Searching for a Strongly Interacting Dark Sector at MoEDAL MAPP

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Schedule

Introduction

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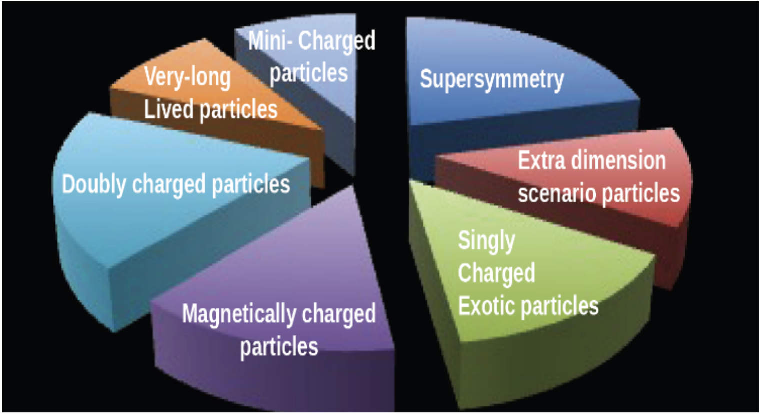
- Carried out first-ever searches for Spin-1 MMs, dyons, MMs produced in heavy-ion collisions via Schwinger mechanism
- Is complementary to General Purpose Detectors such as ATLAS and CMS.

MoEDAL-MAPP Experiment



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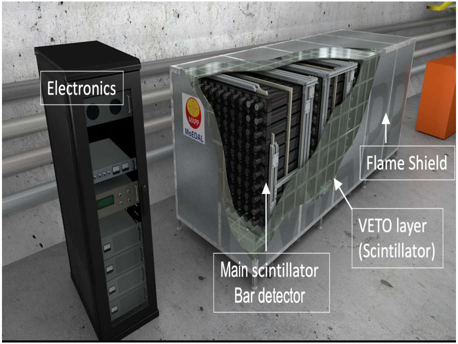
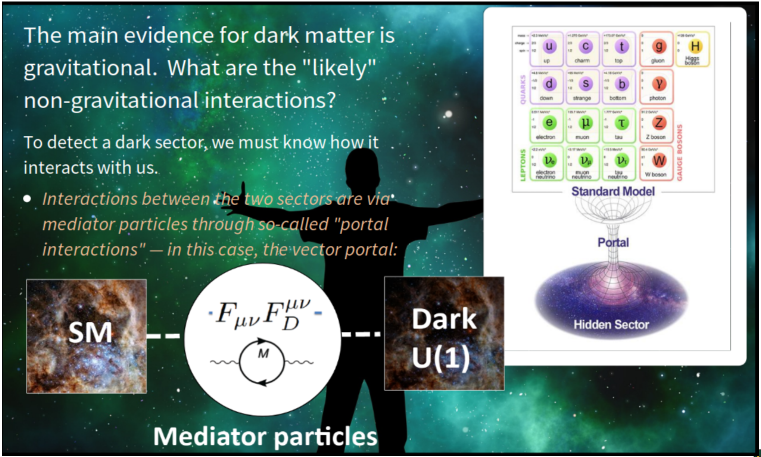
- Sensitivity to charged and neutral LLPs
- The main LHC experiments are not optimized for HIPs, FIPs.

MoEDAL-MAPP1



- Located at UA83, about 100m from the LHCb IP at about 7° from the beam axis
- 400 scintillator bars ($10 \times 10 \times 75cm^3$) readout by PMTs
- Each particle going through covers 3m of scintillator

MAPPing the Dark Sector



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- Another form of mCPs MAPP is looking for is **S**trongly **I**nteracting **M**assive **P**articles

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)

Types of SIMPs

Strongly Interacting Dark Matter have various types:

- Pion-like DM: $m_q << \Lambda_D$
- Quarkonia-like DM: $m_q >> \Lambda_D$
- Intermediate regime ($m_q \sim \Lambda_D$) or Mixed regime ($m_{q1} < \Lambda_D < m_{q2}$)
- 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].

Kinetic Mixing

Instead of adding **one** massless $U'(1)$ gauge field (Holdom phase), we add two fields:

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Where $B'_\mu = \cos\theta_{W'} A'_\mu - \sin\theta_{W'} Z'_\mu$

Izaguirre, E. and Yavin, I., “New window to millicharged particles at the LHC”, *Physical Review D*, vol. 92, no. 3, 2015.

