

Semi-visible jets + X: Illuminating Dark Showers with Radiation

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ABSTRACT: We investigate the potential to search for semi-visible jets (SVJs) at the LHC using initial-state radiation (ISR). Both photon ISR and jet ISR channels are considered, using a benchmark signal model with the decay of a leptophobic Z' mediator forming two SVJs. We compare and extend several techniques to decompose the missing transverse momentum into per-jet contributions, in order to reconstruct the mediator mass and to define a new observable measuring the fraction of invisible dark hadrons. The presence of ISR facilitates the identification of the SVJs, and the resulting boost improves the resolution of the observables, especially for models with high invisible fractions. We combine the two observables to propose a complete search strategy and discuss an extension of the strategy to probe the whole model parameter space.

KEYWORDS: Dark QCD, Dark Matter, New Physics, Semi-visible Jets, Large Hadron Collider

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1 Introduction

Although the standard model (SM) of particle physics has been proven to be a very successful theory whose theoretical predictions agree well with most experimental results, it does not explain all phenomena, such as the origin of dark matter (DM) [1–5]. Searching for DM has been one of the most critical tasks in particle physics. The Large Hadron Collider (LHC) is the only particle collider in the world that can reach a center-of-mass energy of 13.6 TeV, which offers a unique opportunity to search for a wide range of potentially accessible DM candidates. The LHC experiments, such as the CMS and ATLAS collaborations, have diverse DM search programs. Until very recently, they have been focused on models with weakly interacting massive particles (WIMPs) [6], where the DM candidates do not leave any trace in the detector, resulting in an imbalanced distribution of transverse momentum. Therefore, these classic DM searches consider events with large missing transverse momentum (E_T^{miss} , the magnitude of the two-vector \vec{p}_T^{miss}), and are categorized by the types of visible particles that recoil against the DM candidates. A large variety of scenarios have been explored, such as DM candidates recoiling against a jet [7, 8], a top quark [9–11], a vector boson [12, 13], a photon [14], or a Higgs boson [15–17]. This type of search assumes the DM candidates are clearly separated from the objects they recoil against, so they explicitly require \vec{p}_T^{miss} not to overlap with those objects. As a consequence, the traditional search strategies have limited sensitivity to models without this feature.

Dark sectors containing a new confining force $SU(N)$, an analog to quantum chromodynamics (QCD) in the SM, are well motivated from both the theoretical and experimental perspectives. If the scale of the new confining force, referred to as the dark QCD [18], is related to SM QCD, the models are consistent with the DM relic density [19]. Unlike the WIMP models where the DM candidates are produced directly, here the DM candidates are generated during the dark showering. The dark sector contains several flavors of dark quarks (χ_i), which form bound states called dark hadrons that may be either stable or unstable. The stable dark hadrons are DM candidates that will escape detection, while the unstable dark hadrons will decay promptly to SM particles. The mixture of visible and invisible decay products creates a striking feature called a “semi-visible” jet (SVJ) [20, 21]. The previous DM search program at the LHC is not optimal for such signatures, as discussed in Refs. [22, 23].

SVJs are attracting more attention in the LHC physics program. CMS performed the first search for SVJs [22], which considers a heavy mediator, Z' , produced via a s -channel resonant production and decaying to dark quarks. A recent ATLAS analysis probes non-resonant production of SVJs [23]. The community has also identified a set of common model parameters in order to be able to compare results across experiments [24]. One model parameter, r_{inv} , which is the fraction of dark hadrons that are stable and invisible ($N_{\text{stable}}/(N_{\text{stable}} + N_{\text{unstable}})$), governs the experimental signatures. When r_{inv} approaches zero, the signal jets are fully visible rather than semi-visible, but because of the complicated dark showering, they are different from those jets expected in SM. ATLAS has published a result searching for such dark jets [25]. The typical dijet searches [26] have also explored

a large phase space relevant to this scenario. If r_{inv} goes to one, the jets become fully invisible, so traditional DM searches relying on $E_{\text{T}}^{\text{miss}}$ become sensitive. CMS has recently demonstrated the complementary sensitivity of these strategies [27]. So far, the dedicated SVJ search strategies only cover a portion of the overall phase space for intermediate r_{inv} values.

The ATLAS and CMS searches for SVJs require either $E_{\text{T}}^{\text{miss}}$ or hadronic momentum sum triggers. The former exploits the missing energy from the invisible particles from the dark shower, while the latter relies on the high momentum of the visible decay products. Consequently, it is challenging to optimize the search strategy for the entire range of r_{inv} values. In addition, the trigger thresholds are too high to include lower mediator masses. One common strategy adopted in dijet resonance searches to overcome this is to trigger on the initial state radiation (ISR). Though processes with substantial ISR have significantly reduced cross sections, this technique has been demonstrated to be sensitive to mediator masses from 700 down to 200 GeV [28, 29]. The ISR production channel has not yet been explored in the context of dark QCD searches. In this work, we show that it is a promising avenue. The unique features of SVJs also allow us to construct more powerful discriminating variables when the SVJ system is boosted against the energetic ISR. Depending on the mediator mass and the ISR momentum, the two SVJs can either be merged into one large-radius jet, or reconstructed as two separate small-radius jets. In this paper, we consider the latter case.

The benchmark signal process is the s -channel production of a new heavy particle (Z') that subsequently decays to two dark quarks [20, 21]. Figure 1 summarizes the leading-order production diagrams. We consider the scenarios where the ISR object is a jet or a photon, leaving other possibilities, such as a vector boson, to future work.

Figure 1: Feynman diagrams of the two Z' production channels considered in this work: Z' production in association with an ISR gluon (left) and Z' production in association with an ISR photon (right).

The article is organized as follows: Section 2 details the simulation procedure; Section 3 discusses the kinematic properties of the signal and background processes; Section 4 lays out a simple search strategy, followed by a summary of the sensitivity in Section 5; and finally, Section 6 gives an outlook and offers some further thoughts.

2 Simulated Event Samples

All samples used in this work are produced using MADGRAPH5_aMC@NLO 3.5.1 [30] for generation, PYTHIA 8.309 [31] for showering, and DELPHES 3.5.0 [32] for reconstruction. The CMS detector geometry and performance are used for reconstruction.

2.1 Signal Process

The signal grid is defined by the Z' mass and r_{inv} . Two mass points, 0.5 TeV and 1.0 TeV, are included to cover the most relevant kinematic region. Three r_{inv} values, 0.1, 0.5, and 0.9, span the whole r_{inv} range. Since the only change for different r_{inv} values occurs during the showering step, the same generated events are reused. The details of the signal model follow Ref. [22], using the MADGRAPH implementation from Ref. [21]. Important parameters include g_q , the coupling between Z' and SM quarks, which is set to 0.25 for all quark flavors, and g_χ , the coupling between Z' and the dark quarks, which is set to $1/\sqrt{N_c^{\text{dark}}N_f^{\text{dark}}} = 0.5$. The latter takes into account N_c^{dark} , the number of dark colors, and N_f^{dark} , the number of dark flavors, which are both set to 2 in this model. The resulting branching fraction for $Z' \rightarrow \chi\bar{\chi}$, $\mathcal{B}(Z' \rightarrow \chi\bar{\chi})$, is therefore 47%, in agreement with the benchmark for simplified DM models [33]. The dark hadron masses are set to 20 GeV.

