Searching for a Strongly Interacting Dark Sector at MoEDAL MAPP

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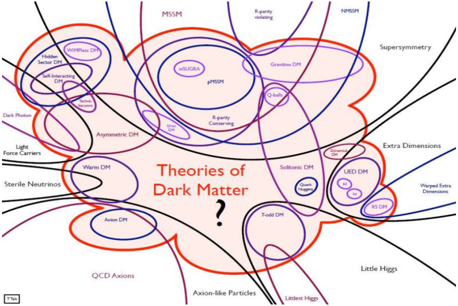
Schedule

Introduction

Quick Review of Dark Matter



Dark Matter must follow two key properties:

- Dark Matter must be stable over the lifetime of the universe
- Dark Matter must also be overall electrically neutral and effectively neutral with the Standard Model

Barletta, W. et al. .. (2014). Planning the Future of U.S. Particle Physics (Snowmass 2013): Chapter 6: Accelerator Capabilities.

Strongly Interacting Dark Matter

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- Self-Interactions

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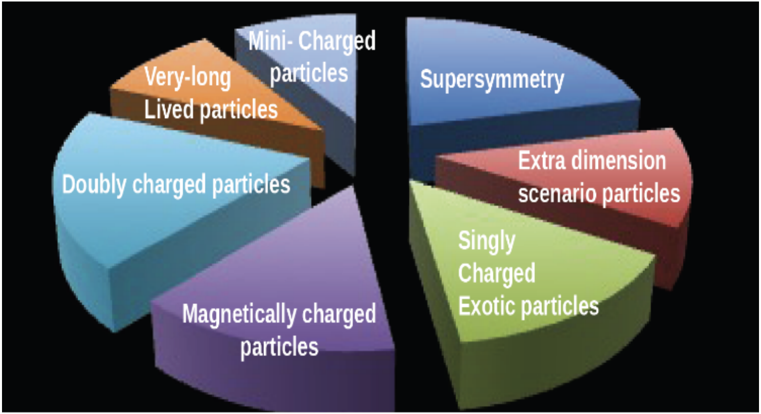
A small minicharged DM subcomponent (0.4%) may resolve the anomalous 21cm hydrogen absorption signal reported by the EDGES Collaboration

G. D. Kribs and E. T. Neil, Int. J. Mod. Phys. A **31** (2016) no.22, 1643004 [arXiv:1604.04627 [hep-ph]].
Berling, Hopper, Krnjaic, McDermott, Phys. Rev. Lett. 121, 011102 (2018)

MoEDAL Experiment

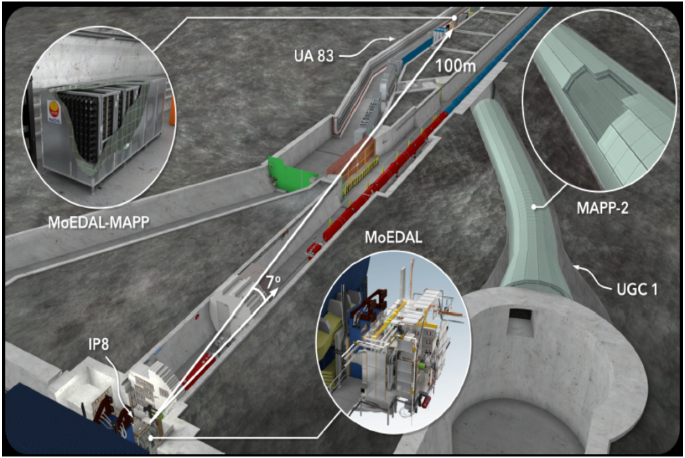
MoEDAL stands for **Mo**nopoles and **E**xotics **D**etector **A**t the **L**HC



