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2 **Semi-Visible Jets and Emerging Jets with Partial** 3 **Event Building**

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5 The nature of dark matter (DM) remains one of the biggest open questions in physics and
6 has eluded astrophysical and cosmological scientists searching for indirect evidence of its
7 existence. In recent years at the Large Hadron Collider (LHC), there has been an increase
8 in efforts to explore the dark sector using LHC data. New studies explore the possibility of
9 accessing the dark sector containing DM with unusual collider topologies.

10 This report explores the recent DM model of dark sector jets with observable signatures called
11 Semi-Visible Jets (SVJ), jets with some fraction of invisible DM particles, and Emerging Jets
12 (EJ), jets with displaced vertices.

13 Due to the constraint of recording information from every proton-proton (pp) collision event at
14 the LHC, the ATLAS experiment at LHC uses a trigger and data acquisition (TDAQ) system
15 that selects and sends interesting events to the data storage system while throwing away the
16 rest. The challenge lies in situations where large backgrounds bury the interesting events and
17 they are thrown out and not identified as signals by the trigger system.

18 Partial Event Building (PEB) poses a solution by storing only part of the detector raw
19 information, together with high level information. This leads to smaller event sizes and allows
20 us to record larger datasets using the same storage space. This report conducts a preliminary
21 feasibility study on triggering on the dark sector and leveraging PEB to search for dark sector
22 models containing the unusual SVJs and EJs.

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1 Introduction

1.1 Dark Matter

The search for dark matter and its nature is one of the most challenging open questions in particle physics.

One traditional dark matter search would be the mono-X searches, where X is the standard model particle and there is a dark matter particle recoiling against it in the opposite direction to balance the momentum [1]. This project looks at other unusual collider final states, wherein the dark matter may not be directionally away from the standard model particle and dark showers produce interesting collider objects such as the Semi-Visible Jets and Emerging Jets [2].

1.2 Dark Sector Model

This report focuses on models where a dark sector quark fragments and hadronizes into dark sector hadrons which then decay and give unusual topologies in the detector. A new mediator particle is introduced that connects the visible and the dark sector [3].

We plot the vertex versus the r_{inv} in Figure 1. The displaced vertex is the displacement of the charged tracks from the interaction point. The r_{inv} is the ratio of the stable dark hadrons and the total dark hadrons. The stable dark hadrons do not decay back into SM particles while unstable dark hadrons may or may not decay back into SM particles [3] [4].

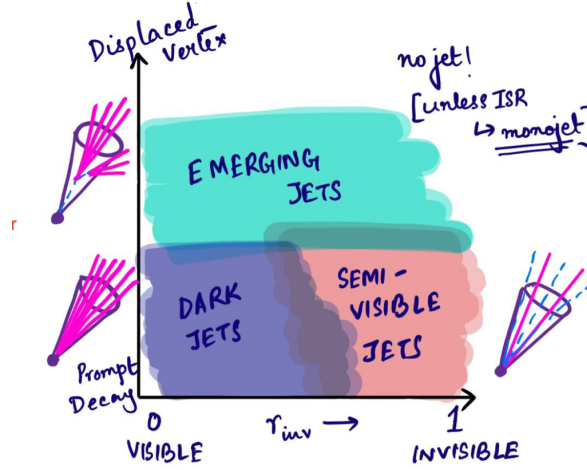


Figure 1: Dark Sector Jets - displaced vertex versus r_{inv} [5]

1.2.1 Semi-Visible Jets

Semi-Visible Jets (SVJ) are produced when dark sector quarks decay partially into standard model quarks and partially into stable dark hadrons that are invisible and this allows us to look at the missing transverse energy as a parameter [6]. Dark matter could be a composite particle that is accessible through a strongly coupled portal and these hidden-sector states would have dark showering similar to quantum chromodynamics (QCD) in the Standard Model (SM). This yields stable, invisible DM along with unstable states which decay back to SM as well. The signature we can look at is characterized by significant missing energy that is aligned along the direction of one of the jets [3].