Handling the signal processes with an ISR photon is straightforward, as we do not expect energetic photons from Z' decays. The signal samples in this channel are generated with an additional photon. Processes with up to one additional parton besides the photon are included as well. The minimum p_T of the additional photon is set to 150 GeV in order to have appreciable acceptance from typical single photon triggers. Each signal sample contains 100,000 events.

The ISR jet channel is more complicated as there are also jets from Z' decays. Furthermore, the p_T of the jets from Z' decays depend on r_{inv} , which makes the acceptance less trivial to estimate. To address this, signal processes in this channel are generated in five bins of the leading jet p_T , ranging from 0 GeV to 500 GeV with a step of 100 GeV, and one inclusive bin with $p_T > 500$ GeV. Up to two additional partons are included. Figure 2 summarizes the product of the cross section and the acceptance after applying the leading jet p_T selection. The cross section drops rapidly as the leading jet p_T increases, while the acceptance shows the opposite trend. The cross sections of the generated samples are taken directly from MADGRAPH5_aMC@NLO 3.5.1 calculations with a merging scale of 45.

Motivated by Figure 2, 240,000 events are generated in total for the 1.0 TeV mass point, with a ratio of 10:5:3:3:2:1 in each bin, to achieve roughly the same amount of events passing the basic selection. For the 0.5 TeV Z' , the acceptance is extremely low when the leading jet p_T is below 500 GeV. Therefore we only generate 10,000 events in each bin to study the kinematic properties, eschewing a detailed sensitivity study for this mass point in this channel.

2.2 Background Process

The main background for this search comes from SM QCD multijet production. Two sets of samples are created. For the photon ISR channel, the sample includes multijet processes

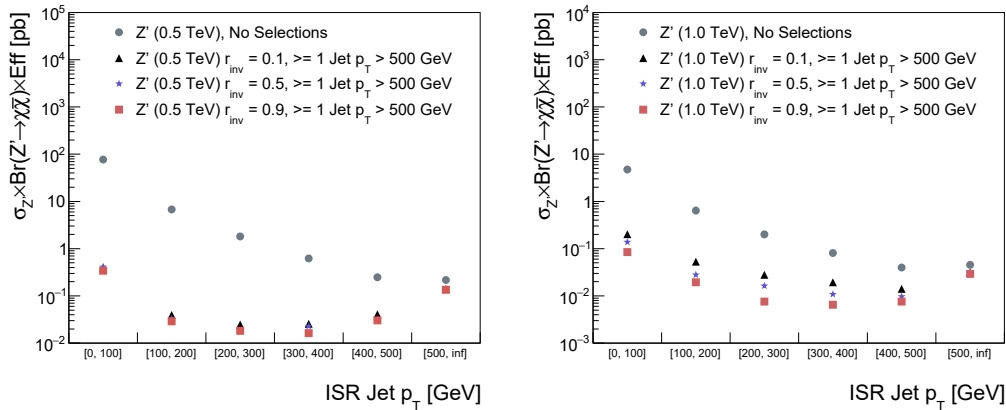


Figure 2: The product of cross section and acceptance for a basic selection (leading jet $p_T > 500$ GeV) applied to Z' production for $m_{Z'} = 0.5$ TeV (left) and $m_{Z'} = 1.0$ TeV (right), shown as a function of the (orthogonal) leading jet p_T selections when generating the samples.

with one photon and up to three jets, where the photon is required to have p_T larger than 150 GeV. For the jet ISR channel, all multijet processes with up to four jets are included, where at least one jet has to pass $p_T > 500$ GeV. Each sample has 500,000 events produced. While applying selections at the generation level can introduce biases, the choices made here are sufficient for the scope of this study.

3 Kinematic Properties

This section discusses some interesting characteristics of the event kinematic properties for both the signal and background processes, in order to motivate the analysis strategy established in Section 4.

3.1 Basic Kinematics

Very loose fiducial selections are applied so that only events containing at least two jets with $p_T > 25$ GeV and $|\eta| < 4.5$ are considered. This is because of the proposed search strategy that relies on observables constructed using the two jets from the Z' and E_T^{miss} , as described in Section 4. The m_T is constructed using the two leading non-ISR jets and E_T^{miss} .

Some signal kinematic variables are strongly correlated with the p_T of the ISR object. Each signal jet originates from a dark quark that undergoes a showering process, producing a stochastic mixture of stable and unstable dark hadrons. If both jets have similar numbers of stable dark hadrons, the transverse component of the missing momentum will be symmetric between the jets and will mostly cancel, even for large r_{inv} . However, when there is an energetic ISR object recoiling against the Z' system, the resulting SVJs become

more collimated. Events with either symmetric or asymmetric invisible components in the SVJs become more similar topologically, as illustrated in Figure 3.

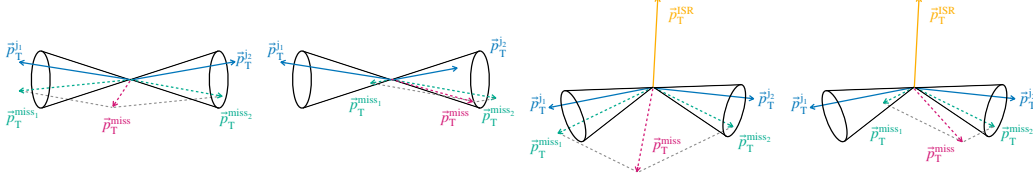


Figure 3: Diagrams illustrating the back-to-back topology and ISR topology, with symmetric and asymmetric invisible components in the SVJs.

Figure 4 shows that E_T^{miss} increases with r_{inv} when the p_T of the ISR object is high, while without an energetic ISR object, the E_T^{miss} depends less on r_{inv} , because of the cancellation of the symmetric invisible components. This enhancement of E_T^{miss} has remarkable impacts on the observables that will be discussed later. Another variable often used in heavy particle search is the rapidity difference y^* , defined as $(Y_1 - Y_2)/2$, where Y_i is the rapidity of a given jet [26]. In heavy particle decays, y^* for the two resulting jets has a smaller absolute value compared to the multijet background. This quantity is less affected than E_T^{miss} by the ISR object.

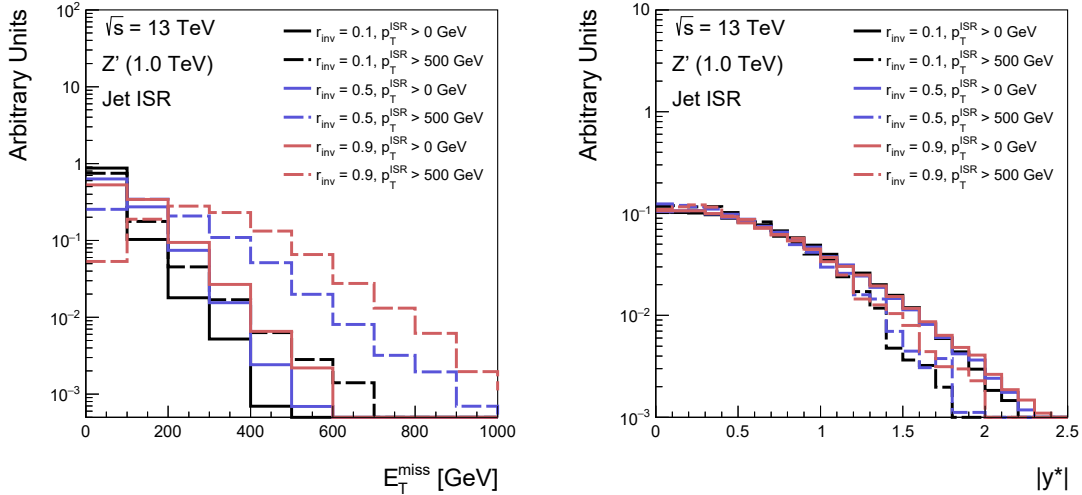


Figure 4: Left: E_T^{miss} distributions of the Z' samples for $m_{Z'} = 1.0$ TeV (right), with various r_{inv} and p_T^{ISR} . Right: $|y^*|$ distributions of the Z' samples for $m_{Z'} = 1.0$ TeV (right), with various r_{inv} and p_T^{ISR} .

