12 SEP 2023

Higgs Hunting 2023

BSM and rare H(125) decays in the ATLAS experiment

MICHAEL CHU

Introduction

Since the discovery in 2012, all experimental observation matches with the SM prediction

A portal to BSM physics:

- Composite Higgs, Additional BSM Higgs bosons
- "SM-like" Higgs boson coupling to $\mathrm{B_{BSM}}$ ←this talk

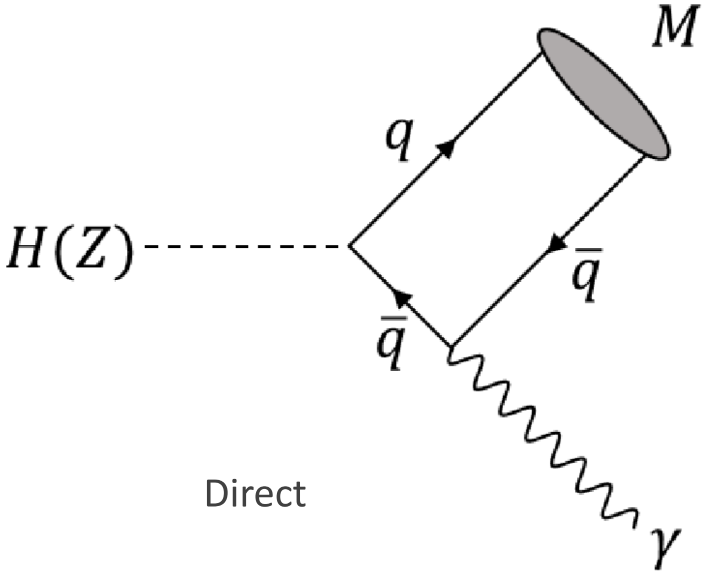
Present today:

- $\mathrm{H} \to \omega\gamma \,/\, \mathrm{K}^{*}\gamma$ (arXiv:2301.09938)
- $\mathrm{H} \to \mathcal{M}\gamma$ (ATL-PHYS-PUB-2023-004)
- $\mathrm{H} \to \gamma\gamma + \mathrm{X}$ (arXiv:2301.10486)
- $\mathrm{H} \to \gamma\gamma_{\mathrm{d}}$ (JHEP07(2023)133)
- $\mathrm{H} \to \mathrm{invisible}$ (arXiv:2301.10731)
- $\mathrm{H} \to \mathrm{LFV}$ (JHEP07(2023)166)

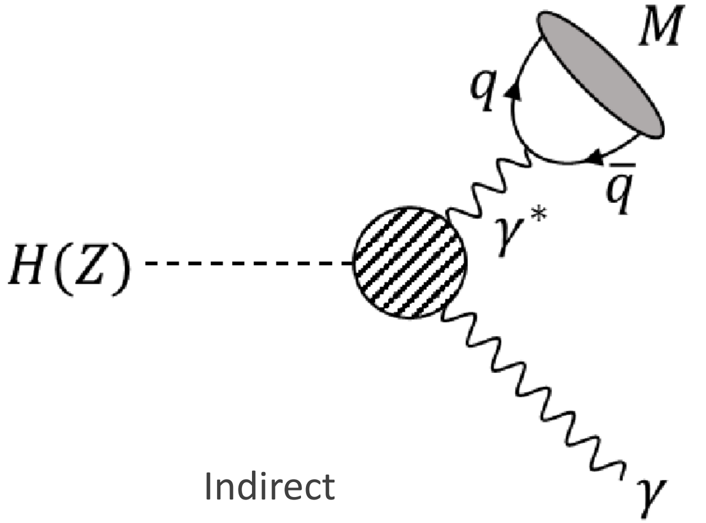
$H \to \omega\gamma$ / $K^*\gamma$

arXiv:2301.09938

- Measurement of Higgs boson coupling to the **first and the second generation of fermions**
- To probe the:
  - **Flavour-conserving coupling** to u and d quarks ($H \to \omega\gamma$)
  - **Flavour-violating coupling** to d and s quarks ($H \to K^*\gamma$)
- SM prediction of such decays are driven by two contributions:
  - '**direct**': scales with Yukawa coupling
  - '**indirect**': $H \to \gamma\gamma \to \mathcal{M}\gamma$ ($\mathcal{M}$ being a meson)
  - The two contributions are typically **destructive interfering**
  - The SM expected branching ratio is of order $< 10^{-6}$
- Major background from **mis-identified meson** from ID tracks originated from a **jet**
  - Estimated by a **non-parametric data-driven model** (arXiv:2112.00650)



Direct



Indirect

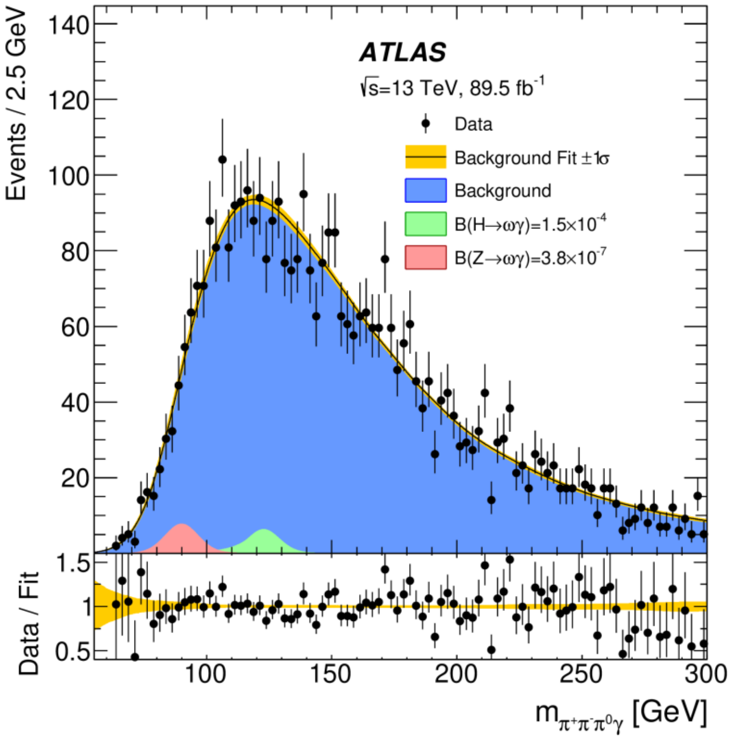
H → ωγ / K*γ

arXiv:2301.09938

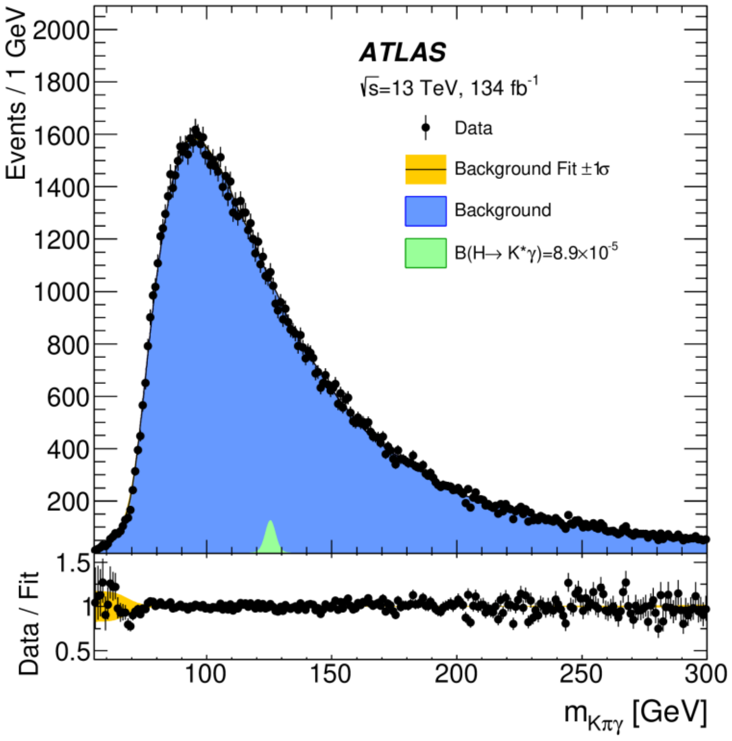
Channel	Mass range [GeV]	Observed (Expected) background	H signal $\mathcal{B} = 10^{-4}$
$H \to \omega\gamma$	115–135	681 (724 ± 16)	33 ± 4
$H \to K^*\gamma$	120–130	10474 (10550 ± 60)	163 ± 15

Channel	95% CL upper limit	
	Expected	Observed
$H \to \omega\gamma$ [10^{-4}]	$3.0^{+1.2}_{-0.8}$	1.5
$H \to K^*\gamma$ [10^{-5}]	$12.2^{+4.9}_{-3.4}$	8.9

- **No significant excess** of events above the SM background expectation is observed



