Search for dark matter particles in events with a hadronically decaying vector boson and missing transverse momentum in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

Danijela Bogavac[1], Sergio Gonzalez[1], Mario Martinez[1], Johannes Balz[2], Duc Bao Ta[2], Jiangliu Hong[3], Xiangke Zhang[3], Ning Zhou[3] Timothy Michael Knight[4]

[1]IFAE-Barcelona, [2]Universität Mainz, [3]Shanghai Jiao Tong University, [4]University of Toronto

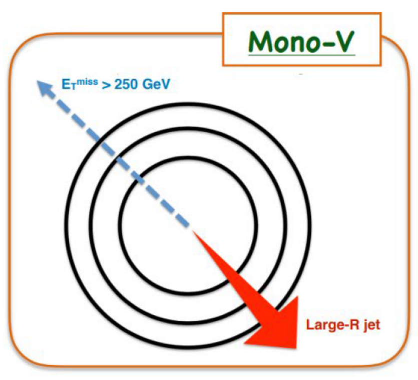
atlas-phys-exotics-monov-hadronic@cern.ch

Abstract

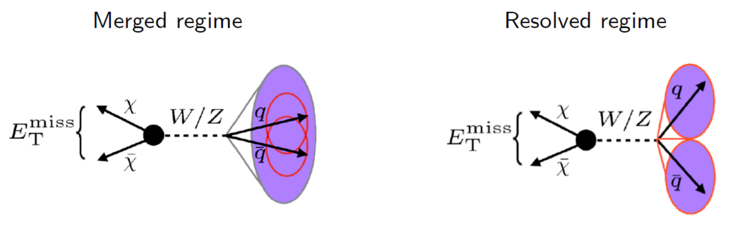
Search for dark matter particles produced in association with a vector boson (V=W, Z) reconstructed in its hadronic final state. The analysis strategy depends on the boost of the vector boson in the final state. At low transverse momentum, the dijet system from the W/Z decay can be reconstructed using jets with cone size, in the eta-phi, space of 0.4 units. The invariant mass of the dijet system allows discriminating the events corresponding to the resonant production of a W/Z boson. At high transverse momentum, the products of the W/Z decays merge, making impossible a straightforward identification of the dijet system. In this case, the analysis strategy is based on the identification of broad jets in the event, with a cone size of about 1.0 units, and the use of jet substructure quantities to isolate jets with an internal structure consistent with the decay of a massive particle. 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.

Analysis Overview

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

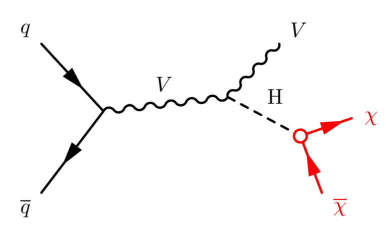


The final state of the analysed signal scenarios contains dark matter recoiling against a vector boson that is consequently often highly boosted, since the missing transverse momentum E_T^{miss} attributed to dark matter particles is of the same order as the vector boson's transverse momentum p_T. The double-pronged hadronic decay of the vector boson is searched for within a large-R jet with radius parameter $R = 1.0$. In addition to this so-called merged regime, a resolved regime is considered in this search, where the separation between the decay products is sufficiently large to be reconstructed as two separate small-R jets with a radius parameter $R = 0.4$.

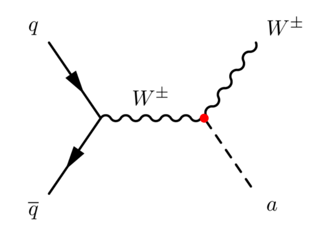


Interpretations with multiple signal models:

