Searching for Minicharged Particles at the LHC's Run-3 with the Phase-I MoEDAL-MAPP Detector

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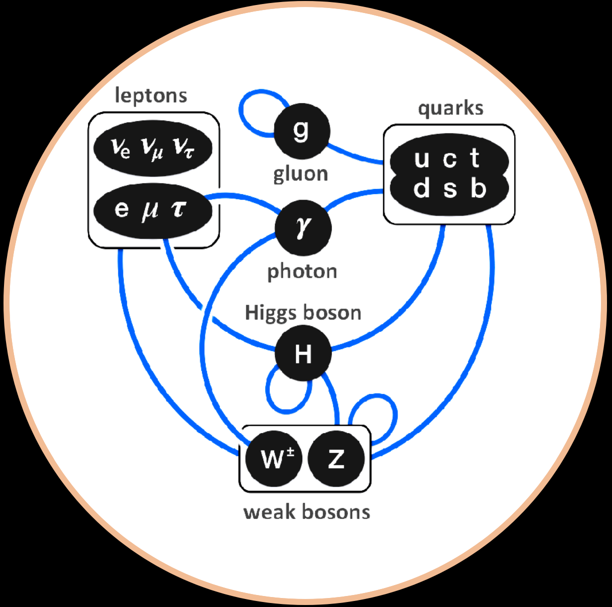
New Physics Remains Unseen at the LHC

What are the possibilities?

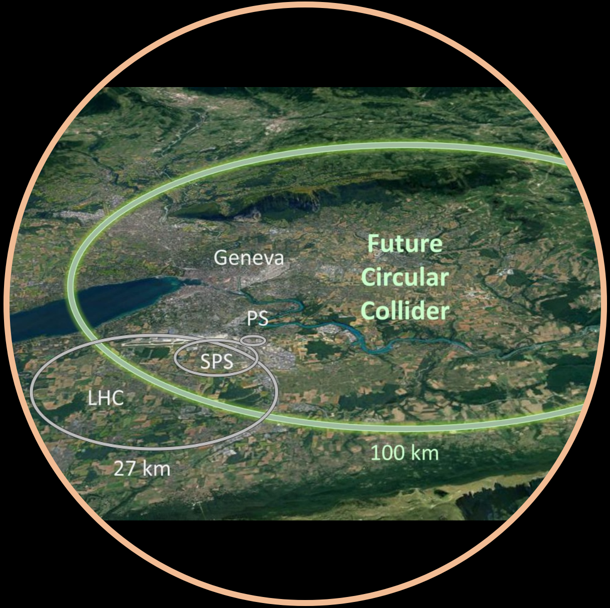


The Standard Model is it

*There is **no** new physics*

New physics exists

but at a mass scale we can't ever reach



New physics exists

but we can only see something at a future collider, e.g., the FCC

$$\sigma << 1\ \mathrm{ab}$$

New physics exists

at our mass scale, but has an extremely small cross-section

...or, perhaps new physics is right under our noses — but we can't see it with our existing "standard" detectors

