Exotic Higgs decays

An update from the sub-working group

Verena Martinez Outschoorn (ATLAS), Alexis Kalogeropoulos (CMS), Andrea Thamm (Theory), Brian Shuve (Theory), **Carlos Vázquez Sierra (LHCb)** 🗣️

The 20th workshop of the LHC Higgs working group @ CERN

IGFAE
Instituto Galego de Física de Altas Enerxías

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Introduction

The goal of the **Exotic Higgs decay sub-group** is to **inform, aggregate, and make recommendations for studies of decays of SM Higgs to beyond Standard Model states.**

- Theory: Brian Shuve (Harvey Mudd College), Andrea Thamm (University of Massachusetts)
- ATLAS: Verena Martinez (University of Massachusetts)
- CMS: Alexis Kalogeropoulos (Kansas State University)
- LHCb: Carlos Vázquez Sierra (Instituto Galego de Física de Altas Enerxías)

This talk

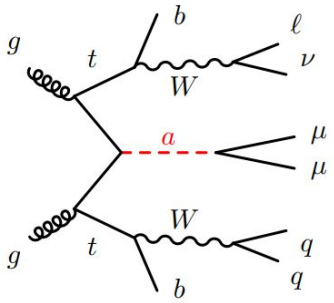
- Focus on **selected experimental results** since last workshop in 2022.
- **Present ideas** and **discuss potential activities** for 2024 and future runs.

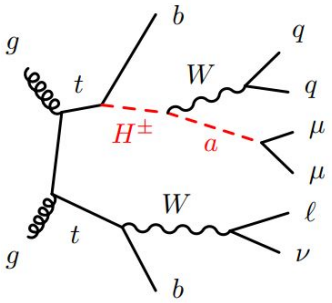
Some **EXP/TH highlights,** not covered in this talk due to time constraints 😔:

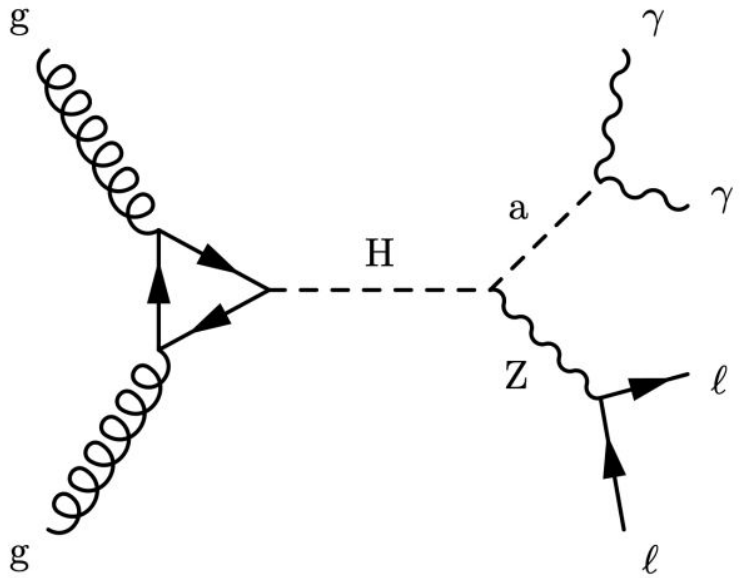
- ATLAS: Exclusive Higgs decays into γ{ω/K*} [PLB 847 (2023) 138292]
- ATLAS: Search for a new Z' gauge boson in 4μ decays [JHEP 07 (2023) 90]
- Dark showers using data scouting [2303.04167]
- Trigger-level track reconstruction for exotic signatures [2211.05720]
- Exotic Higgs decays in VBF + γ [2306.01901]
- Higgs coupling deviations [2202.01228]

This talk

- Higgs coupling deviations [2202.01228]







New pseudoscalar *associated* production

- **ATLAS [2304.14247], 27 Apr ‘23**
- **CMS [2311.00130], 31 Oct ‘23 🎃**

Associated production with top-quark pair

ATLAS [2304.14247], 27 Apr ‘23

arXiv:2304.14247

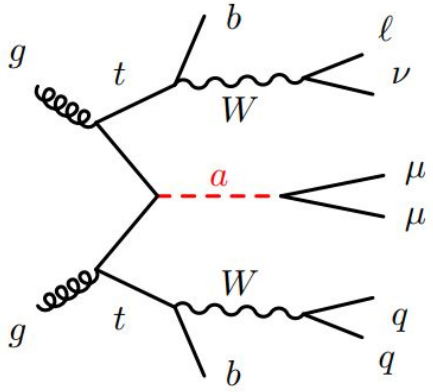
Associated production with top-quark pair

139 fb^{-1} of Run 2 **ATLAS** data.