$H \to \omega\gamma$

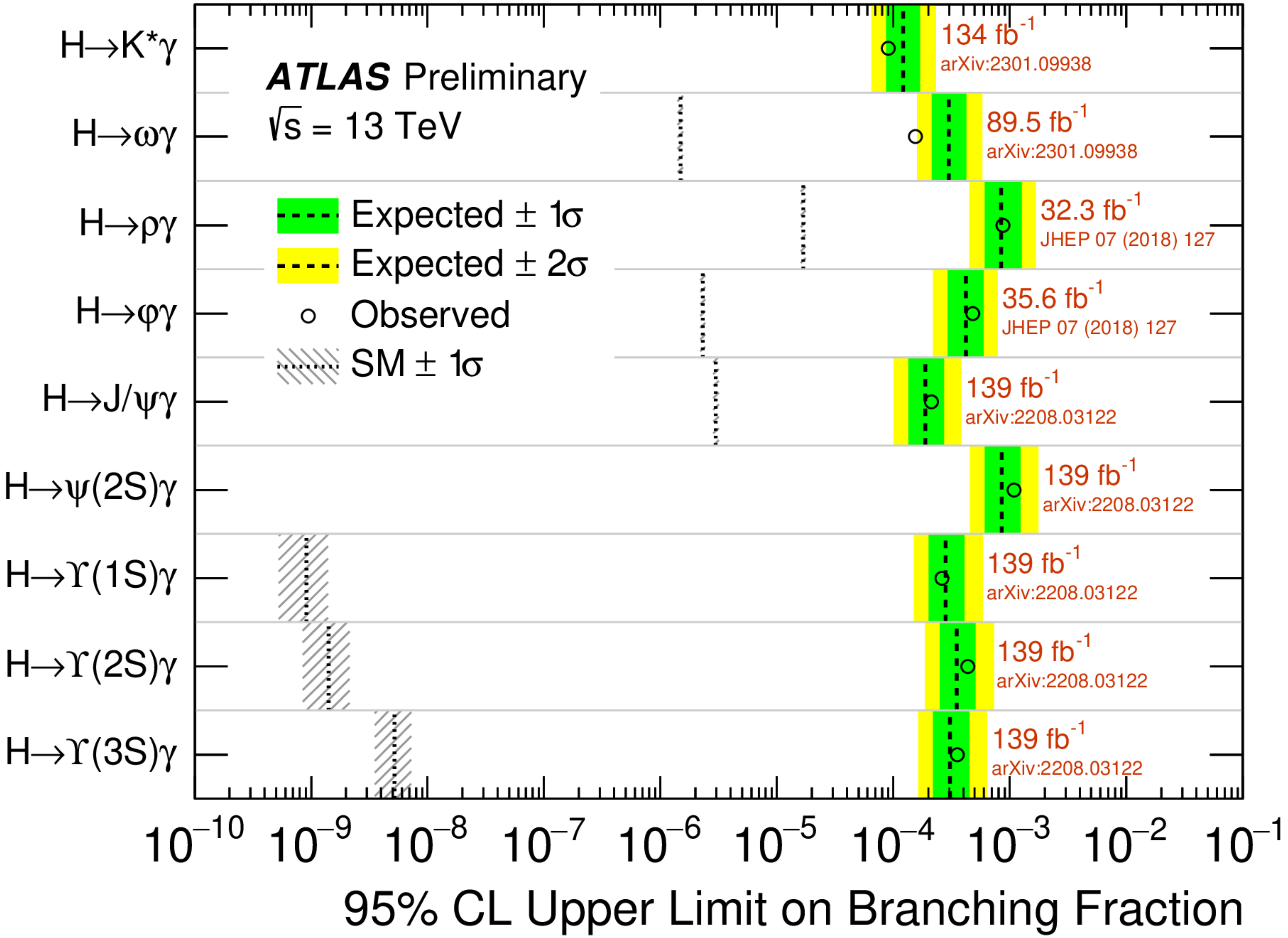


$H \to K^*\gamma$

$H \to \mathcal{M}\gamma$

ATL-PHYS-PUB-2023-004

- Summary of various decays of the **Higgs boson to a meson and a photon**
- **No significant excess** of events is observed



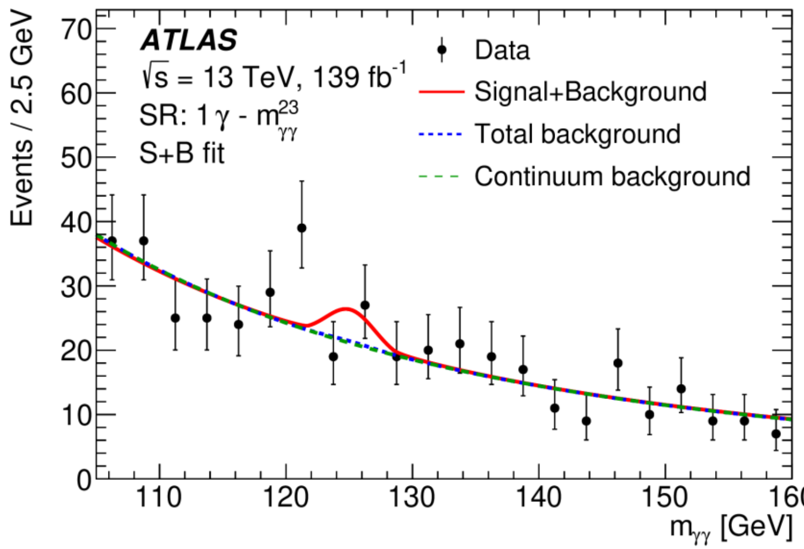
Model-independent search of with $\mathrm{H} \rightarrow \gamma\gamma$

arXiv:2301.10486

- Search for **BSM Higgs + X production**, with $\boldsymbol{H \rightarrow \gamma\gamma}$ **final state**
  - Relatively **clean background**, less systematic uncertainty

- Consider **SRs not covered** by the Higgs coupling analysis (STXS) [arXiv:1610.07922]
  - **Heavy flavour / High jet activity**: Multi-b jet (3 or 4), multijet (4, 6 or 8)
  - **High $\boldsymbol{E_T^{miss}}$**: >100, >200, >300 GeV
  - **Top**: $\ell + b$, t_{lep}, t_{had}
  - **Lepton**: 1ℓ / 2ℓ / 3ℓ / multi-lepton, same sign dilepton
  - **Three photons**

- Background modelling
  - **Resonant background**: modelled using a double-sided crystal function
  - **Continuum background**: fit with data into analytic functions using the spurious signal test [arXiv:1802.04146], **except** for the
    - **Multi-lepton regions**: extrapolated from CRs