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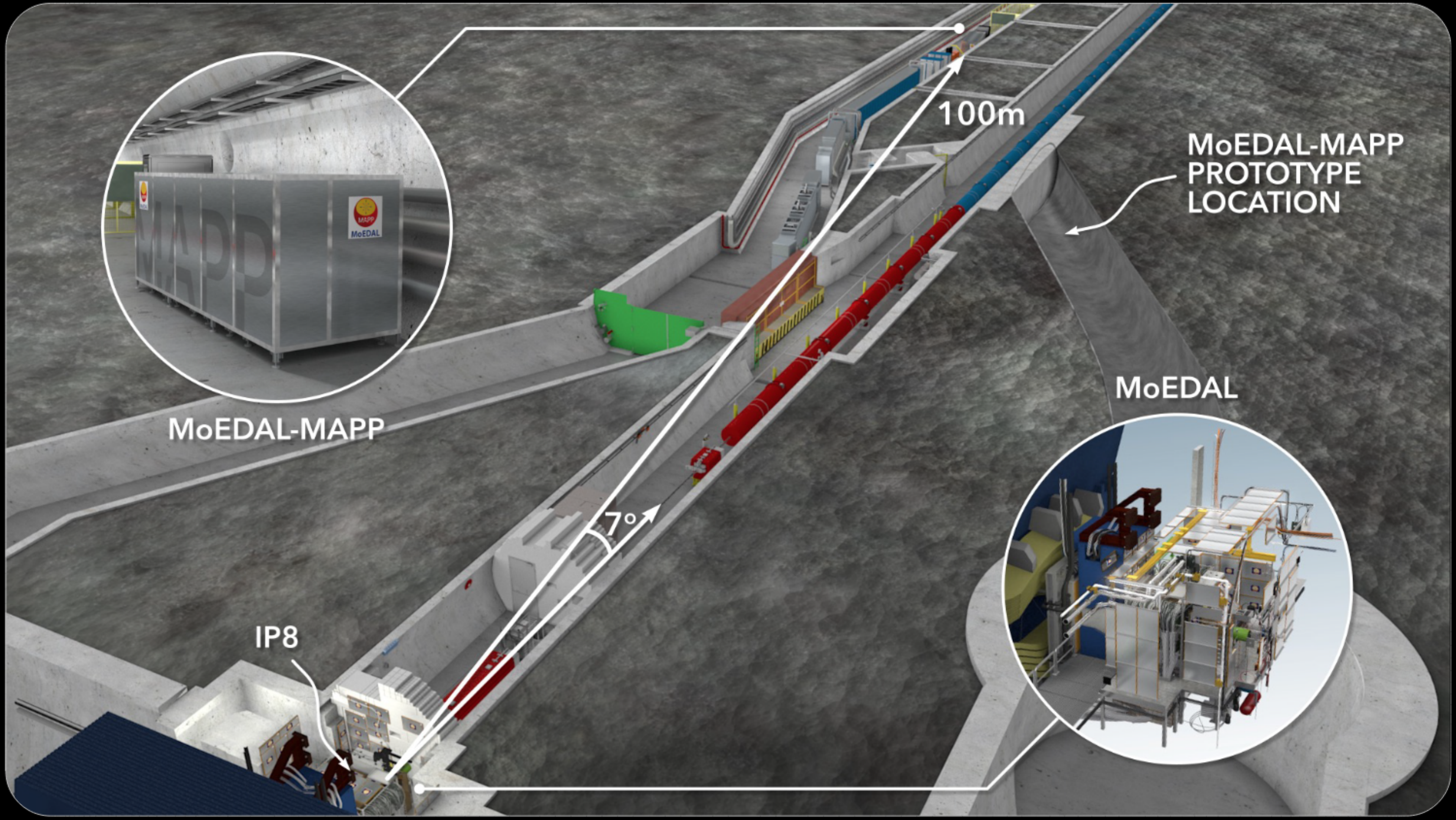
The MoEDAL-MAPP Experiment

MoEDAL's Apparatus for Penetrating Particles

APPROVED IN DEC. 2021 BY THE CERN RESEARCH BOARD!

