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on New Frontiers in Physics
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DARK MATTER SEARCHES AT ATLAS



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on behalf of the ATLAS Collaboration

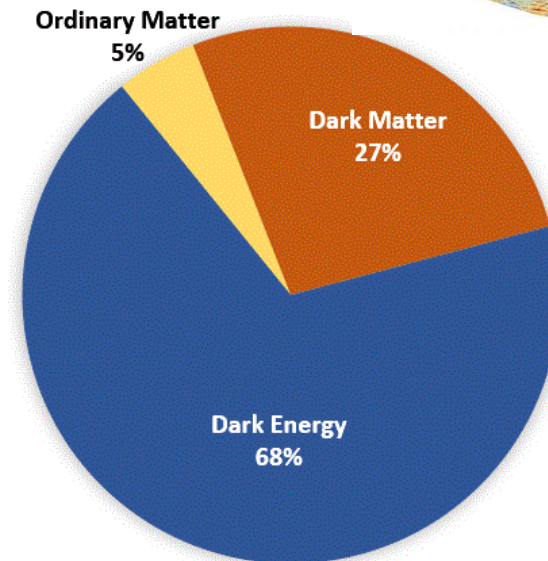
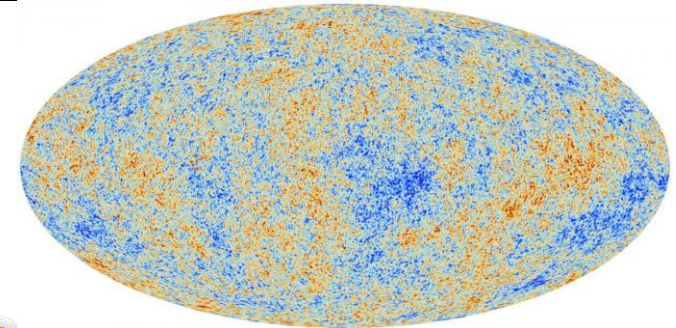
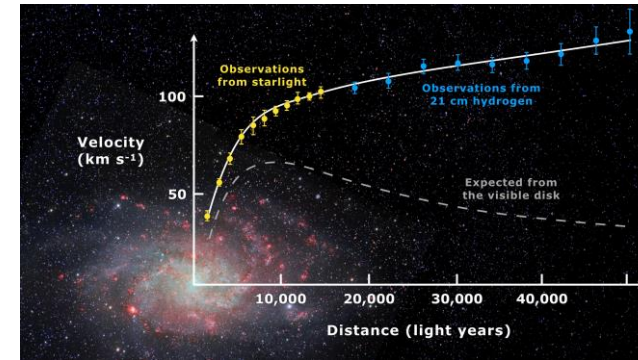
ICNFP2025

OAC, Kolymbari, Crete, Greece — 29.07.2025

Dark matter (state-of-art)

- Astrophysical and cosmological observations (rotation curves, gravitational lensing, CMB, structure formation) imply $\sim 1/4$ of the Universe is made of Dark Matter.
- Yet its nature remains unknown: not part of the Standard Model (SM), invisible to electromagnetic interactions.
- Colliders allow us to produce new particles directly. If DM couples (even weakly) to SM particles, it could be produced at the LHC and escape detection \rightarrow leads to missing transverse momentum (E_T^{miss}).
- Search Strategy
Look for signatures with large E_T^{miss} and visible SM particles.
- Large search programme in LHC/ ATLAS, today:
Dark sector QCD, Higgs and reinterpretations

DARK MATTER SEARCHES AT ATLAS



SEARCH FOR EMERGING JETS FROM DARK QCD IN RUN 3

EXOT-2022-31

Motivation

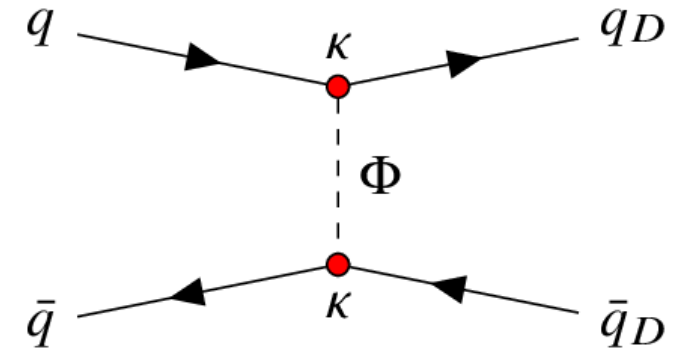
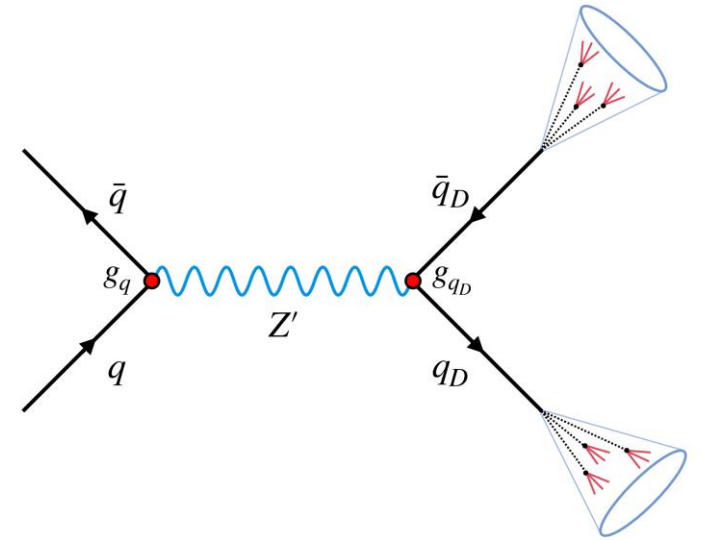
Physics Motivation:

- Search for signs of a dark sector with QCD-like dynamics.
- Dark quarks are confined under a hidden gauge group and hadronize into long-lived dark mesons.
- These dark mesons decay back to SM particles with displaced signatures, forming "emerging jets."

Search Objective:

- First Run 3 ATLAS search for pair-produced emerging jets.
- Consider both:
 - **s-channel Z' mediator** model.
 - **t-channel scalar mediator (Φ)** model.

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Methods & Analysis Strategy

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Dataset:

- $\sqrt{s} = 13.6$ TeV, pp -collisions at from Run 3.
Integrated luminosity: 51.8 fb^{-1} .

Event Selections:

Two complementary strategies:

• Cut-based Analysis:

- Requires jets with low prompt-track fraction.
- Displaced vertex requirements.
- Define "low- m_{jj} " and "high- m_{jj} " regions.
- Specialized triggers used.