In ATLAS, apart from r_{inv} , the model parameters that we look at in SVJ production are the mass of the scalar bi-fundamental mediator (M_ϕ) and mass of the dark hadrons (M_d) [4].

1.2.2 Emerging Jets

Emerging Jets (EJ) are produced when dark quarks undergo dark QCD-like showering which then leads to high multiplicity of long-lived dark hadrons that decay to SM particles with different displacements. This gives jet-like detector objects but with displaced vertices of different displacements within the jet cone [7]. The model parameters that we look at in EJ production are the following: dark confinement scale (Λ_D), mass of the scalar bi-fundamental mediator (Z' mass [GeV]), mass of spin-0 pseudoscalar dark pions (π_D mass [GeV]), mass of spin-1 dark vector meson (ρ_D mass [GeV]), and lifetime [mm].

1.3 ATLAS

1.3.1 The ATLAS Detector

Since ramping up in 2022, the Large Hadron Collider (LHC) is on its Run 3 and the ATLAS experiment operates and records more collisions at an unprecedented energy of 13.6 TeV [8]. The ATLAS detector,

event/signal ID	Emerging Jet Signals		
	801925	801928	801932
dark confinement scale (Λ_{dark})	1.6	1.6	40
Z prime mass [GeV]	600	1500	600
Dark pion mass [GeV]	0.8	0.8	20
Dark rho mass [GeV]	3.2	3.2	80
Lifetime [mm]	1	10	50

(a)

Figure 2: Model Parameters of the Semi-Visible Jet and Emerging Jet Signal Samples

situated at the LHC, is a multipurpose cylindrical particle detector with a solid angle coverage of nearly 4π . At the center of the ATLAS detector is the inner tracking detector (ID) which is covered by a thin superconducting solenoid that provides 2 T axial magnetic field. The materials of this ID are the silicon pixel, silicon microstrip, and transition radiation tracking detectors and these cover a pseudorapidity range of $|\eta| > 2.5$. Next layer of the ATLAS detector is made up of lead/liquid-argon (LAr) sampling calorimeters which measure the energy and position of the electromagnetic showers with high granularity. In the center region $|\eta| < 1.7$, the steel/scintillator-tile calorimeter helps provide hadronic energy measurements. In the end and forward regions, LAr calorimeters that have copper or tungsten absorbers aid in electromagnetic and hadronic shower measurements that go up to $|\eta| = 4.9$. In the outer layer, the muon spectrometer consists of separate trigger and high-precision tracking chambers that operate in a magnetic field that is generated by three large air-core toroidal superconducting magnets that have eight coils each.

For the data simulation, reconstruction, and analysis of real and simulated data, detector operations, and trigger and data acquisition systems of the experiment, an extensive software suite is used [9] [10] [11].

1.3.2 The ATLAS Trigger System

A two-level trigger system is used to select and record interesting events and to achieve a high selection efficiency while reducing the large background rate for rare physics events such as BSM physics. Event selections happen based on physics signatures such as events that contain energetic leptons, photons, jets or missing energy. The trigger system also leverages algorithms through the use of topological information and multivariate methods that conduct the filtering of the analyses done by the collaboration [12].

2 Properties of Jets in Dark Sector Signals

We use 3 Semi-Visible signals and 3 Emerging Jet signals which are defined by the following parameters (see Tables 3(a) 3(b)).

2.1 Properties of Semi-Visible Dark Sector Signal Samples

We plot the scalar jet pT sum (HT) and the missing transverse momentum (met) of the three SVJ signals (see figure 4(a) and figure 4(b)). We observe that all signals have high HT and high met. For the signal with low mediator mass (signal 1, mediator mass = 2000 GeV), there is a peak due to the s-channel resonant contributions as compared to signals having high mediator mass (signal 3, mediator mass = 3000 GeV), we observe a falling off distribution due to the t-channel dominating.

