Vector-Portal Search for Long Lived Dark Matter Particles

Work in progress

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Introduction i

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- The Standard Model of particle physics (SM) is a mathematically tight theory that describes fundamental physics and provides high-precision predictions consistent with decades of experimental studies.
- 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, for which there is abundant astronomical evidence [1], [2], [3].
- Experimentally, dark matter has not yet been observed, and there is not yet any evidence for non-gravitational interactions between dark matter and Standard Model particles.
- Since dark matter particles themselves do not produce signals in the Large Hardon Collider (LHC) detectors, one way to observe them is when they can decay into SM particles or first into DM matter particles and then into SM particles such as muons, through a spin 1 mediator [4], e.g. a dark Z-like boson Z_D, which can interact with the Standard Model sector as well as the dark matter sector[5][6].

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- Dark matter particles may have lifetimes that produce secondary decay vertices in collider experiments that are substantially displaced from the primary interaction vertex. We refer to these signatures as Long Lived Particles or **LLPs**. We have prepared a models, involving dark dark fermions ($pp \rightarrow Z_D \rightarrow \overline{f_{D_1}} f_{D_1} \rightarrow \overline{f_{D_2}} f_{D_2}\ \mu^+\ \mu^-$) shown in **figure 1**, as reference model for a search for long-lived dark matter particles with the Compact Muon Solenoid (CMS) detector at the LHC.
- The Z_D could be produced **directly from proton-proton collisions** or through **kinetic mixing with SM $U(1)_Y$ group**. Both cases are studied here. I will refer to the former model as **Direct production**, and to latter as the **Kinetic mixing production.**
- This study will investigate parameterization of the vertices, the Monte Carlo production of events, and feasibility study of a Z_D search at the LHC in events with 4 muons, using the *MadGraph* framework.
- The maximal lifetime for various couplings of the Z_D to the SM and DM particles are calculated and then implemented in *Madgraph* for calculating the cross section.
- This study is motivated by the paper *"A search for pair production of new light bosons decaying into muons in proton-proton collisions at 13 TeV"*[7] published in 2019.

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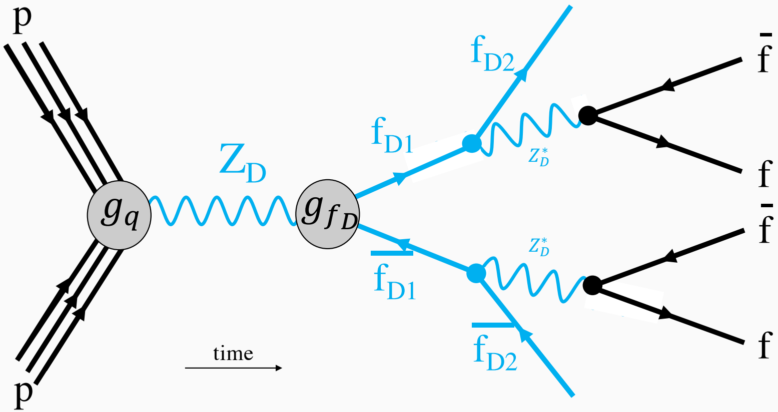

Figure 1: Z_D decays into pair of fermionic dark matter.

Direct production vectoral and axial coupling

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The interaction Lagrangian for $qq \rightarrow Z_D$ is taken to have a vectoral part and an axial part, like Z boson couplings in SM Lagrangian:

$$\mathcal{L}_{SM} = \overline{q}\gamma^{\mu}(g_f^V + g_f^A\gamma^5)qZ_{D_\mu} \tag{1}$$

The couplings of Z_D to dark Dirac fermions, $Z_D \rightarrow \overline{f_{D_1}} f_{D_1}$, could be written in the similar way:

$$\mathcal{L}_{DM} = \overline{f_{D_1}}\gamma^{\mu}({g_f}_D^V + {g_f}_D^A\gamma^5)f_{D_1}Z_{D_\mu} \tag{2}$$

