Dark Matter Showering in $U_D(1)$ dark gauge group

Jinmian Li

Korea Institute for Advanced Study

Based on 1807.00530, J. Chen, P. Ko, H. Li, JL, H. Yokoya

Oct. 19th, 2018

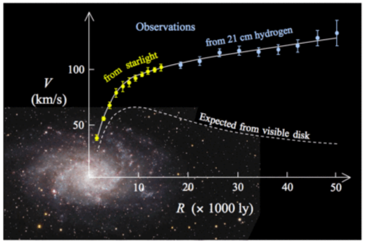
Mini-Workshop on Dark Sector Phenomenology: Models, Satellites, and Colliders

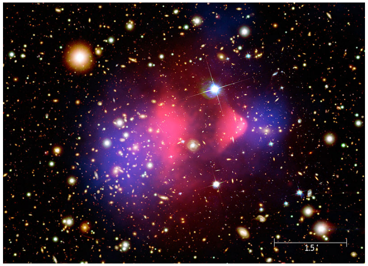
Institute of Physics, Academia Sinica

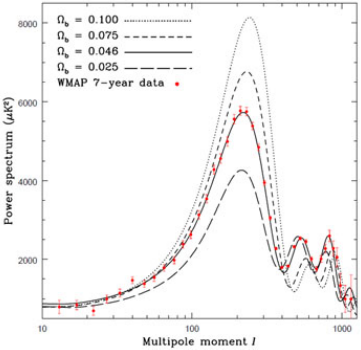
Outline

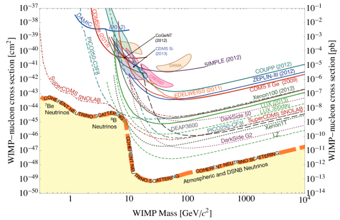
1. Motivation: Dark matter showering?
2. Unbroken $SU_D(N)$ dark sector: brief review
3. Massive dark photon in $U_D(1)$ case: revisit
   - The toy model setup
   - Splitting functions and improvements
   - Dark showering algorithm
   - Benchmark study
   - Toward a realistic search (In progressing ...)
4. Conclusion

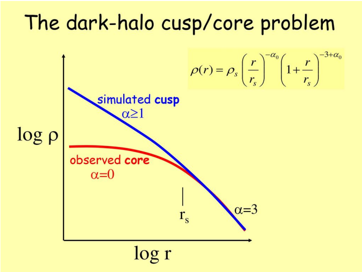
Motivation: Dark matter showering?

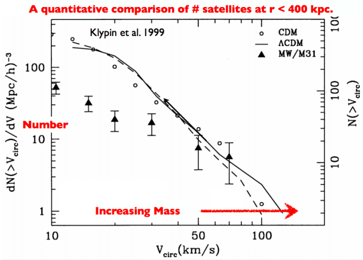












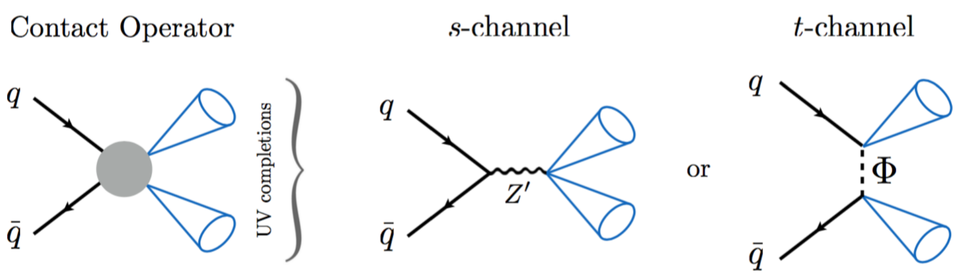
- Dark matter is neutral under SM $U_{\text{EM}}(1)$, does not mean it is neutral under dark $U_D(1)$.
- Hidden sector dark matter can release the tension between DM annihilation and DM direct detection.
- Strongly interaction in dark sector can explain the problems: core-cusp, missing satellites ...

Unbroken $SU_D(N)$ dark sector: minimal setup

- Lagrangian of dark sector, at scale much higher than confinement scale

$$\mathcal{L}_{\text{dark}} = \bar{\chi}_\alpha (i\not{D} - M_\alpha)\chi_\alpha - \frac{1}{4} G^d_{\mu\nu} G^{d\mu\nu}$$

- Dark particles χ_α form bound states at the confinement scale Λ_d.
- Depending on the symmetries of the theory, some fraction of these states are likely to be stable, providing good DM candidates.
- However, many of the mesons should decay back to the visible sector through the portal coupling.
- The portal also gives the dark sector production at colliders.



Semi-invisible jet versus QCD-like jet

The dark sector shower and "hadronization" are implement in Pythia8 (Hidden Vally model). The following facts impact the multiplicity of the dark jet and the relative p_T of the states in the shower:

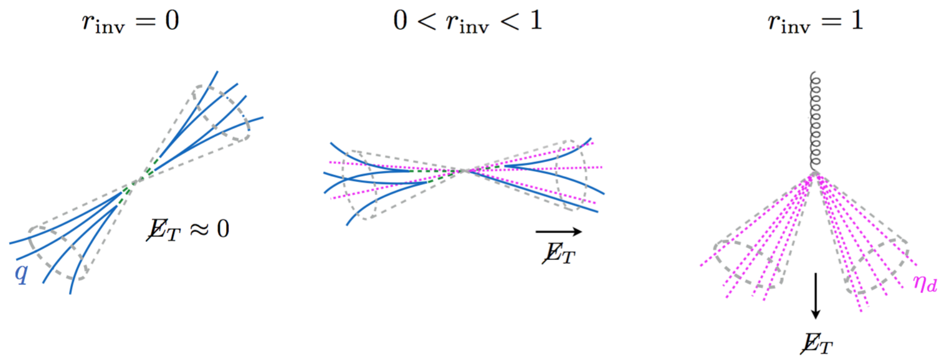
- Spin and CP configurations of the bound states: determine aspects of the decay parametrics.
- Relative number of stable and unstable states in the dark sector.
- Mass splitting between the various mesons/hadrons.