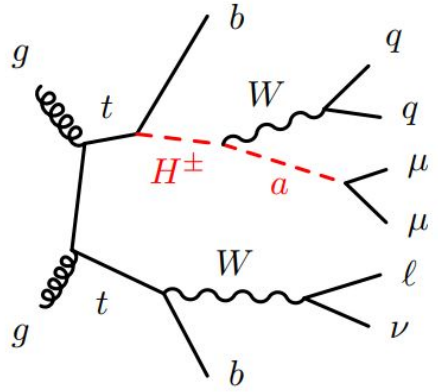
👉 **High m(μμ) resolution.**

Two signal models (right):

- 120 < m(**H**$^{\pm}$) < 160 GeV
- 15 < m(**a**) < 72 GeV



tt**a**, **a**→μμ



tt, t→b**H**$^{\pm}$, **H**$^{\pm}$→W**a**, **a**→μμ

Final states consisting of **μμ** + **lepton from the only leptonic W decay** (**μμμ**, **μμe**):

- **Single-lepton triggers: low pT (~26 GeV) + isolation**, or **high pT + loosened ID.**
- **pT requirements** for **e** (>27 GeV), **μ** (>10 GeV *at least*), and **jets** (>20 GeV),
- **Other requirements** (isolation, η, vertex quality, ID) considered as well.

arXiv:2304.14247

Associated production with top-quark pair

Signal region:

- SR defined for **μμμ** and **μμe**, above Y and below Z.
- Require 3 jets and 1 b-jet present ➜ **only one W decays leptonically.**

Background contributions:

- Dominated by ttZ with Z decaying into low-mass μμ.
- Other subleading components considered.
- Normalization of ttZ from data (CR), others from simulation.

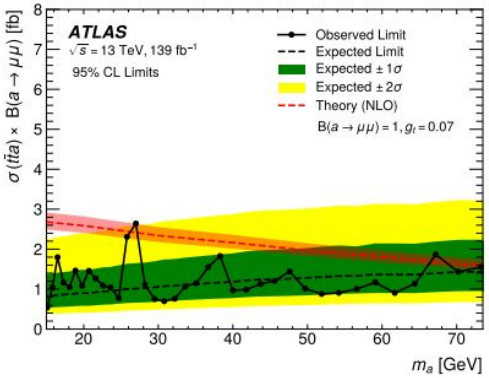
Signal μμ mass modelled with a double Crystal-Ball function, parameters from MC.

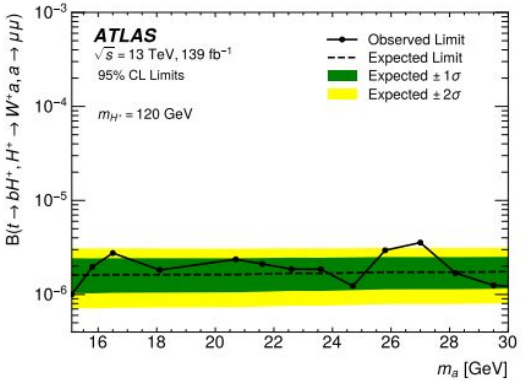
Systematics dominated by μ ID efficiency and modelling of the ttZ background.

arXiv:2304.14247

Associated production with top-quark pair

UL@95% in production x-sections for the two benchmarks, after fit to m(μμ):





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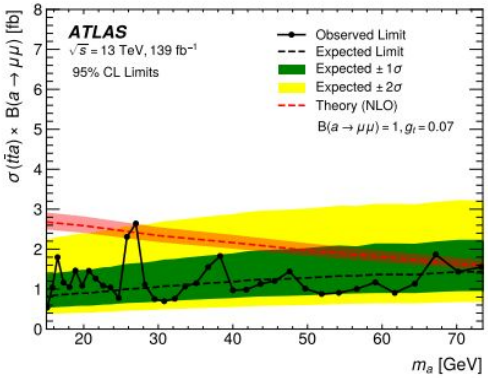
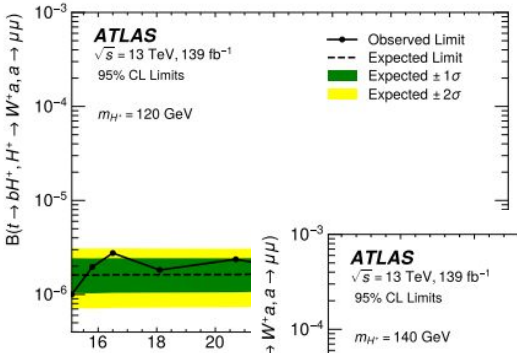
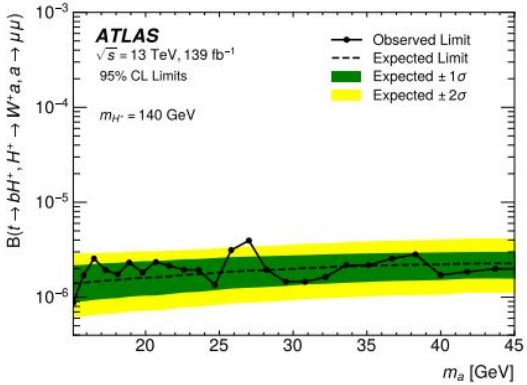
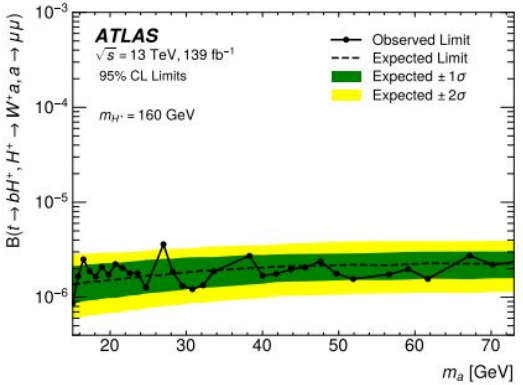








