SUSY 2024
Theory meets Experiment

Fundação
para a Ciência
e a Tecnologia
SFRH/BD/151006/2021

Searches for Dark Matter with the ATLAS Experiment at the LHC

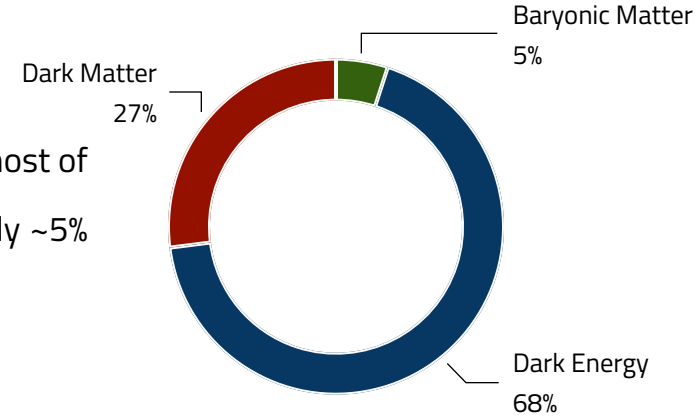
LIP
LABORATÓRIO DE INSTRUMENTAÇÃO
E FÍSICA EXPERIMENTAL DE PARTÍCULAS

ATLAS EXPERIMENT

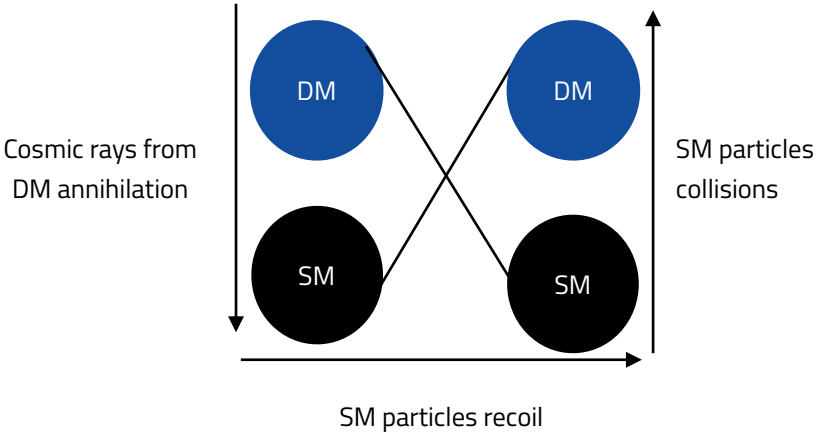
Maura Barros

On behalf of the ATLAS Collaboration

Standard Model and Dark Matter

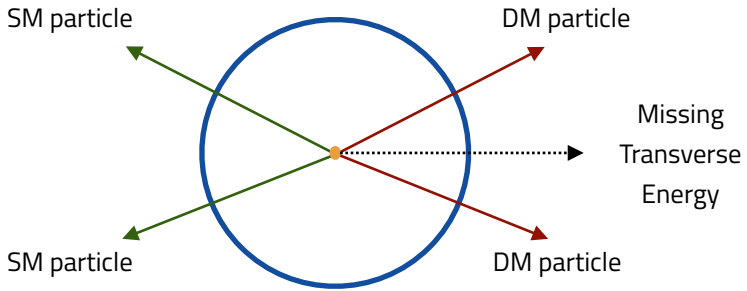


- The **Standard Model (SM)** is a well-tested model that explains successfully most of the present experimental results with high precision. However, it explains only ~5% of the of the Universe
- **Dark Matter (DM)** is the major matter component in the Universe



DM is **invisible** to the detector but it can be produced in collisions at the LHC

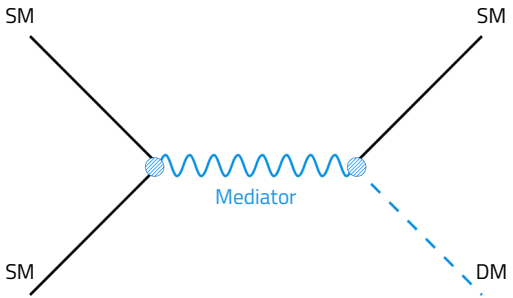
- **SM** particle produced in **association** with **DM**



Dark Matter searches

Dark Matter searches

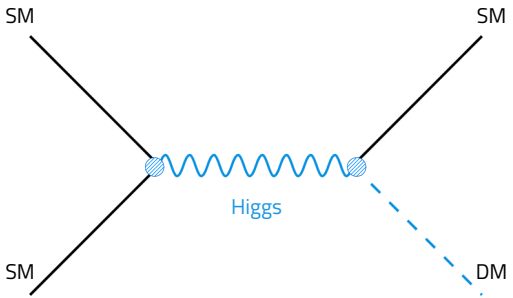
X + E^T_{miss}: Looks for associated production or ISR → semi-visible final state



Dark Matter searches

X + E^T_{miss}: Looks for associated production or ISR → semi-visible final state

Higgs boson: Searches in the Higgs sector



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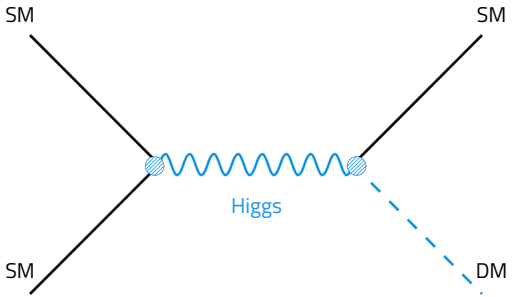
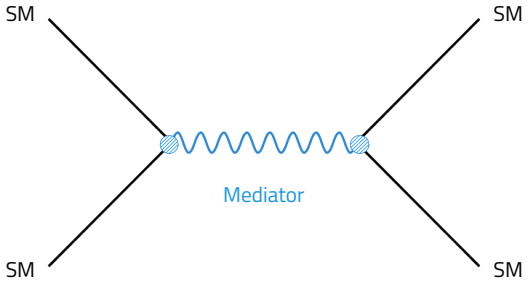
Higgs boson: Searches in the Higgs sector



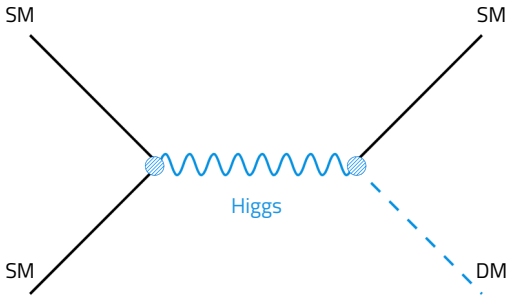


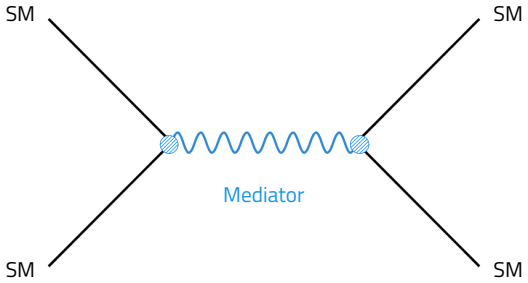
Mediator searches: Looks for a mass peak → visible final state

Dark Matter searches

X + E^T_{miss}: Looks for associated production or ISR → semi-visible final state

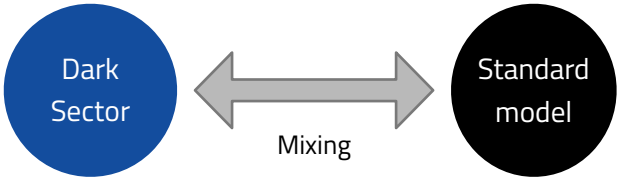
Higgs boson: Searches in the Higgs sector





Mediator searches: Looks for a mass peak → visible final state

Dark sector: Particles from a dark sector that interact with SM particles



Search for DM with ATLAS

Public results can be found here

ATLAS has an extensive program on searching for **DM at the LHC**

Individual searches:

▪ Dark mesons	2405.20061
▪ Mono-top	2402.16561
▪ V(W/Z) + E_{miss}^{T}	2406.01272
▪ Dark Higgs boson decaying into b quarks	ATLAS-CONF-2024-004

Summaries and Combinations:

▪ Dark photon combination	2406.01656
▪ DM models involving s-channel mediator	2404.15930
▪ DM searches interpreted in a 2HDM+a	2306.0064

Individual Searches

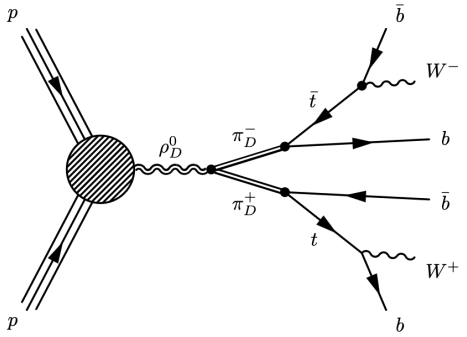
Dark Mesons

2405.20061

Signatures from a dark sector: dark mesons simplified ($SU(2)_L$ gaugephobic) signal model

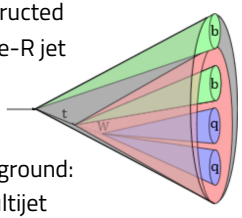
Dark mesons occur as composites of the constituent vector-like fermions. Parameters:

- $m_{\pi_{D'}}$, m_{ρ_D} and N_D ($= 4$)



All hadronic channel

π_D reconstructed from a large-R jet



Dominant background: data-driven multijet

- $H_T > 1150$ GeV
- Lepton veto
- 6 or more $R = 0.4$ jets with $p_T > 25$ GeV, 3 b-tagged
- 2 or more large-R jets with $m_{\text{jet},R=1.2} > 190$ GeV

