Beyond the Standard Model in the Higgs Sector

Simon Grewe on behalf of the ATLAS collaboration

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simon.gabriel.grewe@cern.ch

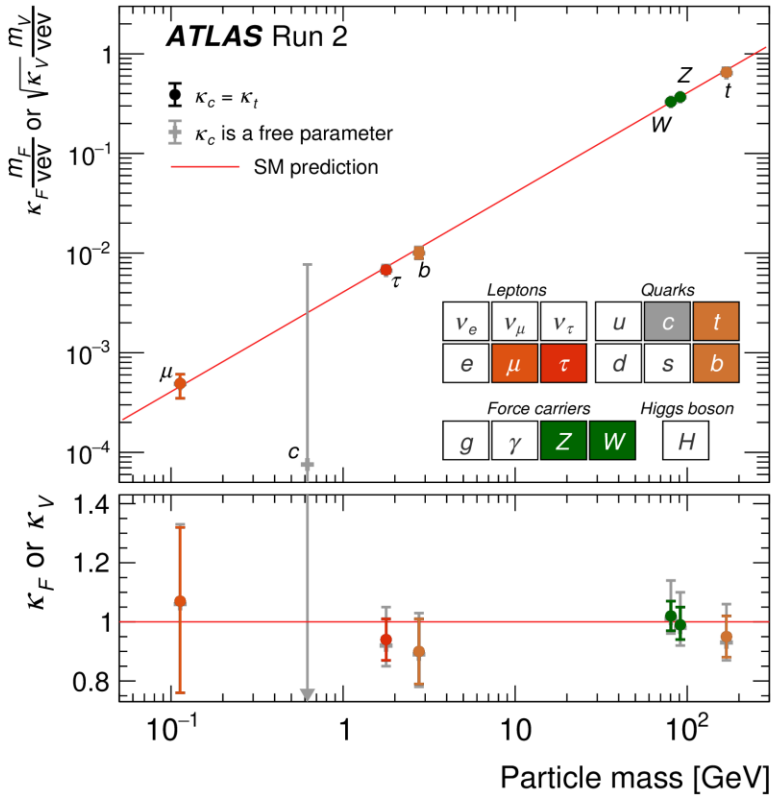
MAX PLANCK INSTITUTE FOR PHYSICS

ATLAS EXPERIMENT

Introduction

No clear sign of BSM in the Higgs sector

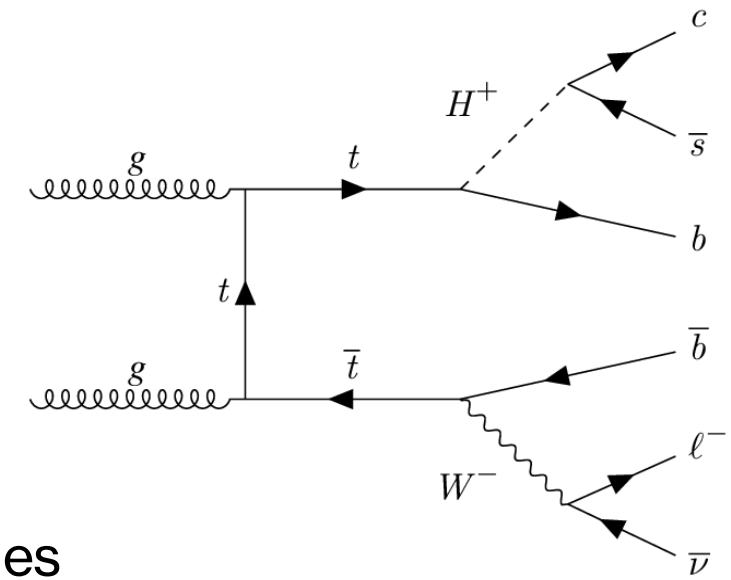
- Besides its tremendous success the standard model has many shortcomings (often connected to the scalar sector)
  - Dark matter
  - Baryon asymmetries
  - Naturalness
- Many proposed solutions require an extended Higgs sector e.g.
  - SUSY
  - Axion models
- Simplest extension **2 Higgs doublet model**:
  - Particle Content: **H^+,H^-,h,H,A**
  - Many more models adding additional singlets, doublet, triplets



Introduction

- Many searches for an extended Higgs sector have been performed by ATLAS : public results
- Related talks:
  - Exotic searches at ATLAS by Gökhan Ünel
  - ATLAS searches for non-minimal and long-lived SUSY scenarios by Risa Ushioda
  - Search for Higgs boson production through resonance decays (CMS) by Rainer Mankel
- Today: Selection of recent direct ATLAS searches for an extended Higgs sector in the full Run 2 Data set (140 fb^{-1}, $\sqrt{s}$=13TeV)
  - $H^{+} \rightarrow cs$
  - $H \rightarrow aa \rightarrow \gamma\gamma\gamma\gamma$
  - $H \rightarrow aa \rightarrow bb\tau\tau$

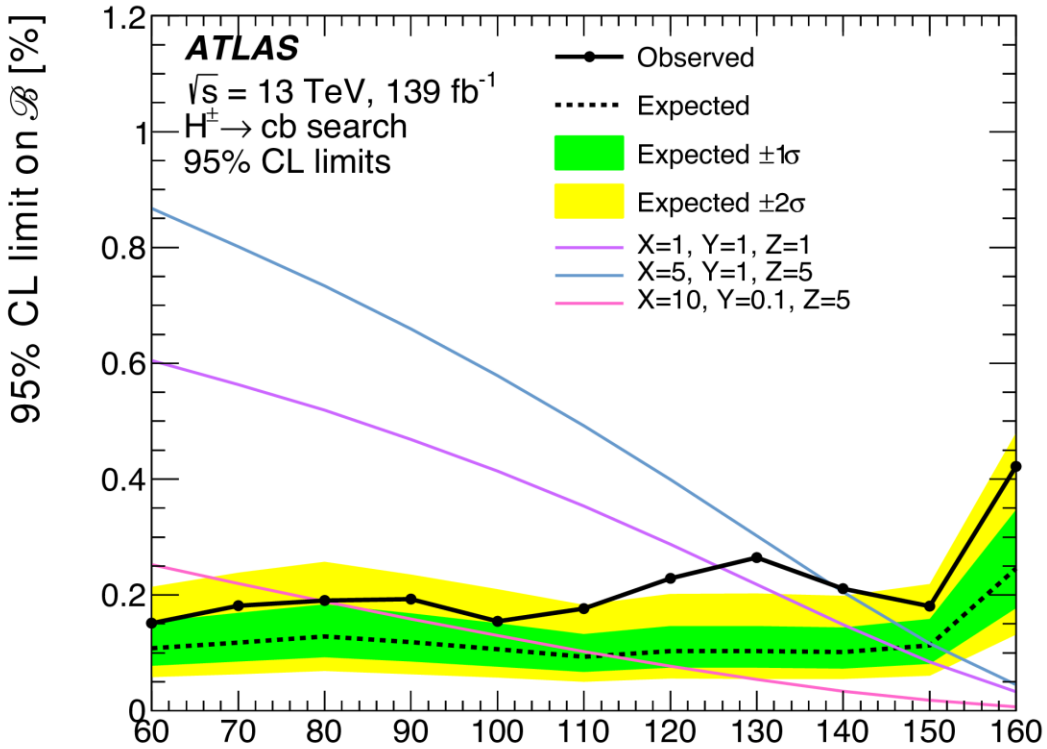
$H^+ \rightarrow cs$



- $t \rightarrow b\, H^+ \rightarrow cs\, b$
  - light H^+[60, 168] GeV
- Light H^+ dominant decay modes
  - $H^+ \rightarrow cs$
  - $H^+ \rightarrow \tau\nu$
  - $(H^+ \rightarrow cb)$ usually smaller than $H^+ \rightarrow cs$ due to CKM-Matrix
- Produced in tt decays
- 1 lepton +jets final state
- Uses simultaneous b and c tagging
  - Uses Pseudo-continuous flavor-tagging

