Beyond the Standard Model in the Higgs sector

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Introduction

- The Standard Model works well but has uncovered points:
  - Strong CP problem
  - Dark matter candidates
  - Baryon asymmetry in the universe
  - (g – 2)μ anomaly

or

?

- An extended Higgs sector can solve some of these problems:

➢ Two-Higgs-doublet model (2HDM) and modifications:
  - 2HDM+scalar boson S (2HDM+S)
  - Next-to-2HDM (N2HDM)
  - General 2HDM with dropped Z_2 symmetry (g2HDM)

➢ Next-to-minimal supersymmetric model (NMSSM)

2HDM

h H	H^+ H^-	A
CP-even	Charged	CP-odd

NMSSM

H_1 H_2 H_3	H^+ H^-	A_1 A_2
CP-even	Charged	CP-odd

In this talk

- Only full Run-2 ATLAS analyses:

  - Search for low mass $X \to \gamma\gamma$, arXiv:2407.07546
  - Search for $H \to aa \to 4\gamma$, Eur. Phys. J. C 84 (2024) 742

  } Low mass resonances

  - Search for heavy $H \to$ multi-l + b-jets, JHEP 12 (2023) 081
  - Search for $X \to 4l + \mathrm{MET/jets}$, arXiv:2401.04742

  } High mass resonances

Search for low mass $X \rightarrow \gamma\gamma$

arXiv:2407.07546

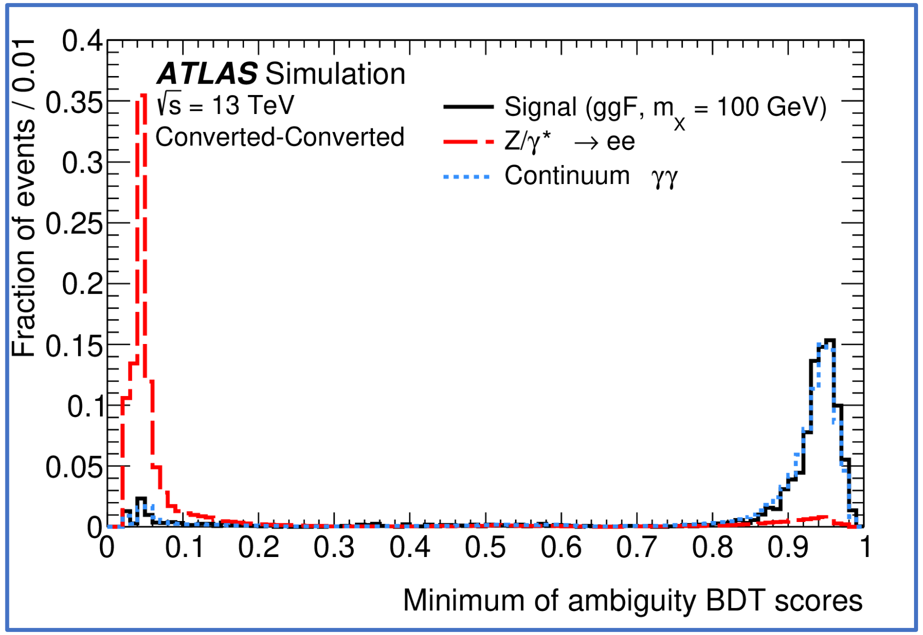
Low mass $X \to \gamma\gamma$: Introduction

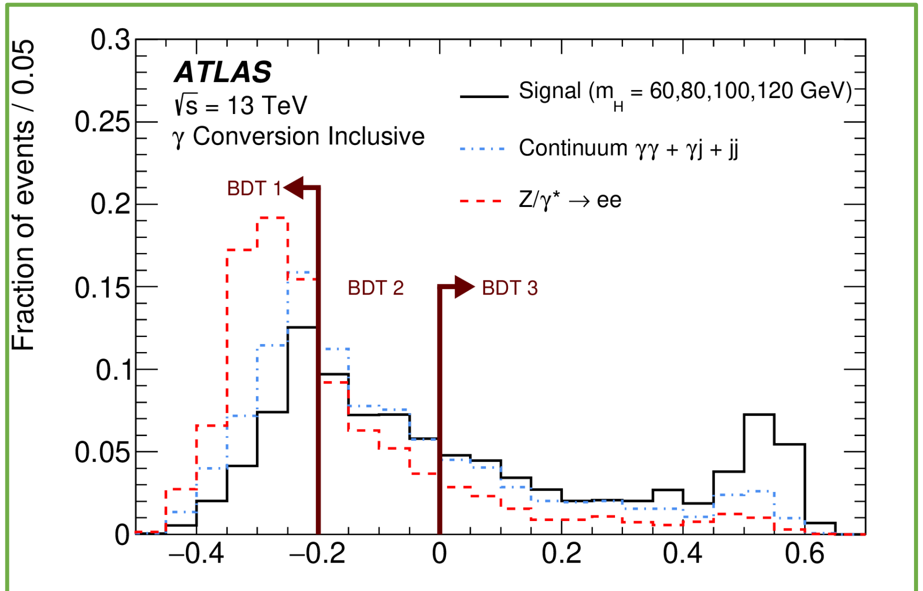
- Looking for spin-0 resonances in the 66 to 110 GeV mass range with 2 photons in the final state
- Benchmark models: 2HDM, N2HDM, NMSSM
- Spin-0 boson can:
  - Act as a scalar partner of dark matter
  - Be an axion and explain baryon asymmetry
- Two approaches:
  - Model-Independent search for X → Only ggF production
  - Model-Dependent search for low-mass Higgs boson → Production modes: $ggF, VBF, t\bar{t}H, WH, ZH$
- Main backgrounds:
  - Continuum background: non-resonant $\gamma\gamma, \gamma j, jj$
  - Resonant Drell-Yan (DY): $Z \to ee$

  } j and e misidentified as γ

Low mass $X \to \gamma\gamma$: Analysis strategy

- For each photon, $E_T/m_{\gamma\gamma} > 22/58 \approx 0.38$ → to guarantee exponentially falling background ($m_{\gamma\gamma} = 58\ GeV$ chosen to maximize signal efficiency)
- Pass the e/γ ambiguity BDT criteria
- 3 event categories depending on conversion of each photon in the pair
- Further categorization in the Model-Dependent search with the category BDT*
- Signal $m_{\gamma\gamma}$ is modelled using a double-sided Crystal-Ball (DSCB)
- Data-driven estimation of backgrounds:
    - Continuum bkg: 2D side-band method
    - DY: modelled with DSCB
- Final fit to the $m_{\gamma\gamma}$ spectra





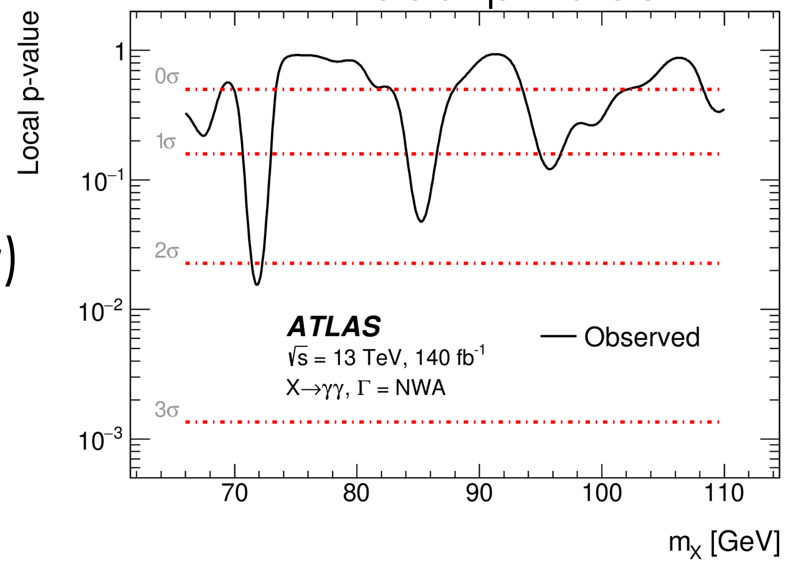
*Full list of categories in backup

Low mass $X \to \gamma\gamma$: Results

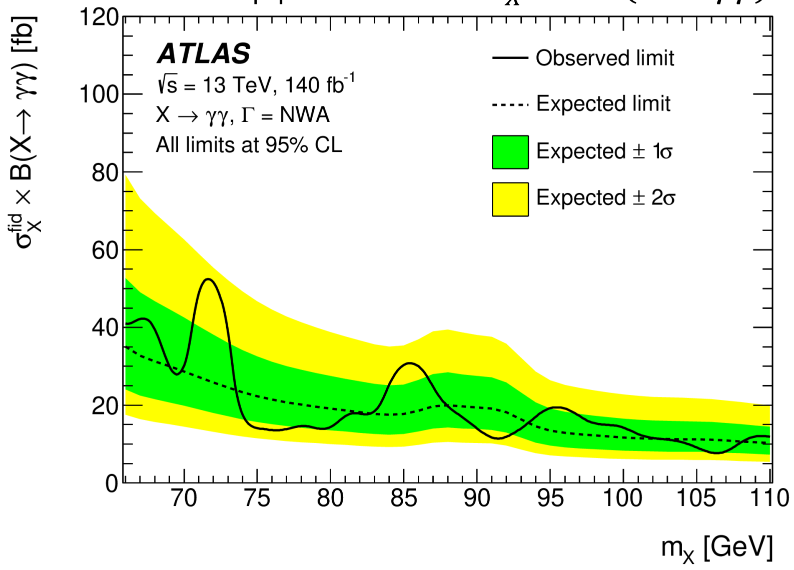
Model-Independent

- Largest deviation for a mass **71.8 GeV** (local significance **2.2σ**)
- Fiducial cross section limits set between **19 – 102 fb**

Local p-value



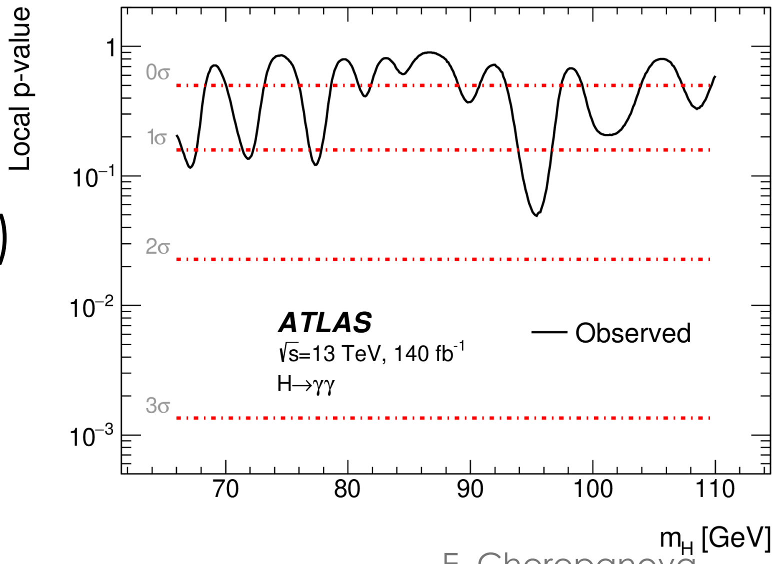
95% CL upper limit on $\sigma_X^{\text{fid}} \times BR(X \to \gamma\gamma)$



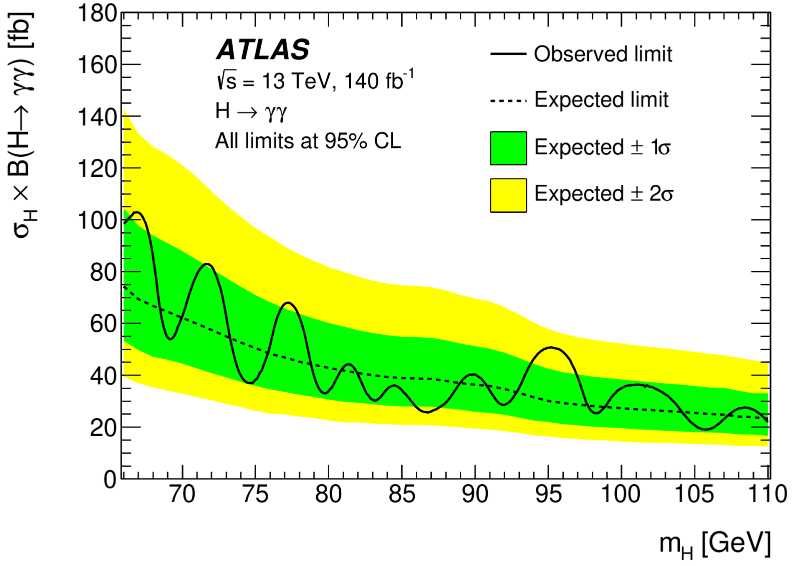
Model-Dependent

- Largest deviation for a mass **95.4 GeV** (local significance **1.7σ**)
- Total cross section limits set between **8 – 53 fb**