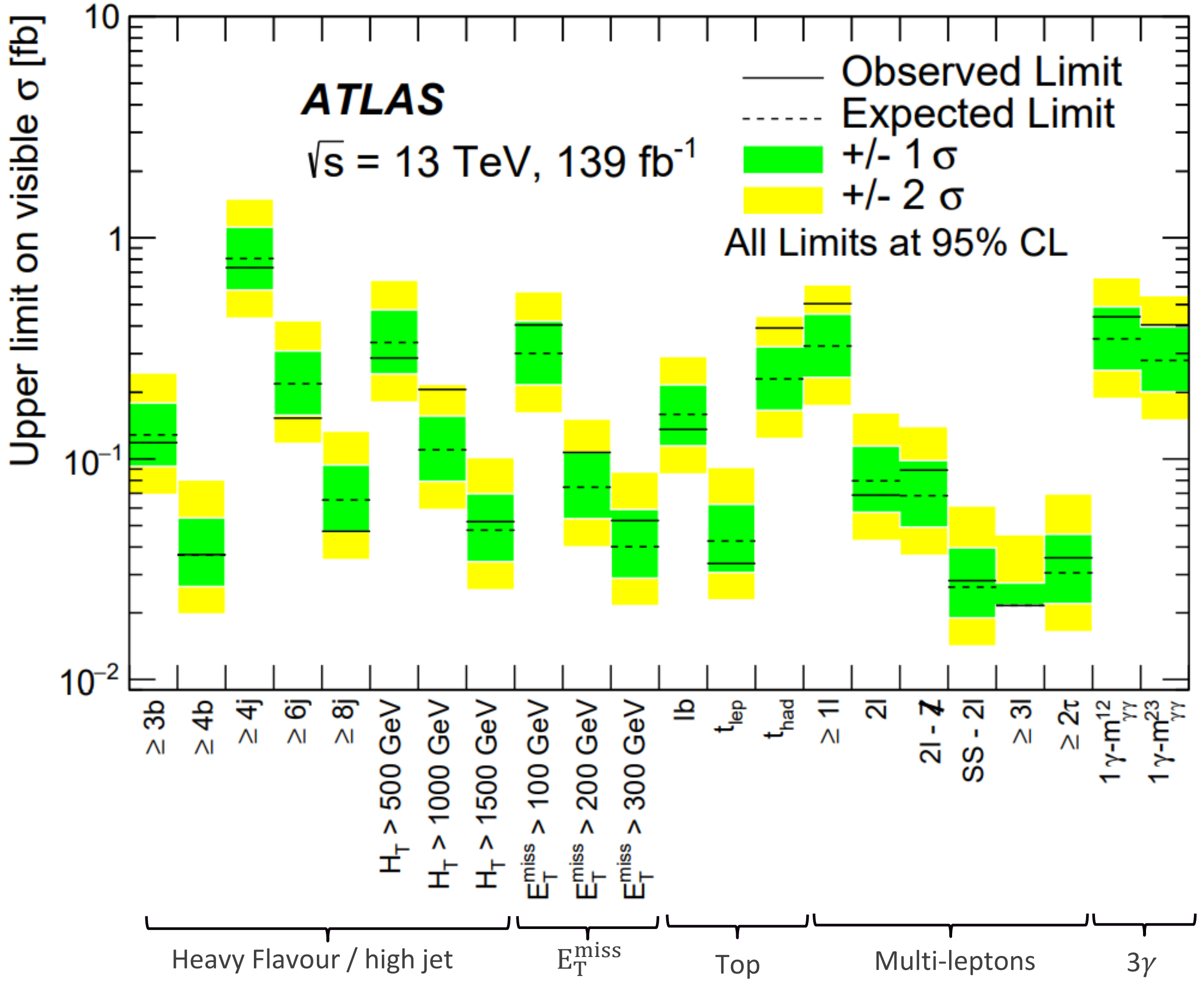


Signal-plus-background fit, 3 photons SR

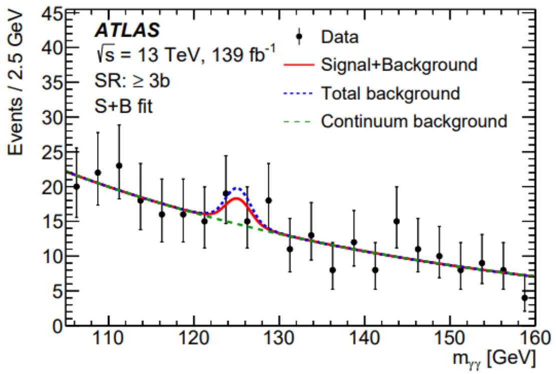
Model-independent search of with $\mathrm{H} \rightarrow \gamma\gamma$

arXiv:2301.10486

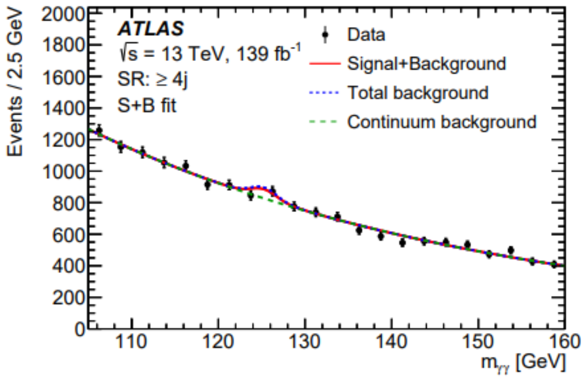
- **No significant excess** seen in any SR
  - Multi-lepton region, which had data-driven estimate, has 0 observed data



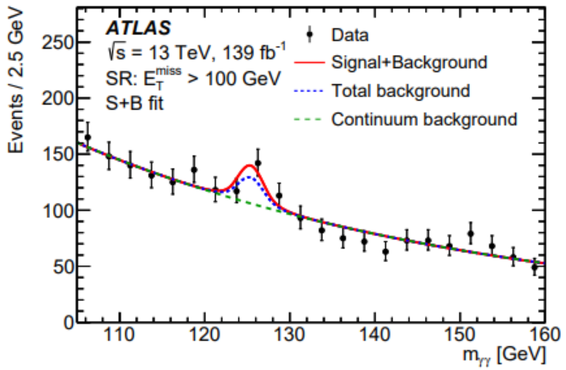
Background-only fit plots



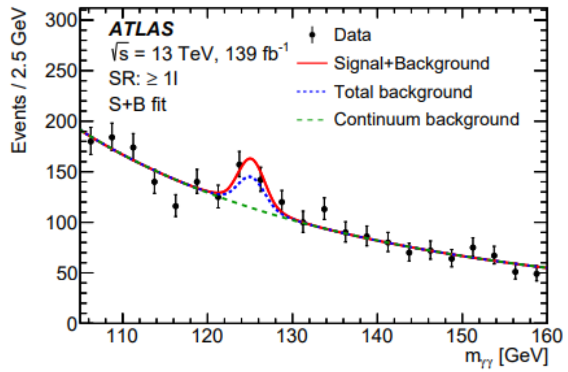
$\geq$3b-jet SR



$\geq$4 multi-jet SR



$E_T^{miss} > 100$ GeV SR



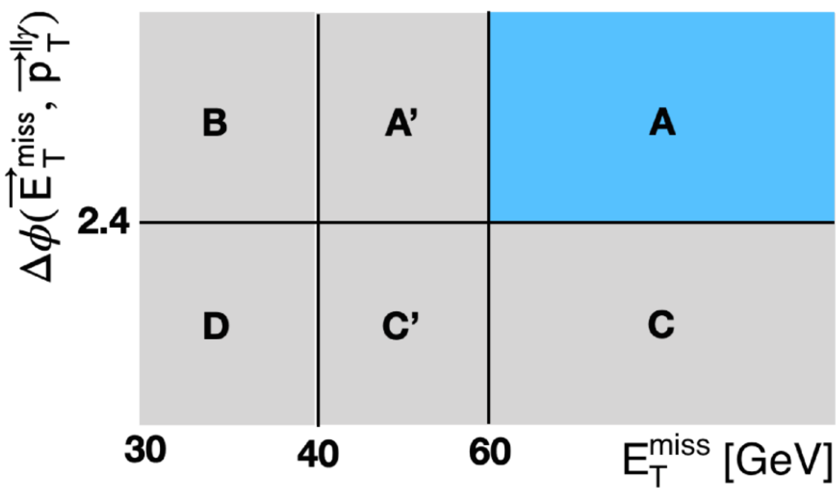
$\geq 1\ell$ SR

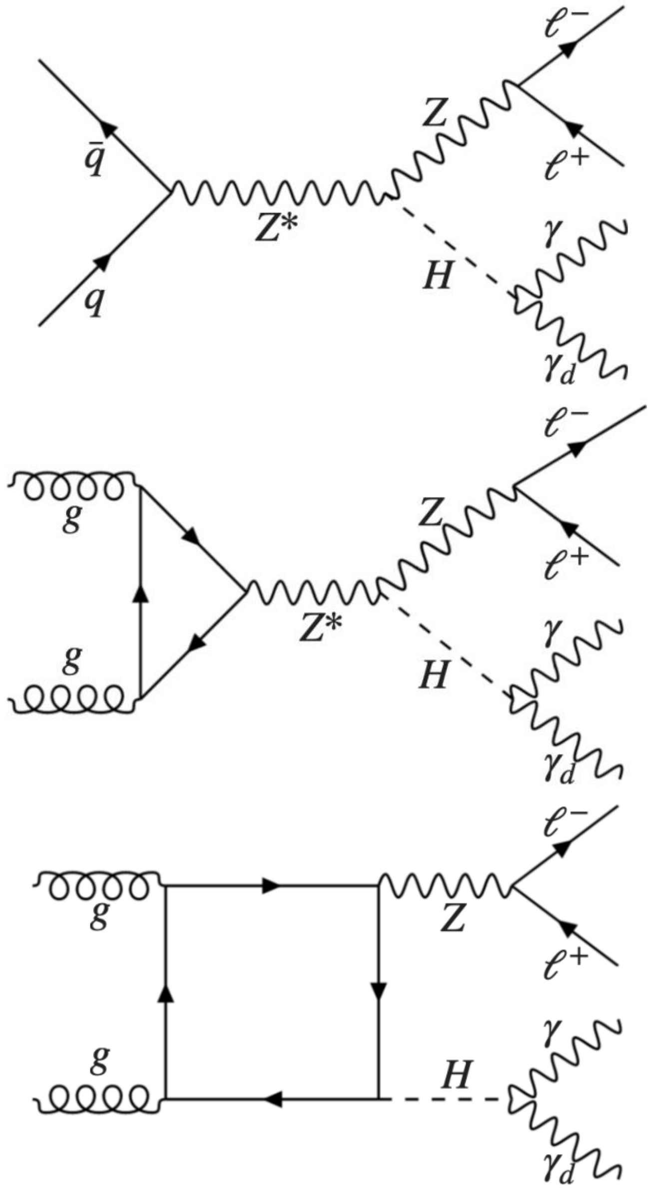
$H \to \gamma\gamma_d$

JHEP07(2023)133

- Search for Higgs boson decaying into a (SM) photon and a **dark photon** (γ_d)
- Exploit the **ZH production mode**
  - $Z \to \ell^+\ell^-$
  - $H \to \gamma\gamma_d$
- Optimized for dark photon searches in the **[0 – 40] GeV mass range**
- Major Backgrounds:
  - Fake E_T^{miss}:
    - "ABCD method"
    - Validation Region (A')
  - $e \to \gamma$ fakes:
    - fake factors of e^+e^- and $e^\pm\gamma$ final states
    - apply to a probe electron CR

The search for **Higgs invisible decays** (to be discussed in **slide 10 - 11**) would share the same signature as dark photon from the **VBF production mode** (arXiv:2109.00925).