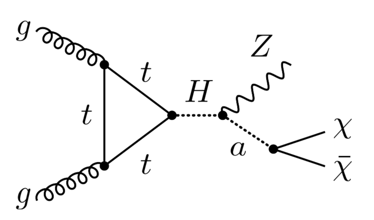
Invisible Higgs



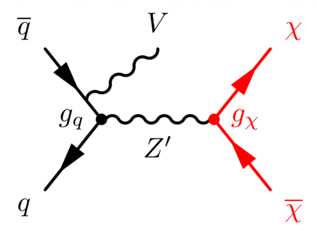
ALPs



2HDM+a



DM axial-vector mediator model

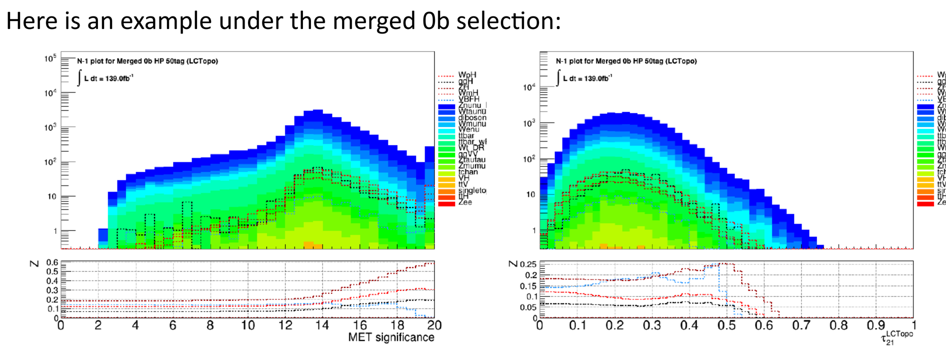


SR reoptimization

- In order to reoptimize the SR we generate N-1 plots and do a Z-scan:

$$Z = \frac{S}{\sqrt{B+(B\cdot\sigma_B)^2}}$$ using from the previous paper ($\sigma_B = 9\%$)

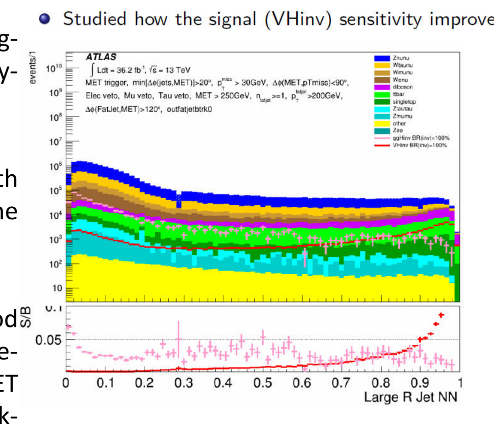
- Here is an example under the merged 0b selection:



quark/gluon tagging

- We want to explore the possiblility to use q/g tagger:Signal processes contain a hadronically decaying vector boson $V(qq)\ H(inv)$:
  - expect two quark jets compatible with V decay dijet mass ≈ W/Z mass or one large R with mass ≈ W/Z mass.
- Number of tracks associated to jet is a very good quark gluon discriminator(if not the best) especially at high jet p_T. Already at lower MET VH(inv) has clearly fewer tracks than main backgrounds.the difference gets even larger at higher MET, could reject large portion of Znunu and Wtaunu background with a cut on nTracks while keeping most of VH(inv) signal.

- Studied how the signal (VHinv) sensitivity improves under various configurations in the **merged** SR.



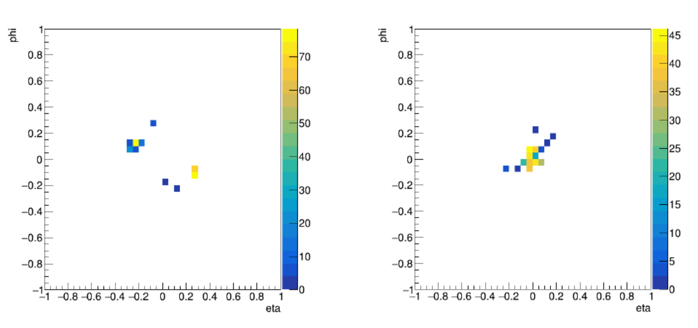
Trained to identify events from the VHinv channel.

- Large R Jet number of tracks
- Large R Jet C2
- NN for W/Z tagging
  - Features: p_T, m, D2, C2, tau21, ntrk
  - NN cut instead of W/Z tag (which uses D2 and m)

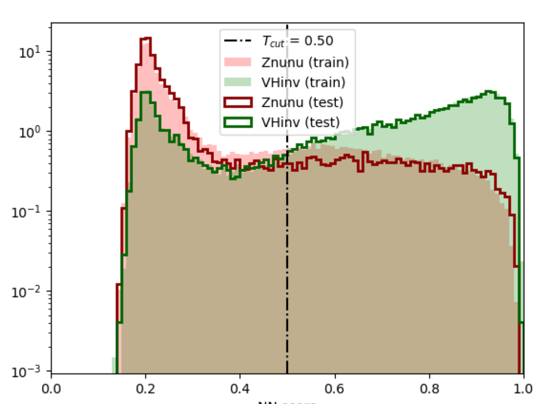
W/Z tagger	exp μ_{sig}
Standard analysis	0.541
NN > 0.75	0.469
NN > 0.80	0.455
NN > 0.90	0.406
NN > 0.95	0.463

