Searches for Axion-Like Particles in ATLAS

*Not always strictly ALPs and not always strictly in Higgs decays

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Introduction

Axion-like-particles (ALPs) 1708.00443 , 2110.10698 , 2111.12751 and many more…

- ALPs can **appear generically** in many SM extensions
  - Solutions to **strong CP problem** (a-la PQ symmetry breaking and the QCD Axion)
  - Can serve as **hidden-sector mediators** ("Axion Portal") and/or **trigger baryogenesis**
  - Or just as **pNGB's** in the **EFT** of UV extensions with (approximate) **global SSB**
- **Couplings** to SM fermions/gauge bosons via **dimension-5** operators:

$$\mathcal{L}^{(D\leq 5)} \supset \frac{\partial^\mu a}{\Lambda} \sum_F \bar{\psi}_F C_F \gamma_\mu \psi_F + g_s^2 C_{GG} \frac{a}{\Lambda} G^A_{\mu\nu} \tilde{G}^{\mu\nu,A} + g^2 C_{WW} \frac{a}{\Lambda} W^A_{\mu\nu} \tilde{W}^{\mu\nu,A} + g'^2 C_{BB} \frac{a}{\Lambda} B_{\mu\nu} \tilde{B}^{\mu\nu}$$

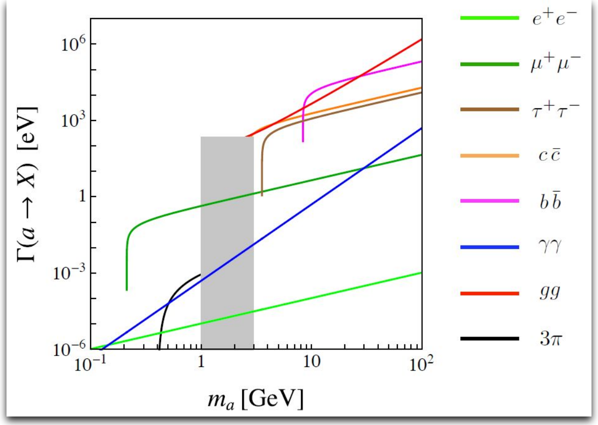
- **Couplings** to SM higgs via **dimension-6 (Haa)** and **dimension-7 (hZa)** operators:

$$\mathcal{L}^{(D\geq 6)} \supset \frac{C_h}{\Lambda^2} (\partial_\mu a)(\partial^\mu a) \phi^\dagger \phi + \frac{C_{Zh}}{\Lambda^3} (\partial^\mu a) \left(\phi^\dagger i D_\mu \phi + h.c.\right) \phi^\dagger \phi$$

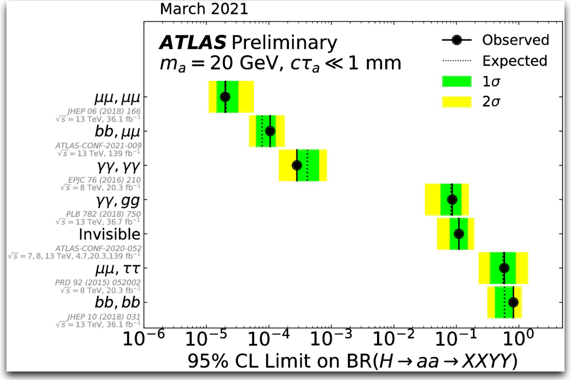
- **Extremely general**, allowing a very rich phenomenology!

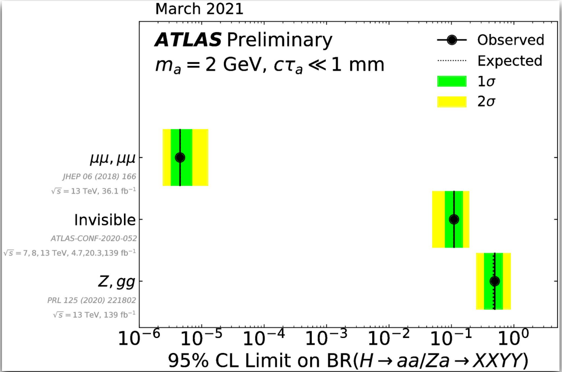
Axion-like-particles (ALPs) [1708.00443](), [2110.10698](), [2111.12751]() and many more…

- **Two key points** to keep in mind, will play a part…
  - Two-body decay $\Delta R \approx \dfrac{2m_a}{p_{T,a}} \rightarrow$ **collimated decay products?**
  - $\Gamma_{a\to VV} \propto m_a^3 |C_{VV}|^2,\ \Gamma_{a\to f\bar{f}} \propto m_a m_f^2 |C_F|^2 \rightarrow$ **prompt** or **long-lived?**
- **Current ATLAS bounds** still allow sizable BSM Higgs BRs
  - **Br(H→undetected) < 12%** (2207.00092 & Nature 607)
  - **Br(H→invisible) < 10.7%** (2301.10731 & PLB 842)
- ATLAS **limits on H→aa (prompt a's)** summarized in ATL-PHYS-PUB-2021-008 **, but…**
  - Some **"outdated"** (e.g. μμττ)
  - Many **advancements** (e.g. GN2)
  - Some **uncovered signatures**…
  - We want more in these plots!
  - So, let's see **some new results!**



1708.00443

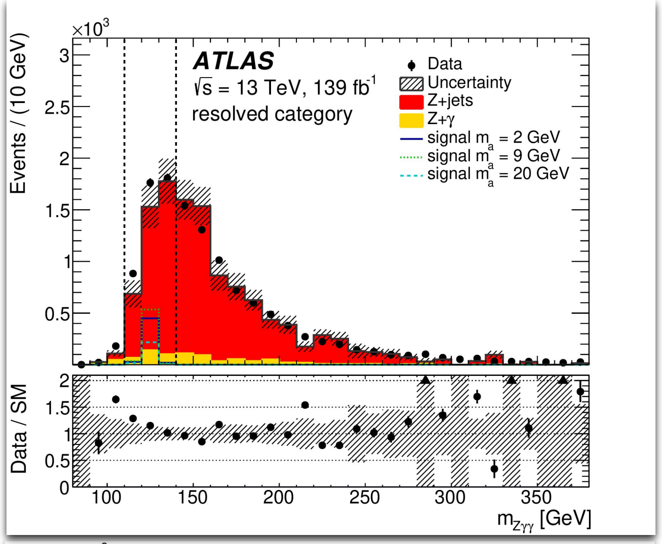


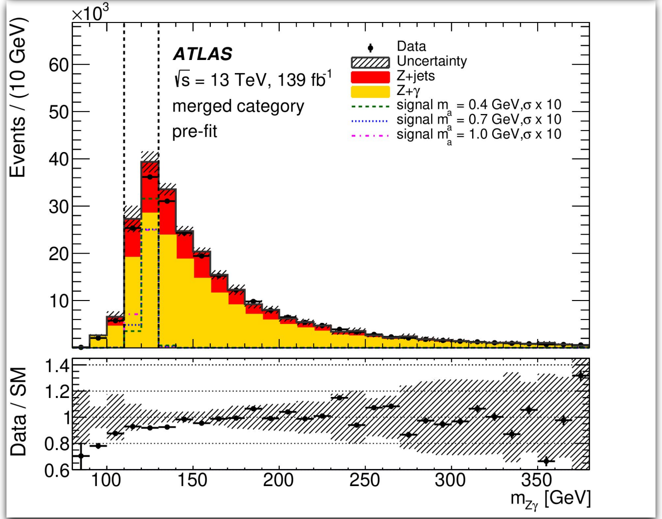


Searches in Higgs Boson Decays

$H\rightarrow Z(ll)a(\gamma\gamma)$ [2312.01942](#) & [PLB](#)

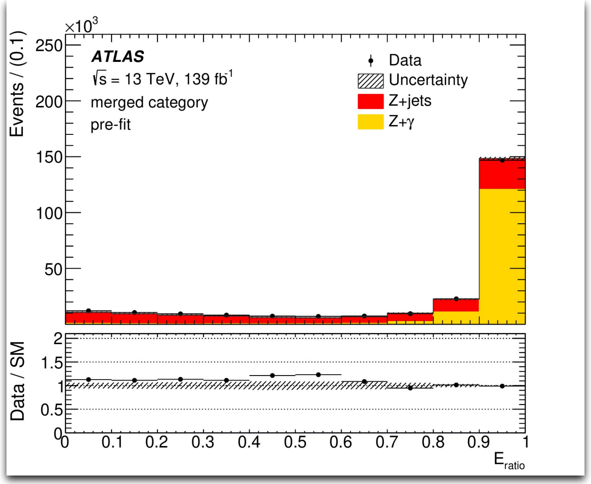
- **Exploring $m_a \in (0.1, 33)$ GeV**
- **"Resolved" SR** (≥2 photons) for large m_a:
  - $\Delta R_{\gamma\gamma}<1.5$ & $\Delta R_{\gamma\gamma} p_{T,\gamma\gamma}/(2m_{\gamma\gamma})$ ratio compatible with unity
  - Calorimeter + (optionally) track-based photon isolation
  - **$m_{Z\gamma\gamma}$ compatible with Higgs mass**
- **"Merged" SR** (≥1 photons) for small m_a (failing resolved):
  - Highest-p_T photon as the $a\rightarrow\gamma\gamma$ candidate
  - Track-based photon isolation only
  - **$m_{Z\gamma}$ compatible with Higgs mass**

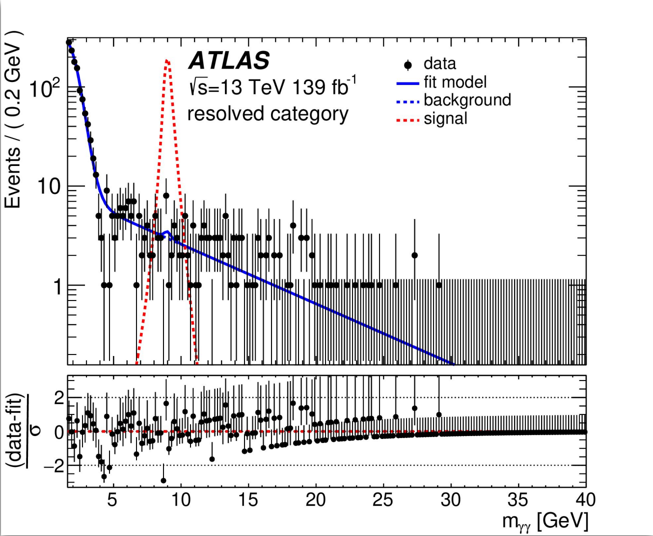


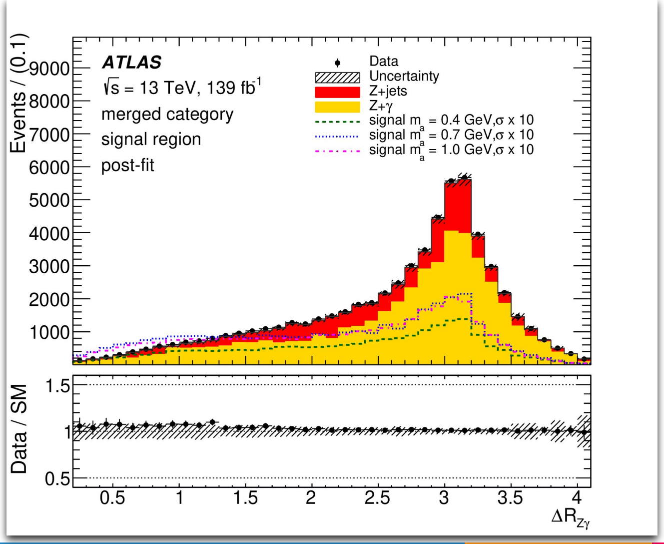


$H \to Z(ll)a(\gamma\gamma)$ 2312.01942 & PLB

- **"Resolved" SR** ($\geq$2 photons) for large m_a:
  - **Fit to $m_{\gamma\gamma}$** using analytic functions
  - Data-driven background estimate from sideband CRs
- **"Merged" SR** ($\geq$1 photons) for small m_a (failing resolved):
  - Photon cluster energy maxima used to suppress Z+Jets
  - **Fit to $\Delta R_{Z\gamma}$** with background shape corrections from data in CRs

