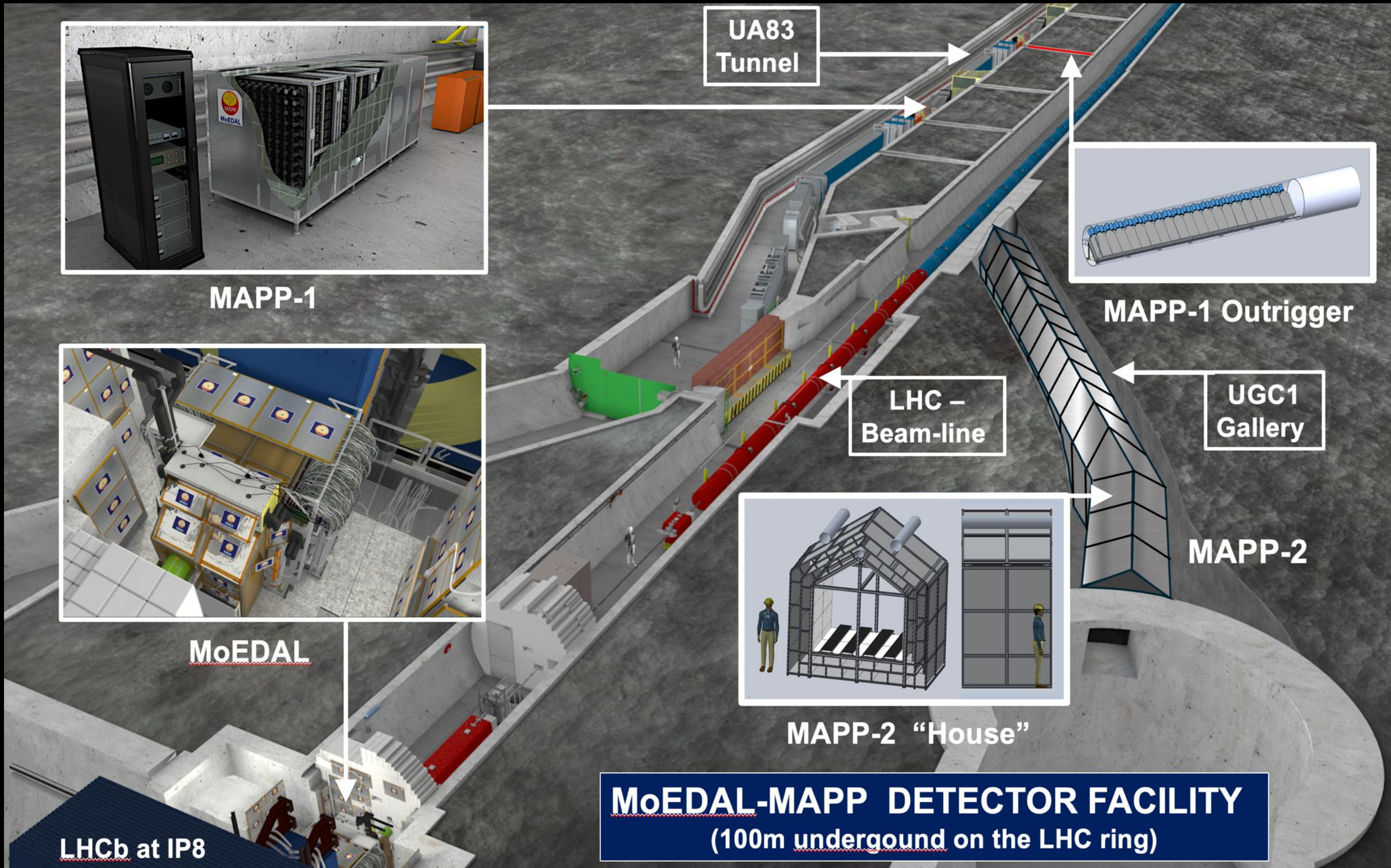
The MoEDAL-MAPP Facility at the LHC

Presentation to the PBC BSM/FPC

James L Pinfold
for the MoEDAL-MAPP Collaboration

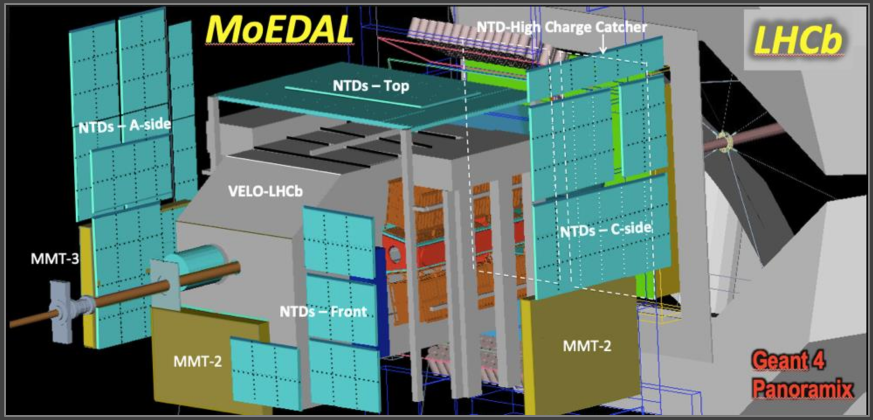
MoEDAL-MAPP a >24 Year Project



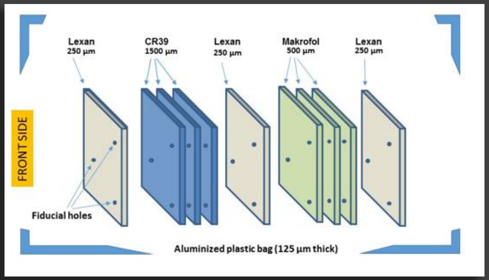
Pseudorapidity Distribution

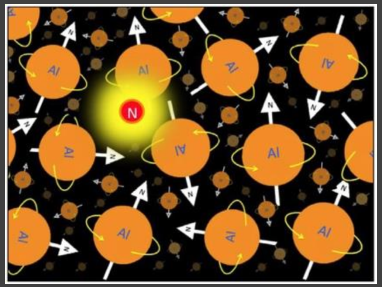
The Phase-0 MoEDAL Detector

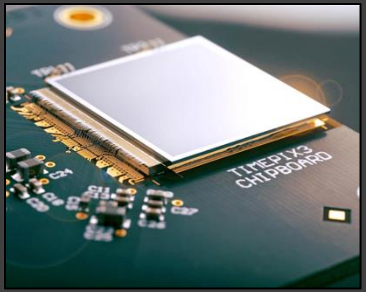
LHC's 1st dedicated search expt. –upgraded for Run-3 with higher eff. & lower thresholds



Searching for 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

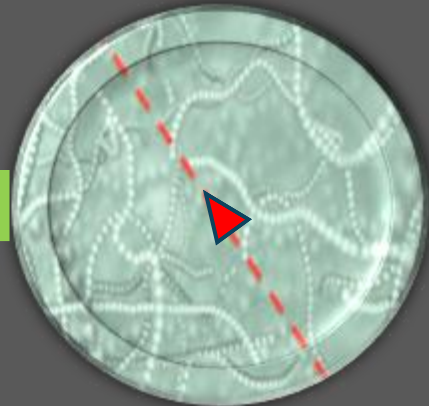
PERMANENT RECORD

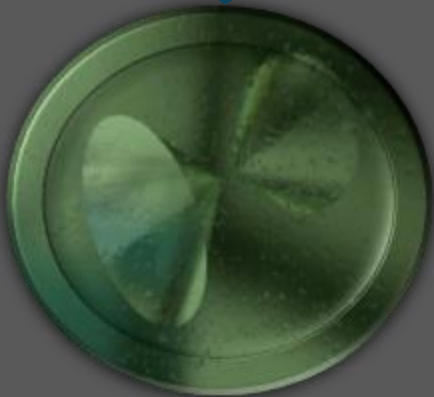
MoEDAL's Remote Detector Facilities

NTD Processing - INFN Bologna

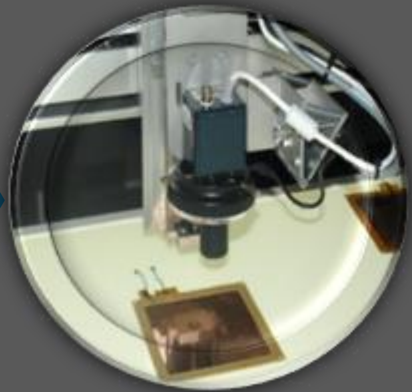
Etching in hot sodium Hydroxide reveals damage

