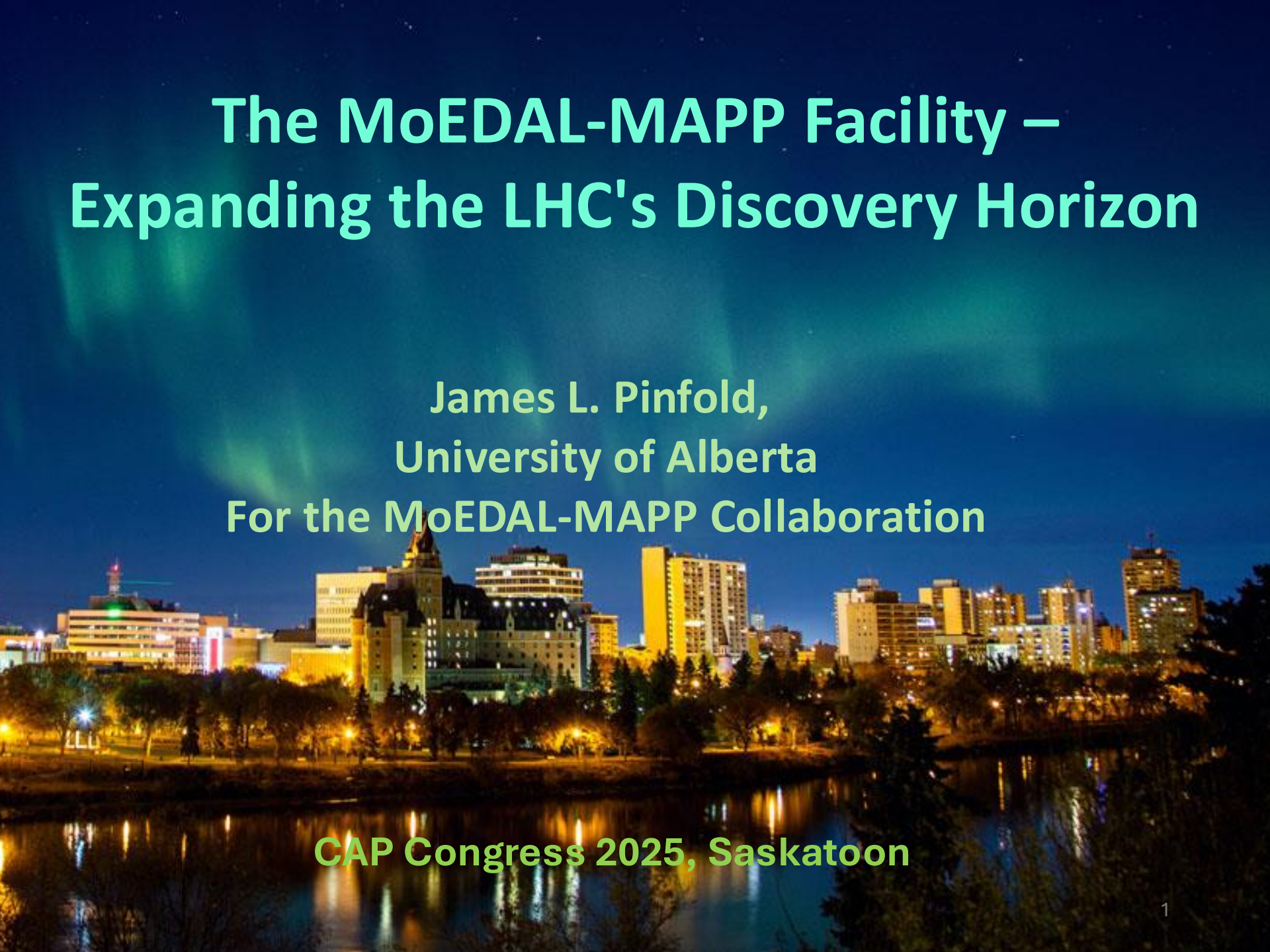
The MoEDAL-MAPP Facility – Expanding the LHC's Discovery Horizon

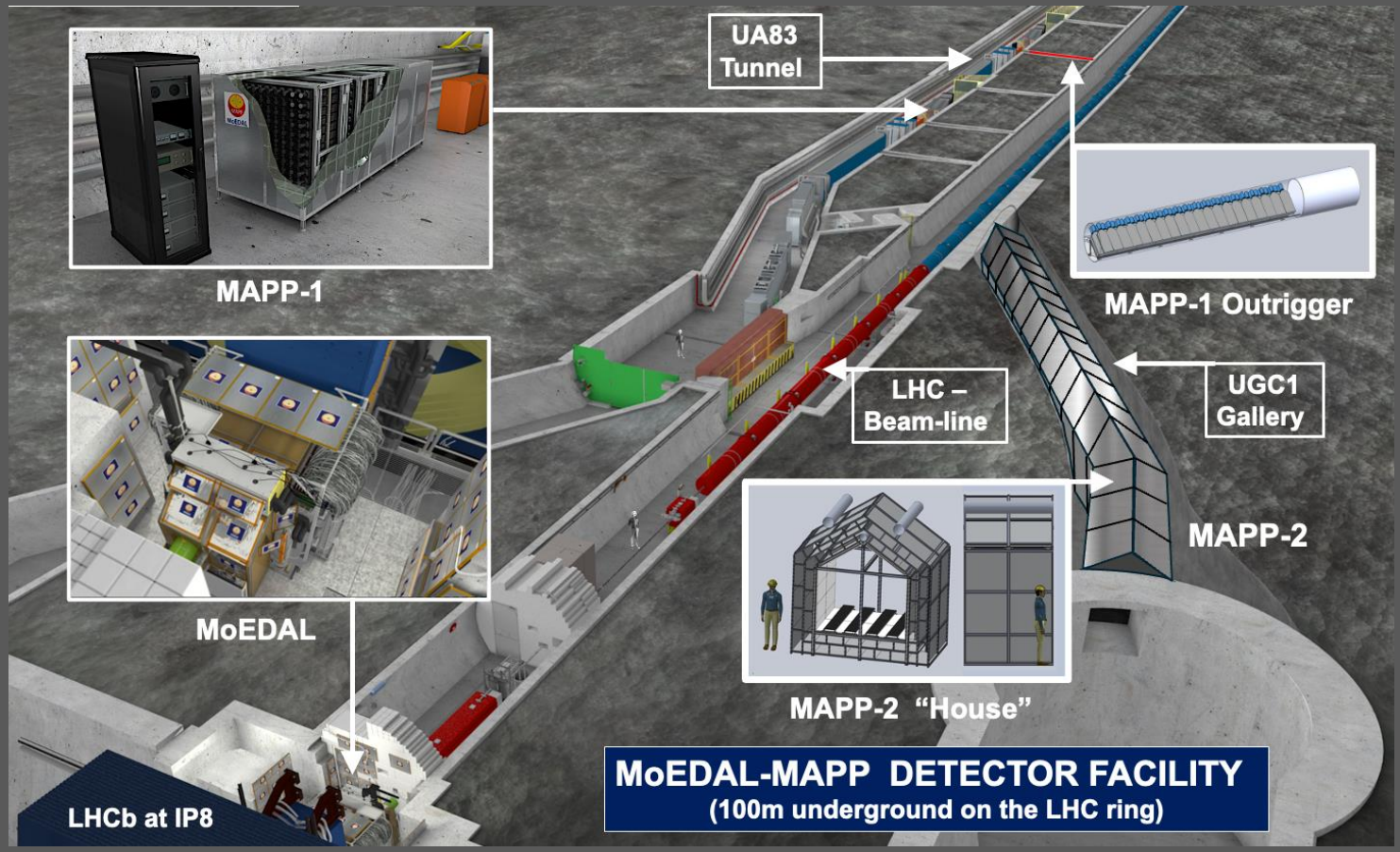
James L. Pinfold,
University of Alberta
For the MoEDAL-MAPP Collaboration



CAP Congress 2025, Saskatoon

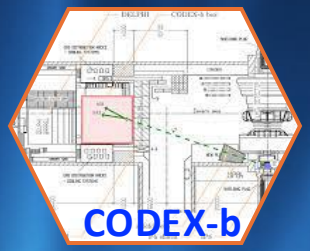
The MoEDAL-MAPP Facility at the LHC

Sensitive to new physics that it is challenging or impossible for ATLAS & CMS to observe

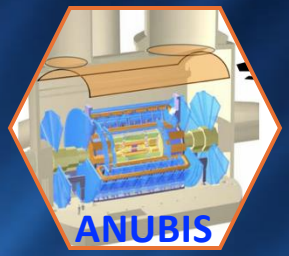


- ***MoEDAL (2010 -)*** *Highly Ionizing Particles (HIPs): Monopoles, dyons, Q-balls, BH-remnants, etc*
- ***MAPP-1 (2021 -) + Outrigger (2025?-)*** *Weakly Ionizing Particles (WIPs): Millicharged particles, Anomalous EDM, etc. + some sensitivity to neutral Long-Lived Particles (LLPs)*
- ***MAPP-2 (2026?)*** *Long-Lived Particles (LLPs): Dark scalars, sterile neutrinos, neutralinos, ALPs,etc*