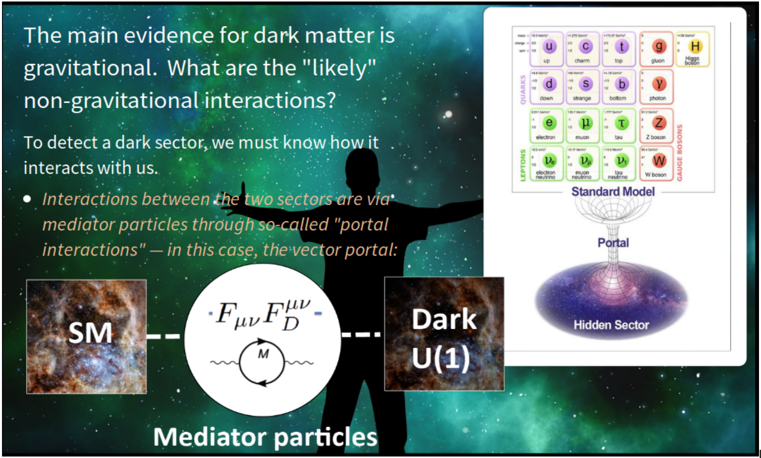
International Journal of Modern Physics A, September 2014, Vol. 29, No. 23

MoEDAL-MAPP

MAPP stands for **M**oEDAL **A**pparatus for **P**enetrating **P**articles



MAPPing the Dark Sector



Types of SIMPs

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- Baryon-like DM
- Dark Glueballs
- Many more...

Our research focuses on Pion-like Dark Matter.

Pion-Like Dark Matter

Meson Dark Matter: Pion-Like

A Lagrangian for a Pion-Like DM is:

$$\mathcal{L} = \frac{f_\pi^2}{4} Tr[(D_\mu U)^\dagger D^\mu U] + \frac{Bf_\pi^2}{2} Tr(M^\dagger U + U^\dagger M) + \mathcal{L}_{G'} + \mathcal{L}_{WZW} + \mathcal{L}_{mix} + \ldots \quad (1)$$

S. Scherer, Introduction to chiral perturbation theory, Adv. Nucl. Phys. 27 (2003) 277 [hep-ph/0210398].

Meson Dark Matter: Pion-Like

Where, in the three light quark case, the meson fields are given by:

$$U = e^{i\frac{\Pi}{f}\pi}, \Pi = \pi^a \lambda^a \tag{2}$$

And

$$\frac{\Pi}{\sqrt{2}} = \begin{pmatrix} \frac{1}{\sqrt{2}}\pi_3 + \frac{1}{\sqrt{6}}\pi_8 & \pi_+ & K_+ \\ -\pi_- & \frac{1}{\sqrt{2}}\pi_3 + \frac{1}{\sqrt{6}}\pi_8 & K_0 \\ K_- & \bar{K}_0 & -\sqrt{\frac{2}{3}}\pi_8 \end{pmatrix} \tag{3}$$

And M is the mass matrix

Kinetic Mixing

Add a **new massless $U'(1)$ gauge field** (A'_μ, dark photon), such that

$$\mathcal{L}_{mix} = -\frac{\kappa}{2} A'_{\mu\nu} B^{\mu\nu} \quad (4)$$

where $A'_{\mu\nu} = \partial_\mu A'_\nu - \partial_\nu A'_\mu$ Since we introduced this new field, it will also have a gauge kinetic term:

$$\mathcal{L}_{G'} = -\frac{1}{4} A'_{\mu\nu} A'^{\mu\nu} \quad (5)$$

Removing the mixing term via the field redefinition $A'_\mu = A'_\mu + \kappa B_\mu$ This would modify the covariant derivative, for example if we have a charged dark fermion, its covariant derivative will change according to:

$$(\partial\!\!\!/ - ie' A'_\mu) \rightarrow (\partial\!\!\!/ - ie' A'_\mu - ie' \kappa B_\mu) \quad (6)$$

WZW Lagrangian

The Wess-Zumino-Witten Lagrangian is:

$$\mathcal{L}_{WZW} = \frac{2N_C}{15\pi^2 f_\pi^5} \epsilon^{\mu\nu\rho\sigma} Tr[\Pi\partial_\mu\Pi\partial_\nu\Pi\partial_\rho\Pi\partial_\sigma\Pi] \quad (7)$$

The Wess-Zumino-Witten term allows for 3 $\rightarrow$ 2 annihilation process, which results in DM self-interactions and helps explaining the galactic structure anomaly and DM abundance.

