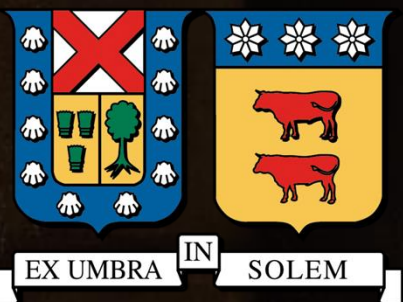




Searches for new scalar particles and non-standard Higgs(125) decays with the ATLAS detector

Edson Carquin

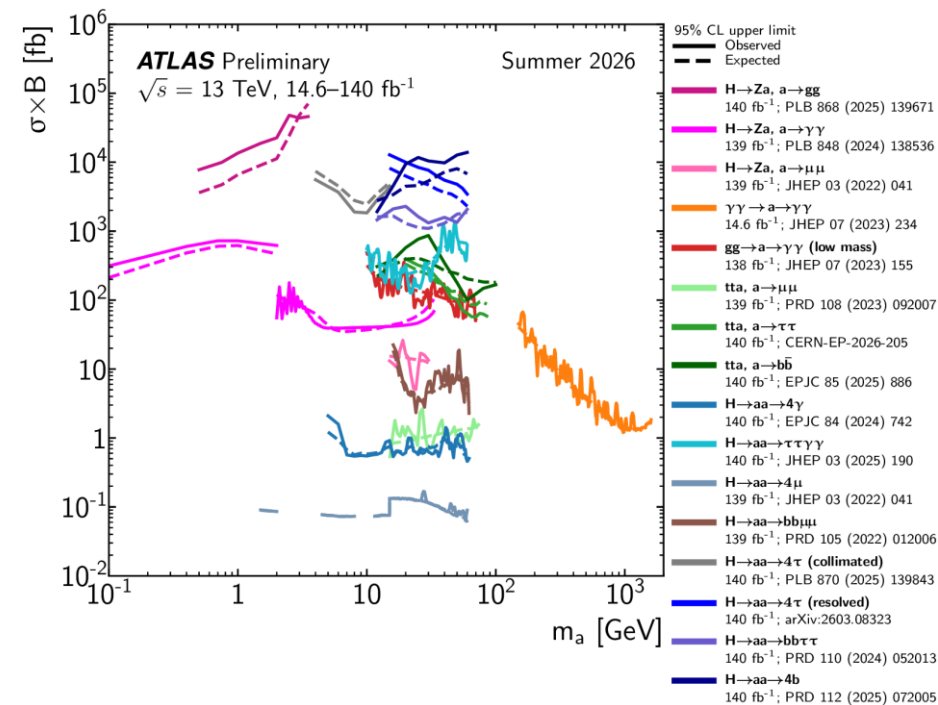
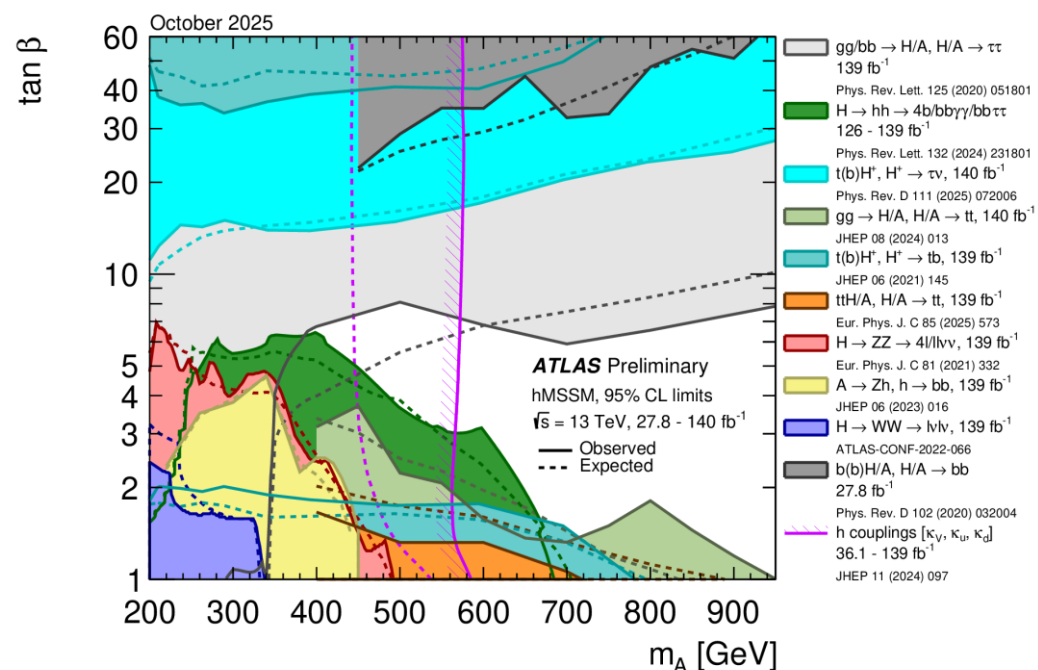
Federico Santa Maria Technical University, Chile
and CERN

On behalf of the ATLAS Collaboration

Introduction

...The search for new Physics continues at the LHC...looking for new scalar particles and non-standard Higgs decays is a promising avenue for a discovery...

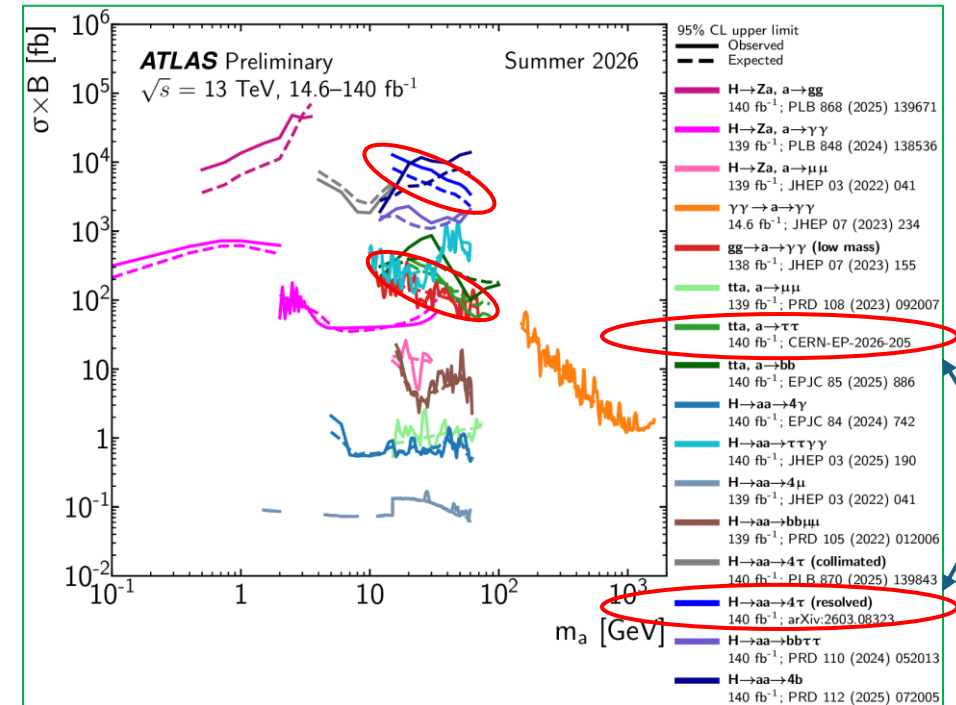
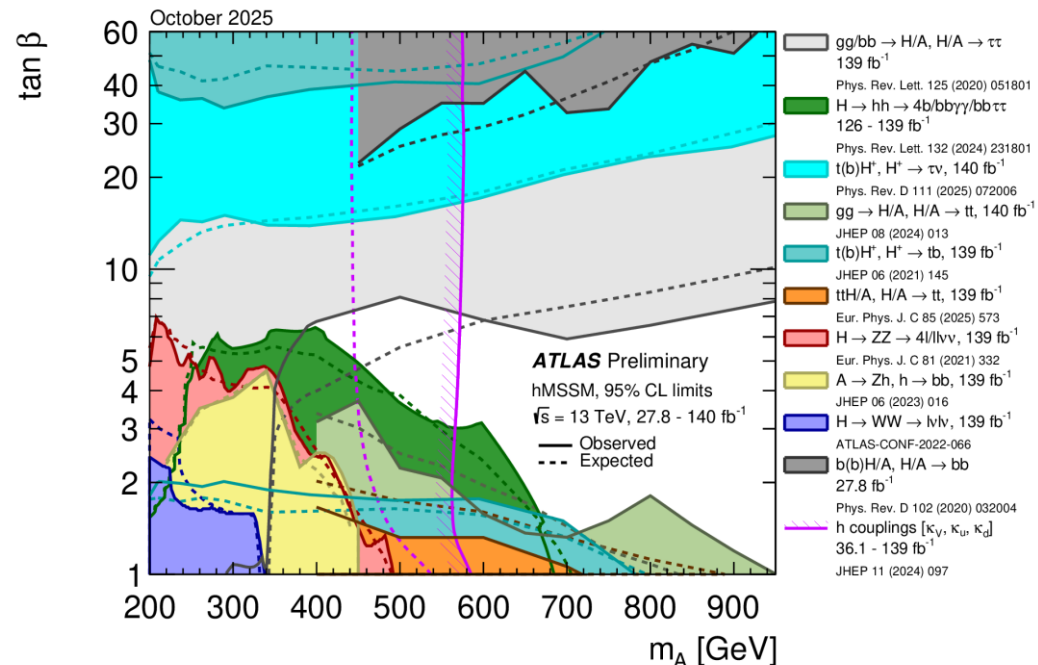
- 1.- Many BSM models contain extra scalars or an extended Higgs sector
- 2.- Because the very narrow SM Higgs decay width would allow an even feeble coupled particle to open a sizeable Branching Ratio decay



Introduction

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- 1.- Many BSM models contain extra scalars or an extended Higgs sector
- 2.- Because the very narrow SM Higgs decay width would allow an even feeble coupled particle to open a sizeable Branching Ratio decay



In this talk

Overview

$$t\bar{t}a(a \rightarrow \tau\tau)$$

Fully hadronic boosted ditau mode

Full RUN 2

$$H \rightarrow \gamma\gamma_d(m_{\gamma_d} = 0)$$

Semi-visible $H(125)$ decay (ggF)

RUN 3

$$H \rightarrow aa \rightarrow \tau^+\tau^-\tau^+\tau^-$$

Semi-leptonic final states

Full RUN 2

$$X \rightarrow \mu\mu$$

Low-mass resonance decay to $\mu^+\mu^-$

Full RUN 2

$$s\chi\chi \rightarrow HH\chi\chi$$

Dark Higgs decay into HH ($\geq 3b$)

