Is there a Higgs mechanism in the dark sector?

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A light dark matter with self interaction is favored by current observables(direct search, small scale structure problem, Sommerfeld enhancement…).

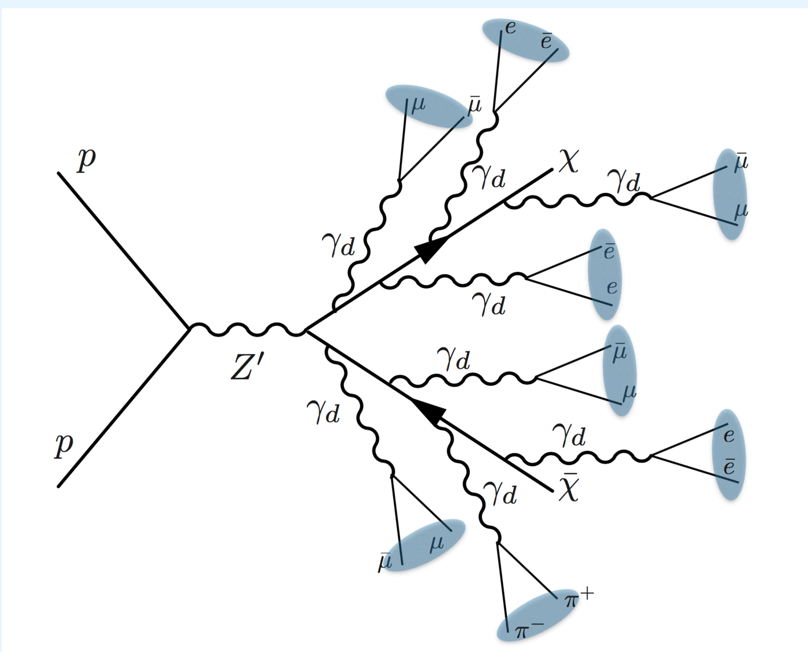
Generally, one can consider a toy model with a U(1)' gauge group:

$$\mathcal{L}' = \bar{\chi}\left(i\partial\!\!\!/ - m_\chi + ig'A\!\!\!/'\right)\chi - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m_{A'}^2 A'_\mu A'^\mu - \frac{\epsilon}{2}F'_{\mu\nu}F^{\mu\nu}$$

Here A' is gauge boson of U(1)'(called dark photon).
ϵ is the kinetic mixing between photon and dark photon.
In a collider, if energetic dark matter can be produced

$$\hat{s} >> m_\chi, m_{A'}$$

Then dark photon radiated from dark matter will result in dark parton shower. Dark photon then decay back to SM particles through kinetic mixing. The most sensitive signal is lepton jet:



Such case has been studied by JHEP 07(2015) 045

One can ask two more questions:

1.Dark photon is massive, so it has longitudinal polarization mode. But why is the longitudinal polarization shower ignored in previous study?

2.What if the dark matter is not vector-like but chiral, and its mass comes from a "dark Higgs mechanism"?

Actually, these two questions are closely related.

Consider a chiral dark matter model with a dark Higgs:

$$\mathcal{L}' = i\bar{\chi}_L(\partial\!\!\!/ + iag'A\!\!\!/')\chi_L + i\bar{\chi}_R(\partial\!\!\!/ + ibg'A\!\!\!/')\chi_R - y\left(\bar{\chi}_L\phi\chi_R + \bar{\chi}_R\phi^*\chi_L\right) - \frac{1}{4}(F'_{\mu\nu})^2 + |(\partial_\mu + i(a-b)g'A'_\mu)\phi|^2 - V(\phi)$$

(ignore chiral anomaly temporarily)
After spontaneous symmetry breaking:

$$\mathcal{L}' = \overline{\chi}(i\partial\!\!\!/ - m_\chi)\chi - g'A_\mu\overline{\chi}(a\gamma^\mu P_L + b\gamma^\mu P_R)\chi - iy\frac{\varphi}{\sqrt{2}}\overline{\chi}\gamma^5\chi - \frac{1}{2}A'_\mu\left(-g^{\mu\nu}\partial^2 + (1-\frac{1}{\xi})\partial^\mu\partial^\nu - m_{A'}^2 g^{\mu\nu}\right)A'_\nu + \frac{1}{2}(\partial_\mu\varphi)^2 - \frac{\xi}{2}m_{A'}^2\varphi^2 + \cdots$$

