Dark photon jets

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Motivation

- BSM physics should exist, but may not be particle-like
- Dark matter expected, despite of null results from direct and indirect detections so far
- Given rich dynamics in SM, natural to think about interactive structure of dark sector
- Dark sector can be explored in QCD aspect through its very weak coupling to SM

Dark photon jets

- Possible to have hidden U(1)’ gauge group---dark photons
- U(1)’ may kinetically mix with SM U(1)
- Light (sub-GeV) DM charged under U(1)’, if produced energetically at collider, radiates collimated dark photons, decaying back to SM particles (leptons, hadrons), and forming jets
- Jet substructures (intensively studied in QCD) of dark photons can reveal DM property

Chirality and mass generation

- Here determine DM fermion is chiral- or vector-like by dark photon jet substructure
- Chirality of DM fermion might be related to mass generation mechanism
- Particle mass usually generated by Higgs mechanism
- For U(1) gauge group, Stueckelberg mechanism is also possible

Higgs mechanism 1964

- Before symmetry breaking

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

$$D_\mu = \partial_\mu - ig'Q_s A'_\mu \qquad s = L/R \qquad Q_{\Phi'} = Q_L - Q_R$$

- After symmetry breaking

vev

$$\Phi' = \frac{1}{\sqrt{2}}(h' + i\phi') \qquad h' \to h' + v_{\Phi'}$$

$$m_{A'} = g'Q_{\Phi'}v_{\Phi'} \qquad m_\chi = \frac{y_\chi v_{\Phi'}}{\sqrt{2}} \qquad m_{h'}^2 = \frac{\lambda_{\Phi'}v_{\Phi'}^2}{2}$$

Stueckelberg mechanism 1938

- Limit of Higgs model with vev going to infinity and Higgs charge, Yukawa coupling to zero in a way that gauge boson and fermion masses stay fixed
- Higgs with infinite mass decouples
- Theory remains renormalizable though not manifestly gauge invariant

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

$Q_L = Q_R$ Higgs charge goes to zero

Higgs vs Stueckelberg

- If DM fermion chiral-like, left- and right-handed fermions can have different U(1)' charges. Bare fermion mass term is forbidden
- Dark Higgs exists to give DM fermion and dark photon masses
- If DM fermion vector-like, left- and right-handed fermions have same charge
- Naturally assume dark photon mass comes from Stueckelberg mechanism. No Higgs

Models and Parameters

- Chiral (Higgs) vs vector model (Stueckelberg)
- Difference characterized by charge ratio Q_L/Q_R