Full RUN 2

$$t\bar{t}a(a \rightarrow \tau\tau)$$

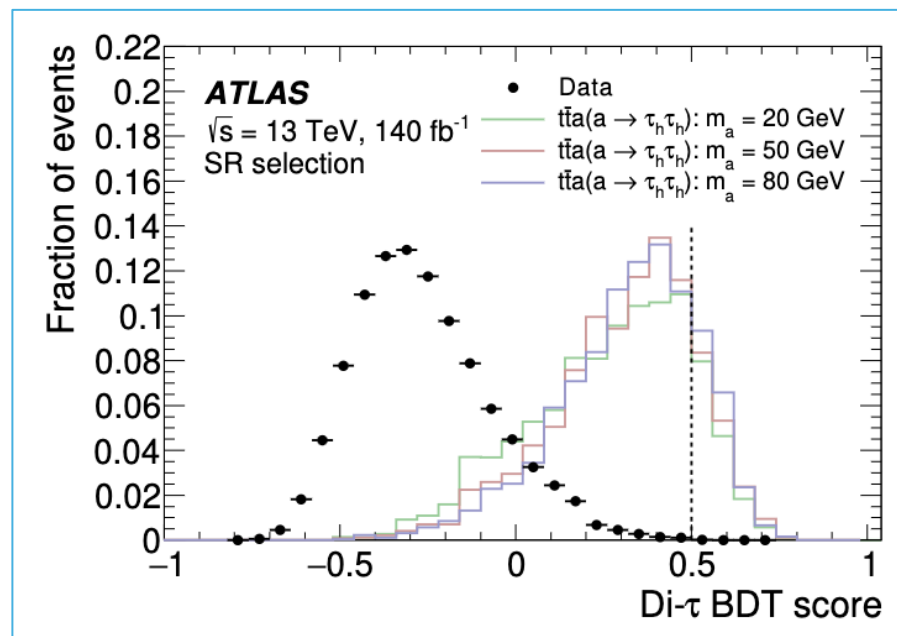
Fully hadronic boosted ditau mode

Full RUN 2

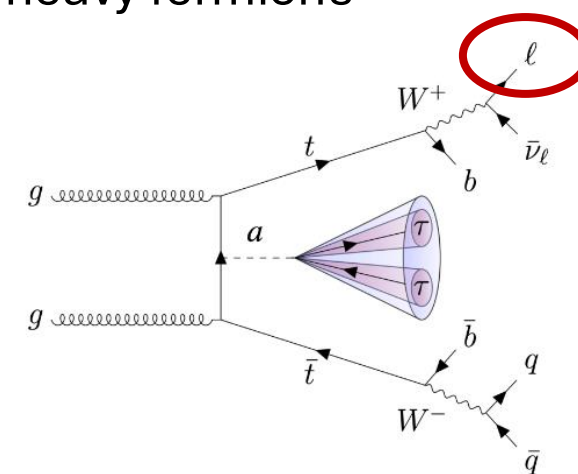
<https://arxiv.org/abs/2607.28484>

The boosted di-tau pair is reconstructed using dedicated jet substructure and boosted object tagging techniques

BDT trained ID method used to distinguish signal like, and fake boosted di-tau objects



Sensitive to scenarios in which the pseudo-scalar couples preferentially to heavy fermions



Boosted a decay topology

Semi-leptonic $t\bar{t}$ final state

Main background comes from $t\bar{t}$ with at least one jet misidentified as a τ_{had}

$t\bar{t}a(a \rightarrow \tau\tau)$

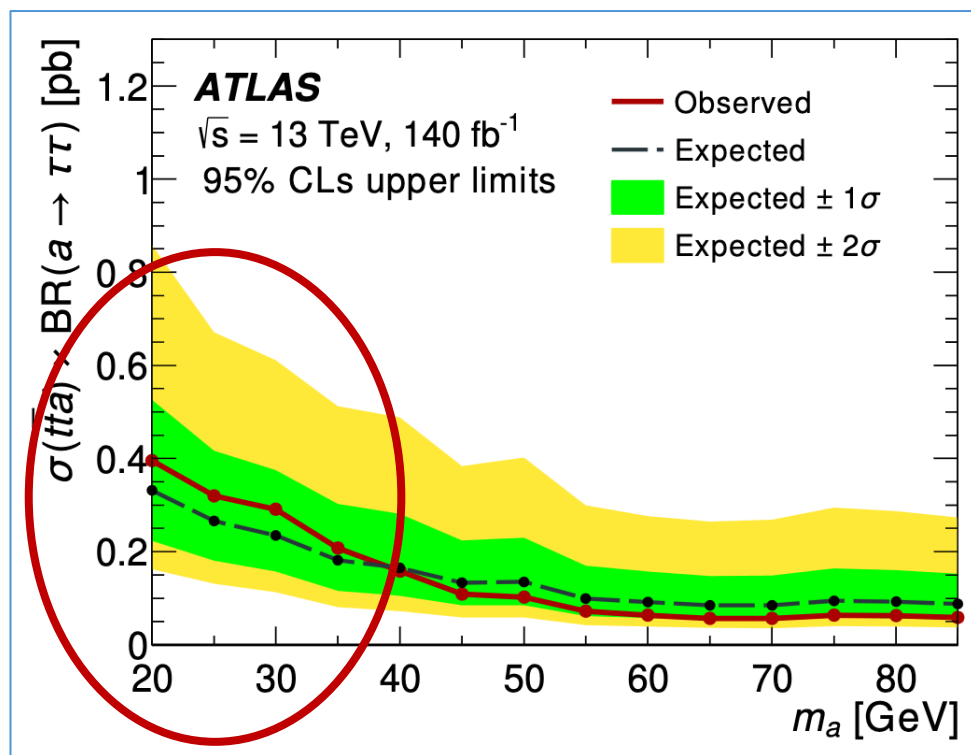
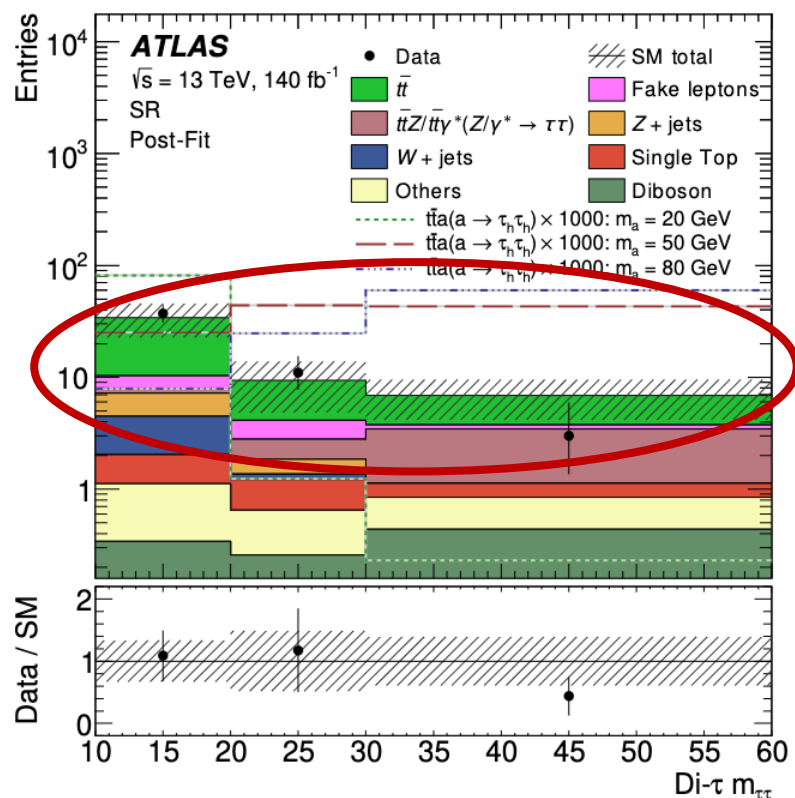
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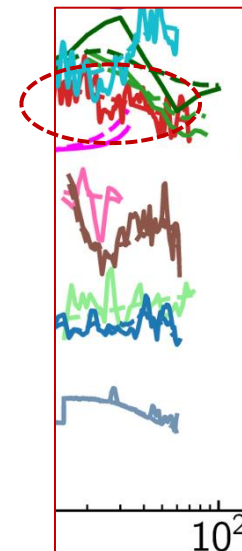
$t\bar{t}$ modelling is estimated from MC simulations and normalized to data in a dedicated CR and extrapolated to the SR

No excess over the SM expectation is found and an upper limit on the model-dependent $XS \times BR$ is derived for a generic 2HDM model



The obtained limit is better than $t\bar{t}a(a \rightarrow b\bar{b})$ but still far from $t\bar{t}a(a \rightarrow \mu\mu)$

(taken from the Summary plot)



The worse limit at low m_a is due to a reduction in the visible $p_{\tau}^{T, \text{subl}}$ affecting the boosted di-tau reconstruction

$$H \rightarrow \gamma\gamma_d (m_{\gamma_d} = 0)$$

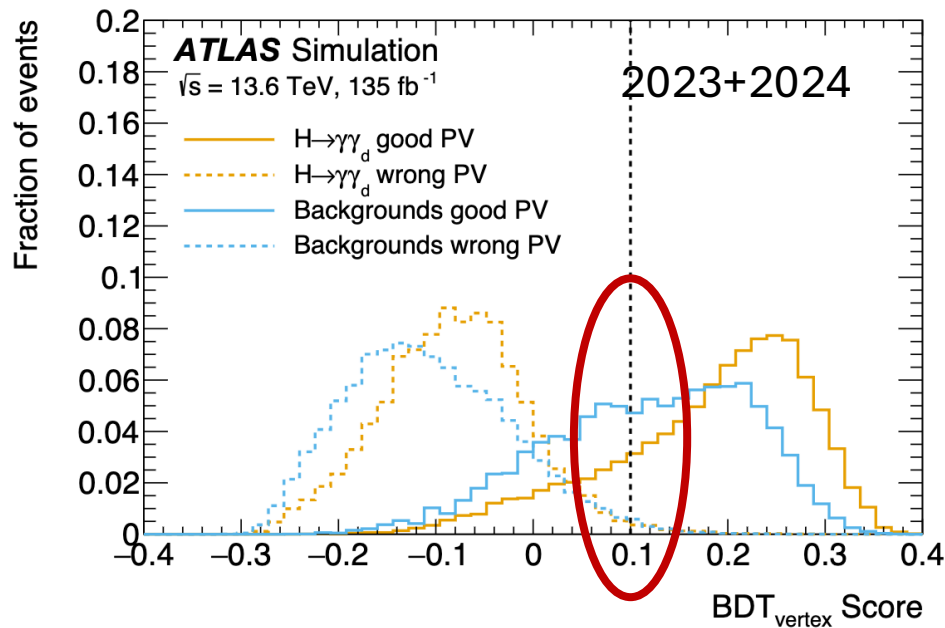
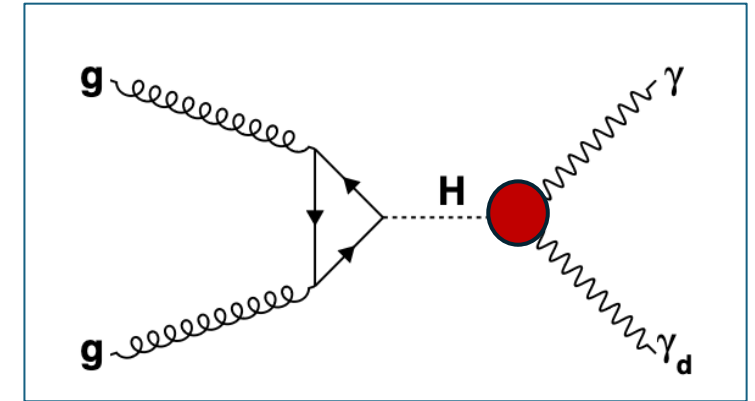
Semi-visible $H(125)$ decay (ggF)



<https://arxiv.org/pdf/2606.14362>

This signature consist in a ggF produced Higgs decaying into a visible photon and an invisible dark photon, i.e. significant p_T^{miss} is expected

ggF mode targeted for the first time given the low trigger threshold required on the photon p_T and p_T^{miss} which required the development of a dedicated topological trigger to be caught



Challenging Primary Vertex (PV) reconstruction could lead to significant fake p_T^{miss}

The “Hidden Valley” scenario was used for modeling the $H \rightarrow \gamma\gamma_d$ decay

In this scenario the Higgs decay through a loop involving additional (pseudo-)scalar BSM fields which couple to the SM and to the Dark sector