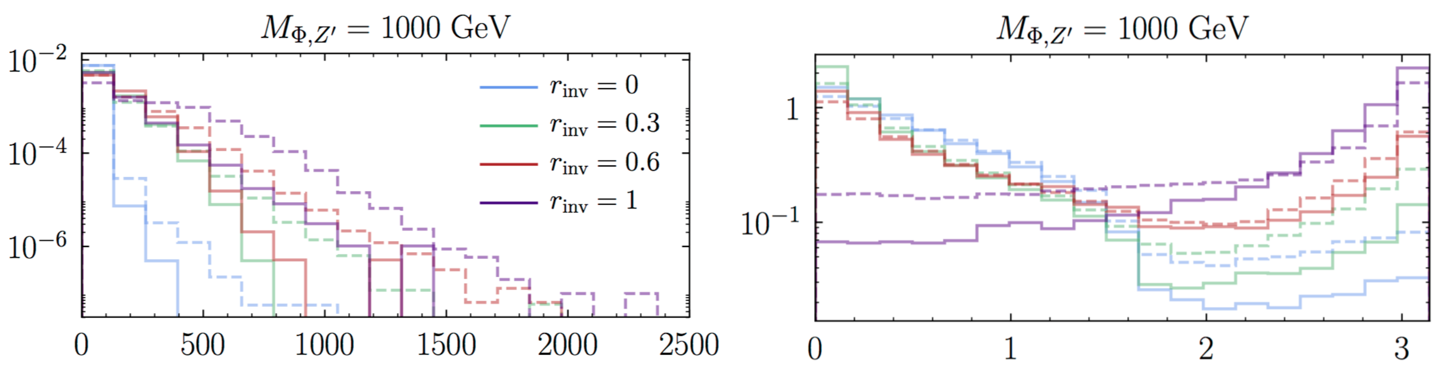
Three important parameter to describe the collider phenomenology:

- The characteristic mass scale for the dark hadrons, M_d.
- The dark strong coupling, α_d.
- $r_{\text{inv}} = \langle \frac{\#\text{ of stable hadrons}}{\#\text{ of hadrons}} \rangle$.
- The portal coupling Λ.

Search for semi-invisible jet

T. Cohen, 1707.05326





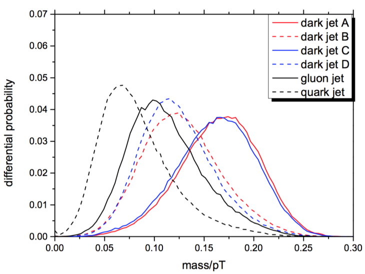
$E_T^{\rm miss}$ $\Delta\phi$

Tagging the QCD-like jet with jet-substructures variables ($r_{\text{inv}} = 0$)

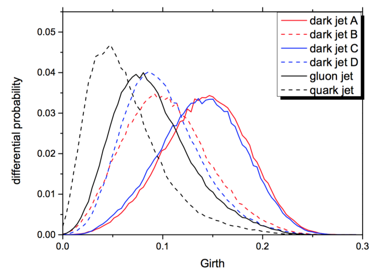
M. Park, 1712.09279

	N_d	n_f	Λ_d (GeV)	$\tilde{m}_{q'}$ (GeV)	m_{π_d} (GeV)	m_{ρ_d} (GeV)	π_d Decay Mode	ρ_d Decay Mode
A	3	2	15	20	10	50	$\pi_d \to c\bar{c}$	$\rho_d \to \pi_d\pi_d$
B	3	6	2	2	2	4.67	$\pi_d \to s\bar{s}$	$\rho_d \to \pi_d\pi_d$
C	3	2	15	20	10	50	$\pi_d \to \gamma'\gamma'$ with $m_{\gamma'} = 4.0GeV$	$\rho_d \to \pi_d\pi_d$
D	3	6	2	2	2	4.67	$\pi_d \to \gamma'\gamma'$ with $m_{\gamma'} = 0.7GeV$	$\rho_d \to \pi_d\pi_d$

$p_T(j) \in [180, 220]$ GeV



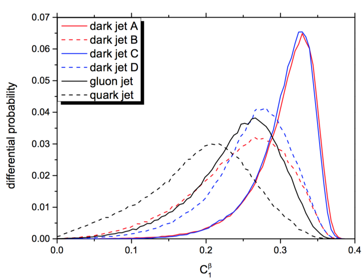
Jet mass



Girth $= \sum_{i \in J} z_i r_i$

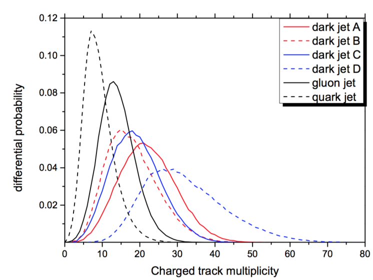
z_i, ith component p_T fraction

r_i is the distance between ith component and jet axis



Two point energy correlation function

$$C_1^{(\beta)} = \sum_{i<j \in J} z_i z_j (R_{ij}^{\beta})$$



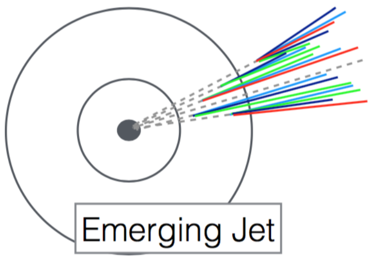
Charge track multiplicity

Emerging jet

P. Shwaller, 1502.05409

Parton shower of dark sector is followed by displaced hadrons/mesons back to SM particles:

- composed dominantly of displaced tracks
- have many different vertices within the jet cone



A case study:

- Signal: $pp \to X_d X_d^\dagger \to (Q_d \bar{q})\ (\bar{Q}_d q)$, $m_X = 1$ TeV

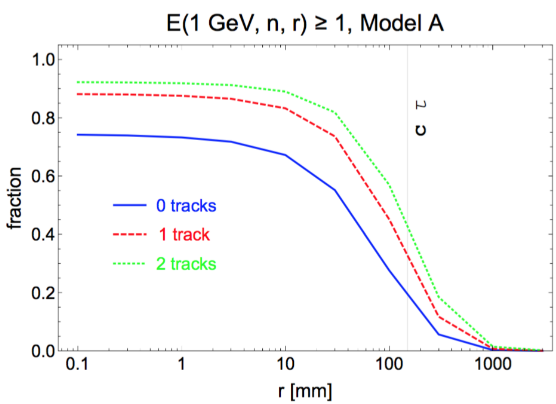
	Model **A**	Model **B**
Λ_d	10 GeV	4 GeV
m_V	20 GeV	8 GeV
m_{π_d}	5 GeV	2 GeV
$c\,\tau_{\pi_d}$	150 mm	5 mm

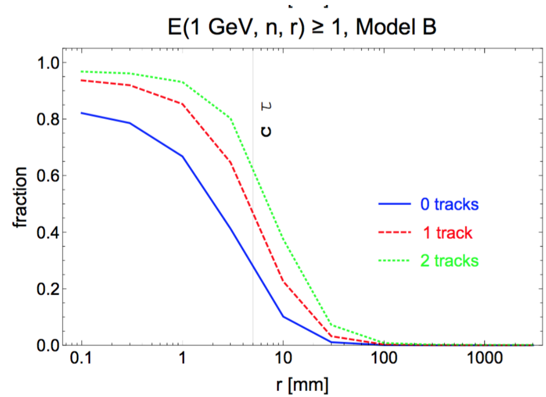
$N_c = 3, \ n_f = 7$

- Dominant background for these sorts of four jet events will be from high p_T QCD

Emerging jet

Definition of Emerging jet $E(p_T^{\min}, n, r)$: a jet with $\leq n$ tracks with $p_T > p_T^{\min}$ originating a transverse distance smaller than r from the interaction point





	Model **A**	Model **B**	QCD 4-jet	Modified PYTHIA
Tree level	14.6	14.6	410,000	410,000
≥ 4 jets, $\lvert\eta\rvert < 2.5$ $p_T(\text{jet}) > 200$ GeV $H_T > 1000$ GeV	4.9	8.5	48,000	48,000
$E(1\,\text{GeV}, 0, 3\,\text{mm}) \geq 1$	3.6	3.5	45	57
$E(1\,\text{GeV}, 0, 3\,\text{mm}) \geq 2$	1.2	0.5	~ 0.08	~ 0.04
$E(1\,\text{GeV}, 0, 100\,\text{mm}) \geq 1$	1.4	$\lesssim 0.01$	8.5	12
$E(1\,\text{GeV}, 0, 100\,\text{mm}) \geq 2$	0.1	$\lesssim 0.01$	$\lesssim 0.02$	$\lesssim 0.02$

Outline

1. Motivation: Dark matter showering?
2. Unbroken $SU_D(N)$ dark sector: brief review
3. Massive dark photon in $U_D(1)$ case: revisit
   - The toy model setup
   - Splitting functions and improvements
   - Dark showering algorithm
   - Benchmark study
   - Toward a realistic search (In progressing ...)
4. Conclusion

The model setup

M. Buschmann, 1505.07459, M. Kim, 1612.02850

$$\mathcal{L}^{\text{chiral}} = -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{\epsilon}{2}F'_{\mu\nu}F^{\mu\nu} + |D_\mu\Phi'|^2 - \frac{\lambda_{\Phi'}}{4}\left(|\Phi'|^2 - \frac{v_{\Phi'}^2}{2}\right)^2 + \sum_{s=L/R} i\overline{\chi}_s \not{D}\chi_s - \left(y_\chi \overline{\chi_L}\Phi'\chi_R + h.c.\right)$$

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

- $D_\mu = \partial_\mu - ig'Q_{L/R}A'_\mu$, $Q_L \neq Q_R$ for chiral case.

$$\mathcal{L}_{\text{int}} \subset g'Q_L A'_\mu \bar{\chi}_L\gamma^\mu\chi_L + g'Q_R A'_\mu\bar{\chi}_R\gamma^\mu\chi_R$$

- Higgs mechanism for chiral case ($\langle\Phi'\rangle = v_{\Phi'}$):

