The Physics of MAPP-mCP: Minicharged Particle Search at UA83

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Overview

1

Minicharged Particles in 'Dark QED'

- Physics model & implementation.

2

Minicharged Particles (mCPs) at MAPP

- Projected limits for Run-3 & HL-LHC.
- mCP Signal vs. EDM Signal.
- Further studies on mCP production and detection.

1

Minicharged Particles in 'Dark QED'

Physics model & simulation

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

Include 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,

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

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

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***.

B. Holdom, *Phys. Lett. B* **166**(2), 196-198 (1986).
A. Haas et al, *Phys. Lett. B* **746**, 117-120 (2015). (arXiv:1410:6816)

Physics Model Implementation

Benchmark Estimates using MadGraph5.

1 **Implement the model** of interest into an appropriate **MC Event generator** SW. We use an **in-house FeynRules model of the Lagrangian on the previous slide**. A corresponding UFO is generated and fed to MG.

J. Alwall et al, *Journal of High Energy Physics* **2014**, 79 (2014). T. Sjöstrand et al, *Computer Physics Communications* **178**(11) (2008).

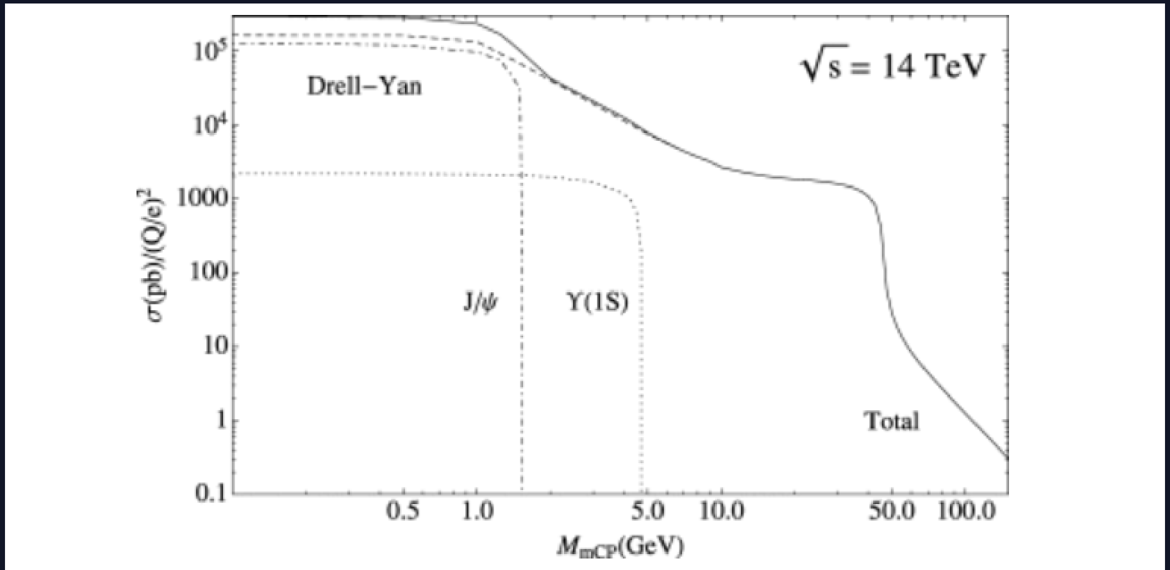
2 **Validate model implementation** using a combination of analytical & numerical calculations and the literature available.

3 Finally, **generate (N ~ L * σ) Monte-Carlo events with the validated model** and **estimate the acceptance of the MAPP-mCP detector for mCPs** with various masses and charges.

Cuts may also be placed throughout this process.

