Search for dark matter with the CMS detector of the LHC at CERN

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Abstract

Despite the discovery of the Higgs boson in 2012, some questions remain open. Thus the introduction of new models that help to explain the remaining pieces is needed. For this purpose, improving the actual particle identification methods, like b tagging, are necessary since b quarks could be the entry to new physics because of their properties. The study aims to correct the double-b tagging efficiency measured in Monte Carlo using the scale factors to match the data efficiency, where the efficiency measured is defined as the number of events that satisfy the double-b tagging requirement divided by the total number of events. In this framework, we study the impact of the scale factor on the reconstruction of a fat jet using the double tagging algorithm on the frame of dark matter searches; considering the simplified model for dark matter called mono-Higgs, we could observe a pair of dark matter particles coupled to a new Z' boson which could decay into a Higgs boson in the dark sector. Furthermore, if this Higgs boson is in the light state of the dark sector, it could decay into standard model particles visible as a pair of boosted b quarks. In this context, we define the scale factors using our double tagging since they are specific to this analysis. The scale factors needed are obtained with data taken during Run II (from 2016 to 2018) of the LHC with the CMS Experiment at CERN and MC events simulating the same conditions.

Introduction

Although the success of the Standard Model, some questions remain open: Mass hierarchy, Neutrino mass, Baryonic asymmetry, and Dark matter. To try to solve them, the Large Hadron Collider (LHC) at CERN was built to accelerate protons or ions and collide at a speed close to light speed at four points around the machine.
At one of these points is the Compact Muon Solenoid (CMS), a multipurpose experiment to detect the particles generated in a proton-proton collision at the LHC. It is designed cylindrically with 15 meters in diameter and 21.6 in length. One of its main features is a superconductor solenoid with a 4T magnetic field, which helps to identify the detected particles.

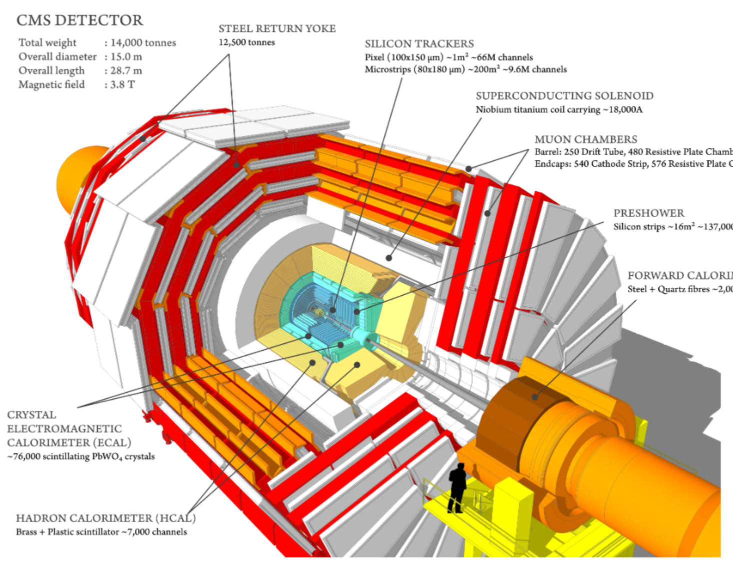

Figure 1: CMS components [1].

The CMS is made up of sub-detectors as shown in Fig 1: The tracking system, electromagnetic calorimeter (ECAL), hadron calorimeter (HCAL), the superconducting solenoid, and the muon detectors. For jet reconstruction and identification, the HCAL sub-detector is vital because it can measure energy and direction from flow jets. The HCAL sub-system comprises three parts: the barrel, the endcap, and the forward calorimeter. It is made of brass and scintillator layers, which detect the tracks passing through the detector and convert them into an electrical signal to obtain the energy.

Jet reconstruction and identification

Jets can be reconstructed using different algorithms which associate clusters of particles close to each other with jets in an iterative process. Examples are the Cambridge/Aachen and anti-kt sequential recombination algorithms. In this study, to reconstruct the jets, we use the anti-kT algorithm [2] with a distance parameter of 1.5 (AK15 for fat jets), which uses the distance, the transverse momentum, rapidity, and azimuth angle of the particles with the radius parameter R.

To identify the jet, we used the DeepAK15 algorithm, which returns probabilities for a jet from the decay of different resonances, in this case, from $b\bar{b}$ quarks. It is based on Machine Learning techniques, using as inputs both the list of particle flow candidates that comprise the jet, and the list of secondary vertices contained in it. We can compose these probabilities into taggers to define our double-b tagger.

