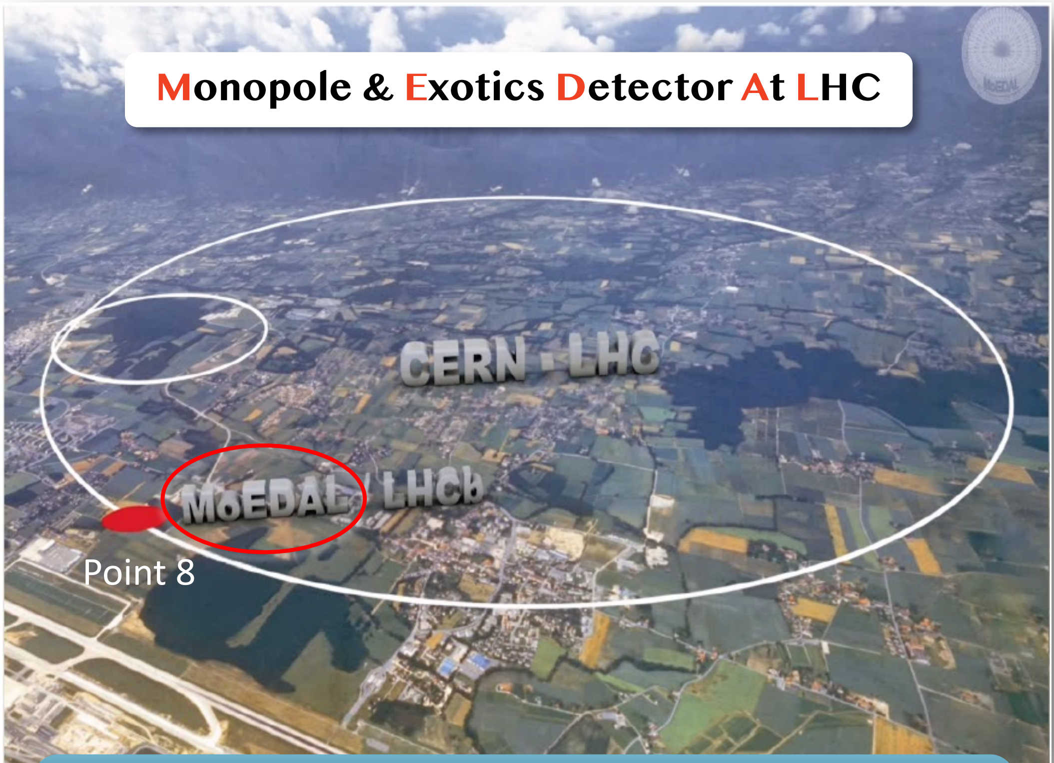
MoEDAL, MAPP and the lifetime frontier

Vasiliki A. Mitsou

for the MoEDAL Collaboration

SUSY-2022
29th International Conference on Supersymmetry and Unification of Fundamental Interactions
27 June – 2 July 2022, Ioannina, Greece

MoEDAL Collaboration



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

~70 physicists from 22 institutions

UNIVERSITY OF ALABAMA
UNIVERSITY OF ALBERTA
INFN & UNIVERSITY OF BOLOGNA
UNIVERSITY OF BRITISH COLUMBIA
UNIVERSITÉ DE GENÈVE
UNIVERSITY OF HELSINKI
UNIVERSITY OF MONTREAL
CERN
CONCORDIA UNIVERSITY
IMPERIAL COLLEGE LONDON
KING'S COLLEGE LONDON
NATIONAL INSTITUTE OF TECHNOLOGY, KURUKSETRA
TECHNICAL UNIVERSITY IN PRAGUE
QUEEN MARY UNIVERSITY OF LONDON
INSTITUTE OF SPACE SCIENCE, ROMANIA
INSTITUTE FOR RESEARCH IN SCHOOLS, CANTERBURY
CENTER FOR QUANTUM SPACETIME, SEOUL
TRACK ANALYSIS SYSTEMS Ltd, BRISTOL
TUFT'S UNIVERSITY
VAASA UNIVERSITIES
IFIC VALENCIA
UNIVERSITY OF VIRGINIA

MoEDAL

MoEDAL physics goals

- MoEDAL has pioneered the search for **long-lived particles**
  - complementary to ATLAS, CMS and LHCb
- MoEDAL is optimised for the detection of (meta)stable **highly ionising** particles
  - high charges (**high z**) ⇒ electric and/or magnetic charges
  - slow moving (**low β**) ⇒ massive

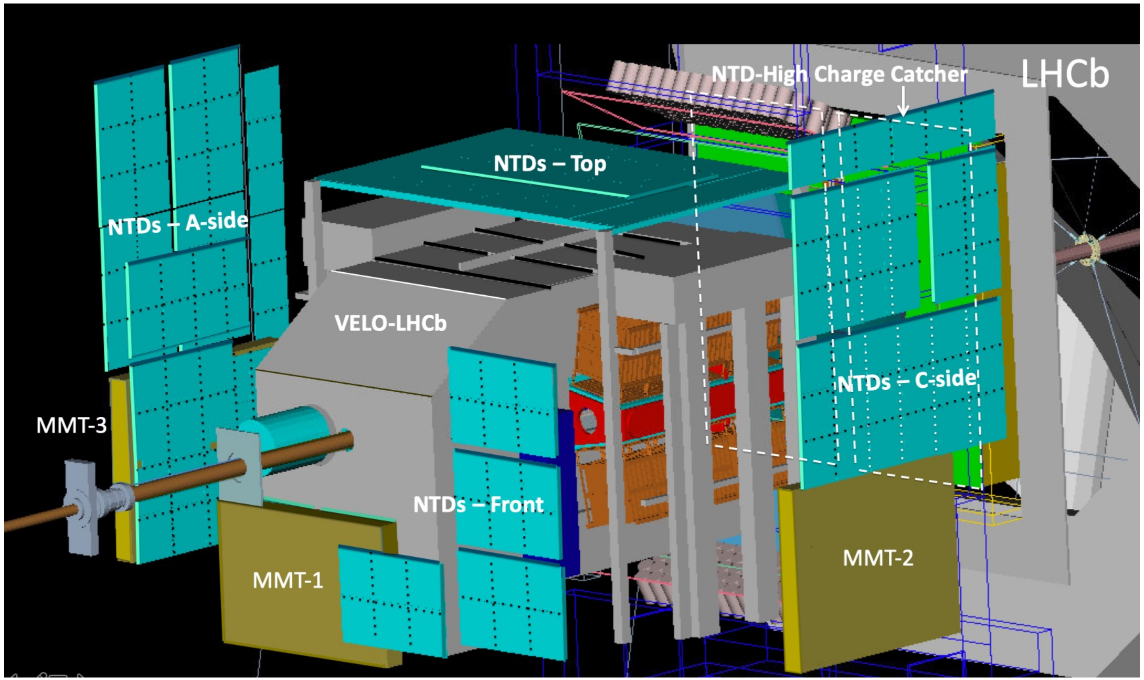
MoEDAL

ATLAS/CMS talks by Jeff Dandoy, Jackson Burzynski on Monday and Leonardo Rossi on Friday

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

Baseline MoEDAL detector

MoEDAL



DETECTOR SYSTEMS

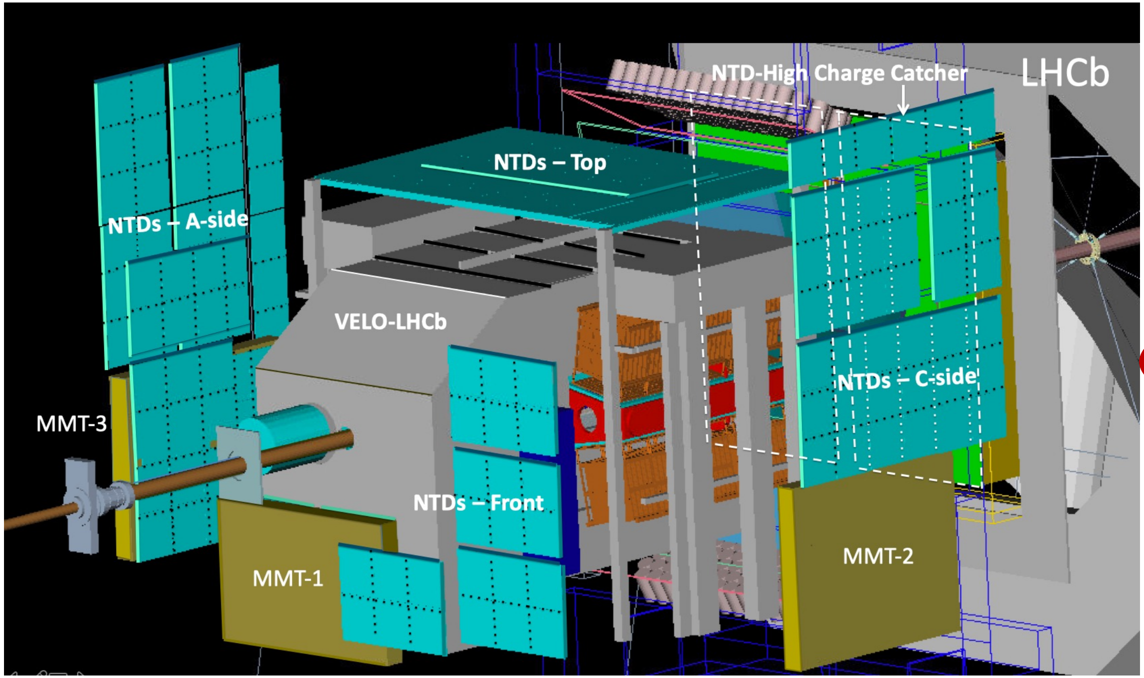
① Nuclear Track Detectors (**NTD**)