arXiv:2407.10096

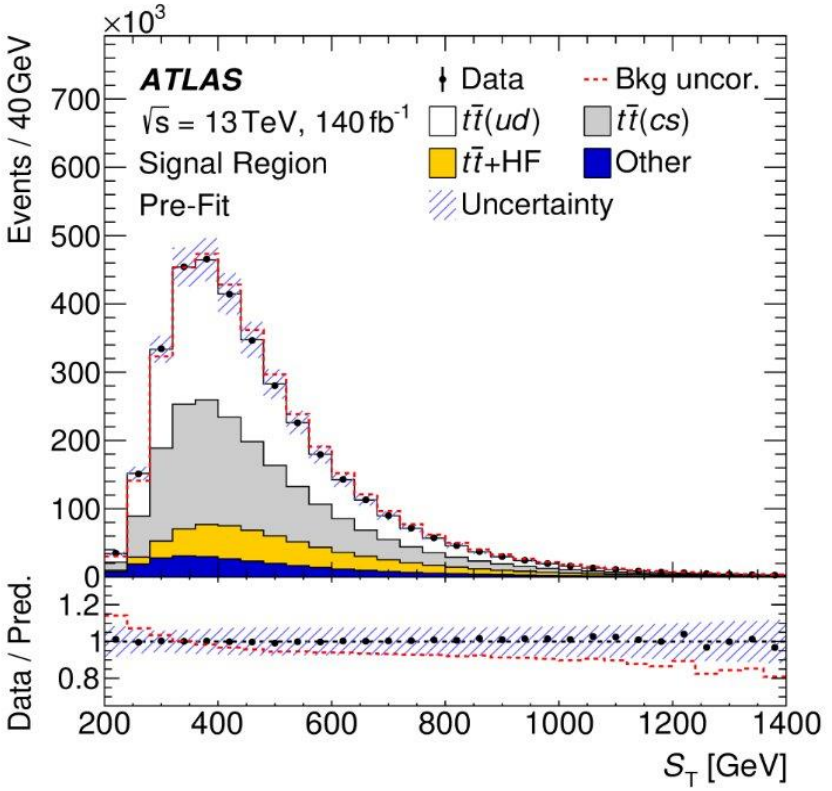
$H^+ \rightarrow cb$ ATLAS observed a 2.5 σ (global) excess around 130 GeV

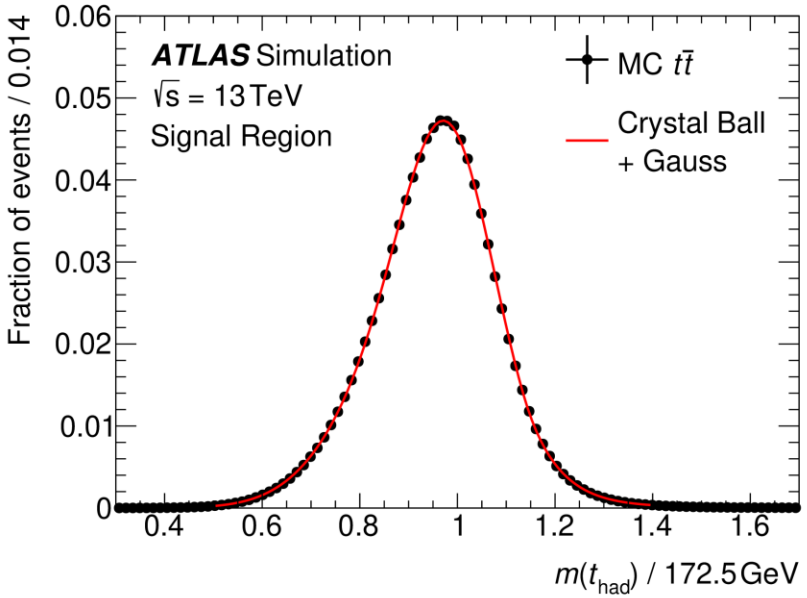


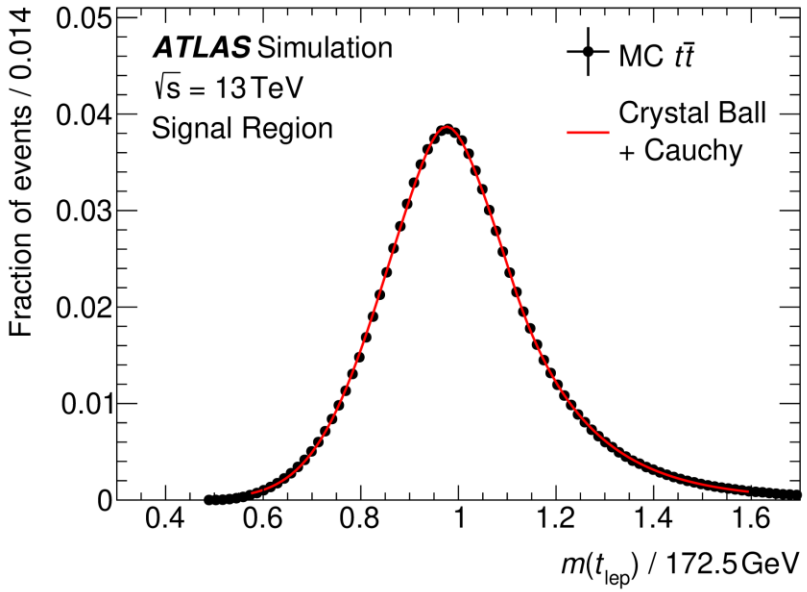
2302.11739

$H^+ \rightarrow cs$

- Mismodelling of dominant SM tt background is corrected by data driven method
- Reconstruct tt system
  - Solve the jet combinatorics by considering every permutation
  - Choose the permutation maximizing $PDF_{t\text{-lep}} \times PDF_{t\text{-had}}$
- BDT trained to distinguish between background signal