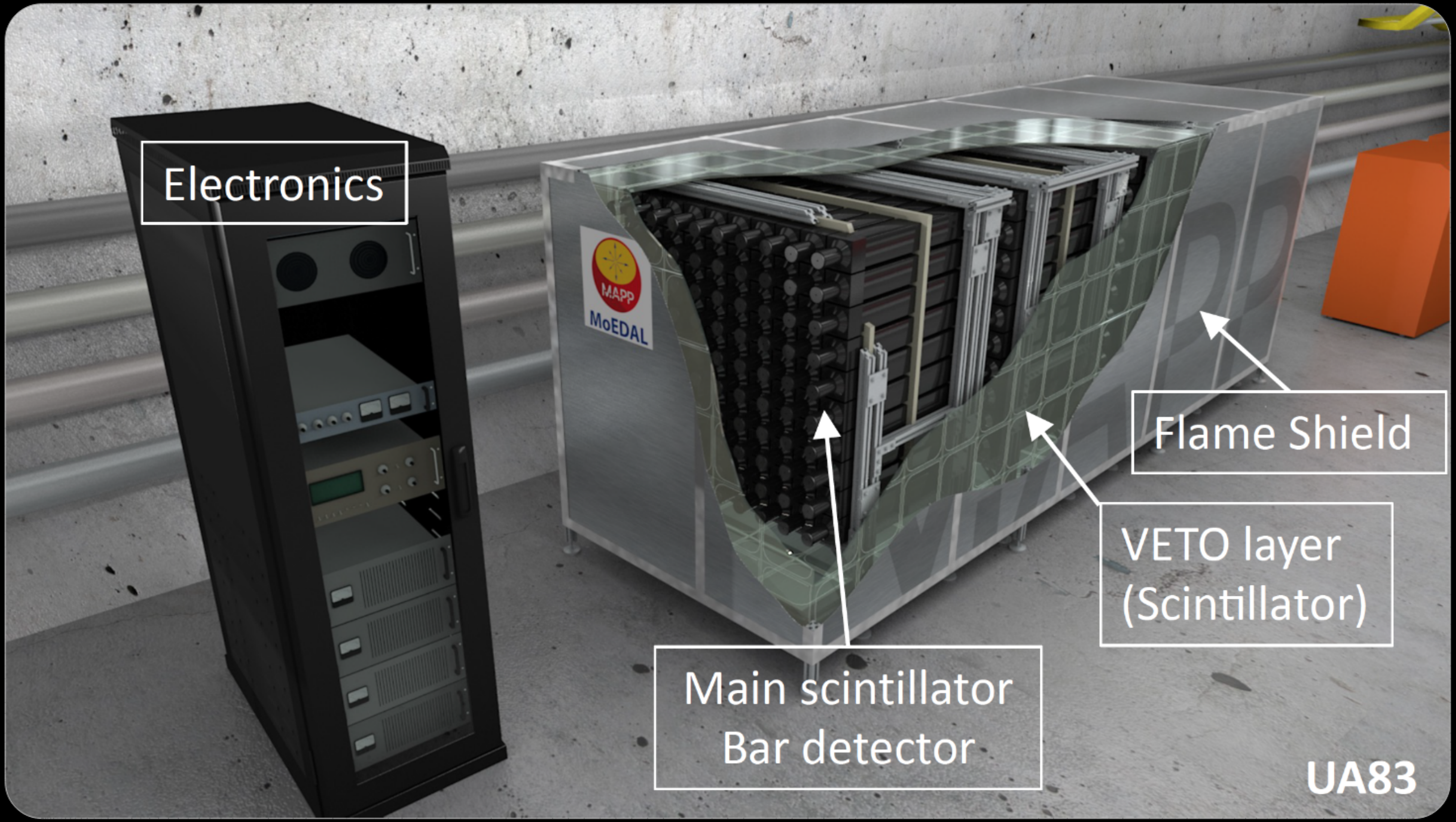
MoEDAL-MAPP Phase-I

Expanding the Physics Reach of MoEDAL Beyond HIPs to Include Feebly-Interacting Particles (FIPs)



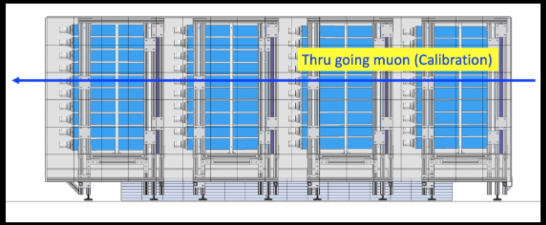
The Phase-I MAPP Detector

400 scintillator bars (10 x 10 x 75 cm) in 4 sections readout by coincidental PMTs protected by a hermetic VETO system

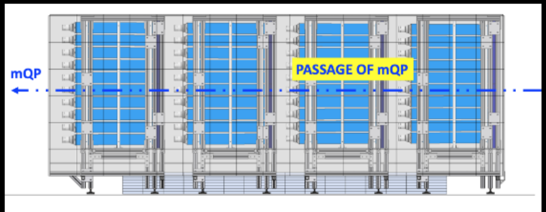


Installation of MAPP Phase-I in UA83

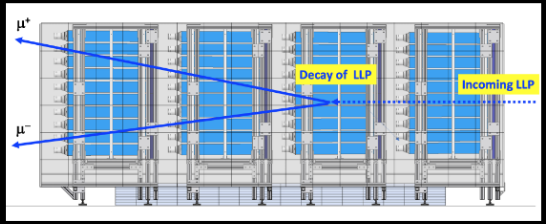
MAPP — Modes of Detection



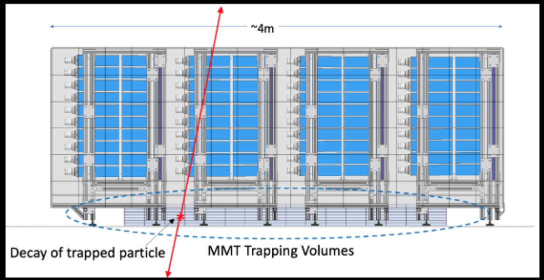
Muons from IP (Calibration)



Millicharged particle detection



Neutral LLP Detection



Charged LLP Detection
(In conjunction with MoEDAL)

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Minicharged Particles (mCPs)

Theory & Motivations

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)

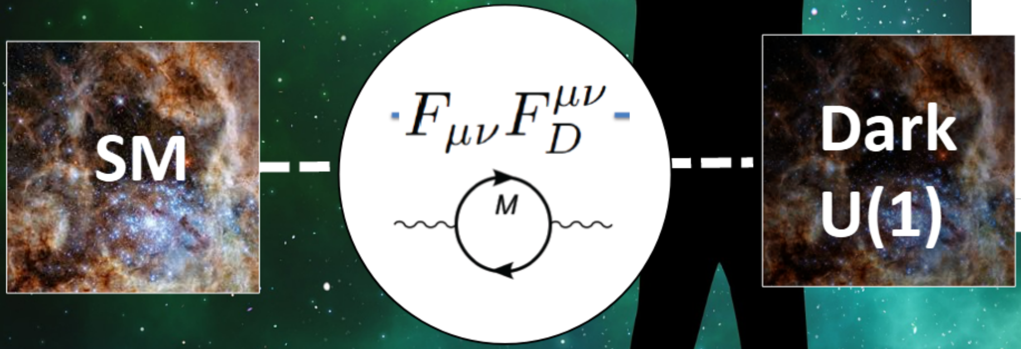
They can be used to **explain the DM abundance**. Additionally, **a minicharged DM fraction can explain the recent 21-cm anomaly** observed by the **EDGES** Collaboration. [J. D. Bowman et al., *Nature* **555**, 67–70 (2018); J. B. Muñoz and A. Loeb, *Nature* **557**, 684-686 (2018); H. Liu, *Phys. Rev. D* **100**, 123011 (2019).]