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

③ **TimePix** radiation background monitor

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

Baseline MoEDAL detector



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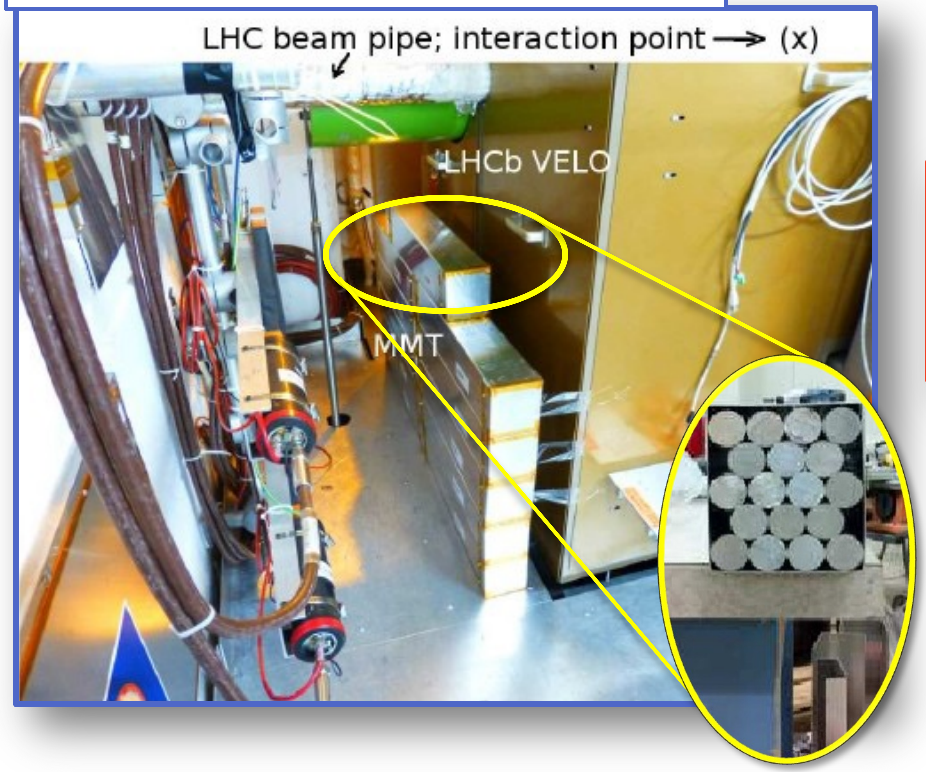
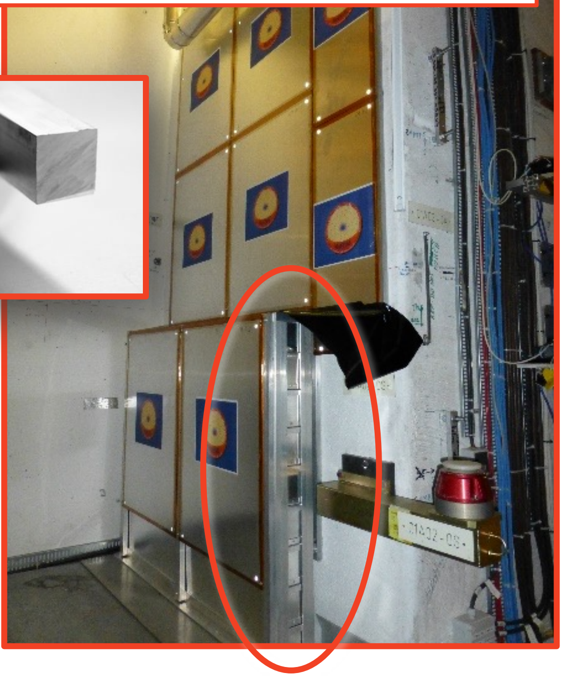
More on NTD in VAM's talk on Tuesday

MMTs deployment

2012
11 boxes each containing 18 Al rods of 60 cm length and 2.54 cm diameter (**160 kg**)

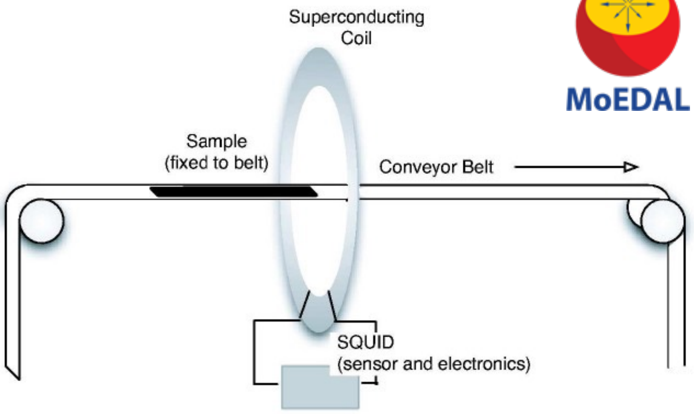


2015-2018
- Installed in forward region under beam pipe & in **sides A & C**
- Approximately **800 kg** of aluminium
- Total 2400 aluminum bars

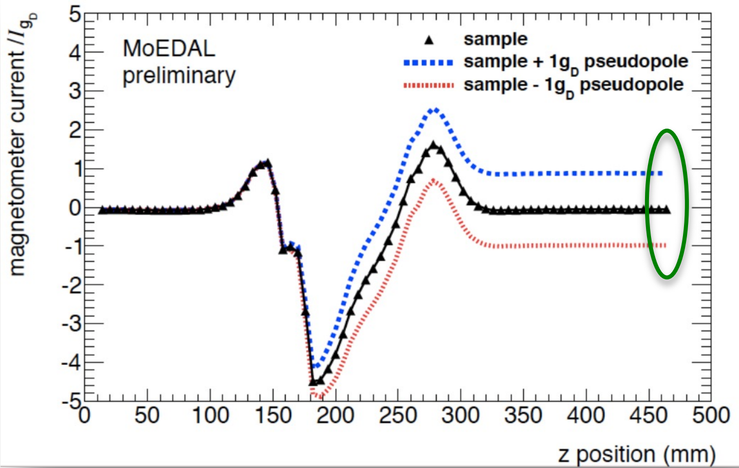


MMT scanning

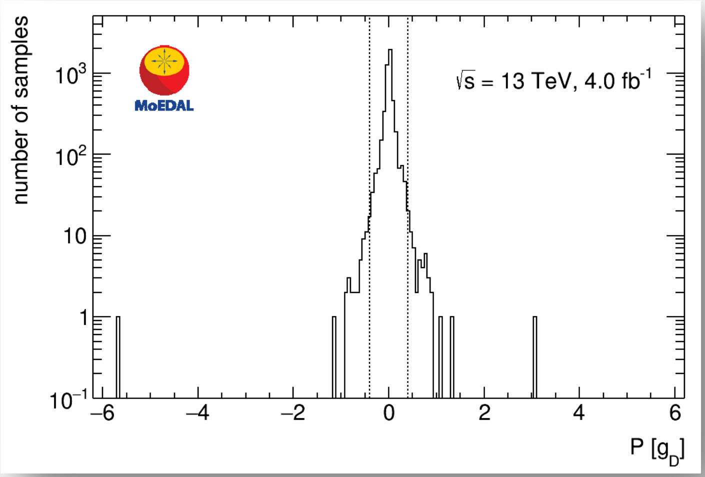
- Monopoles can bind to nuclei and get trapped
- MMTs analysed in superconducting quantum interference device (SQUID) at ETH Zurich
- **Persistent current:** difference between resulting current after and before
- Outliers are **scanned several times** further



