Abstract

The Standard Model (SM) successfully explains almost all experimental results at the electroweak scale $\mathcal{O}(100\ \text{GeV})$. However, there are several theoretical and experimental problems, such as the origin of neutrino masses, the existence of 18 parameters that experiments should determine, and the absence of the Dark Matter (DM) candidate. We will focus on the problems of DM. DM is electrically neutral, long-lived, and has a non-zero mass. Many pieces of evidence suggest the existence of DM, including the galactic rotation curves, the cosmic microwave background, and gravitational lensing. This thesis focuses on the Simplified DM Model, which is an extension of the SM with only DM and mediators added. There are several types of simplified models, and spin variants can classify them for DM and mediators. Among these, the spin-1 mediator model is our interest in this work. In particular, we investigate the possibility of DM searches in proton-photon collisions at the Large Hadron Collider (LHC). We use the Forward Proton Detectors (FPD) to detect protons that lose energy by emitting quasi-real photons for this search. We have studied the effects of these new processes on DM searches.

In the Simplified DM Model with the spin-1 mediator Z' and a fermion ψ, the interaction Lagrangian is given by

$$\mathcal{L}_{\text{int}}^{Z'} = \overline{\psi}\gamma^{\mu}(g_{\psi}^{V} + g_{\psi}^{A}\gamma_5)\psi {Z'}_{\mu},$$

where g_{ψ}^{V} and g_{ψ}^{A} denote vector and axial-vector couplings of the mediator Z' for ψ, respectively. The fermion ψ represents the fermionic DM and the SM fermions. We have four parameters in our setup, the DM mass m_{χ}, the mediator mass $m_{Z'}$, and the couplings of fermions g_{ψ}^{V} and g_{ψ}^{A}. We focus on the process, $pp \to p\gamma p \to pj\chi\bar{\chi}X$, where p is a proton, γ is a photon, j is a jet and X is unspecified.

We studied constraints on m_{χ} and $m_{Z'}$ from the process based on three scenarios for the interactions of the mediator Z' to quarks q and DM χ:

(i) vector couplings only ("vector scenario"),

$$g_{\chi}^{V} = 1.0,\ g_{\chi}^{A} = 0.0,\ g_{q}^{V} = 0.25,\ g_{q}^{A} = 0.0;$$

(ii) axial-vector couplings only ("axial-vector scenario"),

$$g_\chi^V = 0.0,\ g_\chi^A = 1.0,\ g_q^V = 0.0,\ g_q^A = 0.25;$$

(iii) combination of vector and axial-vector couplings ("mixed scenario"),

$$g_\chi^V = \frac{1}{\sqrt{2}},\ g_\chi^A = \frac{1}{\sqrt{2}},\ g_q^V = \frac{1}{4\sqrt{2}},\ g_q^A = \frac{1}{4\sqrt{2}}.$$

For each of the scenarios (i) to (iii), we fixed the p-p collision at the center of mass energy $\sqrt{s} = 14$ TeV and an integrated luminosity $L_{\rm int} = 3000$ fb^{-1} at the LHC.

We found the exclusion limits on the model parameters $(m_\chi, m_{Z'})$ for the three scenarios of the interaction of Z'. As a result of studying the ξ $(= E_\gamma/E_p)$ distribution, severe constraints were required on the parameter space. The lower mass bound on DM χ can be summarized $m_\chi \gtrsim 550$ GeV ($m_{Z'} = 1.2$ TeV) in the vector scenario (i), and $m_\chi \gtrsim 400$ GeV ($m_{Z'} = 1.1$ TeV) in the axial-vector scenario (ii). The limits on DM mass m_χ for the vector and axial-vector scenarios are slightly stronger than the energetic-jet analysis at the ATLAS experiment. Moreover, the lower bound on the m_χ for the mixed scenario has not been studied at the LHC before, and our result gives a limit $m_\chi \gtrsim 500$ GeV at $m_{Z'} = 1.1$ TeV at 95% C.L., respectively. Thus, for DM search, there is an advantage to using the FPD. On the other hand, the mediator mass $m_{Z'} \lesssim 1.4$ TeV is excluded at 95% C.L. for all scenarios (i), (ii), and (iii) when DM mass is relatively small. For comparison, ATLAS and CMS give the lower mass bound on Z' as $m_{Z'} \gtrsim 5$ TeV by dijet invariant-mass searches.