PROCEEDINGS OF SCIENCE

Resonant Searches for Dark Matter Mediators with ATLAS

Anindya Ghosh

On behalf of the ATLAS Collaboration*

The University of Arizona,
1118 E. Fourth Street, Tucson, USA

E-mail: anindya.ghosh@cern.ch

In this proceeding, five key analyses are presented using the full ATLAS Run 2 dataset within the framework of simplified DM models. These models propose that a mediator particle couples to quarks and either SM fermions (f) or DM particles (χ), with possible decays into jets, leptons, or missing transverse energy (E_T^{miss}). The analyses cover the mono-top search, the dark meson search, a combination of searches within the Two-Higgs-Doublet Model with an additional pseudoscalar mediator (2HDM+a), the dark photon search, and the dark Higgs boson search. While no significant excesses have been observed, the searches place stringent constraints on DM model parameter spaces, guiding the search for potential DM-SM interactions.

12th Large Hadron Collider Physics Conference (LHCP2024)
3-7 June 2024
Boston, USA

*Speaker

PoS(LHCP2024)004

1. Introduction

Dark matter (DM) comprises approximately 85% of the universe's total mass, yet its nature remains unknown, as it does not interact with electromagnetic radiation and is detectable only through gravitational effects, like anomalies in galaxy rotation curves and cosmic microwave background anisotropies. A leading hypothesis suggests that DM interacts with Standard Model (SM) particles via a mediator, a hypothetical particle facilitating these otherwise elusive interactions. Resonant searches at the Large Hadron Collider (LHC) aim to identify such mediators, which could decay into SM particles—producing jets, leptons, or photons—and leave characteristic signatures. A resonance, or an enhancement in the production cross-section, would appear as a peak in kinematic distributions and could indicate new physics. This proceeding presents five ATLAS Run 2 analyses within simplified DM models, where a mediator couples to quarks and either SM fermions (f) or DM particles (χ), exploring final states with jets, leptons, or missing transverse energy (E_T^{miss}). While no significant excesses are observed, these results place stringent constraints on DM model parameter spaces, refining potential interactions between DM and the SM.

2. Mono-top

A search for dark matter mediators produced in association with a hadronically decaying single top quark focuses on a mono-top signature [1]. This signature is characterized by a single jet and missing transverse energy (E_T^{miss}), as shown in Figure 1.

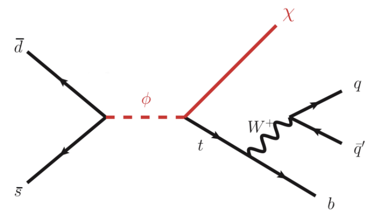
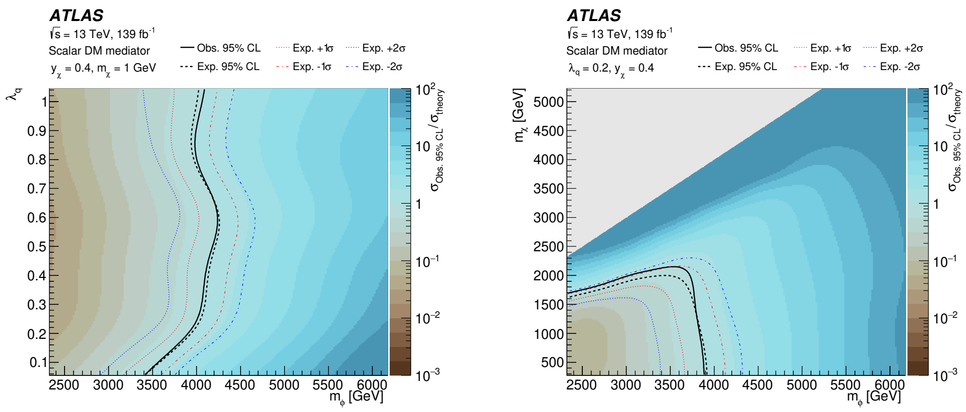


Figure 1: Mono-top production Feynman diagram.