WZW Lagrangian

The Wess-Zumino-Witten Lagrangian is:

$$\mathcal{L}_{WZW} = \frac{2N_C}{15\pi^2 f_\pi^5}\epsilon^{\mu\nu\rho\sigma} Tr[\Pi\partial_\mu\Pi\partial_\nu\Pi\partial_\rho\Pi\partial_\sigma\Pi] \quad (3)$$

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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. 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, as well as study the kinematics of these processes.

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.

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:

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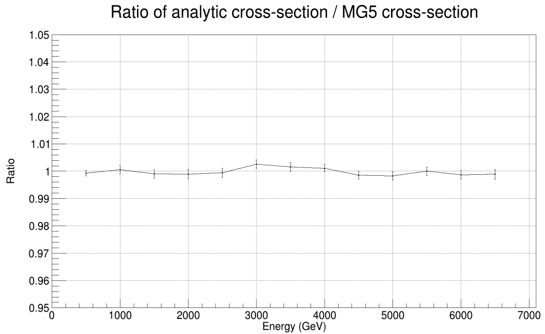
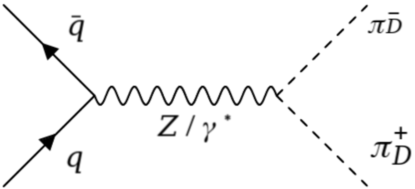


Figure: Ratio vs beam Energy of the process $\pi_D^+\pi_D^- \to \pi_D^0\pi_D^0$

Drell-Yan Process

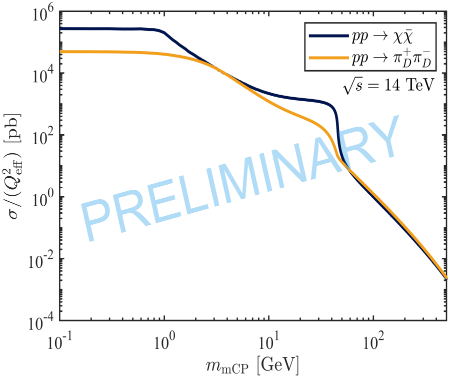
Drell-Yan Process

We want to study Drell-Yan production to two charged dark pions:



Comparison Plots with standard mCP

We compare the cross-section of the Drell-Yan SIMP vs Drell-Yan of standard mCP:



Preliminary Projected Exclusion Limits

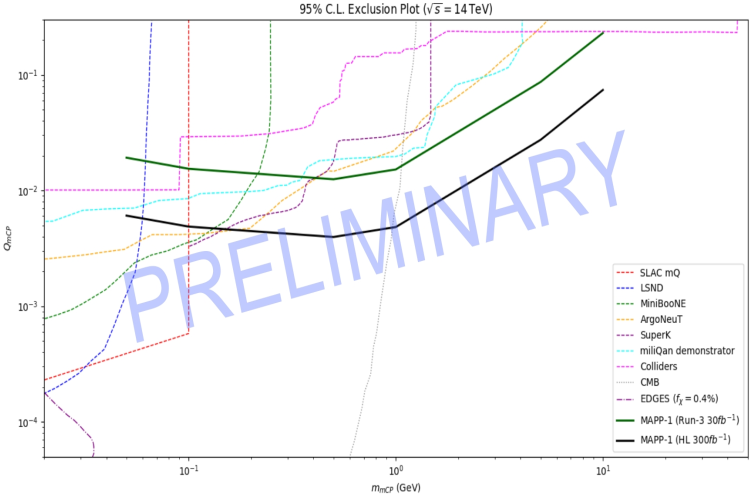
Finding the Q_{eff}

We are looking for a C.L. (Confidence Level) of 95% C.L We use the following formula to solve for Q_{eff}:

$$N_{\sigma} = \sigma Q_{eff} L A \tag{5}$$

Where $L = 30 fb^{-1}$ and $A = \frac{\text{number of particles that traverse the full MAPP detector}}{\text{Total number of particles}}$

Exclusion Plot



Future Work

- Include more mass ranges for the acceptance exclusion plot.

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- Simulate energy loss by using the full detector geometry, as well as the whole region of MoEDAL-MAPP in GEANT4

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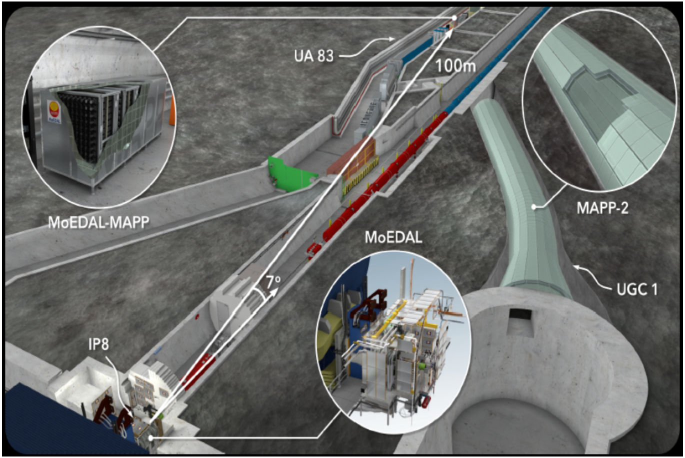
- Simulate energy loss by using the full detector geometry, as well as the whole region of MoEDAL-MAPP in GEANT4
- Include a process dominated by the WZW term: Photon fusion to three dark pions