2.6σ local excess in m(a) = 27 GeV.

Limits compatible with SM.

Associated production with a Z boson

CMS [2311.00130], 31 Oct ‘23

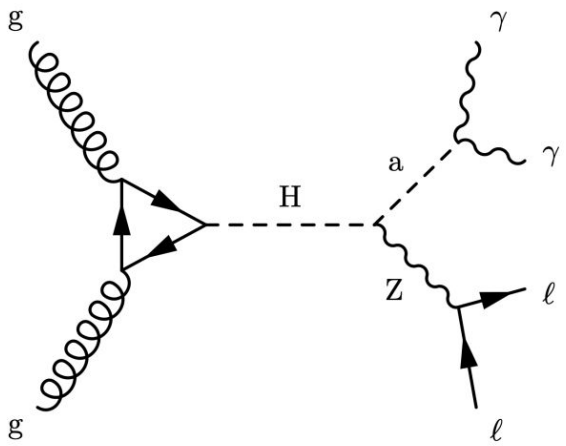
arXiv:2311.00130

Associated production with a Z boson

138 fb^{-1} of Run 2 **CMS** data, search in **1 < m(a) < 30 GeV**.

Signal simulated samples:

- **ggF H→aZ→γγll @ LO** (incl. leptonic τ decays),
- Steps of 1 (5) GeV in m(a) of 1-10 (10-30) GeV,
- Other production modes **negligible** after selection.



H→aZ, a→γγ, Z→ee/μμ

Background simulated samples: DY Z+jets @ LO, **jets** are **misidentified** as γ.

Leading μ(e) with **pT>20(25) GeV,** isolation with FSR recovery to exclude leptons from hadronic decays. **Photons** are required to have **pT>10 GeV.**

Za candidates require 95<m(llγγ)<180 GeV and ΔR(l,γ)>0.4.

Associated production with a Z boson

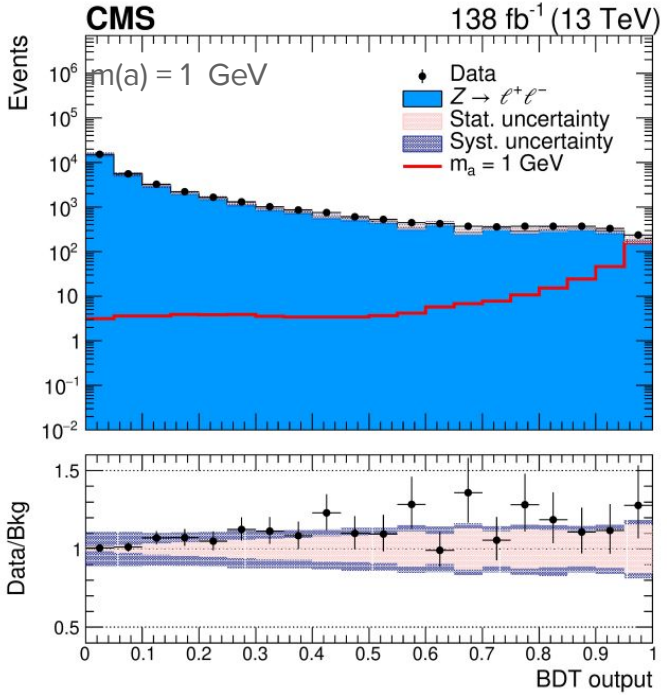
Signal-to-background separation with **BDT uniform in m(llγγ)**, trained with pT, isolations, angular separations and calorimetry variables.

Unbinned ML fit to 95<m(llγγ)<180 GeV:

- **Signal**: n Gaussians (n<5) from MC,
- **Background**: Gaussian with falling spectrum function (turn-on-peak) of various functional forms.