HIP causes damage Zone In NTD plastic





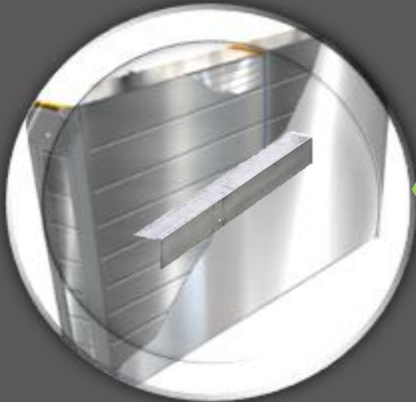
Etch pits reveal path and charge of HIP



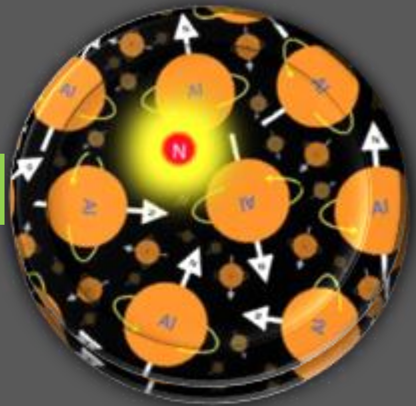
Etch pits measured by optical microscope

MMT Scanning- ETH Zurich

Trapping volumes are Removed for scanning



Monopole is trapped



Trapping volumes are Passed through a SQUID

Monopoles cause a stable current in the SQUID

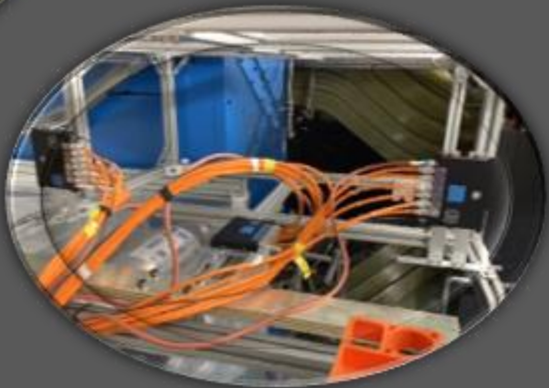
Upgraded MoEDAL Installed for Run-3

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

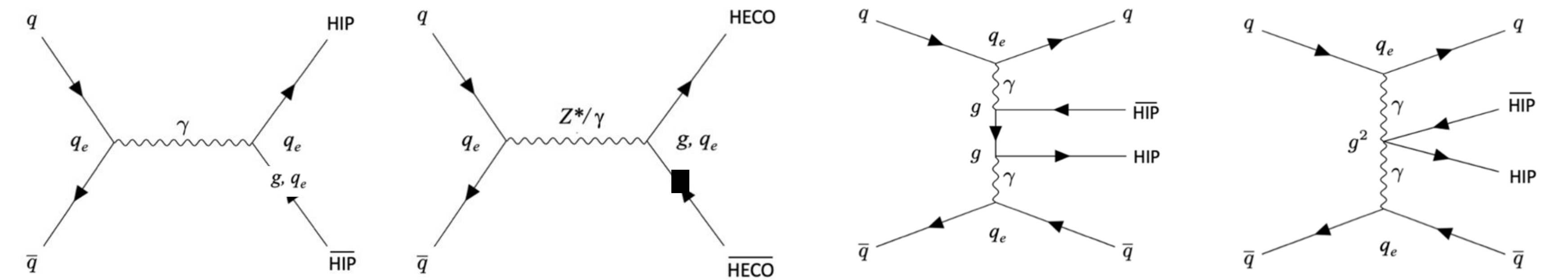


TimePix3 Chips connected to LHC clock

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

Results from HIP Search - DY production



(a) DY production of spin 0, ½, 1 HIPs
(b) DY production of spin ½ HECOs
(c) Four-vertex PF process
(d) Three-vertex PF process

ATLAS

	95% CL lower limits on the mass of HIPs [TeV]						
	$\lvert g\rvert = 1g_D$	$\lvert g\rvert = 2g_D$	$\lvert z\rvert = 20$	$\lvert z\rvert = 40$	$\lvert z\rvert = 60$	$\lvert z\rvert = 80$	$\lvert z\rvert = 100$
DY spin-0	2.1	2.1	1.4	1.8	1.9	1.8	1.7
DY spin-½	2.6	2.5	1.8	2.2	2.2	2.1	1.9
PF spin-0	3.4	3.5	2.1	2.8	2.9	2.8	2.5
PF spin-½	3.6	3.7	2.5	3.1	3.1	3.0	2.5

MOEDAL

TABLE I. 95% CL mass limits for the magnetic monopole search.

Spin	Process	Magnetic charge (g_D) 1	2	3	4	5	6	7	8	9	10
		95% CL mass limits (GeV)									
0	DY	1450	1660	1730	1680	1590	1510	1380	1210	980	790
1/2	DY	2070	2300	2370	2360	2300	2200	2030	1810	1470	1040
1	DY	2180	2410	2510	2520	2460	2370	2240	2090	1870	1550
0	$\gamma\gamma$	3010	3510	3700	3730	3680	3550	3370	3000	2000	–
1/2	$\gamma\gamma$	3240	3730	3920	3940	3880	3800	3590	3000	2500	–
1	$\gamma\gamma$	3650	4100	4220	4230	4170	4080	3960	3500	3000	2000

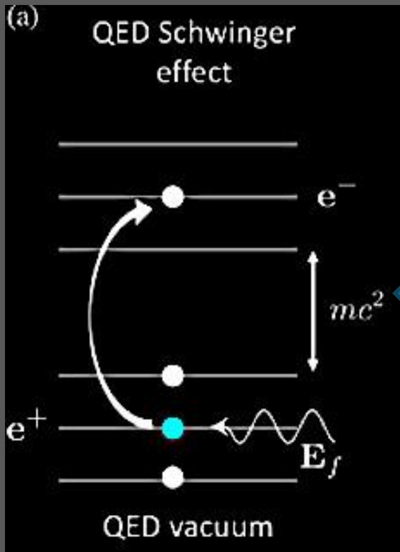
TABLE II. 95% CL mass limits for the HECO search.

Spin	Process/ exchange	Electric charge (e) 10	15	20	25	50	75	100	125	150	175	200	225	250	275	300	325	350	375	400
		95% CL mass limits (GeV)																		
0	DY γ	80	220	400	580	1300	1390	1420	1430	1430	1410	1390	1370	1340	1290	1210	1070	900	500	-
1/2	DY γ	290	620	920	1190	1850	1940	1980	2000	2000	1980	1940	1900	1830	1740	1610	1380	1000	200	-
1/2	DY γ/Z^*	320	620	930	1170	1840	1930	1970	1990	1980	1970	1940	1900	1840	1740	1620	-	-	-	-
1	DY γ	330	640	960	1240	2020	2120	2170	2180	2180	2170	2140	2100	2060	1980	1850	1620	1000	100	-
0	$\gamma\gamma$	300	740	1140	1500	2720	3020	3170	3260	3310	3320	3310	3240	3160	3000	2500	2000	1500	1500	-
1/2	$\gamma\gamma$	410	950	1380	1800	3000	3250	3390	3480	3520	3530	3500	3440	3000	3000	2500	2000	1500	1500	1500
1	$\gamma\gamma$	790	1400	1880	2310	3400	3640	3770	3850	3890	3890	3850	3730	3000	3000	2500	2000	1500	1500	-