One lepton channel

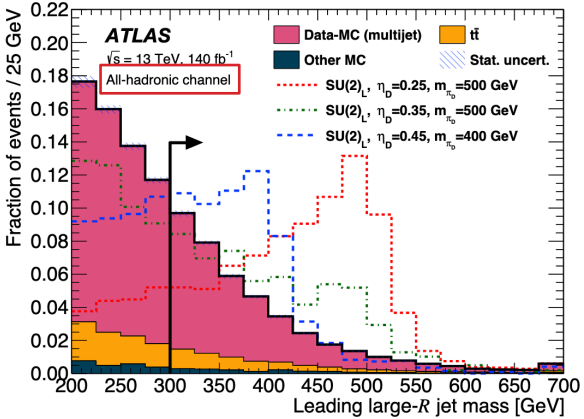
Dominant background: MC Top production simulation

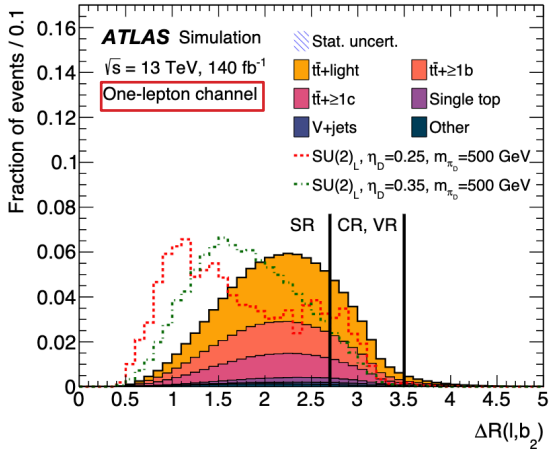
- $H_T > 300$ GeV
- At least 5 jets, 3 or more b-tagged

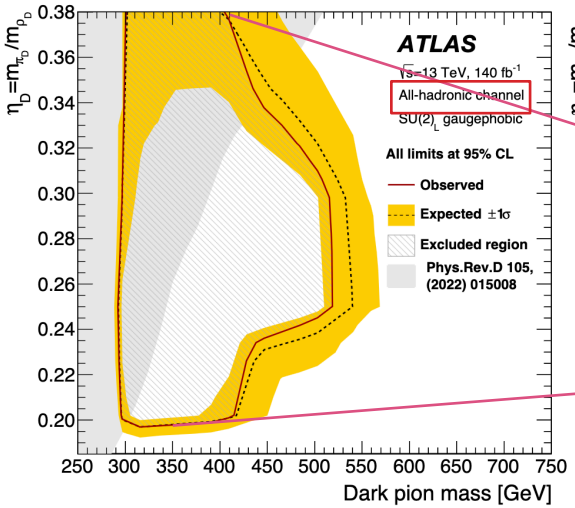
Dark Mesons

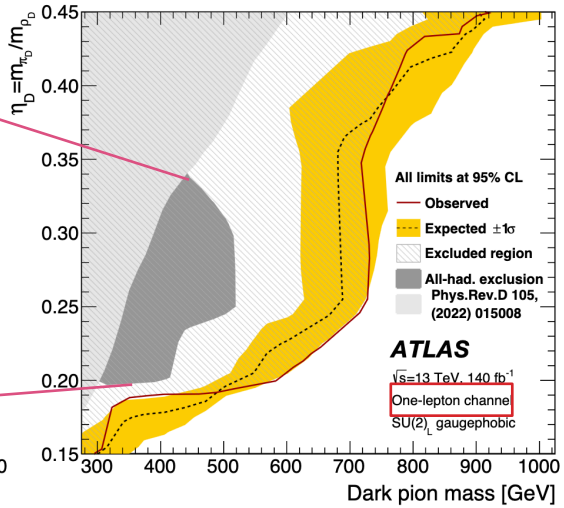
Signal regions, validation regions and control regions are defined:

- small- and large-R jets properties
- Lepton properties for the one lepton channel









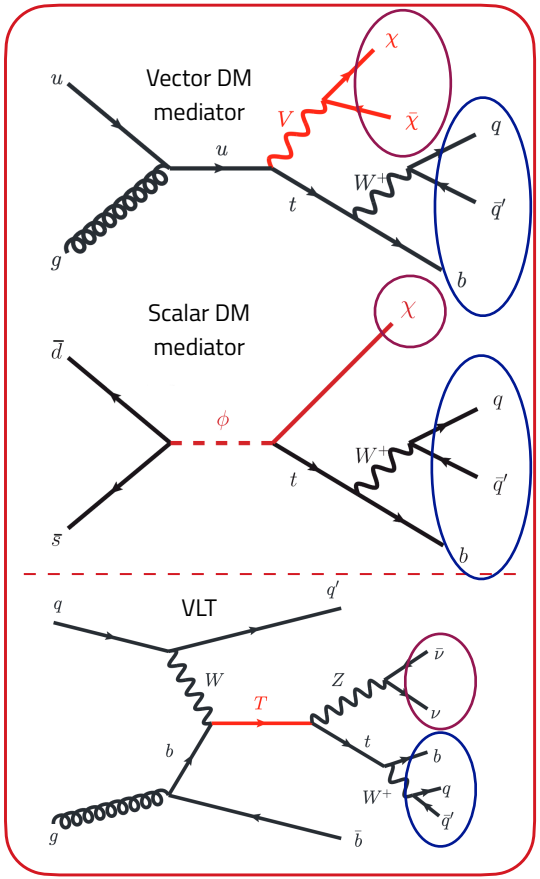
95% CL limits in the $\eta - m_{\pi_D}$ plane for $SU(2)_L$

$m_{\pi_D} < 943$ GeV excluded for $m_{\pi_D}/m_{\rho_D} = 0.45$

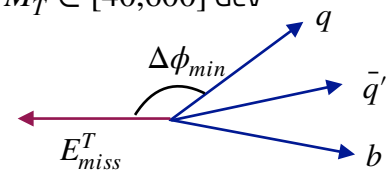
$m_{\pi_D} < 738$ GeV excluded for $m_{\pi_D}/m_{\rho_D} = 0.25$

First direct collider constraints on this type of model!

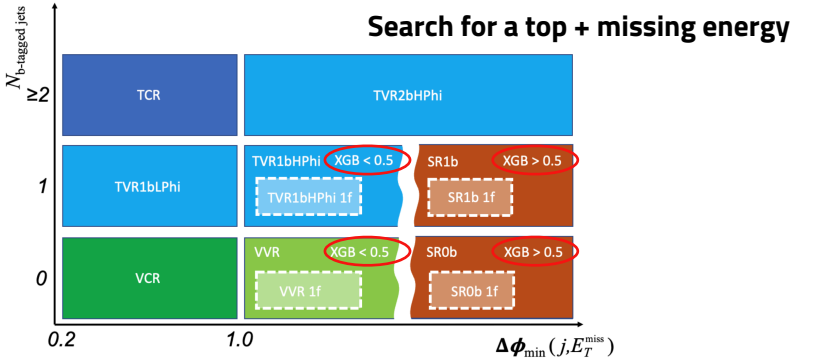
Mono-top



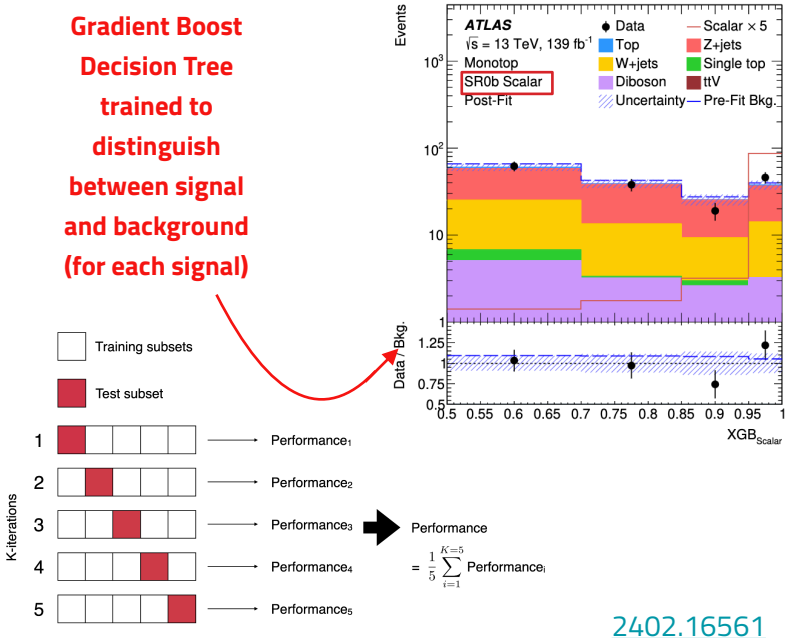
- $E^T_{miss} \geq 250$ GeV
- ≥ 1 top-tagged large-R jet
  $p_T \in [350,2500]$ GeV,
  $|\eta| < 2.0$
- Lepton veto, b-tagging 77% WP
- Exactly zero loose bad jets
- $M_T \in [40,600]$ GeV



