Reconstruction of the transverse momentum of a dark matter mediator using a neural network in regression mode

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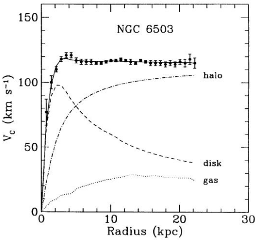
August 25, 2021

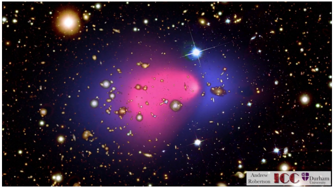
Dark Matter (DM)

Different kind of matter that conforms aprox. 27% of total Universe density. Does not interact with ordinary matter, but presents gravitational effects.

Observational evidence:

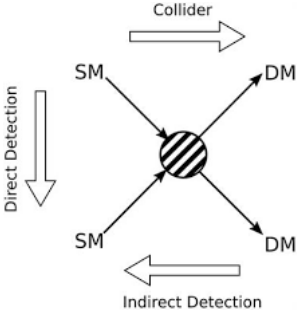
- Velocity dispersions in Coma cluster. Virial Theorem (Zwicky, 1933)
- Galaxy rotation curves. Differences between newtonian dynamics and cosmological observations.
- Gravitational lensing. Mass concentration in apparently empty places.
- Cosmic microwave background. Temperature anisotropies.





Dark Matter searches

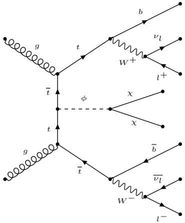
- Direct search: detect on Earth particles that have interacted with DM.
- Indirect search: find DM in outer space that interacts or decays.
- **Collider search**: produce DM particles through proton-proton collisions.



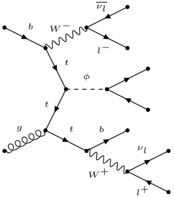
Here we aim for Dark Matter searches in colliders, like the ones being carried at LHC.

Dark Matter production

We focus on DM production searches involving two pair of top quarks or one top quark.
Considering semileptonic decays of W bosons.
Model of Dark Matter: massive mediator ϕ that can be scalar or pseudoscalar.
Couples to a $t\bar{t}$ pair and decays in two Dark Matter fermions χ.



$t\bar{t}$ + DM process



single top + DM process

These are searches of interest at CMS and ATLAS.

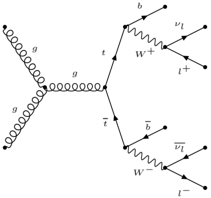
Solution of $t\bar{t}$ system

In a $t\bar{t}$ standard (without DM) process it is possible to solve analytically for neutrino momenta $(p_\nu, p_{\overline{\nu}})$, using the missing transverse energy $(\not{E}_x, \not{E}_y)$ and the constraints in top quark and W boson decays (we measure b quarks and leptons).

However, the introduction of invisible DM adds variables to the system and no constraints, making it unsolvable in an analytical way.

In single top + DM process we also lose one constraint on a top quark.

$$
\begin{aligned}
\not{E}_x &= p_{\nu_x} + p_{\bar{\nu}_x}, \\
\not{E}_y &= p_{\nu_y} + p_{\bar{\nu}_y}, \\
m^2_{W^+} &= (E_{\ell^+} + E_\nu)^2 - (p_{\ell^+_x} + p_{\nu_x})^2, \\
&\quad -(p_{\ell^+_y} + p_{\nu_y})^2 - (p_{\ell^+_z} + p_{\nu_z})^2, \\
m^2_{W^-} &= (E_{\ell^-} + E_{\bar{\nu}})^2 - (p_{\ell^-_x} + p_{\bar{\nu}_x})^2, \\
&\quad -(p_{\ell^-_y} + p_{\bar{\nu}_y})^2 - (p_{\ell^-_z} + p_{\bar{\nu}_z})^2, \\
m^2_t &= (E_b + E_{\ell^+} + E_\nu)^2 - (p_{b_x} + p_{\ell^+_x} + p_{\nu_x})^2, \\
&\quad -(p_{b_y} + p_{\ell^+_y} + p_{\nu_y})^2 - (p_{b_z} + p_{\ell^+_z} + p_{\nu_z})^2, \\
m^2_{\bar{t}} &= (E_{\bar{b}} + E_{\ell^-} + E_{\bar{\nu}})^2 - (p_{\bar{b}_x} + p_{\ell^-_x} + p_{\bar{\nu}_x})^2, \\
&\quad -(p_{\bar{b}_y} + p_{\ell^-_y} + p_{\bar{\nu}_y})^2 - (p_{\bar{b}_z} + p_{\ell^-_z} + p_{\bar{\nu}_z})^2.
\end{aligned}
$$



Objectives

Study the aplication of Artificial Neural Networks (ANN) to predict the momentum of a DM particle.