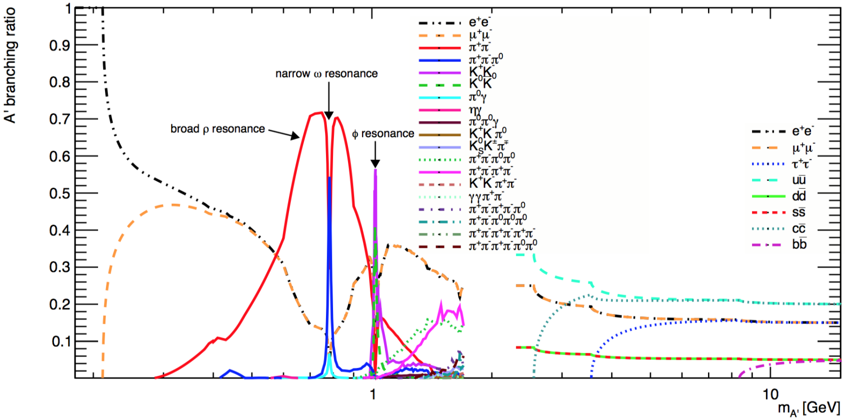
$$m_{A'} = g'Q_{\Phi'}v_{\Phi'},\ m_\chi = y_\chi v_{\Phi'}/\sqrt{2}.$$

- Requiring perturbative Yukawa coupling: $y_\chi/\sqrt{2} < \sqrt{4\pi} \Rightarrow \alpha' \frac{m_\chi^2}{m_{A'}^2} Q_{\Phi'}^2 < 1$.

Decay of dark photon

M. Buschmann, 1505.07459

Induce by the kinetic mixing with the SM photon: $\frac{\epsilon}{2}F'_{\mu\nu}F^{\mu\nu}$

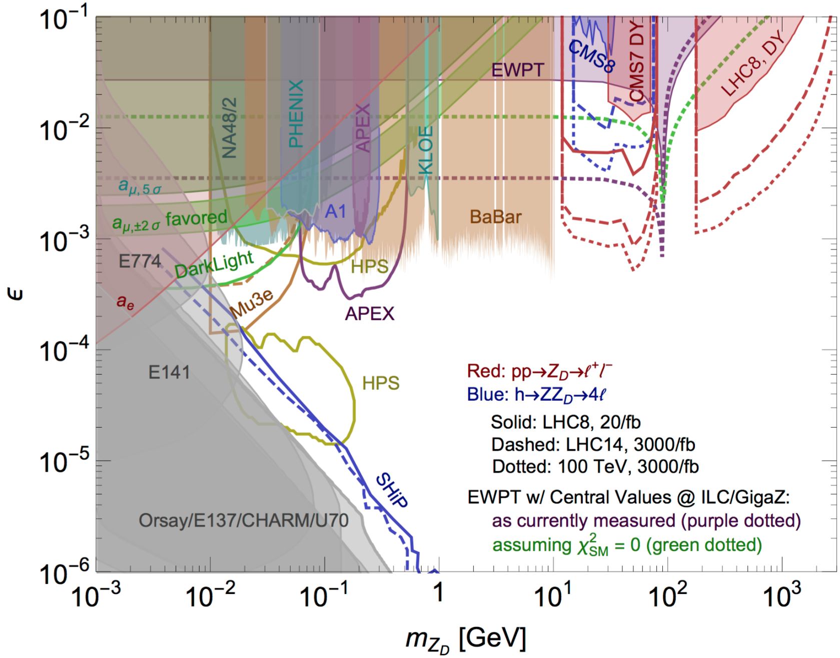


- $\Gamma(A' \to \ell^+\ell^-) = \frac{1}{3}\alpha\epsilon^2 m_{A'}\sqrt{1-4\frac{m_\ell^2}{m_{A'}^2}}(1+2\frac{m_\ell^2}{m_{A'}^2})$
- $\Gamma(A' \to \text{hadrons}) = \Gamma(A' \to \mu^+\mu-)R(s = m_{A'}^2)$,
  $R(s) = \sigma(e^+e^- \to \text{hadrons})/\sigma(e^+e- \to \mu^+\mu-)$; for $m_{A'} \lesssim 2$ GeV.
- $\Gamma(A' \to q_f\bar{q}_f) = N_c Q_{qf}^2 \Gamma(A' \to \ell^+\ell^-)|_{m_\ell = m_{qf}}$; for $m_{A'} \gtrsim 2$ GeV

Dark photon constraints

- Dark photon search experiments

  D. Curtin, 1412.0018



- For $m_{A'} \sim 1$ GeV, kinetic mixing $\epsilon \gtrsim 10^{-5}$, so that A' decays within a length of $\sim \mathcal{O}(1)$ mm.

Splitting functions and improvements

The differential probability of a splitting process

$$\frac{\alpha'}{2\pi}dx\frac{dt}{t}P_{\chi\to\chi\gamma_d}(x,t), \quad x=\frac{E_{\chi,\text{ out}}}{E_{\chi,\text{ in}}}$$

- M. Buschmann et.al, (arXiv:1505.07459), splitting kernel contains only transverse modes in a high energy limit

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

- M. Kim et.al, (arXiv:1612.02850), the longitudinal mode of dark photon is included (for chiral model)

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

1. The helicity information of fermion DM splitting

$$\frac{d\mathcal{P}}{dxdk_T^2}(\chi_s \to \chi_s + A'_T) = \frac{\alpha'}{2\pi} Q_s^2 \frac{1+x^2}{1-x} \frac{k_T^2}{\tilde{k}_T^4},$$

$$\frac{d\mathcal{P}}{dxdk_T^2}(\chi_s \to \chi_{-s} + A'_L) = \frac{\alpha'}{2\pi} \frac{m_\chi^2}{m_{A'}^2} Q_{\Phi'}^2 \frac{1-x}{2} \frac{k_T^2}{\tilde{k}_T^4},$$

- Initial particle in the shower may be polarized.
- In chiral model, the left-handed and right handed components have different $U(1)_D$ charges, thus different splitting probability.
- The radiation of A'_T change the helicity while A'_L is not.
- As an example: take the benchmark point A (will be introduced later) for the Chiral Model, starting from unpolarized DM fermions, we get roughly 70% left-handed DM fermions and 30% right-handed DM fermions in the final states.

