Seeing Light Dark Sectors With Early Data

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May 8, 2009

M. Baumgart, C. Cheung, LTW, J. Ruderman, and I. Yavin, arXiv:0901.0283
C. Cheung, LTW, J. Ruderman, and I. Yavin, arXiv:0902.3246
M. Reece and LTW, arXiv:0904.1743

Talk Outline

1. Motivations of considering the Dark Sector
2. Model ingredients.
3. Signals at the Large Hadron Collider

Dark Matter at the LHC

1. Dark matter: stable, neutral, $\rightarrow \not{E}_T$.
2. $pp \rightarrow \chi_{\rm DM}\chi_{DM} + X$.
   Must recoil against something observable: $X = \gamma$, jet
   Extremely challenging. Not early physics.
3. In bigger frameworks, SUSY, compositeness...
   Well-known signatures: multi-jet and/or multi-lepton $+\not{E}_T$.
   Could be early discovery.
4. In this talk, I will focus on a different possibility:
   GeV^{-1} range dark matter self-interaction at the LHC.
   Unique signature. Could lead to early discovery.

For searches at low energy experiments,
see M. Reece and LTW, arXiv:0904.1743.

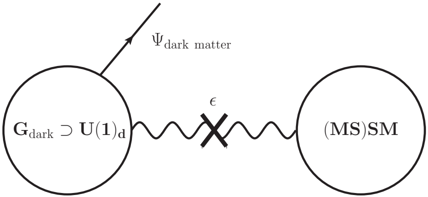
What is a dark sector?

1. Dark matter self-interaction, mediated by a_{dark}.
2. Range of the "dark force" $\simeq m_{a_{\mathrm{dark}}}^{-1} \sim$ GeV.
3. Dark sector couples to SM with tiny couplings, suppressed by ϵ.

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

N. Arkani-Hamed and N. Weiner, arXiv:0810.0714

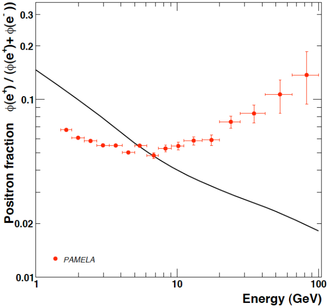
For example:



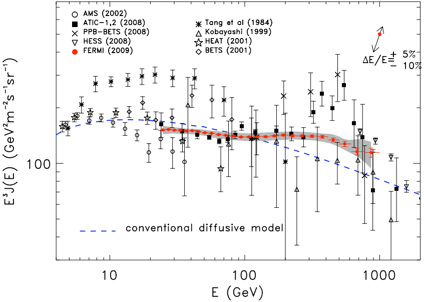
C. Cheung, LTW, J. Ruderman, and I. Yavin, arXiv:0902.3246

Recent evidences of dark matter

The recent interest in dark sector model building is inspired by several observations which can be interpreted as indirect detection of dark matter, in particular, PAMELA, Fermi-LAT.



O. Adriani *et al.*, arXiv:0810.4995.



Abdo, *et. al.* arXiv:0905.0025

Dark Matter interpretation of PAMELA and Fermi-LAT

1. Correct thermal relic abundance requires DM annihilation rate to be

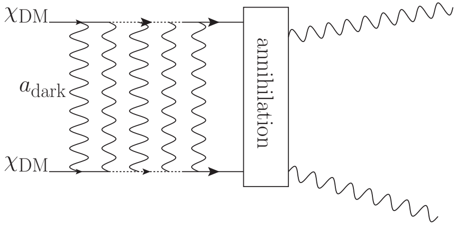
$$\Omega_{\rm DM} h^2 = 0.1 \times \left(\frac{< \sigma v >_{\rm freeze-out}}{3 \times 10^{-26}\ \rm cm^3\ s^{-1}} \right)^{-1}$$

2. Indirect detection rate from DM annihilation

$$R_{e^+,\gamma,\bar{p}\ldots} \propto (n_{\rm DM}^{\rm halo 2}) \times < \sigma v >_{\rm halo}$$