Two main goals:

1. Check if an ANN in regression mode is capable of predicting the transverse momentum of the DM mediator ϕ in $t\bar{t}$ + DM events.
2. Analize if an ANN in regression mode can estimate the transverse momentum of the ϕ mediator in single top + DM events.

Set up

Study performed using simulated data of proton-proton collisions at 13 TeV (Madgraph)

	$t\bar{t}$ + DM	single top + DM
Number of events (scalar)	4,2 million	3 million
Number of events (pseudoscalar)	3,2 million	2,8 million
Mediator masses	50-500 GeV (intervals of 50)	100-500 GeV (intervals of 50) + 1000 GeV

ANN and data have been managed using TMVA (Toolkit for Multivariate Analysis): ROOT framework that provides machine learning techniques for multivariate problems of calssification and regression, oriented to high energy physics.

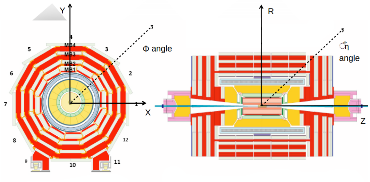
Architecture

Variables involved in training:

- leptons: p_T, ϕ, η
- b quarks: p_T, ϕ, η
- missing energy transverse: magnitude, ϕ

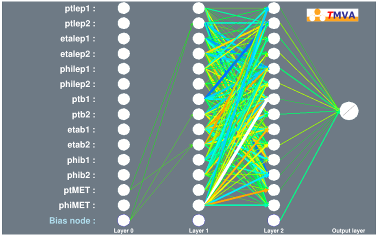
TOTAL:

- $t\bar{t}$+DM: 14 variables.
- single top+DM: 11 variables (only 1 b quark).



ANN architecture: two hidden layers of N neurons.

Also experimented with other architectures.



Figures of merit

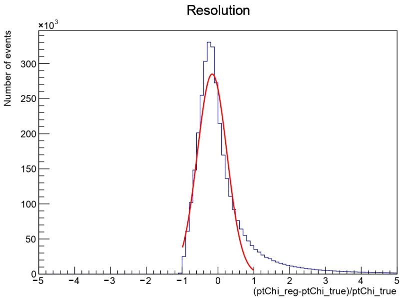
Performance of ANN measured using two main results:

- Resolution histogram: plot the resolution and fit to a gaussian in the bulk of the distribution.

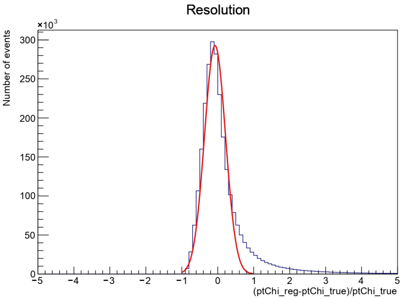
$$\text{Resolution} = \frac{p_{\phi,reg} - p_{\phi,true}}{p_{\phi,true}}$$

- Real ϕ momentum vs. prediction histogram: allows to compare the real and predicted distributions for ϕ momentum.

$t\bar{t}$ + DM. Resolution



(a) Scalar mediator.
$\mu_s = -0.1626 \pm 0.0003$
$\sigma_s = 0.4118 \pm 0.0003$



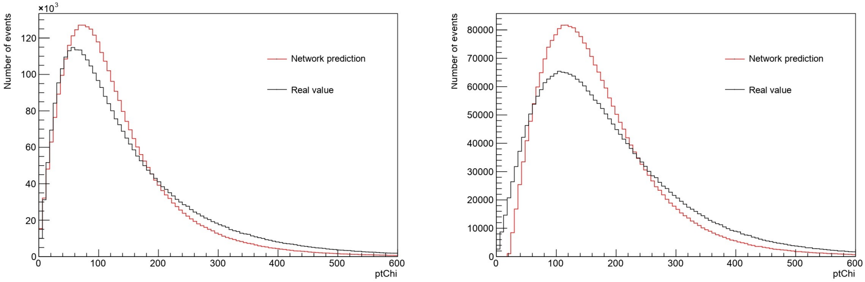
(b) Pseudoescalar mediator.
$\mu_{ps} = (-7.59 \pm 0.03) \cdot 10^{-2}$
$\sigma_{ps} = 0.2918 \pm 0.0002$

Fitting curves in red correspond to gaussian distributions, of mean and sigma indicated above.

Tail in the distributions corresponds to events with low DM mediator momentum $\longrightarrow$ the ANN overestimates the transverse momentum.

Better resolution for pseudoscalar $\longrightarrow$ angular structure of mediator.