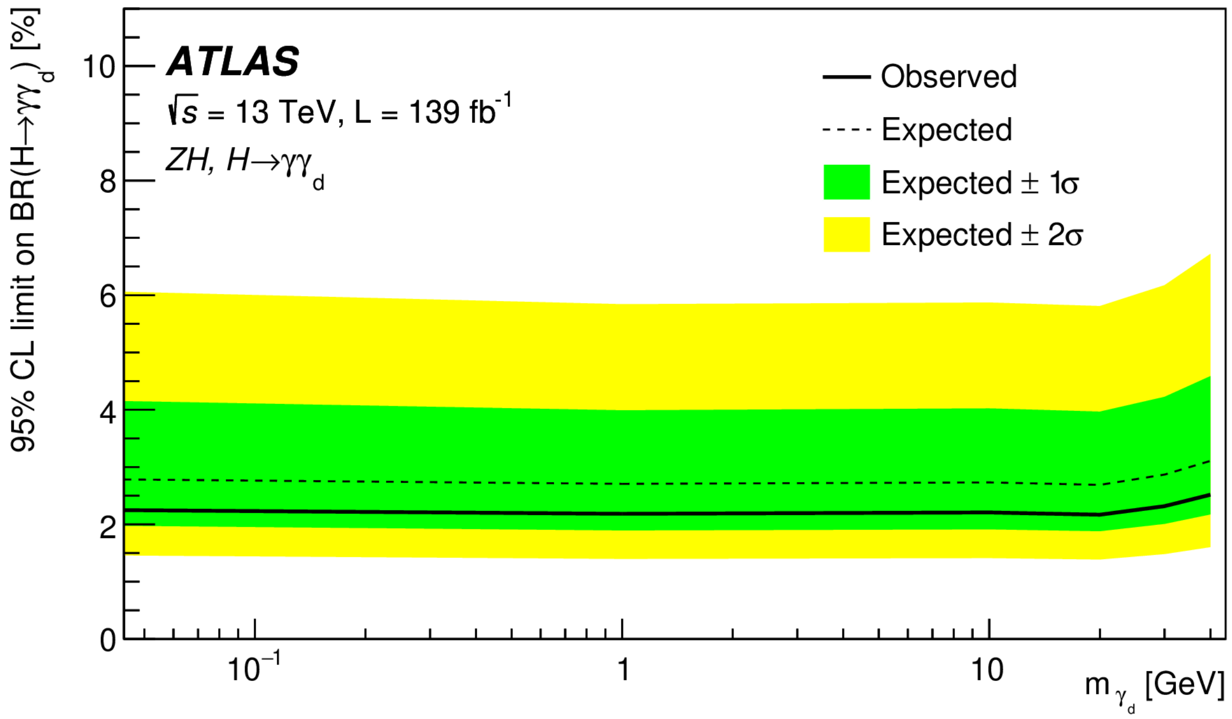




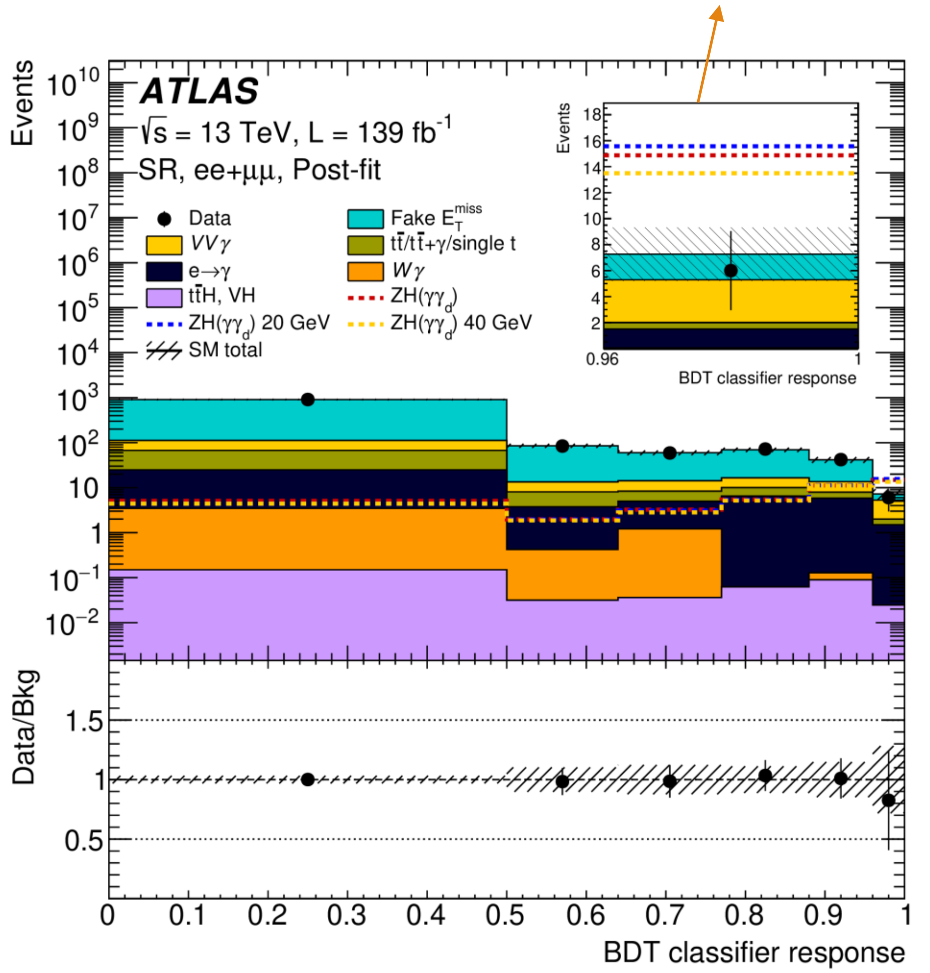
$H \to \gamma\gamma_d$

JHEP07(2023)133

- Discriminant variable: **BDT score** to enhance the analysis sensitivity



Zoomed view of the last BDT bin



post-fit plot in BDT classifier

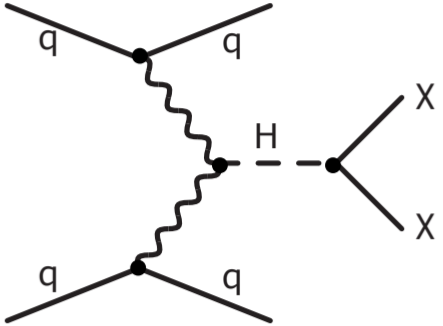
- **No excess of events** above the SM expectation is found
- **Observed (expected) upper limit** of $\mathrm{BR}(\mathrm{H} \to \gamma\gamma_\mathrm{d})$ at 95% CL:
  - massless γ_d: 2.28% (2.82%)
  - massive γ_d: [2.19%, 2.52%] ([2.71%, 3.11%])

  *mass range from 1 to 40 GeV

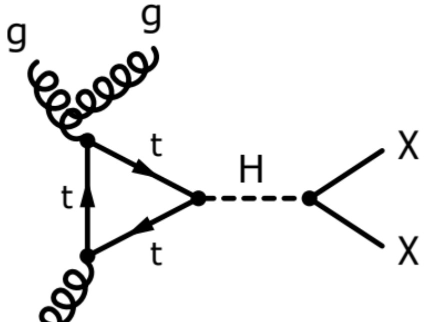
Higgs invisible decays

arXiv:2301.10731

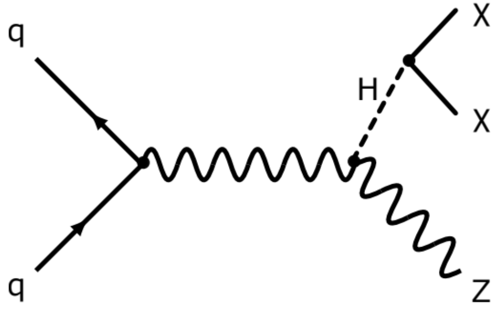
- Search for **invisible (dark matter)** decay of Higgs boson
- This paper presents a **statistical combination** from the following channels
  - VBF Topology (arXiv:2202.07953)
  - ZH Topology (arXiv:2111.08372)
  - ttH Topology (arXiv:2211.05426)
  - ggH + jet Topology (arXiv:2102.10874)
  - VBF + γ Topology (arXiv:2109.00925)
    (This also shares the same signature as $H \to \gamma\gamma_d$ signal)
- **Run 2 combination**
  - Most experimental systematic uncertainties are **correlated** across all channels
  - Background prediction uncertainties are **uncorrelated** due to the different nature of the leading backgrounds
- **Run 1 + Run 2 combination**
  - Most of the uncertainties **are not correlated** between Run 1 and Run 2, due to the different algorithm calibration using data



