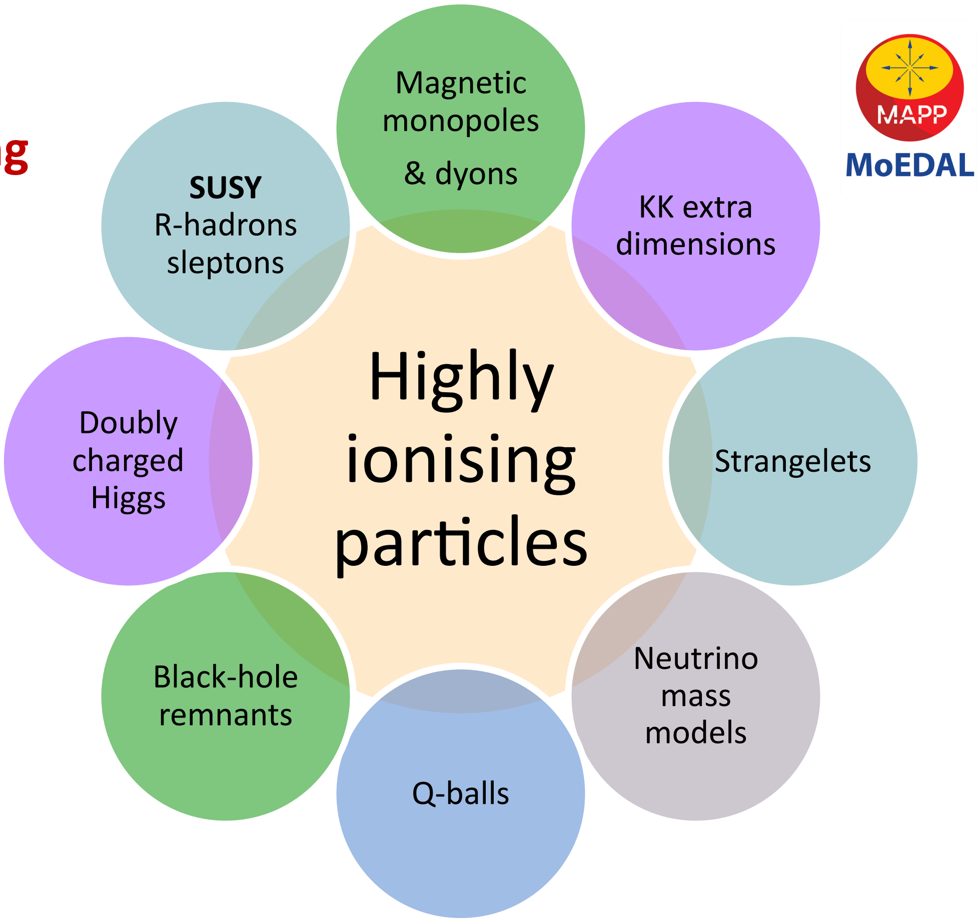
MoEDAL-MAPP and the lifetime frontier

Vasiliki A. Mitsou for the MoEDAL-MAPP Collaboration

MoEDAL – Monopole & Exotics Detector At LHC

MoEDAL detector optimised for detection of (meta)stable **highly ionising particles** (HIPs)

- high charges (**high z**)
  - magnetic → **monopoles**!
  - electric → High-Electric-Charge Objects (**HECOs**)
- slow moving (**low β**) ⇒ massive



MoEDAL physics program
[Int. J. Mod. Phys. A29 (2014) 1430050]

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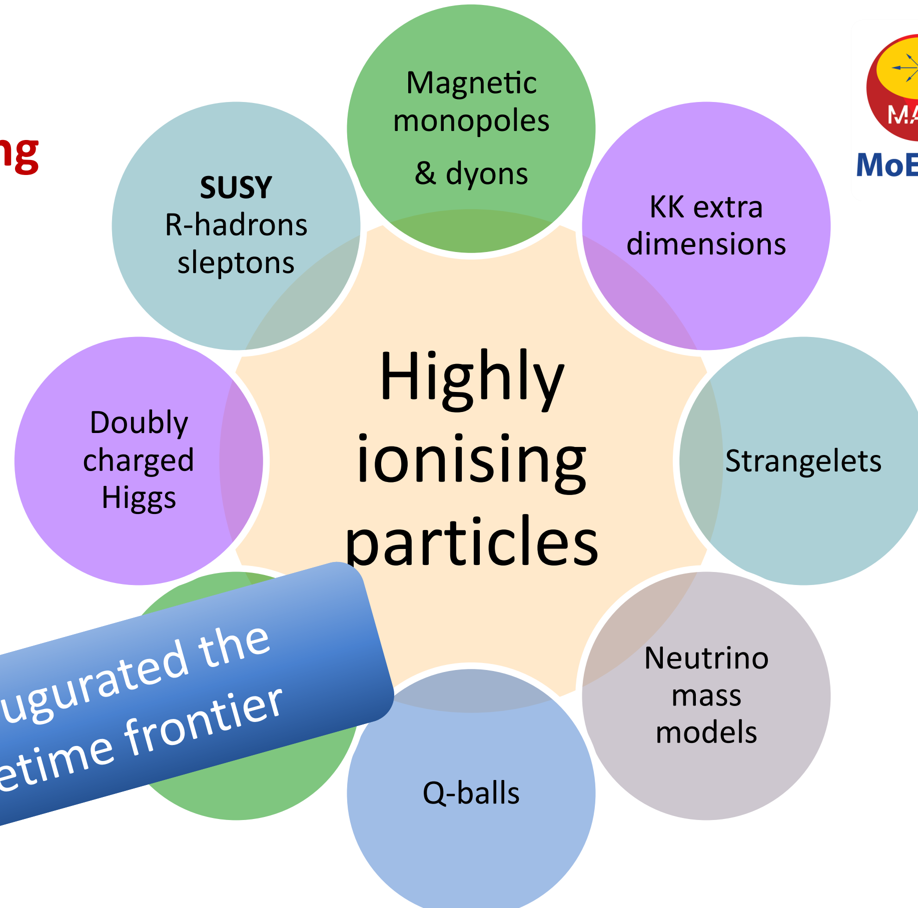
LHC's first dedicated *search* experiment
(approved 2010)

Inaugurated the lifetime frontier



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Int. J. Mod. Phys. A29 (2014) 1430050

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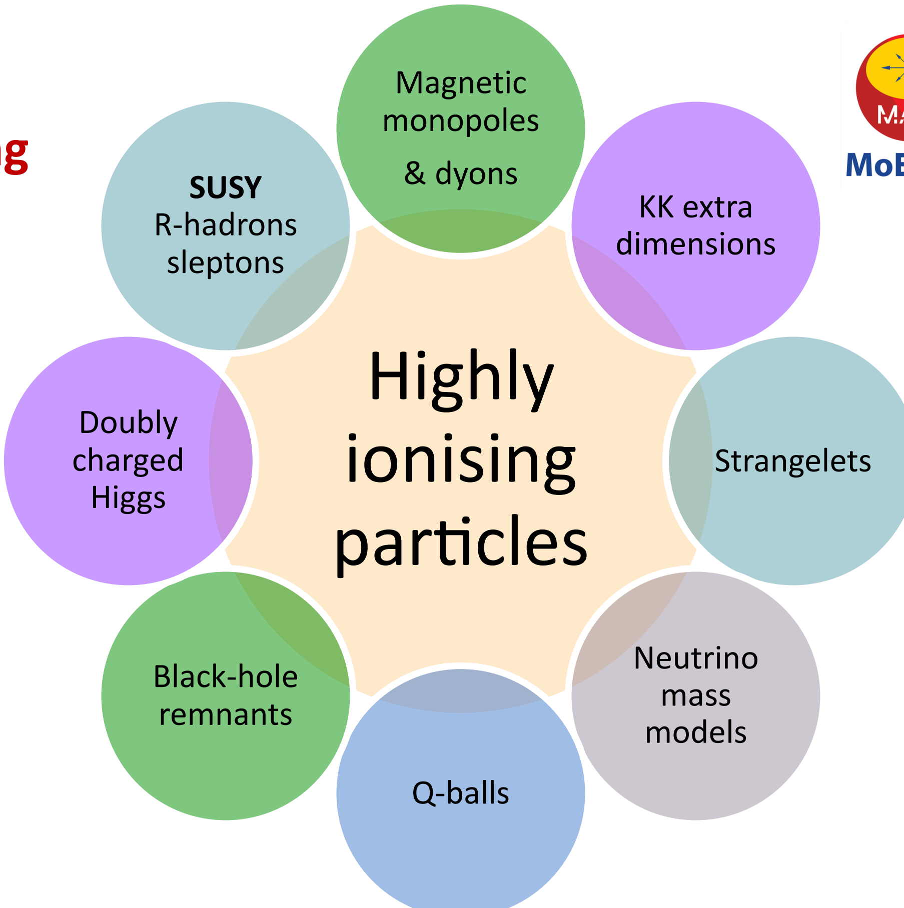
MAPP upgrade designed for *neutral long-lived particless* and *millicharged* particles



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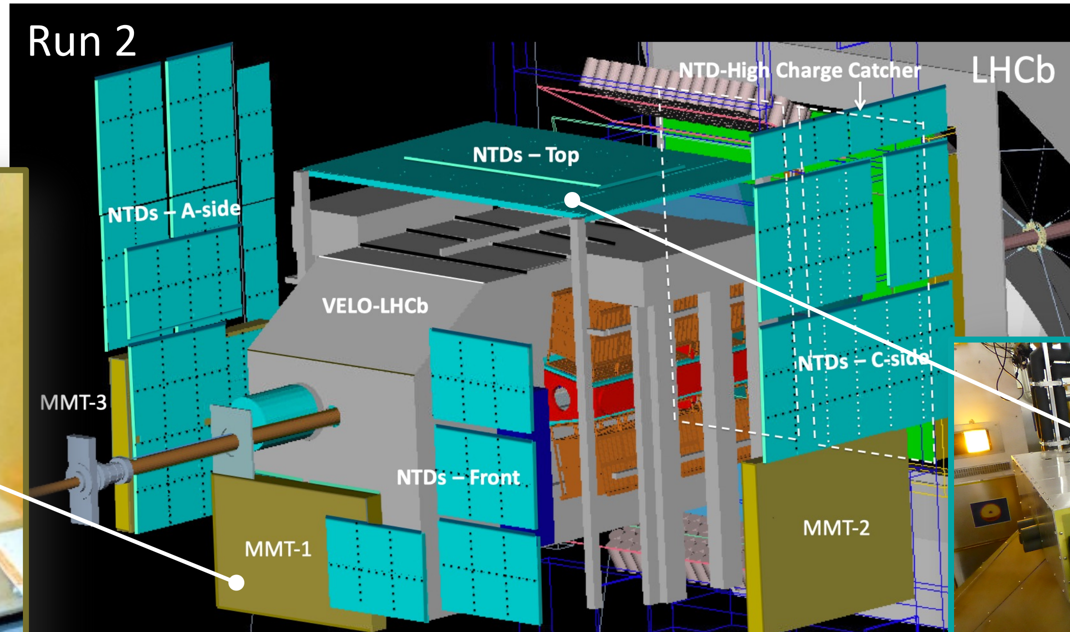
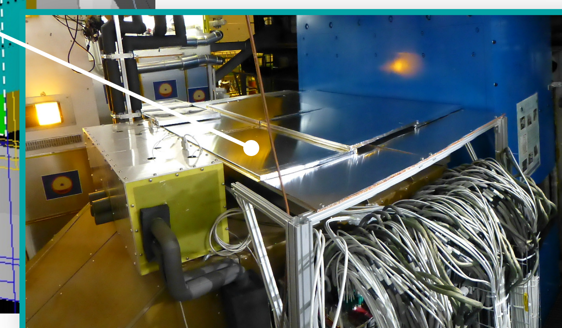
Int. J. Mod. Phys. A29 (2014) 1430050