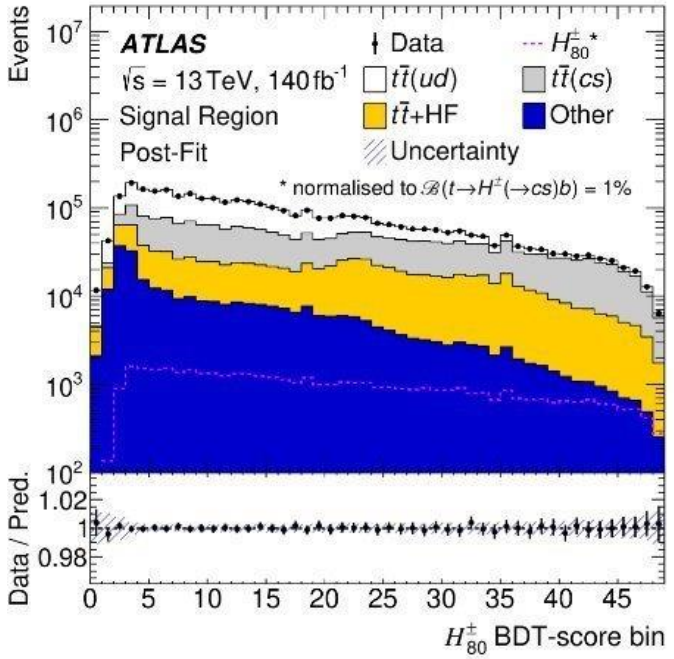


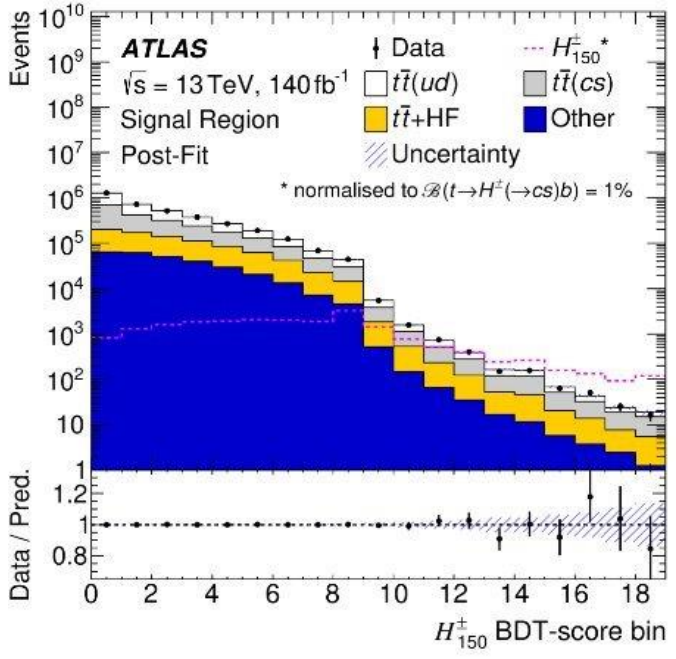


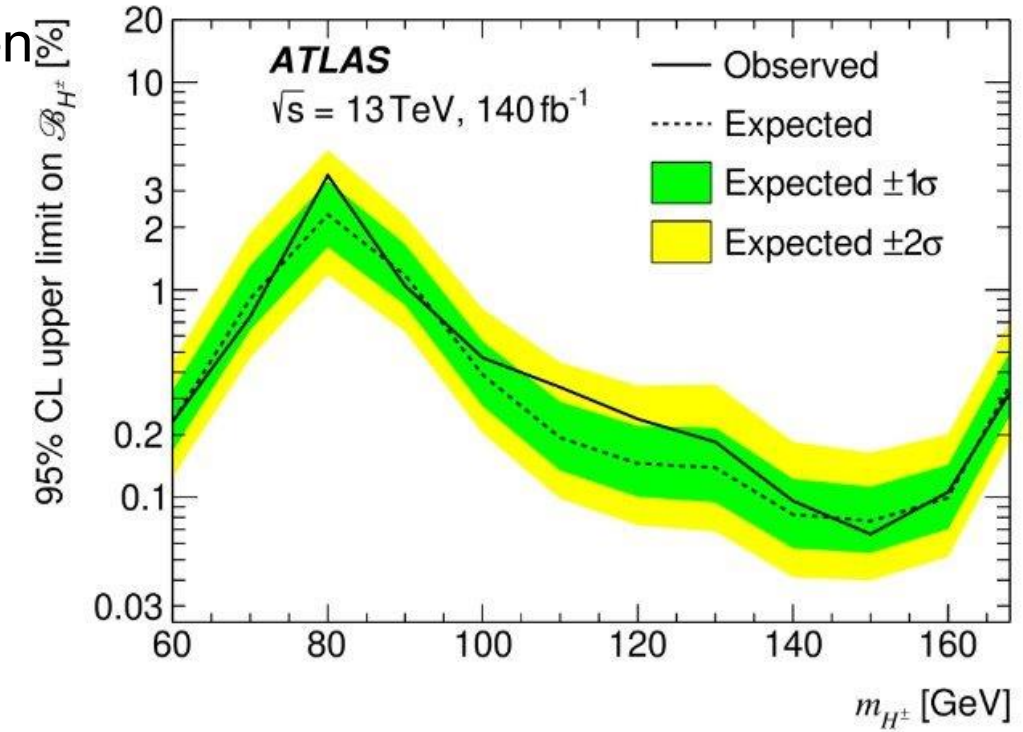
Correction are separately calculated for each jet multiplicity

$H^+ \rightarrow cs$

- Fit BDT-score
- Dominant uncertainties:
  - flavour tagging/MC stat. /tt modelling
- No significant deviation above the SM expectation
  - Set limits on BR(tt→ H^+b)
  - Largest deviation at 110 GeV(1.5 σ)
- Currently strongest limits between 120-160 GeV
  - First direct limits for 60 70 & 168 GeV







h→aa→γγγγ

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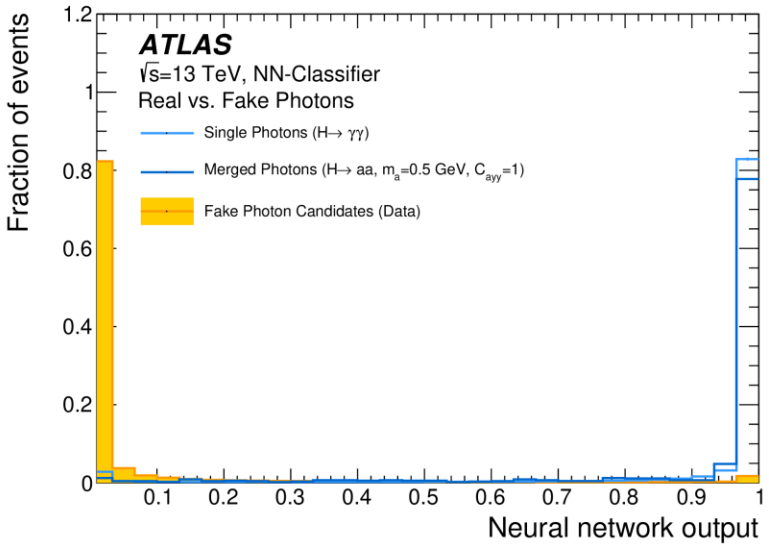
- Search Higgs boson (125 GeV) decaying into 2 **axion like particles a** (ALP) decaying into 4 photons
  - 100MeV<m(a)<62 GeV
- Targets both **prompt**(short lived) and **non-prompt**(long lived) a→ γγ decays
  - Coupling $c_{a\gamma\gamma} < 10^{-5}$ decay outside ATLAS and are thus not probable
- Targets both **resolved** and **merged** a→ γγ decays
- For m(a) < 3.5 GeV strongly collimated di-photons pairs
  - Reconstrued as only one calo cluster/ photon
- Main Background: di-photon and non-resonant multijet

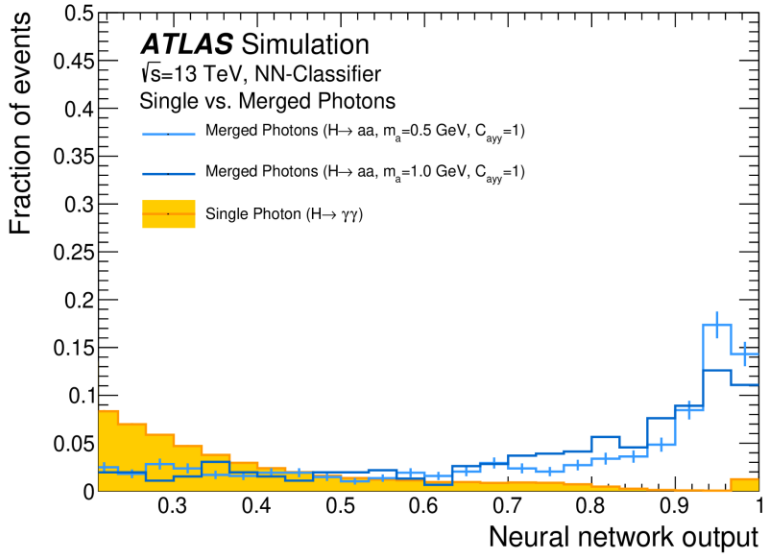
h→aa→γγγγ

Standard photon identification is **inefficient** for **merged photons**
➔Custom merged photon ID based on Neural Networks was developed