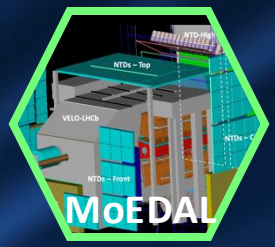
The Caste of "Agile" Detectors Today

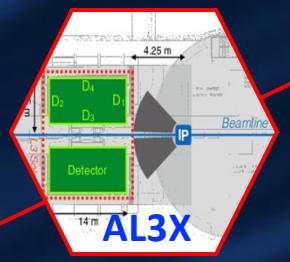

CODEX-b


MATHUSLA


ANUBIS


MilliQan


MoEDAL


AL3X

η=0

η=0.5

η=1

η=1.5

η=2

η=2.5

η=3

η=4

Transverse
$0 < \eta < 1.5$


MAPP-2


MAPP-1

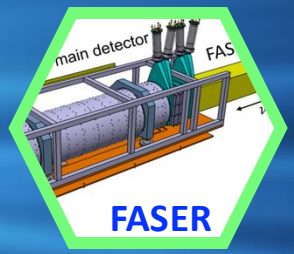
Intermediate
$1.5 < \eta < 4$

Forward
$\eta > 4$

FPF Forward Physics Facility

FASER- 2, FASERnu2,
advSND, FORMOSA, FLARE


FORMOSA



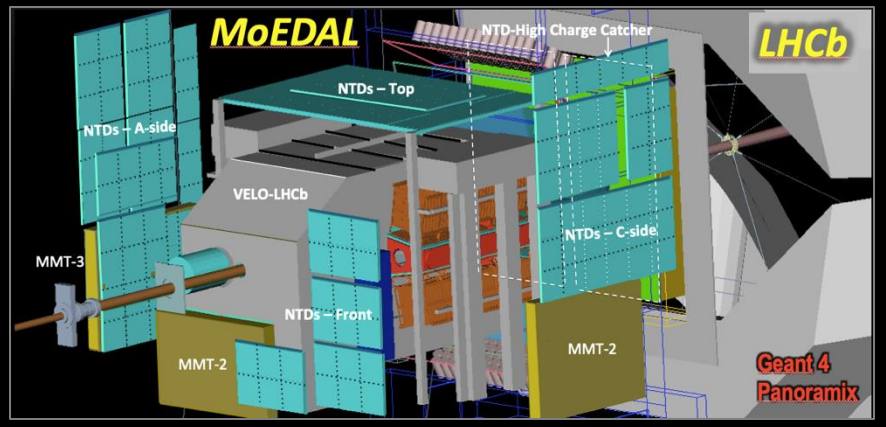
FASER


SND

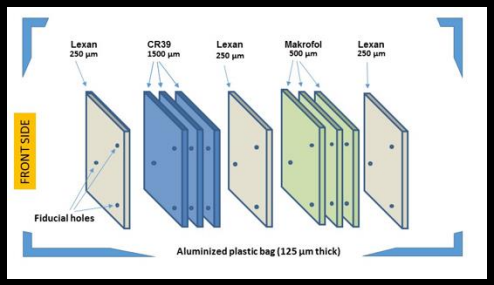

FACET

The MoEDAL Detector

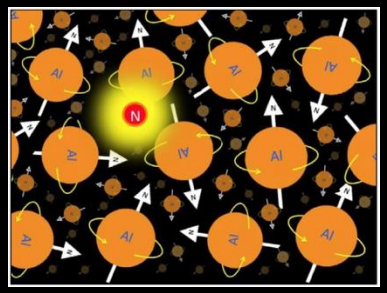
LHC's 1st dedicated search expt. –upgraded for Run-3 with higher eff. & lower thresholds



Searching for Highly Ionizing Particle (HIP) avatars of new physics



NUCLEAR TRACK DETECTOR Plastic array (185 stacks, 12 m^2) – Like a big Camera



TRAPPING DETECTOR ARRAY A tonne of Al to trap Highly Ionizing Particles for analysis

TIMEPIX Array a digital Camera for real time radiation monitoring

NO TRIGGER | **NO SM BACKGROUNDS** | **PERMANENT RECORD**

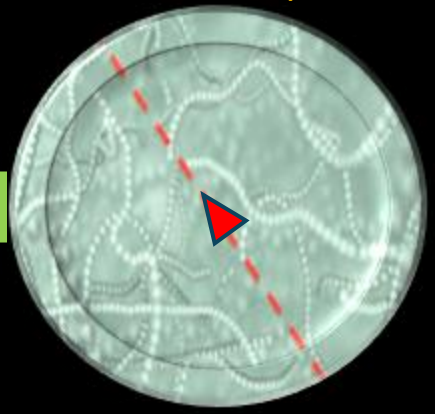
MoEDAL's Remote Detector Facilities

NTD Processing - INFN Bologna

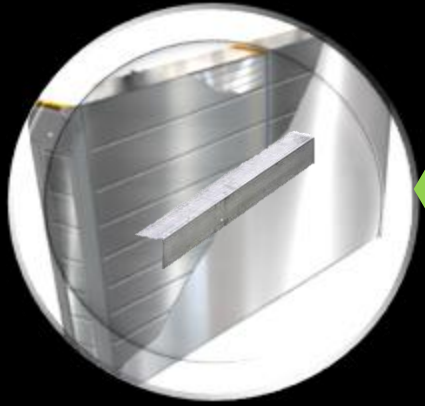
MMT Scanning- ETH Zurich

Etching in hot sodium Hrdroxide reveals damage

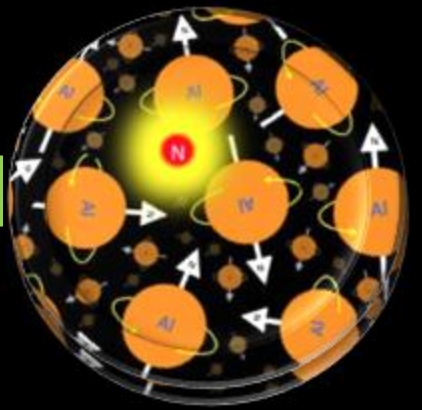
HIP causes damage Zone In NTD plastic

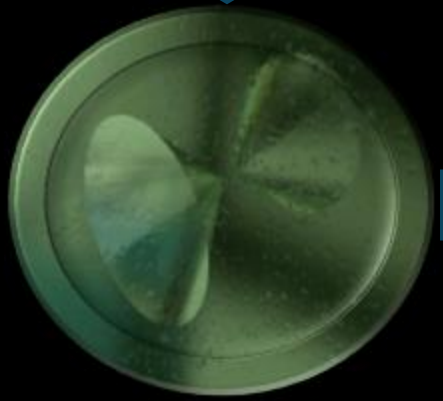


Trapping volumes are Removed for scanning

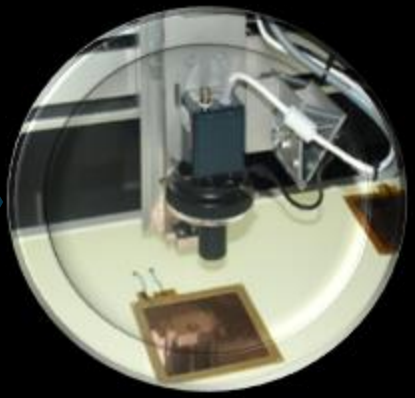


Monopole is trapped





Etch pits reveal path and charge of HIP



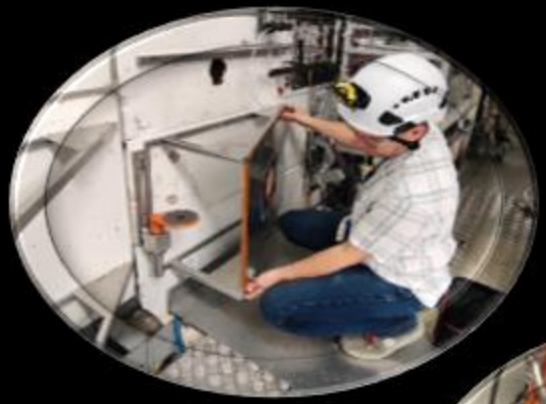
Etch pits measured by optical microscope

Trapping volumes are Passed through a SQUID

Monopoles cause a stable current in the SQUID

Upgraded MoEDAL Installed for Run-3

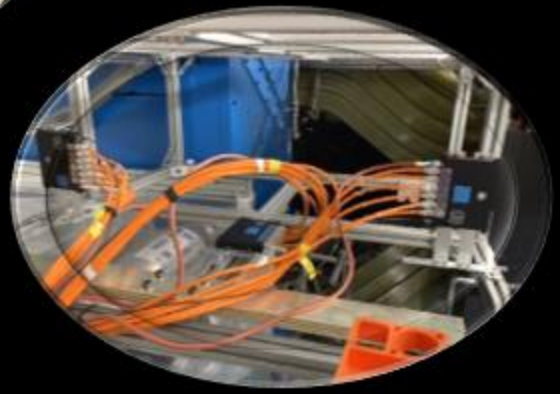
Upgrades to the Run-2 MoEDAL Detector, for Run-3 – completed in March 2023



NTD Stacks Point to IP

VELO-TOP NTD array installed

Forward MMT box reconfigured



TimePix3 Chips connected to LHC clock

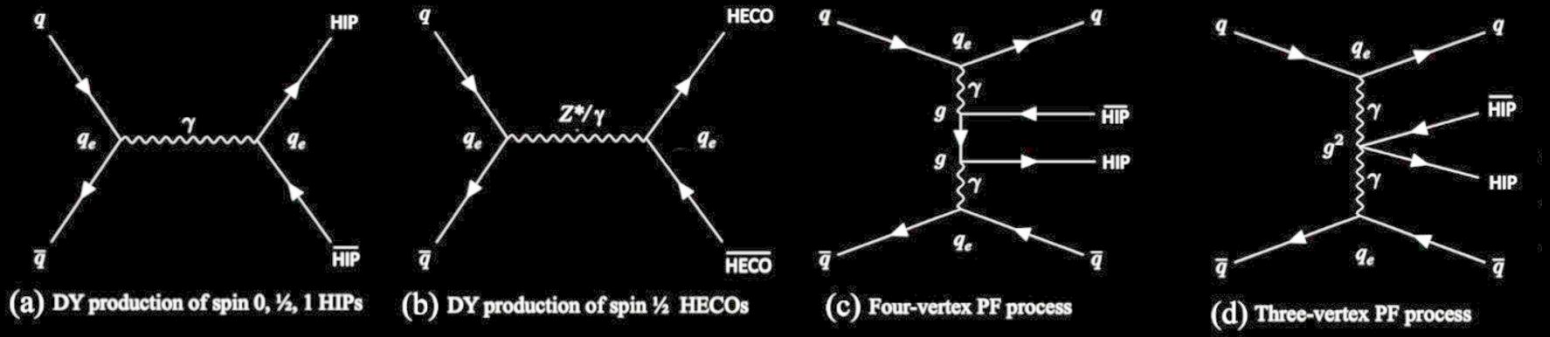
The Search for Highly ionizing particles (HIPs) continues with:

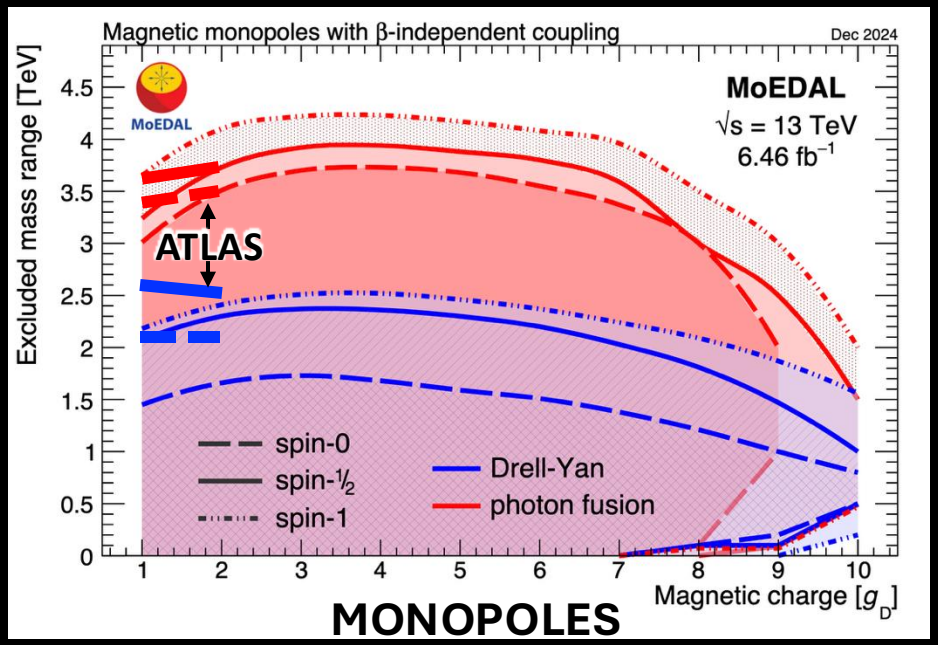
5 x Higher Instantaneous Luminosity at IP8

a) Improved Detector Efficiency
b) X10 lower threshold

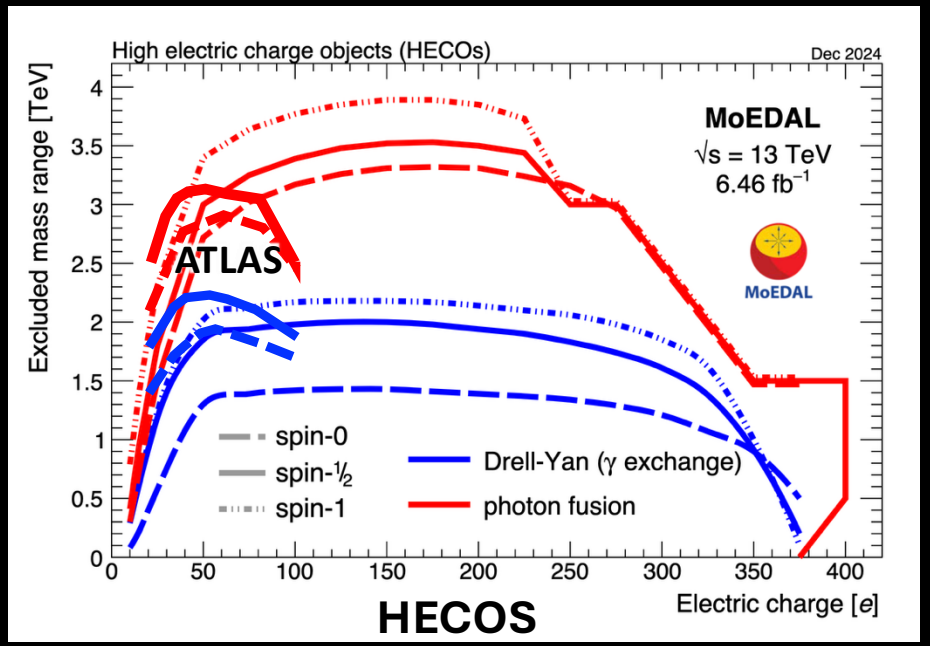
Slightly higher Centre-of-mass Energy

Latest MoEDAL Results on HIPs



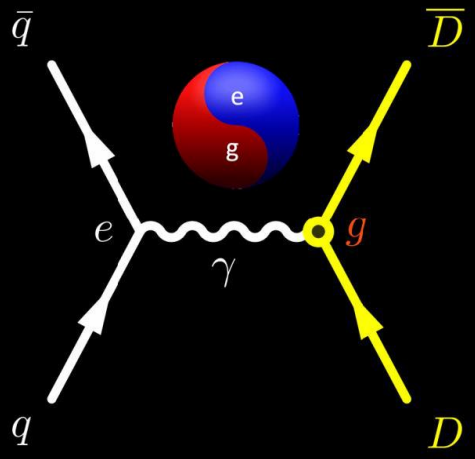


MoEDAL – world's best MM mass limits for $g_d > 1$



MoEDAL – world's best MM mass limits for $Q \geq 70e$

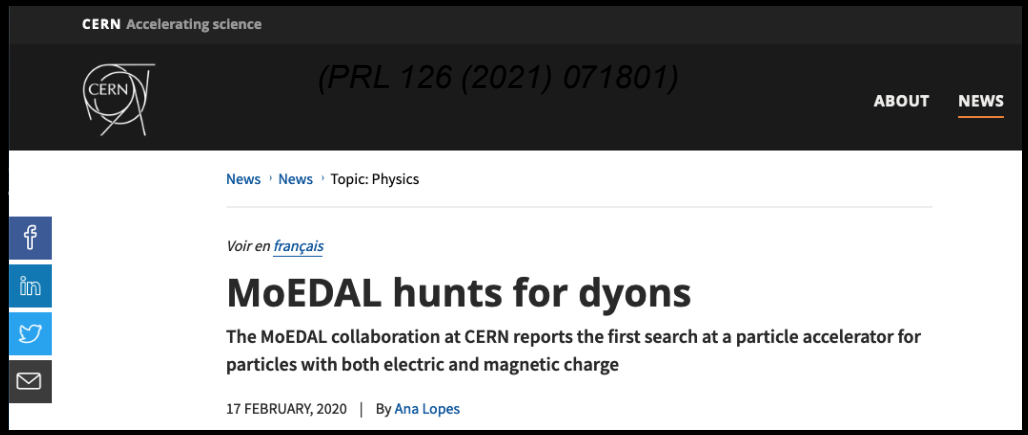
First Direct Search for the Dyon

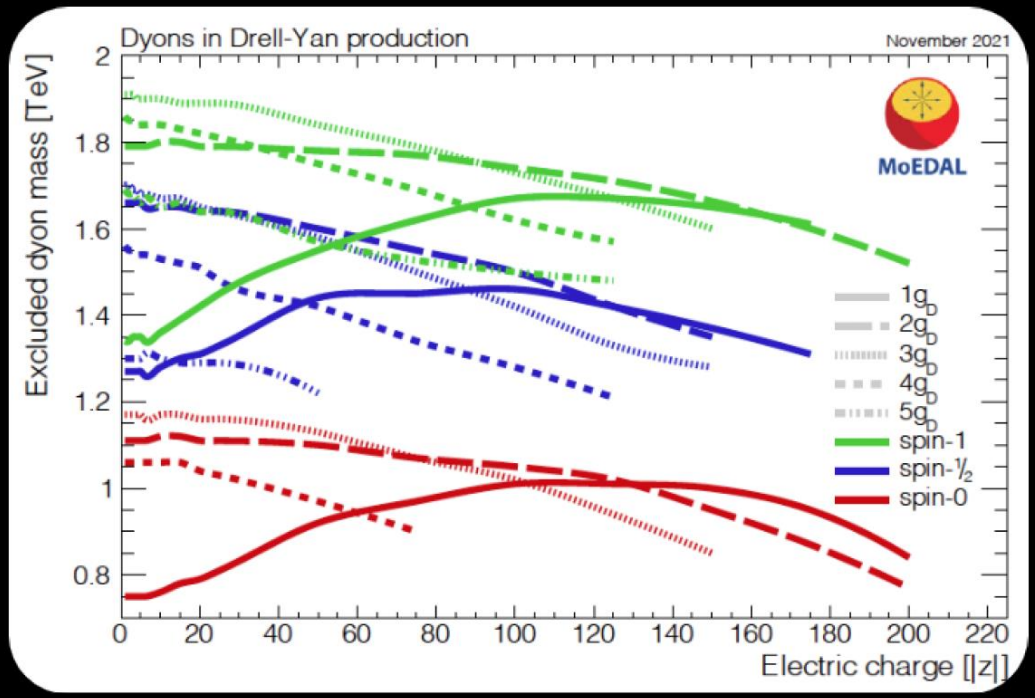


Predicted by Schwinger in 1969 a dyon has electric &magnetic charge

- *Mass limits 750-1910 GeV were set for dyons with ≤5g_D & electric charge ≤ 200e*

