Rare and exotic Higgs decays in ATLAS

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The 21st Workshop of the LHC Higgs Working Group

[**On behalf of the ATLAS collaboration**]

The Higgs boson exists and then...

- **The Higgs boson exists and it's discovered in 2012 → scrutinize its properties and the Higgs sector nature.**
- Combined results set a 95% CL upper limit of 12% on the branching ratio for H boson decays via undetected modes. ▸ arXiv:2207.00092
  - ⇒ **Exotic decays of the Higgs boson remain a high priority.**

- Even with its excellent successes in providing experimental predictions, the SM leaves some phenomena unexplained.
  - hierarchy problem, baryon asymmetry, dark matter/energy etc...
- **Many Beyond Standard Model (BSM) theories predict modified and extended Higgs sectors with additional Scalars** ▸ JHEP02(2015)157, ▸ arXiv:hep-ph/0008192, ▸ arXiv:hep-ph/0305109.

Analysis covered

5 analyses covered

1. Search for $S \to Z_d Z_d \to 4\ell$ arXiv:2410.16781
   - **Where Z_d is a dark boson.**
2. Search for $H \to aa \to bb\tau^+\tau^-$ arXiv:2407.01335
3. Search for $H \to aa \to 4\gamma$ arXiv:2312.03306
   - **Where a is a prompt or long-lived axion-like particle**
4. Search for $H \to Za \to \ell\ell\gamma\gamma$ arXiv:2312.01942
5. Search for $H \to Za \to \ell\ell jj$ arXiv:2411.16361
   - **Where a would manifest as light resonance.**

- Hard to cover a lot in 15 min, but these are the latest results on searches for rare Higgs decays published (in 2024).
- More can be found in the ATLAS public results page ATLAS-Result-Page

Summary

- S is an additional scalar and $m_S \in [30, 115] \cup [130, 800]$ GeV
- 2 SR: SR1 $\Leftrightarrow m_S < 115$ GeV and SR2 $\Leftrightarrow m_S > 130$ GeV.
- **$\langle \mathbf{m}_{\ell\ell} \rangle$ is used as observable in this analysis defined as $\frac{\mathbf{m_{ab}}+\mathbf{m_{cd}}}{2}$ where $\mathbf{m_{ab}}, \mathbf{m_{cd}}$ are the leading and sub-leading di-lepton masses respectively with $\mathbf{m_{ab}} > \mathbf{m_{cd}}$.**
- **Three final states:** $4e, 2e2\mu, 4\mu$.
- **A compatibility cut between the two di-lepton masses is applied** $m_{ab} \sim m_{cd}$.

Additional Scalar S to $Z_d Z_d$ 4-leptons ▸ arXiv:2410.16781

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Background

- Dominant: Non resonant SM ZZ^*.
- WZ, VVV/VBS processes,
- $H \to ZZ \to 4\ell$, J/ψ and Υ
  - $\rightarrow$ these bkgs are estimated From MC.
- $t\bar{t}$ and Z+ Jet.
  - $\rightarrow$ Data-driven method

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Systematics

- The dominant detector systematic is electron uncertainty: ID efficiency (∼17.3% on SR yield).
- The dominant theory systematic is ggZZ (∼35% on SR yield).

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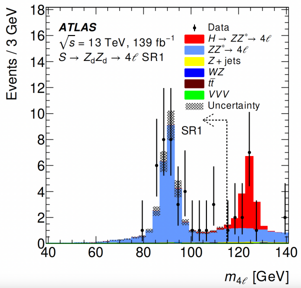
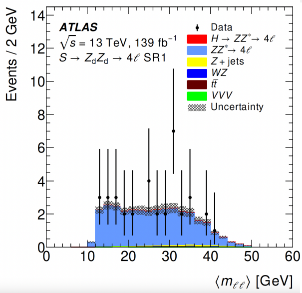
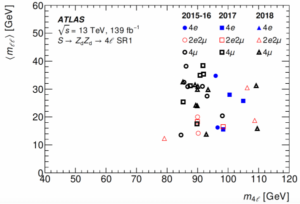
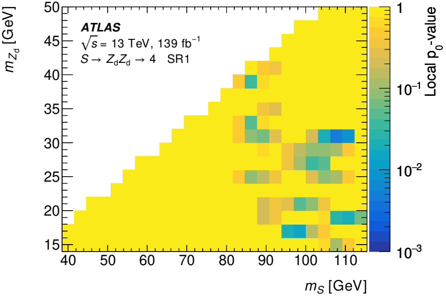






