Dark Sector Portals & Searches for Anomalously Penetrating Particles at the LHC with the MoEDAL-MAPP Experiment

Michael Staelens (staelens@ualberta.ca), PhD Candidate
[On Behalf of the MoEDAL Collaboration]

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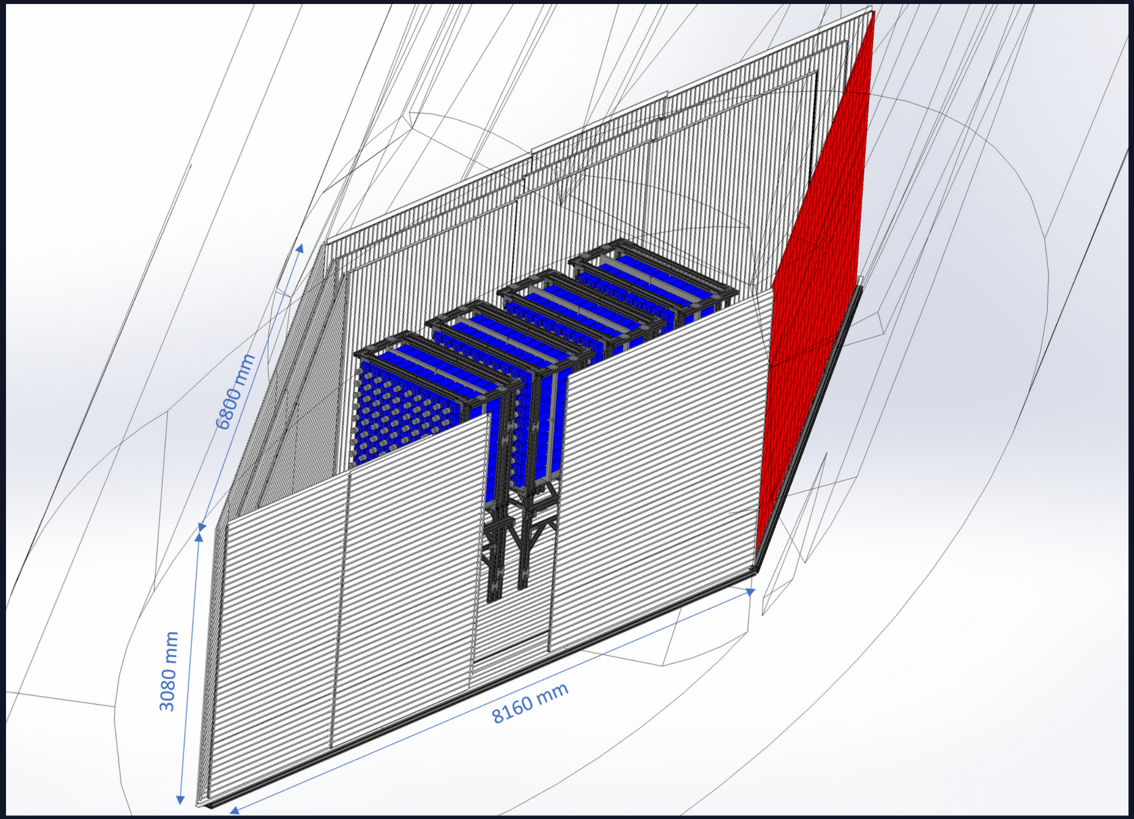
The Monopole and Exotics Detector At the LHC (MoEDAL)

MoEDAL's Apparatus for Penetrating Particles

The MAPP-1 Detector System

An **active scintillation based detector** aimed at the search for **new feebly interacting particles (FIPs)**.
Two subdetectors: **MAPP-mCP** & **MAPP-LLP.**



MAPP-mCP (Phase-I, beginning in Run-3)
Currently **under construction** at the UofA!