Calibration: Typical sample & pseudo-monopole curves

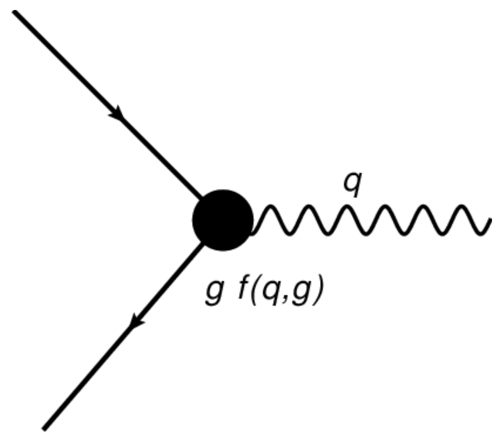


SQUID analysis – Persistent current after first two passages for all samples



MoEDAL, PRL 123 (2019) 021802

Magnetic monopoles in a nutshell



- Why? Because they symmetrise Maxwell's equations
  - electric ↔ magnetic charge duality
- Single magnetic charge (Dirac charge): $g_D = 68.5e$
  - higher charges are integer multiples of Dirac charge: $g = ng_D$, $n = 1, 2, \ldots$
  - if carries electric charge as well, is called **Dyon**
- 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 exponentially suppressed by $e^{-4/\alpha}$
- Monopole spin is not determined by theory → free parameter
- Monopole mass not theoretically fixed → free parameter

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

Results

MoEDAL

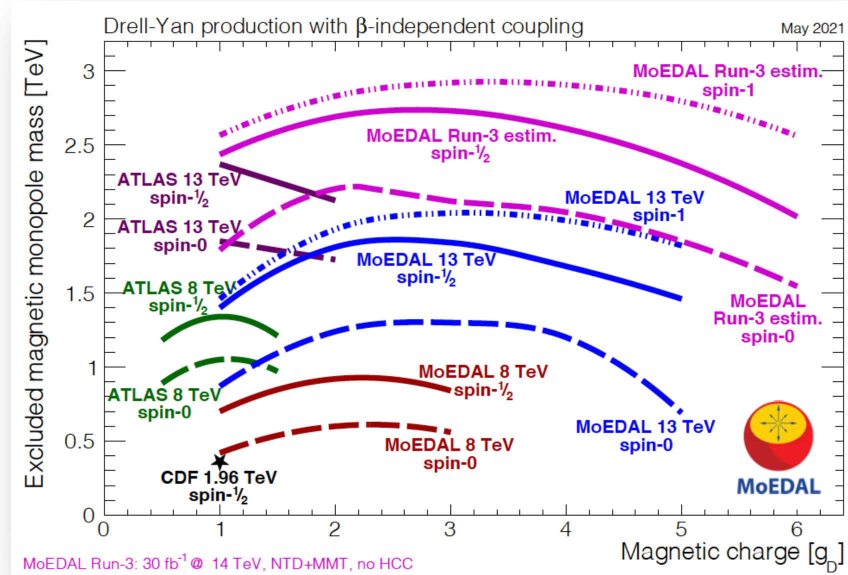
- 2016 – **First monopole results @ 8 TeV** ☛ *CERN Press Release*
  JHEP 1608 (2016) 067 [arXiv:1604.06645]
- 2017 – **First monopole results @ 13 TeV** Phys.Rev.Lett. 118 (2017) 061801 [arXiv:1611.06817]
- 2018 – **MMT results** Phys.Lett.B 782 (2018) 510–516 [arXiv:1712.09849]
  - **spin-1 monopoles ← 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]

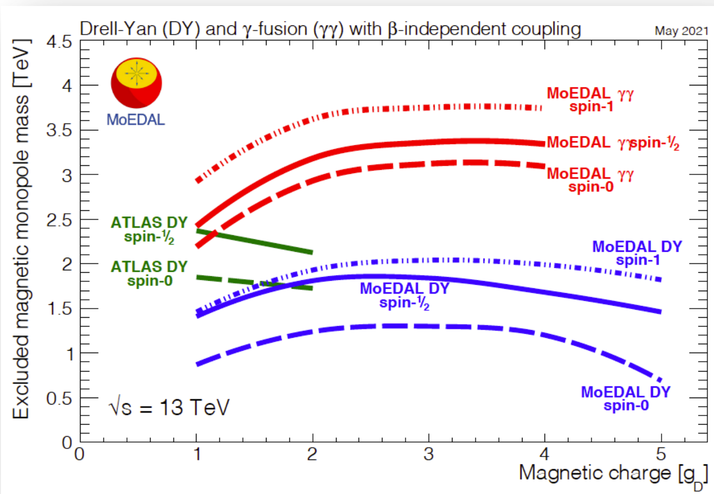
- 2021 – **Schwinger thermal production ← FIRST**
  Nature 602 (2022) 7895, 63 [arXiv:2106.11933]
- 2021 – **NTD & MMT combination ← FIRST NTD analysis** arXiv:2112.05806
  - First limits in highly electrically charged objects

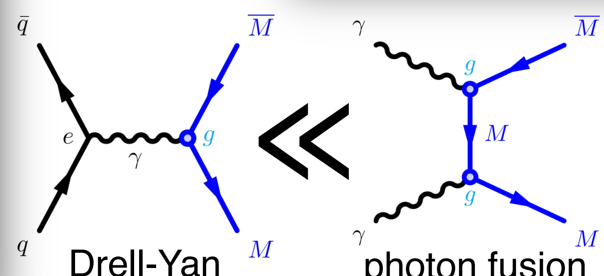
VAM's talk on Tuesday

Magnetic monopole limits

- Novelties in monopole models: β-dependent coupling, spin-1 monopoles, γγ fusion
- MoEDAL set world-best collider limits for **|g| > 2 g_D**
- Overall, MoEDAL achieved extended reach by **combining Drell-Yan and γ-fusion mechanisms**







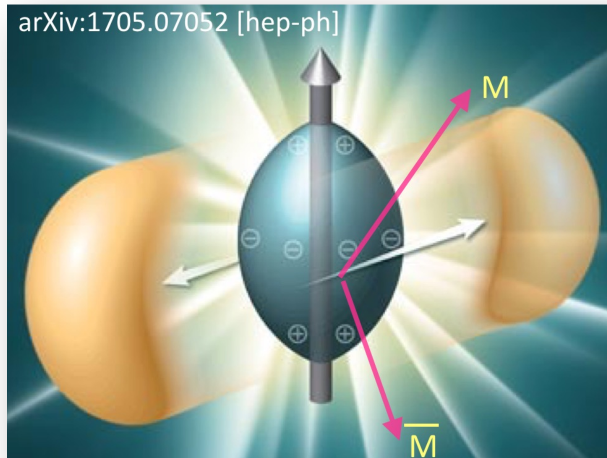
MoEDAL, JHEP 1608 (2016) 067, PRL 118 (2017) 061801, PLB 782 (2018) 510, PRL 123 (2019) 021802, PRL 126 (2021) 071801

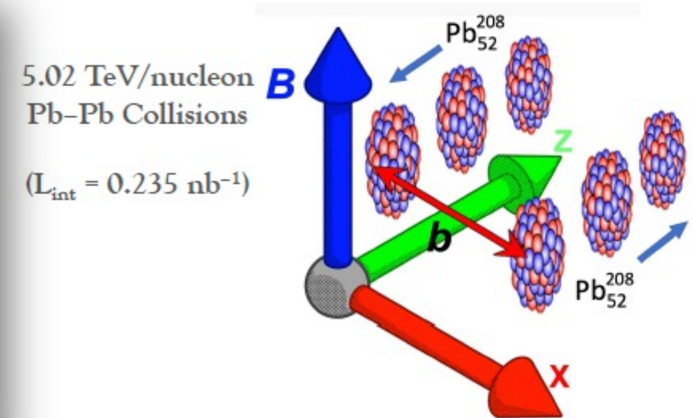
See also, Baines, Mavromatos, VAM, Pinfold, Santra, Eur.Phys.J.C 78 (2018) 966

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

Monopoles via thermal Schwinger mechanism

Monopole-antimonopole pairs may be produced in strong magnetic fields present in heavy-ion collisions





