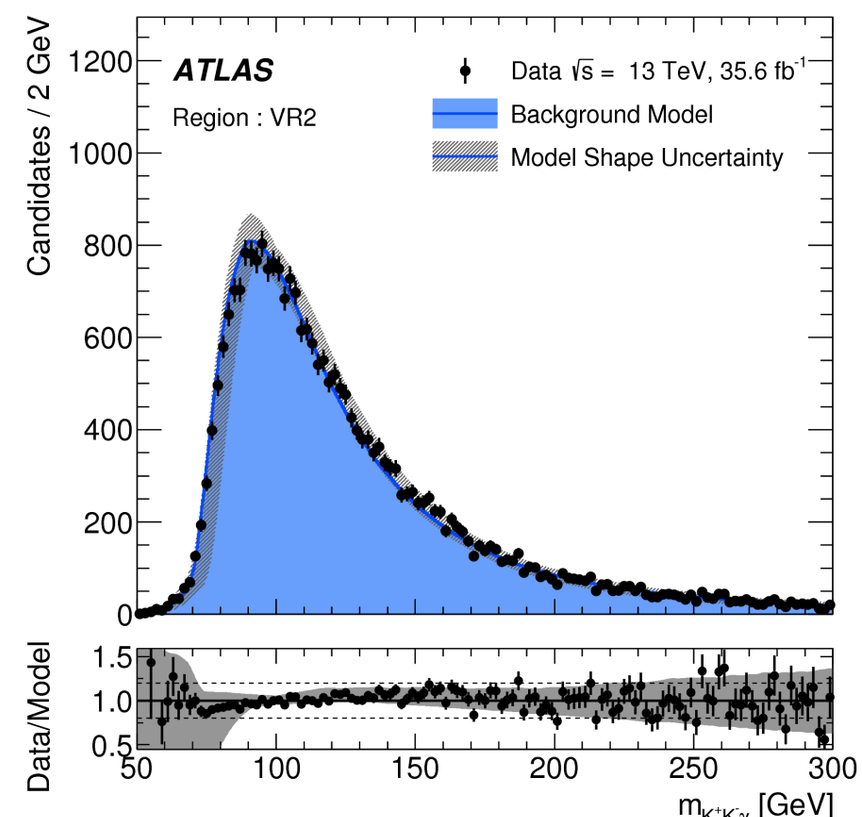
arXiv:1712.02758

H→φγ and ργ: background estimation

- Dominant background comes from multijet and γ+jets
- The background shape is modelled from pseudo-data and the normalisation is free in the final fit
- Pseudo-data is made from a background-dominated generation region (GR) by relaxing cuts on p_T^{KK}, meson and photon isolation
  - Random sampling the distributions of relevant variables: $\eta_{K^+K^-}$, $\varphi_{K^+K^-}$, $m_{K^+K^-}$, $p_T^{K^+K^-}$ for the meson, and, $\Delta\varphi(K^+K^-, \gamma)$, $\Delta\eta(K^+K^-, \gamma)$, p_T^{γ} for the photon, with their correlations considered
- The model is examined in validation regions (VR) in which some of the relaxed cuts are recovered

ργ has similar procedure as above

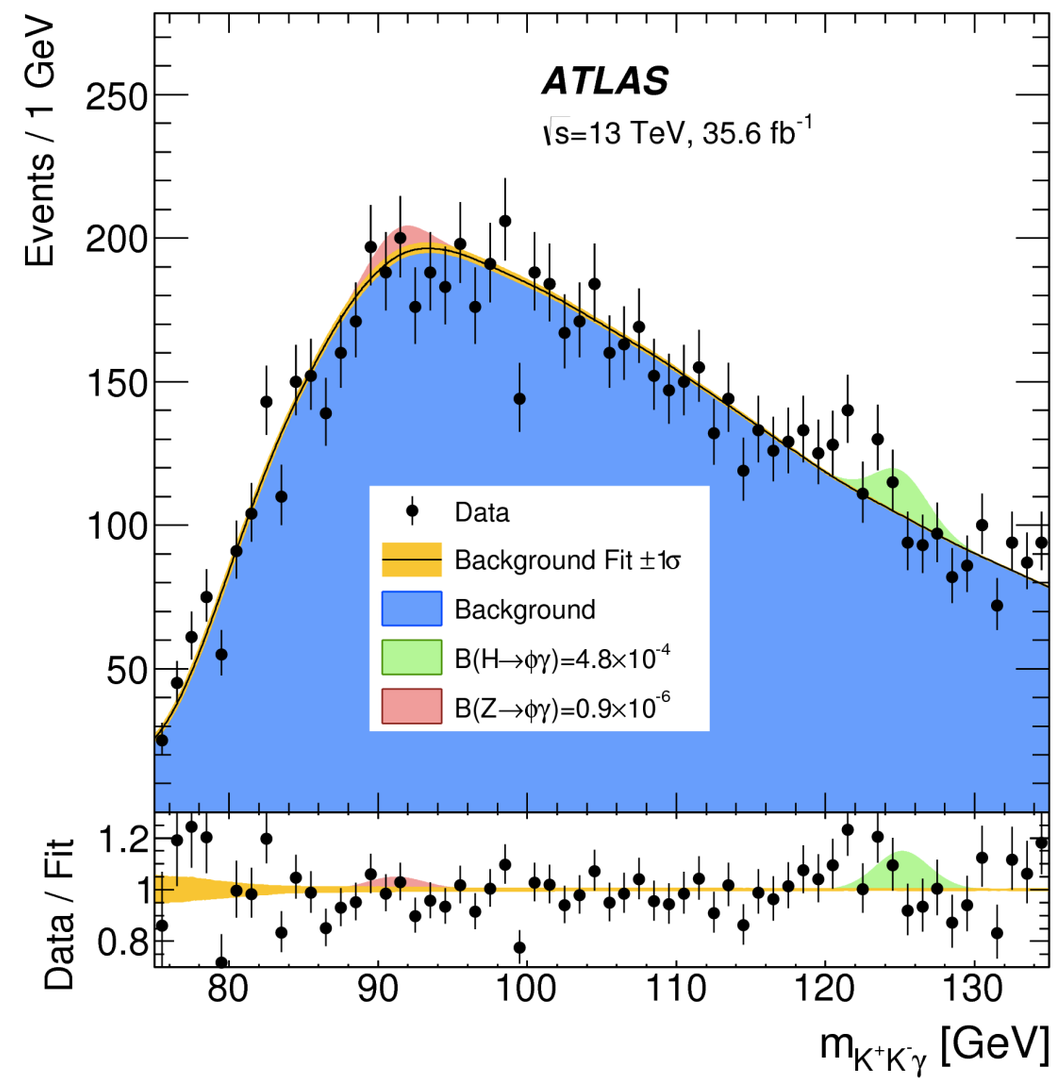




arXiv:1712.02758

H→φγ and ργ: results

- The final fits is performed on m(K+K−γ) and m(π+π-γ) with an unbinned likelihood
- The observed data are consistent with the expected background-only prediction
- Upper limits are set on BRs with the SM Higgs cross section assumed
  - Corresponding to 208 and 52 times of SM predictions for H→φγ and H→ργ



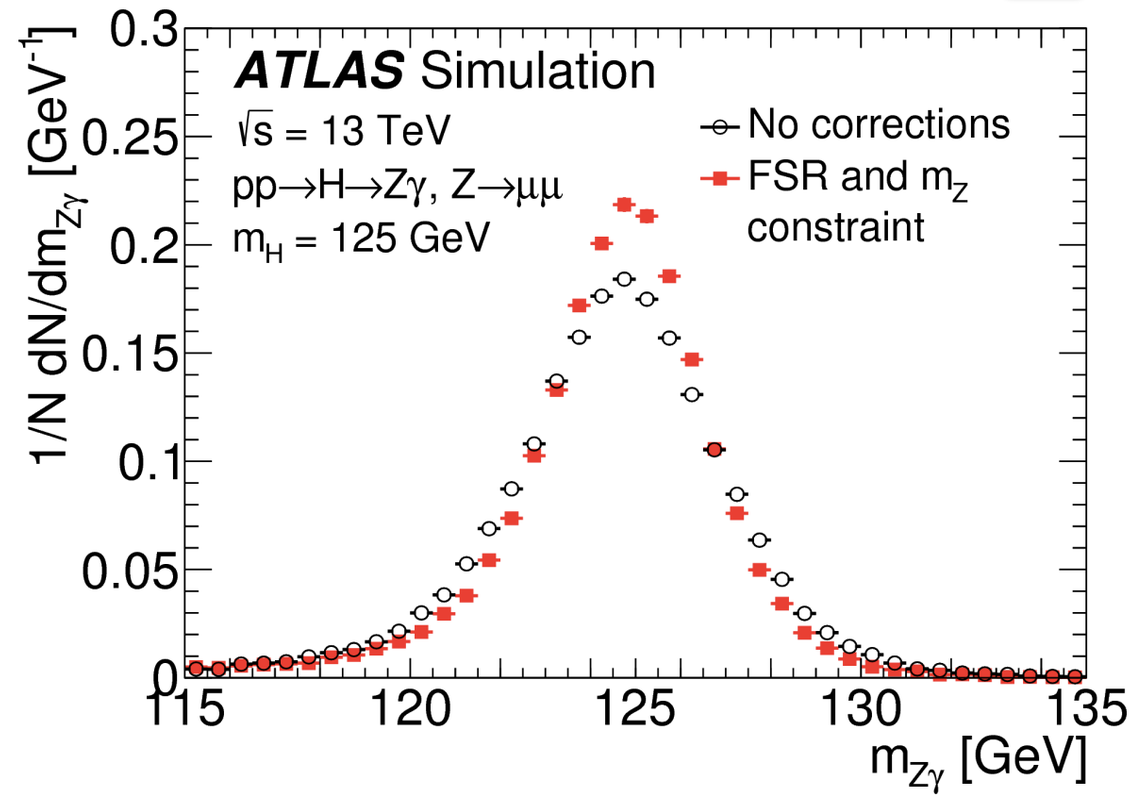
Branching Fraction Limit (95% CL)	Expected	Observed
$\mathcal{B}(H \to \phi\gamma)\,[\,10^{-4}\,]$	$4.2^{+1.8}_{-1.2}$	4.8
$\mathcal{B}(Z \to \phi\gamma)\,[\,10^{-6}\,]$	$1.3^{+0.6}_{-0.4}$	0.9
$\mathcal{B}(H \to \rho\gamma)\,[\,10^{-4}\,]$	$8.4^{+4.1}_{-2.4}$	8.8
$\mathcal{B}(Z \to \rho\gamma)\,[\,10^{-6}\,]$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

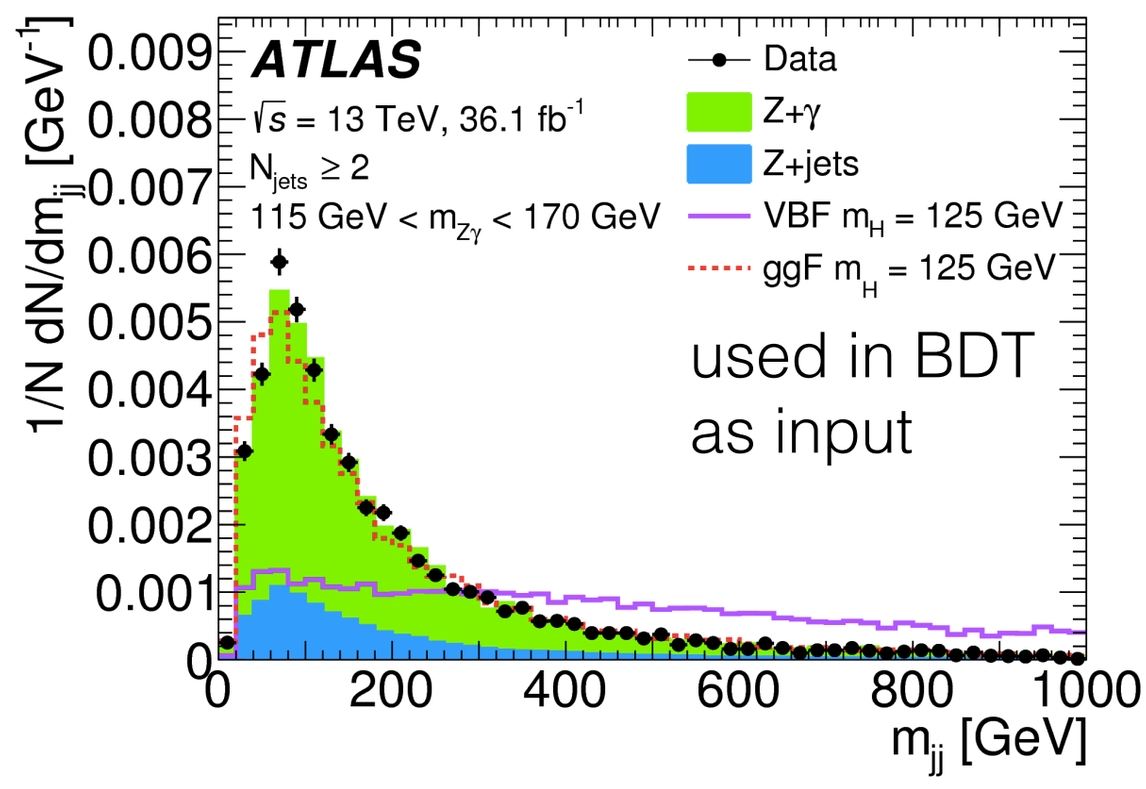
Reduce the limits by a factor of 3 from last ATLAS results BR(H→φγ) < 1.4×10⁻³ (1.5×10⁻³)

JHEP 10 (2017) 112

Higgs decaying to Zγ

- H→Zγ is one of the SM Higgs rare decays and has a BR at 10^{-3} level in the SM, comparable to H→γγ, but very challenging due to Z decays
- It can be enhanced by various BSM sources, such as Higgs compositeness, additional colourless particles in the H→Zγ loop, etc.
- The latest ATLAS result is JHEP 10 (2017) 112
- Only Z→ee/μμ, ggF+VBF+VH are considered, and major selections include
  - Two same-flavour opposite-charge ee/μμ
  - At least one photon
  - m_Z window
  - Categorisation (boosted decision tree, photon p_T etc.)