The kinematic distributions of the multijet background process are also affected by the ISR object, as seen in Figure 5. The E_T^{miss} increases moderately as the p_T of the ISR object goes from 0 to 500 GeV, because there is no genuine source of sizable E_T^{miss} in the multijet process. The main source of E_T^{miss} in multijet events comes from jet mis-

reconstruction caused by detector inefficiency and noise, such as inactive calorimeter cells and beam remnants. By construction, E_T^{miss} is balanced against the other visible objects, so when there exists an energetic ISR object, E_T^{miss} increases correspondingly. The increase is smooth, so in the next section, we will see it does not introduce discontinuities in the main observables. y^* changes similarly for the multijet background and the signal.

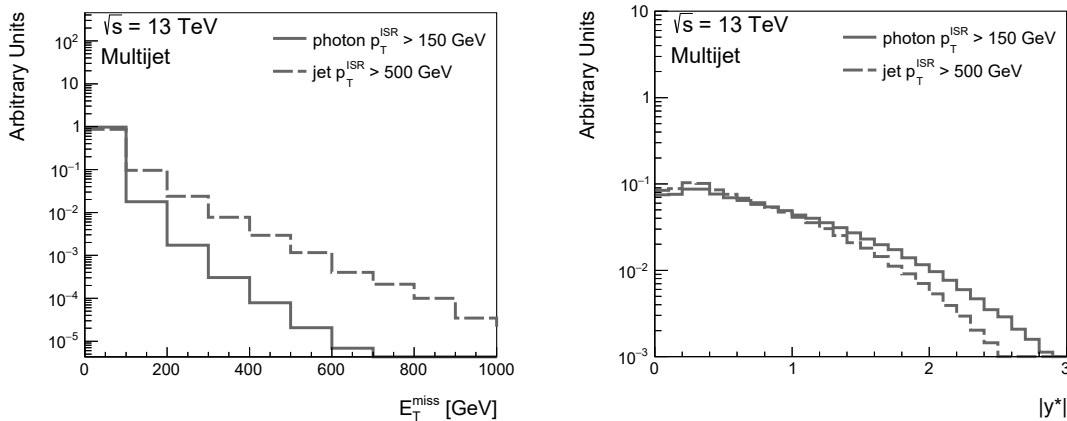


Figure 5: E_T^{miss} (left) and $|y^*|$ (right) distributions of multijet events for $p_T^{\text{ISR}} = 150$ GeV (solid line) and $p_T^{\text{ISR}} = 500$ GeV (dashed line).

3.2 \vec{p}_T^{miss} Decomposition

The challenge in this search is reconstructing the multiple missing transverse momentum contributions that arise from the production of stable bound states during the dark quark hadronization. We compare multiple methods of decomposing the measured \vec{p}_T^{miss} two-vector into components matching the two semi-visible jets in each event.

The first method is the calculation of the m_{T2} mass variable [34] (computed using Ref. [35]). m_{T2} is defined as:

$$m_{T2} \equiv \min \left[\max \left\{ m_T(j_1, \vec{p}_T^{\text{miss}_1}), m_T(j_2, \vec{p}_T^{\text{miss}_2}) \right\} \right], \quad (3.1)$$

where the minimization considers all possible values satisfying:

$$\vec{p}_T^{\text{miss}} = \vec{p}_T^{\text{miss}_1} + \vec{p}_T^{\text{miss}_2}, \quad (3.2)$$

and the transverse mass m_T is defined as:

$$m_T^2(j, \vec{p}_T^{\text{miss}}) = (E_T^j + E_T^{\text{miss}})^2 - (\vec{p}_T^j + \vec{p}_T^{\text{miss}})^2. \quad (3.3)$$

This method was developed for any final-state system with two invisible particles. It naturally produces two missing transverse momentum components, each associated with one of the two jets included in the calculation.

A newer, analytic decomposition was developed specifically for semivisible jet final states [36]. This technique assumes that the visible and invisible transverse momentum

of each semivisible jet are aligned. The ratio between the visible and invisible transverse momentum is strongly correlated with $r_{\text{inv}}/(1 - r_{\text{inv}})$. This leads to the following system of equations that can be solved to find the two coefficients α_1 and α_2 , using Eq. (3.2) as a constraint:

$$\vec{p}_T^{\text{miss}_1} = \alpha_1 \cdot \vec{p}_T^{j_1}, \quad (3.4)$$

$$\vec{p}_T^{\text{miss}_2} = \alpha_2 \cdot \vec{p}_T^{j_2}. \quad (3.5)$$

3.3 Mass Reconstruction

The transverse mass m_T , with the visible component as the massive dijet system, was proposed in Ref. [20] and used in the CMS s -channel search [22] to reconstruct the Z' mediator mass. By default, the multijet background distribution for this type of mass variable has a smoothly falling spectrum, facilitating background estimation. Simply requiring large E_T^{miss} sculpts the background m_T distribution significantly, motivating the introduction of r_T , the ratio between E_T^{miss} and m_T , which was shown to bring a clear sensitivity gain with minimal background sculpting.

Another, more sophisticated method to recover the Z' mass uses the m_{T2} construction: the m_{T2} -assisted on shell (MAOS) technique [37]. MAOS produces the variable m_{MAOS} by promoting the decomposed two-vectors $\vec{p}_T^{\text{miss}_1}$ and $\vec{p}_T^{\text{miss}_2}$ to four-vectors, assigning $p_z^{\text{miss}_1} = p_z^{j_1} (p_T^{\text{miss}_1}/p_T^{j_1})$ and $m^{\text{miss}_1} = 0$, and similarly for the second component. The invariant mass of the two visible four-vectors and the two invisible four-vectors is then an estimate of the mediator mass. This variable was recently shown to be nearly optimal in Ref. [38] for SVJ searches without any ISR.

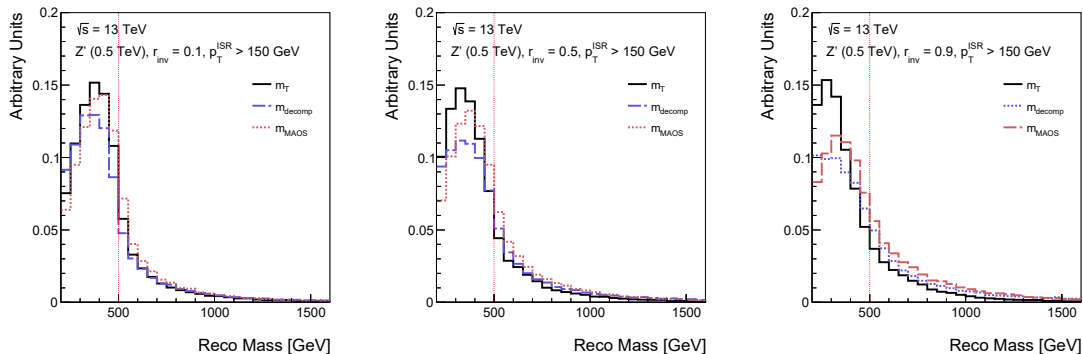


Figure 6: Distributions of different reconstructed mass variables for $m_{Z'} = 0.5$ TeV with $p_T^{\text{ISR}} = 150$ GeV and $r_{\text{inv}} = 0.1$ (left), $r_{\text{inv}} = 0.5$ (center), and $r_{\text{inv}} = 0.9$ (right). The red dashed vertical line shows the theoretical $m_{Z'}$ value.