1st NN classifies Fake and Real photons

2nd NN classifies single and merged photons

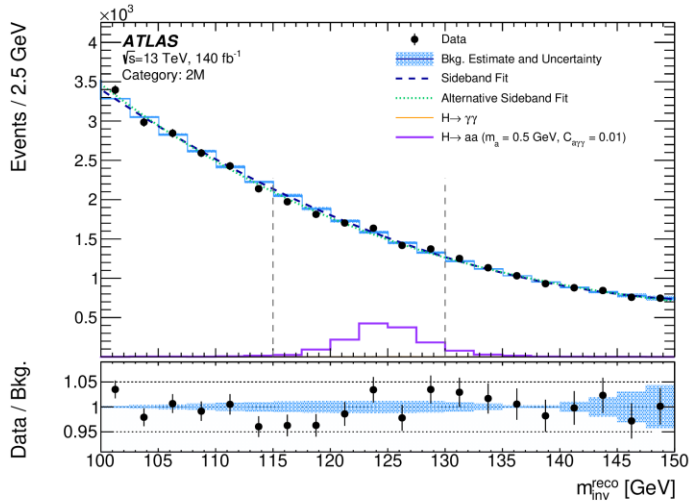


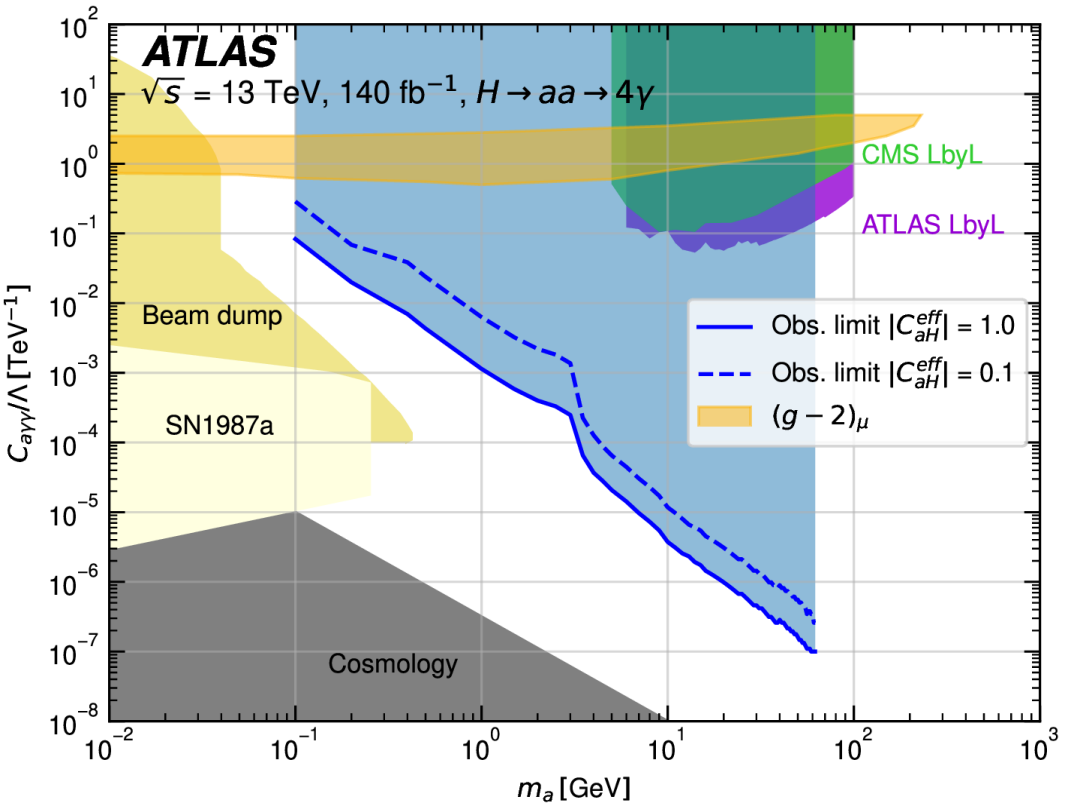


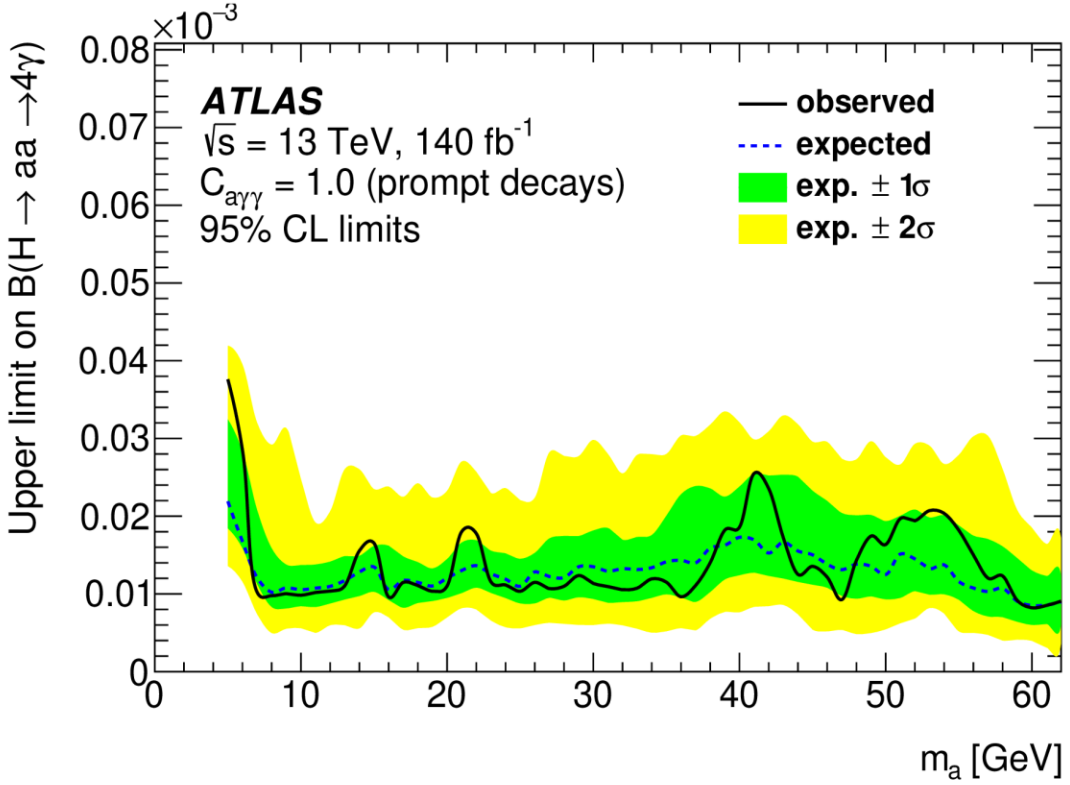
Event Categories:

1. Four reconstrued photons(4S)
2. Three reconstructed photons(3S)
3. Two merged photons(2M)
4. One merged & One single photon(1M1S)
5. Two single photons(2S)

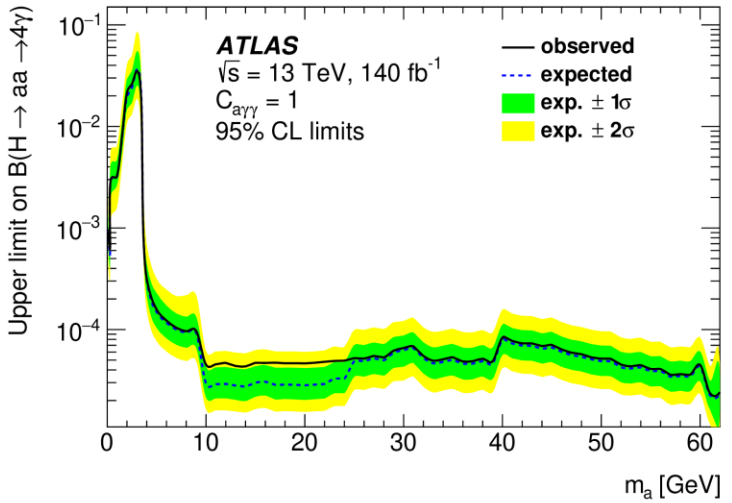
M^{reco}_{inc}=mass of all γ
- SR around Higgs mass
- Sidebands are used for background estimation