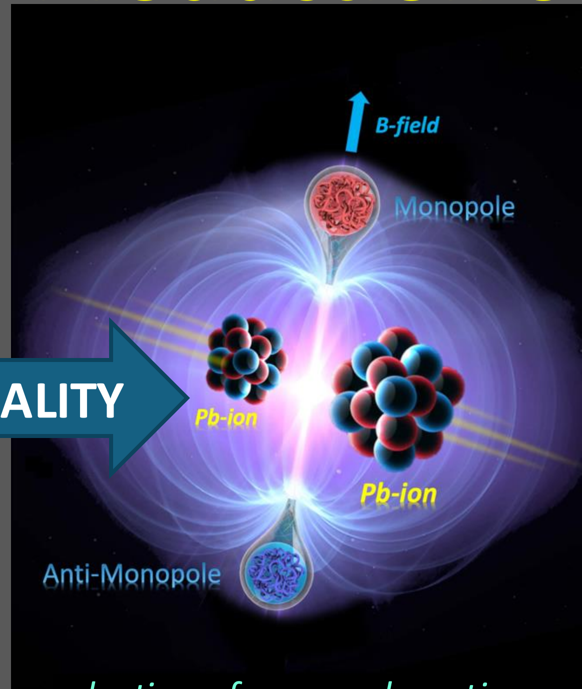
- *MoEDAL presented to the 1st Photon-Photon fusion results at the LHC has the World's best limits (MoEDAL e-Print: 2311.06509 [hep-ex]....to be published in PRL) on :*
  - *Magnetic Charge > 1 g_d*
  - *Electric charge 10e < Q < 20e & 50e < Q ≤ 400e*

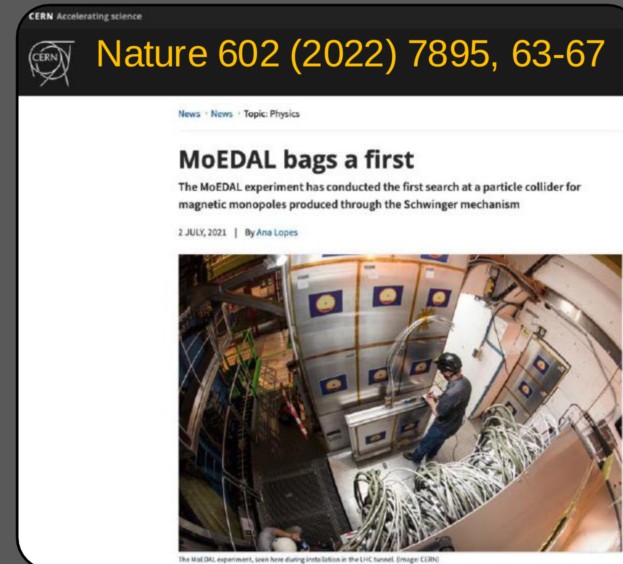
Schwinger Production of Monopole Pairs

MoEDAL



DUALITY





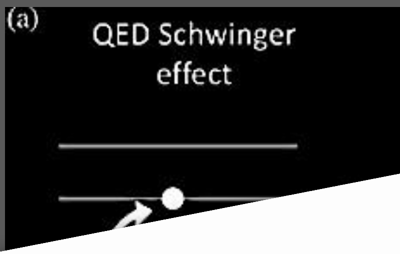
Pair production of electron-positron pairs in a very strong electric field

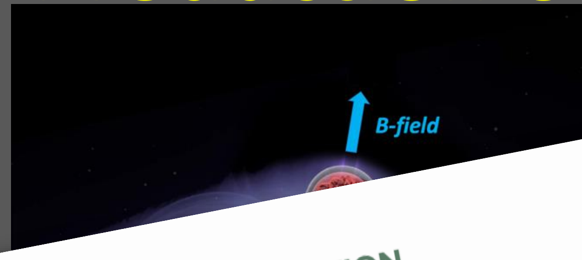
Pair production of monopole-antimonopole pairs in a very strong magnetic field created in ultraperipheral "collisions" of Pb-ions at the LHC can be as much as 10^{16}T.

- ***Limits on Schwinger monopoles of 1 – 3 g_D and masses up to 75 GeV***
- *Advantages of Schwinger monopole production:*
  - *X-section calculation does not suffer from perturbative nature of coupling;*
  - *No exponential suppression for finite-sized monopoles.*

1st time finite sized monopoles detectable?

Schwinger Production of Monopole Pairs





Pair pr... field
pairs in... T.

EDITORS' SUGGESTION

MoEDAL Search in the CMS Beam Pipe for Magnetic Monopoles Produced via the Schwinger Effect

A search for the magnetic monopoles that carry 2 to 45 Dirac units of magnetic charge that could have been produced by heavy-ion collisions places world-leading limits on the monopole masses.

B. Acharya *et al.*
Phys. Rev. Lett. **133**, 071803 (2024)

- ***Lin...***
- *Adv...*
  - *X-... suffer from pe... nature of coupling;*
  - *No exponential suppression for finite-sized monopoles.*

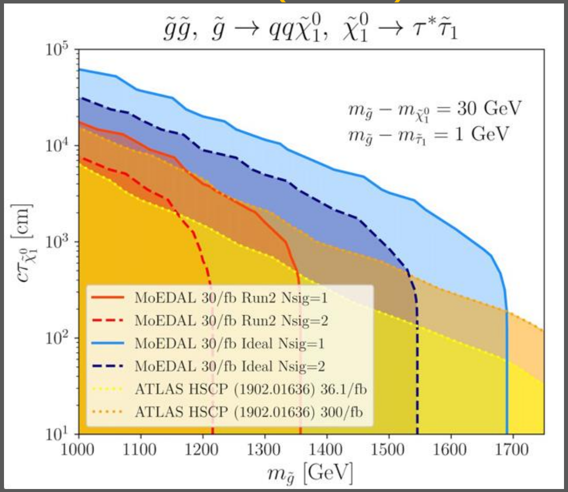
Nature 602 (2022) 7895, 63-67 (Run-1)

