# Status of the MoEDAL & milliQan Experiments

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[On Behalf of the MoEDAL Collaboration]

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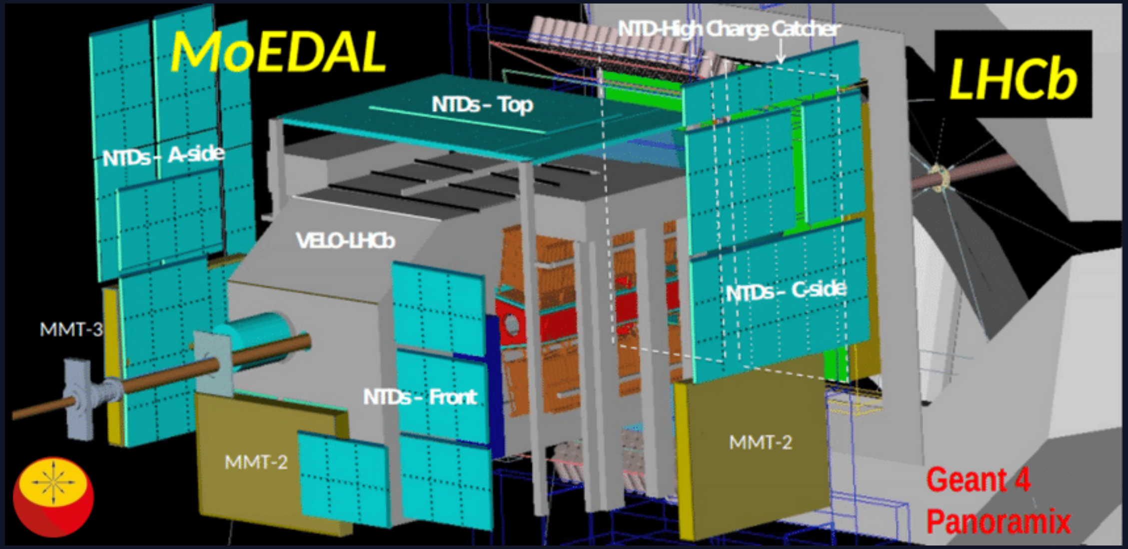
The Monopole and Exotics Detector at the LHC (MoEDAL) Experiment

# MoEDAL Today

# The MoEDAL Detector

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).




Analysis of the NTD uses an etching and scanning procedure to search for any HIP tracks in the material, while the MMT material is analyzed using a SQUID magnetometer.

## MoEDAL Nuclear Track Detector (NTD)

- An array of passive material only sensitive to highly ionizing particles.
- ~200 square meters of plastic material deployed in stacks around the IP.

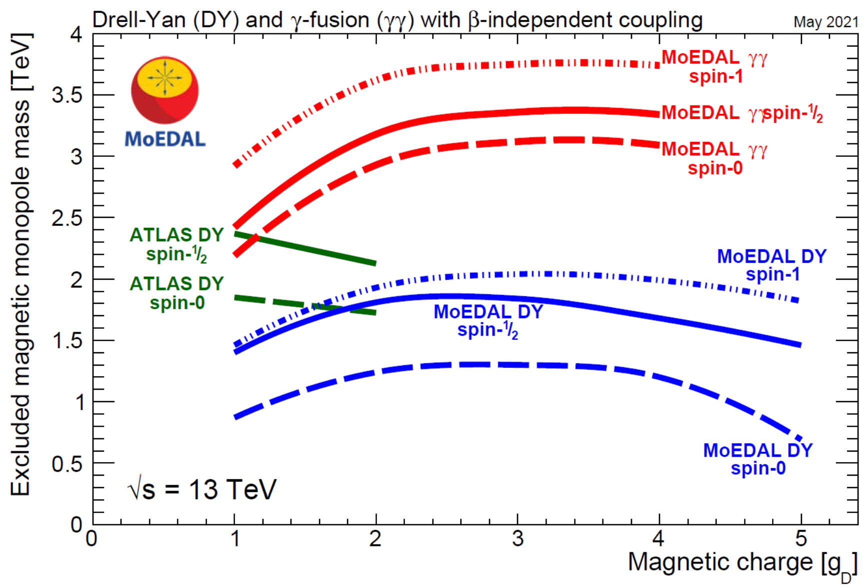
## MoEDAL Magnetic Monopole Trapper (MMT)

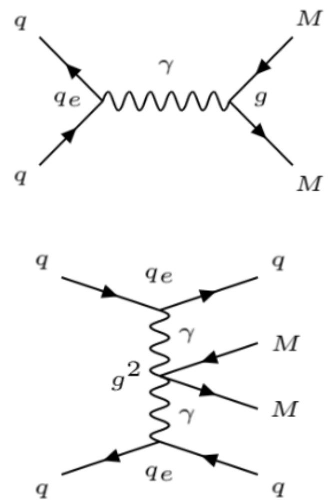
- A ~1 ton array of aluminum deployed around the IP to trap MMs.
- Material is removed every 2 years, along with the NTD material, for analysis.

https://moedal.web.cern.ch/. The MoEDAL Collaboration, Int. J. Mod. Phys. A **29** (2014) 1430050.