A BDT was trained to correctly identify the PV

$$H \rightarrow \gamma\gamma_d (m_{\gamma_d} = 0)$$

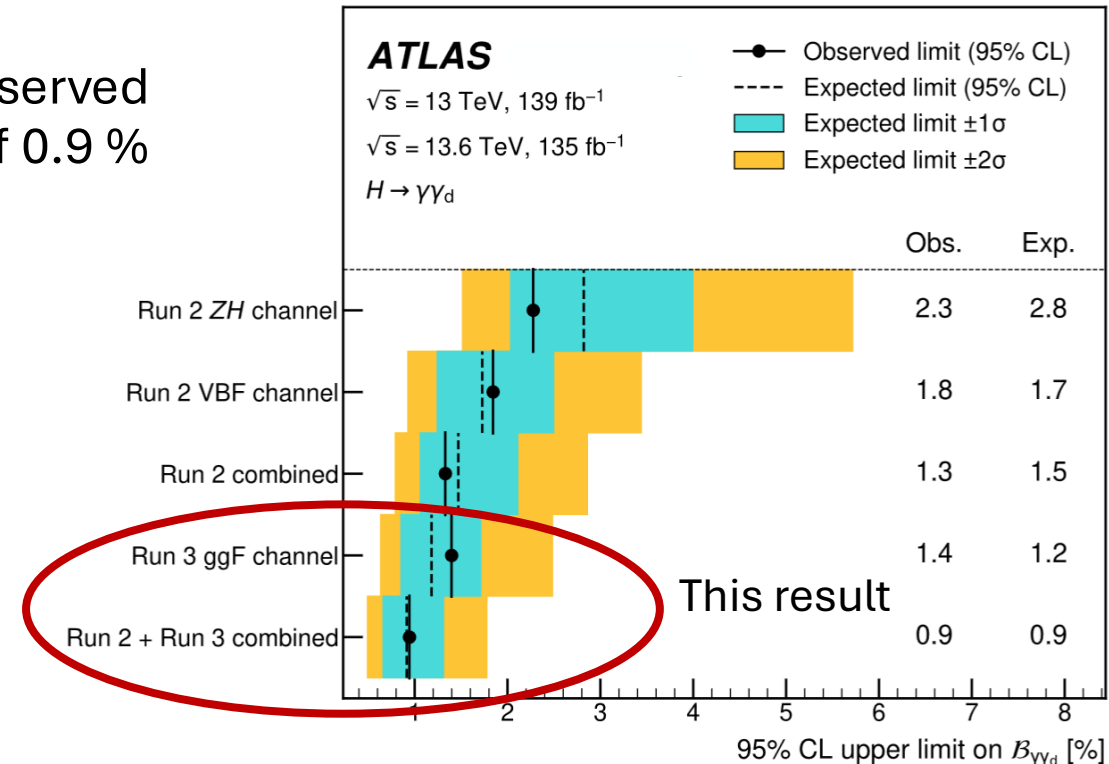
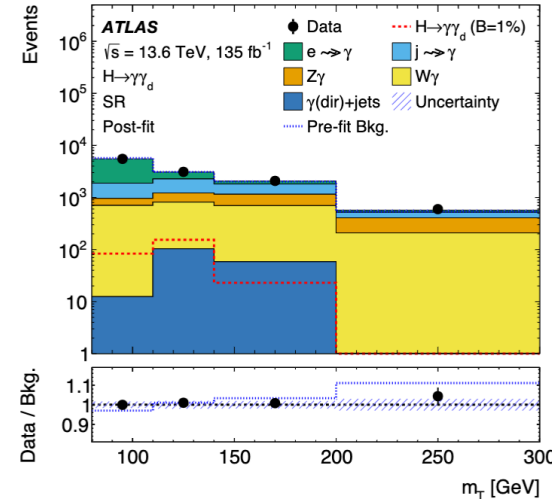
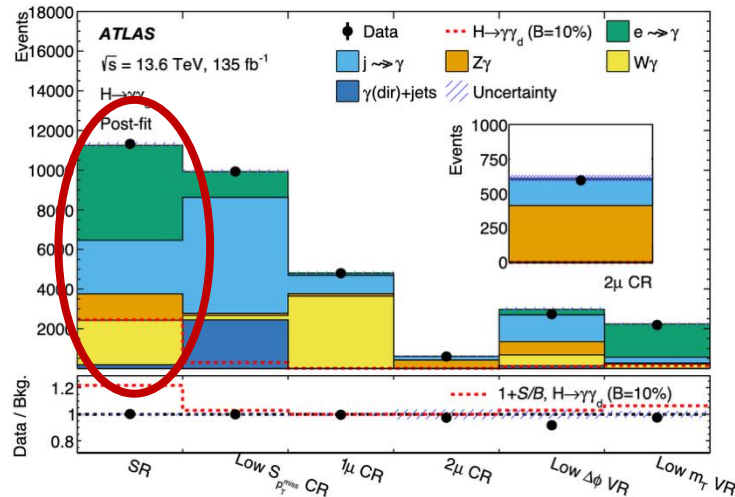
Semi-visible $H(125)$ decay



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- The dominant backgrounds come from fake- γ from e and j
- The normalization of $W\gamma$ and $Z\gamma$ backgrounds are determined in a Background-only fit to the Signal Region ($\mathcal{B}_{\gamma\gamma_d} = 0$) and CRs
- No excess over the SM expectation is found and an observed upper limit is set on $\mathcal{B}_{\gamma\gamma_d}$ of 1.4 % for Run 3 ggF and of 0.9 % after combining with the Run 2 result

The most stringent limits to date for this decay mode



$$H \rightarrow aa \rightarrow \tau^+ \tau^- \tau^+ \tau^-$$

Semi-leptonic final states

Full RUN 2

<https://arxiv.org/abs/2603.08323>

This search is particularly useful to constrain Type-III $2HDM + s$ models at large $\tan\beta$ values, where the new pseudo-scalar decays almost exclusively to τ -leptons

This analysis targets the resolved regime in the mass range $15 \text{ GeV} < m_a < 60 \text{ GeV}$

It complements a previous search by the ATLAS Collaboration focused on the lower mass range $4 \text{ GeV} < m_a < 15 \text{ GeV}$ using boosted ditau reconstruction

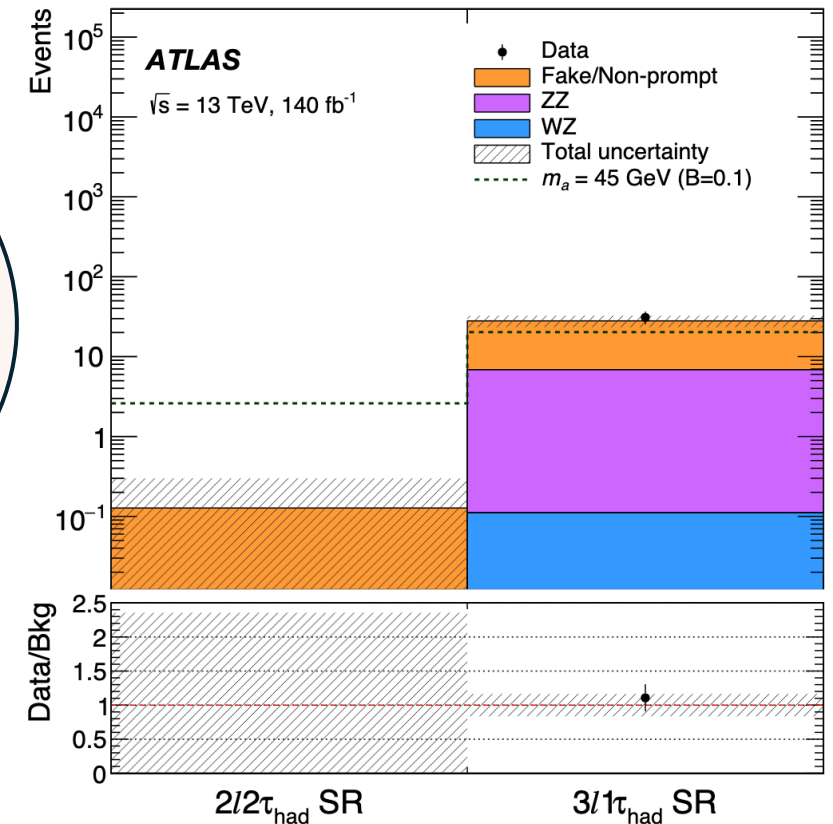
<https://arxiv.org/abs/2503.05463>

2 SRs considered :

- $2l2\tau_{had}$ where the $2l$ and the $2\tau_{had}$ are required to have the same charge with the total charge equal to zero
- $3l1\tau_{had}$ with $3e$ or 3μ , with a total charge of ± 1 and a Z boson veto

Zero data events are observed in the $2l2\tau_h$ SR while 31 events are observed in the $3l1\tau_h$ SR

The main background comes from $j \rightsquigarrow l$ fakes and non-prompt l from B decays



$$H \rightarrow aa \rightarrow \tau^+ \tau^- \tau^+ \tau^-$$

Semi-leptonic final states

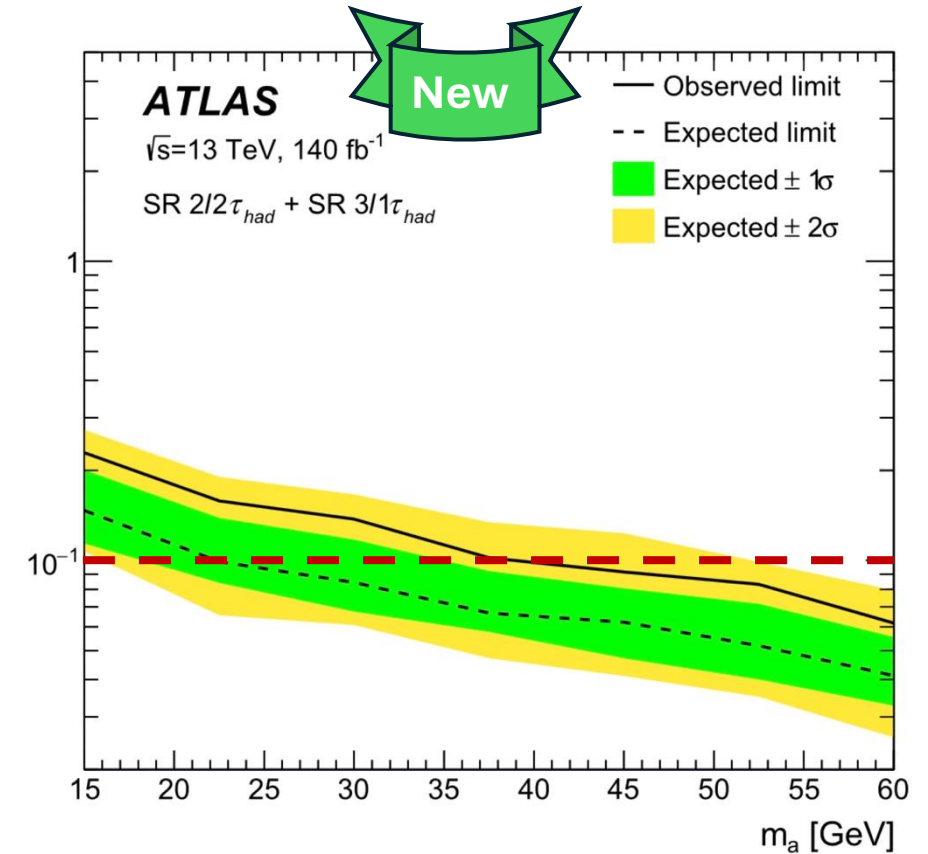
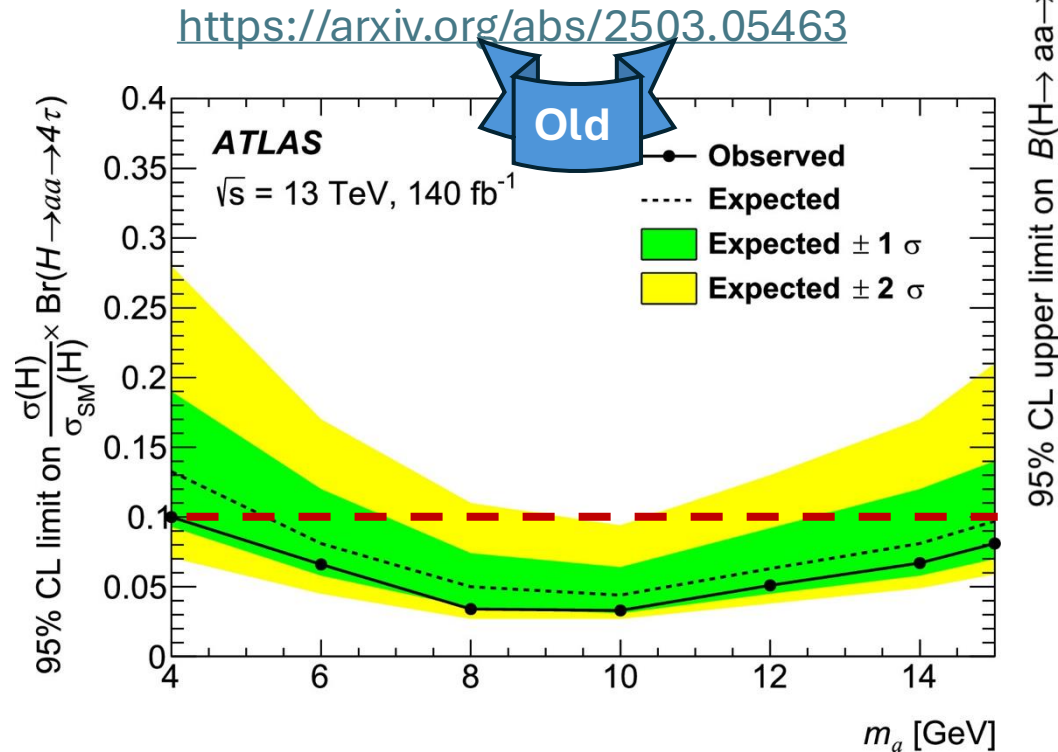
Full RUN 2