$$(Q_L, Q_R) = (2, 0) \quad \text{for the Chiral Model}$$

$$(Q_L, Q_R) = (1, 1) \quad \text{for the Vector Model}$$

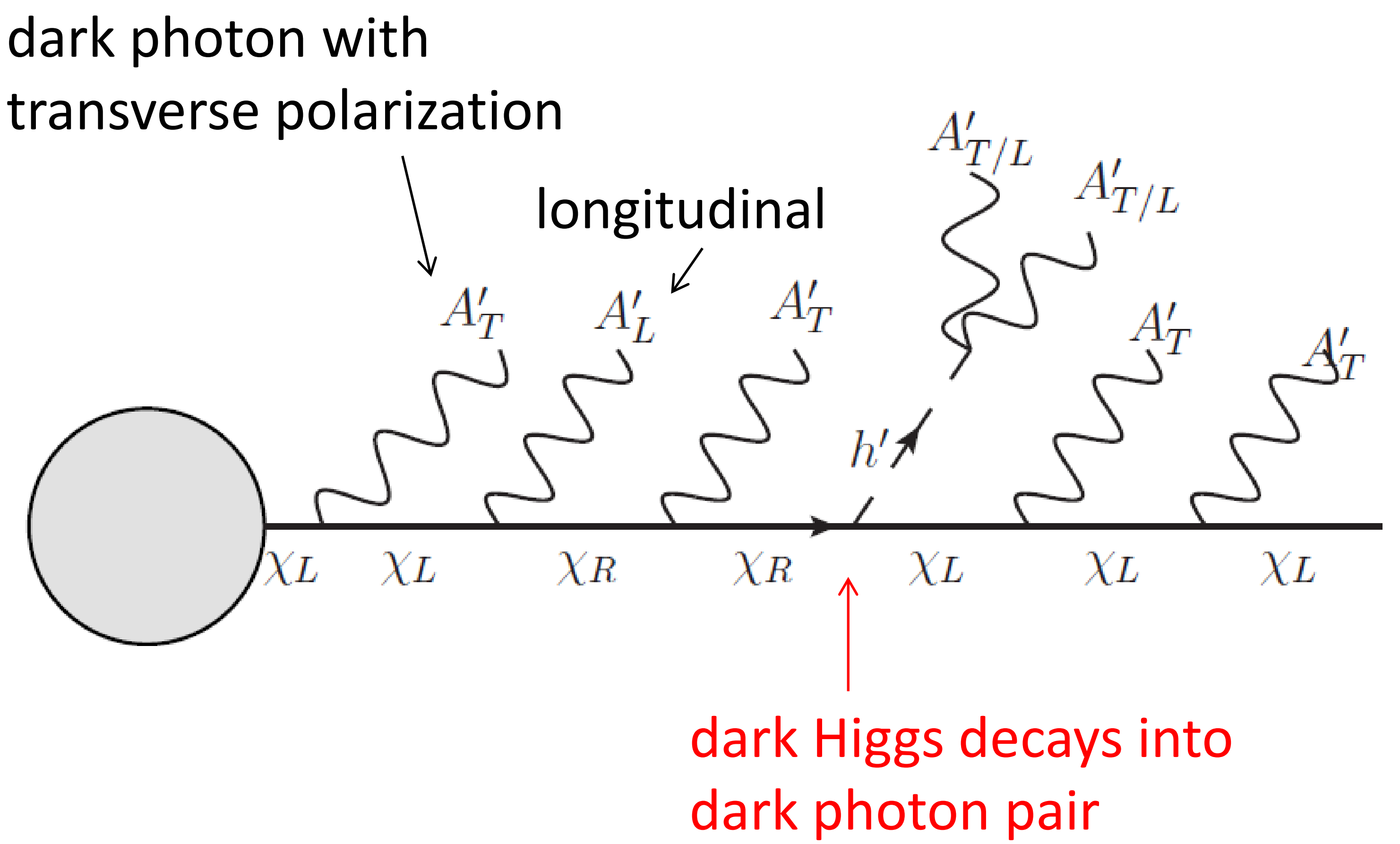
- Benchmark points

point A: $\alpha' = 0.3$ $\quad m_\chi = 0.7$ GeV $\quad m_{A'} = 0.4$ GeV $\quad m_{h'} = 1.0$ GeV,

point B: $\alpha' = 0.15$ $\quad m_\chi = 1.0$ GeV $\quad m_{A'} = 0.4$ GeV $\quad m_{h'} = 1.0$ GeV,

point C: $\alpha' = 0.075$ $\quad m_\chi = 1.4$ GeV $\quad m_{A'} = 0.4$ GeV $\quad m_{h'} = 1.4$ GeV

Dark shower


dark photon with
transverse polarization
longitudinal
A'_T
A'_L
A'_T
$A'_{T/L}$
$A'_{T/L}$
A'_T
A'_T
h'
χ_L
χ_L
χ_R
χ_R
χ_L
χ_L
χ_L
dark Higgs decays into
dark photon pair

Splitting functions

Chen, Han, Tweedie 2016

$$\frac{d\mathcal{P}_{A\to B+C}}{dz\,dk_T^2} \qquad z = \frac{E_C}{E_A}$$

soft singularity

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

$\tilde{k}_T^2 = k_T^2 + \bar{z}^2 m_\chi^2 + z m_{A'}^2$

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

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

vanish for vector model

helicity flip, proportional to fermion mass

Setting

- DM fermion pair production at LHC with c.o.m E=14 TeV through effective operator $(\bar{q}\gamma^{\mu}q)(\bar{\chi}\gamma_{\mu}\chi)$
- Plus associated jet with pT > 200 GeV to have missing energy
- Total width $\Gamma_{A'} \sim \alpha_{\rm em}\epsilon^2 M_{A'}$ corresponding to A' decay length $\mathcal{O}(1)$ mm demands large enough kinetic mixing $\epsilon \gtrsim 8.2 \times 10^{-6}$, so that dark photons mostly decay into SM particles inside collider