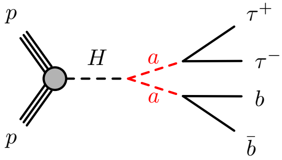
- **Most significant excess found in SR1 at $m_S = 110$ GeV and $m_{Z_d} = 30$ GeV with a local(global) significance of $2.7\sigma (1.6\sigma)$.**
- No significant excess in SR2.
- SR2 results can be found in backup.



Search for $H \to aa \to bb\tau^+\tau^-$ ▸ arXiv:2407.01335

Summary

- 12 GeV $< m_a <$ 60 GeV.
- 3 channels: $e\mu$, $e\tau_{\text{had}}$, $\mu\tau_{\text{had}}$
- 3 categories per channel: 1bjet, >1bjet, 1 DeXTer ▸ Link "B-jet".
- Use a Parameterized NN to enhance sensitivity.



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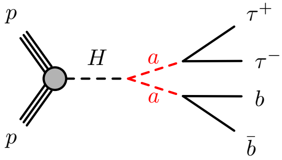

Backgrounds

- main bkg: $t\bar{t}$ and single top events, Z+jets where $Z \to \tau\tau$.
- Other backgrounds: $h \to \tau^+\tau^-$, VV, $t\bar{t}$ in association with a boson $\to ttV$.
- Dedicated control region are defined in each channel for each major background
- Top CR, Z CR, SS CR

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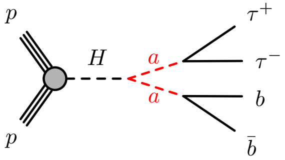

Systematics

- Experimental: muons, electrons, hadronic τ-leptons, jets, and missing transverse energy. Also on DL1r and DeXTer.
- Theory systematics (PDF, α_S, QCD, shower variation). Also on resummation (QSF) and merging (CKKM) scales.
- Full uncertainties and their impact available in the backup.

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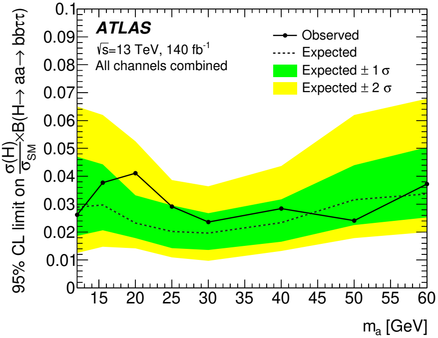
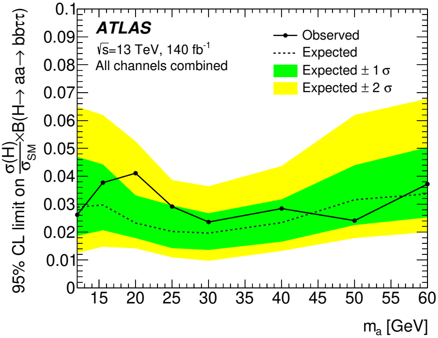
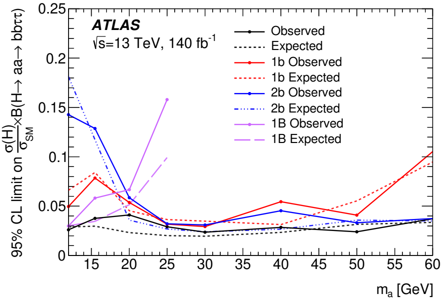


- The observed (solid) 95% C.L. upper limits on $(\sigma(H)/\sigma SM(H))B(H \to aa \to b\bar{b}\tau^+\tau^-)$ as a function of m_a and the expected (dashed) limits under the background-only hypothesis when combining all categories.





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- Limit of the same quantity when considering different categories based on the heavy-flavor objects separately.
- A factor of two improvement at low masses is observed w.r.t. to CMS results arXiv:2402.13358 due to the specific 1B-jet category.