Dominant systematic uncertainties: photon and **electron energy resolutions.**

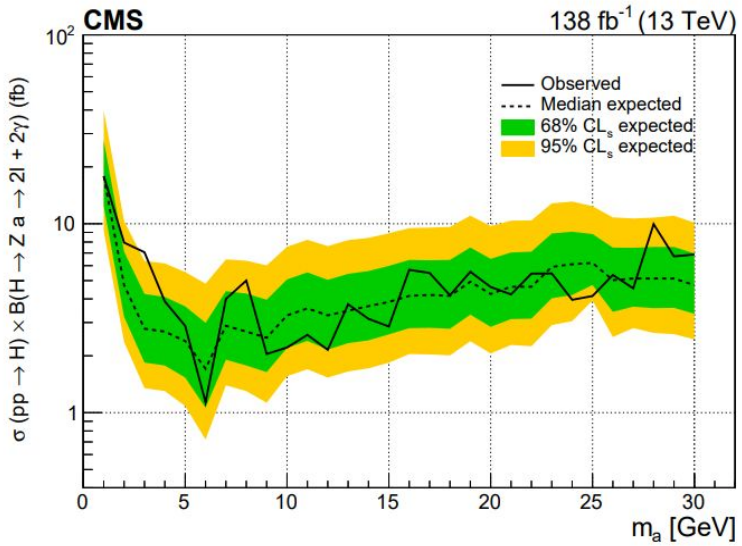
Event categorization as a function of the BDT output:

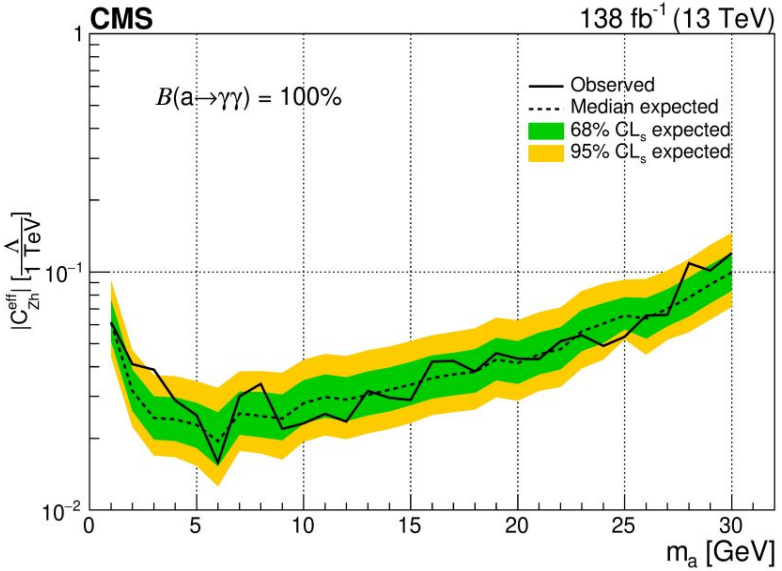


arXiv:2311.00130

Associated production with a Z boson

UL@95% CL on ZH eff. coupling with B(a→γγ)=1, and on production x-sections:





SM compatible, excess for m(a)=3 GeV of **2.6 (1.3)σ** local (global) significance.

New pseudoscalar *pair* production

- **ATLAS H→aa→4γ, 18 Àug ‘23**
- **CMS H→aa→bb{μμ/ττ} 3 Mar ‘23**

Wednesday, 15 November

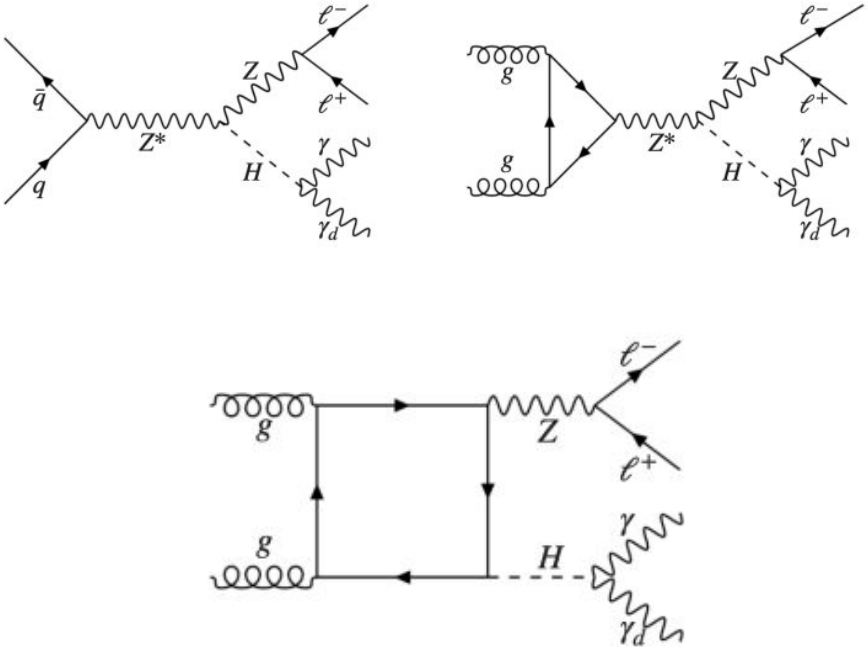
11:00 → 12:30 **WG3 BSM Higgs Parallel: Morning 2**