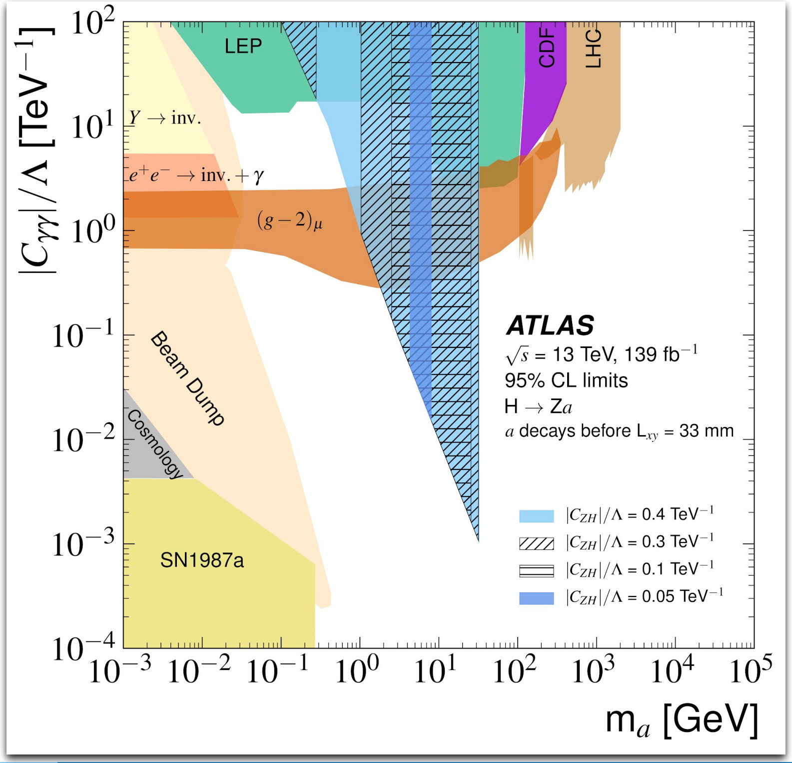


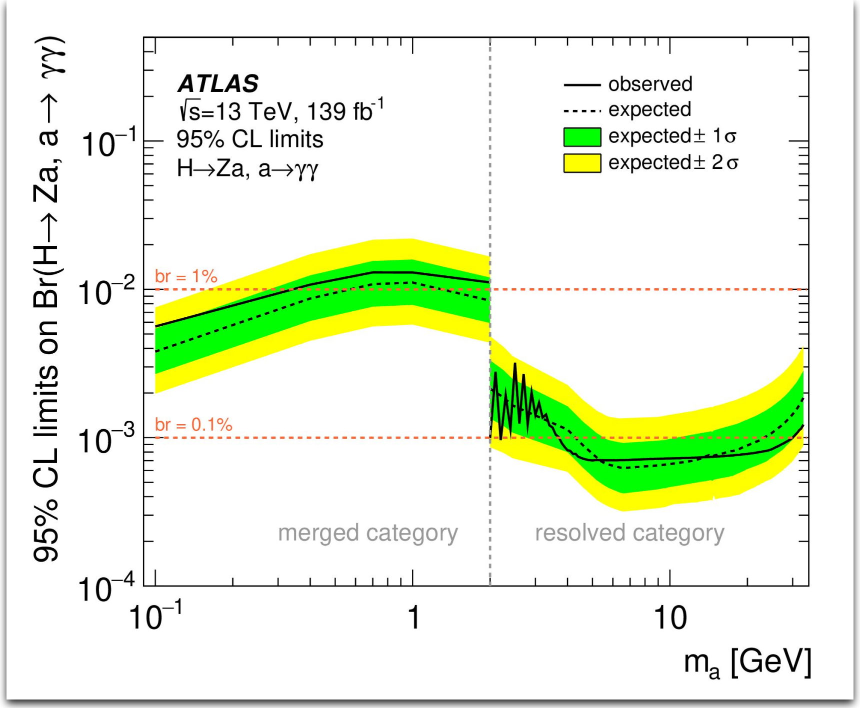




H→Z(ll)a(γγ) [2312.01942](#) & [PLB](#)

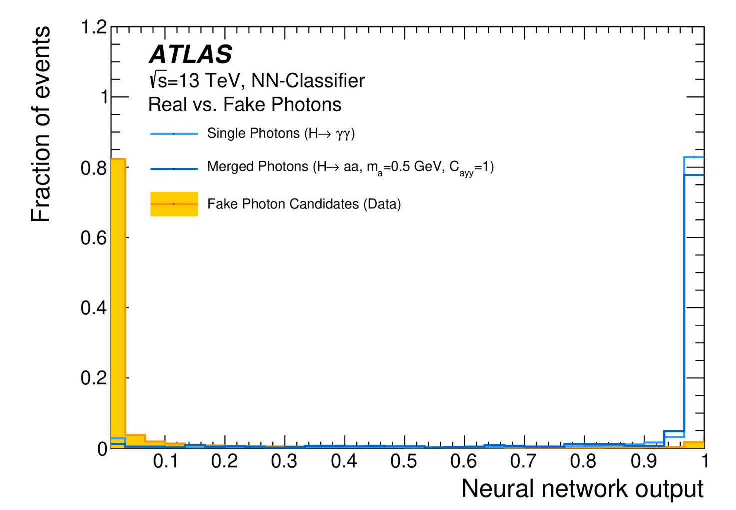
- Post-fit distributions show **no significant excess**
- **Limits** on BR(H→Za)×BR(a→γγ) of **~0.08%-2%**
- Interpreted as **prompt ALP** parameter constraints

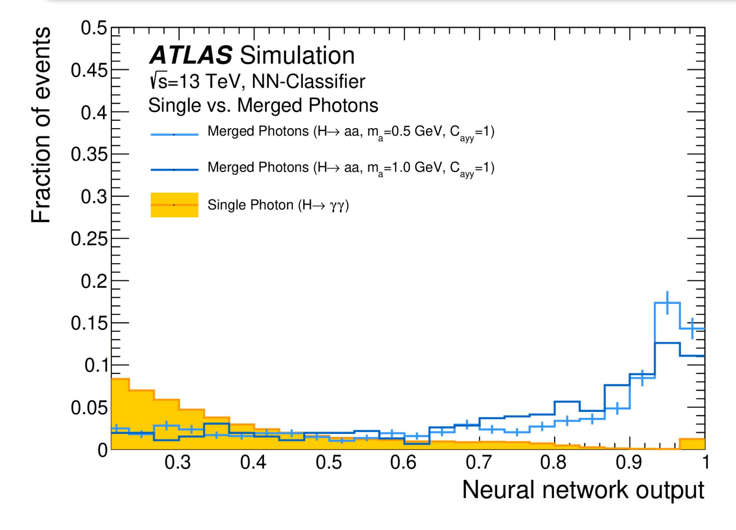




H→aa→γγγγ 2312.03306 & EPJC

- **Exploring $m_a \in$ (0.1 , 62) GeV**, prompt + **long-lived** ALPs
- **Displaced photons** for long-lived ALP sensitivity
  - Consider scenarios with **$|C_{\gamma\gamma}|$ as low as 10^{-5} (!)**
  - **Dedicated uncertainties** for displaced tracks/vertices
- **Track-based** photon isolation
- Two-staged NN approach to **merged photon ID**
  - **First NN** classifies real **photons VS jet** fakes
  - **Second NN** classifies **single VS merged** photons
  - Both use **same set of shower-shape** variables
  - Photon passing **cuts on both NNs** classified as merged
  - **Dedicated uncertainties** for NN classifier

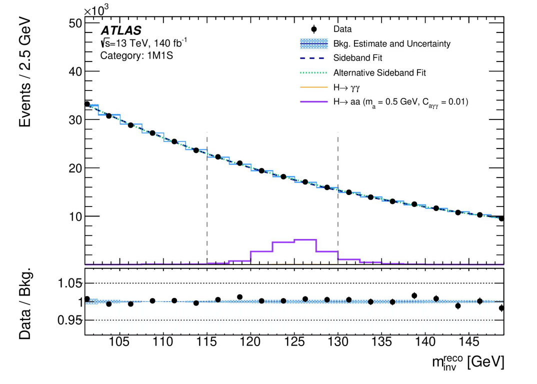


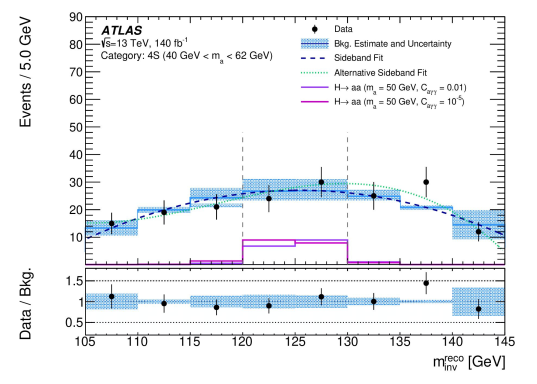


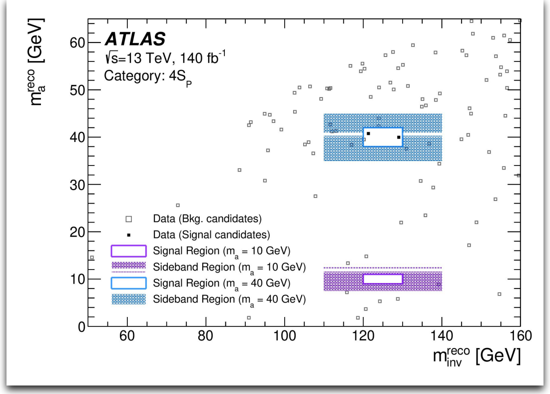
H→aa→γγγγ 2312.03306 & EPJC

- **Event categories** defined by photon multiplicities
  - **nS** = n **Single** photons **;** **nM** = n **Merged** photons
  - m_{inv} **reconstructed** in all event categories
  - m_a **reconstructed in 3S and 4S** categories, pairings from **dedicated NN's** trained on kinematic information
- **Fitting reconstructed** m_{inv} in all categories
- **Data-driven background** estimates from sidebands