Summary 1/2

- Probing unconstrained $m_a - C_{a\gamma\gamma}$ parameter space:
  - $H \to aa \to 4\gamma$.
  - $a \to$ axion-like particles(ALPs)
  - $C_{a\gamma\gamma}$ is the ALP-photon coupling.
  - $0.5 \text{ GeV} \leq m_a \leq 60 \text{ GeV}$
  - $10^{-5} \leq C_{a\gamma\gamma} \leq 1$

Summary 2/2

- 5 categories according to their experimental signature: 4S (single), 3S, 2M(merged), 1M1S, 2S
  - Photon can be fully reconstructed, merged, or missing.
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- Using a sideband in m_H distribution:
  - The range and the function of the fit depends on the category.
  - Signal region is excluded.
- Using a 2D sideband fit approach for prompt case.

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Systematics

- Experimental systematic depends on the category, m_a and $C_{a\gamma\gamma} \to$ from 6.5% to 18% for most categories.
- Except 4S which rises to 40% for $m_a < 15$ GeV and small couplings $C_{a\gamma\gamma}$.
- Theoretical uncertainty $\to$ 6% for all categories.

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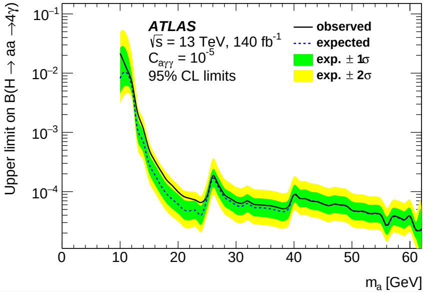
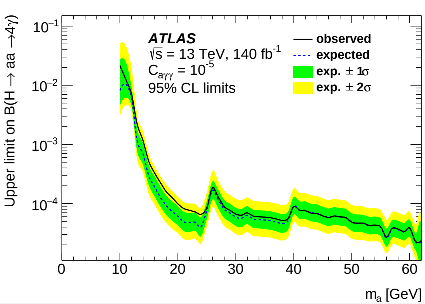
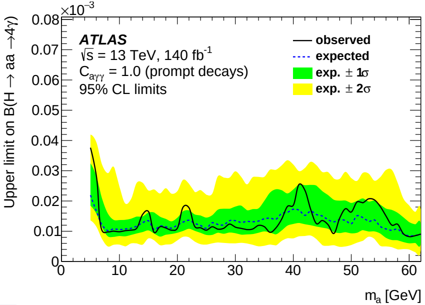
$H \to aa \to 4\gamma$ ▸ arXiv:2312.03306



- **Upper limits on $B(H \to aa \to 4\gamma)$ at 95% CL as a function of the axion mass for $C_{a\gamma\gamma}$=$10^{-5}, 1$ (left, right)**

$H \to aa \to 4\gamma$ arXiv:2312.03306





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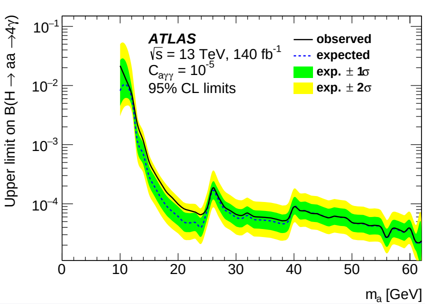

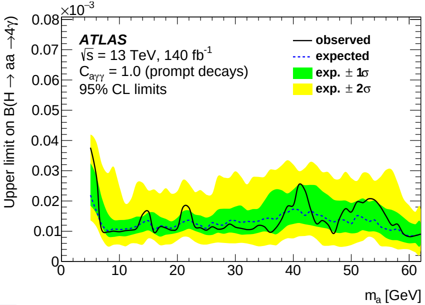

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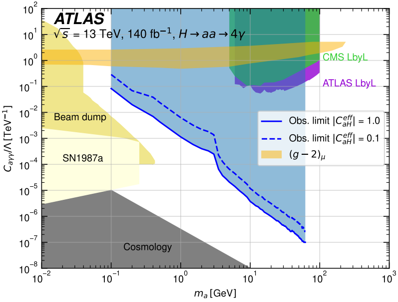
- **Limits on the ALP mass and coupling to photons at 95% CL, assuming $B(a \to \gamma\gamma) = 1$, $\Lambda = 1$ TeV with $|C_{aH}^{\text{eff}}| = 1$ and $|C_{aH}^{\text{eff}}| = 0$ as predicted. Most stringent limits to date.**