- $d\sigma_{n+1} \sim |\mathcal{M}_{n+1}|^2 d\Phi_{n+1} = d\sigma_n \cdot dP_{A\to B+C}$, for massive particle

$$\frac{dP_{A\to B+C}}{dx dk_T^2} \sim \frac{1}{16\pi^2}\frac{x(1-x)}{\tilde{k}_T^4}|\mathcal{M}^{\text{split}}|^2,$$

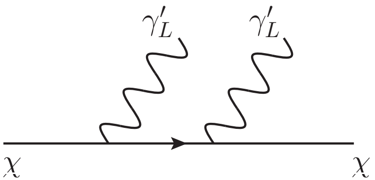
with $\tilde{k}_T^2 = k_T^2 + x m_\chi^2 + (1-x)m_{A'}^2 - x(1-x)m_\chi^2$.
Taylor expansion of $\frac{k_T^2}{\tilde{k}_T^4} \sim \frac{1}{k_T^2} + \frac{m^2}{k_T^4}$.

$$\frac{d\mathcal{P}}{dx dk_T^2}(\chi_s \to \chi_{-s} + A'_T) = \frac{\alpha'}{2\pi}(1-x)(Q_s - Q_{-s}x)^2 \frac{m_\chi^2}{\tilde{k}_T^4}$$

- The fermion dark matter wave function:

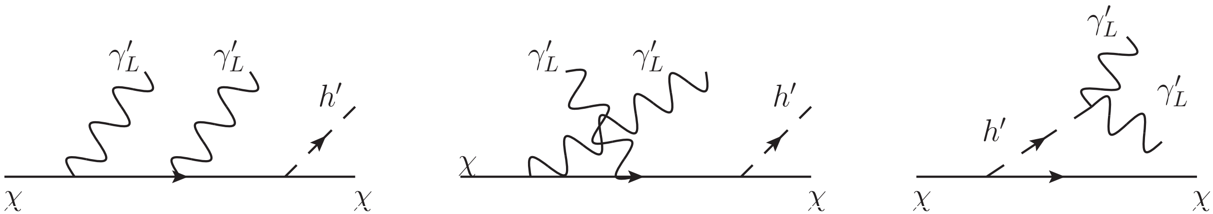
$$u_L \sim \sqrt{2E}\begin{pmatrix} \binom{-\theta/2}{1} \\ \frac{m_\chi}{2E}\binom{-\theta/2}{1} \end{pmatrix}, \qquad u_R \sim \sqrt{2E}\begin{pmatrix} \frac{m_\chi}{2E}\binom{1}{\theta/2} \\ \binom{1}{\theta/2} \end{pmatrix}.$$

Large interference in high-energy splitting:



$$\mathcal{M} \propto \frac{E^2}{m^2_{\gamma'}}$$

Cancelled by including the Higgs contribution



$$\frac{d\mathcal{P}}{dx dk_T^2}(\chi_s \to \chi_s + A'_L) = \frac{\alpha'}{2\pi}\frac{1}{2(1-x)}\left(2Q_s x + (-1)^{s+\frac{1}{2}}\frac{(1-x)^2 m_\chi^2}{m_{A'}^2}Q_{\Phi'}\right)^2 \frac{m_{A'}^2}{\tilde{k}_T^4}$$

- Take into account the symmetry breaking effects by imposing the Goldstone equivalence gauge

$$\epsilon_L^\mu = \frac{k^\mu}{m_{A'}} - \frac{m_{A'}}{n\cdot k}n^\mu$$

- The first term $\frac{k^\mu}{m_{A'}}$ induces a bad high-energy behavior and large interference
- It is identified as the Goldstone mode and removed from the freedom of gauge boson.
- The remnant term $-\frac{m_{A'}}{n\cdot k}n^\mu$ can still receive a compensating ultra-collinear power-enhancement in the region $k_T \sim m_{A'}$.
- The amplitudes involving longitudinal vector bosons are then evaluated by summing diagrams for both the Goldstone and gauge components in GEG.

3. Splitting into dark Higgs boson

$$\frac{d\mathcal{P}}{dx dk_T^2}(\chi_s \to \chi_{-s} + h') = \frac{\alpha'}{2\pi} \frac{m_\chi^2}{m_{A'}^2} Q_{\Phi'}^2 \frac{1-x}{2} \frac{k_T^2}{\tilde{k}_T^4},$$

$$\frac{d\mathcal{P}}{dx dk_T^2}(\chi_s \to \chi_s + h') = \frac{\alpha'}{2\pi} Q_{\Phi'}^2 \frac{(1-x)(1+x)^2}{2} \frac{m_\chi^2}{m_{A'}^2} \frac{m_\chi^2}{\tilde{k}_T^4}$$

- The dark Higgs may be split further. (we do not consider)
- The dark Higgs can decay either into dark matter pair or dark photon pair, depending on the mass hierarchy, gauge and Yukawa couplings.

