Hidden Sector Dark Matter

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Princeton University

July 7, 2009

JTR and T. Volansky, **coming soon...**
C. Cheung, JTR, LT. Wang, and I. Yavin, **coming soon...**

See also:

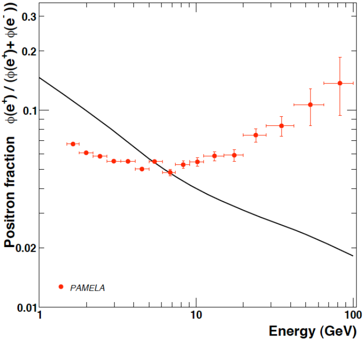
M. Baumgart, C. Cheung, LT. Wang, JTR, and I. Yavin, **0901.0283**
C. Cheung, LT. Wang, JTR, and I. Yavin, **0902.3246**

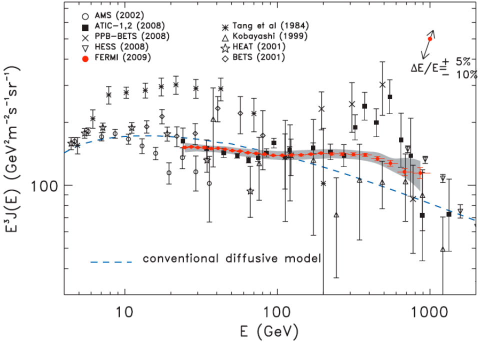
Talk Outline

1. Hidden Sector Dark Matter: Sommerfeld Enhanced Annihilations
2. Tensions for Annihilating Dark Matter
3. Decaying Dark Matter in a Hidden Sector
4. Lepton Jets and Dark Showering

The Motivation

Are we seeing dark matter?





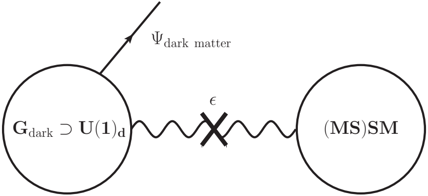
PAMELA requires:
leptons but no antiprotons.

Fermi and Hess set the mass:
$M_{\rm DM} \simeq 2-3$ TeV

For annihilating dark matter, both experiments require a large cross-section relative to thermal freezeout.

Hidden Sector Dark Matter

- The large cross-section and leptophilic signals suggest non-minimal models of dark matter.
- Arkani-Hamed et al. propose that these anomalies can be explained if dark matter is charged under a hidden sector gauge group that kinetically mixes with SM gauge symmetries and is broken at the GeV scale.



N. Arkani-Hamed, D. Finkbeiner, T. Slatyer, and N. Weiner, **0810.0713**.

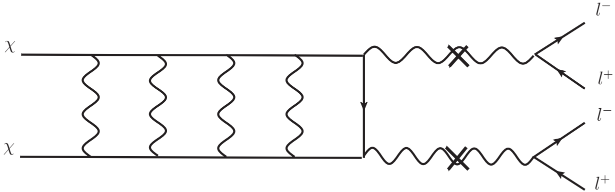
N. Arkani-Hamed and N. Weiner, **0810.0714**

Hidden Sector Dark Matter

- The GeV scale occurs naturally in SUSY, if we are their hidden sector.

- The large cross-section can be due to the Sommerfeld enhancement at low velocity.

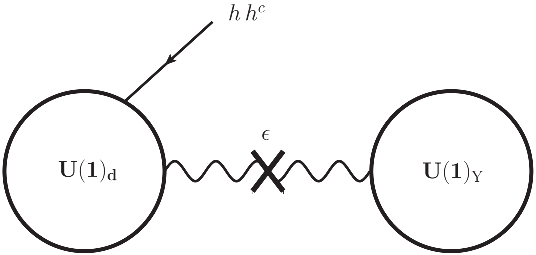
- Dark matter dominantly annihilates into two on-shell γ_d, which decay through kinetic mixing to SM particles with electric charge. Antiprotons are suppressed by kinematics when $m_{\gamma_d} \lesssim 1$ GeV.



$U(1)$ Dark Sector

A minimal realization of this idea:

$$\mathcal{L} \supset \epsilon b_{\mu\nu} F^{\mu\nu} \qquad \epsilon \sim 10^{-3} - 10^{-4}$$



The GeV scale is naturally generated by supersymmetric kinetic mixing:

$$\mathcal{L} \supset -\frac{\epsilon}{2} \int d^2\theta W_d W_Y \quad \Longrightarrow \quad V \supset \epsilon D_d D_Y \quad \Longrightarrow \quad m^2_{\gamma_d} \sim \epsilon M^2_{\mathrm{EW}}$$

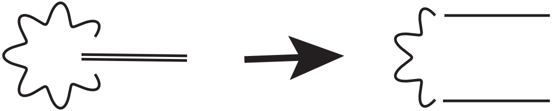
C. Cheung, LT. Wang, JTR, and I. Yavin, **0902.3246**

Dark Matter Splitting

- A dark matter splitting of size $\delta M_{\rm DM} > 100$ keV is required to evade the constraints from direct detection.