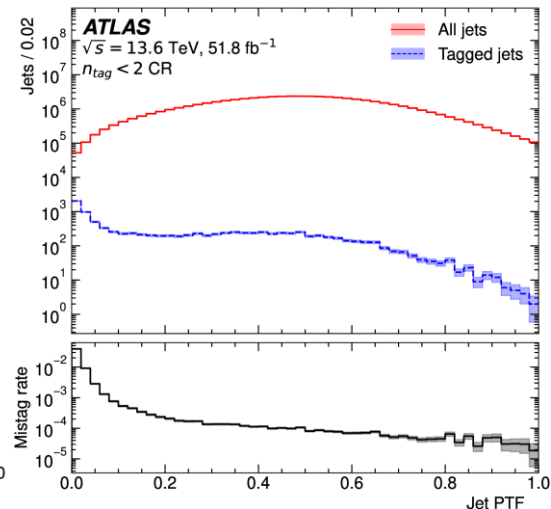
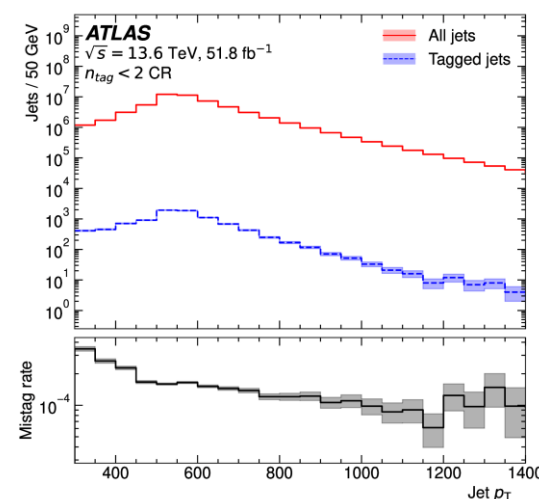
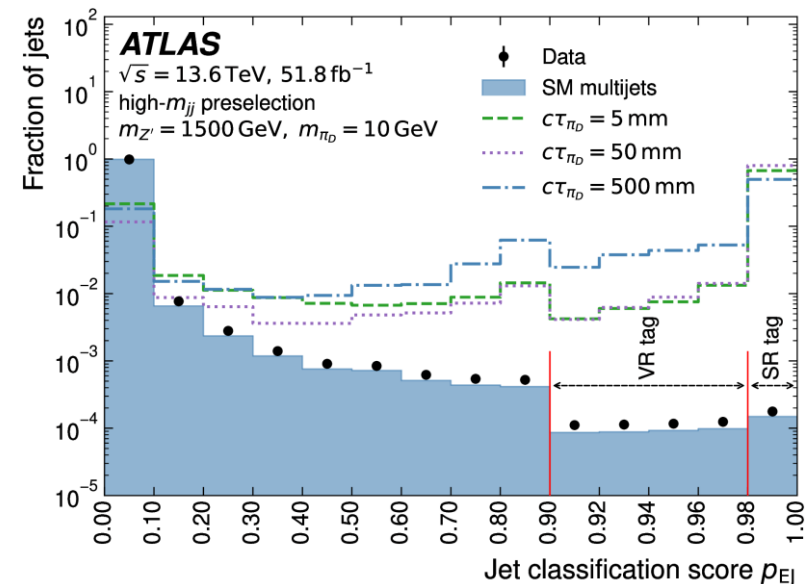
• ML-based Analysis:

- Uses a Graph/Transformer-based jet tagger.
- Trained on track-level features.
- Boosts sensitivity to displaced decay structures.

Background Estimation:

Data-driven mistag rate method.

Control and Validation Regions used for normalization and validate systematic estimation.



Methods & Analysis Strategy

No statistically significant excess above SM expectation.

Exclusion Limits (95% CL):

Z' mediator:

- Cut-based: excluded up to ~ 2.15 TeV.
- ML-based: excluded up to ~ 2.5 TeV.

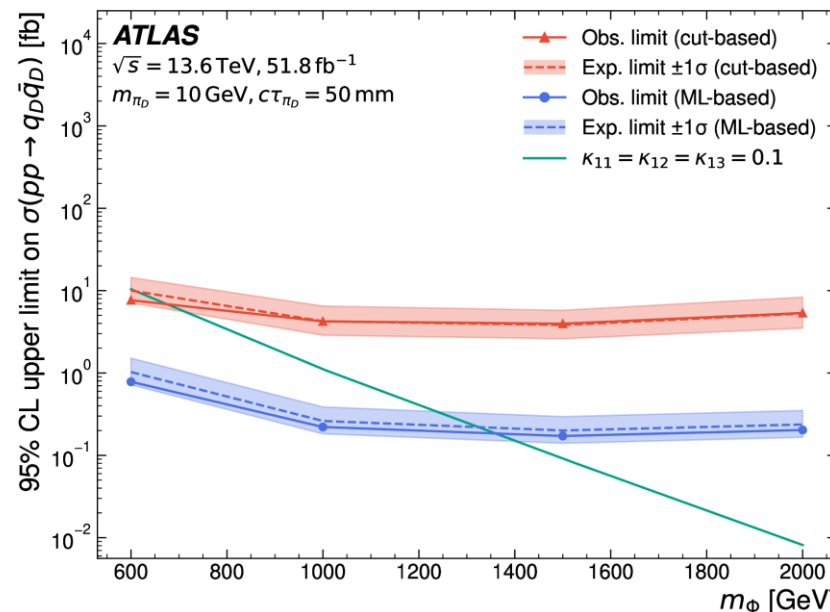
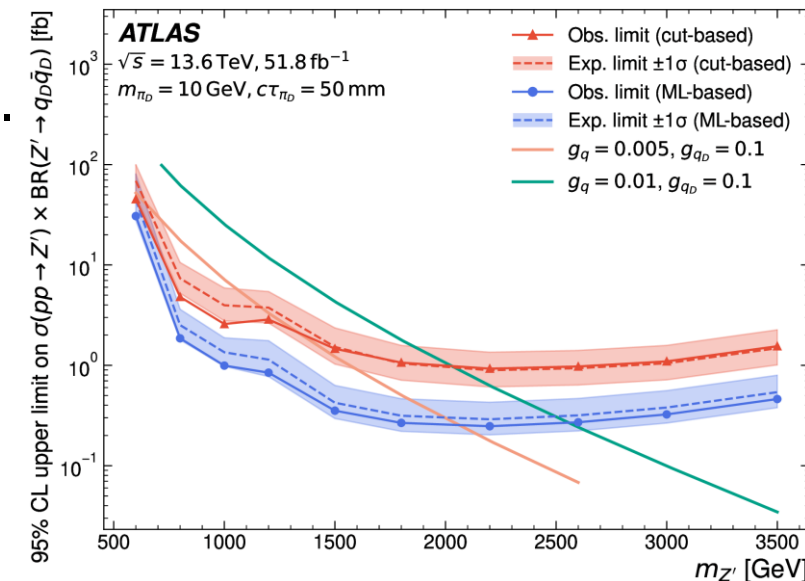
Φ mediator:

- Masses excluded up to ~ 1.35 TeV.

Impact:

First direct limits on emerging jets via Z' and Φ mediators using Run 3 data.

Marks significant progress in searches for dark QCD and hidden valley models.



**SEARCH FOR SVJ OR
ANOMALOUS SIGNATURES.
PHYS. REV. D 112 (2025) 012021**

Motivation

Physics Motivation:

- Hidden Valley Models
Dark-Sector (DS) with complex
QCD-like interactions with a
 Z' mediator
- Couplings to SM/DS: g_q, q_χ

Search Objective:

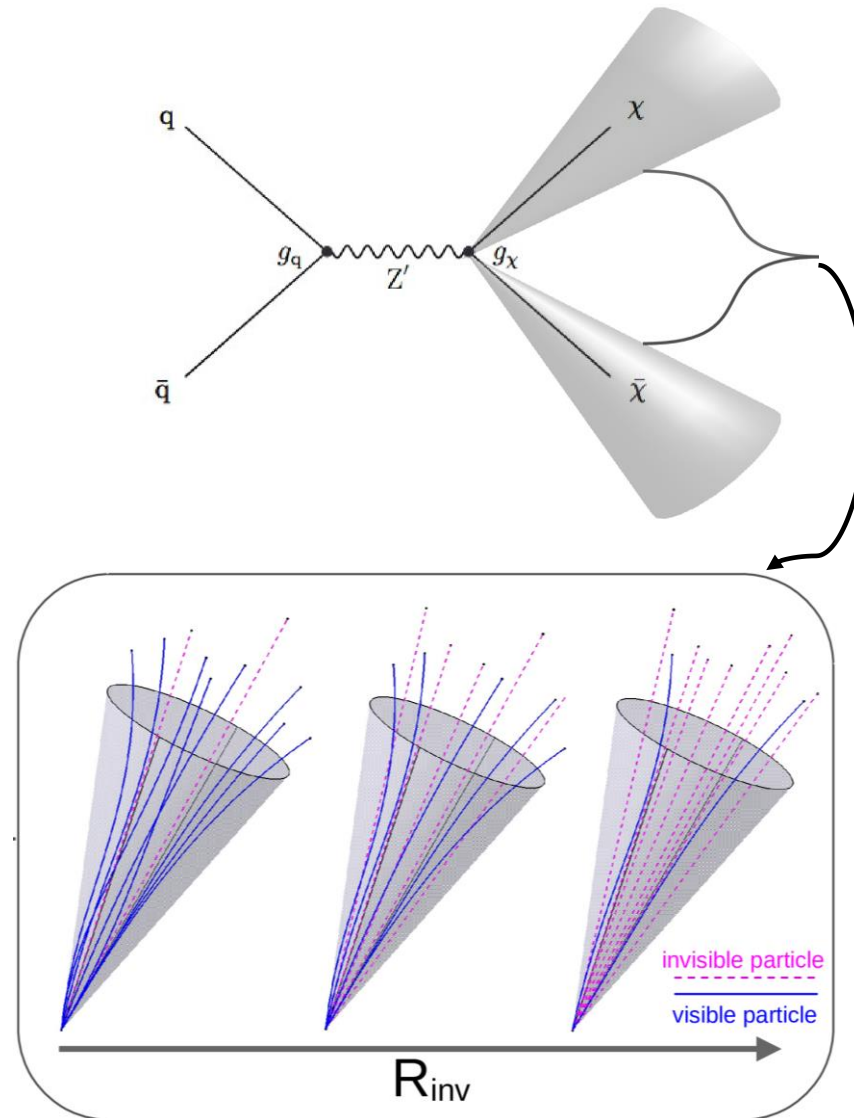
- DS contains:
 - **Stable Dark hadrons** ($\rightarrow E_T^{miss}$ in detector)
 - **Unstable Dark hadrons** (\rightarrow SM particles)
- Semi-Visible Jets (SVJ): Jets aligned with E_T^{miss}