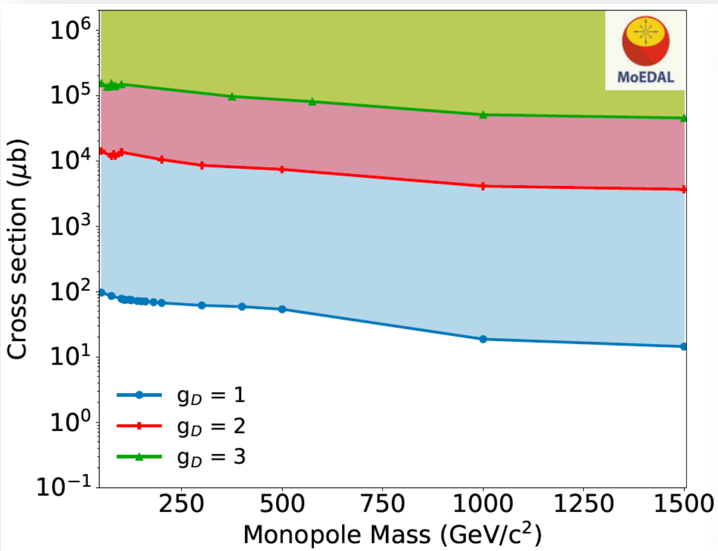
Advantages over DY & γγ-fusion production

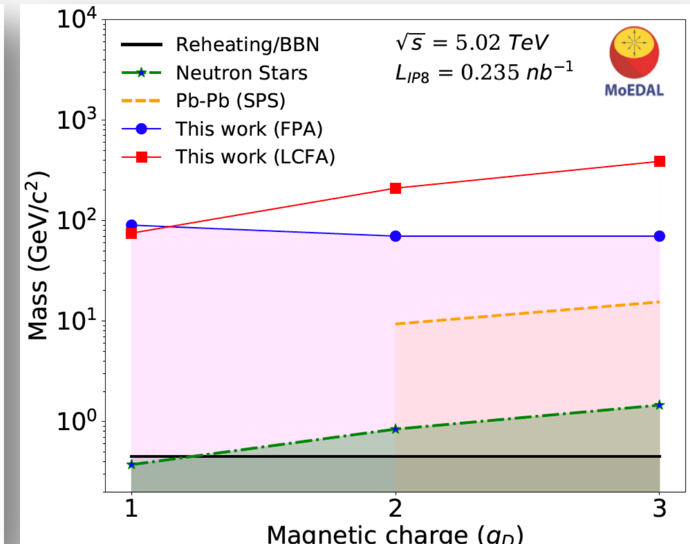
- cross-section calculation using semiclassical techniques ⇒ does not suffer from non-perturbative nature of coupling
- no exponential suppression $e^{-4/\alpha}$ for finite-sized monopoles

Gould, Ho, Rajantie, PRD 100, 015041 (2019), arXiv:2103.14454
Ho & Rajantie, PRD 101, 055003 (2020), PRD 103 (2021) 11, 115033

Schwinger production results

- Exposure of MMTs in 0.235 nb^{-1} of Pb-Pb heavy-ion collisions at 5.02 TeV per nucleon
- Limits on monopoles of 1 – 3 g_D and masses up to 75 GeV
- First limits from collider experiment based on non-perturbative calculation of monopole production cross section
- First direct search sensitive to monopoles that are not point-like

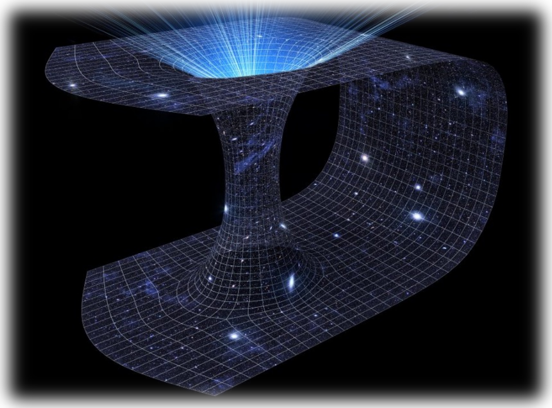




Monopole mass reach appears to be 20–30 times lower than current bounds from ATLAS and MoEDAL, however, this cross-section calculation is theoretically sound

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

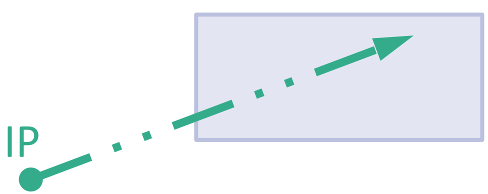
MAPP – Sensitivity to portal models



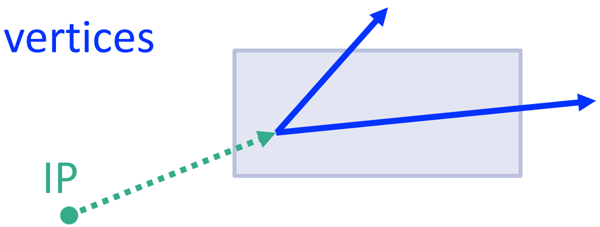
Credit: General Electric

MAPP – MoEDAL Apparatus for Penetrating Particles

MAPP-mQP: sensitive to low ionisation induced by *millicharged* particles (**mCPs**), i.e. particles with charges $\ll 1e$



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



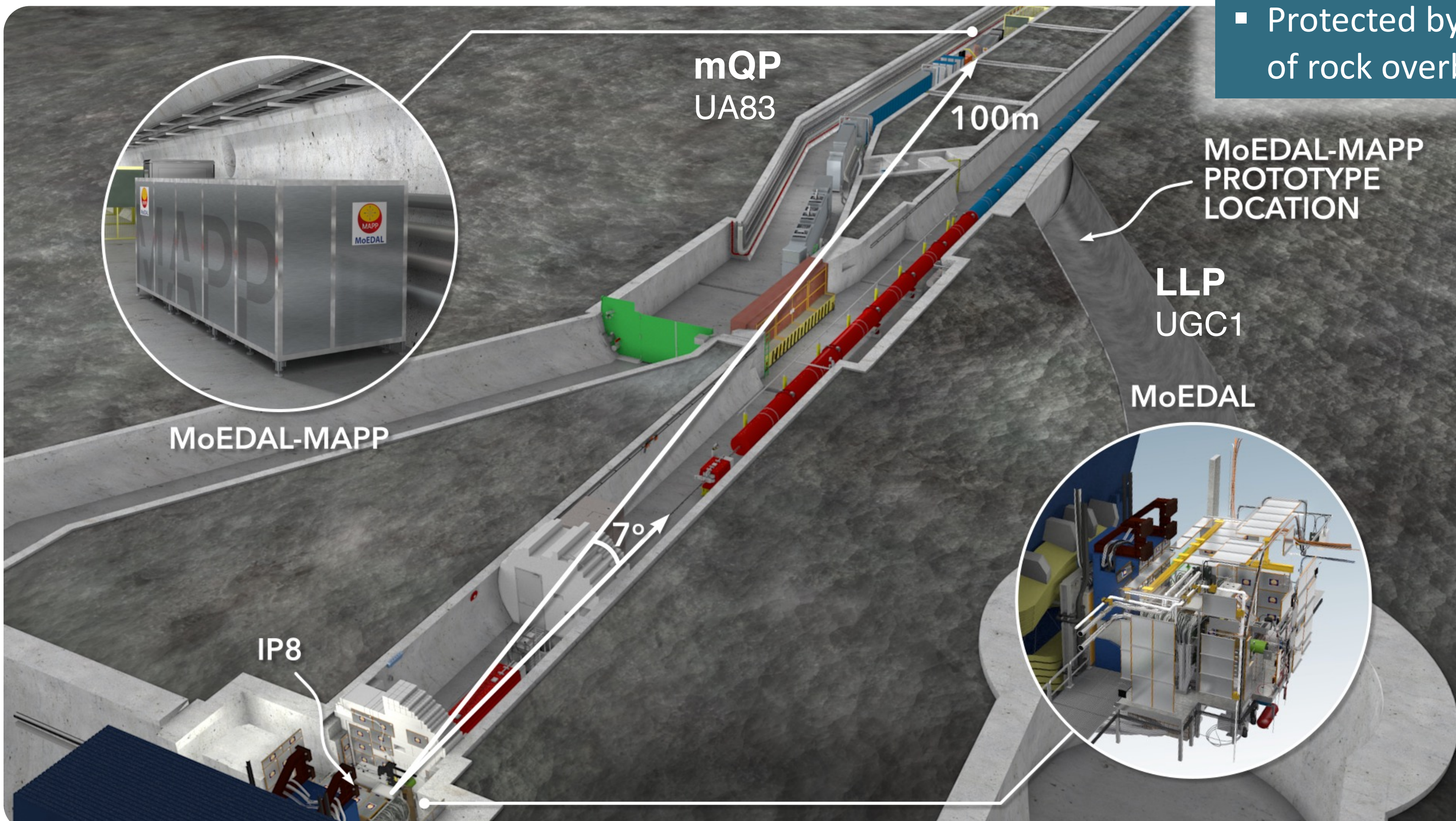
- Phase-1 ***approved*** *by CERN Research Board* on Dec 1st 2021
- **Phase-1** for **Run-3** (2022–2025): **MAPP-mQP** installation in UA83 is underway
  - start taking data in 2023
- **Phase-2 HL-LHC** (2029 –): Reinstall Phase-1 in UA83 and add **MAPP-LLP** in UGC1