$$with \quad m_\chi = yv/\sqrt{2}, \quad m_{A'} = (a-b)g'v$$

Shower process is controlled by splitting kernel: $P_{\chi\to\chi A'}(x,t)$

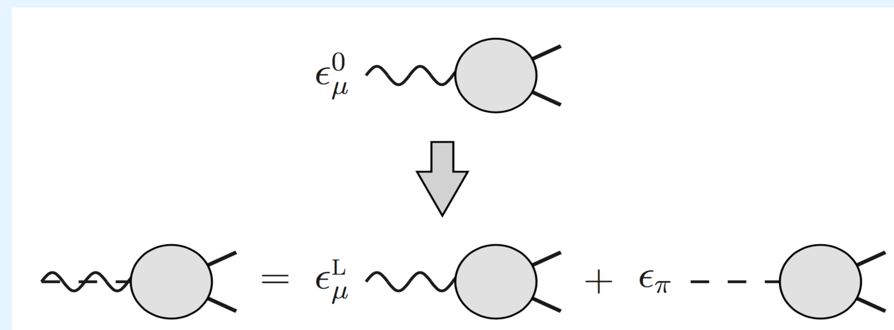
For vector-like dark matter, contribution from transverse polarization is:

$$P_{\chi\to\chi A'}(x,t) = \frac{1+x^2}{1-x}$$

The calculation of longitudinal shower is a little bit tricky:

$\epsilon(\mathbf{p}) \to \frac{E}{m_{A'}}$, when energy of dark photon is much larger than its mass.

A clever gauge choice can be used to tame longitudinal mode's high energy behavior(light cone gauge, Goldstone equivalence gauge…)
BRST symmetry can also do this(Nucl.Phys. B885 (2014) 97-126):



$$\epsilon^L_\mu(\mathrm{p}) \equiv \epsilon^0_\mu(\mathrm{p}) + i\epsilon^s_\mu(\mathrm{p}) = -\frac{m}{E_\mathrm{p}+|\mathrm{p}|}\left\{1, \frac{\mathrm{p}}{|\mathrm{p}|}\right\}$$ ← Suppressed by energy

$$\epsilon_\pi(\mathrm{p}) \equiv -i.$$ ← Goldstone equivalent theorem

In vector-like case, longitudinal polarization can be just ignored in shower process. But in chiral case, longitudinal polarization is replaced by the goldstone boson eaten by dark photon. Then splitting kernel become:

$$P_{\chi\to\chi A'}(x,t) = \frac{1}{2}(a^2+b^2)\frac{1+x^2}{1-x} + \frac{1}{2}(a-b)^2\frac{m_\chi^2}{m_{A'}^2}$$