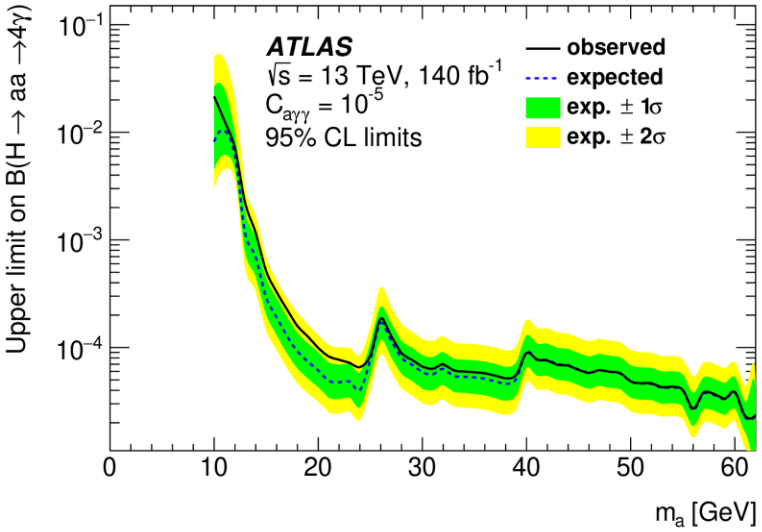






Excludes large part of the parameter space for an ALPs explanation for g-2

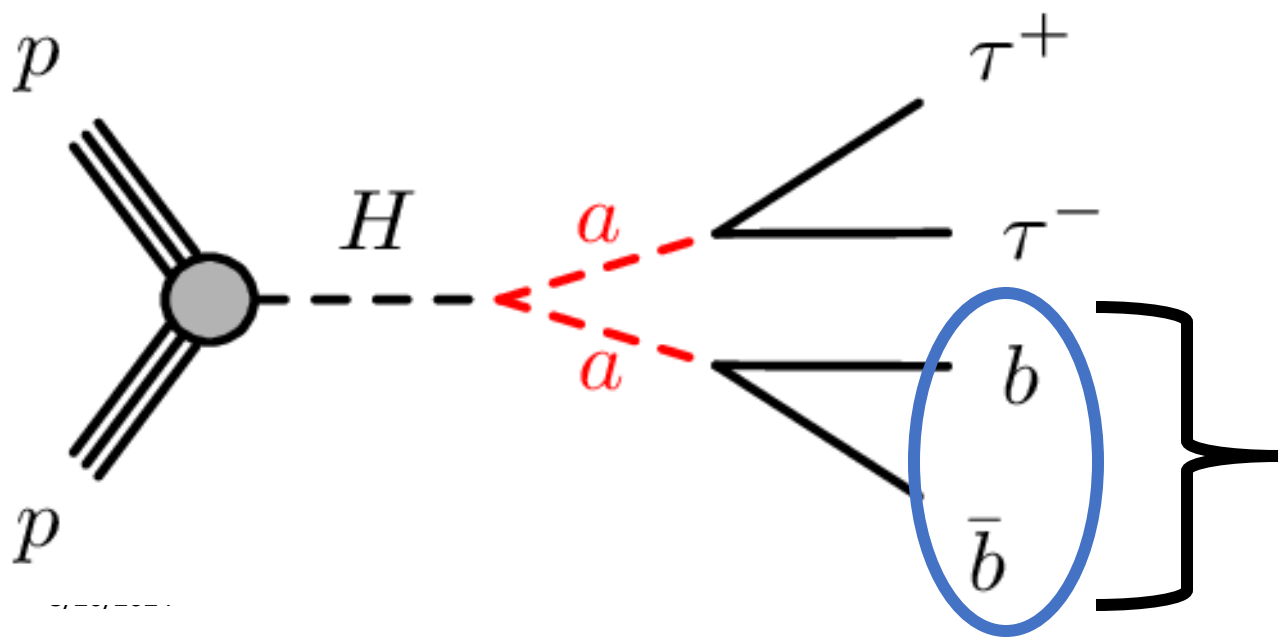




arXiv:2407.01335

h→aa→ bb$\tau\tau$

- Higgs boson (125 GeV) decaying into 2 new light pseudoscalar **a**
- Events selected by single e/μ triggers
  - At least on leptonically decaying τ_{lep}
- Categorize by the decay mode of the τ
- Main background: Z+jet, tt, τ_{had} fakes



Resolved for high m_a

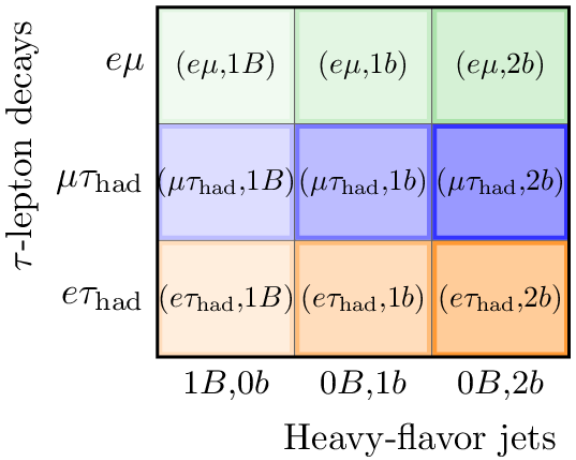
Merged for low m_a

DeXTer Tagger

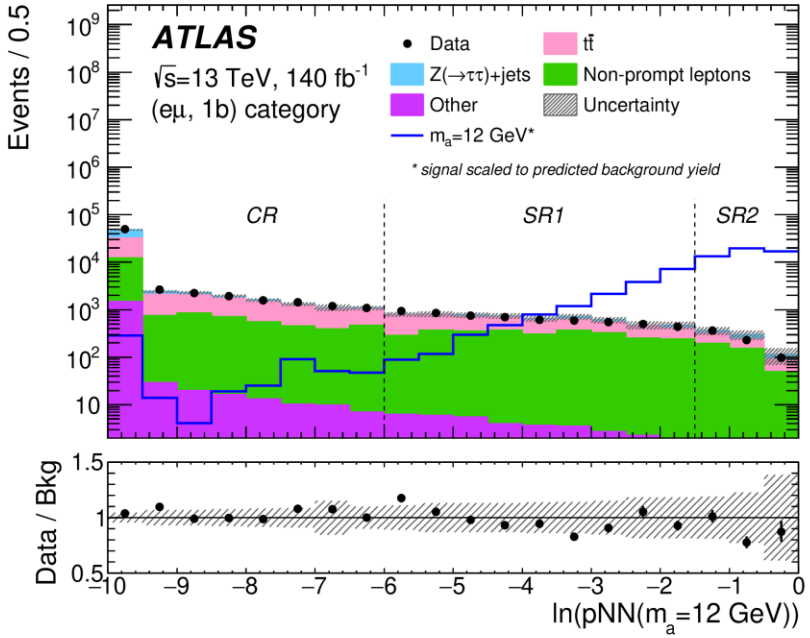
- Identifies low p_T merged di-b jets(B), b-jets, light jets
- Uses reclustered R=0.8 track jets
- Utilizes secondary vertices and tracks information

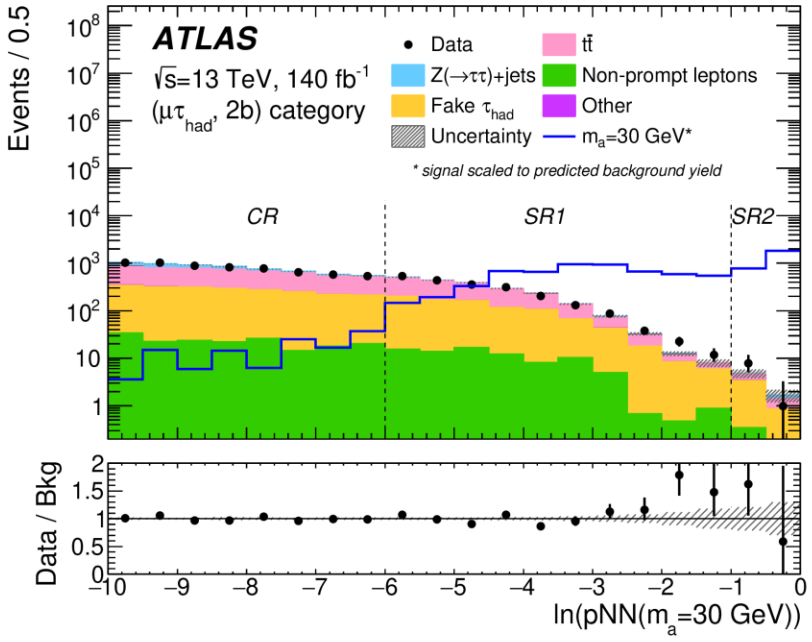
H→aa→ bb$\tau\tau$

- Categories based on τ decay & the number of b/B-jets
- **Missing Mass Calculator** (MMC) is used to reconstruct the ν momenta from a→ $\tau\tau$ decay
  - Uses Markov chain to reconstruct most likely ν momentum
- Mass **parameterized Neural Network** is trained to distinguish between background and signal