- Our $U(1)$ model accomplishes this by coupling dark matter to the light higgs:

$$W = M\Psi\Psi^c + \frac{1}{4\Lambda}\Psi^2\left(h^c\right)^2$$

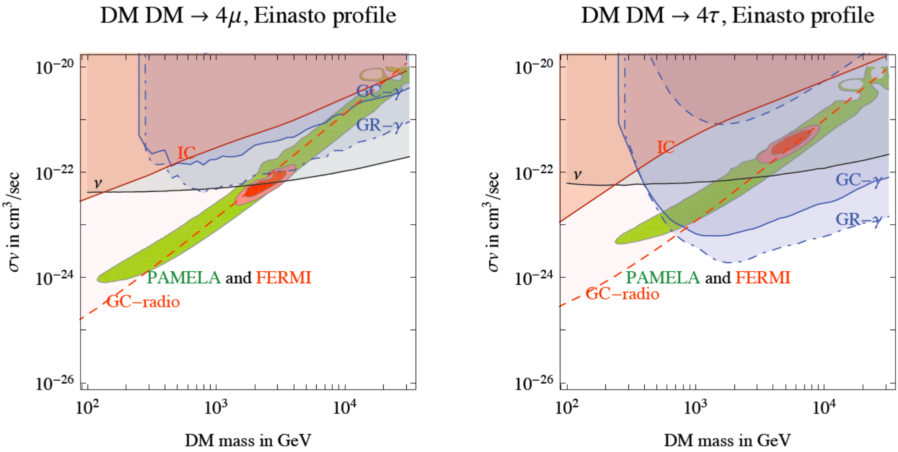


- If $\delta M_{\rm DM} \simeq 100$ keV, this model can explain DAMA through the inelastic dark matter scenario.

D. Tucker-Smith and N. Weiner, (**hep-ph/0101138**).

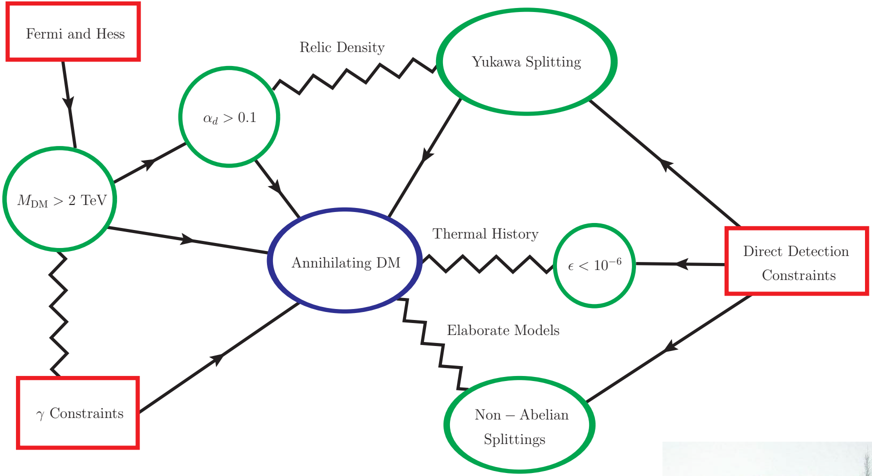
Constraints on Annihilating Dark Matter

There is tension for annihilating dark matter:



P. Meade, M. Papucci, A. Strumia, and T. Volansky, **0905.0480**

A Dark Matter Dream (Catcher)?



Fermi and Hess

Relic Density

Yukawa Splitting

$\alpha_d > 0.1$

$M_{\mathrm{DM}} > 2$ TeV

Thermal History

$\epsilon < 10^{-6}$

Direct Detection Constraints

Annihilating DM

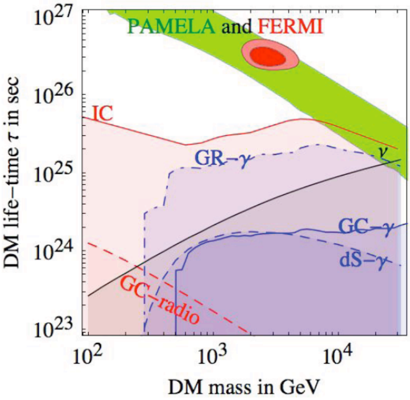
Elaborate Models

γ Constraints

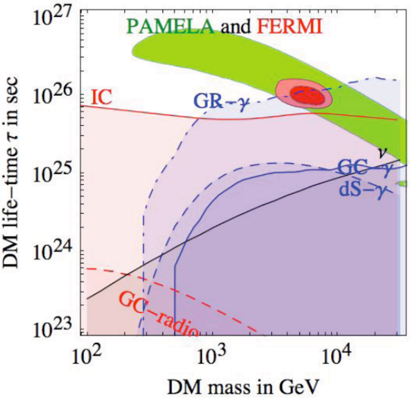
Non – Abelian Splittings

Constraints on Decaying Dark Matter

Decaying dark matter is less constrained:



DM $\rightarrow \mu^+\mu^-$, Einasto profile



DM $\rightarrow \tau^+\tau^-$, Einasto profile

P. Meade, M. Papucci, A. Strumia, and T. Volansky, **0905.0480**

A Hint from Numerology

- Dimension 6 decays suppressed by the GUT scale give dark matter the right lifetime to explain PAMELA and Fermi!

$$\tau \sim \frac{1}{8\pi}\left(\frac{M_{\mathrm{DM}}^5}{M_{\mathrm{GUT}}^4}\right)^{-1} \simeq 10^{26}\ \mathrm{sec}\left(\frac{1\ \mathrm{TeV}}{M_{\mathrm{DM}}}\right)^5\left(\frac{M_{\mathrm{GUT}}}{10^{16}\ \mathrm{GeV}}\right)^4$$

- From an EFT point of view, we should write down all higher dimension operators suppressed by the GUT scale that are allowed by symmetries.

  Dimension-5 decay is ruled out, $\tau \sim$ sec, but dimension-6 decay is possible and can be probed by current experiments.

- Unlike annihilating models of PAMELA and Fermi, the rate is no longer tied to freeze out and no boost factor or Sommerfeld enhancement is required. The usual WIMP cosmology applies.

Decaying Dark Matter Models

In my view, the currently proposed models of decaying dark matter suffer some drawbacks:

- A new SM singlet may decay into MSSM particles and their superpartners.

  Suppressing antiprotons relative to leptons then requires a very particular SUSY spectrum.

  A. Arvanitaki, *et al*., **0812.2075**

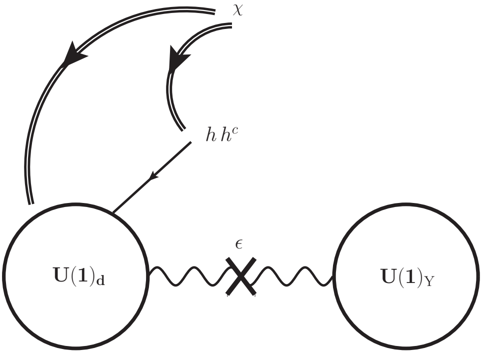
- Dark matter may be the LSP decaying through a small R-parity violating coupling such as $\lambda\, LLe^c$.

  $M_{\rm LSP} \simeq 2 - 3$ TeV means depressing LHC physics and one must engineer very small λ

  K. Ishiwata, S. Matsumoto, and T. Moroi, **0903.0242**

Decays into a Light Hidden Sector

But since the GeV scale occurs naturally in SUSY, what if dark matter decays into a light hidden sector?



Antiprotons are automatically suppressed, models are easy to construct, and we'll see that the collider physics is exciting and optimistic.

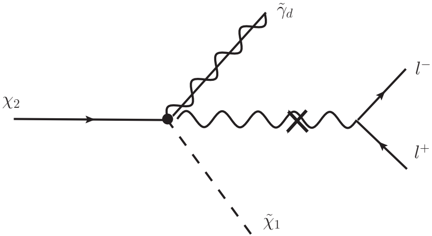
JTR and T. Volansky, **soon...**

Example Decay Operators

Three body decays:

$$\frac{1}{M_{\mathrm{GUT}}^2}\int d^2\theta\,\chi_1\chi_2 W_d^2 \qquad \frac{1}{M_{\mathrm{GUT}}^2}\int d^4\theta\,\chi_1^\dagger\chi_2 h_1^\dagger h_2$$

where $m_{\chi_i} \simeq$ TeV and $m_{h_i} \simeq$ GeV.



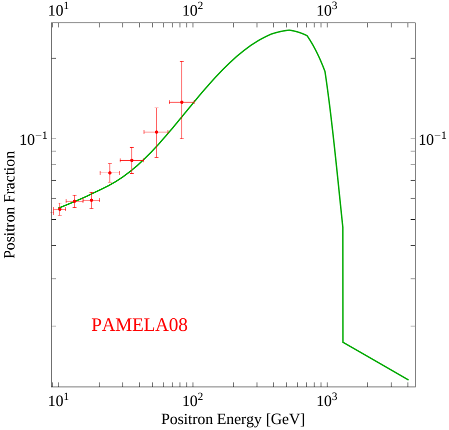
Two body decays will dominate if there are any TeV scale vevs:

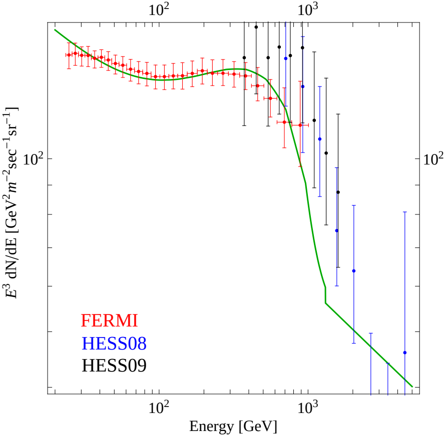
$$\frac{1}{M_{\mathrm{GUT}}^2}\int d^2\theta\,\langle\chi_1\rangle\,\chi_2 W_d^2 \qquad \frac{1}{M_{\mathrm{GUT}}^2}\int d^4\theta\,\langle\chi_1\rangle^*\,\chi_2 h_1^\dagger h_2$$

Preliminary Fits to PAMELA and Fermi

For example, the 2 body decay fits the PAMELA and FERMI excesses with $m_\chi = 2.6$ TeV and $\alpha_d = 0.03$.

Preliminary:



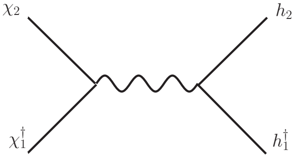


$SU(2)$ Dark Sector

As an example UV completion, suppose that the hidden sector breaks from $SU(2)$ to $U(1)_d$ at the GUT scale.

$$\chi = \begin{pmatrix} \chi_1 \\ \chi_2 \end{pmatrix} \qquad h = \begin{pmatrix} h_1 \\ h_2 \end{pmatrix}$$

Integrating out the heavy gauge fields generates dimension 6 and not dimension 5 decay:



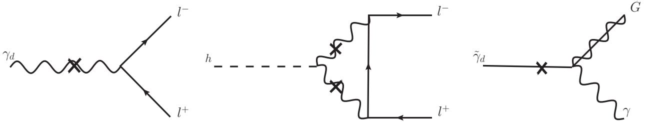
$$\frac{1}{M_{\rm GUT}^2}\int d^4\theta\, \chi_1^\dagger \chi_2 h_1^\dagger h_2$$

GeV-Scale Cosmology

- The GeV scale fields can annihilate efficiently into lighter GeV scale fields.
- But the lightest field in the hidden sector must annihilate through the kinetic mixing and therefore has a large abundance:

$$\sigma \simeq \epsilon^4 \frac{\alpha^2}{\mathrm{GeV}^4} \lesssim 10^{-6}\,\sigma_\chi$$

- For the cosmology to be safe, the lightest field should decay within 10^4 seconds.

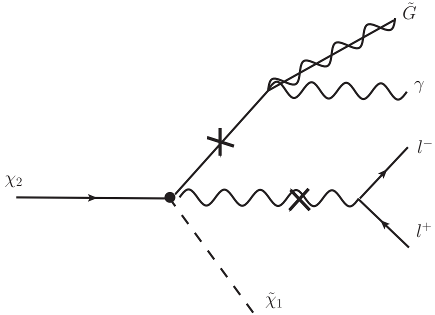


- This constraint is nontrivial if the lightest field is a fermion:

$$\tau \sim 10^3\ \mathrm{s} \left(\frac{\sqrt{F}}{100\ \mathrm{TeV}}\right)^4 \left(\frac{\mathrm{GeV}}{m_{\tilde{h}}}\right)^5 \left(\frac{10^{-3}}{\epsilon}\right)^2$$

Decays into Hard γ Rays

If the lightest state in the hidden sector is a fermion, and if the dark matter decays into this fermion, then dark matter decays must produce hard γ's.

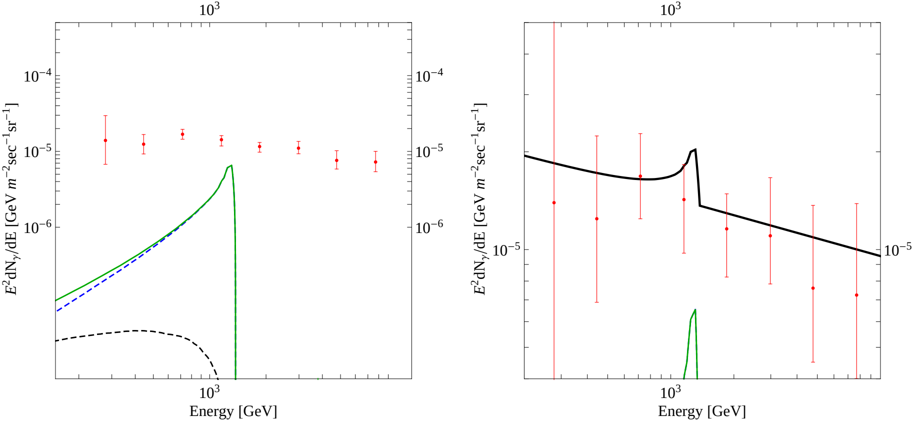


This scenario is probably excluded for annihilating dark matter and is close to the constraints for decaying dark matter, providing a mechanism to differentiate the two scenarios.