Observables

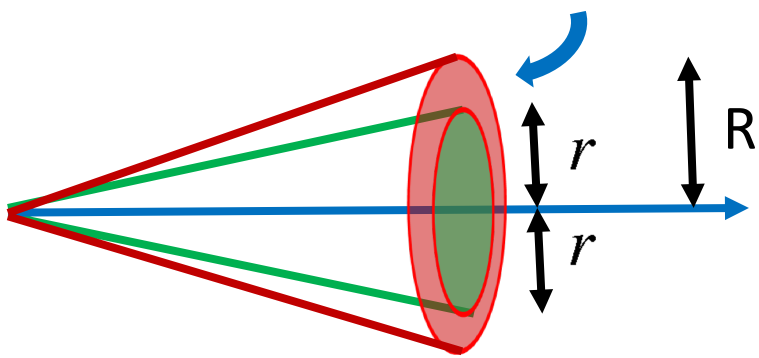
- Implement splitting functions into dark shower
- Final-state dark radiation only, since initial state SM radiation mainly soft (of order GeV) with jet pT cut (of order 100 GeV), and negligible
- Consider IR safe observables, like scalar sum:

$$H_T = \sum_{i=A'} |p_{T_i}|$$

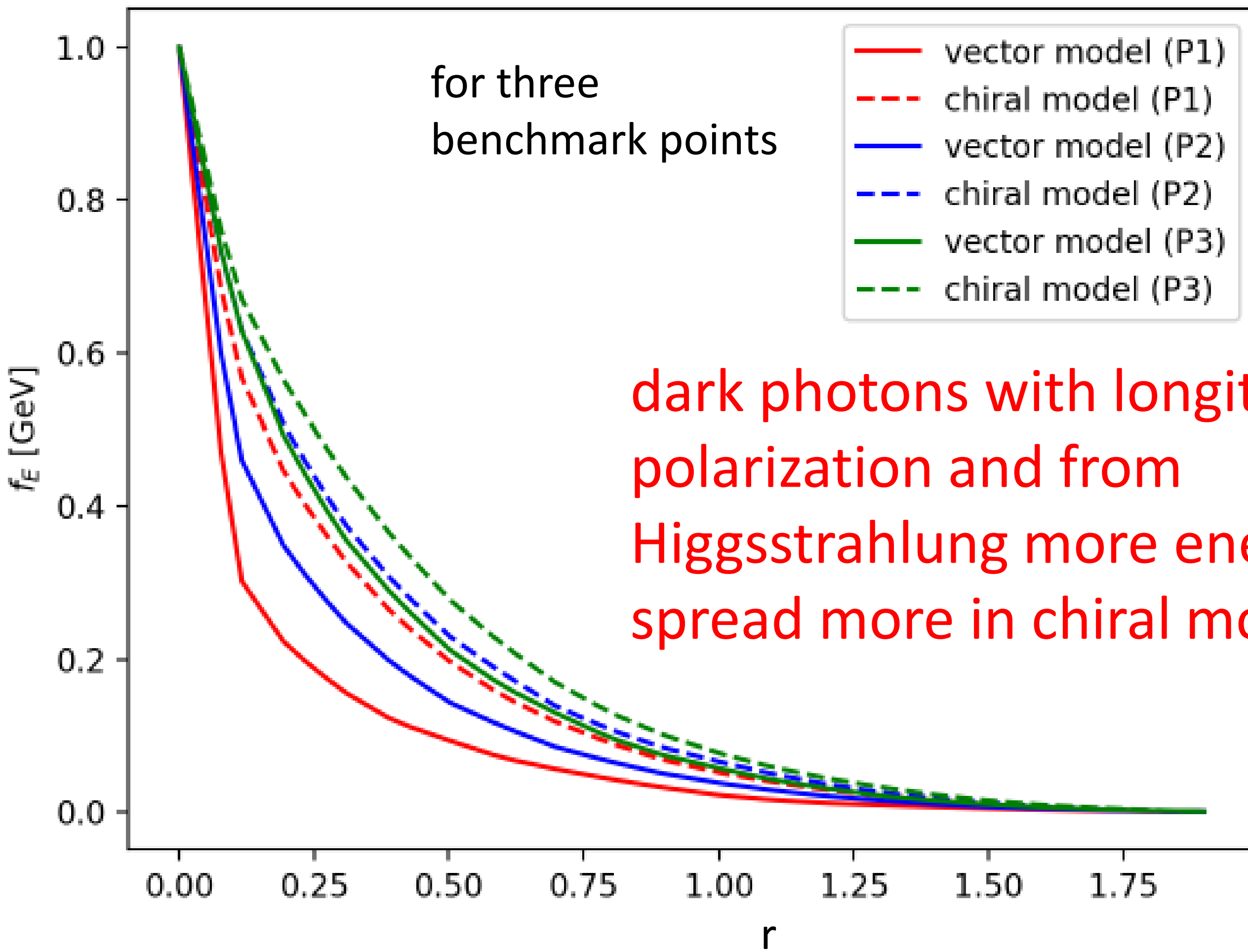
- Number of dark photons $n_{A'}$ is not IR safe at high energy   Zhang, Kim, Lee, Park 2016
- Dark photon Jet substructures