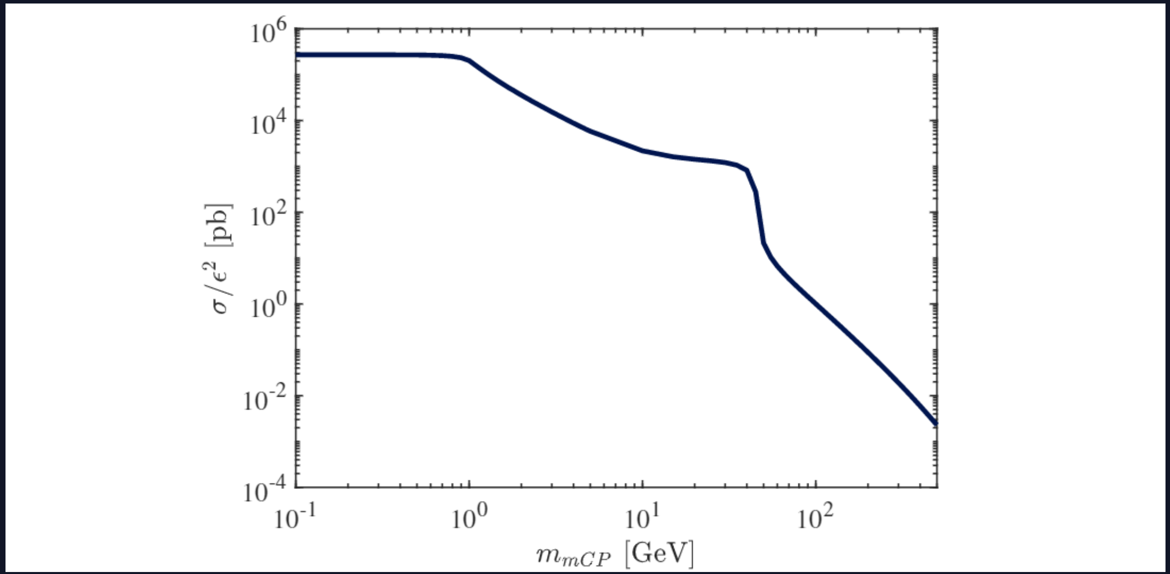
mCPs in 'Dark QED' - Model Validation

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



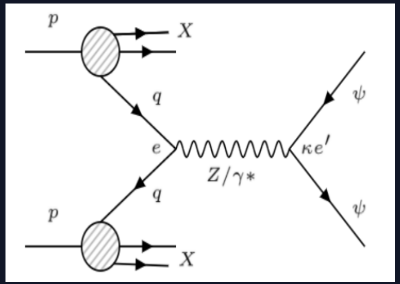
Previously published mCP production cross-section for *pp* collisions.

Published in *Phys. Lett. B* **746**, 117-120 (2015). (arXiv:1410:6816)



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

From ***pp*** collisions at a **center-of-mass energy of 14 TeV**.



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.

2

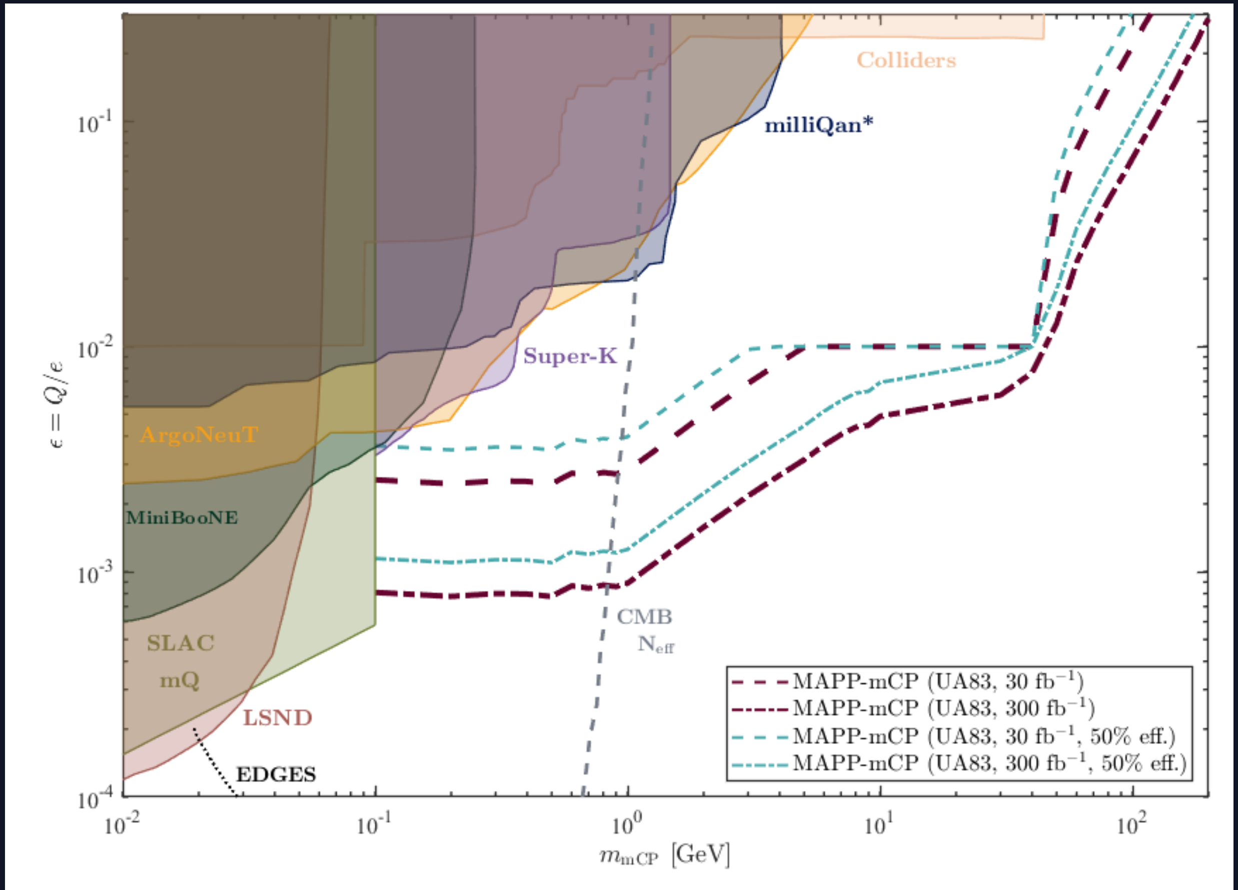
The Physics Performance of MAPP

Minicharged particles in 'Dark QED' at the MAPP Experiment

Sensitivity of MAPP to mCPs - Analysis & Results

Combined Outrigger & Bar detector limits for MAPP-mCP.