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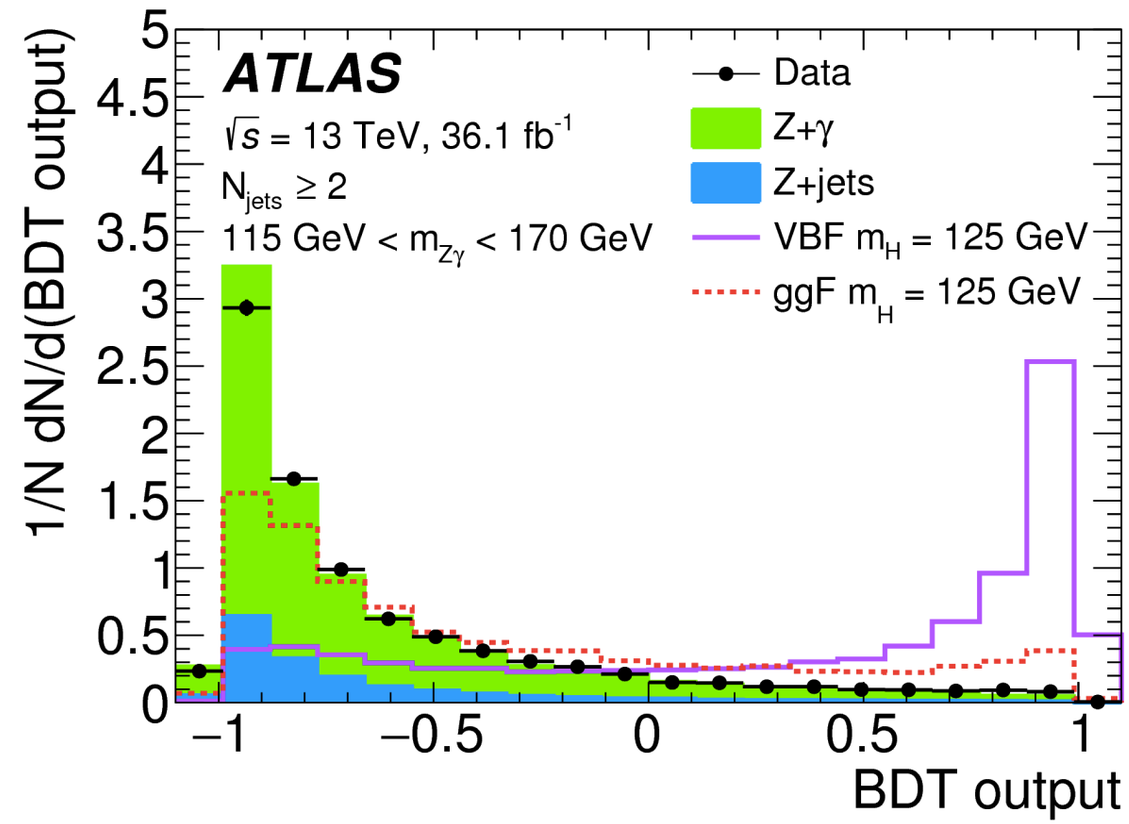
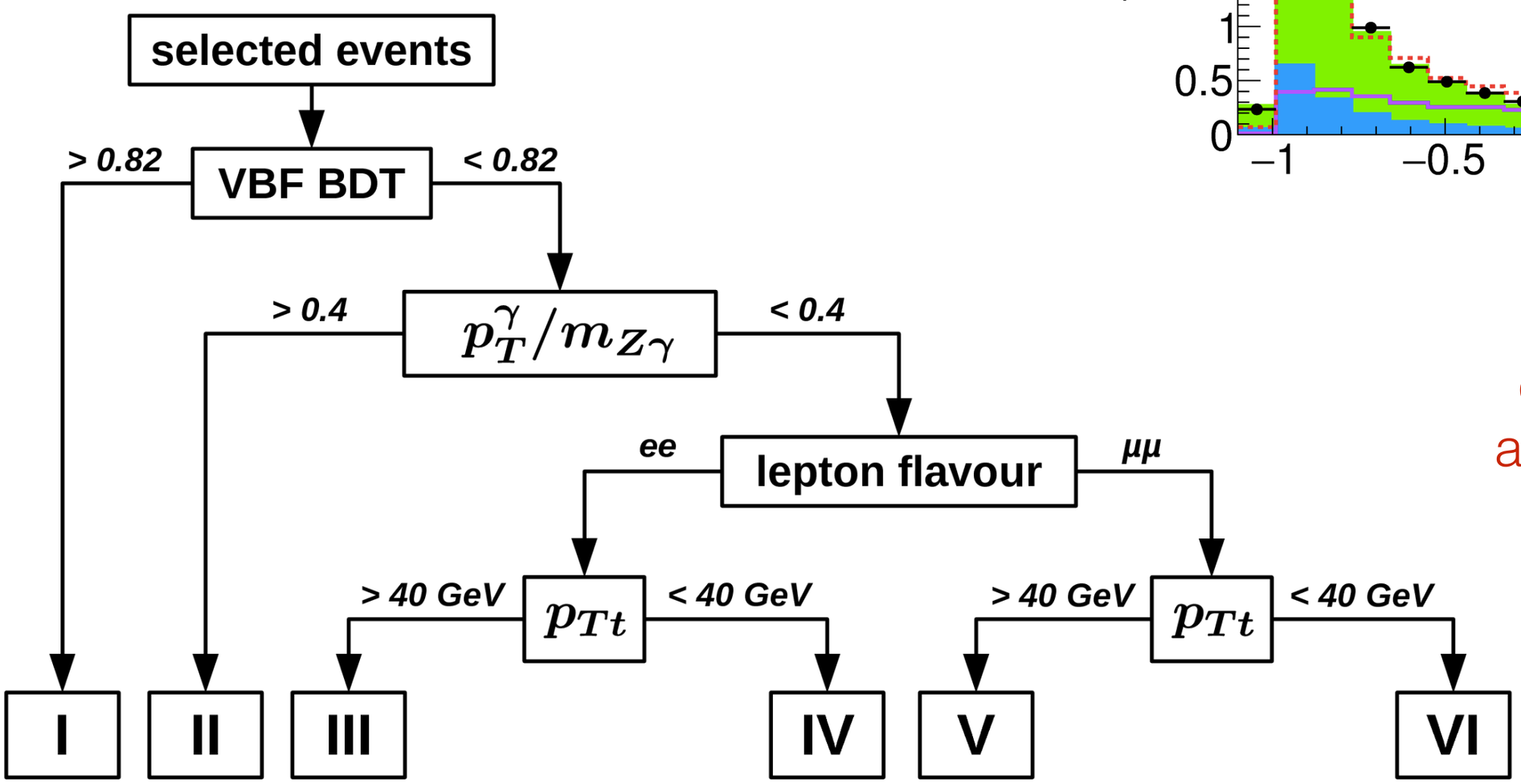
Zγ event categories

Category	Events	S_{90}	$S_{90}/\sqrt{S_{90}+B_{90}}$
VBF-enriched	88	1.2	0.32
High relative p_{T}	443	2.3	0.26
ee high $p_{\mathrm{T}t}$	1053	3.3	0.19
ee low $p_{\mathrm{T}t}$	11707	11.2	0.18
$\mu\mu$ high $p_{\mathrm{T}t}$	1413	4.0	0.22
$\mu\mu$ low $p_{\mathrm{T}t}$	16529	14.5	0.21





$$p_{\mathrm{T}t} = 2|p_x^Z p_y^\gamma - p_x^\gamma p_y^Z|/p_{\mathrm{T}}^{Z\gamma}$$

Category **I** is a VBF-enriched region with a fraction **67.5**% from VBF events

The overall signal efficiency is about **20**% for each production modes

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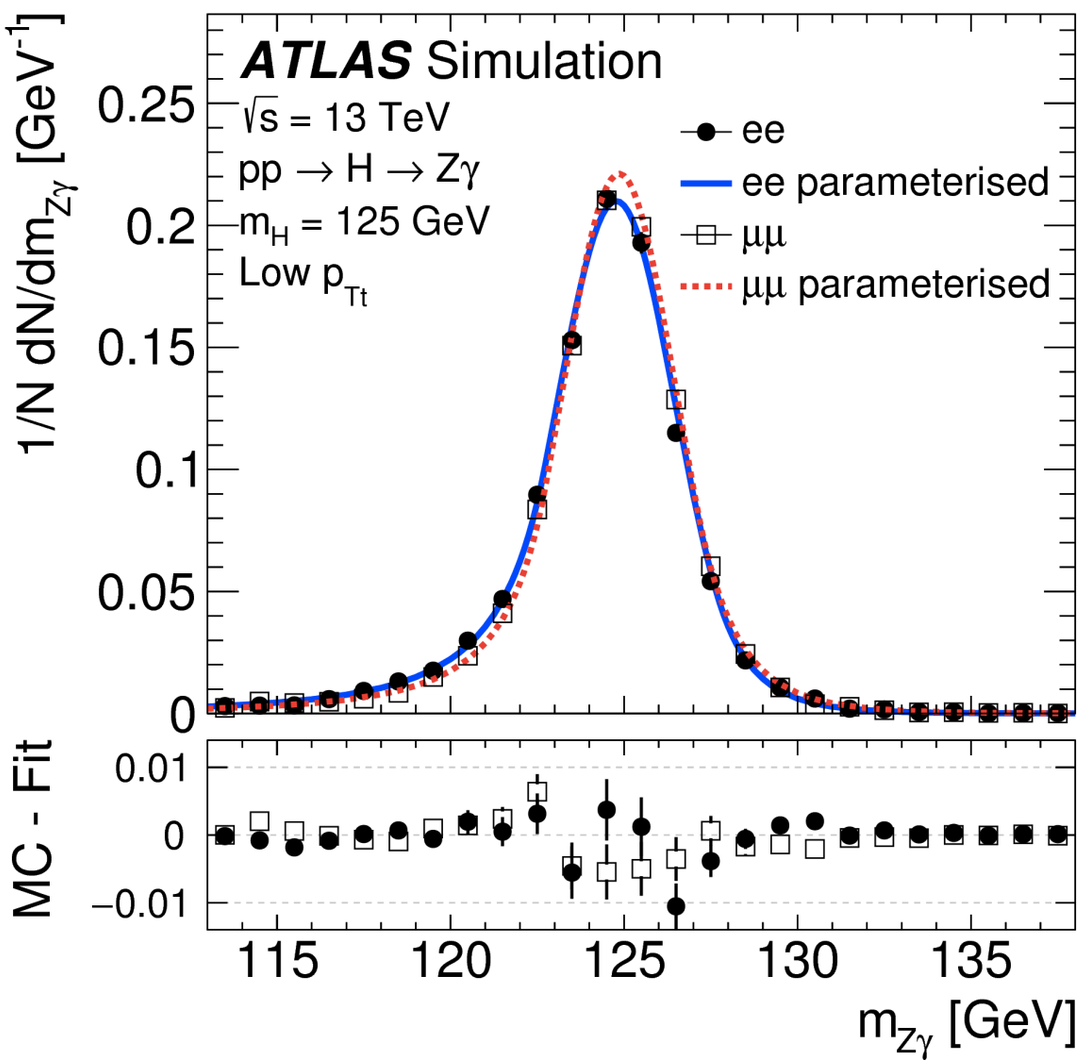
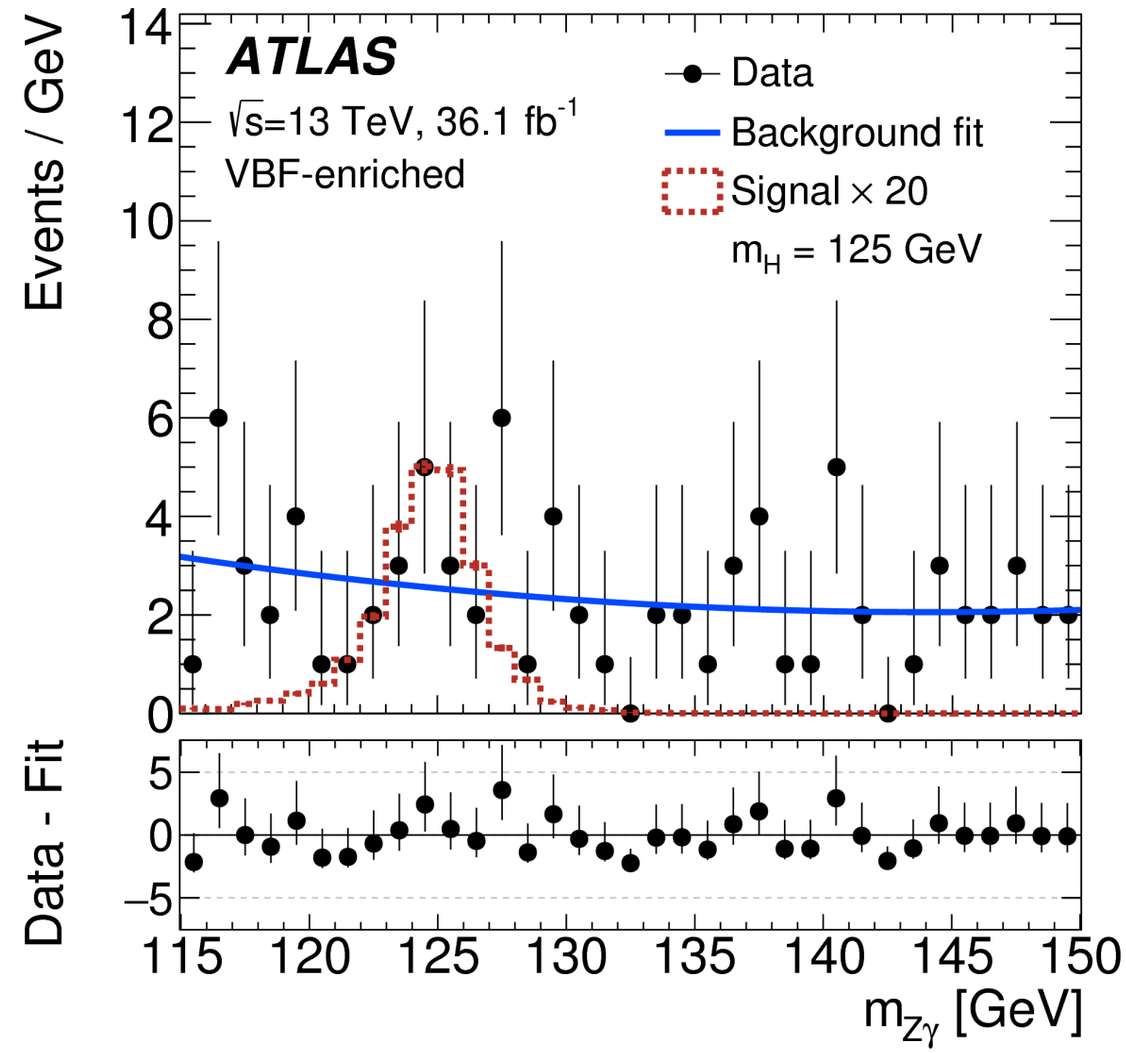
Zγ fits and results

