Dark Shower of Light Dark Matter under Broken $U(1)$

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based on 1807.00530

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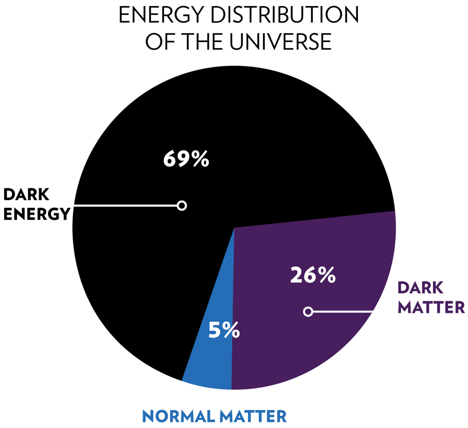
Dark Matter


ENERGY DISTRIBUTION
OF THE UNIVERSE
69%
DARK
ENERGY
26%
DARK
MATTER
5%
NORMAL MATTER

Introduction: Dark Matter Interaction and LHC

Most popular framework is Weakly Interacting Massive Particles (WIMP).

- So far no unambiguous signals

Many alternative scenarios being considered now.

- One possibility is that there is a new interaction in the dark sector.
- Our focus: Dark Matter fermion gauged under a new $U(1)_d$, kinetically mixing with the $U(1)$ in the SM.

LHC gives a unique opportunity to search for and test those scenarios.

Light Dark Matter Shower and lepton jets

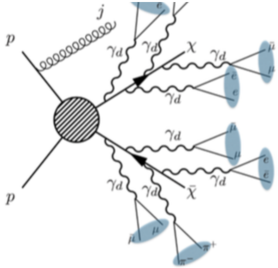


Figure: Dark Shower in Colliders

$pp \to \bar{\chi}\chi$, $\chi \to \chi A'$ (recursive), $A' \to e^+e^-/\mu^+\mu^-$ (lepton jets)

Previous Work

Previous work on this subject:

- Clifford Cheung, Joshua T. Ruderman, Lian-Tao Wang and Itay Yavin, arXiv: 0909.0290
- M. Buschmann, J. Kopp, J. Liu and P. A. N. Machado, JHEP 07, 045 (2015).
- M. Zhang, M. Kim, H. S. Lee and M. Park, arXiv:1612.02850 [hep-ph].
- et.al.

Origin of the gauge boson mass in $U(1)$

For a massive $U(1)$ vector boson, mass can comes from

- Higgs mechanism: requires an additional scalar sector
- Stückelberg mechanism: no scalar sector needed

Interactions between left-handed/right-handed DM fermion and dark photon can be

- The same: vector-like interaction
- Not the same: chiral-like interaction

The two aspects are related.

Chiral Model and Vector Model

DM fermion interacting with a $U(1)$ dark photon.

- DM fermion is chiral-like $\rightarrow$ gauge invariance $\rightarrow$ Higgs mechanism. Chiral Model:

$$\begin{aligned}\mathcal{L} &= -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{\epsilon}{2}F'_{\mu\nu}F^{\mu\nu} + |D_\mu\Phi'|^2 - \frac{\lambda_\Phi}{4}\left(|\Phi'|^2 - \frac{v_{\Phi'}^2}{2}\right)^2 \\ &+ \sum_s \overline{\chi}_s\left(i\not{D} - m_\chi\right)\chi_s - \left(y_\chi\overline{\chi_L}\Phi'\chi_R + h.c.\right)\end{aligned}$$

- DM fermion is vector-like $\rightarrow$ more possibilities $\rightarrow$ simplest one: Vector Model:

$$\mathcal{L} = -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{\epsilon}{2}F'_{\mu\nu}F^{\mu\nu} + \frac{1}{2}m_{A'}^2A'_\mu A'^\mu + \sum_s \overline{\chi}_s\left(i\not{D} - m_\chi\right)\chi_s$$

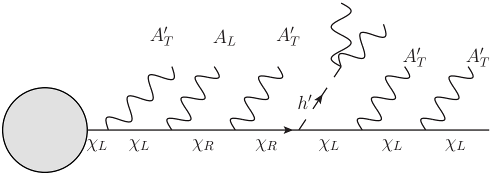


Figure: An example Dark Shower in Chiral Model

The Monte Carlo simulation of parton shower is simulated as recursion of $1 \to 2$ splitting functions. Starting from hard scale μ to infrared cutoff μ_0

Splitting Functions

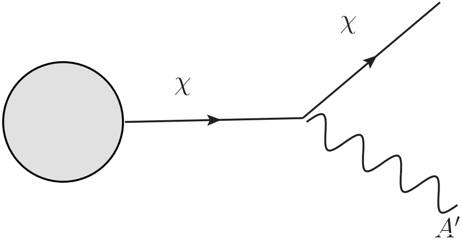
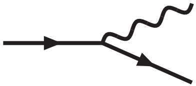


Figure: Collinear splitting function

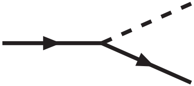
The calculation of splitting function can be reduced into the calculation of $1 \to 2$ splitting amplitude.