3. Assume $< \sigma v >_{\rm halo} \simeq < \sigma v >_{\rm freeze-out} \rightarrow R_{e^+,\gamma,\bar{p}\ldots}$
4. PAMELA and Fermi-LAT excesses need an additional $O(10{\rm s} - 100)$ enhancement.
5. One possible way of getting such a boost: Sommerfeld enhancement

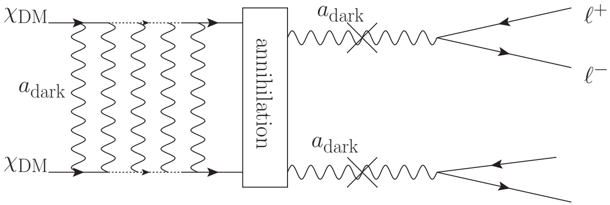
Sommerfeld enhancement



1. Long range self-interaction of dark matter mediated by $a_{\rm dark}$

   range$\sim m_a^{-1}$, coupling $\alpha_{\rm dark}$
2. Enhancement sets in when $m_a \sim \alpha_{\rm dark} M_\chi$
3. Enhancement $\sim \alpha_{\rm dark}/v_{\rm halo}$, $v_{\rm halo} \sim 10^{-3}$.
4. Enhancement cuts off at $M_\chi \cdot v_{\rm halo} < m_a$.
5. $M_\chi \sim 10^2$ GeV, $\alpha_{\rm dark} \sim 0.1 - 0.01$, $\rightarrow m_a \sim$ GeV.

Fermi-LAT and PAMELA signal

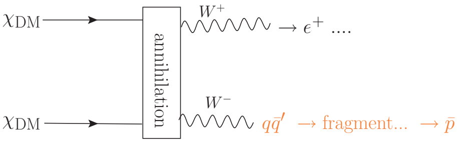


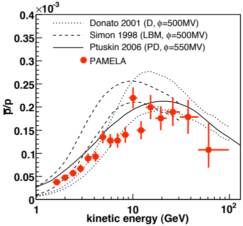
1. Dark matter annihilate into GeV dark sector states, $a_{\rm dark}$.
2. $a_{\rm dark}$ decay back to Standard Model leptons.

Dark sector must connect to the SM. The coupling should be small (consistency with current constraints).
All of these ingredients can be implemented naturally in simple models.

anti-proton flux

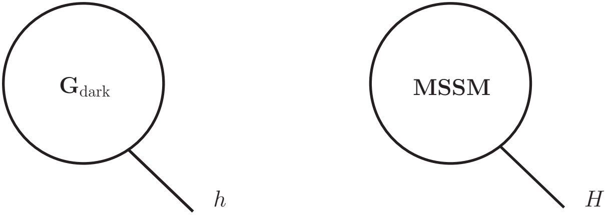
1. Conventional WIMP annihilation also results in excess in anti-proton flux, not observed by PAMELA.





2. Annihilation into GeV scale dark sector states and their subsequent decay will not generate anti-proton due to kinematical suppression.

Dark Sector Models



1. Dark sector interaction: $G_{\rm dark}$. $\alpha_{\rm dark} \sim \alpha_{\rm SM}$.
   Obvious possibility: gauge interaction,
   $< h_{\rm dark} > \sim$ GeV, spontaneously broken.
2. Connection to the SM (MSSM) sector, one example later.
3. Generating the GeV scale, naturally (SUSY, composite).

Various possibilities and constructions.

Earlier proposals:

M. Pospelov, A. Ritz and M. Voloshin, arXiv:0711.4866

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

1. $U(1)$ models.

   E. J. Chun and J. C. Park, arXiv:0812.0308

   C. Cheung, LTW, J. Ruderman, and I. Yavin, arXiv:0902.3246

   A. Katz and R. Sundrum, arXiv:0902.3271

   D. E. Morrissey, D. Poland and K. M. Zurek, arXiv:0904.2567

2. Connection through scalar.

   Y. Nomura and J. Thaler, arXiv:0810.5397

3. Non-abelian dark sector, SUSY with DM as messengers.

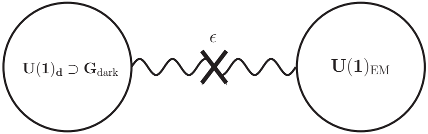
   M. Baumgart, C. Cheung, LTW, J. Ruderman, and I. Yavin, arXiv:0901.0283

4. NMSSM type, Composite...

U(1) dark sector with kinetic mixing

Dark force: choose $G_{\rm dark} = \mathrm{U}(1)$, $a_{\rm dark} = \mathrm{U}(1)$ gauge boson b_μ.