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



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

$$N_{\rm hits} = 3 = \sigma\left(\sqrt{s}, m_{\rm mCP}, \epsilon = 1\right) \times \epsilon^2_{{\rm at},N_{\rm hits}} \times \mathcal{L}^{\rm int}_{\rm LHCb} \times P_{\rm acc}\left(\sqrt{s}, m_{\rm mCP}\right) \times \eta_{\rm det}$$

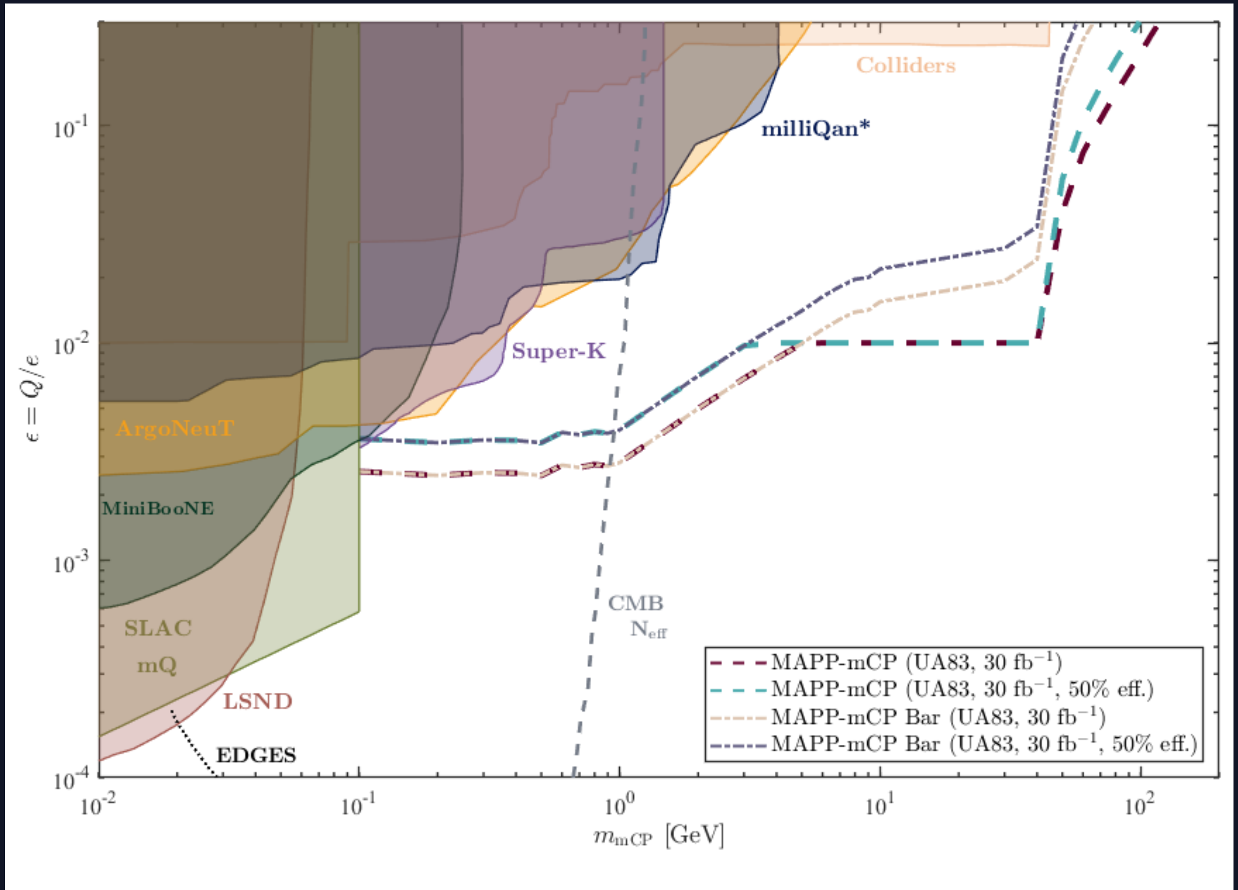
Events were generated based on the x/s and analyzed to estimate the # of 'hits' in MAPP-mCP:

- **Bar & Outrigger positions and geometries** are as **described in MAPP TP 2.0.**
- Study 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** can improve the ranges of MAPP-mCP shown.