- Signals are modelled with double-sided Crystal Ball functions, while backgrounds by Bernstein polynomials (Z+γ taking up 80%)
- No significant excess is found in data. The observed 95% CL limit on σ(pp→H)BR(H→Zγ) is found to be **6.6** times the SM prediction
- Assuming SM production, upper limit on BR(H→Zγ) is **1**%

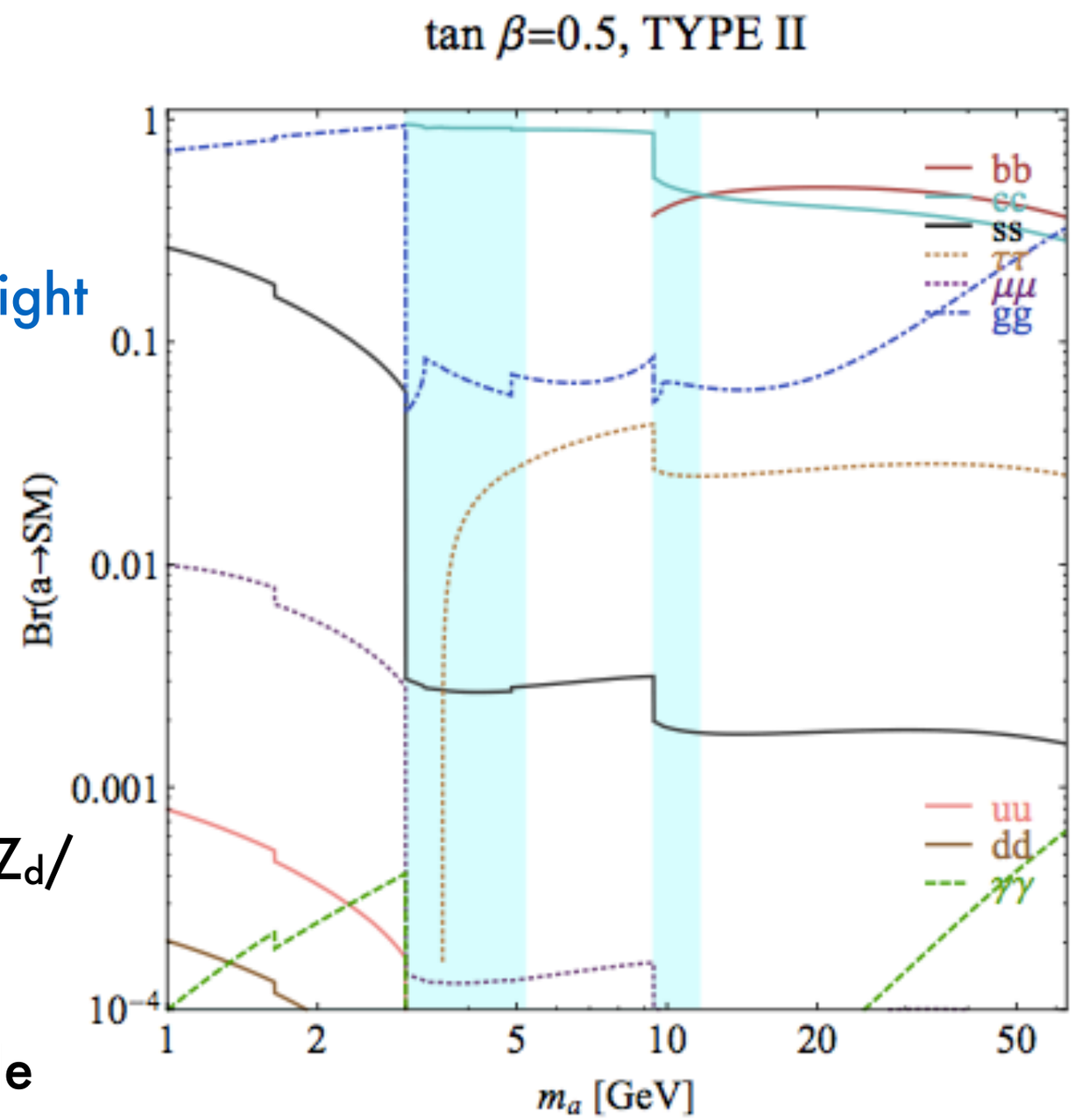




arXiv:1803.11145

Higgs decaying to light bosons

- Many BSM scenarios (2HDM+S, NMSSM, dark matter related etc.) predict non-SM Higgs decays
  - Higgs decaying to a pair of new spin-0 light bosons is one of the most simplest and interesting possibilities
- The light bosons have a rich decay variety into SM particles
- ATLAS latest result includes H→aa→γγjj, arXiv:1803.11145 March 2018, H→ZZ$_d$/Z$_d$Z$_d$/aa→llll arXiv:1802.03388 January 2018
- Previous ATLAS results not in this talk include bbbb(Eur. Phys. J. C 76 (2016) 605), μμττ (Phys. Rev. D92 (2015) 052002), γγγγ (Eur. Phys. J. C **76** (2016) 210),

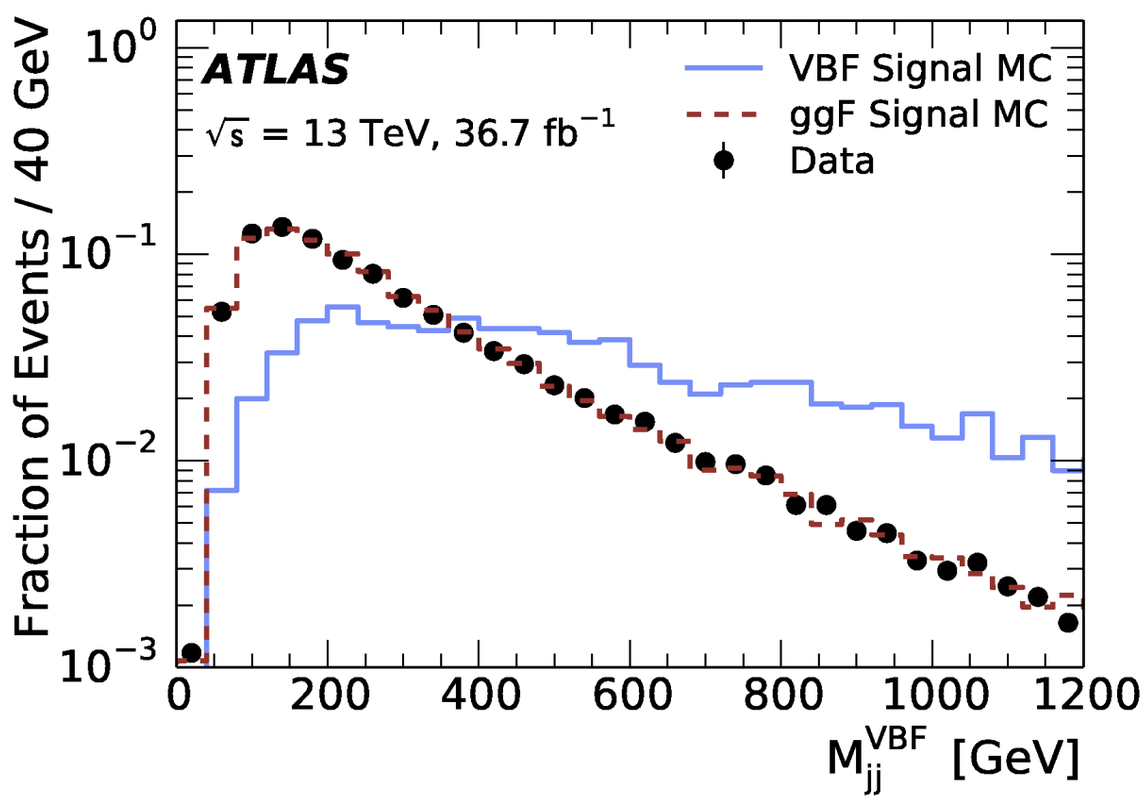


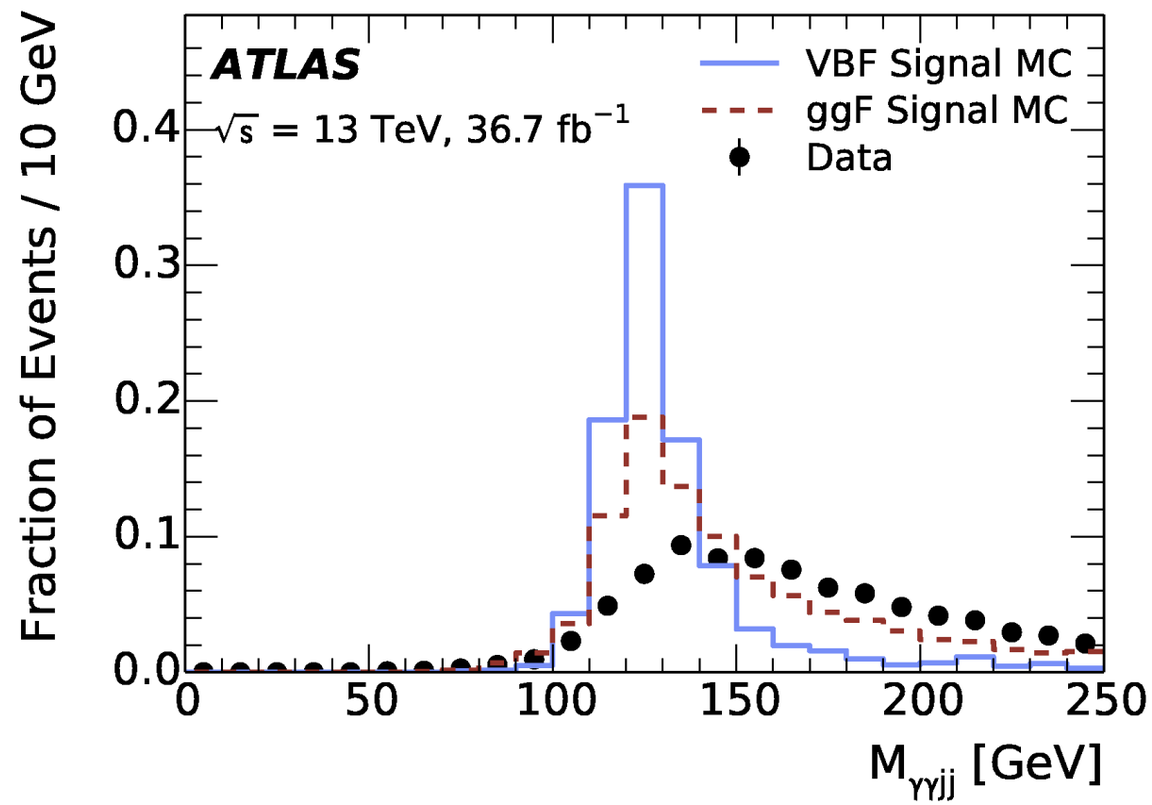
http://exotichiggs.physics.sunysb.edu/

arXiv:1803.11145

γγjj: event selection

- Optimise event selection for the VBF production:
  - At least 2 isolated photons, E_T>27 to 40 depending on the trigger
  - At least 4 jets, leading p_T > 60 GeV, m_{jj}^{VBF} > 500 GeV
  - 100 < $m_{\gamma\gamma jj}$ < 150 GeV
- Define 5 overlapping "$m_{\gamma\gamma}$ regimes" for different signal mass ranges