Direct vectoral and axial coupling

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When there are no decays or production channels, the minimal width (the maximal lifetime) of the Z_D particle is fixed by the choices of g_q and g_{f_d}. Γ^V_{min} signifies vector width and Γ^A_{min} signifies axial width of the Z_D boson. [8], [9], [10]:

$$\Gamma^V_{min} = \frac{g^2_{f_d} M_{Z_D}}{12\pi}\left(1 + \frac{2M^2_{f_D}}{M^2_{Z_D}}\right)\beta_{DM}\theta(M_{Z_D} - 2M_{f_D}) +$$

$$\sum_q \frac{3g^2_q M_{Z_D}}{12\pi}\left(1 + \frac{2m^2_q}{M^2_{Z_D}}\right)\beta_q\theta(M_{Z_D} - 2m_q)$$

$$\Gamma^A_{min} = \frac{g^{\mathbf{2}}_{f_d} M_{Z_D}}{12\pi}\beta^3_{DM}\theta(M_{Z_D} - 2M_{f_D}) + \sum_q \frac{3{g_q}^{\mathbf{2}} M_{Z_D}}{12\pi}\beta^3_q\theta(M_{Z_D} - 2m_q) \ (3)$$

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Lifetime vs. cross-section for various couplings

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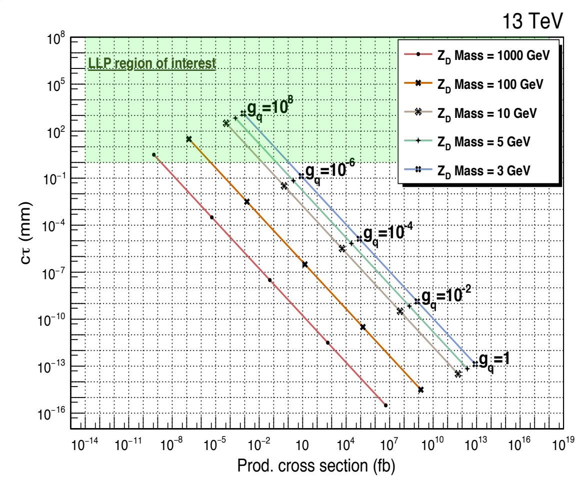

Figure 2: The behavior of the Z_D lifetime vs. Z_D production cross-section (calculated by *MadGraph*), which has a dependency on couplings g_q, based on equation 3. The **LLP** region of interest is highlighted in green.

Kinetic mixing production

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- Extra $U(1)_D$ dark group in addition to the SM gauge group.
- The only coupling of this new gauge sector to the SM is through kinetic mixing, where the non-physical new X_μ boson mixes with the hypercharge gauge boson, B_μ. Nonphysical fields of this model and their definitions are given in **App. i.** [11]

$$SU(2)_L \otimes SU(3)_L \otimes U(1)_Y \otimes U(1)_D \tag{4}$$

$$\mathcal{L}_{int} = -\frac{1}{4}\hat{X}_{\mu\nu}\hat{X}^{\mu\nu} + \frac{\epsilon}{2}\hat{X}_{\mu\nu}\hat{B}^{\mu\nu} \tag{5}$$

Where ϵ is the mixing parameter.

Group	Gauge boson	Coupling constant	Charge
$U1_Y$	B	g_1	Y
$U1_D$	X	e (Electric charge)	Q_X
SU2	W_i	g_w	
SU3	G	g_s	

Z_D Kinetic mixing production couplings

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Couplings to SM fermions are given in the equations 6 and 7[12].

$$\Psi\overline{\Psi}Z : \frac{ig}{c_W}[c_\alpha(1 - s_W t_\alpha \eta)]\left[{T_L}^3 - \frac{(1 - t_\alpha \eta / s_W)}{(1 - s_W t_\alpha \eta)} {s_W}^2 Q\right] \qquad (6)$$

$$\Psi\overline{\Psi}Z_D : \frac{-ig}{c_W}[c_\alpha(t_\alpha + \eta s_W)]\left[{T_L}^3 - \frac{(t_\alpha + \eta / s_W)}{(t_\alpha + \eta s_W)} {s_W}^2 Q\right] \qquad (7)$$

Where $Q = {T_L}^3 + Q_Y$ and $t_\alpha = \frac{s_\alpha}{c_\alpha}$. Other parameters and their definition are given in the **Appendix ii and iii** .