MAPPing the Dark Sector

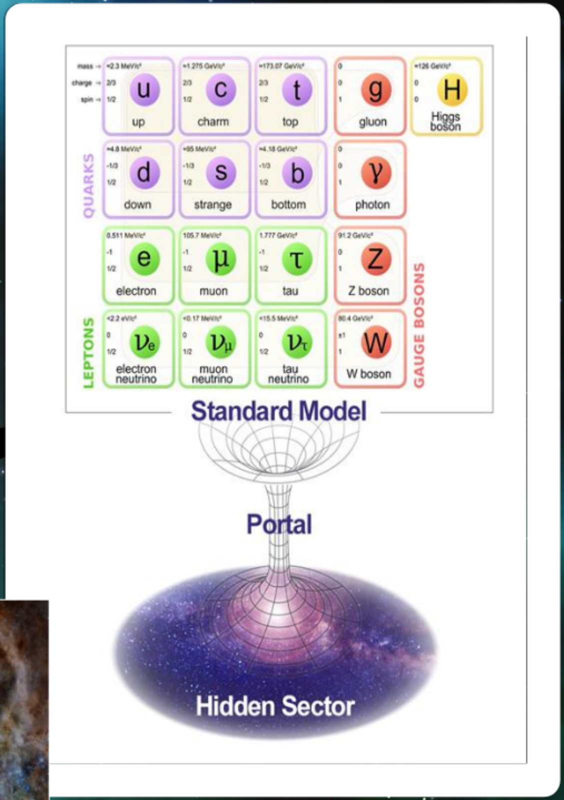
The main evidence for dark matter is gravitational. What are the "likely" non-gravitational interactions?

To detect a dark sector, we must know how it interacts with us.

- *Interactions between the two sectors are via mediator particles through so-called "portal interactions" — in this case, the vector portal:*



Mediator particles



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 χ**,

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

Here, ***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 gauge field** 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, $A'_{\mu} \Rightarrow A'_{\mu} + \kappa B_{\mu}$

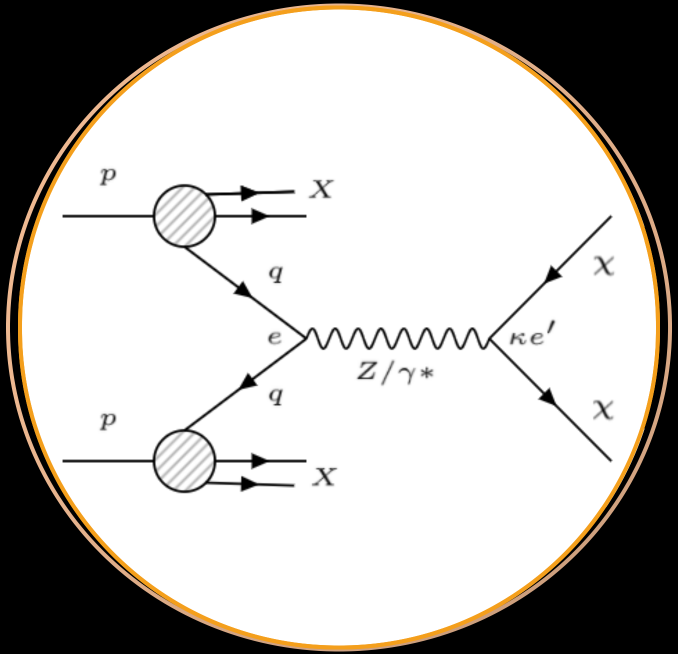
reveals a **coupling between the field χ to the SM hypercharge**, $\mathcal{L} = \mathcal{L}_{\mathrm{SM}} - \frac{1}{4}A'_{\mu\nu}A'^{\mu\nu} + i\bar{\chi}\left(\partial\!\!\!/ + ie'A\!\!\!/' - i\kappa e'B\!\!\!/ + im_{\chi}\right)\chi$

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

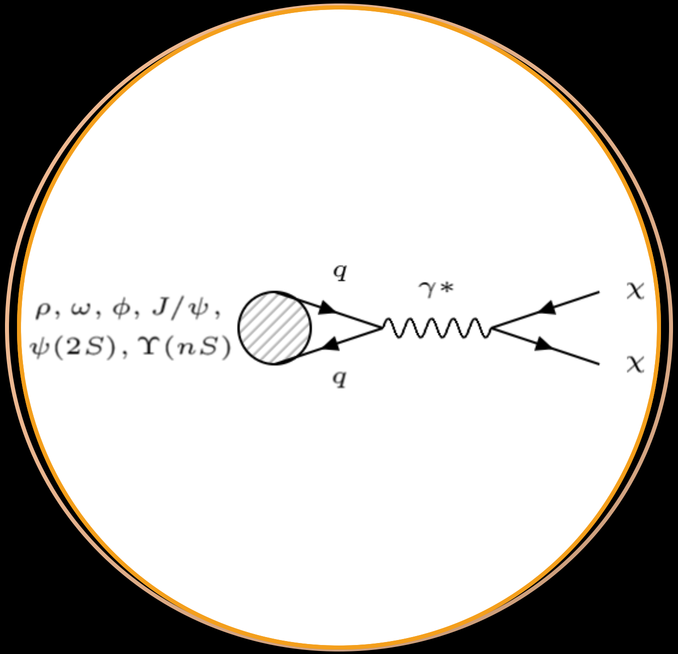
This can be **rewritten** as, $\epsilon = \kappa e' \cos\theta_{\mathrm{W}}/e$, in **units of the electric charge**, ***e***.