Local p-value



95% CL upper limit on $\sigma_X \times BR(X \to \gamma\gamma)$



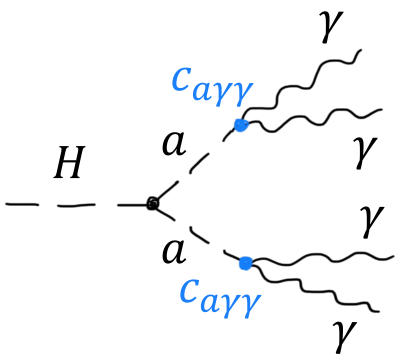
Search for $H \rightarrow aa \rightarrow 4\gamma$

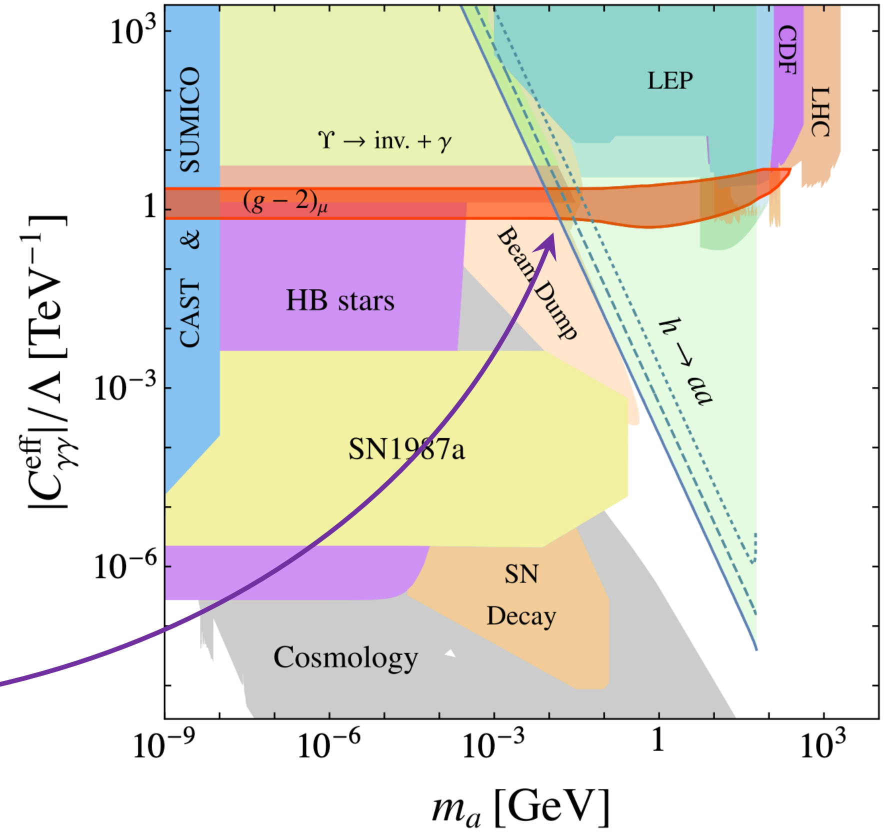
Eur. Phys. J. C 84 (2024) 742

$H \to aa \to 4\gamma$: Introduction

arXiv:1708.00443

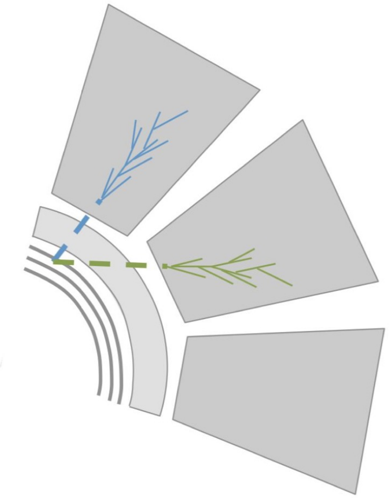
- Looking for the decay of anomalous Higgs boson into two axion-like particles (ALPs) with 4 photons in final state
- Benchmark model: NMSSM





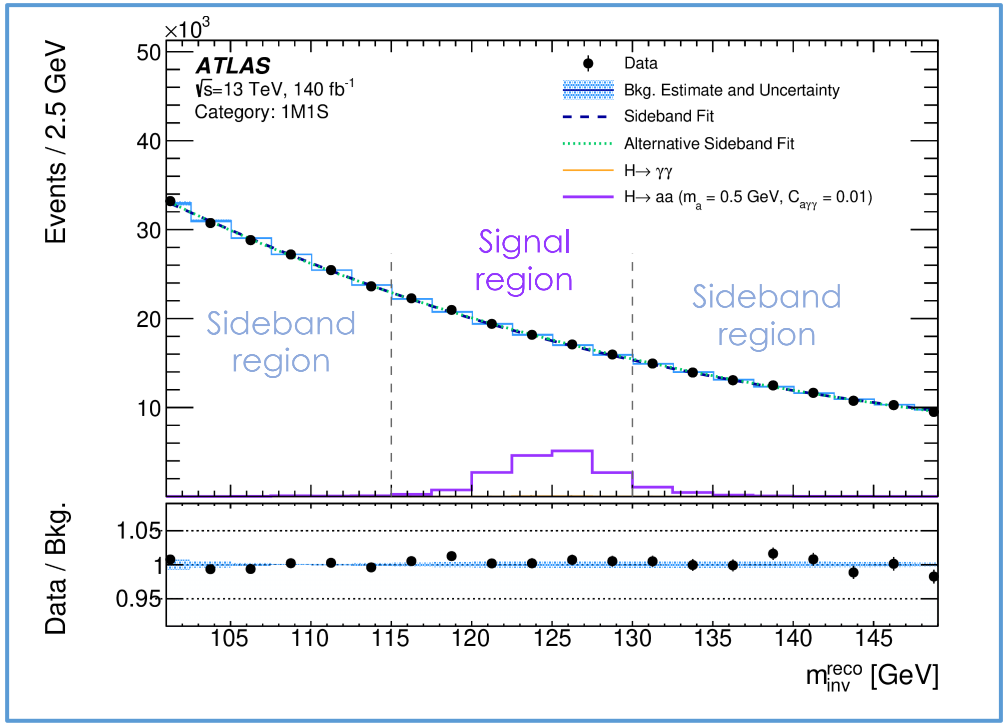
- ALPs can explain anomalous magnetic moment of muon $(g-2)\mu$
- Probing the m_a - $c_{a\gamma\gamma}$ parameter space:
  - $100\ MeV \le m_a \le 60\ GeV$
  - $10^{-5}\ TeV^{-1} \le c_{a\gamma\gamma} \le 1\ TeV^{-1}$
  - Decay length $\tau_a \propto \Lambda^2 / \left(m_a^3 |c_{a\gamma\gamma}|^2\right)$ →

- Looking for long-lived axions and displaced vertices and highly collinear photons

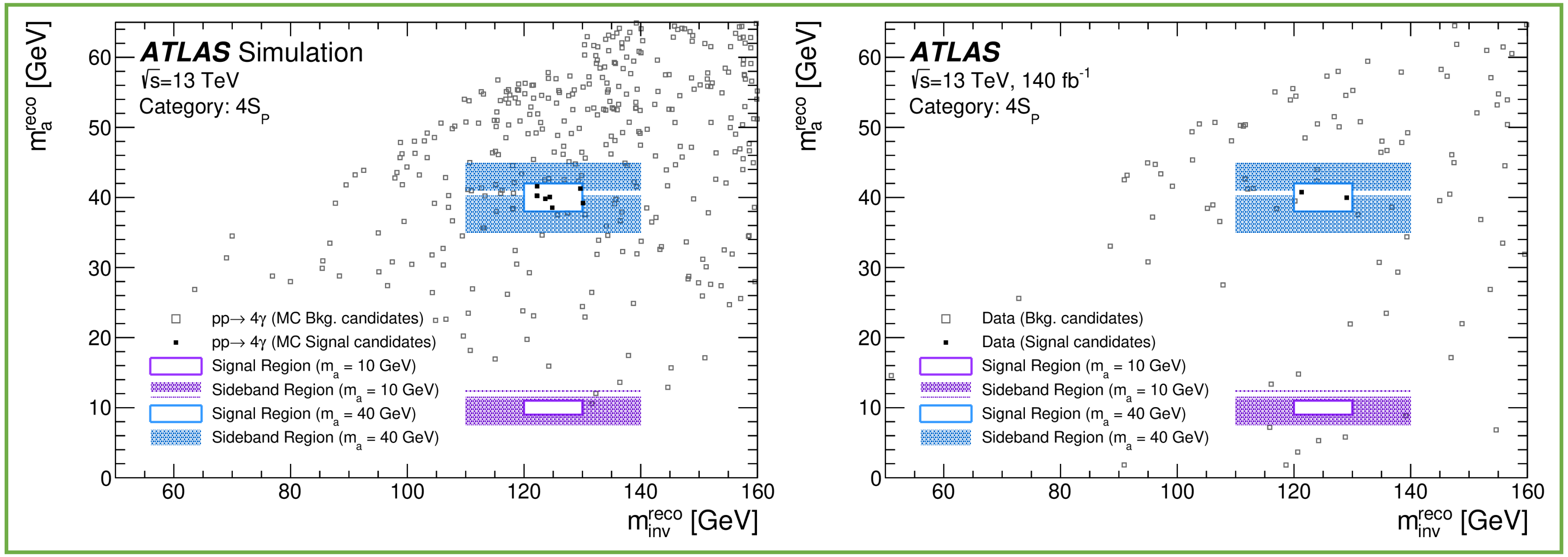


$H \rightarrow aa \rightarrow 4\gamma$: Analysis strategy

- Signal regions:
  - Defined by requiring m_{inv}^{reco} to be near the Higgs boson mass
  - Split per m_a bins
- Long-lived search: $10^{-5} < c_{a\gamma\gamma} < 0.1\ TeV^{-1}$
- Prompt search: $0.1 < c_{a\gamma\gamma} < 1\ TeV^{-1}$