We apply the same procedure to the invisible components from the analytic decomposition, resulting in the new variable m_{decomp} . This combination has not been studied before. We compare all three mass variables for $m_{Z'} = 0.5$ TeV with $p_T^{\text{ISR}} = 150$ GeV in Figure 6 and for $m_{Z'} = 1.0$ TeV with $p_T^{\text{ISR}} = 500$ GeV in Figure 7. For this comparison, we assume that the semivisible jets in each event are always correctly identified (further

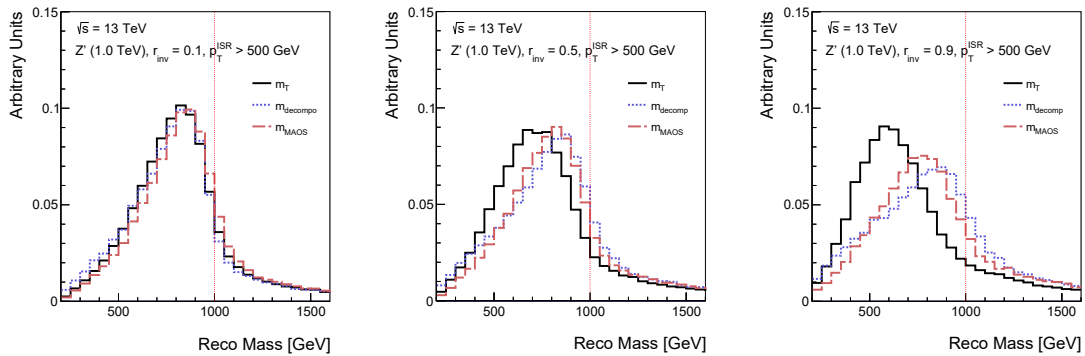


Figure 7: Distributions of different reconstructed mass variables for $m_{Z'} = 1.0$ TeV with $p_T^{\text{ISR}} = 500$ GeV and $r_{\text{inv}} = 0.1$ (left), $r_{\text{inv}} = 0.5$ (center), and $r_{\text{inv}} = 0.9$ (right). The red dashed vertical line shows the theoretical $m_{Z'}$ value.

discussed in Section 4.1). Both m_{MAOS} and m_{decomp} retain better performance than m_T as r_{inv} increases. m_{MAOS} is found to have the best resolution. Importantly, all three variables have similarly falling spectra in multijet background events.

3.4 r_{inv} Reconstruction

We further extend the use of \vec{p}_T^{miss} decomposition techniques to measure r_{inv} on a per-event basis. This is most natural for the analytic decomposition, which is explicitly based on r_{inv} . In this case, we can write $r_{\text{inv}}^i = \alpha_i / (1 + \alpha_i)$ for jet i , and we observe that the signal events tend to have larger r_{inv}^i for both jets. As a consequence, \bar{r}_{inv} , the average of r_{inv}^i , can be used to distinguish signal events from the background. The \bar{r}_{inv} is smaller than the corresponding r_{inv} for various reasons. Events are already required to have two jets with $p_T > 25$ GeV, which acts as a requirement on the visible decay fraction in each jet. In addition, the jet axes are only approximations of the invisible components.

To apply the same principle to the numerical m_{T2} decomposition, we must account for the lack of an explicit α coefficient relating the x and y momenta of each invisible component. We therefore take the average of the corresponding formula applied separately to the x and y momenta:

$$r_{\text{inv}}^i = \frac{1}{2} \left(\frac{p_x^{\text{miss}_i}}{p_x^{j_i} + p_x^{\text{miss}_i}} + \frac{p_y^{\text{miss}_i}}{p_y^{j_i} + p_y^{\text{miss}_i}} \right). \quad (3.6)$$

We then define the average \bar{r}'_{inv} in the same way as \bar{r}_{inv} above.

Comparisons between these two r_{inv} estimators are shown in Figures 8 and 9, and their average values are compared to the theoretical r_{inv} value (specified during signal simulation) in Fig. 10. As r_{inv} increases, both variables become more powerful. However, as studied later in Section 4.3, \bar{r}'_{inv} is not as powerful as \bar{r}_{inv} . There is a clear relationship with the theoretical r_{inv} value, which could be used for calibration when measuring this quantity. Both \bar{r}_{inv} and r_T can be used to enhance sensitivity, as will be investigated in Section 4.

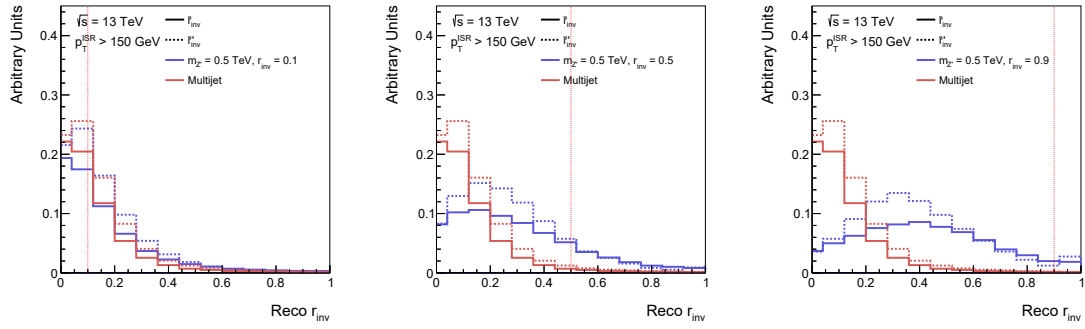


Figure 8: Distributions of r_{inv} estimators for the multijet background and signals with $m_{Z'} = 0.5$ TeV, $p_{\text{T}}^{\text{ISR}} = 150$ GeV, and $r_{\text{inv}} = 0.1$ (left), $r_{\text{inv}} = 0.5$ (center), and $r_{\text{inv}} = 0.9$ (right). The red dashed vertical line shows the theoretical r_{inv} value.

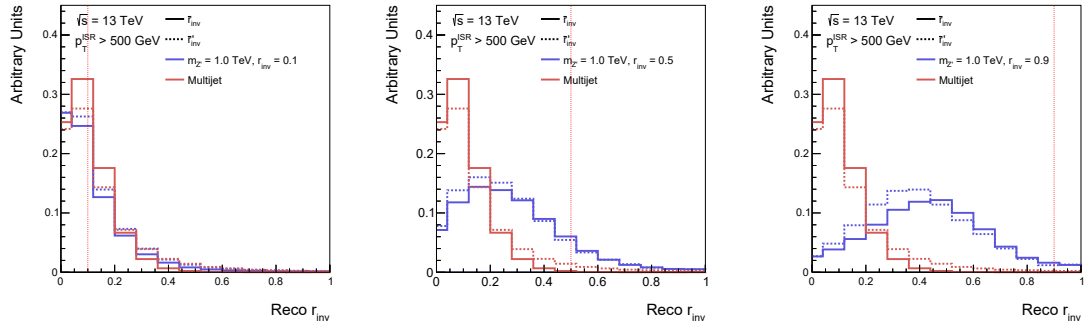


Figure 9: Distributions of r_{inv} estimators for the multijet background and signals with $m_{Z'} = 1.0$ TeV, $p_{\text{T}}^{\text{ISR}} = 500$ GeV, and $r_{\text{inv}} = 0.1$ (left), $r_{\text{inv}} = 0.5$ (center), and $r_{\text{inv}} = 0.9$ (right). The red dashed vertical line shows the theoretical r_{inv} value.

