Search for Dark Matter using Artificial intelligence at the LHC

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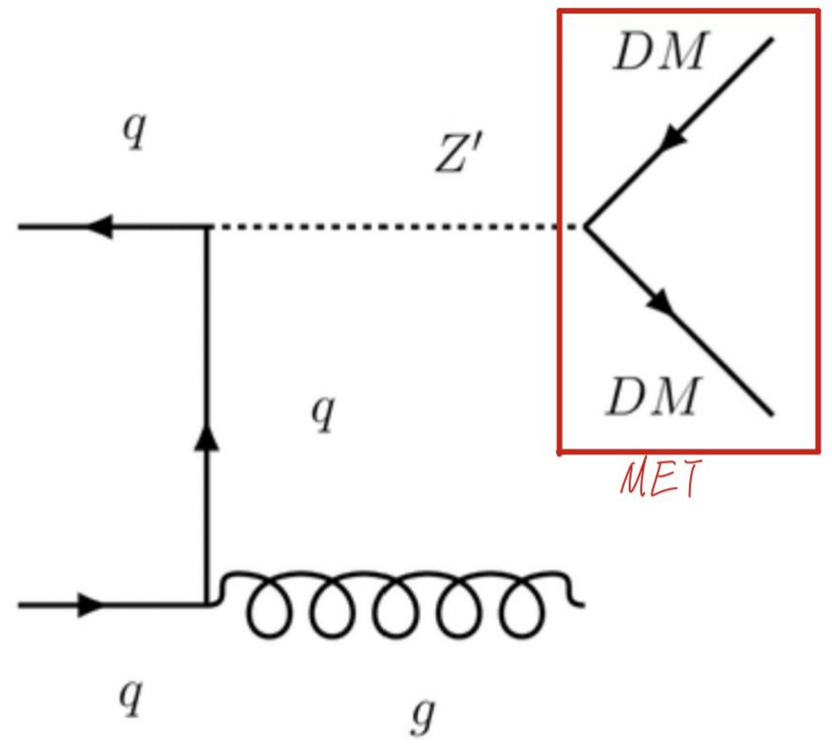
Abstract

The nature of dark matter (DM) is one of the most important open questions in modern physics. Scientists at the Large Hadron Collider (LHC) at CERN in Geneva are studying the proton-proton collisions delivered by the accelerator in the attempt to shed light on this mystery. This project aims to use modern machine learning (ML) tools to improve the searches for DM performed with the data collected by the Compact Muon Solenoid (CMS) experiment.

Search for Dark Matter at the LHC

The standard model (SM) of particle physics provides a very successful description of the fundamental particles and the forces that regulate their interactions. If non-gravitational interaction exists between DM particles and SM particles, DM can be produced at the LHC by colliding protons at high energies

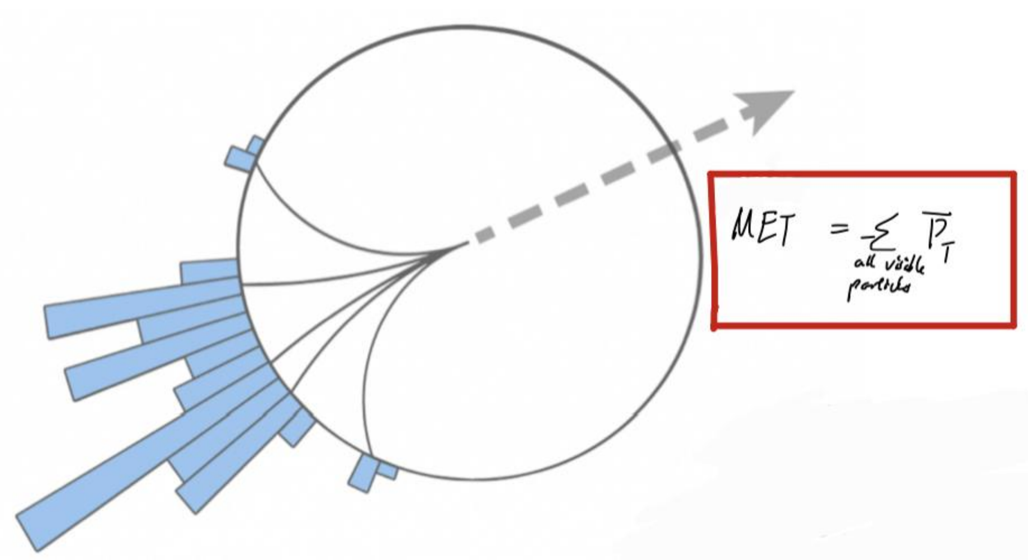


Once produced, since they are weakly interacting, DM particles would not interact with the CMS detector. However, they can manifest themselves as an imbalance in the transverse momentum, if produced in association with visible particles. At CMS, an entire program has been built on searches for DM in events with large missing transverse momentum (MET).