Kinetic mixing is a natural connection between the dark sector and the Standard Model sector.

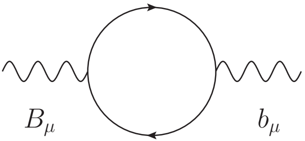


$$\mathcal{L}_{\rm gauge-mix} = \epsilon\; b_{\mu\nu} F_Y^{\mu\nu}$$

We'll see that GUTs imply $\epsilon \sim 10^{-3} - 10^{-4}$.

Generating the kinetic mixing in UV theories

Kinetic mixing is generated by fields charged under both U(1)'s:



$$\epsilon = \frac{g_d g_Y}{16\pi^2} \Sigma_i Q_d^i Q_Y^i \log\left(\frac{M_i^2}{\mu^2}\right)$$

ϵ vanishes if either U(1) is embedded in a GUT, but is generated below the scale of GUT symmetry breaking:

$$\epsilon \sim \frac{g_d g_Y}{16\pi^2} \log\left(\frac{M}{M'}\right) \sim 10^{-3} - 10^{-4}$$

Generating GeV scale: supersymmetry

GeV scale is *required* by kinetic mixing and supersymmetry.

SUSY version of kinetic mixing

$$\mathcal{L} \supset \int d^2\theta W_d W_Y \rightarrow V \supset \epsilon D_d D_Y$$

$$D_d \sim h_{\rm dark}^2 \text{ and } D_Y \sim H_{\rm MSSM}^2$$

After electroweak symmetry breaking,

$< H_{\rm MSSM} > \sim 10^2$ GeV, with $\epsilon \sim 10^{-3} - 10^{-4}$

$\rightarrow$ mass term of $h_{\rm dark} \sim$ GeV.

For an explicit minimal model:

C. Cheung, LTW, J. Ruderman, and I. Yavin, arXiv:0902.3246

Signals of GeV dark force at the Large Hadron Collider

1. Motivated by potential astrophysical observation of DM.
2. Natural to have a GeV sector, simple example:
   Dark force=U(1), kinetic mixing, and supersymmetry.
3. LHC will provide definitive test of such a scenario.
4. Rest of the talk: describing the signature.
   More detailed studies necessary for discovery potential.

For details, see:
M. Baumgart, C. Cheung, LTW, J. Ruderman, and I. Yavin, arXiv:0901.0283

Couplings of the GeV Dark Sector

$$\begin{aligned}\mathcal{L}_{\rm gauge} &\supset -\frac{1}{4}W_{3\mu\nu}W_3^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}b_{\mu\nu}b^{\mu\nu} + \frac{\epsilon}{2}B_{\mu\nu}b^{\mu\nu} \\ &= -\frac{1}{4}Z_{\mu\nu}Z^{\mu\nu} - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}b_{\mu\nu}b^{\mu\nu} \\ &+ \frac{\epsilon}{2}\left(\cos\theta_W F_{\mu\nu} - \sin\theta_W Z_{\mu\nu}\right) b^{\mu\nu}\end{aligned}$$

We remove the kinetic mixing by separately shifting the light fields:

$$\begin{aligned}A_\mu &\rightarrow A_\mu + \epsilon\cos\theta_W b_\mu \\ b_\mu &\rightarrow b_\mu - \epsilon\sin\theta_W Z_\mu\end{aligned}$$

This induces the new interactions:

$$V \supset \epsilon\cos\theta_W b_\mu J^\mu_{\rm EM} - \epsilon\sin\theta_W Z_\mu J^\mu_{\rm dark}$$

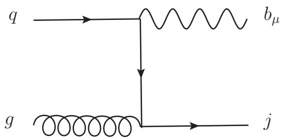
Basic dark sector production at the LHC

$$V \supset \epsilon \cos\theta_W b_\mu J^\mu_{\rm EM} - \epsilon \sin\theta_W Z_\mu J^\mu_{\rm dark}$$

Direct b_μ (γ') prod.