11:00 **Search for $h \to aa \to 2\mu 2b/2b2\tau$ with the CMS experiment**

Speaker: Pallabi Das (Princeton University (US))

11:15 **Search for $h \to aa \to 4\gamma$ with the ATLAS experiment**

Speaker: Peter Kramer (Johannes Gutenberg Universitaet Mainz (DE))



Dark photons from Higgs decays in ZH production

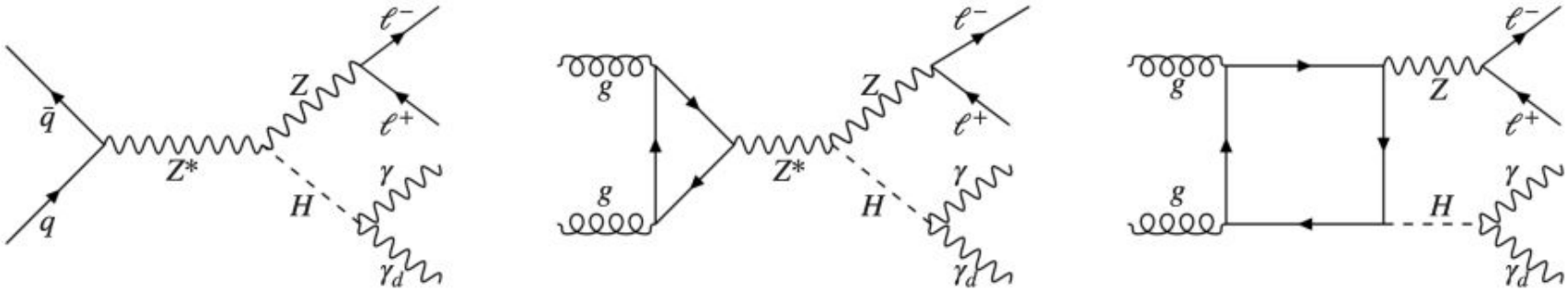
ATLAS, 22 Dec ‘22, [JHEP07(2023)133]

JHEP 07 (2023) 133

Dark photons from Higgs decays in ZH production

Search for ee/μμ (Z) + isolated γ-E_T^{miss} (γ_d):

- 139 fb^{-1} of Run 2 **ATLAS** data, in **$m(\gamma_d) < 40$ GeV.**
- Search on E_T^{miss} from $H \rightarrow \gamma\gamma_d$ with $E\gamma = m(H)/2$ @ H c.o.m.
- **Single-lepton** trigger (low pT + isolation || high pT + no ID),
- **Di-lepton trigger** (looser ID, complement to single-lepton),



Dark photons from Higgs decays in ZH production

Signal MC @ LO: ZH with pT(ee/μμ)>10 GeV, H→γγ$_d$ from HV Pythia for six m(γ$_d$).

Most relevant backgrounds:

- **Irreducible backgrounds** from VVγ (V=W/Z) with V decaying leptonically.
- **Dominant backgrounds**, from fake **E_T^{miss}**, **are reducible**: undetected, mis-id particles, or hadronic jets partially decaying outside of *acc*.

Table 3: Optimised kinematic selections defining the signal region for $\ell^+\ell^-+\gamma+E_T^{miss}$.

Two same flavour, opposite sign, medium ID and loose isolated leptons, with leading $p_T > 27$ GeV, sub-leading $p_T > 20$ GeV
Veto events with additional lepton(s) with loose ID and $p_T > 10$ GeV
$76\ \text{GeV} < m_{\ell\ell} < 116\ \text{GeV}$
Only one tight ID, tight isolation photon with $E_T^{\gamma} > 25$ GeV
$E_T^{miss} > 60$ GeV with $\Delta\phi(\vec{E}_T^{miss}, \vec{p}_T^{\ell\ell\gamma}) > 2.4$ rad
$m_{\ell\ell\gamma} > 100$ GeV
$N_{jet} \leq 2$, with $p_T^{jet} > 30$ GeV, $\lvert\eta\rvert < 4.5$
Veto events with b-jet(s)

+ **BDT** using E_T^{miss} significance, transverse kinematic variables, m(ll) and m(llγ).

