Probing a GeV Dark Sector at Colliders

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Based on:
M. Baumgart, C. Cheung, J. Ruderman, LTW, I. Yavin, arXiv:0901.0283
Matt Reece and LTW, arXiv:0904.1743
C. Cheung, J. Ruderman, LTW, I. Yavin, arXiv:0909.0290
More information at: http://phy-hal.princeton.edu/LeptonJets/index.html (work in progress)
Outline

• Introduction to GeV dark sector
  • Motivation
  • Basic structure
• Survey of signatures and search channels.
• Conclusion.
What is a GeV dark sector?

- Dark matter self-interaction, mediated by

\[ b_{\text{dark}} \subseteq \text{dark sector}. \]

Many scenarios, for example: J. Feng and J Kumar, arXiv:0803.4196

- In addition:

- Range of dark force \( m_{b_{\text{dark}}} \sim 100s \text{ MeV} - \text{GeV} \)

- Dark sector couples to SM with tiny couplings, parameterized by \( \epsilon \) Typically: \( \epsilon \leq 10^{-3} \)
Motivation: dark matter annihilation

- Excesses in cosmic-ray electron and positron.


Also: ATIC, PPB-BETS, EGRET.

Astrophysics interpretation possible.

Here, we focus on the hypothesis of dark matter annihilation as source to the excess.

Leading to testable predictions.
DM interpretation of the excesses:

Arkani-Hamed, Finkbeiner, Slatyer, Weiner 0810.0713
Arkani-Hamed, Weiner 0810.0714
also see Pospelov, Ritz, Voloshin 0711.4866

- Correct thermal relic density fixes DM annihilation rate:

\[ \Omega_{DM} h^2 = 0.1 \times \left( \frac{\langle \sigma v \rangle_{\text{freeze-out}}}{3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}} \right)^{-1} \]

- Cosmic ray flux:

\[ R_{e^+, \gamma, \bar{p}...} \propto (n_{DM}^{\text{halo}^2}) \times \langle \sigma v \rangle_{\text{halo}} \]

Assume \( \langle \sigma v \rangle_{\text{halo}} \lesssim \langle \sigma v \rangle_{\text{freeze-out}} \rightarrow R_{e^+, \gamma, \bar{p}...} \)

- Observed positron and electron excess needs an additional \( O(10s-100) \) enhancement.

For example: P. Meade, M. Papucci, A. Strumia, T. Volansky, arXiv:0905.0480

- To preserve the success of relic density prediction, change late time physics.

- Sommerfeld enhancement: \( \langle \sigma v \rangle_{\text{halo}} \gg \langle \sigma v \rangle_{\text{freeze-out}} \)
Sommerfeld enhancement

Long range self-interaction of dark matter mediated by \( b_{\text{dark}} \)

- range \( \sim m_b^{-1} \), coupling \( \alpha_{\text{dark}} \)

Enhancement sets in when \( m_b \sim \alpha_{\text{dark}} \cdot M_\chi \)

- Enhancement \( \sim \alpha_{\text{dark}} / v_{\text{halo}}, v_{\text{halo}} \sim 10^{-3} \).
- Enhancement cuts off at \( M_\chi \cdot v_{\text{halo}} < m_b \).

- \( M_\chi \sim 10^2 \) GeV, \( \alpha_{\text{dark}} \sim 0.1 - 0.01 \), \( \rightarrow m_b \sim \) GeV.
The observed signal at PAMELA/Fermi

- Dark matter annihilate into dark force carrier, which then decay to SM states, leading to observed excesses.
- Therefore, dark sector states must couple to the SM.
- The coupling has to be small to satisfy current constraints.
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- Range of dark force \( m_{b_{\text{dark}}} \sim 100s \text{ MeV} - \text{GeV} \)
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Solves anti-proton flux “puzzle”

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

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

- Model choices:
  - Dark matter identity.
  - Self-interaction $G_d$ : gauge interaction...
  - GeV scale, dark higgs $h_d : v_d = \langle h_d \rangle \sim \text{GeV}$
  - Supersymmetric scenarios: natural generation of the GeV Scale.
Various constructions:

• ** Earlier proposals:**
  M. Pospelov, A. Ritz and M. Voloshin, arXiv:0711.4866

• **U(1) models:**

• **Non-abelian model, SUSY:**

• **Scalar Portal:**

• **Composite:**

• **More...**
Simplest choice: abelian dark sector

- Simplest self-interaction: \( G_d = U(1)_d \)

- Natural connection to the SM: kinetic mixing

\[ \mathcal{L}_{\text{kin.mix}} = -\frac{\epsilon}{2} b_{\mu\nu} F_{\gamma}^{\mu\nu} \]

- Supersymmetry can be an elegant way of generating the GeV scale.