The search is performed within a simplified dark matter model, focusing on a scalar dark matter mediator (ϕ) produced with a single top quark. The analysis considers mediator masses $m_\phi \in [2500, 6000]$ GeV and dark matter particle masses $m_\chi \in [500, 5500]$ GeV, with coupling parameters $\lambda_q \in [0.2, 1]$ and $y_\chi \in [0.2, 0.6]$. Events are selected using an E_T^{miss} trigger with a threshold of 250 GeV. Backgrounds from $t\bar{t}$ and W+jets are mitigated using a gradient-boosted decision tree (GBDT) discriminant. A profile-likelihood fit using XGBoost, trained with $m_\phi = 4$ TeV, reveals no significant excess. This leads to 95% confidence level (CL) upper limits on the dark matter signal cross-section. For $y_\chi = 0.6$ and $m_\chi = 0.4$ GeV, mediator masses below 4 TeV are excluded, improving upon previous results by 800 GeV. All values of m_χ are excluded for $m_\phi < 3.4$ TeV, and all values of y_χ are excluded for $m_\phi < 2.5$ TeV.

3. Dark meson

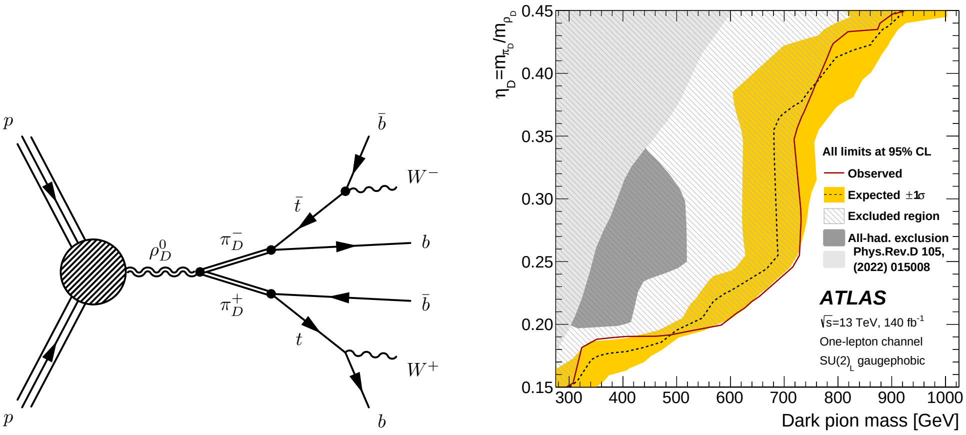
The search for dark mesons decaying to top and bottom quarks [6] investigates the Stealth Dark Matter model [3], which predicts dark matter as composite dark mesons, such as dark pions (π_D^0) and dark rhons (ρ_D). The analysis focuses on the parameter space where $\eta = m_{\pi_D}/m_{\rho_D} < 0.5$



(a) $m_\phi - \lambda_q$ **(b)** $m_\phi - m_\chi$

Figure 2: Observed 95% CL upper limits on the scalar-mediated DM signal cross-section divided by the theoretical value in two planes of the model parameter space: (a) (m_ϕ - λ_q), (b) (m_ϕ - m_χ). The observed (solid) and expected (dashed) 95% CL exclusion limits are shown, with ±1 and ±2 standard deviations around the expected limit.

to ensure on-shell production of dark mesons. Signal regions are studied in both the all-hadronic and one-lepton final states. In the all-hadronic channel, nine signal regions are defined based on jet masses, with a high E_T^{miss} trigger ($E_T^{\text{miss}} > 1150$ GeV) to suppress multijet backgrounds. Limits are extracted via a profile-likelihood fit. In the one-lepton channel, signal regions use lepton and jet variables, with single-lepton triggers and a profile-likelihood fit. No significant excess is observed, and the strongest 95% CL exclusion limits are shown in Figure 3b. Exclusions reach $\lambda_q = 0.20$ and $m_D < 550$ GeV in the all-hadronic channel, while in the one-lepton channel, limits extend to $m_D < 940$ GeV for $\lambda_q = 0.45$ and $m_D < 740$ GeV for $\lambda_q = 0.25$.



