In Search of a Hidden Sector: the Phenomenology of Dark Sector Models

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Question: What is Dark Matter, and why should we care?
Why Should we Care?

There is ample observational evidence for the existence of dark matter!

- Galactic Rotation Curves
- Galaxy Clusters
- CMB
What is Dark Matter?

Luminous Matter (~5%)

Dark Matter (~26%)

Black Holes?

...and?
The Core-Cusp Problem

-In the CDM paradigm, dark matter particles interact with each other only gravitationally and do not collide.

-While the simulations using CDM produce distributions where the density sharply increases at the centre of the galaxies (“cusps”), observations of dwarf galaxies show constant central distributions (“cores”).

-A solution to the core-cusp problem is self-interacting dark matter (SIDM).
What is Dark Matter?

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Dark or Hidden Sector!

Is there a “dark” Standard Model?
We would like to connect the Standard Model to our Hidden Sector, this is done through a “portal” interaction or interactions.

Four commonly discussed portal interactions:

- **Scalar Portal: Dark Higgs**
- **Pseudoscalar Portal: Axion-like Particle**
- **Neutrino Portal: Heavy Neutral Lepton**
- **Vector Portal: Dark Photon**
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The Lagrangian for a dark fermion, $\chi$, coupling to a dark photon that kinetically mixes with the standard model is:

$$\mathcal{L}_D = \bar{\chi}(i\gamma^\mu D_\mu - m_\chi)\chi + \frac{1}{4} A_{\mu\nu} A^{\mu\nu} + \frac{\kappa}{2} B_{\mu\nu} A^{\mu\nu}$$

$A_\mu$ : U(1)$_D$ gauge field  \hspace{1cm} $B_\mu$ : U(1)$_Y$ gauge field

Under the field redefinition: $A_\mu \rightarrow A'_\mu - \kappa B_\mu$

$$\bar{\chi}(i\gamma^\mu \partial_\mu - e'\gamma^\mu A'_\mu + \kappa e'\gamma^\mu B_\mu - m_\chi)\chi + \frac{1}{4} A'_{\mu\nu} A'^{\mu\nu}$$

The Lagrangian for a dark fermion, \( \chi \), coupling to a dark photon that kinetically mixes with the standard model is:

\[
L_D = \bar{\chi}(i\gamma^\mu D_\mu - m_\chi)\chi + \frac{1}{4}F_{\mu\nu}F^{\mu\nu}
\]

where \( F_{\mu\nu} = \partial_{\mu}A_{\nu} - \partial_{\nu}A_{\mu} \)

Under the field redefinition: \( A_\mu \rightarrow A'_\mu - \kappa B_\mu \)

\[
\bar{\chi}(i\gamma^\mu \partial_\mu - e'\gamma^\mu A'_\mu + \kappa e'\gamma^\mu B_\mu - m_\chi)\chi + \frac{1}{4}A'_{\mu\nu}A'^{\mu\nu}
\]

A More General Case: Dark Photon+Dark Z

\[ \mathcal{L} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{DS}} - \frac{\kappa}{2} B'_{\mu\nu} B^{\mu\nu} \]

Standard Model Lagrangian

Dark Sector Lagrangian

Hypercharge Gauge Field

“Dark” Hypercharge: dark Abelian vector field
Three possible phases can be considered:

- Okun phase: $B'_\mu$ is purely massive
- Holdom phase: $B'_\mu$ is massless
- Mixed phase: Both massless and massive dark gauge fields are present

\[
\kappa B'_\mu B'^\mu = \kappa \cos(\theta_W)\cos(\theta'_{W'}) A_1^\mu A_2^{\mu} + \kappa \sin(\theta_W)\sin(\theta_{W'}) Z_1^\mu Z_2^{\mu} - \kappa \sin(\theta_W)\cos(\theta'_{W'}) Z_1^\mu A_2^{\mu} - \kappa \cos(\theta_W)\sin(\theta'_{W'}) A_1^\mu Z_2^{\mu}
\]
After field redefinitions, to order $\kappa$, one gets:

$$\mathcal{L} \supset A \cdot [eJ_{EM} - \kappa \cos(\theta_W)\cos(\theta_W') J_{EM}']$$

Photon now couples to dark EM current

$$\mathcal{L} \supset Z \cdot \left[ \frac{g_2}{\cos(\theta_W)} J_Z + e'\kappa \sin(\theta_W) \cos(\theta_W') J_{EM} - g_2' \tan(\theta_W') \kappa \sin(\theta_W') \left\{ \frac{M_Z^2}{M_Z^2 - M_{Z'}^2} \right\} J_Z \right]$$

Z now couples to dark EM current and dark Z current

$$\mathcal{L} \supset Z' \cdot \left[ \frac{g_2'}{\cos(\theta_W)} J_{Z'} + e'\kappa \sin(\theta_W) \cos(\theta_W') J_{EM} + g_2 \tan(\theta_W) \sin(\theta_W') \kappa \left( \frac{M_Z^2}{M_Z^2 - M_{Z'}^2} \right) J_{Z'} \right]$$

Dark Z now couples to EM current and Z current

The Experimental Context

Large Hadron Collider
MoEDAL is sensitive to many new physics scenarios!