3.5 Combining Observables

As both \bar{r}_{inv} and m_{MAOS} have excellent discriminating power, combining the two may further enhance the search power. Figure 11 shows the $m_{\text{MAOS}}-\bar{r}_{\text{inv}}$ 2D distribution for both the multijet background and the signal. The signal events are clustered in the region determined by the Z' mass and r_{inv} . This opens up new ways to perform this search, as discussed in Section 5.

Similar to m_{T} , m_{MAOS} and \bar{r}_{inv} benefit from the energetic ISR object. The performance of \bar{r}_{inv} drops dramatically as the p_{T} of the ISR object decreases. This is because the decomposition is influenced by the angular separation. This can be clearly appreciated from an extreme example where $\vec{p}_{\text{T}}^{\text{miss}}$ is perfectly aligned with one of the jets. In this situation, the decomposition is ambiguous unless the system is boosted.

This event-level topology can be generalized as a two-body decay with non-interacting final state particles in each decay leg. This behavior is expected in various scenarios such as leptonic $H \rightarrow \tau^+\tau^-$ and $H \rightarrow W^+W^-$ decays. Methods proposed to improve

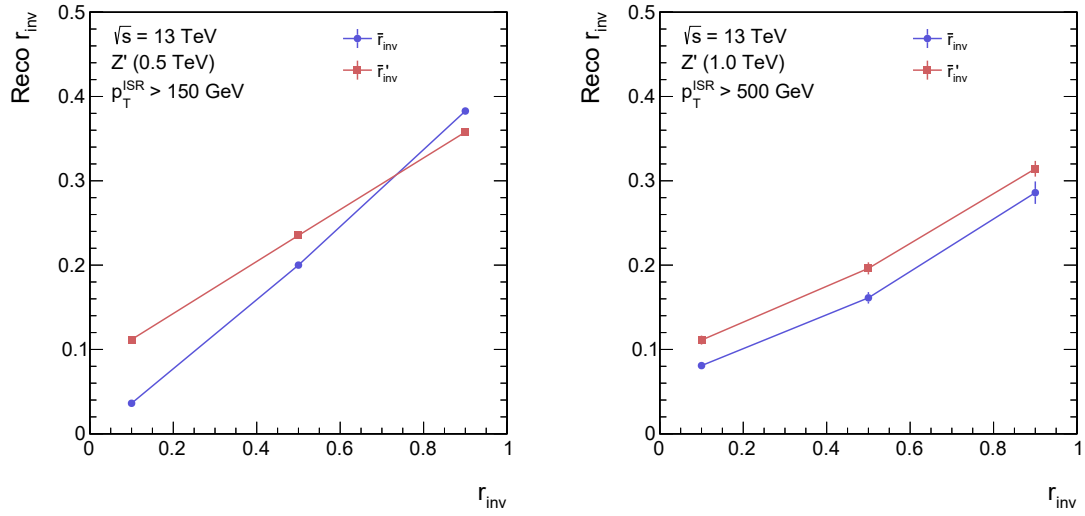


Figure 10: Comparisons of the average values of the two r_{inv} estimators with the theoretical r_{inv} value, for signals with $m_{Z'} = 0.5$ TeV, $p_{\text{T}}^{\text{ISR}} = 150$ GeV (right) and $m_{Z'} = 1.0$ TeV, $p_{\text{T}}^{\text{ISR}} = 500$ GeV (left).

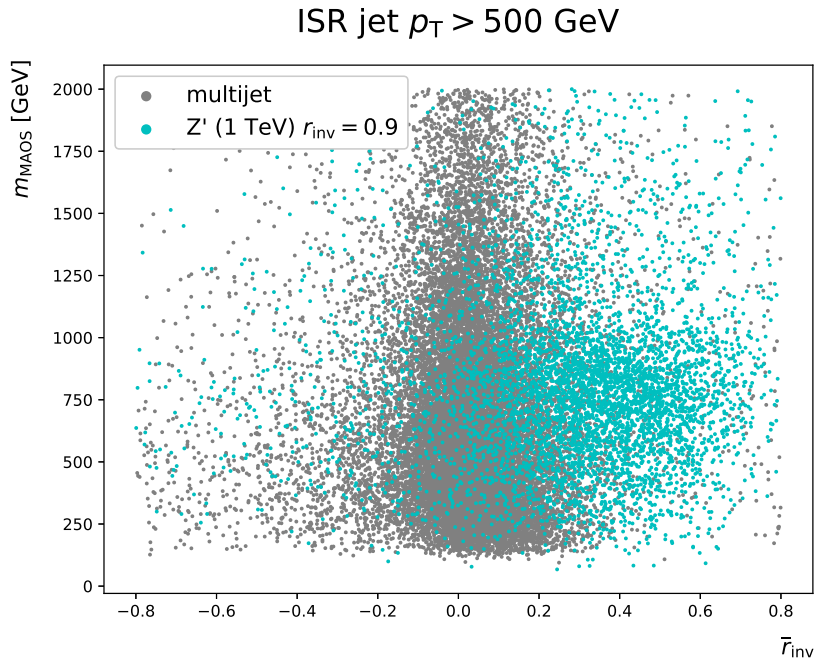


Figure 11: Scatterplot of m_{MAOS} and \bar{r}_{inv} for multijet (grey) and Z' (cyan). The Z' sample has a mass of 1 TeV and an r_{inv} parameter of 0.9. The ISR jet is required to have $p_{\text{T}} > 500$ GeV.

reconstruction of the Higgs mass in semivisible decays can be applied to SVJs as well; in fact, this was the original genesis of the MAOS method. The performance improvement in collinear events has also been discussed in the context of $H \rightarrow \tau^+\tau^-$ [39]. SVJ searches will likely benefit further from more interactions between various communities.

4 Analysis Strategy

In this section, we demonstrate the feasibility of constructing a search for a resonant Z' decaying to dark quarks in the ISR production channels, where the two jets originating from the dark quarks are reconstructed as two separated small-radius ($R = 0.4$) jets. When the Z' mass is very small, using large-radius jets containing the entire boosted Z' system is a better choice, but this is a different strategy not pursued here.

4.1 Jet Matching Method

Experimentally, the two jets from Z' have to be distinguished from the ISR object. In the photon ISR case, simply selecting the leading two jets is sufficient. However, as reported in other resonance searches using an ISR jet, the jet matching is a challenging task. In particular, once the ISR jet and the two jets from the heavy particles have similar p_T , the three jets are well balanced on the transverse plane, forming a triangular topology. It is extremely difficult to disentangle these three jets using basic kinematic properties only. In SVJ models, thanks to the appreciable E_T^{miss} , we are able to identify the two signal jets using $\Delta\phi$ between the jet pair and \vec{p}_T^{miss} , as illustrated in Figure 12. Since the two target jets and E_T^{miss} come from the Z' , when the Z' system is boosted, these three objects are collimated, resulting in smaller separations in $\Delta\phi$. While identifying the correct jets in signal events is critical, ensuring minimal background sculpting is equally important. It is found that minimizing the variable $(\Delta\phi_{j_i,j_k} + \Delta\phi_{j_i,j_k,\vec{p}_T^{\text{miss}}})/2$ gives a smooth background and acceptable matching efficiency. $\Delta\phi_{j_i,j_k}$ is the $\Delta\phi$ between two jets under consideration, and $\Delta\phi_{j_i,j_k,\vec{p}_T^{\text{miss}}}$ is the $\Delta\phi$ between the corresponding dijet system and \vec{p}_T^{miss} . Before the minimisation, the three jets are required to be well-separated by requiring $\Delta\phi$ between each pair to be larger than 0.8.