- $R_{inv} = \frac{\text{Prob. stable Dark hadrons}}{\text{Prob. unstable Dark hadrons}}$

- Span search :

$$2 \text{ TeV} < m_{Z'} < 5 \text{ TeV}$$

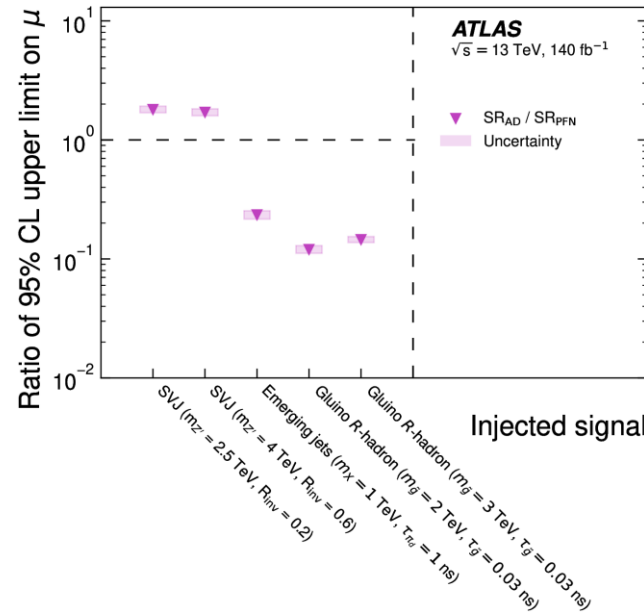
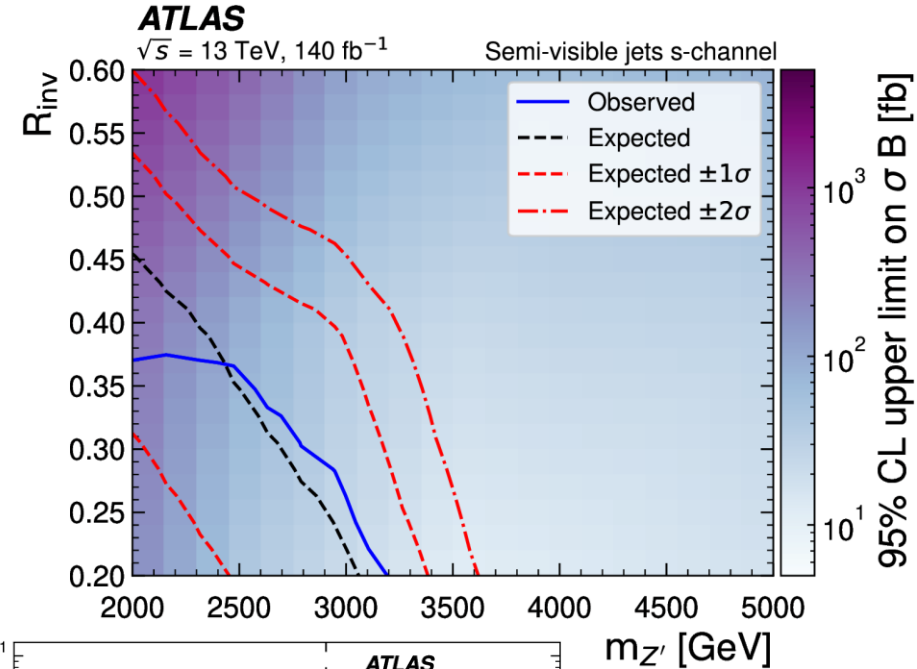
$$0.2 < R_{inv} < 0.6$$



Results

- No significant excess observed in m_T spectra
- PFN-tagged and anomaly-tagged regions both consistent with background
- 2D upper-limits on Z' cross section times Branching ratio in $(m_{Z'}, R_{inv})$
- **Exclude Z' masses 2.0–3.2 TeV**

ANTÉLOPE (a novel idea of combining supervised and unsupervised methods by ATLAS) provides broad sensitivity beyond specific models



SEARCH FOR DM AND DARK HIGGS
BOSON IN THE $b\bar{b}$ FINAL STATE

+ PHYS. REV. LETT. 134 (2025) 121801 +



Motivation

Signal:

- **Dark Higgs boson (s)** decaying into $b\bar{b}$:
$$pp \rightarrow Z' \rightarrow Z' s, \quad Z' \rightarrow \chi\chi, \quad s \rightarrow b\bar{b}$$
- **final states: 2 b -jets** and E_T^{miss} .

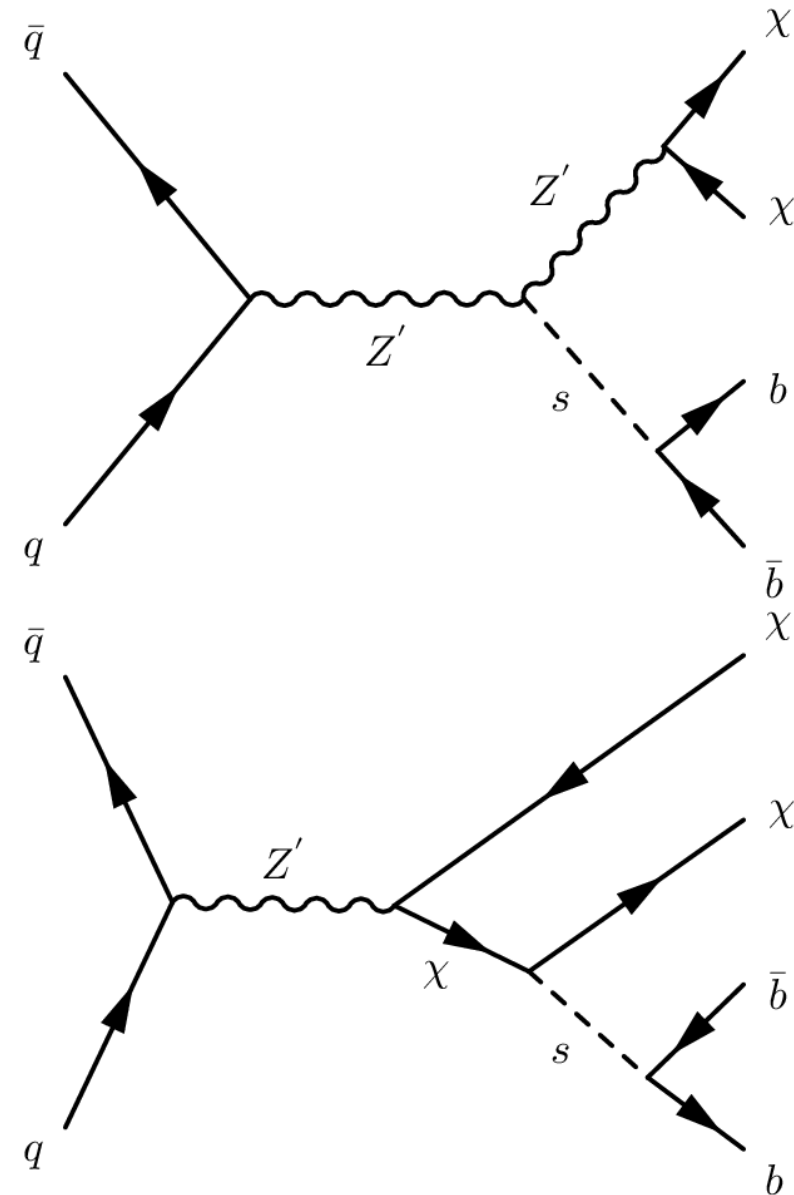
Search for $b\bar{b}$ resonance over smooth background