Semi-visible Jet Signals				Emerging Jet Signals			
event/signal ID	515618	515624	515631	event/signal ID	801925	801928	801932
mediator mass	2000	2500	3000	dark confinement scale (Λ_{dark})	1.6	1.6	40
r_{inv}	4	4	6	Z prime mass [GeV]	600	1500	600
				Dark pion mass [GeV]	0.8	0.8	20
				Dark rho mass [GeV]	3.2	3.2	80
				Lifetime [mm]	1	10	50

(a) Semi-Visible Jet signals

(b) Emerging Jet signals

Figure 3: Model Parameters of the Semi-Visible Jet and Emerging Jet Signal Samples

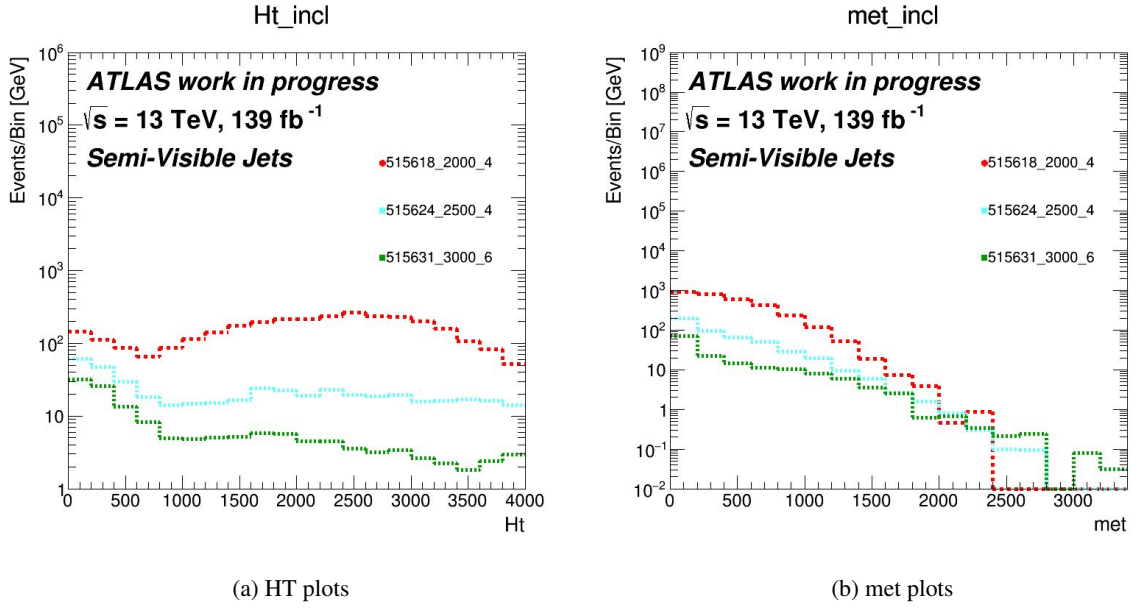


Figure 4: HT and met plots of Semi-Visible Dark Sector Signal Samples

2.2 Properties of Emerging Jet Dark Sector Signal Samples

For the EJ signals, we plot the hadronic transverse momentum or the scalar sum of jet transverse momenta (HT) and the charged fraction of the lead jet (chf) (5(a) 5(b)). We observe that we have high HT events for all 3 signals. However, for the second signal with large mediator mass at 1500 GeV and lifetime of 10 mm, we observe the special nature of Emerging Jets with many jets having very low values of chf. The chf distribution for QCD jets, which have not been plotted here, tends to peak at 60% due to the presence of charged hadrons, and hence has a distinctly different distribution compared to the EJ signals which peak at near zero values.