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

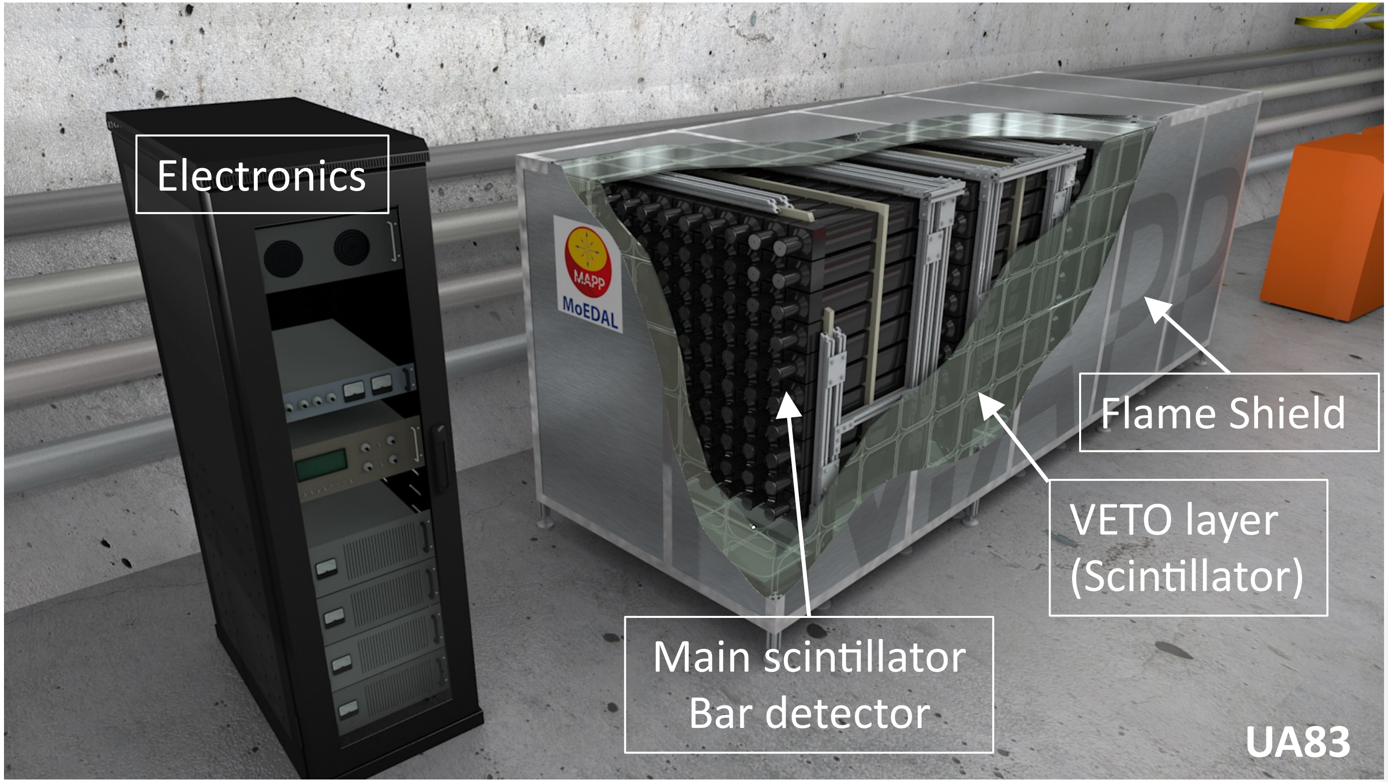
Pinfold,
Phil.Trans.Roy.Soc.Lond.A 377 (2019) 20190382

MAPP location

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



MAPP-mQP Phase-1 detector concept



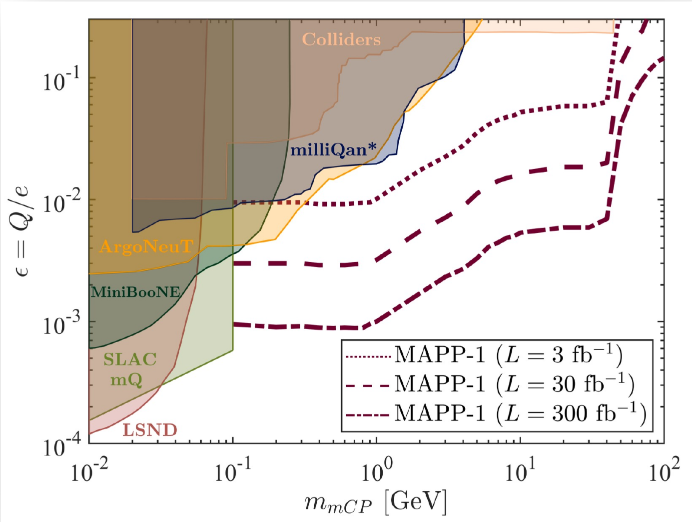
- 400 scintillator bars (10×10×75 cm^3) in 4 sections readout by PMTs
- Protected by a hermetic VETO counter system

Prototype mQP in 2017 in UGC1 gallery

MAPP-mQP Phase-1 installation

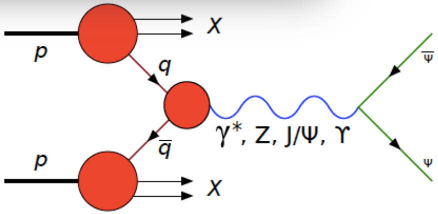
mQP & millicharged particles (mCPs)

Dark photon decays to mCPs

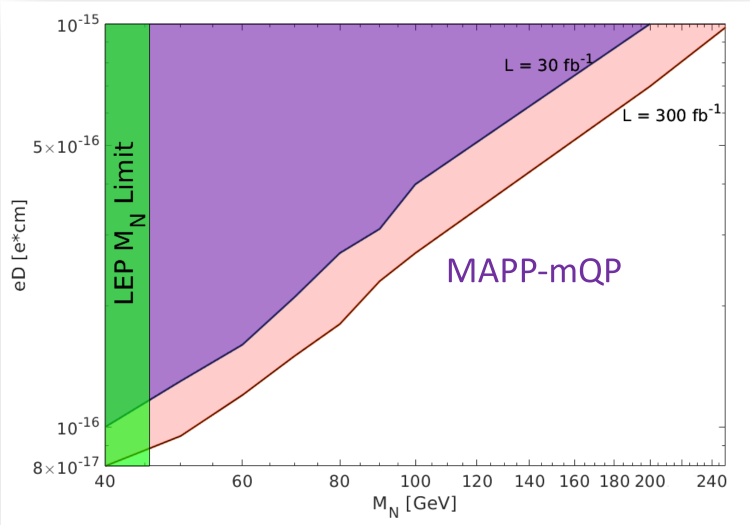


M. Staelens, PhD thesis, U.Alberta, DOI: 10.7939/r3-g8yh-hv16 (2021)

Run-3 sensitivity for dark-photon decays to mCP dark fermions ψ



Heavy neutrino with large EDM

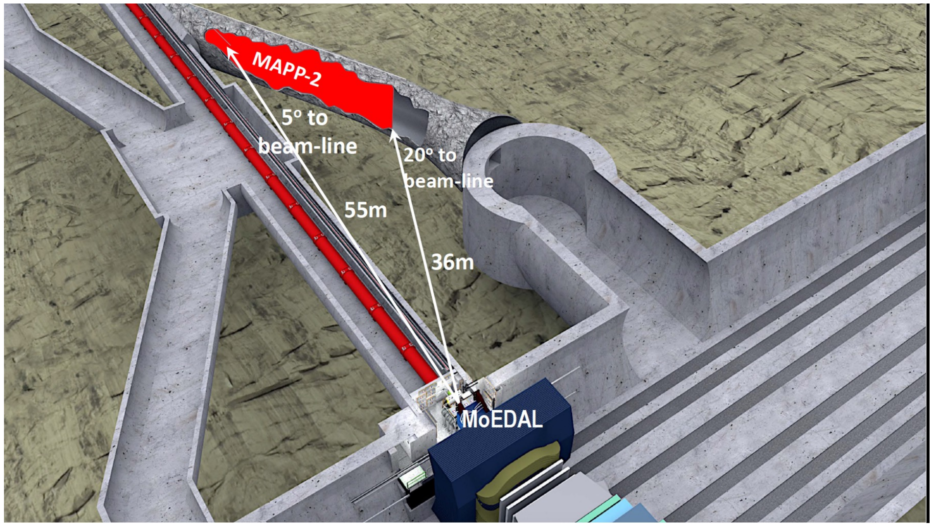


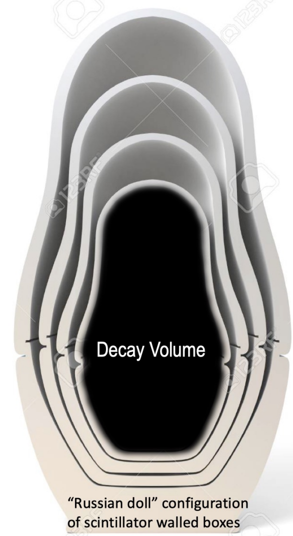
Frank et al, Phys.Lett.B 802 (2020) 135204