Thank You

BACKUP

MoEDAL-MAPP



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:

$$\sigma = \frac{E^2}{12\pi^2 f_\pi^4} \quad (6)$$

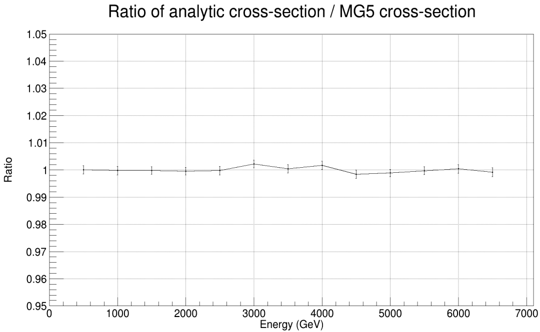


Figure: Ratio vs beam Energy of the process $K_D^+ K_D^- \to K_D^+ K_D^-$

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

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 $\pi_D^0 \to \gamma_D + \gamma_D$ is

$$\Gamma = \frac{\alpha^2 M_{\pi 0}^3}{64\pi^3 f_\pi^2} \tag{7}$$

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

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

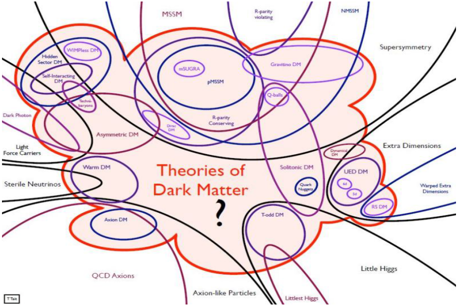
This means that our implementation of the WZW term is correct.

Vertex

The vertex of $\pi_D^+\pi_D^- Z$ is:

$$\frac{3ig_D\kappa}{2c_wF}\left(\kappa s_W^2 s_{W'} + c_W^2\kappa s_{W'}(-\frac{4}{3}-\frac{8}{3}s_{W'}^2) + s_W(-3.525+\frac{8}{3}c_{W'}^2 + 3.525 s_{W'}^2)\right)p_{\pi^-}^{\mu} + \ldots.$$

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.

Meson Dark Matter: Pion-Like

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

$$U = e^{i\frac{\Pi}{f}\pi}, \Pi = \pi^a \lambda^a \tag{8}$$

And

$$\frac{\Pi}{\sqrt{2}} = \begin{pmatrix} \frac{1}{\sqrt{2}}\pi_3 + \frac{1}{\sqrt{6}}\pi_8 & \pi_+ & K_+ \\ -\pi_- & \frac{1}{\sqrt{2}}\pi_3 + \frac{1}{\sqrt{6}}\pi_8 & K_0 \\ K_- & \bar{K}_0 & -\sqrt{\frac{2}{3}}\pi_8 \end{pmatrix} \tag{9}$$

And M is the mass matrix

References for the Exclusion Plot

SLAC mQ (The Millicharged Particle Search) — Phys. Rev. Lett. 81, 1175.
LSND (Liquid Scintillator Neutrino Detector) — Phys. Rev. Lett. 122, 071801. Data from LSND used in their analysis is from Phys. Rev. D 63, 112001.
miniBooNE (Mini Booster Neutrino Experiment) — Phys. Rev. Lett. 122, 071801. Data from miniBooNe used in their analysis is from Phys. Rev. Lett. 121, 221801 and Phys. Rev. Lett. 98, 112004.
Colliders/Accelerators — The collider bounds are combined limits from beam dump experiments and LEP presented in JHEP 2000, 003. There are also two papers that I know of with bounds from CMS (but they only cover e/3 < Q < e), so they are cut-off on my versions of the limit plots.
ArgoNeuT (The Argon Neutrino Teststand) — Phys. Rev. Lett. 124, 131801.
milliQan Demonstrator — Phys. Rev. D 102, 032002.
SuperK — Phys. Rev. D 102, 115032.
CMB N_eff (Indirect) — JHEP 2013, 58; JCAP 2014, 029.