Clustering dark photons

- Anti kT algorithm for radius R=2 to determine jet axis
- Average energy deposit over 10^4 DM jet events
- Find jet profile $f_E(r)$, defined as energy fraction outside cone of radius r < R

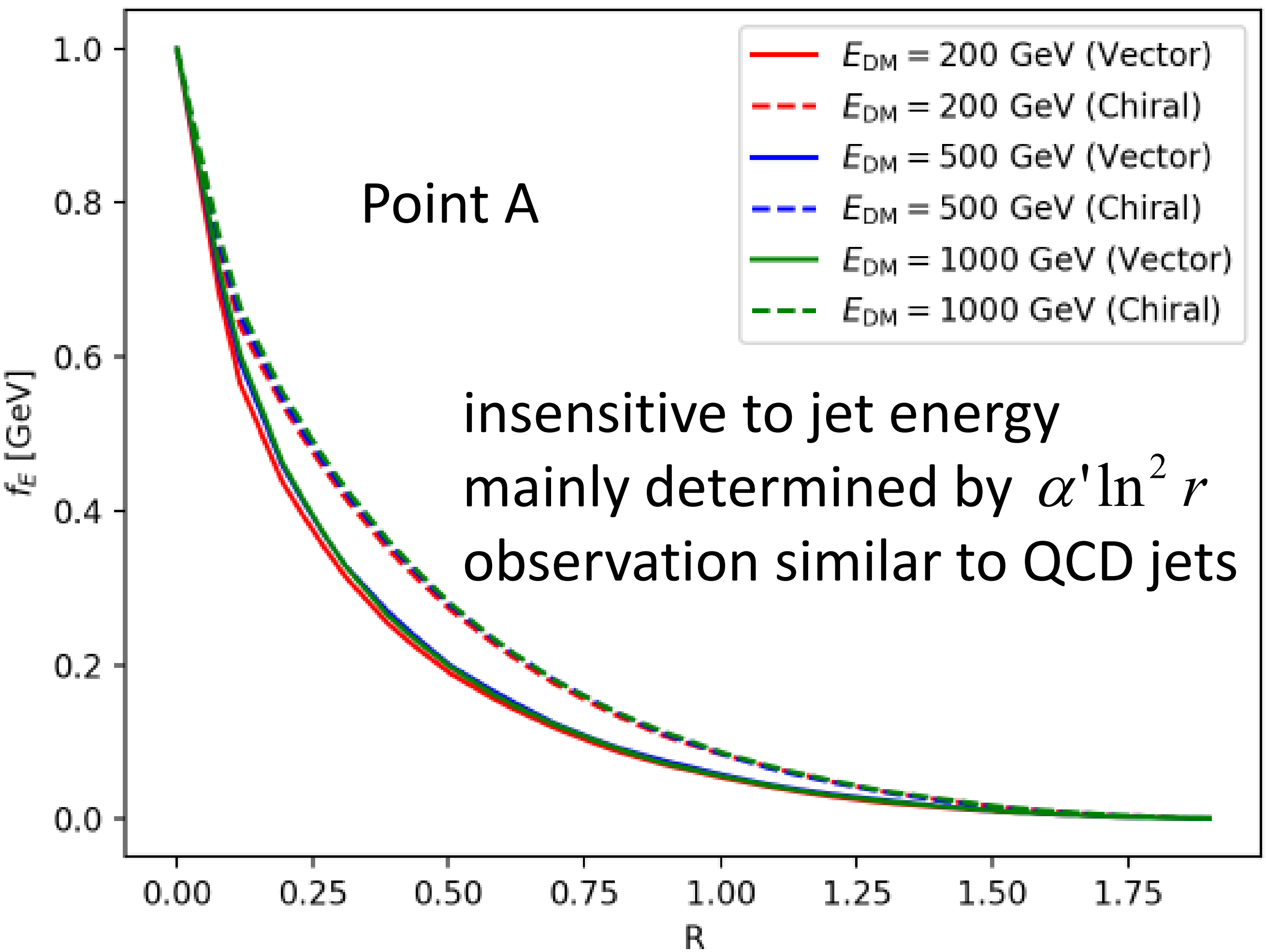


Chiral model gives wider jets

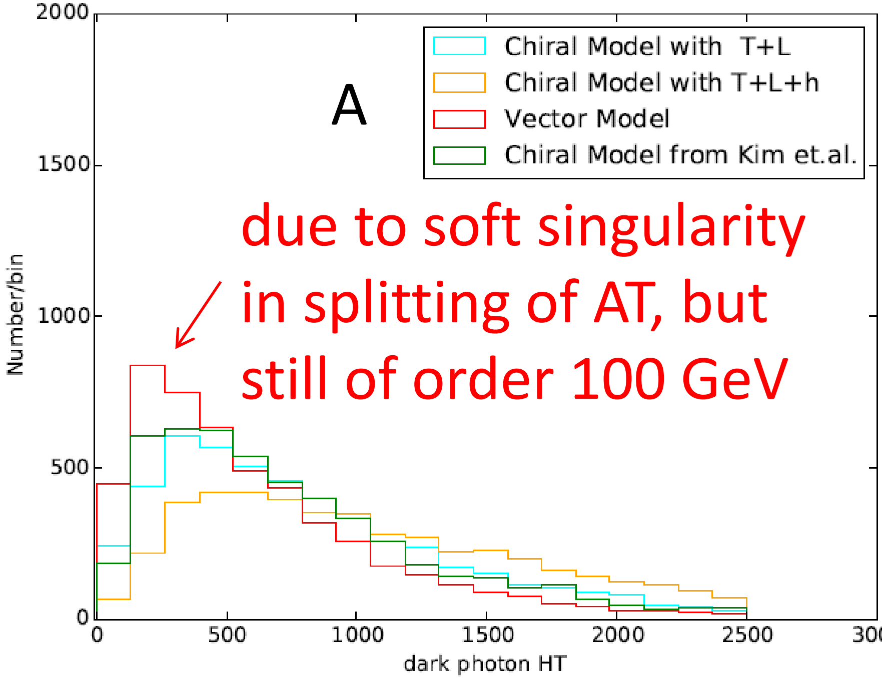


dark photons with longitudinal polarization and from Higgsstrahlung more energetic, spread more in chiral model