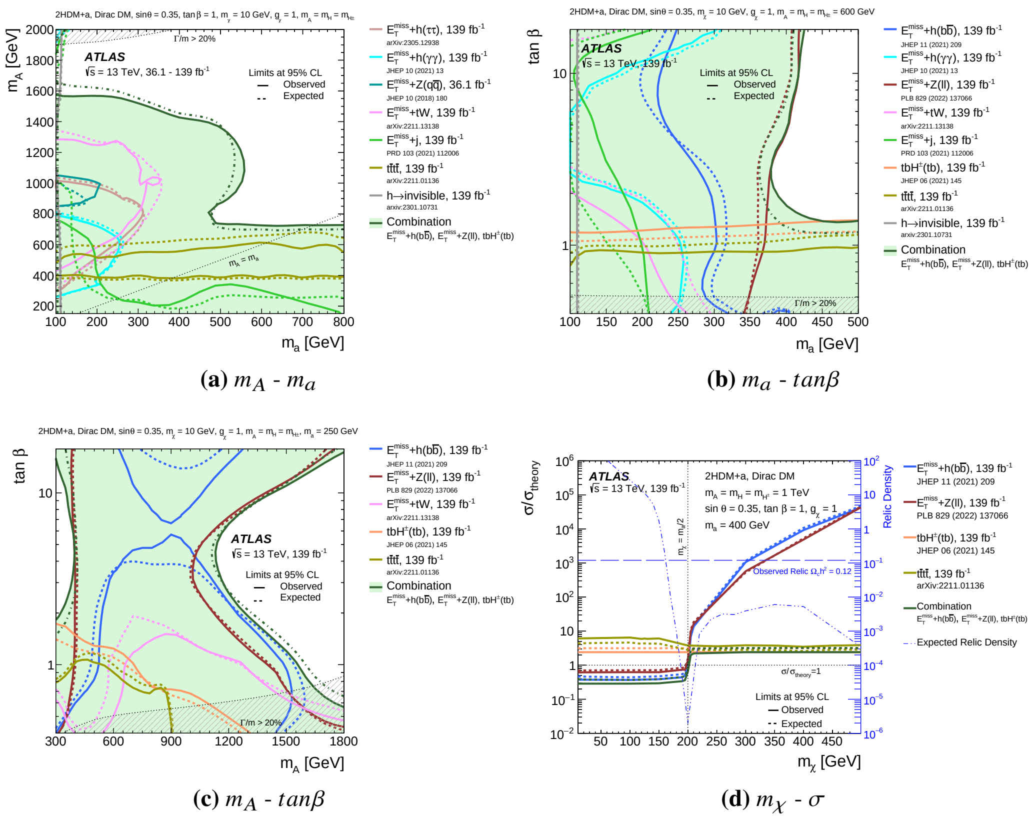
(a) Dark pion production mechanism **(b)** m_{π_D} - η

Figure 3: (a) Resonant dark meson production Feynman diagram. (b) Exclusion contours at 95% CL in the η_D–m_{π_D} plane for $SU(2)_L$ signal models in the one-lepton channel. The observed (solid) and expected (dashed) limits are shown, with the uncertainty band representing the $\pm 1\sigma$ variation on the expected limit. The outer shaded area represents exclusions from the all-hadronic channel.

4. 2HDM+a combination

A combination of dark matter searches [5] constrains the Type-II 2HDM+a model [4], focusing on key parameters: the pseudoscalar mediator mass (m_A), additional Higgs mass (m_H), $\tan\beta$, and the mixing angle ($\sin\theta$). The analysis incorporates multiple channels, including mono-Higgs ($E_T^{\text{miss}} + H \to b\bar{b}$), mono-Z ($E_T^{\text{miss}} + Z \to l\bar{l}$), and charged Higgs ($tbH^+$) searches. Orthogonality between these channels is ensured by using jet and lepton multiplicity, with correlated systematics applied to object reconstruction and uncorrelated systematics for b-tagging.