Limits that MAPP can place on heavy neutrino production with large EDM at Run-3 and HL-LHC at IP8

See also Pran Nath's talk on Saturday

Phase-2: MAPP-2 for HL-LHC

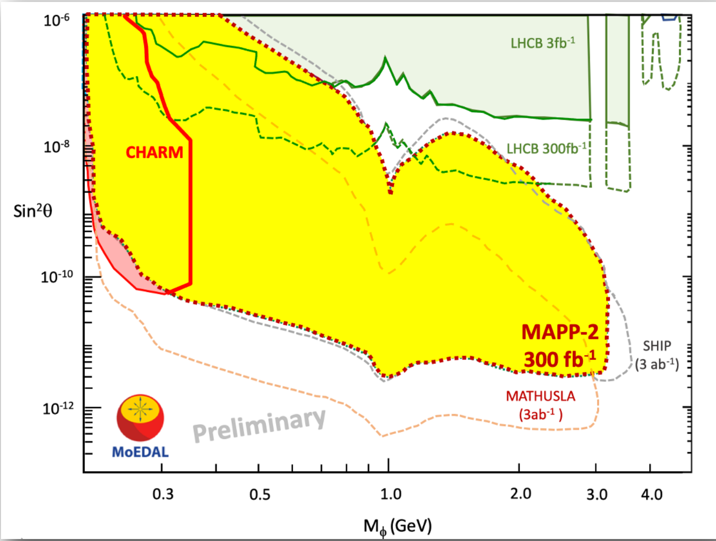




- The UGC1 gallery will be prepared during Long Shutdown 3 prior to HL-LHC
- MAPP-2 detector extends to the full length of the UGC1 gallery
- Detector technology: large scintillator tiles with x-y wavelength shifting optical fibre readout with resolution $\lesssim$ 1cm/measurement
- Tracking detectors formed by 3 or 4 hermetic containers – one within the other – lining UGC1 walls

MAPP-LLP – dark matter & heavy neutrinos

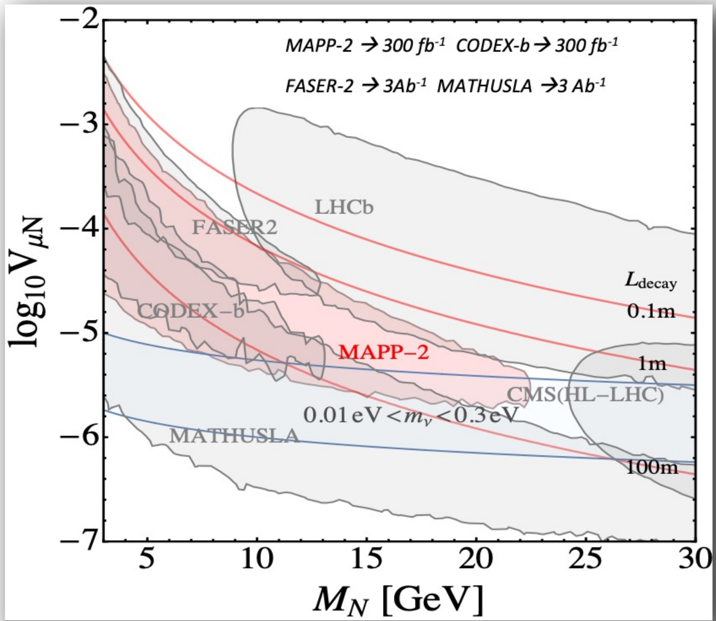
Dark Higgs scenario



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

adopted from Phys.Rev.D 97 (2018) 015023

Heavy neutrino via *Z′* production



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

adopted from Phys.Rev.D 100 (2019) 035005

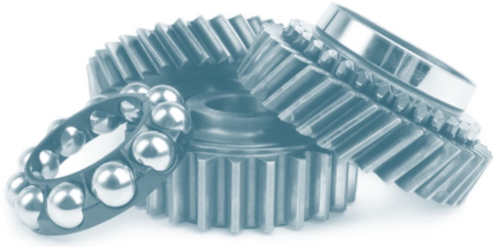
Summary & outlook

- MoEDAL pioneered searches for **long-lived particles**
- Exciting results so far
  - sole contender in **high magnetic charges**
  - sole **dyon** search in accelerator experiment
  - first search for monopoles produced via **Schwinger mechanism**
  - entered the arena of ***electrically* charged particles**
- Upcoming results
  - CMS beam pipe analysis ➜ constrain very high magnetic charges
  - Second NTD analysis ➜ improved sensitivity to electric charges
- Future perspectives
  - MoEDAL baseline redeployed for **Run-3** and planned to operate during **HL-LHC**
  - MAPP will extend reach to **millicharged** particles, **neutral long-lived particles**
    ➜ dark sectors, neutrino portals, SUSY, ...

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

Thank you for your attention!

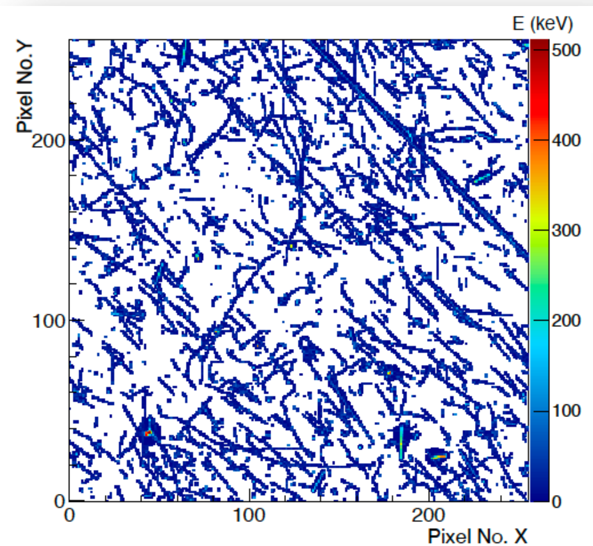
Spares



3 TimePix radiation monitor

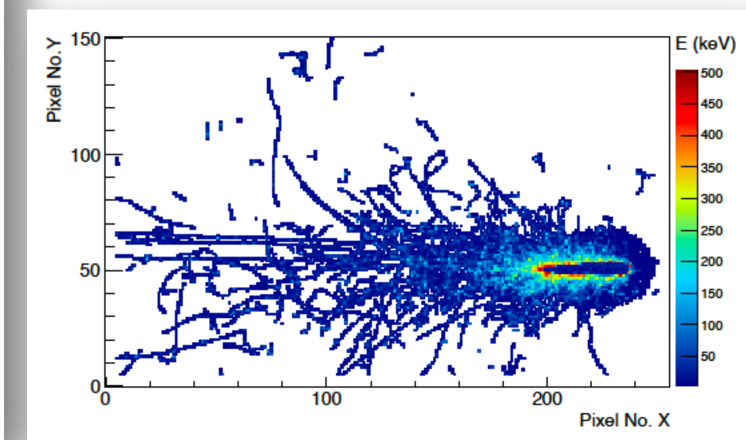
- Timepix chips used to measure online the radiation field and monitor spallation product background
- Essentially act as little electronic “bubble-chambers”
- The only active element in MoEDAL