MoEDAL detector





Located in LHC IP8 in LHCb cavern

- Mostly **passive detectors**; no trigger; no readout
- Permanent physical record of new physics
- No Standard Model physics backgrounds

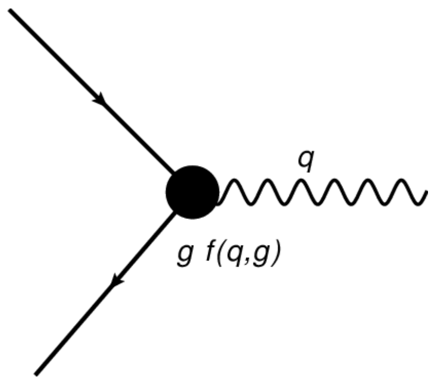
① Nuclear Track Detectors (**NTD**)

② Monopole Trapping detector (**MMT**)
– aluminum bars

③ **TimePix** radiation background monitor

Magnetic monopoles in a nutshell

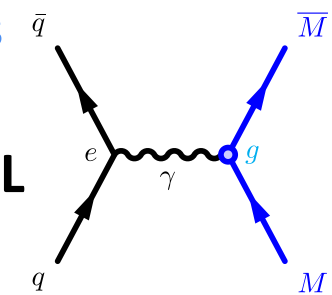
- Why? Because they symmetrise Maxwell's equations
  - to symmetrise Maxwell's equations ⇒ electric–magnetic charge duality
  - electric charge quantisation
  - solutions in Grand Unified Theories (GUTs)
- Single magnetic charge (Dirac charge): $g_D = 68.5e$
  - higher charges are integer multiples of Dirac charge:
    $g = ng_D$, $n = 1, 2, \ldots$
  - > 4700 times more ionising than a minimum ionising particle!
- Photon–monopole coupling constant
  - large: $g/\hbar c \sim 20$ (precise value depends on units)
- Dirac monopole is a *point-like* particle; GUT monopoles are *extended* objects
  - production of composite monopoles suppressed by $e^{-4/\alpha}$
- Monopole spin and mass not theoretically fixed → free parameters



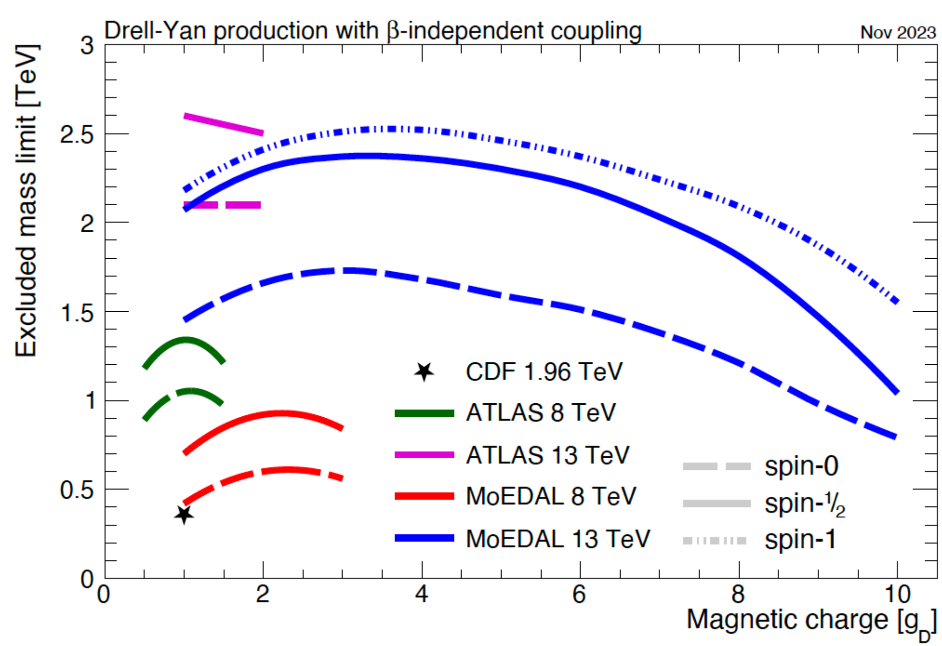
For a review on monopole theory and searches:
Mavromatos & VAM, Int.J.Mod.Phys.A 35 (2020) 2030012

Magnetic monopole limits

- MoEDAL introduced novelties in considered monopole models
  - *β*-dependent coupling
  - spin-1 monopoles
  - γγ fusión
- **ATLAS ↔ MoEDAL complementarity**



MoEDAL set world-best collider limits for **|g| > 2 g_D**

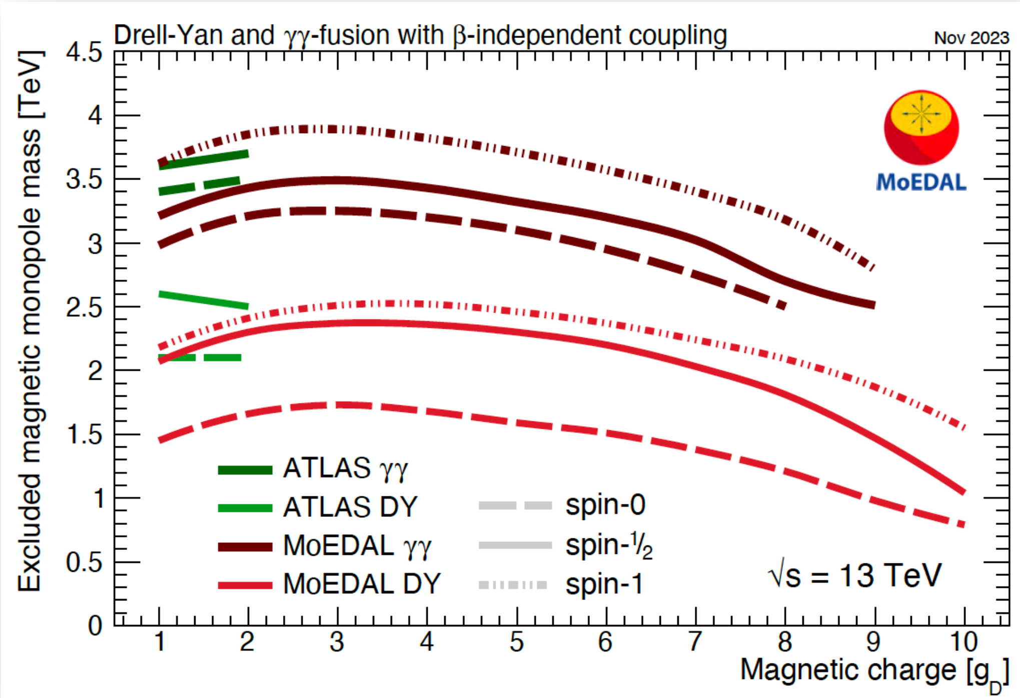


MoEDAL, [JHEP 08 (2016) 067], [PRL 118 (2017) 061801], [PLB 782 (2018) 510], [PRL 123 (2019) 021802], [PRL 126 (2021) 071801], [EPJC 82 (2022) 694], [arXiv:2311.06509 [hep-ex]]

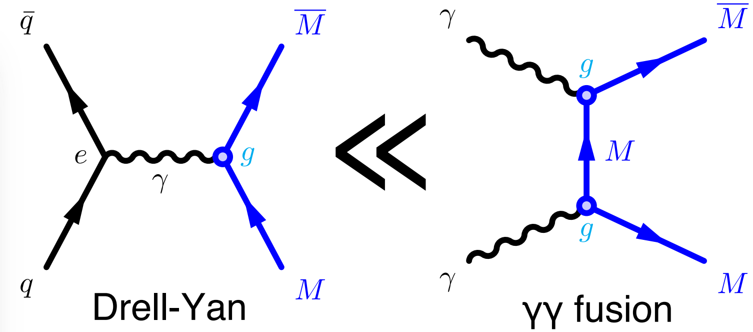
Mass limits extracted with Feynman-*like* diagrams that ignore **non-perturbativity** of **large monopole-photon coupling.**

→ Dyson-Schwinger resummation scheme [Alexandre, Mavromatos, Phys. Rev. D 100 (2019) 096005]

Drell-Yan & γγ-fusion



MoEDAL, Phys.Rev.Lett. 123 (2019) 021802, Eur.Phys.J.C 82 (2022) 694, arXiv:2311.06509 [hep-ex]

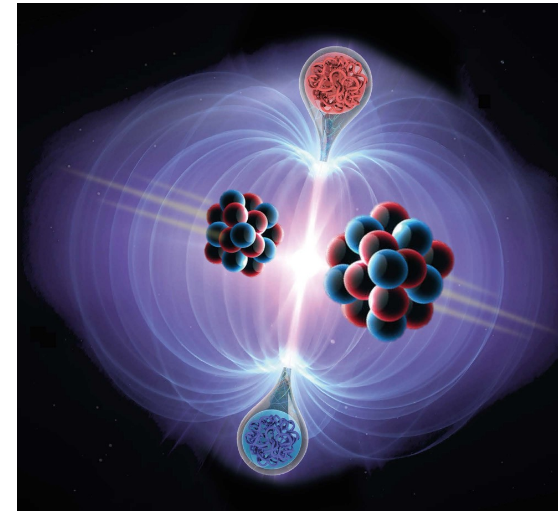


Photon-fusion much higher cross section than Drell-Yan-like at LHC energies

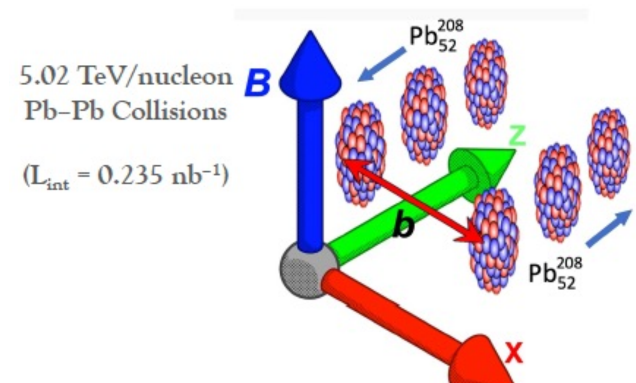
M-γ coupling becomes small (perturbative) in **photon fusion** under certain conditions

Baines, Mavromatos, VAM, Pinfold, Santra, Eur.Phys.J.C 78 (2018) 966

Monopoles via Schwinger mechanism



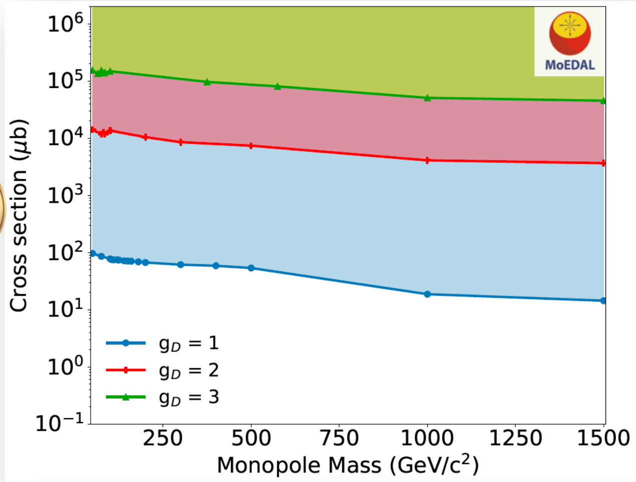
- Schwinger mechanism describes spontaneous creation of e^+e^- pairs in presence of extremely strong **electric field**
- Same mechanism can produce **monopole pairs** in strong ***magnetic* fields**
- Exposure of MMTs in ultraperipheral Pb-Pb collisions
  - peak magnetic field strength 10^{16} T
  - four orders of magnitude greater than strongest known astrophysical magnetic fields: surfaces of magnetars
- Advantages over DY & γγ-fusion production
  - cross-section calculated with semiclassical techniques
  - no suppression e^{-500} for finite-sized monopoles