- $\Delta\phi(E^T_{miss}, jet) < 0.2$

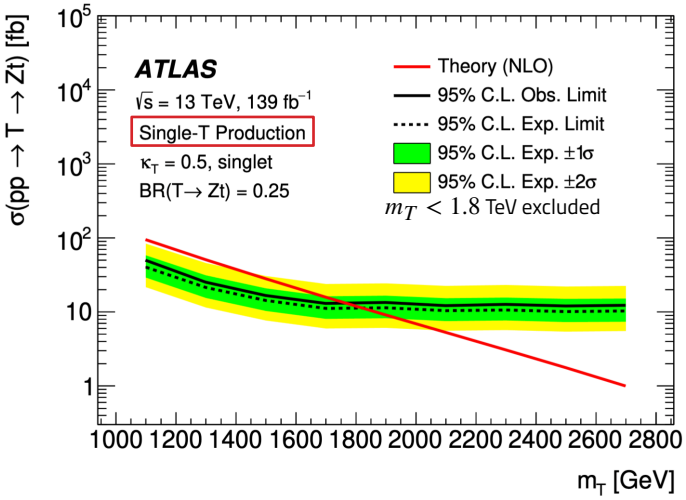


Gradient Boost Decision Tree trained to distinguish between signal and background (for each signal)

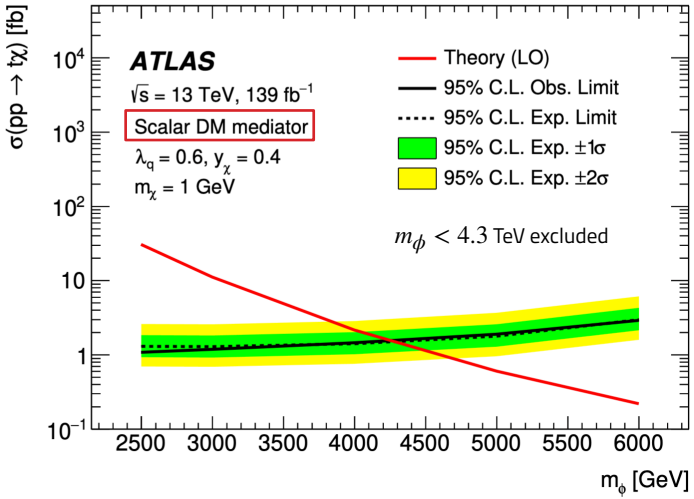


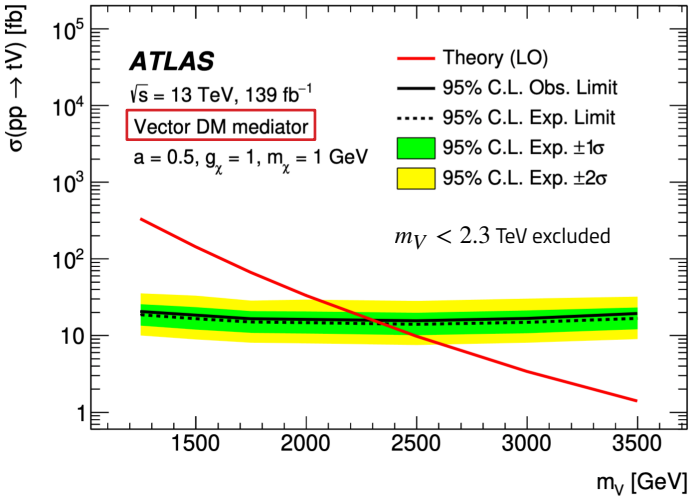
Mono-top

2402.16561



Good agreement between data and SM predictions: 95% CL limits set



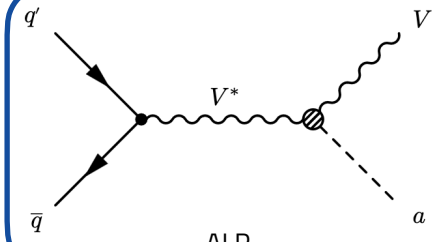


V(W/Z) + E^T_{miss}

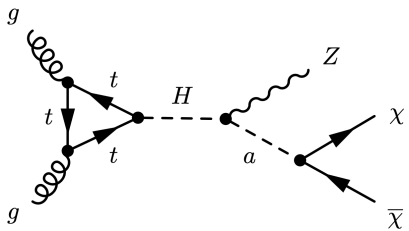
Model independent search

2406.01272

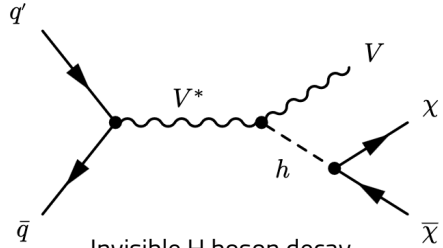
Results are also interpreted for several models



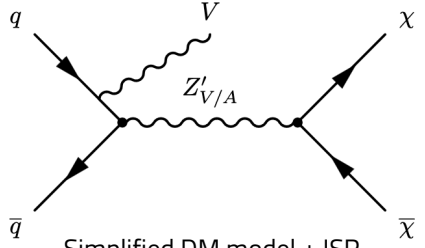
ALP



2HDM+a



Invisible H boson decay



Simplified DM model + ISR

Event selection

PV: at least 2 tracks with $p_T > 500$ MeV

$p^{miss}_{T,\text{nolep}} > 30$ GeV

$\Delta\phi(E^{miss}_{T/T,\text{nolep}}, \text{jets}) > 20°$

$\Delta\phi(E^{miss}_{T/T,\text{nolep}}, p^{miss}_{T/T,\text{nolep}}) < 90°$

$p^{miss}_{T/T,\text{nolep}} > 30$ GeV

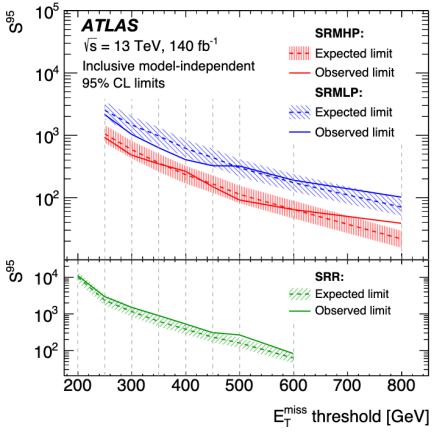
Dominant background:

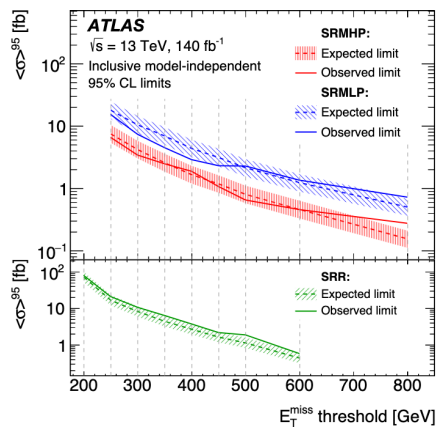
- Z/W + jets
- Top
- Diboson

SR

$$S = \frac{|\mathbf{E^T_{miss}}|}{[\sigma^2_L(1-\rho_{LT})]^{1/2}}$$

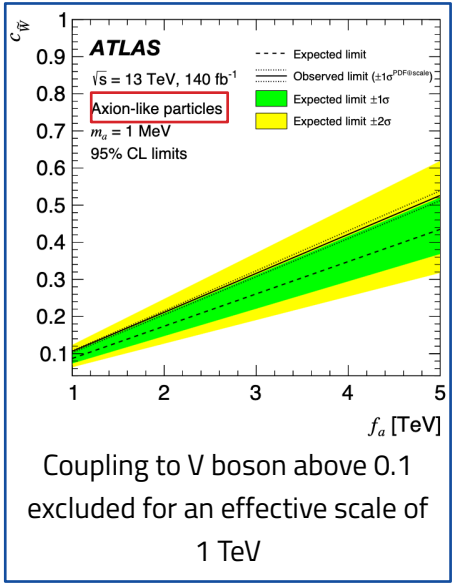
No significant deviation from the SM background expectation!



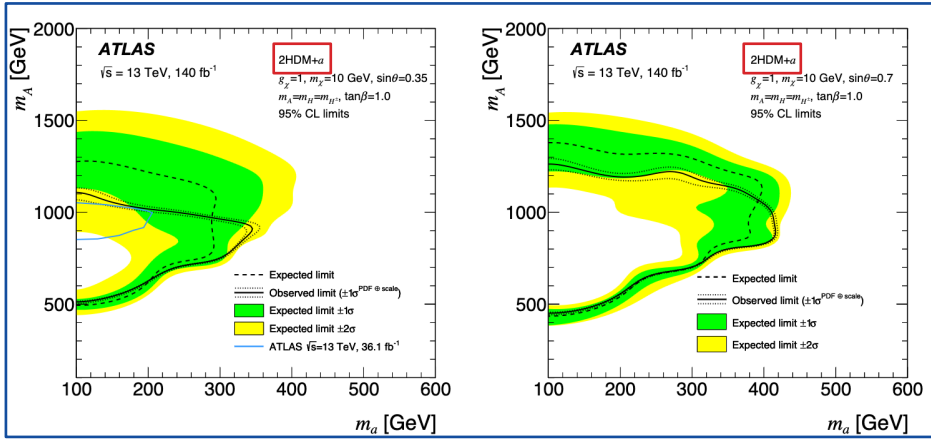


95% CL limits on the visible cross-section ranging from 0.3 fb to 79.5 fb

V(W/Z) + E_{miss}^{T}



Coupling to V boson above 0.1 excluded for an effective scale of 1 TeV

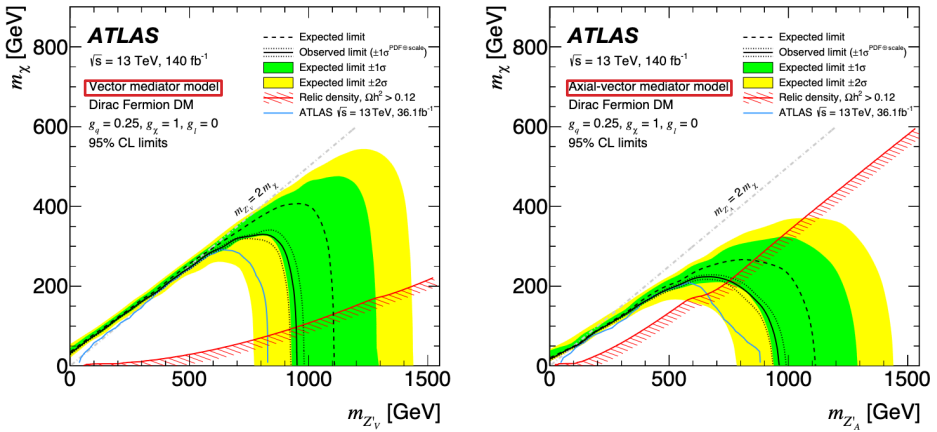


$m_a < 340$ GeV excluded for $m_A = 900$ GeV; $\sin\theta = 0.35$; $\tan\beta = 1.0$