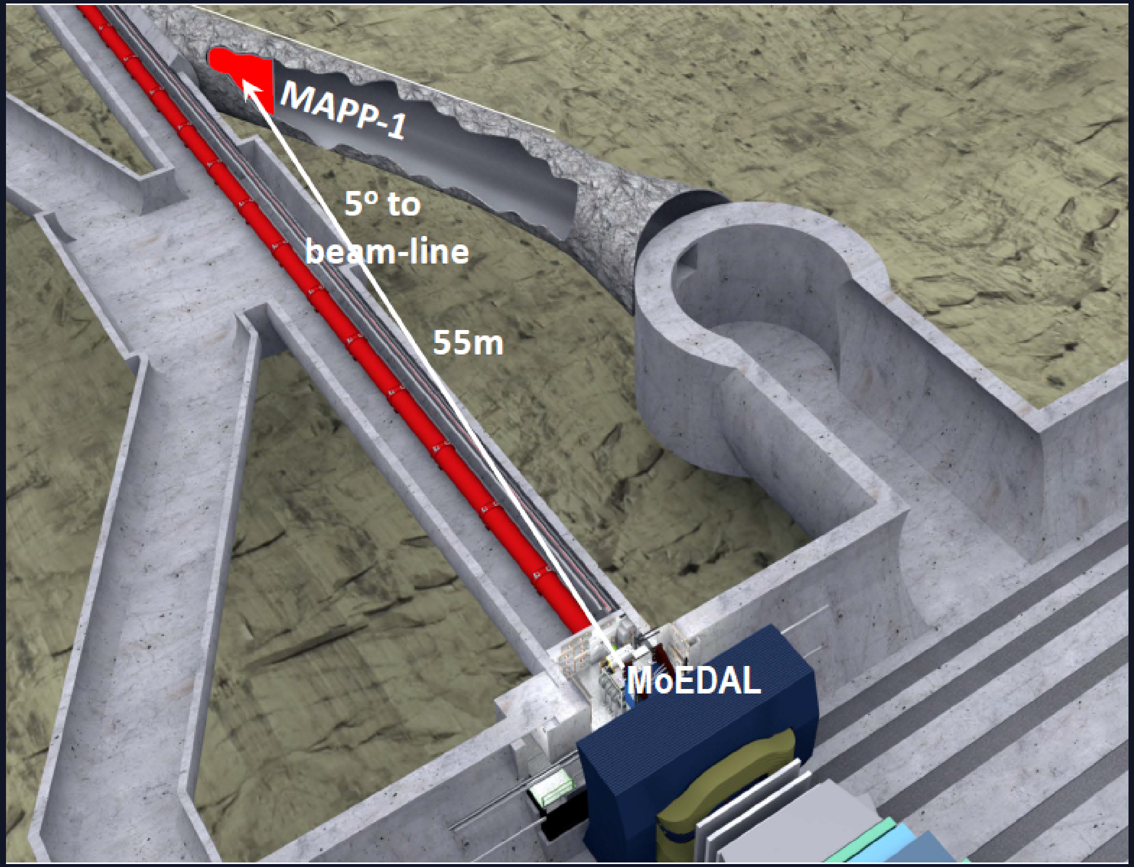
- **Inner core of MAPP-1** with a detector size of roughly 1 m x 1 m x 3 m.
- Search for **minicharged particles - mCPs** ($Q << 1e$).
- Note: Atlas and CMS are limited to ~$e/3$ or greater.

MAPP-LLP (Phase-II, in 2022 during Run-3)

- Nested **outer layers** of the MAPP detector (hodoscope planes).
- Search for new **pseudo-stable neutral long-lived particles (LLPs)** that may **decay in the detector volume**.

Location of the MAPP Detector @ The LHC

Proposed placement is in the UGC1 gallery, adjacent to the MoEDAL detector region.



MAPP-1 (Phases-I & II)

- **Positioned at 5°** w.r.t to the beam axis. **~55 m from IP8.**
- This placement has **~100 m of rock overburden and 25-30 m of rock shielding** between the detector and the IP.
- **Large decay zone of ~10 m** is possible.

MAPP's Physics Program

New Particle	Model	Production	Signal (e.g.)	Run-3	HL
ψ mCP	'Dark QED'	Drell-Yan	$-\left\langle \frac{dE}{dx} \right\rangle \propto Q^2$	✓	✓
Heavy N	CP Violation	Drell-Yan	$-\left\langle \frac{dE}{dx} \right\rangle \propto \alpha D$	✓	✓
ϕ_h	Scalar Portal	$B \to K\phi_h$	$\phi_h \to \ell^+\ell^-$	✓	✓
γ'	Vector Portal	$\pi^0, \eta \to \gamma\gamma'$	$\gamma' \to \ell^+\ell^-$	✗	✓
		$pp \to p\gamma' X$	$\gamma' \to \ell^+\ell^-$	—	—
a	ALP Portal	$\pi^0, \eta \to a\gamma\gamma$	$a \to \gamma\gamma$	✗	✓
HNLs	Minimal Z'_{B-L}	$Z' \to N_s N_s$	$N \to \mu^{\pm} q\bar{q}$	✓	✓
Light $\tilde{\chi}_1^0$	RPV-SUSY	$D_s^{\pm} \to \tilde{\chi}_1^0 e^{\pm}$	$\tilde{\chi}_1^0 \to K^{(*)\pm} e^{\mp}$	✓	✓
Sterile N	νSMEFT	$B, D \to Ne(+X)$	$N \to \pi^{\pm} e^{\mp}$	✓	✓

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MAPP: LHC Physics Performance

Minicharged Particles as a 1st Benchmark study

Why minicharge?!

Insight into the nature of electric charge quantization

Is electric charge quantized? Why? What is the mechanism of electric charge quantization?