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The Wess-Zumino-Witten term allows for $3 \to 2$ annihilation process, which results in DM self-interactions and helps explaining the galactic structure anomaly and DM abundance. It also gives us the $\pi_D\gamma_D\gamma_D$ vertex upon including the gauge fields, specifically from the term:

$$i\frac{ne^2}{48\pi^2}\epsilon^{\mu\nu\rho\sigma}\partial_\nu A_\rho A_\sigma Tr[2Q^2(U\partial_\mu U^\dagger - U^\dagger\partial_\mu U) - QU^\dagger Q\partial_\mu U + QUQ\partial_\mu U^\dagger]$$

The Madgraph Model

Madgraph and Feynrules

We use two key software packages for evaluating our model:
Feynrules is a Mathematica package, which is used for defining parameters and interactions for quantum field theories, especially physics beyond the standard model.
Madgraph is a Monte Carlo event generator which is used to simulate particle interactions to generate cross-section and decay rates.

A. Alloul, N. D. Christensen, C. Degrande, C. Duhr, and B. Fuks, FeynRules 2.0 - A complete toolbox for tree-level phenomenology, Comput. Phys. Commun. 185, 2250 (2014), arXiv:1310.1921 [hep-ph]

Alwall, Johan, et al. “MadGraph 5: Going Beyond.” Journal of High Energy Physics, vol. 2011, no. 6, June 2011. Crossref, https://doi.org/10.1007/jhep06(2011)128.

Sanity and Validity Checks

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- How do we know the cross-sections we are generating are valid?
- We computed the analytical cross-sections of certain processes, and compared it to the cross-sections generated by Madgraph.
- A good way to compare the analytical result with the simulated one is to plot the ratio of the cross sections vs beam energy.

Example: Ratio vs Energy for $\pi_D^+ + \pi_D^- \to \pi_D^0 + \pi_D^0$

For $\pi_D^+ + \pi_D^- \to \pi_D^0 + \pi_D^0$, the analytical cross-section is:

$$\sigma = \frac{E^2}{4\pi f_\pi^4} \tag{8}$$

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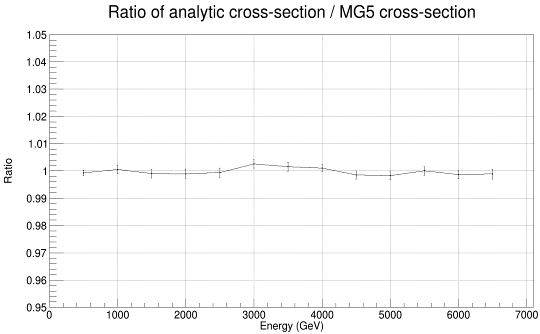

Figure: Ratio vs beam Energy of the process $\pi_D^+\pi_D^- \to \pi_D^0\pi_D^0$

Example: Ratio vs Energy for $K_D^+ + K_D^- \to K_D^+ + K_D^-$

For $K_D^+ + K_D^- \to K_D^+ + K_D^-$, the analytical cross-section is:

$$\sigma = \frac{E^2}{12\pi^2 f_\pi^4} \tag{9}$$

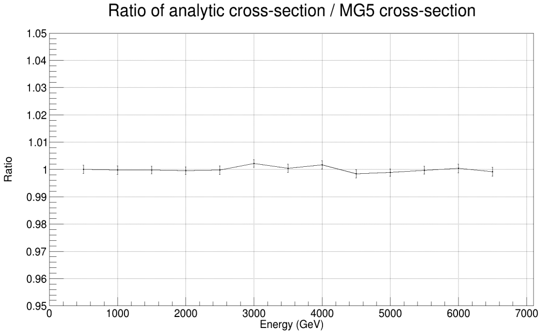

Figure: Ratio vs beam Energy of the process $K_D^+ K_D^- \to K_D^+ K_D^-$

Sanity check for the WZW term: $\pi_D^0 \rightarrow \gamma_D + \gamma_D$

To check whether we have the correct implementation of the Wess-Zumino-Witten term, we can check the generated decay rate by Madgraph to our analytics.
The decay rate for $\pi_D^0 \rightarrow \gamma_D + \gamma_D$ is

$$\Gamma = \frac{\alpha^2 M_{\pi 0}^3}{64\pi^3 f_\pi^2} \tag{10}$$

With $f_\pi = 0.14$, $m_\pi = 0.135$, and $\alpha = \frac{g_D^2}{4\pi}$, we get

$$\Gamma = 3.86459 \times 10^{-9}$$

The decay width generated by Madgraph is

$$\Gamma = 3.865 \times 10^{-9} \pm 5.7 \times 10^{-18}$$

This means that our implementation of the WZW term is correct.

Key Processes and Results

Processes of key interest

We want to look into two key processes in the theory of SIDM:

- **Drell-Yan production of two charged Dark Pions**:
  - Allows us to investigate mili-charged scalars systematically for the experiment.
  - Investigate the effects on parameter space when having a non-zero dark gauge field mass
  - Is a benchmark for "reasonableness" of the parameter choices that give a non-trivial cross section for the photo-fusion process.

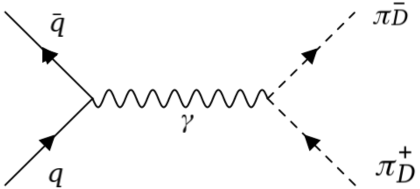

Figure: Drell-Yan production of two charged dark pions

Processes of key interest

- **Photo-fusion to three dark pions**
  - This process would not exist for non pion-like DM, since it is driven by the WZW term.
  - *If* this process has detectable consequences at MAPP and *if* it can be differentiated from other processes that produce scalars, then we may be able to differentiate this model from other mili-charged scalars.

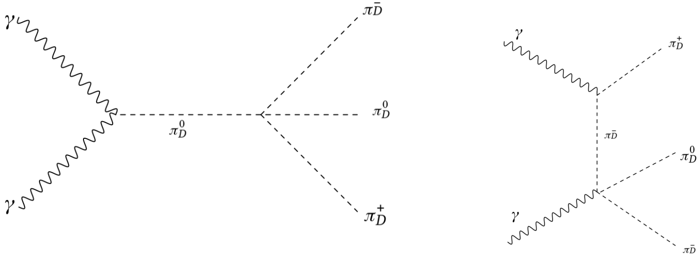

Figure: Photo-fusion to three pions

Cross Section Plots

- We have a lot of free parameters, and one constraint: $\frac{m_\pi}{f_\pi} \lesssim 2\pi$
- This gives us an upper limit on what the pion mass could be. We can also adjust the decay constant at will, as long as the constraint isn't violated.
- We plot the cross-section of both the photo-fusion and Drell-Yan process against the decay constant f, and the effective charge, $\epsilon = \kappa e$