$m_a < 420$ GeV excluded for $m_A = 900$ GeV; $\sin\theta = 0.7$; $\tan\beta = 1.0$

Limits on $B_{H\to inv}$	Expected limit	Observed limit
Merged topology	$0.34^{+0.14}_{-0.09}$	0.38
Resolved topology	$0.54^{+0.23}_{-0.15}$	0.71
Combined	$0.31^{+0.13}_{-0.09}$	0.34

Upper limit on the BR set to 0.34



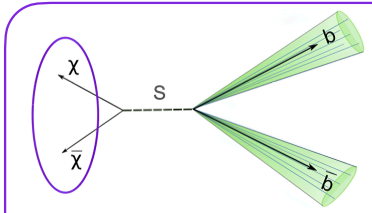
$m_{med} \leq 955$ GeV excluded for $m_\chi = 1$ GeV

$m_{med} \leq 965$ GeV excluded for $m_\chi = 1$ GeV

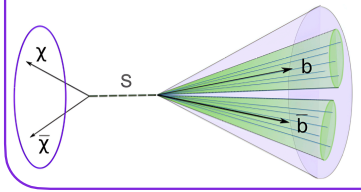
2406.01272

Dark Higgs boson decaying into b quarks

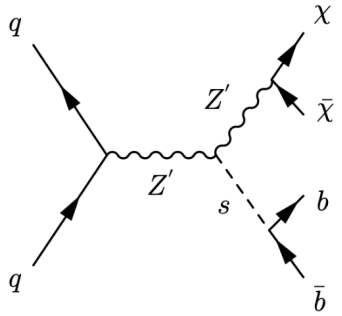
Large E_{miss}^{T} and resonant $b\bar{b}$ production **not probed** directly for $m_{b\bar{b}} < 160$ GeV

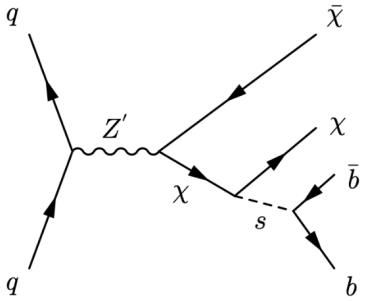


Resolved region: **two small-R** jets to reconstruct S



Boosted region: **one large-R** jets to reconstruct S





Loose/Bad jet veto

$E_{miss}^{T} > 150$ GeV

Light lepton veto (SR) and tau veto

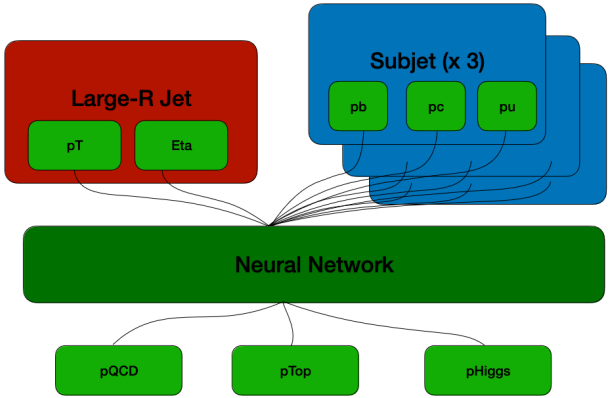
Extended tau veto

$min_{j\in\{1,2,3\}}\Delta\phi(E_T^{miss}, j) > 20°$

$0.7 < \frac{E_T^{miss}}{p_T} < 1.3$

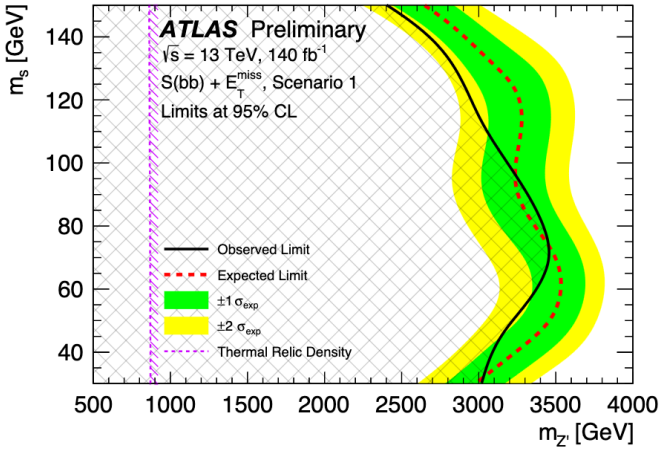
New tagging algorithm!

Optimised for this topology.



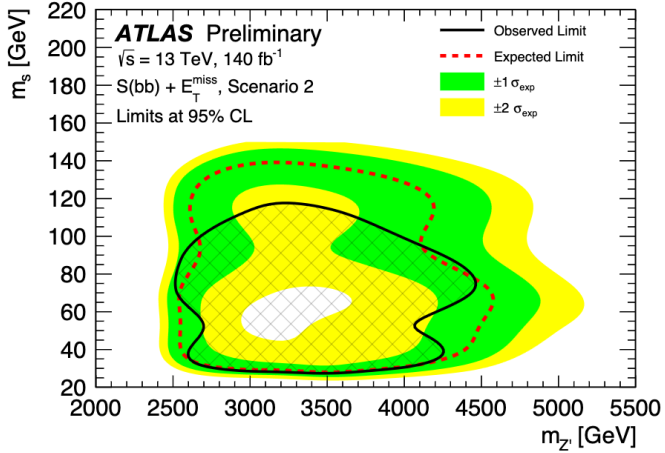
Dark Higgs boson decaying into b quarks

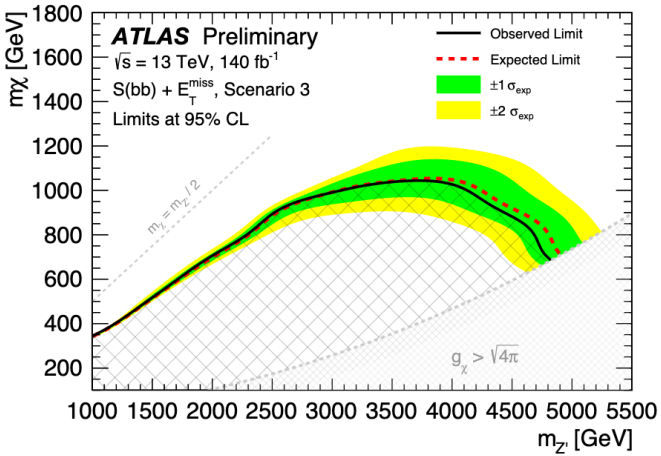
ATLAS-CONF-2024-004



Data in good agreement with SM predictions

For $m_s < 150$ GeV: $m_{Z'} < 3.4$ TeV with $g_\chi = 1, g_q = 0.25$ and $\sin\theta = 0.01$ are excluded; $m_{Z'} < 4.8$ TeV in a relic density inspired benchmark

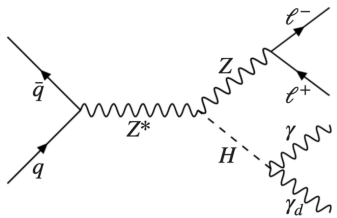
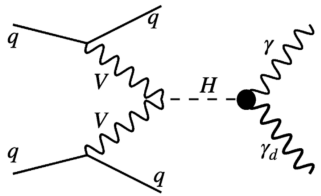
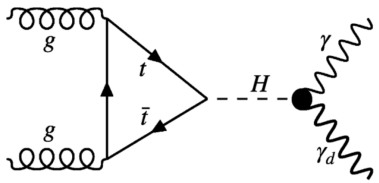




Summaries and Combinations

Dark Photon Combination

Combination of searches for Higgs boson decaying into a visible photon and a massless dark photon

Input analysis	ZH	VBF	ggF
			
SM	$m_H = 125$ GeV; $m_{\gamma_d} \in [0,40]$ GeV	$m_H = 125$ GeV; γ_d massless	
BSM		$m_H \in [60,2000]$ GeV; γ_d massless	$m_H \in [400,2000]$ GeV; γ_d massless
Topology	1 photon, 2 leptons within Z mass window, ≤ 2 jets, MET	1 photon, no leptons, ≥ 2 jets, MET	≥ 1 photon, no leptons, ≤ 1 jets, MET
Main background	Fake MET in $Z\gamma + j$ and $Z + j$ processes $e \rightsquigarrow \gamma$ in SM VV processes Data-driven	$W(\rightarrow l\nu)\gamma + j, Z(\rightarrow \nu\nu)\gamma + j$ where $e \rightsquigarrow \gamma$ MC $j \rightsquigarrow \gamma$ Data-driven	$Z(\rightarrow \nu\nu)\gamma$ (dominant) $\gamma + j, W(\rightarrow l\nu)\gamma, Z(\rightarrow ll)\gamma$ MC $j/e \rightsquigarrow \gamma$ Data-driven

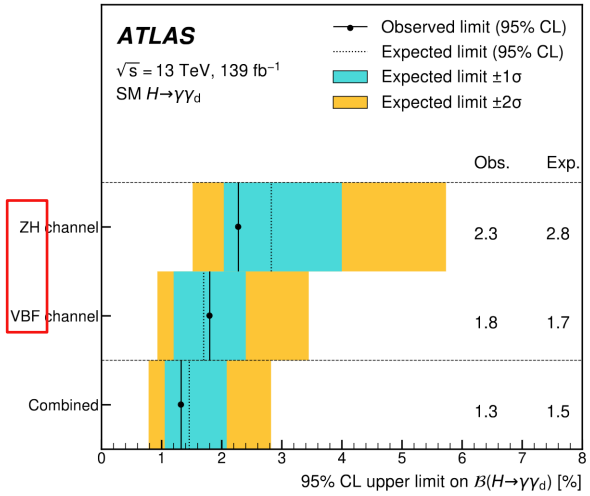
Orthogonality of event selection ensured!