Constraining the Hard γ's

The resulting hard γ's are close to the Hess constraints from the Galactic Center and Galactic Ridge.

Preliminary GR Plots:

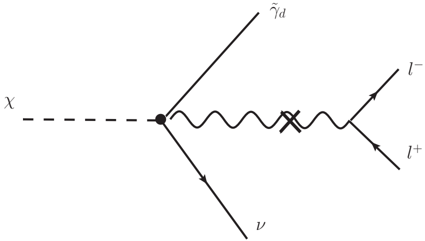


SM Charged DM and Hard Neutrinos

Another possibility is that dark matter is charged under the Standard Model as a $\mathbf{5}+\bar{\mathbf{5}}$ and decays through the operator:

$$\int d^2\theta \, \frac{\chi\, \bar{\mathbf{5}}_f\, W_d^2}{M_{\rm GUT}^2}$$

Dark matter decays then necessarily produce hard neutrinos that are correlated with the lepton signal.



This neutrino signal should be constrained by Super-K and soon, Antares. We're checking!

Decaying the Triplet

- The triplet components of the $\mathbf{5}+\bar{\mathbf{5}}$ must decay faster than dimension 6 because there are strong constraints on stable colored particles.

- This can be accomplished through several different dimension 5 operators:

$$\frac{1}{M_{\mathrm{GUT}}}\int d^2\theta\,\chi^2\bar{\mathbf{5}}_f^2 \qquad \frac{1}{M_{\mathrm{GUT}}}\int d^2\theta\,\chi\mathbf{10}_f^2 s \qquad \frac{1}{M_{\mathrm{GUT}}}\int d^4\theta\,\bar{\chi}\bar{\mathbf{5}}_f^{\dagger} s$$

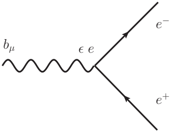
Where s is a singlet with $m_{\chi_2} < m_s < m_{\chi_3}$.

Testing the DM interpretation of PAMELA and FERMI at the LHC

- It may be difficult to determine the source of the cosmic ray anomalies from the astrophysics alone, because the backgrounds are not well understood.

- But a new source of leptons in the sky may also imply new sources of leptons in colliders.

- Kinetic mixing leads to characteristic lepton signatures in colliders, dubbed “lepton jets”.



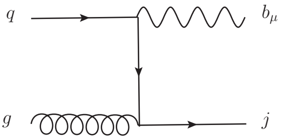
- These signals apply for GeV scale hidden sectors in general, including both the annihilating and decaying models discussed above.

Dark Sector Production

Kinetic mixing implies several production mechanisms in colliders:

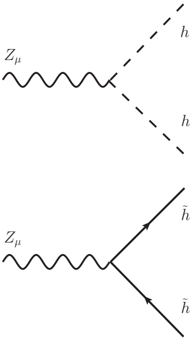
Direct b production

$\epsilon b_\mu J^\mu_{\mathrm{EM}}$



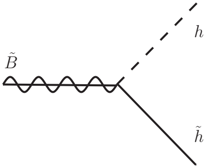
rare Z decay

$\epsilon Z_\mu J^\mu_b$



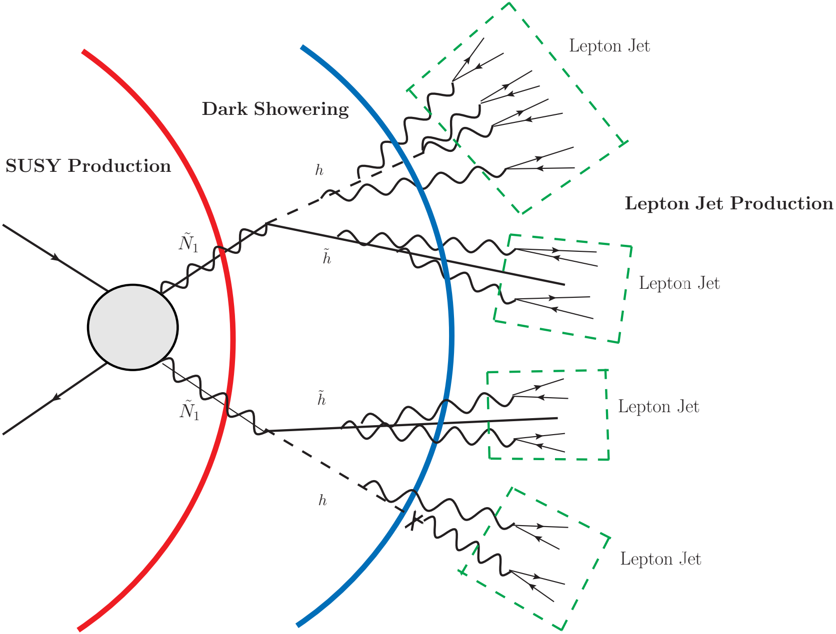
LSP decay

$\epsilon \lambda_{\tilde{B}} \tilde{J}_b$



M. Baumgart, C. Cheung, LT. Wang, JTR, and I. Yavin, **0901.0283**

Lepton Jet Evolution



Dark Sector Factorization

We have implemented a module that simulates these three steps independently:

- **TeV**: SUSY production with Madgraph

  MSSM spectrum → σ_{SUSY}

- **TeV** → **GeV**: dark showering with parton shower

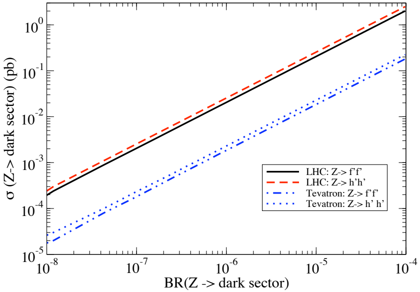
  $(\alpha_{\mathrm{d}}, M_{\mathrm{decay}}) \to \gamma_d$ multiplicity

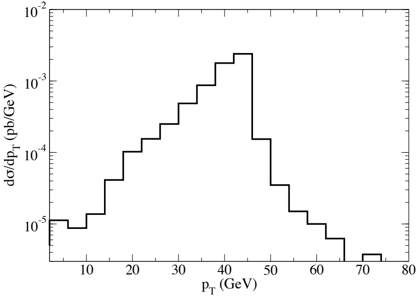
- **GeV**: decays to leptons with phase space

  dark sector spectrum → lepton jets

C. Cheung, JTR, LT. Wang, and I. Yavin, **coming soon...**

Production: Rare Z Decay

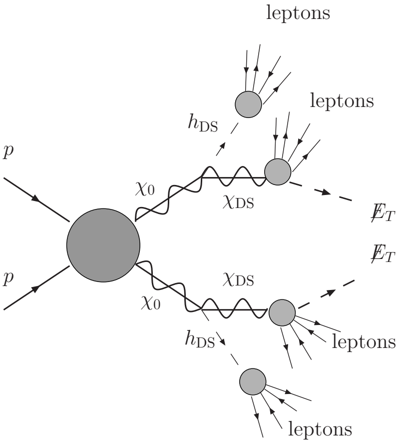


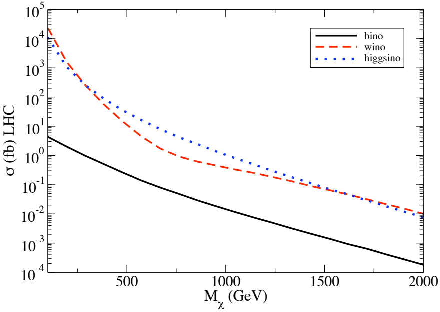


Cut: $|\eta| < 2.4$

SUSY Production

SUSY event topology and electroweak production cross-section:



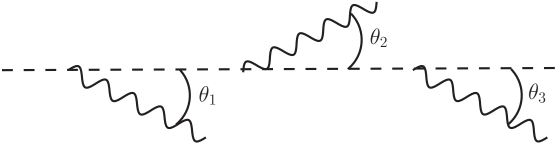


Dark Showering

- The number of radiated dark photons is determined parametrically by the Sudakov double log:

$$N_\gamma \sim \frac{\alpha_d}{2\pi} \log\left(\frac{M_{\mathrm{EW}}^2}{M_{\mathrm{dark}}^2}\right) \log\left(\frac{M_{\mathrm{EW}}^2}{M_{\mathrm{dark}}^2}\right) \sim \frac{\alpha_d}{2\pi} \log \epsilon^{-1} \log \epsilon^{-1}$$

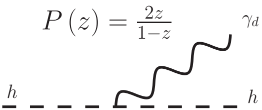
- Abelian hidden showers have no angular ordering and thus produce more dark photons at wider angles.