First ever explicit search for a dyon

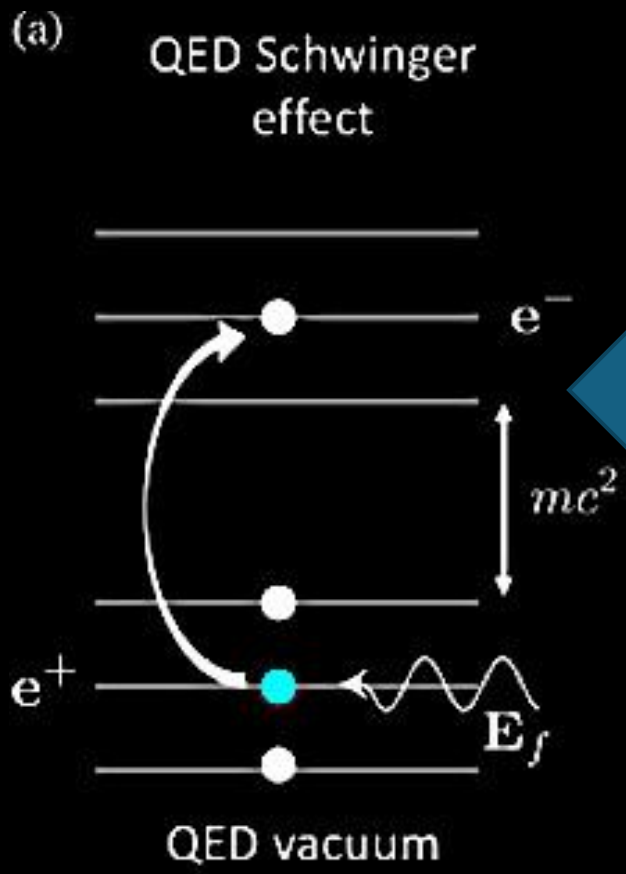




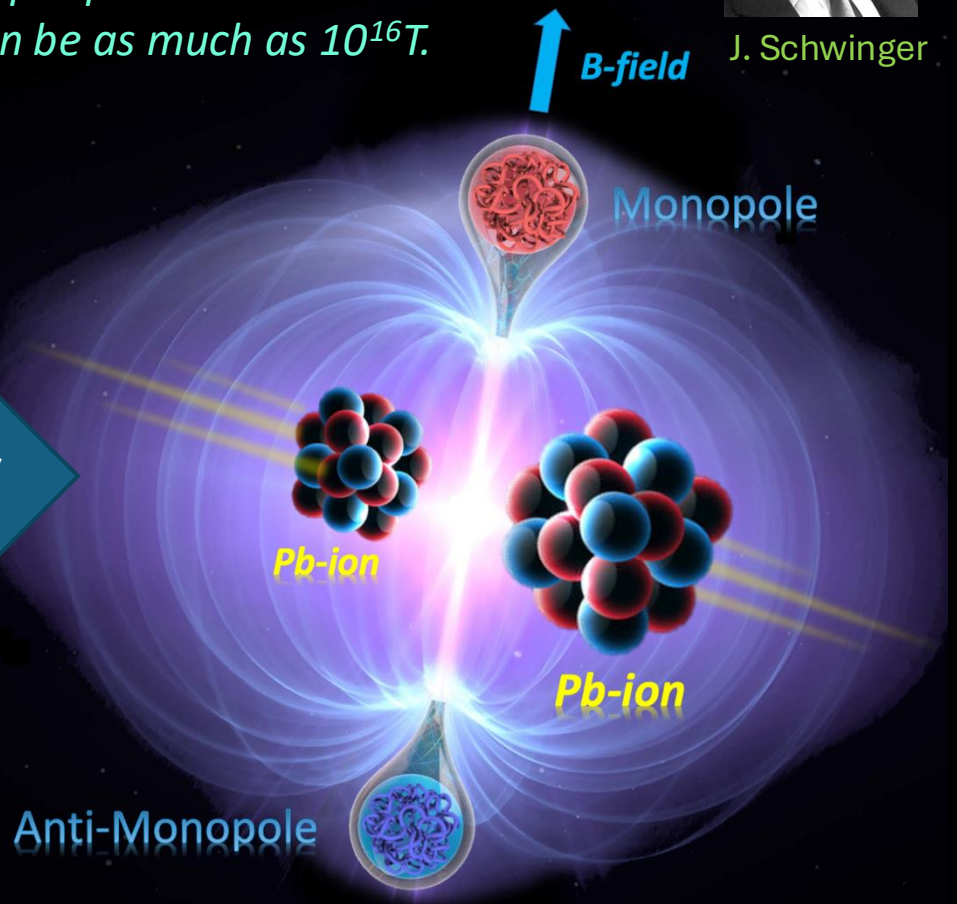
Monopole Production Via the Schwinger Mechanism

The field created in ultraperipheral "collisions" of Pb-ions at the LHC can be as much as 10^{16}T.

J. Schwinger



DUALITY

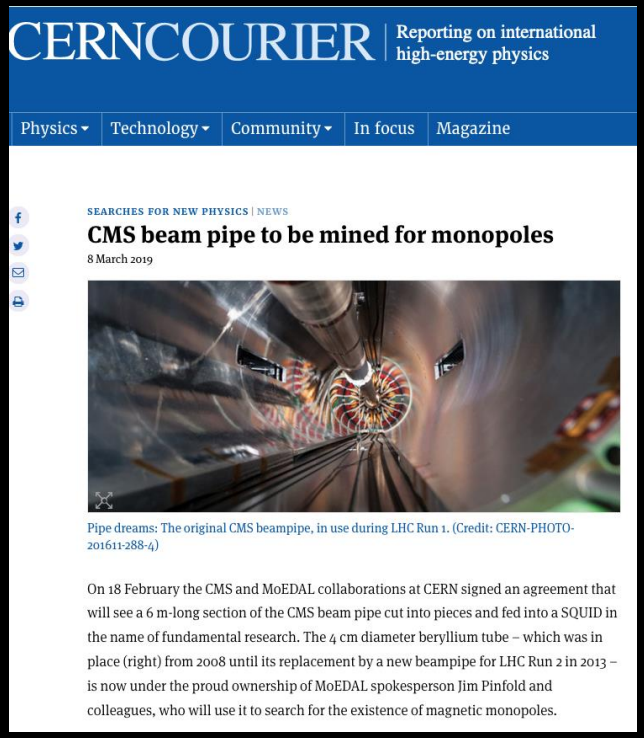


Pair production of electron-positron pairs in a very strong electric field

Pair production of monopole-antimonopole pairs in a very strong magnetic field

James Pinfold

1st Search Sensitive to Composite MMs?



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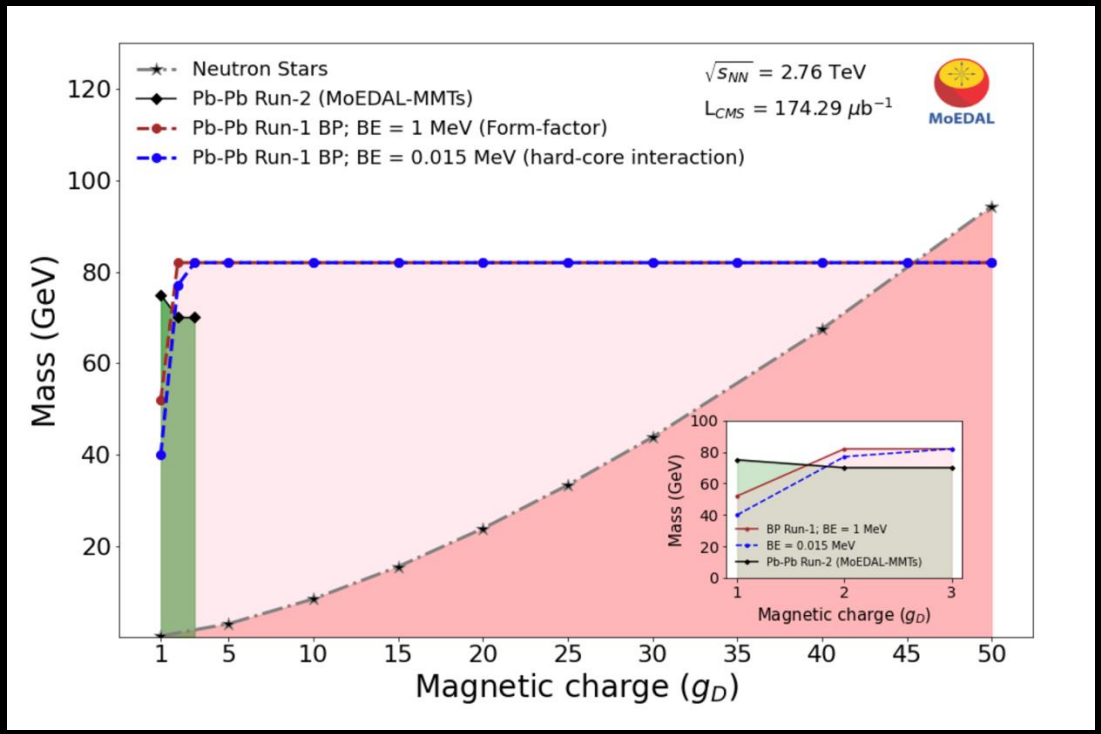
CMS beam pipe to be mined for monopoles

8 March 2019

Pipe dreams: The original CMS beampipe, in use during LHC Run 1. (Credit: CERN-PHOTO-201611-288-4)

On 18 February the CMS and MoEDAL collaborations at CERN signed an agreement that will see a 6 m-long section of the CMS beam pipe cut into pieces and fed into a SQUID in the name of fundamental research. The 4 cm diameter beryllium tube – which was in place (right) from 2008 until its replacement by a new beampipe for LHC Run 2 in 2013 – is now under the proud ownership of MoEDAL spokesperson Jim Pinfold and colleagues, who will use it to search for the existence of magnetic monopoles.