Couplings to DM fermions are taken again in analogy with SM Z:

$$\overline{f_{D1}} f_{D1} Z_D : \gamma^\mu ({g_f}^V_{D_1} + {g_f}^A_{D_1}\gamma^5) \qquad (8)$$

$$\overline{f_{D1}} f_{D2} Z_D : \gamma^\mu ({g_f}^V_{D_2} + {g_f}^A_{D_2}\gamma^5) \qquad (9)$$

Z_D width for Kinetic mixing production

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$$\Gamma(Z_D \to \bar{f}f) = \frac{1}{24\pi m_{Z_D}} \sqrt{1 - \frac{4{m_f}^2}{m_{Z_D}^2}} ({m_{Z_D}}^2({g_L}^2 + {g_R}^2) - {m_f}^2(-6g_L g_R + {g_L}^2 + {g_R}^2)) \quad (10)$$

Where g_L and g_R are derived from the following equation:[12]

$$g_{Z_D f \bar{f}} = \frac{g}{\cos\theta}(-\sin\alpha(t^3\cos\theta^3 - Y\sin\theta^2 + \eta\cos\alpha\sin\theta Y)) \quad (11)$$

Equation 11 gives us g_L by using $T^3 = 1/2$ & $Y = 1/3$ and the same equation gives us g_R by using $T^3 = 0$ & $Y = 4/3$ for **up-like** quarks. Using the values tabulated in table 1 in **Appendix i** for **down-like** quarks, we can find couplings for **down-like** quarks.
$\underline{\alpha}$ is the mixing angle in weak sector and is defined in equation 15 and $\underline{\theta}$ is the Weinberg angle.

Lifetime vs. mixing parameter for various masses

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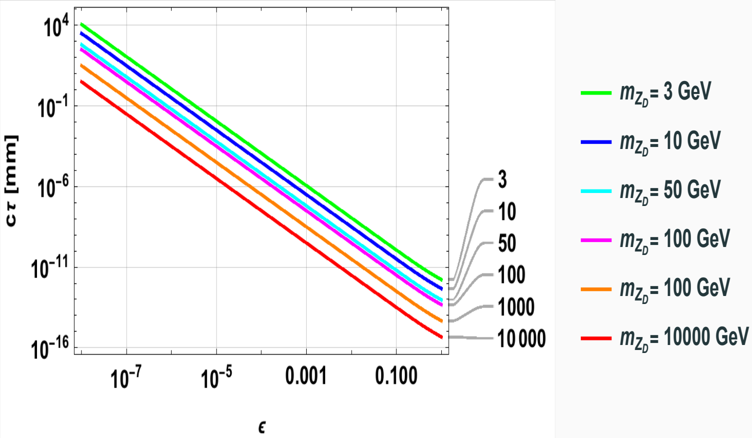

Figure 3: The behavior of the lifetime, $c\tau$ vs. the kinetic mixing parameter, ϵ, for various masses of Z_D. Here $c\tau$ is derived from the inverse of Γ in eq. 10.

Lifetime vs. cross-section for various couplings

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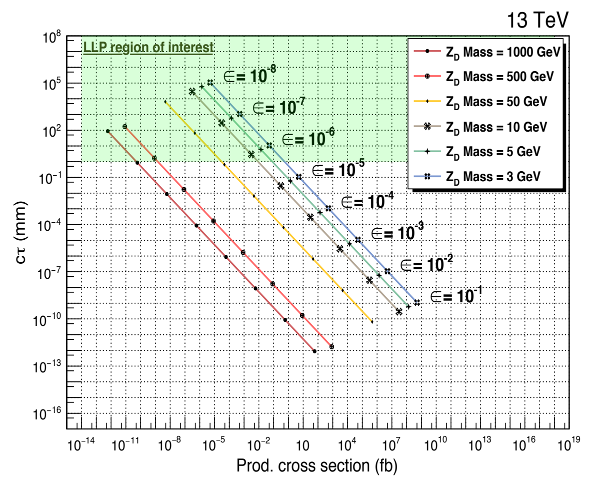

Figure 4: The behavior of the Z_D lifetime vs. the Z_D production cross-section, which has a dependency on mixing parameter ϵ based on equation 10. The **LLP** region of interest is highlighted in green.

Partial widths and branching ratio for a ref. data point i

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Z_D DECAYS			
BR%	Particle#1	Particle#2	Partial width GeV
66.47	f_{D_1}	f_{D2}	2.23×10^2
33.53	f_{D_1}	f_{D_1}	1.13×10^2
3.32×10^{-9}	u	$\bar{u}$	1.12×10^{-8}
3.32×10^{-9}	c	$\bar{c}$	1.12×10^{-8}
2.93×10^{-9}	e^-	e^+	9.86×10^{-9}
2.93×10^{-9}	μ^-	μ^+	9.86×10^{-9}
2.93×10^{-9}	τ^-	τ^+	9.85×10^{-9}
9.77×10^{-10}	d	$\bar{d}$	3.29×10^{-9}
9.77×10^{-10}	s	$\bar{s}$	3.29×10^{-9}
9.66×10^{-10}	b	$\bar{b}$	3.25×10^{-9}
5.86×10^{-10}	ν_τ	$\overline{\nu_\tau}$	1.97×10^{-9}
5.86×10^{-10}	ν_μ	$\overline{\nu_\mu}$	1.97×10^{-9}
5.86×10^{-10}	ν_e	$\overline{\nu_e}$	1.97×10^{-9}
Total BR = 100%		Total width = 3.36×10^2 GeV	

Table 1: Z_D branching ratios and partial widths. Sample parameters listed in tables 7 and 8 in App. iv and v. Values calculated by *Madgraph/MadWidth*.