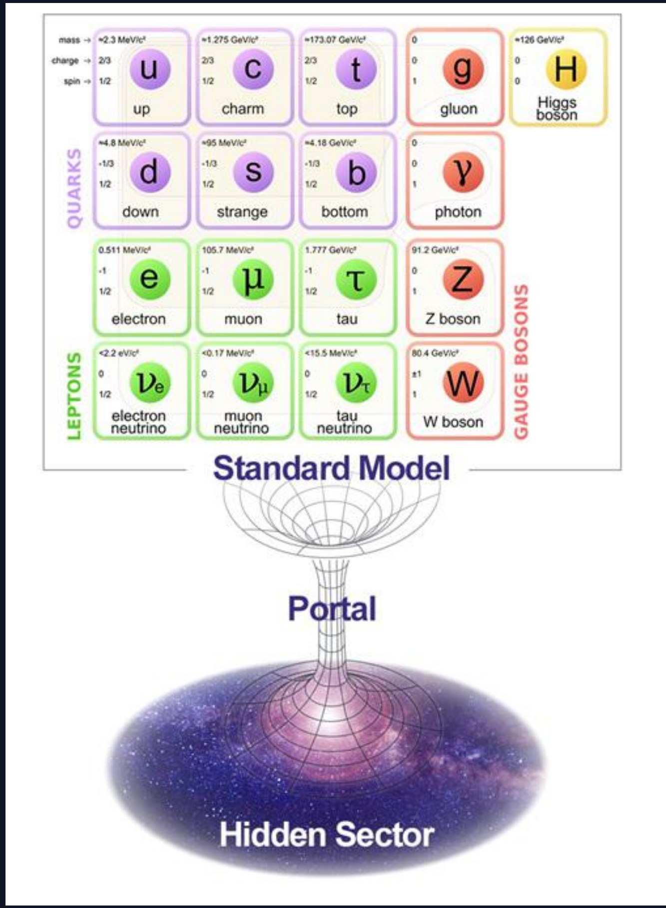
Unconfined mCPs appear in various models

e.g. Superstring models [E. Witten, X.-G. Wen, Nuc. Phys. B **261**, 1985], dark sector portal models [B. Holdom, Phys. Lett. B **166**, 1986], etc.

mCPs connect naturally to the dark sector (via the Vector portal/Dark photon)

They can be used to explain the DM abundance. Additionally, a minicharged DM fraction can explain the recent 21-cm anomaly observed by the (EDGES) Collaboration. [J. D. Bowman et al, Nature **555**, 2018. H. Liu, Phys. Rev. D **100**, 2019.]

Dark Sector Portals



Four commonly discussed portal interactions:

- Scalar Portal ('Dark Higgs') $\mathcal{L} \supset \epsilon_h |h^2||\phi_h^2|$
- Pseudoscalar Portal (AxionLike Particle) $\mathcal{L} \supset \epsilon_a a B^{\mu\nu} \tilde{B}_{\mu\nu}$
- Neutrino Portal (Heavy Neutral Lepton) $\mathcal{L} \supset \epsilon_N LhN$
- **Vector Portal ('Dark Photon')** $\mathcal{L} \supset \epsilon_Y B^{\mu\nu} F'_{\mu\nu}$

mCPs in 'Dark QED' (Kinetic Mixing) - Model

Production via the DY mechanism through a renormalizable kinetic mixing interaction between a new *U'(1)* gauge field (*A'*) and SM hypercharge.

Add to the SM, a new massless *U'(1)* gauge field (*A', the* 'dark photon') and a charged massive fermionic field ψ,

$$\mathcal{L} = \mathcal{L}_{\text{SM}} - \frac{1}{4}A'_{\mu\nu}A'^{\mu\nu} + i\bar{\psi}\left(\partial\!\!\!/ + ie'A\!\!\!/' + im_{mCP}\right)\psi - \frac{\kappa}{2}A'_{\mu\nu}B^{\mu\nu}$$

where the Feynman slash notation has been used, ***e'*** is the charge of the new gauge field ***A'***, and ***B*** is the SM hypercharge gauge field.

Lastly, the field strength of the dark photon is defined in the usual way as, $A'_{\mu\nu} = \partial_\mu A'_\nu - \partial_\nu A'_\mu$

Removing the mixing term through a field redefinition, $A'_\mu \Rightarrow A'_\mu + \kappa B_\mu$ reveals a coupling between the field ψ to the SM hypercharge, $\mathcal{L} = \mathcal{L}_{\text{SM}} - \frac{1}{4}A'_{\mu\nu}A'^{\mu\nu} + i\bar{\psi}\left(\partial\!\!\!/ + ie'A\!\!\!/' - i\kappa e'B\!\!\!/ + im_{mCP}\right)\psi$

Consequently, the new field **ψ** is charged under hypercharge with a **fractional charge** proportional to the mixing parameter, **ϵ**.

This can be written as, $\epsilon = \kappa e' cos\theta_W / e$, in units of the electric charge, ***e***.

Phys. Lett. B **166**, Issue 2, 1986.
Phys. Lett. B **746**, 2015. (arXiv:1410:6816)

Physics Performance Studies

Benchmark Estimates using various MC Event Generators.

1 Implement the model of interest into appropriate MC Event generator SW. (e.g. Madgraph5@aMC_NLO)

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   Fix model if necessary and test again..