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	
$5\text{ GeV} \leq m_a < 25\text{ GeV}$	$120\text{ GeV} < m_{\text{inv}}^{\text{reco}} < 130\text{ GeV}$ $\lvert m_a - m_a^{\text{reco}}\rvert < 1\text{ GeV}$	
$25\text{ GeV} \leq m_a < 40\text{ GeV}$	$120\text{ GeV} < m_{\text{inv}}^{\text{reco}} < 130\text{ GeV}$ $\lvert m_a - m_a^{\text{reco}}\rvert < 2\text{ GeV}$	
$40\text{ GeV} \leq m_a < 50\text{ GeV}$	$120\text{ GeV} < m_{\text{inv}}^{\text{reco}} < 130\text{ GeV}$ $\lvert m_a - m_a^{\text{reco}}\rvert < 3\text{ GeV}$	
$50\text{ GeV} \leq m_a < 55\text{ GeV}$	$120\text{ GeV} < m_{\text{inv}}^{\text{reco}} < 130\text{ GeV}$ $\lvert m_a - m_a^{\text{reco}}\rvert < 5\text{ GeV}$	
$55\text{ GeV} \leq m_a \leq 62\text{ GeV}$	$120\text{ GeV} < m_{\text{inv}}^{\text{reco}} < 130\text{ GeV}$ $\lvert m_a - m_a^{\text{reco}}\rvert < 8\text{ GeV}$	

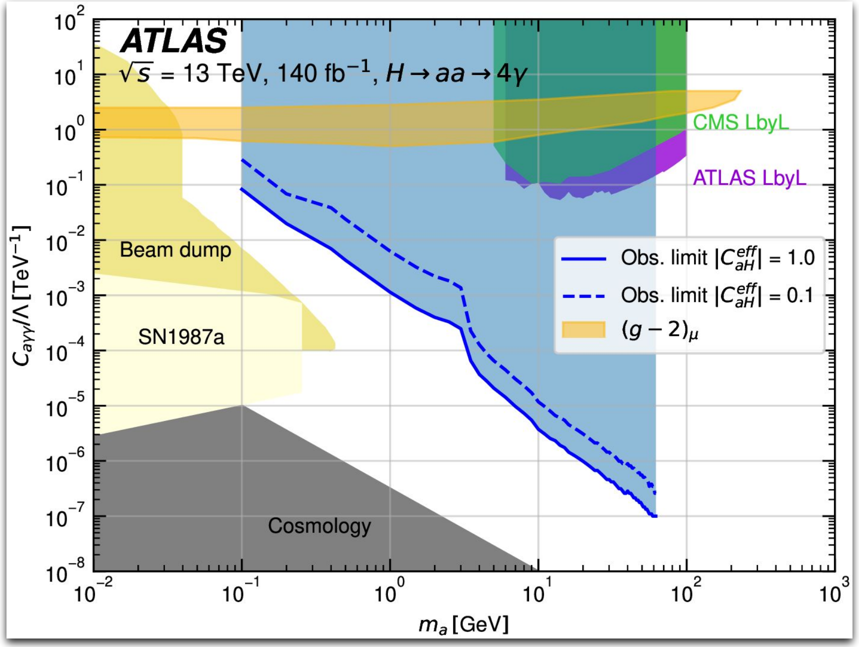


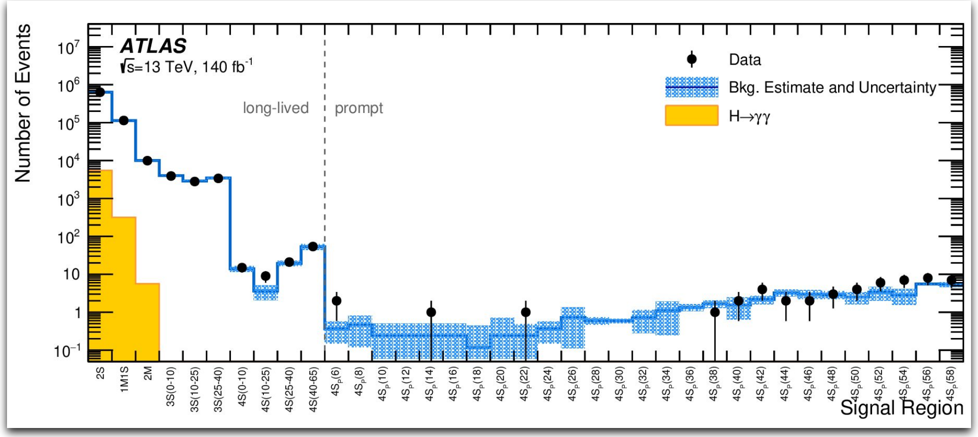


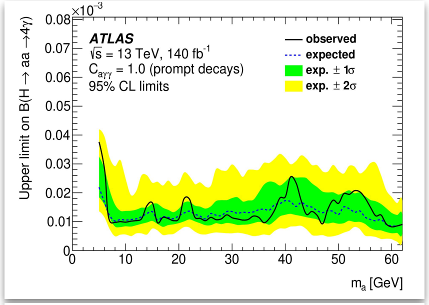


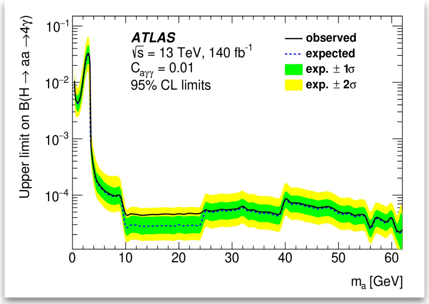
H→aa→γγγγ [2312.03306](#) & [EPJC](#)

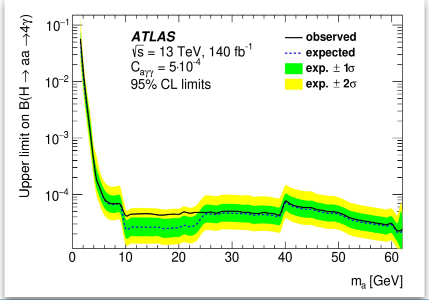
- **No significant excess** observed
- $BR(H\to aa)\times BR(aa\to 4\gamma)$ **limits span ~3 OOMs**
- **Strong constraints** placed on parameter space, **extending to long-lived ALPs**!

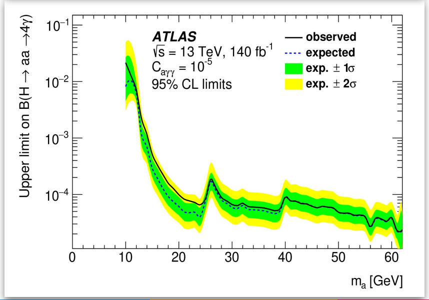








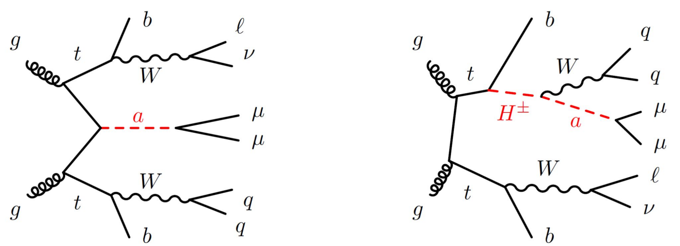




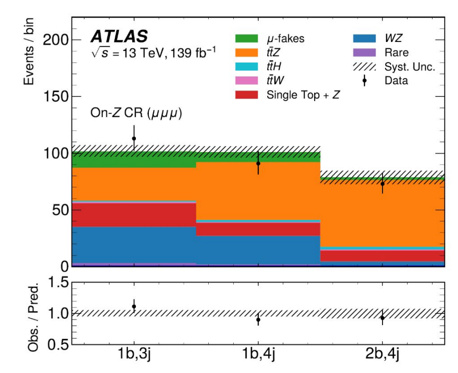
Searches Without Higgs Boson Decays

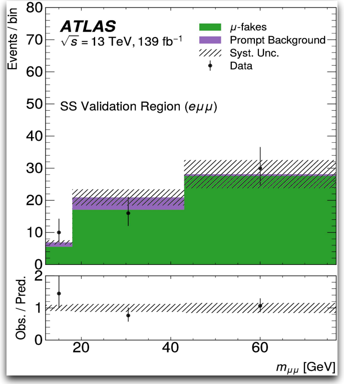
Low-mass a→μμ with $t\bar{t}$ 2304.14247 & PRD

- **Exploring $m_a \in$ (15 , 72) GeV**
- Considering **two different signal models**
  - $t\bar{t}a$ associate production (**limits on σ×BR**)
  - $t\bar{t}$ with t→**H±**b, **H±**→W±a **[$m_{H\pm} \in$ (120 , 160) GeV]**
- **Events categorized** as μμμ/eμμ
- Fit to **$m_{\mu\mu}$ spectrum** in the SR
- **Signal $m_{\mu\mu}$ modelled** as DSCB and extrapolated
- CR to estimate dominant **$t\bar{t}Z$ normalization**
- **Fake-μ** from "isolation-sideband" **data** (FF's)
  - **In all regions**, most constrained by $t\bar{t}$-CR
- **Dominant uncertainty** from statistics



	Signal Regions		on-Z Control Region		$t\bar{t}$ Control Region
Channel	$e\mu\mu$	$\mu\mu\mu$	$e\mu\mu$	$\mu\mu\mu$	$e\mu\mu$
Binning	$m^{a}_{\mu\mu}$	$m^{a}_{\mu\mu}$	$n_{\text{jets}}, n_{b\text{-jets}}$	$n_{\text{jets}}, n_{b\text{-jets}}$	$p_{\text{T}}^{\mu,\text{fake}}$
$n_{\text{electrons}}$	1	0	1	0	1
n_{muons}	2	3	2	3	2
$m_{\mu\mu}$ [GeV]	$12 < m^{a}_{\mu\mu} < 77$ -	$12 < m^{a}_{\mu\mu} < 77$ and $m^{\text{other}}_{\mu\mu} < 77$ or > 107	$77 < m^{a}_{\mu\mu} < 107$ -	$77 < m^{a}_{\mu\mu} < 107$ or $77 < m^{\text{other}}_{\mu\mu} < 107$	$12 < m^{a}_{\mu\mu} < 77$ -
n_{jets}	≥ 3				1 or 2
$n_{b\text{-jets}}$	≥ 1				1