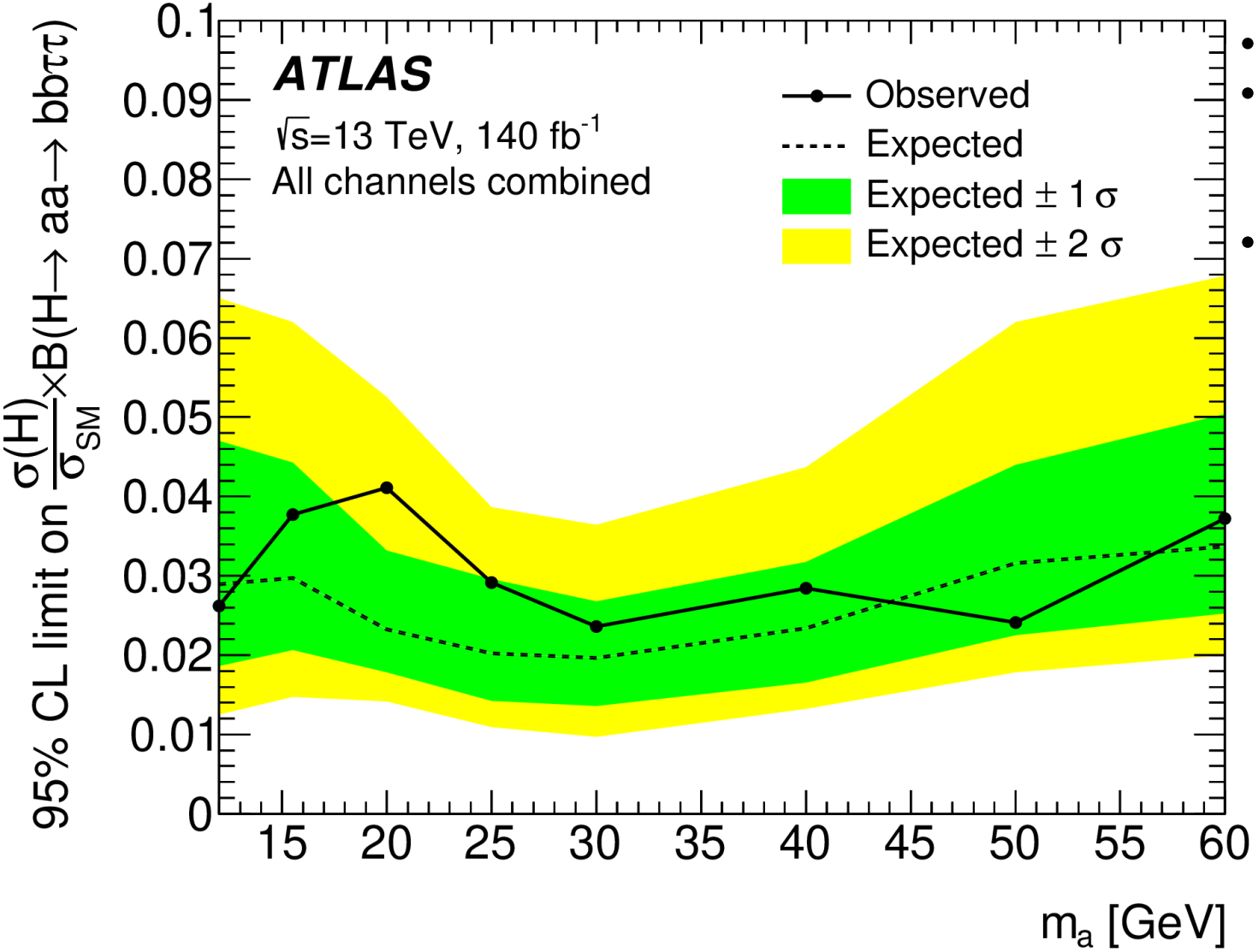


B-jet: merged b-jet pair

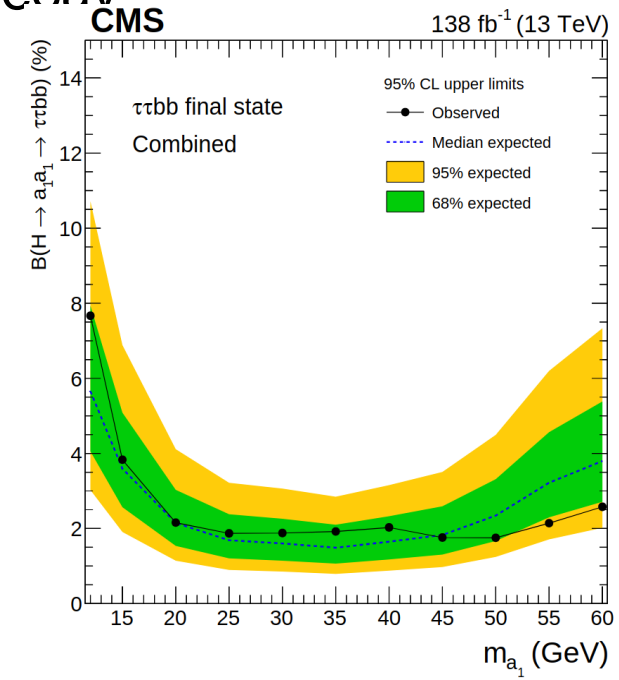




H→aa→ bb$\tau\tau$



- First study of H→aa→bb$\tau\tau$ in ATLAS
- No significant deviation from the SM expectation
  - Set Limits on BR(h→aa→bb$\tau\tau$)
- Significant improvements in the low mass regime w.r.t previous searches due to novel identification of merged a→ bb decay



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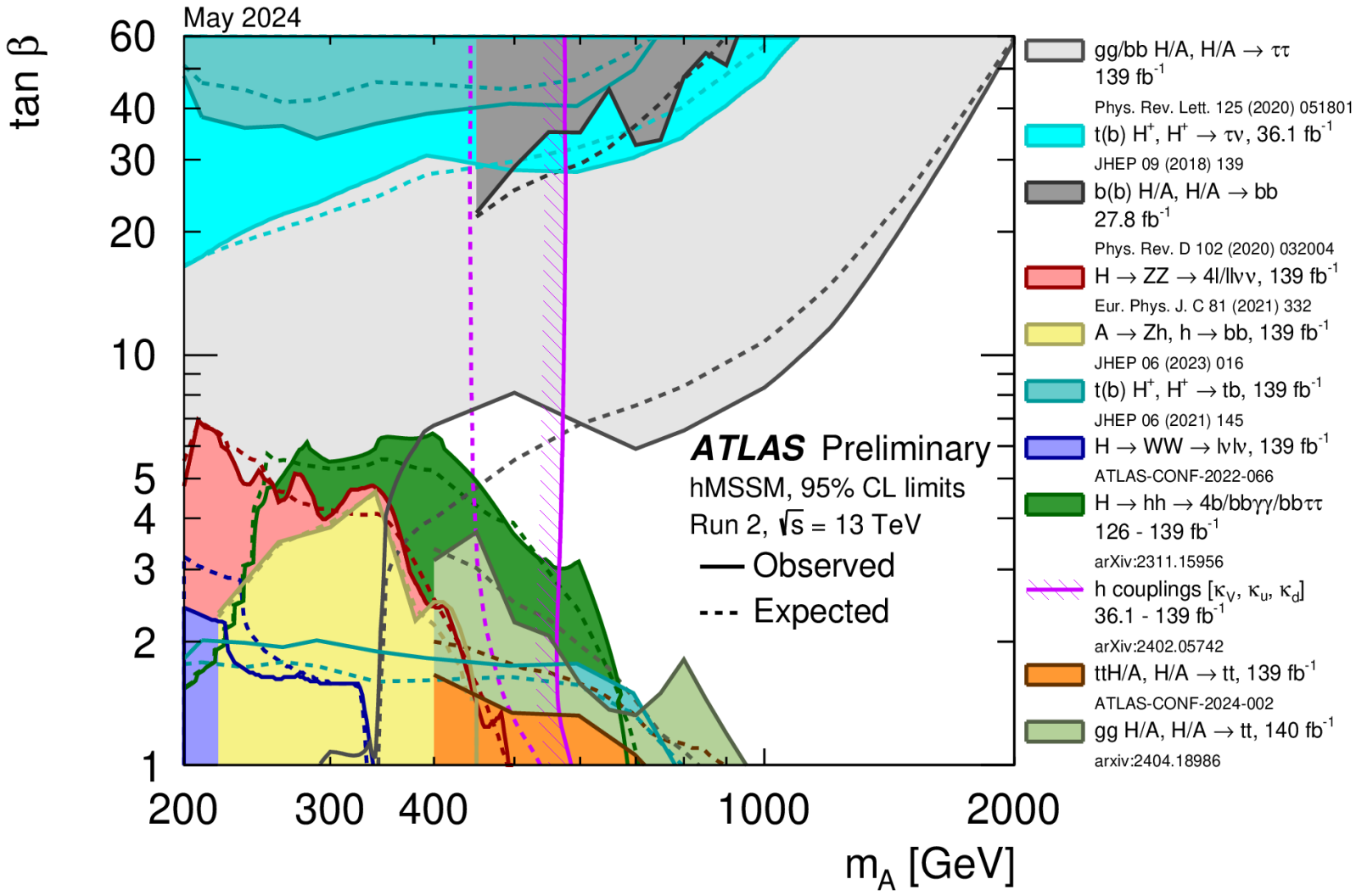
Summary Plot