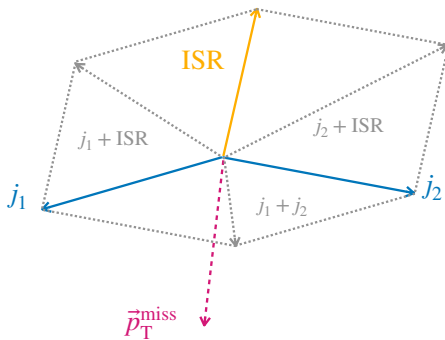


Figure 12: Transverse view of the two jets, ISR object and \vec{p}_T^{miss} .

Figure 13 shows the probabilities of different jet pairs to be selected via the above procedure. As the p_T of the ISR jet increases, the matching efficiency of this method improves. For 500 GeV, the method is over 90% efficient for large r_{inv} values.

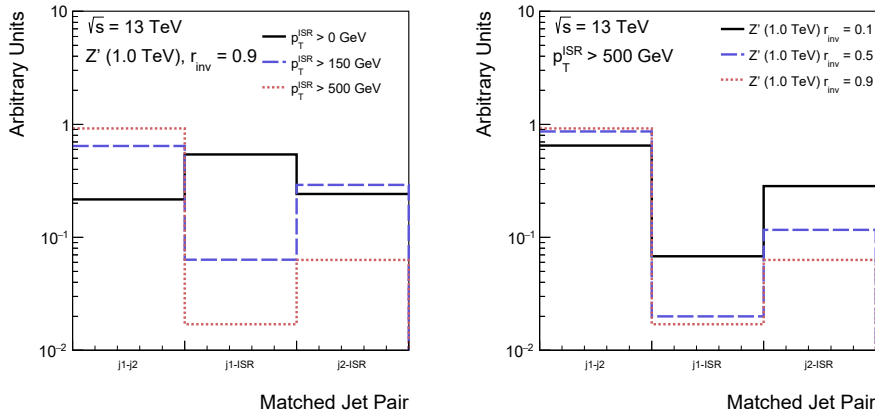


Figure 13: Fractions of various matching configurations for one Z' sample with different ISR p_T selections (left), and for three Z' samples with different r_{inv} parameters when the same ISR p_T selection is applied (right). The first bin on the x -axis corresponds to the case where the matching procedure correctly identifies the two jets from the Z' .

4.2 Basic Selections

The typical threshold for a single isolated photon trigger is about 140 GeV, while the corresponding threshold for a single jet trigger is about 420 GeV [29]. Therefore, the events are categorized into two channels: one requires an energetic photon with $p_T > 150$ GeV, and the other requires a jet with p_T larger than 500 GeV. The thresholds are slightly increased so that the analysis considers events above the trigger turn-on region.

Furthermore, the events are required to contain at least two (three) $R = 0.4$ jets, passing $p_T > 25$ GeV, with $|\eta| < 4.5$, for the photon (jet) ISR channel. In the photon channel, the photon must not overlap with the two leading jets ($\Delta R > 0.4$). The two signal jets are identified as the leading two jets in the photon ISR channel, and the two signal jets are identified via the method mentioned above in the jet ISR channel. The $|y^*|$ variable has been used in numerous dijet resonance searches in the past, so a similar strategy is adopted here. The threshold is chosen to be 0.8, based on a recently published ATLAS result [29] that considers similar kinematic regions.

4.3 Signal Region Categorization

As discussed in Section 3, both \bar{r}_{inv} and \bar{r}'_{inv} have excellent discriminating power for signal with large r_{inv} . Here, we also compare these variables to r_T , since they all involve the E_T^{miss} , though in different ways. The approximate significance S/\sqrt{B} , based on the signal and background yields S and B , is evaluated for a range of values in each variable. The signal yields S and B are evaluated for $1/2m_{Z'} < m_{\text{MAOS}} < 3/2m_{Z'}$, in order to consider the

most pertinent background events in the region near the signal mass peak, which provides the most sensitivity. Figure 14 shows the results for the 0.5 (1.0) TeV Z' in the photon (jet) ISR channels. In the photon ISR channel where the boost is modest, r_T brings better sensitivity, while in the jet ISR channel, \bar{r}_{inv} performs the best except in the very high signal efficiency region. This is expected as \bar{r}_{inv} is more impacted by the boost. It is also clear that \bar{r}'_{inv} is not as efficient as \bar{r}_{inv} in the jet ISR channel.