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

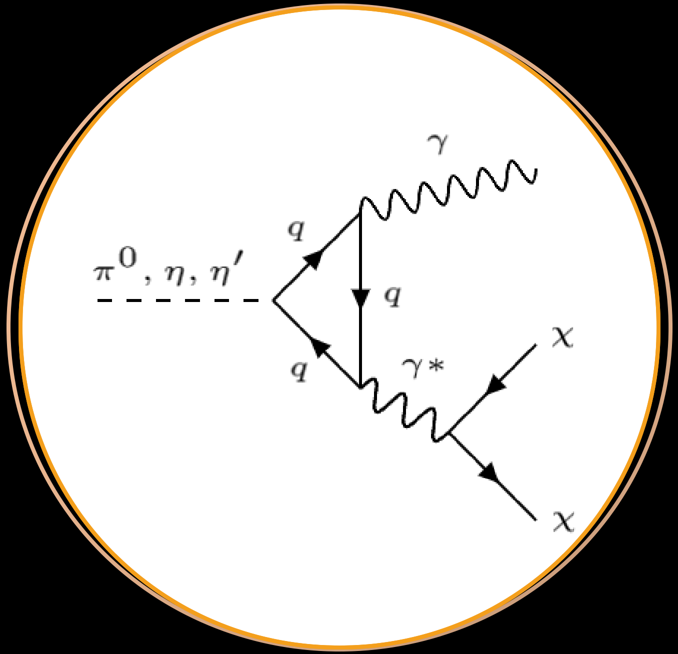
Production of mCPs at Accelerators



via the **Drell-Yan Process**



via **direct decays of vector mesons**



via **Dalitz decays of pseudoscalar mesons**

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Minicharged Particles at MoEDAL-MAPP

Modelling & Results

Model Implementations

1 **The model was implemented** into various **MC Event Generators** (Madgraph5, Pythia8, EPOS-LHC)

We use an in-house FR model of the previously shown Lagrangian for DY production, Pythia8 for the direct decays of heavy quarkonia, and EPOS-LHC for Dalitz decays of pseudoscalars and direct decays of LVMs

2 **Validate model implementation**

A combination of analytical & numerical calculations, and the literature available, were used to validate our model implementations

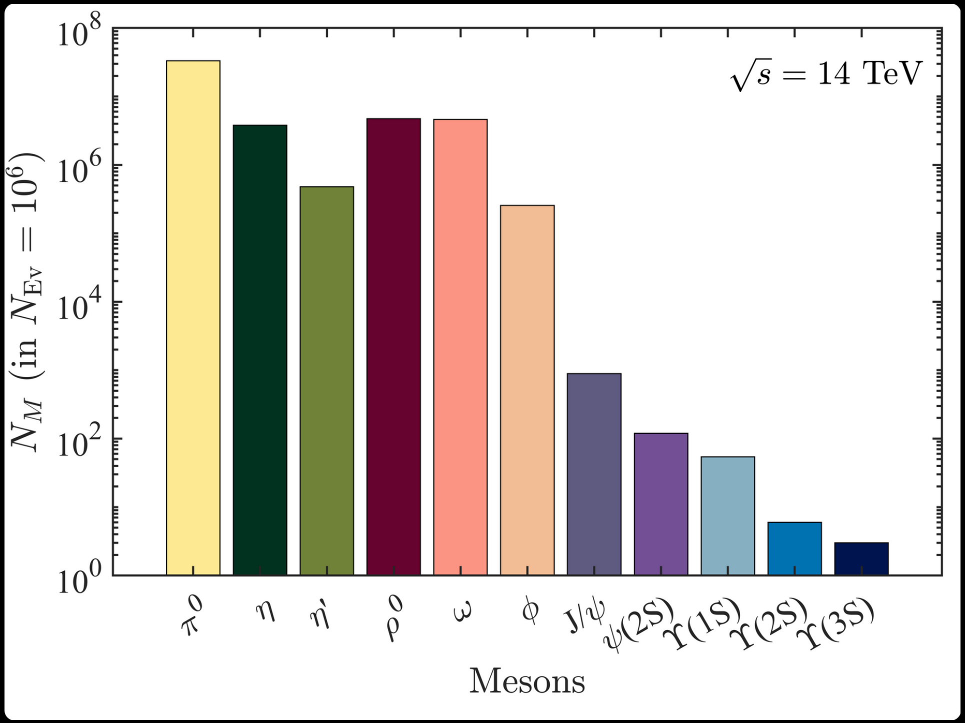
3 Finally, **generate *pp* collision events** with the **validated model**