Three scenarios considered

Heavy Z' (off-shell s production)

Light Z' (on-shell s production)

Enhanced dark-sector coupling



Analysis Strategy

Data:

$140 \text{ fb}^{-1} \sqrt{s} = 13 \text{ TeV } pp\text{-collisions}$

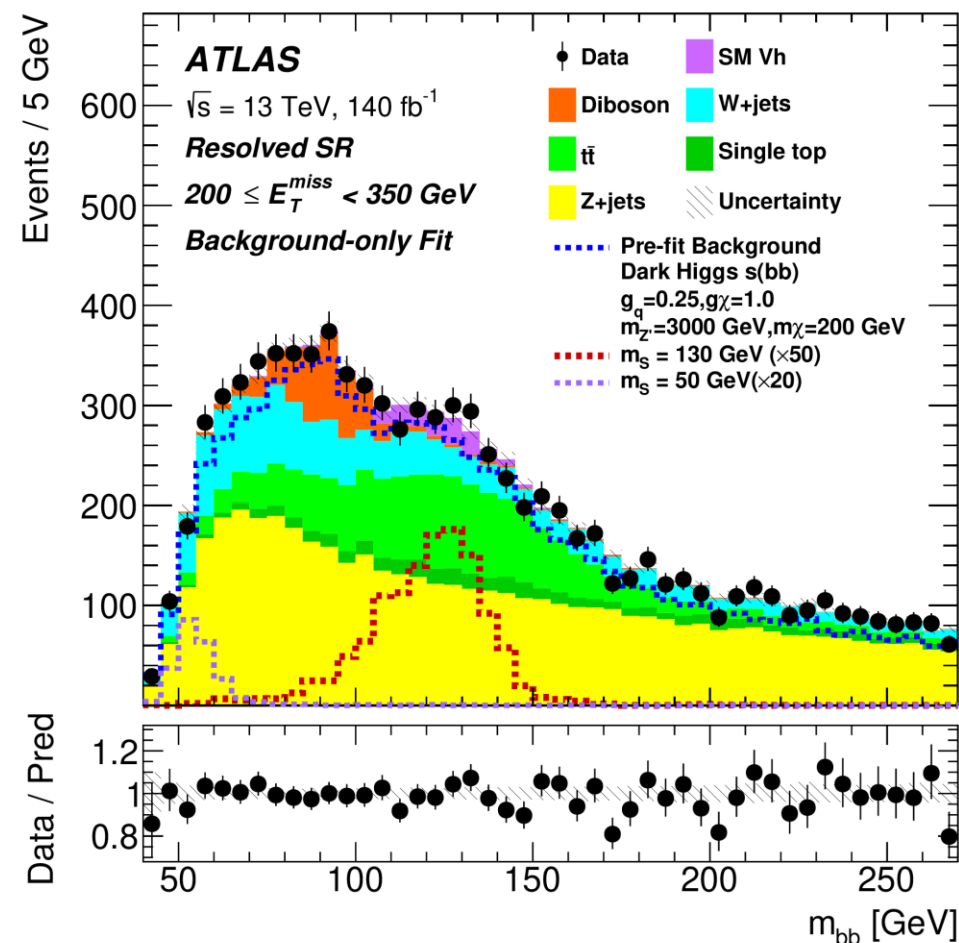
Selections:

Large $E_T^{\text{miss}} > 150 \text{ GeV}$, $N_{b\text{jet}} \geq 2$

Use *resolved* (2 small b-jets) and *merged* (large jet with 2-bjets substructure)

Statistical approach:

Profile likelihood fits in signal regions



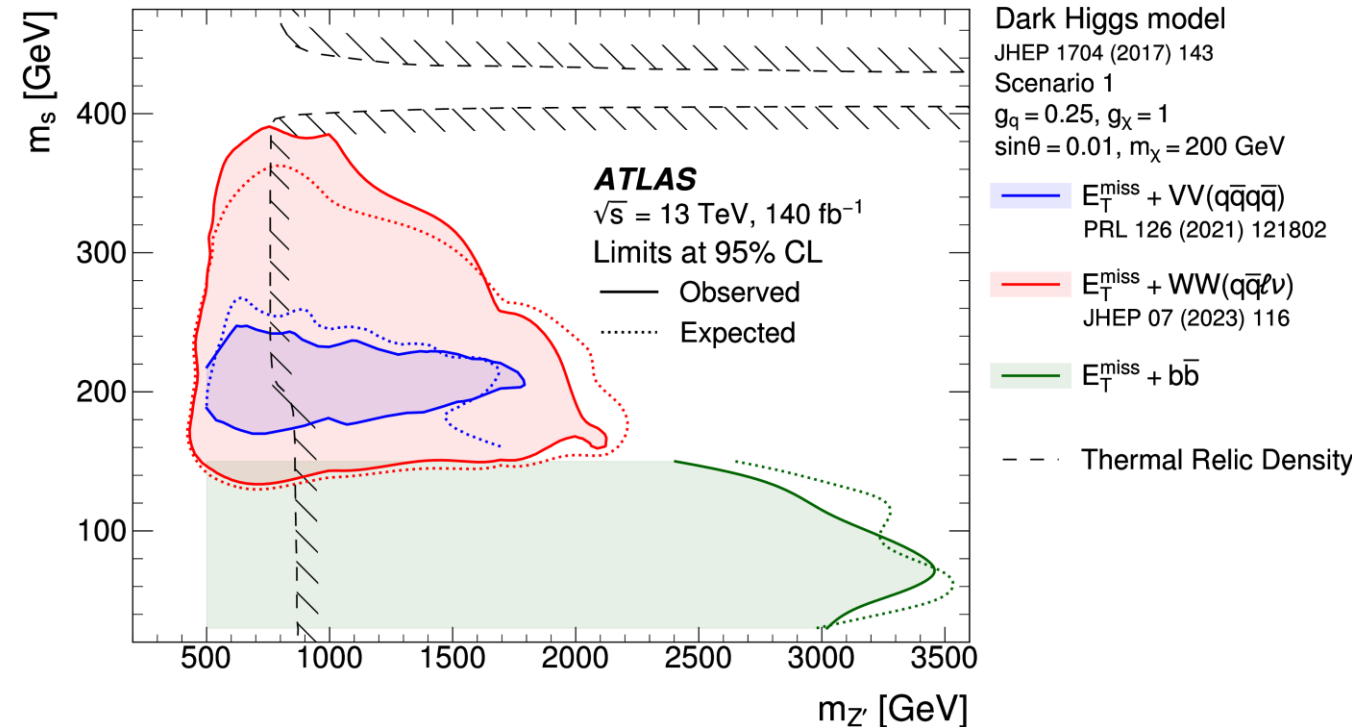
Results

No significant excess observed over the SM

Exclusion limits:

Dark Higgs mass $m_s \in [30, 150]$ GeV excluded

Mediator mass $m_{Z'}$ excluded up to 3 – 4.8 TeV (depending on the scenario)



- + SEARCH FOR DM AND DARK HIGGS +
- BOSON DECAYING INTO A HIGGS •
- BOSON PAIR IN $3b$ OR $4b$

HMBS-2024-13

Motivation

Signal:

- Search for DM produced in association with a **dark Higgs boson (s)** decaying into **SM Higgs bosons:**

SM Higgs bosons:

$$pp \rightarrow Z' \rightarrow Z' s, \quad Z' \rightarrow \chi\chi, \quad s \rightarrow hh$$

- final states:** multiple **b-jets** and E_T^{miss}).