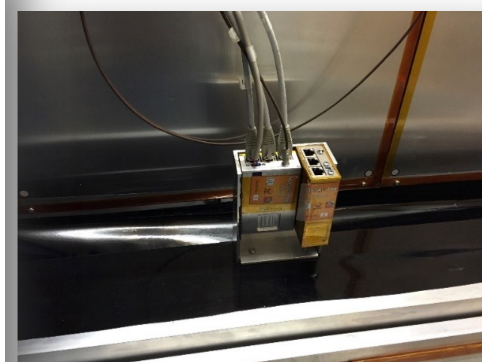
- 256×256 pixel with 55 μm pitch
- Time-of-interaction precision 1.56 ns
- 3D track reconstruction
- Energy deposition measured via time-over-threshold
- Particle ID through *dE/dx*



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

330 GeV Pb-ion measured at the SPS



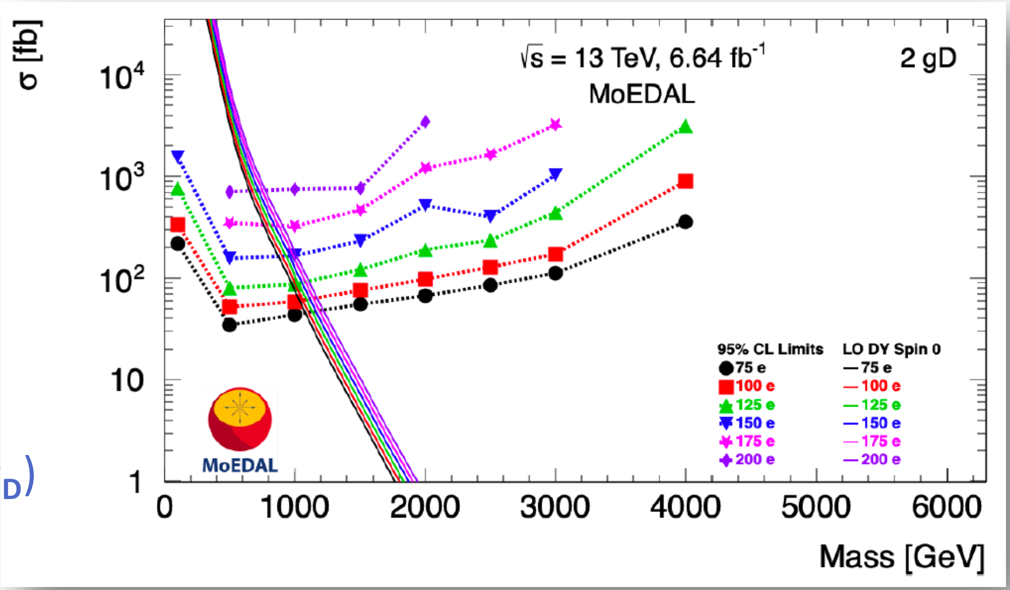


MoEDAL, PoS ICHEP2020 (2021) 720

Dyon search

First explicit accelerator search for direct dyon production

- Dyons possess both electric and magnetic charge
- MMT scanning searching for captured dyons
  - 6.46 fb^{-1} of 13 TeV *pp* collisions during 2015-2018
- Analysis considered
  - dyons of spin 0, ½, 1
  - Drell-Yan production
- Excluded cross sections as low as **30 fb**
- Mass limits **750-1910 GeV** were set for dyons with
  - up to 5 Dirac magnetic charges (**$5g_D$**)
  - electric charge **1e – 200e**



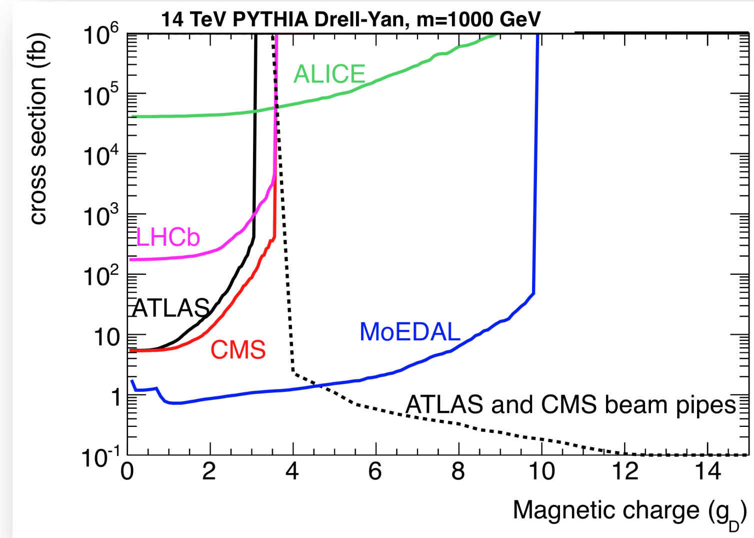
MoEDAL, Phys.Rev.Lett. 126 (2021) 071801 [arXiv:2002.00861]

CMS beam pipe

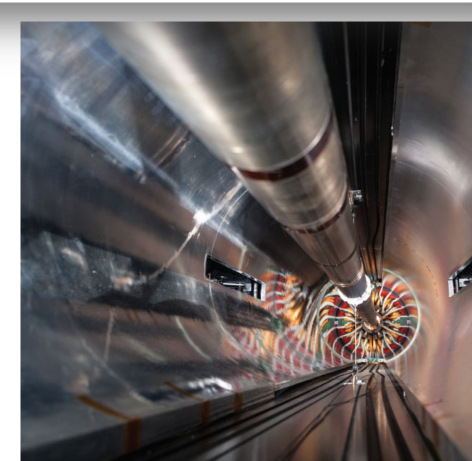
Beam pipe
- most directly exposed piece of material
- covers very high magnetic charges

- **1990's:** materials from CDF, D0 (Tevatron) and H1 (HERA) subject to SQUID scans for trapped monopoles
- **2012:** first pieces of CMS beam pipe tested [EPJC72 (2012) 2212]; far from collision point
- **Feb 2019:** CMS officially transfers ownership of the Run-1 CMS beam pipe to MoEDAL

Beam pipe scanned with SQUID at ETH Zurich.
Results to be released soon



De Roeck et al, EPJC72 (2012) 1985



CERN Courier, Mar-Apr 2019

MoEDAL physics goals

- MoEDAL has pioneered the search for **long-lived particles**
  - complementary to ATLAS, CMS and LHCb
- MoEDAL optimised for detection of meta-stable **highly ionising** particles (HIPs)
  - → high charges (**high z**) ⇒ electric and/or magnetic charges
  - → slow moving (**low β**) ⇒ massive particles

Bethe-Bloch formula

$$-\frac{dE}{dx} = Kz^2\frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_ec^2\beta^2\gamma^2T_{\max}}{I^2} - \beta^2 - \frac{\delta}{2}\right]$$

Figure of merit for large energy loss: ***z/β***

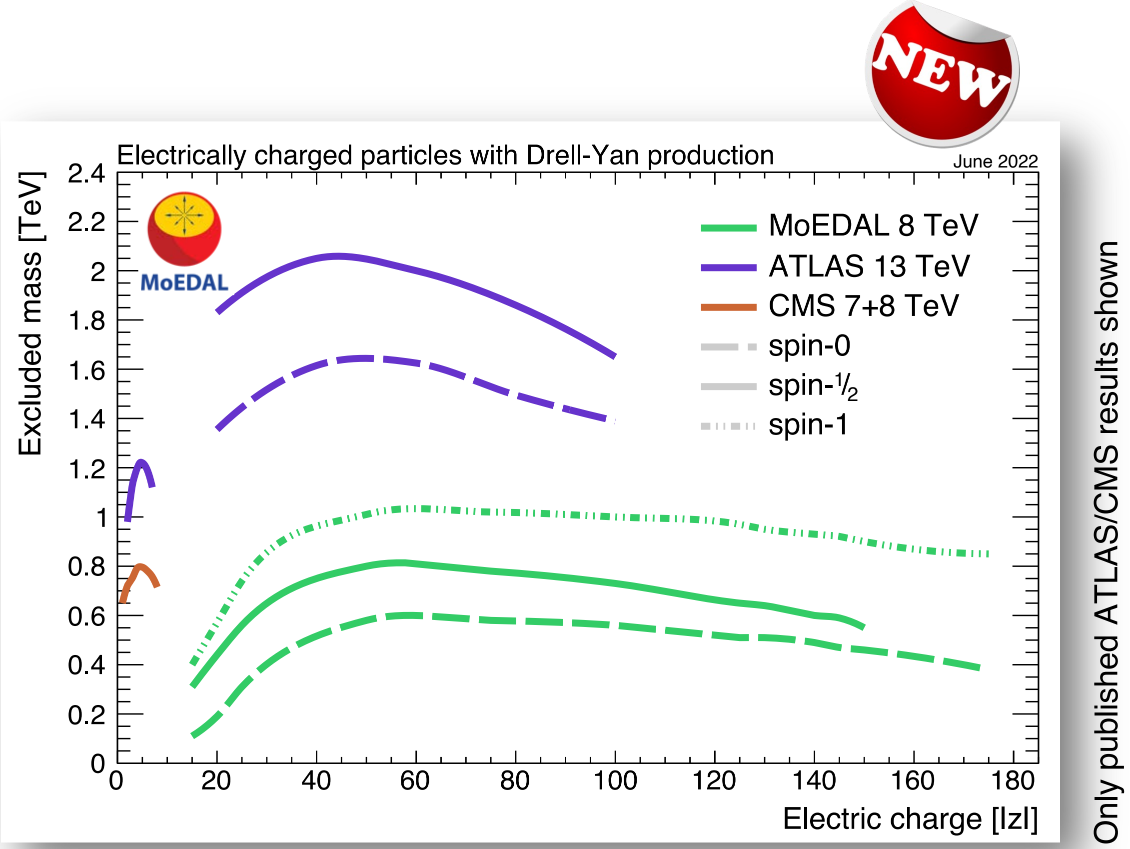
MoEDAL NTDs have a threshold as low as ***z/β* = 5**