Gould, Ho, Rajantie, PRD 100 (2019) 015041, PRD 104 (2021) 015033
Ho & Rajantie, PRD 101 (2020) 055003, PRD 103 (2021) 115033

Schwinger production results

- First limits based on non-perturbative calculation of monopole production cross section
- First direct search sensitive to composite monopoles



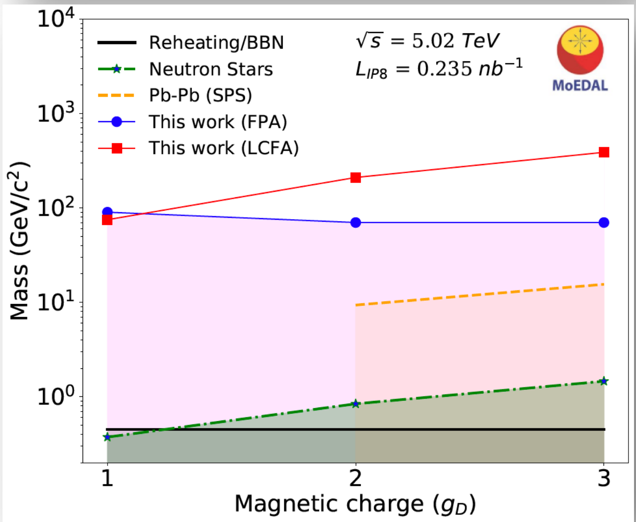
MoEDAL bags a first

The MoEDAL experiment has conducted the first search at a particle collider for magnetic monopoles produced through the Schwinger mechanism

2 JULY, 2021 | By Ana Lopes

Limits on monopoles of 1–3g_D and masses up to 75 GeV

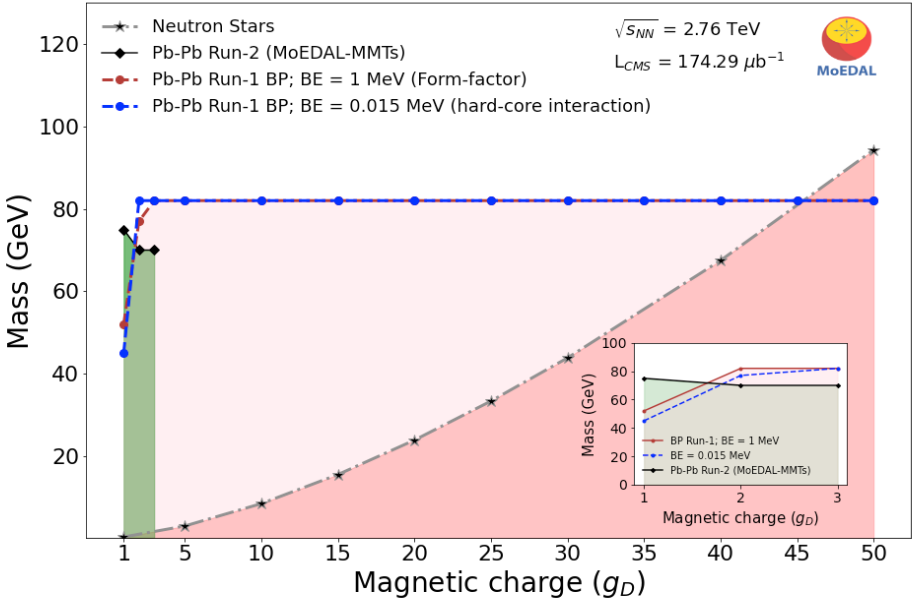
MoEDAL,
Nature 602 (2022) 7895, 63-67



Schwinger production & CMS beam pipe

MoEDAL

- CMS officially transfered ownership of Run-1 beam pipe to MoEDAL
  - 1 mm thick, 3.8 m long made of beryllium
  - most directly exposed piece of material
- Scanned for presence of trapped monopoles by MoEDAL Collaboration
- Composite and point-like monopoles with masses up to 80 GeV excluded



Strongest available constraint for magnetic charges 2 – 45 g_D

PHYSICAL REVIEW LETTERS **133,** 071803 (2024)

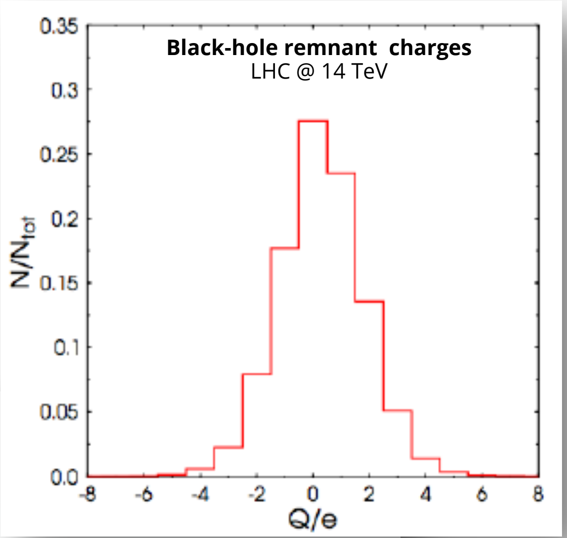
Editors' Suggestion

MoEDAL, Phys.Rev.Lett. 133 (2024) 071803

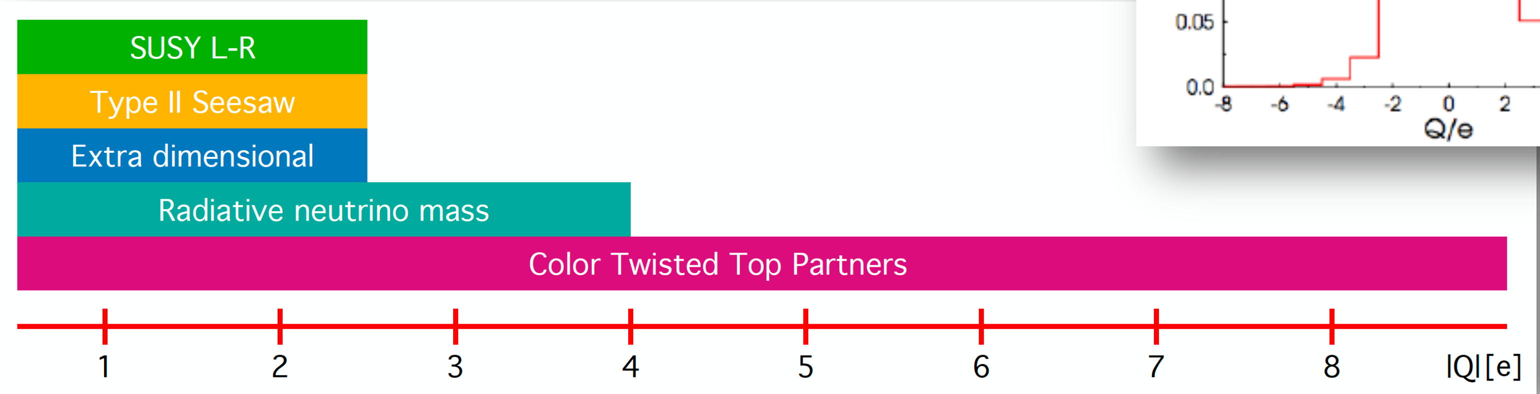
MoEDAL Search in the CMS Beam Pipe for Magnetic Monopoles Produced via the Schwinger Effect

Multiply charged quasi-stable particles

- High Electric Charge Objects (HECOs) predicted in many scenarios of physics beyond the SM
  - finite-sized objects (Q-balls)
  - condensed states (strangelets)
  - microscopic black holes (through their remnants)
  - …
- They eventually decay into other particles



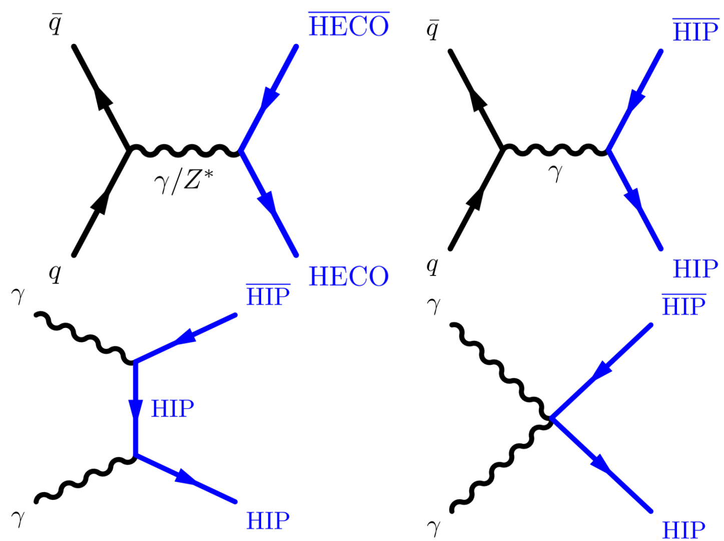
Hossenfelder, Koch, Bleicher, hep-ph/0507140



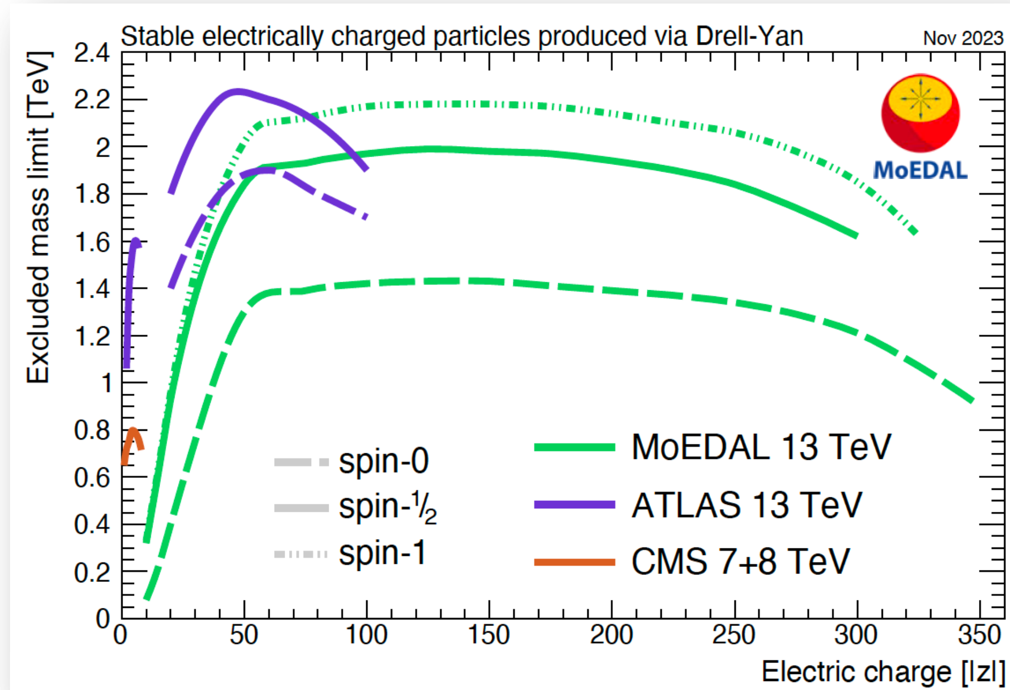
R. Masełek, DISCRETE2020-2021

HECO limits

- Upper limits on production cross section as low as **1 fb**
- Limits on HECOs with electric charges **10*e* – 350*e*** and masses up to **~3.8 TeV**