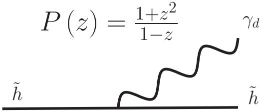


Virtuality-Ordered Parton Shower

- We have implemented a basic virtuality-ordered parton shower Monte Carlo, which is similar to Sherpa* and Pythia.

$$\Gamma\left(t_0\right) = \exp\left[-\int_{M_{\mathrm{dark}}^2}^{t_0^2} \frac{dt}{t} \int dz\, P_{\mathrm{split}}\left(z\right)\right]$$



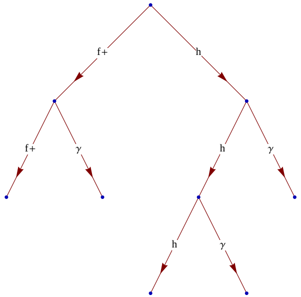


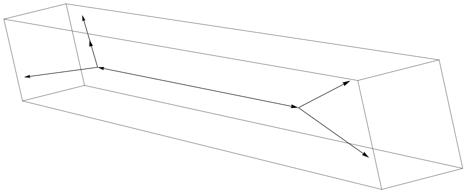
- Energy reshuffling and phase space checks enforce 4-momentum conservation.

* F. Krauss, A. Schalicke, and G. Soff, **hep-ph/0503087**

Sample Showering Event

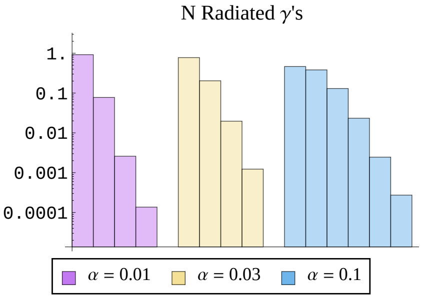
Sample neutralino showering topology and kinematics, in the neutralino restframe:

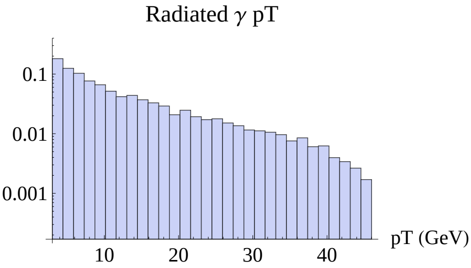




Z Showering

Preliminary results for Z decay showers:

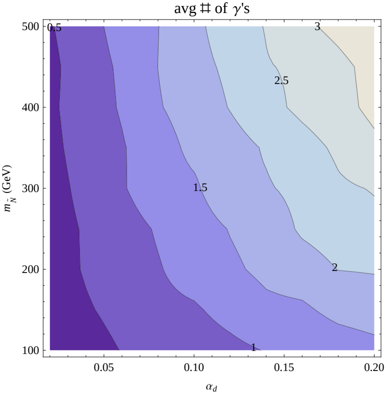


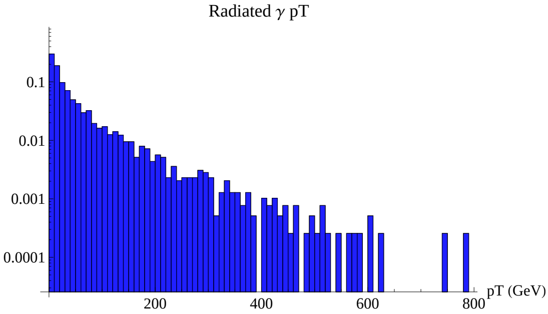


$\alpha = 0.1$

Neutralino Showering

Preliminary result for neutralino decay showers:

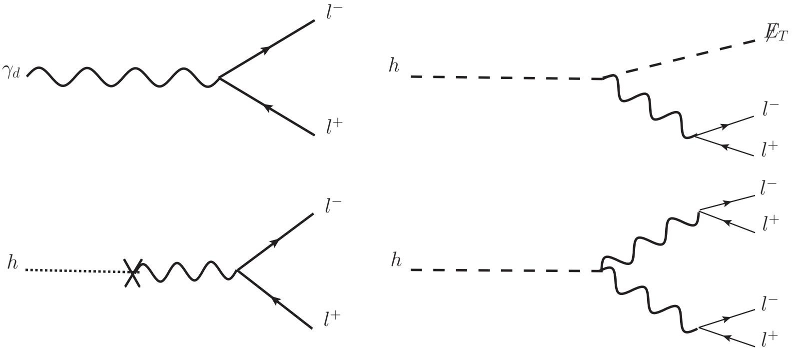




$$\alpha = 0.1 \quad m_{\tilde{N}} = 500 \text{ GeV}$$

Decays to Leptons

- We take the output from the parton shower and decay it into leptons according to phase space.



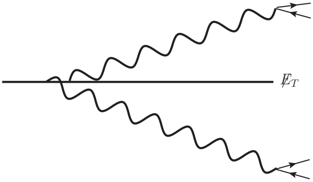
- The resulting leptons are harder than the leptons from showering and have smaller opening angles.

$$\theta \sim \frac{m_{\gamma_d}}{p_T} \sim \sqrt{\epsilon}$$

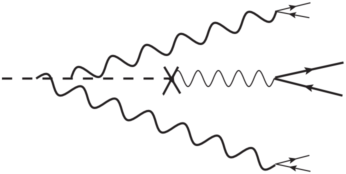
Hollow Lepton Jets vs. Fat Lepton Jets

The dark sector may contain particles that shower but are stable on the detector timescale. We therefore define two types of lepton jets:

- **Hollow Jet:** Missing energy and radiated soft leptons.