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A statistical combination of the two SRs is performed

The observed number of events in both SRs are consistent with the Standard Model background estimate

The obtained limit is largely limited by the statistical uncertainty in the data



$$X \rightarrow \mu\mu$$

Low-mass resonance decay to $\mu^+\mu^-$



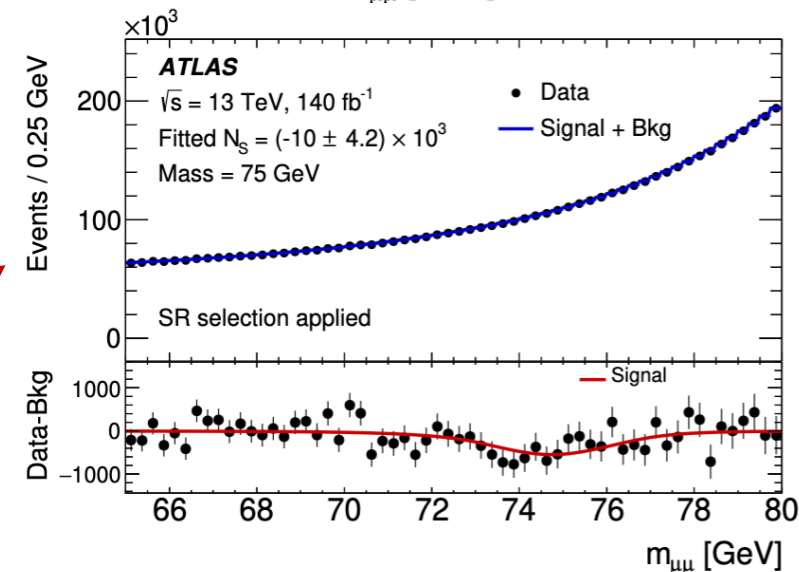
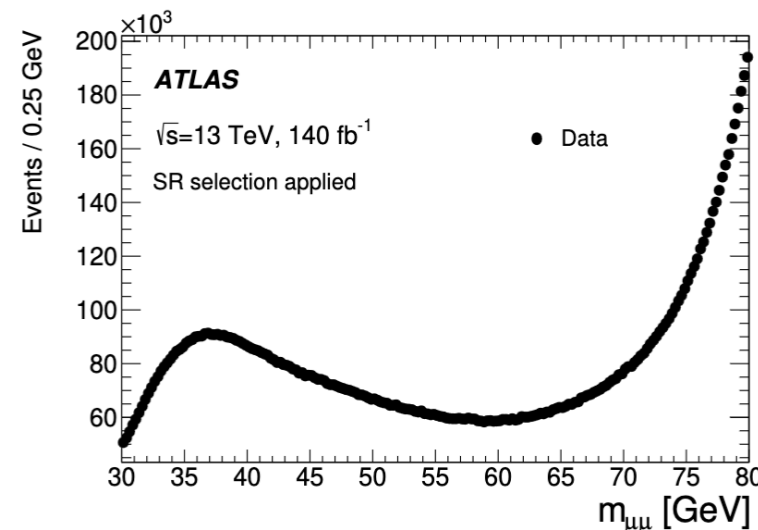
<https://arxiv.org/abs/2601.21361>

Model independent search, targeting the mass range 35 GeV – 75 GeV and adopting a bump-hunting strategy

A Gaussian Process Regression (GPR) machine learning technique to model the background in a $s + b$ fit allowing signal extraction is implemented to overcome trigger threshold effects on the mass shape

Two benchmark models are considered to interpret result in these searches

- A model with an additional $U(1)$ gauge symmetry and a new vector boson Z' mediating the interactions between the SM and the dark sector
- A kinetically mixed dark photon with a mass m_{Z_D} (The hidden Abelian Higgs model HAHM)



Example fit $m_{\mu\mu} = 75 \text{ GeV}$

$$X \rightarrow \mu\mu$$

Low-mass resonance decay to $\mu^+ \mu^-$

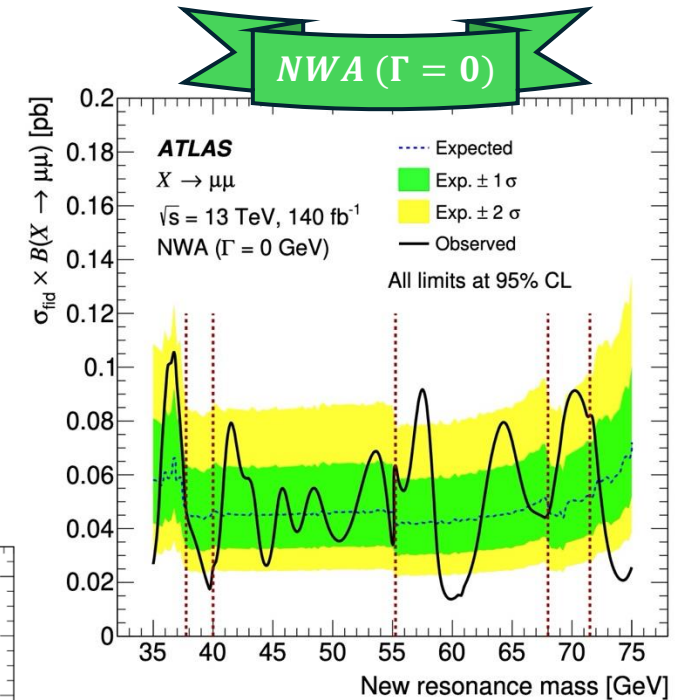
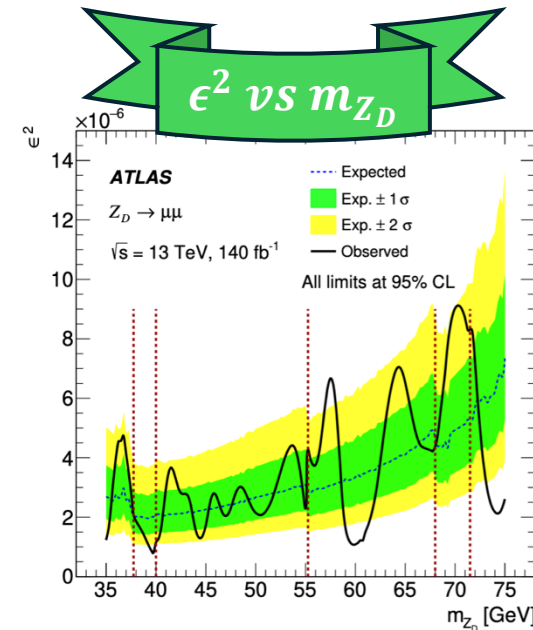
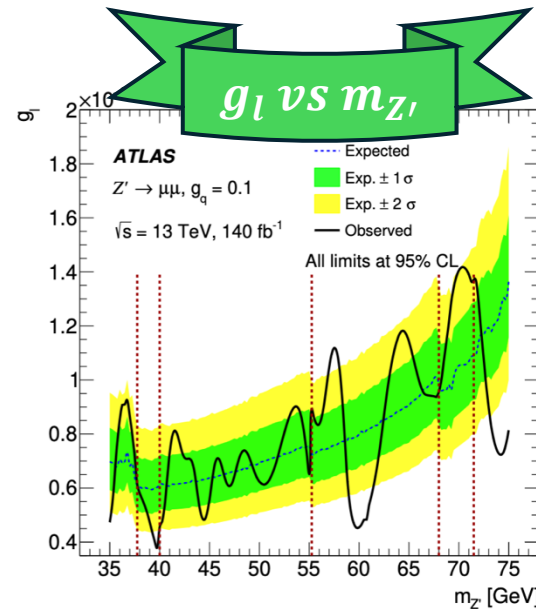
Full RUN 2

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Limits are derived under the narrow-width approximation and are valid for resonances with relative intrinsic widths $\Gamma/m_X < 1\%$ covering a broad class of new physics scenarios with perturbative couplings

Assuming a coupling of 0.1 between the Z' and quarks, an upper limit on the coupling with leptons can be obtained by varying the intrinsic resonance width