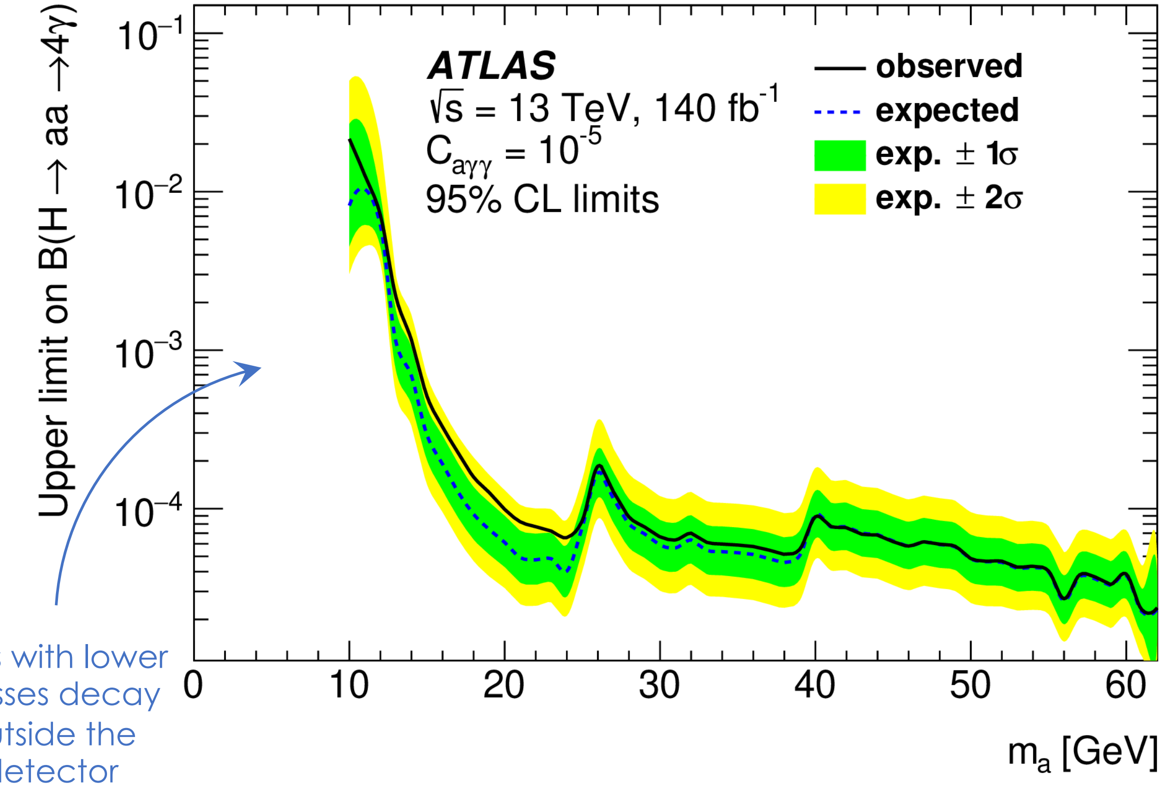
- Data-driven background estimate
- m_{inv}^{reco} sidebands are used for background estimation
- Backgrounds: $h \rightarrow \gamma\gamma$, multi-photon QCD



$H \to aa \to 4\gamma$: Results

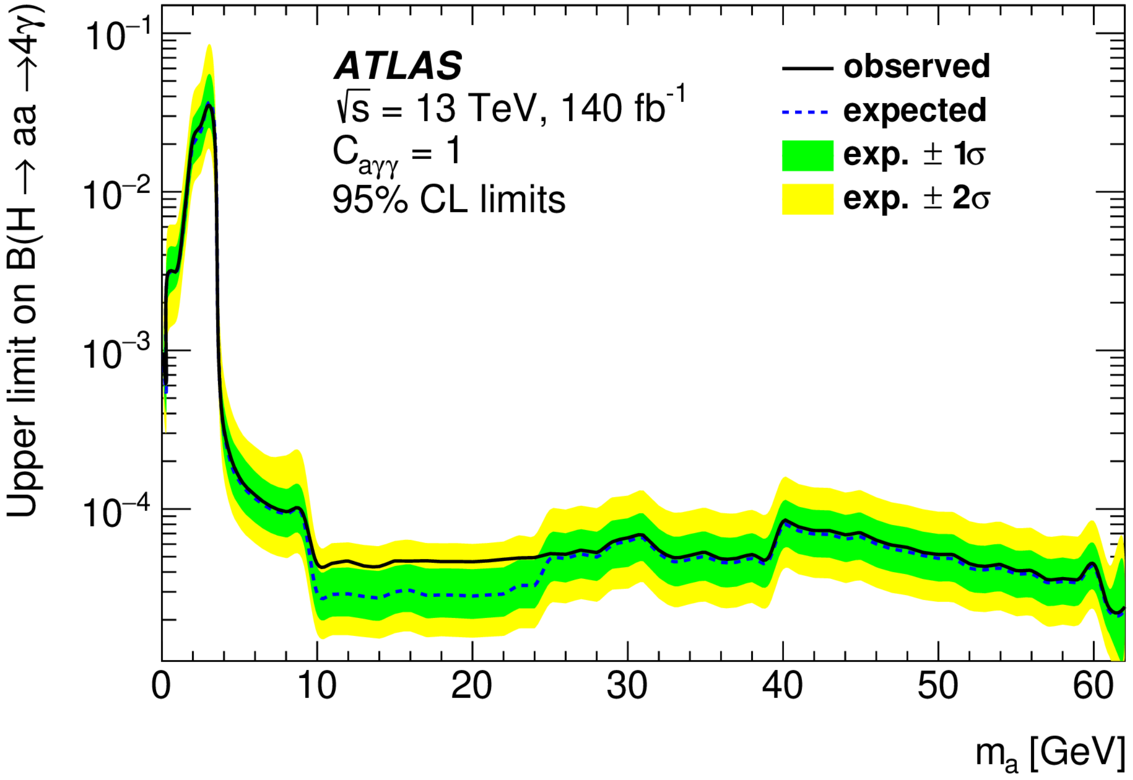
- Upper limits on $B(H \to aa \to 4\gamma)$ at 95% CL for $c_{a\gamma\gamma} = 10^{-5}$ and $c_{a\gamma\gamma} = 1$
- No significant excesses
- Largest deviation in range $10\ GeV \leq m_a \leq 25\ GeV$ (local significance **1.2σ**)

Long-lived search



ALPs with lower masses decay outside the detector volume

Prompt search



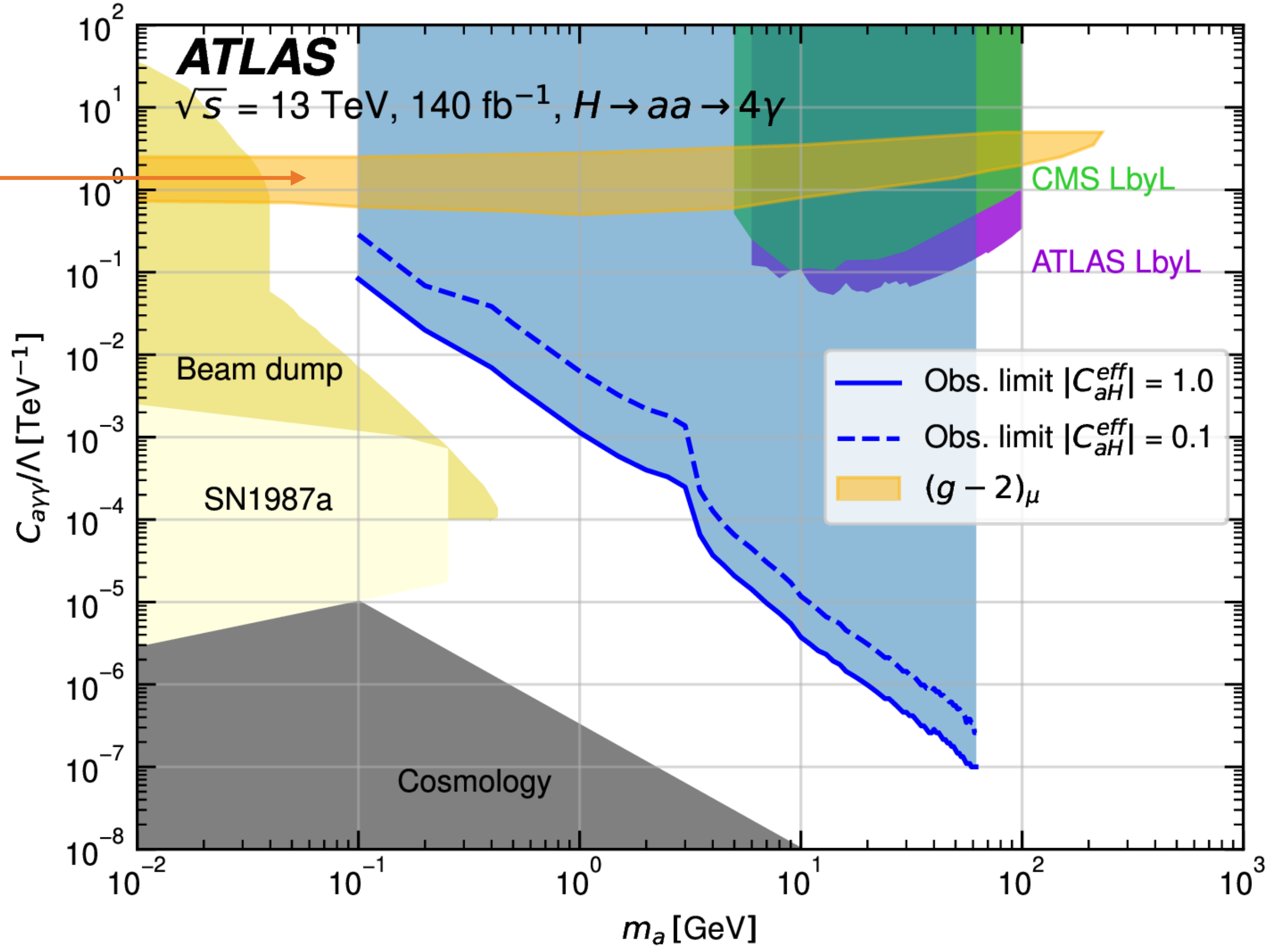
Limits with other coupling values in backups

$H \to aa \to 4\gamma$: Results

- Limits on BR converted into limit on ALP mass and coupling to photons $c_{a\gamma\gamma}$, assuming $B(a \to \gamma\gamma) = 1$, $\Lambda = 1\ TeV$ at 95% CL
- Significantly reduces the allowed parameter space that could explain $(g-2)\mu$

$(g-2)\mu$
arXiv:1708.00443

Beam dump experiments and supernova SN1987a
arXiv:1509.00476



CMS Light-by-Light scatering
arXiv:1810.04602

ATLAS Light-by-Light scatering
arXiv:2008.05355

Search for heavy $H \rightarrow$ multi-l + b-jets

JHEP 12 (2023) 081

$H \to$ multi-l + b-jets: Introduction

- Looking for a heavy scalar that decays with same-sign top, 3-top, 4-top final states

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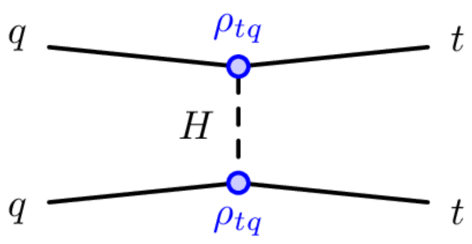

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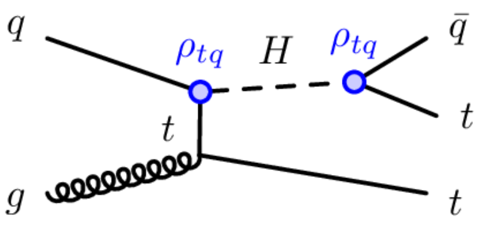

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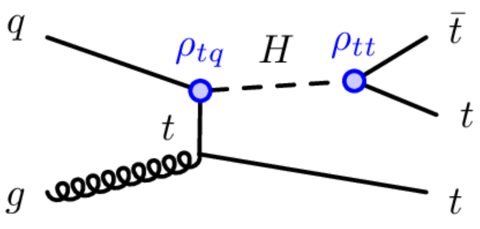

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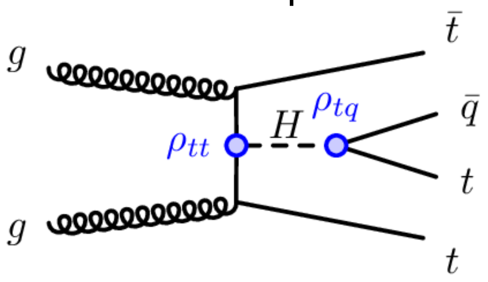