Motivation:

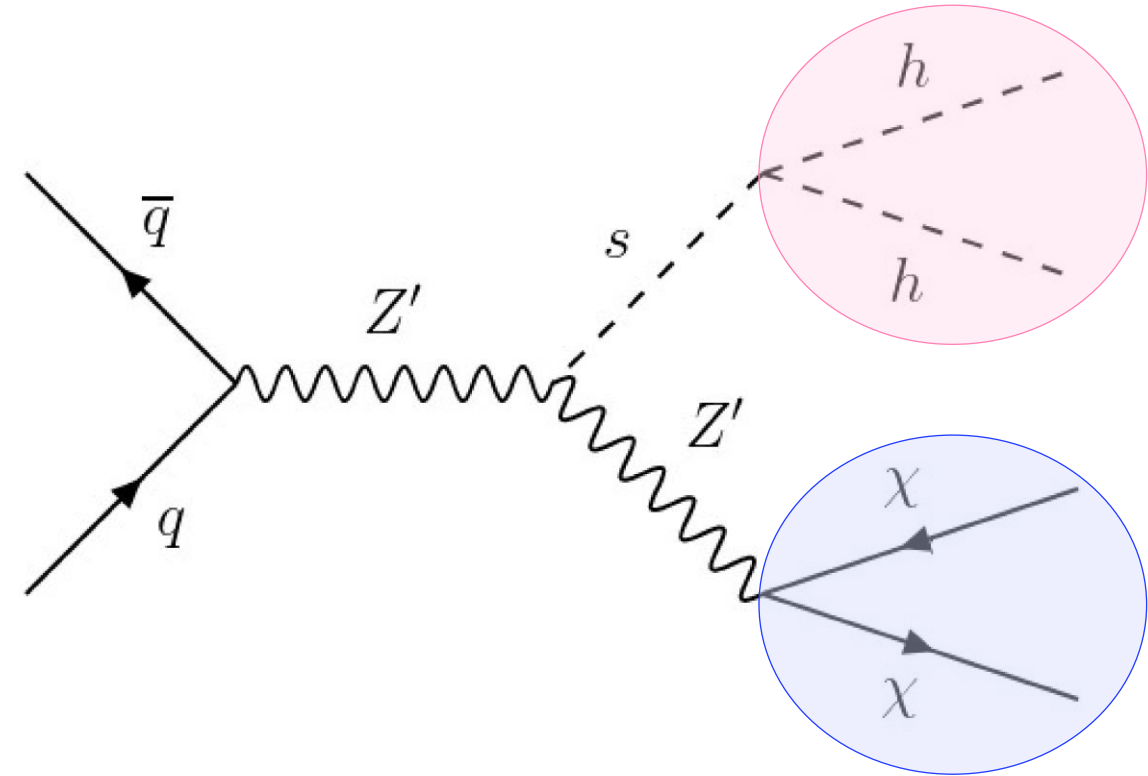
Extensions of the SM,

Higgs acts as a **portal** to the dark sector.

Can reproduce the observed relic density via additional annihilation channels featuring the s (e.g. $\chi\chi \rightarrow ss \rightarrow SM SM$)

Novel signature:

2 Higgs bosons + invisible particles, which is a **unique and unexplored** region of LHC phase space.



Analysis Strategy

Data:

140 fb^{-1} $\sqrt{s} = 13 \text{ TeV}$ pp -collisions

Selections:

Large $E_T^{\text{miss}} > 200 \text{ GeV}$, $N_{bjet} \geq 3$

Use *resolved* ($N_{bjet} \geq 4$) and *merged* ($N_{bjet} = 3$) Higgs reconstruction strategies

Background suppression:

Major backgrounds: $t\bar{t}$, $Z + jet$, Multijet

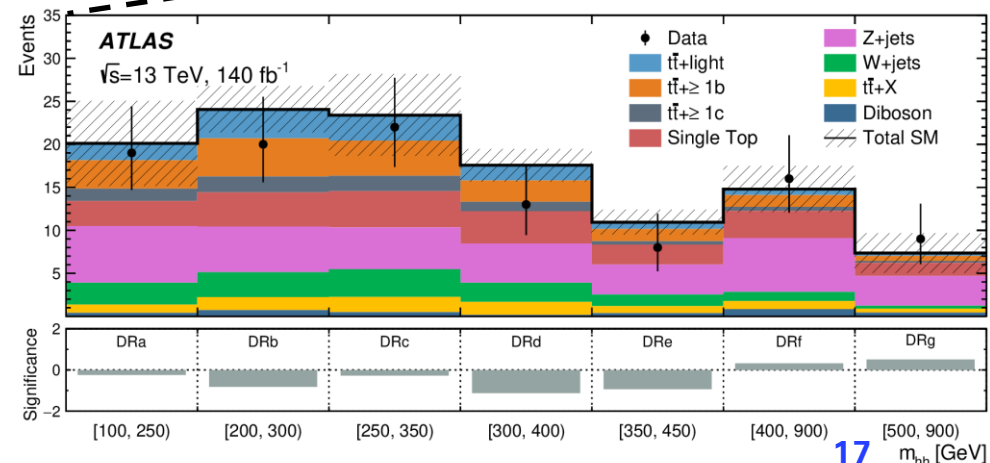
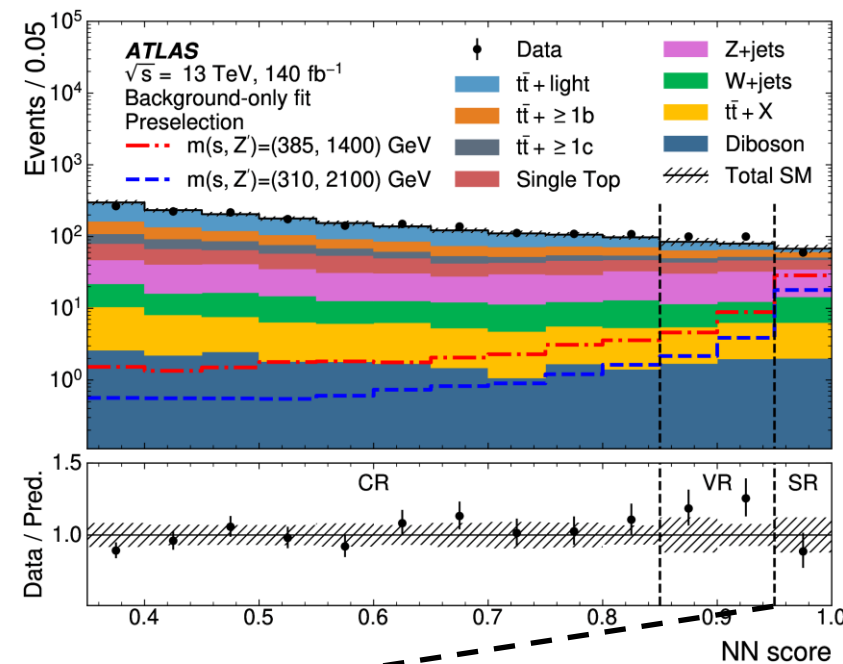
Use of *Neural Networks + Distance Correlation Loss* to separate signal from background

Statistical approach:

Binned likelihood fit to neural network score distributions

CR and VR for background modelling

DARK MATTER SEARCHES AT ATLAS



Results

No significant excess observed over the SM

Exclusion limits:

Dark Higgs mass $m_S \in [250, 400]$ GeV excluded

Mediator mass $m_{Z'}$ excluded up to 2.3 TeV

Provides **new constraints** on dark Higgs portal models

The results complement other

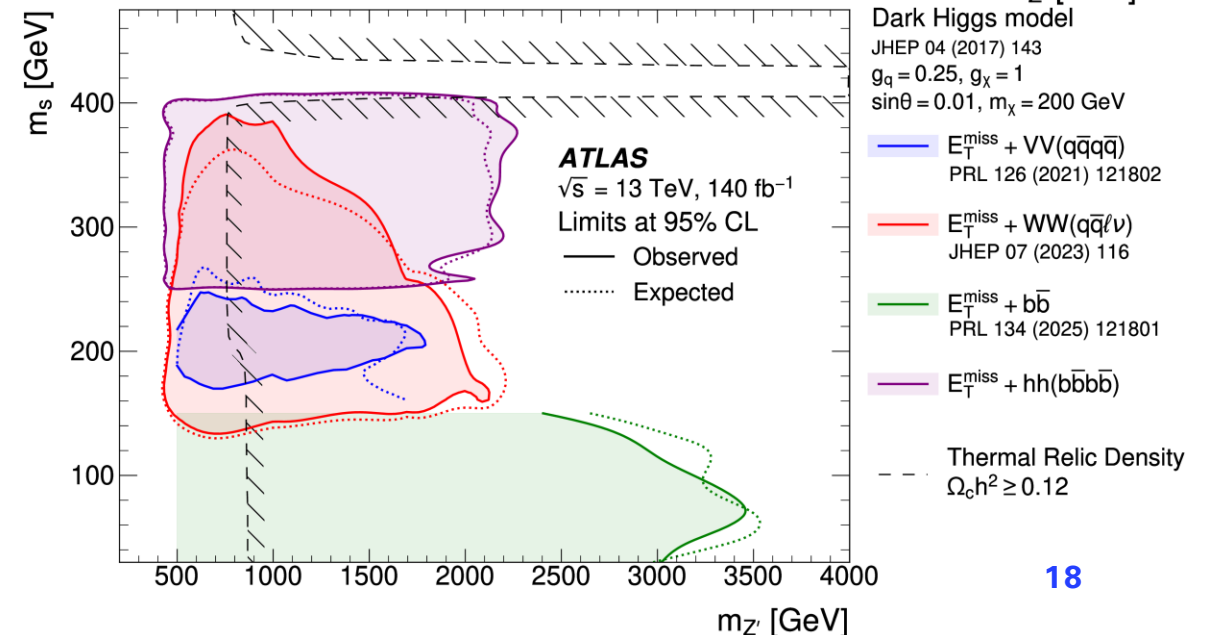
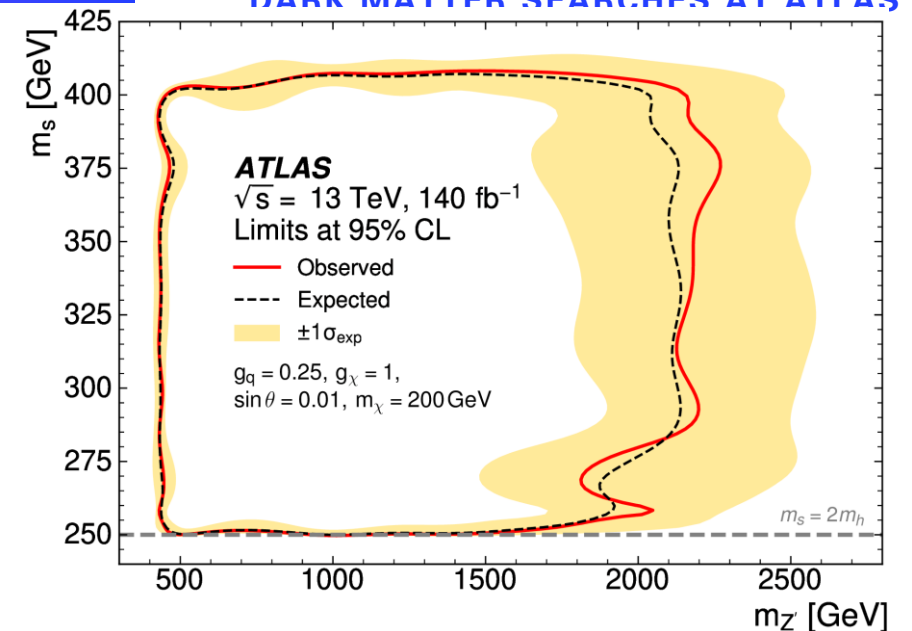
Complementary to:

Lower-mass dark Higgs boson

Extended Higgs sectors collider

DM searches

DARK MATTER SEARCHES AT ATLAS

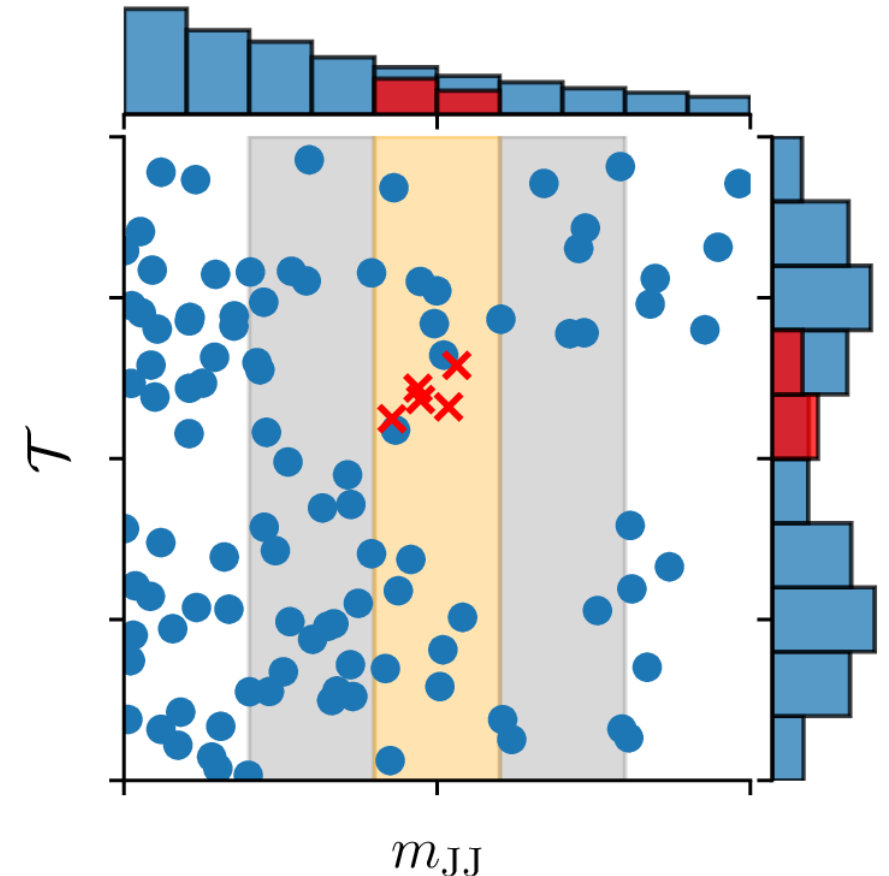


+
• ○ WEAKLY SUPERVISED ANOMALY
○ DETECTION FOR RESONANT NEW
PHYSICS IN THE DIJET FINAL STATE

[HMBS-2024-34](#)

Motivation

- Too many BSM models to search individually
- Use **model-agnostic Anomaly Detection (AD)** to find local excesses in dijet mass spectra.
- **Target signature:** Events with **two large-radius jets**, common in many BSM models (e.g., Z' , W' , excited quarks).
- Full Run 2 ATLAS dataset ($\sqrt{s} = 13$ TeV, 139 fb $^{-1}$).



Analysis Strategy

Data:

13 TeV pp -collisions, 139 fb^{-1}

Event selection: Two high- p_T large- R jets.