Applying a similar approach to the dark photon model governed by the kinetic mixing parameter ϵ , a limit is obtained for ϵ^2 which is proportional to the production cross-section



$$X \rightarrow \mu\mu$$

Low-mass resonance decay to $\mu^+\mu^-$

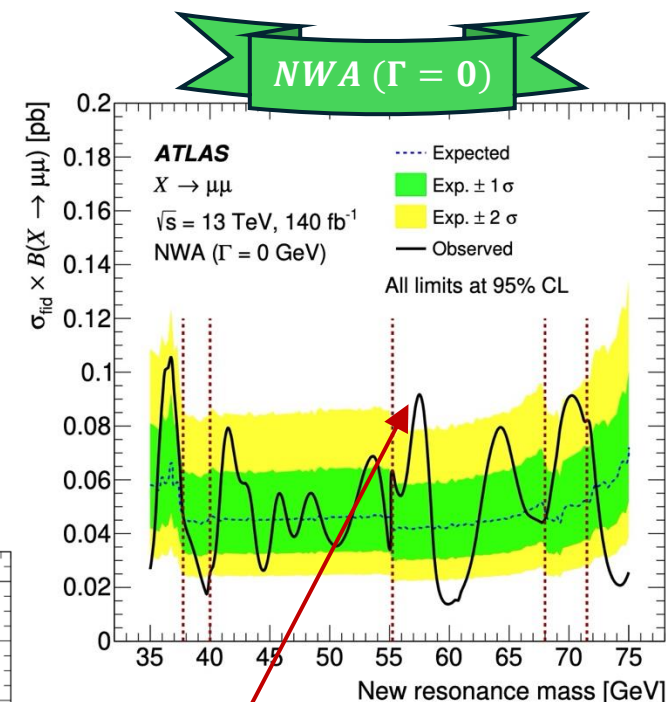
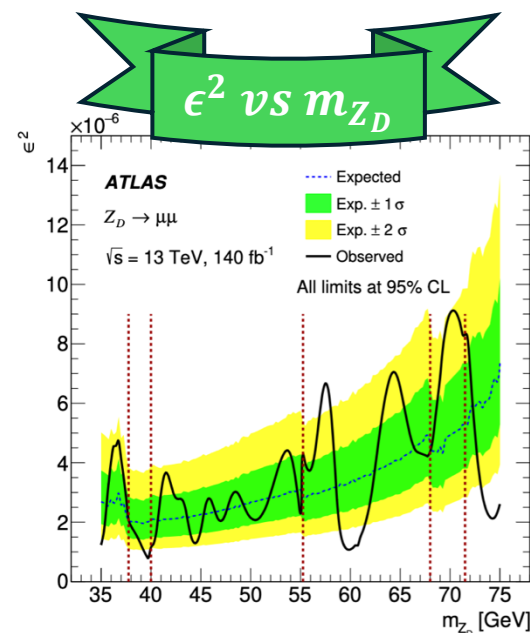
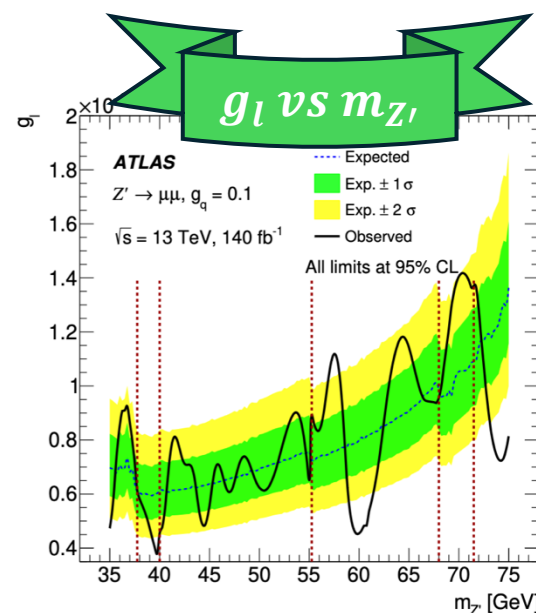


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The largest excess occurs near 57.5 GeV with a local significance of 2.3σ

$$s\chi\chi \rightarrow HH\chi\chi$$

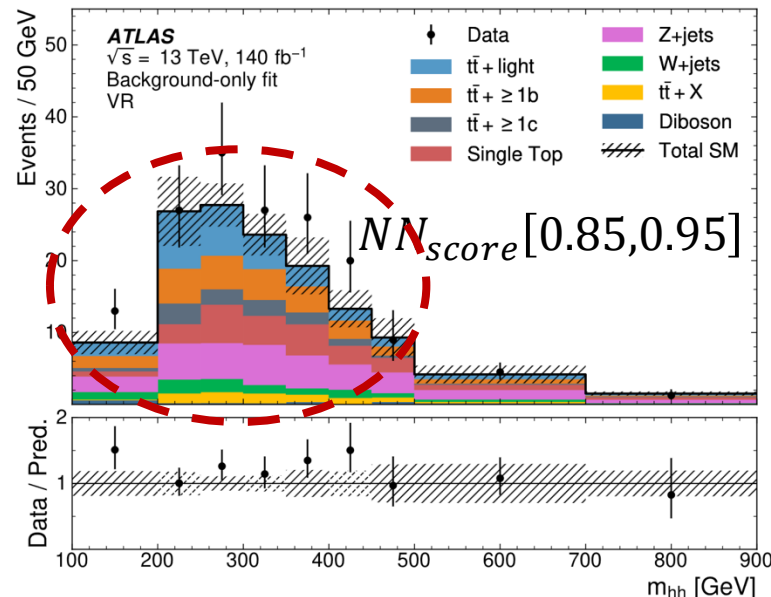
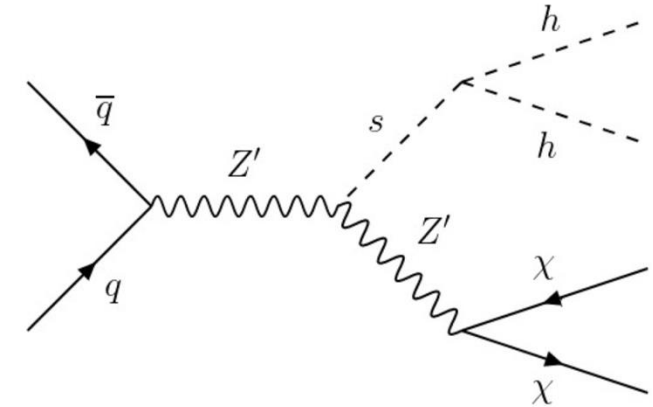
Dark Higgs decay into HH ($\geq 3b$)



<https://arxiv.org/abs/2507.02175>

This is a search for a dark Higgs (s) produced in association with dark matter, the target signature will contain a large amount of p_T^{miss} and at least 3 b -tagged jets

The main backgrounds come from $t\bar{t}$ and $Z(\nu\nu) + jets$ and a NN is trained to discriminate signal and background whilst preserving the shape of the invariant mass distribution of the reconstructed di-Higgs system



The mixing between **SM** and **dark Higgs** should be small to keep consistency with the observed **relic density** and **Higgs** measurements

A dark Higgs is motivated both by the need to generate the masses of dark sector particles and the possibility to relax constraint on dark matter relic abundance by opening a new annihilation channel ($\chi\chi \rightarrow ss$)

$$s\chi\chi \rightarrow HH\chi\chi$$

Dark Higgs decay into HH ($\geq 3b$)

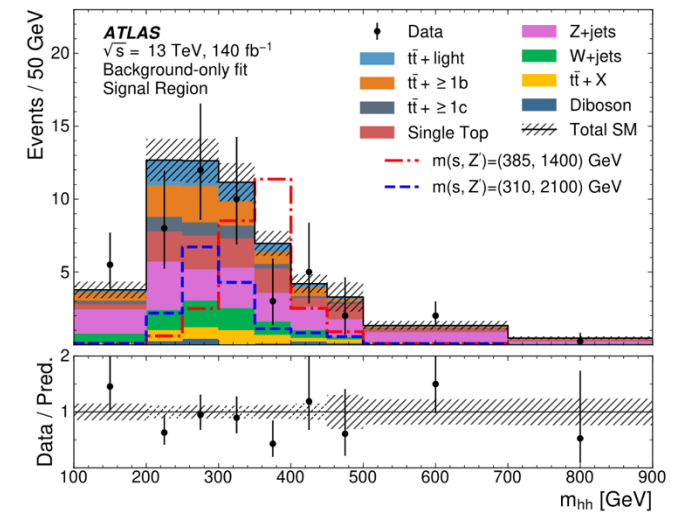
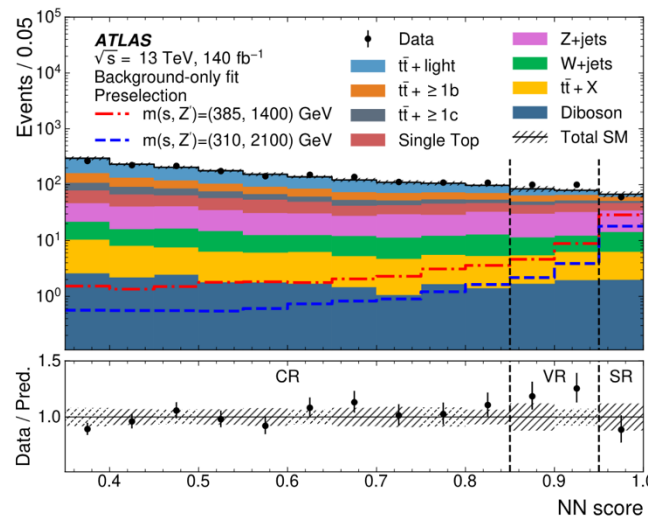
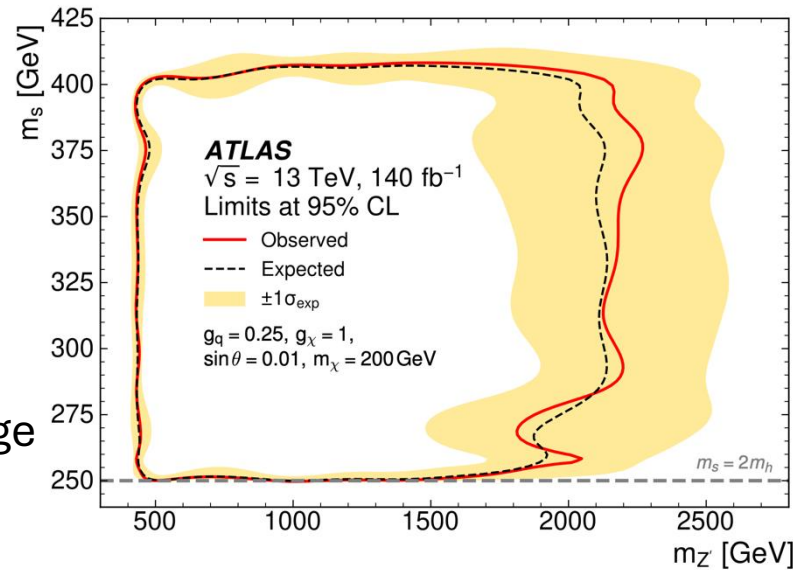


<https://arxiv.org/abs/2507.02175>

No excess over the SM expectations was found and limits on the effective cross-section were imposed as a function of m_s and $m_{Z'}$

Models with dark Higgs masses in the range $250 \text{ GeV} < m_s < 400 \text{ GeV}$ and Z' mediators with masses $< 2.3 \text{ TeV}$ were excluded