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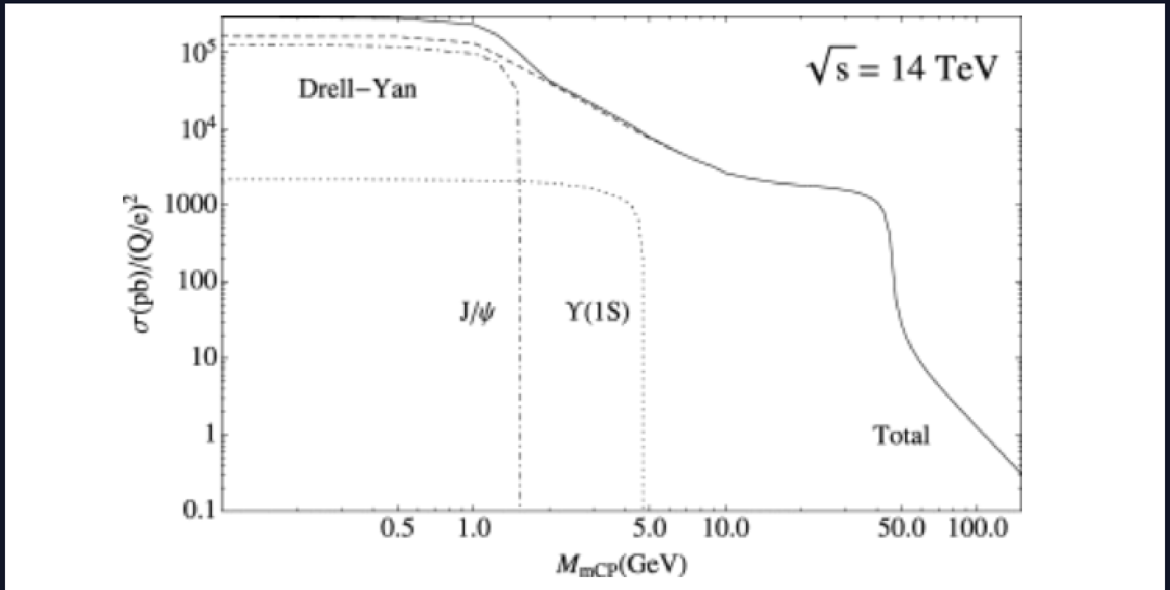
   Fix model if necessary and test again..

3. Finally, generate ($N \sim L * \sigma$) Monte-Carlo events with the validated model and simulate the performance of the MAPP detector to new FIPs

   Cuts may also be placed throughout this process.

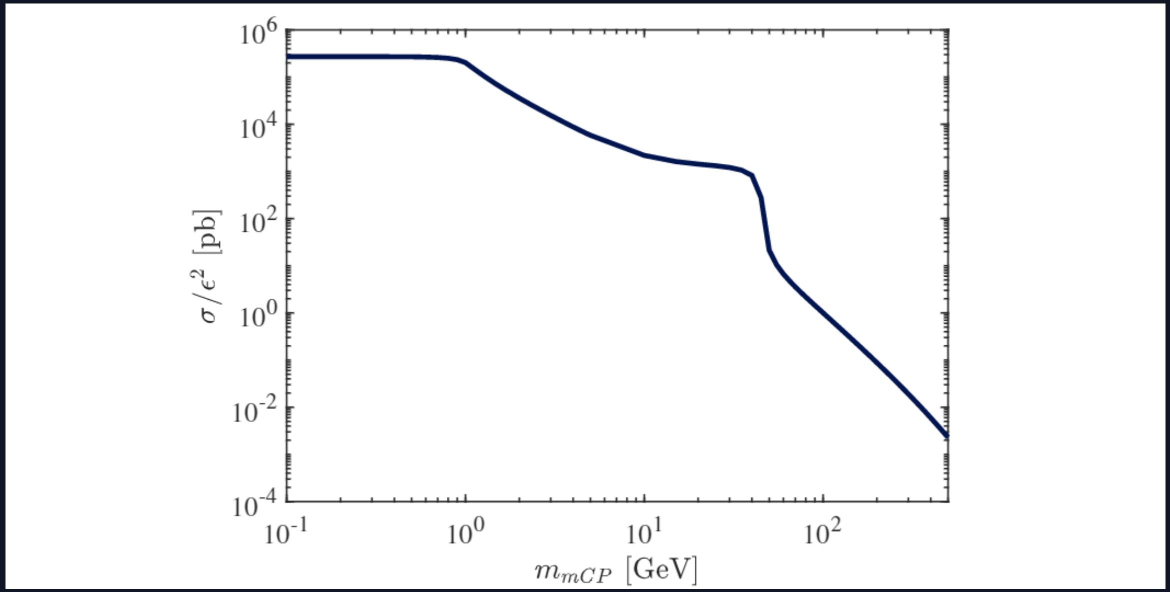
mCPs in 'Dark QED' - Model Validation

Model was implemented into *MG5* and validated using a mixture of comparisons with the literature, and in-house comparisons.