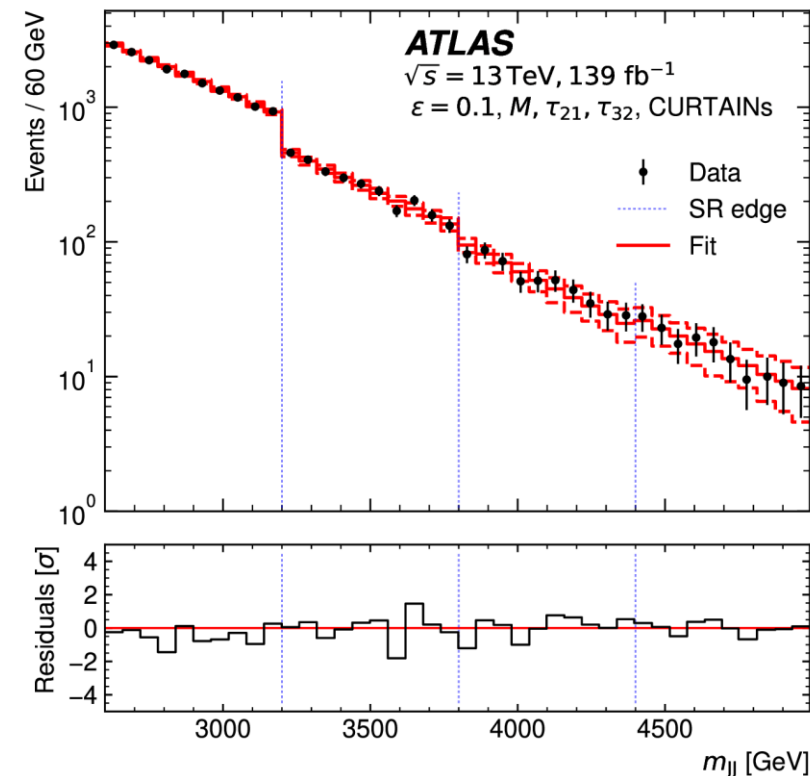
Two machine-learning pipelines:

- *Weakly supervised classifiers* trained on data labeled as "signal-like" vs. "background-like".
- Use jet substructure and kinematics (e.g. mass).

•**Classifier cuts:** Select signal-enriched regions.

•**Mass spectrum analysis:** Look for bumps in dijet mass after cuts.

DARK MATTER SEARCHES AT ATLAS

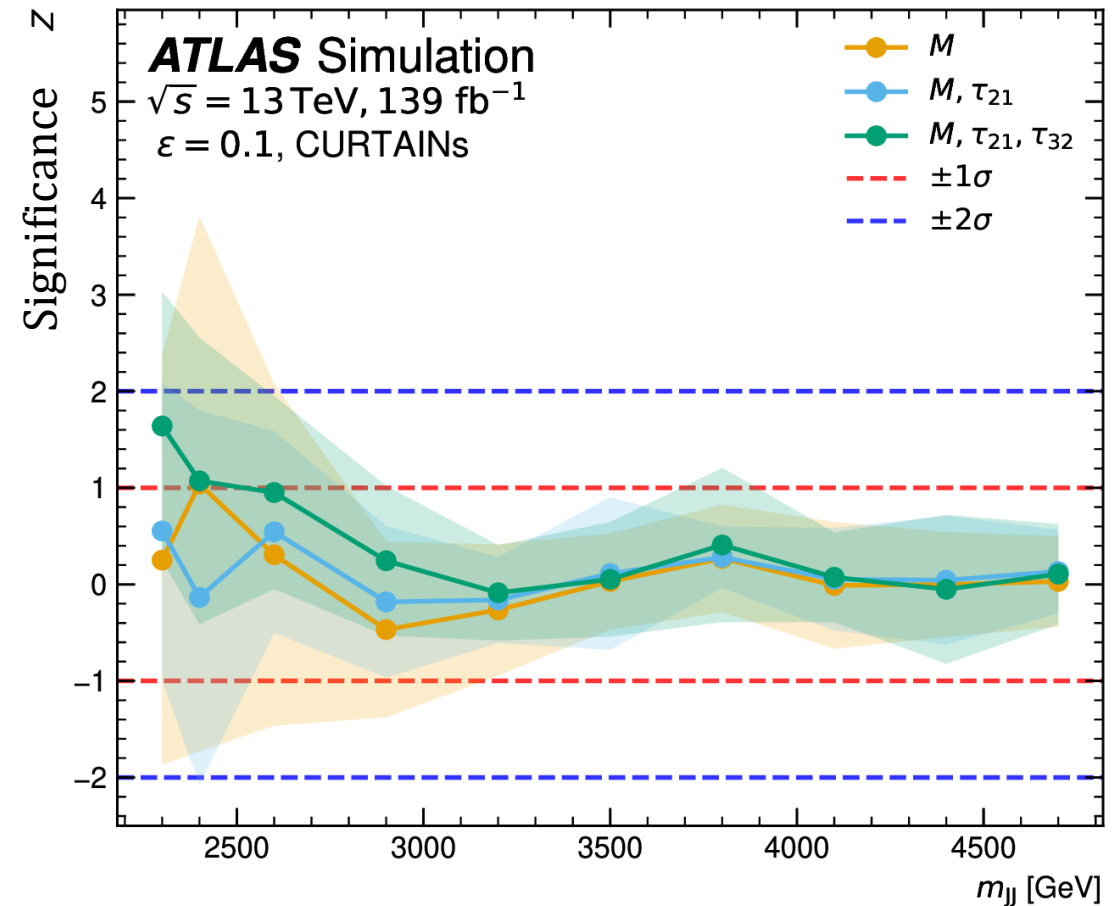


Results

No significant excess observed over the SM

Limits placed on generic resonance production cross-sections.

Potential for future BSM anomaly scans using unsupervised AD ML.



+ REINTERPRETATION OF SEARCHES +
• FOR FV SUSY INTO FV DM MODELS •
○ ATL-PHYS-PUB-2025-010

Motivation

DARK MATTER SEARCHES AT ATLAS

- **Flavour-Violating DM:**

Consider “Dark Minimal Flavour Violation” (DMFV) models with non-universal couplings between DM and SM quarks

- **Top-Flavoured Focus:**

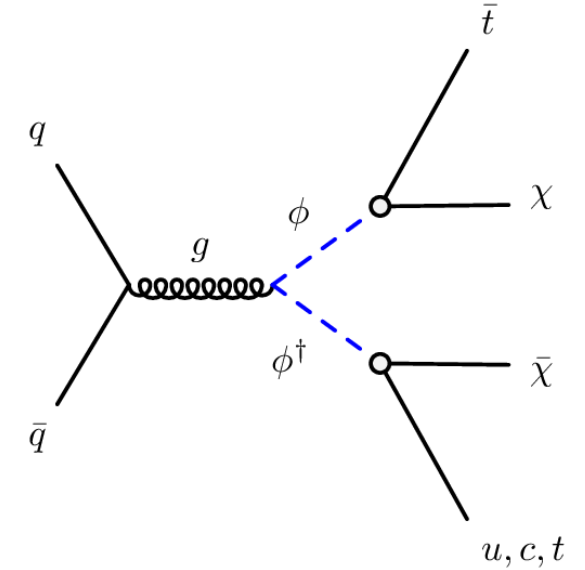
DM particles preferentially couple to 3rd generation quarks via a scalar mediator (ϕ)

- **Benchmark Scenarios:**

Four models (RH-SFF, RH-QDF, LH-QDF1, LH-QDF2) covering left/right-handed couplings and thermal histories.