# MoEDAL's Latest Results for Magnetic Monopole Production at the LHC (Run-2)

Considering production in **p-p** collisions via **Drell-Yan** & **photon fusion** mechanisms and a total integrated luminosity of 6.46 fb-1.



The MoEDAL Collaboration, Phys. Rev. Lett. **123**, 021802 (2019).
MoEDAL has also recently published **the first search for dyons at a collider** as, The MoEDAL Collaboration, Phys. Rev. Lett. **126**, 071801 (2021).

# MoEDAL's Upcoming Results

HIPs - MMs and HECOs using LHC Run-1 & Run-2 data collected with the NTDs.

*In Collaboration wide review.

MMs produced in heavy-ion collisions via the thermal Schwinger mechanism.

*Sent to Nature.

Studies of the exposed CMS beampipe for trapped MMs.

*Analyses in progress.

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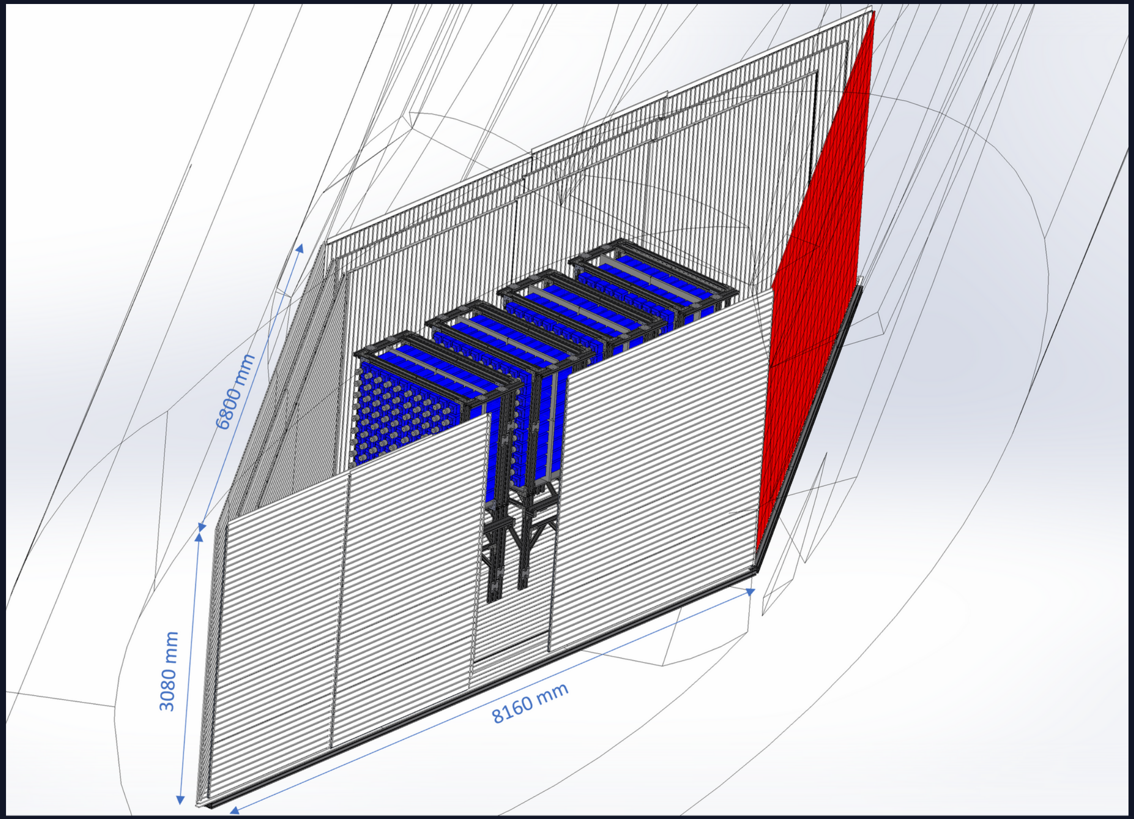
MoEDAL's Apparatus for Penetrating Particles (MAPP)