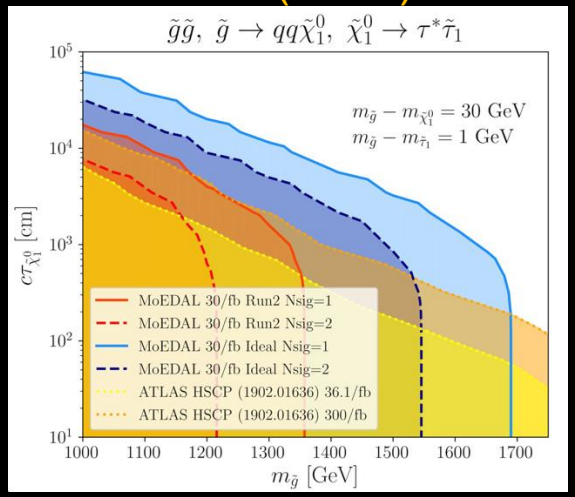
- *The CMS Beampipe was scanned by the MoEDAL experiment using a SQUID magnetometer to search for trapped MMs.*
  - *Limits produced via the Schwinger production are theoretically valid – limits from DY and $\gamma\gamma$ are not due to perturbation theory busting coupling of MMs to photons.*
  - *The Schwinger production of composite MMs is NOT exponentially suppressed by a factor of $e^{-O(500)}$ as is MM production using DY or $\gamma\gamma$ production modes.*

Nature 602 (2022) 7895, 63-67 (Run-1) **Phys. Rev. Lett. 133, 071803 – Published 15 August 2024**

Searching for Long-Lived HIPS

Due to the absence of trigger, timing & SM backgrounds, MoEDAL can relax selection requirements + increase sensitivity to charged, SUSY LLPs

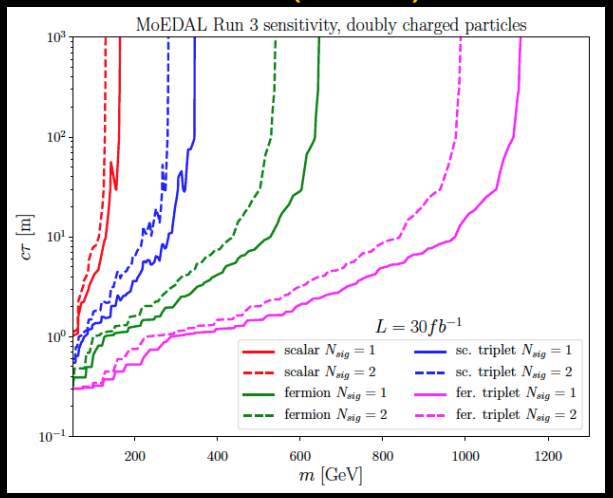
EPJC 80 (2020) 431



MoEDAL can cover the long-lifetime region at Run-2/3 for gluinos, stops, sleptons & charginos

SLEPTONS

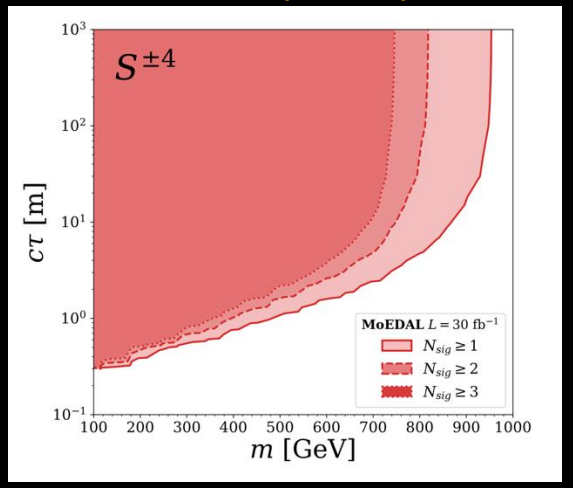
EPJC 80 (2020) 572



Authors added doubly charged scalars & fermions in various SU(2)L rep's, to the SM particle content .

DOUBLY CHARGED

EPJC 81 (2021) 697



In this class of neutrino mass models, the SM is extended with two scalar fields, and 3 pairs of vector-like fermions.

2,3 and 4 CHARGED

- *If sufficiently slow moving, even singly or multiply ($\lesssim 10e$) charged particles may leave a track in NTDs*
- *Supersymmetry offers such long-lived states: sleptons, R-hadrons, charginos*
- *Multiply charged scalars or fermions are, for example, predicted in several neutrino mass models.*

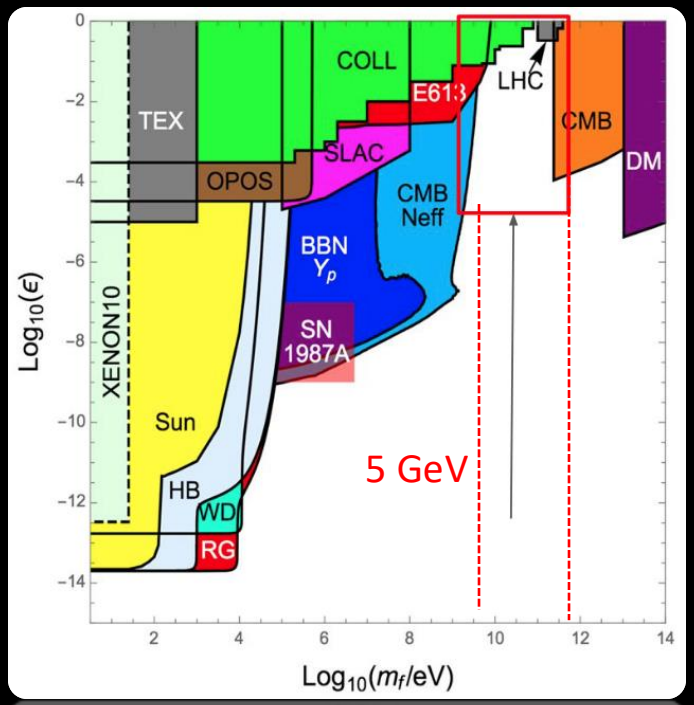
MoEDAL – HIP Innovations

By MoEDAL Theory Board (Chaired by John Ellis) & MoEDAL Experimentalists

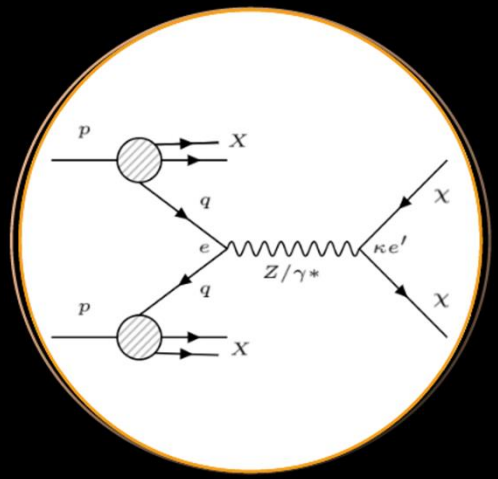
- *MoEDAL constantly innovates, pushing the theory of HIPs as much as the experiment.*
- *Here are some innovations by the MoEDAL Collaboration's experimentalists and theoreticians that are first ever or at least first at the LHC*
  - *Development of the theory of the EW Monopole for LHC physics*
  - *MM β-dependent couplings*
  - *$\gamma\gamma$ - fusion production of HIPs*
  - *p-p cross-sections for Spin-1 HIPs*
  - *Phenomenological treatment of Schwinger production of MMs in p-p collisions*
    - *First ever search at a collider for non-pointlike monopoles.*
  - *Resummation techniques applied to HIPs*

Production of Milli-charged at Colliders

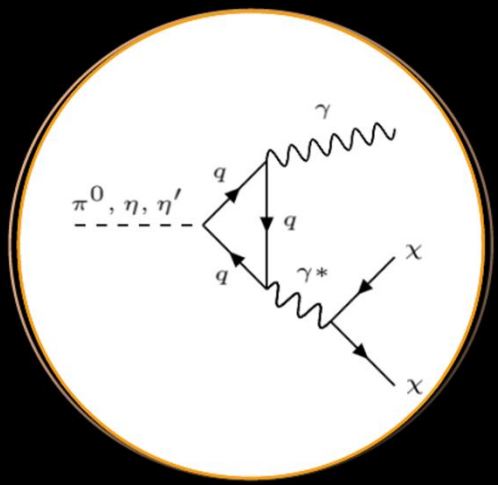
mCPs arise naturally from the dark sector via the Vector Portal/Dark Photon