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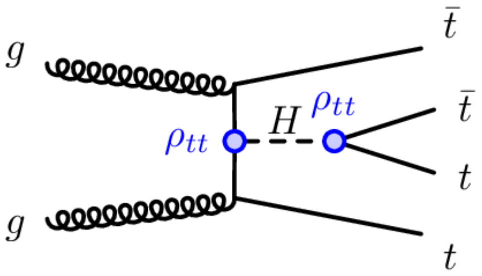
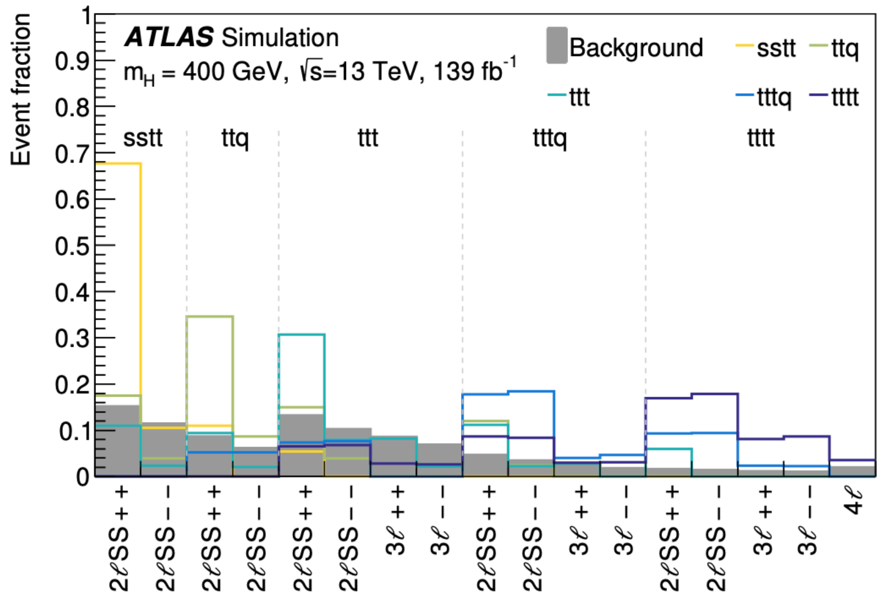


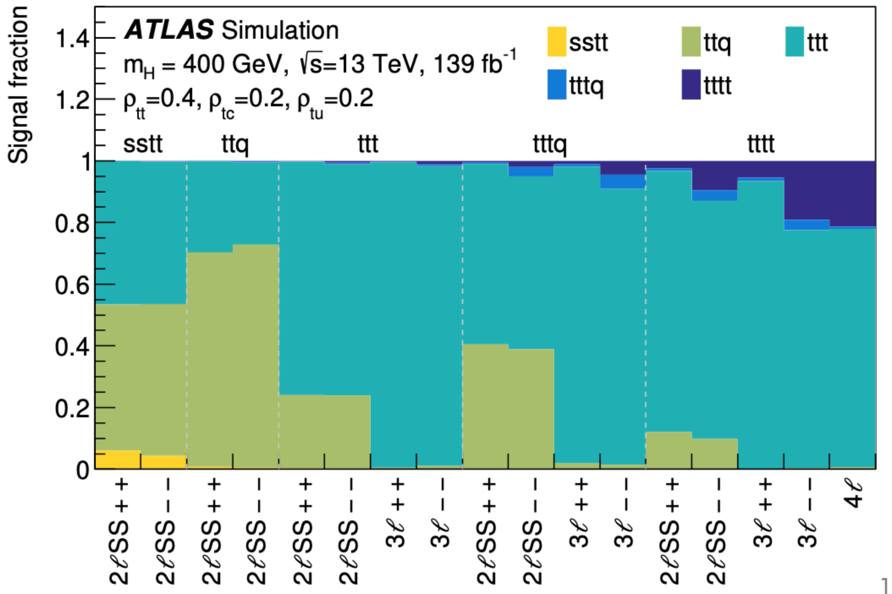
- Benchmark models:
  - General 2HDM without Z_2 symmetry with coupling to tops (g2HDM)
  - R-parity-violating SUSY (not covered in this talk)

- g2HDM:
  - Allows flavor changing neutral Higgs without affecting the alignment limit of the SM Higgs
  - Can address electroweak baryogenesis, strong CP problem, flavor problem
  - Was not tested at the LHC before

$H \to$ multi-l + b-jets: Analysis stratedy

- 17 SRs:
  - A DNN classifies event into 5 orthogonal regions
  - Then splits according to the lepton multiplicity and charge
- Irreducible backgrounds:
  - $t\bar{t}W$ normalized to data
  - VV+HF, $t\bar{t}Z/\gamma^*$+LF modelling corrected in dedicated CRs
  - Material conversion estimated in 2 CRs
- Reducible backgrounds :
  - Fake leptons estimated via template method
  - Charge-flip electrons rate measured in data using $Z \to ee$

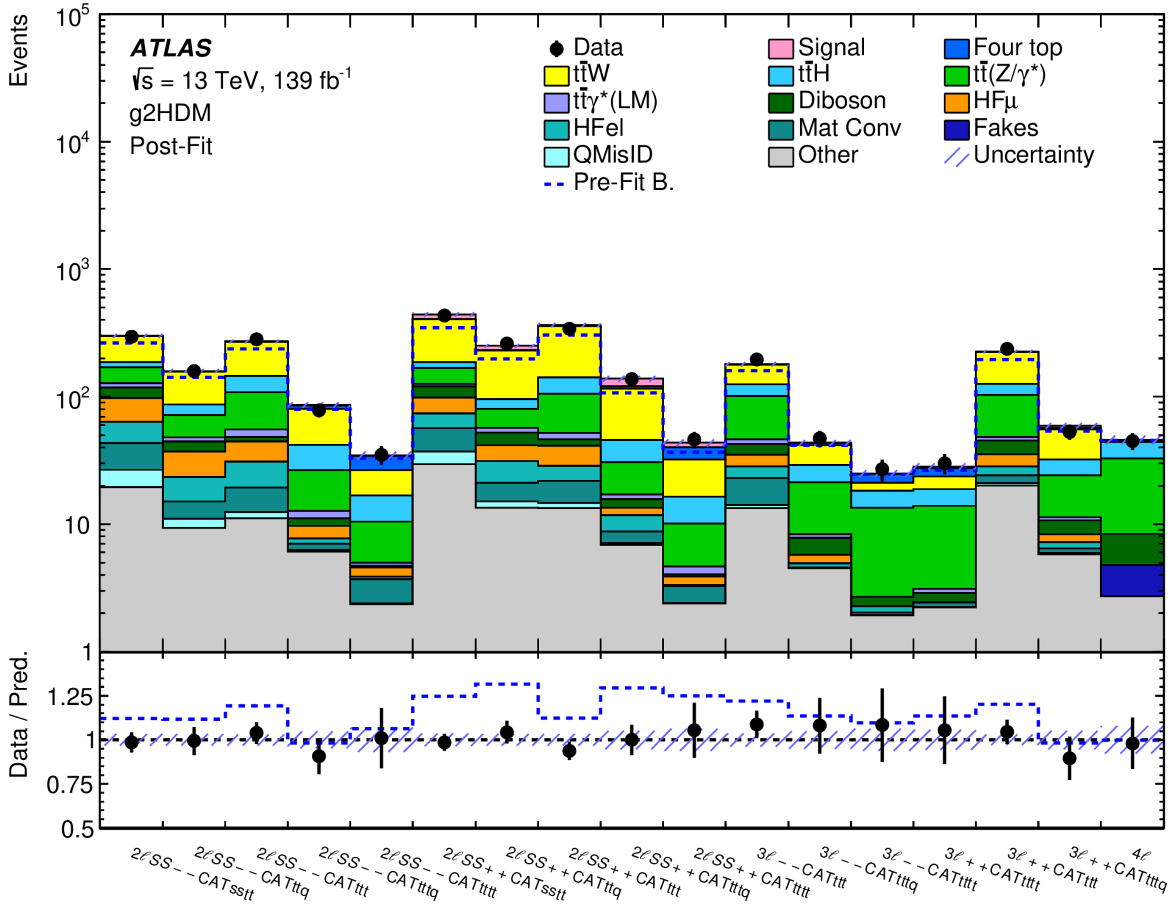




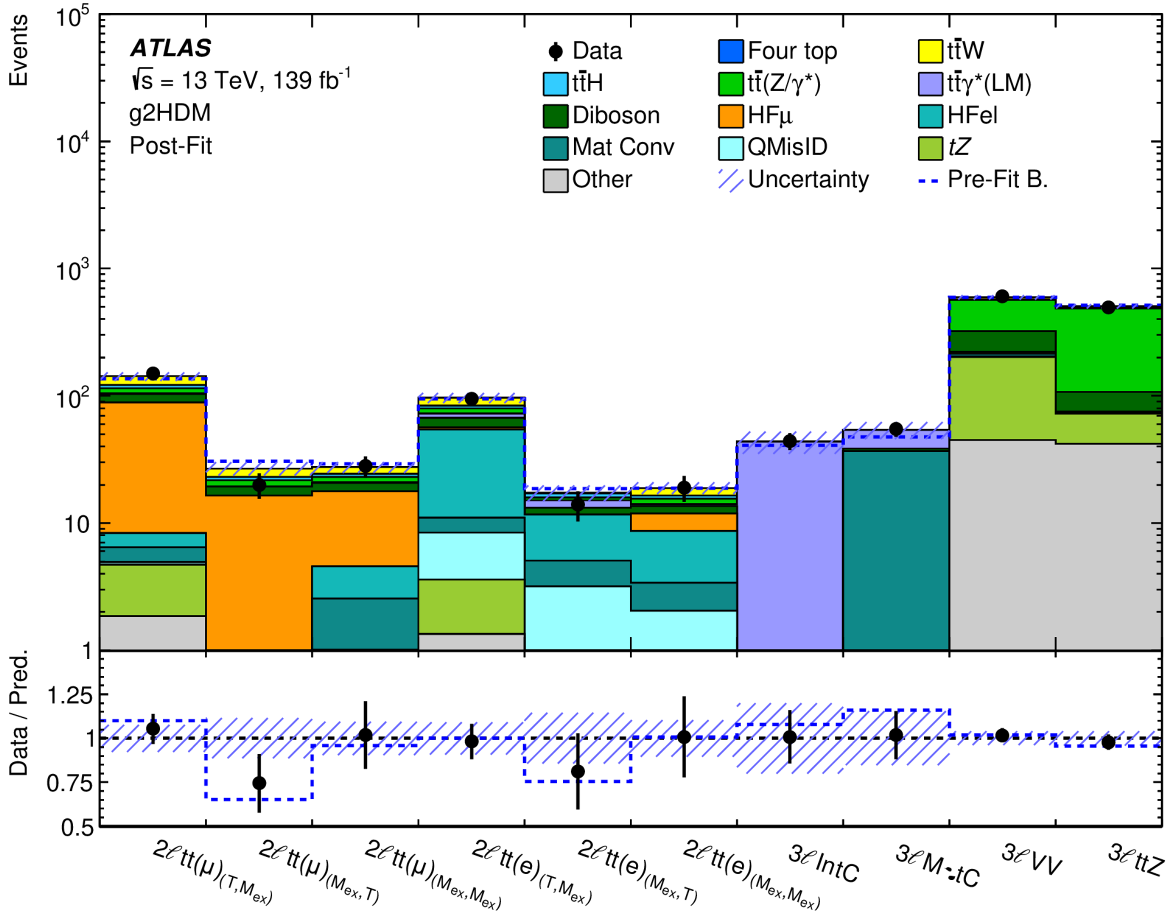
$H \to$ multi-l + b-jets: Results

- Post-fit (and pre-fit) event yields with expected signal $m_H = 900\ GeV$ and couplings $\rho_{tt} = 0.6$, $\rho_{tc} = 0.0$, $\rho_{tu} = 1.1$