# The MAPP Detector Upgrade

# 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!

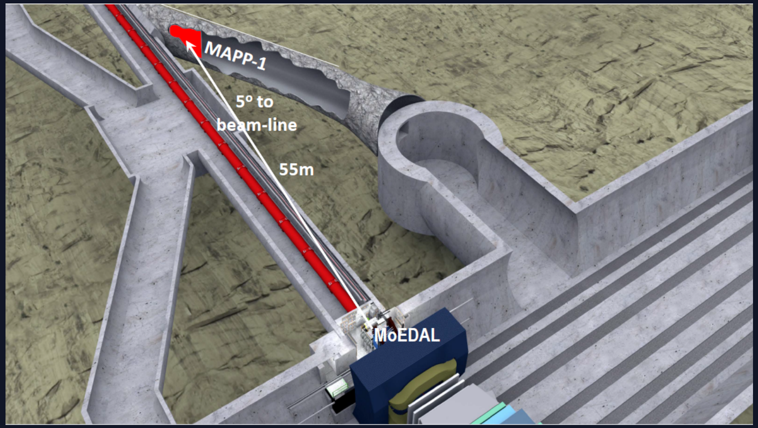
- **Inner core of MAPP-1** with a detector size of roughly 1 m x 1 m x 3 m.
- Search for **minicharged particles - mCPs** ($Q << 1e$).
- Note: Atlas and CMS are limited to ~$e/3$ or greater.

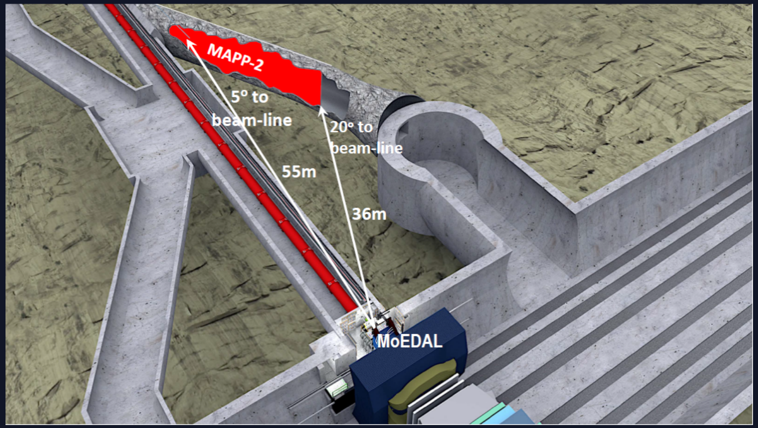
## **MAPP-LLP (Phase-II,** in 2022 during Run-3)

- Nested **outer layers** of the MAPP detector (hodoscope planes).
- Search for new **pseudo-stable neutral particles with long lifetimes** 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)

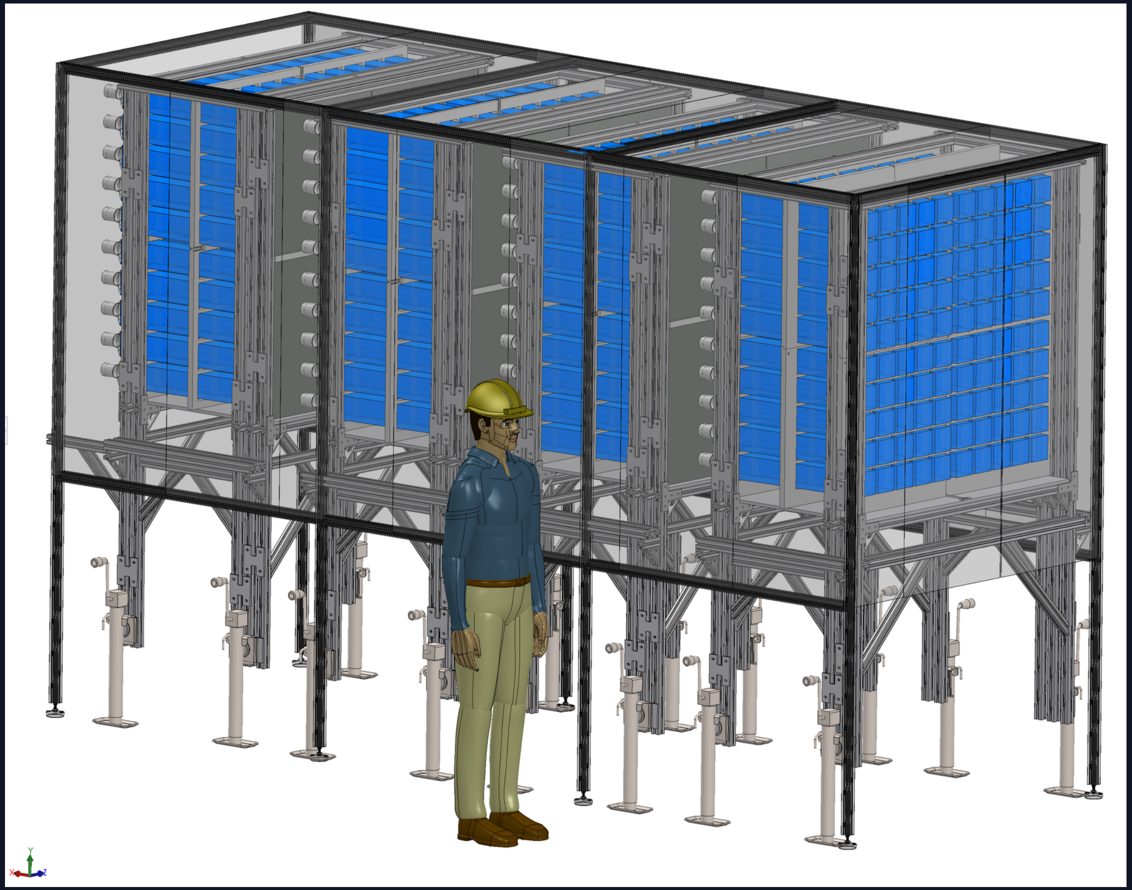
- **Positioned at 5°** w.r.t to the beam axis. **~55 m from IP8.**
- This placement has **~100 m of rock overburden and 25-30 m of rock shielding** between the detector and the IP.
- **Large decay zone of ~10 m** is possible.