$$\frac{d\mathcal{P}}{dz dk_T^2} = \frac{1}{16\pi^2} z\bar{z} \frac{\overline{|\mathcal{M}_{split}|^2}}{\tilde{k}_T^4} \quad (1)$$

Splitting Functions – Unbroken



$$P_{f_s \to f_s + A'_T} \sim \alpha_W \frac{1+(1+z)^2}{z} \cdot \frac{1}{p_T^2}$$

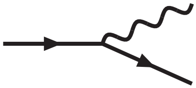


$$P_{f_s \to f_{-s} + A'_L / h'} \sim y_f^2 \frac{z}{2} \cdot \frac{1}{p_T^2}$$

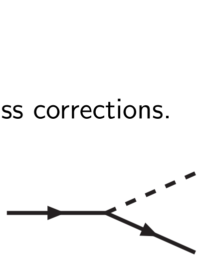
- One preserves helicity, another one flips helicity
- No "fermion $\to$fermion $+$Scalar" splitting in Vector Model

Splitting Functions – Broken

Splittings for next-to-leading power: mass corrections.



$$P_{f_s \to f_{-s} + A'_T} \sim \frac{\alpha'}{2\pi} z \frac{m_\chi^2}{\tilde{p}_T^4}$$



$$P_{f_s \to f_s + A'_L / h'} \sim \frac{\alpha'}{2\pi} \frac{1}{2z} \frac{m_{A'}^2 \text{or} m_{h'}^2}{\tilde{p}_T^4}$$

Implementation of Dark Shower

Charges for χ_L/χ_R

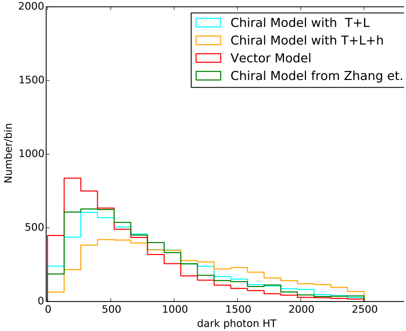
$$
\begin{aligned}
(Q_L, Q_R) &= (2, 0) \quad \text{for Chiral Model} \\
(Q_L, Q_R) &= (1, 1) \quad \text{for Vector Model}
\end{aligned}
$$

Three benchmark points, A, B and C, are chosen as

point A:	$\alpha' = 0.3$	$m_\chi = 0.7$ GeV	$m_{A'} = 0.4$ GeV	$m_{h'} = 1.0$ GeV
point B:	$\alpha' = 0.15$	$m_\chi = 1.0$ GeV	$m_{A'} = 0.4$ GeV	$m_{h'} = 1.0$ GeV
point C:	$\alpha' = 0.075$	$m_\chi = 1.4$ GeV	$m_{A'} = 0.4$ GeV	$m_{h'} = 1.4$ GeV

The Yukawa coupling is as large as possible, i.e. near the perturbative limit $\alpha' \frac{m_\chi^2}{m_{A'}^2} < 1$.

Point A



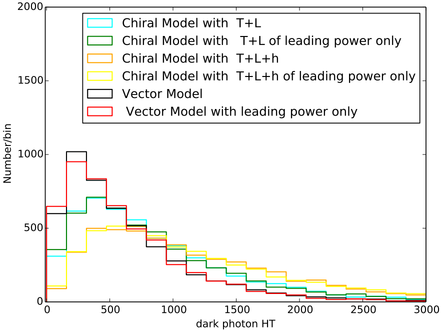


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Figure: H_T distribution. Point A: $\alpha' = 0.3$, $m_\chi = 0.7$ GeV, $m_{A'} = 0.4$ GeV, $m_{h'} = 1.0$ GeV. Left side: Chiral Model v.s. Vector Model; right side: unbroken splittings v.s. full splittings

Point A

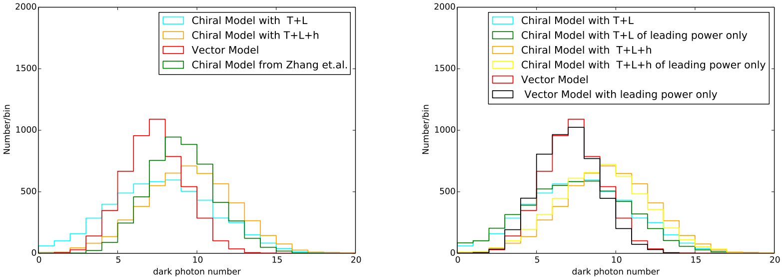

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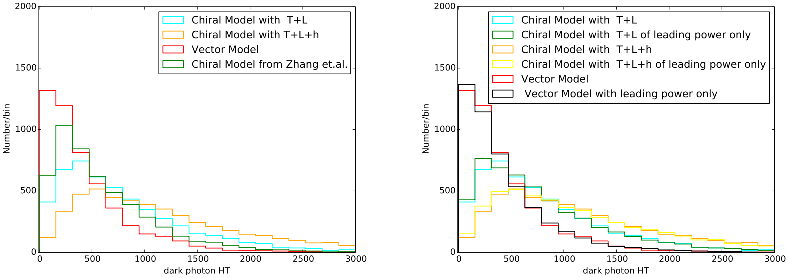
Figure: $n_{A'}$ dark photon number distribution. Point A: $\alpha' = 0.3$, $m_\chi = 0.7$ GeV, $m_{A'} = 0.4$ GeV, $m_{h'} = 1.0$ GeV.