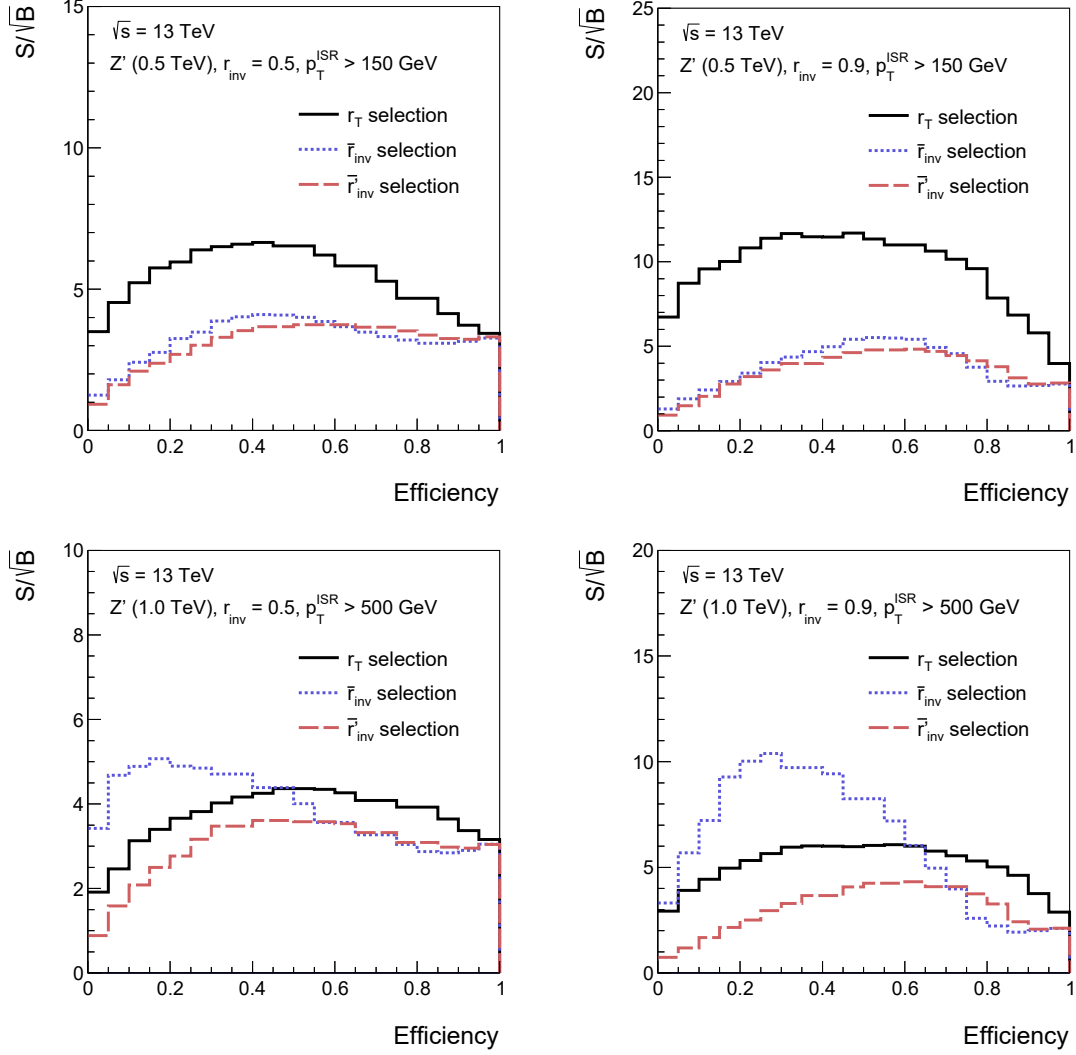


Figure 14: Top: Significance in the photon ISR channel as a function of the signal efficiency for selections on r_T , \bar{r}_{inv} , or \bar{r}'_{inv} . The 0.5 TeV Z' samples with an r_{inv} parameter of 0.5 (left) and 0.9 (right) are considered. Bottom: Significance in the jet ISR channel as a function of the signal efficiency for selections on r_T , \bar{r}_{inv} , or \bar{r}'_{inv} . The 1.0 TeV Z' samples with an r_{inv} parameter of 0.5 (left) and 0.9 (right) are considered.

The photon and jet ISR channels are optimized separately using r_T and \bar{r}_{inv} , respec-

tively, as presented in Figure 15. We apply a cut at 0.4 on r_T (\bar{r}_{inv}) in the photon (jet) ISR channels to estimate the final sensitivity. Table 1 summarizes all the selections applied to achieve the final results. The minimum m_{MAOS} selections for each channel are necessary to ensure a smoothly falling background spectrum. For lower m_{MAOS} values, the multijet background has a peak, arising from Sudakov suppression [40] and any other sculpting from kinematic selections.

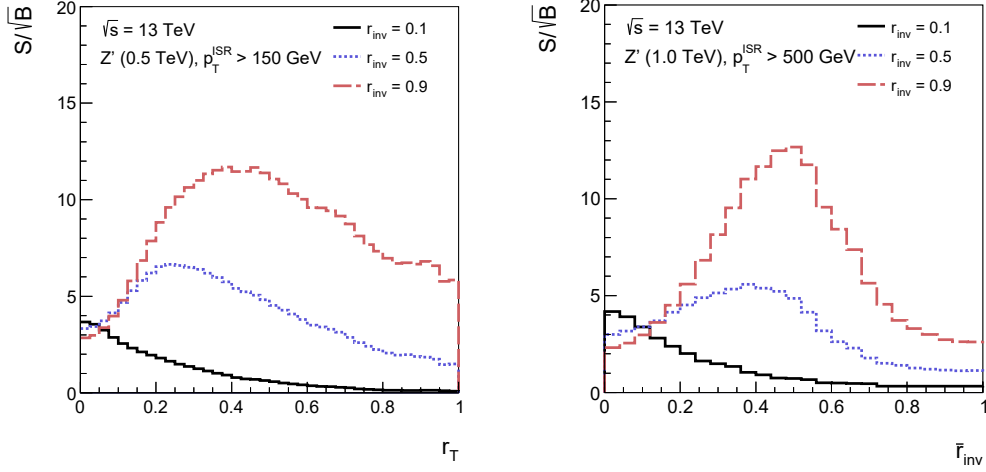


Figure 15: Significance as a function of r_T (left) and \bar{r}_{inv} (right) for the photon ISR channel and jet ISR channel, respectively. In the photon (jet) ISR channel, the 0.5 (1.0) TeV Z' sample is studied with three r_{inv} values.

Table 1: The complete set of signal region selections applied to both the photon ISR and jet ISR channels.

Photon ISR	Jet ISR
≥ 1 photon with $p_T > 150$ GeV	≥ 1 Jet with $p_T > 500$ GeV
≥ 2 jets with $p_T > 25$ GeV, $ \eta < 4.5$	≥ 3 jets with $p_T > 25$ GeV, $ \eta < 4.5$
Jet-photon overlap removal	-
Leading two jets as signal jets	Identify two signal jets via jet matching
$ y^* < 0.8$	
$r_T > 0.4$	$\bar{r}_{\text{inv}} > 0.4$
$m_{\text{MAOS}} > 200$ GeV	$m_{\text{MAOS}} > 400$ GeV

5 Sensitivity Estimation

The traditional background modeling method is to perform a fit to data, as in the CMS analysis [22]. Here we present the ideal sensitivities given perfect background modeling. Since we have identified m_{MAOS} as a better observable, the sensitivities are presented as functions of m_{MAOS} . We apply the selections in Table 1, optimized separately for each channel as discussed in Section 4.3. As seen in Figure 16, thanks to the \bar{r}_{inv} (r_{T}) selection, the significance is increased by a factor of four across the bulk of the m_{MAOS} distribution for 1.0 (0.5) TeV Z' with $r_{\text{inv}} = 0.9$ in the jet (photon) ISR channel.

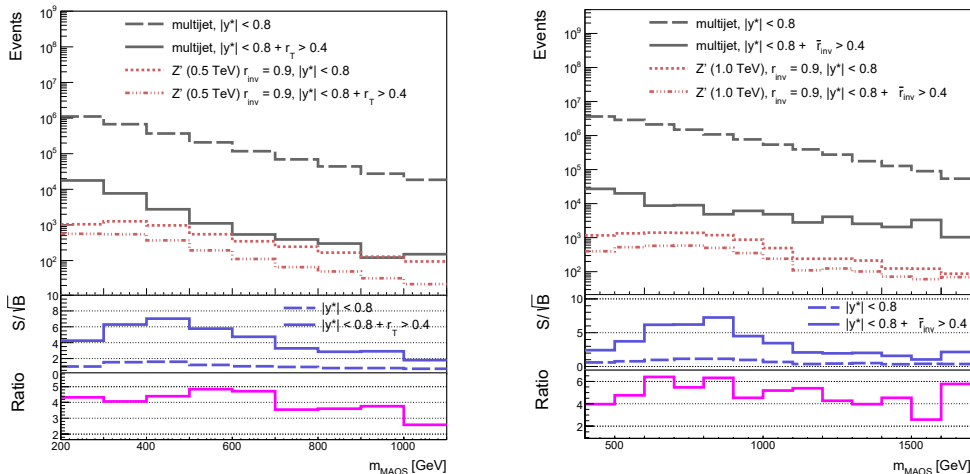


Figure 16: Signal and background distributions in the photon ISR (left) and jet ISR (right) signal regions. The significance is compared between the signal region selections with and without the r_{T} (left) or the \bar{r}_{inv} (right) requirements. The bottom panel presents the ratio between the significance curves in the middle panel.