Summary

- Lepton triggers to select Z events.
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- Resolved category (2γ).
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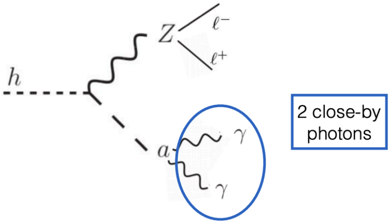

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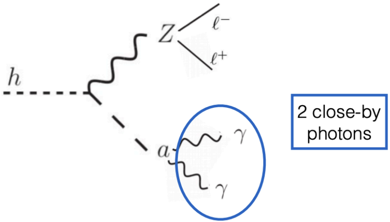
- CR+SR simultaneous fit to estimate $Z\gamma$ (75%) and Zjets backgrounds.



Search for $H \to Za \to \ell\ell\gamma\gamma$ arXiv:2312.01942

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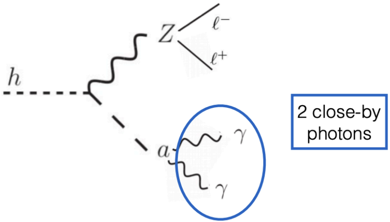

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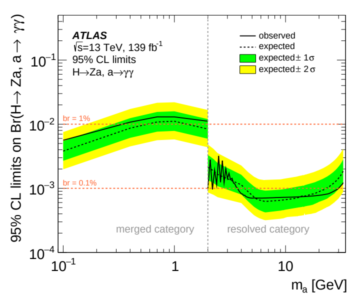
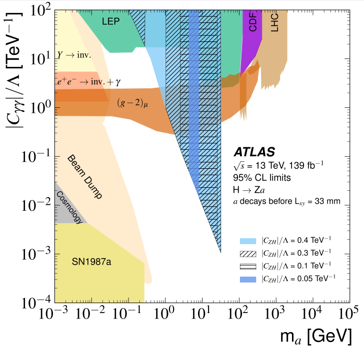
Systematics

- Systematics on signal:
  - Main shape uncertainties coming from photon isolation, electron ID and PU reweighting
  - Signal modelling uncertainty: shape and parameters variation
- Systematics for data-driven background:
- Background modelling uncertainty: spurious signal method

Results

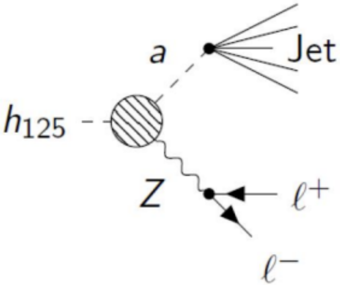




- **Left**: **Expected and observed 95% CL upper limits on $\mathcal{B}(H \to Za, a \to \gamma\gamma)$ vs m_a in the merged ($m_a \leq 2$ GeV) and the resolved ($m_a > 2$ GeV) categories.**
- **Right**: **ATLAS observed 95% CL exclusion contours limits in terms of the ALP mass and its effective coupling to photons, $|C_{\gamma\gamma}|/\Lambda$, for different values of the Higgs coupling to Za, $|C_{ZH}|/\Lambda$.**

Summary

- 0.5 GeV $< m_a <$ 4 GeV, focusing at low masses.
- Hadronic decays of a, reconstructed as a single jet (large boost)
- Z leptonic decays.
- 50 GeV $< m_{\ell\ell jj} <$ 180 GeV.



Search for $H \to Za \to \ell\ell jj$ arXiv:2411.16361

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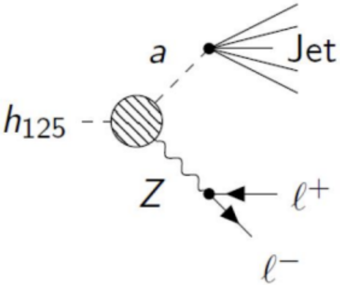

Backgrounds

- Main bkg → Z+jets.
- A reweighing technique is used to estimate bkg:
- 11 training variables are reweighted simultaneously for a high level of MC-Data agreement.