This analysis signature extends significantly the constraints on previous dark Higgs searches by ATLAS and CMS in different final states



$$s\chi\chi \rightarrow HH\chi\chi$$

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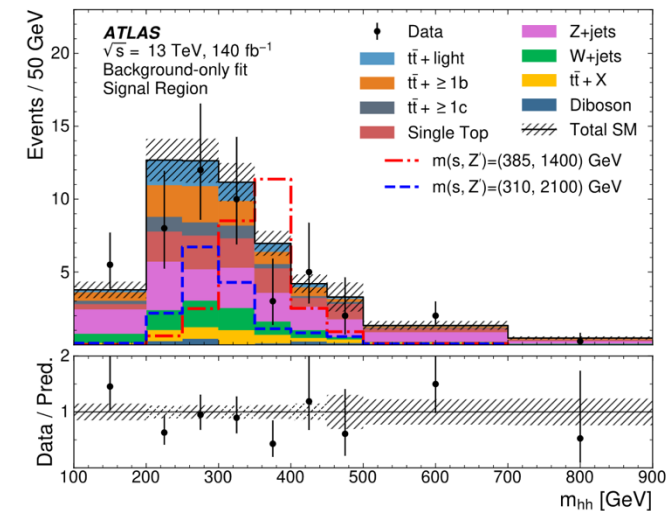
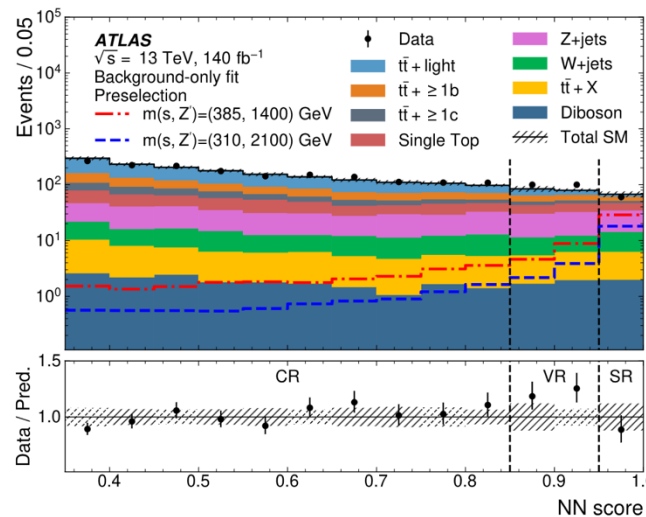
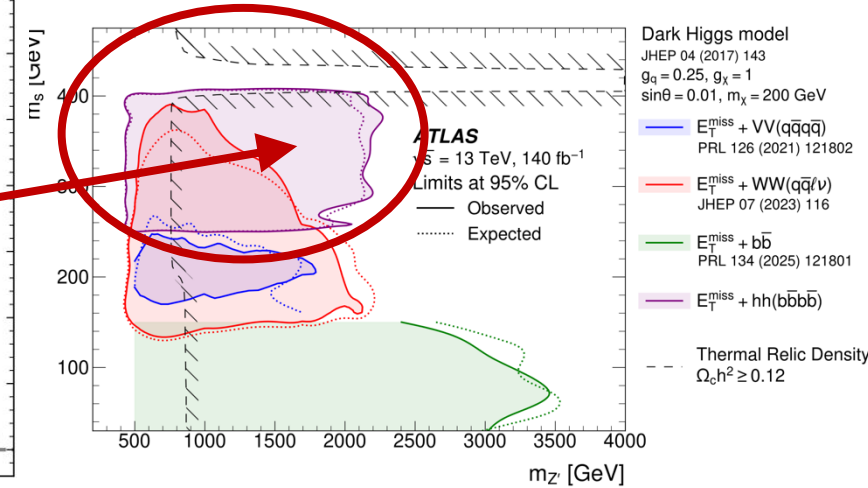
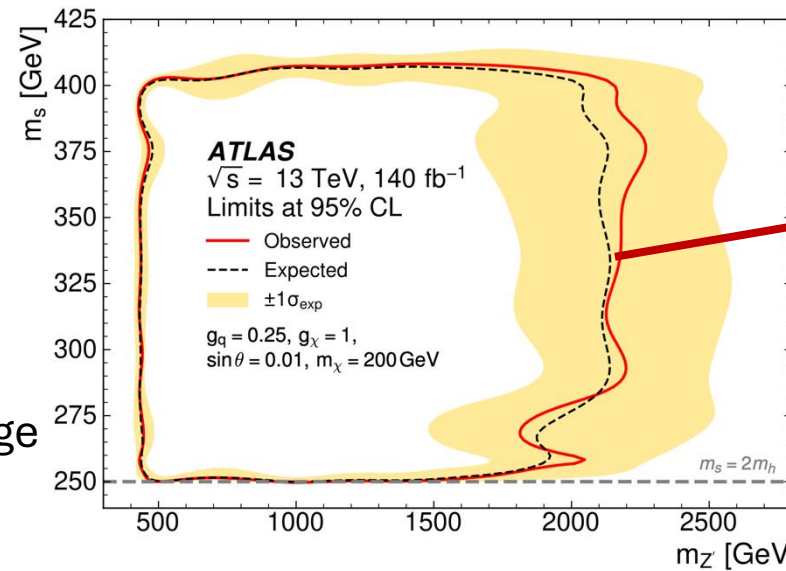
Full RUN 2

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This analysis signature extends significantly the constraints on previous dark Higgs searches by ATLAS and CMS in different final states, by excluding the region at High m_s and $m_{Z'}$ values



Summary

- Several interesting new results have been shown further constraining the parameter space of models featuring new scalars and BSM Higgs interactions
- First semi-visible Higgs decay search to dark photons using Run 3 is shown, targeting a ggF production mode and making use of an innovative trigger strategy to recover low-pT events
- No significant excesses over the SM background expectations was found in any of the analyses, the largest local excess was found (of 2.3σ) in the $X \rightarrow \mu\mu$ search at an invariant mass of 57.5 GeV

Backup

$t\bar{t}a(a \rightarrow \tau\tau)$

Fully hadronic boosted ditau mode



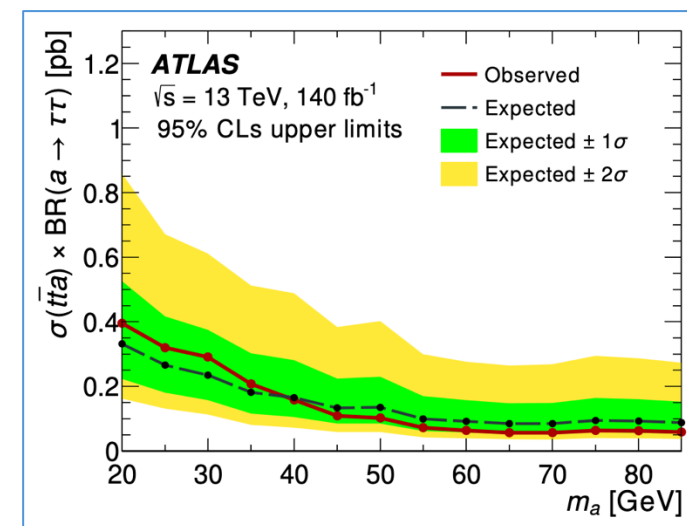
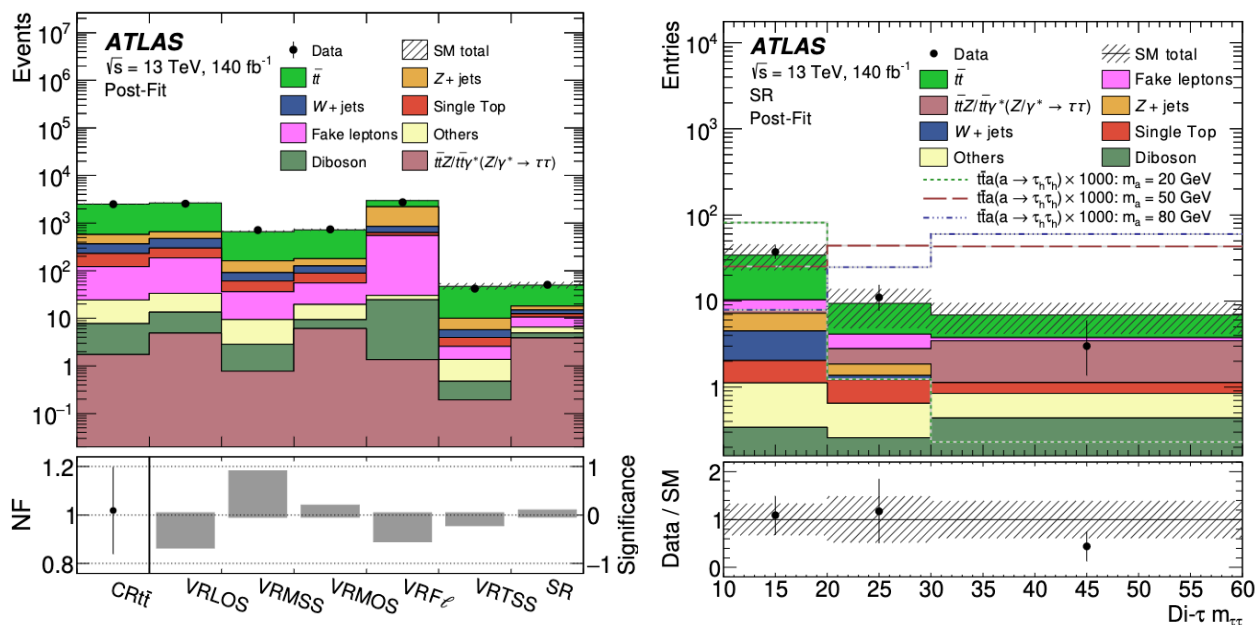
<https://arxiv.org/abs/2607.28484>

$t\bar{t}$ modelling is estimated from MC simulations and normalized to data in a dedicated CR

- It requires the boosted di-tau object to be same sign $Q_{\tau\tau} = +1$ and to pass an orthogonal BDT score selection to the SR ($0.2 < \text{BDT} < 0.35$)
- The $\Delta\phi$ SR selection is removed

The background estimation is validated in a set of regions obtained by varying the boosted di-tau selection criteria

No excess over the SM expectation is found and an upper limit on the model-dependent CS x BR is derived for a generic 2HDM model used to generate light scalar resonance samples



The worse limit at low m_a is due to a reduction in the visible $p_{\tau}^{T,subl}$ affecting the boosted di-tau reconstruction

Two step overlap removal is applied to resolve ambiguities in the reconstruction of multiple objects:

- 1.-Resolve ambiguities between electrons, muons and jets
- 2.-discard boosted ditaus overlapping with e/mu and discard jets if overlapping with the boosted ditau object

Table 1: Summary of the overlap removal procedure applied to resolve ambiguities between selected reconstructed electrons, muons and jets. The procedure is sequential, with each row of the table denoting the criteria applied to objects that are retained after all preceding steps.

Remove	Retain	Criteria
Electron ($p_{T,1}$)	Electron ($p_{T,2}$)	Shared track, $p_{T,1} < p_{T,2}$
Muon	Electron	Shared inner detector track and the muon is calorimeter-tagged
Electron	Muon	Shared inner detector track
Jet	Electron	$\Delta R < 0.2$
Electron	Jet	$\Delta R < 0.4$
Jet	Muon	$\Delta R < 0.2$ and the jet has at most two associated tracks
Muon	Jet	$\Delta R < \min(0.4, 0.04 + 10 \text{ GeV}/p_T(\mu))$