This project aims to improve the accuracy of MET measurements using ML techniques.

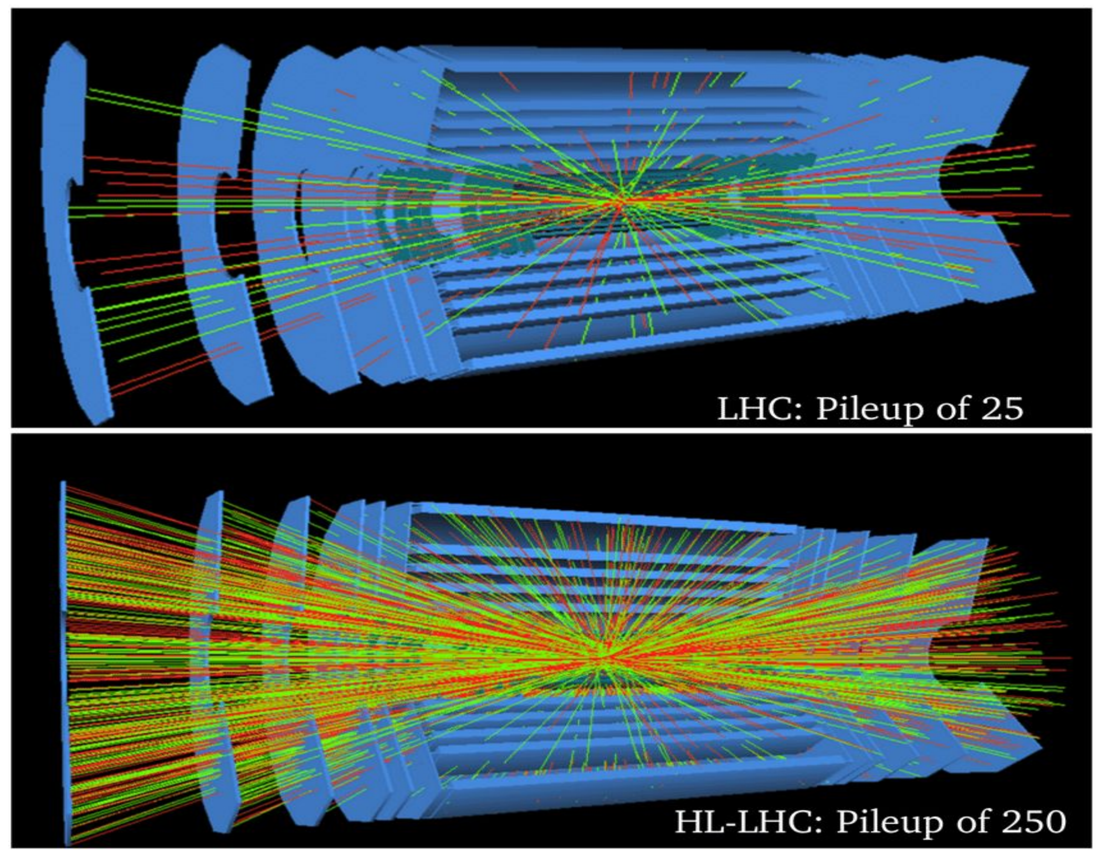
Missing Transverse Momentum

Relying on one of the fundamental laws of physics, the conservation of momentum, we know that, if the transverse momentum of all the visible particles produced in a collision is different from the total transverse momentum before the collision, then some other undetected particle must have been produced. We can therefore derive an equation that defines MET as the portion of the total transverse momentum carried away by the production of undetected particles:



Pileup Interactions

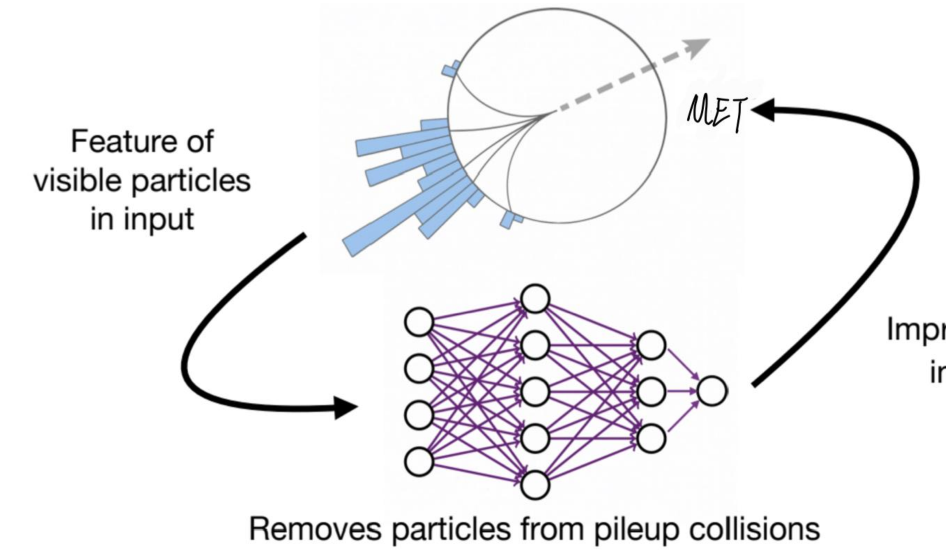
At the LHC, protons are collided in bunches, producing multiple interactions per bunch crossing. This effect is called pile-up.



The ability to distinguish particles produced in the primary interaction from the spurious particles produced in the secondary interactions is key to the CMS physics program.

Machine Learning for MET Reconstruction

The reconstruction of the MET is affected by the presence of particles from pile-up. A probability to be generated in the primary interaction can be assigned to each particle to improve the MET reconstruction. Cutting-edge ML techniques can be used to predict such a probability.

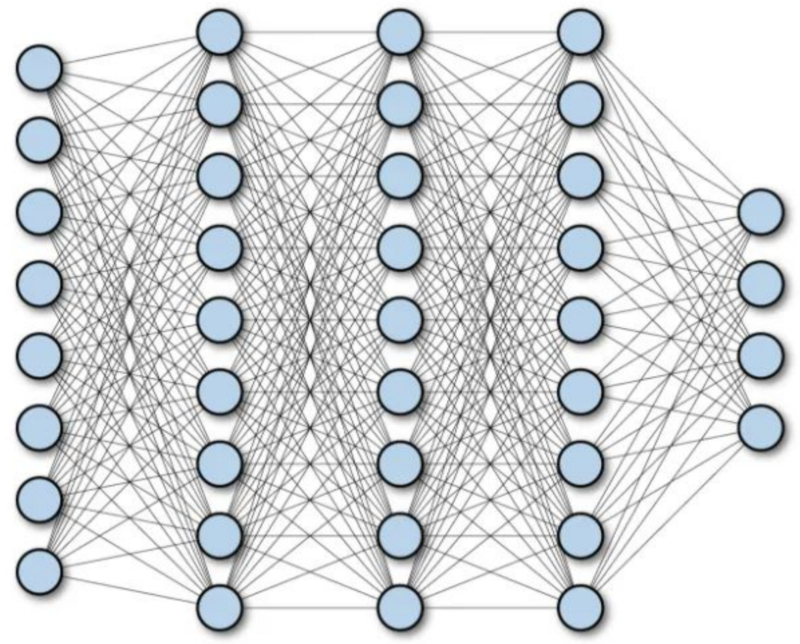


$$MET = -\sum_{\text{all visible particles}} \alpha \, \vec{p}_T$$

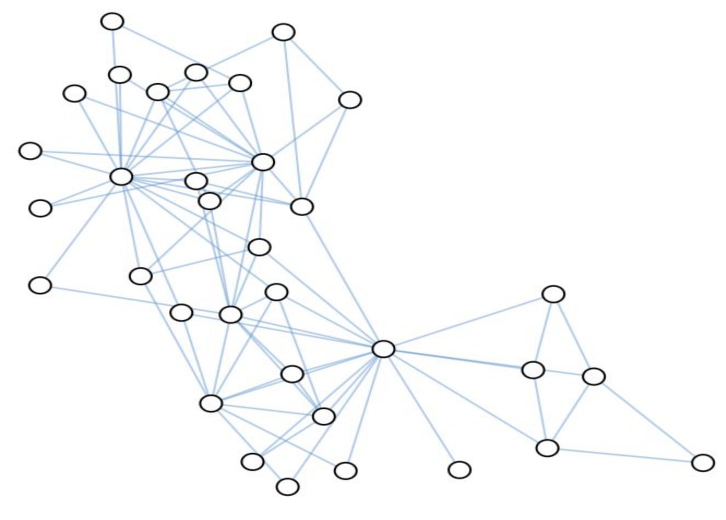
(probabilistic weight: α)

In CMS, two different ML algorithms are used for such a scope, graph neural networks (GNN) and fully connected neural networks (FCNN)

FCNNs optimally operate on regular data with arbitrary size.