## MAPP-2 (Phase-III)

- **A proposed future version of MAPP** which fills the entire cavern (covering from roughly 5-20° w.r.t to the beam axis).

# MAPP-mCP

MAPP's minicharged particle subdetector

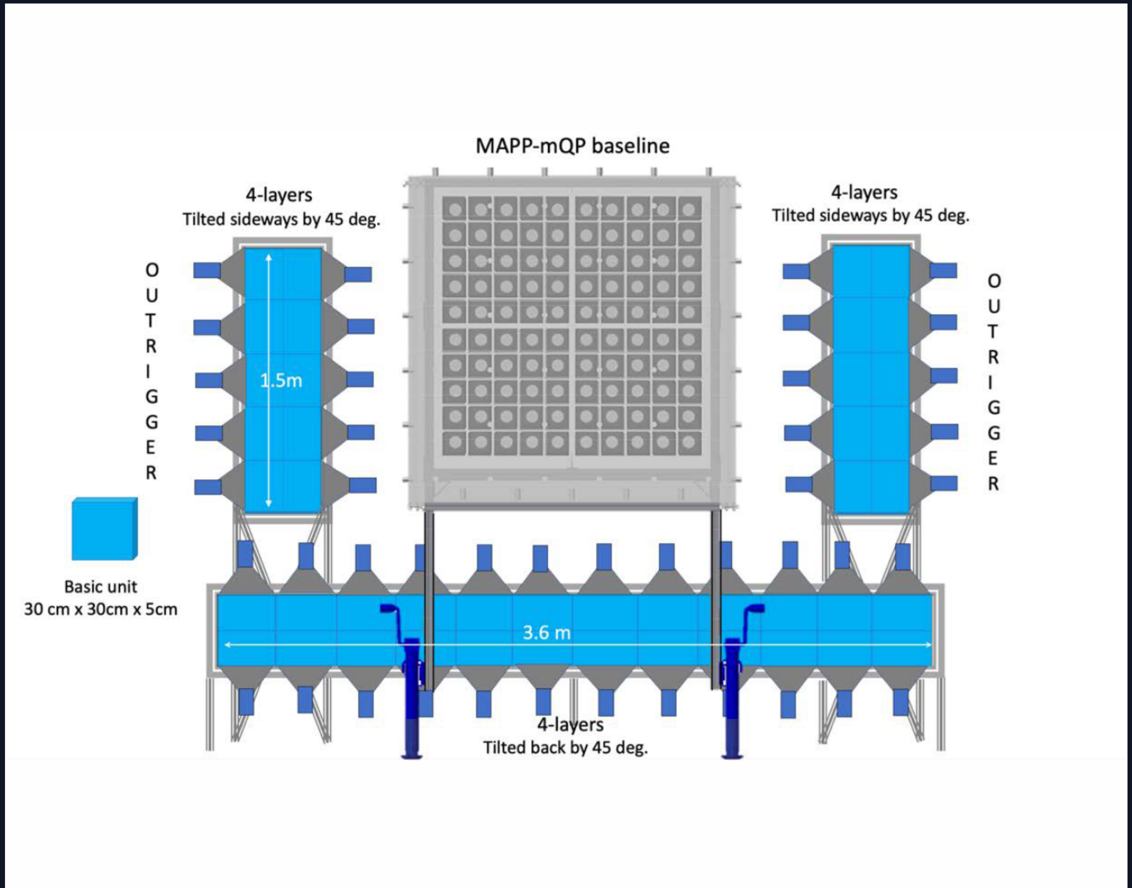


Active scintillation counter detector with a large path length of sensitive scintillator bars.

- 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.
- 'Outrigger' Detector extension which increases the acceptance area of MAPP-mCP considerably is in planning.