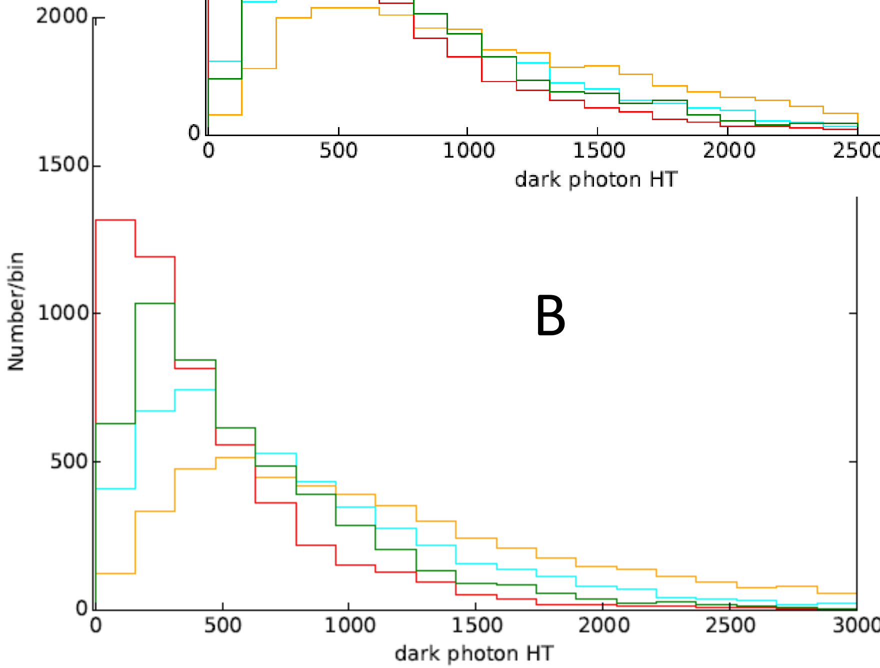
Ideal observable

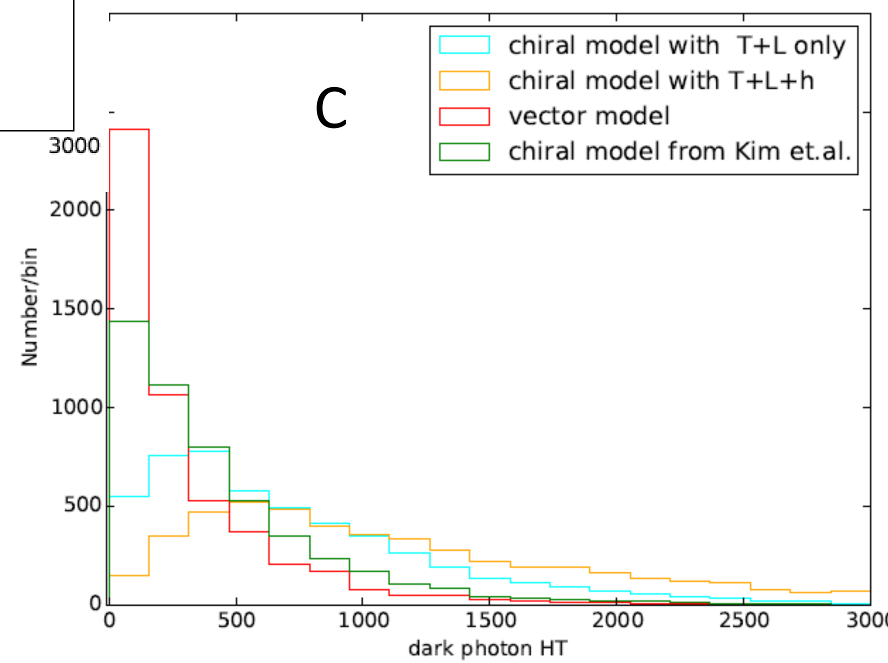


Results for HT



difference between chiral and vector enhanced by Yukawa coupling $\frac{m_\chi}{m_{A'}}$





Summary

- Jet substructures useful for revealing properties of parent particles
- Dark sector may have interactive behavior, and U(1)’ interaction is a simple scenario
- Dark photon jet energy profiles differentiate chiral- and vector-like DM fermions
- Chirality of DM fermion reflects mass generation mechanism
- Deepen our understanding of dark sector