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

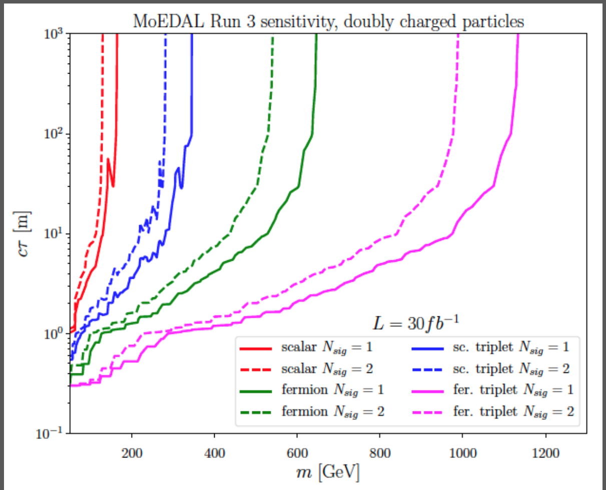
EPJC 80 (2020) 431



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

SLEPTONS

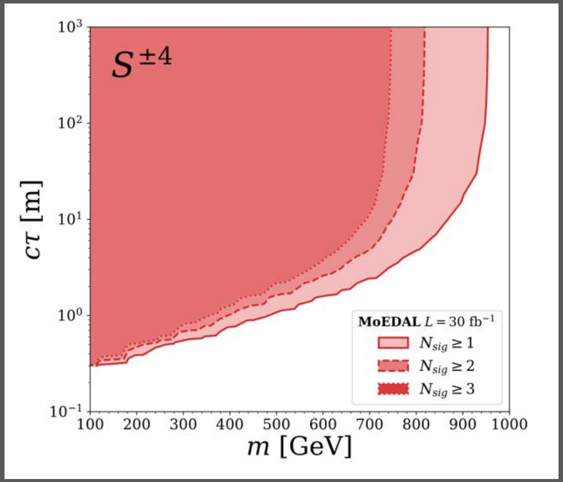
EPJC 80 (2020) 572



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

DOUBLY CHARGED

EPJC 81 (2021) 697

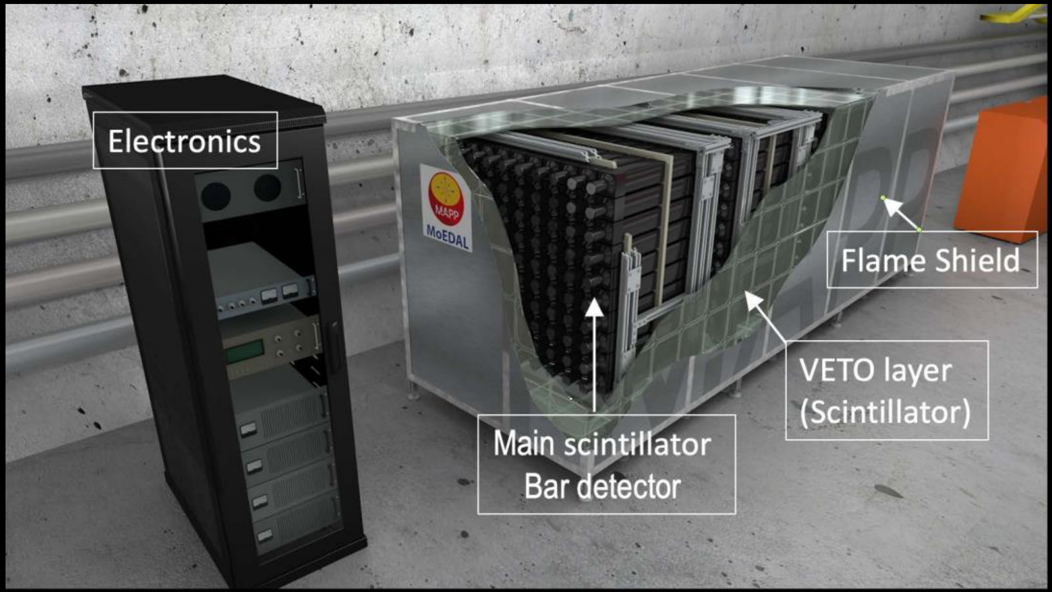


In this class of neutrino mass models, the SM is extended with two scalar fields, and 3 pairs of vector-like fermions.

2,3 and 4 CHARGED

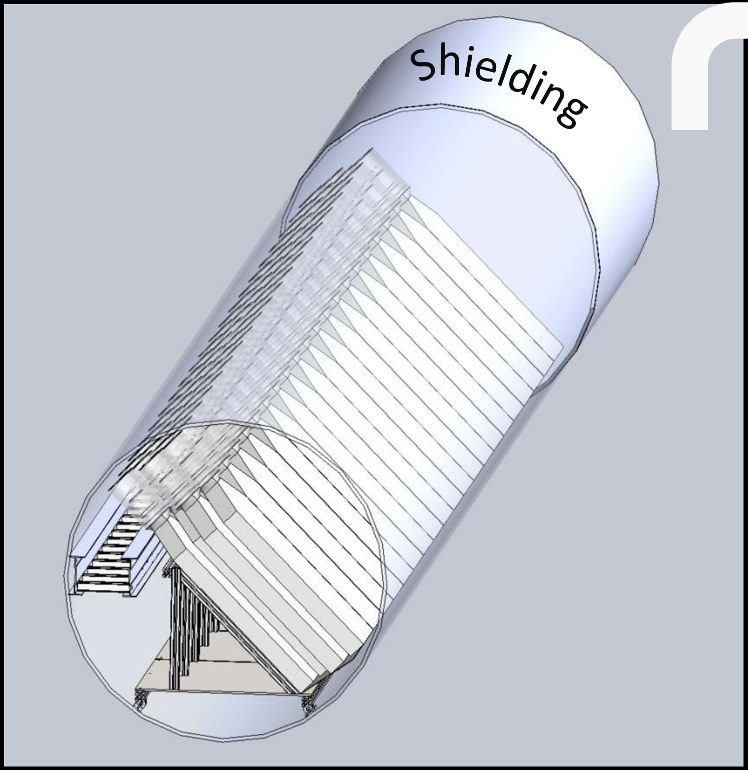
- *If sufficiently slow moving, even singly or multiply ($\lesssim$10e) charged particles may leave a track in NTDs*
- *Supersymmetry offers such long-lived states: sleptons, R-hadrons, charginos*
- *Multiply charged scalars or fermions are, for example, predicted in several neutrino mass models.*

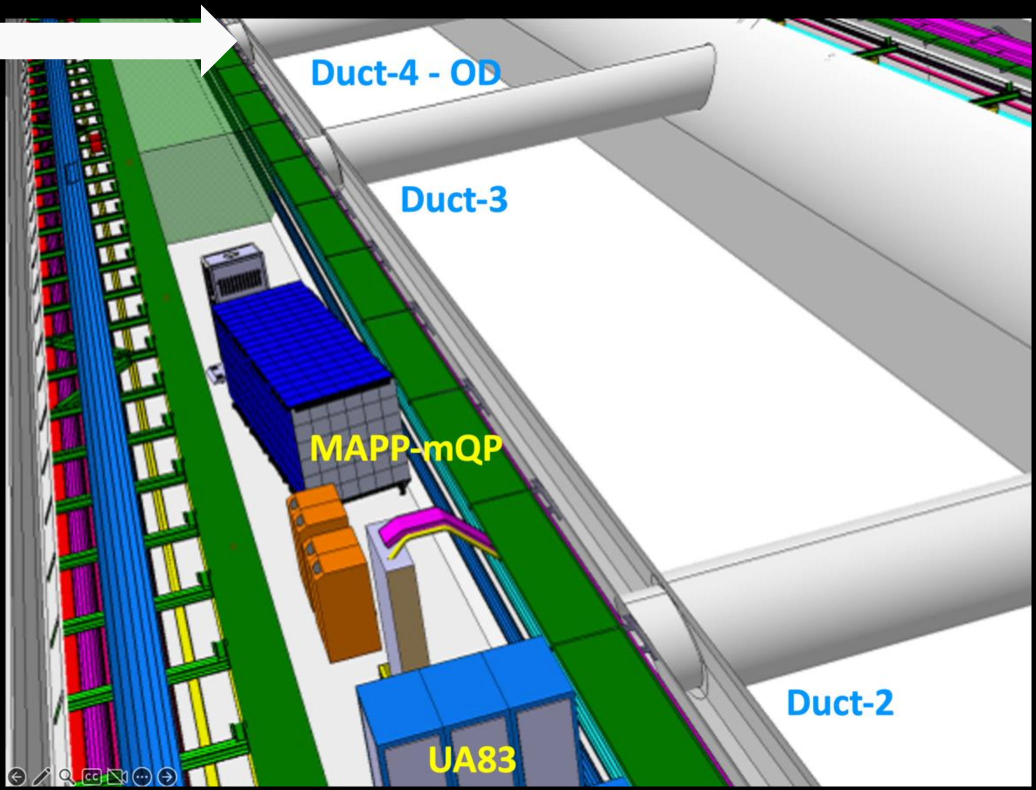
MoEDAL's MAPP-1 Detector @ UA83



- *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-1 is currently being installed. MAPP-1 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

The MAPP-1 Outrigger

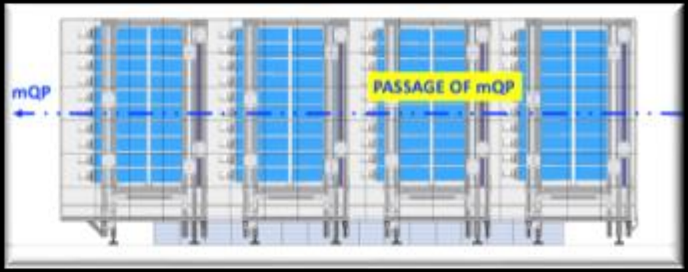




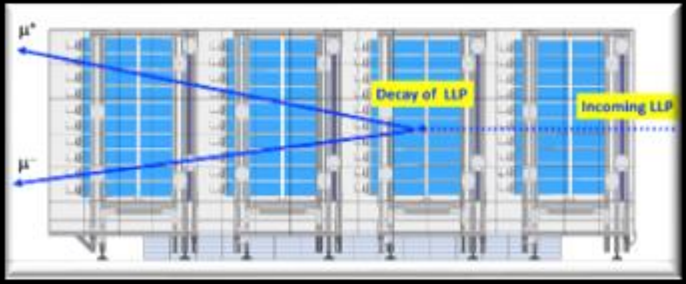
- *OUTRIGGER- A proposed extension of the MAPP bar detector to improve the overall reach for higher mass mCPs (above a few GeV)*
- *4 scintillator planes (each comprised of 20 60 cm x 30 cm x 5 cm sub-planes angled at 45 degrees) readout by coincident PMTs – an effective area of ~2.6m^2*