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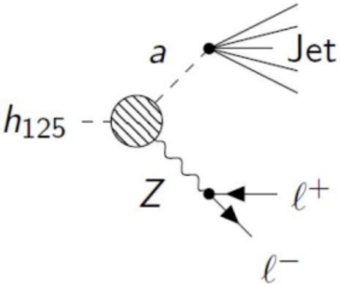

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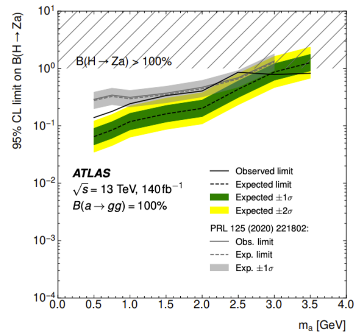
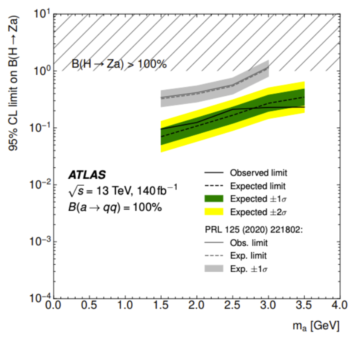
Systematics

- Signal Uncertainties:
  - Experimental uncertainties.
  - PS and hadronization.
- Bkg Uncertainties:
  - Data-driven uncertainty
  - Theory uncertainty, NN performance, JET experimental uncertainties.

Results





- **Expected and observed 95% CL upper limits on $\mathcal{B}(H \to Za)$ vs m_a.**
- **Left corresponds to $\mathcal{B}(a \to gg)$=100% and right corresponds $\mathcal{B}(a \to qq) = 100\%$.**
- **The weaker limits from the previous version of the analysis are also shown.**

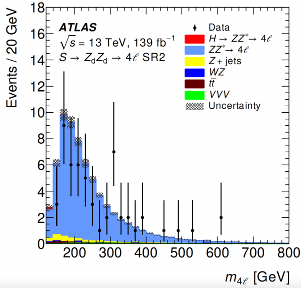
Conclusion

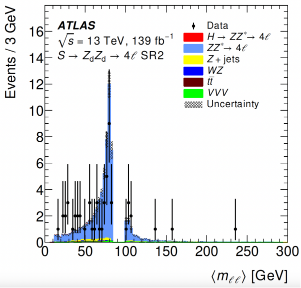
- Searches for Higgs exotic decays and additional scalars in ATLAS are presented focusing on the most recent results.
- Five analyses published this year have been shown, some of them for the first time
- There are still many uncovered interesting searches - stay tuned for updates!!

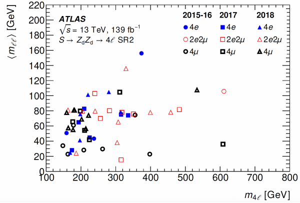
BACKUP

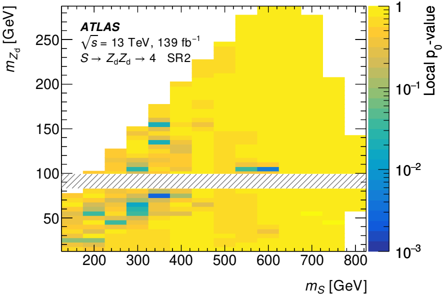
Additional Scalar S to Z_dZ_d 4-leptons

arXiv:2410.16781









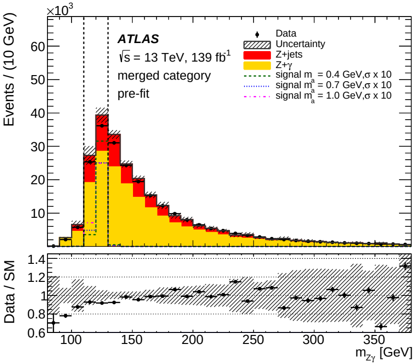
- No significant excess in SR2.