Deep Learning - CNN

- We also train a CNN to discriminate images from the Jet p_T-clusters between VHinv and Znunu:



Most signal image in VHinv   Most bkg image in Znunu

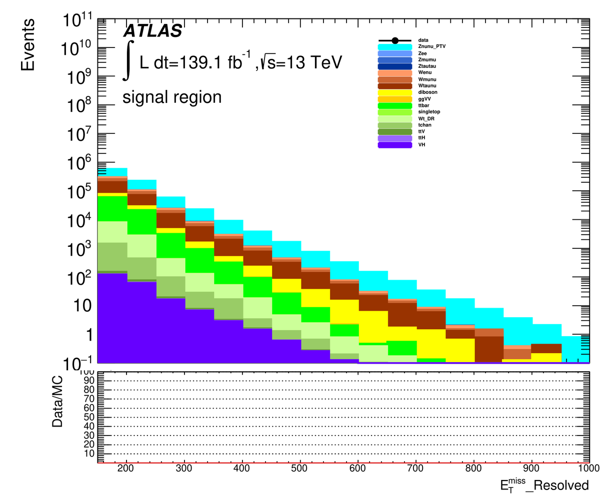


Background Estimation

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.

  - $Z \rightarrow \nu\nu$(irreducible): Two-lepton control region: Zee+jets, $Z\mu\mu$+jets
  - $W + jets$: $e\nu$, $\mu\nu$, $\tau\nu$:not reconstructed lepton, Single-lepton control region: W$\mu\nu$+jets(Wenu+jets)
  - $t\bar{t}$: Semileptonic decay with misreconstructed leptons, Single-lepton control region with b-tagged jets
  - Multijet:Control region selected by inverting the most effective requirement used to discriminate against multijet events:$min[\Delta\Phi(E_T^{miss}, jets)] > 20^o$
  - Jet mass side-band control region: used in the previous analysis to extract a normalization scale factor for the multijet shape



Control Regions

CR2mu0b

Estimating $Z \rightarrow \nu\nu$ contribution.

CR2el0b

Estimating $Z \rightarrow \nu\nu$ contribution.

CR1mu0b

Estimating $W + jets$ contribution.

CR1mu1b

Estimating Top contribution.

- Control region selections:

CR2l0b	CR1l0b	CR1l1b
Preselection	Preselection	Preselection
2 baseline μ/es	1 baseline μ	1 baseline μ
2 signal μ/es	1 signal μ	1 signal μ
$M_{ll} \in [66, 116] GeV$	$M_{l\nu}^T \in [30, 100] GeV$	$M_{l\nu}^T \in [30, 100] GeV$
$E_{T,nol}^{miss} > 150/250 GeV$		
$\geq 1J_{LCTopo}/ \geq 2jets$		
$\Delta\phi(J/jj, E_{T,nol}^{miss}) > 120^o$		
$\Delta\phi(j_0, j_1) < 140^o$(only in resolved)		
$\Sigma p_T^{j_i} > 120/150 GeVfor2/ \geq 3jets$(only in resolved)		
none	b-veto	$\geq 1b_{jet}$
W/Z tagger & W/Z mass window		

- 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.

Limit Setting

Fitting strategy

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

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

where

$$\begin{aligned} N_{ri}^{\text{bkg}} = \kappa^V (N_{ri}^{Z(\nu\nu)\text{+jets}} &+ N_{ri}^{W(\mu\nu)\text{+jets}} + N_{ri}^{W(e\nu)\text{+jets}} + N_{ri}^{W(\tau\nu)\text{+jets}} \\ &+ N_{ri}^{Z(\mu\mu)\text{+jets}} + N_{ri}^{Z(ee)\text{+jets}} + N_{ri}^{Z(\tau\tau)\text{+jets}}) \\ &+ \kappa^t (N_{ri}^{t\bar{t},\text{single-}t}) + N_{ri}^{\text{diboson}} + N_{ri}^{\text{Multi-jet}}. \end{aligned} \quad (2)$$

Process	Nominal normalisation	κ - factor
$Z \rightarrow \nu\nu$ + jets	MC	κ^Z
$W \rightarrow \tau\nu$ + jets	MC	κ^W
$W \rightarrow \mu\nu$ + jets	MC	κ^W
$W \rightarrow e\nu$ + jets	MC	κ^W
$Z \rightarrow \tau\tau$ + jets	MC	κ^Z
$Z \rightarrow \mu\mu$ + jets	MC	κ^Z
$Z \rightarrow ee$ + 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.

$36.1fb^{-1}$ test results compare to previous analysis(DM axial-vector mediator model)