Dark matter searches with jets come from hadronically decaying vector boson at ATLAS

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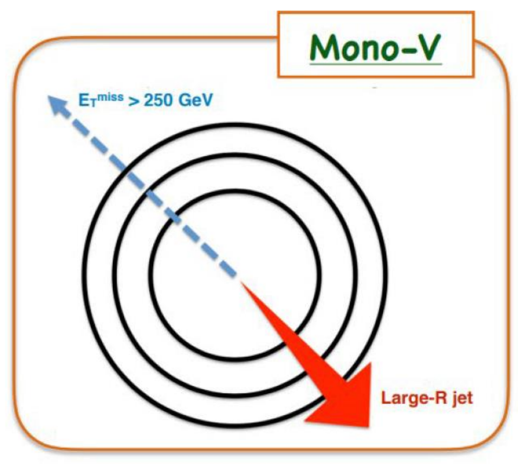
Abstract

Search for dark matter particles produced in association with a vector boson($V = W, Z$) reconstructed in its hadronic final state. The analysis strategy depends on the boost of the vector boson in the final state, searching for dark matter particles in two separate topologies. The SM background contribution is dominated by W/Z+jets production processes. The result will be interpreted in the context of simplified vector and axial-vector DM models, as well as invisible Higgs and Axion-like particle models.

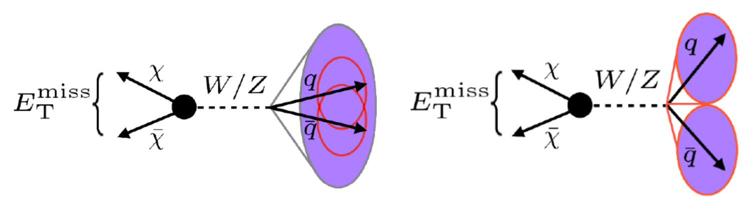
Event Topology

In order to Search for dark matter which focuses on the hadronic decay channel of W/Z bosons ($W/Z \to q\bar{q}$).



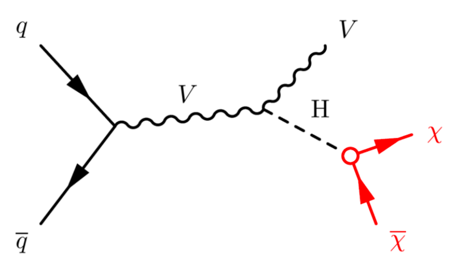
We define two separate event topologies based on the Lorentz boost of the Vector boson:

- Merged regime: The double-pronged hadronic decay of the vector boson is searched for within a large-R jet with radius parameter $R = 1.0$;
- Resolved regime: the separation between the decay products is sufficiently large to be reconstructed as two separate small-R jets with a radius parameter $R = 0.4$.

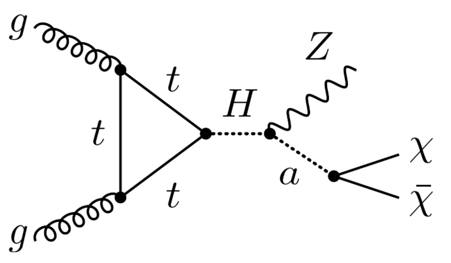


Signal Models

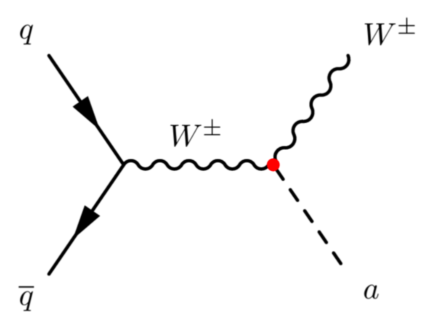
- Invisible Higgs:



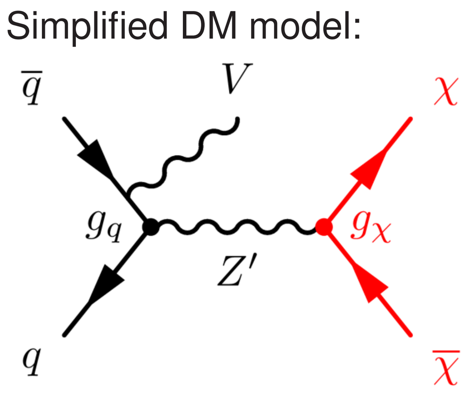
- 2HDM+a:



- ALPs:



- Simplified DM model:



SR Optimization

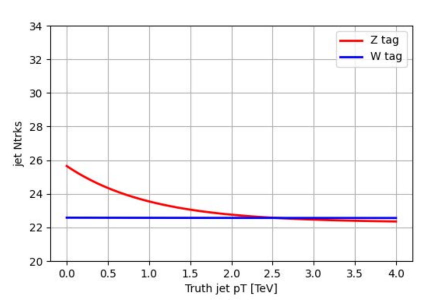
Several studies has been tried to optimize our signal region:

- Large-R Jet collections study;
- W/Z tagger study;
- Do Z-scan to reoptimize the SR;
- q/g tagging;
- CNN method;
- Additional sideband and LP regions;

We finally use 3-var tagger to get better sensitivities (SB and LP regions are added, 6 SRs):

- The three variable tagger adds a cut on N_{trks} to the mass and D_2 cuts.
- Tagging events with $N_{trks} < fit_{Ntrks}(p_T^{jet})$,where

$$fit_{Ntrks}(p_T^{jet}) = A + e^{B \cdot p_T^{jet}} + C$$



merged	resolved
E_T^{miss} trigger, jet cleaning, anti QCD, lepton veto	
$E_T^{miss} > 250GeV$	$E_T^{miss} > 150GeV$
$n_J \geq 1$ and $1 \leq n_j \leq 4$	$2 \leq n_j \leq 4$
$p_T^J > 200$ GeV	$p_T^{j_1} > 45$ GeV
	$\sum_i p_T^{j_i} \geq 120(150)$ GeV for 2 ($\geq$3) jets
$\Delta\phi(E_T^{miss}, J) > 120^\circ$	$\Delta\phi(E_T^{miss}, jj) > 120^\circ$
track $b-$jet veto outside Large-R Jet	$\Delta\phi(j_1, j_2) < 140^\circ$
	fail merged selection
isWtagged or isZtagged	$\Delta R(j_1, j_2) < 1.4$
	$65GeV \leq m_{jj} \leq 105GeV$
low purity: pass mass window, fail substructure	-

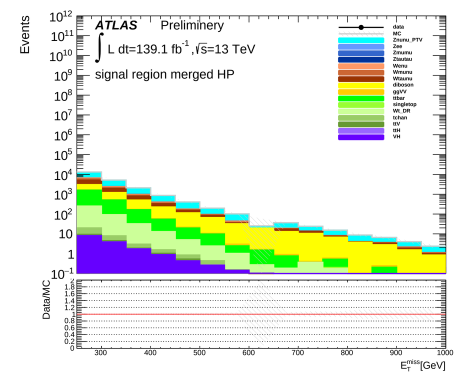
Summary of the signal region selection

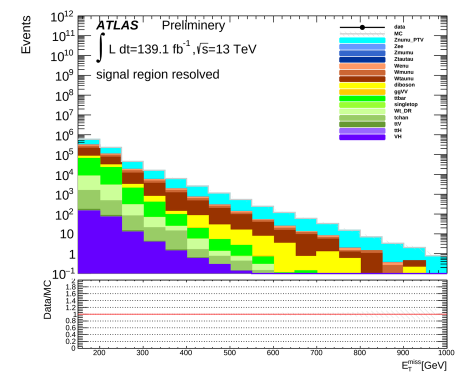
Background Estimation

- Idea

The **main backgrounds** in this analysis are V+jets processes and $t\bar{t}$.
These channels will be constrained using dedicated control regions with leptons in the final state with an strategy similar to the one in the monojet analysis and inspired with the previous iteration of this analysis.

$Z \to \nu\nu$(irreducible) : Two-lepton control region: $Z \to ee$+jets, $Z \to \mu\mu$+jets;
$W + jets$: $e\nu, \mu\nu, \tau\nu$: not reconstructed lepton, single-lepton control region: $W \to \mu\nu$+jets($W \to e\nu$+jets);
$t\bar{t}$: Semileptonic decay with misreconstructed leptons, single-lepton control region with b-tagged jets;
di-boson : not reconstructed leptons or irreducible backgrounds depending on process, small backgrounds, direct estimation by MC predictions;
Multijet : Control region selected by inverting the most effective requirement used to discriminate against multijet events:$min[\Delta\Phi(E_T^{miss}, jets)] > 20^\circ$, residual contamination can be estimated by ABCD method;





- Control Regions(24 CRs)

CR2mu0b
for estimating $Z \to \nu\nu$ contribution in SR.