3 Triggering on Dark Sector Signal Events

Collisions in the LHC correspond to 40 MHz and with the huge amount of data produced, it is impossible for ATLAS to record and process all the information. ATLAS then leverages its trigger and data acquisition

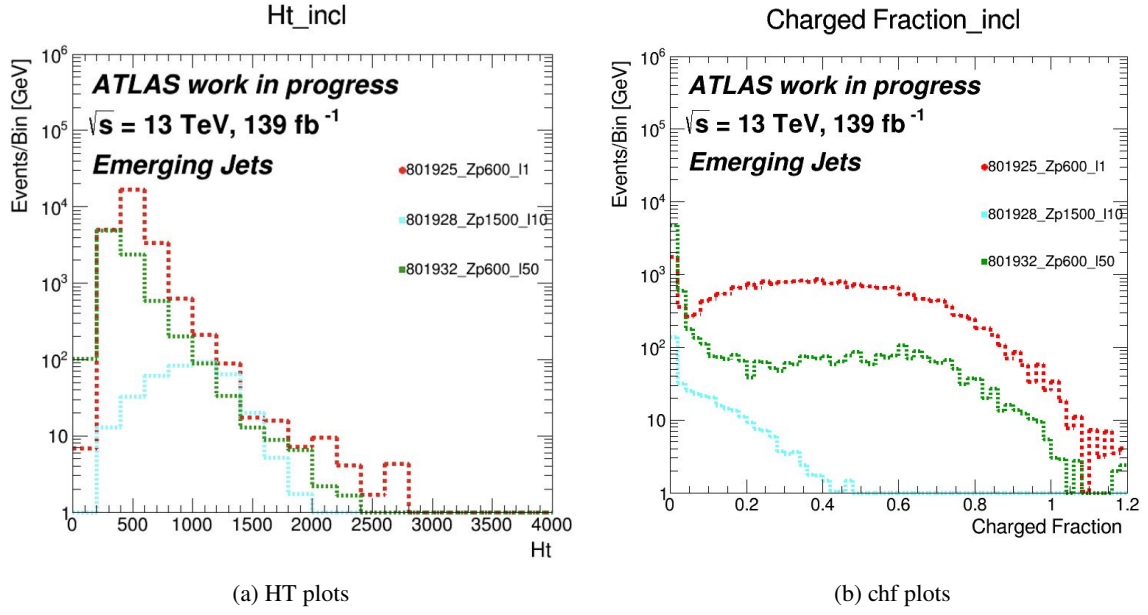


Figure 5: HT and chf plots of Emerging Dark Sector Signal Samples

(TDAQ) system which helps in online event selection and reading out of data for certain events [13]. The trigger system has two steps: the Level-1 Trigger (L1) and the High-Level Trigger (HLT). The L1 is able to reduce the event rate to 100 kHz and it searches for high transverse momentum objects and events with high momentum imbalance in the transverse plane. After selection at L1 level, the Regions of Interests (ROIs) in η and ϕ which have interesting activity goes to the HLT. Since we already have a reduced event rate, we can do more detailed analysis and calculations. Partial event reconstruction is done on the ROI data with better granularity and information from the ID. This causes the event rate to be reduced to 1 kHz [14].

Triggers help us select which events we want to keep for analysis. We currently record all events that have high lead jet p_T and high met but since all of our signals display these properties, we check the performance of the different triggers.

Currently, ATLAS records an event that satisfies any of the following apart from the other triggers which are less interesting for these signals:

1. Single jet trigger - $r = 0.4$ (small-R) jet with offline $p_T > 450$ GeV (labelled as J420)
2. $R = 1.0$ j460 trigger - $r = 1.0$ (large-R) jet with offline $p_T > 500$ GeV (labelled as lcw j460)
3. MET trigger - offline $MET > 200$ GeV (labelled as met)
4. allHT1000 trigger - $HT > 1000$ GeV (labelled as allHT)

We plot the HT of the first SVJ signal and the second EJ signal and applied the three triggers: Single jet trigger, j460 trigger, and MET trigger (see figure 6(a) 6(b)) and compared the distribution to the inclusive (incl), which is the baseline where we keep all events that have at least 2 jets. We see that the 3 triggers successfully record all high HT events but miss the low HT signals as compared to the inclusive distributions.