List of splitting functions

$$\frac{d\mathcal{P}}{dxdk_T^2}(\chi_s \to \chi_s + A'_T) = \frac{\alpha'}{2\pi} Q_s^2 \frac{1+x^2}{1-x} \frac{k_T^2}{\tilde{k}_T^4},$$

$$\frac{d\mathcal{P}}{dxdk_T^2}(\chi_s \to \chi_{-s} + A'_L) = \frac{\alpha'}{2\pi} \frac{m_\chi^2}{m_{A'}^2} Q_{\Phi'}^2 \frac{1-x}{2} \frac{k_T^2}{\tilde{k}_T^4},$$

$$\frac{d\mathcal{P}}{dxdk_T^2}(\chi_s \to \chi_{-s} + A'_T) = \frac{\alpha'}{2\pi}(1-x)(Q_s - Q_{-s}x)^2 \frac{m_\chi^2}{\tilde{k}_T^4}$$

$$\frac{d\mathcal{P}}{dxdk_T^2}(\chi_s \to \chi_s + A'_L) = \frac{\alpha'}{2\pi} \frac{1}{2(1-x)} \left(2Q_s x + (-1)^{s+\frac{1}{2}} \frac{(1-x)^2 m_\chi^2}{m_{A'}^2} Q_{\Phi'} \right)^2 \frac{m_{A'}^2}{\tilde{k}_T^4}$$

$$\frac{d\mathcal{P}}{dxdk_T^2}(\chi_s \to \chi_{-s} + h') = \frac{\alpha'}{2\pi} \frac{m_\chi^2}{m_{A'}^2} Q_{\Phi'}^2 \frac{1-x}{2} \frac{k_T^2}{\tilde{k}_T^4},$$

$$\frac{d\mathcal{P}}{dxdk_T^2}(\chi_s \to \chi_s + h') = \frac{\alpha'}{2\pi} Q_{\Phi'}^2 \frac{(1-x)(1+x)^2}{2} \frac{m_\chi^2}{m_{A'}^2} \frac{m_\chi^2}{\tilde{k}_T^4}$$

The dark shower Algorithm

J. Chen, T. Han and B. Tweedie, arXiv:1611.00788

Evolution of the virtuality t:

- At given virtuality t^0, integrate over x for each splitting function

$$I_i = \int_{x_{\min}}^{x_{\max}} \mathcal{P}(x, t^0) dx, \qquad J_i = \sum_{i=1,i} I_i$$

- Generating an random number between $R = [0, J_N]$. If $J_{j-1} < R < J_j$, select the jth splitting function.
- Calculate the next $t' = t^0 - dt$, $dt = dt^0 \times R^t$ with dt^0 set by hand and $R^t \in [0, 1]$.
- The Sudakov factor is given by

$$\Delta(t^0) = e^{-dt \cdot J_N}$$

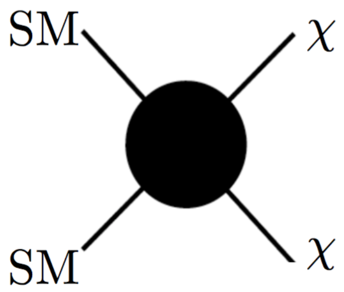
- Generate another random number $R^s \in [0, 1]$, if $R^s > \Delta(t^0)$, do the branching and calculate the kinematic information of daughters
- Continue the evolution with daughters until meeting the cut off.

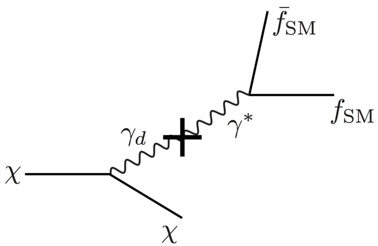
Benchmark study

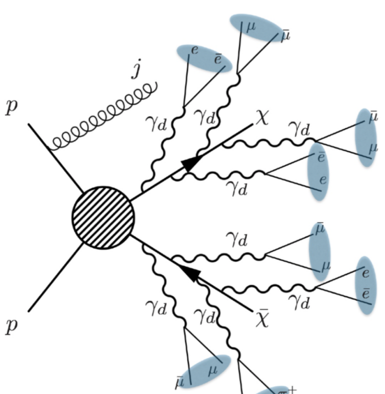
point A:	$\alpha' = 0.3$	$m_\chi = 0.7$ GeV	$m_{A'} = 0.4$ GeV	$m_{h'} = 1.0$ GeV,
point B:	$\alpha' = 0.15$	$m_\chi = 1.0$ GeV	$m_{A'} = 0.4$ GeV	$m_{h'} = 1.0$ GeV,
point C:	$\alpha' = 0.075$	$m_\chi = 1.4$ GeV	$m_{A'} = 0.4$ GeV	$m_{h'} = 1.4$ GeV,

- We choose $(Q_V, Q_A) = (1/2, 1/2)$ for the Chiral Model and $(Q_V, Q_A) = (1, 0)$ for the Vector Model, where $Q_V = \frac{Q_L+Q_R}{2}$ and $Q_A = \frac{Q_L-Q_R}{2}$.
- The Yukawa couplings are $\sim \sqrt{2}\sqrt{4\pi}$, close to the perturbative limit.