Partial widths and branching ratio for a ref. data point ii

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Work in progress

f_{D_1} DECAYS				
BR%	Particle#1	Particle#2	Particle#3	Partial width GeV
17.23	f_{D2}	u	$\bar{u}$	2.91×10^{-13}
16.64	f_{D2}	c	$\bar{c}$	2.81×10^{-13}
15.17	f_{D2}	e^-	e^+	2.56×10^{-13}
15.04	f_{D2}	μ^-	μ^+	2.54×10^{-13}
14.28	f_{D2}	τ^-	τ^+	2.41×10^{-13}
5.08	f_{D2}	d	$\bar{d}$	8.58×10^{-14}
5.04	f_{D2}	s	$\bar{s}$	8.52×10^{-14}
3.02	f_{D2}	ν_e	$\overline{\nu_e}$	5.10×10^{-14}
3.02	f_{D2}	ν_μ	$\overline{\nu_\mu}$	5.10×10^{-14}
3.02	f_{D2}	ν_τ	$\overline{\nu_\tau}$	5.10×10^{-14}
2.47	f_{D2}	b	$\bar{b}$	4.17×10^{-14}
Total BR = 100%			Total width = 1.69×10^{-12} GeV	

Table 2: f_{D_1} branching ratios and partial widths. Sample parameters listed in tables 7 and 8 in App. iv and v. Values calculated by *Madgraph*/*MadWidth*.

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Calculating sensitivity for a reference data point i

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- For calculating the sensitivity we deduce for the expected number of events, N:

$$N = \sigma_{Z_D} \times BR \times \mathcal{L} \tag{12}$$

Where σ_{Z_D} is the **production** cross section, BR is the total branching ratio for $pp \to Z_D \to f_{D_1} f_{D_1} \to f_{D_2} f_{D_2}\, \mu^+ \mu^-$, N is number of signal events, and $\mathcal{L}$ is the intergrated luminosity.

- To produce at least 10 signal events, Considering the luminosities for $Run2$, $Run3$ and $Run4$ at the LHC, we would need cross-section $(\sigma) \times$ branching ratios (BR) tabulated in the table below:

Run#	year	$\mathcal{L}(fb^{-1})$	$\sigma \times BR$ fb
2	$\sim 2016 - 2018$	~ 137	7.32×10^{-2}
3	$\sim 2021 - 2024$	~ 300	3.33×10^{-2}
4	$\sim 2027 - 2030$	~ 3000	3.33×10^{-3}

Table 3: cross section $\times$ branching ratio feasibility of our model for various runs

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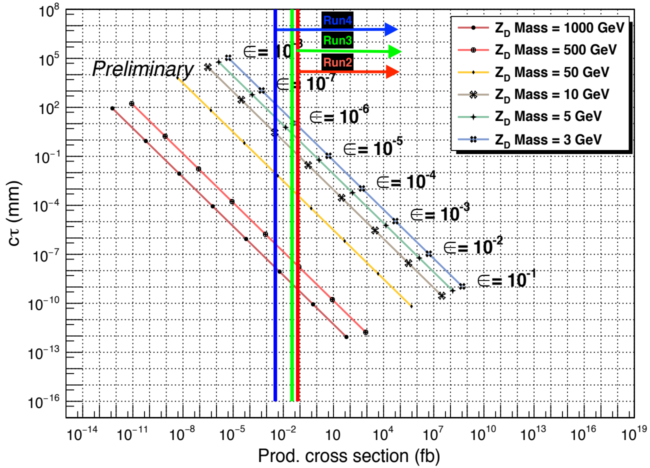

Figure 5: The **Run2** region of feasibility is to the right of the red line, the **Run3** region of feasibility is to the right of the green, and The **Run4** region of feasibility is to the right of the blue based on the values in table 3.

