PAMELA from Dark Matter Annihilations to Vector Leptons

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2 New Decays





5 Models



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- Dark Matter is known to make up approximately 80% of the matter in the universe.
- Cold dark matter undergoes heirarchical clustering and should mirror the visible matter distribution.
- Weakly Interacting Massive Particles (WIMPs) are the leading candidate.

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Dark Matter in the Milky Way

- Particles in our Milky way will occasionally annihilate and produce standard model particles.
- These are expected produce equal numbers of particles and anti-particles.
- Since most astrophysical processes favor matter over antimatter, searching for deviations in the fraction of antimatter could point to dark matter annihilations.
- Many experiments have done this, and an excess in the positron fraction has been found by HEAT, AMS, and now PAMELA.

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PAMELA

- a Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics
- e Has been in orbit for 936 days.
- Released data on the positron fraction and the antiproton fraction.

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Dark Matter Annihilations

- Oark matter annihilates into a heavy vector leptons state.
- e Heavy Vector-like leptons decays into an positron and a Z boson.



Decays via mass mixing

- Start with a lagrangian that mixes a new vector lepton Ξ with light leptons.
- Will get best ratio of hard electrons to antiprotons if it is a has the quantum numbers of a right handed electron.

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Decays via mass mixing

- Start with a lagrangian that mixes a new vector lepton Ξ with light leptons.
- Will get best ratio of hard electrons to antiprotons if it is a has the quantum numbers of a right handed electron.
- So Have two free parameters the dark matter mass and the Ξ mass.

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Decays via mass mixing

● Assume that Ξ has the same quantum numbers as a right handed electron.

$$\mathcal{L} = \lambda \bar{L} e_R H + \mu \bar{\Xi} \Xi + \epsilon \bar{e}_R \bar{\Xi} + y \bar{L} \Xi H.$$
(1)

Gives the fermion mass mixing matrix after electroweak symmetry breaking:

$$\mathbf{M} = \begin{pmatrix} \lambda \mathbf{v} & \epsilon \\ \mathbf{y} \mathbf{v} & \mu \end{pmatrix}.$$
 (2)

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If *e* is small, then the state = marries mostly =, with a small linear combination of the *e_R*. Likewise, *yv* will mix the charged component of the electroweak doublet *L* with =.

Decays via mass mixing

- Ξ can share the same gauge quantum numbers as either a right-handed neutrino, left-handed leptons, or right-handed leptons.
- If Ξ has SU(2) quantum numbers, there will be decays to ν + vector bosons.

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Maximizing the positron energy

- $m_{\Xi} \rightarrow m_X$, spectrum decomposes to annihilation directly to Z + annihilation directly to e^+e^- .
- ② $m_{\Xi} \rightarrow m_X$ the e^{\pm} from Ξ decay becomes soft and the spectrum approaches annihilation directly into Zs.
- Solution By performing appropriate boosts, maximum energy of the hard e^{\pm} when

$$m_{\Xi} = \sqrt{2m_{\chi}m_Z - m_Z^2}.$$
 (3)



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Constraints from Flavor Changing Neutral Currents

Only requirement is that Ξ decays on cosmologically short time scales. Thus we can avoid most constraints if we set the mixing with the light leptons small by setting $\frac{\epsilon}{m_{\Xi}} << 1$.

Constraints from Flavor Changing Neutral Currents

() We can look at the bound from $\mu \to e\gamma$.

$$\left(\frac{\epsilon_{\mu}}{m_{\Xi}}\right)^2 \left(\frac{\epsilon_e}{m_{\Xi}}\right)^2 \lesssim 10^{-12}.$$
 (4)

If there is a large heirarchy between ε_μ and ε_e, there can still be a constraint from Γ(Z → μμ)/Γ(Z → ee) since we are effecting this coupling to the Z. This results in |ε_e/m_Ξ| < 0.05.

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Generating Cosmic Ray signals

- Simulate the process described above in MadGraph, then decay the Z boson in Pythia.
- Take the resulting spectra for electrons, positrons, and antiprotons and feed them into GALPROP for propagation.
- Used NFW profile.
- Opprove Propagation parameters:
 - Alfvén velocity $v_A = 20 \text{ km/s}$.
 - Diffusion coefficient $D = \beta (5.88 \times 10^{28} \text{ cm}^2/\text{s}) (R/4 \text{ GV})^{1/3}$.
 - Height of halo region L = 4 kpc.
 - Background as described in Cholis 2008 (arXiv:0802.2922)

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Fitting procedure

Define boost factor

$$BF = \frac{1}{V_{CR}} \left(\int d^3 x \frac{n_{true}^2(r)}{n^2(r)} \frac{\langle \sigma v \rangle}{\langle \sigma v \rangle_{thermal}} \right).$$
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Fit resulting spectrum to highest 4 bins of PAMELA data to avoid solar modulation.

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- Fit resulting spectrum to highest 4 bins of PAMELA data to avoid solar modulation.
- Since there can be large differences in the propagation of positrons and antiprotons, these should have differing boost factors due to the differences in the propagation region.
- Apply same boost factor from fitting the positron fraction to the antiprotons.

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ATIC fit

- ATIC sees an excess in $e^+ + e^-$ at 500-800 GeV.
- **②** To explain both at the same time, $m_X \sim 800$ GeV.

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ATIC fit

- ATIC sees an excess in $e^+ + e^-$ at 500-800 GeV.
- **②** To explain both at the same time, $m_X \sim 800$ GeV.
- For $m_X = 800$ GeV, $m_{\Xi} = 371$ GeV, and the same boost factor that fits PAMELA, we get a qualitatively similar shape and normalization.