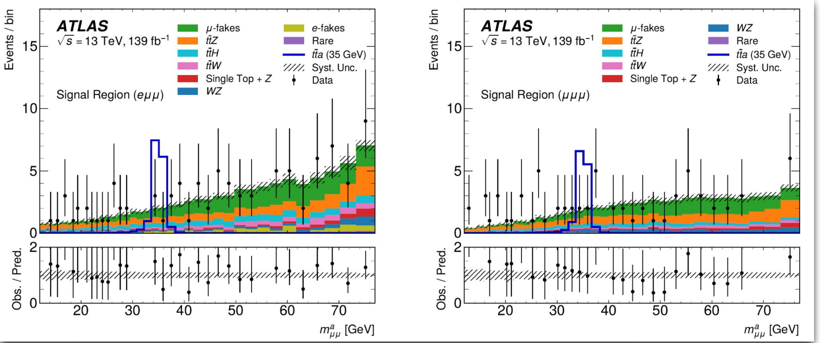


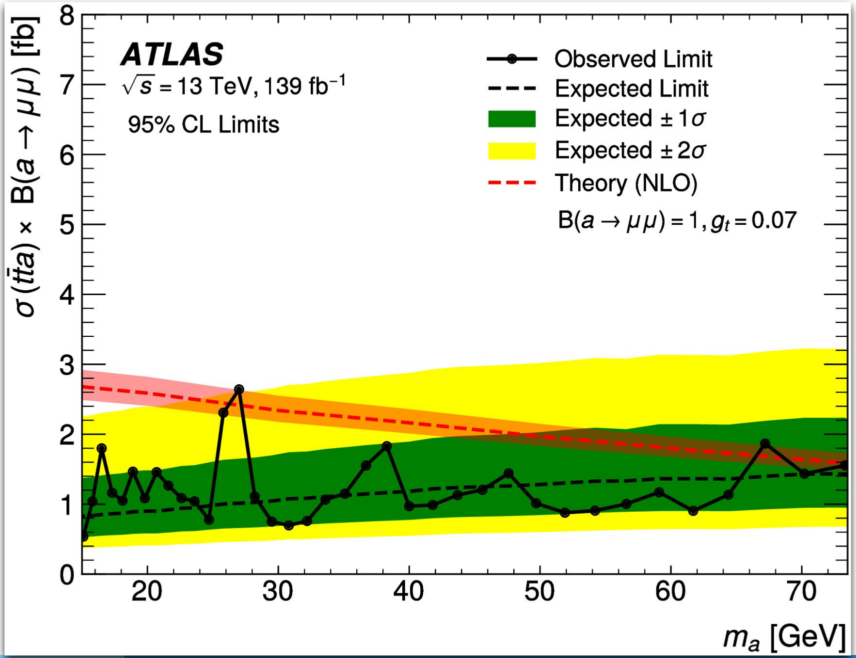


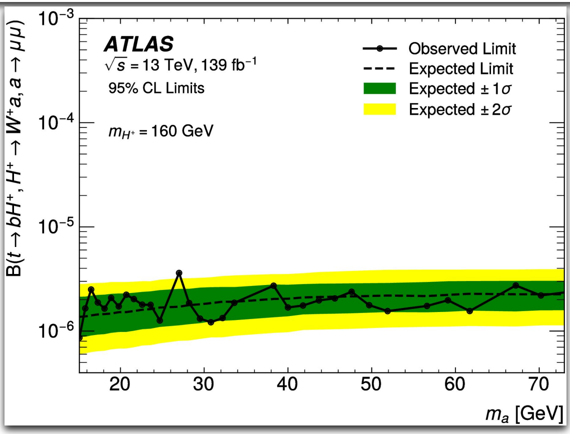
Low-mass $a \to \mu\mu$ with $t\bar{t}$ 2304.14247 & PRD

- Data in **good agreement** with prediction, **small excess** around **m_a = 27 GeV** with **~2.4σ** (local) significance
- Limits on **σ×BR** between **0.5-3 fb** for $t\bar{t}a$ search
- Limits on **BR($t \to H^{\pm}b$, $H^{\pm} \to W^{\pm}a$, $a \to \mu\mu$)** of **~(1-4)×10^{-6}**

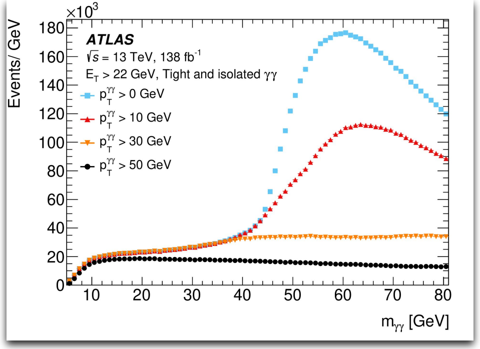
Processes	Signal Regions $e\mu\mu$	Signal Regions $\mu\mu\mu$
μ-fakes	32 ± 12	25 ± 10
$t\bar{t}Z$	22 ± 5	21 ± 5
$t\bar{t}H$	13.1 ± 1.3	8.0 ± 0.8
$t\bar{t}W$	6.9 ± 1.3	4.3 ± 1.0
Single Top + Z	3.3 ± 1.7	3.0 ± 2.0
WZ	6.5 ± 2.2	6.9 ± 1.9
e-fakes	5.4 ± 3.1	0
Rare	2.0 ± 0.5	1.9 ± 0.5
Total Background	92 ± 13	71 ± 11
Data	93	69

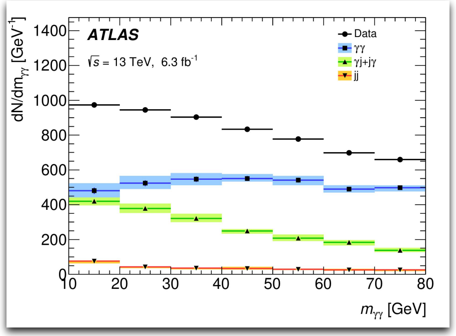




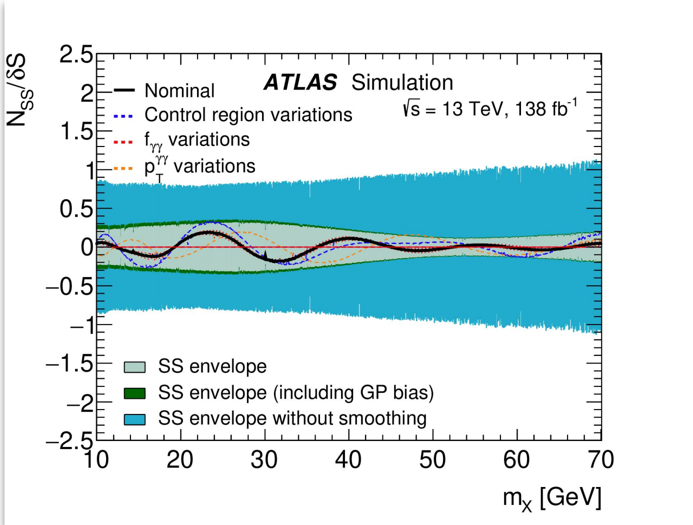


Low mass $a \to \gamma\gamma$ 2211.04172 & JHEP



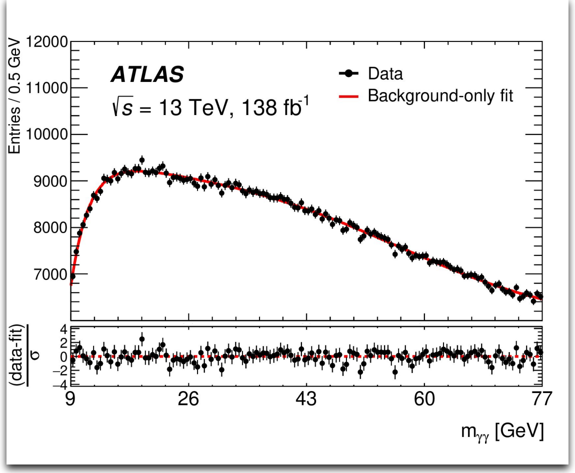


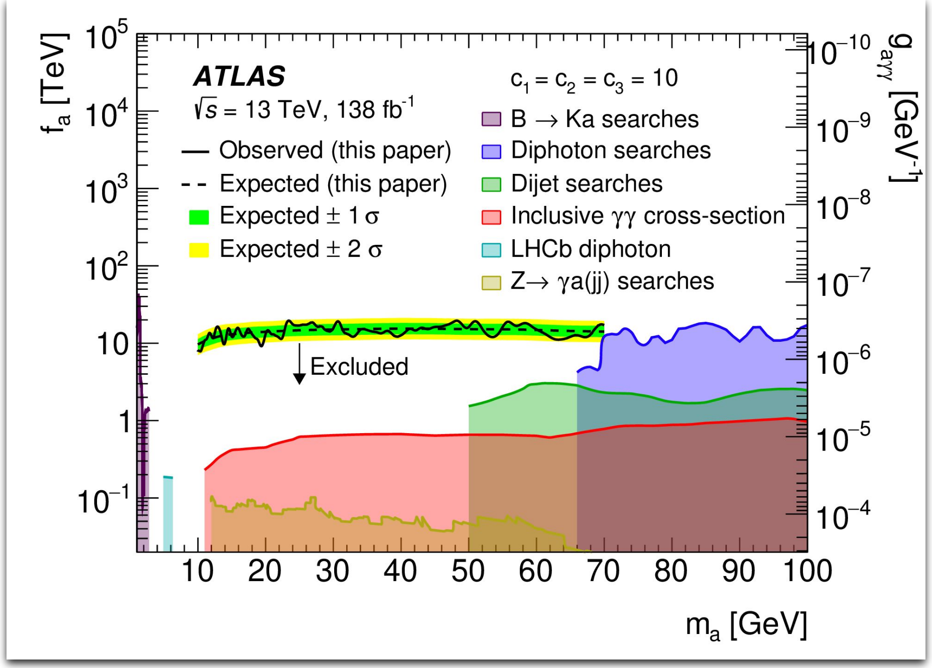
- **Exploring $m_a \in (10, 70)$ GeV**
- Consider **prompt ALP** scenarios
- Two isolated photons, fit to **$m_{\gamma\gamma}$ spectrum**
- $p_T(\gamma\gamma)$>50 GeV **flattens** background, **boosted** $\gamma\gamma$
- **Signal $m_{\gamma\gamma}$ modelled** as DSCB and extrapolated
- **Background modelled** as analytic function
  - **$\gamma\gamma$** from simulation, **γ+jets** and **dijet** from data
  - Relative fractions obtained from **2D sidebands**
  - **Gaussian-Processes** background template smoothing **significantly reduces** spurious signal uncertainty
- **Fiducial volume** defined with truth-level cuts
- Parameterized signal detection efficiency **correction factor**