- **Production Mechanisms:**

- s-channel pair production of mediators ($\phi\phi$)
- t-channel exchange of DM particle
- Radiative production with top pair



Benchmark	m_χ	Couplings	Mixing angles
$D_{\lambda,11} = D_{\lambda,22} ; \theta_{12} = \theta_{23} = 0 ; \delta_{ij} = 0$			
RH-SFF	200 GeV	$D_{\lambda,33} = D_{\lambda,11} + 1.0$	$\sin\theta_{13} = 0.25$
RH-QDF	150 GeV	$D_{\lambda,33} = D_{\lambda,11} + 0.2$	$\sin\theta_{13} = 0.2$
LH-QDF1	150 GeV	$D_{\lambda,33} = D_{\lambda,11} + 0.1$	$\sin\theta_{13} = 0.1$
LH-QDF2	450 GeV	$D_{\lambda,33} = D_{\lambda,11} + 0.2$	$\sin\theta_{13} = 0.2$
Parameters to scan: m_ϕ and $D_{\lambda,11}$			

Analysis Strategy

- **This analysis:**

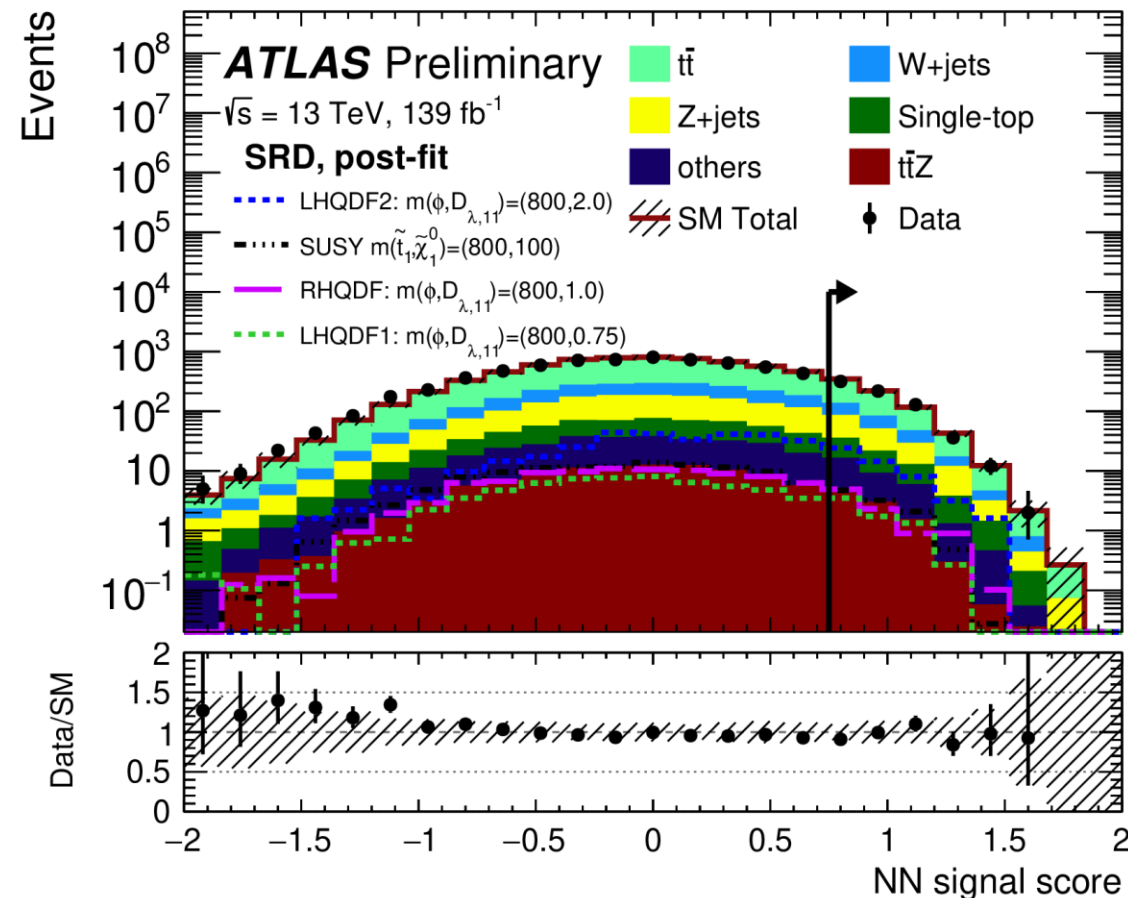
Reinterpreted 139 fb^{-1} ATLAS search for flavour-violating SUSY ($\tilde{t} \rightarrow tc\tilde{\chi}_0^0$) to set limits on flavored DM models

- **Final States Targeted:** $tq + E_T^{miss}$

with hadronic top decays, b-tag, one c-tag, and large E_T^{miss}

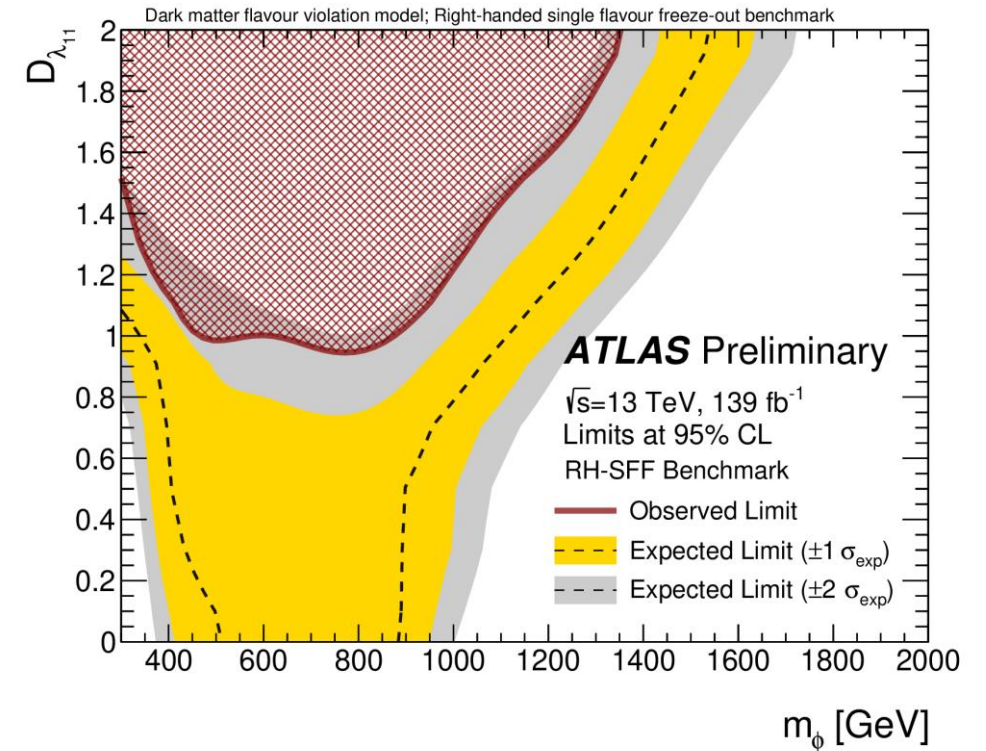
- Reinterpretation of an ATLAS SUSY search using four signal regions (SRA–SRD) based on various variables (e.g. m_{T2} , NN score)

- CR for background estimation.



Results

- First constraints on DMFV models at the LHC.
- Exclude mediator masses up to 1.2 TeV for high coupling
- For lower couplings, mediator mass exclusions vary between 400– 900 GeV depending on the scenario.
- Most sensitive SRs:
 - **SRA/SRC** for high mass difference.
 - **SRD** for compressed regions (especially at low mass).
- Slight ($\sim 1.8\sigma$) excess observed in SRC region (300– 500 GeV)
- Demonstrates reinterpretation of existing searches to constrain new DM models with flavour structure.



OUTLOOK



Conclusions

- ATLAS continues to lead a diverse dark matter search program across a wide range of theoretical scenarios.
- Dedicated searches for:
 - Dark QCD and emerging jets
 - Semi-visible jets and non-standard topologies
 - Anomaly detection using model-agnostic methods
 - Flavour-violating dark matter reinterpretations
 - The reinterpretation of flavour-violating SUSY searches.
- **No significant deviations from Standard Model** expectations have been observed.
- **Robust limits** have been placed on mediator and coupling parameters, with exclusions reaching up to several TeV in mass.
- Run 3 data and future HL-LHC datasets will further enhance the sensitivity to rare and unconventional dark matter signatures. Continued development of reinterpretation frameworks, anomaly detection techniques, and advanced machine learning tools will be crucial