Events are analyzed to estimate the acceptance of the MAPP-I detector for mCPs. Cuts may also be placed throughout this process

Meson Production Rates & Branching Ratios to mCPs

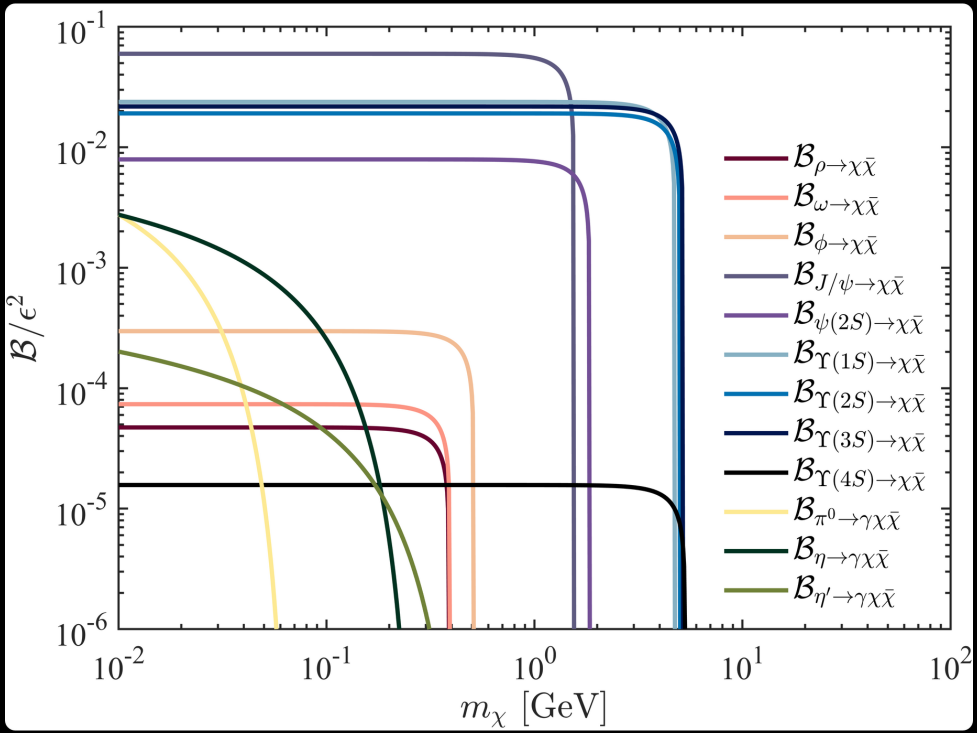
$$\mathcal{B}_{M\to\gamma\chi\bar{\chi}} = \epsilon^2 \alpha_{\rm QED} \mathcal{B}_{M\to\gamma\gamma} \left(\frac{2}{3\pi} \int_{4m_\chi^2/m_M^2}^{1} dz \sqrt{1 - \frac{4m_\chi^2/m_M^2}{z}} \frac{(1-z)^3 \left(2m_\chi^2/m_M^2 + z\right)}{z^2} \right)$$

$$\mathcal{B}_{M\to\chi\bar{\chi}} = \epsilon^2 \mathcal{B}_{M\to ee} \frac{\left(m_M^2 + 2m_\chi^2\right)\sqrt{m_M^2 - 4m_\chi^2}}{\left(m_M^2 + 2m_e^2\right)\sqrt{m_M^2 - 4m_e^2}}$$