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LHC detection

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- The particle can then decay to a Z and electron, leading to a final state of two Z bosons and two leptons.
- For the 6 lepton channel: For $m_{\Xi} = 300$ GeV, the cross section is 5 fb. In 300 fb⁻¹, there are ~ 8 events.
- For the 4 lepton + 2 jets: Similar reach when we account for the background ZZjj.

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Displaced Vertices

- Displaced vertices could give spectacular signals.
- Por this to happen, one needs

$$\left(\frac{\epsilon}{m_{\Xi}}\right)^2 \lesssim 10^{-13} \tag{6}$$

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So there is no reason to expect that this is satisfied (precision bounds are not this tight), but since a few meters is a much shorter distance than a kiloparsec it could happen.

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Tevatron and LEP bounds

- Tevatron discovery potential for quickly decaying Ξ is not so good.
- If mixing is weak and Ξ is long lived, bound from long lived charged particles is ≤ 10 fb. Then $m_{\Xi} > 120$ GeV.
- **③** LEP bound near the kinematic limit of 100 GeV.

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$$\mathcal{L} = y_X \bar{X} X S + y_{\Xi} \bar{\Xi} \Xi S + \epsilon_i \bar{e}_{Ri} \bar{\Xi} - V(S), \tag{7}$$

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Scalar potential

$$V(S) = m_S^2 S^{\dagger} S + \beta S^{\dagger} S^2 + \lambda_S (S^{\dagger} S)^2, \qquad (8)$$

Has a global U(1) symmetry explicitly broken by β. If we allow a vacuum expectation value for S to give mass to the dark matter and Ξ, then a is a pseudo-Goldstone boson with its mass controlled by the symmetry breaking parameter β.

Extension of the Standard Model

• In the limit that $m_a^2/m_\chi^2 << 1$ and $2m_{\Xi} \sim m_\chi$, then $\langle \sigma v \rangle_{\Xi\Xi} \sim (5.56 \times 10^{-24} \frac{cm^3}{s}) y_\chi^2 y_{\Xi}^2 (\frac{300 \ GeV}{m_\chi})^2.$ (9)

Would like this to dominate over annihilations into pseudoscalars.

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$$\frac{\langle \sigma v \rangle_{aa}}{\langle \sigma v \rangle_{\Xi\Xi}} \sim \frac{y_X^2}{y_{\Xi}^2} << 1$$
(10)

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Onclusion - Need some other source of mass for the Dark Matter X.

MSSM Extensions

- The supersymmetric generalization is straightforward.
- Now have a R-parity, which gives an LSP of the MSSM. Need this to be a subdominant component of the dark matter.
- $\textcircled{O} Extra \mathbb{Z}_2 \text{ gives the dark matter stability.}$
- Output Set is the same.

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MSSM Extensions

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- Now have a R-parity, which gives an LSP of the MSSM. Need this to be a subdominant component of the dark matter.
- **③** Extra \mathbb{Z}_2 gives the dark matter stability.
- Everything else is the same.
- Solution New LHC signal: End point of cascades of gluinos. In the cascade there would need to be a neutralino with a large bino component. Bino component of neutralino will have decays to Ξ and Ξ.

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Conclusions

- The recent evidence of an excess of high energy positrons from the PAMELA experiment are possibly the first hints of a dark matter signal.
- If so, the e⁺ data combined with the absence of any p̄ excess calls out for new thinking for dark matter annihilation processes.
- Averted tension with \bar{p} data via annihilation to intermediate vector lepton state.
- This vector-like lepton could be produced in Drell-Yan production at the LHC as a possible confirmation.
- If this vector like lepton is found and no missing energy signals are found, this still gives some understanding of dark matter annihilations.

Could these be the NMSSM

Alternatively, for economy, one might try to embed the supersymetric secnario in the NMSSM, adding only a pair of vector-like leptons, and avoiding the introduction of new S and X fields. The superpotential is then

$$W = W_{MSSM} + \epsilon_j E_j \bar{\Xi} + \lambda' S \Xi \bar{\Xi} + \kappa S^3 + \lambda H_u H_d S.$$
(11)

In this case X is identified with a mixture of higgsino and singlino. For the dark matter annihilation to be primarily into heavy leptons and not into W bosons, the dark matter must be primarily singlino. Achieving a cross section large enough to explain PAMELA requires the lightest pseudoscalar Higgs boson to be primarily singlet.¹

¹It should be noted that such a large cross section will necessitate some non-thermal mode of production of the Dark Matter to match the observed relic density. $\langle \Box \rangle \langle \overline{\Box} \rangle$

Then the annihilation of the dark matter, will either be directly into a pair of pseudoscalars or will proceed through an s-channel pseudoscalar into a pair of vector leptons. Only the second possibility reproduces the scenario discussed here. If $\langle S \rangle = x$ is to simulataneously provide the μ term and the mass of the Ξ , annihilations into pseudoscalars will always be greater than annihilations into Ξ thwarting this scenario. To see this, consider Equation 10. The ratio of annihilation cross sections becomes

$$\frac{\langle \sigma v \rangle_{aa}}{\langle \sigma v \rangle_{\Xi\Xi}} = \frac{\kappa^2}{\lambda'^2 \sqrt{1 - \frac{m_{\Xi}^2}{m_{\chi}^2}}} \sim \frac{\kappa^2}{\lambda'^2 \sqrt{1 - \frac{\lambda'^2}{\kappa^2}}} > 1, \qquad (12)$$

where in the final step we have noted that the ratio of masses in the radical must be less than one. Therefore annihilations into pseudoscalars will dominate. This conclusion could conceivably be