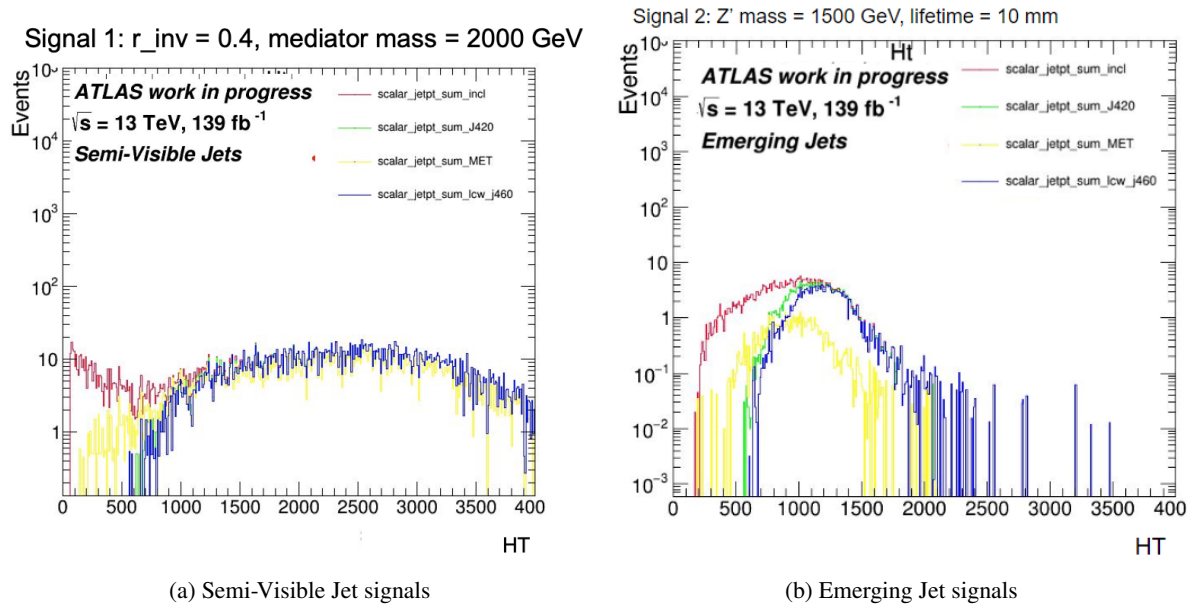


Figure 6: HT plots of events recorded by 3 triggers (Single jet, j460, and met) as well as the inclusive distribution for Semi-Visible Jet signals and Emerging Jet signals. For the allHT trigger, events above 1000 GeV will be recorded

event/signal	small			event/signal	801925	801928	801932
	515618	515624	515631				
mediator mass	2000	2500	3000	dark confinement scale (Λ_{dark})	1.6	1.6	40
r_{inv}	4	4	6	Z' prime mass [GeV]	600	1500	600
efficiency_J420	85%	63%	44%	Dark pion mass [GeV]	0.8	0.8	20
efficiency_MET	71%	56%	50%	Dark rho mass [GeV]	3.2	3.2	80
	large			Lifetime [mm]	1	10	50
efficiency_lcw_j460	91%	79%	67%	efficiency_J420	1%	58%	2%
				efficiency_MET	0%	14%	1%
				efficiency_lcw_j460	1%	47%	1%

(a) Semi-Visible Jet signals (small jet and large jet radius)

(b) Emerging Jets signals

Figure 7: Efficiencies of 3 triggers applied to Semi-Visible Jet signals and Emerging Jet signals

Given that we miss some low HT signals, we then check the efficiency of each trigger or how much each trigger is capturing with respect to the incl. We calculate the values of the plot integrals from the application of the 3 triggers to the SVJ signals 6(a) and EJ signals 6(b). For the SVJ signals, we apply the 3 triggers to small jets and large jets in each signal separately. We apply the pre-selection of at least 2 jets using the same jet collection as used in the trigger. We then measure the efficiency of the trigger relative to these pre-selected events and obtain the following efficiencies 7(a) 7(b).