arXiv:1803.11145

γγjj: background estimation

- Dominant background comes from γγ+multi-jet events, estimated with data-driven method by defining 4 orthogonal regions
  - AB (CD) with photon isolation tight and loose for each (tight for both)
  - AC (BD) are > (<) x_R
- Small correlation between photon isolation and $|m_{jj}-m_{\gamma\gamma}|$ makes the formula hold
  - Closure check is performed in $m_{\gamma\gamma jj}$ sideband and the bias is treated as uncertainty

		Photon requirements	
		TightLoose	TightTight
$\lvert m_{jj}-m_{\gamma\gamma}\rvert$	$> x_R$	A	C
	$\leq x_R$	B	D **Signal region**

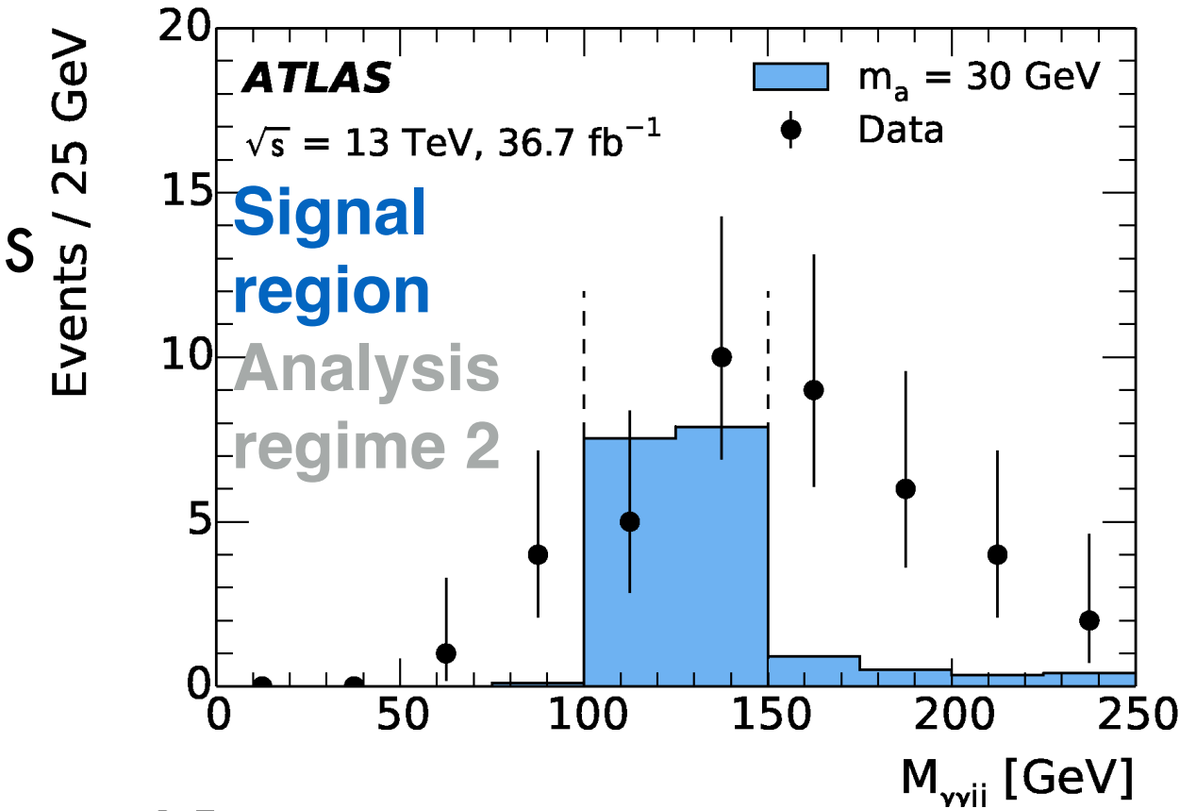
$$N_D^{bkg} = \frac{N_B^{bkg} N_C^{bkg}}{N_A^{bkg}}$$

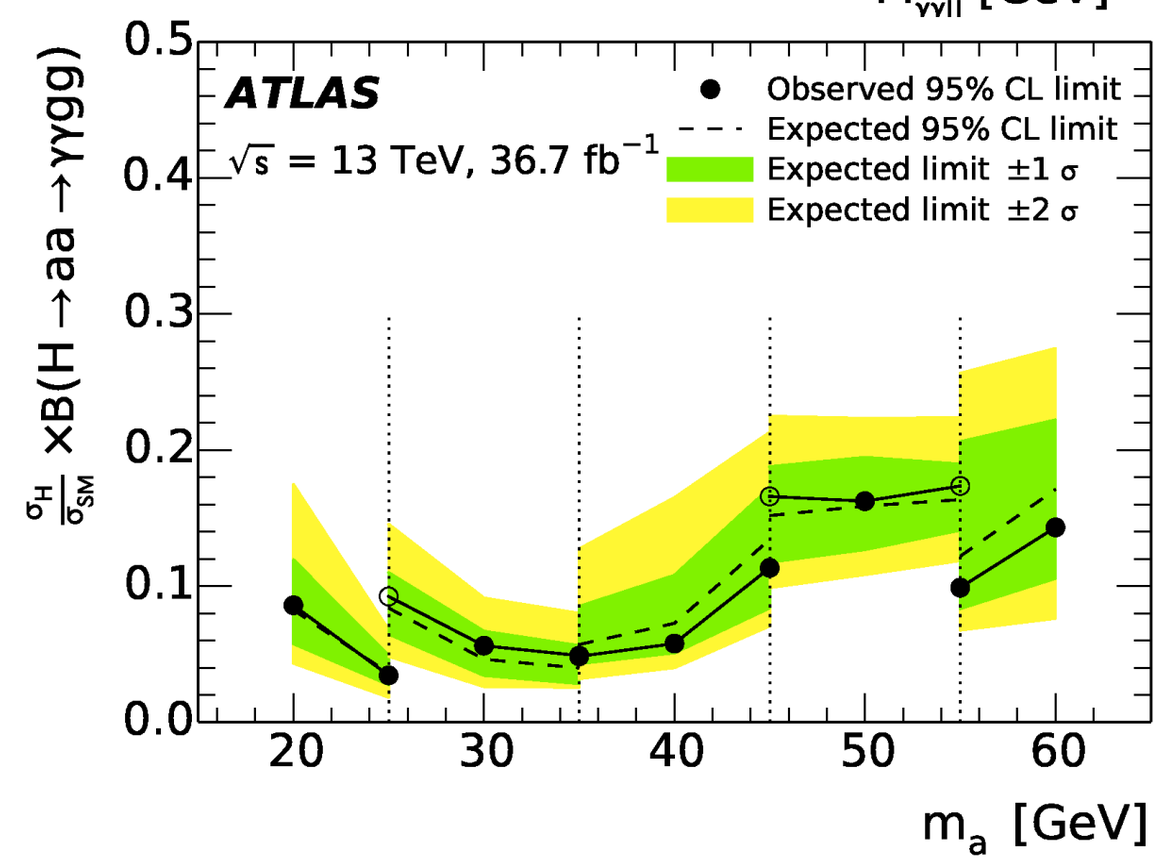
$m_{\gamma\gamma}$ regime	A	B	C	D	Relative closure uncert.	Predicted background yield
1	15	4	28	4	0.50	6^{+7}_{-4}
2	22	6	34	15	0.32	8^{+7}_{-4}
3	12	16	29	26	0.20	37^{+23}_{-14}
4	8	12	19	38	0.21	27^{+22}_{-12}
5	6	20	20	36	0.20	66^{+56}_{-28}

arXiv:1803.11145

γγjj: results

- The final statistical treatment takes both numbers of signal μ_S and background μ_{bkg} as free parameters, as well as τ_B (B/D ratio of events) and τ_C (C/D)
  - A simultaneous fit in all ABCD regions is performed
- No large excess is observed. Upper limits are set on the BRs as a function of the light boson mass