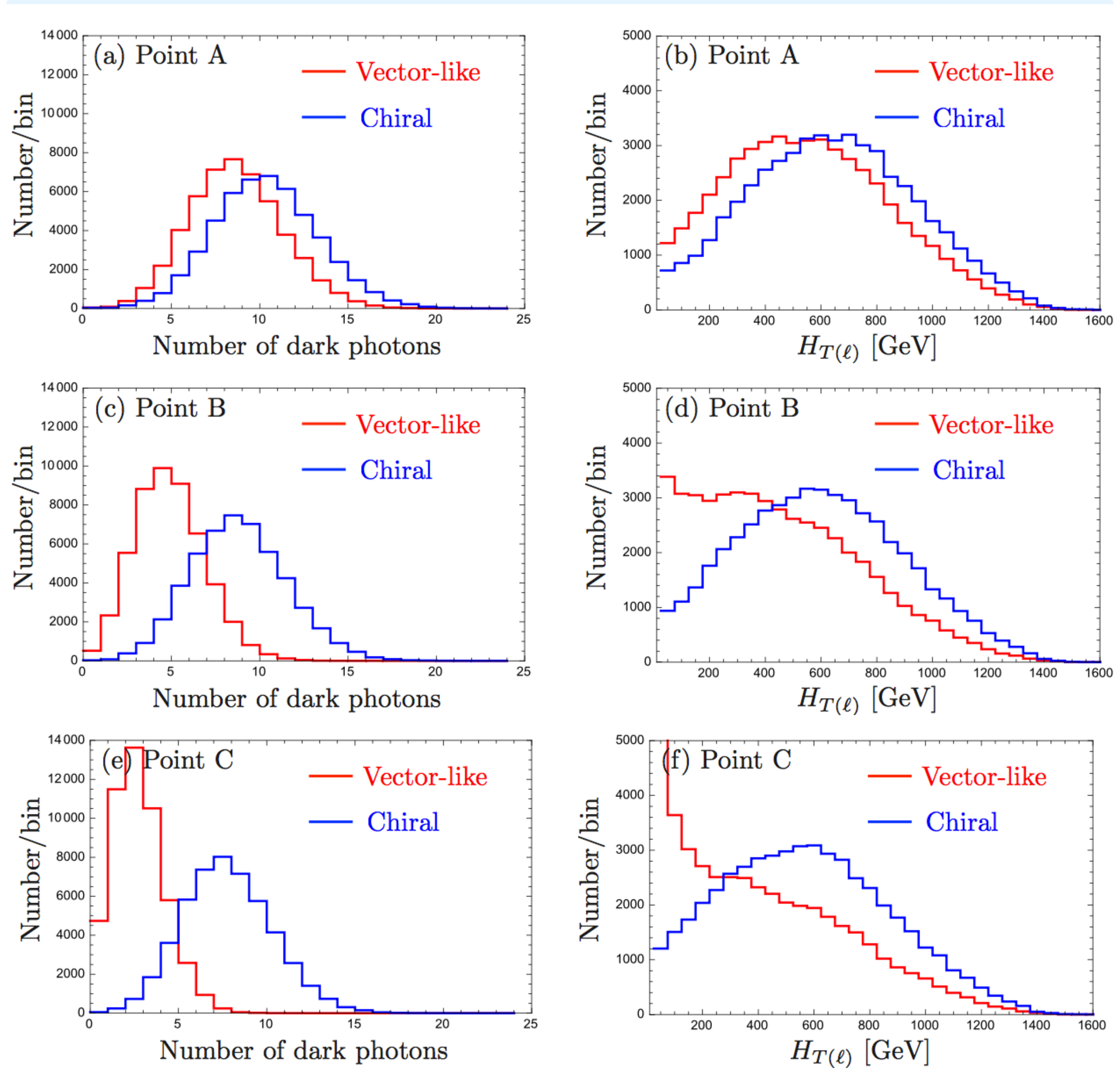
transverse longitudinal

So the shower pattern of chiral model and vector-like model will be different even with the same

$$m_\chi, \quad m_{A'}, \quad \alpha'$$

Consider 3 points:

Benchmark Points (BP)	A	B	C
α'	0.3	0.15	0.075
m_χ (GeV)	0.7	1.0	1.4
m_{γ_d} (GeV)	0.4		



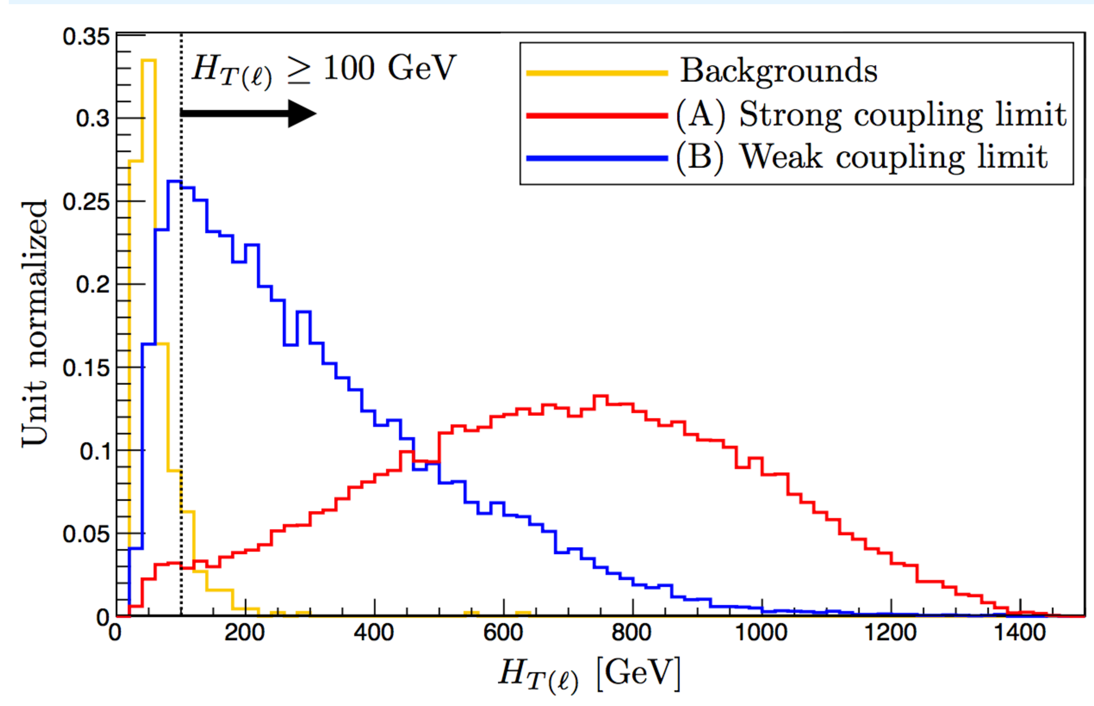
$$H_{T(\ell)} = \sum_{i=\mu^\pm, e^\pm} |p_{T_i}|.$$

Maybe we can use the distribution of H_T(l) to distinguish the nature of dark matter and the mass origin of dark sector. Then we need to consider:

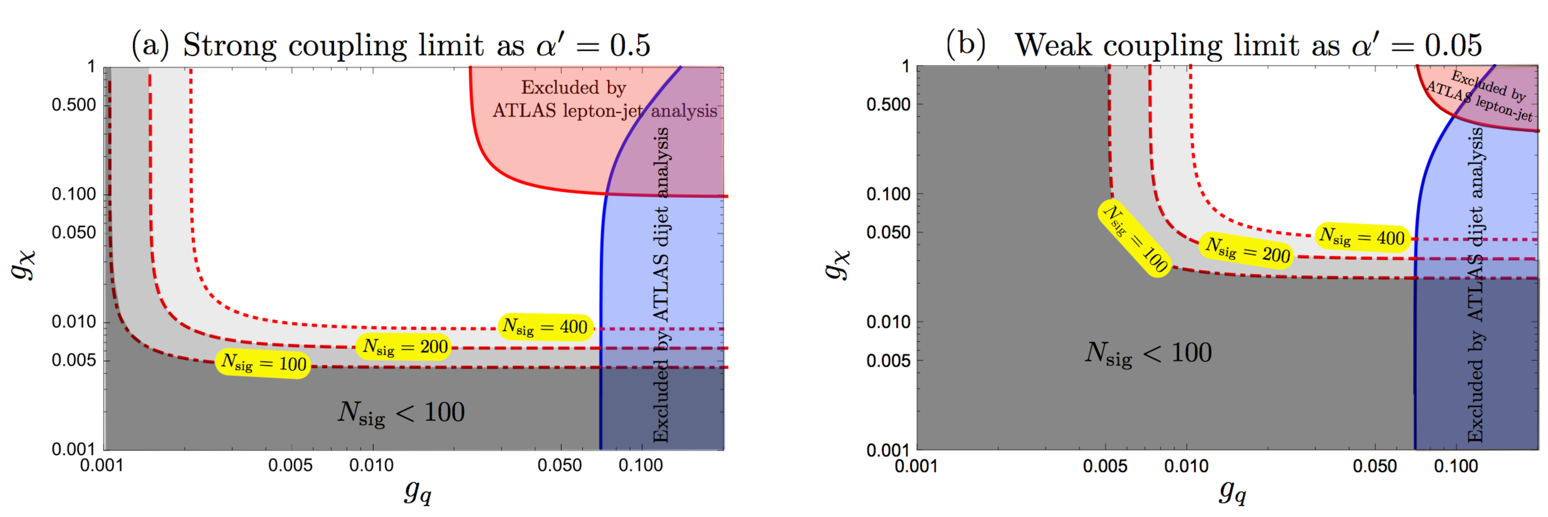
1.What is the parameter space allowed by current limit.(A recast to dijet and lepton-jet reports)

2.Sufficient signal should be produced at future collider. A efficient cut-flow need to be used to cut BKG.

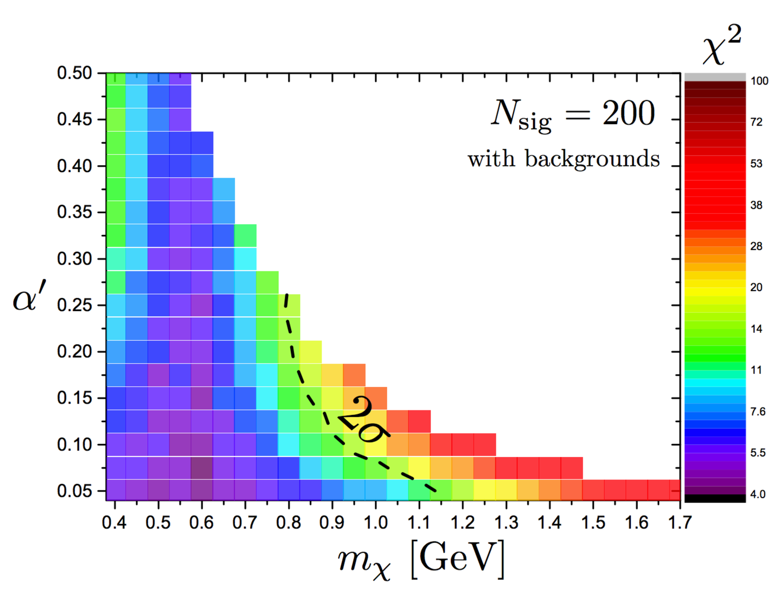
Cut-flow for future search:
lepton-jet, isolation, mass window of lepton jet, H_T(l) cut.
Here is the H_T(l) distribution after front cut:



Combination of current limits and signal number requirement at 3000fb-1 HL-LHC, for both strong dark shower and weak shower:



Distinguishing ability by 200 signal events. The region on the right side of black dash line can be distinguished at 2 sigma sig. level:



Perturbative limit is required here:

$$\alpha'\frac{m_\chi^2}{m_{\gamma_d}^2} \lesssim 1$$