Calculating sensitivity for a reference data point iii

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- The production cross section for this reference sample (tables 7 and 8, $M_{Z_D} = 100 GeV$, $M_{f_{D_1}} = 25 GeV$) is calculated by *Madgraph*:

$$\sigma_{Z_D} = 6.88 \times 10^3 \pm 34 \ fb \tag{13}$$

- The total branching ratio (BR) based on tables 1 and 2 is:

$$\underbrace{0.33}_{Z_D \rightarrow f_{D_1} f_{D_1}} \times \underbrace{(0.15)^2}_{f_{D_1} \rightarrow f_{D_2} \mu^+ \mu^-} \cong 0.01$$

- Given the above values, the total branching $\times$ production cross section is:

$$\sigma_{Z_D} \times BR = 68.8 \ fb \tag{14}$$

which might be within the sensitivity of LHC in Run2 and Run3.

Conculsions

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- We have implemented a model to observe a dark Z boson, with dark fermionic products, which can subsequently decay into standard model fermions.
- Two channels of production for the dark Z is studied and the Long Lived scenarios are studied.
- We have established that the observation of the LLPs within the sensitivity of the LHC might be possible.
- Next steps are simulation for various data points, and data analysis with CMS Run2 and Run3 data.

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Appendix i

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Fields	Definition
B_d	$B_{d_\mu} \to s_w A_\mu - s_w c_\alpha Z_\mu + s_w s_\alpha Z_{d_\mu}$
X_d	$X_{d_\mu} \to s_\alpha Z_\mu + c_\alpha Z_{d_\mu}$
W_i	$W_{i_{\mu},1} \to \frac{W_\mu + W_\mu^\dagger}{\sqrt{2}}$, $W_{i_{\mu},2} \to \frac{-i(W_\mu + W_\mu^\dagger)}{\sqrt{2}}$, $W_{i_{\mu},3} \to s_w A_\mu + c_\alpha c_w Z_\mu - c_w s_\alpha Z_{d_\mu}$
B	$B_\mu \to B_{d_\mu} + \eta X_{d_\mu}$
X	$X_\mu \to \eta\epsilon X_{d_\mu}$

Table 4: Non-physical fields and their definition for kinetic mixing model.

Appendix ii

Work in progress

Parameters	Definition	Description
η		$U(1)_X$ - $U(1)_Y$ mixing parameter (external)
c_w	$\frac{M_W}{M_Z}$	cos of the Weinberg angle
s_w	$\sqrt{1-{c_w}^2}$	sin of the Weinberg angle
c_α	$cos(\alpha)$	cos of mixing angle in weak sector
s_α	$sin(\alpha)$	sin of mixing angle in the weak sector
ϵ	$\frac{-1+\sqrt{1+4\eta^2}}{2\eta}$	kinetic mixing parameter

Table 5: Parameters of the kinetic mixing model.

$$\alpha = -\frac{1}{2} ArcTan\left[\frac{2 s_w \eta}{1 - \Delta Z - {s_w}^2 \eta^2}\right] \quad (15)$$

$$\Delta Z = \frac{{M_X}^2}{{M_{Z_0}}^2} \quad (16)$$

Where M_X is X mass before mixing and M_{Z_0} is Z mass before mixing. ΔZ is referred to as the"*Ratio of scales.*"

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Lepton	T^3	Y
ν_e	1/2	-1
e_L	-1/2	-1
e_R	0	-2
Quark	T^3	Y
u_L	1/2	1/3
d_L	-1/2	1/3
u_R	0	4/3
d_R	0	-2/3

Table 6: Weak iso-spin and hypercharge values.

- The various parameters for a reference data point are tabulated in the following tables.

- The partital widths and branching ratios are calculated using *Madwidth* tool within *Madgraph*. [13]

Coupling vertex	Vectoral coupling	Axial coupling	Comments
$Z_D - f_{D1} - f_{D1}$	-4.85	2.85	Overwritten by Mad-Width and fixed for different mass points
$Z_D - f_{D1} - f_{D2}$	2.85	4.85	
η	10^{-4}		Chosen by the user

Table 7: Coupling constants calculated by *Madgraph* for ref. sample.

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Parameters	Value GeV	comments
M_{Z_D}	100	Chosen by the user
$M_{f_{D_1}}$	25	Chosen by the user
$M_{f_{D_2}}$	2	Chosen by the user
Γ_{Z_D}	3.36×10^{2}	Calculated by *Madgraph*
$\Gamma_{f_{D_1}}$	1.69×10^{-12}	Calculated by *Madgraph*
$\Gamma_{f_{D_2}}$	0.	Calculated by *Madgraph*

Table 8: Parameters calculated by *Madgraph* for ref. sample.