For a very simple and predictive construction:
See also: D. E. Morrissey, D. Poland and K. M. Zurek, arXiv:0904.2567
Kinetic mixing:

- Expected to be there!

- Kinetic mixing between dark photon and SM hypercharge gauge boson $B_\mu$ is generically present in extensions of the Standard Model.

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

- Expected to be small (consistent with constraints).

\[ \epsilon \sim \frac{g_d g_Y}{16\pi^2} \log \left( \frac{M}{M'} \right) \sim 10^{-3} - 10^{-4} \]
Searching for the GeV dark sector:

- Motivated by evidence of dark matter from astrophysical observations.

- Laboratory experiment in controlled environment will provide the definitive tests.

- In addition to searching for 100 GeV - TeV DM particle at high energy colliders, there is good motivation for looking for the GeV sector.

- Dark sector couples very weakly to the SM particles, typically only to EW states.
Dark sector couplings to the SM

\[ \mathcal{L}_{\text{gauge}} \supset -\frac{1}{4} W_{3\mu} W_{3\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} - \frac{1}{4} b_{\mu\nu} b^{\mu\nu} + \frac{\epsilon}{2} B_{\mu\nu} b^{\mu\nu} \]

\[ = -\frac{1}{4} Z_{\mu\nu} Z^{\mu\nu} - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{1}{4} b_{\mu\nu} b^{\mu\nu} \]

\[ + \frac{\epsilon}{2} (\cos \theta_W F_{\mu\nu} - \sin \theta_W Z_{\mu\nu}) b^{\mu\nu} \]

\[ \rightarrow A_\mu \rightarrow A_\mu + \epsilon \cos \theta_W b_\mu \]

\[ b_\mu \rightarrow b_\mu - \epsilon \sin \theta_W Z_\mu \]

\[ \rightarrow V \supset \boxed{\epsilon \cos \theta_W b_\mu J_{\text{EM}}^{\mu}} - \epsilon \sin \theta_W Z_\mu J_{\text{dark}}^{\mu} \]

Couples just like the Standard Model photon, but with a suppressed coupling.

The “dark photon”, sometimes also called

\[ \gamma', \ U\text{-boson}, \ V_\mu, \ or \ \alpha_\mu. \]
Decay of dark photon:

- Dark photon is the only connection, “portal”, to the Standard Model.

- Dark photon decay to SM is always the last stage of dark sector process, giving rise directly to observable signals.

\[ b_{\mu} \quad \rightarrow \quad \ell^\pm, \pi^\pm, K^\pm, ... \]

- \( m_{b_{\mu}} \sim 100 \text{ MeV} - \text{GeV} \), form factors are important in determining decay branching ratios.
Dark Photon decay branching ratios:

- Decay form factor has been measured, known as $R$.

\[
R(s) = \frac{\sigma(e^+e^- \to \text{hadrons}, s)}{\sigma(e^+e^- \to \mu^+\mu^-, s)} = \frac{BR(b_\mu \to \text{hadrons})}{BR(b_\mu \to \mu^+\mu^- (\text{or } e^+e^-))} \quad (m_b = s)
\]

\[
\sim \frac{BR(b_\mu \to \pi^+\pi^-)}{BR(b_\mu \to \mu^+\mu^- (\text{or } e^+e^-))}, \quad \text{for } m_b \leq \text{GeV}
\]

For example: $\pi^+\pi^- : \mu^+\mu^- : e^+e^- \simeq 1 : 1 : 1$ for $m_b \simeq 600 \text{ MeV}$.

I will focus mainly on leptons here.
But, the hadronic final states can be interesting as well.
Life time of dark photon

- Prompt, except for tiny couplings, or very large boost.