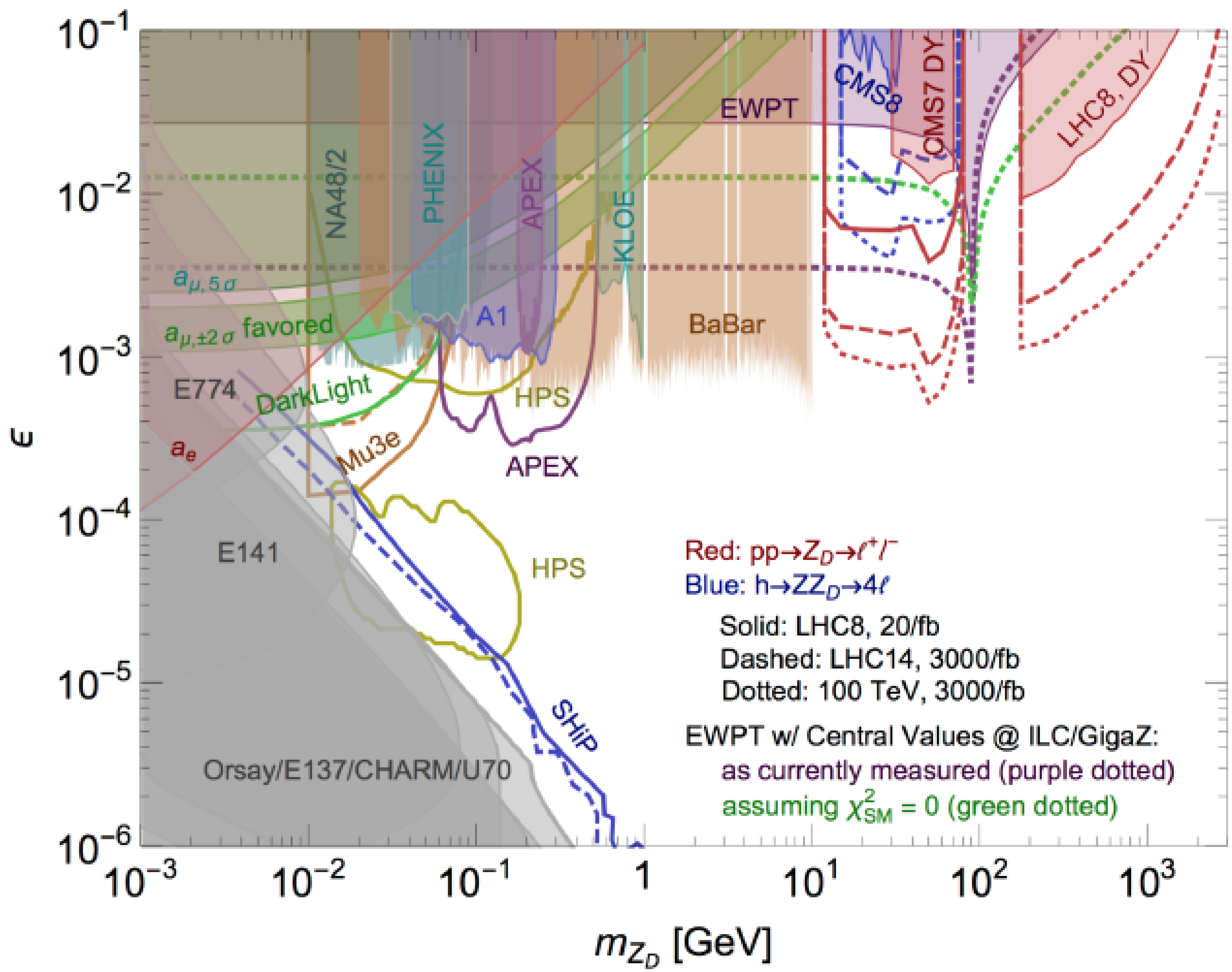
Back-up slides

Dark photons

- Possible to have hidden U(1)′ gauge group---dark photons
- MeV-scale vector mediators charged under U(1)′ enhance DM annihilation rate to get sizable excess in positron flux, Pospelov, Ritz 2009
- Resolve discrepancy between measured and calculated muon anomalous magnetic moment, though other models can too Pospelov 2009; Endo et al. 2012

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.