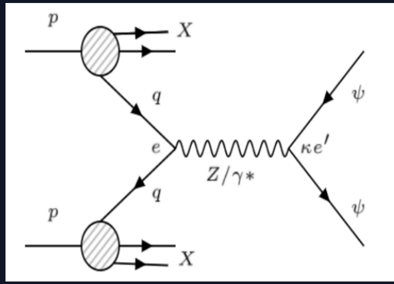


Previously published mCP Production cross-section

Published in Phys. Lett. B **746**, 2015. (arXiv:1410:6816)



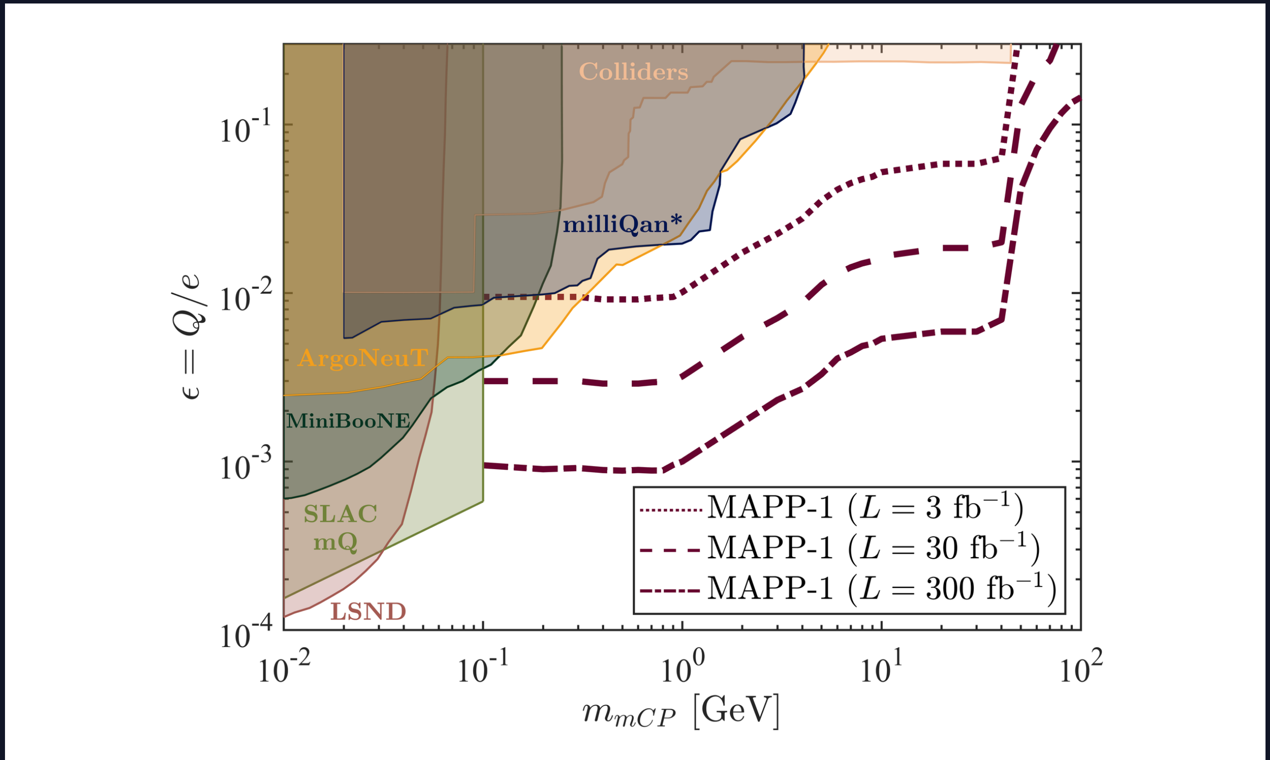
DY Production cross-section for mCPs in our *MG5* model



Additional validations were performed by studying the pseudorapidity distribution of DY produced mCPs and comparing the acceptance of MAPP to mCPs for various detector positions with independent studies performed in the MoEDAL Collaboration.

Sensitivity of MAPP to mCPs - Analysis & Results

95% C.L. exclusion bounds for Drell-Yan pair-produced mCPs @ a C.o.M energy of 14 TeV using Madgraph5



No BGs and an overall detector efficiency of 100% were assumed for ease of comparison.
(Simulations of detector response and efficiency are still ongoing.)

Events were generated based on the x/s and analyzed to estimate the # of 'hits' in MAPP-mCP.

- This was performed across the parameter space of interest.
- A **'hit'** was defined as an mCP with momenta traversing each of the co-linear sections of the MAPP-mCP detector.
- Inclusion of resonant production modes of mCPs could improve the ranges of MAPP-mCP shown.

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Conclusions & Future Outlook

The MAPP-1 Detector System is on schedule for deployment at the LHC's Run-3.