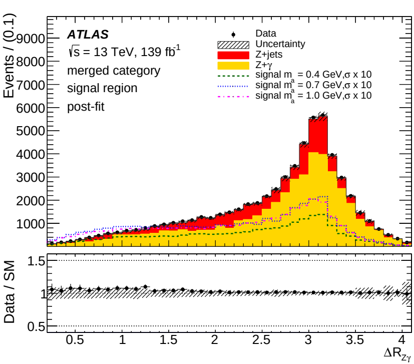
Search for $H \to aa \to bb\tau^+\tau^-$ ▸ arXiv:2407.01335

Uncertainty source	Expected limit on $(\sigma(H)/\sigma_{SM}(H))\mathcal{B}(H \to aa \to b\bar{b}\tau^+\tau^-)$		
	m_a = 12 GeV	m_a = 25 GeV	m_a = 60 GeV
Stat-only limit	1.34	1.79	3.00
Observed limit	2.89	2.02	3.37
MC statistics	1.42	1.81	3.04
Experimental	2.72	1.94	3.21
Detector response	2.43	1.84	3.03
Luminosity and pileup	1.37	–	–
b-tagging	–	1.81	–
B-tagging	2.35	–	–
Jet and E_T^{miss}	–	1.83	–
Electrons	1.36	–	–
Muons	1.35	–	–
Taus	–	–	–
Data-driven normalization	1.58	1.94	3.19
Non-prompt leptons	1.58	1.85	3.16
Non-prompt taus	–	1.86	3.10
MC reweighting	–	–	–
Theoretical modeling	1.38	1.89	3.04
Signal	–	–	–
Background	1.37	1.87	3.03

- Different systematic uncertainties group are considered individually in each line of the table. The larger the difference relative to the expected limit without systematic uncertainties (stat-only), the more important the uncertainty group is for the final result.

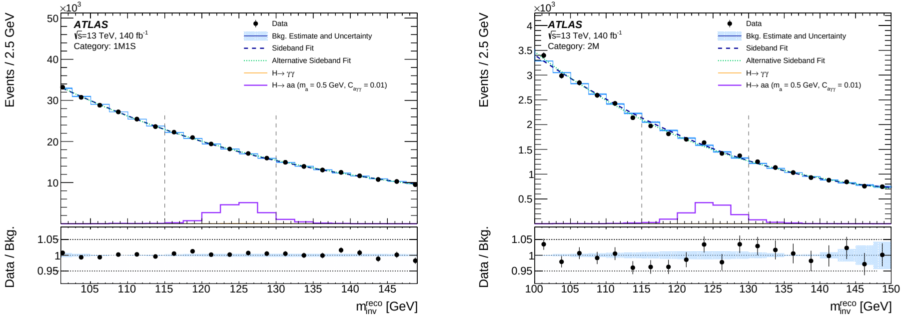
Search for $H \to Za \to \ell\ell\gamma\gamma$ arXiv:2312.01942





Distributions related to the merged category:

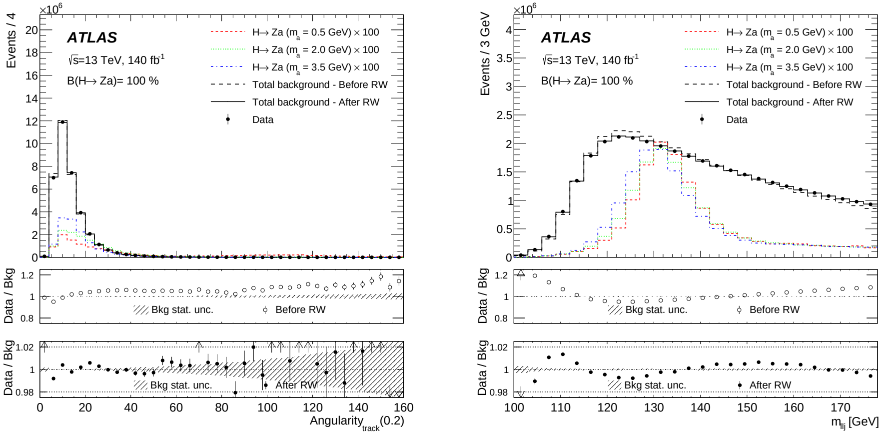
- Left: $m_{Z\gamma}$ distribution along with the range, indicated by vertical dashed lines, in which the merged category events after the E_{ratio} cut are found.
- Right: post-fit final discriminating variable $\delta R_{Z\gamma}$ in the signal region. Signal distributions for ma values used in this category are overlayed for comparison, assuming a branching ratio of the Higgs boson decay to Za times the branching ratio $a \to \gamma\gamma$ of 100%.