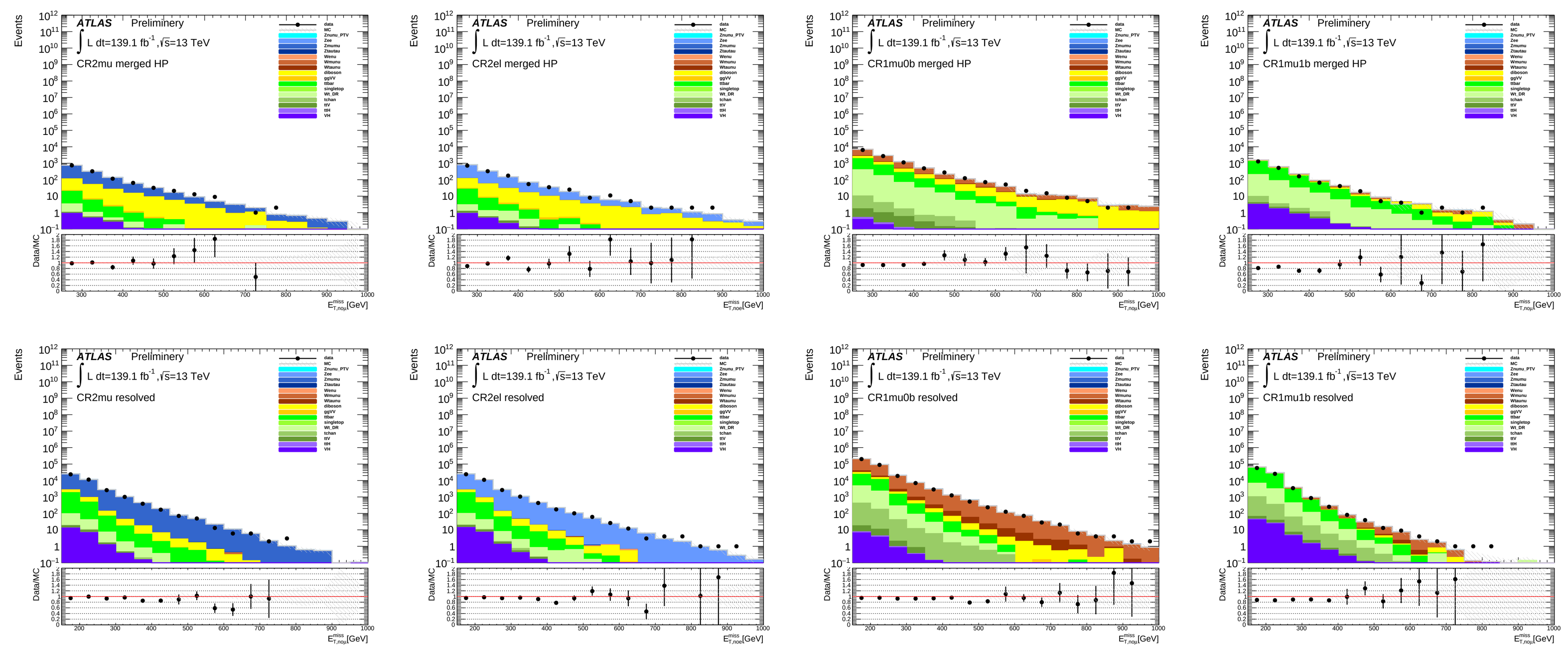
CR2el0b
for estimating $Z \to \nu\nu$ contribution in SR.

CR1mu0b
for estimating $W + jets$ contribution in SR.

CR1l1b:CR1mu1b
for estimating $t\bar{t}$ contribution in SR.

- Control region baseline selections(difference with SR selections):

CR2l0b	CR1l0b	CR1l1b
2 baseline μ/es	1 baseline μ	1 baseline μ
2 signal μ/es	1 signal μ	1 signal μ
$M_{ll} \in [66, 116]GeV$	$M_{l\nu}^T \in [30, 100]GeV$	$M_{l\nu}^T \in [30, 100]GeV$
$E_{T,nol}^{miss} > 150/250GeV$		



Additional analysis regions that can be used to validate and constrain backgrounds is the mass sideband regions and low purity regions:

- The mass-sidebands cover the range between the mass window upper edge and 500 GeV while all the other cuts keep the same with mass window selection.
- The low purity regions, which require all the event should pass full set of merged selection except Large-R jet substructure cuts , are supplementary regions to the merged high purity region.