Meson Production Rate Estimates

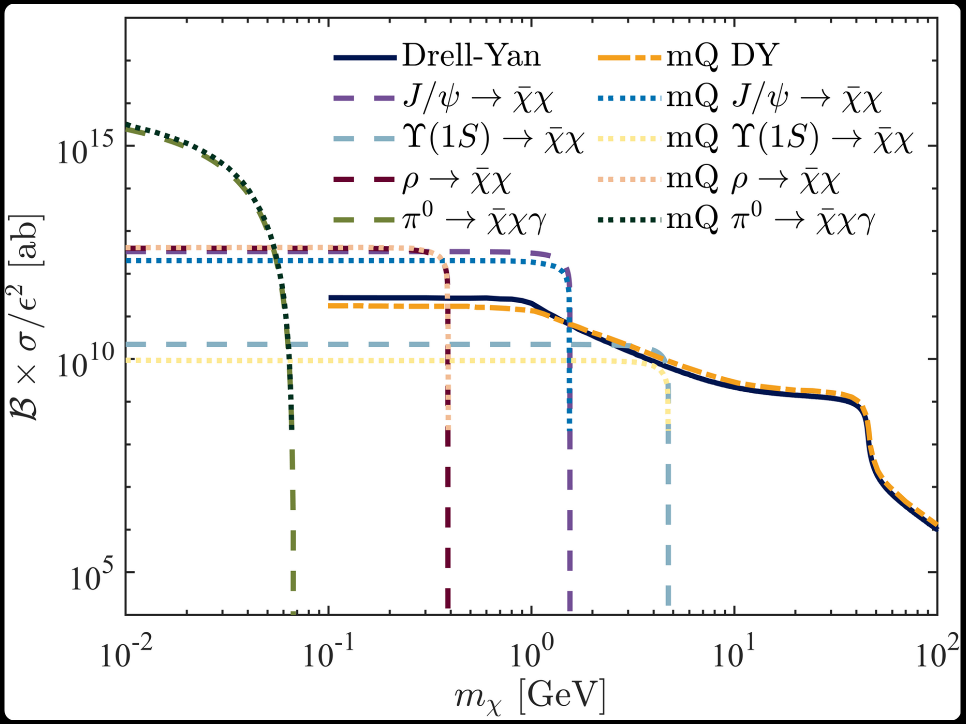
Based on 1 million 14 TeV pp collisions



Normalized Branching Ratios

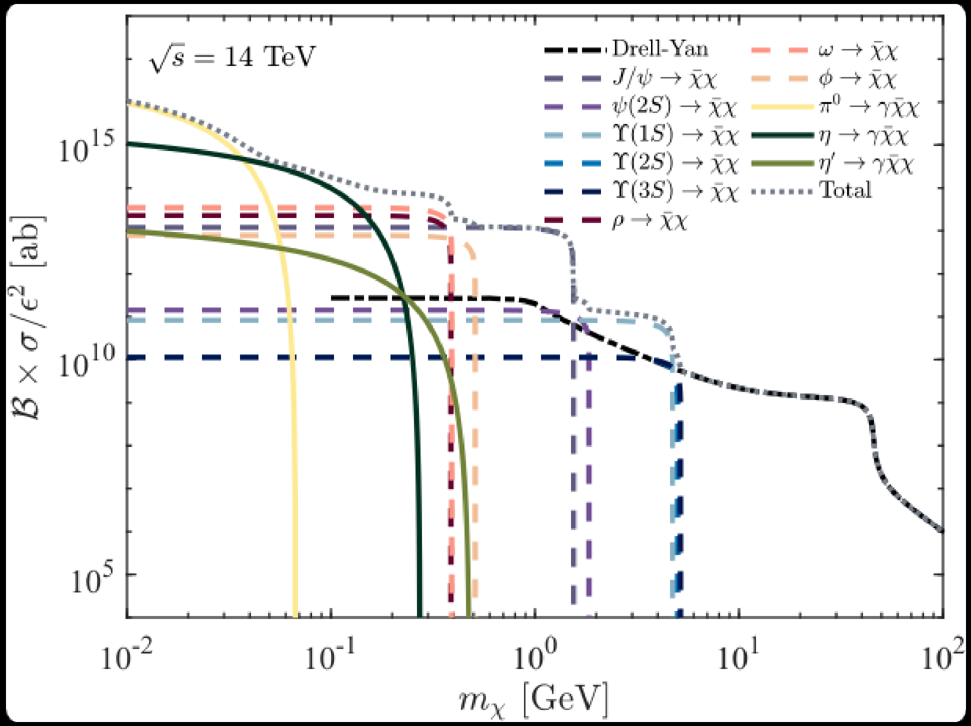
Calculated following Phys. Rev. D **104**, 035014 (2021)
& Phys. Rev. D **100**, 095010 (2019)

Model Validation via X/S Comparisons w/ the Literature



mCP Prod. X/S Estimates Compared w/ milliQan

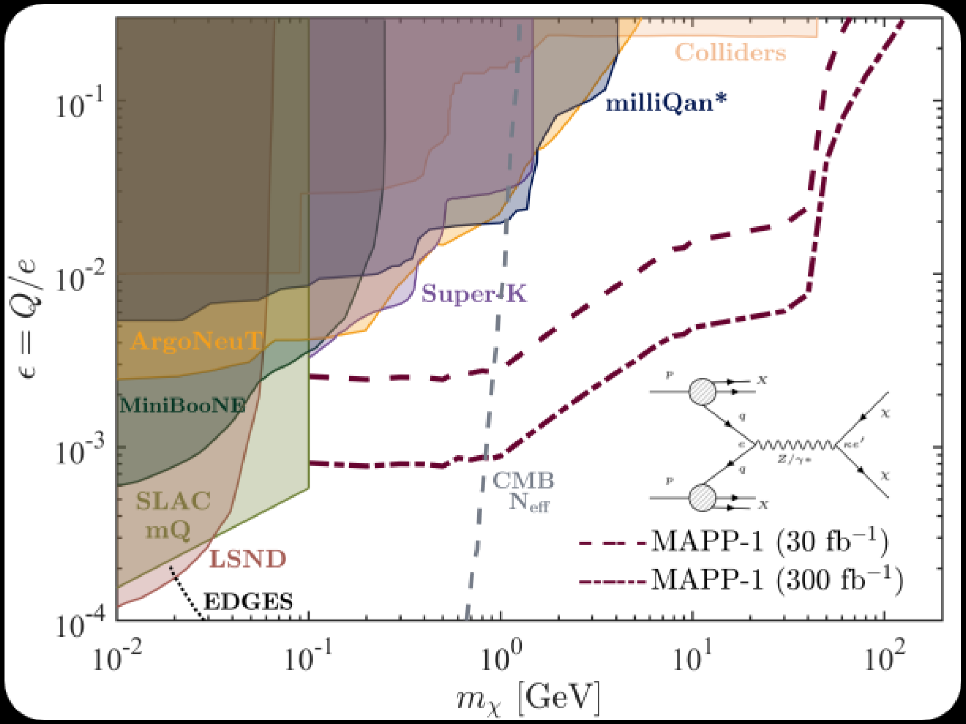
***Drell-Yan → 14 TeV** comparison w/ Phys. Lett. B* **746**, 117–120 (2015) &
***meson decays → 13 TeV, |η| ≤ 2** (parent) w/ Phys. Rev. D* **102**, 032002 (2020)