Energetic DM @ collider







- The portal to the SM sector can be described by an effective coupling $(\bar{q}\gamma^{\mu}q)(\bar{\chi}\gamma_{\mu}\chi)$, by integrating out a heavy vector boson.
- The decay of dark photon is induced by the kinetic mixing, its time scale is assumed to be much larger than DM shower. For all points, $\mathrm{Br}(A' \to ee) = \mathrm{Br}(A' \to \mu\mu) = 0.45$ and $\mathrm{Br}(A' \to \pi\pi) = 0.1$. Assuming $\epsilon \gtrsim 8.2 \times 10^{-6}$, so that A' decays within a length of $\sim \mathcal{O}(1)$ mm.
- Dark Higgs exclusively decay into pairs of dark photons (later than DM shower).
- Consider the DM production at hadron collider, hard initial state radiation to boost the DM pair system, $p_T(j) > 200$ GeV.

Observables to be considered

- The expectation value for the number of radiated dark photon:

$$\langle n_{A'} \rangle \sim \frac{\alpha_{A'}}{2\pi} \int dx \int \frac{dt}{t} \sum P^i_{\chi \to \chi}(x,t)$$

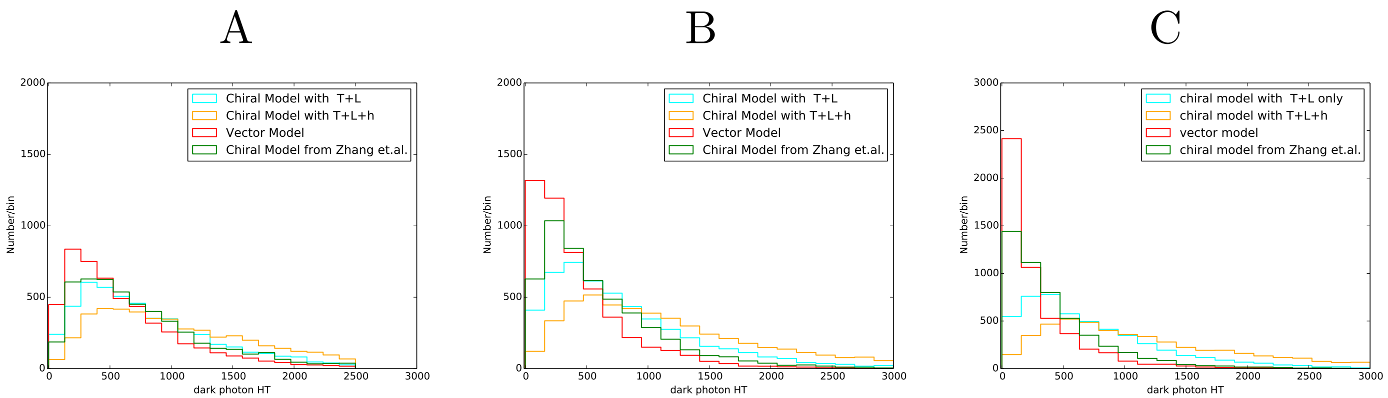
- The probability that χ radiates exactly m dark photons is given by a Poisson distribution

$$p_m = \frac{e^{-\langle n_{A'} \rangle} \langle n_{A'} \rangle^m}{m!}$$

- The scalar sum of the dark photons transverse momenta (that for DM particles are almost the same)

$$H_T(A') = \sum_{i=\text{all } A'} |p_T(A'_i)|$$

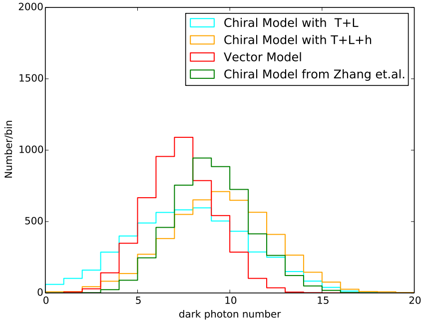
H_T distributions for benchmark points



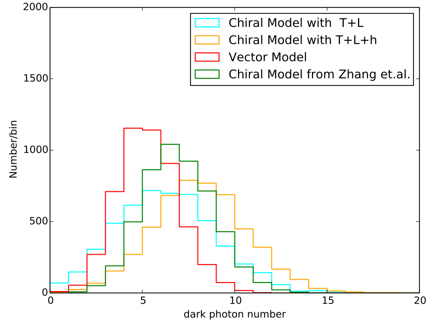
- H_T distribution in the Vector Model is more enhanced at lower value, compared with the Chiral Model.
- The unbroken splitting $\chi_s \to \chi_s A'_T$ contains soft singularity, whereas $\chi_s \to \chi_{-s} A'_L$ and $\chi_s \to \chi_{-s} h'$ do not.
- This feature is most useful, as the Yukawa coupling, characterized by the ratio $\frac{m_\chi}{m_{A'}}$, is comparable to the gauge coupling, from A to C.
- There is also additional contribution from dark Higgs bosons in the Chiral Model.