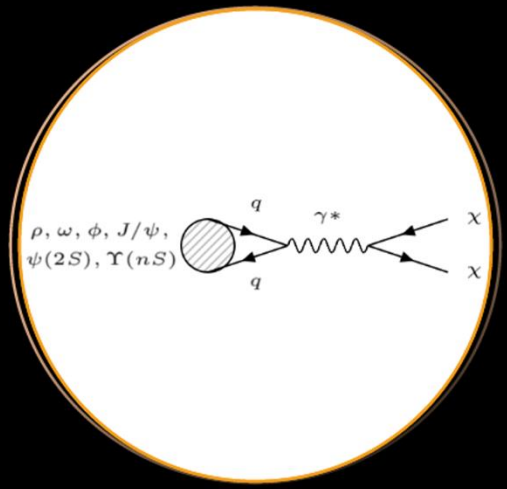
The Sweet Spot
arXiv:1511.01122



Via the Drell-Yan process

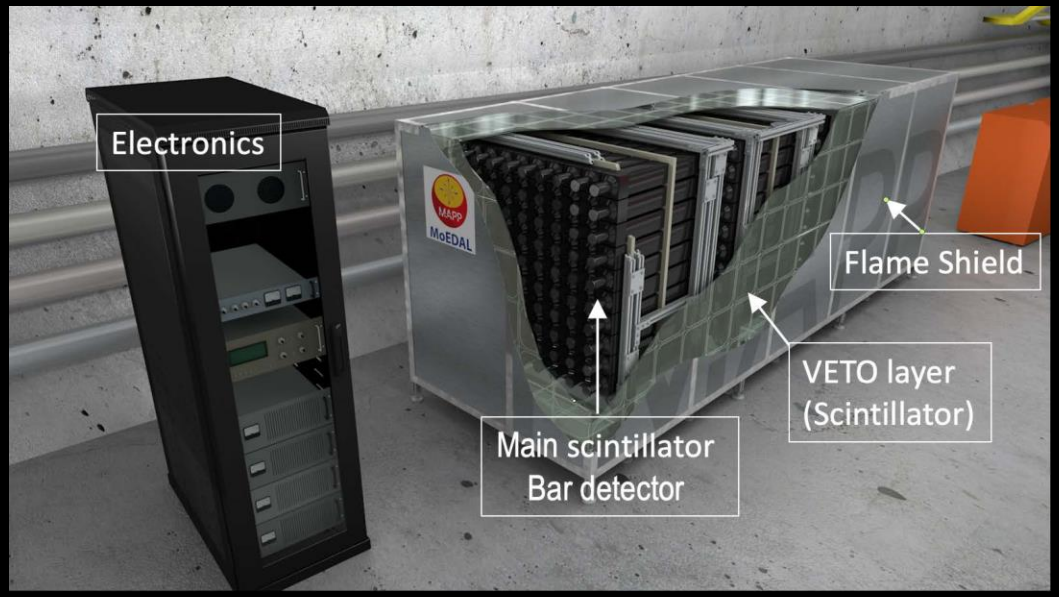


Via Dalitz decays of pseudoscalar mesons



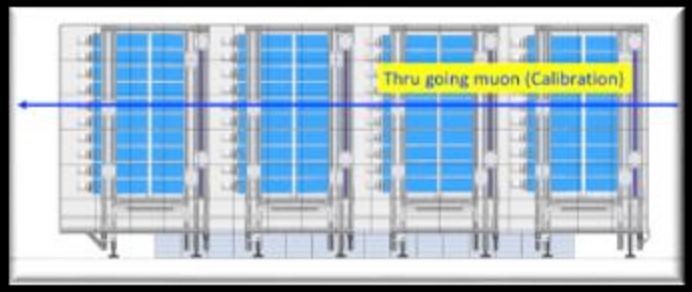
Via direct decays of vector mesons

MoEDAL's MAPP-1 Detector @ UA83

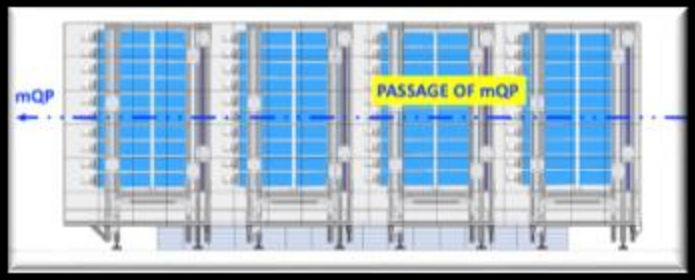


- *400 scintillator bars (10 x 10 x 75 cm^3) in 4 sections readout by 3" PMTs - Protected by a hermetic VETO counter system*
- *MAPP is sensitive to:*
  - *Milli-charged ($10^{-3}c$) particles*
  - *Long-lived neutral particles*
  - *Charged particles (using MoEDAl's MMTs)*
- *Latest paper: "Searching for minicharged particles at the energy frontier with the MoEDAL-MAPP experiment at the LHC", JHEP* 04 (2024) 137

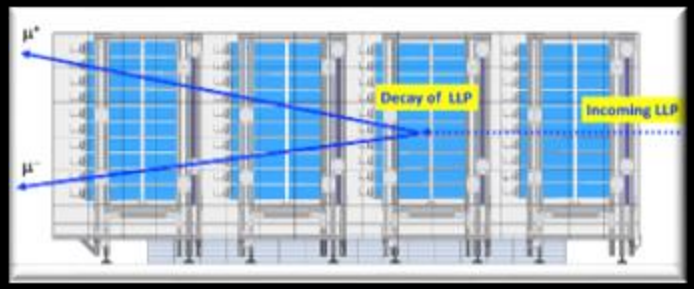
MAPP-1 – Modes of Detection



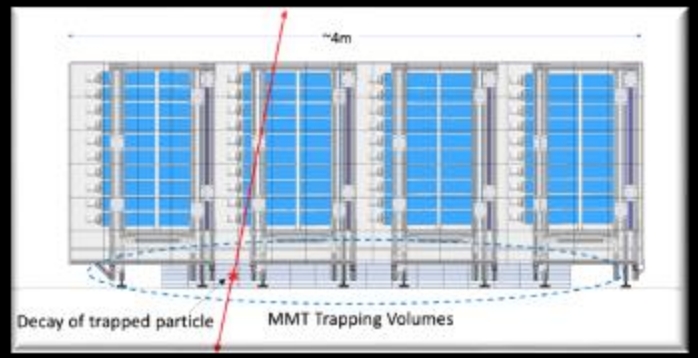
Muons from IP (Calibration)



Millicharged particle detection

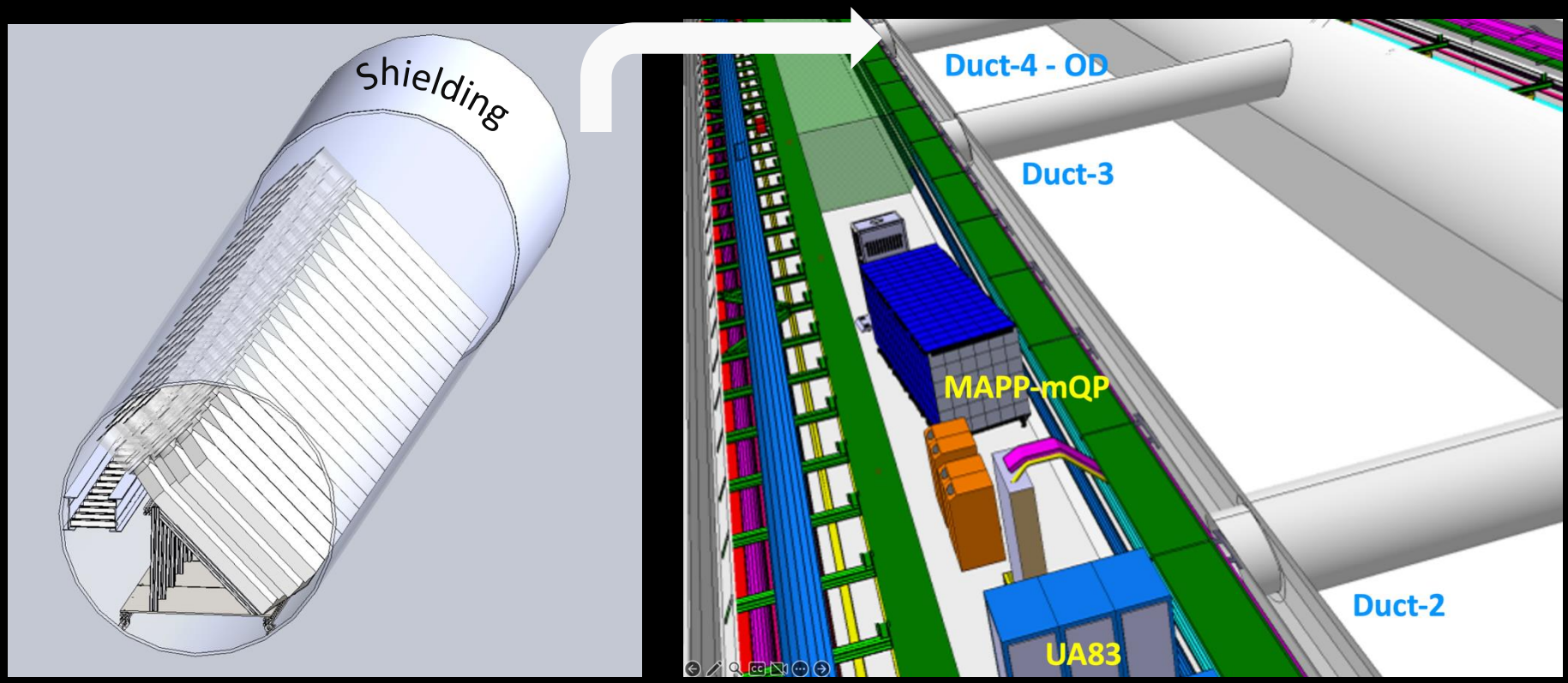


Neutral LLP Detection



Charged LLP Detection
(In conjunction with MoEDAL)

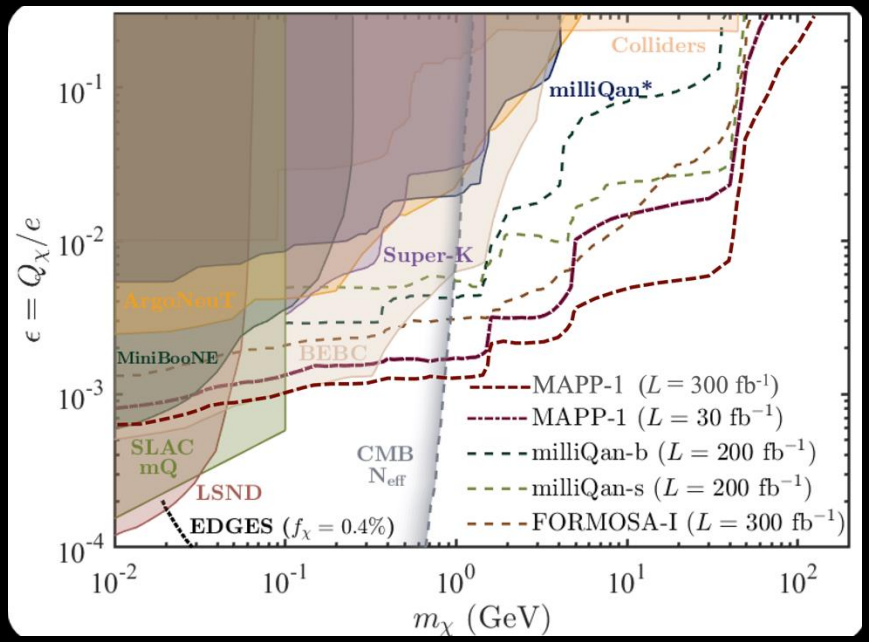
The MAPP-1 Outrigger

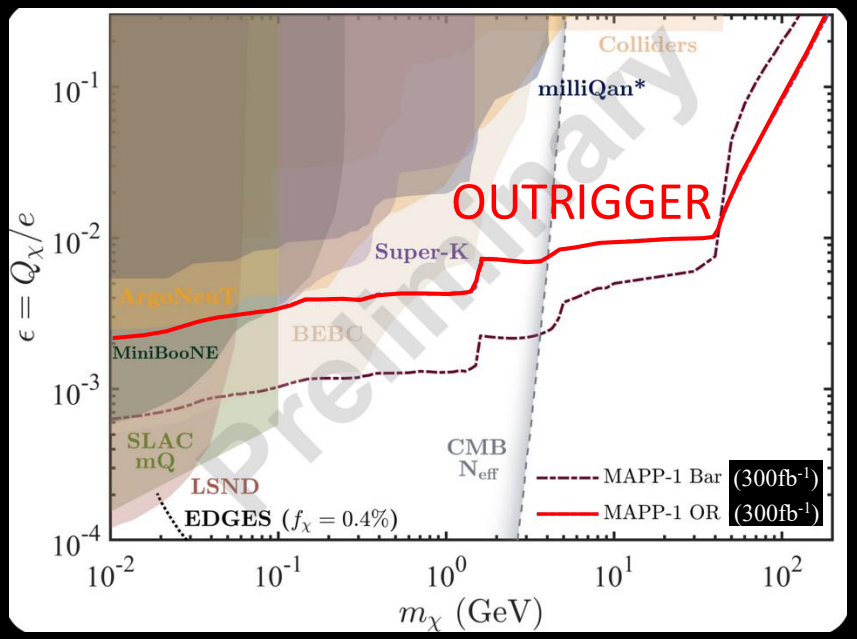


- *OUTRIGGER- A proposed extension of the MAPP bar detector to improve the overall reach for higher mass mCPs (above a few GeV)*
- *4 scintillator planes (each comprised of 20 60 cm x 30 cm x 5 cm sub-planes angled at 45 degrees) readout by coincident PMTs – an effective area of ~2.6m^2*
- *We expect this detector to be installed in 2025-26 year end technical stop.*