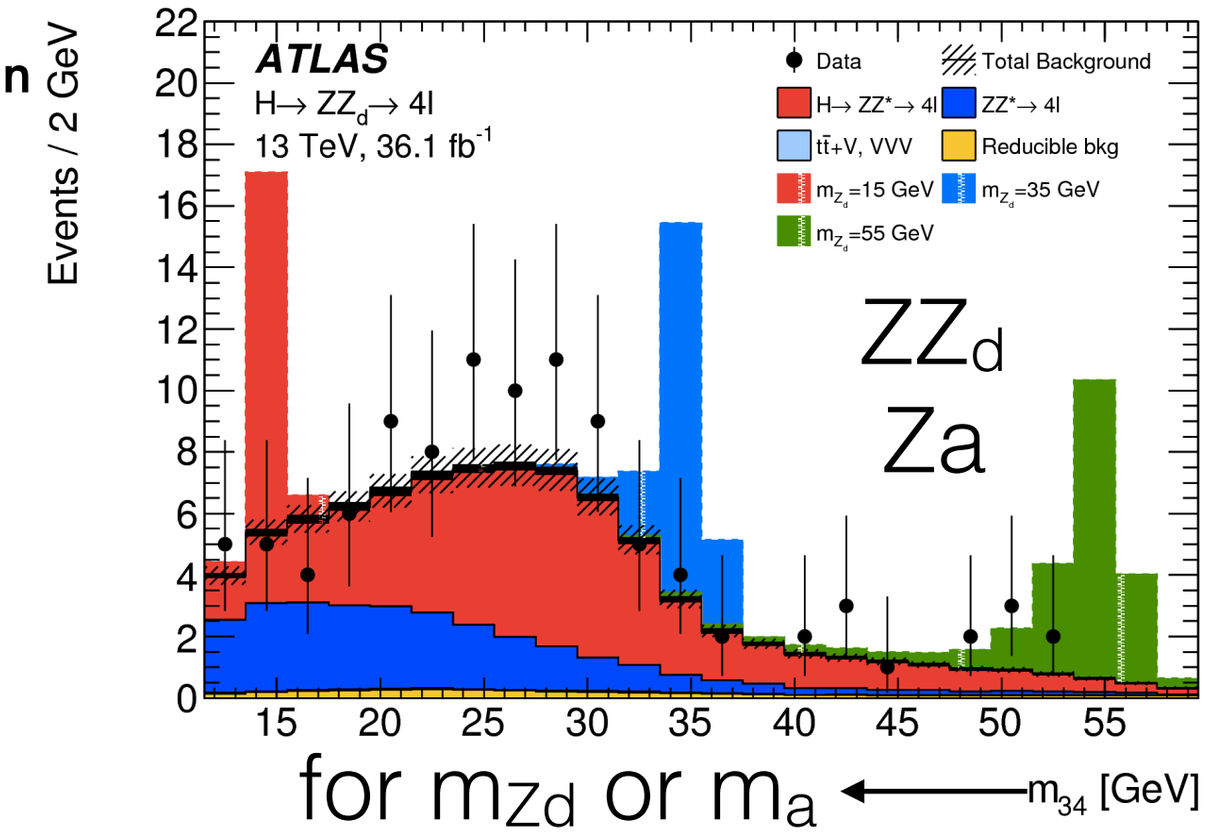


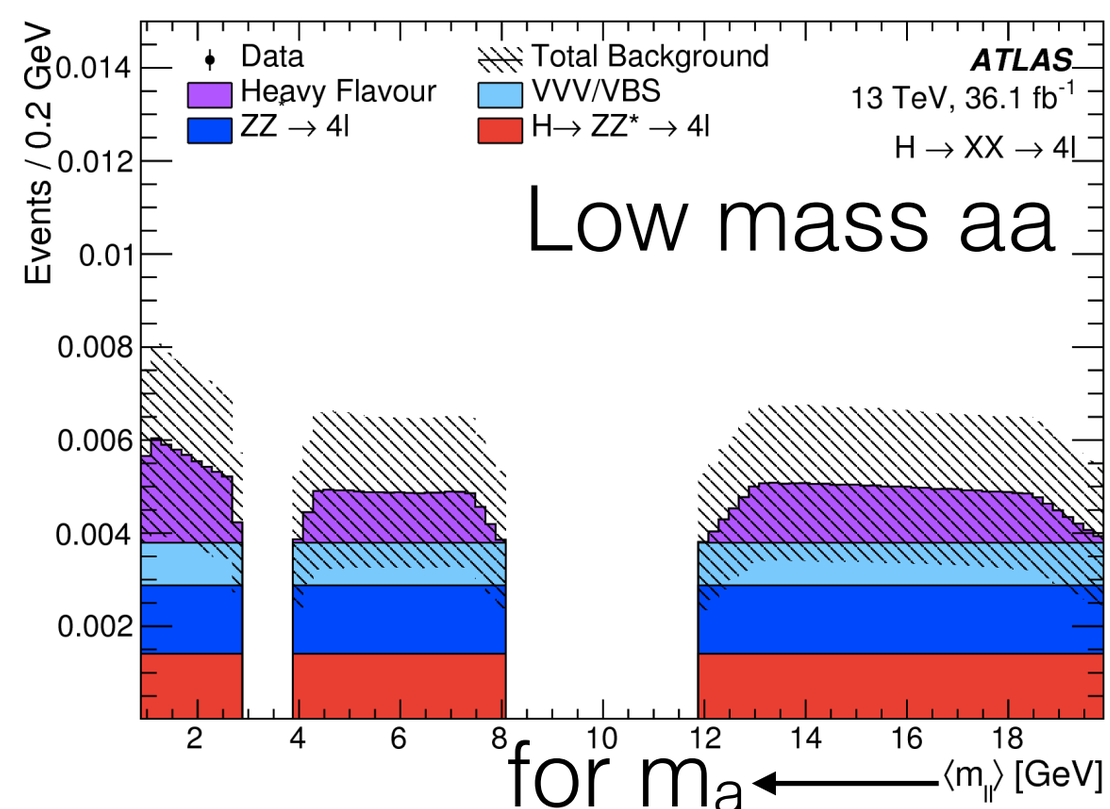


arXiv:1802.03388

4l analysis

- Search for (X stands for Z_d from a SM extension of a dark-sector and a from 2HDM+S)
  - $H \to ZX \to 4l$ in 15 GeV < m_X < 55 GeV
  - $H \to XX \to 4l$ in 15 GeV < m_X < 60 GeV
  - $H \to XX \to 4\mu$ in 1 GeV < m_X < 15 GeV
- Major selections include m_{ll} windows, m_{4l} windows, quarkonia resonance rejection, m_{34}/m_{12}>0.85 (the latter two only for XX)
- Background estimation rely on MC
  - The dominant background is irreducible $H \to ZZ^* \to 4l$
  - For low mass searches, quarkonia heavy flavour, VVV/VBS and ZZ* also contribute largely

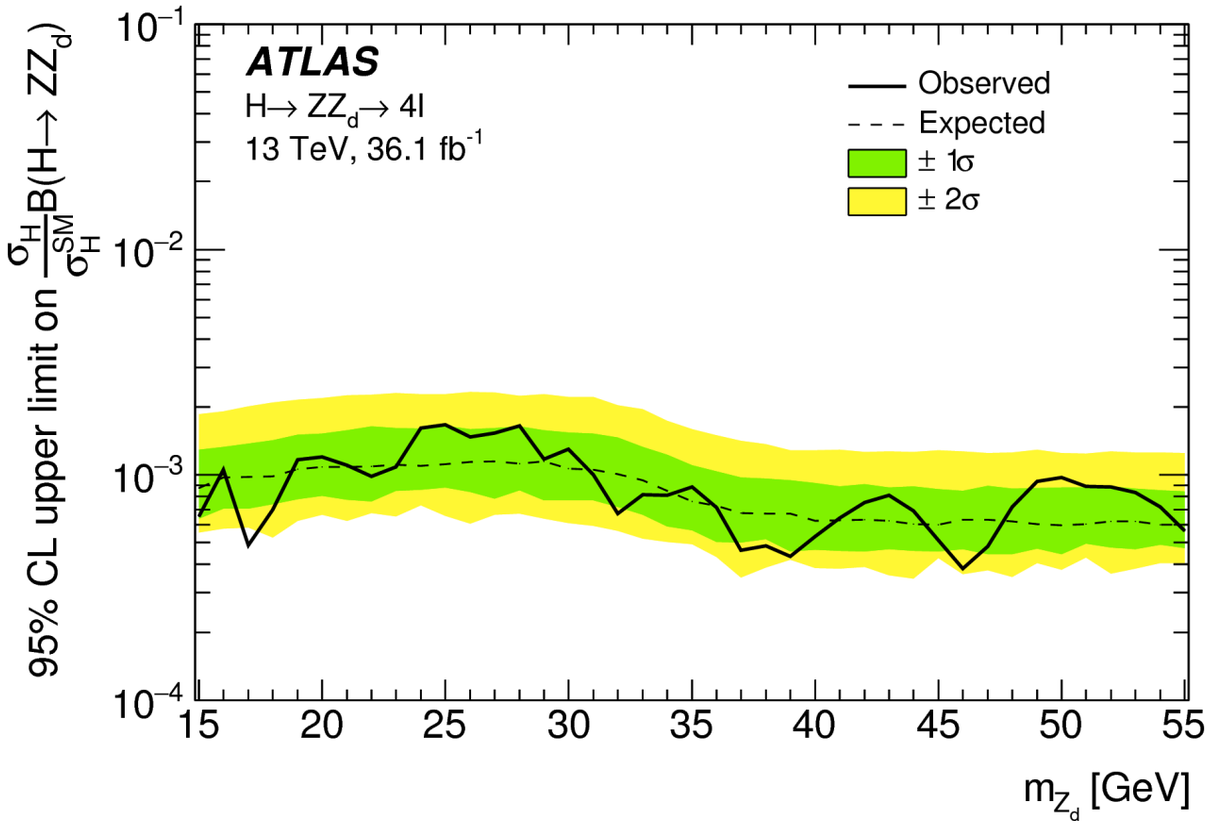


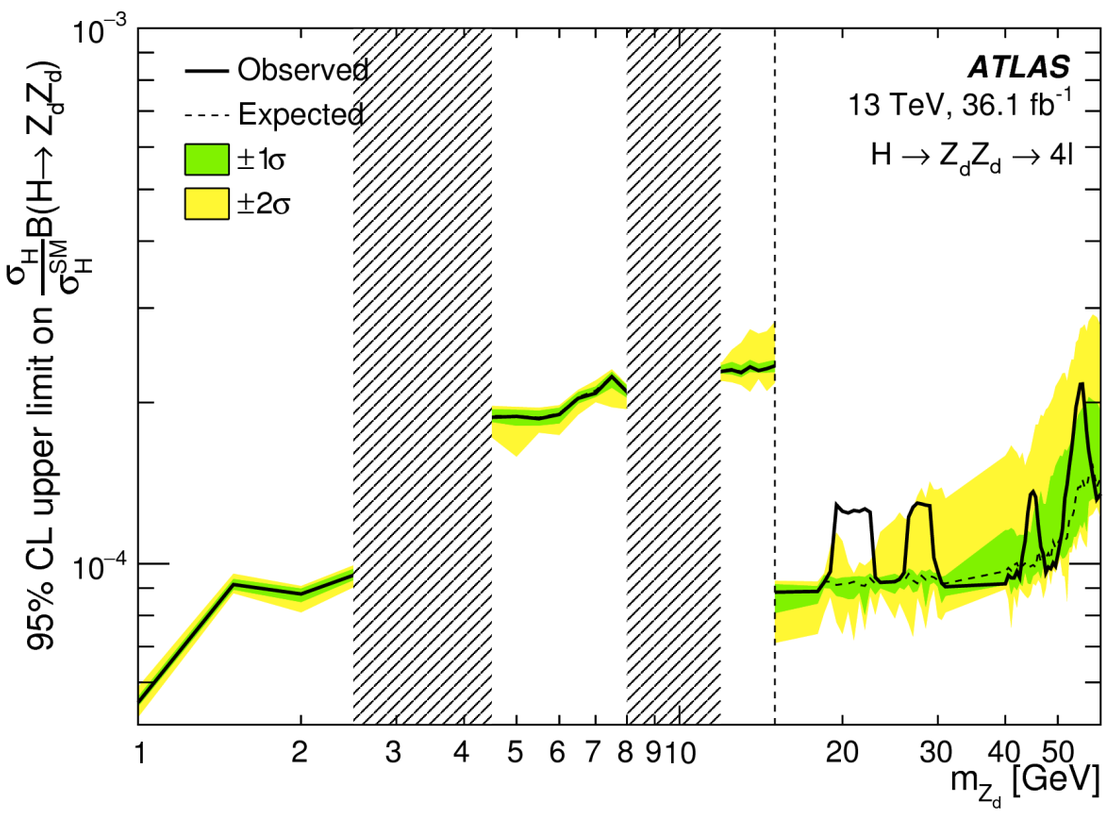


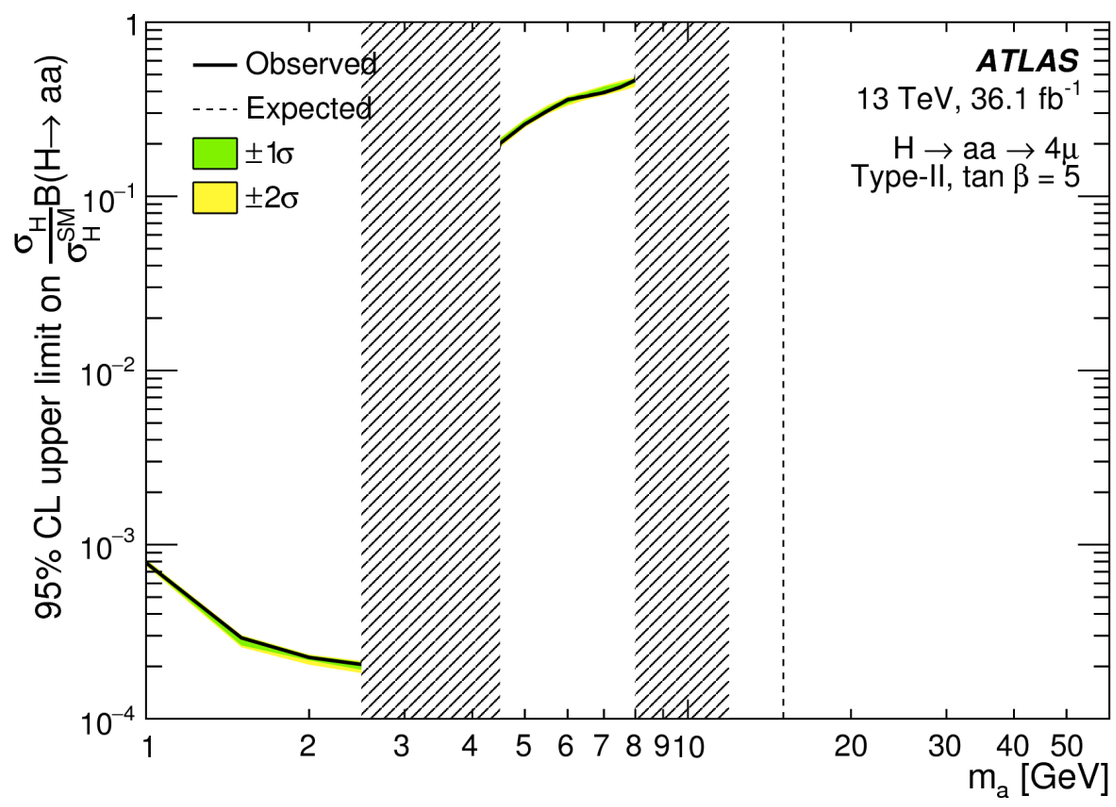
arXiv:1802.03388

4l: results

- No significant data excess is found
- Set limits fiducial cross section (backup) and branching ratio