MAPP-1 – Modes of Detection

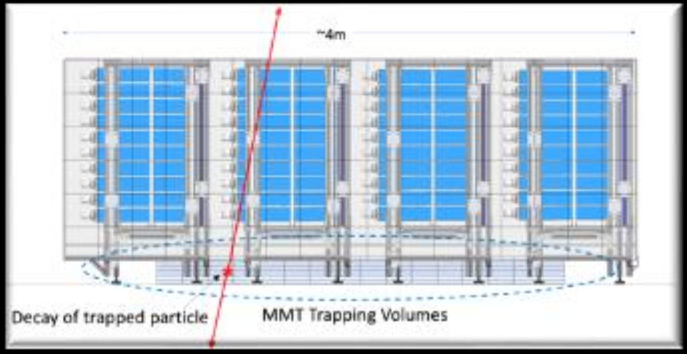
Muons from IP (Calibration)



Millicharged particle detection

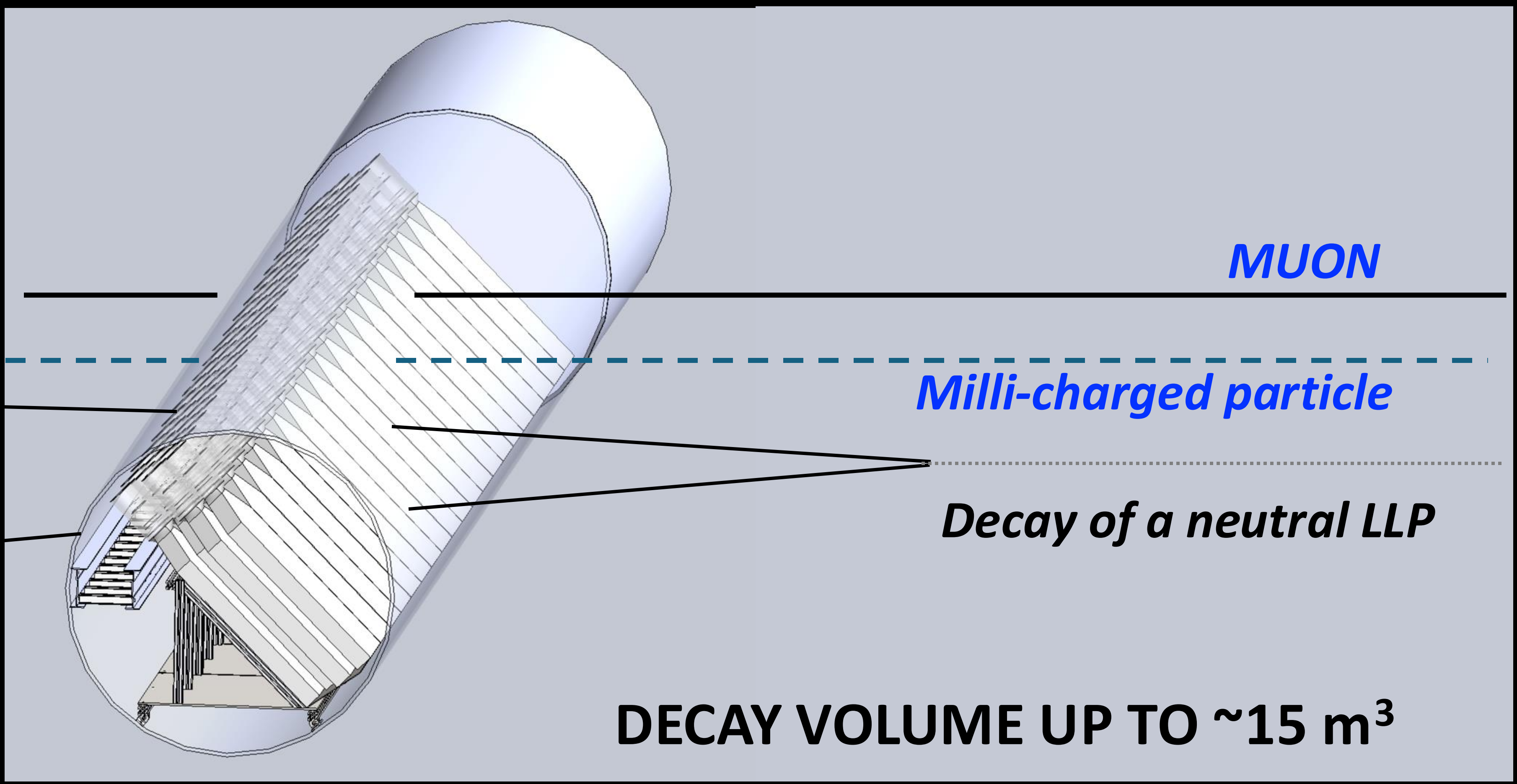


Neutral LLP Detection



Charged LLP Detection
(In conjunction with MoEDAL)

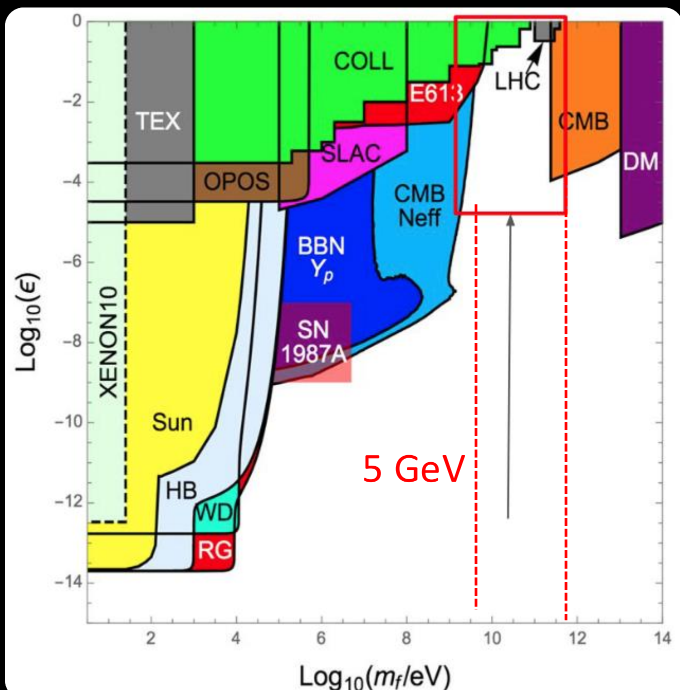
OUTRIGGER – Modes of Detection



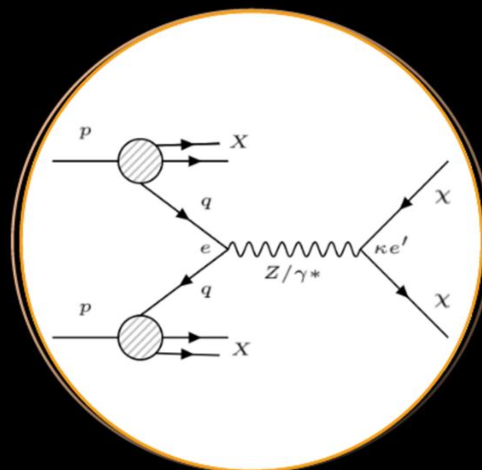
***OUTRIGGER** (embedded in 8m thick concrete wall between UA83 and the beam tunnel.*