For the SVJ ATLAS analysis [15] currently uses the MET trigger but we see that we recover slightly more signal efficiency if we use the large-R trigger.

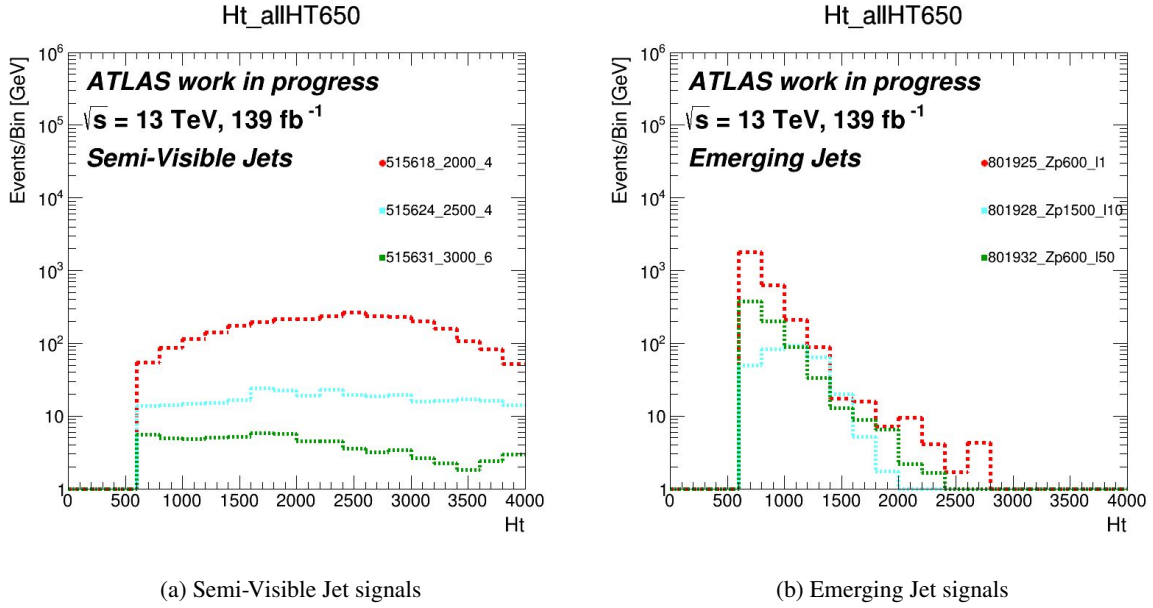


Figure 8: HT plots of allHT650 trigger applied to Semi-Visible Jet signals and Emerging Jet signals

4 Partial Event Building

Even though the ATLAS trigger system is able to record a lot of interesting data it is still limited by the approximately 1kHz output rate, and therefore some of our signal events will not be recorded.

Partial event building (PEB) allows us to select regions of the detector to focus on and gain more information about interesting events. After TDAQ, we can further optimize bandwidth and the resources in the TDAQ through PEB [13].

Since only parts of the detector information will be recorded, we can now trigger on events at lower thresholds than before, capture more events, and decide which regions can be recorded to obtain more in-depth information about the interesting event.

4.1 HT650 for PEB event recording

The rate of events with $HT > 650$ GeV (labelled as allHT650) is too high for them all to be recorded, but we investigate the efficiency of this trigger as a possible candidate for use with PEB.

We look at the HT plots after allHT650 trigger is applied to the Semi-Visible Jet signals and Emerging Jet signals 8(a) 8(b). We again calculate the efficiencies of this new trigger and compare them with the existing triggers (9(a) 9(b)).