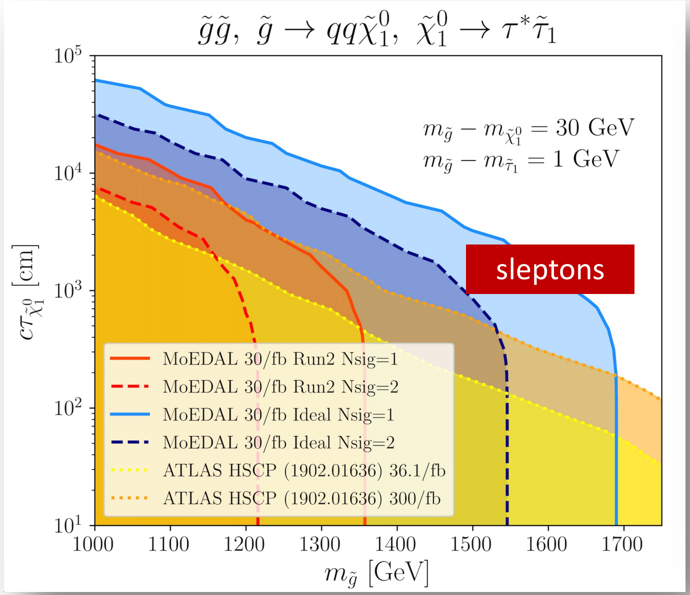
MoEDAL, Eur.Phys.J.C 82 (2022) 694, arXiv:2311.06509 [hep-ex], PRL, to appear



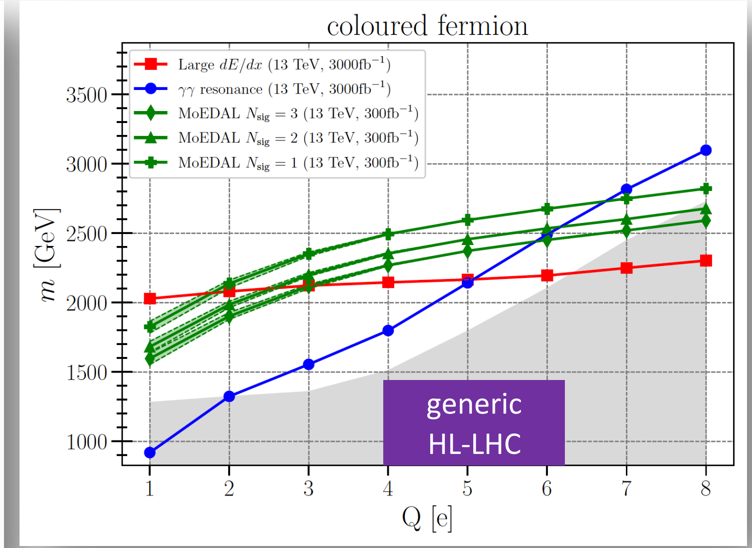
MoEDAL HECOs limits strongest to date, in terms of charge, at any collider experiment

"Low" electric charges

- Supersymmetric singly charged LLPs: sleptons, R-hadrons, charginos
- **Generic multiply charged particles**
- Also, models of ν masses → 2-, 3-, 4-ply charged [Hirsch et al, EPJC 81 (2021) 697]



Felea, VAM et al, EPJC 80 (2020) 431



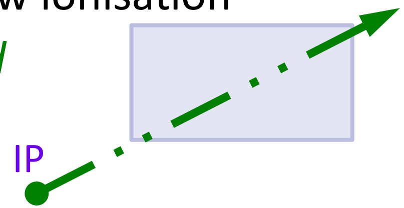
Altakach, Lamba, Masełek, VAM, Sakurai, EPJC 82 (2022) 848

MoEDAL has the best sensitivity at intermediate electric charges at HL-LHC

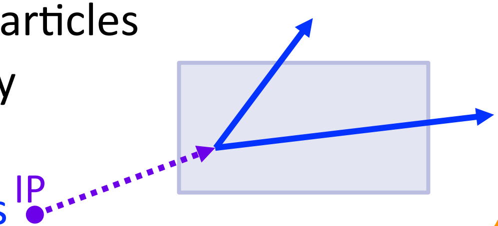
MoEDAL Apparatus for Penetrating Particles

MoEDAL

MAPP-1: sensitive to low ionisation induced by *millicharged* particles,
i.e. charges ≪ 1*e*



MAPP-2: sensitive to very long-lived weakly interacting neutral particles through visible decay products
→ displaced vertices



MoEDAL-MAPP flythrough:
http://www.physixel.com/JLP_MAPP/MAPP_FlyOver1.mp4

MoEDAL contribution to Snowmass, arXiv:2209.03988
Pinfold, Phil.Trans.Roy.Soc.Lond.A 377 (2019) 20190382

MoEDAL gets a new detector

The new detector, known as MAPP, will increase the physics reach of the MoEDAL experiment and the Large Hadron Collider

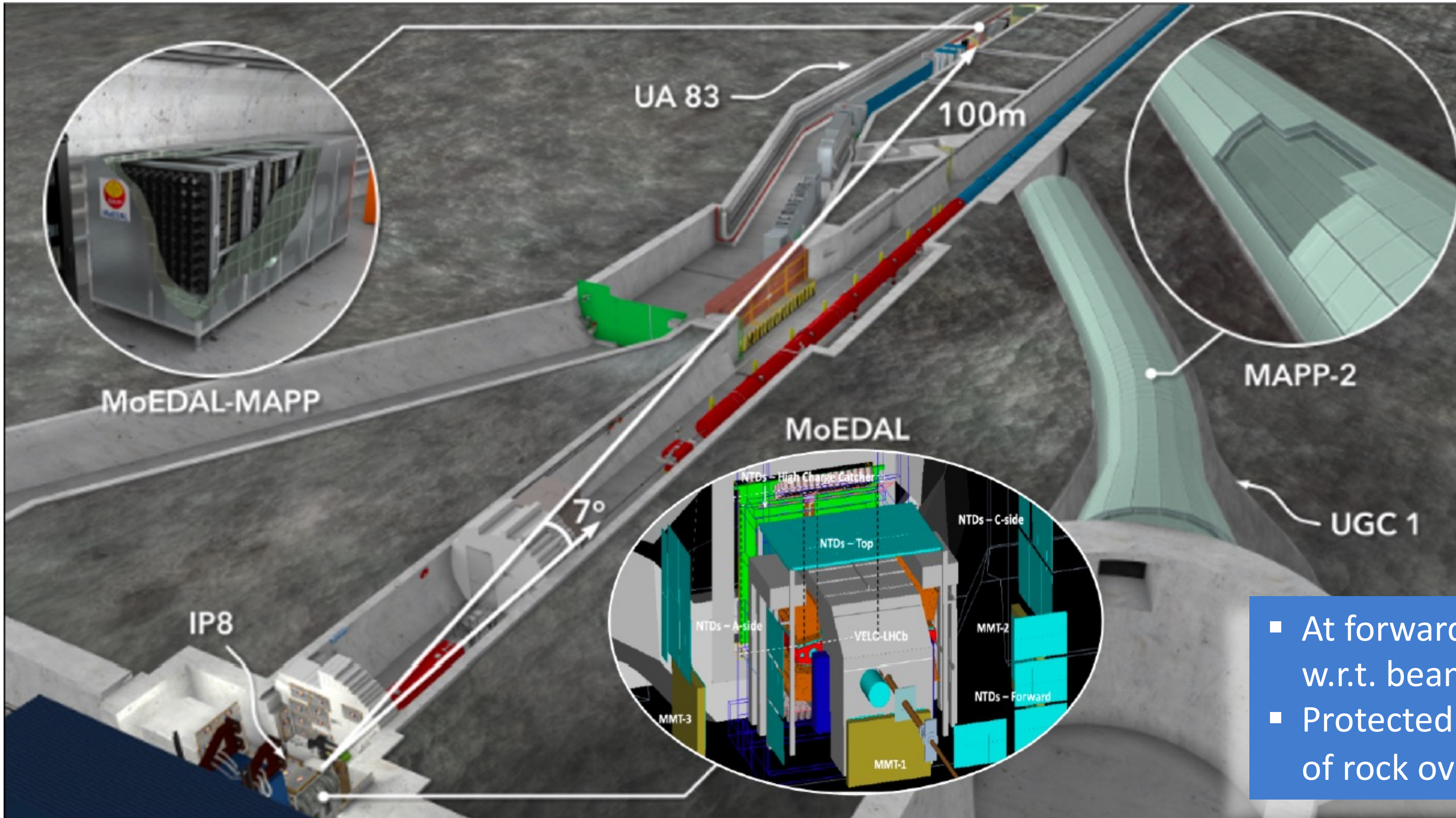
CERN

28 MARCH, 2022 | By Ana Lopes

Installation of the support structure for the MAPP detector components. (Image: CERN)

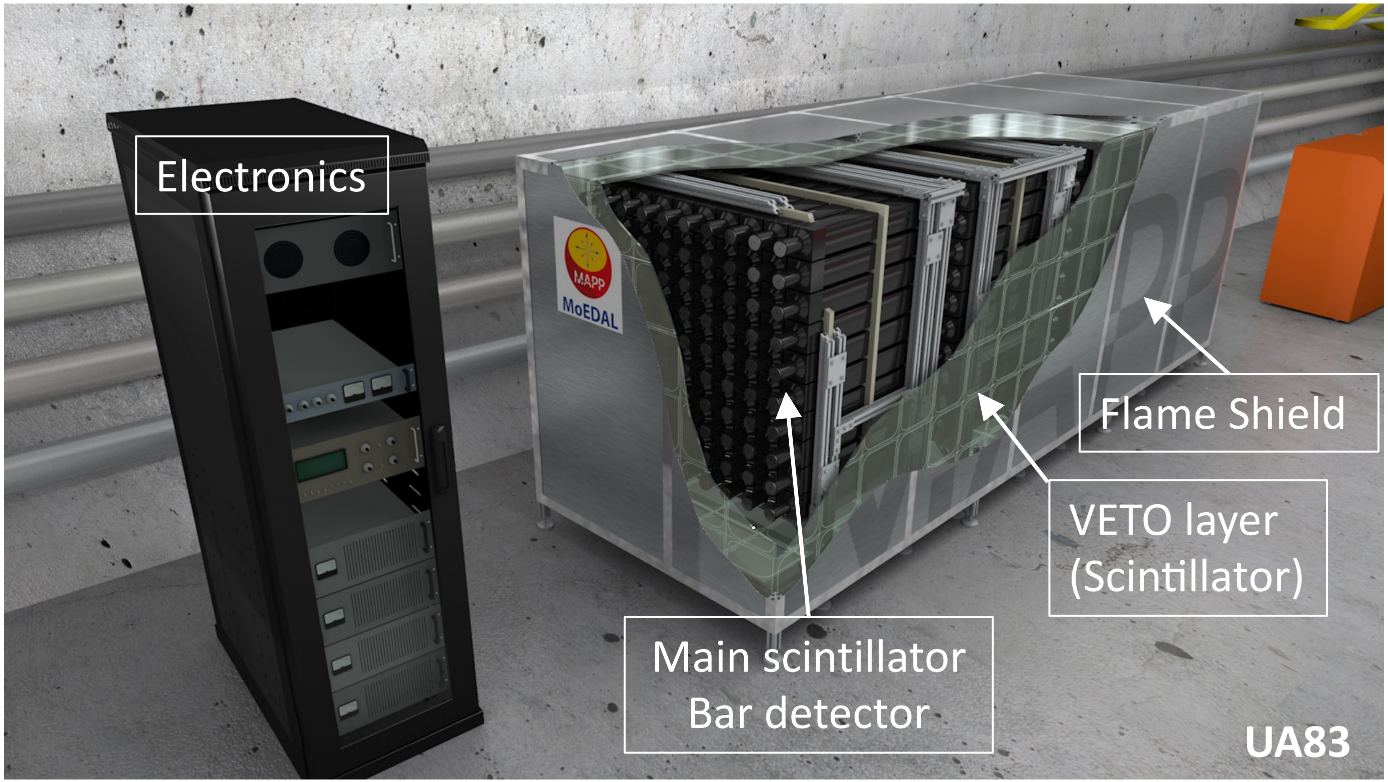
The MoEDAL collaboration at the Large Hadron Collider (LHC) is adding a new detector to its experiment, in time for the start of the next run of the collider this coming summer. Named as the MoEDAL Apparatus for Penetrating Particles, or MAPP for short, the new detector will expand the physics scope of MoEDAL to include searches for minicharged particles and long-lived particles.