- Interpretation of search results in the hMSSM framework
- Large part of the parameter space excluded by extensive search program

Conclusion

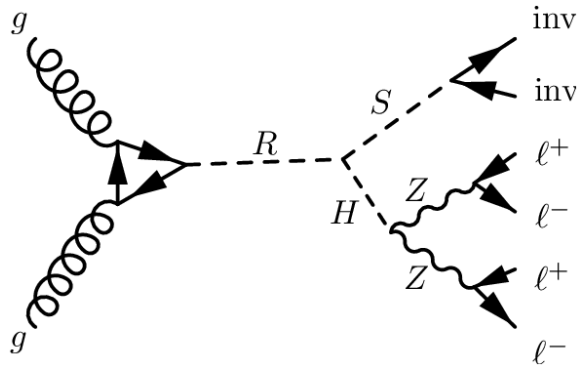
- ATLAS has an extensive search program in the Higgs sector covering many models and final states
- So far **no** strong sign for an extended Higgs sector
- But there **is** Physics beyond the standard model and the Higgs sector is a promising place to search for it and ..
  - There will be a lot more data to explore
  - New analysis techniques to be utilized
  - New models/signatures to be tested

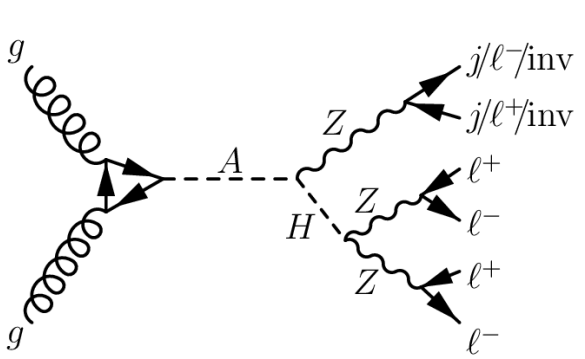
Backup

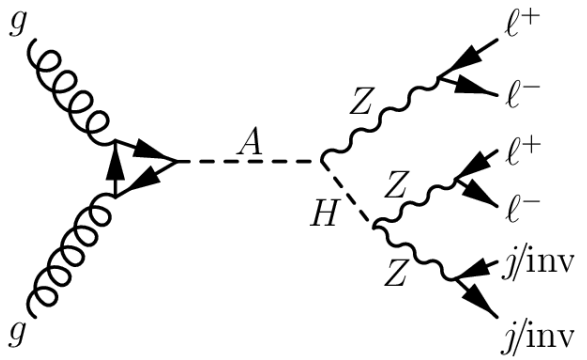
arXiv:2401.04742

4 lepton + E_T^{miss}/jets

- Search for **new Resonance R/A** decaying into a **heavy Higgs boson H** and a **new Scalar S** or Z boson
  - S → invisible (possible DM candidates)
  - H→ ZZ
- S mass fixed at 160 GeV
- In the context of 2HDM+Scalar models (R→SH)
- Or benchmark model for baryogenesis (A→ZH)
- 4 lepton + additional activity final state
  - Missing transverse momentum
  - Jets
  - Additional leptons



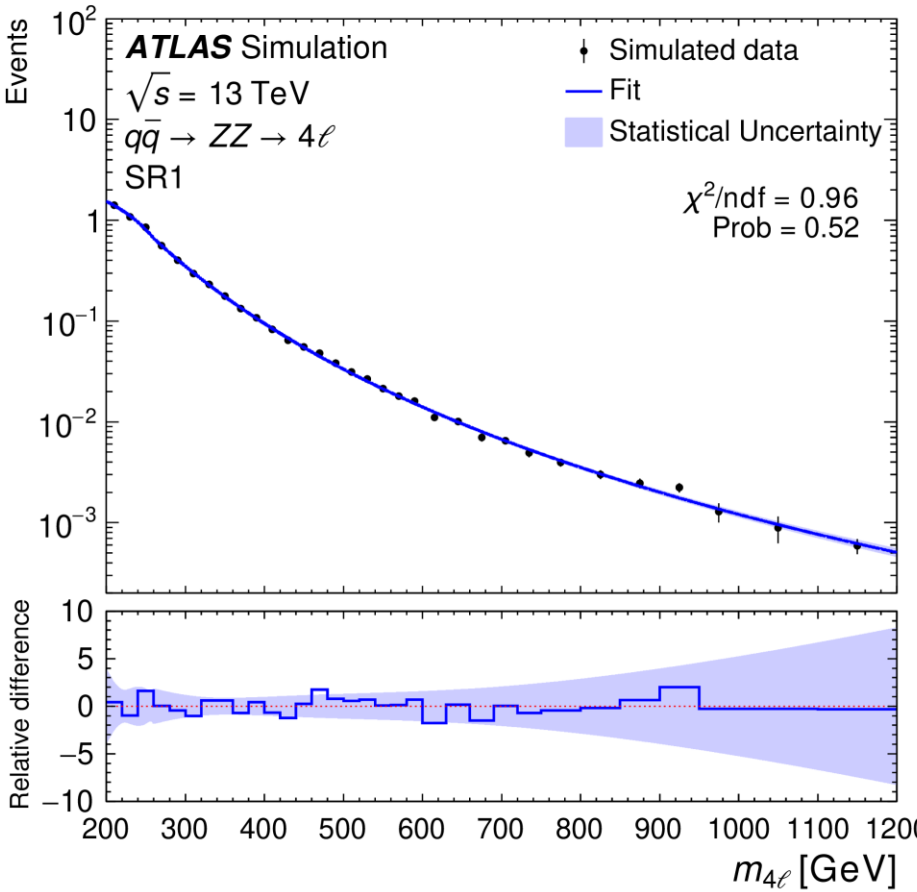




4 lepton + E_T^{miss}/jets

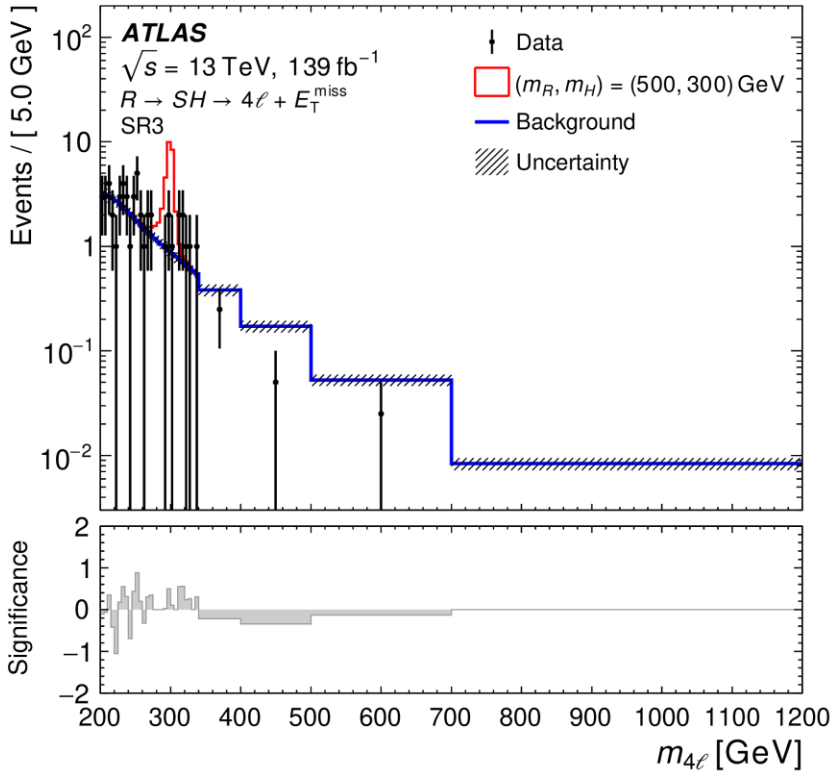
- Background estimation: Shape of the m_{4l} distribution is obtained from simulation using an parametrized empirical function fitted to data
  - Main background: ZZ
  - Decreases statical uncertainties
- Require m_{4l}> 200 GeV
  - 50 GeV<m_Z<106/115 GeV
- Further cuts optimized to increase significance