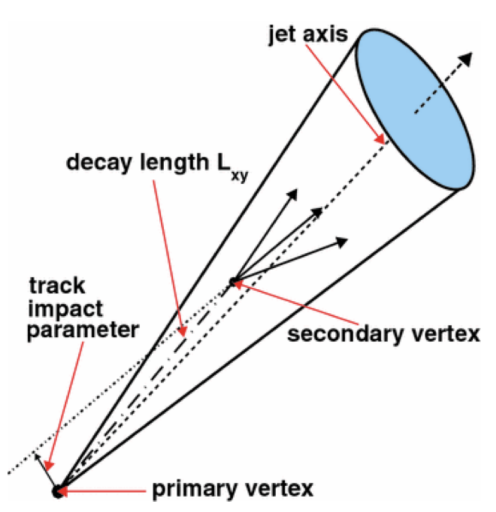

Figure 2: Second vertex from a fat jet.

B tagging and Double b tagging

The algorithm for identification of jets originating from b-quarks is called b tagging, and it looks for displaced tracks and vertices (secondary) within jets. To distinguish b jets in the final state, we can use the properties of b hadrons, such as large proper time and mass, where efficiency track reconstruction is used for almost all b-tagging algorithms. To define our double b tagging, we calculate the AK15 jet mass using some algorithms and variables, such as the SoftDrop [3] jet grooming algorithm. Then, we consider resonances that decay in the bb quark pair like Higgs and Z boson and t quark to define our tagger, including conditions for muons and the jets.

Scale factors

The study aims to obtain the scale factors to correct the double b tagging Monte Carlo (MC) efficiency for a pair of b quarks. We used different jets identification and reconstruction algorithms and the output of the DeepAK15 tagger to define our double b tagger, and its efficiency is defined as follows:

$$\text{Double b tagging Efficiency} = \frac{\text{Number of events that satisfy the double b tagging requirement}}{\text{Total number of events}} \quad (1)$$

Then, after computing the efficiency for MC and data, the efficiency calculated for MC is different if we compare it to the data. Therefore we derive a correction to the MC efficiency, called scale factor (SF), so that it makes the MC efficiency match the data efficiency. The SF is not a correction to MC but instead a correction to the double-b tagging efficiency measured on MC. Therefore the result is a number, and given the way the double-b tagger is derived, it is independent of the mass and p_T of the jet.
The scale factors can be extracted by performing a binned fit using the Higgs Combine tool [4], a based software tool used for statistical analysis which uses an input text-based called Datacard containing the details of the experiment (channels, background sources, sources of systematic uncertainty, etc.).

Results

To perform the results, we used the frame of the mono-Higgs model. This simplified dark matter model proposes that if dark matter mass is generated by a Higgs boson in the dark sector and if it is lighter than dark matter, a new annihilation channel where DM particles annihilate into a pair of dark Higgs bosons (h_s), with subsequent decay into SM states, would be possible. If we assume a small mixing with the SM Higgs boson, the dark Higgs boson decays predominantly into a pair of b quarks [5]. The result is a distinctive signature of significant missing transverse momentum, arising from the decay of a Z' mediator into DM and a highly-boosted large-radius jet.

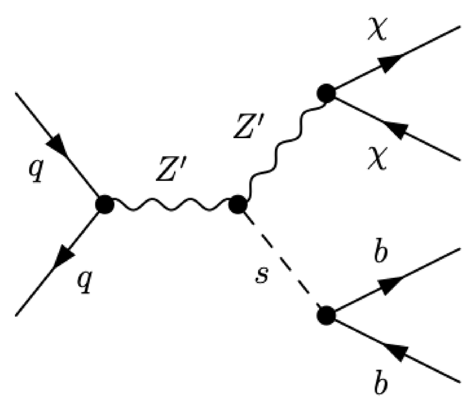

Figure 3: Process leading to a mono-dark-Higgs signal

Fat jets considered in the analysis must have $p_T > 160$ GeV, soft drop mass > 40 GeV, and $|\eta| < 2.4$. The background for H to a pair of b quarks includes processes containing light-flavor hadronic decays with the correct mass scale and processes that include real pair of b hadronic decays but at the wrong mass scale.