Summary

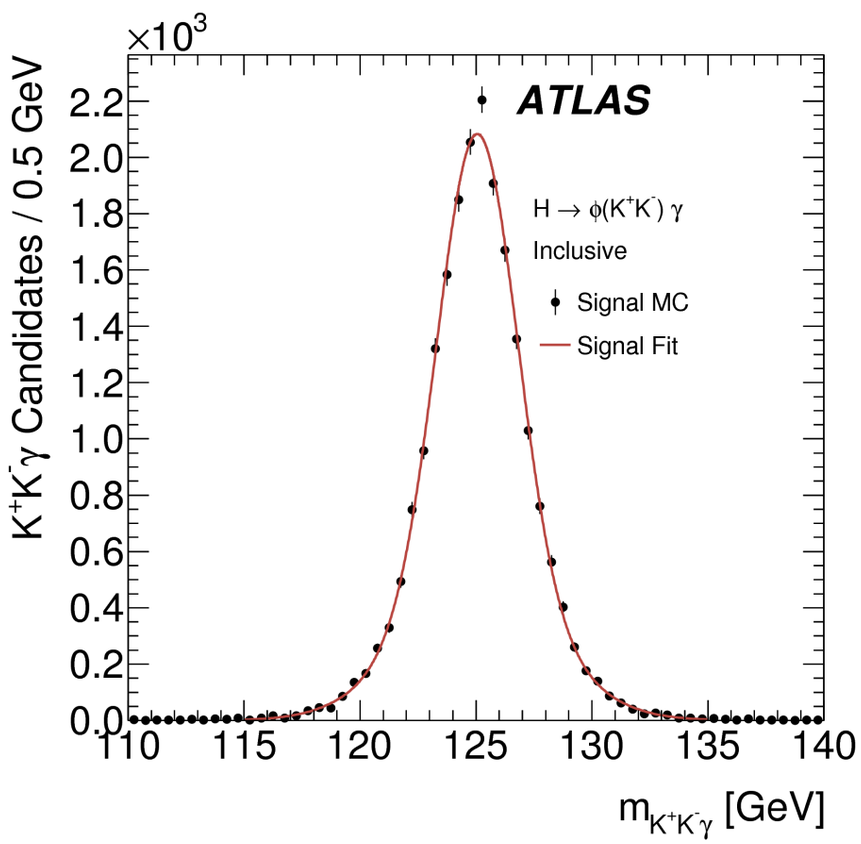
- Various rare and non-SM Higgs decays are probed
  - With no significant data excess, upper limits are set on the BRs
  - Many existing channels are updated with big improvement
  - Many new channels are explored for the first time
- Statistical uncertainty is often the constraining factor
  - The statistics to the end of Run 2 of the LHC can bring free improvements
- Extensive programs are undergoing to cover more final states

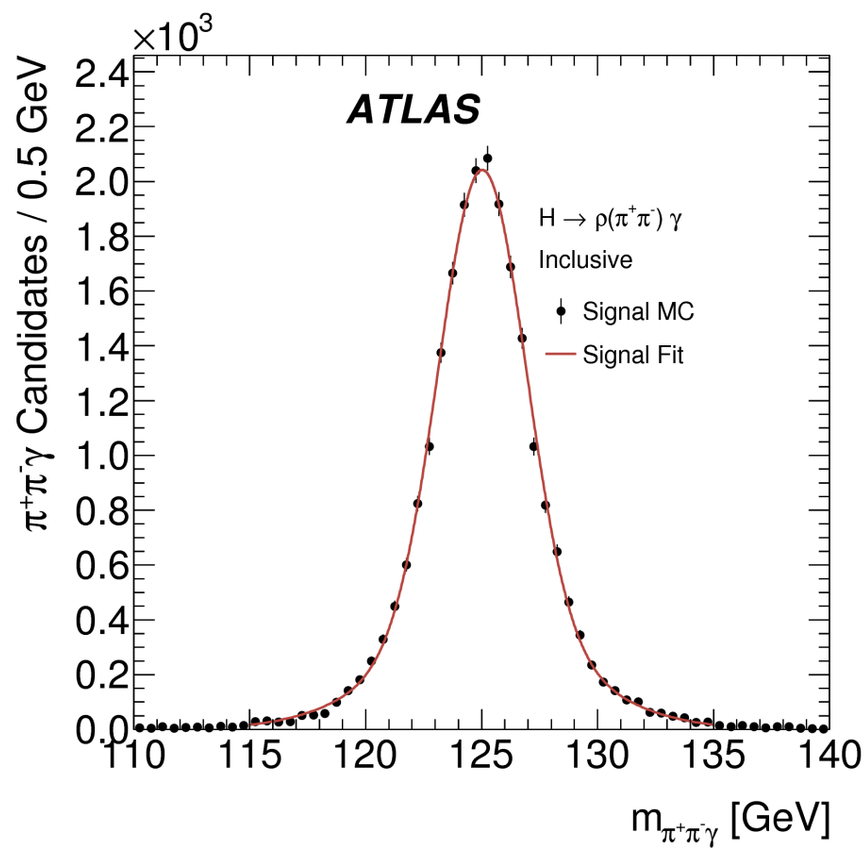
Backup

arXiv:1712.02758

H→φγ and ργ

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%

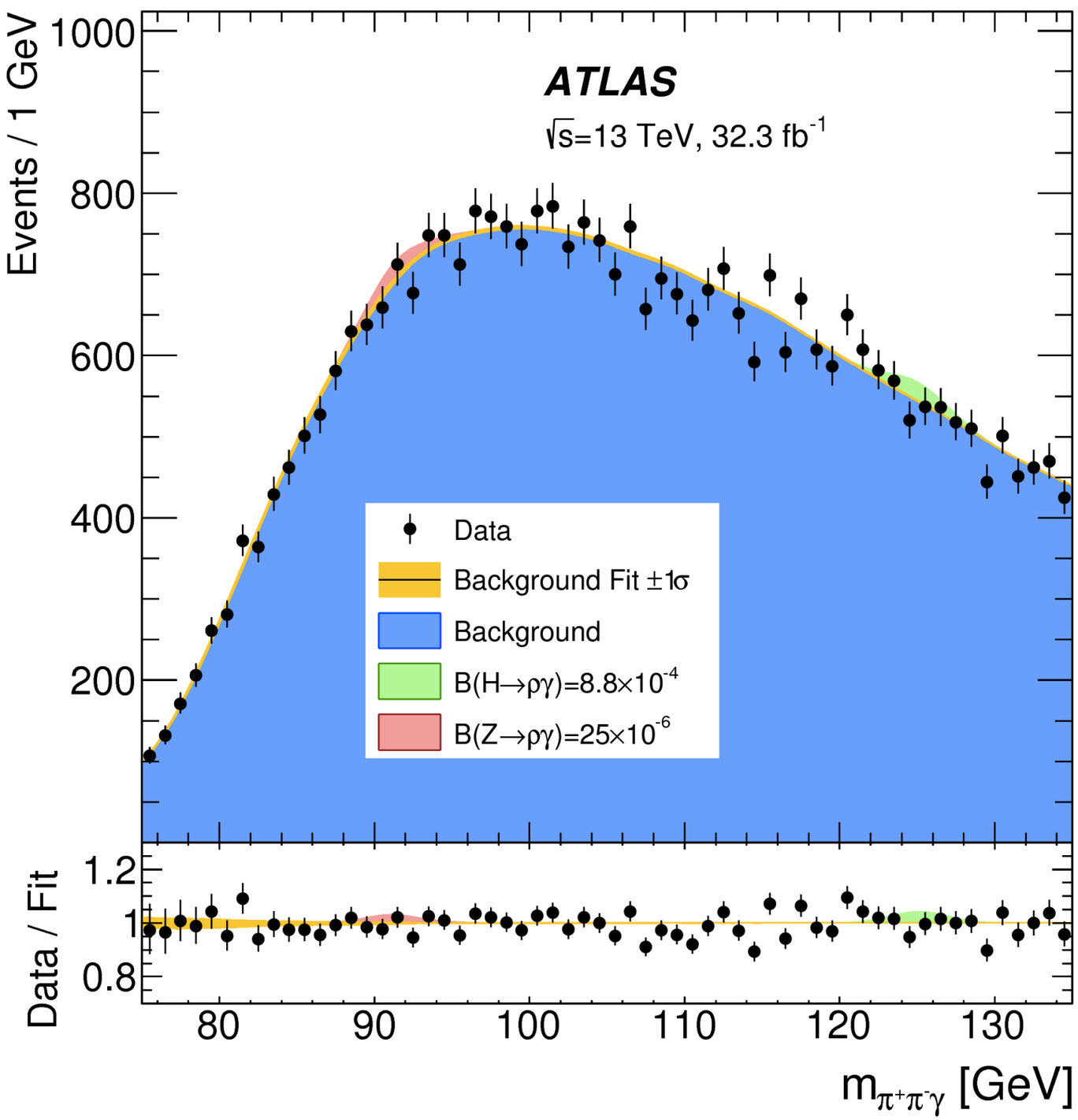


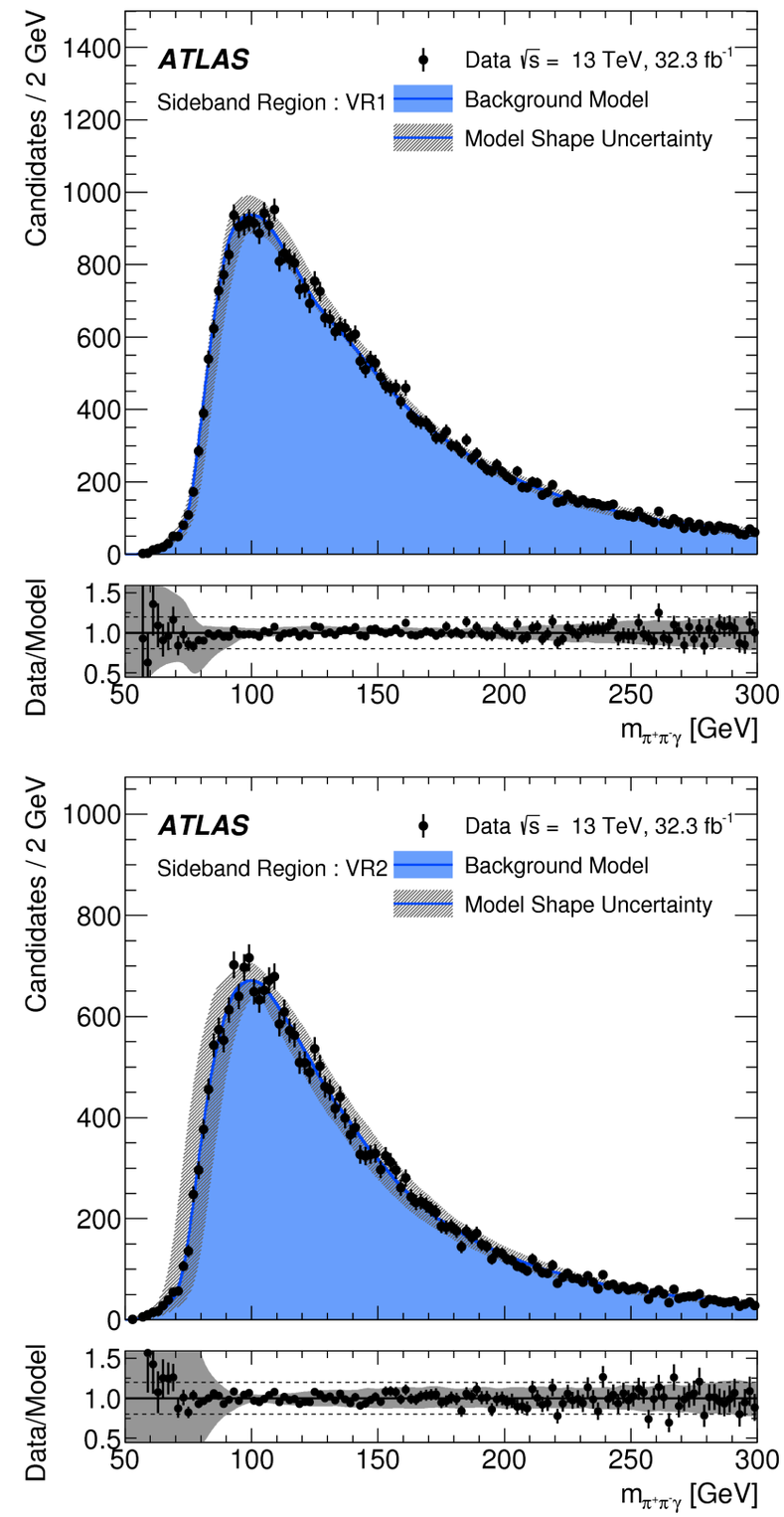


https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HIGG-2016-13/

arXiv:1712.02758

H→φγ and ργ





https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HIGG-2016-13/

Zy

Process	Technique	QCD (gen.)	QCD (norm.)	EW (norm.)
ggF	MiNLO & NNLOPS	NNLO (incl.), NLO ($H+1$-jet)	NNNLO	NLO
VBF	POWHEG	NLO	approx. NNLO	NLO
VH	MiNLO	NLO (incl. and $H+1$-jet)	NNLO	NLO