Sensitivity of MAPP to mCPs - Analysis & Results

Combined detector limits versus bar detector limits for MAPP-mCP.

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



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Distinguishing an mCP Signal From an EDM signal

Differences in the pseudorapidity distributions of these particles for DY pair-production:

- The **pseudorapidity distribution of heavy neutrino production falls off more rapidly** at larger values of absolute pseudorapidity.

Differences in the energy depositions and energy loss profiles:

- $\left(\frac{dE}{dx}\right)_{\text{BB}} \propto \frac{Q^2}{\beta^2} \ln \beta^2$ Vs. $\left(\frac{dE}{dx}\right)_{\text{EDM}} \propto eD\gamma$

In summary, it is **possible in principle**, but would **be quite challenging in practice.**

Future Directions

Backgrounds, energy losses and detailed detector simulations:

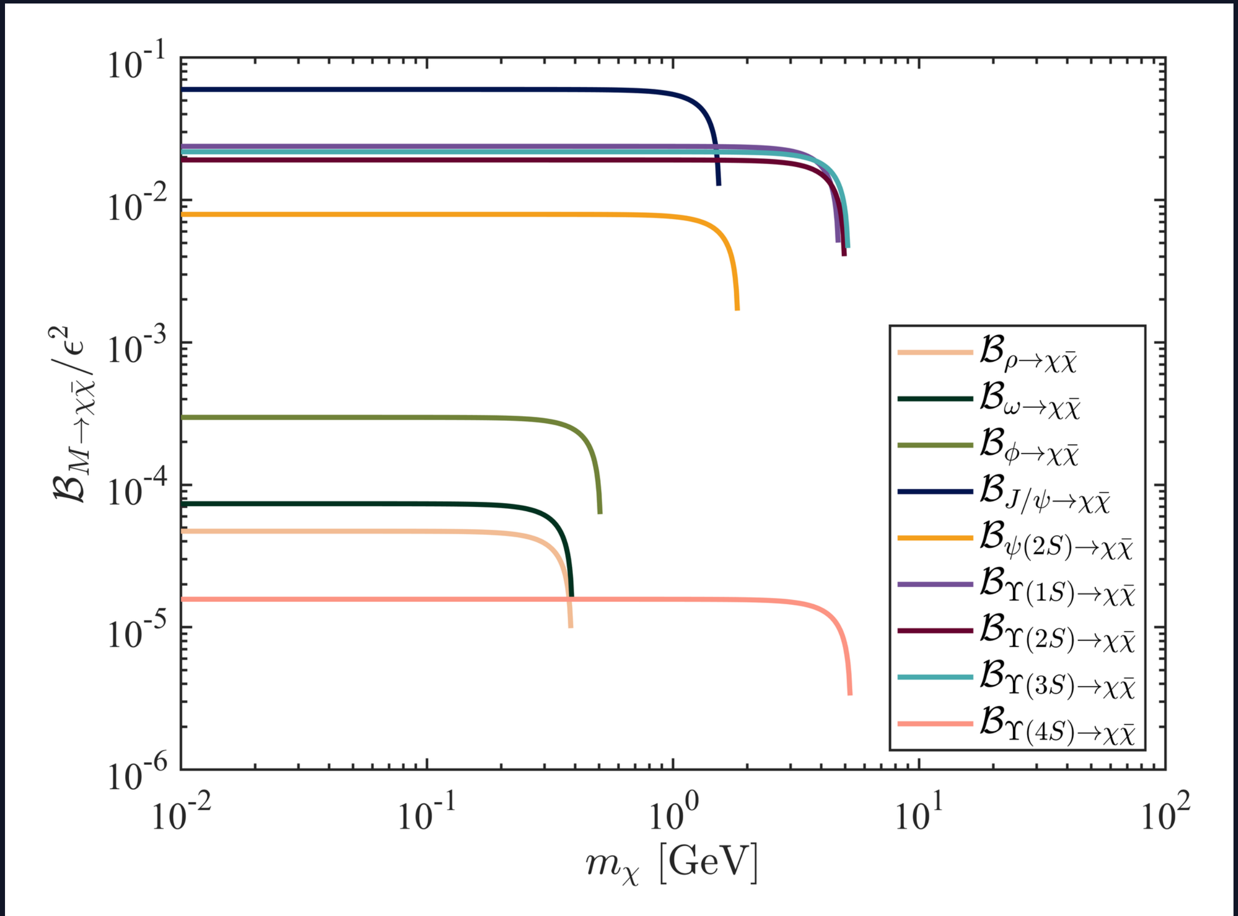
- **mCP E losses in GEANT4** (S. Banik et al., ''Simulation of energy loss of fractionally charged particles using Geant4'', *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 971, 2020).
- **Heavy Neutrino EDM energy losses** can also be calculated in GEANT4.
- **Simulation of the UA83 MoEDAL-MAPP Arena** (SUMMA). **Simulation of cosmic ray backgrounds (EXPACS-PARMA) & beam-related backgrounds.**

Additional production mechanisms via light meson decays:

- **Single Dalitz decays** of light pseudoscalar mesons; **π0 -> γχχ~**, **η -> γχχ~**, **η' -> γχχ~**.
- **Direct decays** of vector mesons; **ρ -> χχ~**, **ω -> χχ~**, **ϕ -> χχ~**, **J/ψ -> χχ~**, **ψ(2S) -> χχ~**, **Υ(nS) -> χχ~**.