Limit Setting

- Fitting strategy

We uses various Control Regions to constrain the most important backgrounds:

Region	Enriched in	p_T^{recoil}	Comment
SR	$Z(\nu\nu)$ + jets, W + jets	E_T^{miss}	
CR2mu	$Z(\mu\mu)$ + jets	$E_{T,nomu}^{miss}$	proxy for $p_T(Z)$
CR2el	$Z(ee)$ + jets	$E_{T,noel}^{miss}$	proxy for $p_T(Z)$
CR1mu0b	$W(\mu\nu)$ + jets	$E_{T,nomu}^{miss}$	proxy for $p_T(W)$
CR1mu1b	$t\bar{t}$	$E_{T,noel}^{miss}$	proxy for $p_T(W)$ from the semi-leptonic $t\bar{t}$

The observable p_T^{recoil} used in the simultaneous fit for the background estimation, for each of the regions used in the fit.

the likelihood $\mathcal{L}$ is defined as:

$$\mathcal{L}(\mu, \kappa, \theta) = \prod_r \prod_i \text{Poisson}\left(N_{ri}^{obs} | N_{ri}^{sig}(\theta) + N_{ri}^{bkg}(\kappa, \theta)\right) f_{constr}(\theta), \quad (1)$$

$$\text{where:} N_{ri}^{bkg} = \kappa^Z \left(N_{ri}^{Z(\nu\nu)\text{+jets}} + N_{ri}^{Z(\mu\mu)\text{+jets}} + N_{ri}^{Z(ee)\text{+jets}} + N_{ri}^{Z(\tau\tau)\text{+jets}}\right)$$
$$+ \kappa^W \left(N_{ri}^{W(\mu\nu)\text{+jets}} + N_{ri}^{W(e\nu)\text{+jets}} + N_{ri}^{W(\tau\nu)\text{+jets}}\right) \quad (2)$$
$$+ \kappa^t \left(N_{ri}^{t\bar{t}}\right) + N_{ri}^{\text{other}} + N_{ri}^{\text{Multi-jet}}.$$

A normalisation factor is computed for each of these backgrounds. We run the fit separately for the merged and the resolved topologies:

Process	Nominal normalisation	κ - factor
$Z \to \nu\nu$ + jets	MC	κ^Z
$W \to \tau\nu$ + jets	MC	κ^W
$W \to \mu\nu$ + jets	MC	κ^W
$W \to e\nu$ + jets	MC	κ^W
$Z \to \tau\tau$ + jets	MC	κ^Z
$Z \to \mu\mu$ + jets	MC	κ^Z
$Z \to ee$ + jets	MC	κ^Z
$t\bar{t}$ and single-t	MC	κ^t
diboson	MC	-
multi-jet	ABCD method	-

Source of the nominal prediction on each of the background processes in the signal region and applied normalisation factor. κ represents the normalisation factor.

- Systematic uncertainties

Systematic uncertainty will be included in the fit ;
Dividing systematics into *experimental* and *theoretical* (or modeling) uncertainties;
Experimental systematics:
Luminosity: uncertainty on the total integrated luminosity
PRW_DATASF: uncertainty on data SF used for computation pileup reweighting
Small-R jet: JESJER, EtaIntercalibration, Mass, flavor composition ,bjet, etc
Track jet: Flavour tagging
Large-R jet: JER , Mass resolution(JMR), D2 resolution , Mass , pT , D2 scale etc
Electron: reconstruction, ID ,energy resolution, isolation
Muon: reconstruction, ID ,energy resolution, isolation
Trigger: MET trigger electron trigger
Theoretical systematics(Currently only consider the W/Z modeling):
QCD: [MUR,MUF]∈{ [0.5,0.5], [0.5,1], [1,0.5], [2,1], [2,2], [2,1],[1,1](nominal)}
PDF: 101 components, 261000(nominal)+261001˜261100
α_S: 270000(up)+269000(down)
Generator tune:13000(CT14nnlo), 25300(MMHTnnlo), 261000(NNPDF,nominal)

The final fit values of the norm factors are listed in below table:

Norm Factor	Fit Value
κ^Z	1.000 ± 0.004
κ^W	0.979 ± 0.004
$\kappa^{t\bar{t}}$	0.845 ± 0.010

Final fit values (invH Exclusion, combined topologies, Asimov) of the norm factors