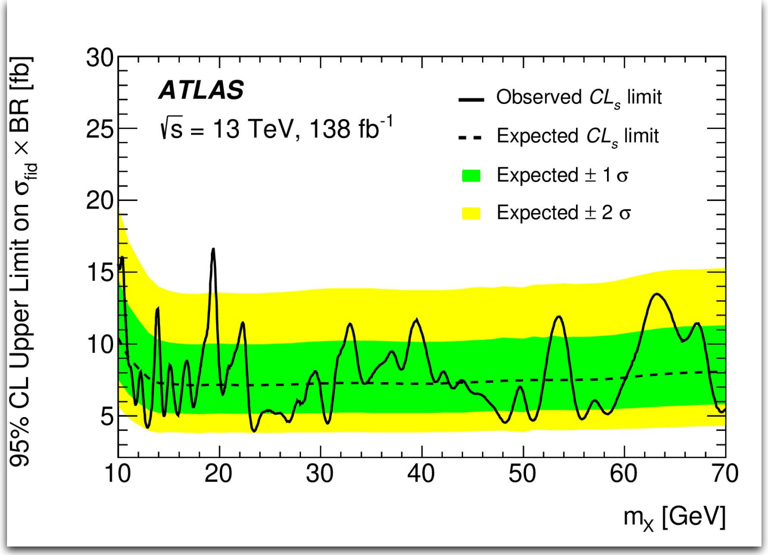


Low mass a→γγ [2211.04172](#) & [JHEP](#)

- Data **consistent with background** prediction, **small excess** at $\mathbf{m_a}$ **= 19.4 GeV** with **~3.1σ (1.5σ)** local (global) significance
- Limits on $\boldsymbol{\sigma_{fid}}$**×BR** between **4-17 fb** are interpreted in the parameter space of a **prompt ALP model** (KSVZ-ALP)







There Will Be More…

Summary and Conclusions

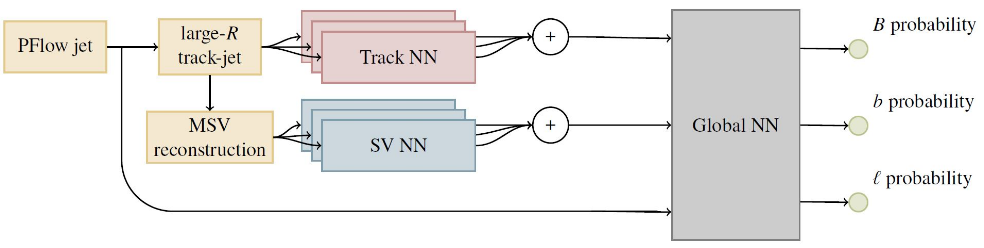
- **ALPs appear generically** in many extensions of the SM with (approximate) global SSB
- ATLAS has a **rich ALP (and low-mass ALP-like) search program**, covering a motivated **wide mass/coupling** range in **multiple final-states**, both **prompt and long-lived**
- **Complementary** to similar searches in CMS and to **constraints from other experiments**
- Presented **several ATLAS results** for searches with and without Higgs decays
  - Most have performed **interpretation in ALP parameter space** yielding robust constraints (**not bad!**)
  - So indeed we have some additions and updates to those old summary plots (**great success!**)
  - We'll keep working hard to produce more results and cover new signatures (**great effort!**)
  - Shout-out to **low-mass a→ττ**, aka "*Holy moly that's a lotta MET*" (2409.20381 , submitted to JHEP)
- Stay (not fine-) tuned, there will be more ("*Run3, precious?*"), and **may the ALPs be with you**!

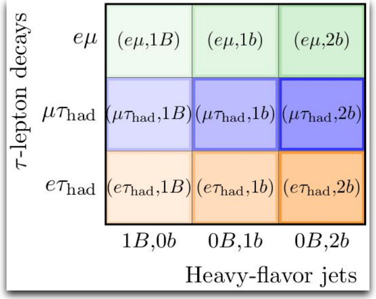
Thanks for your attention!

BACKUP

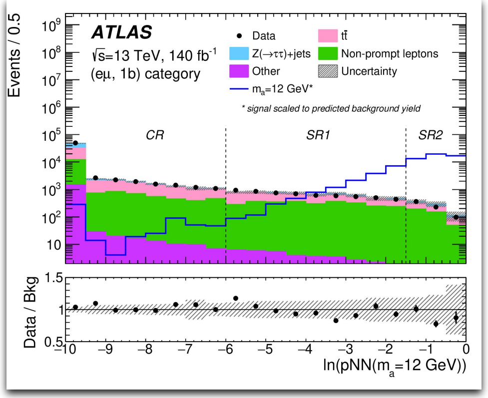
H→aa→bbττ [2407.01335](#) & [PRD](#)

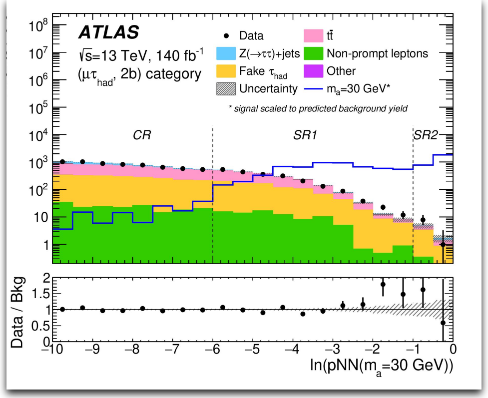
- **Exploring $m_a \in (12, 60)$ GeV**
- Using **novel X→bb tagger** (DeXTer)
  - Low-p_T reclustered R=0.8 track-jet classifier
  - **DeepSet-based**, jet+track+SV features
  - Greatly enhances **low-m_a sensitivity**
  - **Calibrated in data** for efficiency corrections
- **Event categories** defined by ττ decay mode and b/B-jet multiplicities
- CRs to control **background contributions**
- **pNN event discriminant** for each category
- Simultaneous **fit in three pNN bins** (2SR+CR) **across all 9 categories**





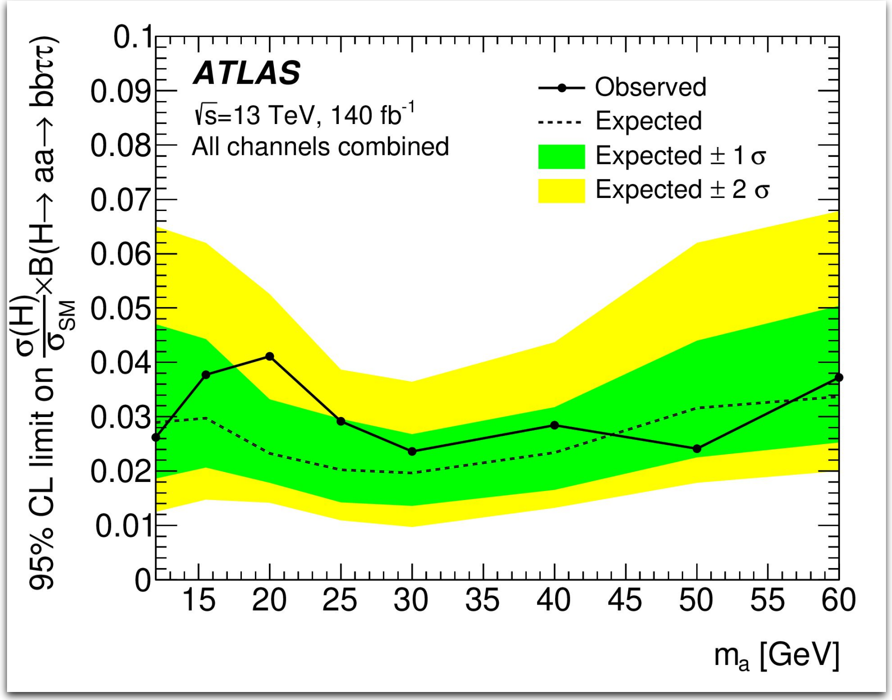
Region	$e\mu$	$e\tau_{had}$ or $\mu\tau_{had}$
Signal region	1 OS signal $e\mu$ pair 0 signal τ_{had} $\Delta R(e,\mu) > 0.1$ $4 < m^{vis}(\tau\tau) < 45$ GeV	1 OS signal $e\tau_{had}$ or $\mu\tau_{had}$ pair 1 signal τ_{had} $\Delta R(\ell,\tau) > 0.2$ $4 < m^{vis}(\tau\tau) < 60$ GeV
	$\Sigma m_T < 120$ GeV 1 B-jet or 1 or 2 b-jets	
Z region	$m^{vis}(\tau\tau) > 45$ GeV	$m^{vis}(\tau\tau) > 60$ GeV
$t\bar{t}$ region	$\Sigma m_T > 120$ GeV, no $m^{vis}(\tau\tau)$ requirement	
SS region	1 SS signal $e\mu$ pair	1 SS signal $e\tau_{had}$ or $\mu\tau_{had}$ pair

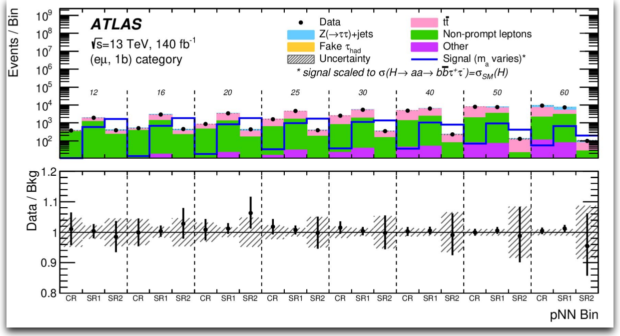


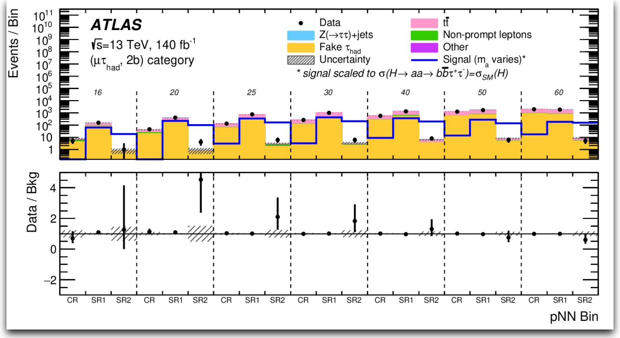


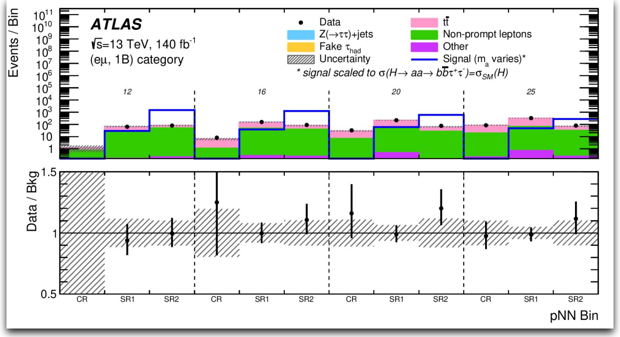
H→aa→bbττ 2407.01335 & PRD

- **No significant excess observed**
- **Limits** on BR(H→aa)×BR(aa→bbττ) **between 2%-4%**
- **Assuming** SM Higgs production cross-section