Plot of $\log \sigma$ vs f

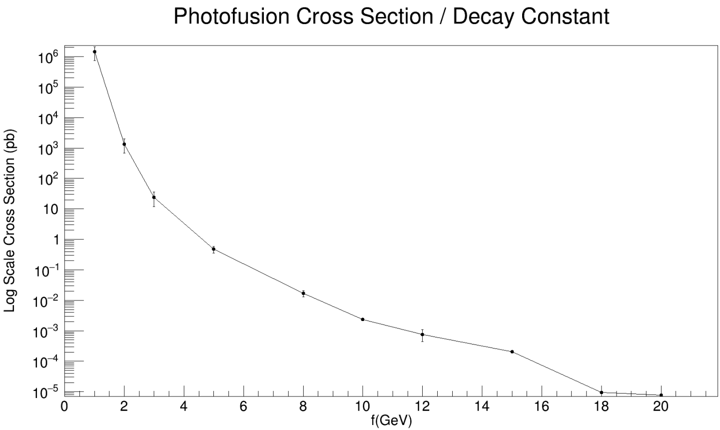

Figure: $\log \sigma$ vs f for photo-fusion process

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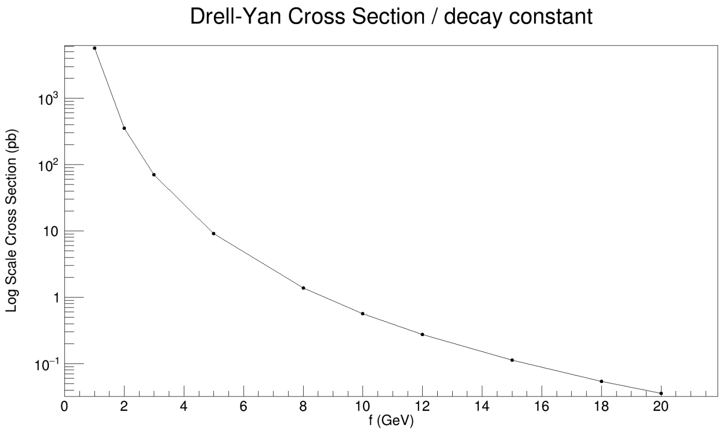

Figure: $\log \sigma$ vs f for Drell-Yan process

Plot of $\log \sigma$ vs $\log \epsilon$

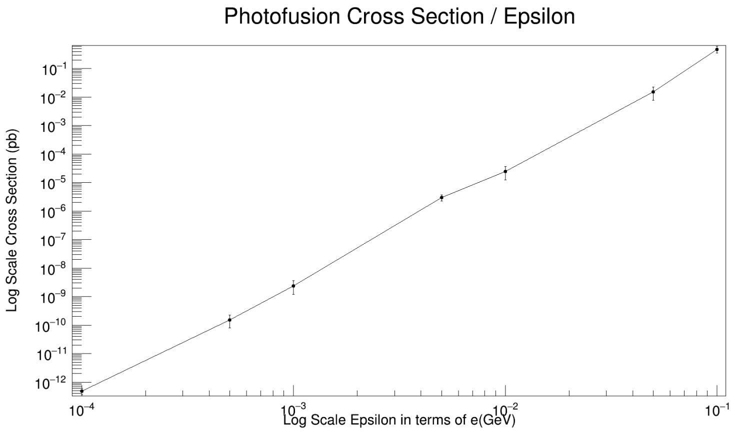

Figure: $\log \sigma$ vs $\log \epsilon$ for photo-fusion process

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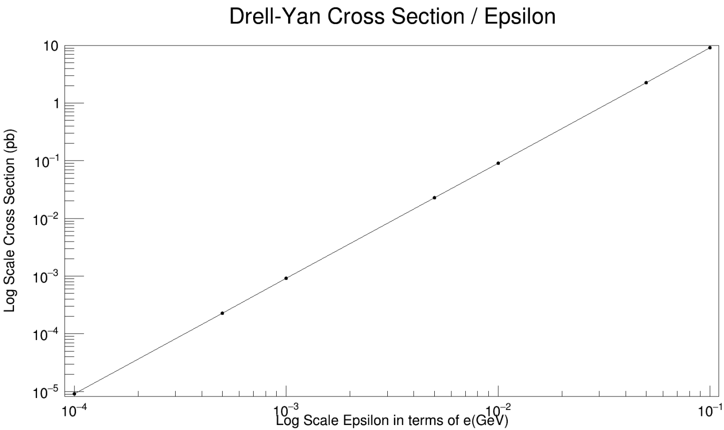

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Thank You!