mCP Prod. X/S Estimates for 14 TeV *pp* Collisions

Projected Exclusion Limits for mCPs @ MAPP-1

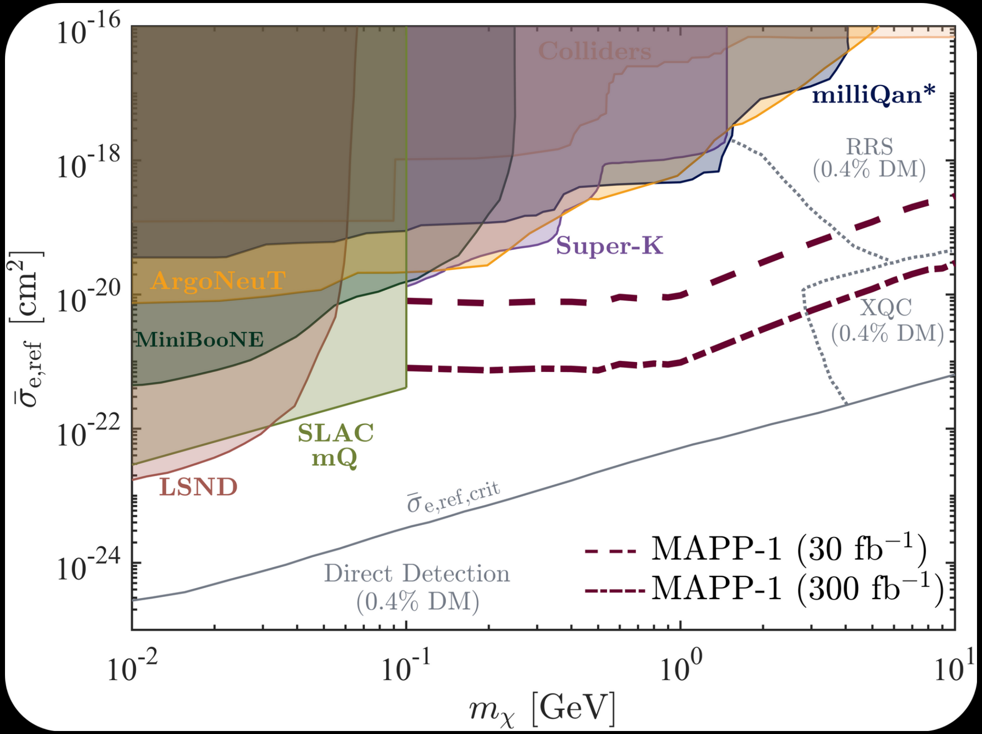
95% C.L. for DY pair-produced mCPs in 14 TeV *pp* collisions



Minicharged Particles (mCPs)

Phys. Lett. B **166**(2), 196–198 (1986); *Phys. Lett. B* **746**, 117–120 (2015)

95% C.L. for mCPs projected onto the mC-SIDM scenario, assuming 0.4% of the DM to be mCPs



Minicharged Strongly-Interacting DM (mC-SIDM)

Phys. Rev. D **104**, 035014 (2021); *Phys. Rev. D* **102**, 115032 (2020); *JCAP* **2018(10)**, 007 (2018); *JCAP* **2019(09)**, 070 (2019)

Conclusions & Future Directions

MAPP-I was approved by the CERN Research Board in Dec. 2021.

Construction and testing are well underway and should be completed in Fall 2022, w/ data taking to begin in 2023!

Projected limits for Run-3 can extend existing bounds on mCPs by over an order of magnitude.

Reaching electric charges as low as ~0.003e, and covering a range of mCP masses from ~0.1–65 GeV.

Updated bounds are currently being calculated, which include all the meson decays discussed.

Detailed studies of mCP energy losses in the detector, signal response & efficiency, and expected BGs are currently underway!

Thank you!

Questions?