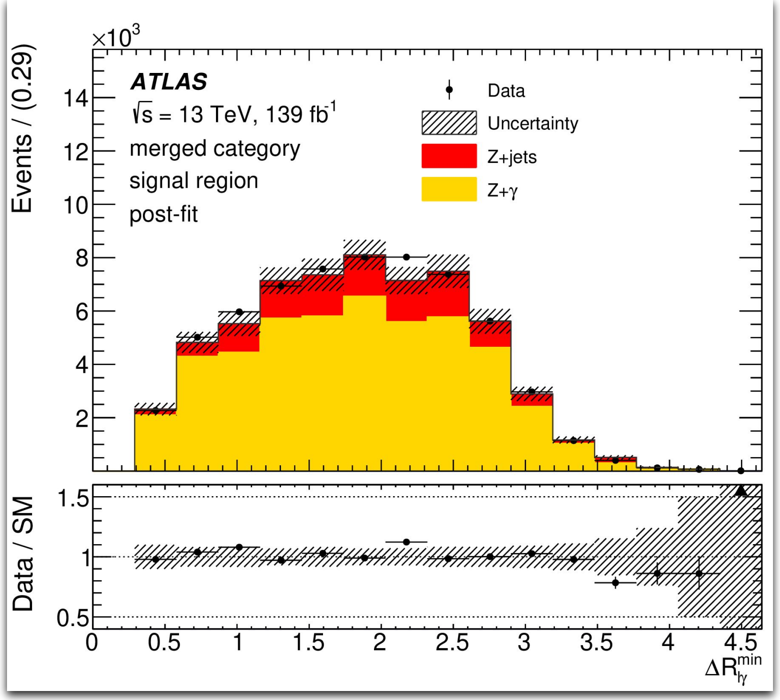


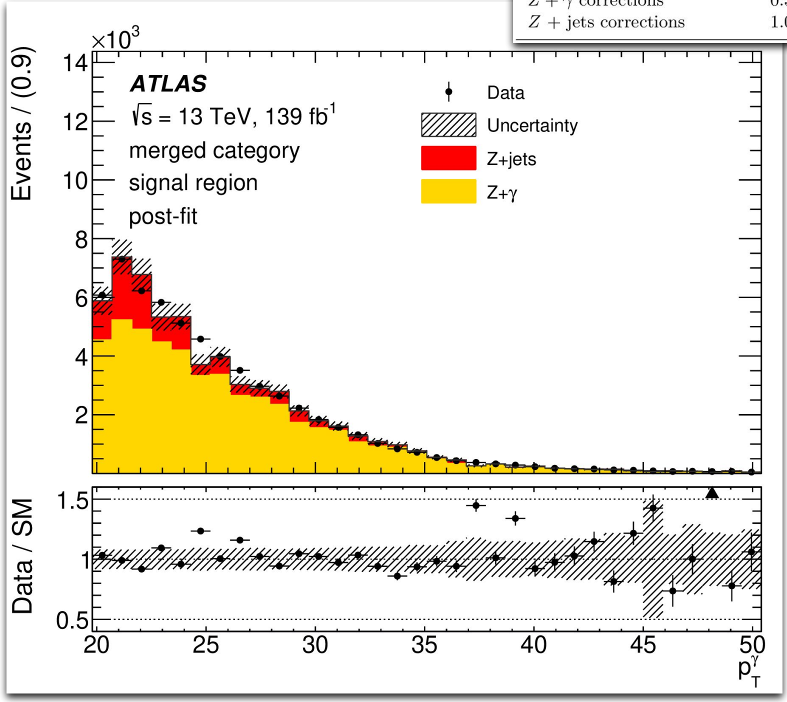


H→Z(ll)a(γγ) 2312.01942 & PLB

- Biggest uncertainty on merged channel from MC stats
- Subdominant uncertainty from signal modelling
- Kinematic distributions in CR validate background modelling

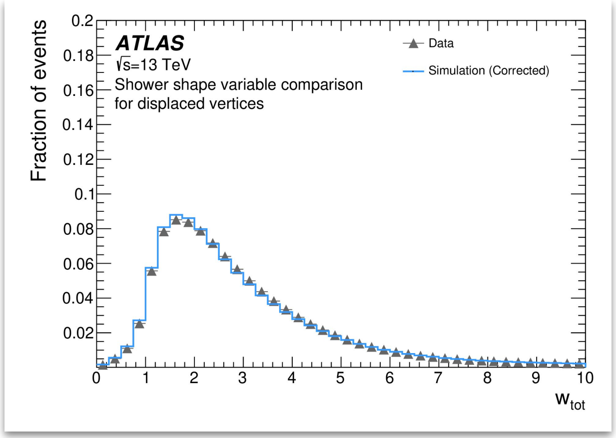
Source	1σ Uncertainty
Total	28%
Data statistical unc.	1.4%
MC statistical unc.	26%
Total background	5.6%
Signal modelling	5.2%
Pile-up	0.2%
Electron identification	0.4%
Photon isolation	0.9%
Muon trigger	0.6%
Muon reconstruction	0.3%
Muon isolation	0.3%
$Z+\gamma$ normalisation	0.8%
$Z+$ jets normalisation	0.9%
$Z+\gamma$ corrections	0.3%
$Z+$ jets corrections	1.0%

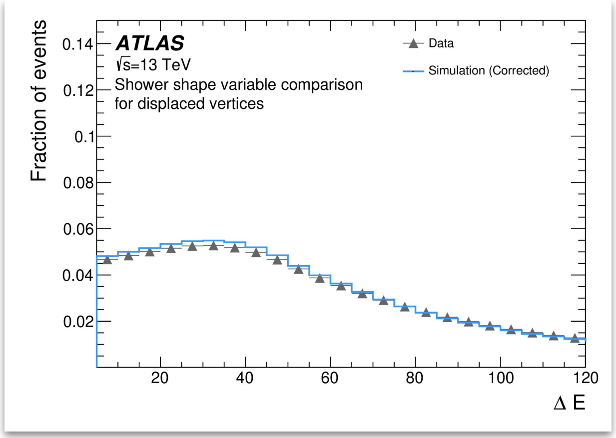


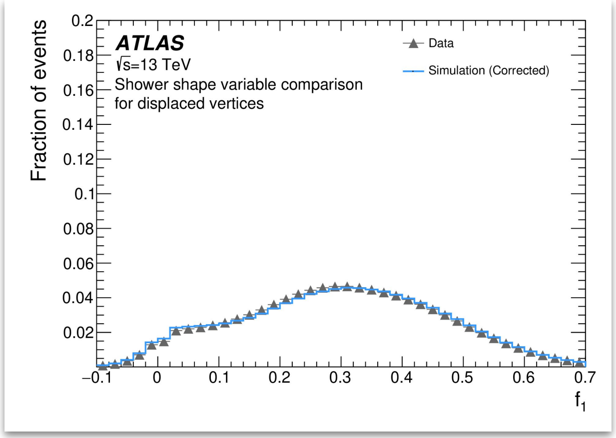


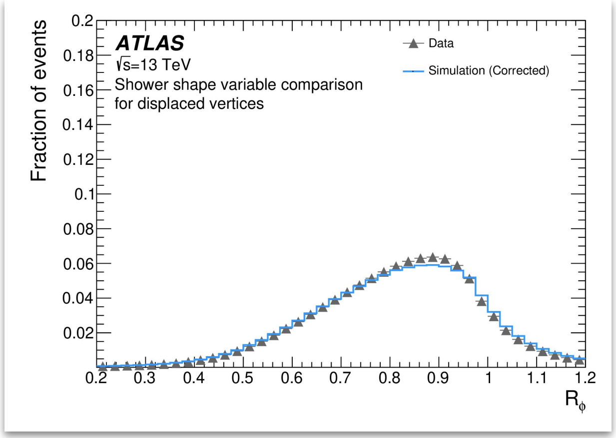
H→aa→γγγγ [2312.03306](#) & [EPJC](#)

- Modelling of (corrected) shower shape variables in displaced vertex reconstruction



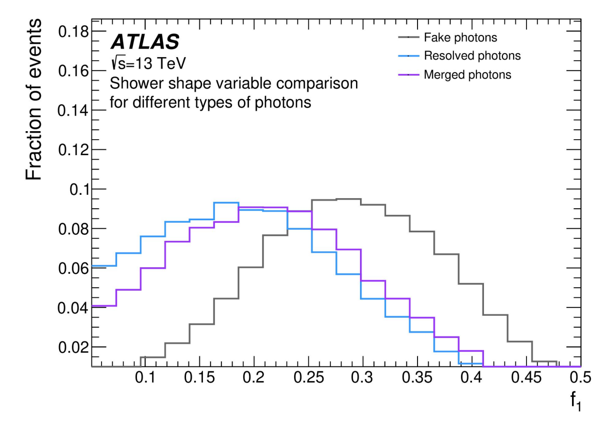


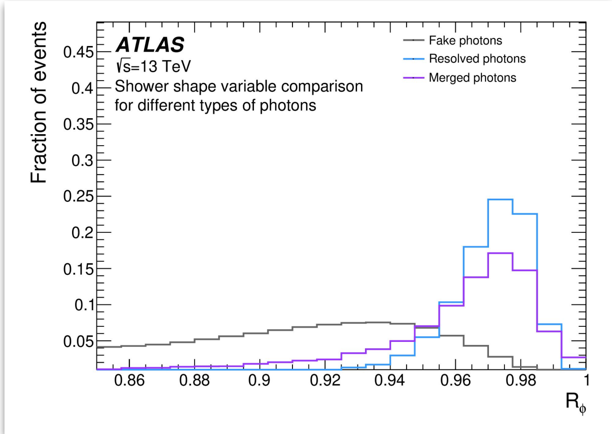


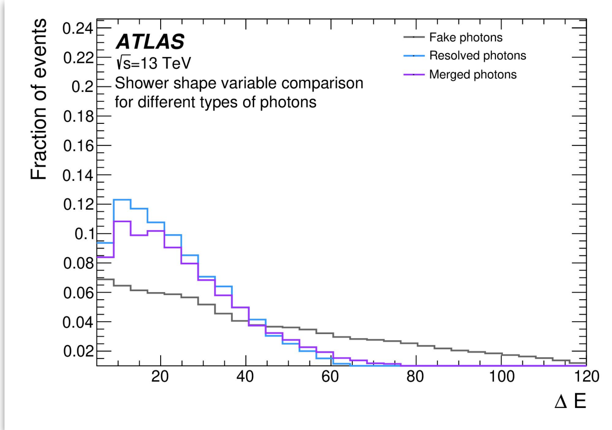


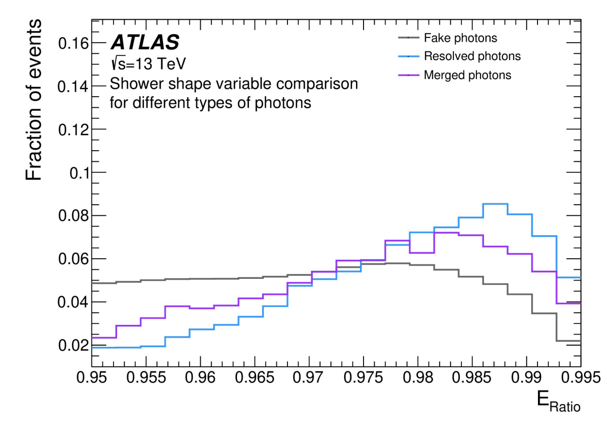
H→aa→γγγγ [2312.03306](#) & [EPJC](#)