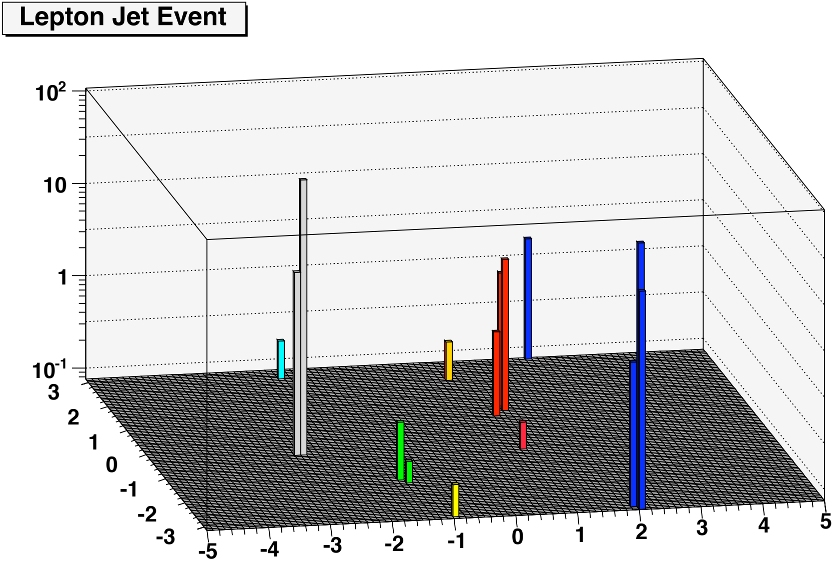


- **Fat Jet:** Hard leptons surrounded by radiated soft leptons.



Lepton Jet Clustering

Lepton jets clustered with FastJet:



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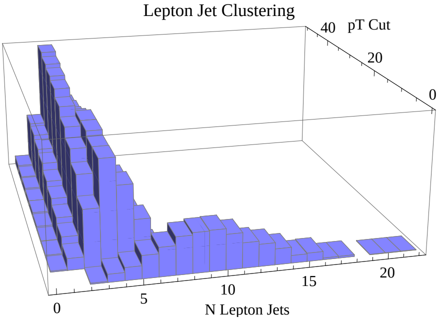
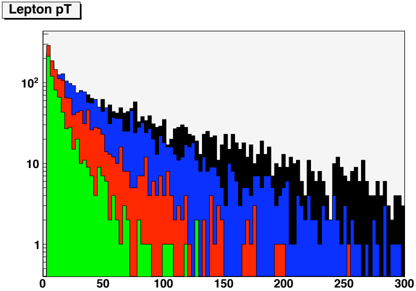
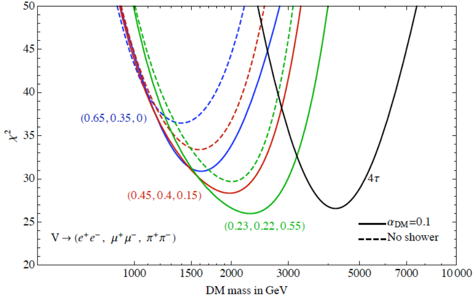
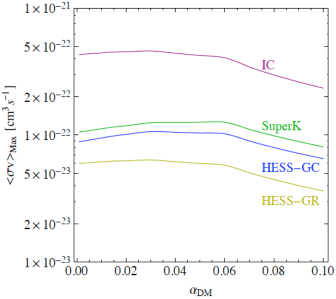




Showering and Astrophysics

- Hidden sector showering improves the combined fit to FERMI and PAMELA and relaxes the constraints.





P. Meade, M. Papucci, A. Strumia, and T. Volansky, **arXiv:0905.0480**

- Hollow jets (if the seed is stable on the galactic length-scale) contribute an extra component to the softer part of the lepton spectrum
- Fits with hollow jets are in progress for the decaying models discussed earlier.

Conclusions

- Annihilating dark matter charged under a GeV scale hidden sector remains a viable candidate for explaining PAMELA and FERMI, although there is tension.
- Decaying dark matter is less constrained, and dimension 6 GUT-scale decays into a GeV scale sector allow for a natural explanation of PAMELA and FERMI without producing antiprotons.
- Hard γ's and ν's can be correlated with PAMELA and FERMI and will be constrained by upcoming experiments. These signals may allow us to differentiate the annihilating and decaying scenarios.
- A GeV scale hidden sector leads to lepton jets in colliders.
- Hidden sector showering increases the lepton multiplicity in colliders and provides a universal probe of the dark sector spectrum.