JHEP 07 (2023) 133

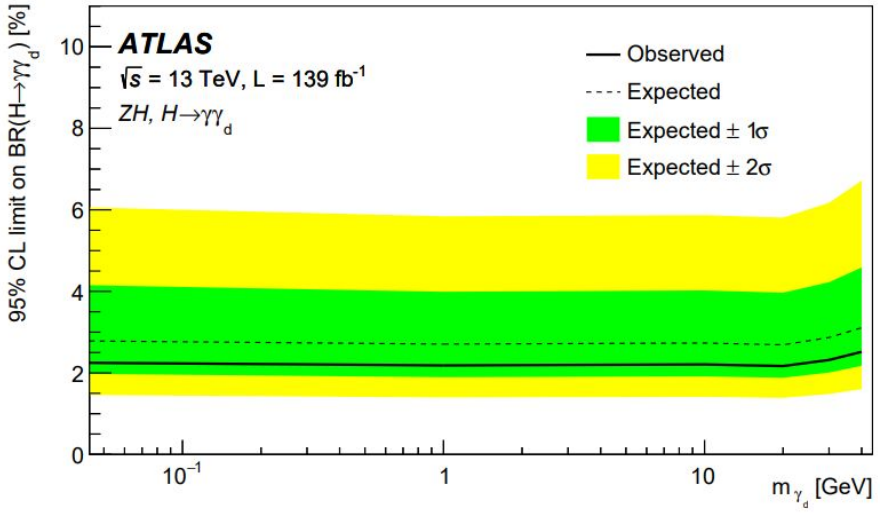
Dark photons from Higgs decays in ZH production

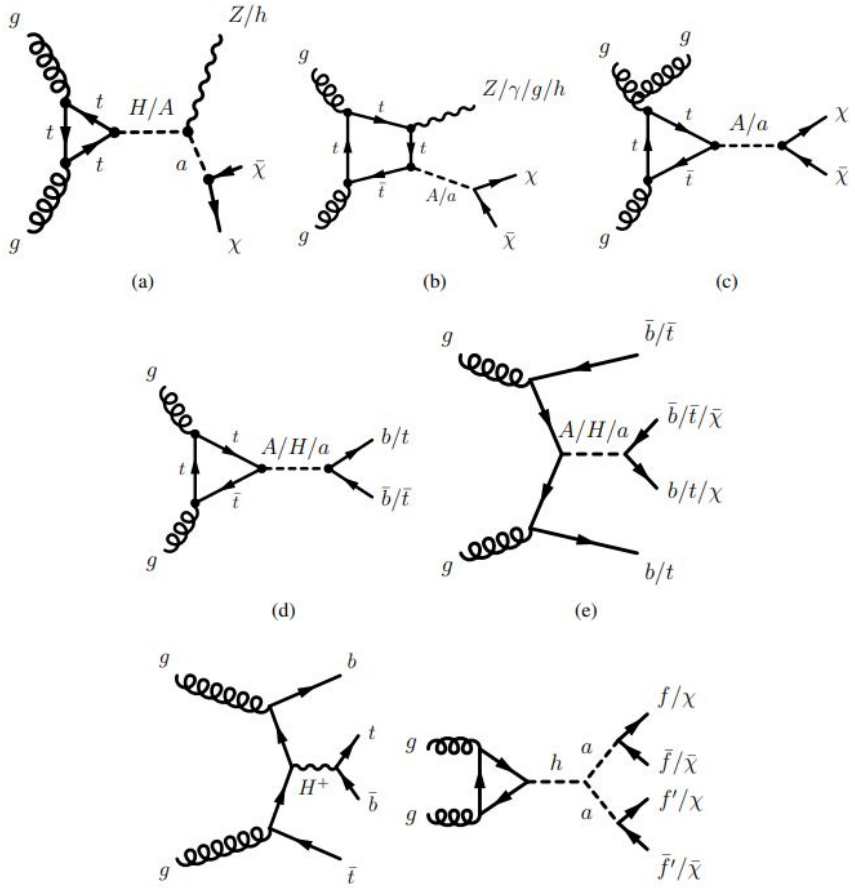
Background treatment:

- Fake E_T^{miss} background estimated with data-driven (ABCD) methods,
- Irreducible background adjusted with a dedicated CR,
- Rest of backgrounds estimated from simulation.

Dominant systematic uncertainties from energy resolutions and fake E_T^{miss} shapes.

UL@95 C.L. on B(H→γγ$_d$) from binned ML fit in SR to the BDT response:





2HDM+a interpretation from dark matter results

ATLAS, 1 Jun ‘23, [2306.00641]

arXiv:2306.00641

2HDM+a interpretation from dark matter results

Various Run 2 ATLAS 139 fb^{-1} dark matter searches interpreted in 2HDM+a:

Scenario		Fixed parameter values					Varied parameters
		$\sin\theta$	m_A [GeV]	m_a [GeV]	m_χ [GeV]	$\tan\beta$	
1	a	0.35	–	–	10	1.0	(m_a, m_A)
	b	0.70	–	–	10	1.0	
2	a	0.35	–	250	10	–	$(m_A, \tan\beta)$
	b	0.70	–	250	10	–	
3	a	0.35	600	–	10	–	$(m_a, \tan\beta)$
	b	0.70	600	–	10	–	
4	a	–	600	200	10	1.0	$\sin\theta$
	b	–	1000	350	10	1.0	
5		0.35	1000	400	–	1.0	m_χ
6		0.35	1200	–	–	1.0	(m_a, m_χ)