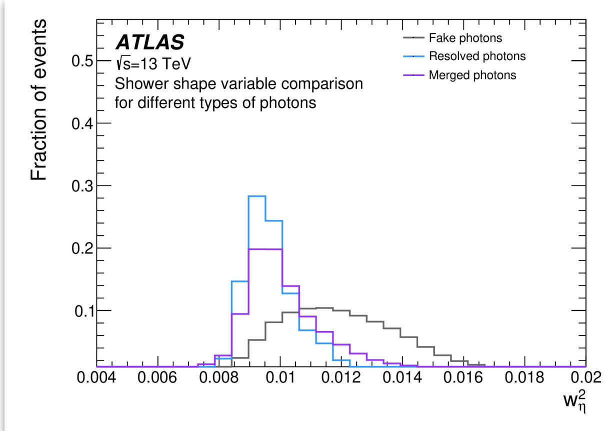
- Shower shape variables in resolved (MC), merged (MC) and fake (data) photons

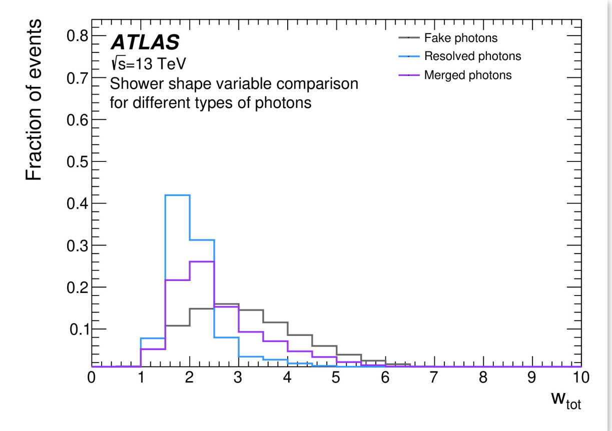






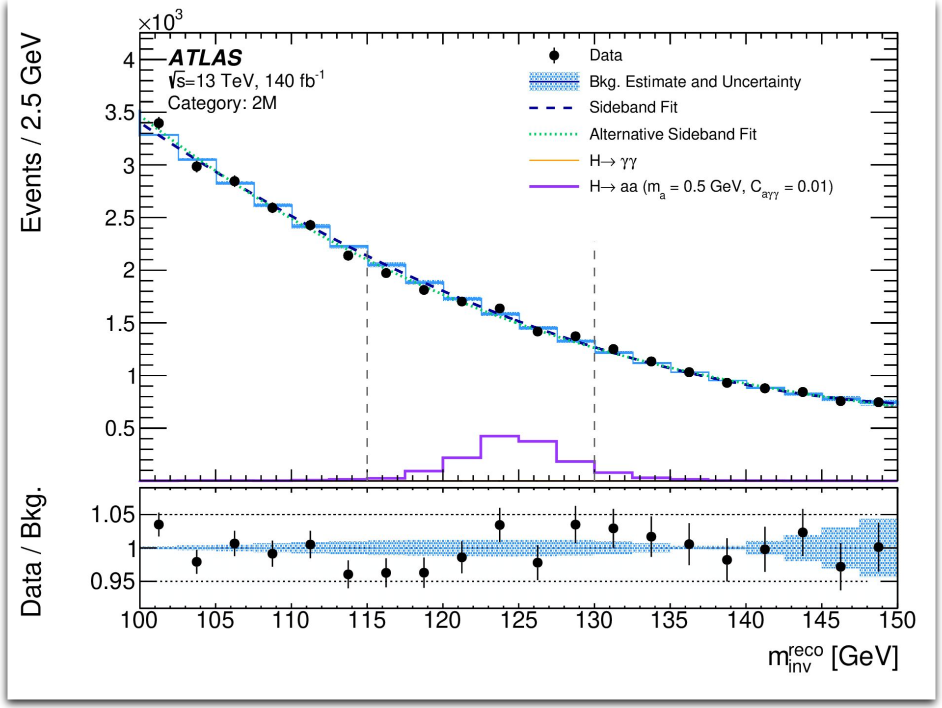


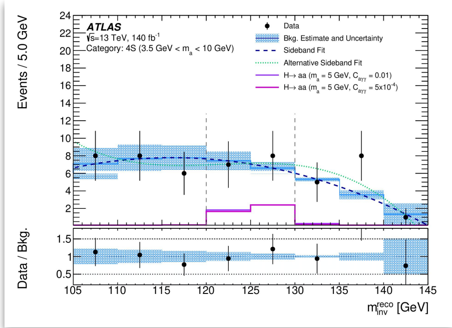


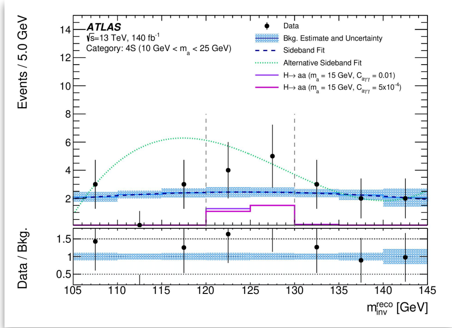


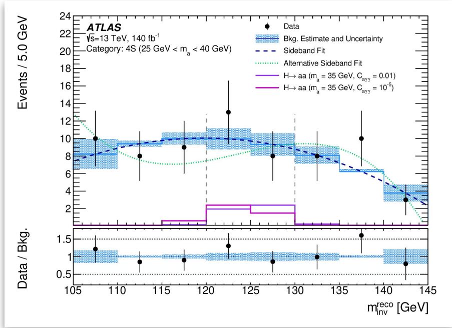
H→aa→γγγγ [2312.03306](https://arxiv.org/abs/2312.03306) & EPJC

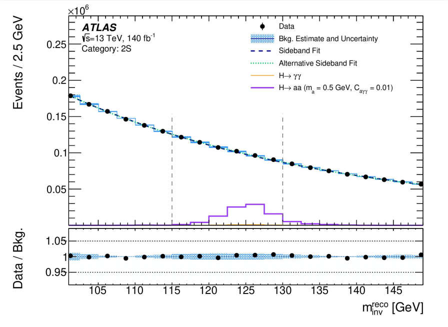
- More m_{inv} distributions with sideband fits
- 2D sideband plots in $4S_p$ region in simulation