The component of the transverse momentum of the $Z\gamma$ system that is perpendicular to the difference of the 3-momenta of the Z boson and the photon candidate ($p_{\mathrm{T}t} = 2|p_x^Z p_y^\gamma - p_x^\gamma p_y^Z|/p_{\mathrm{T}}^{Z\gamma}$),

	ggF		VBF		WH		ZH	
Category	ϵ[%]	f[%]	ϵ[%]	f[%]	ϵ[%]	f[%]	ϵ[%]	f[%]
VBF-enriched	0.25	30.5	6.5	67.5	0.34	1.3	0.24	0.6
High relative p_{T}	1.1	71.5	2.6	14.3	4.0	8.3	4.1	5.3
ee high $p_{\mathrm{T}t}$	1.7	80.8	2.8	11.0	3.2	4.7	3.6	3.3
ee low $p_{\mathrm{T}t}$	7.1	93.2	3.6	4.1	3.7	1.5	4.2	1.1
$\mu\mu$ high $p_{\mathrm{T}t}$	2.2	80.4	3.6	11.3	4.1	4.8	4.2	3.1
$\mu\mu$ low $p_{\mathrm{T}t}$	9.2	93.4	4.7	4.1	4.6	1.5	4.8	1.0
Total efficiency (%)	21.5		23.8		20.2		21.0	
Expected events	35		3.3		1.0		0.7	

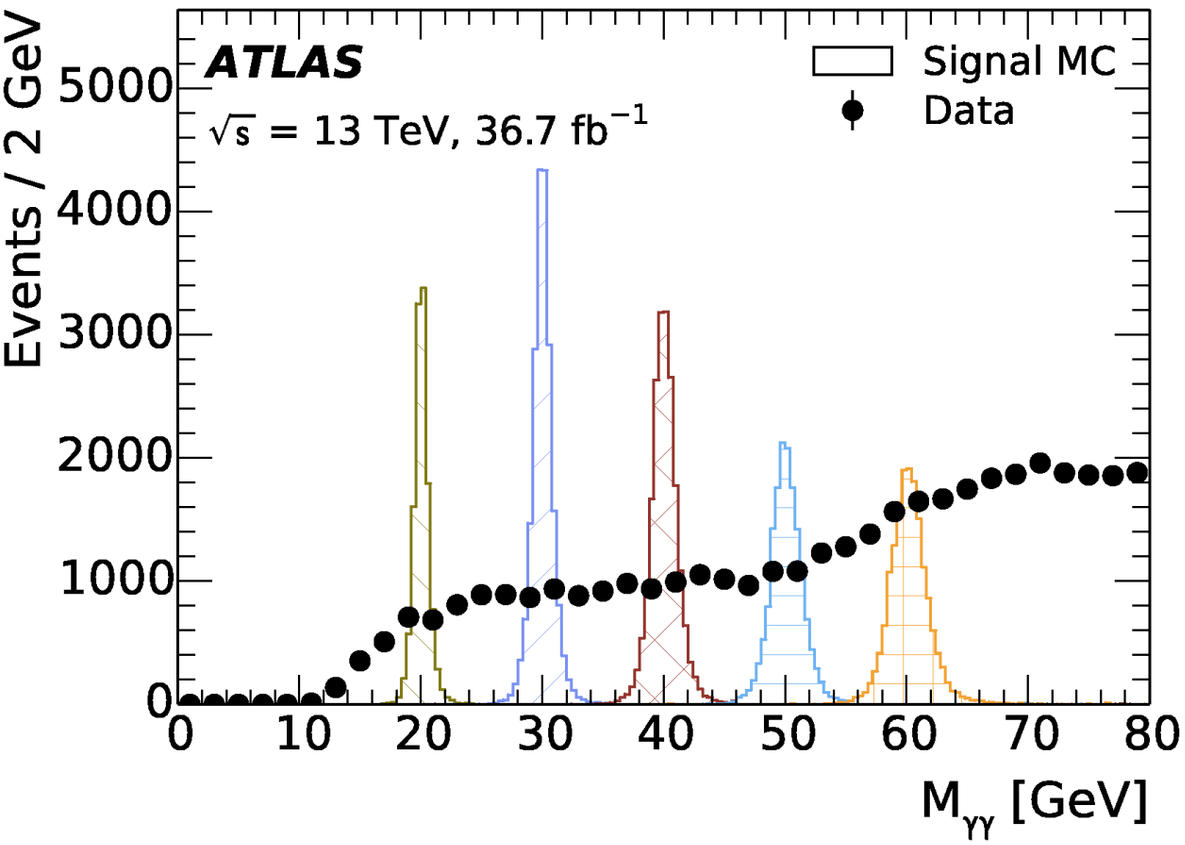
ε: efficiency f: fraction

Zy systematic uncertainties

Sources	$H \to Z\gamma$	$X \to Z\gamma$
Luminosity [%]		
Luminosity	3.2	3.2
Signal efficiency [%]		
Modelling of pile-up interactions	0.02–0.03	< 0.01–0.2
Photon identification efficiency	0.7–1.7	2.0–2.6
Photon isolation efficiency	0.07–0.4	0.6–0.6
Electron identification efficiency	0.0–1.6	0.0–2.6
Electron isolation efficiency	0.0–0.2	0.0–3.5
Electron reconstruction efficiency	0.0–0.4	0.0–1.0
Electron trigger efficiency	0.0–0.1	0.0–0.2
Muon selection efficiency	0.0–1.6	0.0–0.7
Muon trigger efficiency	0.0–3.5	0.0–4.2
MC statistical uncertainty	–	1.2–2.0
Jet energy scale, resolution, and pile-up	0.2–10	–
Total (signal efficiency)	2.1–10	4.0–6.3
Signal modelling on σ_{CB} [%]		
Electron and photon energy scale	0.6–3.5	1.0–4.0
Electron and photon energy resolution	1.1–4.0	4.0–30
Muon momentum scale	0.0–0.5	0.0–3.0
Muon ID resolution	0.0–3.7	0.0–2.0
Muon MS resolution	0.0–1.7	0.0–4.0
Signal modelling on μ_{CB} [%]		
Electron and photon energy scale	0.1–0.2	0.2–0.6
Muon momentum scale	0.0–0.03	0.0–0.03
Higgs mass	0.2	–
Background modelling [Events]		
Spurious signal	1.7–25	0.005–6.1

Sources	
Total cross section and efficiency [%]	
Underlying event	5.3
ggF perturbative order	3.9
ggF PDF and α_{s}	3.2
VBF perturbative order	0.4
VBF PDF and α_{s}	2.1
WH (ZH) perturbative order	0.5 (3.8)
WH (ZH) PDF and α_{s}	1.9 (1.6)
Interference	5.0
$B(H \to Z\gamma)$	5.9
Total (total cross section and efficiency)	10
Category acceptance [%]	
ggF H + 2-jets in VBF-enriched category	0.5–45
ggF BDT variables	0.2–15
ggF Higgs p_{T}	8.4–22
PDF and α_{s}	0.2–2.0
Underlying event	2.9–25
Total (category acceptance)	9.5–49

γγ



Overall signal efficiency

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

$m_{\gamma\gamma}$ 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

γγjj

ggF signal efficiency

$M_{\gamma\gamma}$ regime	m_a [GeV]	Efficiency ($\times 10^{-5}$)			
		A	B	C	D
1	20	$0.25^{+0.17}_{-0.12}$	$0.26^{+0.20}_{-0.11}$	2.4±0.4	2.4±0.8
1	25	0.20±0.22	0.97±0.24	4.5±1.1	5.5±1.2
2	25	0.20±0.22	0.97±0.24	4.5±1.1	5.5±1.2
2	30	0.86±0.24	1.39±0.31	$4.4^{+0.8}_{-1.1}$	8.5±2.0
2	35	1.4±1.1	0.87±1.1	4.1±1.3	9.7±2.3
3	35	$0.31^{+1.40}_{-0.16}$	2.1±0.8	2.9±0.7	11.3±2.7
3	40	0.67±0.25	1.4±0.5	$3.8^{+0.9}_{-1.3}$	10.3±2.3
3	45	2.1±0.9	1.6±0.6	3.0±0.9	7.9±2.5
4	45	2.0±0.9	1.9±0.6	$2.3^{+0.6}_{-0.9}$	8.5±2.0
4	50	0.28±0.14	1.6±0.4	2.4±0.6	9.0±2.2
4	55	0.17±0.06	1.3±0.5	2.4±0.7	8.4±2.0
5	55	0.00±0.23	1.5±0.6	1.5±0.4	9.4±2.2
5	60	$0.16^{+0.19}_{-0.11}$	1.8±0.4	1.8±0.5	8.4±2.2

VBF signal efficiency

$M_{\gamma\gamma}$ regime	m_a [GeV]	Efficiency ($\times 10^{-5}$)			
		A	B	C	D
1	20	4.1±1.6	14±5	27±13	60±17
1	25	$7.3^{+2.4}_{-4.2}$	26^{+6}_{-9}	28±11	150±40
2	25	$7.3^{+2.4}_{-4.2}$	26^{+6}_{-9}	28±11	150±40
2	30	6.9±2.1	31±9	55±18	260^{+60}_{-80}
2	35	8.5±1.8	29±8	84±25	270±60
3	35	3.8±1.5	34±9	52^{+11}_{-25}	310±70
3	40	8.6±3.4	30±9	68^{+14}_{-19}	250±60
3	45	9±5	39±14	75^{+21}_{-28}	180±50
4	45	7^{+4}_{-5}	41±15	58^{+16}_{-22}	210±50
4	50	10.1±2.8	44±14	42^{+18}_{-10}	230^{+60}_{-70}
4	55	3.2±1.1	33±7	50^{+11}_{-16}	200±50
5	55	3.3±1.2	33±7	31±8	230±70
5	60	9±4	34±11	50±16	230±60

γγjj

Maximum fractional impact on the fitted number of signal events μ_S

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

Maximum-likelihood fit values for each of the free parameters

$m_{\gamma\gamma}$ 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

4l: event yields

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→ ZX→ 4ℓ

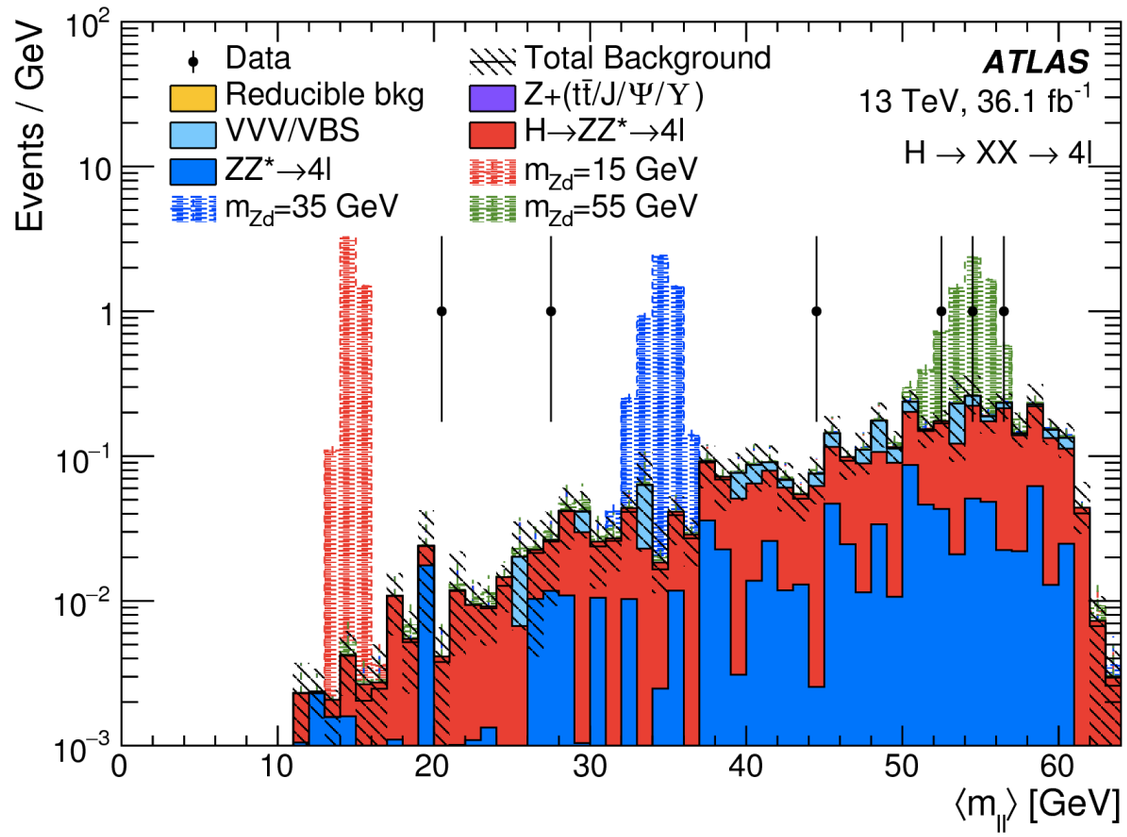
Process	Yield
$ZZ^* \to 4\ell$	0.8 ± 0.1
$H \to ZZ^* \to 4\ell$	2.6 ± 0.3
VVV/VBS	0.51 ± 0.18
$Z + (t\bar{t}/J/\Psi) \to 4\ell$	0.004 ± 0.004
Reducible Background	Negligible
Total	3.9 ± 0.3
Data	6