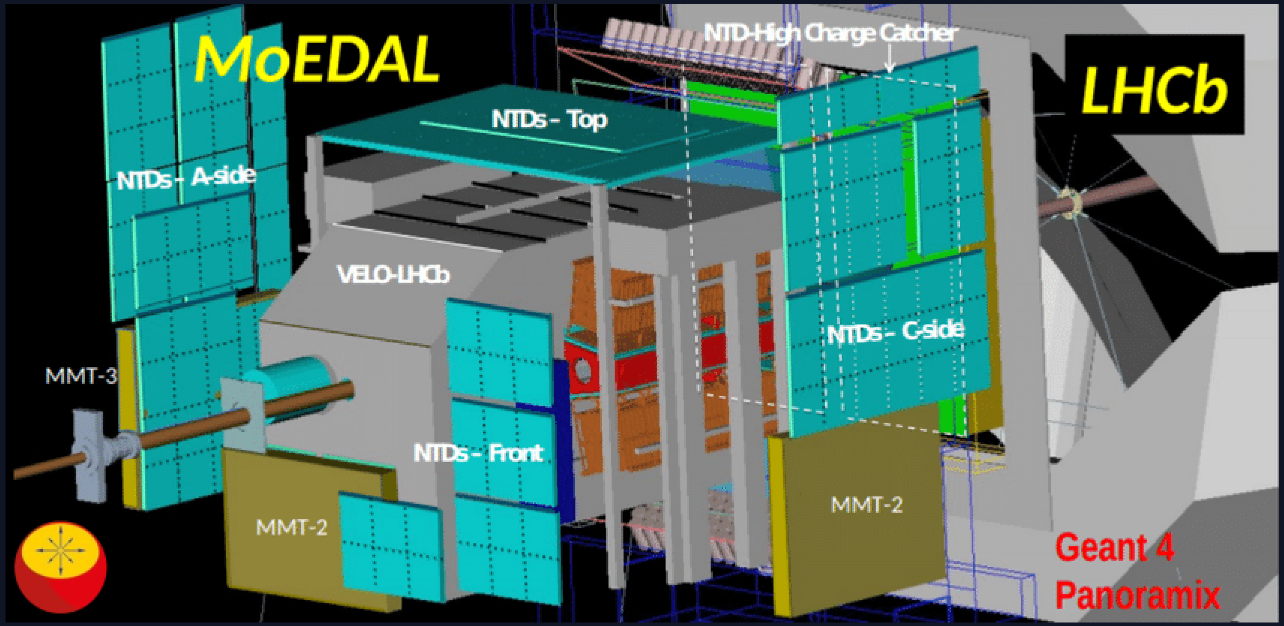
- **Phase-I of MAPP**, **MAPP-mCP**, will enable searches over **unexplored regions** of the mass-mixing parameter space for **mCPs** (in the kinetic mixing portal model shown) that can probe electric charges as low as ~**0.003e** over a mass range of **0.1-75 GeV**, at the LHC's upcoming **Run-3**. At the **HL-LHC**, a factor ~10 increase in the total integrated luminosity will extend the reach to charges as low as ~**0.001e.**
- Updates to these studies which include **effects of tracking and backgrounds** will soon be underway. The inclusion of a new 'outrigger' detector extension will also be considered in further mCP studies.

Thank you!

Questions?

The MoEDAL Experiment

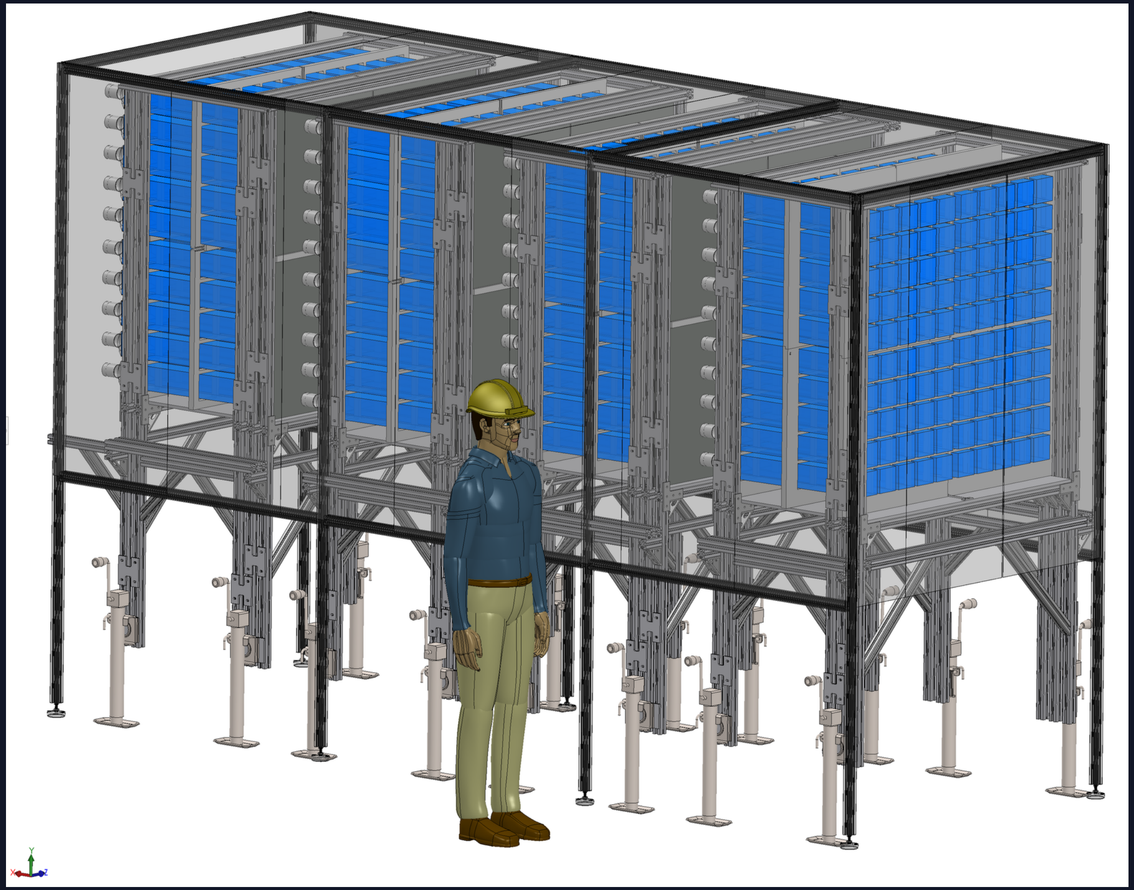
A largely passive detector, analogous to a giant camera that 'photographs' the interaction point with the main purpose of searching for **magnetic monopoles**. The nominal detector system is comprised of **three subdetectors**: **NTD**, **MMT**, and **TimePix** (for radiative background monitoring; not discussed here).