SM Higgs, massless γ_d, targeting $BR(H_{125} \rightarrow \gamma\gamma_d)$

Heavy Higgs, massless γ_d, targeting $\sigma(ggF + VBF) \times BR(H \rightarrow \gamma\gamma_d)$

2406.01656

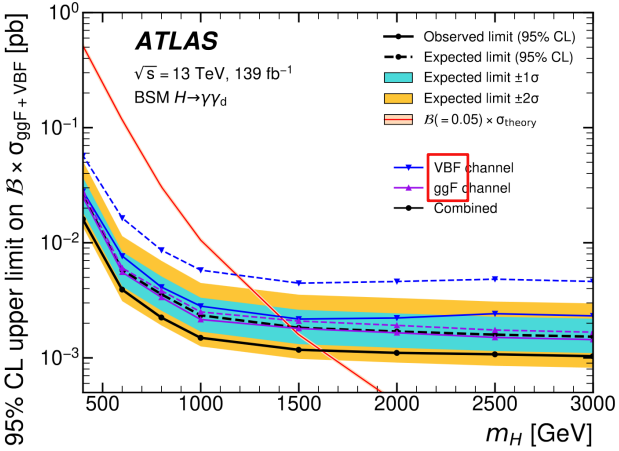
Dark Photon Combination



Observed limit: 1.3

Expected limit:1.5

Improvement of 29% (14%) w.r.t most stringent analysis (VBF)!



$m_{H_{BSM}} < 1600\ (1500)$ GeV excluded for $BR = 0.05$

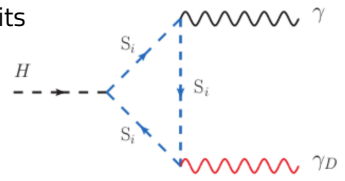
Improvement of 33% (14%) w.r.t. leading ggF!

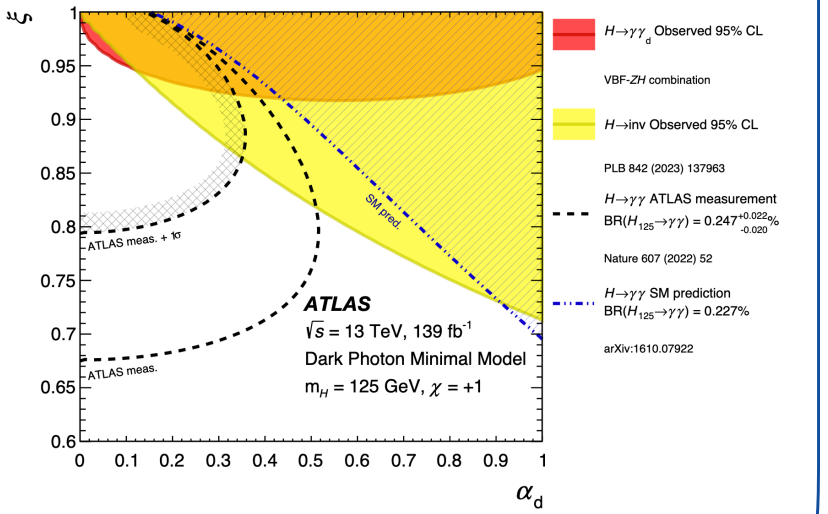
Interpreted

Minimal simplified model

Physics interpretation of ZH+VBF limits

Generic messenger sector: one left-double S_L and one right-singlet S_R of $SU(2)_L$





Results can be translated into constraints in (ξ, α_D) parameter space

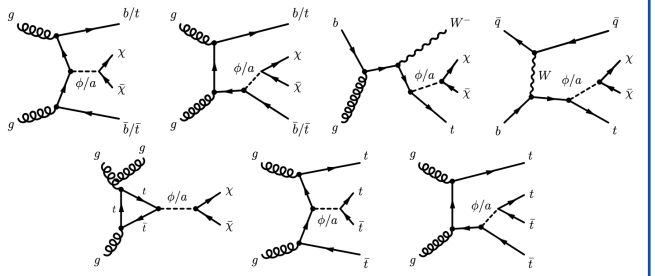
Provides the most stringent constraints on Higgs boson decaying to a photon and a massless dark photon to date!

2406.01656

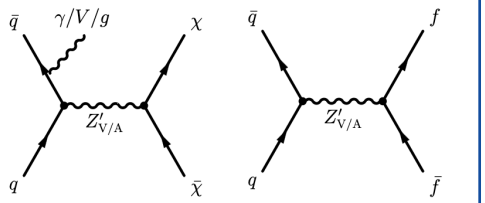
DM models involving s-channel mediator

Simplified models: spin-0 and spin-1 mediator particles

Spin-0: Scalar/Pseudoscalar



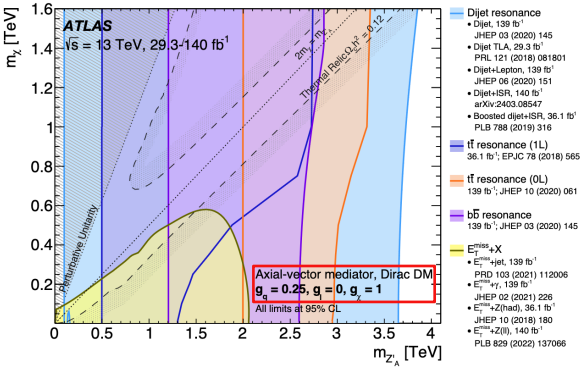
Spin-1: Vector/Axial-Vector

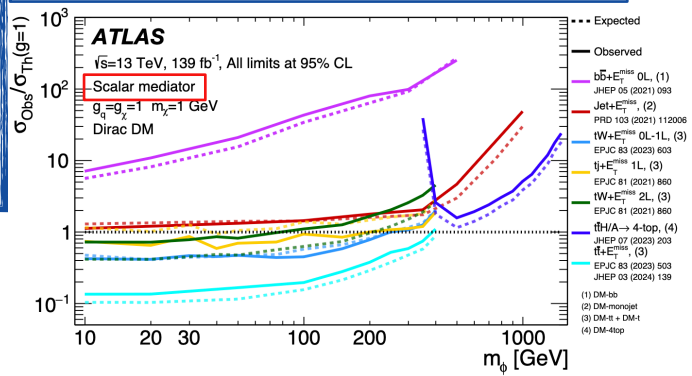


Models

Input analyses

Semi-visible final states	Visible final states
$b\bar{b} + E^T_{miss}$	Dijet and Di-b-jet
$t\bar{t} + E^T_{miss}$	Dijet angular
$t(W/j) + E^T_{miss}$	Dijet TLA
$Jet + E^T_{miss}$	Resolved dijet ISR
$\gamma + E^T_{miss}$	Boosted dijet ISR
$Z(ll) + E^T_{miss}$	Dijet+lepton
$W(qq')/Z(q\bar{q}) + E^T_{miss}$	$t\bar{t}$ resonance
	4-top