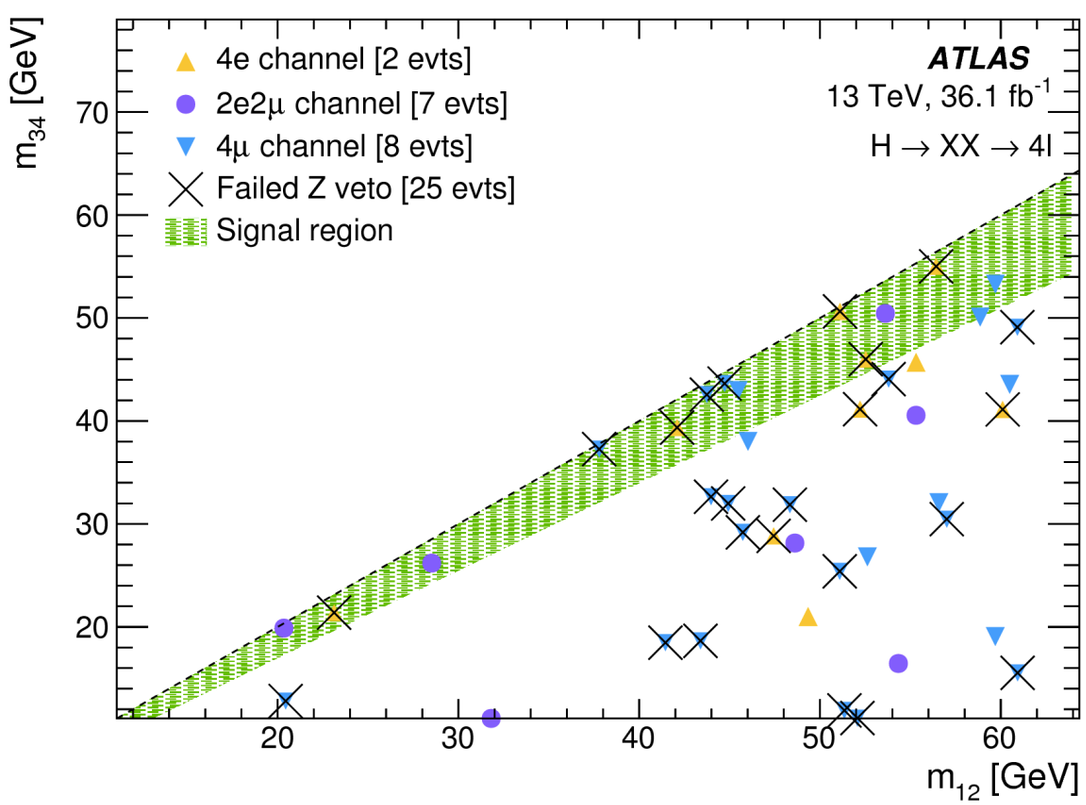
H→ XX → 4ℓ

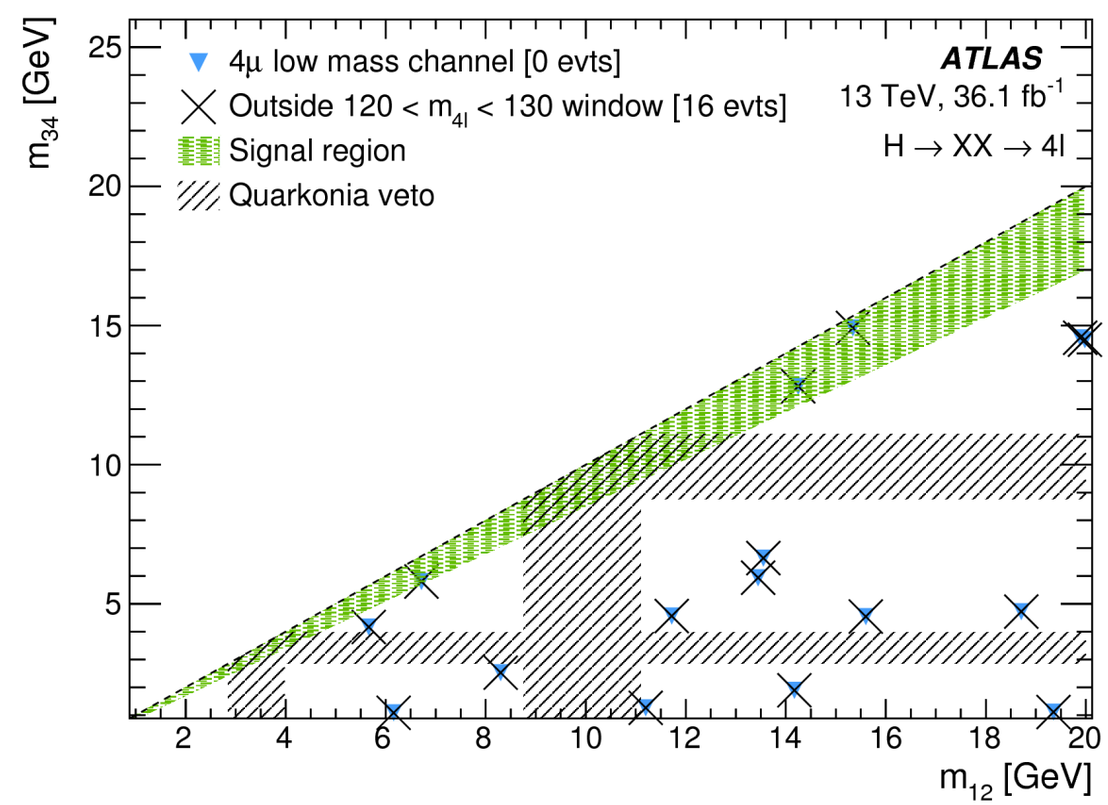
Process	Yield
$ZZ^* \to 4\ell$	0.10 ± 0.01
$H \to ZZ^* \to 4\ell$	0.1 ± 0.1
VVV/VBS	0.06 ± 0.03
Heavy flavour	0.07 ± 0.04
Total	0.4 ± 0.1
Data	0

H→ XX → 4μ

4l: distribution

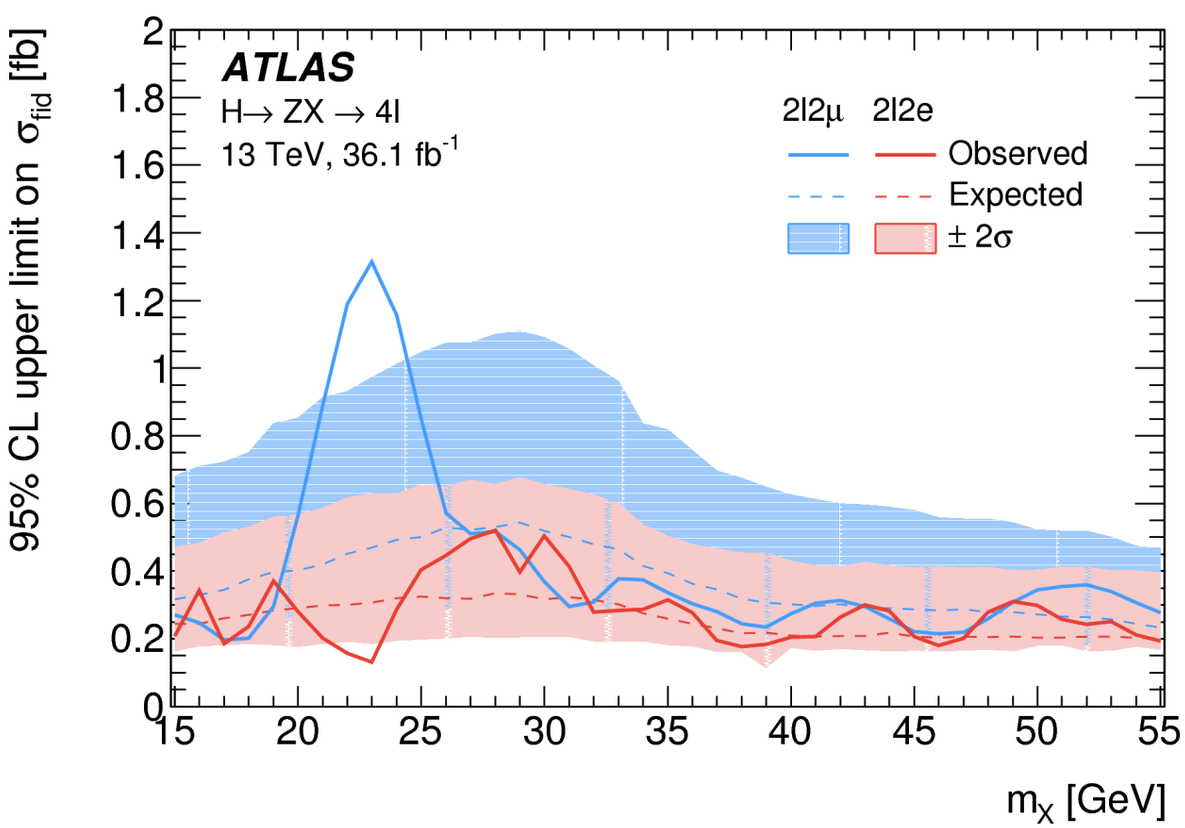


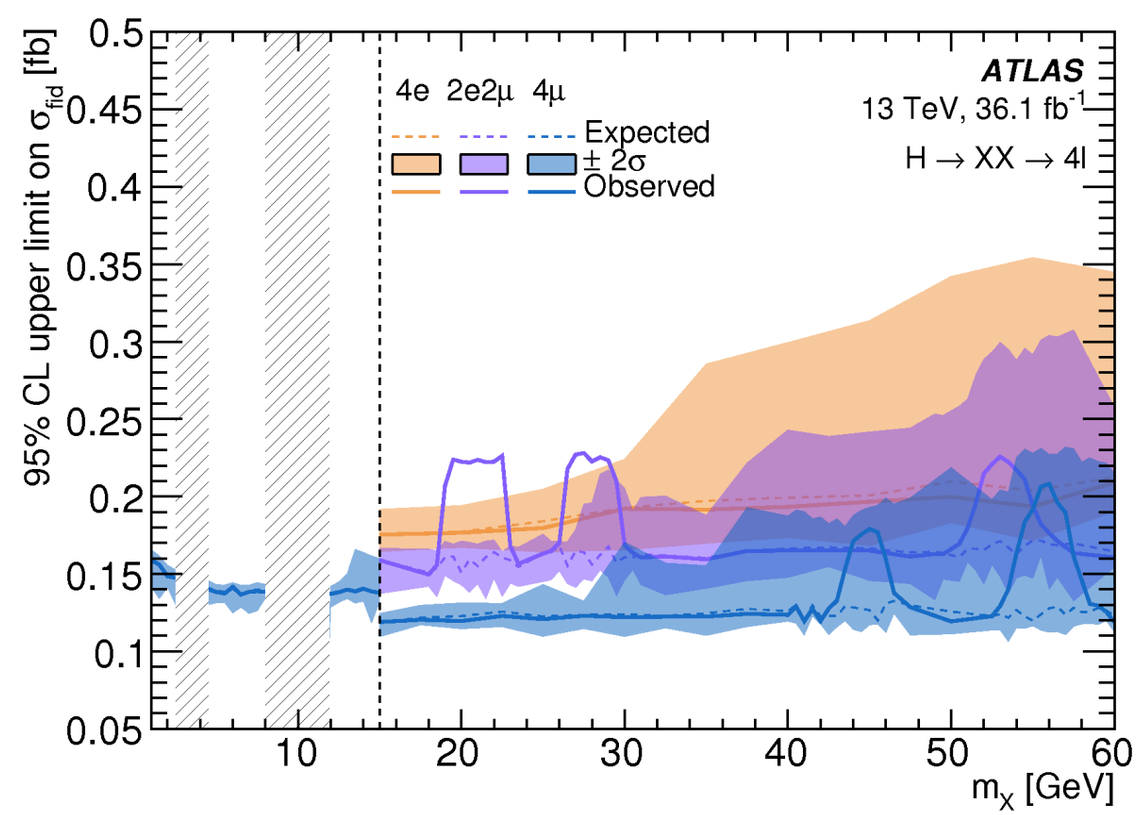




4l: fiducial cross section

	$H \to ZX \to 4\ell$ ($15\ GeV < m_X < 55\ GeV$)	$H \to XX \to 4\ell$ ($15\ GeV < m_X < 60\ GeV$)	$H \to XX \to 4\mu$ ($1\ GeV < m_X < 15\ GeV$)
Electrons	Dressed with prompt photons within $\Delta R = 0.1$ $p_T > 7\ GeV$ $\lvert\eta\rvert < 2.5$		
Muons	Dressed with prompt photons within $\Delta R = 0.1$ $p_T > 5\ GeV$ $\lvert\eta\rvert < 2.7$		
Quadruplet	Three leading-p_T leptons satisfy $p_T > 20$ 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: $(m_{J/\psi} - 0.25\ GeV) < m_{12,34,14,32} < (m_{\psi(2S)} + 0.30\ GeV)$ $(m_{\Upsilon(1S)} - 0.70\ GeV) < m_{12,34,14,32} < (m_{\Upsilon(3S)} + 0.75\ GeV)$	





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4l 8TeV