$$H \rightarrow \gamma\gamma_d (m_{\gamma_d} = 0)$$

Semi-visible $H(125)$ decay

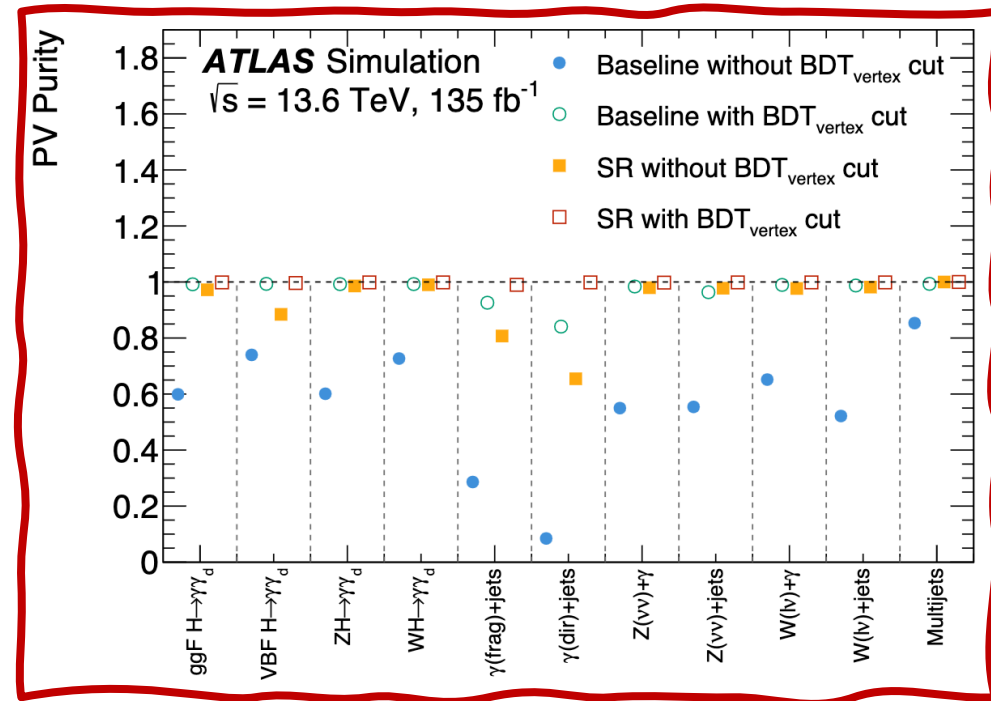
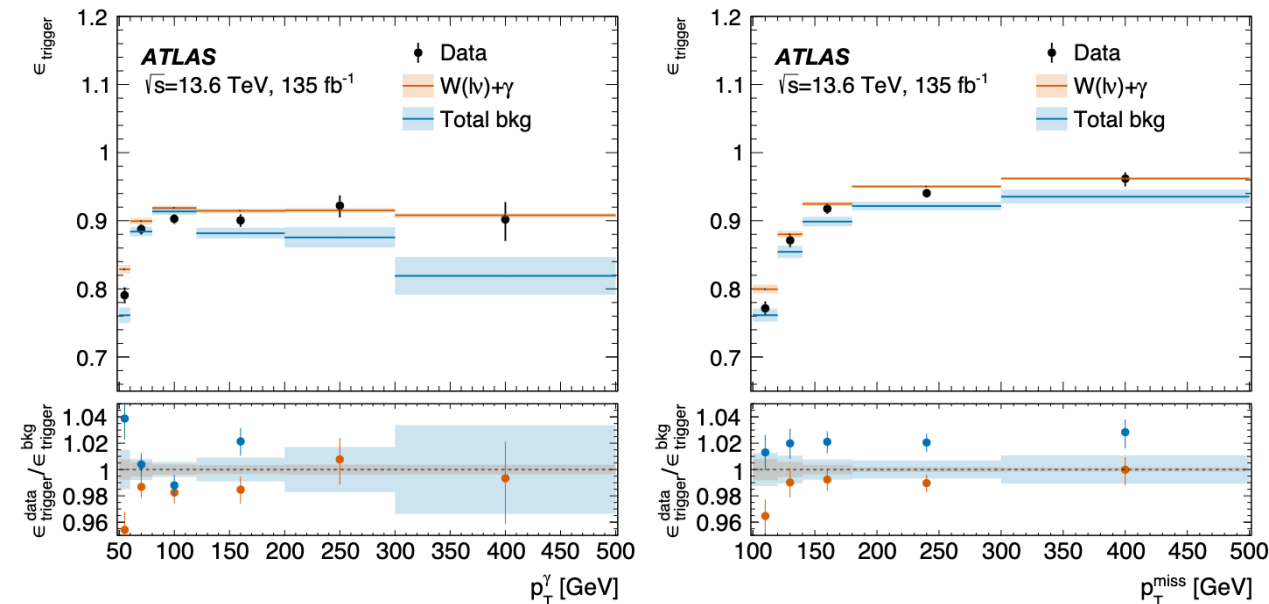


<https://arxiv.org/pdf/2606.14362>

The “Hidden Valley” scenario was used for modeling the $H \rightarrow \gamma\gamma_d$ decay

In this scenario the Higgs decay through a loop involving additional (pseudo-)scalar BSM fields which couple both to the SM and to the Dark sector (BR at the sub-percent level can be achieved)

This signature is targeted for the first time given the low requirements on the photon p_T and $p_{T\text{miss}}$ thresholds and required developments on the trigger side that were implemented just recently (2023)



$H \rightarrow \gamma\gamma_d (m_{\gamma_d} = 0)$ Semi-visible H(125) decay

- Novel data-driven methods were developed to estimate the γ fake backgrounds to either e or j

$$f_{e\gamma} = \frac{N(e \rightsquigarrow \gamma)}{N(e \rightsquigarrow e)},$$

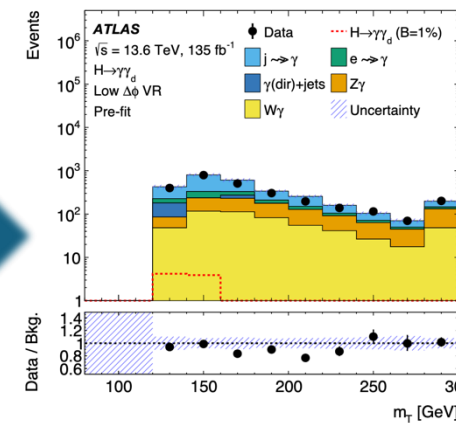
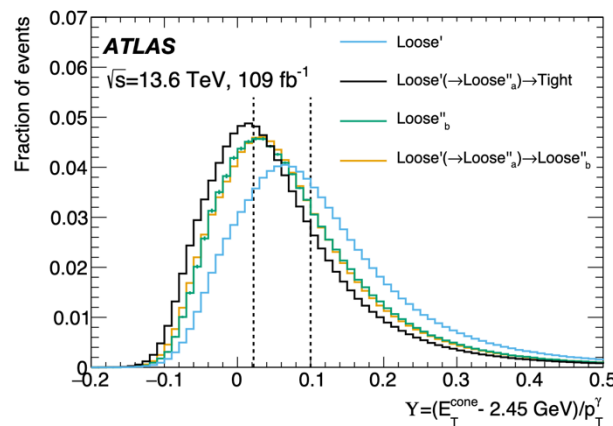
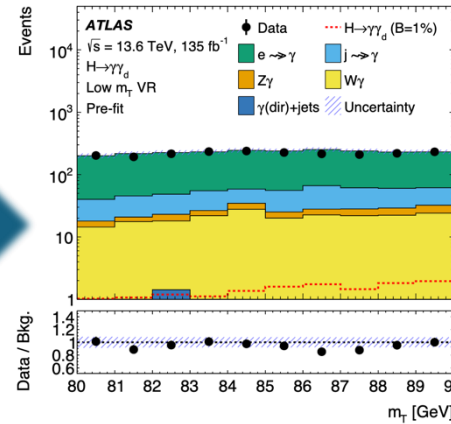
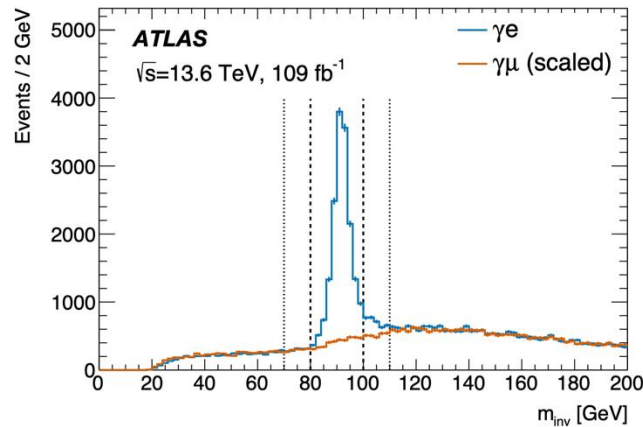
The fake factors for $e \rightsquigarrow \gamma$ ($f_{e\gamma}$) are determined by counting events selected by single- e and double- e triggered events in m_{inv} [80,100] GeV around the Z peak.

- The γe contribution from $(W \rightarrow e\nu)\gamma$ is estimated from $\gamma\mu$ exploiting Lepton universality and subtracted
- The efficiency difference between μ and e reconstruction and between the e and the analysis trigger should be considering in the estimation of $f_{e\gamma}$ as well

$$f_{j\gamma} = \frac{N(j \rightsquigarrow \gamma)}{N(j \rightsquigarrow \gamma^{\text{non-isol}})}$$

The fake factors for $j \rightsquigarrow \gamma$ ($f_{j\gamma}$) are calculated from the ratio of the number of j reconstructed as isolated and non-isolated γ considering extrapolations from different Loose sub-regions obtained by applying selections on each strip shower-shape at the time (a)

- For each extrapolated distribution a different $(f_{j\gamma})_a$ is computed. The final $f_{j\gamma}$ is obtained as the arithmetic mean of all $(f_{j\gamma})_a$



$$X \rightarrow \mu\mu$$

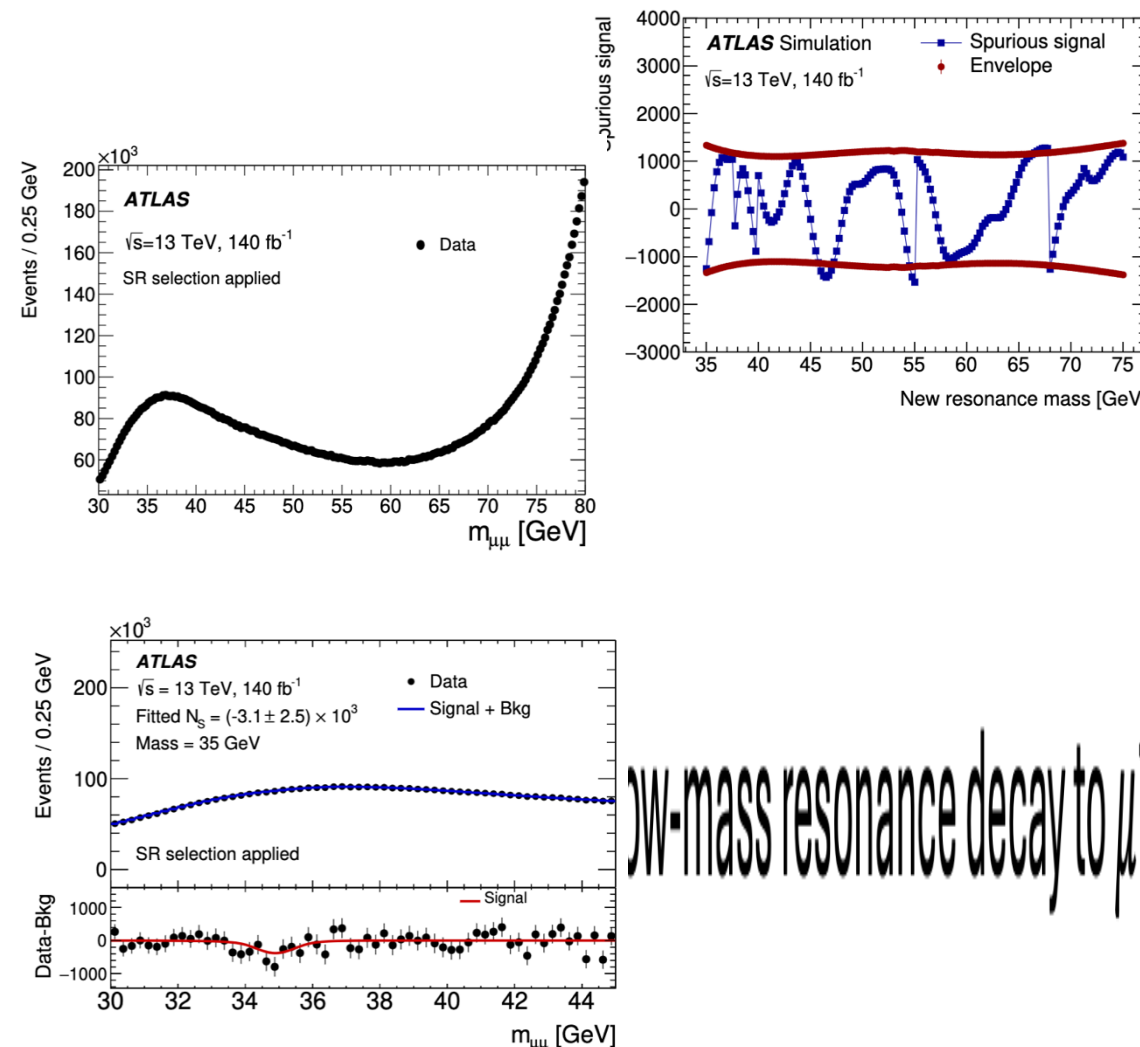
Low-mass resonance decay to $\mu^+ \mu^-$ <https://arxiv.org/abs/2601.21361>