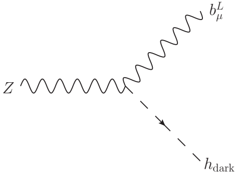
prompt "dark" photon

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

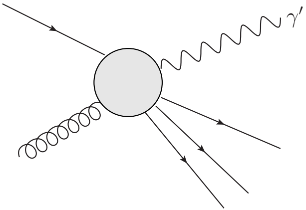


rare Z decay

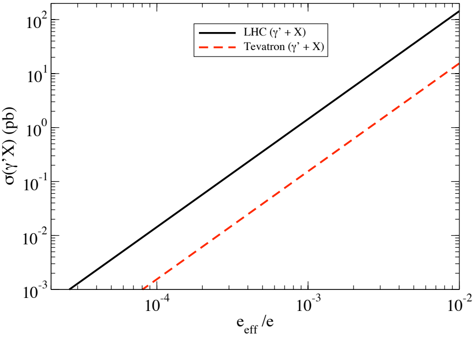
$$\epsilon Z_\mu J^\mu_{\rm dark}$$



Direct Dark Photon Production

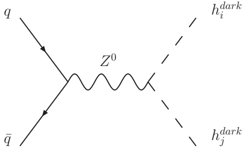


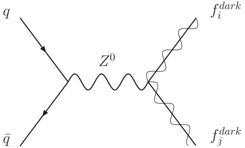
- Cuts: $p_T > 10$ GeV and $|\eta| < 2.4$
- pb-ish rate for $\epsilon \sim 10^{-3}$.



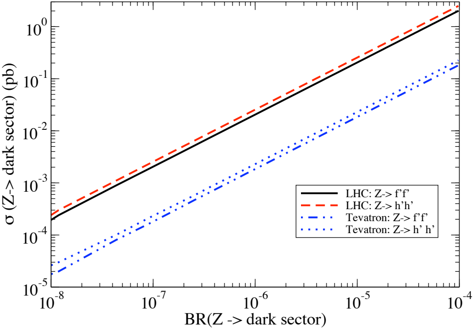
Rare Z Decay

Production and rare decay of Z.



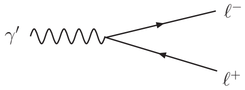


Cut: $|\eta| < 2.4$



Dark Sector Decay: multiple leptons

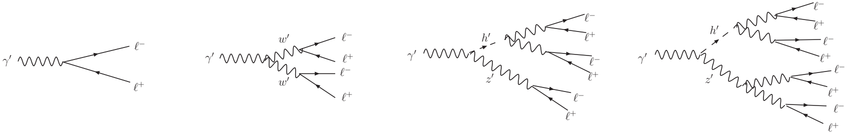
The dark sector decays back through the operator $\epsilon b_\mu J^\mu_{\rm EM}$.



The decay length is dominated by the last step and the decay is generically prompt:

$$c\tau^{b\to {\rm n}\ell}_{2-{\rm body}} \sim \frac{1}{\alpha\epsilon^2 m_b} = 2.7 \times 10^{-6}\ {\rm cm}\ \left(\frac{\rm GeV}{m_{\gamma'}}\right)\left(\frac{10^{-3}}{\epsilon}\right)^2 .$$

Dark sector decay: more leptons

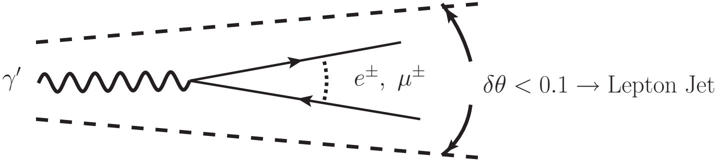


1. > 2 leptons generic in non-abelian models. Cleaner signal.
2. Also possible for three body decays.

Signal of dark sector: lepton-jet

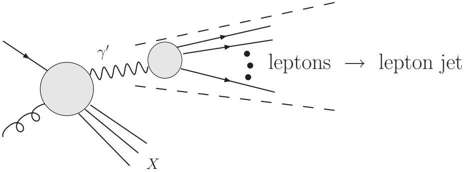
Decay of dark photon leads to highly collimated lepton pair.

"Lepton jet."