$m_{\text{inv}}^{\text{reco}}$ distribution for the nominal signal selection

- The nominal sideband fitting function is shown as the blue dashed line. The estimated background and its systematic variation (obtained from a fit with reduced range) is shown as the blue histogram. The green dotted line shows the alternative fitting function which is used to estimate the spurious signal uncertainty
- The signal region selection on $m_{\text{inv}}^{\text{reco}}$ is indicated using vertical dashed lines.
- Left corresponds to the 1M1S category and right to 2M category.

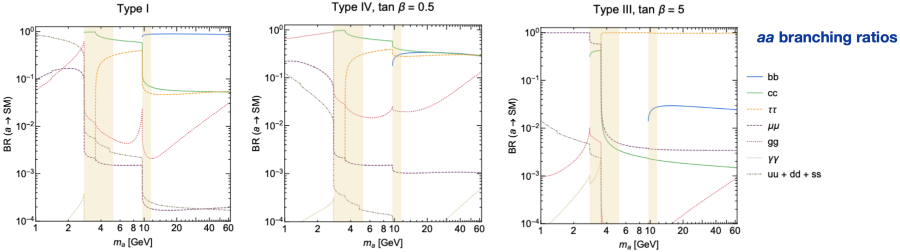
$H \to Za \to \ell\ell jj$ arXiv:2411.16361



- Angularity (left), invariant mass of the lepton pair plus jet system (right) for data, background (pre- and post-reweighting) and three $H \to Za$ signal hypotheses (for $a \to q\bar{q}/gg$ inclusively).
- The signal normalization assumes the SM Higgs boson inclusive production cross-section, $\mathcal{B}(H \to Za) = 100\%$, and it is scaled up by a factor of 100.

- **Add a second Higgs doublet (heavy, not directly detected) and a new light (pseudo)scalar to the SM.**
  - Light scalar can in general decay to SM via its mixing with other scalars in the scalar potential.
  - Alignment limit avoid spoiling the SM-like nature of the 125 GeV Higgs. Higgs can decay to *aa* to about 10% (Higgs coupling limits)

- **A wide range of phenomenology results, including regimes where the pseudo scalar branching ratio to $\tau\tau$ and bb are roughly equal, and decays to bb$\tau\tau$ are up to 45% of the aa decays.**
  - Of course, many decay modes are well motivated, including *bbbb*, $\tau\tau\tau\tau$… but there is no ATLAS *bb*$\tau\tau$ search yet!



AS cut-flow reduced

Quadruplet Ranking	Minimal Δm	Select quadruplet with smallest $\Delta m = \lvert m_{ab} - m_{cd}\rvert$	same
Event Selection	Electron ID	All e in quadruplet pass LooseLH working point	same
	Isolation	All leptons in quadruplet pass FixedCutLoose working point	
	Impact Parameter	$\lvert d_0^{BL} Sig.\rvert < 5(3)$ for $e(\mu)$ in quadruplet	same
	Quarkonia Veto	$(m_{J/\psi} - 0.25 GeV) < m_{ab}, m_{cd}, m_{ad}, m_{cb} < (m_{\psi(2S)} + 0.30 GeV)$ or, $(m_{\Upsilon/(1S)} - 0.70 GeV) < m_{ab}, m_{cd}, m_{ad}, m_{cb} < (m_{\Upsilon(3S)} + 0.75$ GeV$)$	same
	LowMass Veto	$(m_{ab}, m_{cd}, m_{ad}, m_{cb}) > 5$ GeV	same
	ZVeto	$m_{ab} \notin [50, 106]$ GeV	m_{ab} and $m_{cd} \notin [83.2, 99.2]$ GeV, m_{ad} and $m_{cb} \notin [87.2, 95.2]$ GeV
	LooseSR	$(m_{ab}, m_{cd}, m_{ad}, m_{cb}) > 10\, GeV$	same
	H veto	$m_{4\ell} < 115$GeV	$m_{4\ell} > 130$ GeV
	MediumSR	new SR	same
	TightSR	$\lvert E'_{ab}/M_{4l} - 0.5\rvert < 0.008$	same