MAPP locations



- At forward region w.r.t. beam axis
- Protected by ~100 m of rock overburden

MAPP Phase-1 detector concept

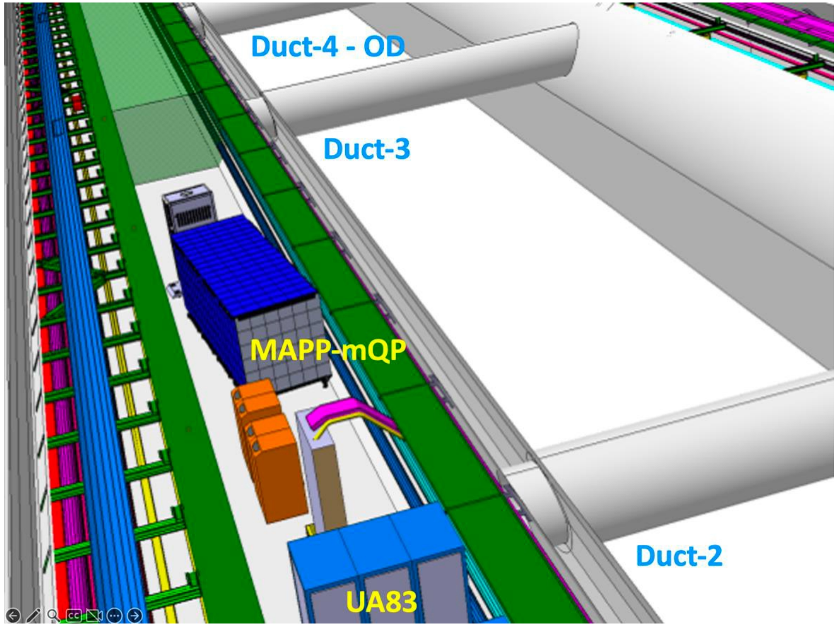


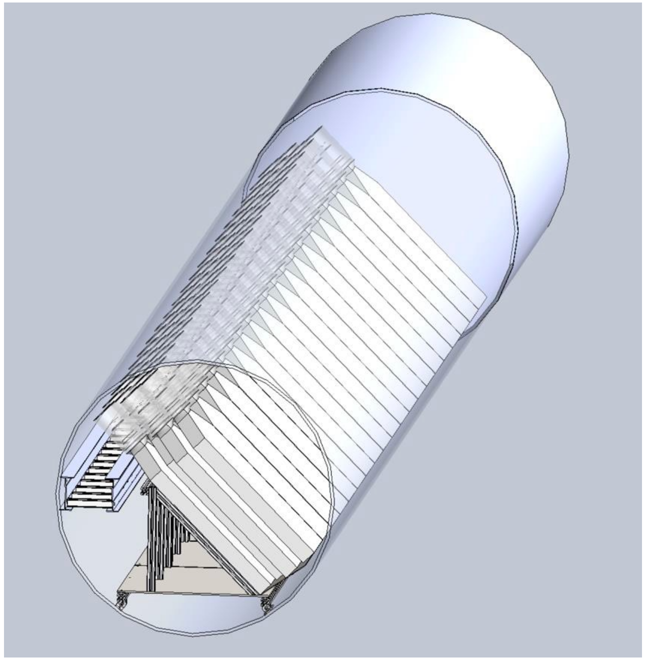
- 400 scintillator bars (10×10×75 cm^3) in 4 sections readout by PMTs
- Protected by a hermetic VETO counter system

MAPP-1 installation @ UA83

Dec 2023

MAPP Outrigger detector



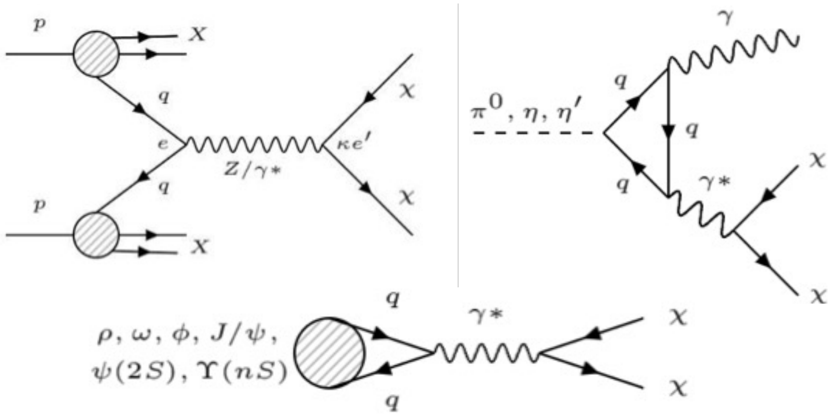


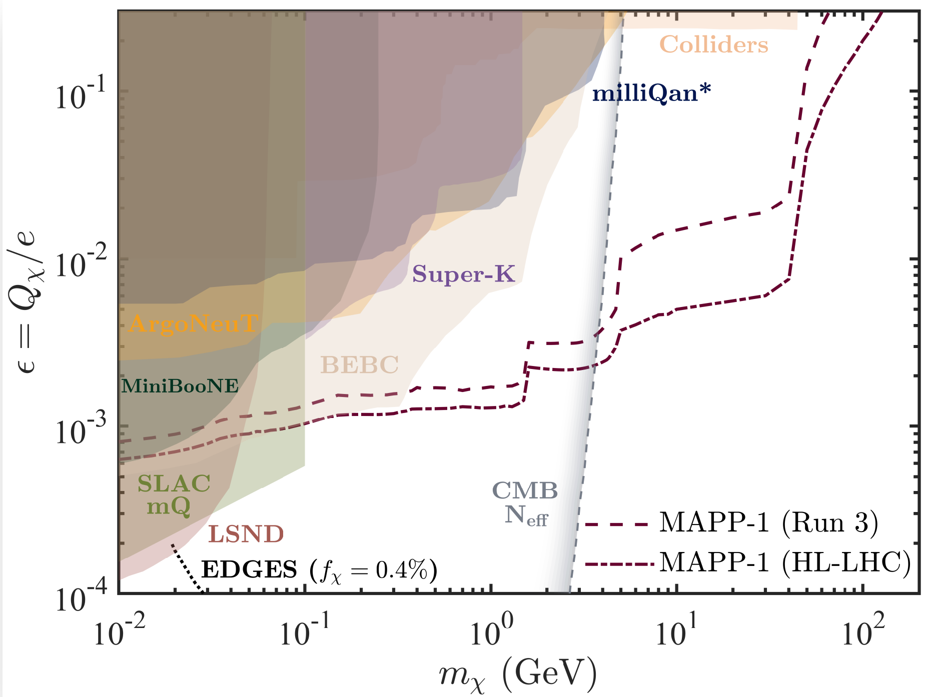
- Proposed to improve the overall reach for higher mass mCPs (above a few GeV)
- 4 layers of scintillator planks with twenty 60cm × 30cm × 5cm each, angled at 45°
- Readout by coincident PMTs – an effective area of ~2.6 m^2

Millicharged particles (mCPs)

MoEDAL

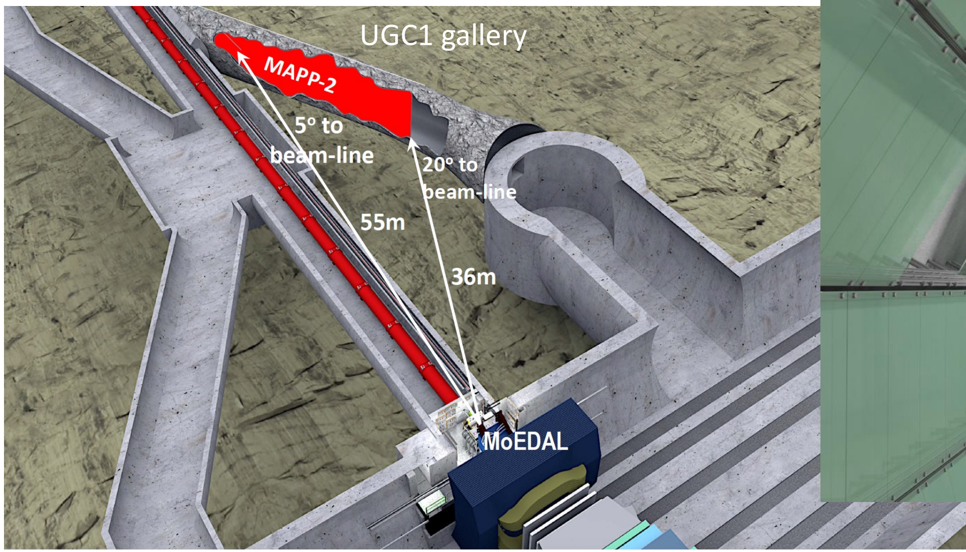
- mCP generated by **massless dark photon**, kinetically mixed with SM hypercharge, that couples to mCP χ
- Production through Drell-Yan and meson decays
- Photoelectron production estimates
- Active veto significantly reduces background

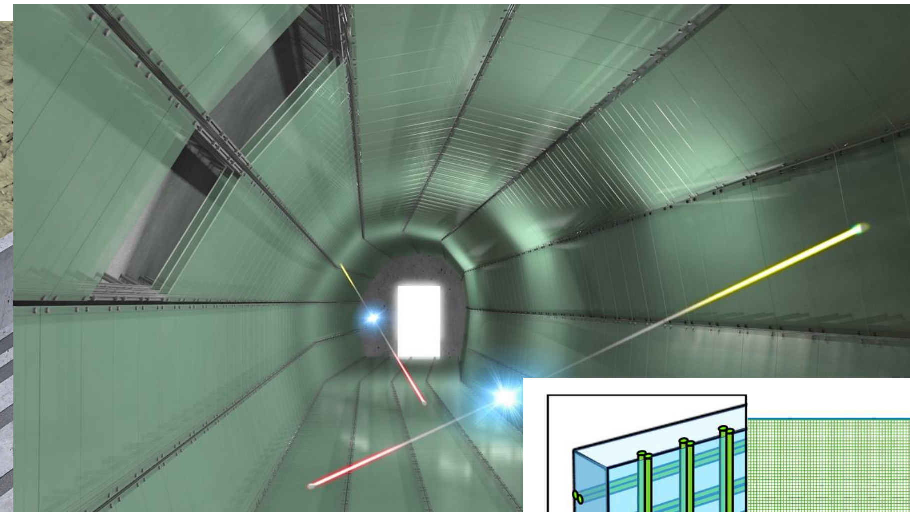


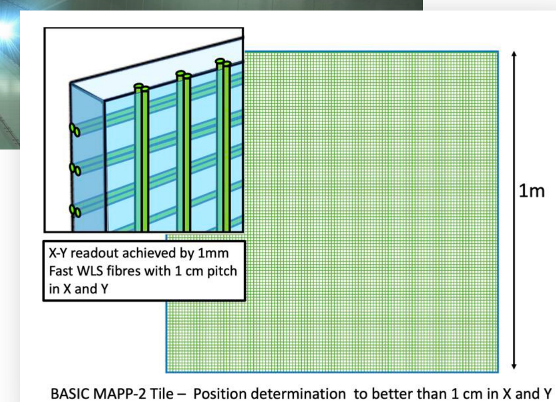


Kalliokoski, VAM, Montigny, Mukhopadhyay, Ouimet, Pinfold, Shaa, Staelens, JHEP 04 (2024) 137