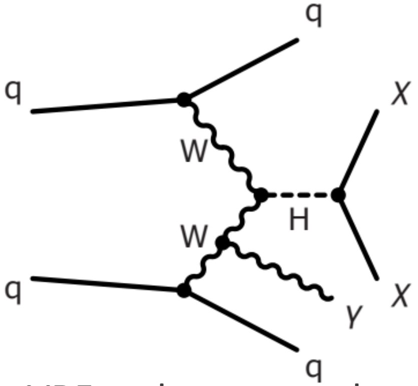
VBF topology



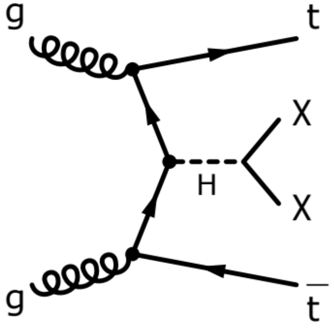
ggH + jet topology



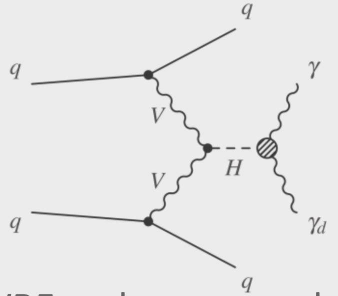
ZH topology



VBF + photon topology



ttH topology



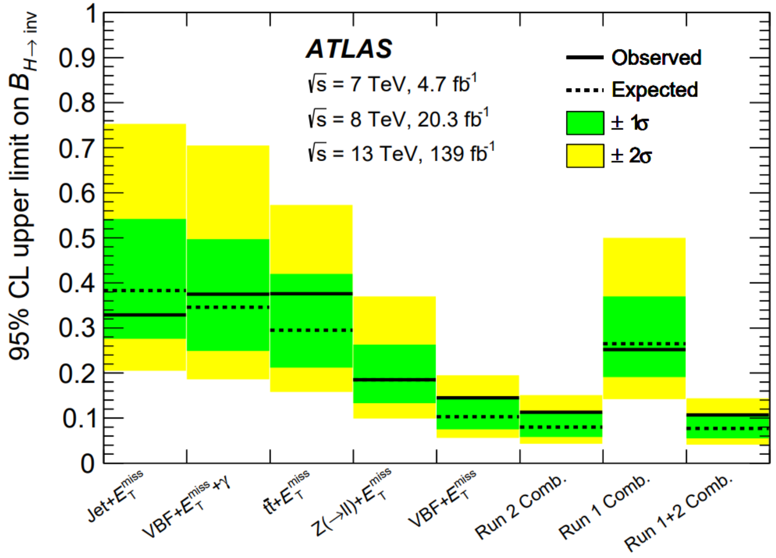
VBF + photon topology
($H \to \gamma\gamma_d$ signal)

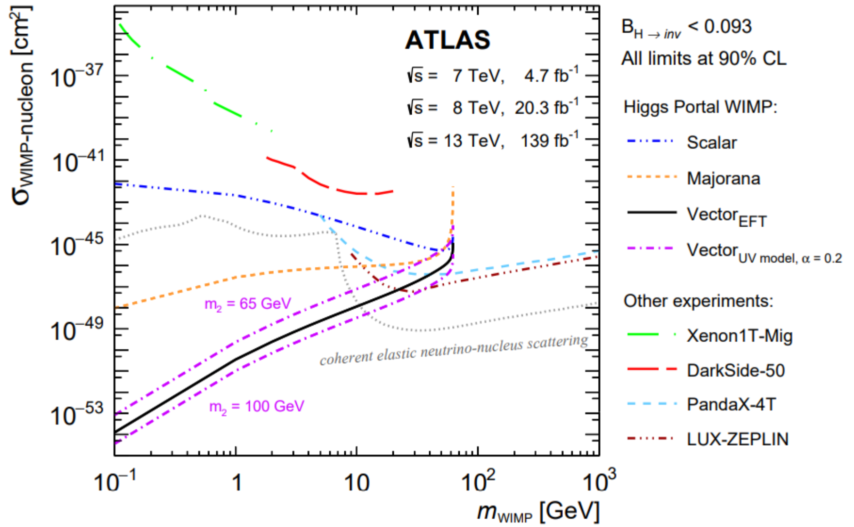
Higgs invisible decays

arXiv:2301.10731

Analysis	Best fit $\mathcal{B}_{H\to \text{inv}}$	Observed 95% U.L.	Expected 95% U.L.
Jet + E_T^{miss}	$-0.09^{+0.19}_{-0.20}$	0.329	$0.383^{+0.157}_{-0.107}$
VBF + E_T^{miss} + γ	$0.04^{+0.17}_{-0.15}$	0.375	$0.346^{+0.151}_{-0.097}$
$t\bar{t}$ + E_T^{miss}	0.08 ± 0.15	0.376	$0.295^{+0.125}_{-0.083}$
$Z(\to \ell\ell)$ + E_T^{miss}	0.00 ± 0.09	0.185	$0.185^{+0.078}_{-0.052}$
VBF + E_T^{miss}	0.05 ± 0.05	0.145	$0.103^{+0.041}_{-0.028}$
Run 2 Comb.	0.04 ± 0.04	0.113	$0.080^{+0.031}_{-0.022}$
Run 1 Comb.	$-0.02^{+0.14}_{-0.13}$	0.252	$0.265^{+0.105}_{-0.074}$
Run 1+2 Comb.	0.04 ± 0.04	0.107	$0.077^{+0.030}_{-0.022}$
VBF ($H \to \gamma\gamma_d$)	-	0.018	$0.017^{+0.007}_{-0.005}$

- Leading systematic uncertainty comes from the **modelling of the W / Z + jets prediction**
- Sub-dominant uncertainties are related to the statistical precision of the data sample
- The 90% CL Run 1 + Run 2 limit of $\mathcal{B}_{H\to inv} < 0.093$ is complemented to the WIMP direct detection experiments



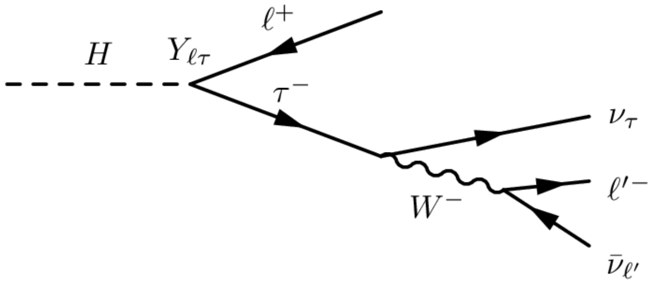


Higgs LFV decays

JHEP07(2023)166

- Search for **Lepton Flavour Violating** (LFV) decay of Higgs boson, with independent signals of
  - $\boldsymbol{H \to e\tau}$
  - $\boldsymbol{H \to \mu\tau}$

The search for $\boldsymbol{H \to e\mu}$ signal is presented in a separated paper [arXiv:1909.10235]



leplep channels

- **Two τ decay modes** are considered:
  - **Leptonically** decaying tau ($\tau_\ell \to \ell\nu\nu$)
  - **Hadronically** decaying tau ($\tau_{had} \to \text{hadrons} + \nu$)

s

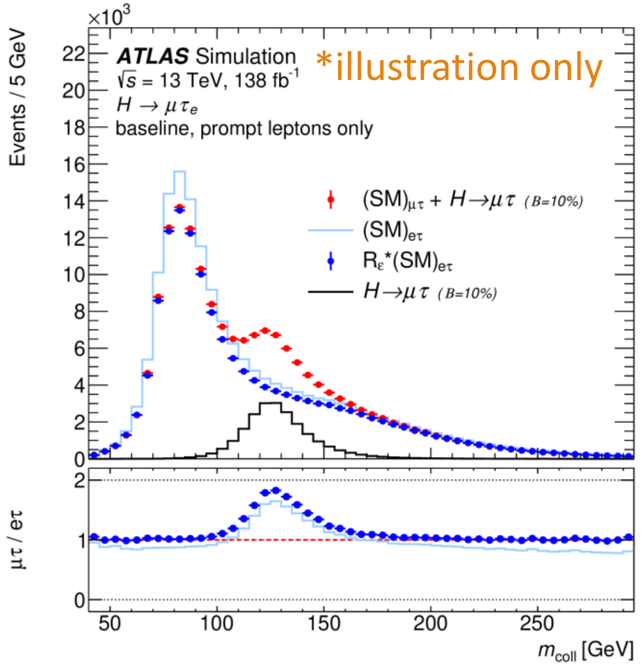
- **Two independent background estimation methods**

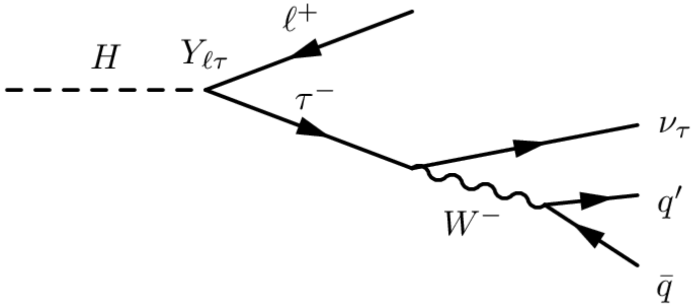
Symmetry-Based Method — leplep channels

- Main background estimated mainly via **data-driven symmetry method**

MC-Based Method — leplep channels, lephad channels

- Main background estimated with **MC templates** and normalisation from CRs
- Fake background data-driven





