Vector-Portal Search for Dark Matter Particles

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I. Introduction

The Standard Model (SM) of particle physics is a mathematically tight theory that describes fundamental physics and provides high-precision predictions consistent with decades of experimental studies. However, there are several important shortcomings that are of primary interest for current research in the field. Related to the research reported here, is the fact that the SM offers no explanation for the existence of dark matter (DM), for which there is abundant astronomical evidence [1], [2]. We consider the existence of a dark boson, Z_D, that couples to the SM sector either *directly*, through vectorial and axial couplings, or via a *Kinetic Mixing (KM)* mechanism. The Z_D would be a gauge boson of a new "dark" $U(1)$ symmetry group with the ability to simultaneously interact with both the Dark Sector and the SM sector. This means it can provide a *vector portal* through which we may detect dark matter in collider experiments.

Specifically, we are interested in scenarios where the produced Z_D decays predominantly into dark scalars or fermions, which each subsequently decays via an off-shell Z_D into SM particles. Dark matter particles may produce prompt signatures or may have significant lifetimes that produce displaced secondary decay vertices in collider experiments. We refer to these latter signatures as *Long-Lived Particles (LLPs)* [3].

We are making a long-term research effort in this area, investigating parameterization of the vertices, Monte Carlo production of events, and feasibility study of a Z_D search at the Large Hadron Collider (LHC) in events with 4 muons, using the $MadGraph5\_aMC@NLO$ framework. In an effort to study LLP signatures, the maximal lifetime for various couplings of the Z_D to the SM and DM particles are calculated and then simulated in $Madgraph$ for calculating the cross section and feasibility of detection in Run II and Run III with the CMS detector.

II. Kinetic Mixing Mode of Production

In this production mode, an extra $U(1)_D$ group is added to the SM gauge groups. The only coupling of this new gauge sector to the SM sector is through kinetic mixing (KM), where the non-physical new X_μ gauge boson mixes with the SM hypercharge gauge boson, B_μ [4], [5]:

$$\mathcal{L}_{int} = -\frac{1}{4}\hat{X}_{\mu\nu}\hat{X}^{\mu\nu} + \frac{\epsilon}{2}\hat{X}_{\mu\nu}\hat{B}^{\mu\nu} \ , \tag{1}$$

where ϵ is the mixing parameter.

Couplings to SM fermions are given in eqs. 2 and 3 [6]:

$$\Psi\overline{\Psi}Z : \frac{ig}{c_W}[c_\alpha(1 - s_W t_\alpha \eta)]\left[{T_L}^3 - \frac{(1 - t_\alpha\eta/s_W)}{(1 - s_W t_\alpha \eta)}{s_W}^2 Q\right] \tag{2}$$

$$\Psi\overline{\Psi}Z_D : \frac{-ig}{c_W}[c_\alpha(t_\alpha + \eta s_W)]\left[{T_L}^3 - \frac{(t_\alpha + \eta/s_W)}{(t_\alpha + \eta s_W)}{s_W}^2 Q\right] \ , \tag{3}$$

where $Q = {T_L}^3 + Q_Y$ and $t_\alpha = \tan\alpha = \frac{\sin\alpha}{\cos\alpha}$.

Z_D couplings to DM fermions and DM scalars are taken in analogy to the SM Z. The Z_D width for the KM mode of production is:

$$\Gamma(Z_D \to \overline{f}f) = \frac{1}{24\pi m_{Z_D}}\sqrt{1 - \frac{4{m_f}^2}{m_{Z_D}^2}}({m_{Z_D}}^2({g_L}^2 + {g_R}^2) - {m_f}^2(-6g_L g_R + {g_L}^2 + {g_R}^2)) \ , \tag{4}$$

where g_L and g_R are left-handed and right-handed couplings of the Z_D to fermions, respectively [6].

Figure 1 shows the behavior of the Z_D lifetime vs. the Z_D production cross-section at the LHC and its dependency on the mixing parameter ϵ, based on equation 4. The LLP region of interest is highlighted in green. This gives a sense of the sensitivity of LHC searches for a kinetically mixed Z_D.

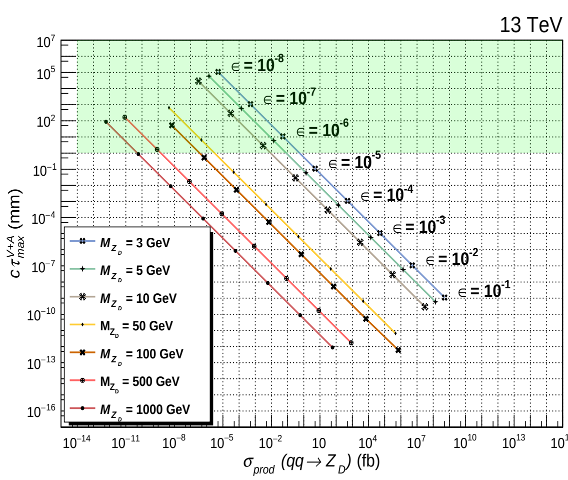

Fig. 1. Z_D lifetime vs. the Z_D production cross-section in kinetic mixing production mode.