Production of mCPs via Meson Decays

Branching ratios calculated for direct decays of vector mesons to mCPs.



Modeling of meson production and decays to mCPs, as well as calculation of acceptances is a current WIP (using Pythia8).

- For many of these decay channels, the **amount of mCPs produced can be quite substantial even at small values of epsilon/charge.**

Thank you!

Questions?

Backup Slides

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

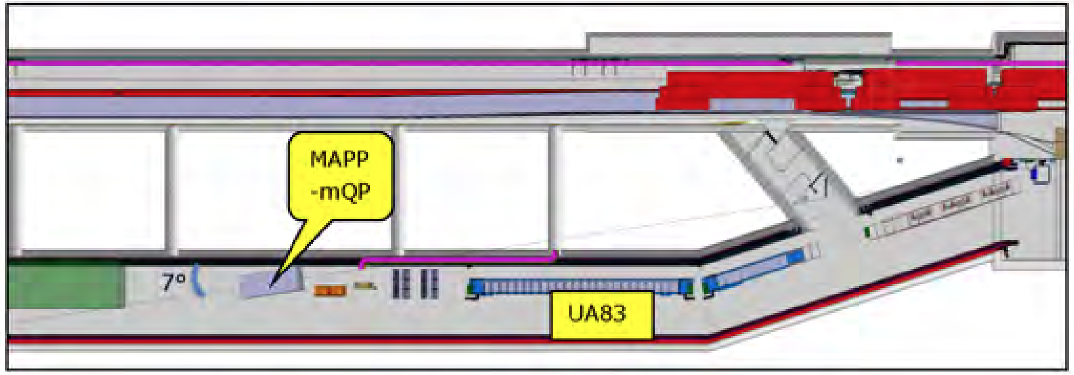
e.g. **Superstring models** [E. Witten and X.-G. Wen, *Nuc. Phys. B* **261**, 651-677 (1985)], **dark sector portal models** [B. Holdom, *Phys. Lett. B* **166**(2), 196-198 (1986)], etc.

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**, 67–70 (2018); J. B. Muñoz and A. Loeb, *Nature* **557**, 684-686 (2018); H. Liu, *Phys. Rev. D* **100**, 123011 (2019).]

Location of the MAPP Detector @ The LHC

Proposed placement in the UA83 area, adjacent to the MoEDAL detector region.



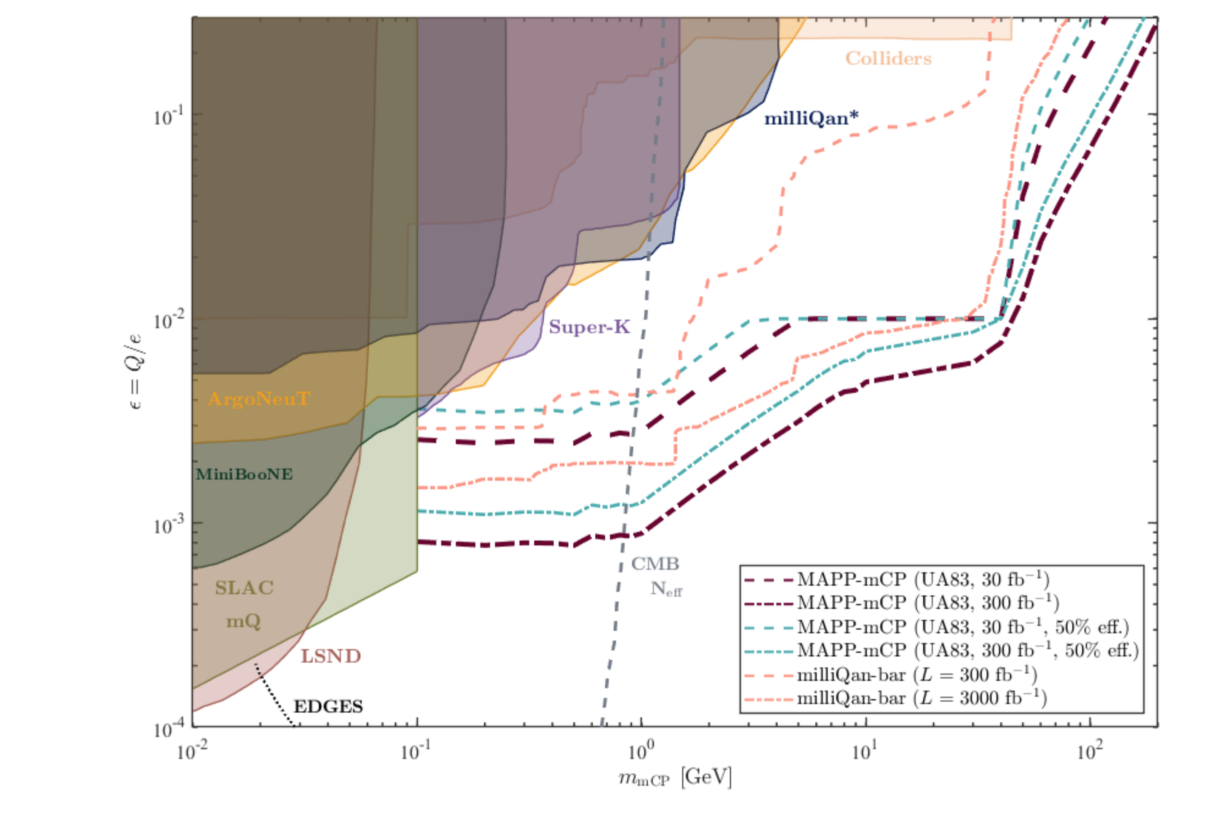
MAPP-mCP (Phase-I)