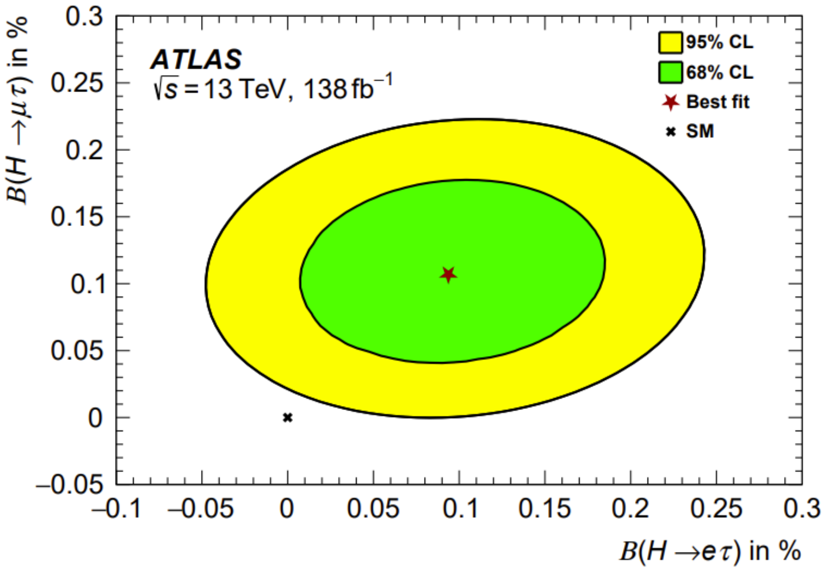
lephad channels

Higgs LFV decays

JHEP07(2023)166

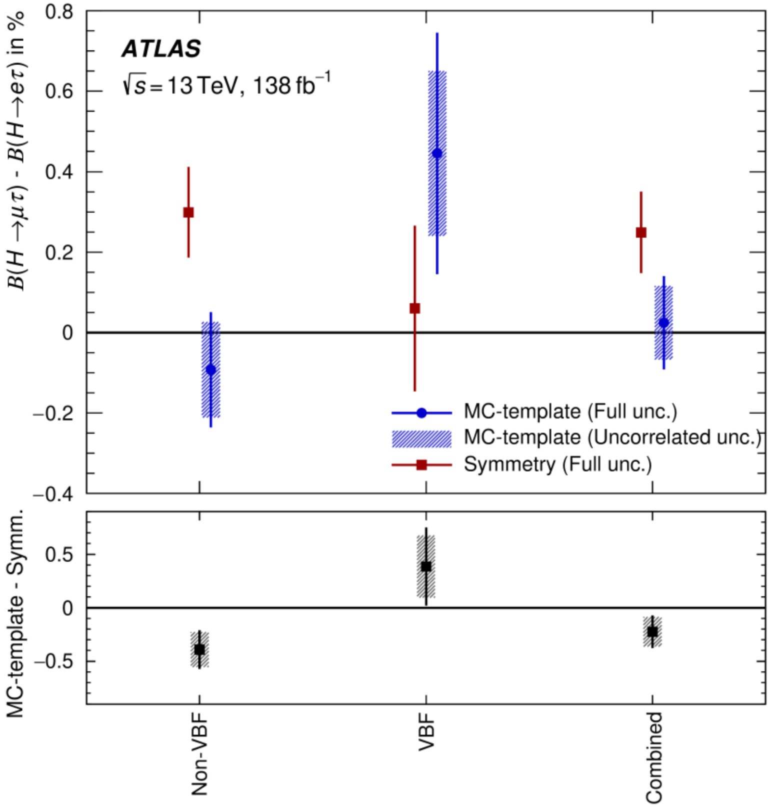
- Signal enhanced by **Boosted Decision Trees** (MC-based) and **Neural Network** (Symmetry-based)

Simultaneous measurement of
$\boldsymbol{H \to e\tau}$ **and** $\boldsymbol{H \to \mu\tau}$



	Obs. (Exp.) 95% Upper Limit
$e\tau$	0.193% (0.114%)
$\mu\tau$	0.183% (0.087%)

Branching Ratio difference (leplep channels only)



- **No significant excess** of signal is observed
- The simultaneous measurement is found to be **compatible with the SM within 2.1** $\boldsymbol{\sigma}$
- The symmetry method favours a **larger branching ratio for** $\boldsymbol{H \to \mu\tau}$ than $H \to e\tau$ signal, with a significance of **2.5** $\boldsymbol{\sigma}$

Summary

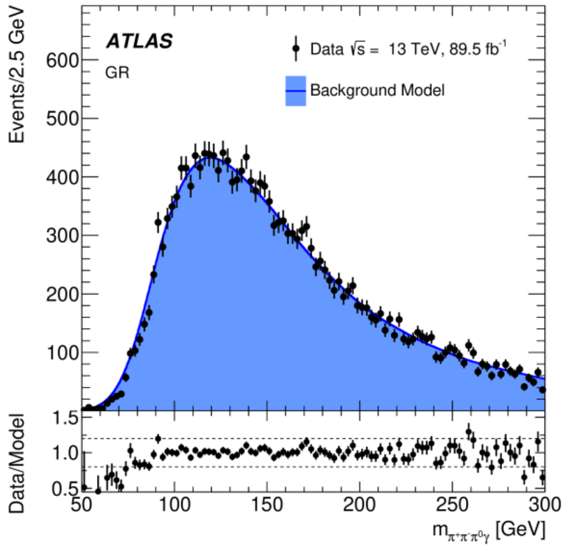
- Analysis in ATLAS covers many BSM, LFV and rare Higgs decays
- Most results with full Run-2 data has been already published
- No significant excess observed
- Run-3 is now ongoing, and we expect an improvement with more data incoming!

Backup

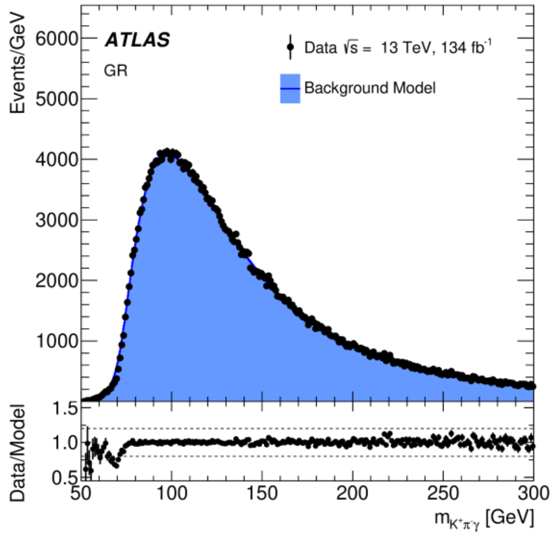
H → ωγ / K*γ

arXiv:2301.09938

- **Final states** of the experiment:
  - H → ωγ: $\omega \to \pi^+\pi^-\pi^0$
  - H → K*γ: $K^* \to K^+\pi^-$
- Major background from **mis-identified meson** from ID tracks originated from a **jet**
  - Estimated by a **non-parametric data-driven model** (arXiv:2112.00650)
  - Model the background in a background-dominated "**Generation Region**"
  - Apply a sampling scheme to extract the most important correlation among the kinematic variables of the estimated background