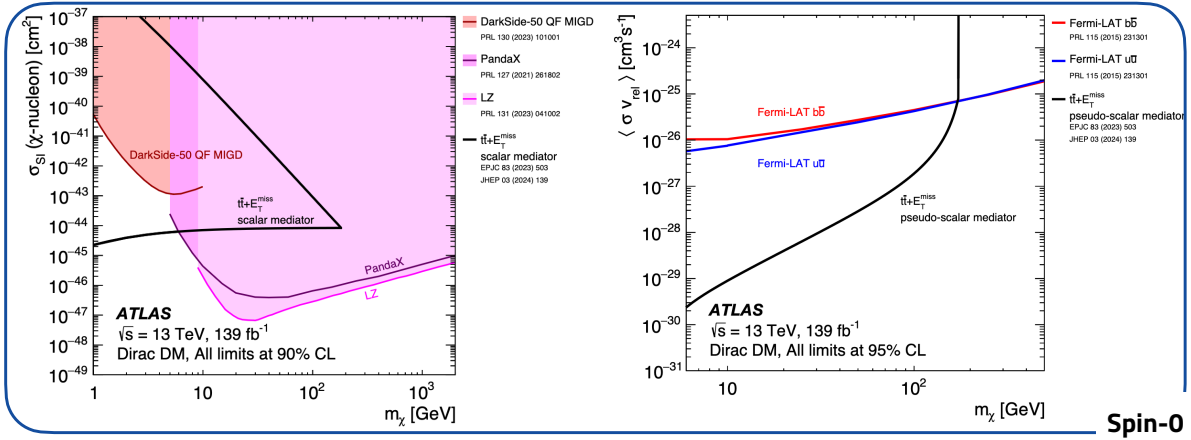




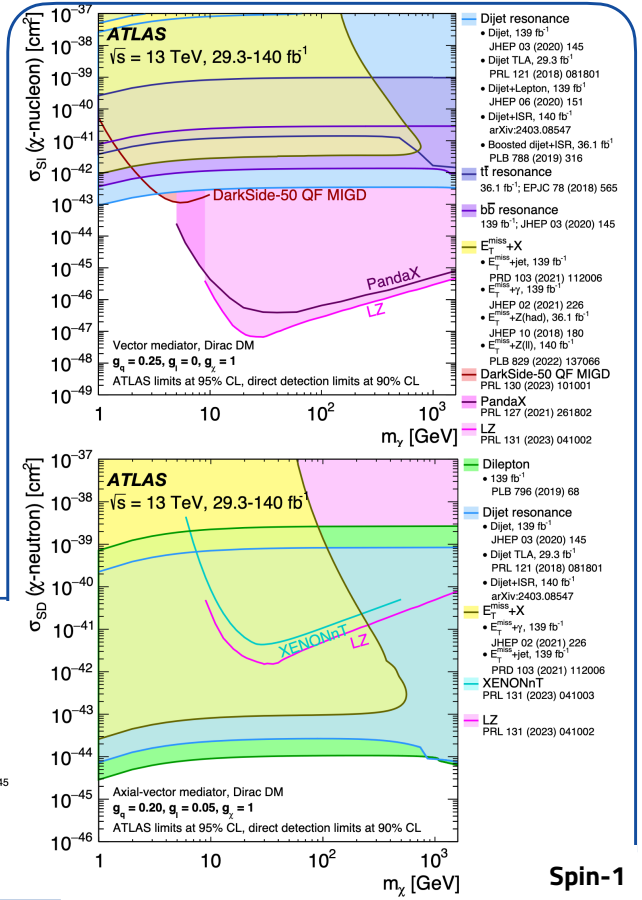
- Spin-0: exclusion limits covering mediator masses from 10 to 1500 GeV are compared for tt+MET, monotop, mono jet and four top final state
- Spin-1: limits set on the hadronic and leptonic couplings for axial-vector masses up to 5 TeV. Exclusion contours are set in the (m_χ, m_{Med}) plane

2404.15930

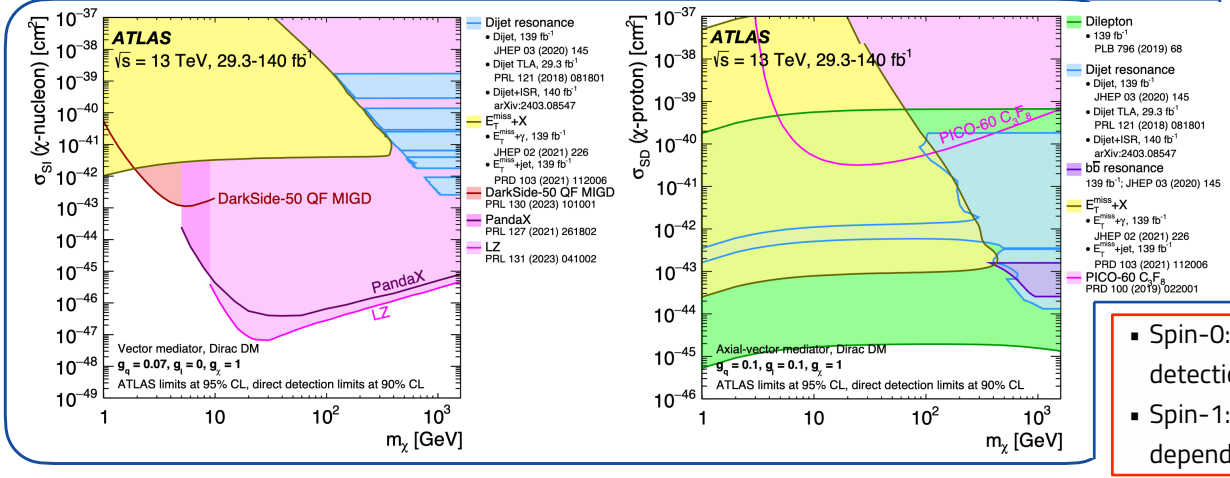
DM models involving s-channel mediator



Spin-0



Spin-1

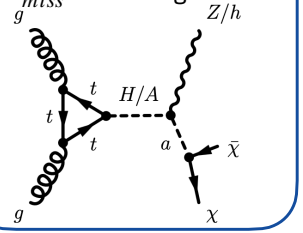


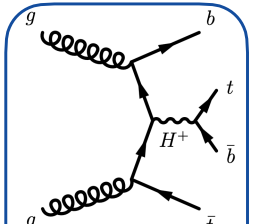
- Spin-0: search extend beyond the exclusion reach of direct detection experiments in the range of small DM mass
- Spin-1: limits particularly stringent in the case of spin-dependent scattering cross-sections [2404.15930](2404.15930)

DM searches interpreted in a 2HDM+a

Searches used to constrain the 2HDM+a model: signatures with and without E_{miss}^T

Resonant production of the $E_{miss}^T + Z/h$ signature





$tbH^{\pm}(tb)$ production

5 free parameters: $m_A = m_H = m_{H^{\pm}}, m_a, m_\chi, \sin\theta, \tan\beta$

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)

Shown for the first time

$E_{miss}^T + Z(ll)$

Selection: E_{miss}^T and **two** high-p_T **leptons** (same flavour, opposite charge)

Dominant backgrounds: ZZ, WZ, Z+jets, and non-resonant

$E_{miss}^T + h(b\bar{b})$

Selection: ≥ 2 b-jets and E_{miss}^T (split into resolved and merged topologies)

Dominant backgrounds: $t\bar{t}$ and $Z/W + j_{hf}$

$H^{\pm} \to tb$

Selection: 1 lepton and ≥ 5 jets (≥ 3 of them b-tagged)

Dominant backgrounds: $t\bar{t} + j$, single-top quark production in the Wt channel

Statistically independent!

Input Analyses

$E_{miss}^T + Z(ll)$; $E_{miss}^T + h(b\bar{b})$; $E_{miss}^T + h(\gamma\gamma)$; $E_{miss}^T + h(\tau\tau)$; $E_{miss}^T + j$;

$h \to$ invisible; $t\bar{t}t\bar{t}$; $H^{\pm} \to tb$; $h \to aa \to f\bar{f}f'\bar{f}'$.

36 fb^{-1} additional searches: $E_{miss}^T + b\bar{b}$; $E_{miss}^T + t\bar{t}$ and $E_{miss}^T + Z/W(qq)$

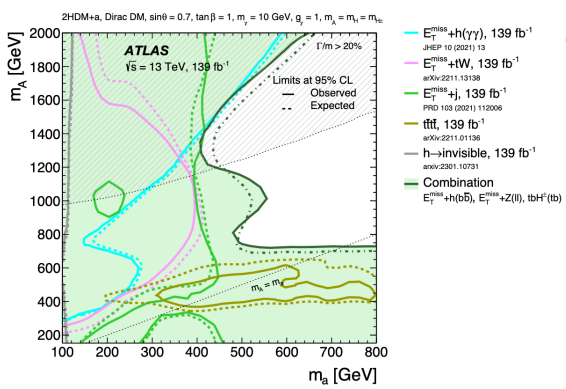
Most sensitive analysis entering statistical combination

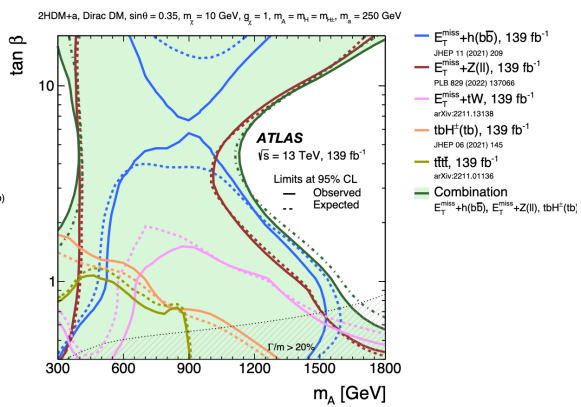
Constraints on 2HDM+a done in 6 scenarios