Point B



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Point B

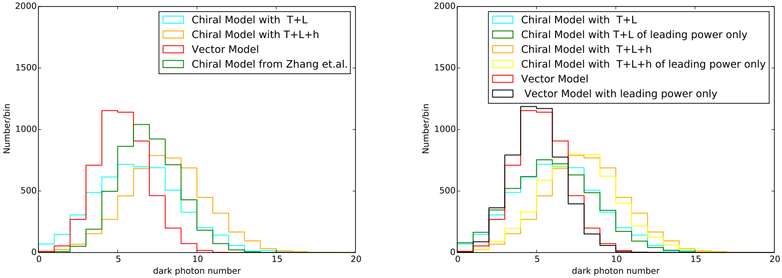
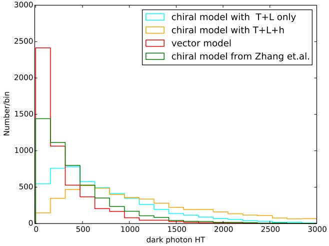


Figure: $n_{A'}$ dark photon number distribution. Point B: $\alpha' = 0.15$, $m_\chi = 1.0$ GeV, $m_{A'} = 0.4$ GeV, $m_{h'} = 1.0$ GeV. Left side: Chiral Model v.s. Vector Model; right side: unbroken splittings v.s. full splittings.

Point C



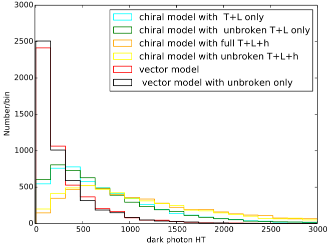
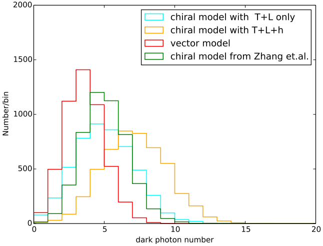


Figure: H_T distribution. Point C: $\alpha' = 0.075$, $m_\chi = 1.4$ GeV, $m_{A'} = 0.4$ GeV, $m_{h'} = 1.4$ GeV. Left side: Chiral Model v.s. Vector Model; right side: unbroken splittings v.s. full splittings.

Point C



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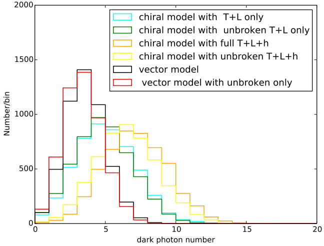

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Figure: $n_{A'}$ dark photon number distribution. Point C: $\alpha' = 0.075$, $m_\chi = 1.4$ GeV, $m_{A'} = 0.4$ GeV, $m_{h'} = 1.4$ GeV. Left side: Chiral Model v.s. Vector Model; right side: unbroken splittings v.s. full splittings.

Short: Summary

- Dark photon is generally softer in Vector Model than in Chiral Model.
- Mass corrections not significant.
- The contributions of dark Higgs boson can be important.

Jet Profile

Jet profile can be described by the variable $f_E(r)$, defined as the energy fraction outside the cone with size $r < R$.

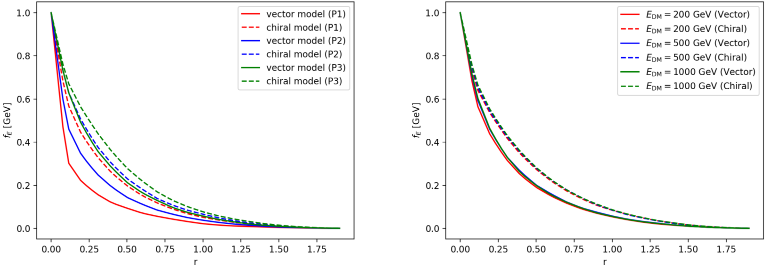

Figure: Left panel: shapes of dark matter jets for three benchmark points in the mono-jet channel ($p_T(j) > 200$ GeV) at 14 TeV LHC. Right panel: shapes of dark matter jets for the point A with different dark matter energies (indicated in the legend).

Conclusions

- We studied the dark shower of the light DM fermion interacting with a dark massive $U(1)$ at the LHC.
- The study is done with two simplified models connecting chirality of DM fermion and the mass origin of the dark vector boson.
- We derive the splitting functions with initial DM fermion, and implement Monte Carlo simulation in LHC.

  1. We specify the helicities of the DM fermions.

  2. Effects of the dark Higgs boson considering different limits of the dark Higgs mass.

  3. We also studied the symmetry breaking effects in the dark shower by incorporating a class of new splitting functions.
- We also studied the jet profile of the lepton jets by dark shower.