MAPP-2 upgrade for HL-LHC



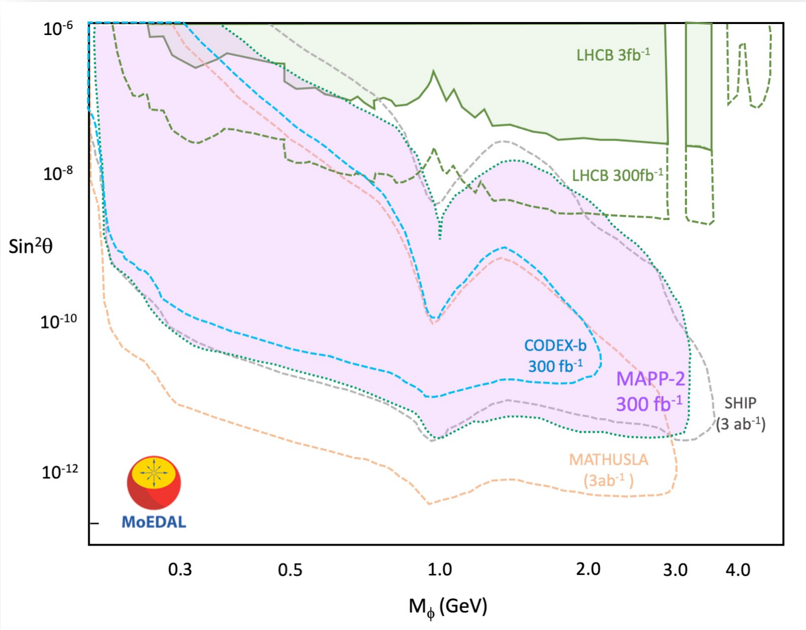




- UGC1 gallery prepared during Long Shutdown 3
- MAPP-2 detector extends to UGC1 full length
- Large scintillator tiles with optical fibre readout by SiPMs
- 3 or 4 hermetic containers – one within the other – lining UGC1 walls

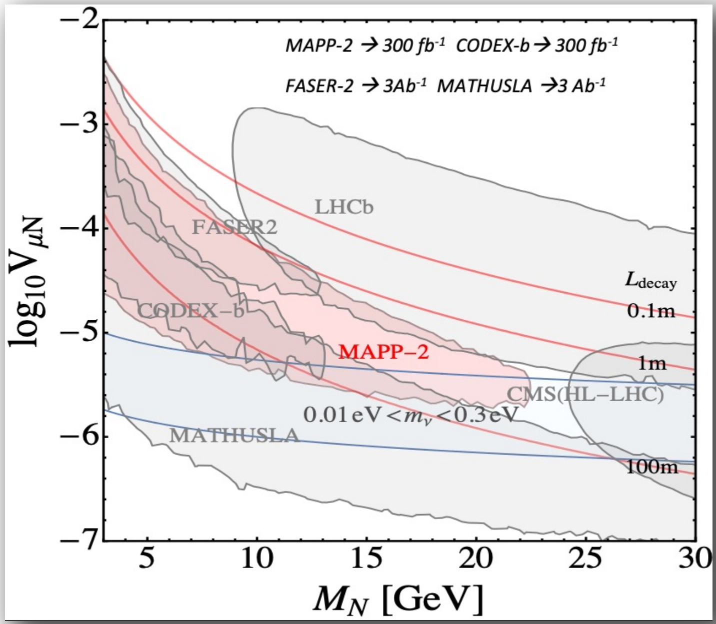
MAPP-LLP – dark matter & heavy neutrinos

Dark Higgs scenario



Dark Higgs ϕ mixes with SM H^0 ($\vartheta_{mixing} \ll 1$), leading to exotic $B \rightarrow X_s\phi$ decays with $\phi \rightarrow \ell^+\ell^-$

Heavy neutrino via *Z′* production



Pair production of RH neutrinos from the decay of a *Z′* boson in the gauged *B-L* model

See also, Deppisch et al, PRD 100 (2019) 035005

MoEDAL contribution to Snowmass, arXiv:2209.03988

Summary & outlook

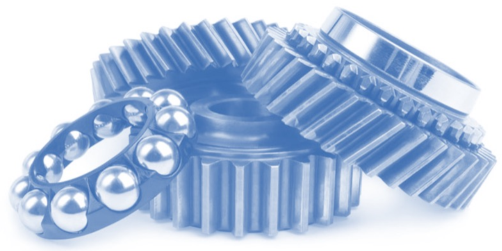
MAPP
MoEDAL

- Exciting results by MoEDAL
  - sole contender in **high magnetic charges**
  - sole **dyon** search in accelerator experiment
  - first search for monopoles produced via **Schwinger mechanism**
  - best sensitivity in **high electric charges**
- **Future perspectives**
  - MoEDAL baseline redeployed for **Run-3** with improved geometry
    - also planned to operate during **HL-LHC**
  - MAPP will extend reach to **millicharged** particles and **neutral long-lived particles**
    - MAPP-1 expected to be commissioned soon and start data-taking in 2025

MoEDAL web page: https://moedal.web.cern.ch/

Thank you for your attention!

Spares

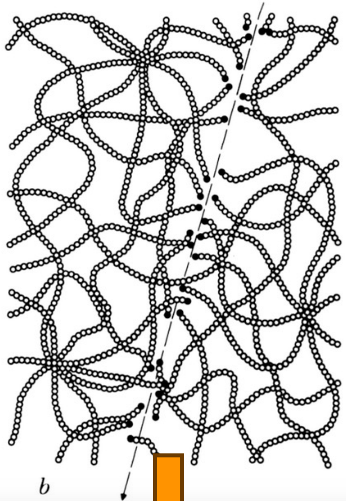


MoEDAL results

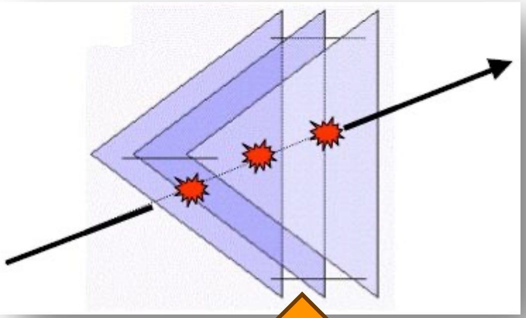
- 2016 – **First results @ 8 TeV** ☛ *CERN Press Release* JHEP 1608 (2016) 067 [arXiv:1604.06645]
- 2017 – **First results @ 13 TeV** Phys.Rev.Lett. 118 (2017) 061801 [arXiv:1611.06817]
- 2018 – **MMT results** Phys.Lett.B 782 (2018) 510–516 [arXiv:1712.09849]
  - **spin-1 monopoles ← FIRST in colliders**
  - β-dependent coupling
- 2019 – **MMT results** Phys.Rev.Lett. 123 (2019) 021802 [arXiv:1903.08491]
  - **photon fusion** interpretation **← FIRST at LHC**
- 2020 – **MMT search for Dyons ← FIRST in colliders**
  Phys.Rev.Lett. 126 (2021) 071801 [arXiv:2002.00861]
- 2021 – **Schwinger production ← FIRST**
  Nature 602 (2022) 7895, 63 [arXiv:2106.11933]
- 2021 – **NTD & MMT @ 8 TeV ← FIRST NTD analysis** Eur.Phys.J.C 82 (2022) 8, 694 [arXiv:2112.05806]
  - first limits on high-electric-charge objects
- 2023 – **NTD & MMT @ 13 TeV** Phys. Rev. Lett., to appear [arXiv:2112.05806]
- 2024 – **CMS beam-pipe & Schwinger @ 8 TeV** Phys.Rev.Lett. 133 (2024) 071803 [arXiv:2402.15682]
  - constraints on very high magnetic charges
  - → Editors' Suggestion

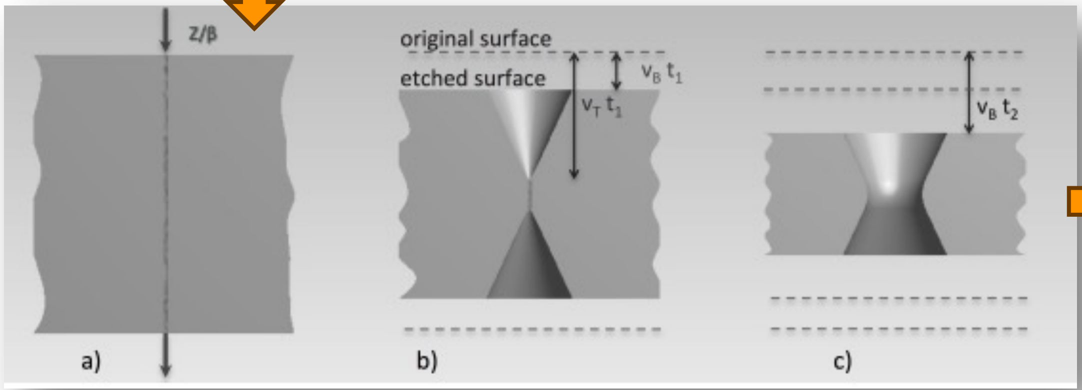
1 Nuclear Track Detectors (NTDs)

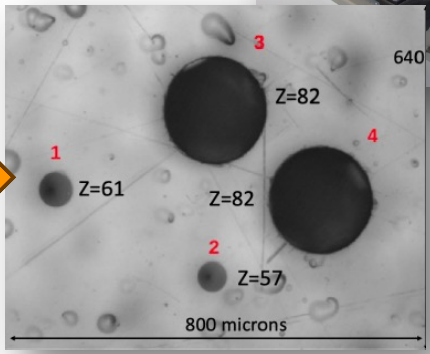
Fleischer, Price, Walker, Sci. Amer. 220 (1969) 30



- HIP passage through plastic NTD marked by *invisible* damage zone (**“latent track”**) along trajectory
- Damage zone revealed as **cone-shaped etch-pit** when sheet is **chemically etched**
- Plastic sheets **scanned** to detect etch-pits
- Looking for *aligned* etch pits in multiple sheets



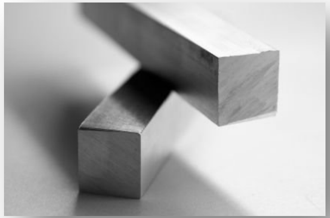


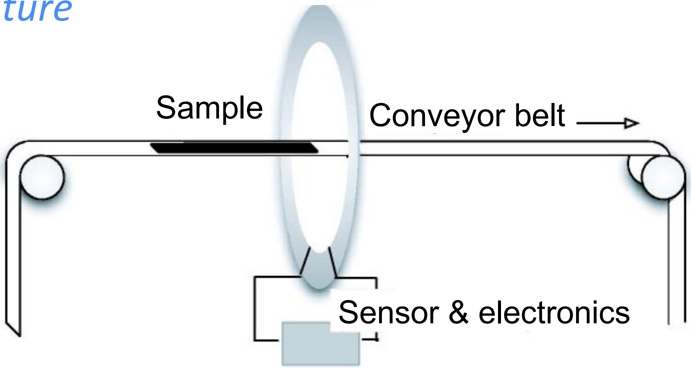


MAPP
MoEDAL

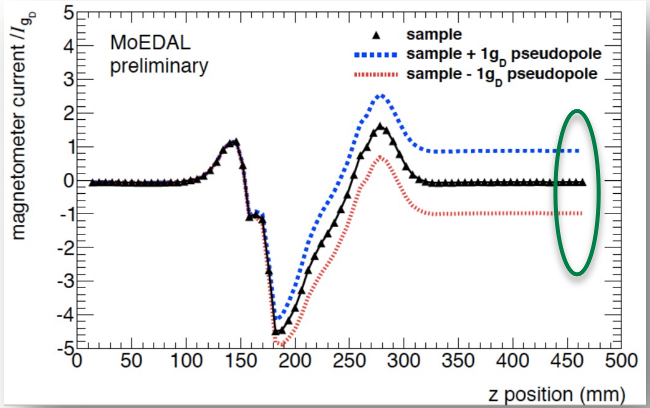
2 MMT: Magnetic Monopole Trapper

- Binding *(trapping)* of monopoles with nuclei and nucleons
- Aluminium MMT volumes scanned in superconducting quantum interference device (SQUID) at ETH Zurich
- MMT bars cut into pieces & fed into SQUID, 1, 2, …
- **Persistent current:** difference between resulting current before and after scanning
  - other than zero → *monopole signature*