Signal regions



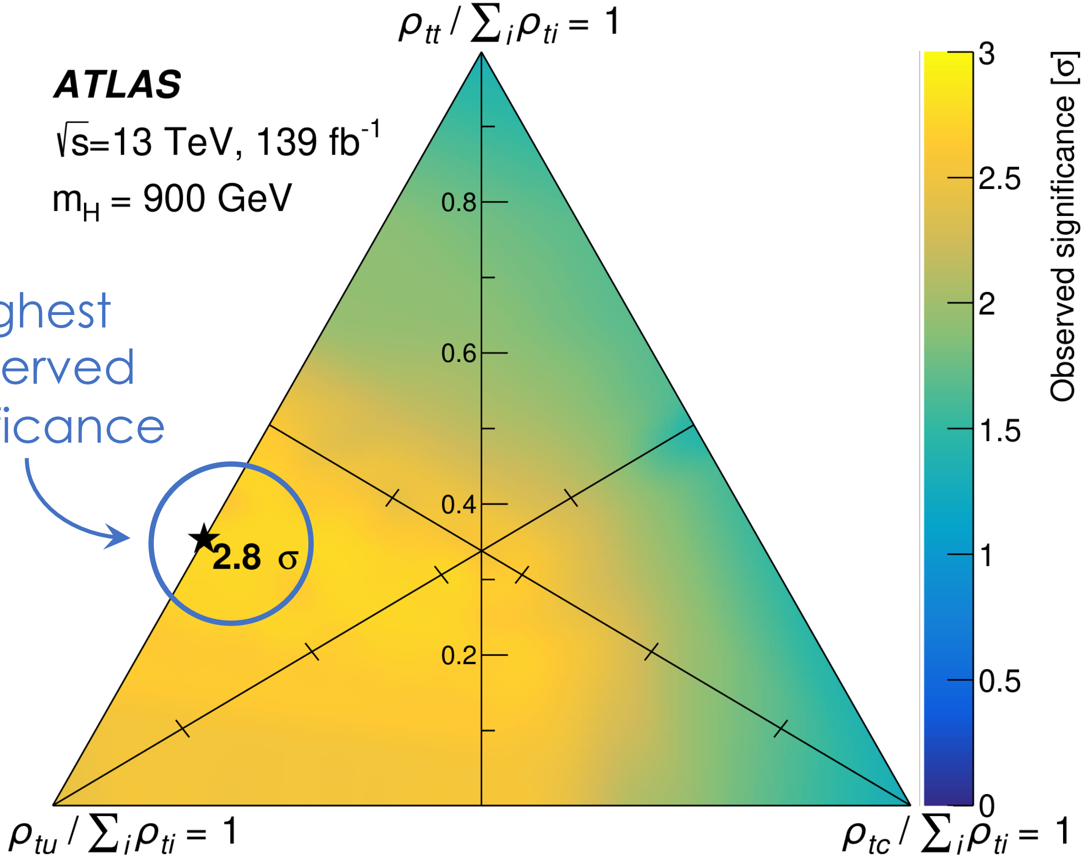
Control regions



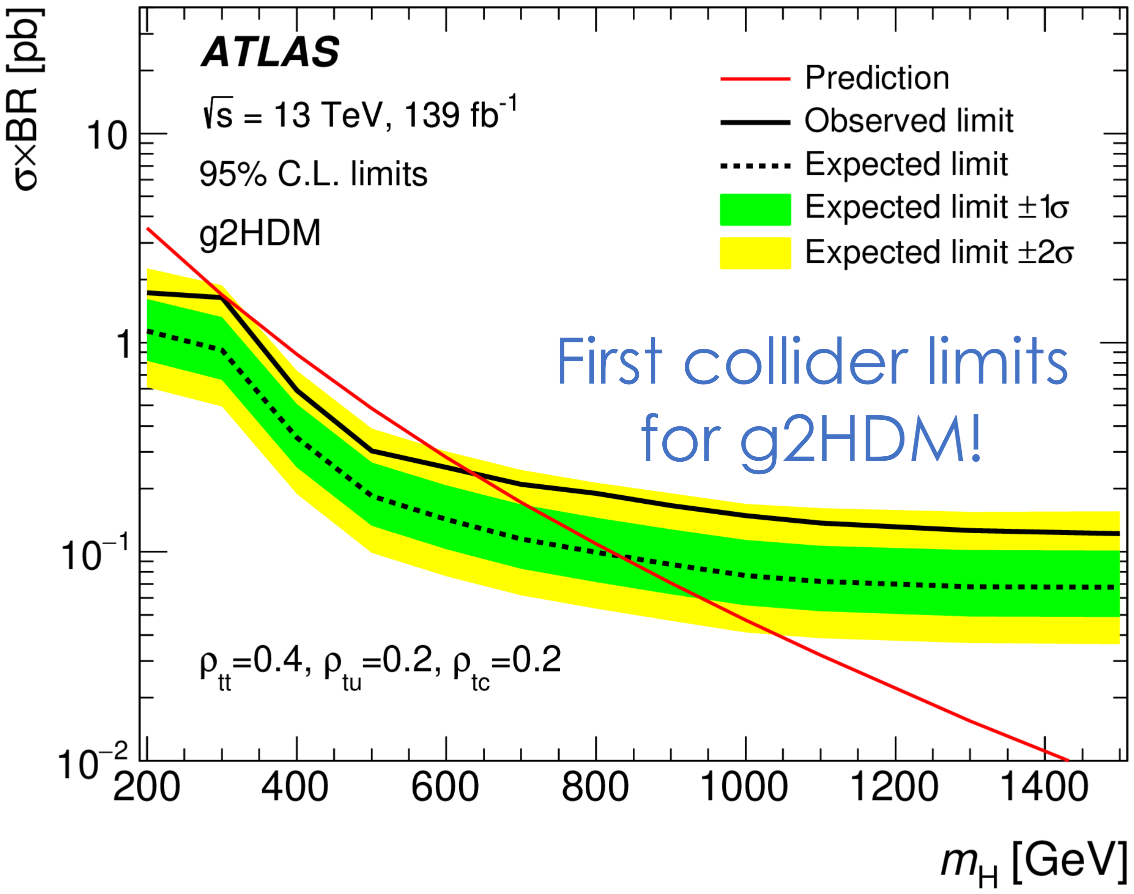
$H \to$ multi-l + b-jets: Results

- Observed significance for a heavy scalar with $m_H = 900\ GeV$ as a function of the coupling values ρ_{tt}, ρ_{tc}, ρ_{tu} normalized to their sum.

Highest observed significance



- Observed and expected exclusion limit at 95% CL for coupling values $\rho_{tt} = 0.4$, $\rho_{tc} = 0.2$, $\rho_{tu} = 0.2$



Limits with other coupling values in backups

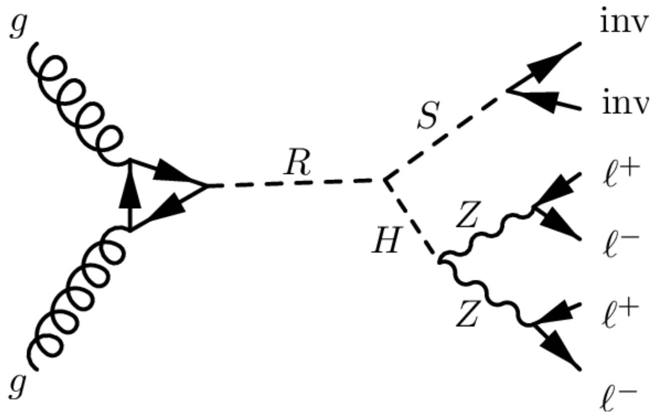
Search for $X \rightarrow 4l + \text{MET/jets}$

arXiv:2401.04742

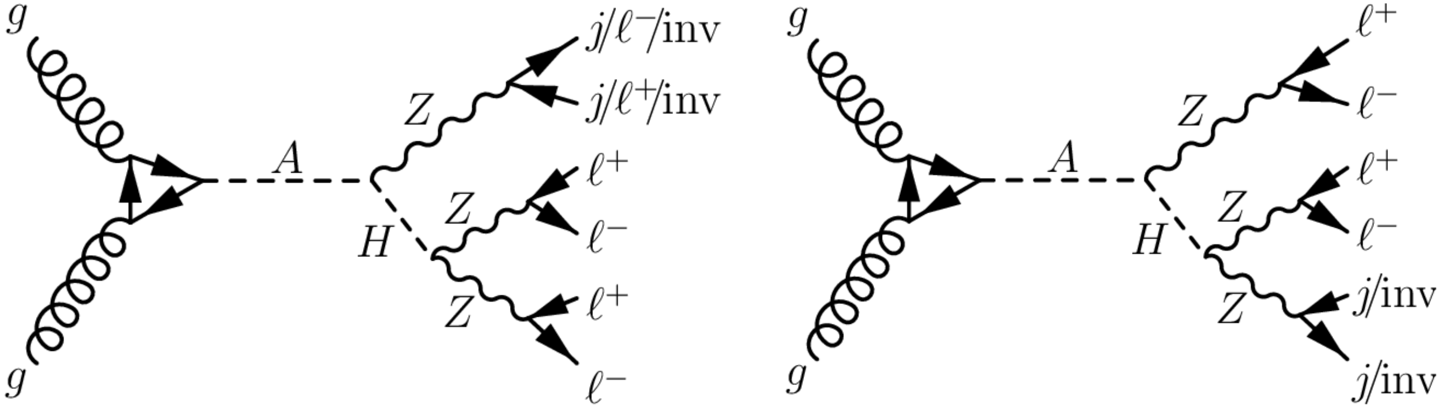
$X \rightarrow 4l + \mathrm{MET/jets}$: Introduction

- Looking for heavy resonances with 4 leptons (e or μ) + missing transverse momenta (MET, E_T^{miss}) or jets in the final state
- Benchmark models:
  - 2HDM+S → scalar S can be a dark matter candidate
  - 2HDM → consistent with baryogenesis scenario
- Masses of the bosons:
  - $390 < m_R < 1300$ GeV
  - $320 < m_A < 1300$ GeV
  - $220 < m_H < 1000$ GeV
  - $m_S = 160$ GeV
- Main backgrounds:
  - $q\bar{q} \rightarrow ZZ$ (~84.6%)
  - $gg \rightarrow ZZ$ (~11.7%)

$R \rightarrow SH \rightarrow 4l + E_T^{miss}$



$A \rightarrow ZH \rightarrow 4l + X$



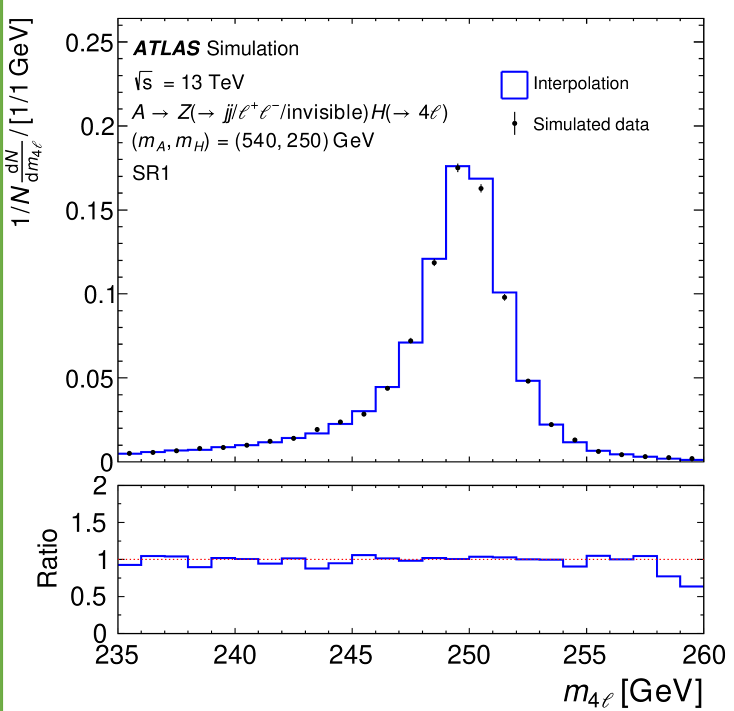
$X \to 4l$ + MET/jets: Analysis strategy