For what follows we will focus on the search for milli-charged particles.
Holdom Phase: Milli-Charged Fermions
Charge-normalized milli-charge fermion production cross-sections at $\sqrt{s} = 14$ TeV. Meson decays are scaled by their respective branching ratios.
Projected 95% confidence level exclusion limits for MAPP-1 for milli-charged fermion produced in pp collisions.

Run 3: $\sqrt{s} = 13.6 \text{ TeV}$, $L_{\text{LHCb}}^{\text{int}} = 30 \text{ fb}^{-1}$

HL-LHC: $\sqrt{s} = 14 \text{ TeV}$, $L_{\text{LHCb}}^{\text{int}} = 300 \text{ fb}^{-1}$

Mixed Phase: Milli-Charged Scalars

We use a model inspired by chiral effective theories of QCD:

\[
\mathcal{L}_{\text{int}}^{2\phi} = \frac{1}{F_0^2} \text{Tr}(D_{\mu}\phi D^\mu \phi) + \frac{BF_0^2}{2} \text{Tr} \left( 2M - \frac{M\phi^2}{2} \right)
\]

\[
\mathcal{L}_{\text{int}}^{4\phi} = \frac{1}{4F_0^2} \text{Tr} \left( -\frac{1}{6} (D_{\mu}\phi D^\mu \phi \phi^2 + D_{\mu}\phi D^\mu \phi \phi + D_{\mu}\phi \phi D^\mu \phi) \\
+ \frac{1}{4} (D_{\mu}\phi \phi + \phi D_{\mu}\phi)(D^\mu \phi \phi + \phi D^\mu \phi) \\
- \frac{1}{6} (D_{\mu}\phi \phi^2 D^\mu \phi + \phi D_{\mu}\phi \phi D^\mu \phi + \phi^2 D_{\mu}\phi D^\mu \phi) \right) \\
+ B_0 F_0^2 \text{Tr} \left( \frac{M\phi^4}{24F_0^4} \right)
\]

\[
\phi = \begin{pmatrix}
\pi_D^0 + \frac{1}{\sqrt{3}} \eta_D \\
\sqrt{2}\pi_D^- \\
\sqrt{2}K_D^- \\
\sqrt{2}K_D^0 \\
-\pi_D^0 + \frac{1}{\sqrt{3}} \eta_D \\
\sqrt{2}K_D^- \\
\sqrt{2}K_D^0 \\
-\frac{2}{\sqrt{3}} \eta_D
\end{pmatrix}
\]
To which we add a Wess-Zumino-Witten like term:

\[
\begin{align*}
n \mathcal{L}_{WZW}^{ext} &= -en(A'_\mu - \kappa \cos \theta_W \cos \theta_W A_\mu)J^\mu \\
&\quad + i \frac{ne^2}{48\pi^2} \epsilon^{\mu\nu\rho\sigma} \partial_\nu (A'_\rho - \kappa \cos \theta_W \cos \theta_W A_\rho) (A'_{\sigma} - \kappa \cos \theta_W \cos \theta_W A_{\sigma}) \\
&\quad \times \text{Tr} \left[ 2Q^2 (U \partial_\mu U^\dagger - U^\dagger \partial_\mu U) - QU^\dagger Q \partial_\mu U + QUQ \partial_\mu U^\dagger \right]
\end{align*}
\]

\[
U(x) = \exp \left( \frac{i \phi(x)}{F_0} \right)
\]

\[
J^\mu = \frac{\epsilon^{\mu\nu\rho\sigma}}{48\pi^2} \text{Tr} \left( Q \partial_\nu U U^\dagger \partial_\rho U U^\dagger \partial_\sigma U U^\dagger + Q U^\dagger \partial_\nu U U^\dagger \partial_\rho U U^\dagger \partial_\sigma U \right)
\]
Case 1: Drell-Yan production of milli-charged scalars
Case 2: photo-fusion production of milli-charged scalars
Projected 95% confidence level exclusion limits for MAPP-1 for milli-charged scalars produced in pp collisions and photo-fusion.

Run 3: $\sqrt{s} = 13.6$ TeV, $L_{\text{LHCb}}^{\text{int}} = 30$ fb$^{-1}$

HL-LHC: $\sqrt{s} = 14$ TeV, $L_{\text{LHCb}}^{\text{int}} = 300$ fb$^{-1}$
Conclusion

• Hidden sector models offer a rich and interesting phenomenology that is accessible at accelerators.

• Indications are that MAPP-1 will access novel parameter space in the search for mCP.

• Much work yet remains to be done!