Typical sample & pseudo-monopole curves

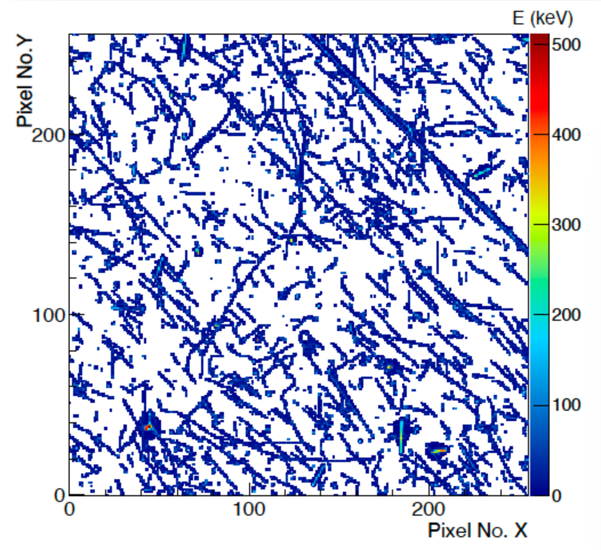


3 TimePix radiation monitor

MoEDAL

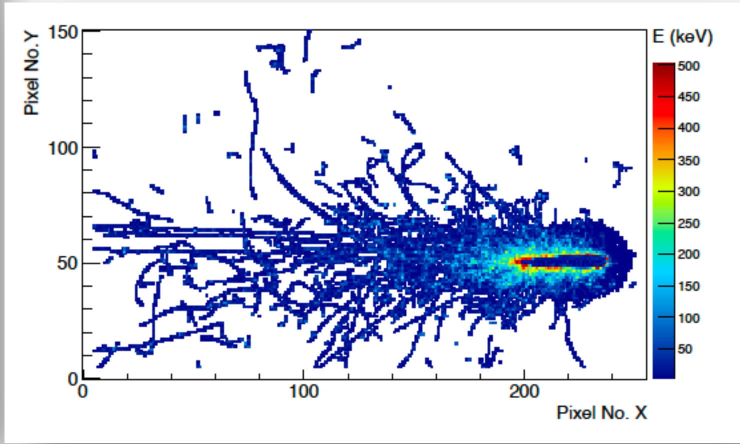
- Timepix chips used to measure online the radiation field and monitor spallation product background
- Essentially act as little electronic “bubble-chambers”
- **The only active element in MoEDAL**

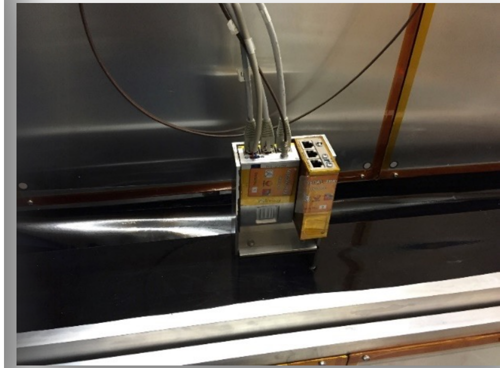
- 256×256 pixel with 55 μm pitch
- Time-of-interaction precision 1.56 ns
- 3D track reconstruction
- Energy deposition measured via time-over-threshold
- Particle ID through *dE/dx*



Tracks accumulated during 1s in MoEDAL during Pb-Pb run

330 GeV Pb-ion measured at the SPS

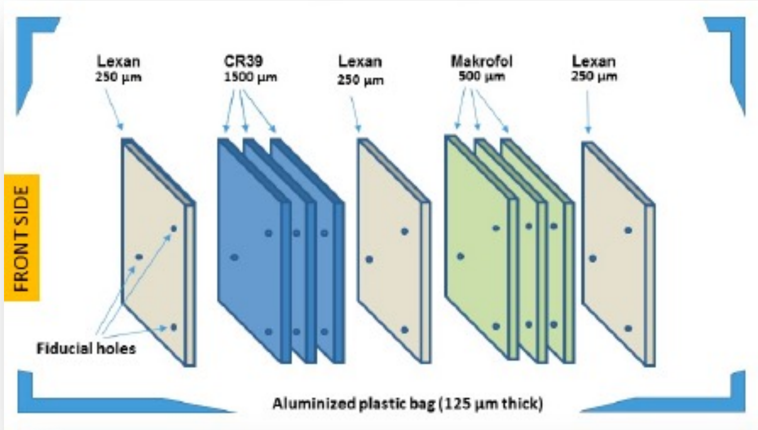


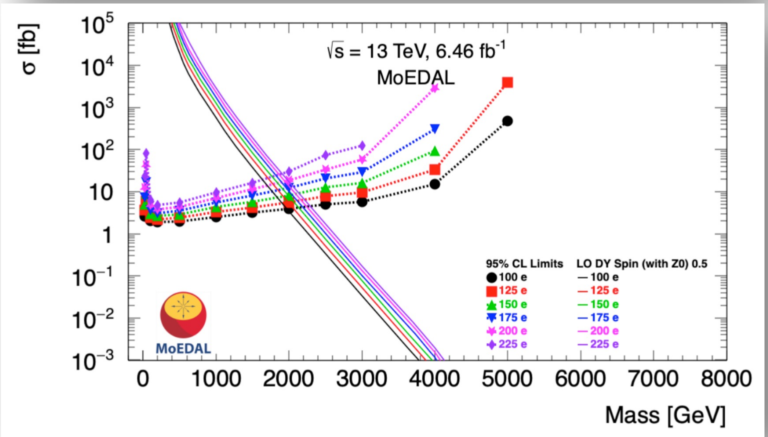


MoEDAL, PoS ICHEP2020 (2021) 720

NTD+MMT search for HECOs & monopoles

- First analysis on *full* **NTD+MMT** detectors
- No HECO or monopole candidate tracks found in NTD scanning after etching
- No monopole candidates found in MMT SQUID analysis
- First MoEDAL analysis considering HECO production via photon fusion

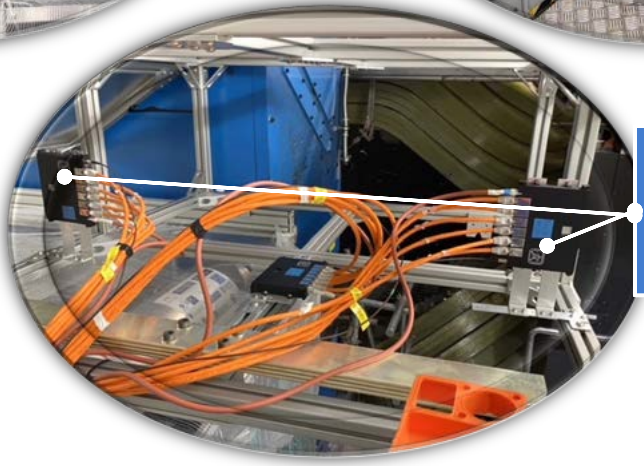




MoEDAL, arXiv:2311.06509 [hep-ex]

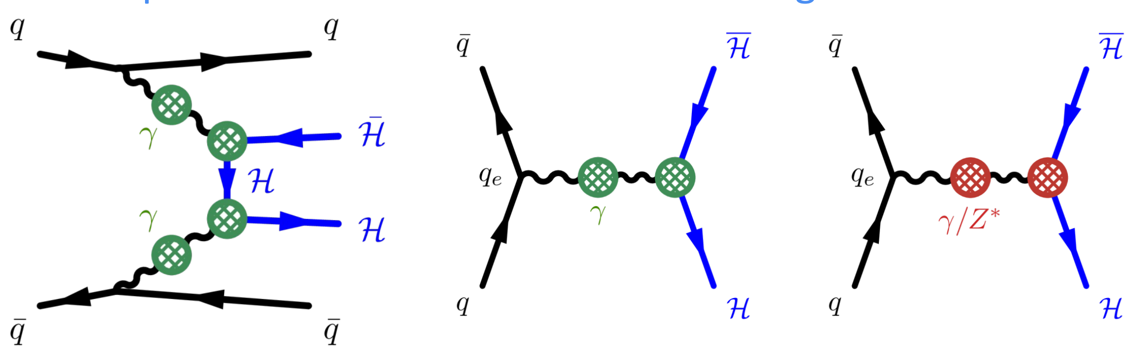
Upgraded MoEDAL installed for Run-3

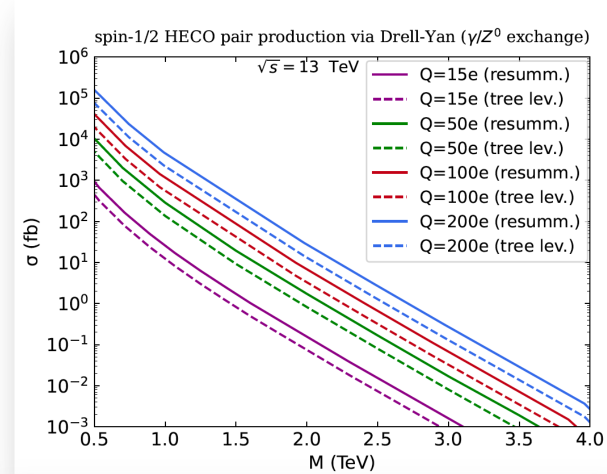
- Upgrades to Run-2 MoEDAL
- Completed in March 2023

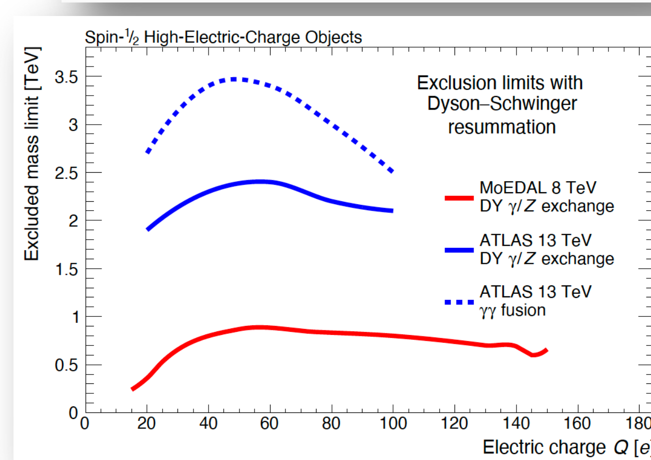


Resummation for large coupling constants

- Large photon-HIP coupling ⇒ perturbation theory breaks down
- **Dyson-Schwinger** resummation for spin-½ HECOs
  - HECO effective mass much larger than bare mass
  - estimated cross section increases with resummation
  - experimental mass bounds more stringent



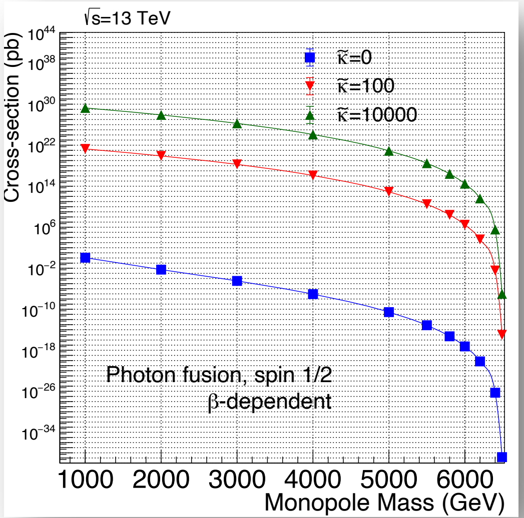




Alexandre, Mavromatos, VAM, Musumeci, Phys.Rev.D 109 (2024) 036026
Musumeci, PoS LHCP2023 (2024) 261