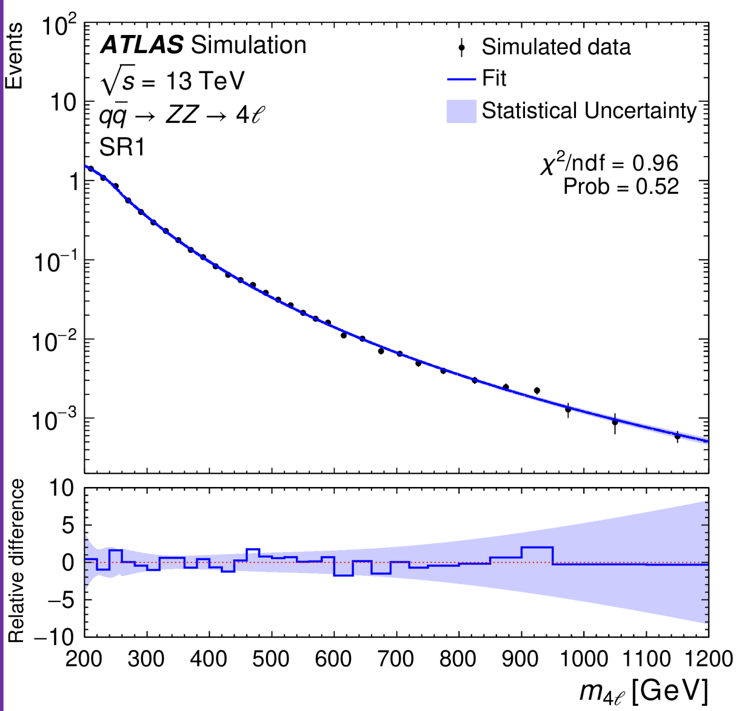
- $m_{4l} > 200\ GeV$
- 3 lepton channels: $4\mu,\ 4e,\ 2\mu 2e$
  - Two same flavor and opposite sign pairs
  - Mass of lepton pair ~mass of Z
  - Combined in the final fit

Signal region	$R \to SH \to 4\ell + E_T^{miss}$ and $A \to ZH \to 4\ell + X$			
SR1	$n_{b\text{-jets}} = 0$	$n_{jets} = 0$	$p_T^{4\ell} > 20$ GeV	E_T^{miss} significance >2.0
SR2		$n_{jets} \geq 1$	$p_T^{4\ell} > 10$ GeV	E_T^{miss} significance > 3.5
SR3			$p_T^{4\ell} < 10$ GeV	$2.5 < E_T^{miss}$ significance < 3.5
	$A \to ZH \to 4\ell + X$			
SR4	$n_{b\text{-jets}} = 0$	$n_{jets} \geq 2$	$\lvert m_{jj} - m_Z \rvert < 20$ GeV	
SR5			$\lvert m_{jj} - m_Z \rvert > 20$ GeV	
SR6		$n_{jets} = 1$		
SR7	$n_{b\text{-jets}} \geq 1$			

- Cut based optimization of regions
- Linear interpolation to generate signal shapes between generated mass planes (m_R, m_H) and (m_A, m_H)
- Background modelled with empirical function*

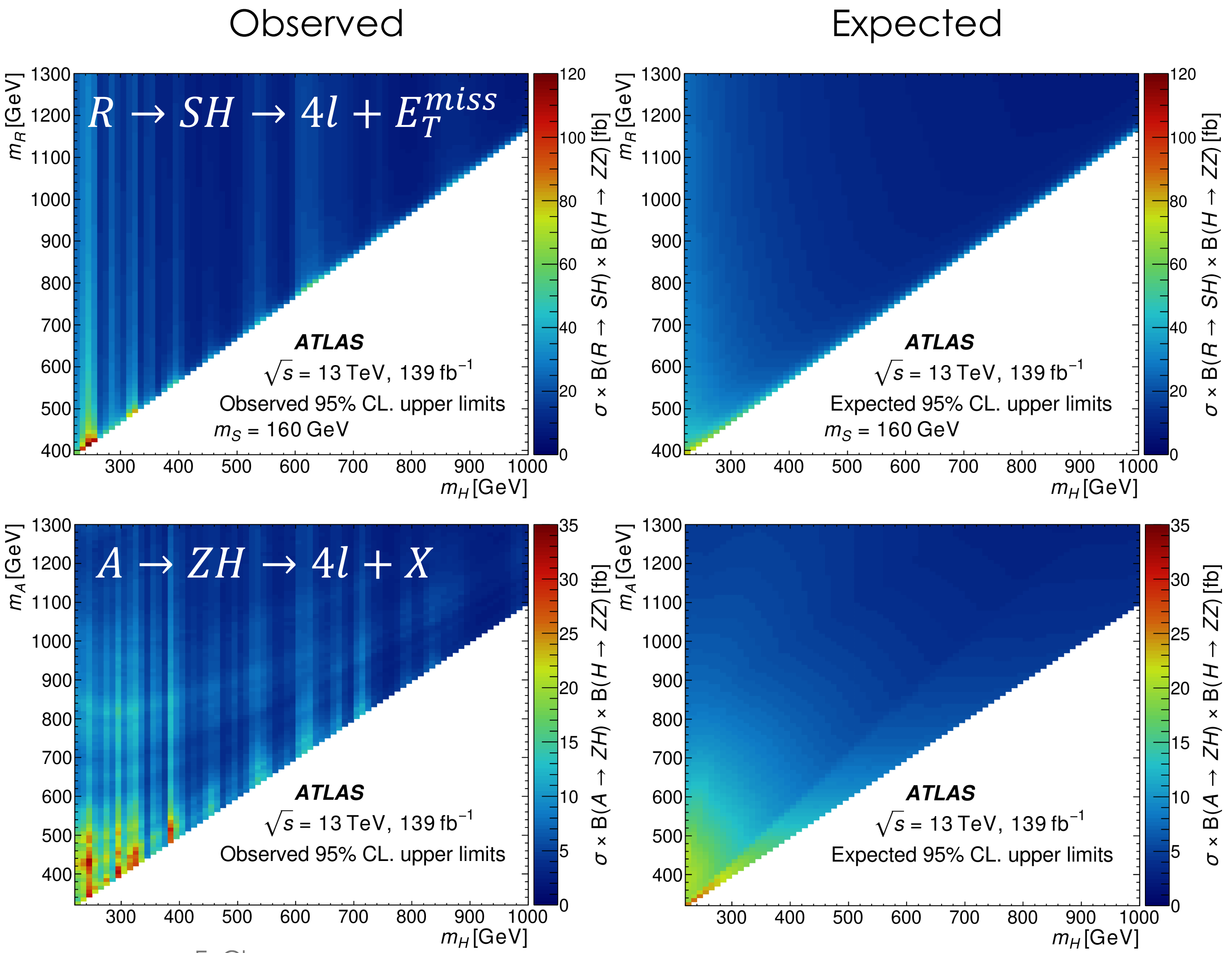
*more in backup





$X \to 4l + \mathrm{MET/jets}$: Results

- Upper limits at 95% CL
- No significant deviation from the SM
- $R \to SH \to 4l + E_T^{miss}$:
  - ➢ Observed: 6.8 – 119.2 fb
  - ➢ Expected: 7.7 – 70.3 fb
- $A \to ZH \to 4l + X$:
  - ➢ Observed: 2.1 – 32.3 fb
  - ➢ Expected: 2.9 – 18.8 fb



Summary and conclusions

- Plenty of possibilities for **new physics** in **the extended Higgs sector**
- Many interesting **searches for anomalous or additional Higgs bosons** are performed by ATLAS
- Could not cover all the work that has been done recently. Check out these results $t \to H^{\pm}b, H^{\pm} \to cb$, $t \to qX, X \to b\bar{b}$, Model independent $W^{\pm}H \to W^{\pm}W^{\pm}W^{\pm} \to l^{\pm}\nu l^{\pm}\nu jj$, $a \to \mu\mu$ in top quark pair events, High mass $Z\gamma$, $H \to Za, a \to \gamma\gamma$
- **No significant deviation** from the SM has been observed so far
- More results with full Run-2 are to be expected
- Some of the analyses will continue in Run-3 and at the HL-LHC → more production and decay channels

  ➢ Stay tuned!

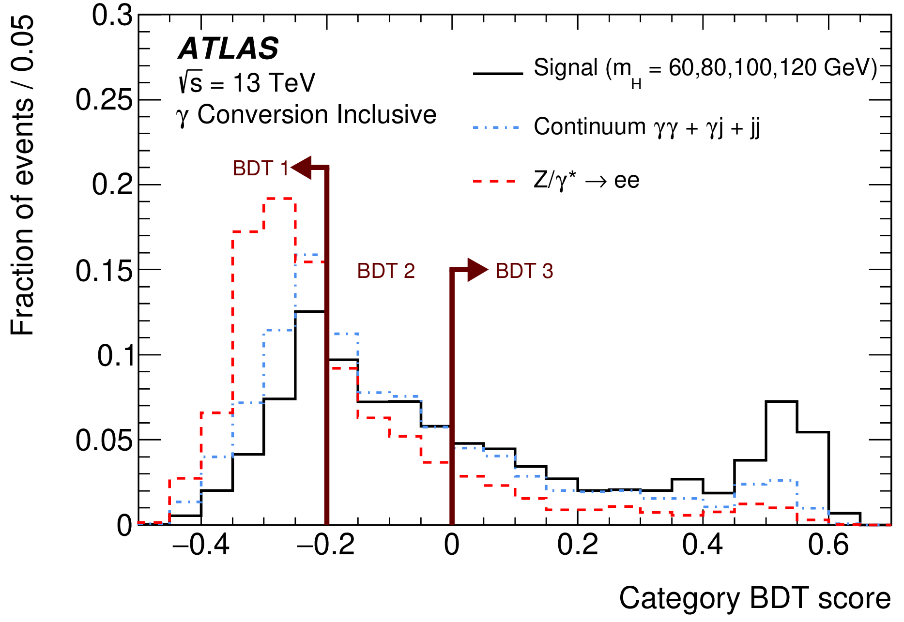
Thank you for your attention!

Back up

Low mass $X \to \gamma\gamma$: Analysis strategy

- Event categorization with the category BDT:

Category	Selection Requirement
Model-Independent categories	
UU	2 unconverted photons
UC	1 converted photon and 1 unconverted photon
CC	2 converted photons
Model-Dependent categories	
UU1	UU and category BDT score < −0.2
UU3	UU and category BDT score [−0.2,0)
UU3	UU and category BDT score >= 0
UC1	UC and category BDT score < −0.2
UC2	UC and category BDT score [0.2,0)
UC3	UC and category BDT score >= 0
CC1	CC and category BDT score < −0.2
CC3	CC and category BDT score [−0.2,0)
CC3	CC and category BDT score >= 0



The expected number of signal events, fractions of each Higgs boson production modes and the number of background events per GeV at $m_{\gamma\gamma} = 90\ GeV$

BDT Category	SM-like Higgs boson (m_H = 90 GeV) Total	ggF [%]	VBF [%]	WH [%]	ZH [%]	$t\bar{t}H$ [%]	Background Total [GeV^{-1}]	DY [GeV^{-1}]
1	741	97.1	1.2	1.0	0.6	0.1	18877	2179
2	942	93.4	2.9	2.1	1.2	0.4	14014	713
3	1187	72.4	13.5	6.7	4.0	3.4	6522	294
Total	2870	85.7	6.8	3.7	2.2	1.6	39413	3186