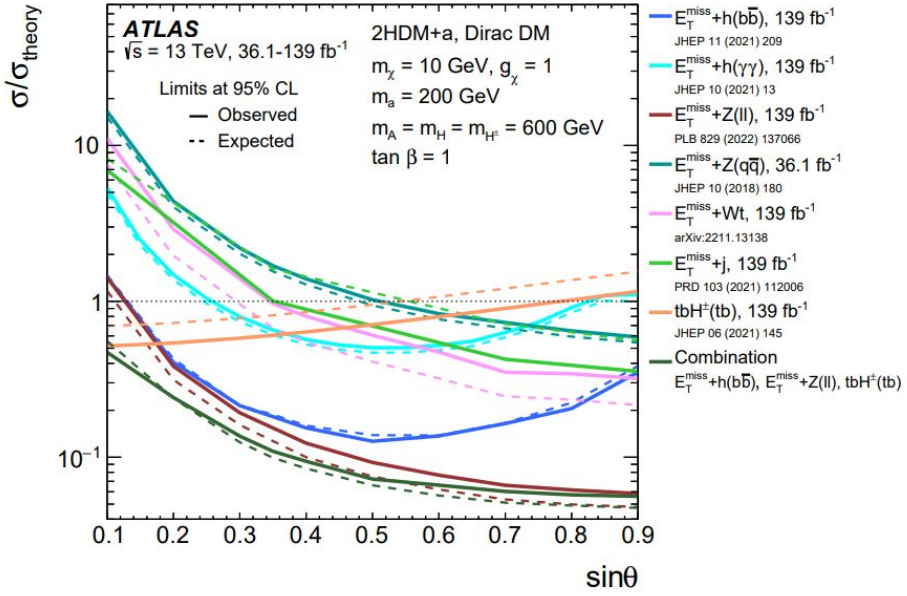
Statistical combination of the analyses → results for the different scenarios.

Analysis/Scenario	1a	1b	2a	2b	3a	3b	4a	4b	5	6
$E_T^{miss} + Z(\ell\ell)$ [74]	x	x	x	x	x	x	x	x	x	
$E_T^{miss} + h(b\bar{b})$ [75]	x	x	x	x	x	x	x	x	x	x
$E_T^{miss} + h(\gamma\gamma)$ [84]	x	x			x	x	x	x		
$E_T^{miss} + h(\tau\tau)$ [78]	x			x						
$E_T^{miss} + tW$ [77]	x	x	x	x	x	x	x	x		
$E_T^{miss} + j$ [45]	x	x			x	x	x	x		
$h \rightarrow$ invisible [86]	x	x			x					x
$E_T^{miss} + Z(q\bar{q})$ [126]	x						x	x		
$E_T^{miss} + b\bar{b}$ [127]							x	x		
$E_T^{miss} + t\bar{t}$ [127, 128]							x	x		
$t\bar{t}t\bar{t}$ [85]	x	x	x	x	x	x	x	x	x	
$tbH^{\pm}(tb)$ [76]	x	x	x	x	x	x	x	x	x	
$h \rightarrow aa \rightarrow f\bar{f}f'\bar{f}'$ [79–83]										x