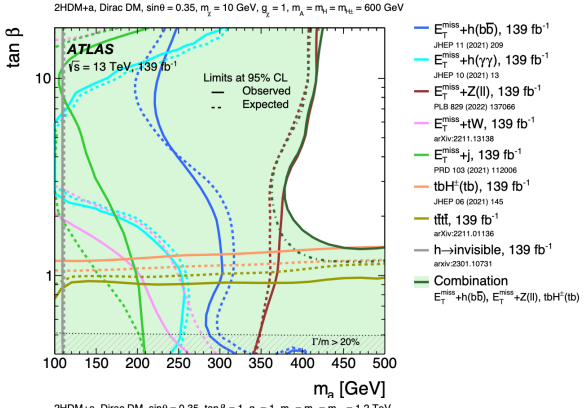
2306.0064

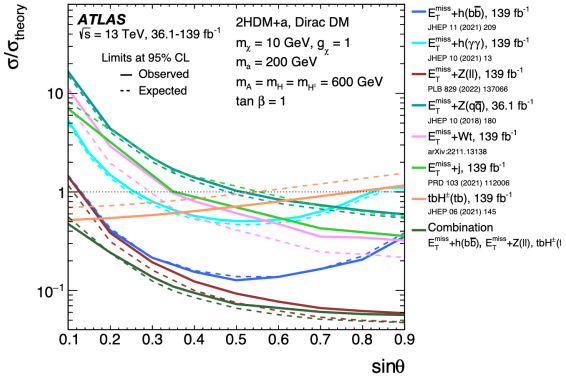
DM searches interpreted in a 2HDM+a

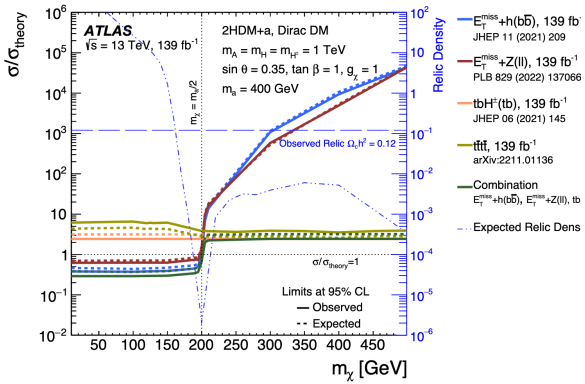
2306.0064

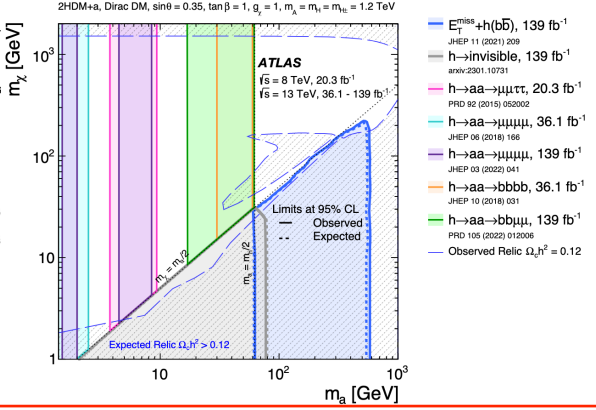












$m_a < 560$ GeV excluded for $m_A = m_H = m_{H^\pm} = 1.2$ TeV; $sin\theta = 0.35$ and $\tan\beta = 1.0$

$m_a < 640$ GeV excluded for $m_A = m_H = m_{H^\pm} = 2.0$ TeV; $sin\theta = 0.7$ and $\tan\beta = 1.0$

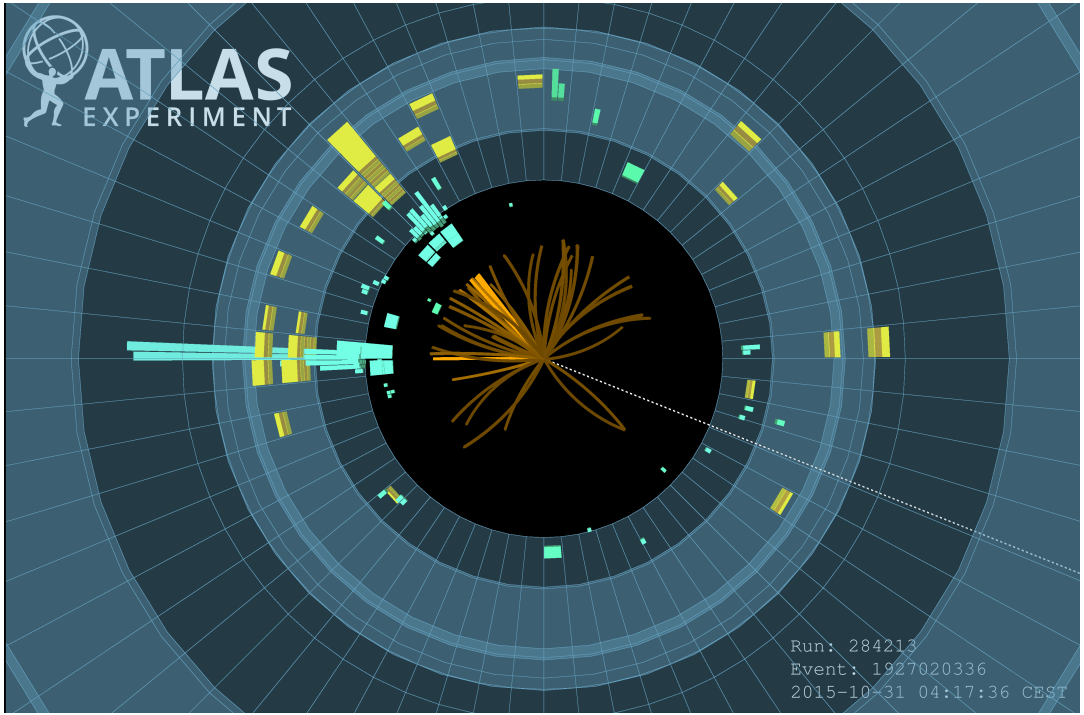
$m_A < 650$ GeV for all m_a range

Summary

- **DM** remains one of the **biggest open questions** in particle physics
- **ATLAS** has a board program of searches for DM
- Combinations and summaries are shown to improve the individual analyses sensitivity

More results to come!

- Run 3 ongoing: some data already available
  - 350 fb^{-1} to be recorded



Thank you !

Backup

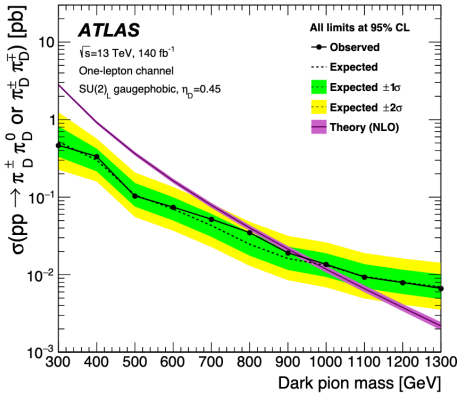
Dark Mesons

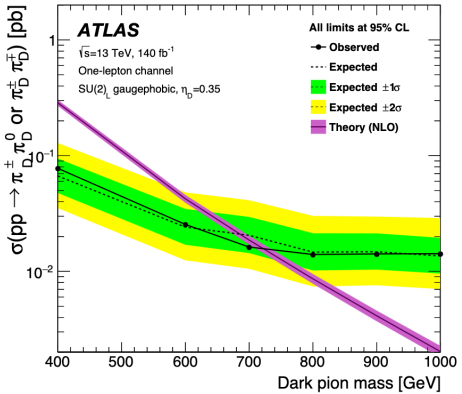
Variable	All-hadronic channel	One-lepton channel
N_{lep}(baseline)	0	1
N_{lep}(signal)	-	1
$N_{jets}(R = 0.4)$	≥ 6	≥ 5
$N_{jets}(R = 1.2)$	≥ 2	-
N_{b-jets}	≥ 3	≥ 3
H_T	≥ 1150 GeV	≥ 300 GeV

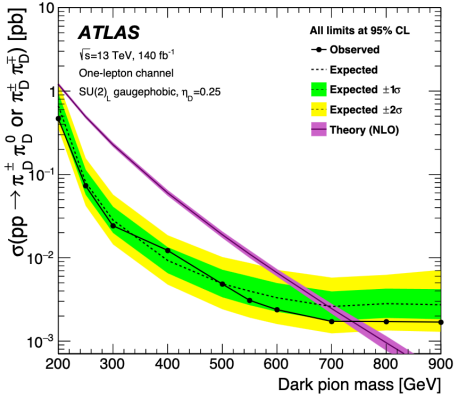
Leading large-R jet

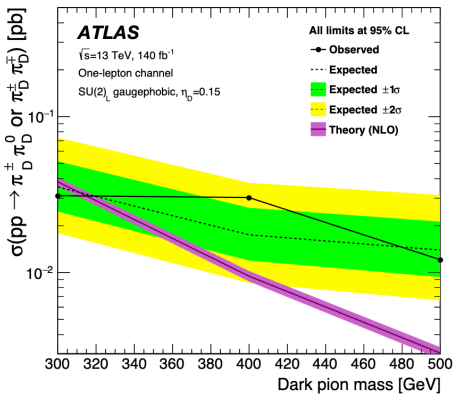
Sub-leading large-R jet	$\pi_{D,1}bb_1$	$\pi_{D,1}b\bar{b}_1$	$\pi_{D,1}bb_1$	$\pi_{D,1}bb_1$
$\pi_{D,2}bb_2$	J	K	L	S
$\pi_{D,2}b\bar{b}_2$	B	D	H	N
$\pi_{D,2}b\bar{b}_2$	E	F	G	M
$\pi_{D,2}b\bar{b}_2$	A	C	I	O

	Tag	Variable	Tag selection	Anti-tag selection
Both large-R jets		$m_{bb}/p_{T,bb}$	> 0.25	> 0.25
Leading large-R jet	bb_1	$\Delta R\,(j, b_2)$	< 1.0	≥ 1.0
Sub-leading large-R jet	bb_2	$\Delta R\,(j, b_2)$	< 1.0	≥ 1.0
Leading large-R jet	$\pi_{D,1}$	$m_{\text{jet,R=1.2}}$	[300 – 325 GeV, 325 – 400 GeV, > 400 GeV]	≤ 300 GeV
Sub-leading large-R jet	$\pi_{D,2}$	$m_{\text{jet,R=1.2}}$	[250 – 300 GeV, 300 – 350 GeV, > 350 GeV]	≤ 250 GeV