$H \rightarrow aa \rightarrow 4\gamma$: Analysis strategy

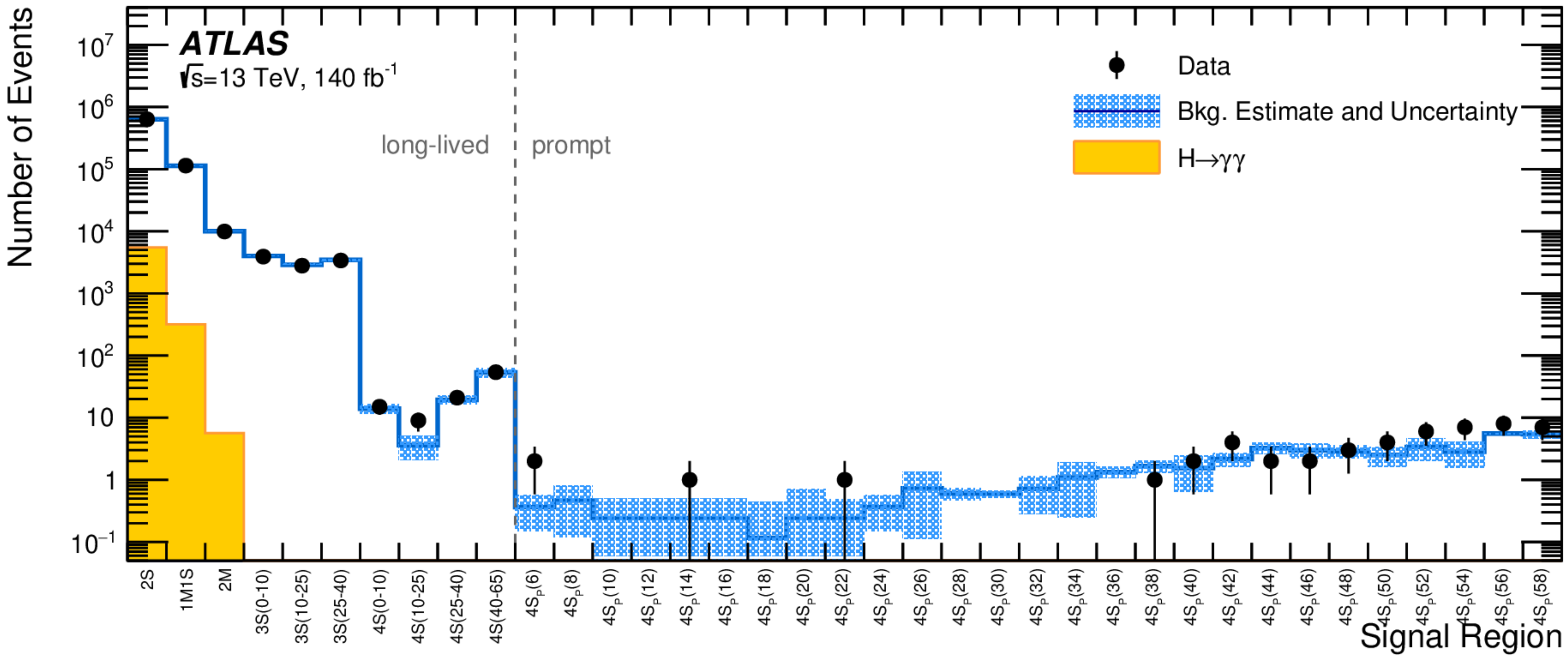
- At least 2 photons
- Di-photon triggers
  - $E_T^{\gamma\, lead} > 35\ GeV$
  - $E_T^{\gamma\, sublead} > 25\ GeV$
- Photon reco categories:

- 4S: at least 1 tight ID γ, all remaining loose ID
- 3S: 3 tight ID γ
- 2M: 2 merged γ, no additional loose ID γ
- 1M1S: exactly 1 merged and 1 loose ID γ
- 2S: 2 tight ID γ, no additional loose ID γ
- $4S_p$: at least 3 tight ID γ, all remaining loose ID

Model Parameters	Signal Region Definition	
Long-lived ALP Search: $C_{a\gamma\gamma} < 0.1$		
	2M, 1M1S and 2S Categories	
$0.1\ \text{GeV} \leq m_a < 3.5\ \text{GeV}$	$115\ \text{GeV} < m_{\text{inv}}^{\text{reco}} < 130\ \text{GeV}$	
	3S Category	4S Category
$3.5\ \text{GeV} \leq m_a < 10\ \text{GeV}$	$105\ \text{GeV} < m_{\text{inv}}^{\text{reco}} < 130\ \text{GeV}$ $0\ \text{GeV} < m_a^{\text{reco}} < 10\ \text{GeV}$	$120\ \text{GeV} < m_{\text{inv}}^{\text{reco}} < 130\ \text{GeV}$ $0\ \text{GeV} < m_a^{\text{reco}} < 12\ \text{GeV}$
$10\ \text{GeV} \leq m_a < 25\ \text{GeV}$	$100\ \text{GeV} < m_{\text{inv}}^{\text{reco}} < 125\ \text{GeV}$ $6\ \text{GeV} < m_a^{\text{reco}} < 26\ \text{GeV}$	$120\ \text{GeV} < m_{\text{inv}}^{\text{reco}} < 130\ \text{GeV}$ $8\ \text{GeV} < m_a^{\text{reco}} < 28\ \text{GeV}$
$25\ \text{GeV} \leq m_a < 40\ \text{GeV}$	$100\ \text{GeV} < m_{\text{inv}}^{\text{reco}} < 125\ \text{GeV}$ $20\ \text{GeV} < m_a^{\text{reco}} < 40\ \text{GeV}$	$120\ \text{GeV} < m_{\text{inv}}^{\text{reco}} < 130\ \text{GeV}$ $23\ \text{GeV} < m_a^{\text{reco}} < 43\ \text{GeV}$
$40\ \text{GeV} \leq m_a \leq 62\ \text{GeV}$	$90\ \text{GeV} < m_{\text{inv}}^{\text{reco}} < 115\ \text{GeV}$ $30\ \text{GeV} < m_a^{\text{reco}} < 65\ \text{GeV}$	$120\ \text{GeV} < m_{\text{inv}}^{\text{reco}} < 130\ \text{GeV}$ $38\ \text{GeV} < m_a^{\text{reco}} < 65\ \text{GeV}$
Prompt ALP Search: $0.1 < C_{a\gamma\gamma} < 1$		
	$4S_p$ Category	
$5\ \text{GeV} \leq m_a < 25\ \text{GeV}$	$120\ \text{GeV} < m_{\text{inv}}^{\text{reco}} < 130\ \text{GeV}$ $\lvert m_a - m_a^{\text{reco}}\rvert < 1\ \text{GeV}$	
$25\ \text{GeV} \leq m_a < 40\ \text{GeV}$	$120\ \text{GeV} < m_{\text{inv}}^{\text{reco}} < 130\ \text{GeV}$ $\lvert m_a - m_a^{\text{reco}}\rvert < 2\ \text{GeV}$	
$40\ \text{GeV} \leq m_a < 50\ \text{GeV}$	$120\ \text{GeV} < m_{\text{inv}}^{\text{reco}} < 130\ \text{GeV}$ $\lvert m_a - m_a^{\text{reco}}\rvert < 3\ \text{GeV}$	
$50\ \text{GeV} \leq m_a < 55\ \text{GeV}$	$120\ \text{GeV} < m_{\text{inv}}^{\text{reco}} < 130\ \text{GeV}$ $\lvert m_a - m_a^{\text{reco}}\rvert < 5\ \text{GeV}$	
$55\ \text{GeV} \leq m_a \leq 62\ \text{GeV}$	$120\ \text{GeV} < m_{\text{inv}}^{\text{reco}} < 130\ \text{GeV}$ $\lvert m_a - m_a^{\text{reco}}\rvert < 8\ \text{GeV}$	

$H \rightarrow aa \rightarrow 4\gamma$: Results

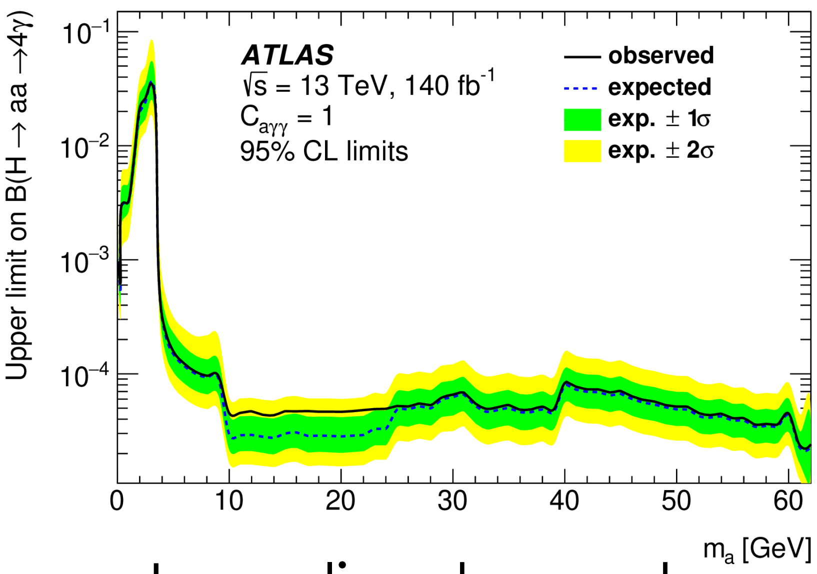
- Number of data and estimated background events in the signal region of the most sensitive categories



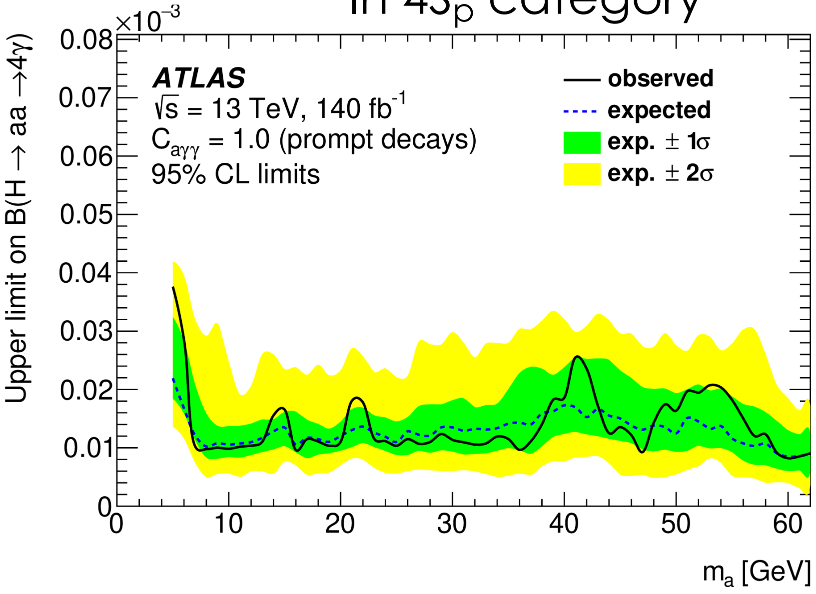
$H \to aa \to 4\gamma$: Results

- Upper limits on $B(H \to aa \to 4\gamma)$ at 95% CL for different ALP-photon coupling values (long-lived search)
- No significant excesses