III. Branching Ratios and Acceptance

Figures 2 and 3 show the behavior of production cross sections, branching ratios, kinematic and geometrical acceptances, and the final products of those three quantities. We are currently evaluating these as indicators of the detectability of the 4-muon signature for the f_D and s_D models.

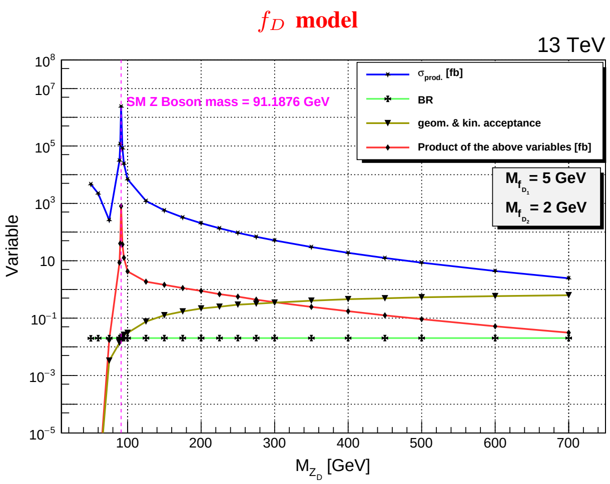

Fig. 2. Z_D mass scan of cross section, BR, and acceptance for KM f_D model at LHC.

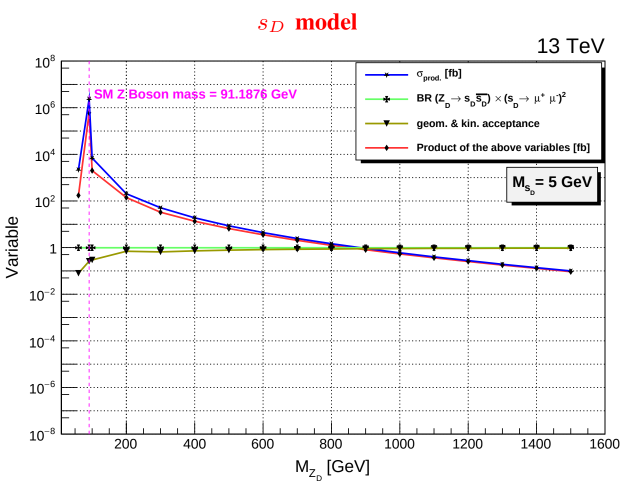

Fig. 3. Z_D mass scan of cross section, BR, and acceptance for KM s_D model at LHC.

IV. Study of Search Sensitivities at an FCC

The Future Circular Collider (FCC) is a proposed post-LHC particle accelerator with center-of-mass collision energy significantly above previous colliders (SPS, Tevatron, LHC) [7]. With a center-of-mass collision energy of 100 TeV (vs. 14 TeV at LHC), an FCC collider could be a "discovery machine" for Dark Matter particles, offering an eightfold increase compared to the current energy reach of the LHC. Figure 4 shows the simulated parameter scan for our dark fermionic model (f_D) at an FCC. A preliminary Z_D boson mass scan shows higher production cross-sections and better reach to higher Z_D masses in the future. We plan to extend our present studies to FCC energies as our contribution to the Snowmass EF studies.

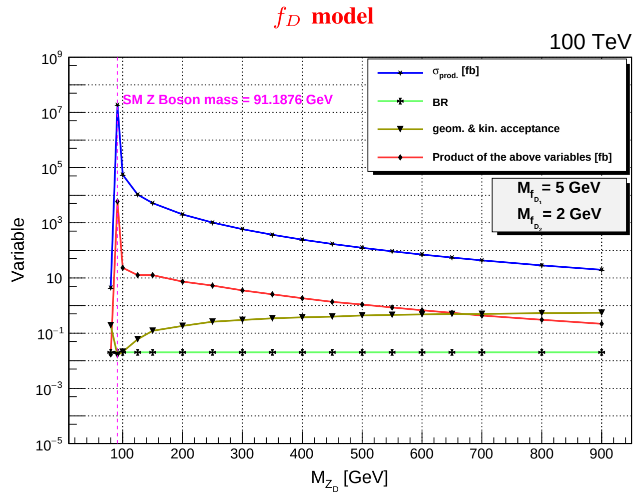

Fig. 4. Z_D mass scan of cross section, BR, and acceptance for KM f_D model at a 100 TeV FCC.

V. Summary

We have modelled production of a dark Z boson, with dark fermionic and scalar decay products, which can subsequently decay into SM muons. We have studied the Kinetic Mixing mode of production for the dark Z, and the feasibility of *LLP* scenarios within our models. Currently, the simulation phase of this analysis with CMS Run II data is ongoing and analysis strategies are being developed. Phase I of this analysis is focused on prompt samples in Run II at the LHC. We will continue with the extension of this analysis to include signatures in Phase II, using the combination of Run II and Run III at the High Luminosity Large Hadron Collider (HL-LHC), and lastly the research will move to include studies for experiments at an FCC.

References

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