- **Positioned at ~7°** w.r.t to the beam axis. **~100 m from IP8.**
- This placement has **~100 m of rock overburden and ~35 m of rock shielding** between the detector and the IP.

Sensitivity of MAPP to mCPs - Analysis & Results

Comparison with milliQan (bar). N.B. Detailed simulations of cosmic ray BGs and mCP energy losses in the detector were included in their projections.

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



$$N_{\text{hits}} = 3 = \sigma\left(\sqrt{s}, m_{\text{mCP}}, \epsilon = 1\right) \times \epsilon^2_{\text{at},N_{\text{hits}}} \times \mathcal{L}^{\text{int}}_{\text{LHCb}} \times P_{\text{acc}}\left(\sqrt{s}, m_{\text{mCP}}\right) \times \eta_{\text{det}}$$

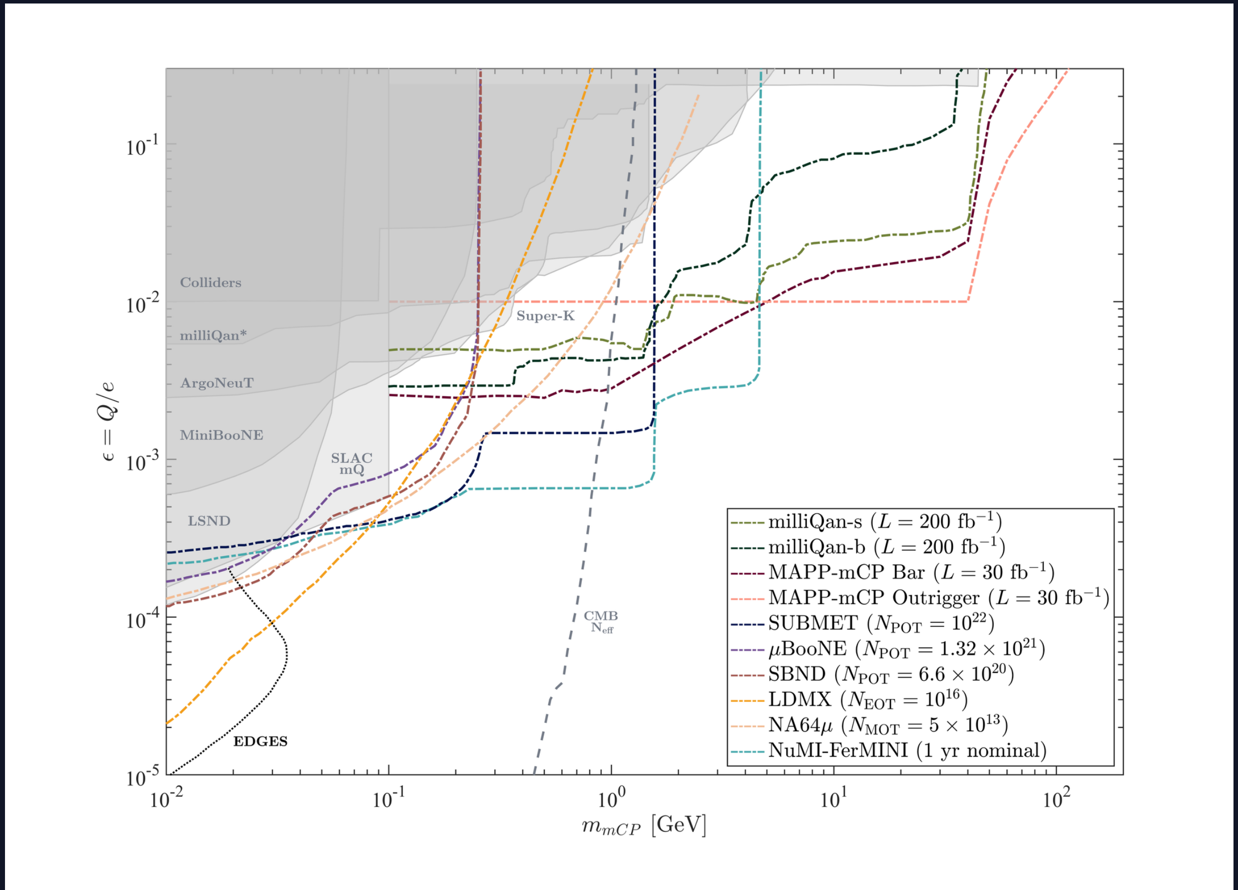
Events were generated based on the x/s and analyzed to estimate the # of 'hits' in MAPP-mCP.