MAPP-1 Sensitivity to Millicharged Matter

milliQan results—Phys. Rev. D 104, 032002 (2021); FORMOSA results—Phys. Rev. D 104, 035014 (2021)

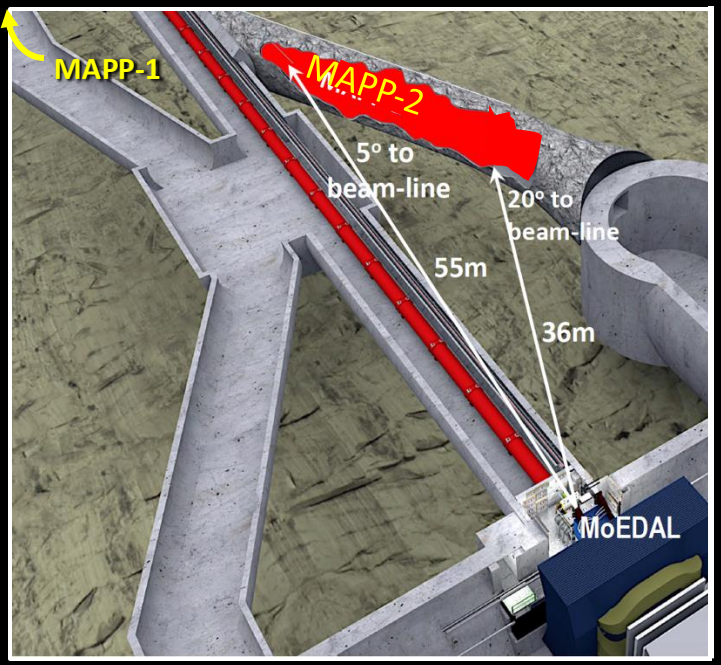


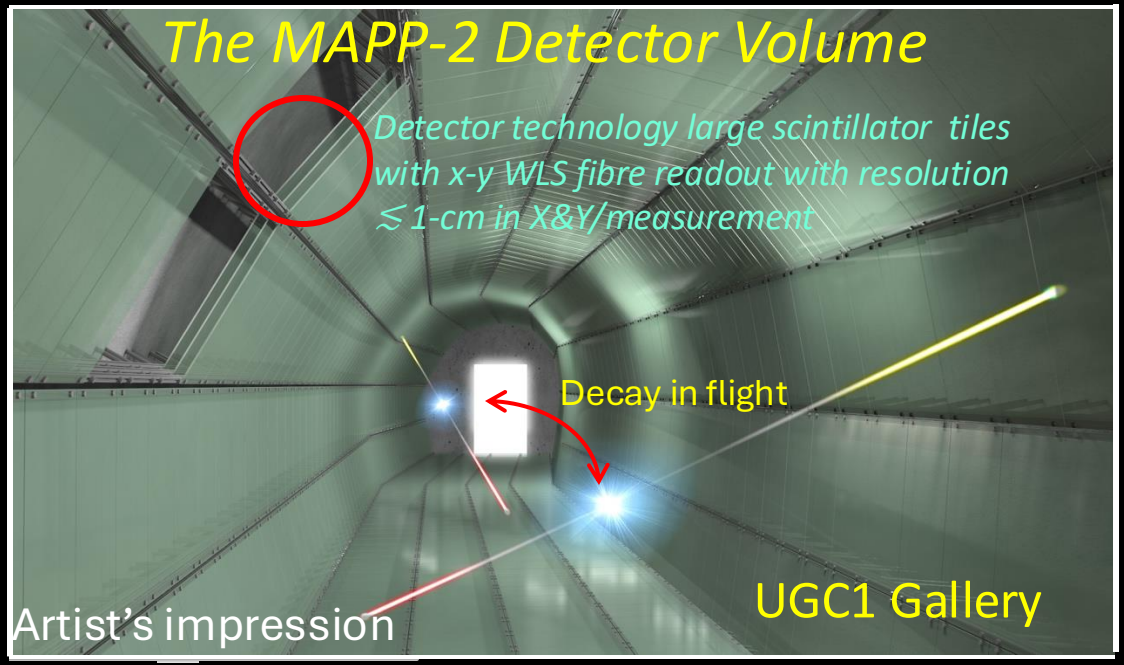


- *The 95% CL exclusion Limits for MAPP-1 for **mCPs produced by DY** mech. + direct decays of heavy quarkonia, light vector mesons, and single Dalitz decays of PS mesons.*
  - *Signal efficiency estimates included*
- *The OUTRIGGER improve the mass reach 130 GeV → 200 GeV*

The Future

Phase-2 → MAPP-2 for HL-LHC





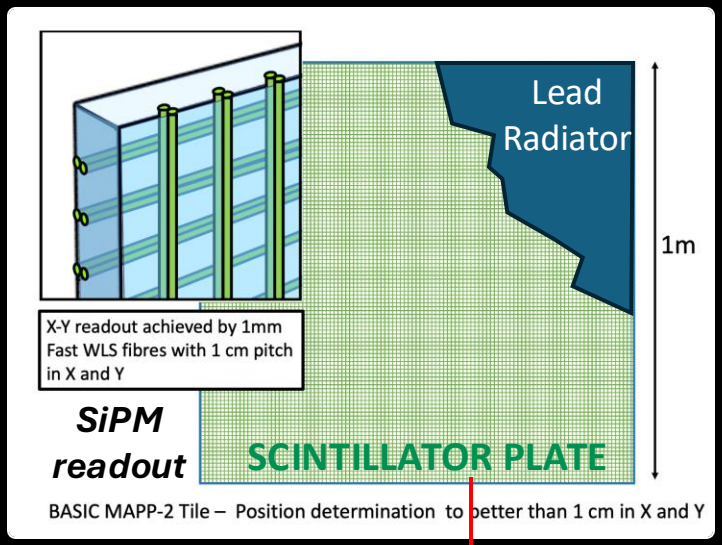
- *The MAPP-2 detector would fill the UGC1 gallery adjacent to LHCb*
  - *The UGC1 gallery would be prepared during LS3 prior to HL-LHC*
  - *The tracking detectors would form 3 hermetic containers - one within the other – lining the walls of UGC1*
- *MAPP-2 ~1200 m^3 of instrumented decay volume – estimated cost < 3M CHF*
- *Designed to detect Long-Lived particle decays to **charged particle & photons***

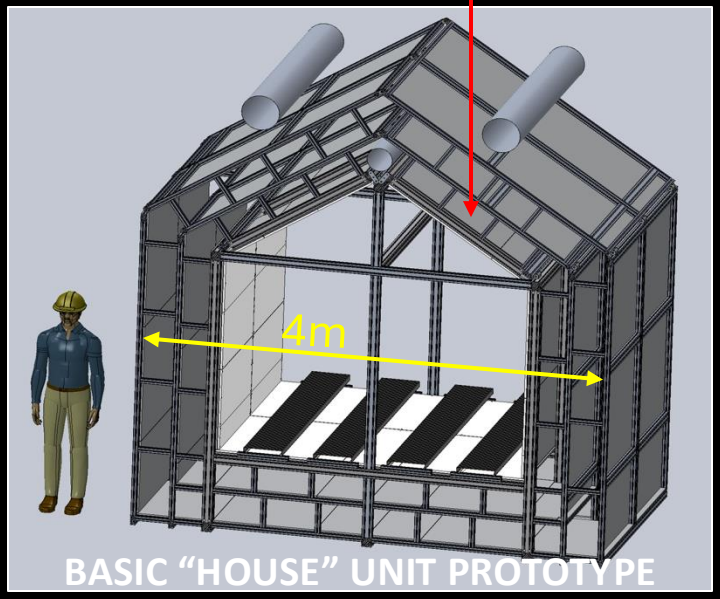
UGC1 Refurbishment

Safety Requirement	Cost	Cost + Contingency
Fire Detection	21,000 CHF	23,100 CHF (10 %)
Emergency Red phone	11,200 CHF	11,760 CHF (5 %)
Electrical Safety	48,200 CHF	53,000 (10 %)
~~Civil Engineering~~ LHCb paid	~~151,000 CHF~~	~~166,100 CHF (10 %)~~
HVAC	45,000 CHF	54,000 CHF (20%)
Access and work at height at UGC1	10,000 CHF	11,000 CHF (10 %)
Radiation Protection Patrol & Access System Requirement	45,000 CHF 4,500 CHF	49,500 CHF (10 %) Patrol System 4,725 CHF (5 %) Sector door
TOTAL	335,900 CHF	373,185 CHF