For a mixing angle $\sin\theta = 0.35$ and an additional Higgs mass $m_H = 1.2$ TeV, the coupling λ_a is excluded up to 560 GeV. Furthermore, the analysis excludes m_A up to 800 GeV for $\sin\theta = 0.35$ and up to 700 GeV for $\sin\theta = 0.7$. The strongest exclusion limits in the λ_a-m_A plane range from 400 GeV for $\sin\theta = 0.4$ to 200 GeV for $\sin\theta = 0.7$. For $m_A > 1.2$ TeV, constraints from $\sin\theta$ are stronger, but do not fully exclude this region of parameter space.



(a) m_A - m_a

(b) m_a - $tan\beta$

(c) m_A - $tan\beta$

(d) m_χ - σ

Figure 4: Observed (solid lines) and expected (dashed lines) 95% CL exclusion regions in the (m_a, m_A) 4a, (m_a, $\tan\beta$) 4b, and (m_A, $\tan\beta$) 4c planes for $\sin\theta = 0.35$. Dashed grey regions indicate where the width of any Higgs boson exceeds 20% of its mass. Exclusion limits for the 2HDM+a model as a function of m_χ are shown in Figure 4d for m_A = 1.0 TeV, m_a = 400 GeV, $\tan\beta$ = 1.0, and $\sin\theta$ = 0.35. The limits are expressed as the ratio of the excluded cross-section to the nominal cross-section, with relic density (dashed line) indicated on the right vertical axis.

PoS(LHCP2024)004

5. Dark photon

The analysis combines searches for the beyond Standard Model Higgs boson, H_{BSM}, decaying into visible particles (γ) and massless dark photons (γ_D) [7]. This study integrates results from two distinct production channels: the gluon fusion (ggF) channel, which uses a single-photon trigger with $E_T^{\gamma} > 150$ GeV, and the vector boson fusion (VBF) channel, which employs an E_T^{miss} trigger with $E_T^{\text{miss}} > 150$ GeV and single-lepton triggers for the $W\gamma$ + jets final state. Both searches scan the H_{BSM} mass range of [400, 3000] GeV. A profile-likelihood fit is performed across all channels to derive combined exclusion limits. No significant excess is observed, and a 95% confidence level (CL) exclusion limit on the cross-section σ is derived as a function of $m_{H_{\text{BSM}}}$, where σ represents the combined Higgs boson production cross-section. The exclusion limits on σ range from 16 fb at $m_{H_{\text{BSM}}} = 400$ GeV to 1.0 fb at $m_{H_{\text{BSM}}} = 3000$ GeV. Assuming a systematic uncertainty of 5%, the analysis excludes $m_{H_{\text{BSM}}} < 1600$ GeV. Furthermore, the combination of the ggF and VBF channels improves the exclusion limit at $m_{H_{\text{BSM}}} = 1500$ GeV by 33%.

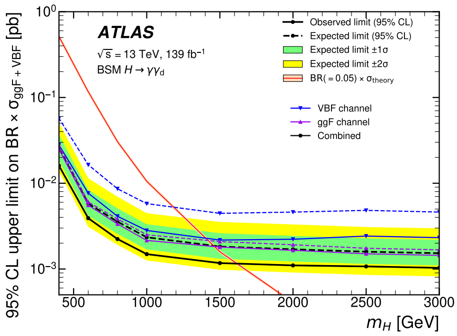
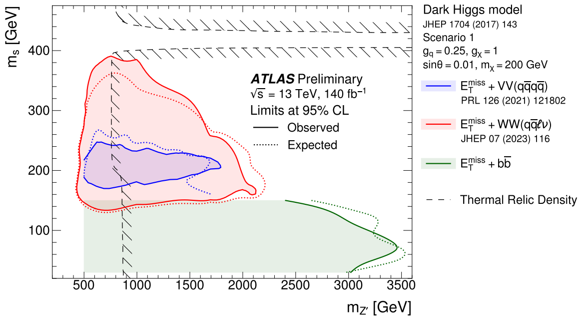