- 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.
- Note: **milliQan & MAPP-mCP cover quite different regions of pseudorapidity** (so there is some complementary).

Sensitivity of MAPP to mCPs - Analysis & Results

Comparison of MAPP-mCP Bar & Outrigger limits with **all other projections available in the literature** for data collected by ~2025.

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.)

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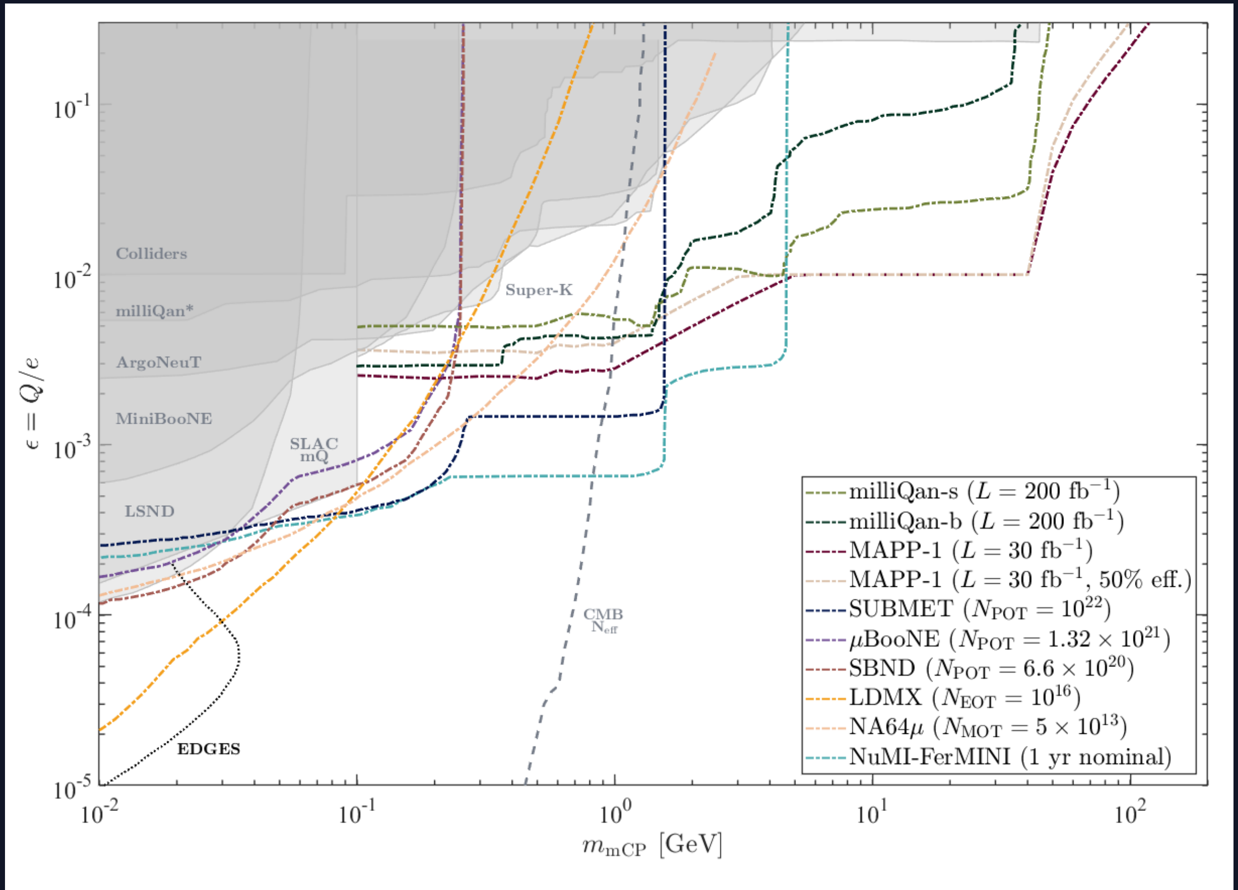
- This was performed across the parameter space of interest.
- A **'hit'** was defined as an mCP with momenta traversing each of the co-linear sections of the MAPP-mCP detector.