Semi-visible Jet Signals				Emerging Jet Signals			
event/signal	515618	515624	515631	event/signal	801925	801928	801932
mediator mass	2000	2500	3000	dark confinement scale (Λ_{dark})	1.6	1.6	40
r_inv	4	4	6	Z prime mass [GeV]	600	1500	600
efficiency_J420	84.73%	62.56%	44.22%	Dark pion mass [GeV]	0.8	0.8	20
efficiency_MET	70.86%	56.12%	49.85%	Dark rho mass [GeV]	3.2	3.2	80
efficiency_lcw_j460	83.03%	61.04%	42.01%	Lifetime [mm]	1	10	50
efficiency_allHT	84.14%	61.56%	40.65%	efficiency_J420	1.03%	58.19%	1.89%
efficiency_allHT650	88.64%	67.89%	48.03%	efficiency_MET	0.00%	13.77%	0.81%
Comparison vs allHT650				efficiency_lcw_j460	0.57%	46.68%	1.25%
allHT650 and J420	4.42%	7.86%	7.93%	efficiency_allHT	1.37%	49.38%	1.87%
allHT650 and allHT	6.33%	10.09%	12.55%	efficiency_allHT650	10.56%	84.69%	8.79%
				Comparison vs allHT650			
				allHT650 and J420	90.28%	31.30%	78.49%
				allHT650 and allHT	87.02%	41.69%	78.72%

(a) Semi-Visible Jet signals

(b) Emerging Jet signals

Figure 9: Comparison of efficiencies of allHT650 trigger vs 4 triggers(single jet, $R = 1.0$ j460, met, and allHT) for Semi-Visible Jet and Emerging Jet signals

4.2 How many Regions of Interest are Required?

There is still the question of which regions we should select and consequently which ATLAS sub-detectors must be tapped. A full, assembled event is about 1.5 MB in ATLAS and because of bandwidth constraints, we can only record a limited number of regions of the detector. There are situations wherein we only need partial events that already have the information needed coming from some ATLAS sub-detectors [14].

The EJ signals we have seen in section §2.2 have displaced particles that are a distinctive characteristic separating them from SM background events. In order to capture this information, we have to identify how many and which regions of the detector are needed.

We leverage the charged fraction (chf), the fraction of the lead jet p_T that is carried off by the primary vertex tracks and we check if this shows the special nature of the EJ. We have plotted the chf of an EJ signal (signal 2, Z' mass = 1500 GeV, lifetime = 10 mm) and we have found that the unusual behavior of the EJ signal is displayed with most of the events having near zero values of chf under the 3 triggers single jet, $R = 1.0$ j460, and MET as shown in Figure 10.

We then check how many jets or regions we should look at in order to capture the nature of the dark sector signals. We plot the chf of the lead jet and the next 4 jets after (in p_T) for Semi-Visible Jet signal 1 and Emerging Jet signal 2. We find that the first three jets are pertinent to capturing the 0-0.05 chf (2 bins) nature of Emerging Jet signal, while the first three jets are QCD-like in the Semi-Visible Jet signal.

For each of the 5 jets, the fraction of events with near zero values of chf (within the first 2 bins) was obtained to further quantify (as shown in Table 12) and compare which jets must be kept.

5 Conclusions

Dark sector models SVJ and EJ have different properties compared to QCD background events as well as distinctive features between them, with SVJ having high met and EJ having many events with low chf values. This tells us the good possibility of searching for them and distinguishing them from background.

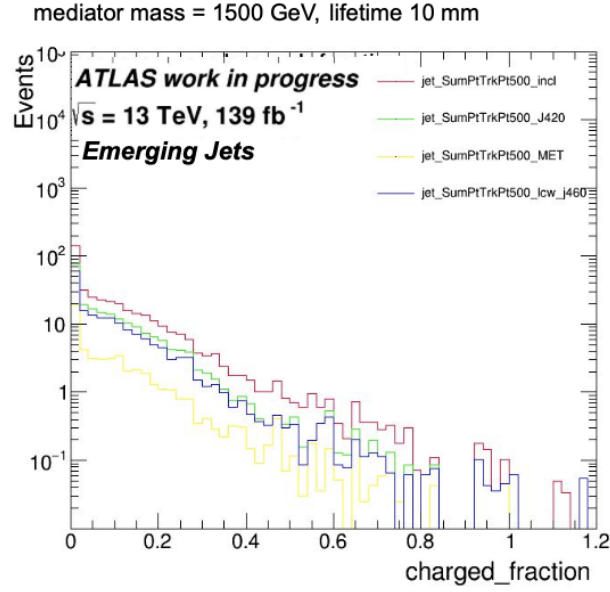


Figure 10: charged fraction plot of EJ Signal 2, Z' mass = 1500 GeV, lifetime = 10 mm, recorded by the 3 triggers single jet, $R = 1.0$ j460, and MET