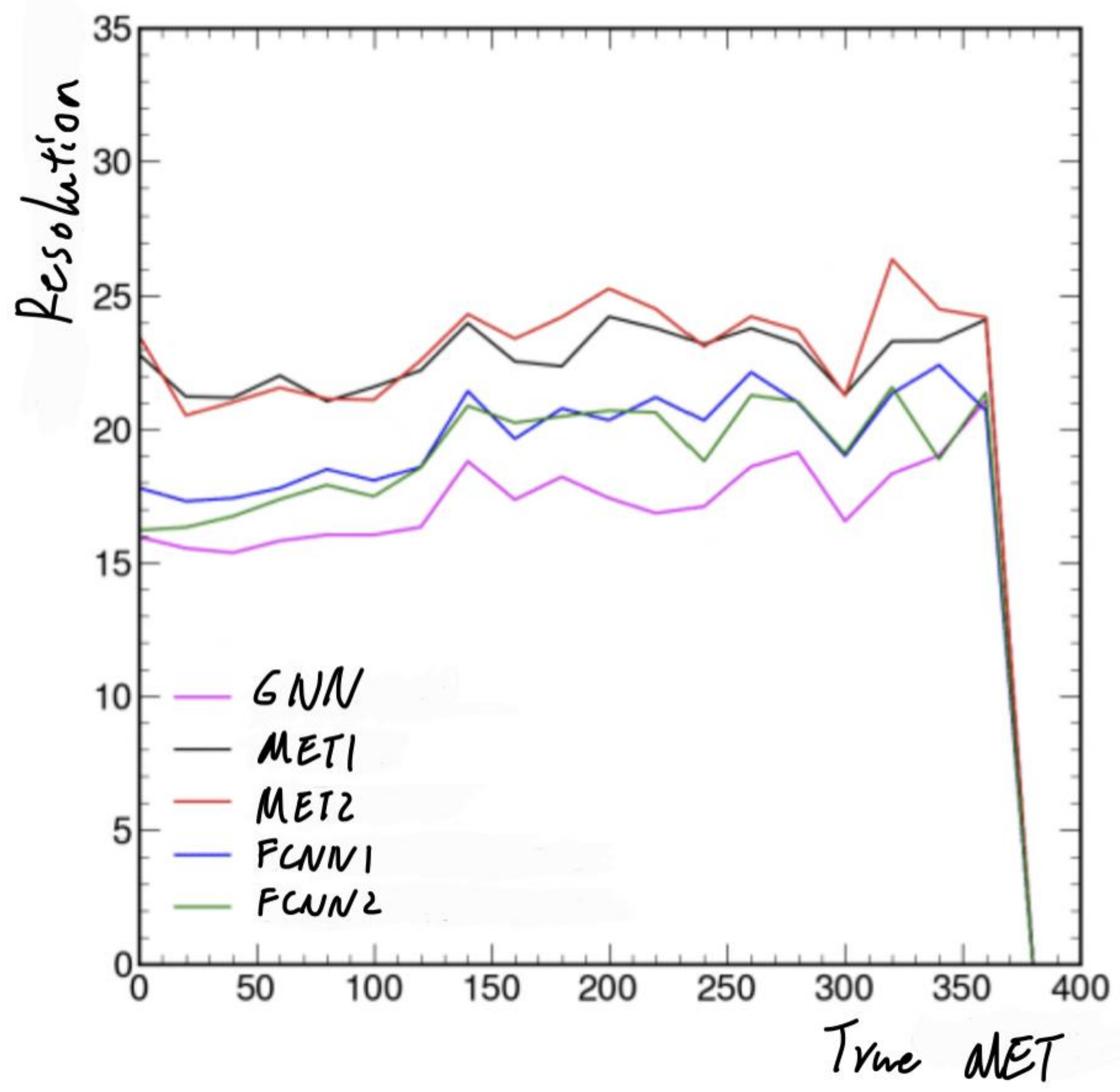
GNNs optimally operate on data that is most naturally represented as a graph. Such data often show no regular structure.



Results

The different algorithm's performances are tested by comparing their resolution where the resolution is given as follows

$$\text{Resolution} = |\text{MET} - \text{True MET}|$$



Conclusions

The utilization of ML techniques show promising results when used for MET reconstruction. They offer a significant improvement in resolution, which in turn will improve the results of those searches for invisible particles that employ MET as the main physics observable, like searches for DM.