The $t\bar{t}$ modeling is bad, hence a truth level reweighting procedure has been performed before the fit.

invH Preliminery Results

The 95%CL upper limit on μ_{sig} is given in Table below for the invisible Higgs models for the combined topologies (default). The limits obtained from the merged and resolved topologies are also shown. The Asimov dataset is used in the SRs:

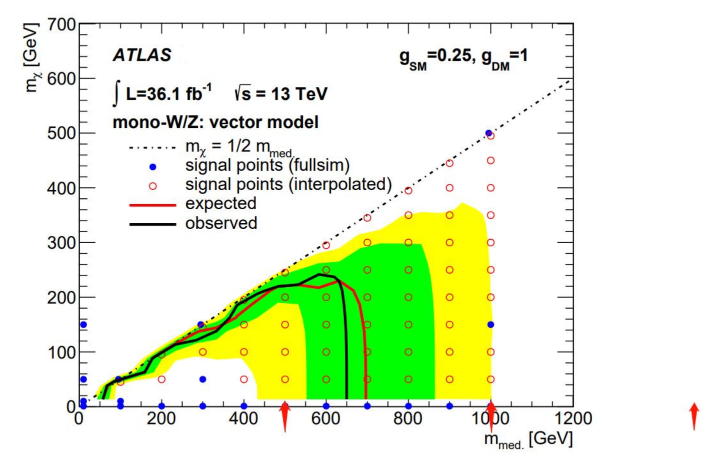
Combined topologies	Resolved topology	Merged topology
0.242	0.610	0.293

The 95% CL upper limit on μ_{sig} for the Invisible Higgs.

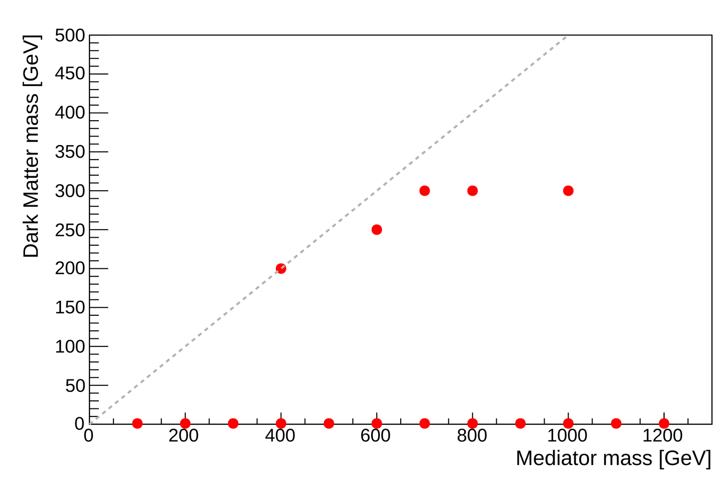
Note that previous iteration of this analysis get the expected upper limit of invH is 0.58.

DM model Preliminery Results

Results of previous iteration of this analysis:

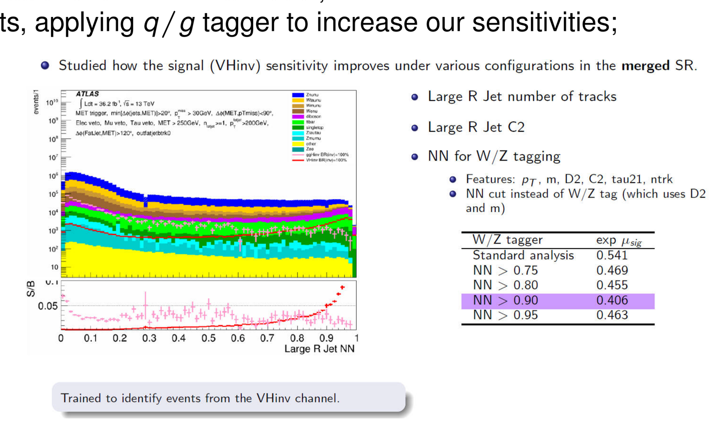


Red arrows represents test points in this analysis, we can estimate the expected limit line by those points and request generate new points to finish the 2D limit:



Future works

- Adding more modeling uncertainties to main backgrounds(V+jets,ttbar and di-boson);
- Give 2D interpretation for Simplified DM model;
- Give interpretations for 2HDM+a model;
- If time permits, applying q/g tagger to increase our sensitivities;



- ALPs will not included in this paper due to person power, can be done by RECAST.