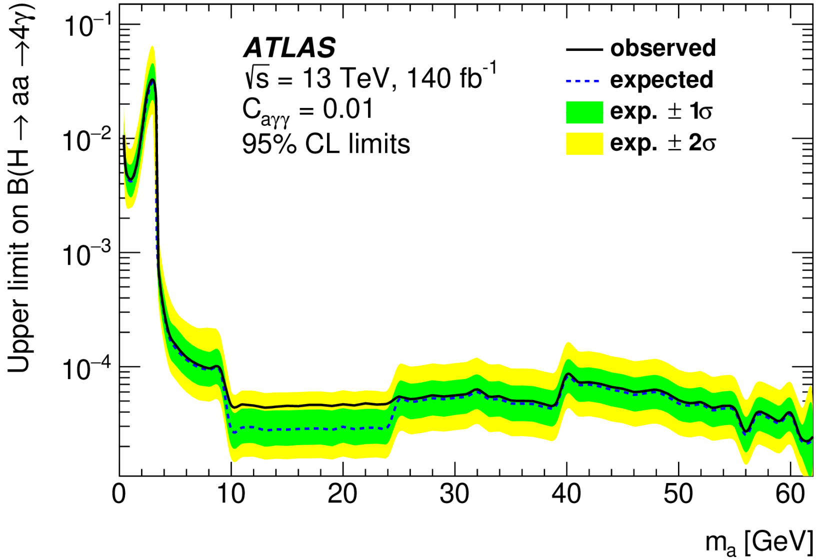
Prompt search

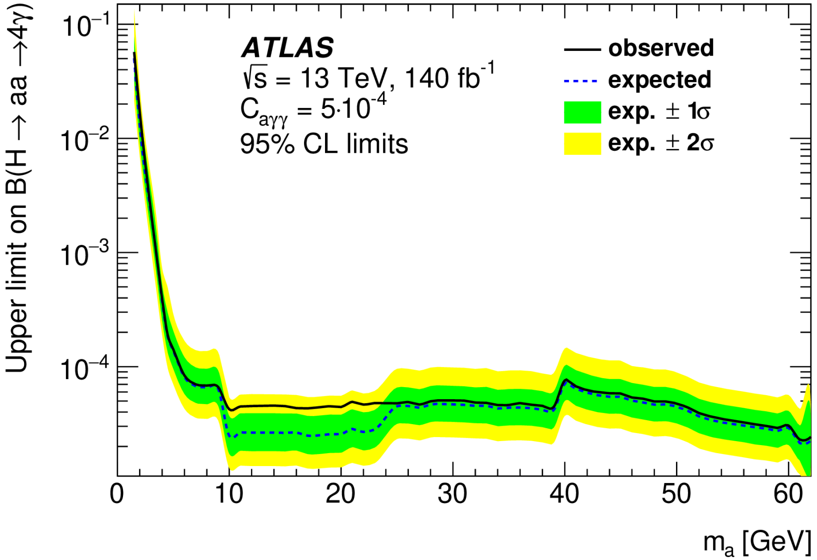


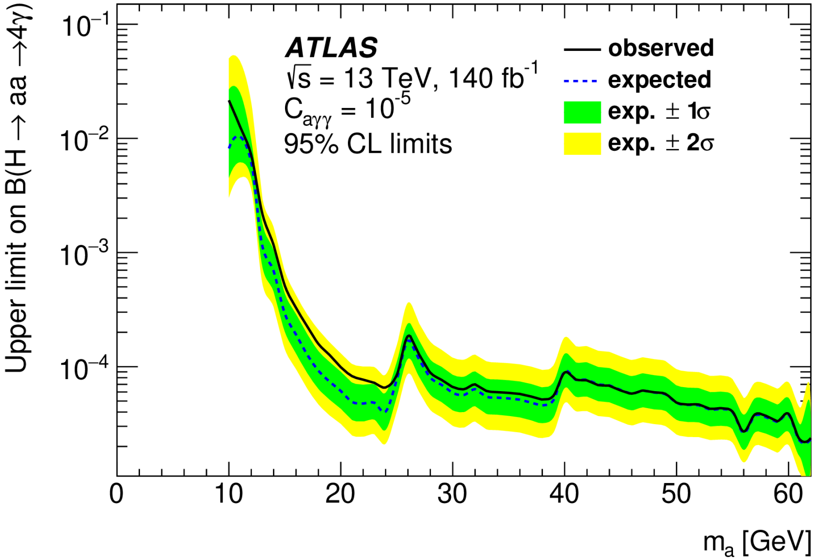
In $4S_p$ category



Long-lived search







$H \to$ multi-l + b-jets: Analysis stratedy

- Description of the loose inclusive ("L"), medium inclusive ("M"), medium exclusive ("M_{ex}"), and tight ("T") lepton definitions.

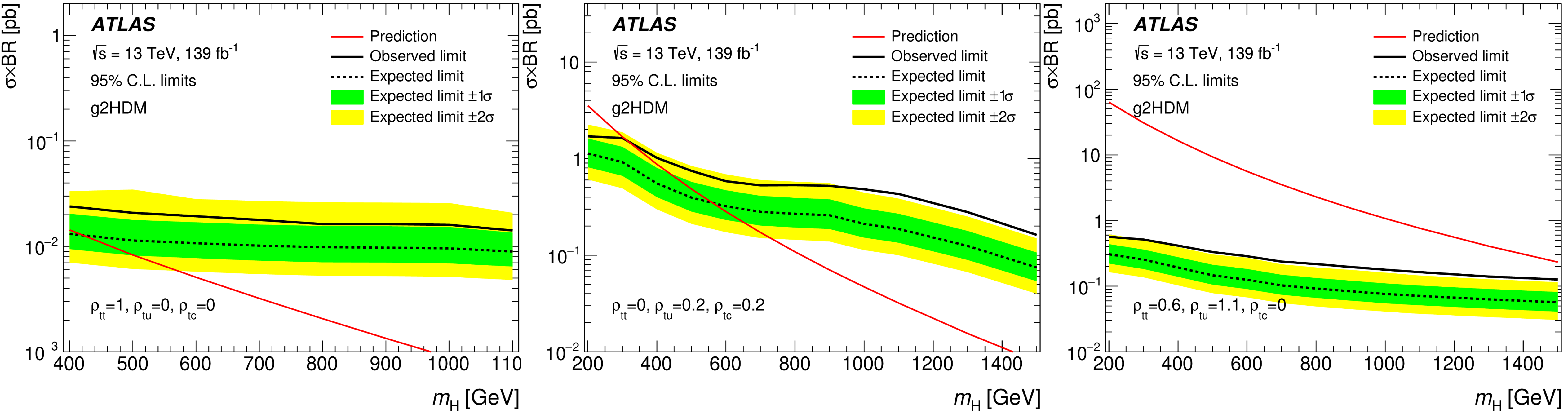
	e				μ			
Lepton categorization	L	M	M_{ex}	T	L	M	M_{ex}	T
Isolation	Yes				Yes			
Non-prompt lepton BDT WP	No	*Tight*	*Tight-not-VeryTight*	*VeryTight*	No	*Tight*	*Tight-not-VeryTight*	*VeryTight*
Identification	Loose	Tight			Loose	Medium		
Electron charge-misassignment veto	No	Yes			Not applicable			
Electron conversion candidate veto	No	Yes (except e^*)			Not applicable			
Transverse impact parameter significance $\lvert d_0 \rvert / \sigma_{d_0}$	< 5				< 3			
Longitudinal impact parameter $\lvert z_0 \sin\theta \rvert$	< 0.5 mm							

- Event selection summary:
  - OS-SF is opposite sign charge and same flavor leptons
  - CAT == DNN category

Lepton category	2ℓSS	3ℓ	4ℓ
Lepton definition	(T,T) with $\geq 1\ b^{60\%}$ || (T,M) with $\geq 2\ b^{77\%}$	(L,T,M) with $\geq 1\ b^{60\%}$ || (L,M,M) with $\geq 2\ b^{77\%}$	(L,L,L,L)
Lepton p_T [GeV]	(20, 20)	(10, 20, 20)	(10, 10, 10, 10)
$m_{\ell^+\ell^-}^{\text{OS-SF}}$ [GeV]	–	> 12	
$\lvert m_{\ell^+\ell^-}^{\text{OS-SF}} - m_Z \rvert$ [GeV]	–	> 10	
N_{jets}	≥ 2		
$N_{b-\text{jets}}$	$\geq 1\ b^{60\%}$ || $\geq 2\ b^{77\%}$		
Region split	(sstt, ttq, ttt, tttq, tttt) $\times (Q^{++}, Q^{--})$	(ttt, tttq, tttt) $\times (Q^{+}, Q^{-})$	–
Region naming	2ℓSS ++ CAT sstt 2ℓSS ++ CAT ttq 2ℓSS ++ CAT ttt 2ℓSS ++ CAT tttq 2ℓSS ++ CAT tttt 2ℓSS −− CAT sstt 2ℓSS −− CAT ttq 2ℓSS −− CAT ttt 2ℓSS −− CAT tttq 2ℓSS −− CAT tttt	3ℓ ++ CAT ttt 3ℓ ++ CAT tttq 3ℓ ++ CAT tttt 3ℓ −− CAT ttt 3ℓ −− CAT tttq 3ℓ −− CAT tttt	4ℓ

$H \rightarrow$ multi-l + b-jets: Results

- Observed and expected exclusion limit at 95% CL for different values of the couplings ρ_{tt}, ρ_{tc}, ρ_{tu}



- Observed and expected exclusion limit at 95% CL for different values of the couplings ρ_{tt}, ρ_{tc}, ρ_{tu}

$X \rightarrow 4l + \mathrm{MET/jets}$: Analysis strategy

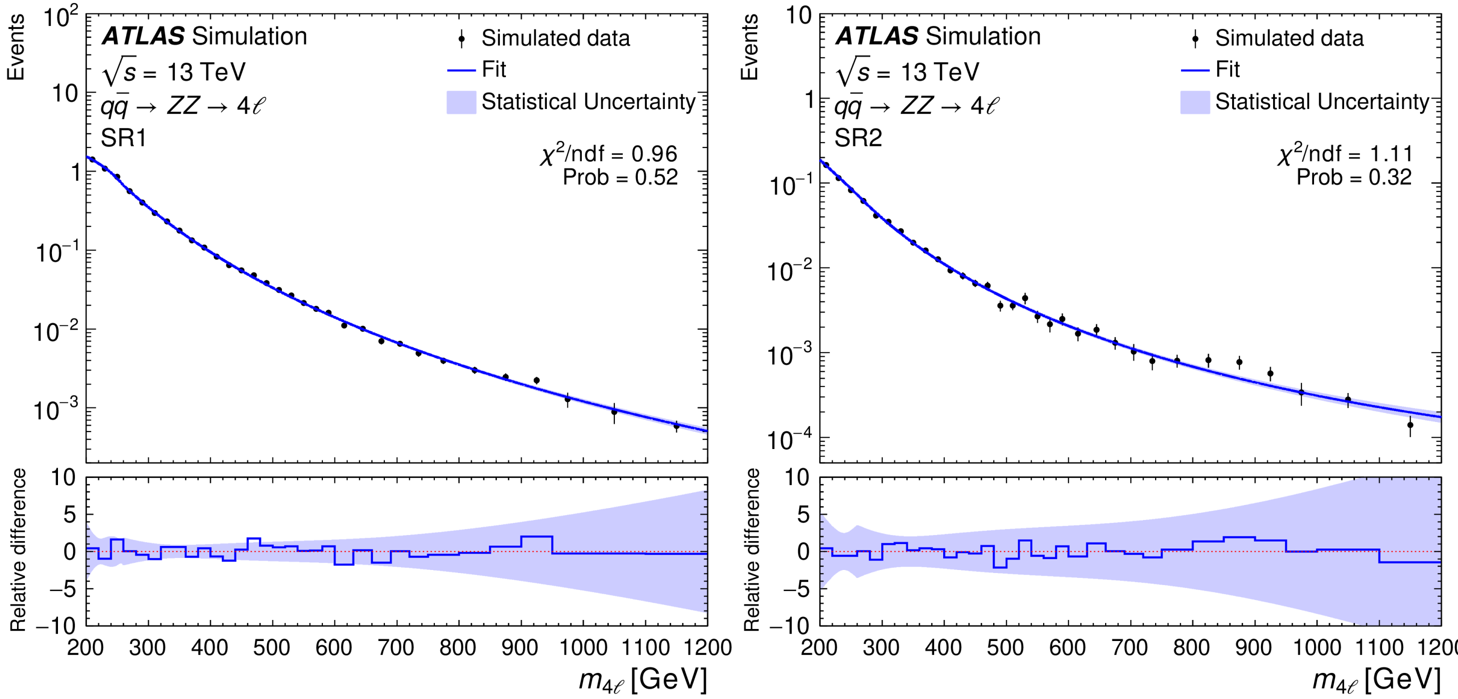
- Background modelled with empirical function for $200 < m_{4l} < 1200\ GeV$:

$$f(m_{4\ell}) = H(m_0 - m_{4\ell})\,f_1(m_{4\ell})\,C_1 + H(m_{4\ell} - m_0)\,f_2(m_{4\ell})\,C_2,$$

$$f_1(m_{4\ell}) = \frac{a_1 \cdot m_{4\ell} + a_2 \cdot m_{4\ell}^2}{1 + \exp\left(\frac{m_{4\ell} - a_1}{a_3}\right)},$$

$$f_2(m_{4\ell}) = \left(1 - \frac{m_{4\ell}}{n_C}\right)^{b_1} \cdot \left(\frac{m_{4\ell}}{n_C}\right)^{\left(b_2 + b_3 \cdot \ln\left(\frac{m_{4\ell}}{n_C}\right)\right)},$$

$$C_1 = \frac{1}{f_1(m_0)}, \qquad C_2 = \frac{1}{f_2(m_0)}.$$



- f_1 models the ZZ threshold around $2 \cdot m_Z$
- f_2 models the high mass tail
- Transition between f_1 and f_2 performed by the Heaviside step function $H(x)$ around m_0
- m_0 is fixed to 260 GeV ($q\bar{q} \rightarrow ZZ$), 240 GeV ($gg \rightarrow ZZ$), 250 GeV(VVV) and 230 GeV (other backgrounds)

$X \to 4l +$ MET/jets: Results

- Observed and expected m_{4l} distributions

$R \to SH \to 4l + E_T^{miss}$

$A \to ZH \to 4l + X$