# MAPP-mCP - 'Outrigger Detector' Extension

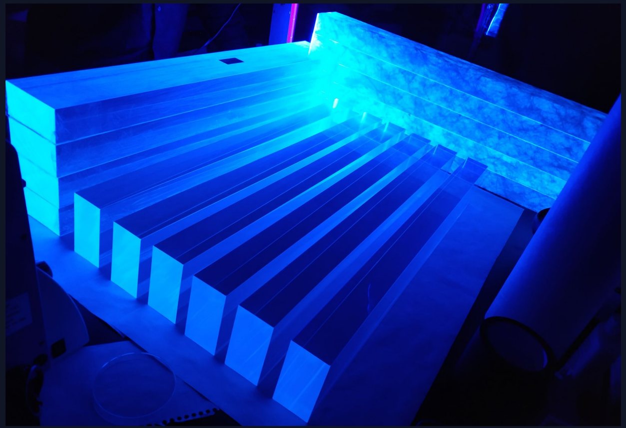
A detector extension in planning..




**In planning since 2020.**

- Lower sensitivity to smaller fractional charges, but much large acceptance area of **~16 square meters deployed in 4 layers**.
- The goal is to increase the sensitive area of MAPP-mCP to **improve the detector reach at larger values of mCP mass and minicharge**.

# MAPP-mCP Construction



Testing will begin this summer!

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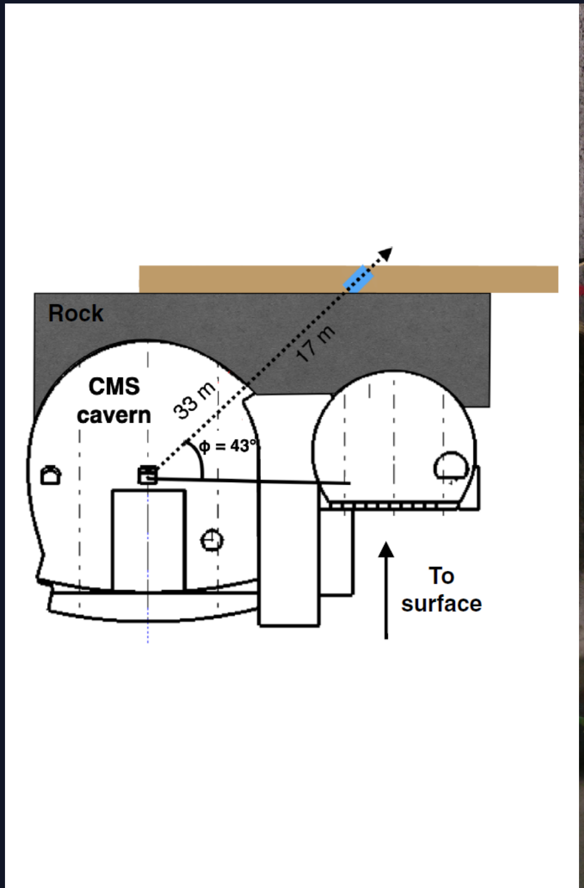
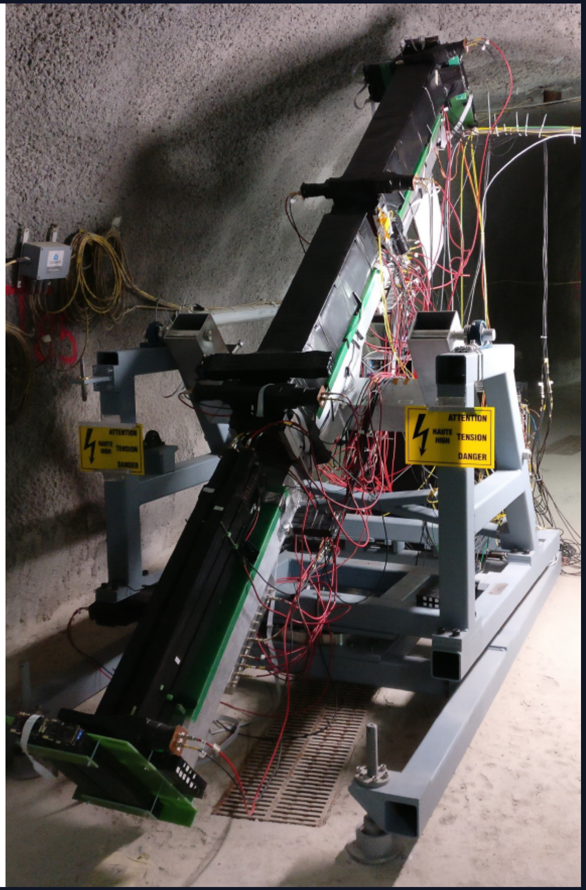
The milliQan Experiment

# The search for millicharged particles at the LHC

# The milliQan Experiment

A planned millicharged particle detector placed in the CMS cavern ~33m from the interaction point (IP5) and aligned towards the IP.