Production of Milli-charged at Colliders

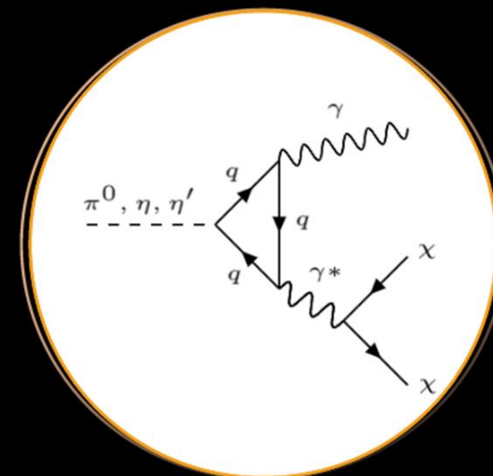
mCPs arise naturally from the dark sector via the Vector Portal/Dark Photon



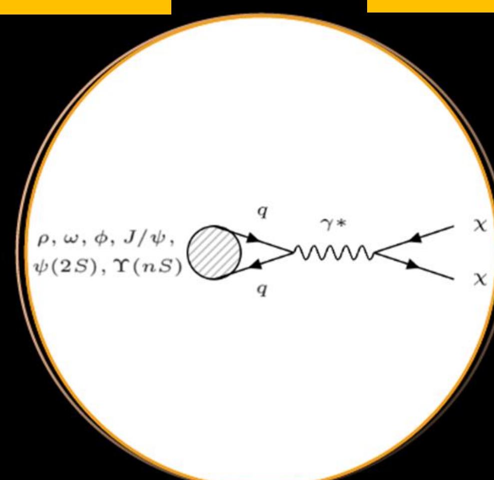
The Sweet Spot
arXiv:1511.01122



DRELL-YAN



DALITZ DECAYS

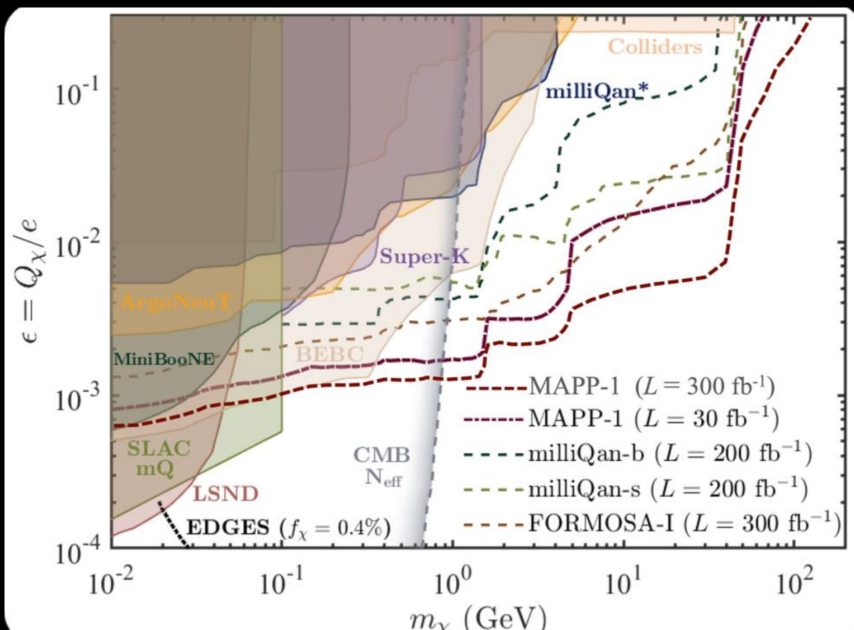


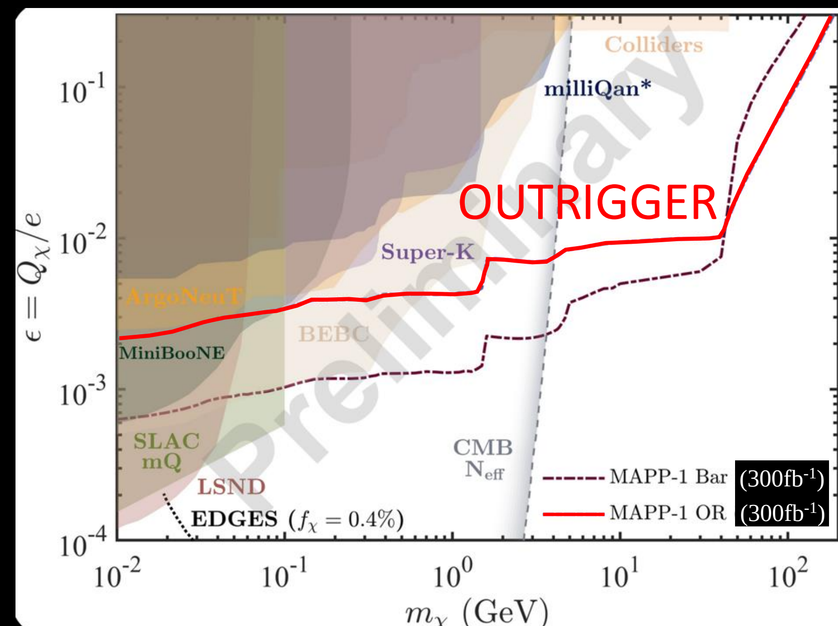
DIRECT DECAYS

MAPP-1 Sensitivity to Millicharged Matter

MoEDAL

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



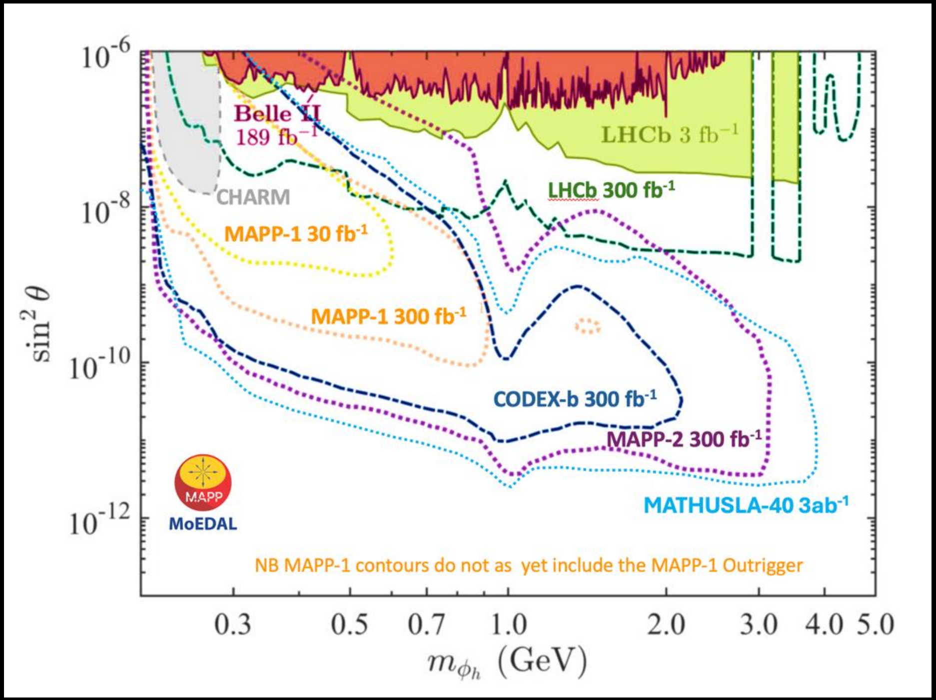


- *The 95% CL exclusion Limits for MAPP-1 for **mCPs produced by DY** mech. + direct decays of heavy quarkonia, light vector mesons, and single Dalitz decays of PS mesons.*
  - *Signal efficiency estimates included*
- *The OUTRIGGER improve the mass reach 130 GeV → 200 GeV*