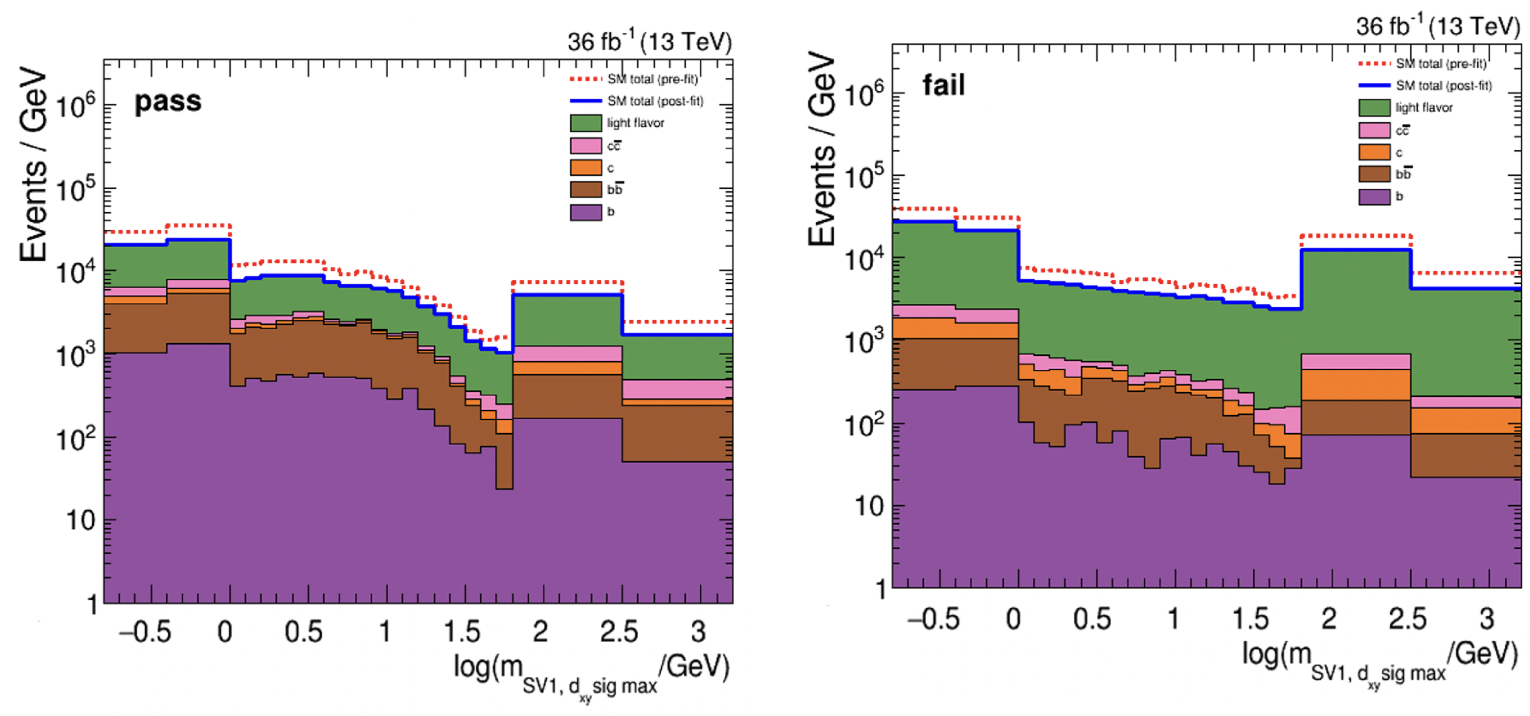

Figure 4: The results after the fitting show the 2D decay length significance using Monte Carlo simulation.

The plots shown contain all the uncertainties to achieve the best agreement between data and MC, with the best SF possible output. We define it as "pass" category if the event with one jet is above a 90 % probability of coming from a b pair resonance. Otherwise, we consider it as "fail."

Conclusions

Applying our double b tagging, we obtain an SF to correct the efficiency of the mono-Higgs model for Run II of the LHC. However, the method could be applied for other analyzes that require efficiency calibration.

References

1. The CMS Experiment at CERN. "DETECTOR" Recovered from: https://cms.cern/detector (2022).
2. Matteo Cacciari et al. The anti-k_T jet clustering algorithm. JHEP04(2008)063.
3. Larkoski, A.J., Marzani, S., Soyez, G. et al. Soft drop. J. High Energ. Phys. 2014, 146 (2014). JHEP05(2014)146. .
4. Higgs PAG https://cms-analysis.github.io/HiggsAnalysis-CombinedLimit/
5. Duerr, M., Grohsjean, A., Kahlhoefer, F. et al. Hunting the dark Higgs. J. High Energ. Phys. 2017, 143 (2017). JHEP04(2017)143