### Early developments in the milliQan Experiment:

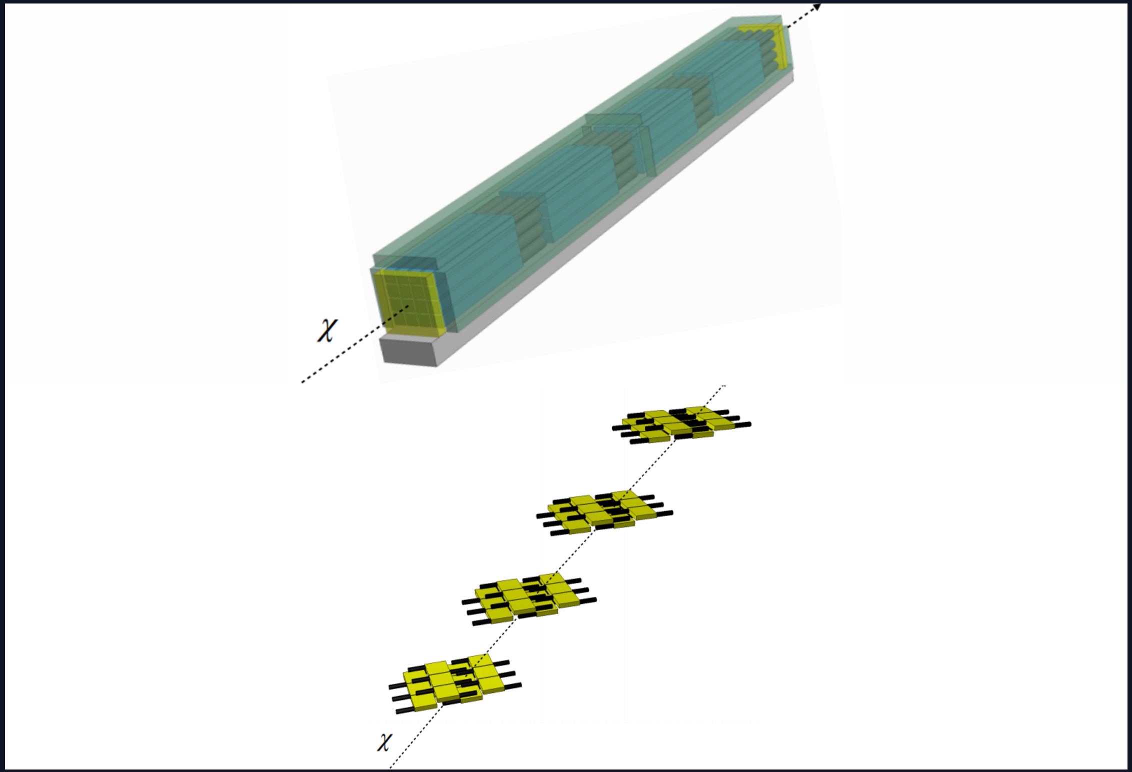
- **2015** - First detector simulation and study published as Phys. Lett. B **746**, 30 June 2015. (arXiv:1410:6816).
- **2016** - milliQan LOI submitted with a full detector design. (arXiv:1607.04669)

### 2018 - milliQan Demonstrator Detector Deployed

- **~1% of the full milliQan detector** volume, deployed in Run-2 (2018).
- Collected **37.5 fb-1 worth of pp collision data** at a C.o.M energy of **13 TeV**.
- Produced **the first search for mCPs at a hadron collider** in 2020 with this data.
- **No mCPs found**. Phys. Rev. D **102**, 032002, 6 August 2020. (arXiv:2005.06518)

# The Full milliQan Detector

A scintillation detector comprising two main detector systems, the **bar** and **slab** detectors.




## milliQan Bar Detector

- **0.2 m x 0.2 m x 3 m** array of plastic scintillator bars.
- **Four layers that each comprise 16 scintillator bars** coupled to high-gain PMTs.
- **Surrounded by an active muon VETO shield**. (6 layers of 5 cm thick scintillator.)