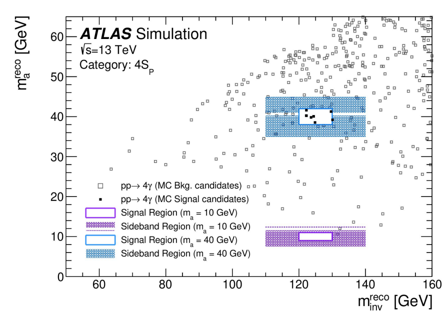








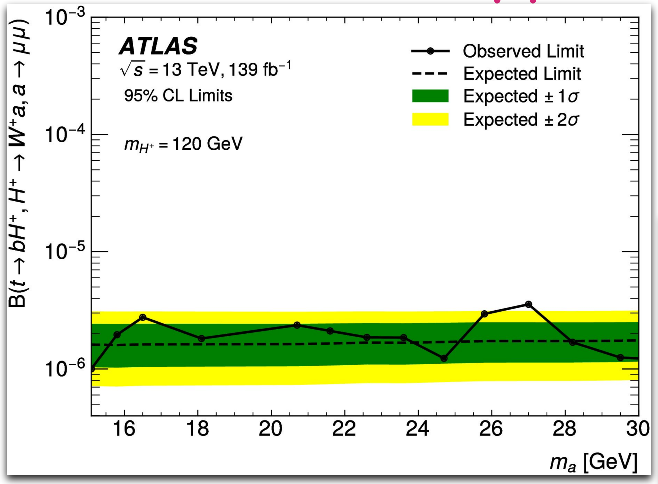


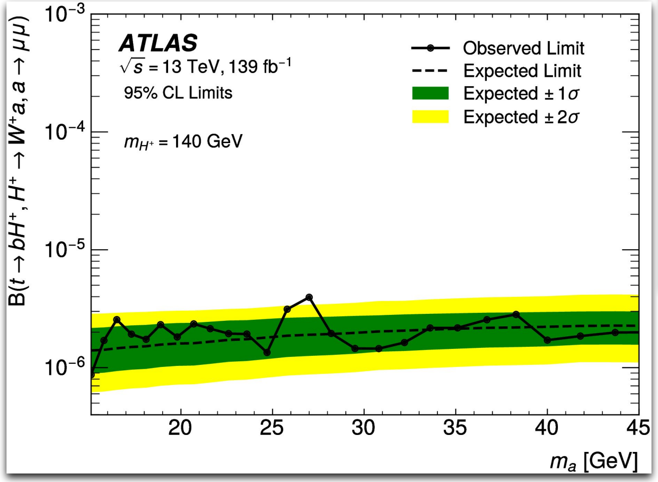


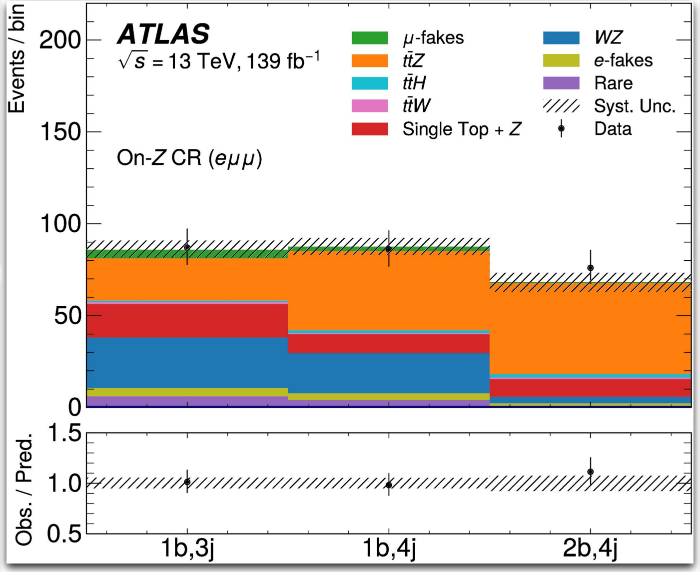
H→aa→γγγγ 2312.03306 & EPJC

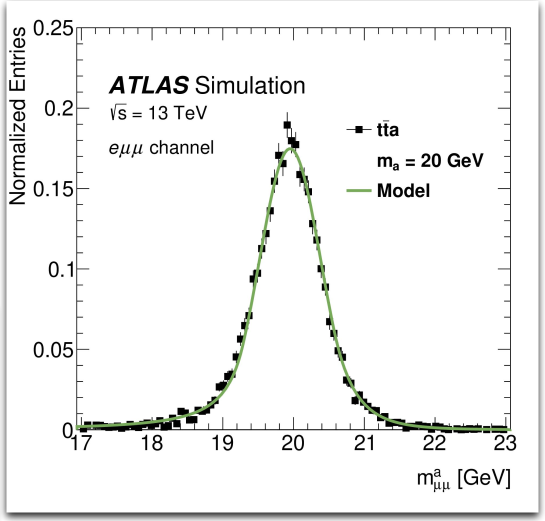
Category	m_a [GeV]	$C_{a\gamma\gamma}$	MC-Stat [%]	Standard Photon [%]	Custom Photon [%]	Trigger [%]	Pile-Up [%]	Modelling/ Theory [%]	Combined [%]
2S	0.5	1	2.12	2.5	2.0	7.4	1.3	3.3	9.06
1S1M	0.5	1	1.64	2.1	5.0	2.5	2.1	3.3	7.32
2M	0.5	1	1.39	2.4	10.3	2.4	2.3	3.3	11.65
2S	1	1	2.77	2.6	1.5	6.4	1.3	3.3	8.38
1S1M	1	1	2.29	2.1	5.0	2.6	2.1	3.3	7.53
2M	1	1	2.27	2.4	10.3	2.5	2.3	3.3	11.81
2S	3	1	1.35	2.9	1.1	6.5	1.3	3.3	8.14
1S1M	3	1	3.82	2.2	5.0	1.9	2.1	3.3	7.96
2M	3	1	14.0	2.2	10.3	1.8	2.3	3.3	18.07
Prompt									
4S	5	1	3.03	9.86	0.0	2.7	3.4	2.1	11.39
4S	10	1	2.36	8.8	0.0	3.2	3.4	2.1	10.45
4S	20	1	2.45	8.6	0.0	2.5	3.4	2.1	10.11
4S	30	1	2.54	8.1	0.0	1.3	3.4	2.1	9.47
4S	40	1	2.34	8.4	0.0	1.4	3.4	2.1	9.69
4S	50	1	1.83	8.7	0.0	1.5	3.4	2.1	9.86
Long-Lived									
4S	10	10^{-5}	37.8	6.496	22.2	0.4155	3.6	3.3	44.59
4S	20	10^{-5}	3.39	7.11	27.17	2.603	3.6	3.3	28.82
4S	30	10^{-5}	2.55	8.388	9.884	1.321	3.6	3.3	14.15
4S	40	10^{-5}	2.25	8.701	3.753	2.183	3.6	3.3	11.11
4S	50	10^{-5}	1.65	8.185	3.259	1.816	3.6	3.3	10.37

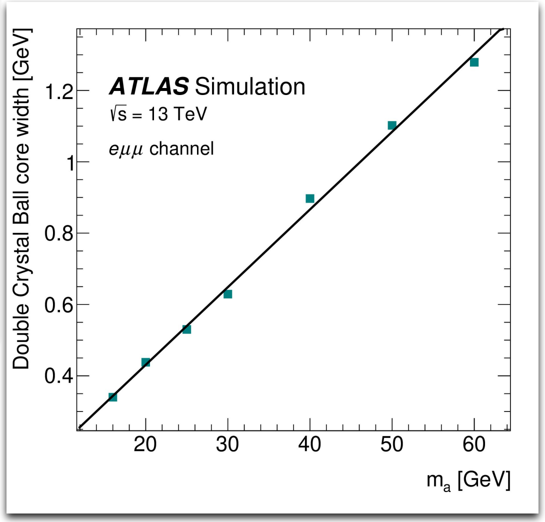
Low-mass a→μμ with $t\bar{t}$ 2304.14247 & PRD



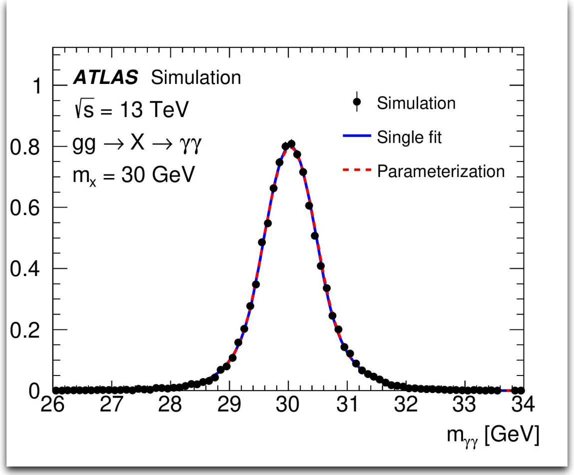


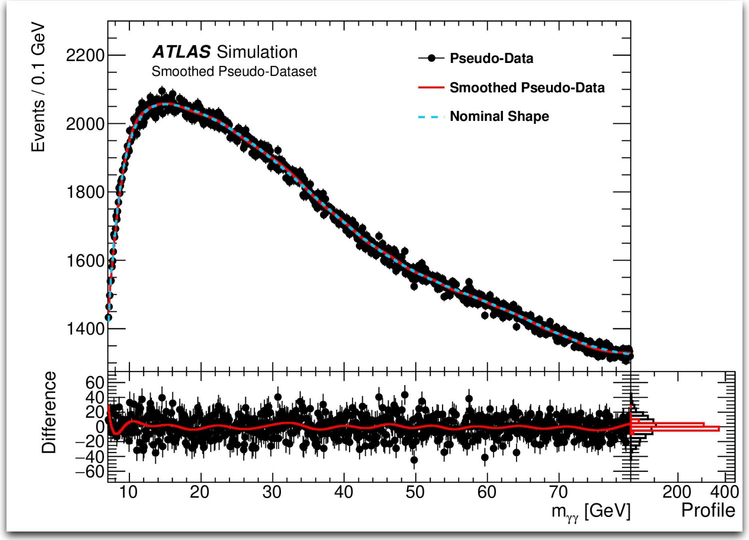


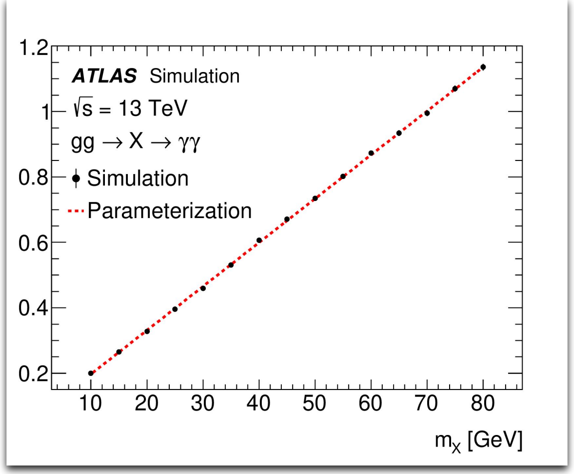


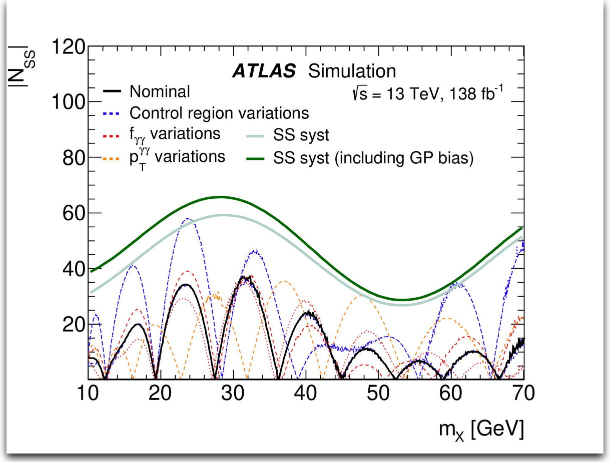


Low mass $a\to\gamma\gamma$ 2211.04172 & JHEP





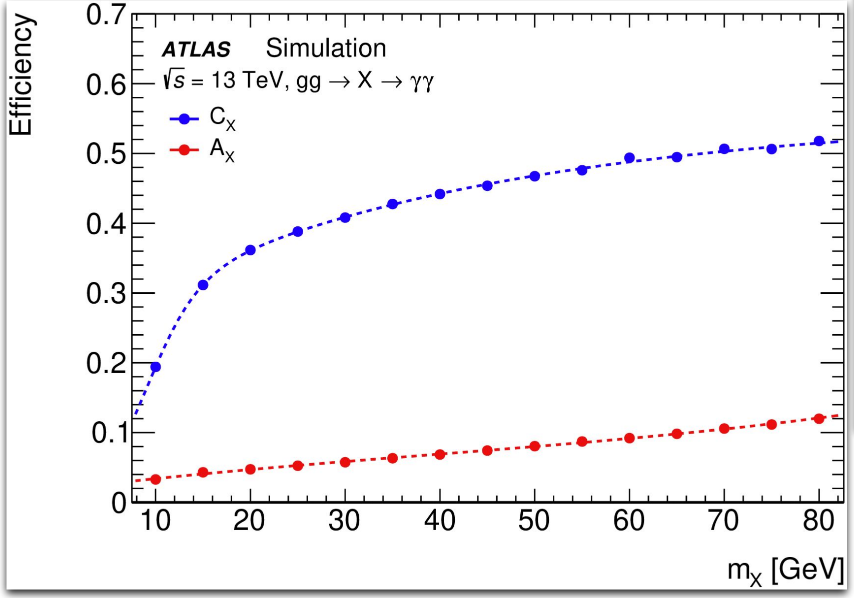




Low mass a→γγ 2211.04172 & JHEP

C_X parametrization
$C_X(m_X[\mathrm{GeV}]) = (0.55 - 0.32\exp(-m_X/38,18))/(1 + 27.05\exp(-m_X/2.62))$

A_X parametrization
$A_X(m_X[\mathrm{GeV}]) = \left(0.02 + \frac{m_X}{605} - \left(\frac{m_X}{259}\right)^2 + \left(\frac{m_X}{199}\right)^3\right)$



Source	Uncertainty
	On $\sigma_{\mathrm{fid}} \cdot \mathcal{B}(X \to \gamma\gamma)$ [%]
Pile-up modelling	±3.5 (at 10 GeV) to ±2 (beyond 15 GeV), mass dependent
Photon energy resolution	±2.5 to ±2.7, mass dependent
Scale and PDFs uncertainties	±2.5 to ±0.5, mass dependent
Trigger on closely spaced photons	±2 (at 10 GeV) to <0.1 (beyond 35 GeV), mass dependent
Photon identification	±2.0
Isolation efficiency	±2.0
Luminosity (2015–2018)	±1.7
Trigger	±1.0
Signal shape modelling	<1
Photon energy scale	negligible
	Background modelling
Spurious signal (relative to δS)	30–65 events (10%–30%), mass dependent