DS resummation for spin-0 HECOs

Photon fusion process

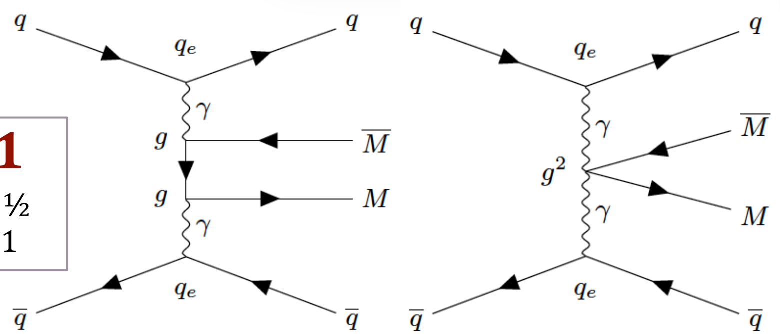


- Both photon fusion and Drell-Yan processes suffer from large γMM couplings making perturbative calculations problematic
- Situation may be resolved in photon fusion with
  - β-dependent photon-monopole coupling
  - magnetic-moment parameter κ
- Perturbative treatment may be guaranteed for
  - very slow monopoles, β → 0
  - parameter κ becomes very large, κ → ∞
  - condition for perturbative coupling:

$$g\kappa'\beta^2 < 1$$

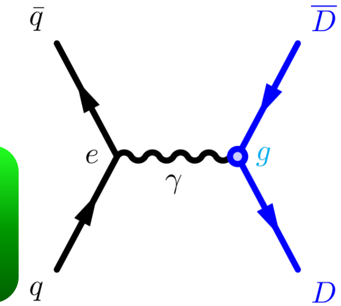
$$\kappa' = \begin{cases} \tilde{\kappa}, & \text{spin } 1/2 \\ \kappa, & \text{spin } 1 \end{cases}$$

- Cross section remains finite at this limit for photon fusion while it vanishes for Drell-Yan



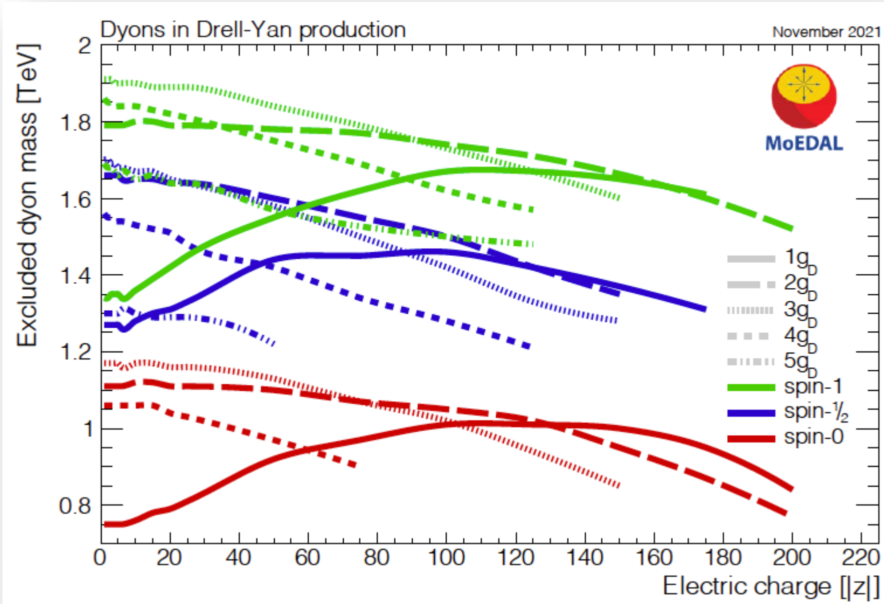
Baines, Mavromatos, VAM, Pinfold, Santra, Eur.Phys.J.C 78 (2018) 966

Dyons: electric & magnetic charge



- MMT scanning searching for captured dyons at 13 TeV
- Mass limits **750-1910 GeV** set for dyons with
  - up to five Dirac magnetic charges (**$5g_D$**)
  - electric charge ***1e – 200e***
- Excluded cross sections as low as **30 fb**
- Previous searches for highly ionising particles would, in principle, also have sensitivity to dyons
  - caution on behaviour under magnetic field

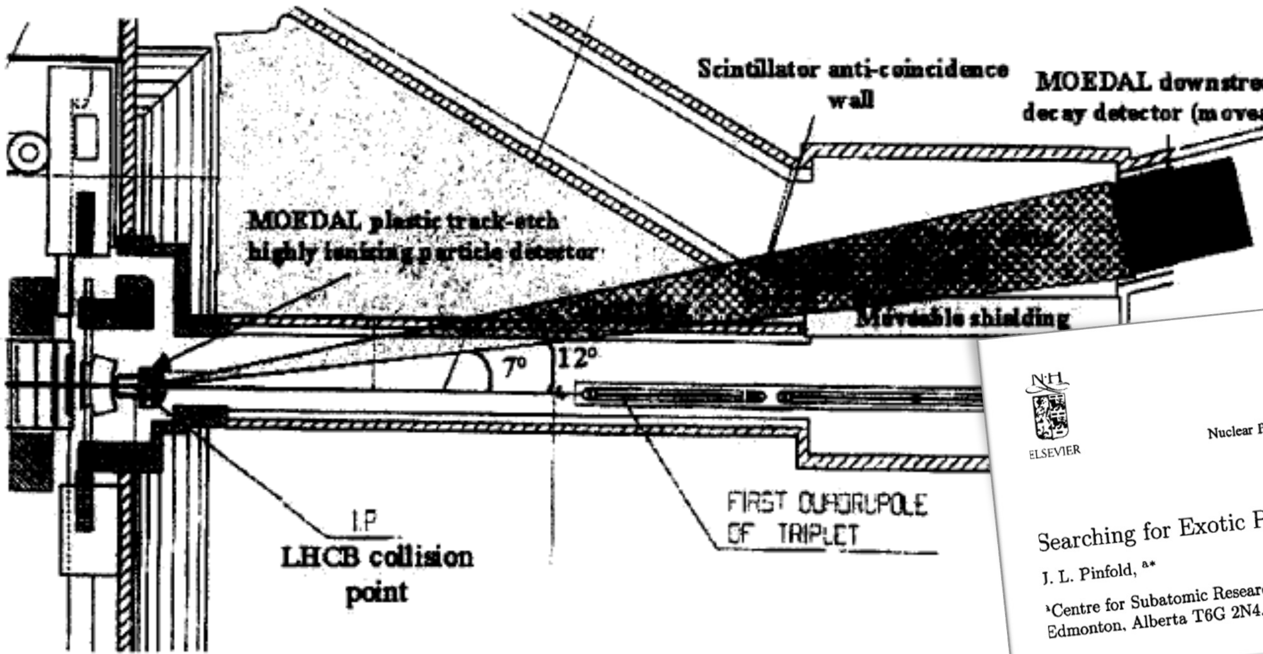
First explicit accelerator search for direct dyon production!



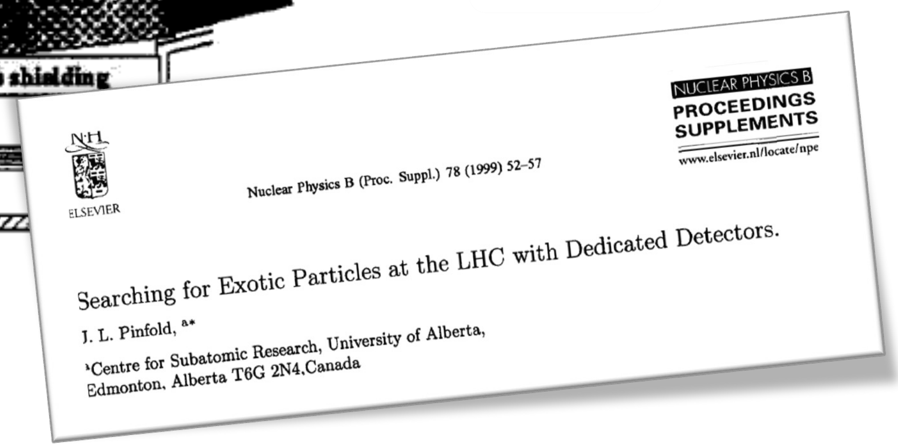
MoEDAL, Phys.Rev.Lett. 126 (2021) 071801

A little history...

- 1999: Original MoEDAL LoI for nominal MoEDAL detector also included a new downstream FIP detector
- 2021: MAPP receives approval from CERN Research Board



MAPP
MoEDAL


NUCLEAR PHYSICS B PROCEEDINGS SUPPLEMENTS

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Nuclear Physics B (Proc. Suppl.) 78 (1999) 52–57

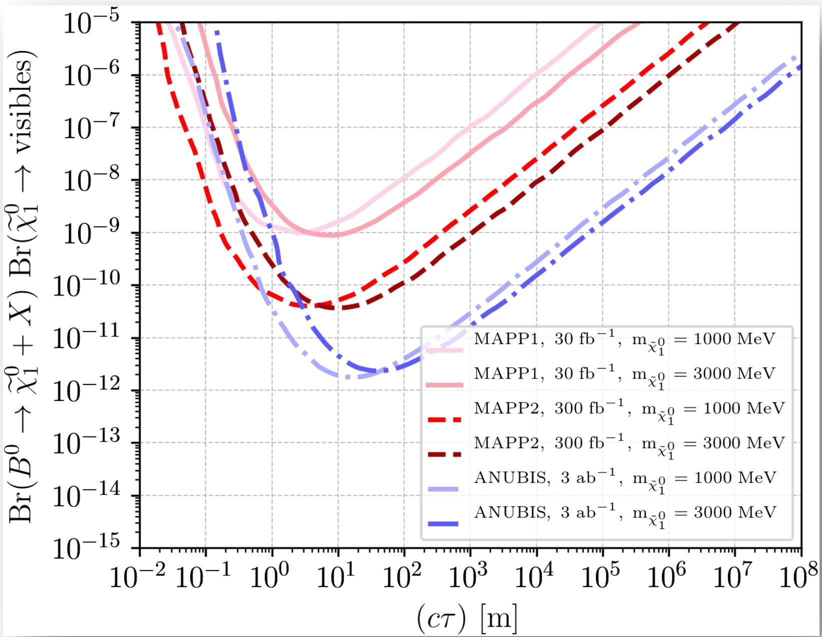
Searching for Exotic Particles at the LHC with Dedicated Detectors.

J. L. Pinfold, [a]*

[a]Centre for Subatomic Research, University of Alberta, Edmonton, Alberta T6G 2N4,Canada

R-parity violating (RPV) supersymmetry

If RPV coupling, λ, λ’, λ’’ small enough, the (N)LSP may be long lived



Dreiner, Günther, Wang, PRD 103 (2021) 075013

$\tilde{\chi}_1^0 \to$ charged

λ'_P for production	λ'_{131}
λ'_D for decay	λ'_{112}
Produced meson(s)	B^0, $\bar{B}^0$
Visible final state(s)	$K^\pm + e^\mp$, $K^{*\pm} + e^\mp$
Invisible final state(s) via λ'_P	None
Invisible final state(s) via λ'_D	$(K_L^0, K_S^0, K^*) + (\nu_e, \bar{\nu}_e)$

RPV couplings

Sensitivity of LLP experiments, such as MAPP, to sterile neutrinos recast to obtain bounds on RPV couplings associated with light neutralino

⬇️

improvement on current bounds on RPV couplings by up to 3–4 orders of magnitude

Dreiner, Köhler, Nangia, Schürmann, Wang, JHEP 08 (2023) 058