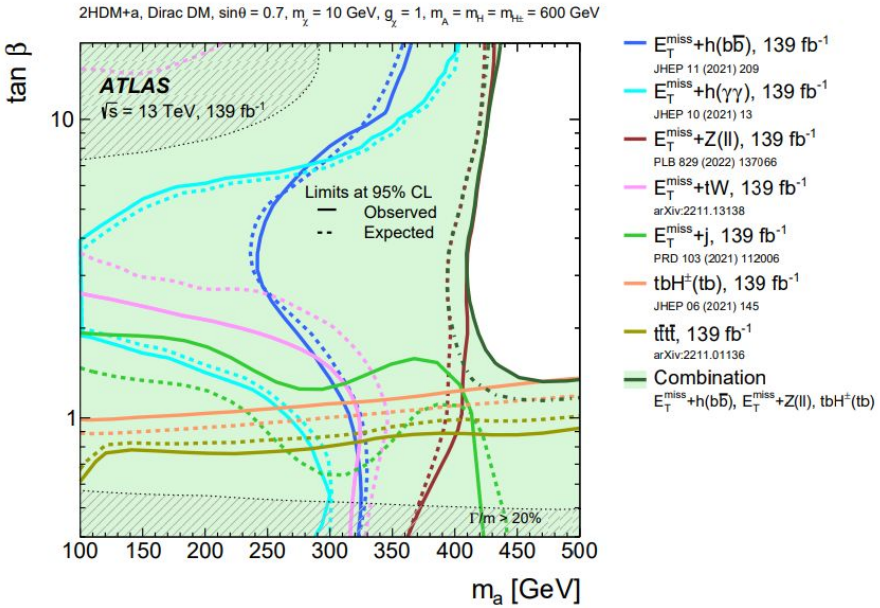
arXiv:2306.00641

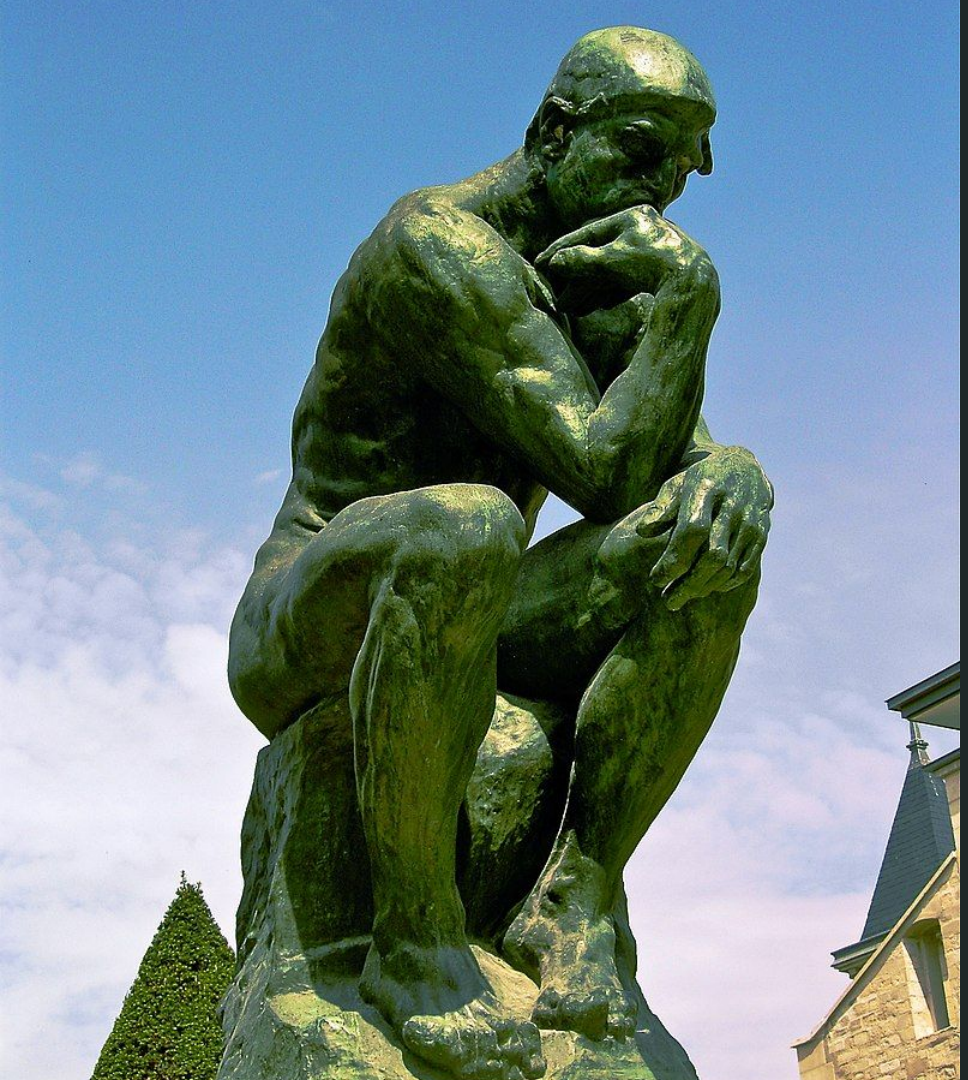
2HDM+a interpretation from dark matter results

Scenario 4a



Scenario 3b





Ideas and plans for the future

Proposed activities for next year

Increase our activity: regular meetings, common projects. Starting point may be to produce a document with summaries and suggestions:

- **Review of current experimental results from Runs 1 and 2,**
- **Suggestions for Run 3, and prospects for the future, *e.g.* HL-LHC.**

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- **Review of current experimental results from Runs 1 and 2,**
- **Suggestions for Run 3, and prospects for the future, *e.g.* HL-LHC.**

But, **we would like to provide a document beyond a review article:**

- Suggest **common benchmarks for searches,**
- Identify **synergies with other sub-working groups,**
- And also with **other working groups**, *e.g.* LLPC LLPs WG and DM WG.
- BSM Higgs decays involving LLPs, semi-visible decays, MET-rich decays, etc.
- **Joint sub-working group + other sub-working groups/WGs workshops?**

Thanks for your attention!