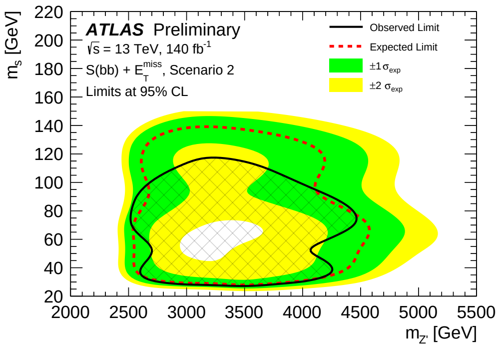
Figure 5: Observed and expected 95% CL upper limits on $BRH_{BSM\to\gamma\gamma_d} \times \sigma(ggF + VBF)$ as a function of the Higgs boson mass m_H . Results obtained from the input channels are overlaid. The expected limit and the corresponding error bands are derived assuming the absence of the $H \to \gamma\gamma_d$ process and with all nuisance parameters profiled to the observed data.

6. Dark Higgs boson

A search for dark matter produced in association with a $b\bar{b}$ resonance in the range $30 < m_{bb} < 150$ GeV is conducted [10], focusing on a dark Higgs model where DM particles (χ) are produced with a dark Higgs boson (s) and a gauge boson Z' [9]. Key model parameters include m_s, $m_{Z'}$, m_χ, the couplings g_q, g_χ, and the mixing angle θ. The analysis considers two final state topologies: boosted (one b-tagged large-R jet) for $m_{Z'} > 150$ GeV, and resolved (two b-tagged small-R jets) for $m_{Z'} < 150$ GeV. Three parameter space scenarios are explored: 1) $m_s \in [30, 150]$ GeV, $m_{Z'} < 4$ TeV, $m_\chi = 200$ GeV, $g_q = 0.25$, $g_\chi = 1.0$, $\sin\theta = 0.01$; 2) $m_s \in [30, 150]$ GeV, $m_{Z'} < 4$ TeV, $m_\chi = 900$ GeV, and varying g_χ; 3) scanning the $(m_{Z'}, m_\chi)$ plane. A profile-likelihood fit is performed, yielding no significant excess. 95% CL limits exclude mediator masses $m_\phi < 3.4$ TeV for $\lambda_\chi = 1$, and up to 4.8 TeV in relic density-inspired models.



(a) Scenario 1: $m_{Z'}$ - m_s



(b) Scenario 2: $m_{Z'}$ - m_s

Figure 6: Observed (expected) exclusion regions at 95% CL for scenario 1 (6a), scenario 2 (6b). The expected $\pm 1\sigma(\pm 2\sigma)$ uncertainty is shown as the filled green (yellow) band. The observed relic density is obtained for $m_{Z'} = 850$ GeV or $m_s \approx 400$ GeV (dashed line) for scenario 1, with the diagonal lines indicating an overabundance of DM. The colored areas of 6a are excluded, with the open contours indicating regions not explored for a given signature.

7. Conclusion

This report presents results from ATLAS's search for dark matter (DM) mediators and exotic bosons, focusing on simplified DM models and composite dark mesons in multiple topologies. In the mono-top analysis, a single jet and missing transverse energy signature (E_T^{miss}) were examined for evidence of a scalar DM mediator ϕ produced alongside a single top quark. No significant excess was observed, and 95% confidence level limits exclude mediator masses below 4 TeV for $y_\chi = 0.6$ and $m_\chi = 0.4$ GeV, extending previous limits by 800 GeV. Limits are also set for $m_\phi < 3.4$ TeV and $m_\phi < 2.5$ TeV depending on m_χ and y_χ values, respectively. For Stealth Dark Matter, composite dark mesons decay via dark pions (π_D^0) and rhons (ρ_D) into top and bottom quarks. The 95% CL exclusions reach $m_D < 550$ GeV in the all-hadronic channel for $\lambda_q = 0.20$ and $m_D < 940$ GeV in the one-lepton channel for $\lambda_q = 0.45$. The 2HDM+a model analysis constrains parameters such as pseudoscalar mass (m_A), additional Higgs mass (m_H), $\tan\beta$, and mixing angle ($\sin\theta$). Exclusions include λ_a up to 560 GeV for $\sin\theta = 0.35$ and $m_H = 1.2$ TeV, and $m_A \sim 800$ GeV for $\sin\theta = 0.35$, extending to 700 GeV at $\sin\theta = 0.7$. In the dark photon search, combined gluon and vector boson fusion channels probe an H_{BSM} boson decaying to a photon and dark photon ($\gamma\gamma_D$), excluding masses below 1600 GeV at 95% CL with limits on σ improving previous exclusions by 33%. The dark Higgs boson search considers DM production alongside a $b\bar{b}$ resonance in the range $30 < m_{bb} < 150$ GeV within a Z'-mediated model, excluding mediator masses $m_\phi < 3.4$ TeV for $\lambda_\chi = 1$, and extending up to 4.8 TeV for relic density models.