Model independent search, targeting the mass range 35 GeV – 75 GeV and adopting a bump-hunting strategy. It implements a Gaussian Process Regression (GPR) machine learning technique to model the background in a $s + b$ fit allowing signal extraction

Since the conventional analytic background parametrizations are particularly difficult to apply in this mass region given the trigger threshold affecting the invariant mass data shape

Two benchmark models are considered to interpret result in this searches

- An extension of the SM considering an additional $U(1)$ gauge symmetry and a new vector boson Z' mediating the interactions between the SM and the dark sector
- A kinetically mixed (between a dark Abelian gauge symmetry $U_D(1)$ and the hypercharge $U_Y(1)$) dark photon with a mass m_{Z_D} (The hidden Abelian Higgs model HAHM)



Low-mass resonance decay to $\mu^+ \mu^-$

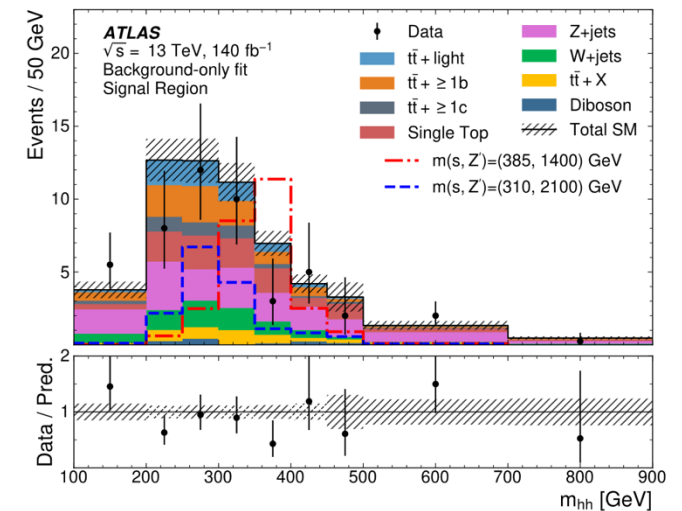
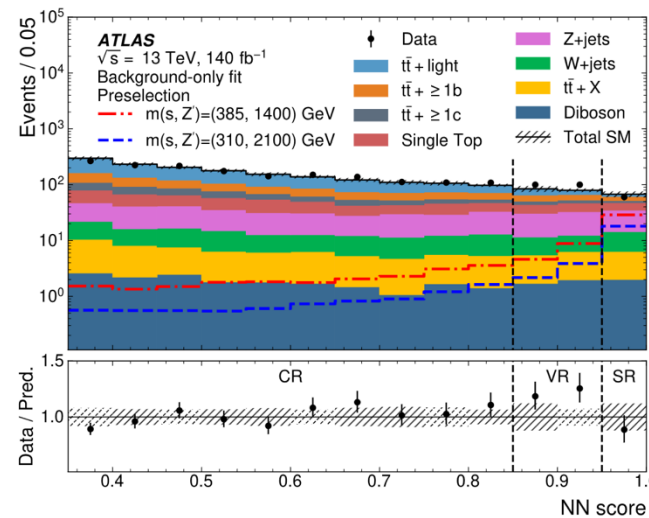
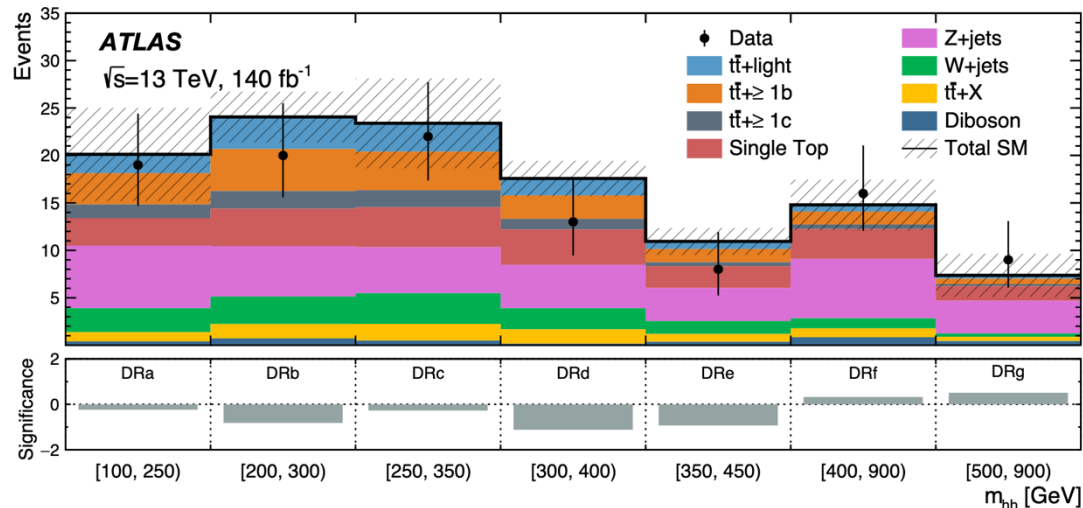
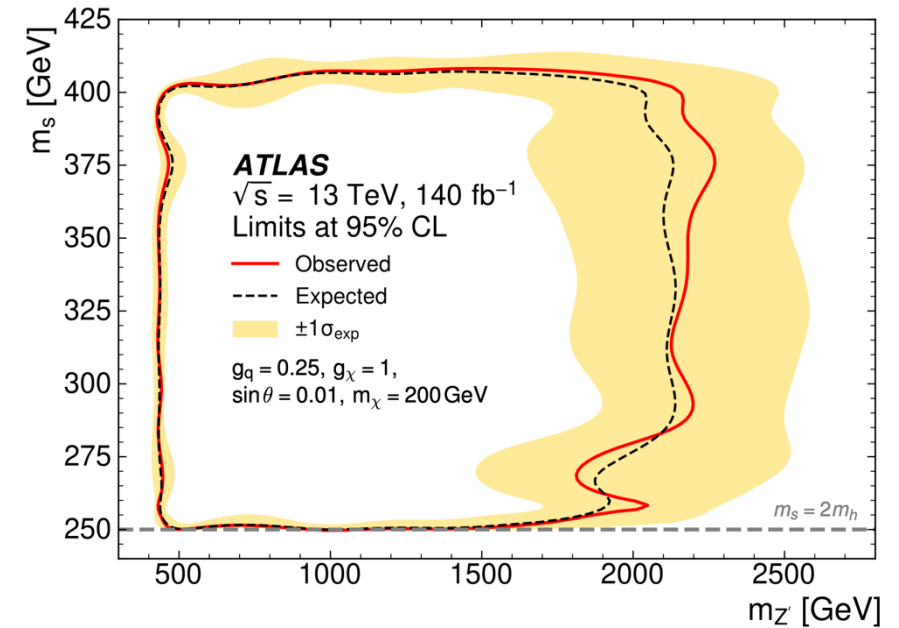
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Model with dark Higgs masses in the range $250 \text{ GeV} < m_s < 400 \text{ GeV}$ and Z' mediators with masses $< 2.3 \text{ TeV}$ were excluded

This analysis signature extends significantly the constraints on previous dark Higgs searches by ATLAS and CMS in different final states

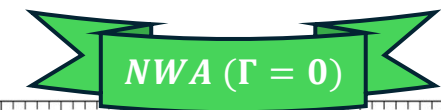


$$X \rightarrow \mu\mu$$

Low-mass resonance decay to $\mu^+\mu^-$



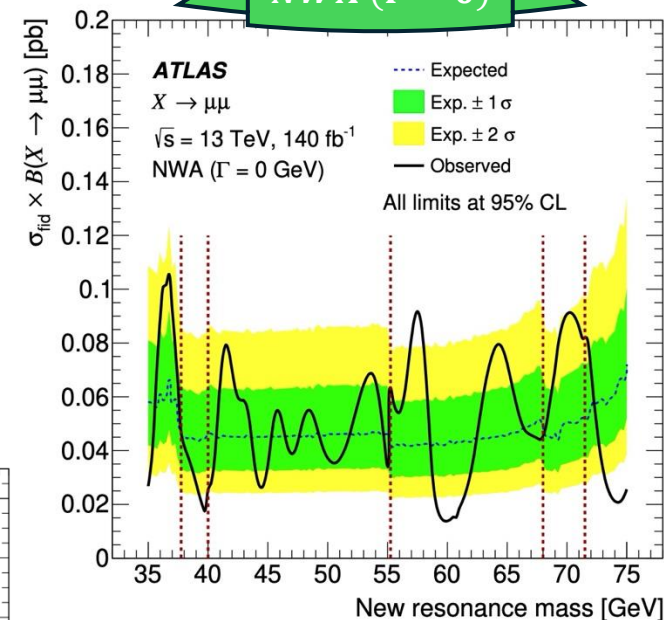
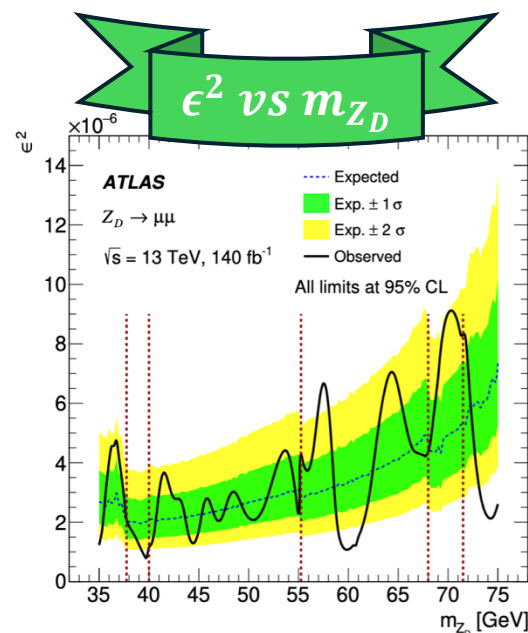
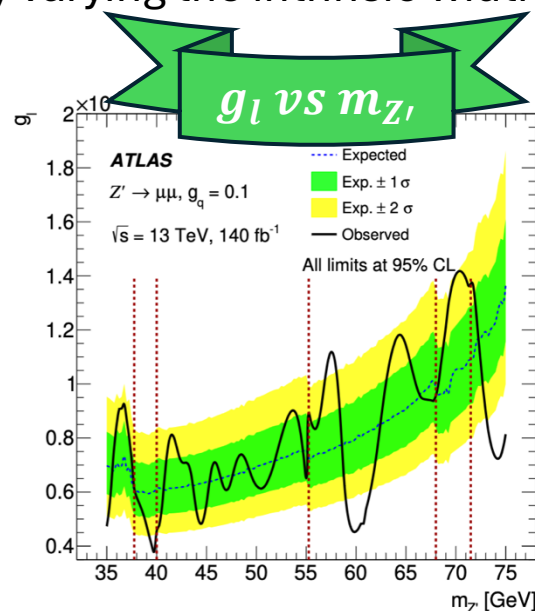
<https://arxiv.org/abs/2601.21361>



Limits are derived under the narrow-width approximation and are valid for resonances with relative intrinsic widths $\Gamma/m_X < 1\%$ covering a broad class of new physics scenarios with perturbative couplings

Assuming a coupling of 0.1 between the Z' and quarks, an upper limit on the coupling with leptons can be obtained by varying the intrinsic width

Applying a similar approach to the dark photon model governed by the kinetic mixing parameter ϵ , a limit is obtained for ϵ^2 which is proportional to the production cross-section



Discontinuities in the limit curve(s) reflect transitions between different sets of hyper-parameters used in the GP background modelling