## milliQan Slab Detector

- Comprised of 40 cm x 60 cm x 5 cm scintillator slabs.
- A total of 48 slabs separated into 4 layers with 3 x 4 slabs per layer.
- Improved reach for higher mass mCPs.

arXiv:2104.07151 - Submitted to Phys. Rev. D

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Run-3 & HL-LHC

# Projected Detector Sensitivities for MAPP & milliQan to mCPs

# 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,

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

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

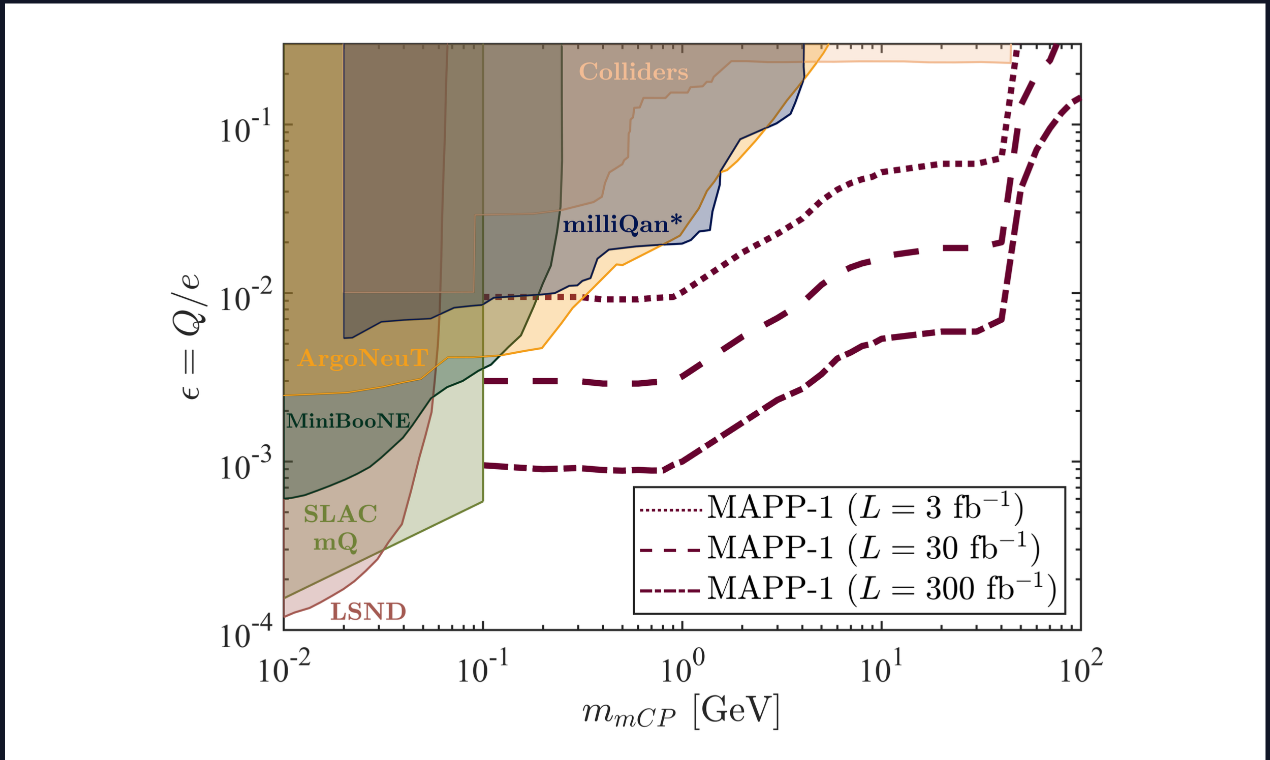
Consequently, the new field **ψ** is charged under hypercharge with a **fractional charge** proportional to the mixing parameter, **ϵ**.

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**, 30 June 2015. (arXiv:1410:6816)

# Sensitivity of MAPP to mCPs - Analysis & Results

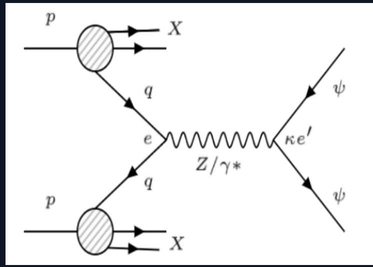
95% C.L. exclusion bounds for Drell-Yan pair-produced mCPs @ a C.o.M energy of 14 TeV using Madgraph5