Increasing Experimental Sensitivity

- *The sensitivity limit of existing experiments at the LHC is ~10^{-3}e set by the light output of regular plastic scintillator (BC408) of ~10K photons/MeV*
- *We could improve sensitivity by using use higher light output scintillators:*
  - ***LANTHANUM BROMIDE** [$LaBr_3$(Ce)]: light output 30K ph/MeV, decay time 20ns. CONS: it has internal activity, currently available in size up to 3" dia. X 3" lng*
  - *For **$CeBr_3$ (cerium bromide)**, the light output is typically high compared to other scintillator materials. The number of photons emitted per MeV of energy deposited in $CeBr_3$ is approximately **40,000 to 50,000 photons per MeV**.*
  - ***SCINTCLEAR™ (SrI_2(Eu))** has an **exceptionally high light yield**, typically around **50,000–60,000 photons per MeV**, which is significantly higher than other common scintillators like **NaI(Tl)** and **$LaBr_3$(Ce)**.*
  - ***Liquid noble gases** also have high scintillation light output than plastic, but WLS is needed to match the sensitivity of currently available PMTs*
- *We are looking at inorganic scintillators to allow us to reduce the "threshold" of detection for mili-charge particle from ~ 10^{-3}e to ~10^{-4} e*

Using MAPP-1 to Search for LLPs

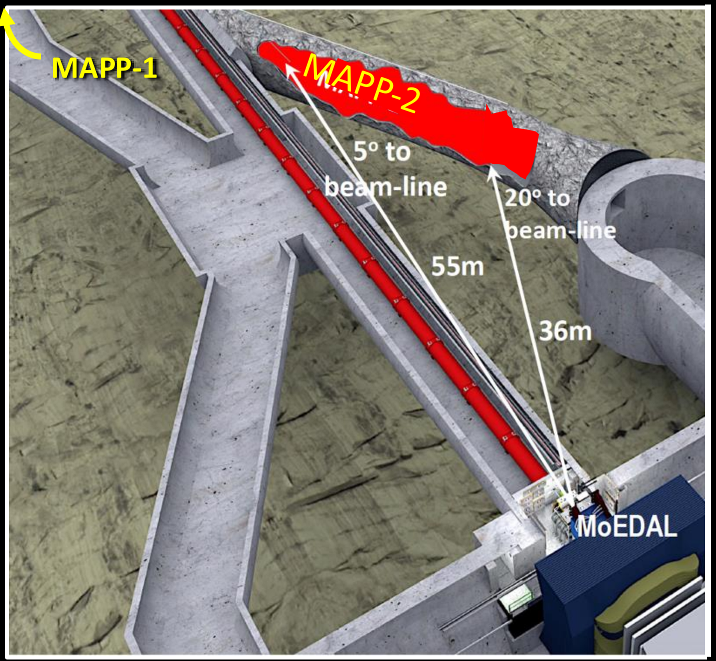


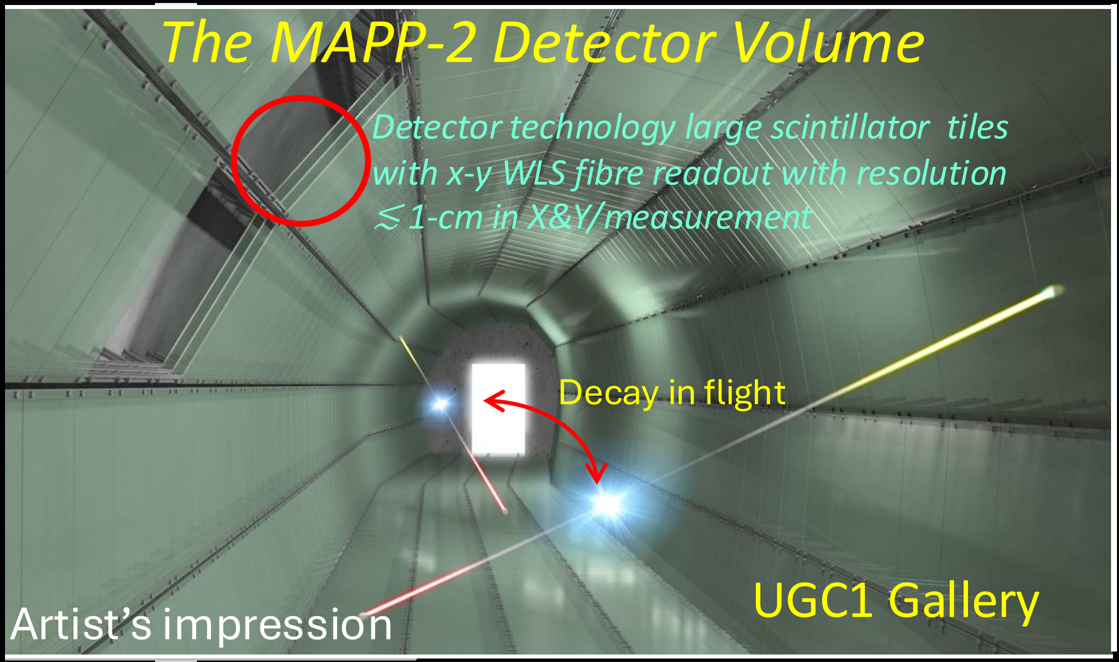
The Higgs mixing portal admits inclusive $B \to X_s\phi$ decays, where φ is a light CP-even scalar that mixes with the Higgs, with mixing angle $\vartheta \ll 1$. See PRD97 (1) (2018) 15023.

- *MAPP-1 + Outrigger has a combined fiducial decay volume of $4m^3$ (MAPP-1) + up to $15m^3$ (Outrigger)*
  - *CODEX-b (10^3 m^3) → CODEX-β ($8m^3$) for Run-3 a >100 reduction in decay volume.*
- *Thus, MAPP-1 + Outrigger is competitive as an LLP search detector until Run-4!*
  - *We envisage MAPP-2 takes over the LLP search starting Run-4*

The Future

Phase-2 → MAPP-2 for HL-LHC





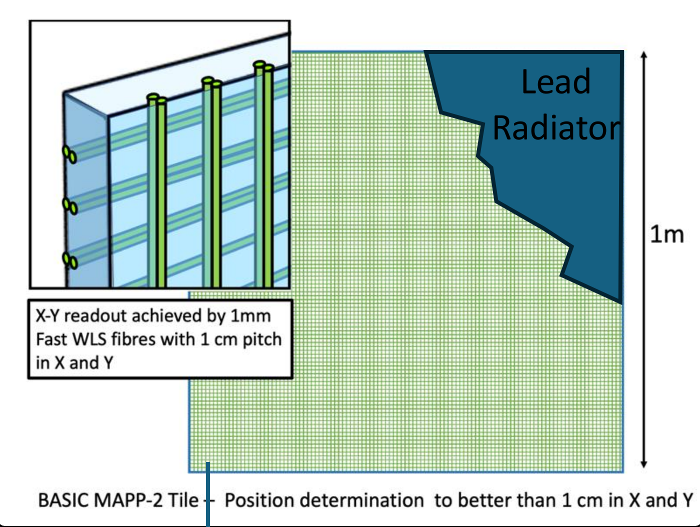
- *The MAPP-2 detector would fill the UGC1 gallery adjacent to LHCb*
  - *The UGC1 gallery would be prepared during LS3 prior to HL-LHC*
  - *The tracking detectors would form 3 or 4 hermetic containers - one within the other – lining the walls of UGC1*
- *MAPP-2 ~1200 m^3 of instrumented decay volume – estimated cost < 3M CHF*
- *Designed to detect Long-Lived particle decays to **charged particle & photons***