Sensitivity of MAPP to mCPs - Analysis & Results

Comparison with all other projections available in the literature for **data collected by ~2025**. (**Combined limits for MAPP-mCP** at **100% & 50% eff.**)

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



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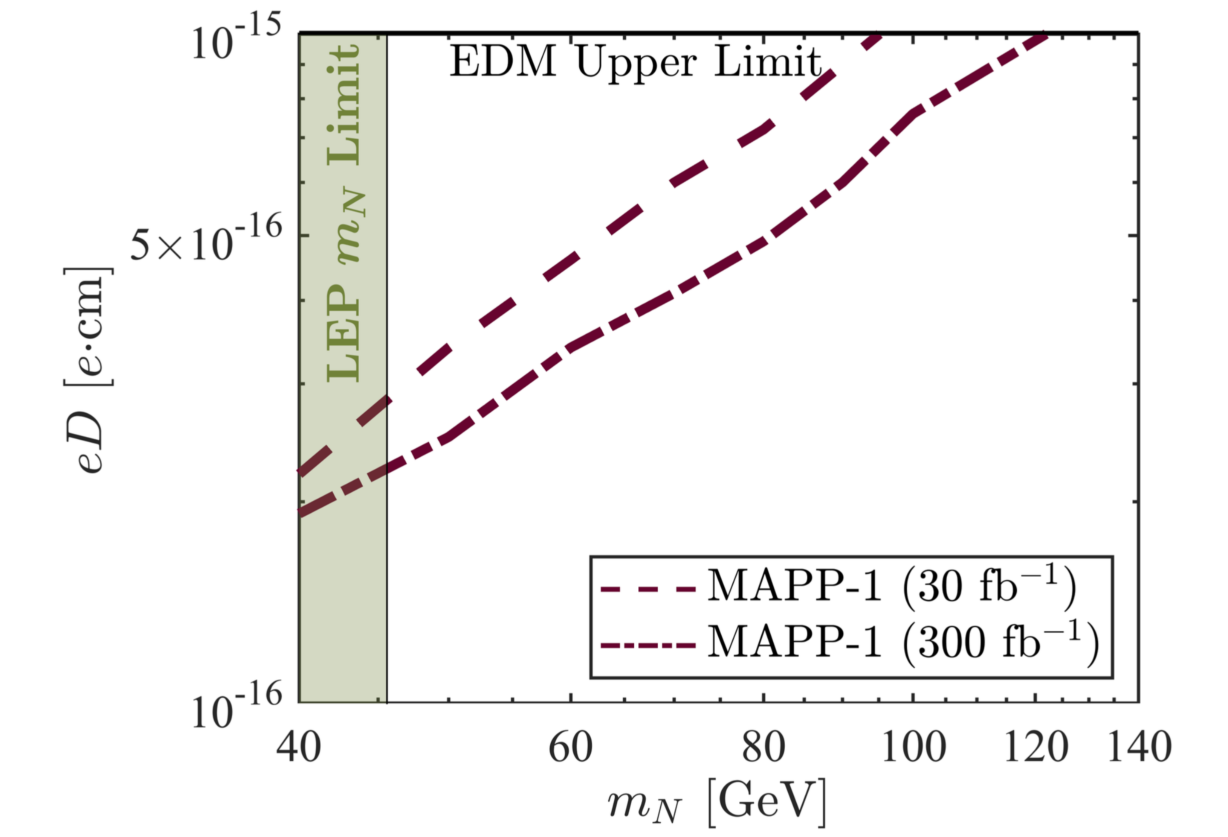
- This was performed across the parameter space of interest.
- A **'hit'** was defined as an mCP with momenta traversing each of the co-linear sections of the MAPP-mCP detector.

Sensitivity of MAPP to Heavy Neutrino EDM

Approximate bounds from rescaling our projected limits on DY pair-produced heavy neutrinos with an excessively large EDM at the LHC;
M. Frank et al., *Phys. Lett. B* **802**, 135204 (2020).

95% C.L. exclusion bounds for Drell-Yan pair-produced heavy neutrinos @ 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.)

$$N_{\rm hits} = 3 = \sigma\left(\sqrt{s}, m_{\rm mCP}, \epsilon = 1\right) \times \epsilon^2_{{\rm at}, N_{\rm hits}} \times \mathcal{L}^{\rm int}_{\rm LHCb} \times P_{\rm acc}\left(\sqrt{s}, m_{\rm mCP}\right) \times \eta_{\rm det}$$

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

- Energy losses were estimated roughly. Cuts applied requiring 400 photons minimum for a `hit' to be accepted.