References

[1] G. Aad *et al.* [ATLAS Collaboration], "Search for new particles in final states with a boosted top quark and missing transverse momentum in proton-proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector," JHEP **05** (2024), 263, doi:10.1007/JHEP05(2024)263, [arXiv:2402.16561 [hep-ex]], CERN-EP-2024-046.

[2] M. Aaboud *et al.* [ATLAS Collaboration], "Search for large missing transverse momentum in association with one top-quark in proton-proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector," JHEP **05** (2019), 041, doi:10.1007/JHEP05(2019)041, [arXiv:1812.09743 [hep-ex]], CERN-EP-2018-301.

[3] T. Appelquist *et al.*, *Stealth Dark Matter: Dark scalar baryons through the Higgs portal*, Phys. Rev. D **92** (2015), 075030, doi:10.1103/PhysRevD.92.075030, [arXiv:1503.04203 [hep-ph]], INT-PUB-15-004, LLNL-JRNL-667446.

[4] M. Bauer, U. Haisch and F. Kahlhoefer, "Simplified dark matter models with two Higgs doublets: I. Pseudoscalar mediators," JHEP **05** (2017), 138 doi:10.1007/JHEP05(2017)138 [arXiv:1701.07427 [hep-ph]].

[5] Aad, Georges and others, *Combination and summary of ATLAS dark matter searches interpreted in a 2HDM with a pseudo-scalar mediator using 139 fb^{-1} of $\sqrt{s} = 13$ TeV pp collision data*, arXiv:2306.00641 [hep-ex], CERN-EP-2023-088, June 2023.

[6] ATLAS Collaboration, *Search for dark mesons decaying to top and bottom quarks in $\sqrt{s} = 13$ TeV pp collisions with the ATLAS detector*, ATLAS-CONF-2024-002, 2024.

[7] Aad, Georges *et al.* (ATLAS Collaboration), Combination of searches for Higgs boson decays into a photon and a massless dark photon using pp collisions at $\sqrt{s}$= 13 TeV with the ATLAS detector, arXiv:2406.01656 [hep-ex], *JHEP* **08** (2024) 153, doi:10.1007/JHEP08(2024)153.

[8] ATLAS Collaboration, *Search for dark matter produced in association with a dark Higgs boson in the $b\bar{b}$ final state using $\sqrt{s} = 13$ TeV collisions recorded with the ATLAS detector*, ATLAS-CONF-2024-004 (2024).

[9] Duerr, Michael and Grohsjean, Alexander and Kahlhoefer, Felix and Penning, Bjoern and Schmidt-Hoberg, Kai and Schwanenberger, Christian, *Hunting the dark Higgs*, arXiv:1701.08780 [hep-ph], JHEP **04** (2017) 143, doi: 10.1007/JHEP04(2017)143.

[10] Aad, Georges and others (ATLAS Collaboration), *Search for dark matter produced in association with a dark Higgs boson in the $b\bar{b}$ final state using pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector*, arXiv:2407.10549 [hep-ex], CERN-EP-2024-170, July 2024.

PoS(LHCP2024)004