Value of $\epsilon$ for which $c\tau = 1$ mm

$$c\tau \sim \alpha\epsilon^2 m_{b\mu}$$

$$= 3 \times 10^{-6} \text{cm} \left( \frac{\text{GeV}}{m_{b\mu}} \right) \left( \frac{10^{-3}}{\epsilon} \right)$$

$m_U = m_{b\mu}$, dark photon mass
Dark Sector self-coupling

- Dark force has finite range.
- Gauge symmetry spontaneously broken.
  \[ \mathcal{L} \supset |D h_d|^2; \quad D_\mu h_d = (i \partial_\mu + g_d b_\mu) h_d \]
  \[ v_d \equiv \langle h_d \rangle \simeq \text{GeV} \]
- Dark photon - dark Higgs coupling

\[ g_{bbh_d} = \frac{m_b^2}{v_d} \]
Decay of dark higgs

\[ h_d \rightarrow b_\mu(b_\mu^{*}) \rightarrow \ell^+ \quad h_d \rightarrow b_\mu(b_\mu^{*}) \rightarrow \ell^- \]

- \( m_{h_d} > m_b \rightarrow 4\ell \) final state
- Can have displaced vertex if \( m_{h_d} < 2m_b \)
  - For example:
    - \( \epsilon = 10^{-3}, \ m_{h_d} = 1.2 \) GeV, \( m_b = 1 \) GeV
    - \( c\tau \simeq 10 \) cm

\[ h_d \rightarrow b_\mu^{*}(b_\mu^{*}) \rightarrow b_\mu^{*}(b_\mu^{*}) \rightarrow b_\mu^{*}(b_\mu^{*}) \rightarrow E_T \]

- For \( m_{h_d} < m_b \)
- Very long lived: \( c\tau \sim 1 - 100 \) km

Thursday, October 1, 2009
Decay in non-minimal models

- Non-minimal models with non-Abelian dark-sector, multiple dark Higgses possible.

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

- A cascade decay in the dark sector before decaying into SM states. Long decay chains, more leptons.
Lepton Jets

- Decay of the dark photon arising from a heavier particle (Z boson, MSSM LSP) leads to a highly collimated lepton pair.

\[ \gamma' \rightarrow e^\pm, \mu^\pm \quad \delta \theta < 0.1 \rightarrow \text{Lepton Jet} \]

Typical \( E_{\gamma'} > 10 \text{ GeV} \)

\[ m_{\gamma'} \sim \text{GeV} \quad \delta \theta \sim m_{\gamma'}/E_{\gamma'} < 0.1 \]

- Arkani-Hamed, Weiner 0810.0714; Baumgart, Cheung, Ruderman, Wang, Yavin 0901.0283; Cheung, Ruderman, Wang, Yavin 0909.0290
Production: just like producing photon

- Associated with a photon.

\[
\begin{align*}
\ell^\pm, \pi^\pm, K^\pm, \ldots
\end{align*}
\]

Leptonic signal: \( \gamma + \ell^+ \ell^- \), \( m_{\ell \ell} = m_{b_\mu} \)
Production: final state radiation

- Just like QED.

- Photon initial states are of course also possible.
Production: “Higgsstrahlung”

For detailed study:
Signal of dark higgsstrahlung:

\[ m_{\ell\ell} = m_b \]
\[ m_{4\ell} = m_{h_d} \]
\[ m_{\ell\ell} = m_b \]

\[ \rightarrow 6\ell \]

Or:

\[ \rightarrow 2\ell + E_T \]
Rare Z decay

\[ V \supset \epsilon \cos \theta_W b_\mu J^\mu_{\text{EM}} - \epsilon \sin \theta_W Z_\mu J^\mu_{\text{dark}} \]

Rare Z decay: BR(\( z \rightarrow \text{dark sector} \)) \( \sim 10^{-6} \)

\[ J^\mu_{\text{dark}} \supset g_d \sum_i q_i (h^\dagger_{di} \partial^\mu h_{di} - h_{di} \partial^\mu h^\dagger_{di}) + \cdots \]
SUSY LSP decay

\[ \mathcal{L}_{\text{gaugino}} = -2i \epsilon \lambda \bar{\sigma}^\mu \partial_\mu \lambda \bar{B} + \text{h.c.} \]

\[ \lambda \bar{b} \rightarrow \lambda \bar{b} + \epsilon \lambda \bar{B} \rightarrow \mathcal{L} \supset \epsilon \lambda \bar{B} \tilde{J}_b \]

\[ \tilde{J}_b = -i \sqrt{2} g_d \sum q_{h_i} \tilde{h}_{di} h_{di} \]

- SUSY LSP has to decay into dark sector states. The subsequent decay give lepton jets.
Topology of a SUSY Lepton Jet Event

- Baumgart, Cheung, Ruderman, LTW, and Yavin
  0901.0283
Conclusion:

- Dark matter in the universe could have self-interactions.
- Recent evidence can be interpreted as suggesting such self-interaction is mediated by GeV dark sector states.
- Production of GeV dark sector results in distinct signals: multiple leptons....
- It is exciting to go into this un-explored territory.