https://moedal.web.cern.ch/. The MoEDAL Collaboration, Int. J. Mod. Phys. A **29,** 1430050 (2014).
MoEDAL's latest exclusion bounds for MMs produced in pp-collisions at the LHC - The MoEDAL Collaboration, Phys. Rev. Lett. **123**, 021802 (2019).
MoEDAL's latest exclusion bounds for dyons produced in pp-collisions at the LHC - The MoEDAL Collaboration, Phys. Rev. Lett. **126**, 071801 (2021).

Backup Slide 1: MAPP-mCP

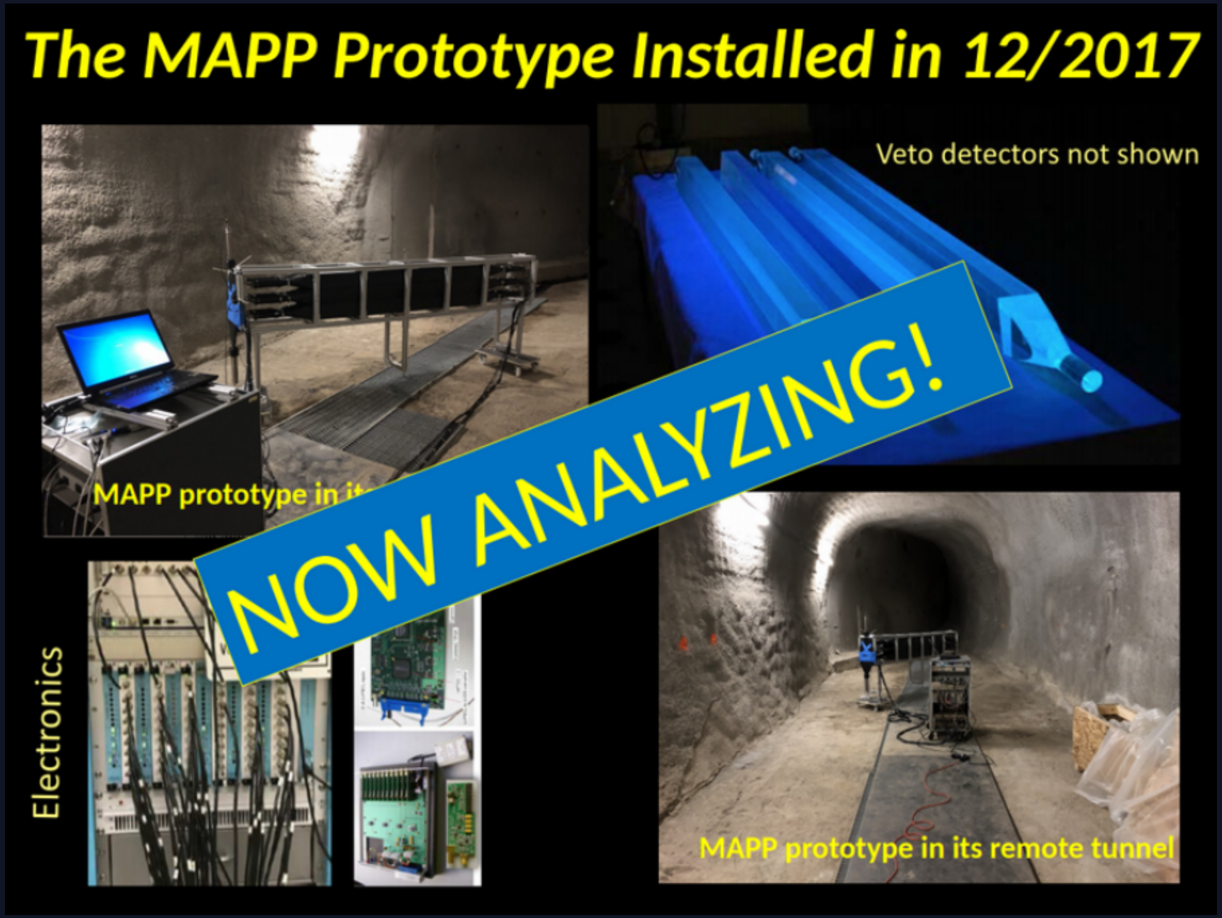
MAPP's minicharged particle subdetector



Active scintillation counter detector with a large path length of sensitive scintillator bars.