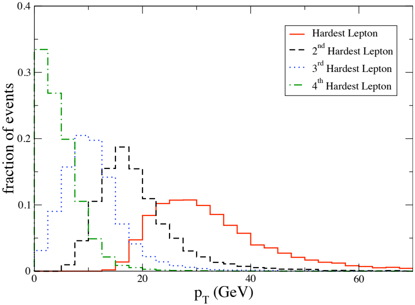


$$\left.\begin{array}{c}\text{Typical } E_{\gamma'} > 10 \text{ GeV} \\ m_{\gamma'} \sim \text{ GeV}\end{array}\right. \rightarrow \ \delta\theta \sim m_{\gamma'}/E_{\gamma'} < 0.1$$

Unique objects.



Lepton jet of muons

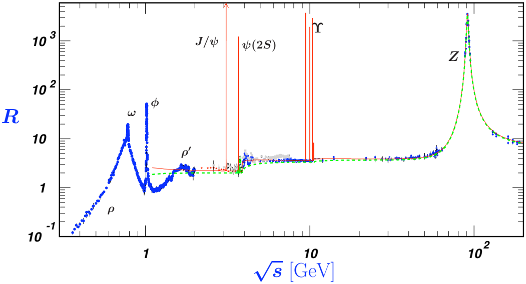


Detailed study necessary understand the ability of identifying highly collimated muons.

1. Should fly apart in while reaching muon system.
2. No hadronic activity around, for pure lepton jet.

However, not just leptons, pions...

GeV E&M coupling has complicated form factors, resonances.



$$R(s) = \frac{\sigma(e^+e^- \to \text{hadrons},\ s)}{\sigma(e^+e^- \to \mu^+\mu^-,\ s)} = \frac{\mathrm{BR}(\gamma' \to \pi^+\pi^-)}{\mathrm{BR}(\gamma' \to \mu^+\mu^-(\text{or } e^+e^-))}\ (m_{\gamma'} = s)$$

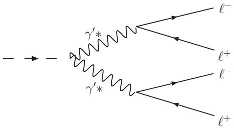
$$\sim \frac{\mathrm{BR}(\gamma' \to \pi^+\pi^-)}{\mathrm{BR}(\gamma' \to \mu^+\mu^-(\text{or } e^+e^-))},\ \text{for } m_{\gamma'} \lesssim \text{GeV}$$

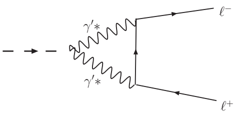
e.g., $\pi^+\pi^- : \mu^+\mu^- : e^+e^- \simeq 1:1:1$ for $m_{\gamma'} \simeq 600$ MeV.

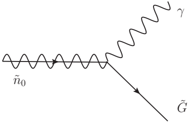
Requiring pure lepton jets (paying BR), or using pion as well?

Can have Missing Energy and Displaced Vertices as well.

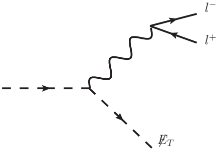
Lepton jets can contain missing energy due to light scalars and fermions, $c\tau 1 - 100$ km:

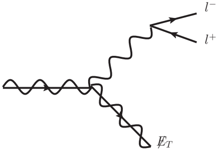






With multiple light scalars or fermions, 3-body decays can produce displaced leptons along with missing energy:

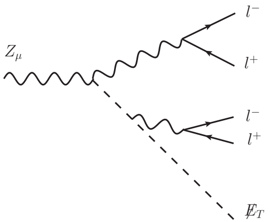


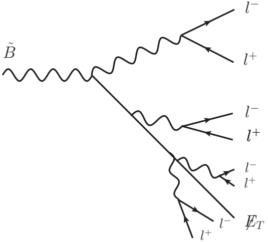


Soft Radiation In the Dark Sector, more leptons

Work in progress with C. Cheung, I. Yavin, and J. Ruderman:

- Soft radiation in the dark sector can greatly enhance the lepton multiplicity in high-energy colliders.