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

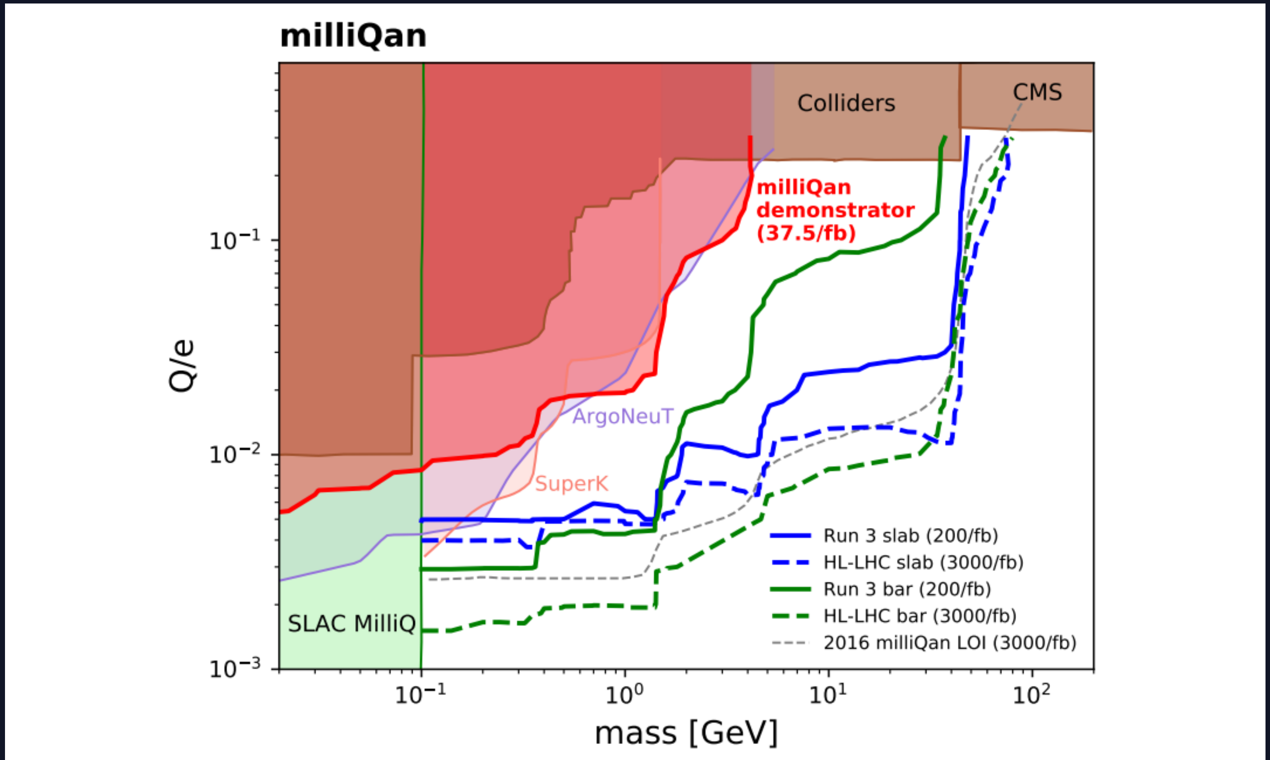
Events were generated based on the x/s and analyzed to estimate the # of 'hits' in MAPP-mCP.

- 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.
- Outrigger detector was not included in this initial study.



Phys. Lett. B **166**, Issue 2, 1986.
Phys. Lett. B **746**, 30 June 2015. (arXiv:1410:6816)

# Sensitivity of milliQan to mCPs - Analysis & Results




N.B. The HL-LHC projections also include improvements to the milliQan detector, such as an increased number of scintillator bars in each layer of the bar detector and an improved active veto, thus reducing the total BG.

More detailed studied than ours, performed at a C.o.M energy of 13 TeV.

- Included production of mCPs via decays of vector mesons and Dalitz decays of light mesons as well (using *Pythia6/8*).
- An mCP-like signal in the detector was selected by requiring a single hit in each of the detector layers, produced in a straight path.
- Further selection criteria and BG rejection were also applied. e.g. timing and energy deposition expected for mCPs in the detector layers.
- Detailed BG estimates were performed using *GEANT4* simulations.
- 95% C.L. exclusion curves were set using a signal + BG hypothesis and a modified frequentist approach.

arXiv:2104.07151 - Submitted to Phys. Rev. D

# Conclusions & Future Outlook

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

- The MAPP-1 detector has sensitivity to significant portions of unexplored parameter space for a total of 8 models studied so far.
- **Phase-I of MAPP**, **MAPP-mCP**, will enable searches over unexplored regions of the mass-mixing parameter space for **mCPs** that can probe electric charges as low as ~**0.003e** over a mass range of **0.1-75 GeV**, in the best-case scenario at the LHC's upcoming **Run-3**. At the **HL-LHC**, a factor ~10 increase in the total integrated luminosity will extend this reach to charges as low as ~**0.001e.**
- Updates to these studies including **the outrigger** and **effects of tracking and backgrounds. Further** studies involving MAPP are also underway.

## The milliQan Experiment is on schedule for Run-3 as well.

- **Demonstrator results represent the first search for mCPs at a hh collider. New exclusion bounds** for mCP masses larger than 0.7 GeV.
- Most recent, detailed study of the future sensitivity of milliQan to mCPs shows **complementary sensitivity to MAPP.**
- **Funding secured** and on schedule for deployment at the **LHC's Run-3 to collect 200 fb-1 of pp collision data.** With this dataset, mCPs could be excluded at the 95% C.L. for a range of masses from **0.1-45 GeV** and for charges as low as **0.003e,** in the best case. At the **HL-LHC**, this reach could be extended to mCP masses as large as **80 GeV,** and charges as low as **0.0018e**, in the best case.

# Thank you!

# Questions?