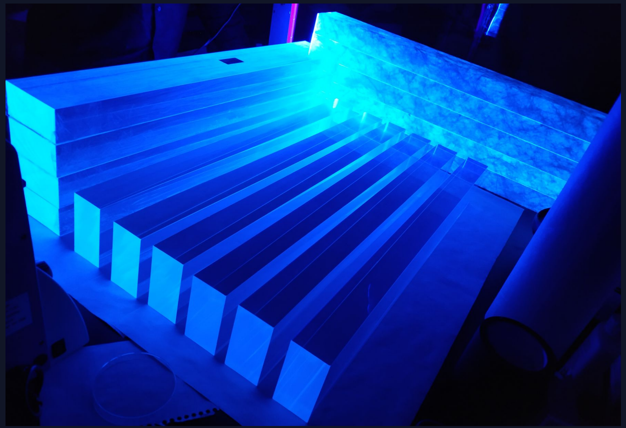
- 10 x 10 grid of 75cm long scintillator bars.
- 4 co-linear sections with low-noise PMTs placed in coincidence to eliminate dark and radiogenic background counts.
- Scintillator, light guides, and LED boards currently worked on @ the UofA.

Backup Slide 2: MAPP-mCP Prototype



- ~10% of the overall detector volume (of MAPP-mCP).
- Acquired several fb-1 of data during LHC's Run-2.

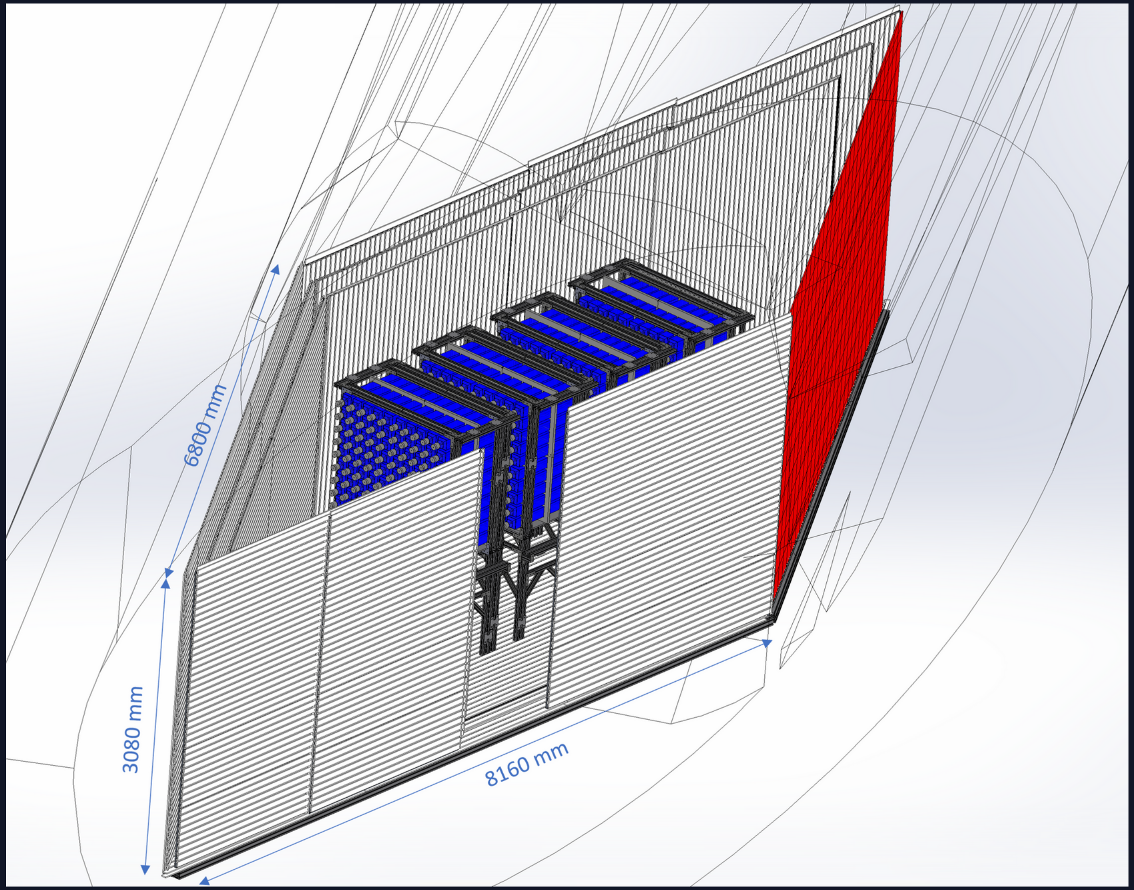
Backup Slide 3: MAPP-mCP Construction



Testing will begin this summer!

Backup Slide 4: MAPP-LLP

MAPP's long-lived particle subdetector



Nested system of fine grain hodoscope detector planes with SiPMs arranged along the planes.

- Three nested rectangular prism shaped detectors surrounding MAPP-mCP.
- Comprised of rectangular subplanes of scintillator (each having size 1.5m x 1.5m x 1.25cm).
- Each subplane has WLS fibres embedded horizontally (*x*) on one surface and vertically (*y*) on the other with a 1 cm pitch.
- WLS fibres are readout by a SiPM at one end.