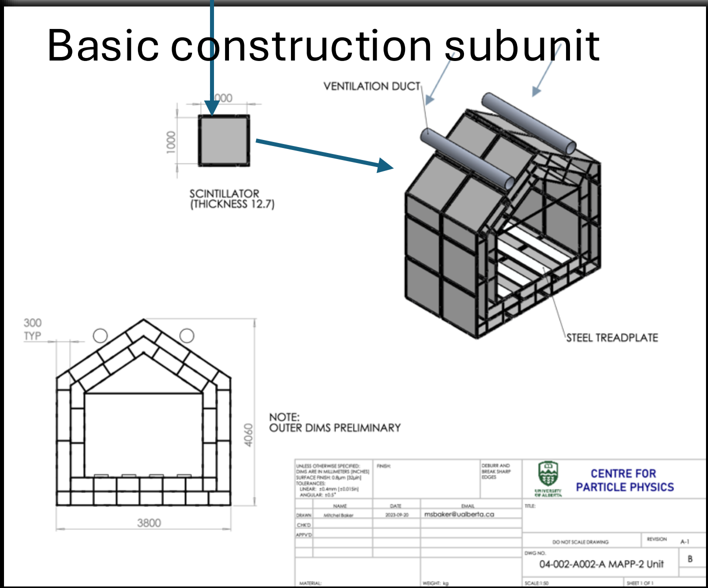
UGC1 Refurbishment

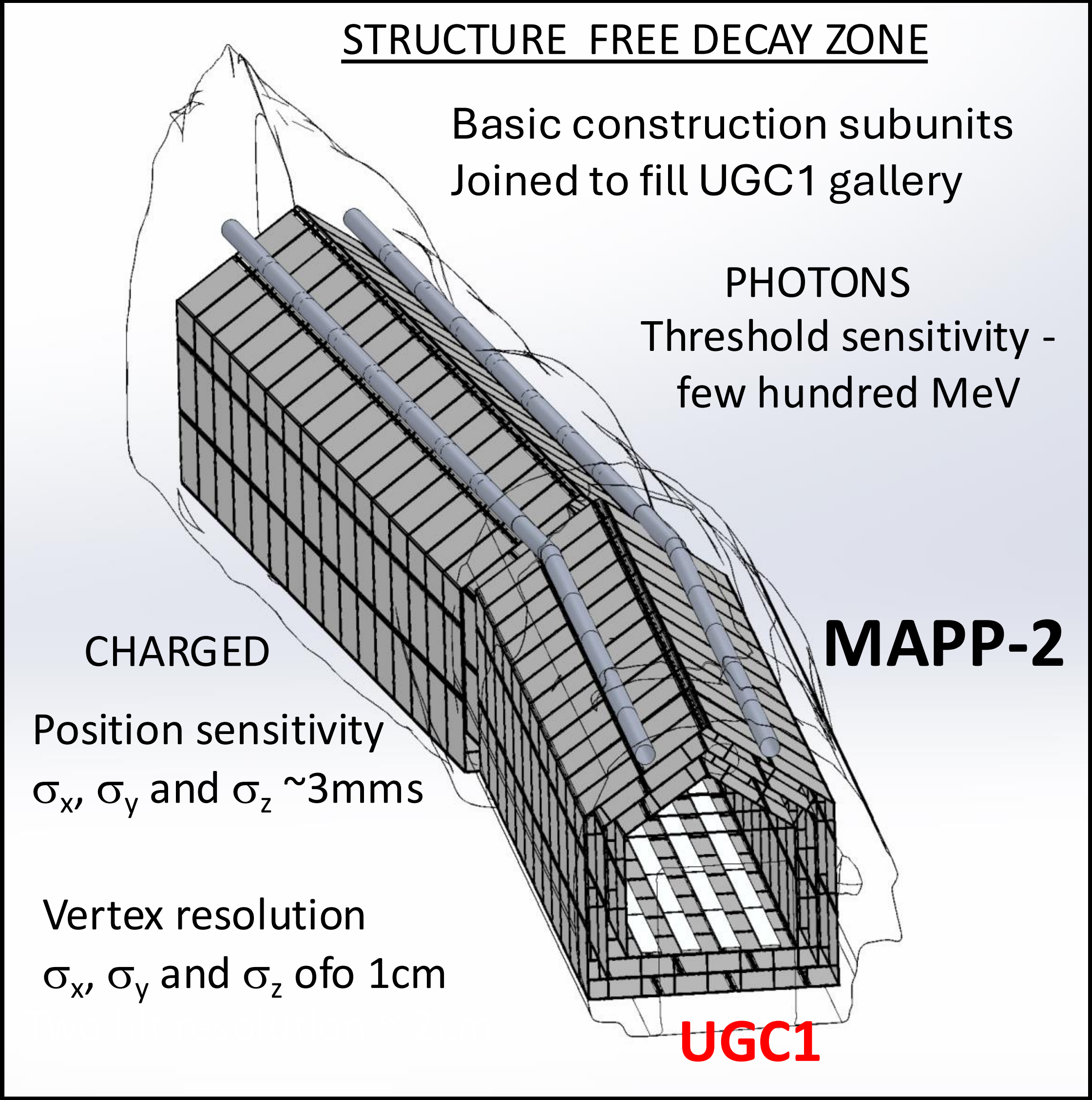
Safety Requirement	Cost	Cost + Contingency
Fire Detection Emergency Red phone	21,000 CHF 11,200 CHF	23,100 CHF (10 %) 11,760 CHF (5 %)
Electrical Safety	48,200 CHF	53,000 (10 %)
Civil Engineering	151,000 CHF	166,100 CHF (10 %)
HVAC	45,000 CHF	54,000 CHF (20%)
Access and work at height at UGC1	10,000 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 ~$0.4 million*
- *MAPP-2 Detector cost ~$2-3 million*
- *Funding requested for work in 2026 awarded in 2025 (if successful)*
- *TP under construction (NoI given)*

Design of MAPP-2 Detector



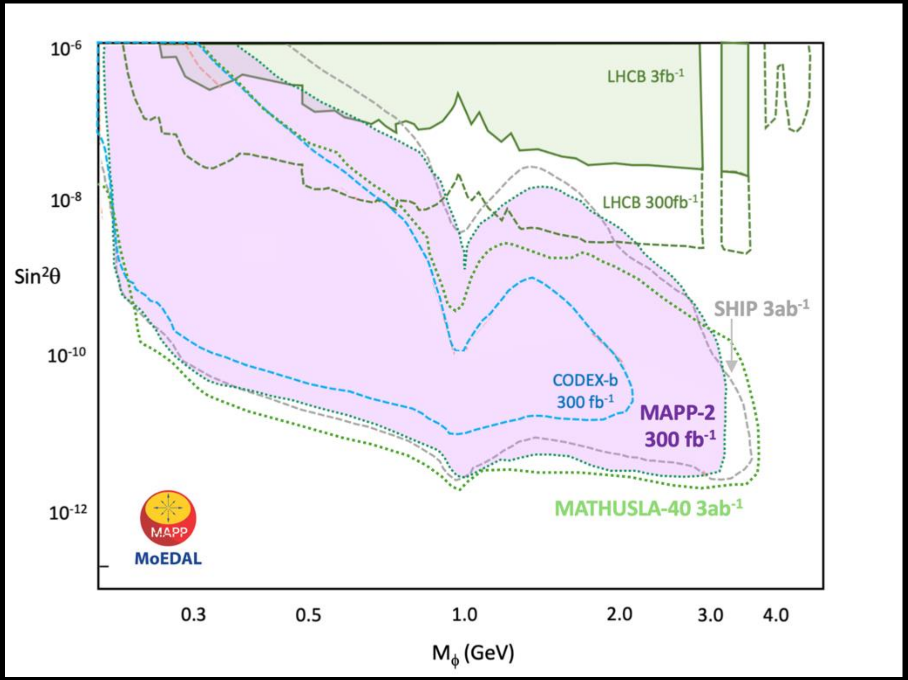




- ***MAPP-2 Detector technology similar to that used for muon tomography***

MAPP-2 Sensitivity to LLPs

- *In the search for dark scalars, MAPP-2 is competitive with SHIP and descoped MATHUSLA and would easily outstrip Codex-b and Codex-β*
- ***STANDOUTS FOR MAPP-2***
  - *One of the very few detectors at **Intermediate pseudorapidity***
  - *One of the very few LP detectors **sensitive to photons and charged particles** with energy/momentum threshold in the few hundred MeV/c / MeV range*
  - ***Scintillator based tracking** detectors (unique for underground LLP detectors that use RPCs)*
  - ***Protected by 30-40m of rock/concrete from IP and from cosmics by a 100m ovrburden***



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