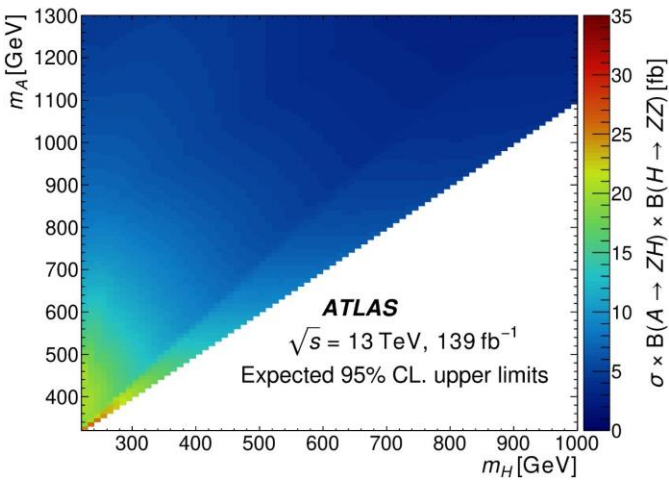
Signal region	$R \to SH \to 4\ell + E_T^{miss}$ and $A \to ZH \to 4\ell + X$			
SR1	$n_{b\text{-jets}} = 0$	$n_{jets} = 0$	$p_T^{4\ell} > 20$ GeV	E_T^{miss} significance >2.0
SR2		$n_{jets} \geq 1$	$p_T^{4\ell} > 10$ GeV	E_T^{miss} significance > 3.5
SR3			$p_T^{4\ell} < 10$ GeV	2.5 < E_T^{miss} significance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

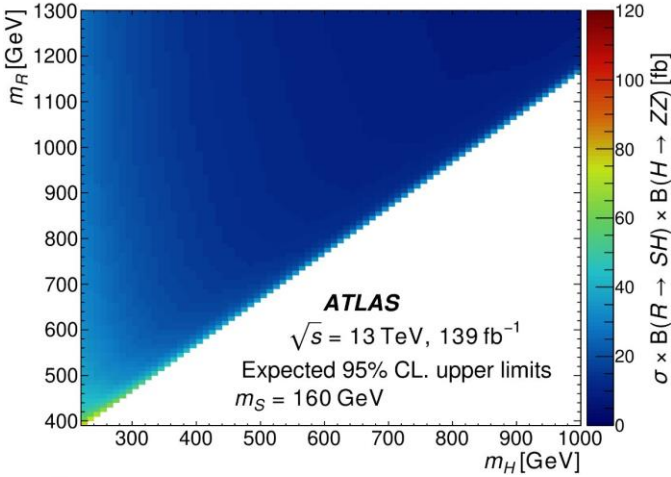


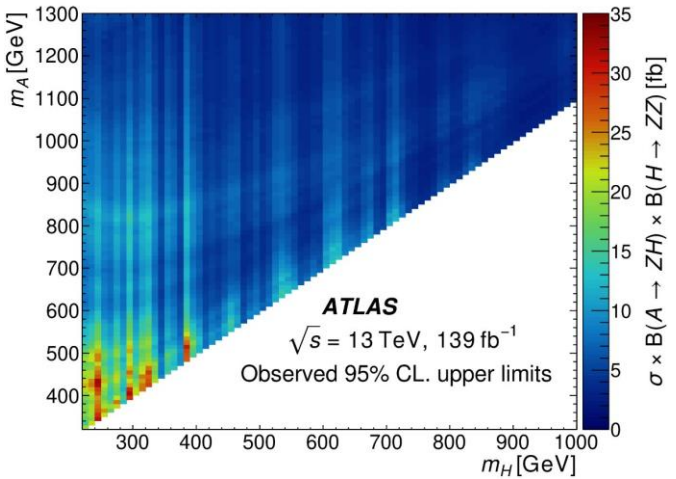
4 lepton + E_T^{miss}/jets

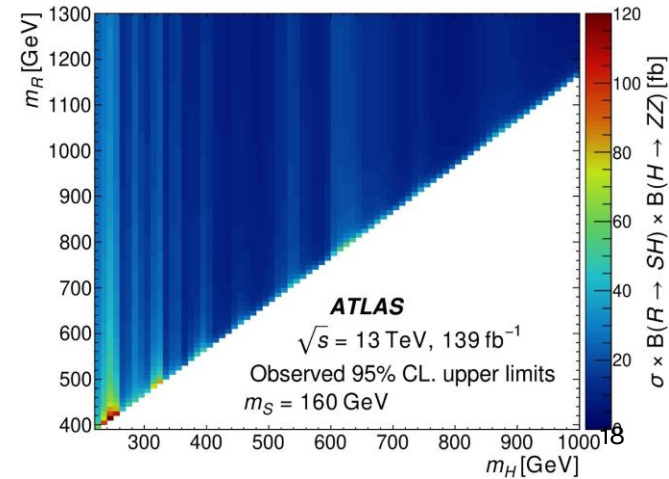
- Fit the m_{4l} distribution
- No significant excess above the SM expectation
  - Largest deviation 2.5σ for the A→ZH→4l+X signal at (mA,mH)=(510,380)











$H^+ \rightarrow cs$

Variable type	Variable name	Definition
Top-quark kinematic variables		
t_{had}	j_1 p_{T}	p_{T} of j_1-labelled jet
	j_2 p_{T}	p_{T} of j_2-labelled jet
	b_{had} p_{T}	p_{T} of b_{had}-jet
	$b_{\text{had}}^{t_{\text{had}}-\text{rest}}$ p	Momentum of b_{had}-jet in t_{had} rest frame
	dijet mass	Invariant mass of j_1+j_2 jets
	(j_1+b_{had}) mass	Invariant mass of j_1+b_{had} jets
	(j_2+b_{had}) mass	Invariant mass of j_2+b_{had} jets
	$\cos\theta$	Boson spin sensitive variable
t_{lep}	b_{lep} p_{T}	p_{T} of b_{lep}-jet
	Lepton p_{T}	p_{T} of reconstructed lepton
	W mass	Invariant mass of reconstructed W boson
	t_{lep} mass	Invariant mass of reconstructed t_{lep}
	t_{lep} p_{T}	p_{T} of reconstructed t_{lep}
$t\bar{t}$-system	$\Delta R(b_{\text{lep}},b_{\text{had}})$	ΔR between the b_{lep}-jet and b_{had}-jet
	$t\bar{t}$ mass	Invariant mass of t_{had}+t_{lep}
Event variables		
Event level	N_{jets}	Number of jets in the event
	S_{T}	Scalar p_{T} sum of all calibrated objects
	$\overline{P}_{t\bar{t}}$	Normalised probability of correct jet labelling
Flavour-tagging variables		
Flavour-tagging score	j_1 PCFT	PCFT score of j_1
	j_2 PCFT	PCFT score of j_2
	b_{had} PCFT	PCFT score of b_{had}-jet
	b_{lep} PCFT	PCFT score of b_{lep}-jet
Number of tags	$N_{c\text{-tagLo}}$	Number of jets passing loose c-tag WP (b-veto)
	$N_{c\text{-tagTi}}$	Number of jets passing tight c-tag WP (b-veto)
	$N_{b\text{-tag70}}$	Number of jets passing 70 % b-tag WP
	$N_{b\text{-tag60}}$	Number of jets passing 60 % b-tag WP