$H \to \omega\gamma$

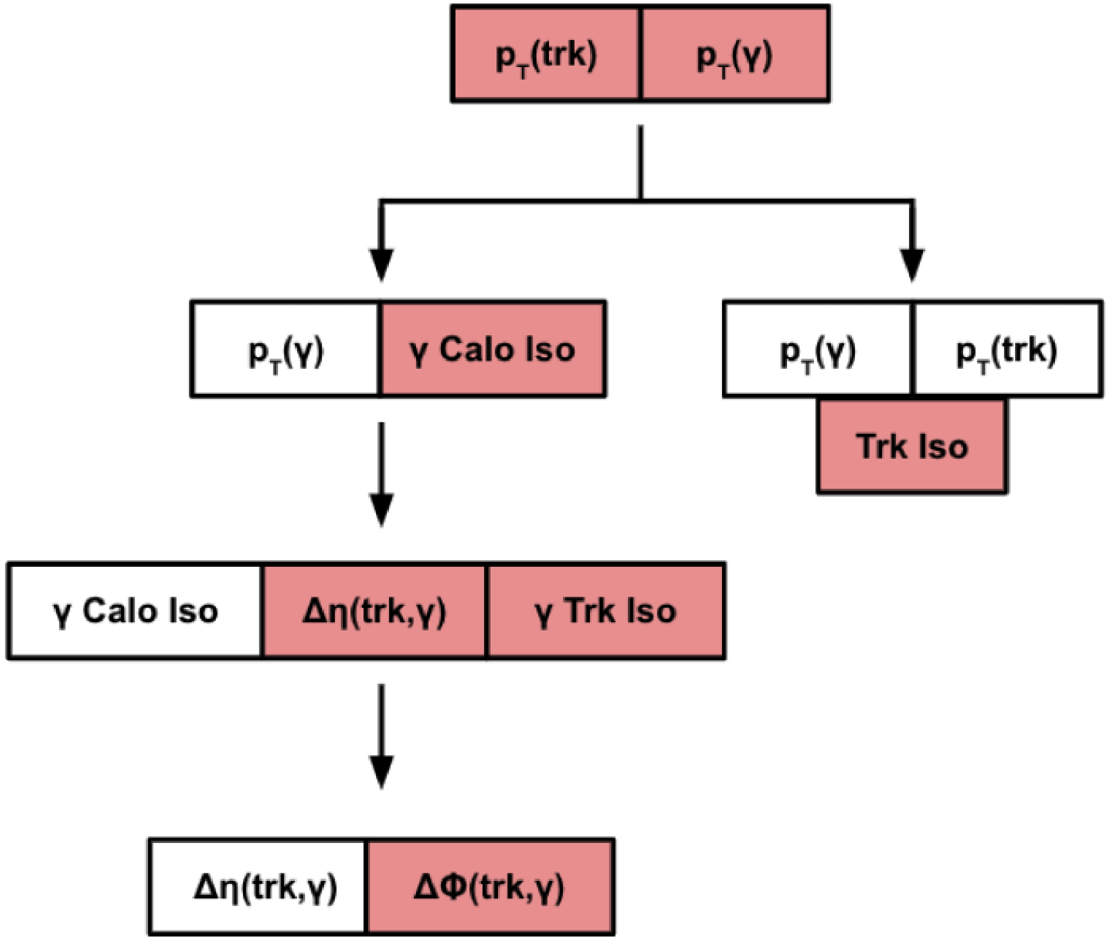


$H \to K^*\gamma$

H to ωγ / K*γ

arXiv:2301.09938

- Non-parametric data-driven model
  - Define a **background-dominated "Generation Region"** (GR), by releasing the nominal isolation requirement
  - **Model kinematic distributions** of these events, **including correlations** between important variables
  - **Draw from distributions** (millions of times) with random numbers + combine together = **pseudo-candidates**
  - Correlations should then be retained in the pseudo-candidates, as well as **behavior after selection**
  - Resulting distribution is **smoothed** with **Gaussian Kernel Density Estimation**



Model-independent search of with $\mathrm{H} \rightarrow \gamma\gamma$

arXiv:2301.10486

Target	Region	Detector level	Particle level
Heavy flavour	$\geq 3b$	$n_{b\text{-jet}} \geq 3$, 85% WP	$n_{b\text{-jet}} \geq 3$
	$\geq 4b$	$n_{b\text{-jet}} \geq 4$, 85% WP	$n_{b\text{-jet}} \geq 4$
High jet activity	$\geq$4j	$n_{\text{jet}} \geq 4$, $\lvert\eta_{\text{jet}}\rvert < 2.5$	$n_{\text{jet}} \geq 4$, $\lvert\eta_{\text{jet}}\rvert < 2.5$
	$\geq$6j	$n_{\text{jet}} \geq 6$, $\lvert\eta_{\text{jet}}\rvert < 2.5$	$n_{\text{jet}} \geq 6$, $\lvert\eta_{\text{jet}}\rvert < 2.5$
	$\geq$8j	$n_{\text{jet}} \geq 8$, $\lvert\eta_{\text{jet}}\rvert < 2.5$	$n_{\text{jet}} \geq 8$, $\lvert\eta_{\text{jet}}\rvert < 2.5$
	$H_{\text{T}} > 500$ GeV	$H_{\text{T}} > 500$ GeV	$H_{\text{T}} > 500$ GeV
	$H_{\text{T}} > 1000$ GeV	$H_{\text{T}} > 1000$ GeV	$H_{\text{T}} > 1000$ GeV
	$H_{\text{T}} > 1500$ GeV	$H_{\text{T}} > 1500$ GeV	$H_{\text{T}} > 1500$ GeV
$E_{\text{T}}^{\text{miss}}$	$E_{\text{T}}^{\text{miss}} >100$ GeV	$E_{\text{T}}^{\text{miss}} > 100$ GeV	$E_{\text{T}}^{\text{miss,tru}} > 100$ GeV
	$E_{\text{T}}^{\text{miss}} >200$ GeV	$E_{\text{T}}^{\text{miss}} > 200$ GeV	$E_{\text{T}}^{\text{miss,tru}} > 200$ GeV
	$E_{\text{T}}^{\text{miss}} >300$ GeV	$E_{\text{T}}^{\text{miss}} > 300$ GeV	$E_{\text{T}}^{\text{miss,tru}} > 300$ GeV
Top	ℓb	$n_{\ell=e,\mu} \geq 1$, $n_{b\text{-jet}} \geq 1$, 70% WP	$n_{\ell=e,\mu} \geq 1$, $n_{b\text{-jet}} \geq 1$
	t_{lep}	$n_{\ell=e,\mu} = 1$, $n_{\text{jet}} = n_{b\text{-jet}} = 1$, 70% WP	$n_{\ell=e,\mu} = 1$, $n_{\text{jet}} = n_{b\text{-jet}} = 1$
	t_{had}	$n_{\ell=e,\mu} = 0$, $n_{\text{jet}} = 3$, $n_{b\text{-jet}} = 1$, 70% WP, $\text{BDT}_{\text{top}} > 0.9$	$n_{\ell=e,\mu} = 0$, $n_{\text{jet}} = 3$, $n_{b\text{-jet}} = 1$
Lepton	$\geq 1\ell$	$n_{\ell=e,\mu} \geq 1$	$n_{\ell=e,\mu} \geq 1$
	2ℓ	ee, $\mu\mu$, or $e\mu$	ee, $\mu\mu$, or $e\mu$
	2ℓ–$\not{Z}$	ee, $\mu\mu$, $e\mu$; $\lvert m_{\ell\ell} - m_Z\rvert > 10$ GeV for same-flavour leptons	ee, $\mu\mu$, $e\mu$; $\lvert m_{\ell\ell} - m_Z\rvert > 10$ GeV for same-flavour leptons
	SS-2ℓ	ee, $\mu\mu$, or $e\mu$ with same charge	ee, $\mu\mu$, or $e\mu$ with same charge
	$\geq 3\ell$	$n_{\ell=e,\mu} \geq 3$	$n_{\ell=e,\mu} \geq 3$
	$\geq 2\tau$	$n_{\tau,\text{had}} \geq 2$	$n_{\tau} \geq 2$
Photon	1γ–$m_{\gamma\gamma}^{12}$	$n_{\gamma} \geq 3$, $m_{\gamma\gamma}$ defined with γ_1,γ_2	$n_{\gamma} \geq 3$, $m_{\gamma\gamma}$ defined with γ_1,γ_2
	1γ–$m_{\gamma\gamma}^{23}$	$n_{\gamma} \geq 3$, $m_{\gamma\gamma}$ defined with γ_2,γ_3	$n_{\gamma} \geq 3$, $m_{\gamma\gamma}$ defined with γ_2,γ_3

Model-independent search of with $\mathrm{H} \to \gamma\gamma$

arXiv:2301.10486

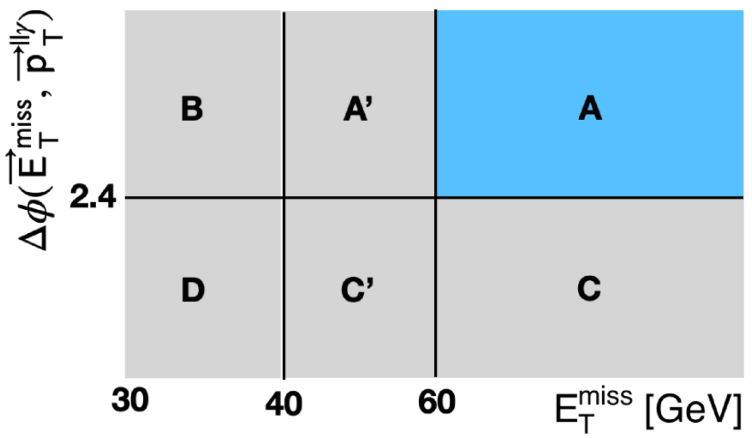
SR	Expected Background			Observed	
	Resonant Higgs	Continuum	Total Background	Observed Yield	Excess Significance [σ]
Heavy flavour					
$\geq 3b$	6.47	23.4	29.9	30	–0.3
$\geq 4b$	0.69	1.22	1.91	1	–0.2
High jet activity					
$\geq$4j	85.2	1330	1420	1404	–0.3
$\geq$6j	16.4	104	121	105	–1.3
$\geq$8j	2.44	6.37	8.81	6	–0.9
$H_{\mathrm{T}} > 500$ GeV	23.9	297	321	310	–0.6
$H_{\mathrm{T}} > 1000$ GeV	1.85	27	28.8	39	1.8
$H_{\mathrm{T}} > 1500$ GeV	0.264	3.9	4.17	4	0.1
$E_{\mathrm{T}}^{\mathrm{miss}}$					
$E_{\mathrm{T}}^{\mathrm{miss}} > 100$ GeV	29	171	200	212	0.8
$E_{\mathrm{T}}^{\mathrm{miss}} > 200$ GeV	4.51	8.06	12.6	16	0.9
$E_{\mathrm{T}}^{\mathrm{miss}} > 300$ GeV	1.15	1.85	3	5	0.8
Top quark					
ℓb	14.9	27	41.9	34	–0.6
t_{lep}	0.281	2.58	2.86	1	–0.7
t_{had}	4.44	96.3	101	111	1.7
Lepton					
$\geq 1\ell$	38.8	183	222	237	1.4
2ℓ	4.24	9.42	13.7	10	–0.5
2ℓ–$\not{Z}$	1.95	7.35	9.3	10	0.7
SS-2ℓ	0.431	0.224	0.655	1	0.2
$\geq 3\ell$	0.02	0.25	0.27	0	–
$\geq 2\tau$	0.256	0.875	1.13	2	0.6
Photon					
1γ–$m_{\gamma\gamma}^{12}$	2.33	119	121	132	0.7
1γ–$m_{\gamma\gamma}^{23}$	0.436	32.8	33.2	42	1.1