Through PEB, we can use lower threshold triggers and record more of the data. allHT650 which lowers cut off to >650 GeV gives a large increase in acceptance of EJ signals.

It was found that for PEB, the 3rd jet has to be included in order to determine the special nature of the EJ signals.

In future studies, a wider variety of signals may be looked at. The EJ PEB can also be compared against a dedicated EJ trigger currently being developed and the CPU and bandwidth requirements of a PEB analysis that targets dark sector signals can be evaluated.

This preliminary feasibility study shows the promising direction of using triggers and PEB for recording and furthering the study of the unusual SVJ and EJ signals.

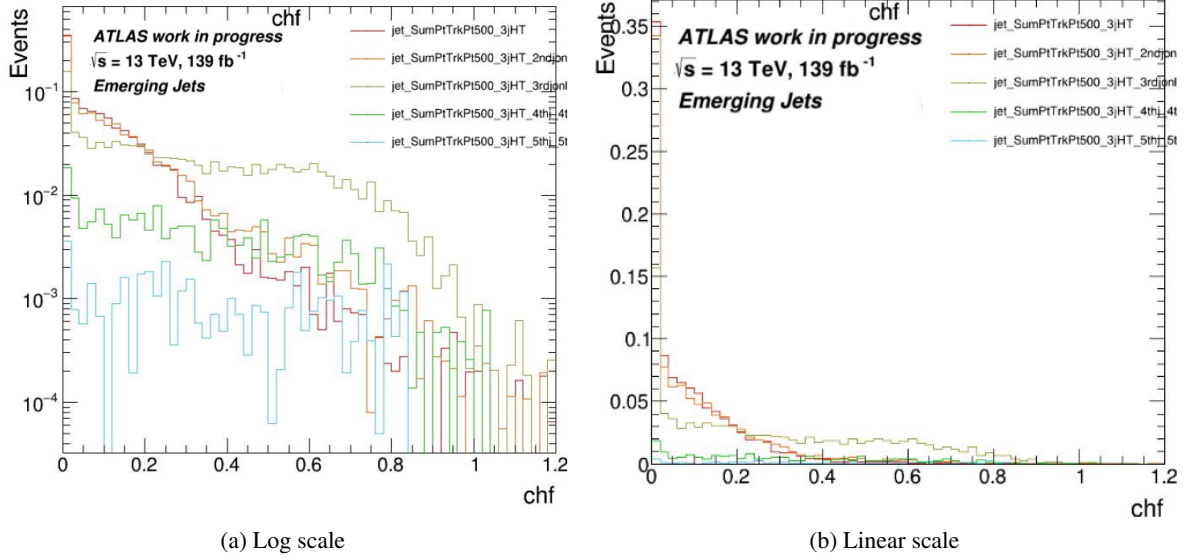


Figure 11: Charged fraction of first 5 jets for EJ signal 2 (Z' mass = 1500 GeV, lifetime = 10 mm)

event/signal	801928
dark confinement scale (Λ_{dark})	1.6
Z' prime mass [GeV]	1500
Dark pion mass [GeV]	0.8
Dark rho mass [GeV]	3.2
Lifetime [mm]	10
leadjet_2bins	44%
2ndjet_2bins	42%
3rdjet_2bins	20%
4thjet_2bins	3%
5thjet_2bins	0%

Figure 12: Fraction of each of the 5 jets with near zero values of chf in EJ signal 2 (Z' mass = 1500 GeV, lifetime = 10 mm)

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