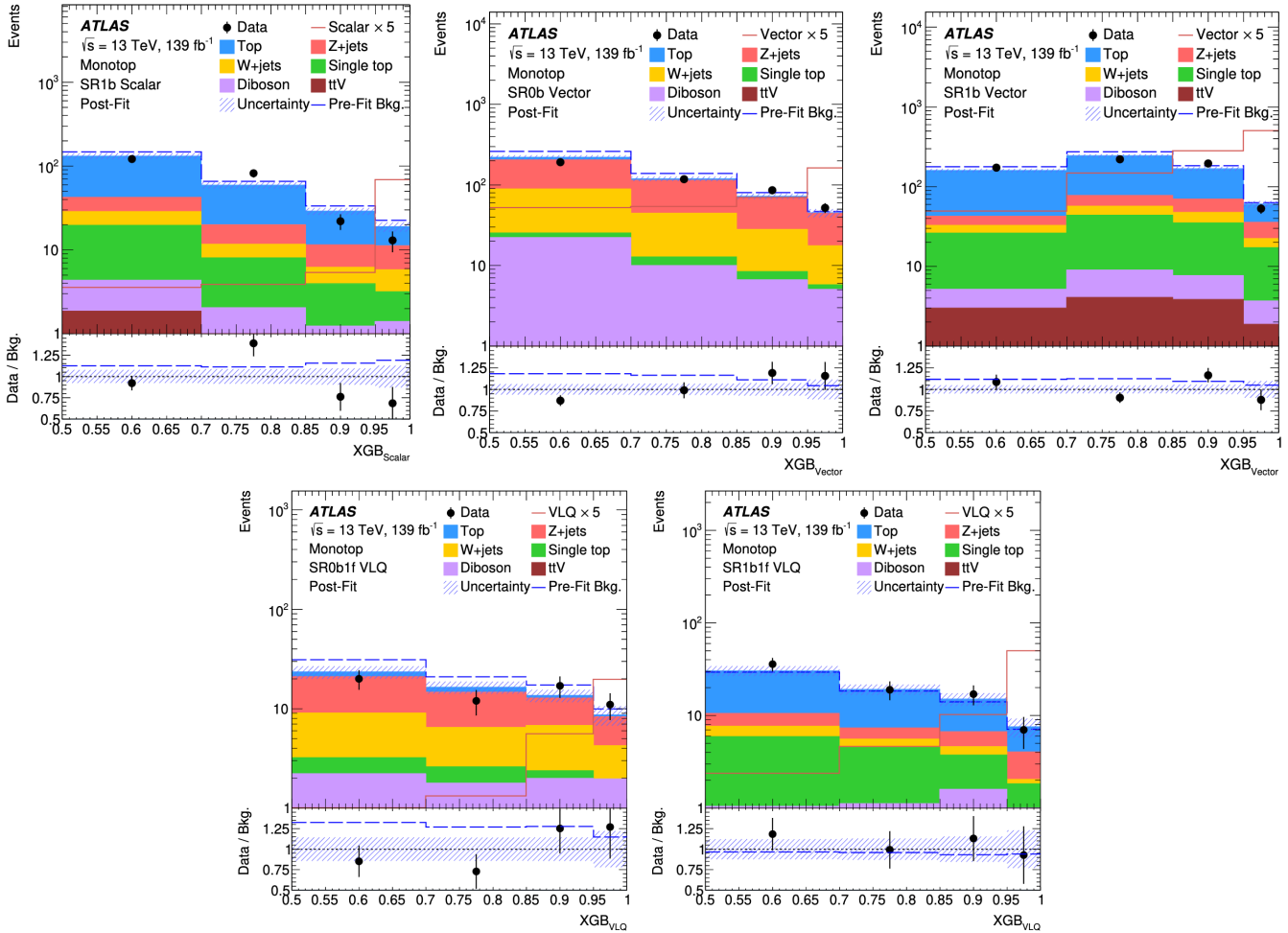








Monotop


ATLAS
√s = 13 TeV, 139 fb-1
Monotop
SR1b Scalar
Post-Fit
Data
Top
W+jets
Diboson
Uncertainty
Scalar × 5
Z+jets
Single top
ttV
Pre-Fit Bkg.
Events
Data / Bkg.
XGBScalar
SR0b Vector
SR1b Vector
XGBVector
SR0b1f VLQ
SR1b1f VLQ
VLQ × 5
XGBVLQ

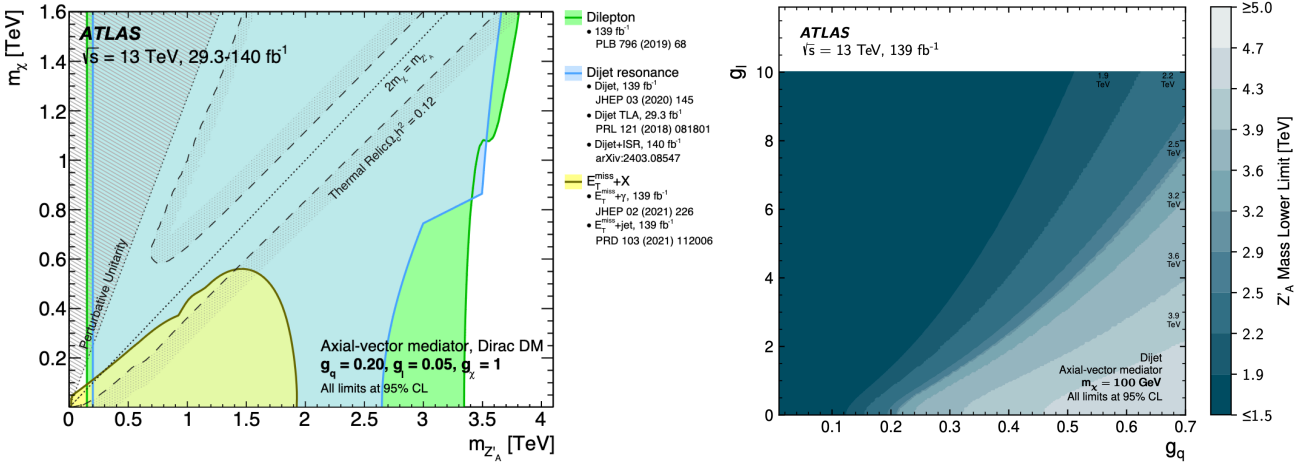
Dark Photon Combination

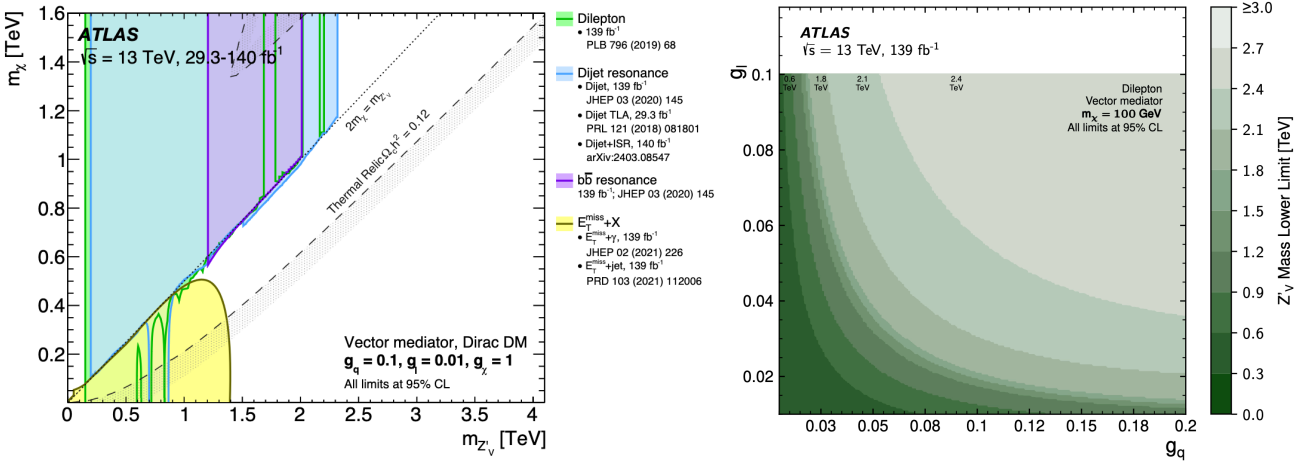
2406.01656

Channels	VBF	ZH	ggF
Trigger	$E_{\mathrm{T}}^{\mathrm{miss}}$	Lepton(s)	Photon
Photons	$= 1, C_{\gamma} > 0.4$	$= 1$	≥ 1
E_{T}^{γ} [GeV]	$\in (15, \max(110, 0.733 \times m_{\mathrm{T}}))$	> 25	> 150
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	> 150	> 60	> 200
Jets	2 or 3, $m_{j_1 j_2} > 250\,\mathrm{GeV}$, $\lvert\Delta\eta_{j_1 j_2}\rvert > 3$ $\eta_{j_1} \cdot \eta_{j_2} < 0$, $\Delta\phi_{j_1 j_2} < 2$, $C_{j_3} < 0.7$	≤ 2	≤ 1
Leptons	$= 0$ (e, μ)	$= 2$, SFOC $m_{\ell\ell} \in (76, 116)$ GeV	$= 0$ (e, μ, τ)
Disc. variables	m_{jj} and m_{T} in SR and 4 CRs	BDT score and 1 CR	$E_{\mathrm{T}}^{\mathrm{miss}}$
Reference	[28]	[29]	[30]
Processes considered in the combination	VBF, ggF	ZH	ggF, VBF
Combination scenario	SM, BSM	SM	BSM

2404.15930

DM models involving s-channel mediator





DM searches interpreted in a 2HDM+a