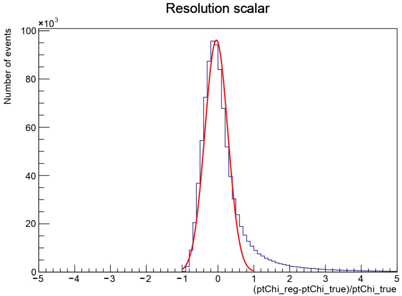
$t\bar{t}$ + DM. Distribution



(a) Scalar mediator. (b) Pseudoescalar mediator.

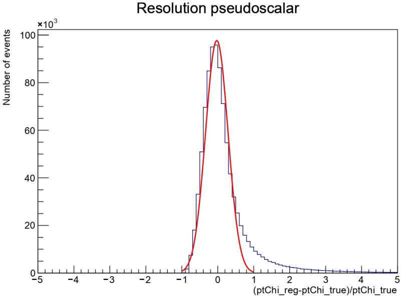
The ANN reproduces the real distribution of the DM mediator momentum.

Single top + DM. Resolution



(a) Scalar mediator.

$$\mu_s = (-4.60 \pm 0.05) \cdot 10^{-2}$$
$$\sigma_s = 0.3023 \pm 0.0002$$



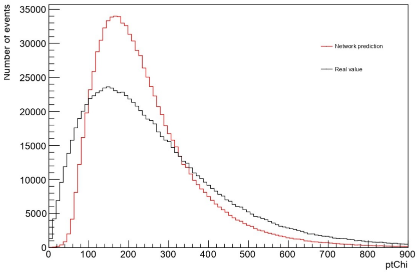
(b) Pseudoescalar mediator.

$$\mu_{ps} = (-2.72 \pm 0.05) \cdot 10^{-2}$$
$$\sigma_{ps} = 0.2973 \pm 0.0002$$

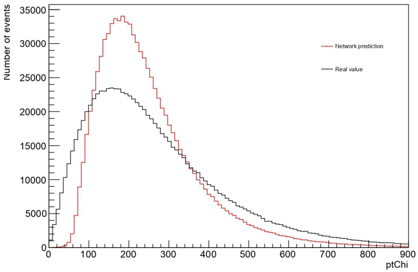
Fitting curves in red correspond to gaussian distributions, of mean and sigma indicated above.

Again the tail in the distributions corresponds to low DM mediator momentum $\longrightarrow$ the ANN overestimates the transverse momentum.

Single top + DM. Distribution



(a) Scalar mediator.



(b) Pseudoescalar mediator.

The ANN reproduces the real distribution of the DM mediator momentum.

Difficulties for low momentum events (<50 GeV).

Conclusions

1. A study to use an ANN to predict the transverse momentum of a mediator of Dark Matter has been presented.
2. The study shows that the reconstruction is possible for both $t\bar{t}$ + DM and single top + DM models with a resolution of about 30-40%.
3. The DM mediator momentum is relevant in itself but could also be useful to discriminate signal from background.
4. The performance of the ANN is worse for cases with low Dark Matter mediator momentum (more frequent in low mass models).

End

Thank you for listening!

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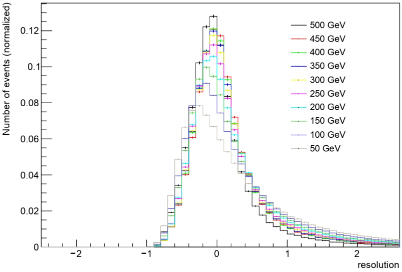
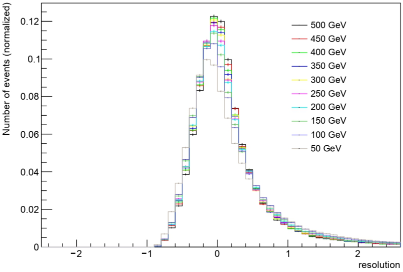
Backup

$t\bar{t}$ + DM

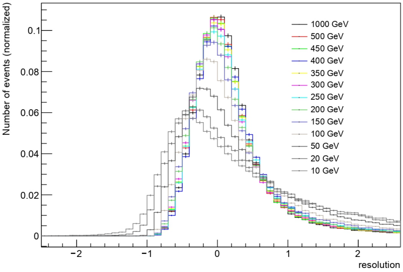


(a) Scalar.

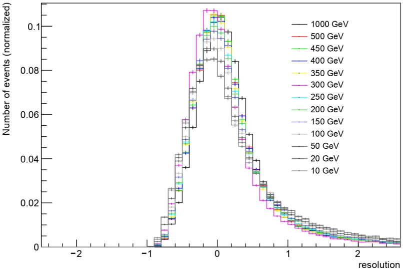


(b) Pseudoescalar.

Single top + DM



(a) Scalar.



(b) Pseudoescalar.

Events in tail