The fact that \bar{r}_{inv} is a reasonable estimator of r_{inv} , forming a localized feature, motivates an exploration of using its full distribution rather than just as a selection. Figure 17 shows the significance in the $m_{\text{MAOS}}-\bar{r}_{\text{inv}}$ 2D plane, for the 1 TeV Z' with various r_{inv} parameters, where a local peak is formed in each case. Scanning this 2D plane is a viable search strategy. However, the background modeling is more challenging. Figures 8 and 9 show that the \bar{r}_{inv} distribution is smooth in both multijet and signal, which makes it possible to model this variable via a parameterization. Another advantage of this approach is that it provides a unified strategy for various r_{inv} and mass combinations without choosing a particular \bar{r}_{inv} selection.

The sensitivity can be further quantified by computing the limits on $\sigma_{Z'}\mathcal{B}(Z' \rightarrow \chi\bar{\chi})$ at the 95% confidence level (CL) using the asymptotic approximation to the CL_s method [41]. The expected limits from both the 1D and 2D approaches are evaluated for the jet ISR channel, as a function of the Z' mass. Two additional signal mass points, 750 GeV and 1250 GeV, are added to show the trend. The exclusion limits are calculated in PYHF 0.7.6 [42, 43], where the background estimate is taken directly from the simulated multijet samples. In the

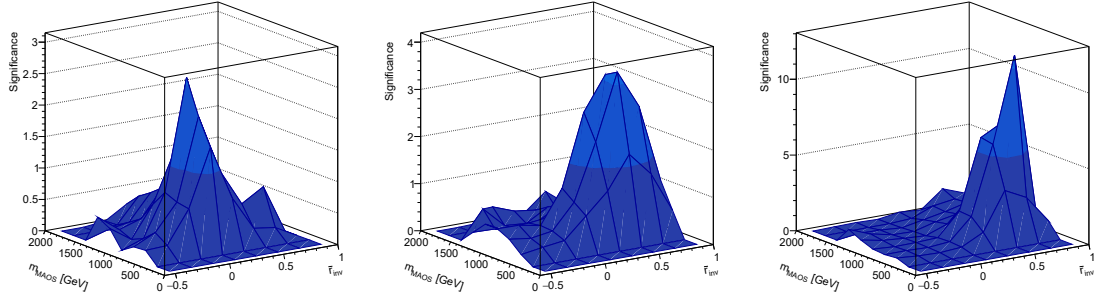


Figure 17: The significance distribution in the $m_{\text{MAOS}}-\bar{r}_{\text{inv}}$ plane in the jet ISR channel for the 1.0 TeV Z' with $r_{\text{inv}} = 0.1$ (left), 0.5 (middle) and 0.9 (right).

1D approach, the m_{MAOS} distribution after applying the $\bar{r}_{\text{inv}} > 0.4$ selection is considered, while the 2D approach utilizes the entire $m_{\text{MAOS}}-\bar{r}_{\text{inv}}$ 2D plane¹. Figure 18 compares the expected limits between these two strategies, which clearly motivates further development of the 2D approach.

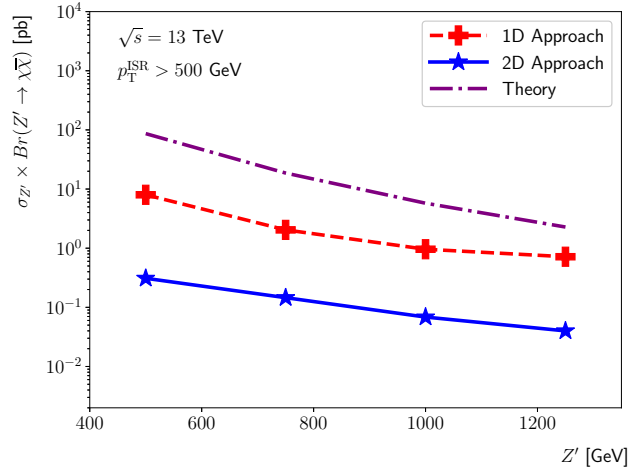


Figure 18: Expected limits at 95% CL obtained in the jet ISR channel, as functions of the Z' mass. The 1D approach (dashed line) applies the $\bar{r}_{\text{inv}} > 0.4$ cut before scanning the m_{MAOS} spectrum, and the 2D approach (solid line) directly considers the $m_{\text{MAOS}}-\bar{r}_{\text{inv}}$ 2D plane. The predicted $\sigma_{Z'}\mathcal{B}$ from MADGRAPH5_aMC@NLO 3.5.1 [30] is also displayed (dashed dotted line).

¹PYHF 0.7.6 currently does not support an optimal 2D treatment, where the correlations between neighboring bins are all taken into account. The 2D input is flattened into a 1D dataset, i.e. a list of values in the $\bar{r}_{\text{inv}}-m_{\text{MAOS}}$ bins.

6 Outlook

This work considers the case where two semi-visible jets (SVJs) are produced along with initial state radiation (ISR), proving that this production channel is a promising avenue for semi-visible jet searches. Besides allowing us to overcome the trigger threshold limitation, the presence of an energetic ISR object brings other advantages. We derive several observables to reconstruct properties of the semi-visible jet process that show great potential. Assuming that each invisible decay component is aligned with the corresponding visible jet, an analytic \vec{p}_T^{miss} decomposition facilitates an estimation of the invisible fraction for each jet, which can be averaged to find the event-level invisible fraction \bar{r}_{inv} . The separation power of this observable is enhanced as the ISR p_T increases. The reconstructed mediator mass m_{MAOS} is found using a different, numerical \vec{p}_T^{miss} decomposition based on m_{T2} and promoting the two invisible components to four-vectors with the m_{T2} -assisted on shell (MAOS) scheme [37]. The signal m_{MAOS} resolution suffers almost no degradation as r_{inv} increases, when the ISR p_T is significant. In addition, the matching ambiguity in the jet ISR channel is mitigated thanks to the alignment of E_T^{miss} with the signal jets, and we propose a method that gives good matching efficiency with minimal background distortion.

The analysis sensitivity is studied in detail for a 0.5 (1.0) TeV Z' with $r_{\text{inv}} = 0.9$ in the photon (jet) ISR channel. If only m_{MAOS} is used as the search variable, the sensitivity can be greatly increased by cutting on the ratio of E_T^{miss} and m_T (\bar{r}_{inv}). Further, the \bar{r}_{inv} of the signal is similarly localized, so a search in the $m_{\text{MAOS}}-\bar{r}_{\text{inv}}$ 2D plane merits investigation. A preliminary examination of the expected limits shows that the 2D approach is an order of magnitude more sensitive. This conclusion applies to mediator masses below 1 TeV and other r_{inv} values as well. Observables constructed using E_T^{miss} are not invariant with respect to the ISR object p_T , so a thorough survey is needed to optimize the search strategy.

It is possible to apply a unified search strategy to explore a wide range of the r_{inv} model parameter using the techniques developed in this work. Even when r_{inv} approaches unity, a mass resonance can be reconstructed. As recently pointed out in Ref. [44], jet substructure variables suffer from large modeling uncertainties in the context of dark QCD. This study explores only simple physics objects, which makes it applicable to various showering models. The advantages of jet substructure variables and machine learning in SVJ searches were studied by previous publications [22, 45–48], and the findings in this work could be combined with those methods. In particular, a single \vec{p}_T^{miss} decomposition that provides optimal reconstruction for both the mediator mass and invisible fraction could potentially be achieved using interpretable machine learning [38]. We point out that the event-level topological features are similar between SVJ and other processes such as Higgs decays with both visible and invisible final state particles. We look forward to seeing the ISR production channels probed in SVJ searches by the LHC experiments.

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