Supersymmetric dark sector at the LHC

Supersymmetric kinetic mixing includes gaugino mixing:

$$\mathcal{L}_{\text{gaugino}} \supset -2i\epsilon\lambda_{\tilde{b}}\bar{\sigma}^{\mu}\partial_{\mu}\lambda_{\tilde{B}} + \text{h.c.}$$

Remove the mixing by shifting the lighter gaugino:

$$\lambda_{\tilde{b}} \rightarrow \lambda_{\tilde{b}} + \epsilon\lambda_{\tilde{B}}$$

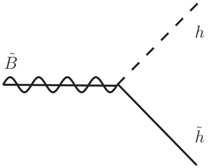
And we have the new interaction:

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

LSP is not the end of SUSY decay chain

LSP decay

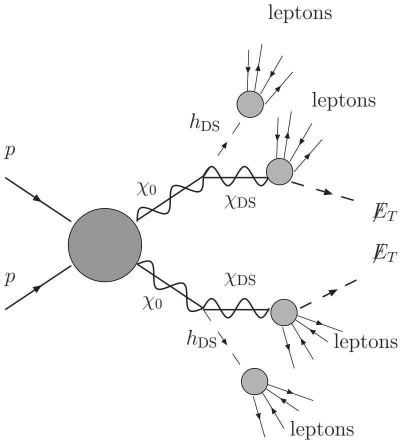
$\epsilon \lambda_{\tilde{B}} \tilde{J}_b$

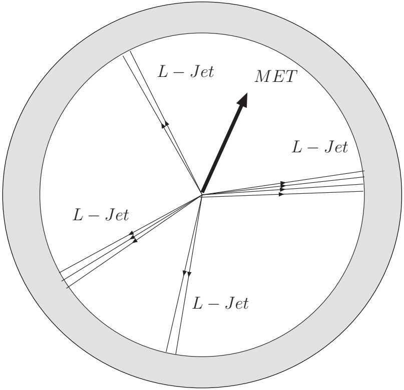


1. Significantly change SUSY phenomenology.
2. Scenario with light gluino and/or squark:
   large ($1 - 10$ pb) rates
   multi-jet and/or multi-lepton decay chain
   lepton jets at the end of the decay chain
   $\longrightarrow$ early discovery of dark sector.

SUSY LSP production event topology

The topology of a typical SUSY event:

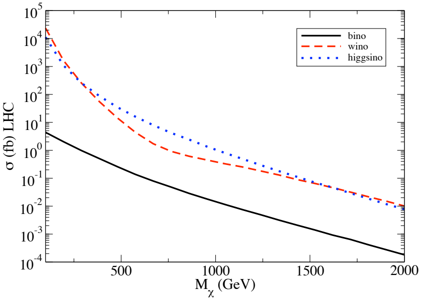




Extended Discovery Reach for Electroweak-inos

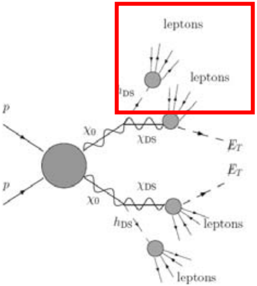
1. Direct electroweak-ino production is difficult in conventional MSSM. Impossible for LSP.
   NLSP, low rate, large background from di-boson.
2. Lepton jets at the end of the SUSY decay chain will greatly enhancing the Tevatron and LHC reach.

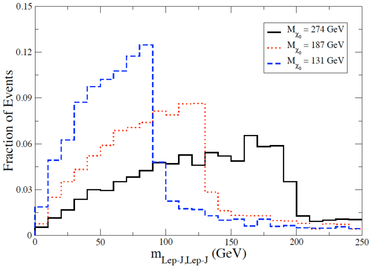
- ino prod. rate at the LHC.
  $m_{\rm squark} = 750$ GeV



Reconstruction of SUSY decay

Lepton jets allow us to understand the kinematics better.
For example:





Measuring the mass of the LSP.

Conclusions

- We should look for light hidden sectors with suppressed couplings to SM fields. SUSY and kinetic mixing together naturally generate GeV scale.

- Dark matter charged under a GeV scale hidden sector naturally explains PAMELA.

- Current low energy experiments can probe the parameter space with couplings on the larger side $\epsilon \sim 10^{-3}$. A dedicated fixed target experiment should be able to discover or exclude the GeV dark sector.

- Light hidden sectors connected by kinetic mixing produce lepton jets in colliders. The LHC may spectacularly confirm dark matter models of this type.