Dark photon number distributions for benchmark points

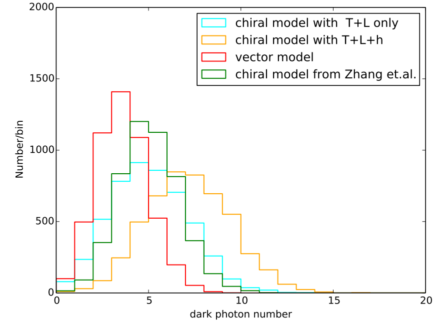
A



B

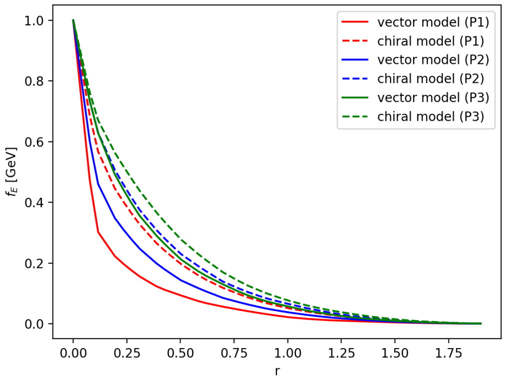


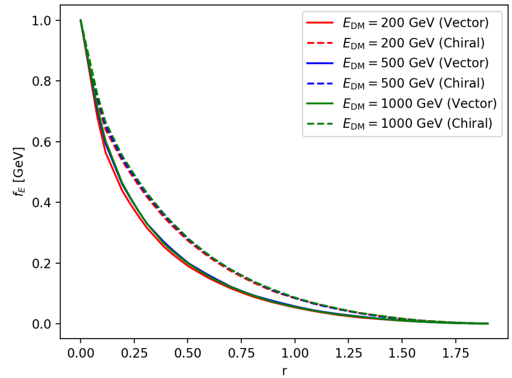
C



- Peak in the $n_{A'}$ distribution is generally higher, while the peak position is smaller, in the Vector Model than in the Chiral Model.
- Additional emissions of longitudinally polarized dark photons and dark Higgs bosons in the Chiral Model.
- From A to C, reduced gauge coupling.

The jet profile for each cases





- Cluster the final state particles radiated by a DM fermion using the anti-k_t jet algorithm for the jet radius $R = 2$ to determine the jet axis
- Jet profile is described by the variable $f_E(r)$, defined as the energy fraction outside the cone with the radius $r < R$.
- The jets are broader in the Chiral Model than in the Vector Model, soft singularity in the momentum fraction for transversely polarized γ_D.
- The jet profile is mainly determined by the DM fermion chirality, and almost independent of the DM energy.

ATLAS, arXiv:1511.05542 **Search for a new, light boson with a mass of about 1 GeV and decaying promptly to jets of collimated electrons and/or muons (lepton-jets)**

Lepton jet:

- Starting from the hardest track, find the next hard track within $\Delta R = 0.5$.
- Sum two track momentum to give the lepton-jet candidate.
- Subsequent tracks within $\Delta R = 0.5$ of the lepton-jet candidate are added iteratively.
- Tracks that are added to a lepton-jet candidate are removed from consideration for subsequent LJ candidates.
- Additional lepton-jets are built from the remaining tracks in the list following the same procedure
- Each lepton-jet candidate contains at least two tracks ($p_T > 5$ GeV).

Muon jet: If at least two muons with $p_T > 10$ GeV are found within $\Delta R = 0.5$ of the lepton-jet but no electrons.

Backgrounds

- Hadronic multijet (hadrons being misidentified as leptons, Data driven)
- Diboson ($WW, WZ, ZZ, \gamma\gamma$, MC)

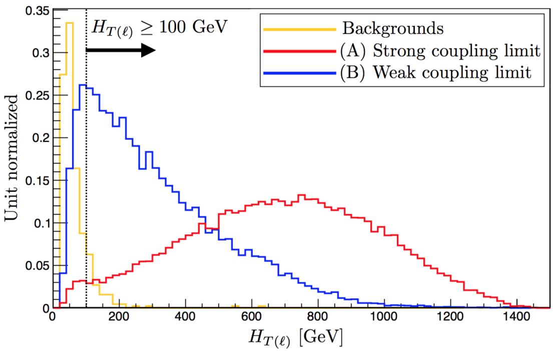
Discriminating variables (muon-jets)

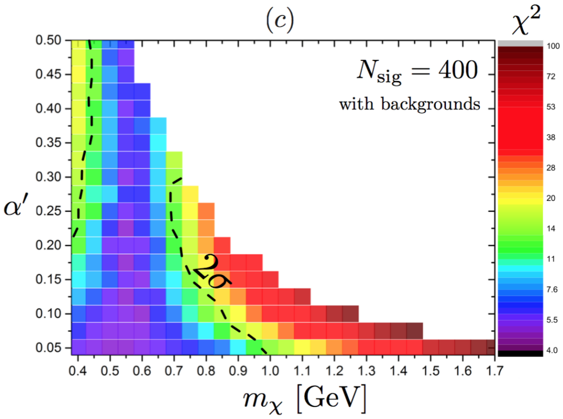
- Track isolation: ratio of the scalar sum of the p_T of the ID tracks, excluding the muon tracks, within $\Delta R = 0.5$ around the muLJ direction, to the pT of the muLJ (< 0.25).
- Calorimeter isolation: ratio of the total transverse energy in the calorimeter within $\Delta R = 0.2$ from the leading muon of a muLJ to the pT of that muon (< 0.15).

Channel	Hadronic multijet	All BKGs	Observation
muLJ-muLJ	2.9 ± 0.6	4.4 ± 1.1	4

Toward a realistic search - future prospects

- More discriminating variable specified to models
- Distinguishing the vector-DM and chiral-DM cases.





- Distinguishing the DM internal parameters, such as DM mass, DM spin, ...
- Indirect detection signals?

Conclusion

- Dark sector could have gauge symmetry.
- Dark matter shower under unbroken $SU(N)$ and unbroken/broken $U(1)$ have been established.
- The mass origin in $U(1)$ dark sector can affect the pattern of dark photon radiation.
- LHC may not only find dark matter (dark sector), but also able to measure properties of a dark sector.