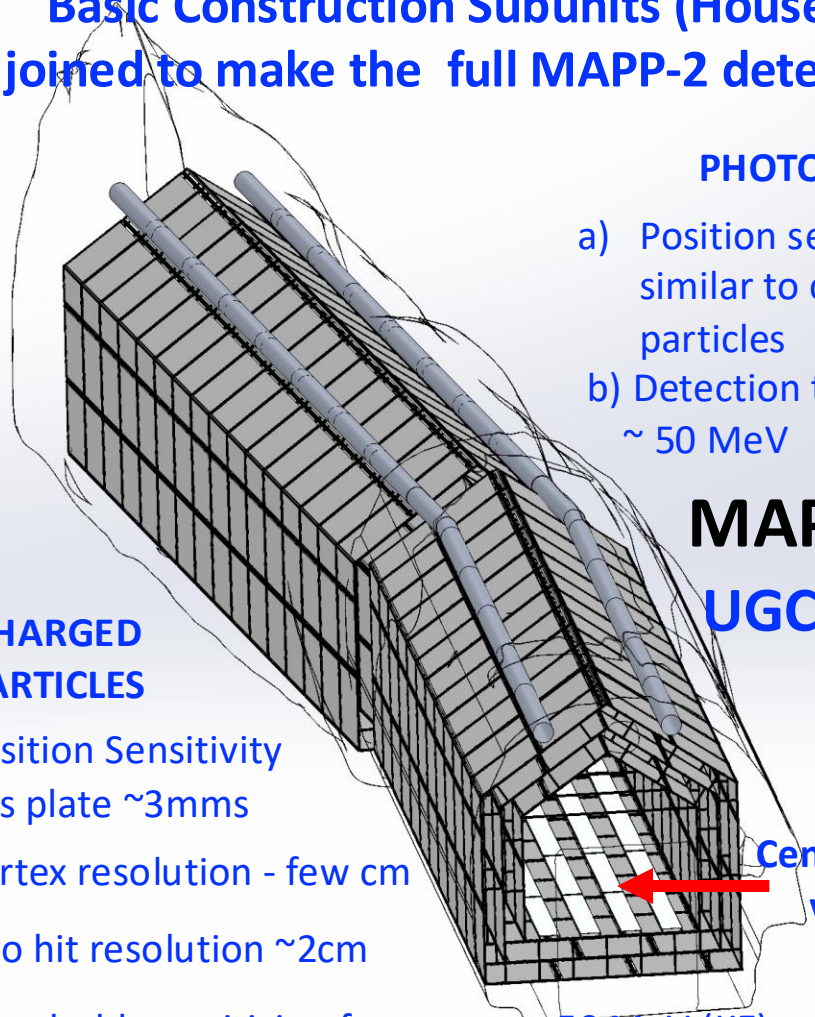
- *Civil work ~185K CHF*
- *MAPP-2 Detector cost 7M→8M CHF*
- *CFI-IF funding requested to start work available in 2026 (if successful)*
- *TP under construction (NoI given)*

Design of MAPP-2 Detector





Basic Construction Subunits (Houses) joined to make the full MAPP-2 detector



PHOTONS

a) Position sensitivity similar to charge particles

b) Detection threshold ~ 50 MeV

MAPP-2

UGC1

CHARGED PARTICLES

a) Position Sensitivity across plate ~3mms

b) Vertex resolution - few cm

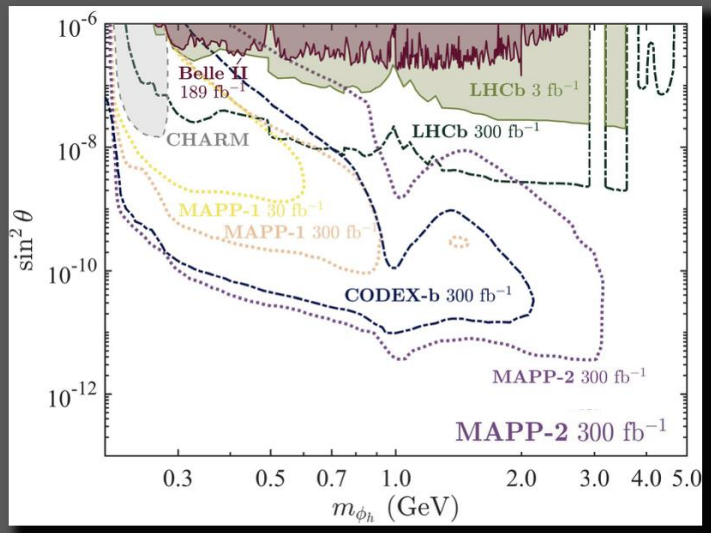
c) Two hit resolution ~2cm

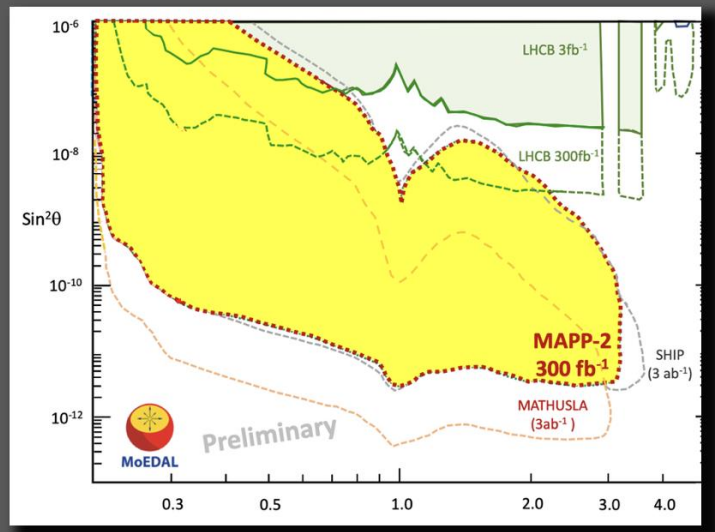
d) Threshold sensitivity for muons ~ 50 MeV (KE)

Central decay volume

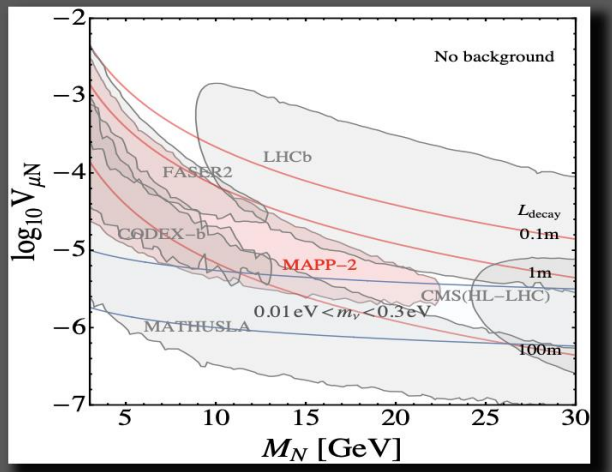
MAPP-2 Detector technology similar to that used for muon tomography

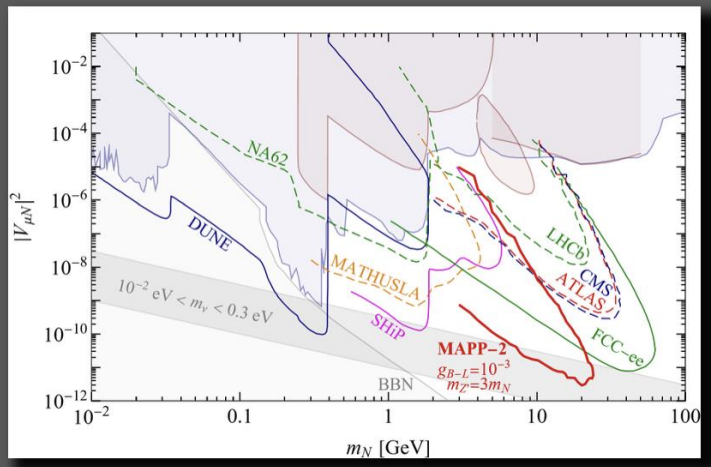
MAPP-2 – Sensitivity Benchmarks





The Higgs mixing portal admits inclusive B → $X_s\phi$ decays, where φ is a light CP-even scalar that mixes with the Higgs, with mixing angle $\vartheta \ll 1$. See PRD97 (1) (2018) 15023.





*Pair production of right-handed neutrinos from the decay of an additional neutral Z^0 boson in the gauged **B-L** model – Phys. Rev. D100 (2019), 035005.*

Final Words

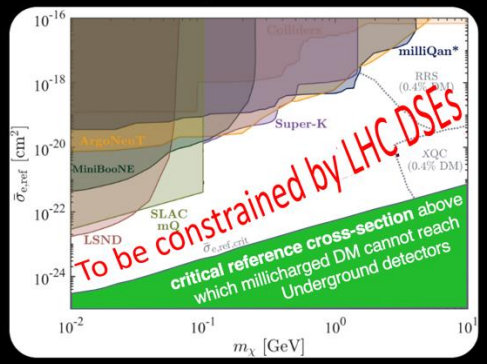
"New directions in science are launched by new tools much more often than by new concepts." Freeman Dyson

- ***MoEDAL-MAPP pioneered the use of Dedicated Search Detectors at the LHC. These detectors are the new tools now being used to reveal physics beyond the SM at the LHC and beyond***
- ***WE ALWAYS NEED NEW COLLABORATORS – IF YOU ARE INTERESTED, PLEASE contact jpinfold@ualberta.ca***

EXTRA SLIDES

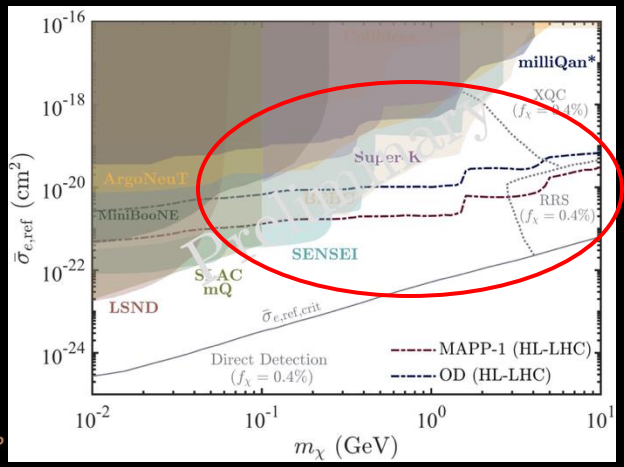
MAPP & OD Expected reach: Millicharged Strongly Interacting DM

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)



- *In 2018, the EDGES Expt. reported the detection of an anomaly in the 21-cm H absorption spectrum indicating more absorption than expected. For this, either cooling of the H gas or radiative heating of the CMB is necessary.*
  - *A resolution of the anomaly involves introducing a small mini-charged component of DM, feebly interacting with H gas thru Coulomb interactions, leading to its cooling*
  - *One group (PRD 98 103529, 2018) suggested that 0.4% fraction of DM composed of mCPs would be sufficient to solve the problem as well as cosmologically allowed*
  - *MAPP-1 can help solve this problem from cross-section above σ_{crit}*