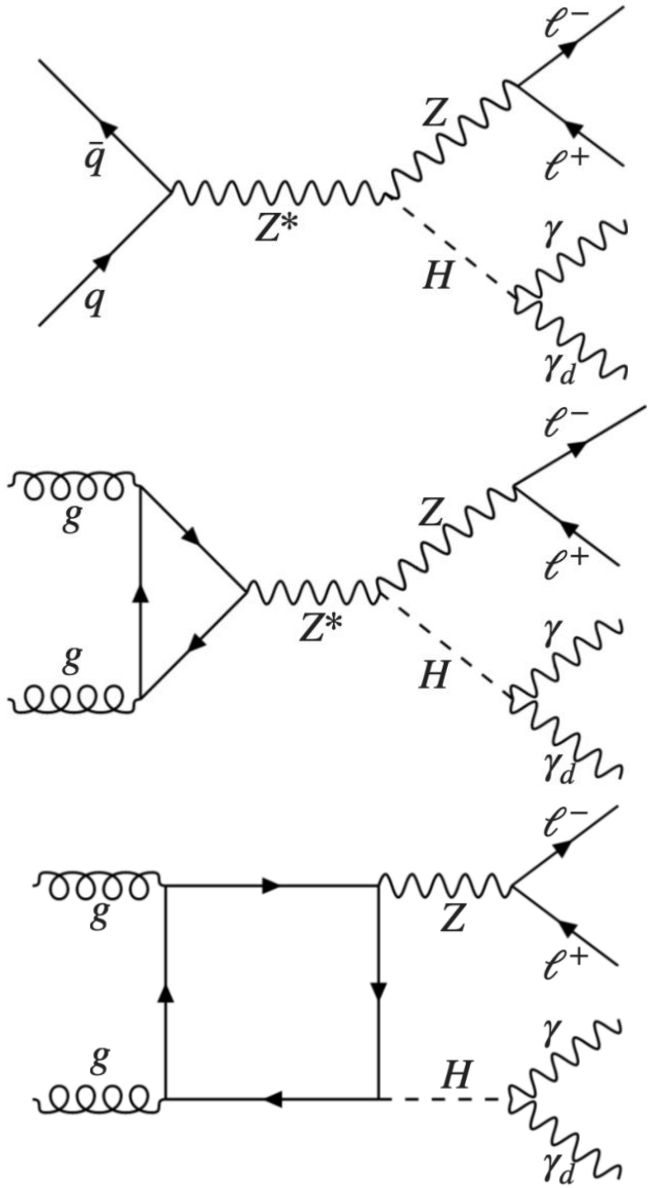
$\mathrm{H} \to \gamma\gamma_\mathrm{d}$

JHEP07(2023)133

- Search for Higgs boson decaying into a (SM) photon and a **dark photon** (γ_d)
- Exploit the **ZH production mode**
  - $Z \to \ell^+\ell^-$
  - $H \to \gamma\gamma_d$
- The **final state** consist of
  - Two same-flavour, opposite-charge electrons or muons,
  - An isolated photon, and
  - Missing transverse momentum
- Optimized for dark photon searches in the **[0 – 40] GeV mass range**
- Major Backgrounds:
  - Fake E_T^{miss}:
    - "ABCD method"
    - Validation Region (A')
  - $e \to \gamma$ fakes:
    - fake factors of e^+e^- and $e^{\pm}\gamma$ final states
    - apply to a probe electron CR

The search for **Higgs invisible decays** (to be discussed in **slide 10 - 11**) would share the same signature as dark photon from the **VBF production mode** (arXiv:2109.00925).

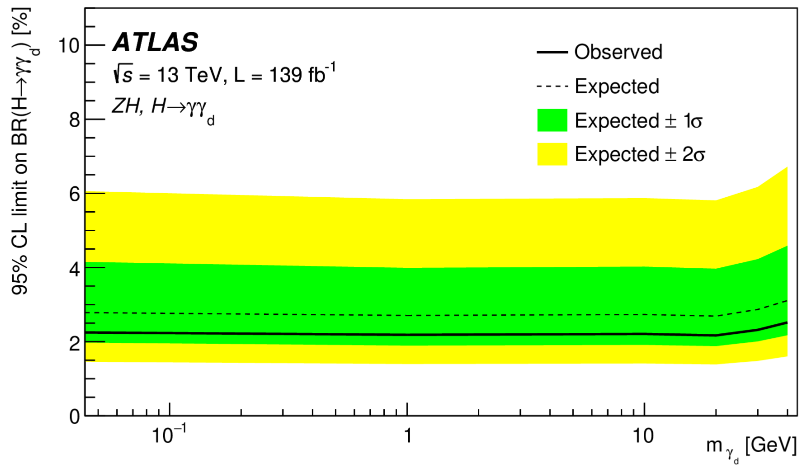




$\mathrm{H} \to \gamma\gamma_\mathrm{d}$

JHEP07(2023)133

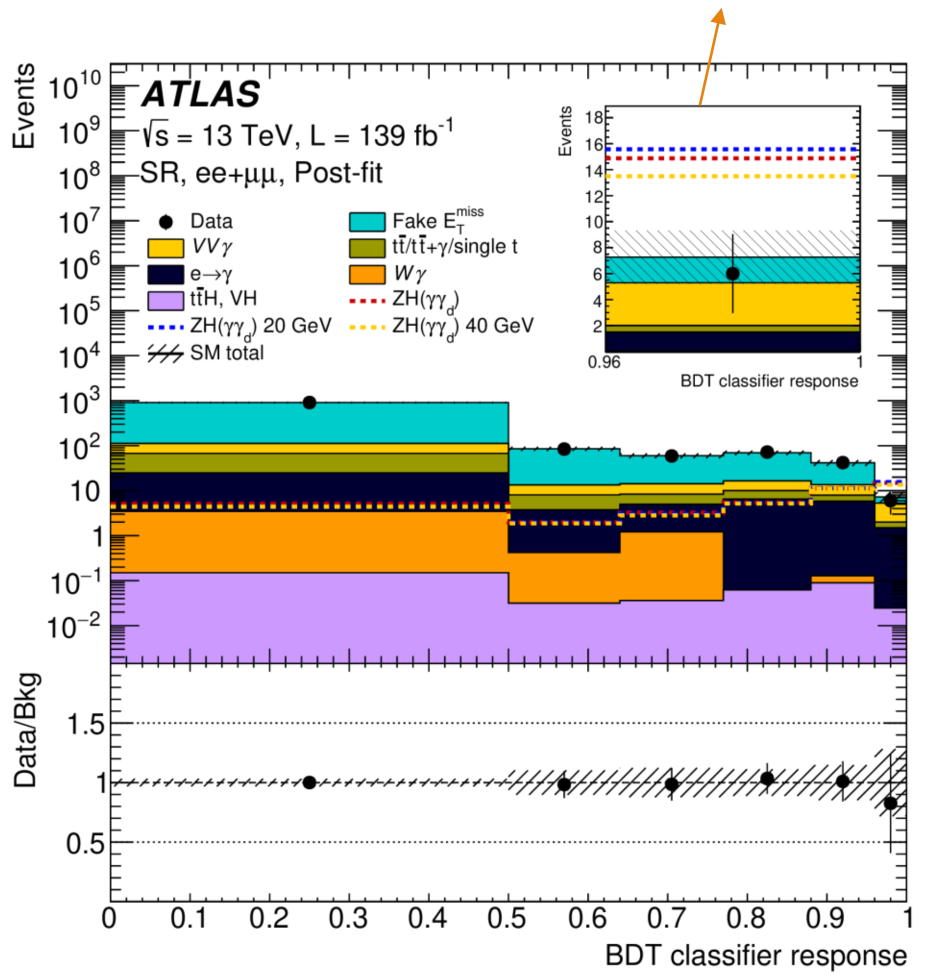
- Discriminant variable: **BDT score** to enhance the analysis sensitivity
  - Input variables: $\sigma_{E_T^{miss}}$, $m_T(p_T^{\gamma}, E_T^{miss})$, $m_{\ell\ell}$, $m_{\ell\ell\gamma}$, p_T^{γ}, $\frac{|E_T^{miss}+p_T^{\gamma}|-p_T^{\ell\ell}}{p_T^{\ell\ell}}$
  - **Binning optimized** to obtain the best expected sensitivity, while keeping low statistical uncertainties in each bin
  - Results consistent among different dark photon mass



- **No excess of events** above the SM expectation is found
- **Observed (expected) upper limit** of $\mathrm{BR}(\mathrm{H} \to \gamma\gamma_\mathrm{d})$ at 95% CL:
  - massless γ_d: 2.28% (2.82%)
  - massive γ_d: [2.19%, 2.52%] ([2.71%, 3.11%])

  *mass range from 1 to 40 GeV

Zoomed view of the last BDT bin



post-fit plot in BDT classifier

Higgs LFV decays

JHEP07(2023)166

- Choice of analysis methods when combining the channels and categories