MoEDAL

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

HECOs summary

- MoEDAL set limits on HECOs with electric charges in the range **15*e* – 175*e*** and masses from **110 – 1020 GeV**
- In comparison, ATLAS has set limits on HECOs of **20*e* – 100*e*** [PRL 124, 031802 (2020)]

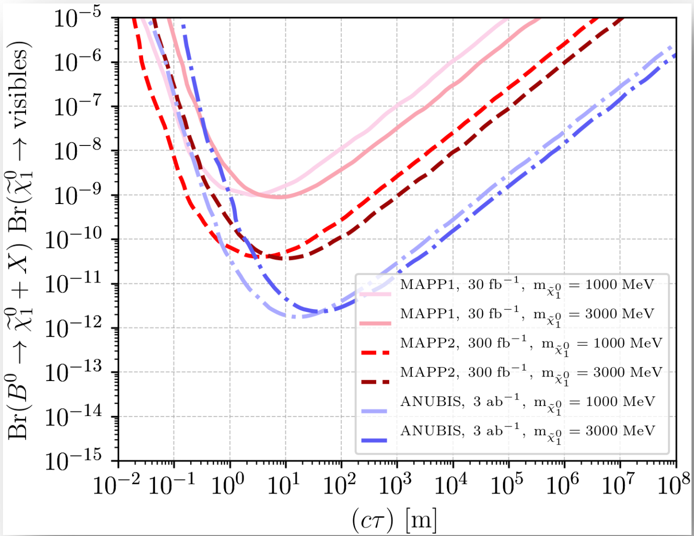


MoEDAL HECOs limits are the strongest to date, in terms of charge, at any collider experiment

MAPP-LLP – physics potential

R-parity violating SUSY

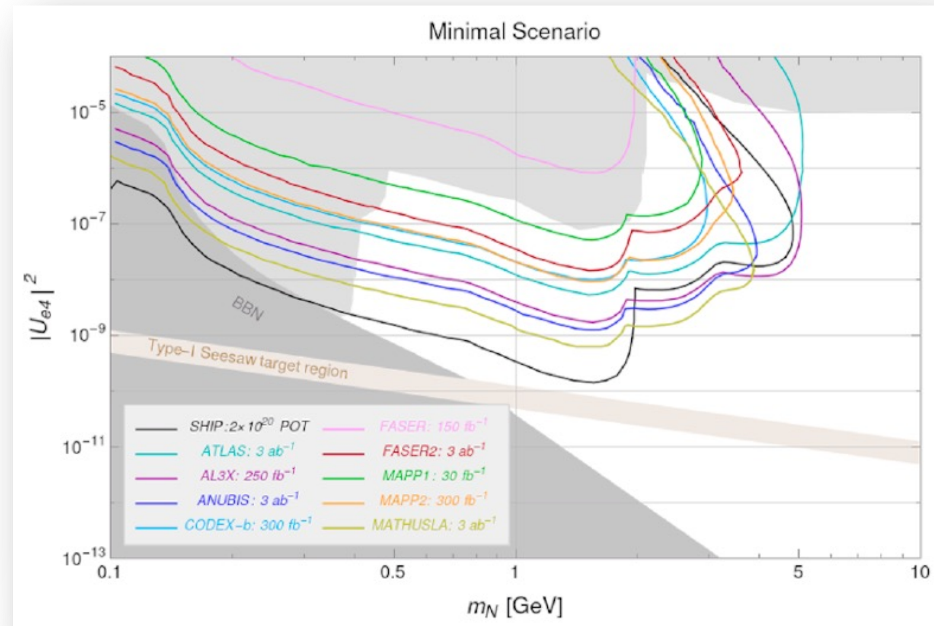
Dreiner, Günther, Wang, Phys.Rev.D 103 (2021) 075013



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 (λ'_{131}, λ'_{112})

Sterile neutrinos

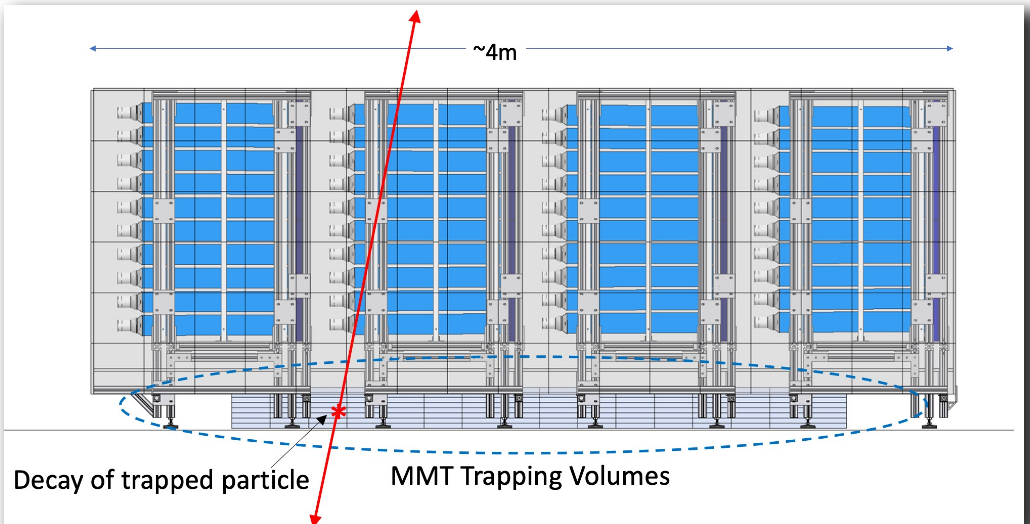


Minimal scenario: interactions purely mediated by *W*- and *Z*-bosons via active-sterile neutrino mixing

De Vries, Dreiner, Günther, Wang, Zhou, JHEP 03 (2021) 148

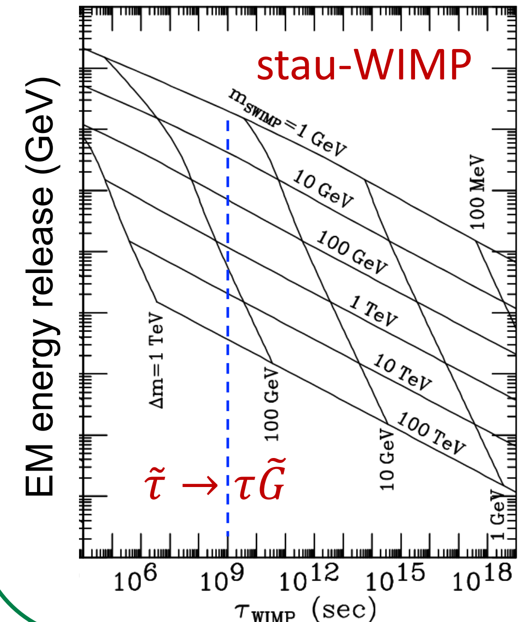
MAPP, MMT and extremely long lived particles

- After exposure and SQUID scan, MMTs to be monitored for decaying *electrically charged* particles possibly trapped in their volume
  - MMTs to be placed under MAPP
  - sensitive to charged particles (e, μ, hadrons) and photons
- Estimated probed lifetimes **~10 yrs**



J. Pinfold, Universe 5 (2019) no.2, 47

- **SuperWIMP model for cold dark matter, WIMP → SM + SWIMP**
- SuperWIMP particles may explain the observed lithium under-abundance



Feng, Rajaraman, Takayama, Phys. Rev. D 68, 063504 (2003)